
The ITK Software Guide
Book 1: Introduction and Development
Guidelines
Fourth Edition
Updated for ITK version 5.4.6

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<https://itk.org>
<https://discourse.itk.org/>



The purpose of computing is Insight, not numbers.

Richard Hamming

ABSTRACT

The National Library of Medicine Insight Segmentation and Registration Toolkit, shortened as the Insight Toolkit ([ITK](#)), is an open-source software toolkit for performing registration and segmentation. *Segmentation* is the process of identifying and classifying data found in a digitally sampled representation. Typically the sampled representation is an image acquired from such medical instrumentation as CT or MRI scanners. *Registration* is the task of aligning or developing correspondences between data. For example, in the medical environment, a CT scan may be aligned with a MRI scan in order to combine the information contained in both.

ITK is a cross-platform software. It uses a build environment known as [CMake](#) to manage platform-specific project generation and compilation process in a platform-independent way. ITK is implemented in C++. ITK's implementation style employs generic programming, which involves the use of templates to generate, at compile-time, code that can be applied *generically* to any class or data-type that supports the operations used by the template. The use of C++ templating means that the code is highly efficient and many issues are discovered at compile-time, rather than at run-time during program execution. It also means that many of ITK's algorithms can be applied to arbitrary spatial dimensions and pixel types.

An automated wrapping system integrated with ITK generates an interface between C++ and a high-level programming language [Python](#). This enables rapid prototyping and faster exploration of ideas by shortening the edit-compile-execute cycle. In addition to automated wrapping, the [SimpleITK](#) project provides a streamlined interface to ITK that is available for C++, Python, Java, CSharp, R, Tcl and Ruby.

Developers from around the world can use, debug, maintain, and extend the software because ITK is an open-source project. ITK uses a model of software development known as Extreme Programming. Extreme Programming collapses the usual software development methodology into a simultaneous iterative process of design-implement-test-release. The key features of Extreme Programming are communication and testing. Communication among the members of the ITK community is what helps manage the rapid evolution of the software. Testing is what keeps the software stable. An extensive testing process supported by the system known as [CDash](#) measures the quality of ITK

code on a daily basis. The ITK Testing Dashboard is updated continuously, reflecting the quality of the code at any moment.

The most recent version of this document is available online at <https://itk.org/ItkSoftwareGuide.pdf>. This book is a guide for developing software with ITK; it is the first of two companion books. This book covers building and installation, general architecture and design, as well as the process of contributing in the ITK community. The second book covers detailed design and functionality for reading and writing images, filtering, registration, segmentation, and performing statistical analysis.

CONTRIBUTORS

The Insight Toolkit ([ITK](https://itk.org)) has been created by the efforts of many talented individuals and prestigious organizations. It is also due in great part to the vision of the program established by Dr. Terry Yoo and Dr. Michael Ackerman at the National Library of Medicine.

This book lists a few of these contributors in the following paragraphs. Not all developers of ITK are credited here, so please visit the Web pages at <https://itk.org/ITK/project/parti.html> for the names of additional contributors, as well as checking the GIT source logs for code contributions.

The following is a brief description of the contributors to this software guide and their contributions.

Luis Ibáñez is principal author of this text. He assisted in the design and layout of the text, implemented the bulk of the $\LaTeX$ and CMake build process, and was responsible for the bulk of the content. He also developed most of the example code found in the `Insight/Examples` directory.

Will Schroeder helped design and establish the organization of this text and the `Insight/Examples` directory. He is principal content editor, and has authored several chapters.

Lydia Ng authored the description for the registration framework and its components, the section on the multiresolution framework, and the section on deformable registration methods. She also edited the section on the resampling image filter and the sections on various level set segmentation algorithms.

Joshua Cates authored the iterators chapter and the text and examples describing watershed segmentation. He also co-authored the level-set segmentation material.

Jisung Kim authored the chapter on the statistics framework.

Julien Jomier contributed the chapter on spatial objects and examples on model-based registration using spatial objects.

Karthik Krishnan reconfigured the process for automatically generating images from all the examples. Added a large number of new examples and updated the Filtering and Segmentation chapters

for the second edition.

Stephen Aylward contributed material describing spatial objects and their application.

Tessa Sundaram contributed the section on deformable registration using the finite element method.

Mark Foskey contributed the examples on the `itk::AutomaticTopologyMeshSource` class.

Mathieu Malaterre contributed the entire section on the description and use of DICOM readers and writers based on the GDCM library. He also contributed an example on the use of the `VTKImageIO` class.

Gavin Baker contributed the section on how to write composite filters. Also known as minipipeline filters.

Since the software guide is generated in part from the ITK source code itself, many ITK developers have been involved in updating and extending the ITK documentation. These include **David Doria**, **Bradley Lowekamp**, **Mark Foskey**, **Gaëtan Lehmann**, **Andreas Schuh**, **Tom Vercauteren**, **Cory Quammen**, **Daniel Blezek**, **Paul Hughtett**, **Matthew McCormick**, **Josh Cates**, **Arnaud Gelas**, **Jim Miller**, **Brad King**, **Gabe Hart**, **Hans Johnson**.

Hans Johnson, **Kent Williams**, **Constantine Zakkaroff**, **Xiaoxiao Liu**, **Ali Ghayoor**, and **Matthew McCormick** updated the documentation for the initial ITK Version 4 release.

Luis Ibáñez and **Sébastien Barré** designed the original Book 1 cover. **Xiaoxiao Liu**, **Bill Lorensen**, **Luis Ibáñez**, and **Matthew McCormick** created the 3D printed anatomical objects that were photographed by **Sébastien Barré** for the Book 2 cover. **Steve Jordan** designed the layout of the covers.

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Part I

Introduction

WELCOME

Welcome to the *Insight Segmentation and Registration Toolkit (ITK) Software Guide*. This book has been updated for ITK 5.4.6 and later versions of the Insight Toolkit software.

ITK is an open-source, object-oriented software system for image processing, segmentation, and registration. Although it is large and complex, ITK is designed to be easy to use once you learn about its basic object-oriented and implementation methodology. The purpose of this Software Guide is to help you learn just this, plus to familiarize you with the important algorithms and data representations found throughout the toolkit.

ITK is a large system. As a result, it is not possible to completely document all ITK objects and their methods in this text. Instead, this guide will introduce you to important system concepts and lead you up the learning curve as fast and efficiently as possible. Once you master the basics, take advantage of the many resources available ¹, including example materials, which provide cookbook recipes that concisely demonstrate how to achieve a given task, the Doxygen pages, which document the specific algorithm parameters, and the knowledge of the many ITK community members (see Section 1.4 on page 7).

The Insight Toolkit is an open-source software system. This means that the community surrounding ITK has a great impact on the evolution of the software. The community can make significant contributions to ITK by providing code reviews, bug patches, feature patches, new classes, documentation, and discussions. Please feel free to contribute your ideas through the ITK community discussion.

The Insight Toolkit is built on the principle that patents are undesirable in an open-source software. Thus, the community strives to keep the Insight Toolkit free from any patented code, algorithm or method.

¹<https://www.itk.org/ITK/help/documentation.html>

1.1 Organization

This software guide is divided into three parts. Part I is a general introduction to ITK, with a description of how to install the Insight Toolkit on your computer. This includes how to build the library from its source code. Part II introduces basic system concepts such as an overview of the system architecture, and how to build applications in the C++ and Python programming languages. Part II also describes the design of data structures and application of analysis methods within the system. Part III is for the ITK contributor and explains how to create your own classes, extend the system, and be an active participant in the project.

1.2 How to Learn ITK

The key to learning how to use ITK is to become familiar with its palette of objects and the ways to combine them. There are three categories of documentation to help with the learning process: high level guidance material (the Software Guide), “cookbook” demonstrations on how to achieve concrete objectives (the examples), and detailed descriptions of the application programming interface (the Doxygen² documentation). These resources are combined in the three recommended stages for learning ITK.

In the first stage, thoroughly read this introduction, which provides an overview of some of the key concepts of the system. It also provides guidance on how to build and install the software. After running your first “hello world” program, you are well on your way to advanced computational image analysis!

The next stage is to execute a few examples and gain familiarity with the available documentation. By running the examples, one can gain confidence in achieving results and is introduced the mechanics of the software system. There are two example resources,

1. the `Examples` directory of the ITK source code repository³.
2. the Sphinx documented ITK Sphinx Examples⁴

To gain familiarity with the available documentation, browse the sections available in Part II and Part III of this guide. Also, browse the Doxygen application programming interface (API) documentation for the classes applied in the examples.

Finally, mastery of ITK involves integration of information from multiple sources. the second companion book is a reference to algorithms available, and Part III introduces how to extend them to your needs and participate in the community. Individual examples are a detailed starting point to achieve certain tasks. In practice, the Doxygen documentation becomes a frequent reference as an index of

²<https://itk.org/Doxygen/index.html>

³See Section [Obtaining the Software](#) on page 10)

⁴<https://itk.org/ITKExamples>

the classes available, their descriptions, and the syntax and descriptions of their methods. When examples and Doxygen documentation are insufficient, the software unit tests thoroughly demonstrate how the code is utilized. Last, but not least, the source code itself is an extremely valuable resource. The code is the most detailed, up-to-date, and definitive description of the software. A great deal of attention and effort is directed to the code's readability, and its value cannot be understated.

The following sections describe how to obtain the software, summarize the software functionality in each directory, and how to locate data.

1.3 Software Organization

To begin your ITK odyssey, you will first need to know something about ITK's software organization and directory structure. It is helpful to know enough to navigate through the code base to find examples, code, and documentation.

ITK resources are organized into multiple Git repositories. The ITK library source code are in the ITK⁵ Git repository. The Sphinx Examples are in the ITKSphinxExamples⁶ repository. The sources for this guide are in the ITKSoftwareGuide⁷ repository.

The ITK repository contains the following subdirectories:

- `ITK/Documentation` — migration guides and Doxygen infrastructure.
- `ITK/Examples` — a suite of simple, well-documented examples used by this guide, illustrating important ITK concepts.
- `ITK/Modules` — the heart of the software; the location of the majority of the source code.
- `ITK/Testing` — a collection of the test files, including raw binary, and MD5 and SHA512 hash files, which are used to link with the ITK data servers to download test data. This test data is used by tests in `ITK/Modules` to produce the ITK Quality Dashboard using CDash. (see Section 10.2 on page 228.)
- `ITK/Utilities` — the scripts that support source code development. For example, CTest and Doxygen support.
- `ITK/Wrapping` — the wrapping code to build interfaces between the C++ library and various interpreted languages (currently Python is supported).

The source code directory structure—found in `ITK/Modules`—is the most important to understand.

⁵<https://github.com/InsightSoftwareConsortium/ITK.git>

⁶<https://github.com/InsightSoftwareConsortium/ITKSphinxExamples.git>

⁷<https://github.com/InsightSoftwareConsortium/ITKSoftwareGuide.git>

- `ITK/Modules/Bridge` — classes used to connect with the other analysis libraries or visualization libraries, such as `OpenCV`⁸ and `VTK`⁹.
- `ITK/Modules/Compatibility` — collects together classes for backwards compatibility with ITK Version 3, and classes that are deprecated – i.e. scheduled for removal from future versions of ITK.
- `ITK/Modules/Core` — core classes, macro definitions, type aliases, and other software constructs central to ITK. The classes in `Core` are the only ones always compiled as part of ITK.
- `ITK/Modules/External` — a directory to place in development or non-publicized modules.
- `ITK/Modules/Filtering` — image processing filters.
- `ITK/Modules/IO` — classes that support the reading and writing of images, transforms, and geometry.
- `ITK/Modules/Numerics` — a collection of numeric modules, including FEM, Optimization, Statistics, Neural Networks, etc.
- `ITK/Modules/Registration` — classes for registration of images or other data structures to each other.
- `ITK/Modules/Remote` — a group of modules distributed outside of the main ITK source repository (most of them are hosted on github.com) whose source code can be downloaded via CMake when configuring ITK.
- `ITK/Modules/Segmentation` — classes for segmentation of images or other data structures.
- `ITK/Modules/ThirdParty` — various third-party libraries that are used to implement image file I/O and mathematical algorithms. (Note: ITK's mathematical library is based on the `VXL/VNL` software package¹⁰).
- `ITK/Modules/Video` — classes for input, output and processing of static and real-time data with temporal components.

The Doxygen documentation is an essential resource when working with ITK, but it is not contained in a separate repository. Each ITK class is implemented with a `.h` and `.cxx/.hxx` file (`.hxx` file for templated classes). All methods found in the `.h` header files are documented and provide a quick way to find documentation for a particular method. Doxygen uses this header documentation to produce its HTML output.

The extensive Doxygen web pages describe in detail every class and method in the system. It also contains inheritance and collaboration diagrams, listing of event invocations, and data members.

⁸<https://opencv.org>

⁹<https://www.vtk.org>

¹⁰<https://vxl.github.io>

heavily hyper-linked to other classes and to the source code. The nightly generated Doxygen documentation is online at <https://itk.org/Doxygen/html/>. Archived versions for each feature release are also available online; for example, the documentation for the 4.4.0 release are available at <https://itk.org/Doxygen44/html/>.

1.4 The Insight Community and Support

Joining the community discussion is strongly recommended. This is one of the primary resources for guidance and help regarding the use of the toolkit. You can subscribe to the community list online at

<https://discourse.itk.org/>

ITK transitioned to [Discourse](#) on September 2017. [Discourse](#) is a next generation, open source discussion platform that functions as a mailing list, discussion forum, and long-form chat room. Discourse is a simple, modern, and fun platform that facilitates civilized discussions.

ITK maintainers developed a [Getting Started Guide](#) to help people joining the discussion, subscribing to updates, or setting their preferences.

The previous mailing list resources can be reached at <https://itk.org/ITK/help/mailing.html>.

ITK was created from its inception as a collaborative, community effort. Research, teaching, and commercial uses of the toolkit are expected. If you would like to participate in the community, there are a number of possibilities. For details on participation, see Part III of this book.

- Interaction with other community members is encouraged on the ITK discussion by both asking as answering questions. When issues are discovered, patches submitted to the code review system are welcome. Performing code reviews, even by novice members, is encouraged. Improvements and extensions to the documentation are also welcome.
- Research partnerships with members of the Insight Software Consortium are encouraged. Both NIH and NLM will likely provide limited funding over the next few years and will encourage the use of ITK in proposed work.
- For those developing commercial applications with ITK, support and consulting are available from Kitware ¹¹. Kitware also offers short ITK courses either at a site of your choice or periodically at Kitware offices.
- Educators may wish to use ITK in courses. Materials are being developed for this purpose, e.g., a one-day, conference course and semester-long graduate courses. Check the Wiki¹² for a listing.

¹¹<https://www.kitware.com>

¹²<https://itk.org/Wiki/ITK/Documentation>

1.5 A Brief History of ITK

In 1999 the US National Library of Medicine of the National Institutes of Health awarded six three-year contracts to develop an open-source registration and segmentation toolkit, that eventually came to be known as the Insight Toolkit (ITK) and formed the basis of the Insight Software Consortium. ITK's NIH/NLM Project Manager was Dr. Terry Yoo, who coordinated the six prime contractors composing the Insight consortium. These consortium members included three commercial partners—GE Corporate R&D, Kitware, Inc., and MathSoft—and three academic partners—University of North Carolina (UNC), University of Tennessee (UT) (Ross Whitaker subsequently moved to University of Utah), and University of Pennsylvania (UPenn). The Principle Investigators for these partners were, respectively, Bill Lorensen at GE CRD, Will Schroeder at Kitware, Vikram Chalana at Insightful, Stephen Aylward with Luis Ibáñez at UNC (Luis is now at Google), Ross Whitaker with Josh Cates at UT, and Dimitri Metaxas at UPenn (now at Rutgers). In addition, several subcontractors rounded out the consortium including Peter Raitu at Brigham & Women's Hospital, Celina Imielinska and Pat Molholt at Columbia University, Jim Gee at UPenn's Grasp Lab, and George Stetten at the University of Pittsburgh.

In 2002 the first official public release of ITK was made available. In addition, the National Library of Medicine awarded thirteen contracts to several organizations to extend ITK's capabilities. The NLM has funded maintenance of the toolkit over the years, and a major funding effort was started in July 2010 that culminated with the release of ITK 4.0.0 in December 2011. The ITK community completed a major modernization of the toolkit's interface, architectural improvements for improved performance, and Python packages for rapid prototyping with ITK 5.0.0, released in May 2019.

CONFIGURING AND BUILDING ITK

This chapter describes the process for configuring and compiling ITK on your system. Keep in mind that ITK is a toolkit, and as such, once it is installed on your computer it does not provide an application to run. What ITK does provide is a large set of libraries which can be used to create your own applications. Besides the toolkit proper, ITK also includes an extensive set of examples and tests that introduce ITK concepts and show how to use ITK in your own projects.

Some of the examples distributed with ITK depend on third party libraries, some of which may need to be installed separately. For the initial build of ITK, you may want to ignore these extra libraries and just compile the toolkit itself.

ITK has been developed and tested across different combinations of operating systems, compilers, and hardware platforms including Microsoft Windows, Linux on various architectures, UNIX, macOS, and Mingw-w64. Dedicated community members and Kitware are committed to providing long-term support of the most prevalent development environments (e.g. Clang and Visual Studio) for building ITK.

Compiler variants will be supported for the duration that the associated operating system vendors commit to in their long-term stable platforms. For example the gcc compilers supported will mirror the compiler support in the RedHat lifecycle, the Apple Clang compilers will mirror the support lifecycle of the compiler by Apple, and the Visual Studio series support will follow lifecycle deprecation of the compiler versions.

For example, the following development and compiler environments are supported in ITK for the date at which the document was generated:

- GCC 7 and newer
- Visual Studio 2019 (technically MSVC toolset v142) and newer
- Xcode 10.0 (Apple Clang version 10.0.0, LLVM Clang 5) and newer

If you are currently using an outdated compiler this may be an excellent excuse for upgrading this old piece of software! Support for different platforms is evident on the ITK quality dashboard (see

Section 10.2 on page 228).

2.1 Obtaining the Software

There are two different ways to access the ITK source code:

Periodic releases Official releases are available on the ITK web site¹. They are released twice a year, and announced on the ITK web pages and discussion. However, they may not provide the latest and greatest features of the toolkit.

Continuous repository checkout Direct access to the Git source code repository² provides immediate availability to the latest toolkit additions. But, on any given day the source code may not be stable as compared to the official releases.

This software guide assumes that you are using the current released version of ITK, available on the ITK web site. If you are a new user, we recommend the released version of the software. It is more consistent than the code available from the Git repository (see Section 2.1.2). When working from the repository, please be aware of the ITK quality testing dashboard. The Insight Toolkit is heavily tested using the open-source CDash regression testing system³. Before updating the repository, make sure that the dashboard is *green*, indicating stable code. (Learn more about the ITK dashboard and quality assurance process in Section 10.2 on page 228.)

2.1.1 Downloading Packaged Releases

ITK can be downloaded without cost from the following web site:

<https://www.itk.org/ITK/resources/software.html>

On the web page, choose the tarball that better fits your system. The options are `.zip` and `.tar.gz` files. The first type is better suited for Microsoft-Windows, while the second one is the preferred format for UNIX systems.

Once you unzip or untar the file a directory called `InsightToolkit-5.4.6` will be created in your disk and you will be ready to start the configuration process described in Section 2.2.1 on page 12.

2.1.2 Downloading From Git

Git is a free and open source distributed version control system. For more information about Git please see Section 10.1 on page 227. (Note: please make sure that you access the software via Git

¹<https://itk.org/ITK/resources/software.html>

²<https://itk.org/ITK.git>

³<https://open.cdash.org/index.php?project=Insight>

only when the ITK quality dashboard indicates that the code is stable.)

Access ITK via Git using the following commands (under a Git Bash shell):

```
git clone git://itk.org/ITK.git
```

This will trigger the download of the software into a directory named `ITK`. Any time you want to update your version, it will be enough to change into this directory, `ITK`, and type:

```
git pull
```

Once you obtain the software you are ready to configure and compile it (see Section 2.2.1 on page 12). First, however, we recommend reading the following sections that describe the organization of the software and joining the discussion.

2.1.3 Data

The Insight Toolkit was designed to support the Visible Human Project and its associated data. This data is available from the National Library of Medicine at https://www.nlm.nih.gov/research/visible/visible_human.html.

Another source of data can be obtained from the ITK Web site at either of the following:

<https://www.itk.org/ITK/resources/links.html>
<ftp://public.kitware.com/pub/itk/Data/>.

2.2 Using CMake for Configuring and Building ITK

The challenge of supporting ITK across platforms has been solved through the use of CMake⁴, a cross-platform, open-source build system. CMake controls the software compilation process with simple platform and compiler-independent configuration files. CMake is quite sophisticated—it supports complex environments requiring system introspection, compiler feature testing, and code generation.

CMake generates native Makefiles or workspaces to be used with the corresponding development environment of your choice. For example, on UNIX and MinGW systems, CMake generates Makefiles; under Microsoft Windows CMake generates Visual Studio workspaces; CMake is also capable of generating appropriate build files for other development environments, e.g., Eclipse. The information used by CMake is provided in `CMakeLists.txt` files that are present in every directory of the ITK source tree. Along with the specification of project structure and code dependencies these

⁴www.cmake.org

files specify the information that need to be provided to CMake by the user during project configuration stage. Typical configuration options specified by the user include paths to utilities installed on your system and selection of software features to be included.

An ITK build requires only CMake and a C++ compiler. ITK ships with all the third party library dependencies required, and these dependencies are used during compilation unless the use of a system version is requested during CMake configuration.

2.2.1 Preparing CMake

CMake can be downloaded at no cost from

<https://cmake.org/download/>

You can download binary versions for most of the popular platforms including Microsoft Windows, macOS, Linux, PowerPC and IRIX. Alternatively you can download the source code and build CMake on your system. Follow the instructions provided on the CMake web page for downloading and installing the software. The minimum version of CMake has been evolving along with the version of ITK. For example, the current version of ITK (5.4.6) requires the minimum CMake version to be 3.9.5.

CMake provides a terminal-based interface (Figure 2.1) on platforms support the `curses` library. For most platforms CMake also provides a GUI based on the Qt library. Figure 2.1 shows the terminal-based CMake interface for Linux and CMake GUI for Microsoft Windows.

Running CMake to configure and prepare for compilation a new project initially requires two pieces of information: where the source code directory is located, and where the compiled code is to be produced. These are referred to as the *source directory* and the *binary directory* respectively. We recommend setting the binary directory to be different than the source directory in order to produce an *out-of-source* build.

If you choose to use the terminal-based version of CMake (`ccmake`) the binary directory needs to be created first and then CMake is invoked from the binary directory with the path to the source directory. For example:

```
mkdir ITK-build
cd ITK-build
ccmake ../ITK
```

In the GUI version of CMake (`cmake-gui`) the source and binary directories are specified in the appropriate input fields (Figure 2.1) and the application will request a confirmation to create a new binary directory if it does not exist.

CMake runs in an interactive mode which allows iterative selection of options followed by configuration according to the updated options. This iterative process proceeds until no more options

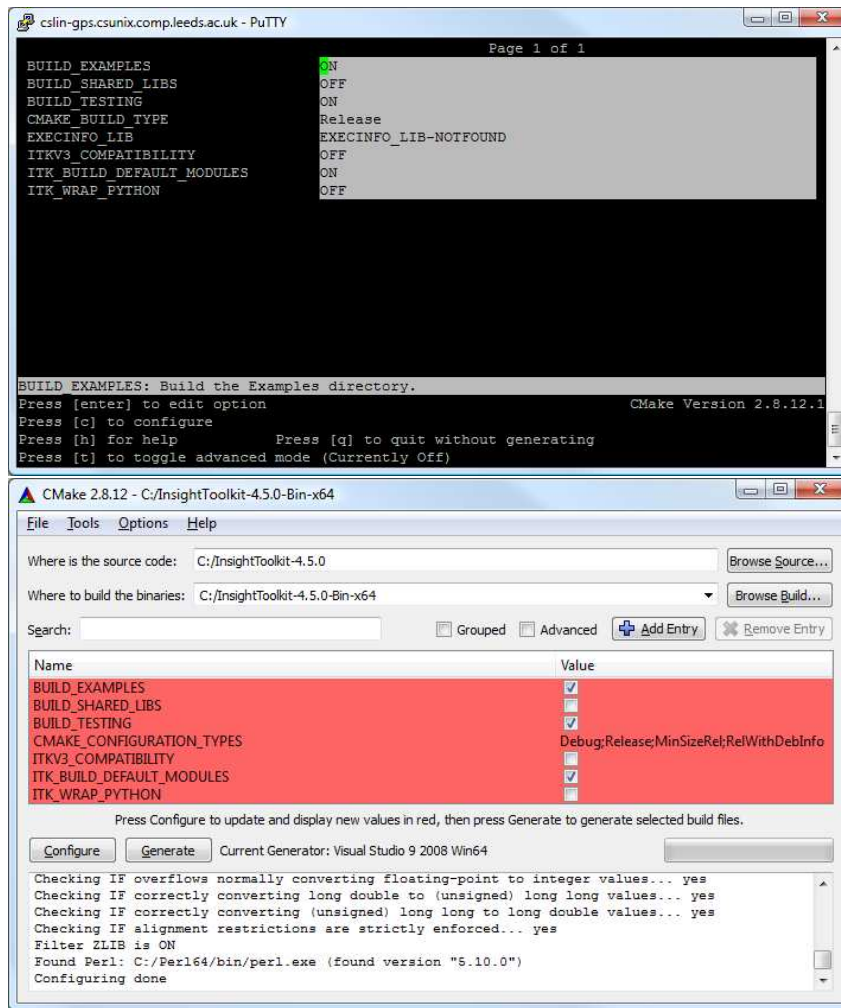


Figure 2.1: CMake user interfaces: at the top is the interface based on the `curses` library supported by UNIX/Linux systems, below is the Microsoft Windows version of the CMake GUI based on the Qt library (CMake GUI is also available on UNIX/Linux systems).

remain to be specified. At this point, a generation step produces the appropriate build files for your configuration.

This interactive configuration process can be better understood by imagining the traversal of a path in a decision tree. Every selected option introduces the possibility that new, dependent options may become relevant. These new options are presented by CMake at the top of the options list in its interface. Only when no new options appear after a configuration iteration can you be sure that

the necessary decisions have all been made. At this point build files are generated for the current configuration.

2.2.2 Configuring ITK

Start terminal-based CMake interface `ccmake` on Linux and UNIX, or the graphical user interface `cmake-gui` on Microsoft Windows. Remember to run `ccmake` from the binary directory on Linux and UNIX. On Windows, specify the source and binary directories in the GUI, then set and modify the configuration and build option in the interface as necessary.

The examples distributed with the toolkit provide a helpful resource for learning how to use ITK components but are not essential for compiling the toolkit itself. The testing section of the source tree includes a large number of small programs that exercise the capabilities of ITK classes. Enabling the compilation of the examples and unit tests will considerably increase the build time. In order to speed up the build process, you can disable the compilation of the unit tests and examples. This is done by setting the variables `BUILD_TESTING` and `BUILD_EXAMPLES` to `OFF`.

Most CMake variables in ITK have sensible default values. Each time a CMake variable is changed, it is necessary to re-run the configuration step. In the terminal-based version of the interface the configuration step is triggered by hitting the “c” key. In the GUI version this is done by clicking on the “Configure” button.

When no new options appear highlighted in CMake, you can proceed to generate Makefiles, a Visual Studio workspace, or other appropriate build files depending on your preferred development environment. This is done in the GUI interface by clicking on the “Generate” button. In the terminal-based version this is done by hitting the “g” key. After the generation process the terminal-based version of CMake will quit silently. The GUI window of CMake can be left open for further refinement of configuration options as described in the next section. With this scenario it is important to generate new build files to reflect the latest configuration changes. In addition, the new build files need to be reloaded if the project is open in the integrated development environment such as Visual Studio or Eclipse.

2.2.3 Advanced Module Configuration

Following the default configuration introduced in 2.2.2, the majority of the toolkit will be built. The modern modular structure of the toolkit makes it possible to customize the ITK library by choosing which modules to include in the build. ITK was officially modularized in version 4.0.0 released in December of 2011. Developers have been testing and improving the modular structure since then. The toolkit currently contains more than 100 regular/internal modules and many remote modules, while new ITK modules are being developed.

`ITK_BUILD_DEFAULT_MODULES` is the CMake option to build all default modules in the toolkit, by default this option is `ON` as shown in Figure 2.1. The default modules include most internal ITK modules except the ones that depend on external third party libraries (such as `ITKVtkGlue`,

ITKVideoBridgeOpenCV, ITKVideoBridgeVXL, etc.) and several modules containing legacy code (ITKReview, ITKDeprecated and ITKV3Compatibility).

Apart from the default mode of selecting the modules for building the ITK library there are two other approaches module selection: the group mode, and the advanced module mode. When `ITK_BUILD_DEFAULT_MODULES` is set to `OFF`, the selection of modules to be included in the ITK library can be customized by changing the variables enabling group and advanced module selection.

ITKGroup_{group name} variables for group module selection are visible when ITK_BUILD_DEFAULT_MODULES is OFF. The ITK source code tree is organized in such way that a group of modules characterized by close relationships or similar functionalities stay in one subdirectory. Currently there are 11 groups (excluding the External and Remote groups). The CMake ITKGroup_{group name} options are created for the convenient enabling or disabling of multiple modules at once. The ITKGroup_Core group is selected by default as shown in Figure 2.2. When a group is selected, all modules in the group and their depending modules are enabled. When a group variable is set to OFF, all modules in the group, except the ones that are required by other enabled modules, are disabled.

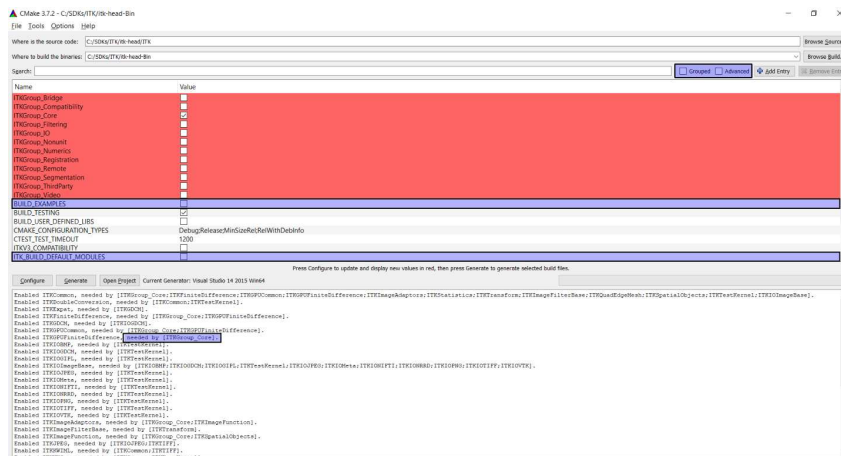


Figure 2.2: CMake GUI shows the ITK Group options.

If you are not sure about which groups to turn on, but you do have a list of specific modules to be included in your ITK library, you can certainly skip the Group options and use the `Module_{module name}` options only. Whatever modules you select, their dependent modules are automatically enabled. In the advanced mode of the CMake GUI, you can manually toggle the build of the non-default modules via the `Module_{module name}` variables. In Figure 2.3 all default modules' `Module_{module name}` variables are shown disabled for toggling since they are enabled via the `ITK_BUILD_DEFAULT_MODULES` set to `ON` variable.

However, not all modules will be visible in the CMake GUI at all times due to the various levels of controls in the previous two modes. If some modules are already enabled by other modes, these modules are set as internal variables and are hidden in the CMake GUI. For example, `Module_--`

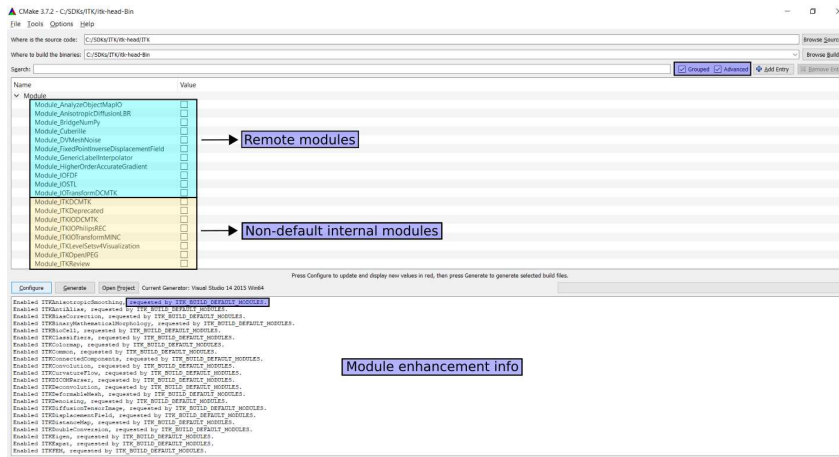


Figure 2.3: CMake GUI for configuring ITK: the advanced mode shows options for non-default ITK Modules.

ITKFoo variable is hidden when the module ITKFoo is enabled in either of the following scenarios:

1. module ITKBar is enabled and depends on ITKFoo,
2. ITKFoo belongs to the group ITKGroup_FooAndBar and the group is enabled
3. ITK_BUILD_DEFAULT_MODULES is ON and ITKFoo is a default module.

To find out why a particular module is enabled, check the CMake configuration messages where the information about enabling or disabling the modules is displayed (Figure 2.3); these messages are sorted in alphabetical order by module names.

Those who prefer to build ITK using the command line are referred to the online cmake command-line tool documentation⁵. Only some typical use cases are shown here for reference.

- **Example 1:** Build all default modules.

```
cmake [-DITK_BUILD_DEFAULT_MODULES:BOOL=ON]
      ../ITK-build
```

As ITK_BUILD_DEFAULT_MODULES is ON by default, the above can also be accomplished by

```
cmake ../ITK-build
```

- **Example 2:** Enable specific group(s) of modules.

⁵<https://cmake.org/cmake/help/latest/manual/cmake.1.html>


```
cmake -DITK_BUILD_DEFAULT_MODULES:BOOL=OFF
      -DBUILD_EXAMPLES:BOOL=OFF
      -DITKGroup_{Group1}:BOOL=ON
      [-DITKGroup_{Group2}:BOOL=ON]
      ../ITK-build
```

where `ITKGroup_GroupN` could be, for example, `ITKGroup_Filtering` or `ITKGroup_Registration` for the Filtering and Registration groups, respectively.

- **Example 3:** Enable specific modules.

```
cmake -DITK_BUILD_DEFAULT_MODULES:BOOL=OFF
      -DBUILD_EXAMPLES:BOOL=OFF
      -DModule_{Module1}:BOOL=ON
      [-DModule_{Module2}:BOOL=ON]
      ../ITK-build
```

where `Module_Module1` could be, for example, `Module_ITKFEM` for the non-default, built-in FEM module, or `Module_Cuberille` for the Cuberille remote module.

- **Example 4:** Enable examples.

```
cmake -DITK_BUILD_DEFAULT_MODULES:BOOL=ON
      -DBUILD_EXAMPLES:BOOL=ON
      ../ITK-build
```

Note that `BUILD_EXAMPLES` is OFF by default, and `BUILD_EXAMPLES=ON` requires `ITK_BUILD_DEFAULT_MODULES=ON`.

2.2.4 Static and Shared Libraries

ITK libraries can be built as *static libraries*, i.e. files whose functions and variables are included in a binary during the link phase of the build cycle. Alternatively, ITK libraries can be built as *shared libraries*, where libraries are dynamically linked to a binary. In this case, functions and variables are shared at runtime according to their symbols.

By enabling the standard CMake configuration variable, `BUILD_SHARED_LIBS`, ITK modules with the `ENABLE_SHARED` option (see Section 9.1) will be built as shared libraries.

Static libraries are preferred when creating a stand-alone executable. An application can be distributed as a single file when statically linked. Additional effort is not required to package library dependencies, configure the system to find library dependencies at runtime, or define symbol export specifications. However, care should be taken to only link static libraries *once* into the binaries used by an application. Failure to do so can result in duplicated global variables and, consequently, undefined or undesirable behavior.

Shared libraries should be used when ITK is linked to more than one binary in an application. This reduces binary size and ensures that singleton variables are unique across the application.

An advanced CMake configuration variable, `ITK_TEMPLATE_VISIBILITY_DEFAULT` defines the symbol visibility attribute on template classes to *default* on systems that require it to perform `dynamic_cast`'s on pointers passed across binaries. The default value can be disabled only when it is known that template classes are not implicitly instantiated and passed across binaries.

2.2.5 Compiling ITK

To initiate the build process after generating the build files on Linux or UNIX, simply type `make` in the terminal if the current directory is set to the ITK binary directory. If using Visual Studio, first load the workspace named `ITK.sln` from the binary directory specified in the CMake GUI and then start the build by selecting “Build Solution” from the “Build” menu or right-clicking on the `ALL_BUILD` target in the Solution Explorer pane and selecting the “Build” context menu item.

The build process can take anywhere from 15 minutes to a couple of hours, depending on the build configuration and the performance of your system. If testing is enabled as part of the normal build process, about 2400 test programs will be compiled. In this case, you will then need to run `ctest` to verify that all the components of ITK have been correctly built on your system.

2.2.6 Installing ITK on Your System

When the build process is complete an ITK binary distribution package can be generated for installation on your system or on a system with compatible specifications (such as hardware platform and operating system) as well as suitable development environment components (such as C++ compiler and CMake). The default prefix for installation destination directory needs to be specified during CMake configuration process prior to compiling ITK. The installation destination prefix can be set through the CMake cache variable `CMAKE_INSTALL_PREFIX`.

Typically distribution packages are generated to provide a “clean” form of the software which is isolated from the details of the build process (separate from the source and build trees). Due to the intended use of ITK as a toolkit for software development the step of generating ITK binary packages for installing ITK on other systems has limited application and thus it can be treated as optional. However, the step for generating binary distribution packages has a much wide application for distributing software developed with ITK. Further details on configuring and generating binary packages with CMake can be found in the CMake tutorial⁶.

2.3 Cross compiling ITK

This section describes the procedure to follow to cross compile ITK for another system. Cross compiling involves a *build system*, the system where the executables are built, and the *target system*, the system where the executables are intended to run.

⁶<https://cmake.org/cmake-tutorial/>

Currently, the best way to cross-compile ITK is to use [dockcross](#).

For example, the commands to build for Linux-ARMv7 are:

```
git clone https://github.com/InsightSoftwareConsortium/ITK
docker run --rm dockcross/linux-armv7 > ./dockcross-linux-armv7
chmod +x ./dockcross-linux-armv7
mkdir ITK-build
./dockcross-linux-armv7 cmake -BITK-build -HITK -GNinja
./dockcross-linux-armv7 ninja -CITK-build
```

2.4 Getting Started With ITK

The simplest way to create a new project with ITK is to create two new directories somewhere in your disk, one to hold the source code and one to hold the binaries and other files that are created in the build process. For this example, create a `HelloWorldITK` directory to hold the source and a `HelloWorldITK-build` directory to hold the binaries. The first file to place in the source directory is a `CMakeLists.txt` file that will be used by CMake to generate a Makefile (if you are using Linux or UNIX) or a Visual Studio workspace (if you are using Microsoft Windows). The second source file to be created is an actual C++ program that will exercise some of the large number of classes available in ITK. The details of these files are described in the following section.

Once both files are in your directory you can run CMake in order to configure your project. Under UNIX/Linux, you can `cd` to your newly created binary directory and launch the terminal-based version of CMake by entering “`ccmake ../HelloWorldITK`” in the terminal. Note the “`../HelloWorldITK`” in the command line to indicate that the `CMakeLists.txt` file is up one directory and in `HelloWorldITK`. In CMake GUI which can be used under Microsoft Windows and UNIX/Linux, the source and binary directories will have to be specified prior to the configuration and build file generation process.

Both the terminal-based and GUI versions of CMake will require you to specify the directory where ITK was built in the CMake variable `ITK_DIR`. The ITK binary directory will contain a file named `ITKConfig.cmake` generated during ITK configuration process with CMake. From this file, CMake will recover all information required to configure your new ITK project.

After generating the build files, on UNIX/Linux systems the project can be compiled by typing `make` in the terminal provided the current directory is set to the project’s binary directory. In Visual Studio on Microsoft Windows the project can be built by loading the workspace named `HelloWorldITK.sln` from the binary directory specified in the CMake GUI and selecting “Build Solution” from the “Build” menu or by right-clicking on the `ALL_BUILD` target in the Solution Explorer pane and selecting the “Build” context menu item.

The resulting executable, which will be called `HelloWorld`, can be executed on the command line. If on Microsoft Windows, please note that double-clicking on the icon of the executable will quickly launch a command line window, run the executable and close the window right away, not giving you time to see the output. It is therefore preferable to run the executable from the DOS command line

by starting the `cmd.exe` shell first.

2.5 Using ITK as an External Library

For a project that uses ITK as an external library, it is recommended to specify the individual ITK modules in the `COMPONENTS` argument in the `find_package` CMake command:

```
find_package(ITK REQUIRED COMPONENTS Module1 Module2)
include(\${ITK_USE_FILE})
```

e.g.

```
find_package(ITK REQUIRED
  COMPONENTS
    MorphologicalContourInterpolation
    ITKSmoothing
    ITKIOImageBase
    ITKIONRRD
  )
include(\${ITK_USE_FILE})
```

If you would like to use the CMake ExternalProject Module⁷ to download ITK source code when building your ITK application (a.k.a. Superbuild ITK), here is a basic CMake snippet for setting up a Superbuild in an ITK application project using CMake:

```
ExternalProject_Add(ITK
  GIT_REPOSITORY \${git_protocol}://github.com/InsightSoftwareConsortium/ITK.git"
  GIT_TAG "<tag id>" # specify the commit id or the tag id
  SOURCE_DIR <ITK source tree path>
  BINARY_DIR <ITK build tree path>
  CMAKE_GENERATOR \${gen}
  CMAKE_ARGS
    \${ep_common_args}
    -DBUILD_SHARED_LIBS:BOOL=OFF
    -DBUILD_EXAMPLES:BOOL=OFF
    -DBUILD_TESTING:BOOL=OFF
    -DITK_BUILD_DEFAULT_MODULES:BOOL=ON
    [-DModule_LevelSetv4Visualization:BOOL=ON]
  INSTALL_COMMAND ""
  DEPENDS
[VTK] [DCMTK] # if some of the modules requested require extra third party libraries
)
```

More exemplary configurations for superbuild ITK projects can be found in: Slicer⁸, BrainsTools⁹,

⁷<https://cmake.org/cmake/help/latest/module/ExternalProject.html>

⁸<https://github.com/Slicer/Slicer>

⁹<https://github.com/BRAINSia/BRAINSTools>

ITK Wiki Examples¹⁰, ITK Sphinx Examples¹¹, and ITK Software Guide¹².

2.5.1 Hello World!

This section provides and explains the contents of the two files which need to be created for your new project. These two files can be found in the `ITK/Examples/Installation` directory.

The `CMakeLists.txt` file contains the following lines:

```
project(HelloWorld)

find_package(ITK REQUIRED)
include(${ITK_USE_FILE})

add_executable(HelloWorld HelloWorld.cxx)

target_link_libraries(HelloWorld ${ITK_LIBRARIES})
```

The first line defines the name of your project as it appears in Visual Studio or Eclipse; this line will have no effect with UNIX/Linux Makefiles. The second line loads a CMake file with a predefined strategy for finding ITK. If the strategy for finding ITK fails, CMake will report an error which can be corrected by providing the location of the directory where ITK was compiled or installed on your system. In this case the path to the ITK's binary/installation directory needs to be specified as the value of the `ITK_DIR` CMake variable. The line `include(${ITK_USE_FILE})` loads the `UseITK.cmake` file which contains the configuration information about the specified ITK build. The line starting with `add_executable` call defines as its first argument the name of the executable that will be produced as result of this project. The remaining argument(s) of `add_executable` are the names of the source files to be compiled. Finally, the `target_link_libraries` call specifies which ITK libraries will be linked against this project. Further details on creating and configuring CMake projects can be found in the CMake tutorial¹³ and CMake online documentation¹⁴.

The source code for this section can be found in the file `HelloWorld.cxx`.

The following code is an implementation of a small ITK program. It tests including header files and linking with ITK libraries.

```
#include "itkImage.h"
#include <iostream>
```

¹⁰<https://github.com/InsightSoftwareConsortium/ITKWikiExamples>

¹¹<https://github.com/InsightSoftwareConsortium/ITKSphinxExamples>

¹²<https://github.com/InsightSoftwareConsortium/ITKSoftwareGuide>

¹³<https://cmake.org/cmake-tutorial/>

¹⁴<https://cmake.org/documentation/>

```
int
main()
{
    using ImageType = itk::Image<unsigned short, 3>;

    auto image = ImageType::New();

    std::cout << "ITK Hello World !" << std::endl;

    return EXIT_SUCCESS;
}
```

This code instantiates a 3D image¹⁵ whose pixels are represented with type `unsigned short`. The image is then constructed and assigned to a `itk::SmartPointer`. Although later in the text we will discuss `SmartPointers` in detail, for now think of it as a handle on an instance of an object (see section 3.2.4 for more information). The `itk::Image` class will be described in Section 4.1.

By this point you have successfully configured and compiled ITK, and created your first simple program! If you have experienced any difficulties while following the instructions provided in this section, please join the community discussion (see Section 1.4 on page 7) and post questions there.

¹⁵Also known as a *volume*.

Part II

Architecture

SYSTEM OVERVIEW

The purpose of this chapter is to provide you with an overview of the *Insight Toolkit* system. We recommend that you read this chapter to gain an appreciation for the breadth and area of application of ITK.

3.1 System Organization

The Insight Toolkit consists of several subsystems. A brief description of these subsystems follows. Later sections in this chapter—and in some cases additional chapters—cover these concepts in more detail.

Essential System Concepts. Like any software system, ITK is built around some core design concepts. Some of the more important concepts include generic programming, smart pointers for memory management, object factories for adaptable object instantiation, event management using the command/observer design paradigm, and multi-threading support.

Numerics. ITK uses VXL's VNL numerics libraries. These are easy-to-use C++ wrappers around the Netlib Fortran numerical analysis routines ¹.

Data Representation and Access. Two principal classes are used to represent data: the `itk::Image` and `itk::Mesh` classes. In addition, various types of iterators and containers are used to hold and traverse the data. Other important but less popular classes are also used to represent data such as `itk::Histogram` and `itk::SpatialObject`.

Data Processing Pipeline. The data representation classes (known as *data objects*) are operated on by *filters* that in turn may be organized into data flow *pipelines*. These pipelines maintain state and therefore execute only when necessary. They also support multi-threading, and are streaming capable (i.e., can operate on pieces of data to minimize the memory footprint).

¹<https://www.netlib.org>

IO Framework. Associated with the data processing pipeline are *sources*, filters that initiate the pipeline, and *mappers*, filters that terminate the pipeline. The standard examples of sources and mappers are *readers* and *writers* respectively. Readers input data (typically from a file), and writers output data from the pipeline.

Spatial Objects. Geometric shapes are represented in ITK using the spatial object hierarchy. These classes are intended to support modeling of anatomical structures. Using a common basic interface, the spatial objects are capable of representing regions of space in a variety of different ways. For example: mesh structures, image masks, and implicit equations may be used as the underlying representation scheme. Spatial objects are a natural data structure for communicating the results of segmentation methods and for introducing anatomical priors in both segmentation and registration methods.

Registration Framework. A flexible framework for registration supports four different types of registration: image registration, multiresolution registration, PDE-based registration, and FEM (finite element method) registration.

FEM Framework. ITK includes a subsystem for solving general FEM problems, in particular non-rigid registration. The FEM package includes mesh definition (nodes and elements), loads, and boundary conditions.

Level Set Framework. The level set framework is a set of classes for creating filters to solve partial differential equations on images using an iterative, finite difference update scheme. The level set framework consists of finite difference solvers including a sparse level set solver, a generic level set segmentation filter, and several specific subclasses including threshold, Canny, and Laplacian based methods.

Wrapping. ITK uses a unique, powerful system for producing interfaces (i.e., “wrappers”) to interpreted languages such as Python. The CastXML² tool is used to produce an XML description of arbitrarily complex C++ code. An interface generator script is then used to transform the XML description into wrappers using the SWIG³ package.

3.2 Essential System Concepts

This section describes some of the core concepts and implementation features found in ITK.

3.2.1 Generic Programming

Generic programming is a method of organizing libraries consisting of generic—or reusable—software components [8]. The idea is to make software that is capable of “plugging together” in

²<https://github.com/CastXML/CastXML>

³<https://www.swig.org/>

an efficient, adaptable manner. The essential ideas of generic programming are *containers* to hold data, *iterators* to access the data, and *generic algorithms* that use containers and iterators to create efficient, fundamental algorithms such as sorting. Generic programming is implemented in C++ with the *template* programming mechanism and the use of the STL Standard Template Library [1].

C++ templating is a programming technique allowing users to write software in terms of one or more unknown types `T`. To create executable code, the user of the software must specify all types `T` (known as *template instantiation*) and successfully process the code with the compiler. The `T` may be a native type such as `float` or `int`, or `T` may be a user-defined type (e.g., a `class`). At compile-time, the compiler makes sure that the templated types are compatible with the instantiated code and that the types are supported by the necessary methods and operators.

ITK uses the techniques of generic programming in its implementation. The advantage of this approach is that an almost unlimited variety of data types are supported simply by defining the appropriate template types. For example, in ITK it is possible to create images consisting of almost any type of pixel. In addition, the type resolution is performed at compile time, so the compiler can optimize the code to deliver maximal performance. The disadvantage of generic programming is that the analysis performed at compile time increases the time to build an application. Also, the increased complexity may produce difficult to decipher error messages due to even the simplest syntax errors. For those unfamiliar with templated code and generic programming, we recommend the two books cited above.

3.2.2 Include Files and Class Definitions

In ITK, classes are defined by a maximum of two files: a header file (`.h`) and an implementation file (`.cxx`) if defining a non-templated class, and a `.hxx` file if defining a templated class. The header files contain class declarations and formatted comments that are used by the Doxygen documentation system to automatically produce HTML manual pages.

In addition to class headers, there are a few other important header files.

`itkMacro.h` is found in the `Modules/Core/Common/include` directory and defines standard system-wide macros (such as `Set/Get`, constants, and other parameters).

`itkNumericTraits.h` is found in the `Modules/Core/Common/include` directory and defines numeric characteristics for native types such as its maximum and minimum possible values.

3.2.3 Object Factories

Most classes in ITK are instantiated through an *object factory* mechanism. That is, rather than using the standard C++ class constructor and destructor, instances of an ITK class are created with the static class `New()` method. In fact, the constructor and destructor are `protected`: so it is generally not possible to construct an ITK instance on the stack. (Note: this behavior pertains to classes that are derived from `itk::LightObject`. In some cases the need for speed or reduced memory

footprint dictates that a class is not derived from `LightObject`. In this case instances may be created on the stack. An example of such a class is the `itk::EventObject`.)

The object factory enables users to control run-time instantiation of classes by registering one or more factories with `itk::ObjectFactoryBase`. These registered factories support the method `CreateInstance(classname)` which takes as input the name of a class to create. The factory can choose to create the class based on a number of factors including the computer system configuration and environment variables. For example, a particular application may wish to deploy its own class implemented using specialized image processing hardware (i.e., to realize a performance gain). By using the object factory mechanism, it is possible to replace the creation of a particular ITK filter at run-time with such a custom class. (Of course, the class must provide the exact same API as the one it is replacing.) For this, the user compiles his class (using the same compiler, build options, etc.) and inserts the object code into a shared library or DLL. The library is then placed in a directory referred to by the `ITK_AUTOLOAD_PATH` environment variable. On instantiation, the object factory will locate the library, determine that it can create a class of a particular name with the factory, and use the factory to create the instance. (Note: if the `CreateInstance()` method cannot find a factory that can create the named class, then the instantiation of the class falls back to the usual constructor.)

In practice, object factories are used mainly (and generally transparently) by the ITK input/output (IO) classes. For most users the greatest impact is on the use of the `New()` method to create a class. Generally the `New()` method is declared and implemented via the macro `itkNewMacro()` found in `Modules/Core/Common/include/itkMacro.h`.

3.2.4 Smart Pointers and Memory Management

By their nature, object-oriented systems represent and operate on data through a variety of object types, or classes. When a particular class is instantiated, memory allocation occurs so that the instance can store data attribute values and method pointers (i.e., the `vtable`). This object may then be referenced by other classes or data structures during normal operation of the program. Typically, during program execution, all references to the instance may disappear at which point the instance must be deleted to recover memory resources. Knowing when to delete an instance, however, is difficult. Deleting the instance too soon results in program crashes; deleting it too late causes memory leaks (or excessive memory consumption). This process of allocating and releasing memory is known as memory management.

In ITK, memory management is implemented through reference counting. This compares to another popular approach—garbage collection—used by many systems, including Java. In reference counting, a count of the number of references to each instance is kept. When the reference goes to zero, the object destroys itself. In garbage collection, a background process sweeps the system identifying instances no longer referenced in the system and deletes them. The problem with garbage collection is that the actual point in time at which memory is deleted is variable. This is unacceptable when an object size may be gigantic (think of a large 3D volume gigabytes in size). Reference counting deletes memory immediately (once all references to an object disappear).

Reference counting is implemented through a `Register()/Delete()` member function interface.

All instances of an ITK object have a `Register()` method invoked on them by any other object that references them. The `Register()` method increments the instances' reference count. When the reference to the instance disappears, a `Delete()` method is invoked on the instance that decrements the reference count—this is equivalent to an `UnRegister()` method. When the reference count returns to zero, the instance is destroyed.

This protocol is greatly simplified by using a helper class called a `itk::SmartPointer`. The smart pointer acts like a regular pointer (e.g. supports operators `->` and `*`) but automatically performs a `Register()` when referring to an instance, and an `UnRegister()` when it no longer points to the instance. Unlike most other instances in ITK, `SmartPointers` can be allocated on the program stack, and are automatically deleted when the scope that the `SmartPointer` was created in is closed. As a result, you should *rarely if ever call `Register()` or `Delete()` in ITK*. For example:

```
MyRegistrationFunction()
{ /* <----- Start of scope */

    // here an interpolator is created and associated to the
    // "interp" SmartPointer.
    auto interp = InterpolatorType::New();

} /* <----- End of scope */
```

In this example, reference counted objects are created (with the `New()` method) with a reference count of one. Assignment to the `SmartPointer interp` does not change the reference count. At the end of scope, `interp` is destroyed, the reference count of the actual interpolator object (referred to by `interp`) is decremented, and if it reaches zero, then the interpolator is also destroyed.

Note that in ITK `SmartPointers` are always used to refer to instances of classes derived from `itk::LightObject`. Method invocations and function calls often return “real” pointers to instances, but they are immediately assigned to a `SmartPointer`. Raw pointers are used for non-`LightObject` classes when the need for speed and/or memory demands a smaller, faster class. Raw pointers are preferred for multi-threaded sections of code.

3.2.5 Error Handling and Exceptions

In general, ITK uses exception handling to manage errors during program execution. Exception handling is a standard part of the C++ language and generally takes the form as illustrated below:

```
try
{
    //...try executing some code here...
}
catch (const itk::ExceptionObject & exp)
{
    //...if an exception is thrown catch it here
}
```

A particular class may throw an exception as demonstrated below (this code snippet is taken from `itk::ByteSwapper`:

```
switch (sizeof(T))
{
    // non-error cases go here followed by error case
    default:
        ByteSwapperError e(__FILE__, __LINE__);
        e.SetLocation("SwapBE");
        e.SetDescription("Cannot swap number of bytes requested");
        throw e;
}
```

Note that `itk::ByteSwapperError` is a subclass of `itk::ExceptionObject`. In fact, all ITK exceptions derive from `ExceptionObject`. In this example a special constructor and C++ preprocessor variables `__FILE__` and `__LINE__` are used to instantiate the exception object and provide additional information to the user. You can choose to catch a particular exception and hence a specific ITK error, or you can trap *any* ITK exception by catching `ExceptionObject`.

3.2.6 Event Handling

Event handling in ITK is implemented using the Subject/Observer design pattern [3] (sometimes referred to as the Command/Observer design pattern). In this approach, objects indicate that they are watching for a particular event—invoked by a particular instance—by registering with the instance that they are watching. For example, filters in ITK periodically invoke the `itk::ProgressEvent`. Objects that have registered their interest in this event are notified when the event occurs. The notification occurs via an invocation of a command (i.e., function callback, method invocation, etc.) that is specified during the registration process. (Note that events in ITK are subclasses of `EventObject`; look in `itkEventObject.h` to determine which events are available.)

To recap using an example: various objects in ITK will invoke specific events as they execute (from `ProcessObject`):

```
this->InvokeEvent(ProgressEvent());
```

To watch for such an event, registration is required that associates a command (e.g., callback function) with the event: `Object::AddObserver()` method:

```
unsigned long progressTag =
    filter->AddObserver(ProgressEvent(), itk::Command *);
```

When the event occurs, all registered observers are notified via invocation of the associated `Command::Execute()` method. Note that several subclasses of `Command` are available supporting const and non-const member functions as well as C-style functions. (Look in `Modules/Core/Common/include/itkCommand.h` to find pre-defined subclasses of `Command`. If nothing suitable is found, derivation is another possibility.)

3.2.7 Multi-Threading

Multi-threading is handled in ITK through a high-level design abstraction. This approach provides portable multi-threading and hides the complexity of differing thread implementations on the many systems supported by ITK. For example, the class `itk::PlatformMultiThreader` provides support for multi-threaded execution by directly using platform-specific primitives such as `pthread_create`. `itk::TBBSMultiThreader` uses Intel's Thread Building Blocks cross-platform library, which can do dynamic workload balancing across multiple processes. This means that `outputRegionForThread` might have different sizes which change over time, depending on overall processor load. All multi-threader implementations derive from `itk::MultiThreaderBase`.

Multi-threading is typically employed by an algorithm during its execution phase. For example, in the class `itk::ImageSource` (a superclass for most image processing filters) the `GenerateData()` method uses the following methods:

```
this->GetMultiThreader()
->template ParallelizeImageRegion<OutputImageDimension>(
    this->GetOutput()->GetRequestedRegion(),
    [this](const OutputImageRegionType & outputRegionForThread) {
        this->DynamicThreadedGenerateData(outputRegionForThread);
    },
    this);
```

In this example each thread invokes `DynamicThreadedGenerateData` method of the derived filter. The `ParallelizeImageRegion` method takes care to divide the image into different regions that do not overlap for write operations. `ImageSource's GenerateData()` passes this pointer to `ParallelizeImageRegion`, which allows `ParallelizeImageRegion` to update the filter's progress after each region has been processed.

If a filter has some serial part in the middle, in addition to initialization done in `BeforeThreadedGenerateData()` and finalization done in `AfterThreadedGenerateData()`, it can parallelize more than one method in its own version of `GenerateData()`, such as done by `itk::CannyEdgeDetectionImageFilter`:

```
::GenerateData()
{
    this->UpdateProgress(0.0f);
    Superclass::AllocateOutputs();
    // Small serial section
    this->UpdateProgress(0.01f);

    ProgressTransformer progress1(0.01f, 0.45f, this);
    // Calculate 2nd order directional derivative
    this->GetMultiThreader()
        ->template ParallelizeImageRegion<TOutputImage::ImageDimension>(
            this->GetOutput()->GetRequestedRegion(),
            [this](const OutputImageRegionType & outputRegionForThread) {
                this->ThreadedCompute2ndDerivative(outputRegionForThread);
            },
            progress1.GetProcessObject());
```

```

ProgressTransformer progress2(0.45f, 0.9f, this);
// Calculate the gradient of the second derivative
this->GetMultiThreader()
->template ParallelizeImageRegion<TOutputImage::ImageDimension>(
    this->GetOutput()->GetRequestedRegion(),
    [this](const OutputImageRegionType & outputRegionForThread) {
        this->ThreadedCompute2ndDerivativePos(outputRegionForThread);
    },
    progress2.GetProcessObject());

// More processing
this->UpdateProgress(1.0f);
}

```

When invoking `ParallelizeImageRegion` multiple times from `GenerateData()`, either `nullptr` or a `itk::ProgressTransformer` object should be passed instead of `this`, otherwise progress will go from 0% to 100% more than once. And this will at least confuse any other class watching the filter's progress events, even if it does not cause a crash. So the filter's author should estimate how long each part of `GenerateData()` takes, and construct and pass `ProgressTransformer` objects as in the example above.

With ITK version 5.0, the Multi-Threading mechanism has been refactored. What was previously `itk::MultiThreader`, is now a hierarchy of classes. `itk::PlatformMultiThreader` is a slightly cleaned-up version of the old class - `MultipleMethodExecute` and `SpawnThread` methods have been deprecated. But much of its content has been moved to `itk::MultiThreaderBase`. And classes should use the multi-threaders via `MultiThreaderBase` interface, to allow the end user the flexibility to select the multi-threader at run time. This also allows the filter to benefit from future improvements in threading such as addition of a new multi-threader implementation.

The backwards compatible `ThreadedGenerateData(Region, ThreadId)` method signature has been kept, for use in filters that must know their thread number. To use this signature, a filter must invoke `this->DynamicMultiThreadingOff();` before `Update();` is called by the filter's user or downstream filter in the pipeline. The best place for invoking `this->DynamicMultiThreadingOff();` is the filter's constructor.

In image filters and other descendants of `ProcessObject`, method `SetNumberOfWorkUnits` controls the level of parallelism. Load balancing is possible when `NumberOfWorkUnits` is greater than the number of threads. In most places where developer would like to restrict number of threads, work units should be changed instead. `itk::MultiThreaderBase`'s `MaximumNumberOfThreads` should not generally be changed, except when testing performance and scalability, profiling and sometimes debugging code.

The general philosophy in ITK regarding thread safety is that accessing different instances of a class (and its methods) is a thread-safe operation. Invoking methods on the same instance in different threads is to be avoided.

3.3 Numerics

ITK uses the VNL numerics library to provide resources for numerical programming combining the ease of use of packages like Mathematica and Matlab with the speed of C and the elegance of C++. It provides a C++ interface to the high-quality Fortran routines made available in the public domain by numerical analysis researchers. ITK extends the functionality of VNL by including interface classes between VNL and ITK proper.

The VNL numerics library includes classes for:

Matrices and vectors. Standard matrix and vector support and operations on these types.

Specialized matrix and vector classes. Several special matrix and vector classes with special numerical properties are available. Class `vnل_diagonal_matrix` provides a fast and convenient diagonal matrix, while fixed size matrices and vectors allow “fast-as-C” computations (see `vnل_matrix_fixed<T,n,m>` and example subclasses `vnل_double_3x3` and `vnل_double_3`).

Matrix decompositions. Classes `vnل_svd<T>`, `vnل_symmetric_eigensystem<T>`, and `vnل_generalized_eigensystem`.

Real polynomials. Class `vnل_real_polynomial` stores the coefficients of a real polynomial, and provides methods of evaluation of the polynomial at any x , while class `vnل_rpoly_roots` provides a root finder.

Optimization. Classes `vnل_levenberg_marquardt`, `vnل_amoeba`, `vnل_conjugate_gradient`, `vnل_lbfgs` allow optimization of user-supplied functions either with or without user-supplied derivatives.

Standardized functions and constants. Class `vnل_math` defines constants (π , e , ϵ ...) and simple functions (`sqr`, `abs`, `rnd`...). Class `numeric_limits` is from the ISO standard document, and provides a way to access basic limits of a type. For example `numeric_limits<short>::max()` returns the maximum value of a short.

Most VNL routines are implemented as wrappers around the high-quality Fortran routines that have been developed by the numerical analysis community over the last forty years and placed in the public domain. The central repository for these programs is the “netlib” server.⁴ The National Institute of Standards and Technology (NIST) provides an excellent search interface to this repository in its *Guide to Available Mathematical Software (GAMS)*,⁵ both as a decision tree and a text search.

ITK also provides additional numerics functionality. A suite of optimizers, that use VNL under the hood and integrate with the registration framework are available. A large collection of statistics functions—not available from VNL—are also provided in the `Insight/Numerics/Statistics` directory. In addition, a complete finite element (FEM) package is available, primarily to support the deformable registration in ITK.

⁴<https://www.netlib.org/>

⁵<https://gams.nist.gov>

3.4 Data Representation

There are two principle types of data represented in ITK: images and meshes. This functionality is implemented in the classes `itk::Image` and `itk::Mesh`, both of which are subclasses of `itk::DataObject`. In ITK, data objects are classes that are meant to be passed around the system and may participate in data flow pipelines (see Section 3.5 on page 35 for more information).

`itk::Image` represents an n -dimensional, regular sampling of data. The sampling direction is parallel to direction matrix axes, and the origin of the sampling, inter-pixel spacing, and the number of samples in each direction (i.e., image dimension) can be specified. The sample, or pixel, type in ITK is arbitrary—a template parameter `TPixel` specifies the type upon template instantiation. (The dimensionality of the image must also be specified when the image class is instantiated.) The key is that the pixel type must support certain operations (for example, addition or difference) if the code is to compile in all cases (for example, to be processed by a particular filter that uses these operations). In practice, most applications will use a C++ primitive type (e.g., `int`, `float`) or a pre-defined pixel type and will rarely create a new type of pixel class.

One of the important ITK concepts regarding images is that rectangular, continuous pieces of the image are known as *regions*. Regions are used to specify which part of an image to process, for example in multi-threading, or which part to hold in memory. In ITK there are three common types of regions:

1. `LargestPossibleRegion`—the image in its entirety.
2. `BufferedRegion`—the portion of the image retained in memory.
3. `RequestedRegion`—the portion of the region requested by a filter or other class when operating on the image.

The `itk::Mesh` class represents an n -dimensional, unstructured grid. The topology of the mesh is represented by a set of *cells* defined by a type and connectivity list; the connectivity list in turn refers to points. The geometry of the mesh is defined by the n -dimensional points in combination with associated cell interpolation functions. `Mesh` is designed as an adaptive representational structure that changes depending on the operations performed on it. At a minimum, points and cells are required in order to represent a mesh; but it is possible to add additional topological information. For example, links from the points to the cells that use each point can be added; this provides implicit neighborhood information assuming the implied topology is the desired one. It is also possible to specify boundary cells explicitly, to indicate different connectivity from the implied neighborhood relationships, or to store information on the boundaries of cells.

The mesh is defined in terms of three template parameters: 1) a pixel type associated with the points, cells, and cell boundaries; 2) the dimension of the points (which in turn limits the maximum dimension of the cells); and 3) a “mesh traits” template parameter that specifies the types of the containers and identifiers used to access the points, cells, and/or boundaries. By using the mesh traits carefully, it is possible to create meshes better suited for editing, or those better suited for “read-only” operations, allowing a trade-off between representation flexibility, memory, and speed.

Mesh is a subclass of `itk::PointSet`. The `PointSet` class can be used to represent point clouds or randomly distributed landmarks, etc. The `PointSet` class has no associated topology.

3.5 Data Processing Pipeline

While data objects (e.g., images and meshes) are used to represent data, *process objects* are classes that operate on data objects and may produce new data objects. Process objects are classed as *sources*, *filter objects*, or *mappers*. Sources (such as readers) produce data, filter objects take in data and process it to produce new data, and mappers accept data for output either to a file or some other system. Sometimes the term *filter* is used broadly to refer to all three types.

The data processing pipeline ties together data objects (e.g., images and meshes) and process objects. The pipeline supports an automatic updating mechanism that causes a filter to execute if and only if its input or its internal state changes. Further, the data pipeline supports *streaming*, the ability to automatically break data into smaller pieces, process the pieces one by one, and reassemble the processed data into a final result.

Typically data objects and process objects are connected together using the `SetInput()` and `GetOutput()` methods as follows:

```
using FloatImage2DType = itk::Image<float, 2>;

itk::RandomImageSource<FloatImage2DType>::Pointer random;
random = itk::RandomImageSource<FloatImage2DType>::New();
random->SetMin(0.0);
random->SetMax(1.0);

itk::ShrinkImageFilter<FloatImage2DType, FloatImage2DType>::Pointer shrink;
shrink = itk::ShrinkImageFilter<FloatImage2DType, FloatImage2DType>::New();
shrink->SetInput(random->GetOutput());
shrink->SetShrinkFactors(2);

itk::ImageFileWriter<FloatImage2DType>::Pointer writer;
writer = itk::ImageFileWriter<FloatImage2DType>::New();
writer->SetInput(shrink->GetOutput());
writer->SetFileName("test.raw");
writer->Update();
```

In this example the source object `itk::RandomImageSource` is connected to the `itk::ShrinkImageFilter`, and the shrink filter is connected to the mapper `itk::ImageFileWriter`. When the `Update()` method is invoked on the writer, the data processing pipeline causes each of these filters to execute in order, culminating in writing the final data to a file on disk.

3.6 Spatial Objects

The ITK spatial object framework supports the philosophy that the task of image segmentation and registration is actually the task of object processing. The image is but one medium for representing objects of interest, and much processing and data analysis can and should occur at the object level and not based on the medium used to represent the object.

ITK spatial objects provide a common interface for accessing the physical location and geometric properties of and the relationship between objects in a scene that is independent of the form used to represent those objects. That is, the internal representation maintained by a spatial object may be a list of points internal to an object, the surface mesh of the object, a continuous or parametric representation of the object's internal points or surfaces, and so forth.

The capabilities provided by the spatial objects framework supports their use in object segmentation, registration, surface/volume rendering, and other display and analysis functions. The spatial object framework extends the concept of a “scene graph” that is common to computer rendering packages so as to support these new functions. With the spatial objects framework you can:

1. Specify a spatial object's parent and children objects. In this way, a liver may contain vessels and those vessels can be organized in a tree structure.
2. Query if a physical point is inside an object or (optionally) any of its children.
3. Request the value and derivatives, at a physical point, of an associated intensity function, as specified by an object or (optionally) its children.
4. Specify the coordinate transformation that maps a parent object's coordinate system into a child object's coordinate system.
5. Compute the bounding box of a spatial object and (optionally) its children.
6. Query the resolution at which the object was originally computed. For example, you can query the resolution (i.e., voxel spacing) of the image used to generate a particular instance of a `itk::BlobSpatialObject`.

Currently implemented types of spatial objects include: Blob, Ellipse, Group, Image, Line, Surface, and Tube. The `itk::Scene` object is used to hold a list of spatial objects that may in turn have children. Each spatial object can be assigned a color property. Each spatial object type has its own capabilities. For example, the `itk::TubeSpatialObject` indicates the point where it is connected with its parent tube.

There are a limited number of spatial objects in ITK, but their number is growing and their potential is huge. Using the nominal spatial object capabilities, methods such as marching cubes or mutual information registration can be applied to objects regardless of their internal representation. By having a common API, the same method can be used to register a parametric representation of a heart with an individual's CT data or to register two segmentations of a liver.

3.7 Wrapping

While the core of ITK is implemented in C++, Python bindings can be automatically generated and ITK programs can be created using Python. The wrapping process in ITK is capable of handling generic programming (i.e., extensive use of C++ templates). Systems like VTK, which use their own wrapping facility, are non-templated and customized to the coding methodology found in the system, like object ownership conventions. Even systems like SWIG that are designed for general wrapper generation have difficulty with ITK code because general C++ is difficult to parse. As a result, the ITK wrapper generator uses a combination of tools to produce language bindings.

1. CastXML is a Clang-based tool that produces an XML description of an input C++ program.
2. The `igenerator.py` script in the ITK source tree processes XML information produced by CastXML and generates standard input files (*.i files) to the next tool (SWIG), indicating what is to be wrapped and how to wrap it.
3. SWIG produces the appropriate Python bindings.

To learn more about the wrapping process, please see the section on module wrapping, Section 9.5. The wrapping process is orchestrated by a number of CMake macros found in the `Wrapping` directory. The result of the wrapping process is a set of shared libraries (.so in Linux or .dlls on Windows) that can be used by interpreted languages.

There is almost a direct translation from C++, with the differences being the particular syntactical requirements of each language. For example, to dilate an image using a custom structuring element using the Python wrapping:

```
inputImage = sys.argv[1]
outputImage = sys.argv[2]
radiusValue = int(sys.argv[3])

PixelType = itk.UC
Dimension = 2
ImageType = itk.Image[PixelType, Dimension]

reader = itk.ImageFileReader[ImageType].New()
reader.SetFileName(inputImage)

StructuringElementType = itk.FlatStructuringElement[Dimension]
structuringElement = StructuringElementType.Ball(radiusValue)

dilateFilter = itk.BinaryDilateImageFilter[
    ImageType, ImageType, StructuringElementType
].New()
dilateFilter.SetInput(reader.GetOutput())
dilateFilter.SetKernel(structuringElement)
```

The same code in C++ would appear as follows:

```
const char *      inputImage = argv[1];
const char *      outputImage = argv[2];
const unsigned int radiusValue = atoi(argv[3]);

using PixelType = unsigned char;
constexpr unsigned int Dimension = 2;

using ImageType = itk::Image<PixelType, Dimension>;
using ReaderType = itk::ImageFileReader<ImageType>;
auto reader = ReaderType::New();
reader->SetFileName(inputImage);

using StructuringElementType = itk::FlatStructuringElement<Dimension>;
StructuringElementType::RadiusType radius;
radius.Fill(radiusValue);
StructuringElementType structuringElement =
    StructuringElementType::Ball(radius);

using BinaryDilateImageFilterType = itk::
    BinaryDilateImageFilter<ImageType, ImageType, StructuringElementType>;

BinaryDilateImageFilterType::Pointer dilateFilter =
    BinaryDilateImageFilterType::New();
dilateFilter->SetInput(reader->GetOutput());
dilateFilter->SetKernel(structuringElement);
```

This example demonstrates an important difference between C++ and a wrapped language such as Python. Templated classes must be instantiated prior to wrapping. That is, the template parameters must be specified as part of the wrapping process. In the example above, the `ImageFileReader[ImageType]` indicates that this class, implementing an image source, has been instantiated using an input and output image type of two-dimensional unsigned char values (i.e., UC). To see the types available for a given filter, use the `.GetTypes()` method.

```
print(itk.ImageFileReader.GetTypes())
```

Typically just a few common types are selected for the wrapping process to avoid an explosion of types and hence, library size. To add a new type, re-run the wrapping process to produce new libraries. Some high-level options for these types, such as common pixels types and image dimensions, are specified during CMake configuration. The types of specific classes that should be instantiated, based on these basic options, are defined by the `*.wrap` files in the wrapping directory of a module.

Conversion of common, basic wrapped ITK classes to native Python types is supported. For example, conversion between the `itk::Index` and Python list or tuple is possible:

```
Dimension = 3
index = itk.Index[Dimension]()
index_as_tuple = tuple(index)
```

```
index_as_list = list(index)

region = itk.ImageRegion[Dimension]()
region.SetIndex((0, 2, 0))
```

The advantage of interpreted languages is that they do not require the lengthy compile/link cycle of a compiled language like C++. Moreover, they typically come with a suite of packages that provide useful functionalities. For example, the Python ecosystem provides a variety of powerful tools for creating sophisticated user interfaces. In the future it is likely that more applications and tests will be implemented in the various interpreted languages supported by ITK. Other languages like Java, Ruby, Tcl could also be wrapped in the future.

3.7.1 Python Setup

Install Stable Python Packages

Binary python packages are available in PyPI and can be installed in Python distributions downloaded from Python.org, from system package managers like *apt* or *homebrew*, or from distributions like Anaconda.

To install the ITK Python package, run:

```
python -m pip install --upgrade pip
python -m pip install itk
```

Install Latest Python Packages

Binary python packages are built nightly from the Git master branch, and they can be installed by running:

```
python -m pip install --upgrade pip
python -m pip install itk \
    -f https://github.com/InsightSoftwareConsortium/ITKPythonPackage/releases/tag/latest
```

Build Python Packages from Source

In order to access the Python interface of ITK, make sure to compile with the CMake `ITK_WRAP_PYTHON` option. In addition, choose which pixel types and dimensions to build into the wrapped interface. Supported pixel types are represented in the CMake configuration as variables named `ITK_WRAP_<pixel type>`. Supported image dimensions are enumerated in the semicolon-delimited list `ITK_WRAP_DIMS`, the default value of which is `2;3` indicating support for 2- and 3-dimensional images. The Release CMake build configuration is recommended.

After configuration, check to make sure that the values of the following variables are set correctly:

- PYTHON_INCLUDE_DIR
- PYTHON_LIBRARY
- PYTHON_EXECUTABLE

particularly if there are multiple Python installations on the system.

Python wrappers can be accessed from the build tree without installing the library. An environment to access the `itk` Python module can be configured using the Python `virtualenv` tool, which provides an isolated working copy of Python without interfering with Python installed at the system level. Once the `virtualenv` package is installed on your system, create the virtual environment within the directory ITK was built in. Copy the `WrapITK.pth` file to the `lib/python2.7/site-packages` on Unix and `Lib/site-packages` on Windows, of the `virtualenv`. For example,

```
virtualenv --system-site-packages wrapitk-venv
cd wrapitk-venv/lib/python2.7/site-packages
cp /path/to/ITK-Wrapped/Wrapping/Generators/Python/WrapITK.pth .
cd ../../../../wrapitk-venv/bin
./python /usr/bin/ipython
import itk
```

On Windows, it is also necessary to add the ITK build directory containing the `.dll` files to your `PATH` environmental variable if ITK is built with the CMake option `BUILD_SHARED_LIBS` enabled. For example, the directory containing `.dll` files for an ITK build at `C:\ITK-build` when built with Visual Studio in the Release configuration is `C:\ITK-build\bin\Release`.

DATA REPRESENTATION

This chapter introduces the basic classes responsible for representing data in ITK. The most common classes are `itk::Image`, `itk::Mesh` and `itk::PointSet`.

4.1 Image

The `itk::Image` class follows the spirit of [Generic Programming](#), where types are separated from the algorithmic behavior of the class. ITK supports images with any pixel type and any spatial dimension.

4.1.1 Creating an Image

The source code for this section can be found in the file `Image1.cxx`.

This example illustrates how to manually construct an `itk::Image` class. The following is the minimal code needed to instantiate, declare and create the `Image` class.

First, the header file of the `Image` class must be included.

```
#include "itkImage.h"
```

Then we must decide with what type to represent the pixels and what the dimension of the image will be. With these two parameters we can instantiate the `Image` class. Here we create a 3D image with unsigned short pixel data.

```
using ImageType = itk::Image<unsigned short, 3>;
```

The image can then be created by invoking the `New()` operator from the corresponding image type and assigning the result to a `itk::SmartPointer`.

```
auto image = ImageType::New();
```

In ITK, images exist in combination with one or more *regions*. A region is a subset of the image and indicates a portion of the image that may be processed by other classes in the system. One of the most common regions is the *LargestPossibleRegion*, which defines the image in its entirety. Other important regions found in ITK are the *BufferedRegion*, which is the portion of the image actually maintained in memory, and the *RequestedRegion*, which is the region requested by a filter or other class when operating on the image.

In ITK, manually creating an image requires that the image is instantiated as previously shown, and that regions describing the image are then associated with it.

A region is defined by two classes: the `itk::Index` and `itk::Size` classes. The origin of the region within the image is defined by the `Index`. The extent, or size, of the region is defined by the `Size`. When an image is created manually, the user is responsible for defining the image size and the index at which the image grid starts. These two parameters make it possible to process selected regions.

The `Index` is represented by an n-dimensional array where each component is an integer indicating—in topological image coordinates—the initial pixel of the image.

```
ImageType::IndexType start;  
  
start[0] = 0; // first index on X  
start[1] = 0; // first index on Y  
start[2] = 0; // first index on Z
```

The region size is represented by an array of the same dimension as the image (using the `itk::Size` class). The components of the array are unsigned integers indicating the extent in pixels of the image along every dimension.

```
ImageType::SizeType size;  
  
size[0] = 200; // size along X  
size[1] = 200; // size along Y  
size[2] = 200; // size along Z
```

Having defined the starting index and the image size, these two parameters are used to create an `itk::ImageRegion` object which basically encapsulates both concepts. The region is initialized with the starting index and size of the image.

```
ImageType::RegionType region;  
  
region.SetSize(size);  
region.SetIndex(start);
```

Finally, the region is passed to the `Image` object in order to define its extent and origin. The `SetRegions` method sets the *LargestPossibleRegion*, *BufferedRegion*, and *RequestedRegion* simultaneously. Note that none of the operations performed to this point have allocated memory for the image pixel data. It is necessary to invoke the `Allocate()` method to do this. `Allocate` does not require any arguments since all the information needed for memory allocation has already been provided by the region.

```
image->SetRegions(region);  
image->Allocate();
```

In practice it is rare to allocate and initialize an image directly. Images are typically read from a source, such as a file or data acquisition hardware. The following example illustrates how an image can be read from a file.

4.1.2 Reading an Image from a File

The source code for this section can be found in the file `Image2.cxx`.

The first thing required to read an image from a file is to include the header file of the `itk::ImageFileReader` class.

```
#include "itkImageFileReader.h"
```

Then, the image type should be defined by specifying the type used to represent pixels and the dimensions of the image.

```
using PixelType = unsigned char;  
constexpr unsigned int Dimension = 3;  
  
using ImageType = itk::Image<PixelType, Dimension>;
```

Using the image type, it is now possible to instantiate the image reader class. The image type is used as a template parameter to define how the data will be represented once it is loaded into memory. This type does not have to correspond exactly to the type stored in the file. However, a conversion based on C-style type casting is used, so the type chosen to represent the data on disk must be sufficient to characterize it accurately. Readers do not apply any transformation to the pixel data other than casting from the pixel type of the file to the pixel type of the `ImageFileReader`. The following illustrates a typical instantiation of the `ImageFileReader` type.

```
using ReaderType = itk::ImageFileReader<ImageType>;
```

The reader type can now be used to create one reader object. A `itk::SmartPointer` (defined by the `::Pointer` notation) is used to receive the reference to the newly created reader. The `New()` method is invoked to create an instance of the image reader.

```
auto reader = ReaderType::New();
```

The minimal information required by the reader is the filename of the image to be loaded in memory. This is provided through the `SetFileName()` method. The file format here is inferred from the filename extension. The user may also explicitly specify the data format using the `itk::ImageIOBase` class (a list of possibilities can be found in the inheritance diagram of this class.).

```
const char * filename = argv[1];  
reader->SetFileName(filename);
```

Reader objects are referred to as pipeline source objects; they respond to pipeline update requests and initiate the data flow in the pipeline. The pipeline update mechanism ensures that the reader only executes when a data request is made to the reader and the reader has not read any data. In the current example we explicitly invoke the `Update()` method because the output of the reader is not connected to other filters. In normal application the reader's output is connected to the input of an image filter and the update invocation on the filter triggers an update of the reader. The following line illustrates how an explicit update is invoked on the reader.

```
reader->Update();
```

Access to the newly read image can be gained by calling the `GetOutput()` method on the reader. This method can also be called before the update request is sent to the reader. The reference to the image will be valid even though the image will be empty until the reader actually executes.

```
ImageType::Pointer image = reader->GetOutput();
```

Any attempt to access image data before the reader executes will yield an image with no pixel data. It is likely that a program crash will result since the image will not have been properly initialized.

4.1.3 Accessing Pixel Data

The source code for this section can be found in the file `Image3.cxx`.

This example illustrates the use of the `SetPixel()` and `GetPixel()` methods. These two methods provide direct access to the pixel data contained in the image. Note that these two methods are relatively slow and should not be used in situations where high-performance access is required. Image iterators are the appropriate mechanism to efficiently access image pixel data. (See Chapter 6 on page 137 for information about image iterators.)

The individual position of a pixel inside the image is identified by a unique index. An index is an array of integers that defines the position of the pixel along each dimension of the image. The

`IndexType` is automatically defined by the image and can be accessed using the scope operator `itk::Index`. The length of the array will match the dimensions of the associated image.

The following code illustrates the declaration of an index variable and the assignment of values to each of its components. Please note that no `SmartPointer` is used to access the `Index`. This is because `Index` is a lightweight object that is not intended to be shared between objects. It is more efficient to produce multiple copies of these small objects than to share them using the `SmartPointer` mechanism.

The following lines declare an instance of the index type and initialize its content in order to associate it with a pixel position in the image.

```
const ImageType::IndexType pixelIndex = {  
    { 27, 29, 37 }  
}; // Position of {X,Y,Z}
```

Having defined a pixel position with an index, it is then possible to access the content of the pixel in the image. The `GetPixel()` method allows us to get the value of the pixels.

```
ImageType::PixelType pixelValue = image->GetPixel(pixelIndex);
```

The `SetPixel()` method allows us to set the value of the pixel.

```
image->SetPixel(pixelIndex, pixelValue + 1);
```

Please note that `GetPixel()` returns the pixel value using copy and not reference semantics. Hence, the method cannot be used to modify image data values.

Remember that both `SetPixel()` and `GetPixel()` are inefficient and should only be used for debugging or for supporting interactions like querying pixel values by clicking with the mouse.

4.1.4 Defining Origin and Spacing

The source code for this section can be found in the file `Image4.cxx`.

Even though **ITK** can be used to perform general image processing tasks, the primary purpose of the toolkit is the processing of medical image data. In that respect, additional information about the images is considered mandatory. In particular the information associated with the physical spacing between pixels and the position of the image in space with respect to some world coordinate system are extremely important.

Image origin, voxel directions (i.e. orientation), and spacing are fundamental to many applications. Registration, for example, is performed in physical coordinates. Improperly defined spacing, direction, and origins will result in inconsistent results in such processes. Medical images with no spatial

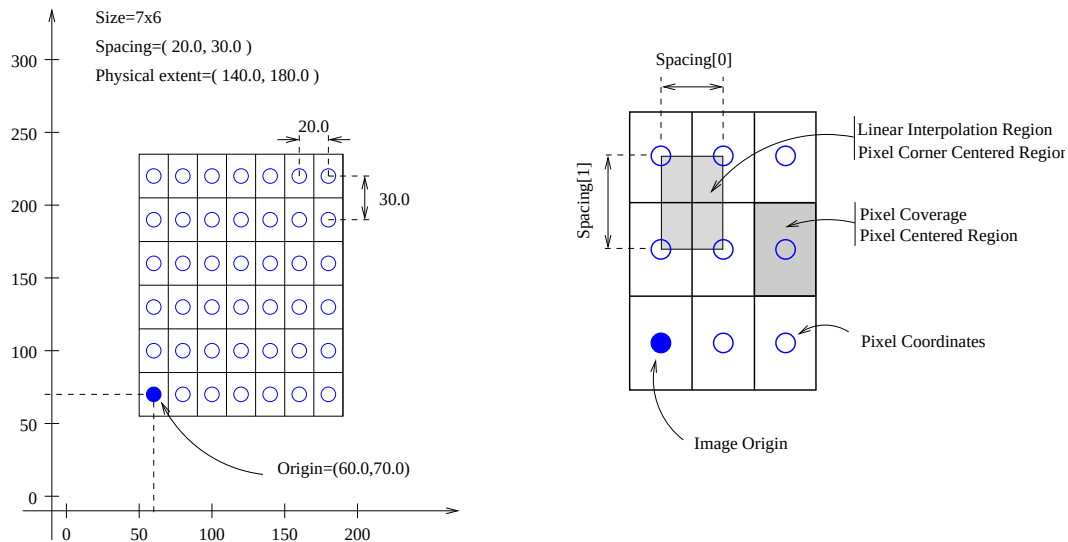


Figure 4.1: Geometrical concepts associated with the ITK image.

information should not be used for medical diagnosis, image analysis, feature extraction, assisted radiation therapy or image guided surgery. In other words, medical images lacking spatial information are not only useless but also hazardous.

Figure 4.1 illustrates the main geometrical concepts associated with the `itk::Image`. In this figure, circles are used to represent the center of pixels. The value of the pixel is assumed to exist as a Dirac delta function located at the pixel center. Pixel spacing is measured between the pixel centers and can be different along each dimension. The image origin is associated with the coordinates of the first pixel in the image. For this simplified example, the voxel lattice is perfectly aligned with physical space orientation, and the image direction is therefore an identity mapping. If the voxel lattice samples were rotated with respect to physical space, then the image direction would contain a rotation matrix.

A *pixel* is considered to be the rectangular region surrounding the pixel center holding the data value.

Image spacing is represented in a `FixedArray` whose size matches the dimension of the image. In order to manually set the spacing of the image, an array of the corresponding type must be created. The elements of the array should then be initialized with the spacing between the centers of adjacent pixels. The following code illustrates the methods available in the `itk::Image` class for dealing with spacing and origin.

```
ImageType::SpacingType spacing;

// Units (e.g., mm, inches, etc.) are defined by the application.
spacing[0] = 0.33; // spacing along X
spacing[1] = 0.33; // spacing along Y
```

```
spacing[2] = 1.20; // spacing along Z
```

The array can be assigned to the image using the `SetSpacing()` method.

```
image->SetSpacing(spacing);
```

The spacing information can be retrieved from an image by using the `GetSpacing()` method. This method returns a reference to a `FixedArray`. The returned object can then be used to read the contents of the array. Note the use of the `const` keyword to indicate that the array will not be modified.

```
const ImageType::SpacingType & sp = image->GetSpacing();

std::cout << "Spacing = ";
std::cout << sp[0] << ", " << sp[1] << ", " << sp[2] << std::endl;
```

The image origin is managed in a similar way to the spacing. A `Point` of the appropriate dimension must first be allocated. The coordinates of the origin can then be assigned to every component. These coordinates correspond to the position of the first pixel of the image with respect to an arbitrary reference system in physical space. It is the user's responsibility to make sure that multiple images used in the same application are using a consistent reference system. This is extremely important in image registration applications.

The following code illustrates the creation and assignment of a variable suitable for initializing the image origin.

```
// coordinates of the center of the first pixel in N-D
ImageType::PointType newOrigin;
newOrigin.Fill(0.0);
image->SetOrigin(newOrigin);
```

The origin can also be retrieved from an image by using the `GetOrigin()` method. This will return a reference to a `Point`. The reference can be used to read the contents of the array. Note again the use of the `const` keyword to indicate that the array contents will not be modified.

```
const ImageType::PointType & origin = image->GetOrigin();

std::cout << "Origin = ";
std::cout << origin[0] << ", " << origin[1] << ", " << origin[2]
    << std::endl;
```

The image direction matrix represents the orientation relationships between the image samples and physical space coordinate systems. The image direction matrix is an orthonormal matrix that describes the possible permutation of image index values and the rotational aspects that are needed

to properly reconcile image index organization with physical space axis. The image directions is a $N \times N$ matrix where N is the dimension of the image. An identity image direction indicates that increasing values of the 1st, 2nd, 3rd index element corresponds to increasing values of the 1st, 2nd and 3rd physical space axis respectively, and that the voxel samples are perfectly aligned with the physical space axis.

The following code illustrates the creation and assignment of a variable suitable for initializing the image direction with an identity.

```
// coordinates of the center of the first pixel in N-D
ImageType::DirectionType direction;
direction.SetIdentity();
image->SetDirection(direction);
```

The direction can also be retrieved from an image by using the `GetDirection()` method. This will return a reference to a `Matrix`. The reference can be used to read the contents of the array. Note again the use of the `const` keyword to indicate that the matrix contents can not be modified.

```
const ImageType::DirectionType & direct = image->GetDirection();

std::cout << "Direction = " << std::endl;
std::cout << direct << std::endl;
```

Once the spacing, origin, and direction of the image samples have been initialized, the image will correctly map pixel indices to and from physical space coordinates. The following code illustrates how a point in physical space can be mapped into an image index for the purpose of reading the content of the closest pixel.

First, a `itk::Point` type must be declared. The point type is templated over the type used to represent coordinates and over the dimension of the space. In this particular case, the dimension of the point must match the dimension of the image.

```
using PointType = itk::Point<double, ImageType::ImageDimension>;
```

The `itk::Point` class, like an `itk::Index`, is a relatively small and simple object. This means that no `itk::SmartPointer` is used here and the objects are simply declared as instances, like any other C++ class. Once the point is declared, its components can be accessed using traditional array notation. In particular, the `[]` operator is available. For efficiency reasons, no bounds checking is performed on the index used to access a particular point component. It is the user's responsibility to make sure that the index is in the range $\{0, Dimension - 1\}$.

```
PointType point;
point[0] = 1.45; // x coordinate
point[1] = 7.21; // y coordinate
point[2] = 9.28; // z coordinate
```


The image will map the point to an index using the values of the current spacing and origin. An index object must be provided to receive the results of the mapping. The index object can be instantiated by using the `IndexType` defined in the image type.

```
ImageType::IndexType pixelIndex;
```

The `TransformPhysicalPointToIndex()` method of the image class will compute the pixel index closest to the point provided. The method checks for this index to be contained inside the current buffered pixel data. The method returns a boolean indicating whether the resulting index falls inside the buffered region or not. The output index should not be used when the returned value of the method is false.

The following lines illustrate the point to index mapping and the subsequent use of the pixel index for accessing pixel data from the image.

```
const bool isInside =
    image->TransformPhysicalPointToIndex(point, pixelIndex);
if (isInside)
{
    ImageType::PixelType pixelValue = image->GetPixel(pixelIndex);
    pixelValue += 5;
    image->SetPixel(pixelIndex, pixelValue);
}
```

Remember that `GetPixel()` and `SetPixel()` are very inefficient methods for accessing pixel data. Image iterators should be used when massive access to pixel data is required.

The following example illustrates the mathematical relationships between image index locations and its corresponding physical point representation for a given `Image`.

Let us imagine that a graphical user interface exists where the end user manually selects the voxel index location of the left eye in a volume with a mouse interface. We need to convert that index location to a physical location so that laser guided surgery can be accurately performed. The `TransformIndexToPhysicalPoint` method can be used for this.

```
const ImageType::IndexType LeftEyeIndex = GetIndexFromMouseClicked();
ImageType::PointType LeftEyePoint;
image->TransformIndexToPhysicalPoint(LeftEyeIndex, LeftEyePoint);
```

For a given index $\vec{I}$ in 3D, the physical location $\vec{P}$ is calculated as following:

$$\begin{pmatrix} P_1 \\ P_2 \\ P_3 \end{pmatrix} = \begin{pmatrix} O_1 \\ O_2 \\ O_3 \end{pmatrix} + \begin{pmatrix} D_{1,1} & D_{1,2} & D_{1,3} \\ D_{2,1} & D_{2,2} & D_{2,3} \\ D_{3,1} & D_{3,2} & D_{3,3} \end{pmatrix} * \begin{pmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_3 \end{pmatrix} * \begin{pmatrix} I_1 \\ I_2 \\ I_3 \end{pmatrix} \quad (4.1)$$

Where:

$\vec{I}$: image space index.

$\vec{P}$: resulting physical space position of the image index $\vec{I}$.

$\vec{O}$: physical space origin of the first image index.

$\mathcal{D}$: direction cosines matrix (orthonormal). It represents the orientation relationship between the image and the physical space coordinate system.

$\vec{S}$: physical spacing between pixels of the same axis.

The operation can be thought as a particular case of the linear transform:

$$\vec{P} = \vec{O} + \mathcal{A} \cdot \vec{I} \quad (4.2)$$

where $\mathcal{A}$:

$$\mathcal{A} = \begin{pmatrix} D_{1,1} \cdot S_1 & D_{1,2} \cdot S_2 & D_{1,3} \cdot S_3 \\ D_{2,1} \cdot S_1 & D_{2,2} \cdot S_2 & D_{2,3} \cdot S_3 \\ D_{3,1} \cdot S_1 & D_{3,2} \cdot S_2 & D_{3,3} \cdot S_3 \end{pmatrix} \quad (4.3)$$

In matlab syntax the conversions are:

```
% Non-identity Spacing and Direction
spacing=diag( [0.9375, 0.9375, 1.5] );
direction=[0.998189, 0.0569345, -0.0194113;
0.0194429, -7.38061e-08, 0.999811;
0.0569237, -0.998378, -0.00110704];
point = origin + direction * spacing * LeftEyeIndex
```

A corresponding mathematical expansion of the C/C++ code is:

```
using MatrixType =
    itk::Matrix<itk::SpacePrecisionType, Dimension, Dimension>;
MatrixType SpacingMatrix;
SpacingMatrix.Fill(0.0F);

const ImageType::SpacingType & ImageSpacing = image->GetSpacing();
SpacingMatrix(0, 0) = ImageSpacing[0];
SpacingMatrix(1, 1) = ImageSpacing[1];
SpacingMatrix(2, 2) = ImageSpacing[2];

const ImageType::DirectionType & ImageDirectionCosines =
    image->GetDirection();
const ImageType::PointType & ImageOrigin = image->GetOrigin();

using VectorType = itk::Vector<double, Dimension>;
VectorType LeftEyeIndexVector;
LeftEyeIndexVector[0] = LeftEyeIndex[0];
LeftEyeIndexVector[1] = LeftEyeIndex[1];
LeftEyeIndexVector[2] = LeftEyeIndex[2];

ImageType::PointType LeftEyePointByHand =
    ImageOrigin + ImageDirectionCosines * SpacingMatrix * LeftEyeIndexVector;
```

4.1.5 RGB Images

The term RGB (Red, Green, Blue) stands for a color representation commonly used in digital imaging. RGB is a representation of the human physiological capability to analyze visual light using three spectral-selective sensors [7, 9]. The human retina possess different types of light sensitive cells. Three of them, known as *cones*, are sensitive to color [5] and their regions of sensitivity loosely match regions of the spectrum that will be perceived as red, green and blue respectively. The *rods* on the other hand provide no color discrimination and favor high resolution and high sensitivity.¹ A fifth type of receptors, the *ganglion cells*, also known as circadian² receptors are sensitive to the lighting conditions that differentiate day from night. These receptors evolved as a mechanism for synchronizing the physiology with the time of the day. Cellular controls for circadian rhythms are present in every cell of an organism and are known to be exquisitely precise [6].

The RGB space has been constructed as a representation of a physiological response to light by the three types of *cones* in the human eye. RGB is not a Vector space. For example, negative numbers are not appropriate in a color space because they will be the equivalent of “negative stimulation” on the human eye. In the context of colorimetry, negative color values are used as an artificial construct for color comparison in the sense that

$$ColorA = ColorB - ColorC \quad (4.4)$$

is just a way of saying that we can produce *ColorB* by combining *ColorA* and *ColorC*. However, we must be aware that (at least in emitted light) it is not possible to *subtract light*. So when we mention Equation 4.4 we actually mean

$$ColorB = ColorA + ColorC \quad (4.5)$$

On the other hand, when dealing with printed color and with paint, as opposed to emitted light like in computer screens, the physical behavior of color allows for subtraction. This is because strictly speaking the objects that we see as red are those that absorb all light frequencies except those in the red section of the spectrum [9].

The concept of addition and subtraction of colors has to be carefully interpreted. In fact, RGB has a different definition regarding whether we are talking about the channels associated to the three color sensors of the human eye, or to the three phosphors found in most computer monitors or to the color inks that are used for printing reproduction. Color spaces are usually non linear and do not even form a group. For example, not all visible colors can be represented in RGB space [9].

ITK introduces the `itk::RGBPixel` type as a support for representing the values of an RGB color space. As such, the `RGBPixel` class embodies a different concept from the one of an `itk::Vector` in space. For this reason, the `RGBPixel` lacks many of the operators that may be naively expected from it. In particular, there are no defined operations for subtraction or addition.

¹The human eye is capable of perceiving a single isolated photon.

²The term *Circadian* refers to the cycle of day and night, that is, events that are repeated with 24 hours intervals.

When you intend to find the “Mean” of two `RGBType` pixels, you are assuming that the color in the visual “middle” of the two input pixels can be calculated through a linear operation on their numerical representation. This is unfortunately not the case in color spaces due to the fact that they are based on a human physiological response [7].

If you decide to interpret RGB images as simply three independent channels then you should rather use the `itk::Vector` type as pixel type. In this way, you will have access to the set of operations that are defined in Vector spaces. The current implementation of the `RGBPixel` in ITK presumes that RGB color images are intended to be used in applications where a formal interpretation of color is desired, therefore only the operations that are valid in a color space are available in the `RGBPixel` class.

The following example illustrates how RGB images can be represented in ITK.

The source code for this section can be found in the file `RGBImage.cxx`.

Thanks to the flexibility offered by the [Generic Programming](#) style on which ITK is based, it is possible to instantiate images of arbitrary pixel type. The following example illustrates how a color image with RGB pixels can be defined.

A class intended to support the RGB pixel type is available in ITK. You could also define your own pixel class and use it to instantiate a custom image type. In order to use the `itk::RGBPixel` class, it is necessary to include its header file.

```
#include "itkRGBPixel.h"
```

The RGB pixel class is templated over a type used to represent each one of the red, green and blue pixel components. A typical instantiation of the templated class is as follows.

```
using PixelType = itk::RGBPixel<unsigned char>;
```

The type is then used as the pixel template parameter of the image.

```
using ImageType = itk::Image<PixelType, 3>;
```

The image type can be used to instantiate other filter, for example, an `itk::ImageFileReader` object that will read the image from a file.

```
using ReaderType = itk::ImageFileReader<ImageType>;
```

Access to the color components of the pixels can now be performed using the methods provided by the `RGBPixel` class.

```
PixelType onePixel = image->GetPixel(pixelIndex);
```

```
PixelType::ValueType red = onePixel.GetRed();
PixelType::ValueType green = onePixel.GetGreen();
PixelType::ValueType blue = onePixel.GetBlue();
```

The subindex notation can also be used since the `itk::RGBPixel` inherits the `[]` operator from the `itk::FixedArray` class.

```
red = onePixel[0]; // extract Red component
green = onePixel[1]; // extract Green component
blue = onePixel[2]; // extract Blue component

std::cout << "Pixel values:" << std::endl;
std::cout << "Red = "
    << itk::NumericTraits<PixelType::ValueType>::PrintType(red)
    << std::endl;
std::cout << "Green = "
    << itk::NumericTraits<PixelType::ValueType>::PrintType(green)
    << std::endl;
std::cout << "Blue = "
    << itk::NumericTraits<PixelType::ValueType>::PrintType(blue)
    << std::endl;
```

4.1.6 Vector Images

The source code for this section can be found in the file `VectorImage.cxx`.

Many image processing tasks require images of non-scalar pixel type. A typical example is an image of vectors. This is the image type required to represent the gradient of a scalar image. The following code illustrates how to instantiate and use an image whose pixels are of vector type.

For convenience we use the `itk::Vector` class to define the pixel type. The `Vector` class is intended to represent a geometrical vector in space. It is not intended to be used as an array container like the `std::vector` in `STL`. If you are interested in containers, the `itk::VectorContainer` class may provide the functionality you want.

The first step is to include the header file of the `Vector` class.

```
#include "itkVector.h"
```

The `Vector` class is templated over the type used to represent the coordinate in space and over the dimension of the space. In this example, we want the vector dimension to match the image dimension, but this is by no means a requirement. We could have defined a four-dimensional image with three-dimensional vectors as pixels.

```
using PixelType = itk::Vector<float, 3>;
using ImageType = itk::Image<PixelType, 3>;
```

The `Vector` class inherits the operator `[]` from the `itk::FixedArray` class. This makes it possible to access the `Vector`'s components using index notation.

```
ImageType::PixelType pixelValue;
pixelValue[0] = 1.345; // x component
pixelValue[1] = 6.841; // y component
pixelValue[2] = 3.295; // z component
```

We can now store this vector in one of the image pixels by defining an index and invoking the `SetPixel()` method.

```
image->SetPixel(pixelIndex, pixelValue);
```

4.1.7 Importing Image Data from a Buffer

The source code for this section can be found in the file `Image5.cxx`.

This example illustrates how to import data into the `itk::Image` class. This is particularly useful for interfacing with other software systems. Many systems use a contiguous block of memory as a buffer for image pixel data. The current example assumes this is the case and feeds the buffer into an `itk::ImportImageFilter`, thereby producing an image as output.

Here we create a synthetic image with a centered sphere in a locally allocated buffer and pass this block of memory to the `ImportImageFilter`. This example is set up so that on execution, the user must provide the name of an output file as a command-line argument.

First, the header file of the `itk::ImportImageFilter` class must be included.

```
#include "itkImage.h"
#include "itkImportImageFilter.h"
```

Next, we select the data type used to represent the image pixels. We assume that the external block of memory uses the same data type to represent the pixels.

```
using PixelType = unsigned char;
constexpr unsigned int Dimension = 3;

using ImageType = itk::Image<PixelType, Dimension>;
```

The type of the `ImportImageFilter` is instantiated in the following line.

```
using ImportFilterType = itk::ImportImageFilter<PixelType, Dimension>;
```

A filter object created using the `New()` method is then assigned to a `SmartPointer`.

```
auto importFilter = ImportFilterType::New();
```

This filter requires the user to specify the size of the image to be produced as output. The `SetRegion()` method is used to this end. The image size should exactly match the number of pixels available in the locally allocated buffer.

```
ImportFilterType::SizeType size;

size[0] = 200; // size along X
size[1] = 200; // size along Y
size[2] = 200; // size along Z

ImportFilterType::IndexType start;
start.Fill(0);

ImportFilterType::RegionType region;
region.SetIndex(start);
region.SetSize(size);

importFilter->SetRegion(region);
```

The origin of the output image is specified with the `SetOrigin()` method.

```
const itk::SpacePrecisionType origin[Dimension] = { 0.0, 0.0, 0.0 };
importFilter->SetOrigin(origin);
```

The spacing of the image is passed with the `SetSpacing()` method.

```
// spacing isotropic volumes to 1.0
const itk::SpacePrecisionType spacing[Dimension] = { 1.0, 1.0, 1.0 };
importFilter->SetSpacing(spacing);
```

Next we allocate the memory block containing the pixel data to be passed to the `ImportImageFilter`. Note that we use exactly the same size that was specified with the `SetRegion()` method. In a practical application, you may get this buffer from some other library using a different data structure to represent the images.

```
const unsigned int numberOfPixels = size[0] * size[1] * size[2];
auto * localBuffer = new PixelType[numberOfPixels];
```

Here we fill up the buffer with a binary sphere. We use simple `for()` loops here, similar to those found in the C or FORTRAN programming languages. Note that ITK does not use `for()` loops in its internal code to access pixels. All pixel access tasks are instead performed using an `itk::ImageIterator` that supports the management of n-dimensional images.

```
constexpr double radius2 = radius * radius;
PixelType *      it = localBuffer;

for (unsigned int z = 0; z < size[2]; ++z)
{
    const double dz =
        static_cast<double>(z) - static_cast<double>(size[2]) / 2.0;
    for (unsigned int y = 0; y < size[1]; ++y)
    {
        const double dy =
            static_cast<double>(y) - static_cast<double>(size[1]) / 2.0;
        for (unsigned int x = 0; x < size[0]; ++x)
        {
            const double dx =
                static_cast<double>(x) - static_cast<double>(size[0]) / 2.0;
            const double d2 = dx * dx + dy * dy + dz * dz;
            *it++ = (d2 < radius2) ? 255 : 0;
        }
    }
}
```

The buffer is passed to the `ImportImageFilter` with the `SetImportPointer()` method. Note that the last argument of this method specifies who will be responsible for deleting the memory block once it is no longer in use. A false value indicates that the `ImportImageFilter` will not try to delete the buffer when its destructor is called. A true value, on the other hand, will allow the filter to delete the memory block upon destruction of the import filter.

For the `ImportImageFilter` to appropriately delete the memory block, the memory must be allocated with the C++ `new()` operator. Memory allocated with other memory allocation mechanisms, such as C `malloc` or `calloc`, will not be deleted properly by the `ImportImageFilter`. In other words, it is the application programmer's responsibility to ensure that `ImportImageFilter` is only given permission to delete the C++ `new` operator-allocated memory.

```
const bool importImageFilterWillOwnTheBuffer = true;
importFilter->SetImportPointer(
    localBuffer, numberOfPixels, importImageFilterWillOwnTheBuffer);
```

Finally, we can connect the output of this filter to a pipeline. For simplicity we just use a writer here, but it could be any other filter.

```
using WriterType = itk::ImageFileWriter<ImageType>;
auto writer = WriterType::New();

writer->SetFileName(argv[1]);
writer->SetInput(importFilter->GetOutput());
```

Note that we do not call `delete` on the buffer since we pass `true` as the last argument of `SetImportPointer()`. Now the buffer is owned by the `ImportImageFilter`.

4.2 PointSet

4.2.1 Creating a PointSet

The source code for this section can be found in the file `PointSet1.cxx`.

The `itk::PointSet` is a basic class intended to represent geometry in the form of a set of points in N -dimensional space. It is the base class for the `itk::Mesh` providing the methods necessary to manipulate sets of points. Points can have values associated with them. The type of such values is defined by a template parameter of the `itk::PointSet` class (i.e., `TPixelType`). Two basic interaction styles of PointSets are available in ITK. These styles are referred to as *static* and *dynamic*. The first style is used when the number of points in the set is known in advance and is not expected to change as a consequence of the manipulations performed on the set. The dynamic style, on the other hand, is intended to support insertion and removal of points in an efficient manner. Distinguishing between the two styles is meant to facilitate the fine tuning of a `PointSet`'s behavior while optimizing performance and memory management.

In order to use the `PointSet` class, its header file should be included.

```
#include "itkPointSet.h"
```

Then we must decide what type of value to associate with the points. This is generally called the `PixelType` in order to make the terminology consistent with the `itk::Image`. The `PointSet` is also templated over the dimension of the space in which the points are represented. The following declaration illustrates a typical instantiation of the `PointSet` class.

```
using PointSetType = itk::PointSet<unsigned short, 3>;
```

A `PointSet` object is created by invoking the `New()` method on its type. The resulting object must be assigned to a `SmartPointer`. The `PointSet` is then reference-counted and can be shared by multiple objects. The memory allocated for the `PointSet` will be released when the number of references to the object is reduced to zero. This simply means that the user does not need to be concerned with invoking the `Delete()` method on this class. In fact, the `Delete()` method should **never** be called directly within any of the reference-counted ITK classes.

```
auto pointsSet = PointSetType::New();
```

Following the principles of Generic Programming, the `PointSet` class has a set of associated defined types to ensure that interacting objects can be declared with compatible types. This set of type definitions is commonly known as a set of *traits*. Among the traits of the `PointSet` class is `PointType`, which is used by the point set to represent points in space. The following declaration takes the point type as defined in the `PointSet` traits and renames it to be conveniently used in the global namespace.

```
using PointType = PointSetType::PointType;
```

The `PointType` can now be used to declare point objects to be inserted in the `PointSet`. Points are fairly small objects, so it is inconvenient to manage them with reference counting and smart pointers. They are simply instantiated as typical C++ classes. The `Point` class inherits the `[]` operator from the `itk::Array` class. This makes it possible to access its components using index notation. For efficiency's sake no bounds checking is performed during index access. It is the user's responsibility to ensure that the index used is in the range $\{0, \text{Dimension} - 1\}$. Each of the components in the point is associated with space coordinates. The following code illustrates how to instantiate a point and initialize its components.

```
PointType p0;
p0[0] = -1.0; // x coordinate
p0[1] = -1.0; // y coordinate
p0[2] = 0.0; // z coordinate
```

Points are inserted in the `PointSet` by using the `SetPoint()` method. This method requires the user to provide a unique identifier for the point. The identifier is typically an unsigned integer that will enumerate the points as they are being inserted. The following code shows how three points are inserted into the `PointSet`.

```
pointsSet->SetPoint(0, p0);
pointsSet->SetPoint(1, p1);
pointsSet->SetPoint(2, p2);
```

It is possible to query the `PointSet` in order to determine how many points have been inserted into it. This is done with the `GetNumberOfPoints()` method as illustrated below.

```
const unsigned int numberOfPoints = pointsSet->GetNumberOfPoints();
std::cout << numberOfPoints << std::endl;
```

Points can be read from the `PointSet` by using the `GetPoint()` method and the integer identifier. The point is stored in a pointer provided by the user. If the identifier provided does not match an existing point, the method will return `false` and the contents of the point will be invalid. The following code illustrates point access using defensive programming.

```
PointType pp;
bool pointExists = pointsSet->GetPoint(1, &pp);

if (pointExists)
{
    std::cout << "Point is = " << pp << std::endl;
}
```

`GetPoint()` and `SetPoint()` are not the most efficient methods to access points in the `PointSet`. It is preferable to get direct access to the internal point container defined by the *traits* and use iterators to walk sequentially over the list of points (as shown in the following example).

4.2.2 Getting Access to Points

The source code for this section can be found in the file `PointSet2.cxx`.

The `itk::PointSet` class uses an internal container to manage the storage of `itk::Points`. It is more efficient, in general, to manage points by using the access methods provided directly on the points container. The following example illustrates how to interact with the point container and how to use point iterators.

The type is defined by the *traits* of the `PointSet` class. The following line conveniently takes the `PointsContainer` type from the `PointSet` traits and declares it in the global namespace.

```
using PointsContainer = PointSetType::PointsContainer;
```

The actual type of `PointsContainer` depends on what style of `PointSet` is being used. The dynamic `PointSet` uses `itk::MapContainer` while the static `PointSet` uses `itk::VectorContainer`. The vector and map containers are basically ITK wrappers around the STL classes `std::map` and `std::vector`. By default, `PointSet` uses a static style, and therefore the default type of point container is `VectorContainer`. Both map and vector containers are templated over the type of element they contain. In this case they are templated over `PointType`. Containers are reference counted objects, created with the `New()` method and assigned to a `itk::SmartPointer`. The following line creates a point container compatible with the type of the `PointSet` from which the trait has been taken.

```
auto points = PointsContainer::New();
```

Points can now be defined using the `PointType` trait from the `PointSet`.

```
using PointType = PointSetType::PointType;
PointType p0;
PointType p1;
p0[0] = -1.0;
p0[1] = 0.0;
p0[2] = 0.0; // Point 0 = { -1, 0, 0 }
p1[0] = 1.0;
p1[1] = 0.0;
p1[2] = 0.0; // Point 1 = { 1, 0, 0 }
```

The created points can be inserted in the `PointsContainer` using the generic method `InsertElement()` which requires an identifier to be provided for each point.

```
unsigned int pointId = 0;
points->InsertElement(pointId++, p0);
points->InsertElement(pointId++, p1);
```

Finally, the `PointsContainer` can be assigned to the `PointSet`. This will substitute any previously existing `PointsContainer` assigned to the `PointSet`. The assignment is done using the `SetPoints()` method.

```
pointSet->SetPoints(points);
```

The `PointsContainer` object can be obtained from the `PointSet` using the `GetPoints()` method. This method returns a pointer to the actual container owned by the `PointSet` which is then assigned to a `SmartPointer`.

```
PointsContainer::Pointer points2 = pointSet->GetPoints();
```

The most efficient way to sequentially visit the points is to use the iterators provided by `PointsContainer`. The `Iterator` type belongs to the traits of the `PointsContainer` classes. It behaves pretty much like the STL iterators.³ The `Points` iterator is not a reference counted class, so it is created directly from the traits without using `SmartPointers`.

```
using PointsIterator = PointsContainer::Iterator;
```

The subsequent use of the iterator follows what you may expect from a STL iterator. The iterator to the first point is obtained from the container with the `Begin()` method and assigned to another iterator.

```
PointsIterator pointIterator = points->Begin();
```

The `++` operator on the iterator can be used to advance from one point to the next. The actual value of the Point to which the iterator is pointing can be obtained with the `Value()` method. The loop for walking through all the points can be controlled by comparing the current iterator with the iterator returned by the `End()` method of the `PointsContainer`. The following lines illustrate the typical loop for walking through the points.

```
PointsIterator end = points->End();
while (pointIterator != end)
{
    PointType p = pointIterator.Value(); // access the point
    std::cout << p << std::endl;       // print the point
    ++pointIterator;                   // advance to next point
}
```

Note that as in STL, the iterator returned by the `End()` method is not a valid iterator. This is called a past-end iterator in order to indicate that it is the value resulting from advancing one step after visiting the last element in the container.

³If you dig deep enough into the code, you will discover that these iterators are actually ITK wrappers around STL iterators.

The number of elements stored in a container can be queried with the `Size()` method. In the case of the `PointSet`, the following two lines of code are equivalent, both of them returning the number of points in the `PointSet`.

```
std::cout << pointSet->GetNumberOfPoints() << std::endl;
std::cout << pointSet->GetPoints()->Size() << std::endl;
```

4.2.3 Getting Access to Data in Points

The source code for this section can be found in the file `PointSet3.cxx`.

The `itk::PointSet` class was designed to interact with the `Image` class. For this reason it was found convenient to allow the points in the set to hold values that could be computed from images. The value associated with the point is referred as `PixelType` in order to make it consistent with image terminology. Users can define the type as they please thanks to the flexibility offered by the Generic Programming approach used in the toolkit. The `PixelType` is the first template parameter of the `PointSet`.

The following code defines a particular type for a pixel type and instantiates a `PointSet` class with it.

```
using PixelType = unsigned short;
using PointSetType = itk::PointSet<PixelType, 3>;
```

Data can be inserted into the `PointSet` using the `SetPointData()` method. This method requires the user to provide an identifier. The data in question will be associated to the point holding the same identifier. It is the user's responsibility to verify the appropriate matching between inserted data and inserted points. The following line illustrates the use of the `SetPointData()` method.

```
unsigned int dataId = 0;
PixelType value = 79;
pointSet->SetPointData(dataId++, value);
```

Data associated with points can be read from the `PointSet` using the `GetPointData()` method. This method requires the user to provide the identifier to the point and a valid pointer to a location where the pixel data can be safely written. In case the identifier does not match any existing identifier on the `PointSet` the method will return `false` and the pixel value returned will be invalid. It is the user's responsibility to check the returned boolean value before attempting to use it.

```
const bool found = pointSet->GetPointData(dataId, &value);
if (found)
{
    std::cout << "Pixel value = " << value << std::endl;
}
```

The `SetPointData()` and `GetPointData()` methods are not the most efficient way to get access to point data. It is far more efficient to use the Iterators provided by the `PointDataContainer`.

Data associated with points is internally stored in `PointDataContainers`. In the same way as with points, the actual container type used depend on whether the style of the `PointSet` is static or dynamic. Static point sets will use an `itk::VectorContainer` while dynamic point sets will use an `itk::MapContainer`. The type of the data container is defined as one of the traits in the `PointSet`. The following declaration illustrates how the type can be taken from the traits and used to conveniently declare a similar type on the global namespace.

```
using PointDataContainer = PointSetType::PointDataContainer;
```

Using the type it is now possible to create an instance of the data container. This is a standard reference counted object, henceforth it uses the `New()` method for creation and assigns the newly created object to a `SmartPointer`.

```
auto pointData = PointDataContainer::New();
```

Pixel data can be inserted in the container with the method `InsertElement()`. This method requires an identified to be provided for each point data.

```
unsigned int pointId = 0;

PixelType value0 = 34;
PixelType value1 = 67;

pointData->InsertElement(pointId++, value0);
pointData->InsertElement(pointId++, value1);
```

Finally the `PointDataContainer` can be assigned to the `PointSet`. This will substitute any previously existing `PointDataContainer` on the `PointSet`. The assignment is done using the `SetPointData()` method.

```
pointSet->SetPointData(pointData);
```

The `PointDataContainer` can be obtained from the `PointSet` using the `GetPointData()` method. This method returns a pointer (assigned to a `SmartPointer`) to the actual container owned by the `PointSet`.

```
PointDataContainer::Pointer pointData2 = pointSet->GetPointData();
```

The most efficient way to sequentially visit the data associated with points is to use the iterators provided by `PointDataContainer`. The `Iterator` type belongs to the traits of the `PointsContainer` classes. The iterator is not a reference counted class, so it is just created directly from the traits without using `SmartPointers`.

```
using PointDataIterator = PointDataContainer::Iterator;
```

The subsequent use of the iterator follows what you may expect from a STL iterator. The iterator to the first point is obtained from the container with the `Begin()` method and assigned to another iterator.

```
PointDataIterator pointDataIterator = pointData2->Begin();
```

The `++` operator on the iterator can be used to advance from one data point to the next. The actual value of the `PixelType` to which the iterator is pointing can be obtained with the `Value()` method. The loop for walking through all the point data can be controlled by comparing the current iterator with the iterator returned by the `End()` method of the `PointsContainer`. The following lines illustrate the typical loop for walking through the point data.

```
PointDataIterator end = pointData2->End();
while (pointDataIterator != end)
{
    PixelType p = pointDataIterator.Value(); // access the pixel data
    std::cout << p << std::endl;           // print the pixel data
    ++pointDataIterator;                    // advance to next pixel/point
}
```

Note that as in STL, the iterator returned by the `End()` method is not a valid iterator. This is called a *past-end* iterator in order to indicate that it is the value resulting from advancing one step after visiting the last element in the container.

4.2.4 RGB as Pixel Type

The source code for this section can be found in the file `RGBPointSet.cxx`.

The following example illustrates how a point set can be parameterized to manage a particular pixel type. In this case, pixels of RGB type are used. The first step is then to include the header files of the `itk::RGBPixel` and `itk::PointSet` classes.

```
#include "itkRGBPixel.h"
#include "itkPointSet.h"
```

Then, the pixel type can be defined by selecting the type to be used to represent each one of the RGB components.

```
using PixelType = itk::RGBPixel<float>;
```

The newly defined pixel type is now used to instantiate the `PointSet` type and subsequently create a point set object.

```
using PointSetType = itk::PointSet<PixelType, 3>;
auto pointSet = PointSetType::New();
```

The following code generates a circle and assigns RGB values to the points. The components of the RGB values in this example are computed to represent the position of the points.

```
PointSetType::PixelType pixel;
PointSetType::PointType point;
unsigned int      pointId = 0;
constexpr double  radius = 3.0;

for (unsigned int i = 0; i < 360; ++i)
{
    const double angle = i * itk::Math::pi / 180.0;
    point[0] = radius * std::sin(angle);
    point[1] = radius * std::cos(angle);
    point[2] = 1.0;
    pixel.SetRed(point[0] * 2.0);
    pixel.SetGreen(point[1] * 2.0);
    pixel.SetBlue(point[2] * 2.0);
    pointSet->SetPoint(pointId, point);
    pointSet->SetPointData(pointId, pixel);
    pointId++;
}
```

All the points on the `PointSet` are visited using the following code.

```
using PointIterator = PointSetType::PointsContainer::ConstIterator;
PointIterator pointIterator = pointSet->GetPoints()->Begin();
PointIterator pointEnd = pointSet->GetPoints()->End();
while (pointIterator != pointEnd)
{
    point = pointIterator.Value();
    std::cout << point << std::endl;
    ++pointIterator;
}
```

Note that here the `ConstIterator` was used instead of the `Iterator` since the pixel values are not expected to be modified. ITK supports const-correctness at the API level.

All the pixel values on the `PointSet` are visited using the following code.

```
using PointDataIterator = PointSetType::PointDataContainer::ConstIterator;
PointDataIterator pixelIterator = pointSet->GetPointData()->Begin();
PointDataIterator pixelEnd = pointSet->GetPointData()->End();
while (pixelIterator != pixelEnd)
```



```

{
    pixel = pixelIterator.Value();
    std::cout << pixel << std::endl;
    ++pixelIterator;
}

```

Again, please note the use of the `ConstIterator` instead of the `Iterator`.

4.2.5 Vectors as Pixel Type

The source code for this section can be found in the file `PointSetWithVectors.cxx`.

This example illustrates how a point set can be parameterized to manage a particular pixel type. It is quite common to associate vector values with points for producing geometric representations. The following code shows how vector values can be used as the pixel type on the `PointSet` class. The `itk::Vector` class is used here as the pixel type. This class is appropriate for representing the relative position between two points. It could then be used to manage displacements, for example.

In order to use the vector class it is necessary to include its header file along with the header of the point set.

```

#include "itkVector.h"
#include "itkPointSet.h"

```

The `Vector` class is templated over the type used to represent the spatial coordinates and over the space dimension. Since the `PixelType` is independent of the `PointType`, we are free to select any dimension for the vectors to be used as pixel type. However, for the sake of producing an interesting example, we will use vectors that represent displacements of the points in the `PointSet`. Those vectors are then selected to be of the same dimension as the `PointSet`.

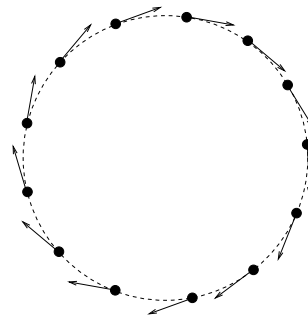


Figure 4.2: Vectors as `PixelType`.

```

constexpr unsigned int Dimension = 3;
using PixelType = itk::Vector<float, Dimension>;

```

Then we use the `PixelType` (which are actually `Vectors`) to instantiate the `PointSet` type and subsequently create a `PointSet` object.

```
using PointSetType = itk::PointSet<PixelType, Dimension>;
auto pointSet = PointSetType::New();
```

The following code is generating a sphere and assigning vector values to the points. The components of the vectors in this example are computed to represent the tangents to the circle as shown in Figure 4.2.

```
PointSetType::PixelType tangent;
PointSetType::PointType point;

unsigned int    pointId = 0;
constexpr double radius = 300.0;

for (unsigned int i = 0; i < 360; ++i)
{
    const double angle = i * itk::Math::pi / 180.0;
    point[0] = radius * std::sin(angle);
    point[1] = radius * std::cos(angle);
    point[2] = 1.0; // flat on the Z plane
    tangent[0] = std::cos(angle);
    tangent[1] = -std::sin(angle);
    tangent[2] = 0.0; // flat on the Z plane
    pointSet->SetPoint(pointId, point);
    pointSet->SetPointData(pointId, tangent);
    pointId++;
}
```

We can now visit all the points and use the vector on the pixel values to apply a displacement on the points. This is along the spirit of what a deformable model could do at each one of its iterations.

```
using PointDataIterator = PointSetType::PointDataContainer::ConstIterator;
PointDataIterator pixelIterator = pointSet->GetPointData()->Begin();
PointDataIterator pixelEnd = pointSet->GetPointData()->End();

using PointIterator = PointSetType::PointsContainer::Iterator;
PointIterator pointIterator = pointSet->GetPoints()->Begin();
PointIterator pointEnd = pointSet->GetPoints()->End();

while (pixelIterator != pixelEnd && pointIterator != pointEnd)
{
    pointIterator.Value() = pointIterator.Value() + pixelIterator.Value();
    ++pixelIterator;
    ++pointIterator;
}
```

Note that the `ConstIterator` was used here instead of the normal `Iterator` since the pixel values are only intended to be read and not modified. ITK supports const-correctness at the API level.

The `itk::Vector` class has overloaded the `+` operator with the `itk::Point`. In other words, vectors can be added to points in order to produce new points. This property is exploited in the center of the loop in order to update the points positions with a single statement.

We can finally visit all the points and print out the new values

```
pointIterator = pointSet->GetPoints()->Begin();
pointEnd = pointSet->GetPoints()->End();
while (pointIterator != pointEnd)
{
    std::cout << pointIterator.Value() << std::endl;
    ++pointIterator;
}
```

Note that `itk::Vector` is not the appropriate class for representing normals to surfaces and gradients of functions. This is due to the way vectors behave under affine transforms. ITK has a specific class for representing normals and function gradients. This is the `itk::CovariantVector` class.

4.2.6 Normals as Pixel Type

The source code for this section can be found in the file `PointSetWithCovariantVectors.cxx`.

It is common to represent geometric objects by using points on their surfaces and normals associated with those points. This structure can be easily instantiated with the `itk::PointSet` class.

The natural class for representing normals to surfaces and gradients of functions is the `itk::CovariantVector`. A covariant vector differs from a vector in the way it behaves under affine transforms, in particular under anisotropic scaling. If a covariant vector represents the gradient of a function, the transformed covariant vector will still be the valid gradient of the transformed function, a property which would not hold with a regular vector.

The following example demonstrates how a `CovariantVector` can be used as the `PixelType` for the `PointSet` class. The example illustrates how a deformable model could move under the influence of the gradient of a potential function.

In order to use the `CovariantVector` class it is necessary to include its header file along with the header of the point set.

```
#include "itkCovariantVector.h"
#include "itkPointSet.h"
```

The `CovariantVector` class is templated over the type used to represent the spatial coordinates and over the space dimension. Since the `PixelType` is independent of the `PointType`, we are free to select any dimension for the covariant vectors to be used as pixel type. However, we want to illustrate here the spirit of a deformable model. It is then required for the vectors representing gradients to be of the same dimension as the points in space.

```
constexpr unsigned int Dimension = 3;
using PixelType = itk::CovariantVector<float, Dimension>;
```

Then we use the `PixelType` (which are actually `CovariantVectors`) to instantiate the `PointSet` type and subsequently create a `PointSet` object.

```
using PointSetType = itk::PointSet<PixelType, Dimension>;
auto pointSet = PointSetType::New();
```

The following code generates a circle and assigns gradient values to the points. The components of the `CovariantVectors` in this example are computed to represent the normals to the circle.

```
PointSetType::PixelType gradient;
PointSetType::PointType point;

unsigned int    pointId = 0;
constexpr double radius = 300.0;

for (unsigned int i = 0; i < 360; ++i)
{
    const double angle = i * std::atan(1.0) / 45.0;
    point[0] = radius * std::sin(angle);
    point[1] = radius * std::cos(angle);
    point[2] = 1.0; // flat on the Z plane
    gradient[0] = std::sin(angle);
    gradient[1] = std::cos(angle);
    gradient[2] = 0.0; // flat on the Z plane
    pointSet->SetPoint(pointId, point);
    pointSet->SetPointData(pointId, gradient);
    pointId++;
}
```

We can now visit all the points and use the vector on the pixel values to apply a deformation on the points by following the gradient of the function. This is along the spirit of what a deformable model could do at each one of its iterations. To be more formal we should use the function gradients as forces and multiply them by local stress tensors in order to obtain local deformations. The resulting deformations would finally be used to apply displacements on the points. However, to shorten the example, we will ignore this complexity for the moment.

```
using PointDataIterator = PointSetType::PointDataContainer::ConstIterator;
PointDataIterator pixelIterator = pointSet->GetPointData()->Begin();
PointDataIterator pixelEnd = pointSet->GetPointData()->End();

using PointIterator = PointSetType::PointsContainer::Iterator;
PointIterator pointIterator = pointSet->GetPoints()->Begin();
PointIterator pointEnd = pointSet->GetPoints()->End();

while (pixelIterator != pixelEnd && pointIterator != pointEnd)
{
    point = pointIterator.Value();
    gradient = pixelIterator.Value();
    for (unsigned int i = 0; i < Dimension; ++i)
    {
```

```
    point[i] += gradient[i];  
  }  
  pointIterator.Value() = point;  
  ++pixelIterator;  
  ++pointIterator;  
}
```

The `CovariantVector` class does not overload the `+` operator with the `itk::Point`. In other words, `CovariantVectors` can not be added to points in order to get new points. Further, since we are ignoring physics in the example, we are also forced to do the illegal addition manually between the components of the gradient and the coordinates of the points.

Note that the absence of some basic operators on the ITK geometry classes is completely intentional with the aim of preventing the incorrect use of the mathematical concepts they represent.

4.3 Mesh

4.3.1 Creating a Mesh

The source code for this section can be found in the file `Mesh1.cxx`.

The `itk::Mesh` class is intended to represent shapes in space. It derives from the `itk::PointSet` class and hence inherits all the functionality related to points and access to the pixel-data associated with the points. The mesh class is also N -dimensional which allows a great flexibility in its use.

In practice a `Mesh` class can be seen as a `PointSet` to which cells (also known as elements) of many different dimensions and shapes have been added. Cells in the mesh are defined in terms of the existing points using their point-identifiers.

As with `PointSet`, a `Mesh` object may be *static* or *dynamic*. The first is used when the number of points in the set is known in advance and not expected to change as a consequence of the manipulations performed on the set. The dynamic style, on the other hand, is intended to support insertion and removal of points in an efficient manner. In addition to point management, the distinction facilitates optimization of performance and memory management of cells.

In order to use the `Mesh` class, its header file should be included.

```
#include "itkMesh.h"
```

Then, the type associated with the points must be selected and used for instantiating the `Mesh` type.

```
using PixelType = float;
```

The `Mesh` type extensively uses the capabilities provided by [Generic Programming](#). In particular, the `Mesh` class is parameterized over `PixelType`, spatial dimension, and (optionally) a parameter set

called `MeshTraits`. `PixelType` is the type of the value associated with each point (just as is done with `PointSet`). The following illustrates a typical instantiation of `Mesh`.

```
constexpr unsigned int Dimension = 3;
using MeshType = itk::Mesh<PixelType, Dimension>;
```

Meshes typically require large amounts of memory. For this reason, they are reference counted objects, managed using `itk::SmartPointers`. The following line illustrates how a mesh is created by invoking the `New()` method on `MeshType` and assigning the result to a `SmartPointer`.

```
auto mesh = MeshType::New();
```

Management of points in a `Mesh` is identical to that in a `PointSet`. The type of point associated with the mesh can be obtained through the `PointType` trait. The following code shows the creation of points compatible with the mesh type defined above and the assignment of values to its coordinates.

```
MeshType::PointType p0;
MeshType::PointType p1;
MeshType::PointType p2;
MeshType::PointType p3;

p0[0] = -1.0;
p0[1] = -1.0;
p0[2] = 0.0; // first point ( -1, -1, 0 )
p1[0] = 1.0;
p1[1] = -1.0;
p1[2] = 0.0; // second point ( 1, -1, 0 )
p2[0] = 1.0;
p2[1] = 1.0;
p2[2] = 0.0; // third point ( 1, 1, 0 )
p3[0] = -1.0;
p3[1] = 1.0;
p3[2] = 0.0; // fourth point ( -1, 1, 0 )
```

The points can now be inserted into the `Mesh` using the `SetPoint()` method. Note that points are copied into the mesh structure, meaning that the local instances of the points can now be modified without affecting the `Mesh` content.

```
mesh->SetPoint(0, p0);
mesh->SetPoint(1, p1);
mesh->SetPoint(2, p2);
mesh->SetPoint(3, p3);
```

The current number of points in a mesh can be queried with the `GetNumberOfPoints()` method.

```
std::cout << "Points = " << mesh->GetNumberOfPoints() << std::endl;
```

The points can now be efficiently accessed using the `Iterator` to the `PointsContainer` as was done in the previous section for the `PointSet`.

```
using PointsIterator = MeshType::PointsContainer::Iterator;
```

A point iterator is initialized to the first point with the `Begin()` method of the `PointsContainer`.

```
PointsIterator pointIterator = mesh->GetPoints()->Begin();
```

The `++` operator is used to advance the iterator from one point to the next. The value associated with the `Point` to which the iterator is pointing is obtained with the `Value()` method. The loop for walking through all the points is controlled by comparing the current iterator with the iterator returned by the `End()` method of the `PointsContainer`. The following illustrates the typical loop for walking through the points of a mesh.

```
PointsIterator end = mesh->GetPoints()->End();
while (pointIterator != end)
{
    MeshType::PointType p = pointIterator.Value(); // access the point
    std::cout << p << std::endl;                 // print the point
    ++pointIterator;                             // advance to next point
}
```

4.3.2 Inserting Cells

The source code for this section can be found in the file `Mesh2.cxx`.

A `itk::Mesh` can contain a variety of cell types. Typical cells are the `itk::LineCell`, `itk::TriangleCell`, `itk::QuadrilateralCell`, `itk::TetrahedronCell`, and `itk::PolygonCell`. Additional flexibility is provided for managing cells at the price of a bit more of complexity than in the case of point management.

The following code creates a polygonal line in order to illustrate the simplest case of cell management in a mesh. The only cell type used here is the `LineCell`. The header file of this class must be included.

```
#include "itkLineCell.h"
```

For consistency with `Mesh`, cell types have to be configured with a number of custom types taken from the mesh traits. The set of traits relevant to cells are packaged by the `Mesh` class into the `CellType` trait. This trait needs to be passed to the actual cell types at the moment of their instantiation. The following line shows how to extract the `Cell` traits from the `Mesh` type.

```
using CellType = MeshType::CellType;
```

The `LineCell` type can now be instantiated using the traits taken from the `Mesh`.

```
using LineType = itk::LineCell<CellType>;
```

The main difference in the way cells and points are managed by the `Mesh` is that points are stored by copy on the `PointsContainer` while cells are stored as pointers in the `CellsContainer`. The reason for using pointers is that cells use C++ polymorphism on the mesh. This means that the mesh is only aware of having pointers to a generic cell which is the base class of all the specific cell types. This architecture makes it possible to combine different cell types in the same mesh. Points, on the other hand, are of a single type and have a small memory footprint, which makes it efficient to copy them directly into the container.

Managing cells by pointers adds another level of complexity to the `Mesh` since it is now necessary to establish a protocol to make clear who is responsible for allocating and releasing the cells' memory. This protocol is implemented in the form of a specific type of pointer called the `CellAutoPointer`. This pointer, based on the `itk::AutoPointer`, differs in many respects from the `SmartPointer`. The `CellAutoPointer` has an internal pointer to the actual object and a boolean flag that indicates whether the `CellAutoPointer` is responsible for releasing the cell memory when the time comes for its own destruction. It is said that a `CellAutoPointer` *owns* the cell when it is responsible for its destruction. At any given time many `CellAutoPointers` can point to the same cell, but only **one** `CellAutoPointer` can own the cell.

The `CellAutoPointer` trait is defined in the `MeshType` and can be extracted as follows.

```
using CellAutoPointer = CellType::CellAutoPointer;
```

Note that the `CellAutoPointer` points to a generic cell type. It is not aware of the actual type of the cell, which could be (for example) a `LineCell`, `TriangleCell` or `TetrahedronCell`. This fact will influence the way in which we access cells later on.

At this point we can actually create a mesh and insert some points on it.

```
auto mesh = MeshType::New();

MeshType::PointType p0;
MeshType::PointType p1;
MeshType::PointType p2;

p0[0] = -1.0;
p0[1] = 0.0;
p0[2] = 0.0;
p1[0] = 1.0;
p1[1] = 0.0;
p1[2] = 0.0;
p2[0] = 1.0;
p2[1] = 1.0;
p2[2] = 0.0;
```



```
mesh->SetPoint(0, p0);  
mesh->SetPoint(1, p1);  
mesh->SetPoint(2, p2);
```

The following code creates two `CellAutoPointers` and initializes them with newly created cell objects. The actual cell type created in this case is `LineType`. Note that cells are created with the normal `new C++` operator. The `CellAutoPointer` takes ownership of the received pointer by using the method `TakeOwnership()`. Even though this may seem verbose, it is necessary in order to make it explicit that the responsibility of memory release is assumed by the `AutoPointer`.

```
CellAutoPointer line0;  
CellAutoPointer line1;  
  
line0.TakeOwnership(new LineType);  
line1.TakeOwnership(new LineType);
```

The `LineCells` should now be associated with points in the mesh. This is done using the identifiers assigned to points when they were inserted in the mesh. Every cell type has a specific number of points that must be associated with it.⁴ For example, a `LineCell` requires two points, a `TriangleCell` requires three, and a `TetrahedronCell` requires four. Cells use an internal numbering system for points. It is simply an index in the range $\{0, \text{NumberOfPoints} - 1\}$. The association of points and cells is done by the `SetPointId()` method, which requires the user to provide the internal index of the point in the cell and the corresponding `PointIdentifier` in the `Mesh`. The internal cell index is the first parameter of `SetPointId()` while the mesh point-identifier is the second.

```
line0->SetPointId(0, 0); // line between points 0 and 1  
line0->SetPointId(1, 1);  
  
line1->SetPointId(0, 1); // line between points 1 and 2  
line1->SetPointId(1, 2);
```

Cells are inserted in the mesh using the `SetCell()` method. It requires an identifier and the `AutoPointer` to the cell. The `Mesh` will take ownership of the cell to which the `CellAutoPointer` is pointing. This is done internally by the `SetCell()` method. In this way, the destruction of the `CellAutoPointer` will not induce the destruction of the associated cell.

```
mesh->SetCell(0, line0);  
mesh->SetCell(1, line1);
```

After serving as an argument of the `SetCell()` method, a `CellAutoPointer` no longer holds ownership of the cell. It is important not to use this same `CellAutoPointer` again as argument to `SetCell()` without first securing ownership of another cell.

The number of Cells currently inserted in the mesh can be queried with the `GetNumberOfCells()` method.

⁴Some cell types like polygons have a variable number of points associated with them.

```
std::cout << "Cells = " << mesh->GetNumberOfCells() << std::endl;
```

In a way analogous to points, cells can be accessed using Iterators to the CellsContainer in the mesh. The trait for the cell iterator can be extracted from the mesh and used to define a local type.

```
using CellIterator = MeshType::CellsContainer::Iterator;
```

Then the iterators to the first and past-end cell in the mesh can be obtained respectively with the `Begin()` and `End()` methods of the CellsContainer. The CellsContainer of the mesh is returned by the `GetCells()` method.

```
CellIterator cellIterator = mesh->GetCells()->Begin();
CellIterator end = mesh->GetCells()->End();
```

Finally, a standard loop is used to iterate over all the cells. Note the use of the `Value()` method used to get the actual pointer to the cell from the CellIterator. Note also that the value returned is a pointer to the generic CellType. This pointer must be downcast in order to be used as actual LineCell types. Safe down-casting is performed with the `dynamic_cast` operator, which will throw an exception if the conversion cannot be safely performed.

```
while (cellIterator != end)
{
    MeshType::CellType * cellptr = cellIterator.Value();
    auto * line = dynamic_cast<LineType *>(cellptr);
    if (line == nullptr)
    {
        continue;
    }
    std::cout << line->GetNumberOfPoints() << std::endl;
    ++cellIterator;
}
```

4.3.3 Managing Data in Cells

The source code for this section can be found in the file `Mesh3.cxx`.

Just as custom data can be associated with points in the mesh, it is also possible to associate custom data with cells. The type of the data associated with the cells can be different from the data type associated with points. By default, however, these two types are the same. The following example illustrates how to access data associated with cells. The approach is analogous to the one used to access point data.

Consider the example of a mesh containing lines on which values are associated with each line. The mesh and cell header files should be included first.

```
#include "itkMesh.h"
#include "itkLineCell.h"
```

Then the `PixelType` is defined and the mesh type is instantiated with it.

```
using PixelType = float;
using MeshType = itk::Mesh<PixelType, 2>;
```

The `itk::LineCell` type can now be instantiated using the traits taken from the `Mesh`.

```
using CellType = MeshType::CellType;
using LineType = itk::LineCell<CellType>;
```

Let's now create a `Mesh` and insert some points into it. Note that the dimension of the points matches the dimension of the `Mesh`. Here we insert a sequence of points that look like a plot of the `log()` function. We add the `vnl_math::eps` value in order to avoid numerical errors when the point id is zero. The value of `vnl_math::eps` is the difference between 1.0 and the least value greater than 1.0 that is representable in this computer.

```
auto mesh = MeshType::New();

using PointType = MeshType::PointType;
PointType point;

constexpr unsigned int numberOfPoints = 10;
for (unsigned int id = 0; id < numberOfPoints; ++id)
{
    point[0] = static_cast<PointType::ValueType>(id); // x
    point[1] = std::log(static_cast<double>(id) + itk::Math::eps); // y
    mesh->SetPoint(id, point);
}
```

A set of line cells is created and associated with the existing points by using point identifiers. In this simple case, the point identifiers can be deduced from cell identifiers since the line cells are ordered in the same way.

```
CellType::CellAutoPointer line;
const unsigned int numberOfCells = numberOfPoints - 1;
for (unsigned int cellId = 0; cellId < numberOfCells; ++cellId)
{
    line.TakeOwnership(new LineType);
    line->SetPointId(0, cellId); // first point
    line->SetPointId(1, cellId + 1); // second point
    mesh->SetCell(cellId, line); // insert the cell
}
```

Data associated with cells is inserted in the `itk::Mesh` by using the `SetCellData()` method. It requires the user to provide an identifier and the value to be inserted. The identifier should match

one of the inserted cells. In this simple example, the square of the cell identifier is used as cell data. Note the use of `static_cast` to `PixelType` in the assignment.

```
for (unsigned int cellId = 0; cellId < numberOfCells; ++cellId)
{
    mesh->SetCellData(cellId, static_cast<PixelType>(cellId * cellId));
}
```

Cell data can be read from the Mesh with the `GetCellData()` method. It requires the user to provide the identifier of the cell for which the data is to be retrieved. The user should provide also a valid pointer to a location where the data can be copied.

```
for (unsigned int cellId = 0; cellId < numberOfCells; ++cellId)
{
    auto value = static_cast<PixelType>(0.0);
    mesh->GetCellData(cellId, &value);
    std::cout << "Cell " << cellId << " = " << value << std::endl;
}
```

Neither `SetCellData()` or `GetCellData()` are efficient ways to access cell data. More efficient access to cell data can be achieved by using the Iterators built into the `CellDataContainer`.

```
using CellDataIterator = MeshType::CellDataContainer::ConstIterator;
```

Note that the `ConstIterator` is used here because the data is only going to be read. This approach is exactly the same already illustrated for getting access to point data. The iterator to the first cell data item can be obtained with the `Begin()` method of the `CellDataContainer`. The past-end iterator is returned by the `End()` method. The cell data container itself can be obtained from the mesh with the method `GetCellData()`.

```
CellDataIterator cellDataIterator = mesh->GetCellData()->Begin();
CellDataIterator end = mesh->GetCellData()->End();
```

Finally, a standard loop is used to iterate over all the cell data entries. Note the use of the `Value()` method to get the value associated with the data entry. `PixelType` elements are copied into the local variable `cellValue`.

```
while (cellDataIterator != end)
{
    PixelType cellValue = cellDataIterator.Value();
    std::cout << cellValue << std::endl;
    ++cellDataIterator;
}
```

4.3.4 Customizing the Mesh

The source code for this section can be found in the file `MeshTraits.cxx`.

This section illustrates the full power of [Generic Programming](#). This is sometimes perceived as *too much of a good thing*!

The toolkit has been designed to offer flexibility while keeping the complexity of the code to a moderate level. This is achieved in the Mesh by hiding most of its parameters and defining reasonable defaults for them.

The generic concept of a mesh integrates many different elements. It is possible in principle to use independent types for every one of such elements. The mechanism used in generic programming for specifying the many different types involved in a concept is called *traits*. They are basically the list of all types that interact with the current class.

The `itk::Mesh` is templated over three parameters. So far only two of them have been discussed, namely the `PixelType` and the `Dimension`. The third parameter is a class providing the set of traits required by the mesh. When the third parameter is omitted a default class is used. This default class is the `itk::DefaultStaticMeshTraits`. If you want to customize the types used by the mesh, the way to proceed is to modify the default traits and provide them as the third parameter of the Mesh class instantiation.

There are two ways of achieving this. The first is to use the existing `itk::DefaultStaticMeshTraits` class. This class is itself templated over six parameters. Customizing those parameters could provide enough flexibility to define a very specific kind of mesh. The second way is to write a traits class from scratch, in which case the easiest way to proceed is to copy the `DefaultStaticMeshTraits` into another file and edit its content. Only the first approach is illustrated here. The second is discouraged unless you are familiar with Generic Programming, feel comfortable with C++ templates, and have access to an abundant supply of (Colombian) coffee.

The first step in customizing the mesh is to include the header file of the Mesh and its static traits.

```
#include "itkMesh.h"
#include "itkDefaultStaticMeshTraits.h"
```

Then the MeshTraits class is instantiated by selecting the types of each one of its six template arguments. They are in order

PixelType. The value type associated with every point.

PointDimension. The dimension of the space in which the mesh is embedded.

MaxTopologicalDimension. The highest dimension of the mesh cells.

CoordRepType. The type used to represent spacial coordinates.

InterpolationWeightType. The type used to represent interpolation weights.

CellPixelType. The value type associated with every cell.

Let's define types and values for each one of those elements. For example, the following code uses points in 3D space as nodes of the Mesh. The maximum dimension of the cells will be two, meaning that this is a 2D manifold better known as a *surface*. The data type associated with points is defined to be a four-dimensional vector. This type could represent values of membership for a four-class segmentation method. The value selected for the cells are 4×3 matrices, which could have for example the derivative of the membership values with respect to coordinates in space. Finally, a double type is selected for representing space coordinates on the mesh points and also for the weight used for interpolating values.

```
constexpr unsigned int PointDimension = 3;
constexpr unsigned int MaxTopologicalDimension = 2;

using PixelType = itk::Vector<double, 4>;
using CellDataType = itk::Matrix<double, 4, 3>;

using CoordinateType = double;
using InterpolationWeightType = double;

using MeshTraits = itk::DefaultStaticMeshTraits<PixelType,
                                                PointDimension,
                                                MaxTopologicalDimension,
                                                CoordinateType,
                                                InterpolationWeightType,
                                                CellDataType>;

using MeshType = itk::Mesh<PixelType, PointDimension, MeshTraits>;
```

The `itk::LineCell` type can now be instantiated using the traits taken from the Mesh.

```
using CellType = MeshType::CellType;
using LineType = itk::LineCell<CellType>;
```

Let's now create an Mesh and insert some points on it. Note that the dimension of the points matches the dimension of the Mesh. Here we insert a sequence of points that look like a plot of the $\log()$ function.

```
auto mesh = MeshType::New();

using PointType = MeshType::PointType;
PointType point;

constexpr unsigned int numberOfPoints = 10;
for (unsigned int id = 0; id < numberOfPoints; ++id)
{
```

```

point[0] = 1.565; // Initialize points here
point[1] = 3.647; // with arbitrary values
point[2] = 4.129;
mesh->SetPoint(id, point);
}

```

A set of line cells is created and associated with the existing points by using point identifiers. In this simple case, the point identifiers can be deduced from cell identifiers since the line cells are ordered in the same way. Note that in the code above, the values assigned to point components are arbitrary. In a more realistic example, those values would be computed from another source.

```

CellType::CellAutoPointer line;
const unsigned int      numberOfCells = numberOfPoints - 1;
for (unsigned int cellId = 0; cellId < numberOfCells; ++cellId)
{
    line.TakeOwnership(new LineType);
    line->SetPointId(0, cellId); // first point
    line->SetPointId(1, cellId + 1); // second point
    mesh->SetCell(cellId, line); // insert the cell
}

```

Data associated with cells is inserted in the Mesh by using the `SetCellData()` method. It requires the user to provide an identifier and the value to be inserted. The identifier should match one of the inserted cells. In this example, we simply store a `CellDataType` dummy variable named `value`.

```

for (unsigned int cellId = 0; cellId < numberOfCells; ++cellId)
{
    CellDataType value;
    mesh->SetCellData(cellId, value);
}

```

Cell data can be read from the Mesh with the `GetCellData()` method. It requires the user to provide the identifier of the cell for which the data is to be retrieved. The user should provide also a valid pointer to a location where the data can be copied.

```

for (unsigned int cellId = 0; cellId < numberOfCells; ++cellId)
{
    CellDataType value;
    mesh->GetCellData(cellId, &value);
    std::cout << "Cell " << cellId << " = " << value << std::endl;
}

```

Neither `SetCellData()` or `GetCellData()` are efficient ways to access cell data. Efficient access to cell data can be achieved by using the Iterators built into the `CellDataContainer`.

```

using CellDataIterator = MeshType::CellDataContainer::ConstIterator;

```

Note that the `ConstIterator` is used here because the data is only going to be read. This approach is identical to that already illustrated for accessing point data. The iterator to the first cell data item can be obtained with the `Begin()` method of the `CellDataContainer`. The past-end iterator is returned by the `End()` method. The cell data container itself can be obtained from the mesh with the method `GetCellData()`.

```
CellDataIterator cellDataIterator = mesh->GetCellData()->Begin();
CellDataIterator end = mesh->GetCellData()->End();
```

Finally a standard loop is used to iterate over all the cell data entries. Note the use of the `Value()` method used to get the actual value of the data entry. `PixelType` elements are returned by copy.

```
while (cellDataIterator != end)
{
    CellDataType cellValue = cellDataIterator.Value();
    std::cout << cellValue << std::endl;
    ++cellDataIterator;
}
```

4.3.5 Topology and the K-Complex

The source code for this section can be found in the file `MeshKComplex.cxx`.

The `itk::Mesh` class supports the representation of formal topologies. In particular the concept of *K-Complex* can be correctly represented in the Mesh. An informal definition of K-Complex may be as follows: a K-Complex is a topological structure in which for every cell of dimension N , its boundary faces (which are cells of dimension $N - 1$) also belong to the structure.

This section illustrates how to instantiate a K-Complex structure using the mesh. The example structure is composed of one tetrahedron, its four triangle faces, its six line edges and its four vertices.

The header files of all the cell types involved should be loaded along with the header file of the mesh class.

```
#include "itkMesh.h"
#include "itkLineCell.h"
#include "itkTetrahedronCell.h"
```

Then the `PixelType` is defined and the mesh type is instantiated with it. Note that the dimension of the space is three in this case.

```
using PixelType = float;
using MeshType = itk::Mesh<PixelType, 3>;
```

The cell type can now be instantiated using the traits taken from the Mesh.


```
using CellType = MeshType::CellType;
using VertexType = itk::VertexCell<CellType>;
using LineType = itk::LineCell<CellType>;
using TriangleType = itk::TriangleCell<CellType>;
using TetrahedronType = itk::TetrahedronCell<CellType>;
```

The mesh is created and the points associated with the vertices are inserted. Note that there is an important distinction between the points in the mesh and the `itk::VertexCell` concept. A `VertexCell` is a cell of dimension zero. Its main difference as compared to a point is that the cell can be aware of neighborhood relationships with other cells. Points are not aware of the existence of cells. In fact, from the pure topological point of view, the coordinates of points in the mesh are completely irrelevant. They may as well be absent from the mesh structure altogether. `VertexCells` on the other hand are necessary to represent the full set of neighborhood relationships on the K-Complex.

The geometrical coordinates of the nodes of a regular tetrahedron can be obtained by taking every other node from a regular cube.

```
auto mesh = MeshType::New();

MeshType::PointType point0;
MeshType::PointType point1;
MeshType::PointType point2;
MeshType::PointType point3;

point0[0] = -1;
point0[1] = -1;
point0[2] = -1;
point1[0] = 1;
point1[1] = 1;
point1[2] = -1;
point2[0] = 1;
point2[1] = -1;
point2[2] = 1;
point3[0] = -1;
point3[1] = 1;
point3[2] = 1;

mesh->SetPoint(0, point0);
mesh->SetPoint(1, point1);
mesh->SetPoint(2, point2);
mesh->SetPoint(3, point3);
```

We proceed now to create the cells, associate them with the points and insert them on the mesh. Starting with the tetrahedron we write the following code.

```
CellType::CellAutoPointer cellpointer;

cellpointer.TakeOwnership(new TetrahedronType);
cellpointer->SetPointId(0, 0);
```

```
cellpointer->SetPointId(1, 1);
cellpointer->SetPointId(2, 2);
cellpointer->SetPointId(3, 3);
mesh->SetCell(0, cellpointer);
```

Four triangular faces are created and associated with the mesh now. The first triangle connects points 0,1,2.

```
cellpointer.TakeOwnership(new TriangleType);
cellpointer->SetPointId(0, 0);
cellpointer->SetPointId(1, 1);
cellpointer->SetPointId(2, 2);
mesh->SetCell(1, cellpointer);
```

The second triangle connects points 0, 2, 3 .

```
cellpointer.TakeOwnership(new TriangleType);
cellpointer->SetPointId(0, 0);
cellpointer->SetPointId(1, 2);
cellpointer->SetPointId(2, 3);
mesh->SetCell(2, cellpointer);
```

The third triangle connects points 0, 3, 1 .

```
cellpointer.TakeOwnership(new TriangleType);
cellpointer->SetPointId(0, 0);
cellpointer->SetPointId(1, 3);
cellpointer->SetPointId(2, 1);
mesh->SetCell(3, cellpointer);
```

The fourth triangle connects points 3, 2, 1 .

```
cellpointer.TakeOwnership(new TriangleType);
cellpointer->SetPointId(0, 3);
cellpointer->SetPointId(1, 2);
cellpointer->SetPointId(2, 1);
mesh->SetCell(4, cellpointer);
```

Note how the CellAutoPointer is reused every time. Reminder: the `itk::AutoPointer` loses ownership of the cell when it is passed as an argument of the `SetCell()` method. The AutoPointer is attached to a new cell by using the `TakeOwnership()` method.

The construction of the K-Complex continues now with the creation of the six lines on the tetrahedron edges.

```
cellpointer.TakeOwnership(new LineType);
cellpointer->SetPointId(0, 0);
```

```

cellpointer->SetPointId(1, 1);
mesh->SetCell(5, cellpointer);

cellpointer.TakeOwnership(new LineType);
cellpointer->SetPointId(0, 1);
cellpointer->SetPointId(1, 2);
mesh->SetCell(6, cellpointer);

cellpointer.TakeOwnership(new LineType);
cellpointer->SetPointId(0, 2);
cellpointer->SetPointId(1, 0);
mesh->SetCell(7, cellpointer);

cellpointer.TakeOwnership(new LineType);
cellpointer->SetPointId(0, 1);
cellpointer->SetPointId(1, 3);
mesh->SetCell(8, cellpointer);

cellpointer.TakeOwnership(new LineType);
cellpointer->SetPointId(0, 3);
cellpointer->SetPointId(1, 2);
mesh->SetCell(9, cellpointer);

cellpointer.TakeOwnership(new LineType);
cellpointer->SetPointId(0, 3);
cellpointer->SetPointId(1, 0);
mesh->SetCell(10, cellpointer);

```

Finally the zero dimensional cells represented by the `itk::VertexCell` are created and inserted in the mesh.

```

cellpointer.TakeOwnership(new VertexType);
cellpointer->SetPointId(0, 0);
mesh->SetCell(11, cellpointer);

cellpointer.TakeOwnership(new VertexType);
cellpointer->SetPointId(0, 1);
mesh->SetCell(12, cellpointer);

cellpointer.TakeOwnership(new VertexType);
cellpointer->SetPointId(0, 2);
mesh->SetCell(13, cellpointer);

cellpointer.TakeOwnership(new VertexType);
cellpointer->SetPointId(0, 3);
mesh->SetCell(14, cellpointer);

```

At this point the Mesh contains four points and fifteen cells enumerated from 0 to 14. The points can be visited using PointContainer iterators.

```

using PointIterator = MeshType::PointsContainer::ConstIterator;
PointIterator pointIterator = mesh->GetPoints()->Begin();

```

```

PointIterator pointEnd = mesh->GetPoints()->End();

while (pointIterator != pointEnd)
{
    std::cout << pointIterator.Value() << std::endl;
    ++pointIterator;
}

```

The cells can be visited using CellsContainer iterators.

```

using CellIterator = MeshType::CellsContainer::ConstIterator;

CellIterator cellIterator = mesh->GetCells()->Begin();
CellIterator cellEnd = mesh->GetCells()->End();

while (cellIterator != cellEnd)
{
    CellType * cell = cellIterator.Value();
    std::cout << cell->GetNumberOfPoints() << std::endl;
    ++cellIterator;
}

```

Note that cells are stored as pointer to a generic cell type that is the base class of all the specific cell classes. This means that at this level we can only have access to the virtual methods defined in the CellType.

The point identifiers to which the cells have been associated can be visited using iterators defined in the CellType trait. The following code illustrates the use of the PointIdIterators. The PointIdsBegin() method returns the iterator to the first point-identifier in the cell. The PointIdsEnd() method returns the iterator to the past-end point-identifier in the cell.

```

using PointIdIterator = CellType::PointIdIterator;

PointIdIterator pointIditer = cell->PointIdsBegin();
PointIdIterator pointIdend = cell->PointIdsEnd();

while (pointIditer != pointIdend)
{
    std::cout << *pointIditer << std::endl;
    ++pointIditer;
}

```

Note that the point-identifier is obtained from the iterator using the more traditional *iterator notation instead the Value() notation used by cell-iterators.

Up to here, the topology of the K-Complex is not completely defined since we have only introduced the cells. ITK allows the user to define explicitly the neighborhood relationships between cells. It is clear that a clever exploration of the point identifiers could have allowed a user to figure out the neighborhood relationships. For example, two triangle cells sharing the same two point identifiers

will probably be neighbor cells. Some of the drawbacks on this implicit discovery of neighborhood relationships is that it takes computing time and that some applications may not accept the same assumptions. A specific case is surgery simulation. This application typically simulates bistoury cuts in a mesh representing an organ. A small cut in the surface may be made by specifying that two triangles are not considered to be neighbors any more.

Neighborhood relationships are represented in the mesh by the notion of *BoundaryFeature*. Every cell has an internal list of cell-identifiers pointing to other cells that are considered to be its neighbors. Boundary features are classified by dimension. For example, a line will have two boundary features of dimension zero corresponding to its two vertices. A tetrahedron will have boundary features of dimension zero, one and two, corresponding to its four vertices, six edges and four triangular faces. It is up to the user to specify the connections between the cells.

Let's take in our current example the tetrahedron cell that was associated with the cell-identifier 0 and assign to it the four vertices as boundaries of dimension zero. This is done by invoking the `SetBoundaryAssignment()` method on the `Mesh` class.

```
MeshType::CellIdentifier cellId = 0; // the tetrahedron

int dimension = 0; // vertices

MeshType::CellFeatureIdentifier featureId = 0;

mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 11);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 12);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 13);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 14);
```

The `featureId` is simply a number associated with the sequence of the boundary cells of the same dimension in a specific cell. For example, the zero-dimensional features of a tetrahedron are its four vertices. Then the zero-dimensional feature-Ids for this cell will range from zero to three. The one-dimensional features of the tetrahedron are its six edges, hence its one-dimensional feature-Ids will range from zero to five. The two-dimensional features of the tetrahedron are its four triangular faces. The two-dimensional feature ids will then range from zero to three. The following table summarizes the use on indices for boundary assignments.

Dimension	CellType	FeatureId range	Cell Ids
0	VertexCell	[0:3]	{11,12,13,14}
1	LineCell	[0:5]	{5,6,7,8,9,10}
2	TriangleCell	[0:3]	{1,2,3,4}

In the code example above, the values of `featureId` range from zero to three. The cell identifiers of the triangle cells in this example are the numbers {1,2,3,4}, while the cell identifiers of the vertex cells are the numbers {11,12,13,14}.

Let's now assign one-dimensional boundary features of the tetrahedron. Those are the line cells with

identifiers {5,6,7,8,9,10}. Note that the feature identifier is reinitialized to zero since the count is independent for each dimension.

```
cellId = 0;    // still the tetrahedron
dimension = 1; // one-dimensional features = edges
featureId = 0; // reinitialize the count

mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 5);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 6);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 7);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 8);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 9);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 10);
```

Finally we assign the two-dimensional boundary features of the tetrahedron. These are the four triangular cells with identifiers {1,2,3,4}. The featureId is reset to zero since feature-Ids are independent on each dimension.

```
cellId = 0;    // still the tetrahedron
dimension = 2; // two-dimensional features = triangles
featureId = 0; // reinitialize the count

mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 1);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 2);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 3);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 4);
```

At this point we can query the tetrahedron cell for information about its boundary features. For example, the number of boundary features of each dimension can be obtained with the method `GetNumberOfBoundaryFeatures()`.

```
cellId = 0; // still the tetrahedron

MeshType::CellFeatureCount n0; // number of zero-dimensional features
MeshType::CellFeatureCount n1; // number of one-dimensional features
MeshType::CellFeatureCount n2; // number of two-dimensional features

n0 = mesh->GetNumberOfCellBoundaryFeatures(0, cellId);
n1 = mesh->GetNumberOfCellBoundaryFeatures(1, cellId);
n2 = mesh->GetNumberOfCellBoundaryFeatures(2, cellId);
```

The boundary assignments can be recovered with the method `GetBoundaryAssignment()`. For example, the zero-dimensional features of the tetrahedron can be obtained with the following code.

```
dimension = 0;
for (unsigned int b0 = 0; b0 < n0; ++b0)
{
    MeshType::CellIdentifier id;
```

```

bool found = mesh->GetBoundaryAssignment(dimension, cellId, b0, &id);
if (found)
    std::cout << id << std::endl;
}

```

The following code illustrates how to set the edge boundaries for one of the triangular faces.

```

cellId = 2;    // one of the triangles
dimension = 1; // boundary edges
featureId = 0; // start the count of features

mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 7);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 9);
mesh->SetBoundaryAssignment(dimension, cellId, featureId++, 10);

```

4.3.6 Representing a PolyLine

The source code for this section can be found in the file `MeshPolyLine.cxx`.

This section illustrates how to represent a classical *PolyLine* structure using the `itk::Mesh`

A *PolyLine* only involves zero and one dimensional cells, which are represented by the `itk::VertexCell` and the `itk::LineCell`.

```

#include "itkMesh.h"
#include "itkLineCell.h"

```

Then the `PixelType` is defined and the mesh type is instantiated with it. Note that the dimension of the space is two in this case.

```

using PixelType = float;
using MeshType = itk::Mesh<PixelType, 2>;

```

The cell type can now be instantiated using the traits taken from the `Mesh`.

```

using CellType = MeshType::CellType;
using VertexType = itk::VertexCell<CellType>;
using LineType = itk::LineCell<CellType>;

```

The mesh is created and the points associated with the vertices are inserted. Note that there is an important distinction between the points in the mesh and the `itk::VertexCell` concept. A `VertexCell` is a cell of dimension zero. Its main difference as compared to a point is that the cell can be aware of neighborhood relationships with other cells. Points are not aware of the existence of cells. In fact, from the pure topological point of view, the coordinates of points in the mesh are completely

irrelevant. They may as well be absent from the mesh structure altogether. VertexCells on the other hand are necessary to represent the full set of neighborhood relationships on the Polyline.

In this example we create a polyline connecting the four vertices of a square by using three of the square sides.

```
auto mesh = MeshType::New();

MeshType::PointType point0;
MeshType::PointType point1;
MeshType::PointType point2;
MeshType::PointType point3;

point0[0] = -1;
point0[1] = -1;
point1[0] = 1;
point1[1] = -1;
point2[0] = 1;
point2[1] = 1;
point3[0] = -1;
point3[1] = 1;

mesh->SetPoint(0, point0);
mesh->SetPoint(1, point1);
mesh->SetPoint(2, point2);
mesh->SetPoint(3, point3);
```

We proceed now to create the cells, associate them with the points and insert them on the mesh.

```
CellType::CellAutoPointer cellpointer;

cellpointer.TakeOwnership(new LineType);
cellpointer->SetPointId(0, 0);
cellpointer->SetPointId(1, 1);
mesh->SetCell(0, cellpointer);

cellpointer.TakeOwnership(new LineType);
cellpointer->SetPointId(0, 1);
cellpointer->SetPointId(1, 2);
mesh->SetCell(1, cellpointer);

cellpointer.TakeOwnership(new LineType);
cellpointer->SetPointId(0, 2);
cellpointer->SetPointId(1, 0);
mesh->SetCell(2, cellpointer);
```

Finally the zero dimensional cells represented by the `itk::VertexCell` are created and inserted in the mesh.

```
cellpointer.TakeOwnership(new VertexType);
cellpointer->SetPointId(0, 0);
```



```

mesh->SetCell(3, cellpointer);

cellpointer.TakeOwnership(new VertexType);
cellpointer->SetPointId(0, 1);
mesh->SetCell(4, cellpointer);

cellpointer.TakeOwnership(new VertexType);
cellpointer->SetPointId(0, 2);
mesh->SetCell(5, cellpointer);

cellpointer.TakeOwnership(new VertexType);
cellpointer->SetPointId(0, 3);
mesh->SetCell(6, cellpointer);

```

At this point the Mesh contains four points and three cells. The points can be visited using PointContainer iterators.

```

using PointIterator = MeshType::PointsContainer::ConstIterator;
PointIterator pointIterator = mesh->GetPoints()->Begin();
PointIterator pointEnd = mesh->GetPoints()->End();

while (pointIterator != pointEnd)
{
    std::cout << pointIterator.Value() << std::endl;
    ++pointIterator;
}

```

The cells can be visited using CellsContainer iterators.

```

using CellIterator = MeshType::CellsContainer::ConstIterator;

CellIterator cellIterator = mesh->GetCells()->Begin();
CellIterator cellEnd = mesh->GetCells()->End();

while (cellIterator != cellEnd)
{
    CellType * cell = cellIterator.Value();
    std::cout << cell->GetNumberOfPoints() << std::endl;
    ++cellIterator;
}

```

Note that cells are stored as pointer to a generic cell type that is the base class of all the specific cell classes. This means that at this level we can only have access to the virtual methods defined in the CellType.

The point identifiers to which the cells have been associated can be visited using iterators defined in the CellType trait. The following code illustrates the use of the PointIdIterator. The PointIdsBegin() method returns the iterator to the first point-identifier in the cell. The PointIdsEnd() method returns the iterator to the past-end point-identifier in the cell.

```

using PointIdIterator = CellType::PointIdIterator;

PointIdIterator pointIditer = cell->PointIdsBegin();
PointIdIterator pointIdend = cell->PointIdsEnd();

while (pointIditer != pointIdend)
{
    std::cout << *pointIditer << std::endl;
    ++pointIditer;
}

```

Note that the point-identifier is obtained from the iterator using the more traditional `*iterator` notation instead the `Value()` notation used by cell-iterators.

4.3.7 Simplifying Mesh Creation

The source code for this section can be found in the file `AutomaticMesh.cxx`.

The `itk::Mesh` class is extremely general and flexible, but there is some cost to convenience. If convenience is exactly what you need, then it is possible to get it, in exchange for some of that flexibility, by means of the `itk::AutomaticTopologyMeshSource` class. This class automatically generates an explicit K-Complex, based on the cells you add. It explicitly includes all boundary information, so that the resulting mesh can be easily traversed. It merges all shared edges, vertices, and faces, so no geometric feature appears more than once.

This section shows how you can use the `AutomaticTopologyMeshSource` to instantiate a mesh representing a K-Complex. We will first generate the same tetrahedron from Section 4.3.5, after which we will add a hollow one to illustrate some additional features of the mesh source.

The header files of all the cell types involved should be loaded along with the header file of the mesh class.

```

#include "itkTriangleCell.h"
#include "itkAutomaticTopologyMeshSource.h"

```

We then define the necessary types and instantiate the mesh source. Two new types are `IdentifierType` and `IdentifierArrayType`. Every cell in a mesh has an identifier, whose type is determined by the mesh traits. `AutomaticTopologyMeshSource` requires that the identifier type of all vertices and cells be `unsigned long`, which is already the default. However, if you created a new mesh traits class to use string tags as identifiers, the resulting mesh would not be compatible with `itk::AutomaticTopologyMeshSource`. An `IdentifierArrayType` is simply an `itk::Array` of `IdentifierType` objects.

```

using PixelType = float;
using MeshType = itk::Mesh<PixelType, 3>;

```

```

using PointType = MeshType::PointType;

using MeshSourceType = itk::AutomaticTopologyMeshSource<MeshType>;
using IdentifierArrayType = MeshSourceType::IdentifierArrayType;

MeshSourceType::Pointer meshSource;

meshSource = MeshSourceType::New();

```

Now let us generate the tetrahedron. The following line of code generates all the vertices, edges, and faces, along with the tetrahedral solid, and adds them to the mesh along with the connectivity information.

```

meshSource->AddTetrahedron(meshSource->AddPoint(-1, -1, -1),
                           meshSource->AddPoint(1, 1, -1),
                           meshSource->AddPoint(1, -1, 1),
                           meshSource->AddPoint(-1, 1, 1));

```

The function `AutomaticTopologyMeshSource::AddTetrahedron()` takes point identifiers as parameters; the identifiers must correspond to points that have already been added. `AutomaticTopologyMeshSource::AddPoint()` returns the appropriate identifier type for the point being added. It first checks to see if the point is already in the mesh. If so, it returns the ID of the point in the mesh, and if not, it generates a new unique ID, adds the point with that ID, and returns the ID.

Actually, `AddTetrahedron()` behaves in the same way. If the tetrahedron has already been added, it leaves the mesh unchanged and returns the ID that the tetrahedron already has. If not, it adds the tetrahedron (and all its faces, edges, and vertices), and generates a new ID, which it returns.

It is also possible to add all the points first, and then add a number of cells using the point IDs directly. This approach corresponds with the way the data is stored in many file formats for 3D polygonal models.

First we add the points (in this case the vertices of a larger tetrahedron). This example also illustrates that `AddPoint()` can take a single `PointType` as a parameter if desired, rather than a sequence of floats. Another possibility (not illustrated) is to pass in a C-style array.

```

PointType p;
IdentifierArrayType idArray(4);

p[0] = -2;
p[1] = -2;
p[2] = -2;
idArray[0] = meshSource->AddPoint(p);

p[0] = 2;
p[1] = 2;
p[2] = -2;

```

```

idArray[1] = meshSource->AddPoint(p);

p[0] = 2;
p[1] = -2;
p[2] = 2;
idArray[2] = meshSource->AddPoint(p);

p[0] = -2;
p[1] = 2;
p[2] = 2;
idArray[3] = meshSource->AddPoint(p);

```

Now we add the cells. This time we are just going to create the boundary of a tetrahedron, so we must add each face separately.

```

meshSource->AddTriangle(idArray[0], idArray[1], idArray[2]);
meshSource->AddTriangle(idArray[1], idArray[2], idArray[3]);
meshSource->AddTriangle(idArray[2], idArray[3], idArray[0]);
meshSource->AddTriangle(idArray[3], idArray[0], idArray[1]);

```

Actually, we could have called, e.g., `AddTriangle( 4, 5, 6 )`, since IDs are assigned sequentially starting at zero, and `idArray[0]` contains the ID for the fifth point added. But you should only do this if you are confident that you know what the IDs are. If you add the same point twice and don't realize it, your count will differ from that of the mesh source.

You may be wondering what happens if you call, say, `AddEdge(0, 1)` followed by `AddEdge(1, 0)`. The answer is that they do count as the same edge, and so only one edge is added. The order of the vertices determines an orientation, and the first orientation specified is the one that is kept.

Once you have built the mesh you want, you can access it by calling `GetOutput()`. Here we send it to `cout`, which prints some summary data for the mesh.

In contrast to the case with typical filters, `GetOutput()` does not trigger an update process. The mesh is always maintained in a valid state as cells are added, and can be accessed at any time. It would, however, be a mistake to modify the mesh by some other means until `AutomaticTopologyMeshSource` is done with it, since the mesh source would then have an inaccurate record of which points and cells are currently in the mesh.

4.3.8 Iterating Through Cells

The source code for this section can be found in the file `MeshCellsIteration.cxx`.

Cells are stored in the `itk::Mesh` as pointers to a generic cell `itk::CellInterface`. This implies that only the virtual methods defined on this base cell class can be invoked. In order to use methods that are specific to each cell type it is necessary to down-cast the pointer to the actual type of the cell. This can be done safely by taking advantage of the `GetType()` method that allows to identify the actual type of a cell.

Let's start by assuming a mesh defined with one tetrahedron and all its boundary faces. That is, four triangles, six edges and four vertices.

The cells can be visited using CellsContainer iterators . The iterator Value() corresponds to a raw pointer to the CellType base class.

```
using CellIterator = MeshType::CellsContainer::ConstIterator;

CellIterator cellIterator = mesh->GetCells()->Begin();
CellIterator cellEnd = mesh->GetCells()->End();

while (cellIterator != cellEnd)
{
    CellType * cell = cellIterator.Value();
    std::cout << cell->GetNumberOfPoints() << std::endl;
    ++cellIterator;
}
```

In order to perform down-casting in a safe manner, the cell type can be queried first using the GetType() method. Codes for the cell types have been defined with an enum type on the itkCellInterface.h header file. These codes are :

- VERTEX_CELL
- LINE_CELL
- TRIANGLE_CELL
- QUADRILATERAL_CELL
- POLYGON_CELL
- TETRAHEDRON_CELL
- HEXAHEDRON_CELL
- QUADRATIC_EDGE_CELL
- QUADRATIC_TRIANGLE_CELL

The method GetType() returns one of these codes. It is then possible to test the type of the cell before down-casting its pointer to the actual type. For example, the following code visits all the cells in the mesh and tests which ones are actually of type LINE_CELL. Only those cells are down-casted to LineType cells and a method specific for the LineType is invoked.

```
cellIterator = mesh->GetCells()->Begin();
cellEnd = mesh->GetCells()->End();

while (cellIterator != cellEnd)
```

```

{
    CellType * cell = cellIterator.Value();
    if (cell->GetType() == itk::CellGeometryEnum::LINE_CELL)
    {
        auto * line = static_cast<LineType *>(cell);
        std::cout << "dimension = " << line->GetDimension();
        std::cout << " # points = " << line->GetNumberOfPoints();
        std::cout << std::endl;
    }
    ++cellIterator;
}

```

In order to perform different actions on different cell types a `switch` statement can be used with cases for every cell type. The following code illustrates an iteration over the cells and the invocation of different methods on each cell type.

```

cellIterator = mesh->GetCells()->Begin();
cellEnd = mesh->GetCells()->End();

while (cellIterator != cellEnd)
{
    CellType * cell = cellIterator.Value();
    switch (cell->GetType())
    {
        case itk::CellGeometryEnum::VERTEX_CELL:
        {
            std::cout << "VertexCell : " << std::endl;
            auto * line = dynamic_cast<VertexType *>(cell);
            std::cout << "dimension = " << line->GetDimension() << std::endl;
            std::cout << "# points = " << line->GetNumberOfPoints() << std::endl;
            break;
        }
        case itk::CellGeometryEnum::LINE_CELL:
        {
            std::cout << "LineCell : " << std::endl;
            auto * line = dynamic_cast<LineType *>(cell);
            std::cout << "dimension = " << line->GetDimension() << std::endl;
            std::cout << "# points = " << line->GetNumberOfPoints() << std::endl;
            break;
        }
        case itk::CellGeometryEnum::TRIANGLE_CELL:
        {
            std::cout << "TriangleCell : " << std::endl;
            auto * line = dynamic_cast<TriangleType *>(cell);
            std::cout << "dimension = " << line->GetDimension() << std::endl;
            std::cout << "# points = " << line->GetNumberOfPoints() << std::endl;
            break;
        }
        default:
        {
            std::cout << "Cell with more than three points" << std::endl;
            std::cout << "dimension = " << cell->GetDimension() << std::endl;
            std::cout << "# points = " << cell->GetNumberOfPoints() << std::endl;
        }
    }
}

```

```

        break;
    }
}
++cellIterator;
}

```

4.3.9 Visiting Cells

The source code for this section can be found in the file `MeshCellVisitor.cxx`.

In order to facilitate access to particular cell types, a convenience mechanism has been built-in on the `itk::Mesh`. This mechanism is based on the *Visitor Pattern* presented in [3]. The visitor pattern is designed to facilitate the process of walking through an heterogeneous list of objects sharing a common base class.

The first requirement for using the `CellVisitor` mechanism is to include the `CellInterfaceVisitor` header file.

```
#include "itkCellInterfaceVisitor.h"
```

The typical mesh types are now declared.

```

using PixelType = float;
using MeshType = itk::Mesh<PixelType, 3>;

using CellType = MeshType::CellType;

using VertexType = itk::VertexCell<CellType>;
using LineType = itk::LineCell<CellType>;
using TriangleType = itk::TriangleCell<CellType>;
using TetrahedronType = itk::TetrahedronCell<CellType>;

```

Then, a custom `CellVisitor` class should be declared. In this particular example, the visitor class is intended to act only on `TriangleType` cells. The only requirement on the declaration of the visitor class is that it must provide a method named `Visit()`. This method expects as arguments a cell identifier and a pointer to the *specific* cell type for which this visitor is intended. Nothing prevents a visitor class from providing `Visit()` methods for several different cell types. The multiple methods will be differentiated by the natural C++ mechanism of function overload. The following code illustrates a minimal cell visitor class.

```

class CustomTriangleVisitor
{
public:
    using TriangleType = itk::TriangleCell<CellType>;
    void
    Visit(unsigned long cellId, TriangleType * t)

```

```

{
    std::cout << "Cell # " << cellId << " is a TriangleType ";
    std::cout << t->GetNumberOfPoints() << std::endl;
}
CustomTriangleVisitor() = default;
virtual ~CustomTriangleVisitor() = default;
};

```

This newly defined class will now be used to instantiate a cell visitor. In this particular example we create a class `CustomTriangleVisitor` which will be invoked each time a triangle cell is found while the mesh iterates over the cells.

```

using TriangleVisitorInterfaceType =
    itk::CellInterfaceVisitorImplementation<PixelType,
                                           MeshType::CellTraits,
                                           TriangleType,
                                           CustomTriangleVisitor>;

```

Note that the actual `CellInterfaceVisitorImplementation` is templated over the `PixelType`, the `CellTraits`, the `CellType` to be visited and the `Visitor` class that defines with will be done with the cell.

A visitor implementation class can now be created using the normal invocation to its `New()` method and assigning the result to a `itk::SmartPointer`.

```

auto triangleVisitor = TriangleVisitorInterfaceType::New();

```

Many different visitors can be configured in this way. The set of all visitors can be registered with the `MultiVisitor` class provided for the mesh. An instance of the `MultiVisitor` class will walk through the cells and delegate action to every registered visitor when the appropriate cell type is encountered.

```

using CellMultiVisitorType = CellType::MultiVisitor;
auto multiVisitor = CellMultiVisitorType::New();

```

The visitor is registered with the `Mesh` using the `AddVisitor()` method.

```

multiVisitor->AddVisitor(triangleVisitor);

```

Finally, the iteration over the cells is triggered by calling the method `Accept()` on the `itk::Mesh`.

```

mesh->Accept(multiVisitor);

```

The `Accept()` method will iterate over all the cells and for each one will invite the `MultiVisitor` to attempt an action on the cell. If no visitor is interested on the current cell type the cell is just ignored and skipped.

`MultiVisitors` make it possible to add behavior to the cells without having to create new methods on the cell types or creating a complex visitor class that knows about every `CellType`.

4.3.10 More on Visiting Cells

The source code for this section can be found in the file `MeshCellVisitor2.cxx`.

The following section illustrates a realistic example of the use of Cell visitors on the `itk::Mesh`. A set of different visitors is defined here, each visitor associated with a particular type of cell. All the visitors are registered with a `MultiVisitor` class which is passed to the mesh.

The first step is to include the `CellInterfaceVisitor` header file.

```
#include "itkCellInterfaceVisitor.h"
```

The typical mesh types are now declared.

```
using PixelType = float;
using MeshType = itk::Mesh<PixelType, 3>;

using CellType = MeshType::CellType;

using VertexType = itk::VertexCell<CellType>;
using LineType = itk::LineCell<CellType>;
using TriangleType = itk::TriangleCell<CellType>;
using TetrahedronType = itk::TetrahedronCell<CellType>;
```

Then, custom `CellVisitor` classes should be declared. The only requirement on the declaration of each visitor class is to provide a method named `Visit()`. This method expects as arguments a cell identifier and a pointer to the *specific* cell type for which this visitor is intended.

The following `Vertex` visitor simply prints out the identifier of the point with which the cell is associated. Note that the cell uses the method `GetPointId()` without any arguments. This method is only defined on the `VertexCell`.

```
class CustomVertexVisitor
{
public:
    void
    Visit(unsigned long cellId, VertexType * t)
    {
        std::cout << "cell " << cellId << " is a Vertex " << std::endl;
        std::cout << "    associated with point id = ";
        std::cout << t->GetPointId() << std::endl;
    }
    virtual ~CustomVertexVisitor() = default;
};
```

The following `Line` visitor computes the length of the line. Note that this visitor is slightly more complicated since it needs to get access to the actual mesh in order to get point coordinates from the

point identifiers returned by the line cell. This is done by holding a pointer to the mesh and querying the mesh each time point coordinates are required. The mesh pointer is set up in this case with the `SetMesh()` method.

```
class CustomLineVisitor
{
public:
    CustomLineVisitor()
        : m_Mesh(nullptr)
    {}
    virtual ~CustomLineVisitor() = default;

    void
    SetMesh(MeshType * mesh)
    {
        m_Mesh = mesh;
    }

    void
    Visit(unsigned long cellId, LineType * t)
    {
        std::cout << "cell " << cellId << " is a Line " << std::endl;
        LineType::PointIdIterator pit = t->PointIdsBegin();
        MeshType::PointType p0;
        MeshType::PointType p1;
        m_Mesh->GetPoint(*pit++, &p0);
        m_Mesh->GetPoint(*pit++, &p1);
        const double length = p0.EuclideanDistanceTo(p1);
        std::cout << " length = " << length << std::endl;
    }

private:
    MeshType::Pointer m_Mesh;
};
```

The `Triangle` visitor below prints out the identifiers of its points. Note the use of the `PointIdIterator` and the `PointIdsBegin()` and `PointIdsEnd()` methods.

```
class CustomTriangleVisitor
{
public:
    void
    Visit(unsigned long cellId, TriangleType * t)
    {
        std::cout << "cell " << cellId << " is a Triangle " << std::endl;
        LineType::PointIdIterator pit = t->PointIdsBegin();
        LineType::PointIdIterator end = t->PointIdsEnd();
        while (pit != end)
        {
            std::cout << " point id = " << *pit << std::endl;
            ++pit;
        }
    }
};
```

```

}
virtual ~CustomTriangleVisitor() = default;
};

```

The `TetrahedronVisitor` below simply returns the number of faces on this figure. Note that `GetNumberOfFaces()` is a method exclusive of 3D cells.

```

class CustomTetrahedronVisitor
{
public:
    void
    Visit(unsigned long cellId, TetrahedronType * t)
    {
        std::cout << "cell " << cellId << " is a Tetrahedron " << std::endl;
        std::cout << "    number of faces = ";
        std::cout << t->GetNumberOfFaces() << std::endl;
    }
    virtual ~CustomTetrahedronVisitor() = default;
};

```

With the cell visitors we proceed now to instantiate `CellVisitor` implementations. The visitor classes defined above are used as template arguments of the cell visitor implementation.

```

using VertexVisitorInterfaceType =
    itk::CellInterfaceVisitorImplementation<PixelType,
                                           MeshType::CellTraits,
                                           VertexType,
                                           CustomVertexVisitor>;

using LineVisitorInterfaceType =
    itk::CellInterfaceVisitorImplementation<PixelType,
                                           MeshType::CellTraits,
                                           LineType,
                                           CustomLineVisitor>;

using TriangleVisitorInterfaceType =
    itk::CellInterfaceVisitorImplementation<PixelType,
                                           MeshType::CellTraits,
                                           TriangleType,
                                           CustomTriangleVisitor>;

using TetrahedronVisitorInterfaceType =
    itk::CellInterfaceVisitorImplementation<PixelType,
                                           MeshType::CellTraits,
                                           TetrahedronType,
                                           CustomTetrahedronVisitor>;

```

Note that the actual `CellInterfaceVisitorImplementation` is templated over the `PixelType`, the `CellTraits`, the `CellType` to be visited and the `Visitor` class defining what to do with the cell.

A visitor implementation class can now be created using the normal invocation to its `New()` method and assigning the result to a `itk::SmartPointer`.

```
auto vertexVisitor = VertexVisitorInterfaceType::New();  
  
auto lineVisitor = LineVisitorInterfaceType::New();  
  
auto triangleVisitor = TriangleVisitorInterfaceType::New();  
  
auto tetrahedronVisitor = TetrahedronVisitorInterfaceType::New();
```

Remember that the `LineVisitor` requires the pointer to the mesh object since it needs to get access to actual point coordinates. This is done by invoking the `SetMesh()` method defined above.

```
lineVisitor->SetMesh(mesh);
```

Looking carefully you will notice that the `SetMesh()` method is declared in `CustomLineVisitor` but we are invoking it on `LineVisitorInterfaceType`. This is possible thanks to the way in which the `VisitorInterfaceImplementation` is defined. This class derives from the visitor type provided by the user as the fourth template parameter. `LineVisitorInterfaceType` is then a derived class of `CustomLineVisitor`.

The set of visitors should now be registered with the `MultiVisitor` class that will walk through the cells and delegate action to every registered visitor when the appropriate cell type is encountered. The following lines create a `MultiVisitor` object.

```
using CellMultiVisitorType = CellType::MultiVisitor;  
auto multiVisitor = CellMultiVisitorType::New();
```

Every visitor implementation is registered with the `Mesh` using the `AddVisitor()` method.

```
multiVisitor->AddVisitor(vertexVisitor);  
multiVisitor->AddVisitor(lineVisitor);  
multiVisitor->AddVisitor(triangleVisitor);  
multiVisitor->AddVisitor(tetrahedronVisitor);
```

Finally, the iteration over the cells is triggered by calling the method `Accept()` on the `Mesh` class.

```
mesh->Accept(multiVisitor);
```

The `Accept()` method will iterate over all the cells and for each one will invite the `MultiVisitor` to attempt an action on the cell. If no visitor is interested on the current cell type, the cell is just ignored and skipped.

4.4 Path

4.4.1 Creating a PolyLineParametricPath

The source code for this section can be found in the file

PolyLineParametricPath1.cxx.

This example illustrates how to use the `itk::PolyLineParametricPath`. This class will typically be used for representing in a concise way the output of an image segmentation algorithm in 2D. The `PolyLineParametricPath` however could also be used for representing any open or close curve in N-Dimensions as a linear piece-wise approximation.

First, the header file of the `PolyLineParametricPath` class must be included.

```
#include "itkPolyLineParametricPath.h"
```

The path is instantiated over the dimension of the image. In this example the image and path are two-dimensional.

```
constexpr unsigned int Dimension = 2;

using ImageType = itk::Image<unsigned char, Dimension>;

using PathType = itk::PolyLineParametricPath<Dimension>;

ImageType::ConstPointer image = reader->GetOutput();
auto path = PathType::New();
path->Initialize();

using ContinuousIndexType = PathType::ContinuousIndexType;
ContinuousIndexType cindex;

using ImagePointType = ImageType::PointType;
ImagePointType origin = image->GetOrigin();

ImageType::SpacingType spacing = image->GetSpacing();
ImageType::SizeType size = image->GetBufferedRegion().GetSize();

ImagePointType point;

point[0] = origin[0] + spacing[0] * size[0];
point[1] = origin[1] + spacing[1] * size[1];

using ContinuousIndexValueType = ContinuousIndexType::ValueType;

cindex =
    image->TransformPhysicalPointToContinuousIndex<ContinuousIndexValueType>(
        origin);
path->AddVertex(cindex);
cindex =
```

```
image->TransformPhysicalPointToContinuousIndex<ContinuousIndexValueType>(
    point);
path->AddVertex(cindex);
```

SPATIAL OBJECTS

This chapter introduces the basic classes that describe `itk::SpatialObjects`.

5.1 Introduction

We promote the philosophy that many of the goals of medical image processing are more effectively addressed if we consider them in the broader context of object processing. ITK's Spatial Object class hierarchy provides a consistent API for querying, manipulating, and interconnecting objects in physical space. Via this API, methods can be coded to be invariant to the data structure used to store the objects being processed. By abstracting the representations of objects to support their representation by data structures other than images, a broad range of medical image analysis research is supported; key examples are described in the following.

Model-to-image registration. A mathematical instance of an object can be registered with an image to localize the instance of that object in the image. Using SpatialObjects, mutual information, cross-correlation, and boundary-to-image metrics can be applied without modification to perform spatial object-to-image registration.

Model-to-model registration. Iterative closest point, landmark, and surface distance minimization methods can be used with any ITK transform, to rigidly and non-rigidly register image, FEM, and Fourier descriptor-based representations of objects as SpatialObjects.

Atlas formation. Collections of images or SpatialObjects can be integrated to represent expected object characteristics and their common modes of variation. Labels can be associated with the objects of an atlas.

Storing segmentation results from one or multiple scans. Results of segmentations are best stored in physical/world coordinates so that they can be combined and compared with other segmentations from other images taken at other resolutions. Segmentation results from hand drawn contours, pixel labelings, or model-to-image registrations are treated consistently.

Capturing functional and logical relationships between objects. SpatialObjects can have parent and children objects. Queries made of an object (such as to determine if a point is inside of the object) can be made to integrate the responses from the children object. Transformations applied to a parent can also be propagated to the children. Thus, for example, when a liver model is moved, its vessels move with it.

Conversion to and from images. Basic functions are provided to render any SpatialObject (or collection of SpatialObjects) into an image.

IO. SpatialObject reading and writing to disk is independent of the SpatialObject class hierarchy. Meta object IO (through `itk::MetaImageIO`) methods are provided, and others are easily defined.

Tubes, blobs, images, surfaces. Are a few of the many SpatialObject data containers and types provided. New types can be added, generally by only defining one or two member functions in a derived class.

In the remainder of this chapter several examples are used to demonstrate the many spatial objects found in ITK and how they can be organized into hierarchies. Further the examples illustrate how to use SpatialObject transformations to control and calculate the position of objects in space.

5.2 Hierarchy

Spatial objects can be combined to form a hierarchy as a tree. By design, a SpatialObject can have one parent and only one. Moreover, each transform is stored within each object, therefore the hierarchy cannot be described as a Directed Acyclic Graph (DAG) but effectively as a tree. The user is responsible for maintaining the tree structure, no checking is done to ensure a cycle-free tree.

The source code for this section can be found in the file `SpatialObjectHierarchy.cxx`.

This example describes how `itk::SpatialObject` can form a hierarchy. This first example also shows how to create and manipulate spatial objects.

```
#include "itkSpatialObject.h"
```

First, we create two spatial objects and give them the names `First Object` and `Second Object`, respectively.

```
using SpatialObjectType = itk::SpatialObject<3>;

auto object1 = SpatialObjectType::New();
object1->GetProperty().SetName("First Object");

auto object2 = SpatialObjectType::New();
object2->GetProperty().SetName("Second Object");
```


We then add the second object to the first one by using the `AddChild()` method. As a result `object2` becomes a child of `object1`.

```
object1->AddChild(object2);
```

Whenever the parameters of an object, including its parent-child relationships are changed, we must then call the `Update()` method so that the object-to-parent transforms and bounding box internally managed by each object are maintained. Calling `Update()` on an object automatically causes the `Update()` function of each child to be called.

```
object1->Update();
```

`object1->Update();`

```
if (object2->HasParent())
{
    std::cout << "Name of the parent of the object2: ";
    std::cout << object2->GetParent()->GetProperty().GetName() << std::endl;
}
```

To access the list of children of the object, the `GetChildren()` method returns a pointer to the (STL) list of children.

```
SpatialObjectType::ChildrenListType * childrenList = object1->GetChildren();
std::cout << "object1 has " << childrenList->size() << " child"
          << std::endl;

SpatialObjectType::ChildrenListType::const_iterator it =
    childrenList->begin();
while (it != childrenList->end())
{
    std::cout << "Name of the child of the object 1: ";
    std::cout << (*it)->GetProperty().GetName() << std::endl;
    ++it;
}
```

Do NOT forget to delete the list of children since the `GetChildren()` function creates an internal list.

```
delete childrenList;
```

An object can also be removed by using the `RemoveChild()` method, and then calling `Update()` on the now-orphaned child.

```
object1->RemoveChild(object2);
object2->Update();
```

Then, we can query the number of children an object has with the `GetNumberOfChildren()` method.

```
std::cout << "Number of children for object1: ";
std::cout << object1->GetNumberOfChildren() << std::endl;
```

The `Clear()` method erases all the information regarding the object as well as the data. This method is usually overloaded by derived classes. Note that the Parent-Child relationships of the object are NOT reset when `Clear()` is called; however, the object-to-parent transform is reset to Identity. As a result, `Update()` should be called before the object is re-used, to re-compute convenience member variables and values. To remove the children of a node, use the `RemoveAllChildren()` function.

```
object1->Clear();
object1->RemoveAllChildren();
```

The output of this first example looks like the following:

```
Name of the parent of the object2: First Object
object1 has 1 child
Name of the child of the object 1: Second Object
Number of children for object1: 0
```

5.3 Transformations

The source code for this section can be found in the file `SpatialObjectTransforms.cxx`.

This example describes the different transformations and the Object and World "spaces" associated with a spatial object.

Object Space . `SpatialObjects` have one primary coordinate space that is readily available to them, their `ObjectSpace`. This is the space in which the object was inherently defined. No transforms are applied to the points/values that get/set into this space. All children of an object are added into this space.

ObjectToParentTransform . `SpatialObjects` have only one transform that they directly control, their `ObjectToParentTransform`. This transform specifies how an object's `ObjectSpace` is transformed to fit into its parent's `ObjectSpace`. The `ObjectToParentTransform` is an affine transform, and it is confirmed to be invertible when assigned, or the assignment fails.

WorldSpace . `WorldSpace` is not directly controlled by any `SpatialObject` except the `SpatialObject` at the top level of the parent-child tree hierarchy of `Spatial Objects`. That is, any `SpatialObject` that does not have a parent exists in a `WorldSpace` that is defined by applying its `ObjectToParentTransform` to its `ObjectSpace`.

Several member functions and variables are available to every `SpatialObject` so that they can readily access the `WorldSpace` in which they exist:

ProtectedComputeObjectToWorldTransform() : This function is called whenever `Update()` is called. It composes the object's `ObjectToParentTransform` with its parent's cached `ObjectToWorldTransform`, to determine the transform from the object's `ObjectSpace` to `WorldSpace`. This transform is always invertible. This call will cause all children objects to also update their cached `ObjectToWorldTransform`. This function should be called on the top level object (via `Update()`) once all children object's `ObjectToParentTransforms` have been set. This function should be called on children objects when their `ObjectToParentTransforms` have been changed.

GetObjectToWorldTransform() : Returns the cached `ObjectToWorldTransform`. It is the user's responsibility to call `Update()` (and thereby `ProtectedComputeObjectToWorldTransform()`) when necessary, prior to calling `GetObjectToWorldTransform()`, otherwise the returned transform may be "stale."

SetObjectToWorldTransform() : This function updates the object's `ObjectToParentTransform`, using an inverse of the parent's cached `ObjectToWorldTransform`, so that the composition of those transforms equal the transform passed to this function. If an object has no parent, its `ObjectToParentTransform` is equal to its `ObjectToWorldTransform`.

Like the first example, we create two spatial objects and give them the names `First Object` and `Second Object`, respectively.

```
using SpatialObjectType = itk::SpatialObject<2>;
using TransformType = SpatialObjectType::TransformType;

auto object1 = SpatialObjectType::New();
object1->GetProperty().SetName("First Object");

auto object2 = SpatialObjectType::New();
object2->GetProperty().SetName("Second Object");
object1->AddChild(object2);
```

First we define a scaling factor of 2 for the `object2`. This is done by setting the `Scale` of the `ObjectToParentTransform`.

Note that this scaling would also apply to the children of `object2`, if it had children. If you wish to scale an object, but not its children, then those children aren't actually "children", but they are siblings. So, you should insert a `GroupSpatialObject` that holds both the object and its siblings as children. Then you can manipulate the object's transform/scaling independent of its siblings in that group, and if you wish to transform the object and its siblings, you apply that transform to the group.

```
double scale[2];
```

```
scale[0] = 2;
scale[1] = 2;
object2->GetModifiableObjectToParentTransform()->Scale(scale);
```

Next, we apply an offset on the `ObjectToParentTransform` to `object1` which will also cause a translation of its child, `object2`.

```
TransformType::OffsetType object1Offset;
object1Offset[0] = 4;
object1Offset[1] = 3;
object1->GetModifiableObjectToParentTransform()->SetOffset(object1Offset);
```

To realize the previous operations on the transformations, we should invoke the `Update()` that recomputes all dependent transformations.

By calling this function on `object1`, it will also descend to its children, thereby also updating the `ObjectToWorldTransform` for `object2`.

```
object1->Update();
```

We can now display the `ObjectToWorldTransform` for both objects. One should notice that the only valid members of the Affine transformation are a `Matrix` and an `Offset`. For instance, when we invoke the `Scale()` method the internal `Matrix` is recomputed to reflect this change.

The `AffineTransform` performs the following computation

$$X' = R \cdot (S \cdot X - C) + C + V \quad (5.1)$$

Where R is the rotation matrix, S is a scaling factor, C is the center of rotation and V is a translation vector or offset. Therefore the affine matrix M and the affine offset T are defined as:

$$M = R \cdot S \quad (5.2)$$

$$T = C + V - R \cdot C \quad (5.3)$$

This means that `Scale()` and `GetOffset()` as well as the `GetMatrix()` might not be set to the expected value, especially if the transformation results from a composition with another transformation since the composition is done using the `Matrix` and the `Offset` of the affine transformation.

Next, we show the two affine transformations corresponding to the two objects.

First, the `ObjectToParentTransform` for `object2`:

```
std::cout << "object2 ObjectToParent Matrix: " << std::endl;
std::cout << object2->GetObjectToParentTransform()->GetMatrix()
    << std::endl;
std::cout << "object2 ObjectToParent Offset: ";
std::cout << object2->GetObjectToParentTransform()->GetOffset()
    << std::endl;
```

Second, the `ObjectToWorldTransform` that is derived from the parent-child hierarchy and the composition of the corresponding `ObjectToParentTransforms`, computed by called to `Update()`, and cached for efficient subsequent use, for `object2`:

```
std::cout << "object2 ObjectToWorld Matrix: " << std::endl;
std::cout << object2->GetObjectToWorldTransform()->GetMatrix() << std::endl;
std::cout << "object2 ObjectToWorld Offset: ";
std::cout << object2->GetObjectToWorldTransform()->GetOffset() << std::endl;
```

We can also update an object's `ObjectToParentTransform` by changing its `ObjectToWorldTransform` and then calling `ComputeObjectToParentTransform()`, which changes the `ObjectToParentTransform` so as to achieve the cached `ObjectToWorldTransform`.

```
TransformType::OffsetType Object1ToWorldOffset;
Object1ToWorldOffset[0] = 3;
Object1ToWorldOffset[1] = 3;
object1->GetModifiableObjectToWorldTransform()->SetOffset(
    Object1ToWorldOffset);
object1->ComputeObjectToParentTransform();
```

Finally, we display the resulting affine transformations. First, for the `ObjectToParentTransform` for `object1`.

```
std::cout << "object1 ObjectToParent Matrix: " << std::endl;
std::cout << object1->GetObjectToParentTransform()->GetMatrix()
    << std::endl;
std::cout << "object1 ObjectToParent Offset: ";
std::cout << object1->GetObjectToParentTransform()->GetOffset()
    << std::endl;
```

Second, for the `ObjectToWorldTransform` for `object2`.

```
std::cout << "object2 ObjectToWorld Matrix: " << std::endl;
std::cout << object2->GetObjectToWorldTransform()->GetMatrix() << std::endl;
std::cout << "object2 ObjectToWorld Offset: ";
std::cout << object2->GetObjectToWorldTransform()->GetOffset() << std::endl;
```

Also, as a child is disconnected from its parent, it should not move; so its `ObjectToParentTransform` should be updated to match its `ObjectToWorldTransform`.

```
object1->RemoveChild(object2);
object2->Update();

std::cout << "object2 ObjectToWorld Matrix: " << std::endl;
std::cout << object2->GetObjectToWorldTransform()->GetMatrix() << std::endl;
std::cout << "object2 ObjectToWorld Offset: ";
std::cout << object2->GetObjectToWorldTransform()->GetOffset() << std::endl;
```

```
std::cout << "object2 ObjectToParent Matrix: " << std::endl;
std::cout << object2->GetObjectToParentTransform()->GetMatrix()
    << std::endl;
std::cout << "object2 ObjectToParent Offset: ";
std::cout << object2->GetObjectToParentTransform()->GetOffset()
    << std::endl;
```

The output of this second example looks like the following:

```
object2 ObjectToParent Matrix:
2 0
0 2
object2 ObjectToParent Offset: 0 0
object2 ObjectToWorld Matrix:
2 0
0 2
object2 ObjectToWorld Offset: 4 3

object1 ObjectToParent Matrix:
1 0
0 1
object1 ObjectToParent Offset: 3 3
object2 ObjectToWorld Matrix:
2 0
0 2
object2 ObjectToWorld Offset: 7 6

object2 ObjectToParent Matrix:
2 0
0 2
object2 ObjectToParent Offset: 7 6
object2 ObjectToWorld Matrix:
2 0
0 2
object2 ObjectToWorld Offset: 7 6
```

5.4 Types of Spatial Objects

This section describes in detail the variety of spatial objects implemented in ITK.

5.4.1 ArrowSpatialObject

The source code for this section can be found in the file `ArrowSpatialObject.cxx`.

This example shows how to create an `itk::ArrowSpatialObject`. Let's begin by including the appropriate header file.

```
#include "itkArrowSpatialObject.h"
```

The `itk::ArrowSpatialObject`, like many `SpatialObjects`, is templated over the dimensionality of the object.

```
using ArrowType = itk::ArrowSpatialObject<3>;
auto myArrow = ArrowType::New();
```

The position of the arrow in the object (local) coordinate frame is defined using the `SetPositionInObjectSpace()` method. By default the position is set to the origin of the space. This is the "tip" of the arrow.

```
ArrowType::PointType pos;
pos.Fill(1);
myArrow->SetPositionInObjectSpace(pos);
```

The length of the arrow in the local coordinate frame is done using the `SetLengthInObjectSpace()` method. By default the length is set to 1. This is the euclidean distance spanned by the arrow's tail from its tip (position).

```
myArrow->SetLengthInObjectSpace(2);
```

The direction of the arrow can be set using the `SetDirectionInObjectSpace()` method. This is the direction the tail of the arrow extends from the position. By default the direction is set along the X axis (first direction).

```
ArrowType::VectorType direction;
direction.Fill(0);
direction[1] = 1.0;
myArrow->SetDirectionInObjectSpace(direction);
```

5.4.2 BlobSpatialObject

The source code for this section can be found in the file `BlobSpatialObject.cxx`.

`itk::BlobSpatialObject` defines an n-dimensional blob. This class derives from `itk::itkPointBasedSpatialObject`. A blob is defined as a list of points which compose the object.

Let's start by including the appropriate header file.

```
#include "itkBlobSpatialObject.h"
```

BlobSpatialObject is templated over the dimension of the space. A BlobSpatialObject contains a list of SpatialObjectPoints. Basically, a SpatialObjectPoint has a position and a color.

```
#include "itkSpatialObjectPoint.h"
```

First we declare several standard type definitions.

Every Point-Based SpatialObject also provides type definitions for their SpatialObject point type (e.g., BlobPointType for BlobSpatialObject) as well as for a physical space point (e.g., an `itk::Point`).

Then, we create a list of points and we set the position of each point in the local coordinate system using the `SetPositionInObjectSpace()` method. We also set the color of each point to be red.

```
BlobType::BlobPointListType list;

for (unsigned int i = 0; i < 4; ++i)
{
    BlobPointType p;
    PointType      pnt;
    pnt[0] = i;
    pnt[1] = i + 1;
    pnt[2] = i + 2;
    p.SetPositionInObjectSpace(pnt);
    p.SetRed(1);
    p.SetGreen(0);
    p.SetBlue(0);
    p.SetAlpha(1.0);
    list.push_back(p);
}
```

Next, we create the blob and set its name using the `SetName()` function. We also set its Identification number with `SetId()` and we add the list of points previously created and call `Update()` so that the object can update its transforms, bounding boxes, and other cached convenience member variables.

```
BlobPointer blob = BlobType::New();
blob->GetProperty().SetName("My Blob");
blob->SetId(1);
blob->SetPoints(list);
blob->Update();
```

The `GetPoints()` method returns a reference to the internal list of points of the object.


```
BlobType::BlobPointListType pointList = blob->GetPoints();
std::cout << "The blob contains " << pointList.size();
std::cout << " points" << std::endl;
```

Then we can access the points using standard STL iterators and `GetPositionInWorldSpace()` and `GetColor()` functions return respectively the position and the color of the point.

`GetPositionInWorldSpace()` applies the `ObjectToParentTransforms` of all of the parent objects to this point. Since this object has no parents and since this object's `ObjectToParentTransform` is the identify transform (by default), these world space positions are the same as the object space positions that were set.

```
BlobType::BlobPointListType::const_iterator it = blob->GetPoints().begin();
while (it != blob->GetPoints().end())
{
    std::cout << "Position = " << (*it).GetPositionInWorldSpace()
              << std::endl;
    std::cout << "Color = " << (*it).GetColor() << std::endl;
    ++it;
}
```

5.4.3 EllipseSpatialObject

The source code for this section can be found in the file `EllipseSpatialObject.cxx`.

`itk::EllipseSpatialObject` defines an n-dimensional ellipse. Like other spatial objects this class derives from `itk::SpatialObject`. Let's start by including the appropriate header file.

```
#include "itkEllipseSpatialObject.h"
```

Like most of the `SpatialObjects`, the `itk::EllipseSpatialObject` is templated over the dimension of the space. In this example we create a 3-dimensional ellipse.

```
using EllipseType = itk::EllipseSpatialObject<3>;
auto myEllipse = EllipseType::New();
```

Then we set a radius for each dimension. By default the radius is set to 1. Additionally, after setting the `SpatialObject`'s radius, we call `Update()` to update all transforms, bounding box, and other convenience variables within the class that its other member functions (e.g., `IsInsideInWorldSpace()`) depend upon.

```
EllipseType::ArrayType radius;
for (unsigned int i = 0; i < 3; ++i)
{
```

```

    radius[i] = i;
}

myEllipse->SetRadiusInObjectSpace(radius);
myEllipse->Update();

```

Or if we have the same radius in each dimension we can do

```

myEllipse->SetRadiusInObjectSpace(2.0);
myEllipse->Update();

```

We can then display the current radius by using the `GetRadiusInObjectSpace()` function:

```

EllipseType::ArrayType myCurrentRadius =
    myEllipse->GetRadiusInObjectSpace();
std::cout << "Current radius is " << myCurrentRadius << std::endl;

```

Like other `SpatialObjects`, we can query the object if a point is inside the object by using the `IsInsideInWorldSpace(itk::Point)` function. This function expects the point to be in world coordinates.

```

itk::Point<double, 3> insidePoint;
insidePoint.Fill(1.0);
if (myEllipse->IsInsideInWorldSpace(insidePoint))
{
    std::cout << "The point " << insidePoint;
    std::cout << " is really inside the ellipse" << std::endl;
}

itk::Point<double, 3> outsidePoint;
outsidePoint.Fill(3.0);
if (!myEllipse->IsInsideInWorldSpace(outsidePoint))
{
    std::cout << "The point " << outsidePoint;
    std::cout << " is really outside the ellipse" << std::endl;
}

```

All spatial objects can be queried for a value at a point. The `IsEvaluableAtInWorldSpace()` function returns a boolean to know if the object is evaluable at a particular point.

```

if (myEllipse->IsEvaluableAtInWorldSpace(insidePoint))
{
    std::cout << "The point " << insidePoint;
    std::cout << " is evaluable at the point " << insidePoint << std::endl;
}

```

If the object is evaluable at that point, the `ValueAtInWorldSpace()` function returns the current value at that position. Most of the objects returns a boolean value which is set to true when the point

is inside the object and false when it is outside. However, for some objects, it is more interesting to return a value representing, for instance, the distance from the center of the object or the distance from the boundary.

```
double value;
myEllipse->ValueAtInWorldSpace(insidePoint, value);
std::cout << "The value inside the ellipse is: " << value << std::endl;
```

Like other spatial objects, we can also query the bounding box of the object by using `GetMyBoundingBoxInWorldSpace()`. The resulting bounding box is the world space.

```
const EllipseType::BoundingBoxType * boundingBox =
    myEllipse->GetMyBoundingBoxInWorldSpace();
std::cout << "Bounding Box: " << boundingBox->GetBounds() << std::endl;
```

5.4.4 GaussianSpatialObject

The source code for this section can be found in the file `GaussianSpatialObject.cxx`.

This example shows how to create a `itk::GaussianSpatialObject` which defines a Gaussian in an n-dimensional space. This object is particularly useful to query the value at a point in physical space. Let's begin by including the appropriate header file.

```
#include "itkGaussianSpatialObject.h"
```

The `itk::GaussianSpatialObject` is templated over the dimensionality of the object.

```
using GaussianType = itk::GaussianSpatialObject<3>;
auto myGaussian = GaussianType::New();
```

The `SetMaximum()` function is used to set the maximum value of the Gaussian.

```
myGaussian->SetMaximum(2);
```

The radius of the Gaussian is defined by the `SetRadiusInObjectSpace()` method. By default the radius is set to 1.0.

```
myGaussian->SetRadiusInObjectSpace(3);
```

The standard `ValueAt()` function is used to determine the value of the Gaussian at a particular point in physical space.

```

itk::Point<double, 3> pt;
pt[0] = 1;
pt[1] = 2;
pt[2] = 1;
double value;
myGaussian->ValueAtInWorldSpace(pt, value);
std::cout << "ValueAtInWorldSpace(" << pt << ") = " << value << std::endl;

```

5.4.5 GroupSpatialObject

The source code for this section can be found in the file `GroupSpatialObject.cxx`.

A `itk::GroupSpatialObject` does not have any data associated with it. It can be used to group objects or to add transforms to a current object. In this example we show how to use a `GroupSpatialObject`.

Let's begin by including the appropriate header file.

```
#include "itkGroupSpatialObject.h"
```

The `itk::GroupSpatialObject` is templated over the dimensionality of the object.

```

using GroupType = itk::GroupSpatialObject<3>;
auto myGroup = GroupType::New();

```

Next, we create an `itk::EllipseSpatialObject` and add it to the group.

```

using EllipseType = itk::EllipseSpatialObject<3>;
auto myEllipse = EllipseType::New();
myEllipse->SetRadiusInObjectSpace(2);

myGroup->AddChild(myEllipse);

```

We then translate the group by 10mm in each direction. Therefore the ellipse is translated in physical space at the same time.

```

GroupType::VectorType offset;
offset.Fill(10);
myGroup->GetModifiableObjectToParentTransform()->SetOffset(offset);
myGroup->Update();

```

We can then query if a point is inside the group using the `IsInsideInWorldSpace()` function. We need to specify in this case that we want to consider all the hierarchy, therefore we set the depth to 2.

```

GroupType::PointType point;
point.Fill(10);
std::cout << "Is my point " << point
          << " inside?: " << myGroup->IsInsideInWorldSpace(point, 2)
          << std::endl;

```

Like any other SpatialObjects we can remove the ellipse from the group using the `RemoveChild()` method.

```

myGroup->RemoveChild(myEllipse);

```

With ITKv5, the `GroupSpatialObject` also replaces the `SceneSpatialObject`. Much of the functionality is unchanged.

The source code for this section can be found in the file `SceneSpatialObject.cxx`.

This example describes how to use the `itk::GroupSpatialObject` as a replacement to ITKv4's `SceneSpatialObject`. This example begins by including the appropriate header file.

```

#include "itkGroupSpatialObject.h"

```

A `GroupSpatialObject` is templated over the dimension of the space which requires all the objects referenced by the `GroupSpatialObject` to have the same dimension.

First we define some type definitions and we create the `GroupSpatialObject`.

```

using GroupSpatialObjectType = itk::GroupSpatialObject<3>;
auto scene = GroupSpatialObjectType::New();

```

Then we create two `itk::EllipseSpatialObject`s.

```

using EllipseType = itk::EllipseSpatialObject<3>;
auto ellipse1 = EllipseType::New();
ellipse1->SetRadiusInObjectSpace(1);
ellipse1->SetId(1);
auto ellipse2 = EllipseType::New();
ellipse2->SetId(2);
ellipse2->SetRadiusInObjectSpace(2);

```

Then we add the two ellipses into the `GroupSpatialObject`.

```

scene->AddChild(ellipse1);
scene->AddChild(ellipse2);

```

We can query the number of object in the `GroupSpatialObject` with the `GetNumberOfObjects()` function. This function takes two optional arguments: the depth at which we should count the number of objects (default is set to infinity) and the name of the object to count (default is set to `ITK_NULLPTR`). This allows the user to count, for example, only ellipses.

```
std::cout << "Number of objects in the GroupSpatialObject = ";
std::cout << scene->GetNumberOfChildren() << std::endl;
```

The `GetObjectById()` returns the first object in the `GroupSpatialObject` that has the specified identification number.

```
std::cout << "Object in the GroupSpatialObject with an ID == 2: "
<< std::endl;
scene->GetObjectById(2)->Print(std::cout);
```

Objects can also be removed from the `GroupSpatialObject` using the `RemoveChild()` function.

```
scene->RemoveChild(ellipse1);
```

The list of current objects in the `GroupSpatialObject` can be retrieved using the `GetChildren()` method. Like the `GetNumberOfChildren()` method, `GetChildren()` can take two arguments: a search depth and a matching name.

```
GroupSpatialObjectType::ObjectListType * myObjectList =
    scene->GetChildren();
std::cout << "Number of children in the GroupSpatialObject = ";
std::cout << myObjectList->size() << std::endl;
```

In some cases, it is useful to define the hierarchy by using `ParentId()` and the current identification number. This results in having a flat list of `SpatialObjects` in the `GroupSpatialObject`. Therefore, the `GroupSpatialObject` provides the `FixParentChildHierarchyUsingParentIds()` method which reorganizes the Parent-Child hierarchy based on identification numbers.

```
scene->FixParentChildHierarchyUsingParentIds();
```

The scene can also be cleared by using the `RemoveAllChildren()` function.

```
scene->RemoveAllChildren();
```

5.4.6 ImageSpatialObject

The source code for this section can be found in the file `ImageSpatialObject.cxx`.

An `itk::ImageSpatialObject` contains an `itk::Image` but adds the notion of spatial transformations and parent-child hierarchy. Let's begin the next example by including the appropriate header file.

```
#include "itkImageSpatialObject.h"
```

We first create a simple 2D image of size 10 by 10 pixels.

```
using Image = itk::Image<short, 2>;
auto image = Image::New();
Image::SizeType size = { { 10, 10 } };
Image::RegionType region;
region.SetSize(size);
image->SetRegions(region);
image->Allocate();
```

Next we fill the image with increasing values.

```
using Iterator = itk::ImageRegionIterator<Image>;
Iterator it(image, region);
short pixelValue = 0;

for (it.GoToBegin(); !it.IsAtEnd(); ++it, ++pixelValue)
{
    it.Set(pixelValue);
}
```

We can now define the `ImageSpatialObject` which is templated over the dimension and the pixel type of the image.

```
using ImageSpatialObject = itk::ImageSpatialObject<2, short>;
auto imageSO = ImageSpatialObject::New();
```

Then we set the `itkImage` to the `ImageSpatialObject` by using the `SetImage()` function.

```
imageSO->SetImage(image);
imageSO->Update();
```

At this point we can use `IsInsideInWorldSpace()`, `IsInsideInObjectSpace()`, `ValueAtInWorldSpace()`, `ValueAtInObjectSpace()`, `DerivativeAtInWorldSpace()`, and `DerivativeAtInObjectSpace()` functions inherent in `SpatialObjects`. The `IsInsideInWorldSpace()` value can be particularly useful when dealing with registration.

```
using Point = itk::Point<double, 2>;
Point insidePoint;
insidePoint.Fill(9);

if (imageSO->IsInsideInWorldSpace(insidePoint))
{
    std::cout << insidePoint << " is inside the image." << std::endl;
}
```

The `ValueAtInWorldSpace()` returns the value of the closest pixel, i.e. no interpolation, to a given physical point.

```
double returnedValue;
imageSO->ValueAtInWorldSpace(insidePoint, returnedValue);
std::cout << "ValueAt(" << insidePoint << ") = " << returnedValue
    << std::endl;
```

The derivative at a specified position in space can be computed using the `DerivativeAtInWorldSpace()` function. The first argument is the point in physical coordinates where we are evaluating the derivatives. The second argument is the order of the derivation, and the third argument is the result expressed as a `itk::Vector`. Derivatives are computed iteratively using finite differences and, like the `ValueAtInWorldSpace()`, no interpolator is used.

```
ImageSpatialObject::DerivativeVectorType returnedDerivative;
imageSO->DerivativeAtInWorldSpace(insidePoint, 1, returnedDerivative);
std::cout << "First derivative at " << insidePoint;
std::cout << " = " << returnedDerivative << std::endl;
```

5.4.7 ImageMaskSpatialObject

The source code for this section can be found in the file `ImageMaskSpatialObject.cxx`.

An `itk::ImageMaskSpatialObject` is similar to the `itk::ImageSpatialObject` and derived from it. However, the main difference is that the `IsInsideInWorldSpace()` returns true if the pixel intensity in the image is not zero.

The supported pixel types does not include `itk::RGBPixel`, `itk::RGBAPixel`, etc. So far it only allows to manage images of simple types like unsigned short, unsigned int, or `itk::Vector`. Let's begin by including the appropriate header file.

```
#include "itkImageMaskSpatialObject.h"
```

The `ImageMaskSpatialObject` is templated over the dimensionality.

```
using ImageMaskSpatialObject = itk::ImageMaskSpatialObject<3>;
```

Next we create an `itk::Image` of size 50x50x50 filled with zeros except a bright square in the middle which defines the mask.

```
using PixelType = ImageMaskSpatialObject::PixelType;
using ImageType = ImageMaskSpatialObject::ImageType;
using Iterator = itk::ImageRegionIterator<ImageType>;
```



```

auto          image = ImageType::New();
ImageType::SizeType  size = { { 50, 50, 50 } };
ImageType::IndexType index = { { 0, 0, 0 } };
ImageType::RegionType region;

region.SetSize(size);
region.SetIndex(index);

image->SetRegions(region);
image->Allocate(true); // initialize buffer to zero

ImageType::RegionType insideRegion;
ImageType::SizeType  insideSize = { { 30, 30, 30 } };
ImageType::IndexType insideIndex = { { 10, 10, 10 } };
insideRegion.SetSize(insideSize);
insideRegion.SetIndex(insideIndex);

Iterator it(image, insideRegion);
it.GoToBegin();

while (!it.IsAtEnd())
{
    it.Set(itk::NumericTraits<PixelType>::max());
    ++it;
}

```

Then, we create an ImageMaskSpatialObject.

```

auto maskSO = ImageMaskSpatialObject::New();

```

We then pass the corresponding pointer to the image.

```

maskSO->SetImage(image);
maskSO->Update();

```

We can then test if a physical `itk::Point` is inside or outside the mask image. This is particularly useful during the registration process when only a part of the image should be used to compute the metric.

```

ImageMaskSpatialObject::PointType inside;
inside.Fill(20);
std::cout << "Is my point " << inside << " inside my mask? "
          << maskSO->IsInsideInWorldSpace(inside) << std::endl;
ImageMaskSpatialObject::PointType outside;
outside.Fill(45);
std::cout << "Is my point " << outside << " outside my mask? "
          << !maskSO->IsInsideInWorldSpace(outside) << std::endl;

```

5.4.8 LandmarkSpatialObject

The source code for this section can be found in the file `LandmarkSpatialObject.cxx`.

`itk::LandmarkSpatialObject` contains a list of `itk::SpatialObjectPoint`s which have a position and a color. Let's begin this example by including the appropriate header file.

```
#include "itkLandmarkSpatialObject.h"
```

`LandmarkSpatialObject` is templated over the dimension of the space.

Here we create a 3-dimensional landmark.

```
using LandmarkType = itk::LandmarkSpatialObject<3>;
using LandmarkPointer = LandmarkType::Pointer;
using LandmarkPointType = LandmarkType::LandmarkPointType;
using PointType = LandmarkType::PointType;

LandmarkPointer landmark = LandmarkType::New();
```

Next, we set some properties of the object like its name and its identification number.

```
landmark->GetProperty().SetName("Landmark1");
landmark->SetId(1);
```

We are now ready to add points into the landmark. We first create a list of `SpatialObjectPoint` and for each point we set the position and the color.

```
LandmarkType::LandmarkPointListType list;

for (unsigned int i = 0; i < 5; ++i)
{
    LandmarkPointType p;
    PointType pnt;
    pnt[0] = i;
    pnt[1] = i + 1;
    pnt[2] = i + 2;
    p.SetPositionInObjectSpace(pnt);
    p.SetColor(1, 0, 0, 1);
    list.push_back(p);
}
```

Then we add the list to the object using the `SetPoints()` method. Calling `Update()` afterwards ensures that World Space representations are also updated to match changes in the `SpatialObject`'s parameters.

```
landmark->SetPoints(list);
landmark->Update();
```

The current point list can be accessed using the `GetPoints()` method. The method returns a reference to the (STL) list.

```
size_t nPoints = landmark->GetPoints().size();
std::cout << "Number of Points in the landmark: " << nPoints << std::endl;

LandmarkType::LandmarkPointListType::const_iterator it =
    landmark->GetPoints().begin();
while (it != landmark->GetPoints().end())
{
    std::cout << "Position: " << (*it).GetPositionInObjectSpace()
              << std::endl;
    std::cout << "Color: " << (*it).GetColor() << std::endl;
    ++it;
}
```

5.4.9 LineSpatialObject

The source code for this section can be found in the file `LineSpatialObject.cxx`.

`itk::LineSpatialObject` defines a line in an n -dimensional space. A line is defined as a list of points which compose the line, i.e a polyline. We begin the example by including the appropriate header files.

```
#include "itkLineSpatialObject.h"
```

`LineSpatialObject` is templated over the dimension of the space. A `LineSpatialObject` contains a list of `LineSpatialObjectPoints`. A `LineSpatialObjectPoint` has a position, $n - 1$ normals and a color. Each normal is expressed as a `itk::CovariantVector` of size N .

First, we define some type definitions and we create our line.

```
using LineType = itk::LineSpatialObject<3>;
using LinePointer = LineType::Pointer;
using LinePointType = LineType::LinePointType;

using PointType = LineType::PointType;
using CovariantVectorType = LineType::CovariantVectorType;

LinePointer Line = LineType::New();
```

We create a point list and we set the position of each point in the local coordinate system using the `SetPositionInObjectSpace()` method. We also set the color of each point to red.

The two normals are set using the `SetNormalInObjectSpace()` function; the first argument is the normal itself and the second argument is the index of the normal.

```

LineType::LinePointListType list;

for (unsigned int i = 0; i < 3; ++i)
{
    LinePointType p;
    PointType      pnt;
    pnt[0] = i;
    pnt[1] = i + 1;
    pnt[2] = i + 2;
    p.SetPositionInObjectSpace(pnt);
    p.SetColor(1, 0, 0, 1);

    CovariantVectorType normal1;
    CovariantVectorType normal2;
    for (unsigned int j = 0; j < 3; ++j)
    {
        normal1[j] = j;
        normal2[j] = j * 2;
    }

    p.SetNormalInObjectSpace(normal1, 0);
    p.SetNormalInObjectSpace(normal2, 1);
    list.push_back(p);
}

```

Next, we set the name of the object using `SetName()`. We also set its identification number with `SetId()` and we set the list of points previously created.

```

Line->GetProperty().SetName("Line1");
Line->SetId(1);
Line->SetPoints(list);
Line->Update();

```

The `GetPoints()` method returns a reference to the internal list of points of the object.

```

LineType::LinePointListType pointList = Line->GetPoints();
std::cout << "Number of points representing the line: ";
std::cout << pointList.size() << std::endl;

```

Then we can access the points using standard STL iterators. The `GetPositionInObjectSpace()` and `GetColor()` functions return respectively the position and the color of the point. Using the `GetNormalInObjectSpace(unsigned int)` function we can access each normal.

```

LineType::LinePointListType::const_iterator it = Line->GetPoints().begin();
while (it != Line->GetPoints().end())
{
    std::cout << "Position = " << (*it).GetPositionInObjectSpace()
              << std::endl;
    std::cout << "Color = " << (*it).GetColor() << std::endl;
    std::cout << "First normal = " << (*it).GetNormalInObjectSpace(0)

```

```

        << std::endl;
    std::cout << "Second normal = " << (*it).GetNormalInObjectSpace(1)
        << std::endl;
    std::cout << std::endl;
    ++it;
}

```

5.4.10 MeshSpatialObject

The source code for this section can be found in the file `MeshSpatialObject.cxx`.

A `itk::MeshSpatialObject` contains a pointer to an `itk::Mesh` but adds the notion of spatial transformations and parent-child hierarchy. This example shows how to create an `itk::MeshSpatialObject`, use it to form a binary image, and write the mesh to disk.

Let's begin by including the appropriate header file.

```

#include "itkSpatialObjectToImageFilter.h"
#include "itkMeshSpatialObject.h"
#include "itkSpatialObjectReader.h"
#include "itkSpatialObjectWriter.h"

```

The `MeshSpatialObject` wraps an `itk::Mesh`, therefore we first create a mesh.

```

using MeshTrait = itk::DefaultDynamicMeshTraits<float, 3, 3>;
using MeshType = itk::Mesh<float, 3, MeshTrait>;
using CellTraits = MeshType::CellTraits;
using CellInterfaceType = itk::CellInterface<float, CellTraits>;
using TetraCellType = itk::TetrahedronCell<CellInterfaceType>;
using PointType = MeshType::PointType;
using CellType = MeshType::CellType;
using CellAutoPointer = CellType::CellAutoPointer;

```

```

auto myMesh = MeshType::New();

MeshType::CoordRepType testPointCoords[4][3] = {
    { 0, 0, 0 }, { 9, 0, 0 }, { 9, 9, 0 }, { 0, 0, 9 }
};

MeshType::PointIdentifier tetraPoints[4] = { 0, 1, 2, 4 };

int i;
for (i = 0; i < 4; ++i)
{
    myMesh->SetPoint(i, PointType(testPointCoords[i]));
}

myMesh->SetCellsAllocationMethod(

```

```

    itk::MeshEnums::MeshClassCellsAllocationMethod::
        CellsAllocatedDynamicallyCellByCell);
    CellAutoPointer testCell1;
    testCell1.TakeOwnership(new TetraCellType);
    testCell1->SetPointIds(tetraPoints);

```

```

myMesh->SetCell(0, testCell1);

```

We then create a `MeshSpatialObject` which is templated over the type of mesh previously defined...

```

using MeshSpatialObjectType = itk::MeshSpatialObject<MeshType>;
auto myMeshSpatialObject = MeshSpatialObjectType::New();

```

... and pass the `Mesh` pointer to the `MeshSpatialObject`

```

myMeshSpatialObject->SetMesh(myMesh);
myMeshSpatialObject->Update();

```

The actual pointer to the passed mesh can be retrieved using the `GetMesh()` function, just like any other `SpatialObjects`.

```

myMeshSpatialObject->GetMesh();

```

The `GetBoundingBoxInWorldSpace()`, `ValueAtInWorldSpace()`, `IsInsideInWorldSpace()`, and related functions in `ObjectSpace` can be used to access important information.

```

std::cout
    << "Mesh bounds : "
    << myMeshSpatialObject->GetMyBoundingBoxInWorldSpace()->GetBounds()
    << std::endl;
MeshSpatialObjectType::PointType myPhysicalPoint;
myPhysicalPoint.Fill(1);
std::cout << "Is my physical point inside? : "
    << myMeshSpatialObject->IsInsideInWorldSpace(myPhysicalPoint)
    << std::endl;

```

Now that we have defined the `MeshSpatialObject`, we can save the actual mesh using the `itk::SpatialObjectWriter`. In order to do so, we need to specify the type of `Mesh` we are writing.

```

using WriterType = itk::SpatialObjectWriter<3, float, MeshTrait>;
auto writer = WriterType::New();

```

Then we set the mesh spatial object and the name of the file and call the `Update()` function.

```
writer->SetInput(myMeshSpatialObject);
writer->SetFileName("myMesh.meta");
writer->Update();
```

Reading the saved mesh is done using the `itk::SpatialObjectReader`. Once again we need to specify the type of mesh we intend to read.

```
using ReaderType = itk::SpatialObjectReader<3, float, MeshTrait>;
auto reader = ReaderType::New();
```

We set the name of the file we want to read and call update

```
reader->SetFileName("myMesh.meta");
reader->Update();
```

Next, we show how to create a binary image of a `MeshSpatialObject` using the `itk::SpatialObjectToImageFilter`. The resulting image will have ones inside and zeros outside the mesh. First we define and instantiate the `SpatialObjectToImageFilter`.

```
using ImageType = itk::Image<unsigned char, 3>;
using GroupType = itk::GroupSpatialObject<3>;
using SpatialObjectToImageFilterType =
    itk::SpatialObjectToImageFilter<GroupType, ImageType>;
auto imageFilter = SpatialObjectToImageFilterType::New();
```

Then we pass the output of the reader, i.e the `MeshSpatialObject`, to the filter.

```
imageFilter->SetInput(reader->GetGroup());
```

Finally we trigger the execution of the filter by calling the `Update()` method. Note that depending on the size of the mesh, the computation time can increase significantly.

```
imageFilter->Update();
```

Then we can get the resulting binary image using the `GetOutput()` function.

```
ImageType::Pointer myBinaryMeshImage = imageFilter->GetOutput();
```

5.4.11 SurfaceSpatialObject

The source code for this section can be found in the file `SurfaceSpatialObject.cxx`.

`itk::SurfaceSpatialObject` defines a surface in n -dimensional space. A `SurfaceSpatialObject` is defined by a list of points which lie on the surface. Each point has a position and a normal. The example begins by including the appropriate header file.

```
#include "itkSurfaceSpatialObject.h"
```

SurfaceSpatialObject is templated over the dimension of the space. A SurfaceSpatialObject contains a list of SurfaceSpatialObjectPoints. A SurfaceSpatialObjectPoint has a position, a normal and a color.

First we define some type definitions

```
using SurfaceType = itk::SurfaceSpatialObject<3>;
using SurfacePointer = SurfaceType::Pointer;

using SurfacePointType = SurfaceType::SurfacePointType;
using CovariantVectorType = SurfaceType::CovariantVectorType;
using PointType = SurfaceType::PointType;

SurfacePointer surface = SurfaceType::New();
```

We create a point list and we set the position of each point in the local coordinate system using the SetPositionInObjectSpace() method. We also set the color of each point to red.

```
SurfaceType::SurfacePointListType list;

for (unsigned int i = 0; i < 3; ++i)
{
    SurfacePointType p;
    PointType pnt;
    pnt[0] = i;
    pnt[1] = i + 1;
    pnt[2] = i + 2;
    p.SetPositionInObjectSpace(pnt);
    p.SetColor(1, 0, 0, 1);
    CovariantVectorType normal;
    for (unsigned int j = 0; j < 3; ++j)
    {
        normal[j] = j;
    }
    p.SetNormalInObjectSpace(normal);
    list.push_back(p);
}
```

Next, we create the surface and set his name using SetName(). We also set its Identification number with SetId() and we add the list of points previously created.

```
surface->GetProperty().SetName("Surface1");
surface->SetId(1);
surface->SetPoints(list);
surface->Update();
```

The GetPoints() method returns a reference to the internal list of points of the object.


```
SurfaceType::SurfacePointListType pointList = surface->GetPoints();
std::cout << "Number of points representing the surface: ";
std::cout << pointList.size() << std::endl;
```

Then we can access the points using standard STL iterators. `GetPositionInObjectSpace()` and `GetColor()` functions return respectively the position and the color of the point. `GetNormalInObjectSpace()` returns the normal as a `itk::CovariantVector`.

```
SurfaceType::SurfacePointListType::const_iterator it =
    surface->GetPoints().begin();
while (it != surface->GetPoints().end())
{
    std::cout << "Position = " << (*it).GetPositionInObjectSpace()
        << std::endl;
    std::cout << "Normal = " << (*it).GetNormalInObjectSpace() << std::endl;
    std::cout << "Color = " << (*it).GetColor() << std::endl;
    std::cout << std::endl;
    it++;
}
```

5.4.12 TubeSpatialObject

`itk::TubeSpatialObject` is a class for the representation of tubular structures using `SpatialObjects`. In particular, it is intended to be used to represent vascular networks extracted from 2D and 3D images. It can also be used to represent airways, nerves, bile ducts, and more.

The class `itk::DTITubeSpatialObject` is derived from this class and adds constructs for representing fiber tracts from diffusion tensor images.

The source code for this section can be found in the file `TubeSpatialObject.cxx`.

`itk::TubeSpatialObject` defines an n-dimensional tube. A tube is defined as a list of centerline points which have a position, a radius, some normals and other properties. Let's start by including the appropriate header file.

```
#include "itkTubeSpatialObject.h"
```

`TubeSpatialObject` is templated over the dimension of the space. A `TubeSpatialObject` contains a list of `TubeSpatialObjectPoints`.

First we define some type definitions and we create the tube.

```
using TubeType = itk::TubeSpatialObject<3>;
using TubePointer = TubeType::Pointer;

using TubePointType = TubeType::TubePointType;
```

```

using PointType = TubeType::PointType;
using CovariantVectorType = TubePointType::CovariantVectorType;

TubePointer tube = TubeType::New();

```

We create a point list and we set:

1. The position of each point in the local coordinate system using the `SetPositionInObjectSpace()` method.
2. The radius of the tube at this position using `SetRadiusInObjectSpace()`.
3. The two normals at the tube is set using `SetNormal1InObjectSpace()` and `SetNormal2InObjectSpace()`.
4. The color of the point is set to red in our case.

```

TubeType::TubePointListType list;
for (i = 0; i < 5; ++i)
{
    TubePointType p;
    PointType pnt;
    pnt[0] = i;
    pnt[1] = i + 1;
    pnt[2] = i + 2;
    p.SetPositionInObjectSpace(pnt);
    p.SetRadiusInObjectSpace(1);
    CovariantVectorType normal1;
    CovariantVectorType normal2;
    for (unsigned int j = 0; j < 3; ++j)
    {
        normal1[j] = j;
        normal2[j] = j * 2;
    }

    p.SetNormal1InObjectSpace(normal1);
    p.SetNormal2InObjectSpace(normal2);
    p.SetColor(1, 0, 0, 1);

    list.push_back(p);
}

```

Next, we create the tube and set its name using `SetName()`. We also set its identification number with `SetId()` and, at the end, we add the list of points previously created.

```

tube->GetProperty().SetName("Tube1");
tube->SetId(1);
tube->SetPoints(list);
tube->Update();

```

The `GetPoints()` method return a reference to the internal list of points of the object.

```
TubeType::TubePointListType pointList = tube->GetPoints();
std::cout << "Number of points representing the tube: ";
std::cout << pointList.size() << std::endl;
```

The `ComputeTangentAndNormals()` function computes the normals and the tangent for each point using finite differences.

```
tube->ComputeTangentsAndNormals();
```

Then we can access the points using STL iterators. `GetPositionInObjectSpace()` and `GetColor()` functions return respectively the position and the color of the point. `GetRadiusInObjectSpace()` returns the radius at that point. `GetNormal1InObjectSpace()` and `GetNormal2InObjectSpace()` functions return a `itk::CovariantVector` and `GetTangentInObjectSpace()` returns a `itk::Vector`.

```
TubeType::TubePointListType::const_iterator it = tube->GetPoints().begin();
i = 0;
while (it != tube->GetPoints().end())
{
    std::cout << std::endl;
    std::cout << "Point #" << i << std::endl;
    std::cout << "Position: " << (*it).GetPositionInObjectSpace()
    << std::endl;
    std::cout << "Radius: " << (*it).GetRadiusInObjectSpace() << std::endl;
    std::cout << "Tangent: " << (*it).GetTangentInObjectSpace() << std::endl;
    std::cout << "First Normal: " << (*it).GetNormal1InObjectSpace()
    << std::endl;
    std::cout << "Second Normal: " << (*it).GetNormal2InObjectSpace()
    << std::endl;
    std::cout << "Color = " << (*it).GetColor() << std::endl;
    it++;
    i++;
}
```

5.4.13 DTITubeSpatialObject

The source code for this section can be found in the file `DTITubeSpatialObject.cxx`.

`itk::DTITubeSpatialObject` derives from `itk::TubeSpatialObject`. It represents a fiber tracts from Diffusion Tensor Imaging. A `DTITubeSpatialObject` is described as a list of center-line points which have a position, a radius, normals, the fractional anisotropy (FA) value, the ADC value, the geodesic anisotropy (GA) value, the eigenvalues and vectors as well as the full tensor matrix.

Let's start by including the appropriate header file.

```
#include "itkDTITubeSpatialObject.h"
```

DTITubeSpatialObject is templated over the dimension of the space. A DTITubeSpatialObject contains a list of DTITubeSpatialObjectPoints.

First we define some type definitions and we create the tube.

```
using DTITubeType = itk::DTITubeSpatialObject<3>;
using DTITubePointType = DTITubeType::DTITubePointType;
using PointType = DTITubeType::PointType;

auto dtiTube = DTITubeType::New();
```

We create a point list and we set:

1. The position of each point in the local coordinate system using the `SetPositionInObjectSpace()` method.
2. The radius of the tube at this position using `SetRadiusInObjectSpace()`.
3. The FA value using `AddField(DTITubePointType::FA)`.
4. The ADC value using `AddField(DTITubePointType::ADC)`.
5. The GA value using `AddField(DTITubePointType::GA)`.
6. The full tensor matrix supposed to be symmetric definite positive value using `SetTensorMatrix()`.
7. The color of the point is set to red in our case.

```
DTITubeType::DTITubePointListType list;
for (i = 0; i < 5; ++i)
{
    DTITubePointType p;
    PointType pnt;
    pnt[0] = i;
    pnt[1] = i + 1;
    pnt[2] = i + 2;
    p.SetPositionInObjectSpace(pnt);
    p.SetRadiusInObjectSpace(1);
    p.AddField(
        itk::DTITubeSpatialObjectPointEnums::DTITubeSpatialObjectPointField::FA,
        i);
    p.AddField(itk::DTITubeSpatialObjectPointEnums::
        DTITubeSpatialObjectPointField::ADC,
        2 * i);
    p.AddField(
        itk::DTITubeSpatialObjectPointEnums::DTITubeSpatialObjectPointField::GA,
        3 * i);
}
```

```

p.AddField("Lambda1", 4 * i);
p.AddField("Lambda2", 5 * i);
p.AddField("Lambda3", 6 * i);
auto * v = new float[6];
for (unsigned int k = 0; k < 6; ++k)
{
    v[k] = k;
}
p.SetTensorMatrix(v);
delete[] v;
p.SetColor(1, 0, 0, 1);
list.push_back(p);
}

```

Next, we create the tube and set its name using `SetName()`. We also set its identification number with `SetId()` and, at the end, we add the list of points previously created.

```

dtiTube->GetProperty().SetName("DTITube");
dtiTube->SetId(1);
dtiTube->SetPoints(list);
dtiTube->Update();

```

The `GetPoints()` method return a reference to the internal list of points of the object.

```

DTITubeType::DTITubePointListType pointList = dtiTube->GetPoints();
std::cout << "Number of points representing the fiber tract: ";
std::cout << pointList.size() << std::endl;

```

Then we can access the points using STL iterators. `GetPositionInObjectSpace()` and `GetColor()` functions return respectively the position and the color of the point.

```

DTITubeType::DTITubePointListType::const_iterator it =
    dtiTube->GetPoints().begin();
i = 0;
while (it != dtiTube->GetPoints().end())
{
    std::cout << std::endl;
    std::cout << "Point #" << i << std::endl;
    std::cout << "Position: " << (*it).GetPositionInObjectSpace()
    << std::endl;
    std::cout << "Radius: " << (*it).GetRadiusInObjectSpace() << std::endl;
    std::cout << "FA: "
    << (*it).GetField(itk::DTITubeSpatialObjectPointEnums::
        DTITubeSpatialObjectPointField::FA)
    << std::endl;
    std::cout << "ADC: "
    << (*it).GetField(itk::DTITubeSpatialObjectPointEnums::
        DTITubeSpatialObjectPointField::ADC)
    << std::endl;
    std::cout << "GA: "

```

```

        << (*it).GetField(itk::DTITubeSpatialObjectPointEnums::
                        DTITubeSpatialObjectPointField::GA)
        << std::endl;
std::cout << "Lambda1: " << (*it).GetField("Lambda1") << std::endl;
std::cout << "Lambda2: " << (*it).GetField("Lambda2") << std::endl;
std::cout << "Lambda3: " << (*it).GetField("Lambda3") << std::endl;
std::cout << "TensorMatrix: " << (*it).GetTensorMatrix()[0] << " : ";
std::cout << (*it).GetTensorMatrix()[1] << " : ";
std::cout << (*it).GetTensorMatrix()[2] << " : ";
std::cout << (*it).GetTensorMatrix()[3] << " : ";
std::cout << (*it).GetTensorMatrix()[4] << " : ";
std::cout << (*it).GetTensorMatrix()[5] << std::endl;
std::cout << "Color = " << (*it).GetColor() << std::endl;
++it;
++i;
}

```

5.5 Read/Write SpatialObjects

The source code for this section can be found in the file `ReadWriteSpatialObject.cxx`.

Reading and writing `SpatialObjects` is a fairly simple task. The classes `itk::SpatialObjectReader` and `itk::SpatialObjectWriter` are used to read and write these objects, respectively. (Note these classes make use of the MetaIO auxiliary I/O routines and therefore have a `.meta` file suffix.)

We begin this example by including the appropriate header files.

```

#include "itkSpatialObjectReader.h"
#include "itkSpatialObjectWriter.h"
#include "itkEllipseSpatialObject.h"

```

Next, we create a `SpatialObjectWriter` that is templated over the dimension of the object(s) we want to write.

```

using WriterType = itk::SpatialObjectWriter<3>;
auto writer = WriterType::New();

```

For this example, we create an `itk::EllipseSpatialObject`.

```

using EllipseType = itk::EllipseSpatialObject<3>;
auto ellipse = EllipseType::New();
ellipse->SetRadiusInObjectSpace(3);

```

Finally, we set to the writer the object to write using the `SetInput()` method and we set the name of the file with `SetFileName()` and call the `Update()` method to actually write the information.

```
writer->SetInput(ellipse);
writer->SetFileName("ellipse.meta");
writer->Update();
```

Now we are ready to open the freshly created object. We first create a `SpatialObjectReader` which is also templated over the dimension of the object in the file. This means that the file should contain only objects with the same dimension.

```
using ReaderType = itk::SpatialObjectReader<3>;
auto reader = ReaderType::New();
```

Next we set the name of the file to read using `SetFileName()` and we call the `Update()` method to read the file.

```
reader->SetFileName("ellipse.meta");
reader->Update();
```

To get the objects in the file you can call the `GetGroup()` method. Calls to `GetGroup()` returns a pointer to a `itk::GroupSpatialObject`.

```
ReaderType::GroupType * group = reader->GetGroup();
std::cout << "Number of objects in the group: ";
std::cout << group->GetNumberOfChildren() << std::endl;
```

5.6 Statistics Computation via SpatialObjects

The source code for this section can be found in the file `SpatialObjectToImageStatisticsCalculator.cxx`.

This example describes how to use the `itk::SpatialObjectToImageStatisticsCalculator` to compute statistics of an `itk::Image` only in a region defined inside a given `itk::SpatialObject`.

```
#include "itkSpatialObjectToImageStatisticsCalculator.h"
```

We first create a test image using the `itk::RandomImageSource`

```
using ImageType = itk::Image<unsigned char, 2>;
using RandomImageSourceType = itk::RandomImageSource<ImageType>;
auto randomImageSource = RandomImageSourceType::New();
ImageType::SizeValueType size[2];
size[0] = 10;
size[1] = 10;
randomImageSource->SetSize(size);
randomImageSource->Update();
ImageType::Pointer image = randomImageSource->GetOutput();
```

Next we create an `itk::EllipseSpatialObject` with a radius of 2. We also move the ellipse to the center of the image.

```
using EllipseType = itk::EllipseSpatialObject<2>;
auto ellipse = EllipseType::New();
ellipse->SetRadiusInObjectSpace(2);
EllipseType::PointType offset;
offset.Fill(5);
ellipse->SetCenterInObjectSpace(offset);
ellipse->Update();
```

Then we can create the `itk::SpatialObjectToImageStatisticsCalculator`.

```
using CalculatorType =
    itk::SpatialObjectToImageStatisticsCalculator<ImageType, EllipseType>;
auto calculator = CalculatorType::New();
```

We pass a pointer to the image to the calculator.

```
calculator->SetImage(image);
```

We also pass the `SpatialObject`. The statistics will be computed inside the `SpatialObject` (Internally the calculator is using the `IsInside()` function).

```
calculator->SetSpatialObject(ellipse);
```

At the end we trigger the computation via the `Update()` function and we can retrieve the mean and the covariance matrix using `GetMean()` and `GetCovarianceMatrix()` respectively.

```
calculator->Update();
std::cout << "Sample mean = " << calculator->GetMean() << std::endl;
std::cout << "Sample covariance = " << calculator->GetCovarianceMatrix();
```


ITERATORS

This chapter introduces the *image iterator*, an important generic programming construct for image processing in ITK. An iterator is a generalization of the familiar C programming language pointer used to reference data in memory. ITK has a wide variety of image iterators, some of which are highly specialized to simplify common image processing tasks.

The next section is a brief introduction that defines iterators in the context of ITK. Section 6.2 describes the programming interface common to most ITK image iterators. Sections 6.3–6.4 document specific ITK iterator types and provide examples of how they are used.

6.1 Introduction

Generic programming models define functionally independent components called *containers* and *algorithms*. Container objects store data and algorithms operate on data. To access data in containers, algorithms use a third class of objects called *iterators*. An iterator is an abstraction of a memory pointer. Every container type must define its own iterator type, but all iterators are written to provide a common interface so that algorithm code can reference data in a generic way and maintain functional independence from containers.

The iterator is so named because it is used for *iterative*, sequential access of container values. Iterators appear in `for` and `while` loop constructs, visiting each data point in turn. A C pointer, for example, is a type of iterator. It can be moved forward (incremented) and backward (decremented) through memory to sequentially reference elements of an array. Many iterator implementations have an interface similar to a C pointer.

In ITK we use iterators to write generic image processing code for images instantiated with different combinations of pixel type, pixel container type, and dimensionality. Because ITK image iterators are specifically designed to work with *image* containers, their interface and implementation is optimized for image processing tasks. Using the ITK iterators instead of accessing data directly through the `itk::Image` interface has many advantages. Code is more compact and often generalizes automatically to higher dimensions, algorithms run much faster, and iterators simplify tasks such as

multithreading and neighborhood-based image processing.

6.2 Programming Interface

This section describes the standard ITK image iterator programming interface. Some specialized image iterators may deviate from this standard or provide additional methods.

6.2.1 Creating Iterators

All image iterators have at least one template parameter that is the image type over which they iterate. There is no restriction on the dimensionality of the image or on the pixel type of the image.

An iterator constructor requires at least two arguments, a smart pointer to the image to iterate across, and an image region. The image region, called the *iteration region*, is a rectilinear area in which iteration is constrained. The iteration region must be wholly contained within the image. More specifically, a valid iteration region is any subregion of the image within the current `BufferedRegion`. See Section 4.1 for more information on image regions.

There is a const and a non-const version of most ITK image iterators. A non-const iterator cannot be instantiated on a non-const image pointer. Const versions of iterators may read, but may not write pixel values.

Here is a simple example that defines and constructs a simple image iterator for an `itk::Image`.

```
using ImageType = itk::Image<float, 3>;
using ConstIteratorType = itk::ImageRegionConstIterator<ImageType>;
using IteratorType = itk::ImageRegionIterator<ImageType>;

ImageType::Pointer image = SomeFilter->GetOutput();

ConstIteratorType constIterator(image, image->GetRequestedRegion());
IteratorType iterator(image, image->GetRequestedRegion());
```

6.2.2 Moving Iterators

An iterator is described as *walking* its iteration region. At any time, the iterator will reference, or “point to”, one pixel location in the N-dimensional (ND) image. *Forward iteration* goes from the beginning of the iteration region to the end of the iteration region. *Reverse iteration*, goes from just past the end of the region back to the beginning. There are two corresponding starting positions for iterators, the *begin* position and the *end* position. An iterator can be moved directly to either of these two positions using the following methods.

- **GoToBegin()** Points the iterator to the first valid data element in the region.

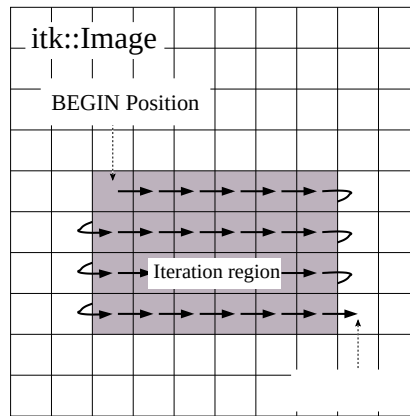


Figure 6.1: Normal path of an iterator through a 2D image. The iteration region is shown in a darker shade. An arrow denotes a single iterator step, the result of one `++` operation.

- **GoToEnd()** Points the iterator to *one position past* the last valid element in the region.

Note that the end position is not actually located within the iteration region. This is important to remember because attempting to dereference an iterator at its end position will have undefined results.

ITK iterators are moved back and forth across their iterations using the decrement and increment operators.

- **operator++()** Increments the iterator one position in the positive direction. Only the prefix increment operator is defined for ITK image iterators.
- **operator--()** Decrements the iterator one position in the negative direction. Only the prefix decrement operator is defined for ITK image iterators.

Figure 6.1 illustrates typical iteration over an image region. Most iterators increment and decrement in the direction of the fastest increasing image dimension, wrapping to the first position in the next higher dimension at region boundaries. In other words, an iterator first moves across columns, then down rows, then from slice to slice, and so on.

In addition to sequential iteration through the image, some iterators may define random access operators. Unlike the increment operators, random access operators may not be optimized for speed and require some knowledge of the dimensionality of the image and the extent of the iteration region to use properly.

- **operator+=(OffsetType)** Moves the iterator to the pixel position at the current index plus specified `itk::Offset`.

- **operator--(OffsetType)** Moves the iterator to the pixel position at the current index minus specified Offset.
- **SetPosition(IndexType)** Moves the iterator to the given `itk::Index` position.

The `SetPosition()` method may be extremely slow for more complicated iterator types. In general, it should only be used for setting a starting iteration position, like you would use `GoToBegin()` or `GoToEnd()`.

Some iterators do not follow a predictable path through their iteration regions and have no fixed beginning or ending pixel locations. A conditional iterator, for example, visits pixels only if they have certain values or connectivities. Random iterators, increment and decrement to random locations and may even visit a given pixel location more than once.

An iterator can be queried to determine if it is at the end or the beginning of its iteration region.

- **bool IsAtEnd()** True if the iterator points to *one position past* the end of the iteration region.
- **bool IsAtBegin()** True if the iterator points to the first position in the iteration region. The method is typically used to test for the end of reverse iteration.

An iterator can also report its current image index position.

- **IndexType GetIndex()** Returns the Index of the image pixel that the iterator currently points to.

For efficiency, most ITK image iterators do not perform bounds checking. It is possible to move an iterator outside of its valid iteration region. Dereferencing an out-of-bounds iterator will produce undefined results.

6.2.3 Accessing Data

ITK image iterators define two basic methods for reading and writing pixel values.

- **PixelType Get()** Returns the value of the pixel at the iterator position.
- **void Set(PixelType)** Sets the value of the pixel at the iterator position. Not defined for const versions of iterators.

The `Get()` and `Set()` methods are inlined and optimized for speed so that their use is equivalent to dereferencing the image buffer directly. There are a few common cases, however, where using `Get()` and `Set()` do incur a penalty. Consider the following code, which fetches, modifies, and then writes a value back to the same pixel location.

```
it.Set(it.Get() + 1);
```

As written, this code requires one more memory dereference than is necessary. Some iterators define a third data access method that avoids this penalty.

- **PixelType &Value()** Returns a reference to the pixel at the iterator position.

The `Value()` method can be used as either an lval or an rval in an expression. It has all the properties of `operator*`. The `Value()` method makes it possible to rewrite our example code more efficiently.

```
it.Value()++;
```

Consider using the `Value()` method instead of `Get()` or `Set()` when a call to `operator=` on a pixel is non-trivial, such as when working with vector pixels, and operations are done in-place in the image. The disadvantage of using `Value` is that it cannot support image adapters (see Section 7 on page 175 for more information about image adapters).

6.2.4 Iteration Loops

Using the methods described in the previous sections, we can now write a simple example to do pixel-wise operations on an image. The following code calculates the squares of all values in an input image and writes them to an output image.

```
ConstIteratorType in(inputImage, inputImage->GetRequestedRegion());
IteratorType      out(outputImage, inputImage->GetRequestedRegion());

for (in.GoToBegin(), out.GoToBegin(); !in.IsAtEnd(); ++in, ++out)
{
    out.Set(in.Get() * in.Get());
}
```

Notice that both the input and output iterators are initialized over the same region, the `RequestedRegion` of `inputImage`. This is good practice because it ensures that the output iterator walks exactly the same set of pixel indices as the input iterator, but does not require that the output and input be the same size. The only requirement is that the input image must contain a region (a starting index and size) that matches the `RequestedRegion` of the output image.

Equivalent code can be written by iterating through the image in reverse. The syntax is slightly more awkward because the *end* of the iteration region is not a valid position and we can only test whether the iterator is strictly *equal* to its beginning position. It is often more convenient to write reverse iteration in a `while` loop.

```
in.GoToEnd();
out.GoToEnd();
while (!in.IsAtBegin())
```

```
{
    --in;
    --out;
    out.Set(in.Get() * in.Get());
}
```

6.3 Image Iterators

This section describes iterators that walk rectilinear image regions and reference a single pixel at a time. The `itk::ImageRegionIterator` is the most basic ITK image iterator and the first choice for most applications. The rest of the iterators in this section are specializations of `ImageRegionIterator` that are designed make common image processing tasks more efficient or easier to implement.

6.3.1 ImageRegionIterator

The source code for this section can be found in the file `ImageRegionIterator.cxx`.

The `itk::ImageRegionIterator` is optimized for iteration speed and is the first choice for iterative, pixel-wise operations when location in the image is not important. `ImageRegionIterator` is the least specialized of the ITK image iterator classes. It implements all of the methods described in the preceding section.

The following example illustrates the use of `itk::ImageRegionConstIterator` and `ImageRegionIterator`. Most of the code constructs introduced apply to other ITK iterators as well. This simple application crops a subregion from an image by copying its pixel values into to a second, smaller image.

We begin by including the appropriate header files.

```
#include "itkImageRegionIterator.h"
```

Next we define a pixel type and corresponding image type. ITK iterator classes expect the image type as their template parameter.

```
constexpr unsigned int Dimension = 2;

using PixelType = unsigned char;
using ImageType = itk::Image<PixelType, Dimension>;

using ConstIteratorType = itk::ImageRegionConstIterator<ImageType>;
using IteratorType = itk::ImageRegionIterator<ImageType>;
```

Information about the subregion to copy is read from the command line. The subregion is defined by an `itk::ImageRegion` object, with a starting grid index and a size (Section 4.1).

```

ImageType::RegionType inputRegion;

ImageType::RegionType::IndexType inputStart;
ImageType::RegionType::SizeType size;

inputStart[0] = std::stoi(argv[3]);
inputStart[1] = std::stoi(argv[4]);

size[0] = std::stoi(argv[5]);
size[1] = std::stoi(argv[6]);

inputRegion.SetSize(size);
inputRegion.SetIndex(inputStart);

```

The destination region in the output image is defined using the input region size, but a different start index. The starting index for the destination region is the corner of the newly generated image.

```

ImageType::RegionType outputRegion;

ImageType::RegionType::IndexType outputStart;

outputStart[0] = 0;
outputStart[1] = 0;

outputRegion.SetSize(size);
outputRegion.SetIndex(outputStart);

```

After reading the input image and checking that the desired subregion is, in fact, contained in the input, we allocate an output image. It is fundamental to set valid values to some of the basic image information during the copying process. In particular, the starting index of the output region is now filled up with zero values and the coordinates of the physical origin are computed as a shift from the origin of the input image. This is quite important since it will allow us to later register the extracted region against the original image.

```

auto outputImage = ImageType::New();
outputImage->SetRegions(outputRegion);
const ImageType::SpacingType & spacing = inputImage->GetSpacing();
const ImageType::PointType & inputOrigin = inputImage->GetOrigin();
double outputOrigin[Dimension];

for (unsigned int i = 0; i < Dimension; ++i)
{
    outputOrigin[i] = inputOrigin[i] + spacing[i] * inputStart[i];
}

outputImage->SetSpacing(spacing);
outputImage->SetOrigin(outputOrigin);
outputImage->Allocate();

```

The necessary images and region definitions are now in place. All that is left to do is to create the iterators and perform the copy. Note that image iterators are not accessed via smart pointers so they

are light-weight objects that are instantiated on the stack. Also notice how the input and output iterators are defined over the *same corresponding region*. Though the images are different sizes, they both contain the same target subregion.

```
ConstIteratorType inputIt(inputImage, inputRegion);
IteratorType      outputIt(outputImage, outputRegion);

inputIt.GoToBegin();
outputIt.GoToBegin();

while (!inputIt.IsAtEnd())
{
    outputIt.Set(inputIt.Get());
    ++inputIt;
    ++outputIt;
}
```

The while loop above is a common construct in ITK. The beauty of these four lines of code is that they are equally valid for one, two, three, or even ten dimensional data, and no knowledge of the size of the image is necessary. Consider the ugly alternative of ten nested for loops for traversing an image.

Let's run this example on the image `FatMRISlice.png` found in `Examples/Data`. The command line arguments specify the input and output file names, then the *x, y* origin and the *x, y* size of the cropped subregion.

```
ImageRegionIterator FatMRISlice.png ImageRegionIteratorOutput.png 20 70
210 140
```

The output is the cropped subregion shown in Figure 6.2.

6.3.2 ImageRegionIteratorWithIndex

The source code for this section can be found in the file `ImageRegionIteratorWithIndex.cxx`.

The “WithIndex” family of iterators was designed for algorithms that use both the value and the location of image pixels in calculations. Unlike `itk::ImageRegionIterator`, which calculates an index only when asked for, `itk::ImageRegionIteratorWithIndex` maintains its index location as a member variable that is updated during the increment or decrement process. Iteration speed is penalized, but the index queries are more efficient.

The following example illustrates the use of `ImageRegionIteratorWithIndex`. The algorithm mirrors a 2D image across its *x*-axis (see `itk::FlipImageFilter` for an ND version). The algorithm makes extensive use of the `GetIndex()` method.

We start by including the proper header file.

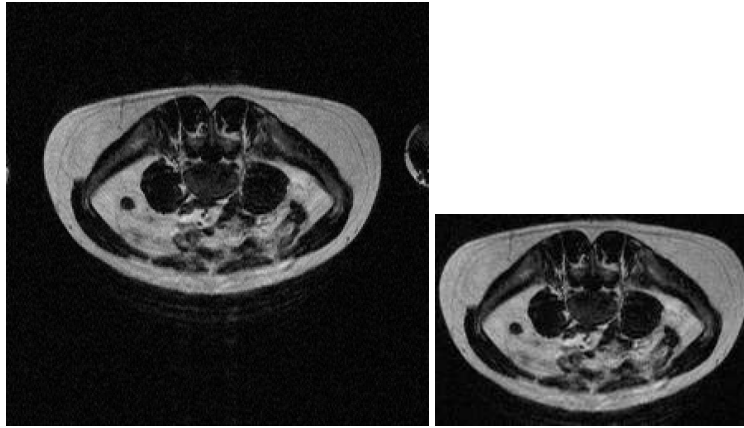


Figure 6.2: Cropping a region from an image. The original image is shown at left. The image on the right is the result of applying the `ImageRegionIterator` example code.

```
#include "itkImageRegionIteratorWithIndex.h"
```

For this example, we will use an RGB pixel type so that we can process color images. Like most other ITK image iterator, `ImageRegionIteratorWithIndex` class expects the image type as its single template parameter.

```
constexpr unsigned int Dimension = 2;

using RGBPixelType = itk::RGBPixel<unsigned char>;
using ImageType = itk::Image<RGBPixelType, Dimension>;

using IteratorType = itk::ImageRegionIteratorWithIndex<ImageType>;
```

An `ImageType` smart pointer called `inputImage` points to the output of the image reader. After updating the image reader, we can allocate an output image of the same size, spacing, and origin as the input image.

```
auto outputImage = ImageType::New();
outputImage->SetRegions(inputImage->GetRequestedRegion());
outputImage->CopyInformation(inputImage);
outputImage->Allocate();
```

Next we create the iterator that walks the output image. This algorithm requires no iterator for the input image.

```
IteratorType outputIt(outputImage, outputImage->GetRequestedRegion());
```

This axis flipping algorithm works by iterating through the output image, querying the iterator for its index, and copying the value from the input at an index mirrored across the x -axis.

```
ImageType::IndexType requestedIndex =
    outputImage->GetRequestedRegion().GetIndex();
ImageType::SizeType requestedSize =
```

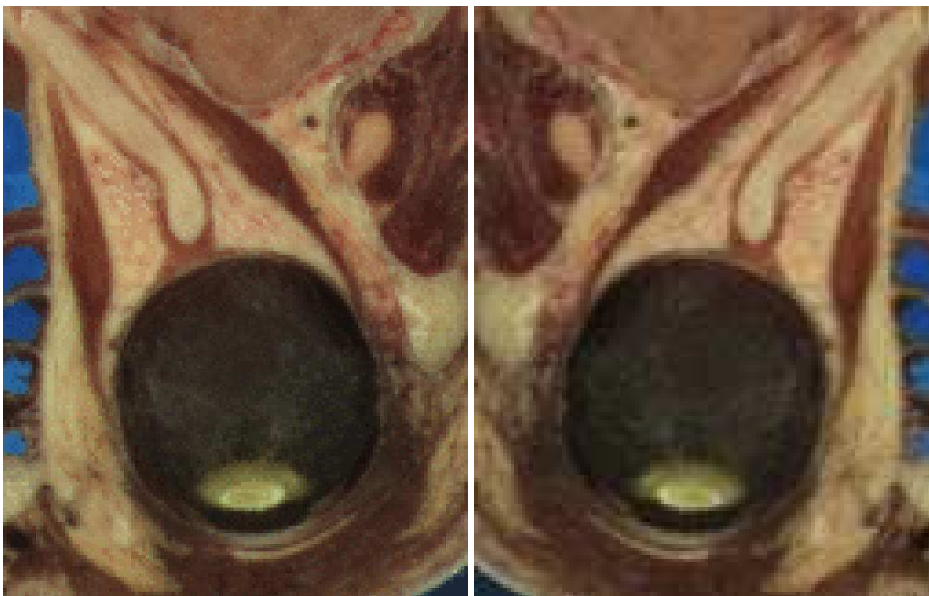


Figure 6.3: Results of using `ImageRegionIteratorWithIndex` to mirror an image across an axis. The original image is shown at left. The mirrored output is shown at right.

```
outputImage->GetRequestedRegion().GetSize();

for (outputIt.GoToBegin(); !outputIt.IsAtEnd(); ++outputIt)
{
    ImageType::IndexType idx = outputIt.GetIndex();
    idx[0] = requestedIndex[0] + requestedSize[0] - 1 - idx[0];
    outputIt.Set(inputImage->GetPixel(idx));
}
```

Let's run this example on the image `VisibleWomanEyeSlice.png` found in the `Examples/Data` directory. Figure 6.3 shows how the original image has been mirrored across its x -axis in the output.

6.3.3 ImageLinearIteratorWithIndex

The source code for this section can be found in the file `ImageLinearIteratorWithIndex.cxx`.

The `itk::ImageLinearIteratorWithIndex` is designed for line-by-line processing of an image. It walks a linear path along a selected image direction parallel to one of the coordinate axes of the image. This iterator conceptually breaks an image into a set of parallel lines that span the selected image dimension.

Like all image iterators, movement of the `ImageLinearIteratorWithIndex` is constrained within an image region R . The line ℓ through which the iterator moves is defined by selecting a direction and an origin. The line ℓ

extends from the origin to the upper boundary of R . The origin can be moved to any position along the lower boundary of R .

Several additional methods are defined for this iterator to control movement of the iterator along the line ℓ and movement of the origin of ℓ .

- **NextLine ()** Moves the iterator to the beginning pixel location of the next line in the image. The origin of the next line is determined by incrementing the current origin along the fastest increasing dimension of the subspace of the image that excludes the selected dimension.
- **PreviousLine ()** Moves the iterator to the *last valid pixel location* in the previous line. The origin of the previous line is determined by decrementing the current origin along the fastest increasing dimension of the subspace of the image that excludes the selected dimension.
- **GoToBeginOfLine ()** Moves the iterator to the beginning pixel of the current line.
- **GoToEndOfLine ()** Moves the iterator to *one past* the last valid pixel of the current line.
- **GoToReverseBeginOfLine ()** Moves the iterator to the *last valid pixel* of the current line.
- **IsAtReverseEndOfLine ()** Returns true if the iterator points to *one position before* the beginning pixel of the current line.
- **IsAtEndOfLine ()** Returns true if the iterator points to *one position past* the last valid pixel of the current line.

The following code example shows how to use the `ImageLinearIteratorWithIndex`. It implements the same algorithm as in the previous example, flipping an image across its x -axis. Two line iterators are iterated in opposite directions across the x -axis. After each line is traversed, the iterator origins are stepped along the y -axis to the next line.

Headers for both the const and non-const versions are needed.

```
#include "itkImageLinearIteratorWithIndex.h"
```

The RGB image and pixel types are defined as in the previous example. The `ImageLinearIteratorWithIndex` class and its const version each have single template parameters, the image type.

```
using IteratorType = itk::ImageLinearIteratorWithIndex<ImageType>;
using ConstIteratorType = itk::ImageLinearConstIteratorWithIndex<ImageType>;
```

After reading the input image, we allocate an output image that of the same size, spacing, and origin.

```
auto outputImage = ImageType::New();
outputImage->SetRegions(inputImage->GetRequestedRegion());
outputImage->CopyInformation(inputImage);
outputImage->Allocate();
```

Next we create the two iterators. The const iterator walks the input image, and the non-const iterator walks the output image. The iterators are initialized over the same region. The direction of iteration is set to 0, the x dimension.

```
ConstIteratorType inputIt(inputImage, inputImage->GetRequestedRegion());
IteratorType      outputIt(outputImage, inputImage->GetRequestedRegion());

inputIt.SetDirection(0);
outputIt.SetDirection(0);
```

Each line in the input is copied to the output. The input iterator moves forward across columns while the output iterator moves backwards.

```
for (inputIt.GoToBegin(), outputIt.GoToBegin(); !inputIt.IsAtEnd();
     outputIt.NextLine(), inputIt.NextLine())
{
    inputIt.GoToBeginOfLine();
    outputIt.GoToEndOfLine();
    while (!inputIt.IsAtEndOfLine())
    {
        --outputIt;
        outputIt.Set(inputIt.Get());
        ++inputIt;
    }
}
```

Running this example on `VisibleWomanEyeSlice.png` produces the same output image shown in Figure 6.3.

The source code for this section can be found in the file `ImageLinearIteratorWithIndex2.cxx`.

This example shows how to use the `itk::ImageLinearIteratorWithIndex` for computing the mean across time of a 4D image where the first three dimensions correspond to spatial coordinates and the fourth dimension corresponds to time. The result of the mean across time is to be stored in a 3D image.

```
#include "itkImageLinearConstIteratorWithIndex.h"
```

First we declare the types of the images, the 3D and 4D readers.

```
using PixelType = unsigned char;
using Image3DType = itk::Image<PixelType, 3>;
using Image4DType = itk::Image<PixelType, 4>;

using Reader4DType = itk::ImageFileReader<Image4DType>;
using Writer3DType = itk::ImageFileWriter<Image3DType>;
```

Next, define the necessary types for indices, points, spacings, and size.

```
auto image3D = Image3DType::New();
using Index3DType = Image3DType::IndexType;
using Size3DType = Image3DType::SizeType;
using Region3DType = Image3DType::RegionType;
using Spacing3DType = Image3DType::SpacingType;
using Origin3DType = Image3DType::PointType;

using Index4DType = Image4DType::IndexType;
using Size4DType = Image4DType::SizeType;
```

```
using Spacing4DType = Image4DType::SpacingType;
using Origin4DType = Image4DType::PointType;
```

Here we make sure that the values for our resultant 3D mean image match up with the input 4D image.

```
for (unsigned int i = 0; i < 3; ++i)
{
    size3D[i] = size4D[i];
    index3D[i] = index4D[i];
    spacing3D[i] = spacing4D[i];
    origin3D[i] = origin4D[i];
}

image3D->SetSpacing(spacing3D);
image3D->SetOrigin(origin3D);

Region3DType region3D;
region3D.SetIndex(index3D);
region3D.SetSize(size3D);

image3D->SetRegions(region3D);
image3D->Allocate();
```

Next we iterate over time in the input image series, compute the average, and store that value in the corresponding pixel of the output 3D image.

```
IteratorType it(image4D, region4D);
it.SetDirection(3); // Walk along time dimension
it.GoToBegin();
while (!it.IsAtEnd())
{
    SumType sum{};
    it.GoToBeginOfLine();
    index4D = it.GetIndex();
    while (!it.IsAtEndOfLine())
    {
        sum += it.Get();
        ++it;
    }
    MeanType mean =
        static_cast<MeanType>(sum) / static_cast<MeanType>(timeLength);

    index3D[0] = index4D[0];
    index3D[1] = index4D[1];
    index3D[2] = index4D[2];

    image3D->SetPixel(index3D, static_cast<PixelType>(mean));
    it.NextLine();
}
```

As you can see, we avoid to use a 3D iterator to walk over the mean image. The reason is that there is no guarantee that the 3D iterator will walk in the same order as the 4D. Iterators just adhere to their contract of visiting every pixel, but do not enforce any particular order for the visits. The linear iterator guarantees it will

visit the pixels along a line of the image in the order in which they are placed in the line, but does not state in what order one line will be visited with respect to other lines. Here we simply take advantage of knowing the first three components of the 4D iterator index, and use them to place the resulting mean value in the output 3D image.

6.3.4 ImageSliceIteratorWithIndex

The source code for this section can be found in the file `ImageSliceIteratorWithIndex.cxx`.

The `itk::ImageSliceIteratorWithIndex` class is an extension of `itk::ImageLinearIteratorWithIndex` from iteration along lines to iteration along both lines and planes in an image. A *slice* is a 2D plane spanned by two vectors pointing along orthogonal coordinate axes. The slice orientation of the slice iterator is defined by specifying its two spanning axes.

- **SetFirstDirection()** Specifies the first coordinate axis direction of the slice plane.
- **SetSecondDirection()** Specifies the second coordinate axis direction of the slice plane.

Several new methods control movement from slice to slice.

- **NextSlice()** Moves the iterator to the beginning pixel location of the next slice in the image. The origin of the next slice is calculated by incrementing the current origin index along the fastest increasing dimension of the image subspace which excludes the first and second dimensions of the iterator.
- **PreviousSlice()** Moves the iterator to the *last valid pixel location* in the previous slice. The origin of the previous slice is calculated by decrementing the current origin index along the fastest increasing dimension of the image subspace which excludes the first and second dimensions of the iterator.
- **IsAtReverseEndOfSlice()** Returns true if the iterator points to *one position before* the beginning pixel of the current slice.
- **IsAtEndOfSlice()** Returns true if the iterator points to *one position past* the last valid pixel of the current slice.

The slice iterator moves line by line using `NextLine()` and `PreviousLine()`. The line direction is parallel to the *second* coordinate axis direction of the slice plane (see also Section 6.3.3).

The next code example calculates the maximum intensity projection along one of the coordinate axes of an image volume. The algorithm is straightforward using `ImageSliceIteratorWithIndex` because we can coordinate movement through a slice of the 3D input image with movement through the 2D planar output.

Here is how the algorithm works. For each 2D slice of the input, iterate through all the pixels line by line. Copy a pixel value to the corresponding position in the 2D output image if it is larger than the value already contained there. When all slices have been processed, the output image is the desired maximum intensity projection.

We include a header for the const version of the slice iterator. For writing values to the 2D projection image, we use the linear iterator from the previous section. The linear iterator is chosen because it can be set to follow the same path in its underlying 2D image that the slice iterator follows over each slice of the 3D image.

```
#include "itkImageSliceConstIteratorWithIndex.h"
#include "itkImageLinearIteratorWithIndex.h"
```

The pixel type is defined as `unsigned short`. For this application, we need two image types, a 3D image for the input, and a 2D image for the intensity projection.

```
using PixelType = unsigned short;
using ImageType2D = itk::Image<PixelType, 2>;
using ImageType3D = itk::Image<PixelType, 3>;
```

A slice iterator type is defined to walk the input image.

```
using LinearIteratorType = itk::ImageLinearIteratorWithIndex<ImageType2D>;
using SliceIteratorType =
    itk::ImageSliceConstIteratorWithIndex<ImageType3D>;
```

The projection direction is read from the command line. The projection image will be the size of the 2D plane orthogonal to the projection direction. Its spanning vectors are the two remaining coordinate axes in the volume. These axes are recorded in the direction array.

```
auto projectionDirection = static_cast<unsigned int>(std::stoi(argv[3]));

unsigned int i, j;
unsigned int direction[2];
for (i = 0, j = 0; i < 3; ++i)
{
    if (i != projectionDirection)
    {
        direction[j] = i;
        j++;
    }
}
```

The direction array is now used to define the projection image size based on the input image size. The output image is created so that its common dimension(s) with the input image are the same size. For example, if we project along the x axis of the input, the size and origin of the y axes of the input and output will match. This makes the code slightly more complicated, but prevents a counter-intuitive rotation of the output.

```
ImageType2D::RegionType region;
ImageType2D::RegionType::SizeType size;
ImageType2D::RegionType::IndexType index;

ImageType3D::RegionType requestedRegion = inputImage->GetRequestedRegion();

index[direction[0]] = requestedRegion.GetIndex()[direction[0]];
index[1 - direction[0]] = requestedRegion.GetIndex()[direction[1]];
size[direction[0]] = requestedRegion.GetSize()[direction[0]];
size[1 - direction[0]] = requestedRegion.GetSize()[direction[1]];

region.SetSize(size);
region.SetIndex(index);

auto outputImage = ImageType2D::New();

outputImage->SetRegions(region);
outputImage->Allocate();
```

Next we create the necessary iterators. The const slice iterator walks the 3D input image, and the non-const linear iterator walks the 2D output image. The iterators are initialized to walk the same linear path through a slice. Remember that the *second* direction of the slice iterator defines the direction that linear iteration walks within a slice.

```
SliceIteratorType inputIt(inputImage, inputImage->GetRequestedRegion());
LinearIteratorType outputIt(outputImage, outputImage->GetRequestedRegion());

inputIt.SetFirstDirection(direction[1]);
inputIt.SetSecondDirection(direction[0]);

outputIt.SetDirection(1 - direction[0]);
```

Now we are ready to compute the projection. The first step is to initialize all of the projection values to their nonpositive minimum value. The projection values are then updated row by row from the first slice of the input. At the end of the first slice, the input iterator steps to the first row in the next slice, while the output iterator, whose underlying image consists of only one slice, rewinds to its first row. The process repeats until the last slice of the input is processed.

```
outputIt.GoToBegin();
while (!outputIt.IsAtEnd())
{
    while (!outputIt.IsAtEndOfLine())
    {
        outputIt.Set(itk::NumericTraits<unsigned short>::NonpositiveMin());
        ++outputIt;
    }
    outputIt.NextLine();
}

inputIt.GoToBegin();
outputIt.GoToBegin();

while (!inputIt.IsAtEnd())
{
    while (!inputIt.IsAtEndOfSlice())
    {
        while (!inputIt.IsAtEndOfLine())
        {
            outputIt.Set(std::max(outputIt.Get(), inputIt.Get()));
            ++inputIt;
            ++outputIt;
        }
        outputIt.NextLine();
        inputIt.NextLine();
    }
    outputIt.GoToBegin();
    inputIt.NextSlice();
}
```

Running this example code on the 3D image `Examples/Data/BrainProtonDensity3Slices.mha` using the *z*-axis as the axis of projection gives the image shown in Figure 6.4.

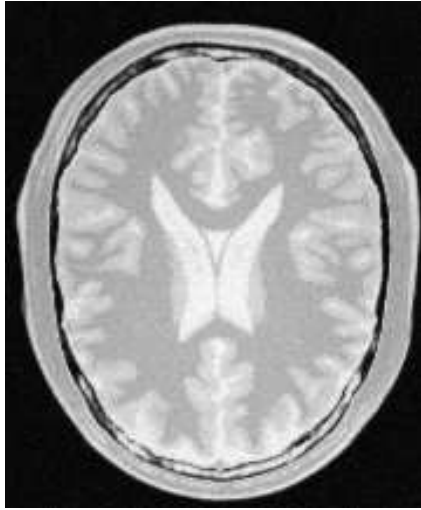


Figure 6.4: The maximum intensity projection through three slices of a volume.

6.3.5 ImageRandomConstIteratorWithIndex

The source code for this section can be found in the file `ImageRandomConstIteratorWithIndex.cxx`.

`itk::ImageRandomConstIteratorWithIndex` was developed to randomly sample pixel values. When incremented or decremented, it jumps to a random location in its image region.

The user must specify a sample size when creating this iterator. The sample size, rather than a specific image index, defines the end position for the iterator. `IsAtEnd()` returns `true` when the current sample number equals the sample size. `IsAtBegin()` returns `true` when the current sample number equals zero. An important difference from other image iterators is that `ImageRandomConstIteratorWithIndex` may visit the same pixel more than once.

Let's use the random iterator to estimate some simple image statistics. The next example calculates an estimate of the arithmetic mean of pixel values.

First, include the appropriate header and declare pixel and image types.

```
#include "itkImageRandomConstIteratorWithIndex.h"

constexpr unsigned int Dimension = 2;

using PixelType = unsigned short;
using ImageType = itk::Image<PixelType, Dimension>;
using ConstIteratorType = itk::ImageRandomConstIteratorWithIndex<ImageType>;
```

The input image has been read as `inputImage`. We now create an iterator with a number of samples set by command line argument. The call to `ReinitializeSeed` seeds the random number generator. The iterator is

	<i>Sample Size</i>			
	10	100	1000	10000
RatLungSlice1.mha	50.5	52.4	53.0	52.4
RatLungSlice2.mha	46.7	47.5	47.4	47.6
BrainT1Slice.png	47.2	64.1	68.0	67.8

Table 6.1: Estimates of mean image pixel value using the `ImageRandomConstIteratorWithIndex` at different sample sizes.

initialized over the entire valid image region.

```
ConstIteratorType inputIt(inputImage, inputImage->GetRequestedRegion());
inputIt.SetNumberOfSamples(std::stoi(argv[2]));
inputIt.ReinitializeSeed();
```

Now take the specified number of samples and calculate their average value.

```
float mean = 0.0f;
for (inputIt.GoToBegin(); !inputIt.IsAtEnd(); ++inputIt)
{
    mean += static_cast<float>(inputIt.Get());
}
mean = mean / std::stod(argv[2]);
```

/* The following table shows the results of running this example on several of the data files from Examples/Data with a range of sample sizes.

*/

6.4 Neighborhood Iterators

In ITK, a pixel neighborhood is loosely defined as a small set of pixels that are locally adjacent to one another in an image. The size and shape of a neighborhood, as well the connectivity among pixels in a neighborhood, may vary with the application.

Many image processing algorithms are neighborhood-based, that is, the result at a pixel i is computed from the values of pixels in the ND neighborhood of i . Consider finite difference operations in 2D. A derivative at pixel index $i = (j, k)$, for example, is taken as a weighted difference of the values at $(j + 1, k)$ and $(j - 1, k)$. Other common examples of neighborhood operations include convolution filtering and image morphology.

This section describes a class of ITK image iterators that are designed for working with pixel neighborhoods. An ITK neighborhood iterator walks an image region just like a normal image iterator, but instead of only referencing a single pixel at each step, it simultaneously points to the entire ND neighborhood of pixels. Extensions to the standard iterator interface provide read and write access to all neighborhood pixels and information such as the size, extent, and location of the neighborhood.

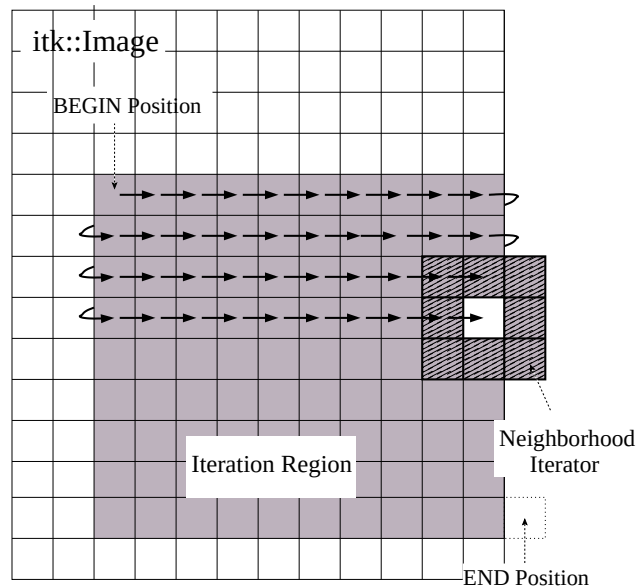


Figure 6.5: Path of a 3x3 neighborhood iterator through a 2D image region. The extent of the neighborhood is indicated by the hashing around the iterator position. Pixels that lie within this extent are accessible through the iterator. An arrow denotes a single iterator step, the result of one ++ operation.

Neighborhood iterators use the same operators defined in Section 6.2 and the same code constructs as normal iterators for looping through an image. Figure 6.5 shows a neighborhood iterator moving through an iteration region. This iterator defines a 3x3 neighborhood around each pixel that it visits. The *center* of the neighborhood iterator is always positioned over its current index and all other neighborhood pixel indices are referenced as offsets from the center index. The pixel under the center of the neighborhood iterator and all pixels under the shaded area, or *extent*, of the iterator can be dereferenced.

In addition to the standard image pointer and iteration region (Section 6.2), neighborhood iterator constructors require an argument that specifies the extent of the neighborhood to cover. Neighborhood extent is symmetric across its center in each axis and is given as an array of N distances that are collectively called the *radius*. Each element d of the radius, where $0 < d < N$ and N is the dimensionality of the neighborhood, gives the extent of the neighborhood in pixels for dimension N . The length of each face of the resulting ND hypercube is $2d + 1$ pixels, a distance of d on either side of the single pixel at the neighbor center. Figure 6.6 shows the relationship between the radius of the iterator and the size of the neighborhood for a variety of 2D iterator shapes.

The radius of the neighborhood iterator is queried after construction by calling the `GetRadius()` method. Some other methods provide some useful information about the iterator and its underlying image.

- **SizeType GetRadius()** Returns the ND radius of the neighborhood as an `itk::Size`.
- **const ImageType *GetImagePointer()** Returns the pointer to the image referenced by the iterator.
- **unsigned long Size()** Returns the size in number of pixels of the neighborhood.

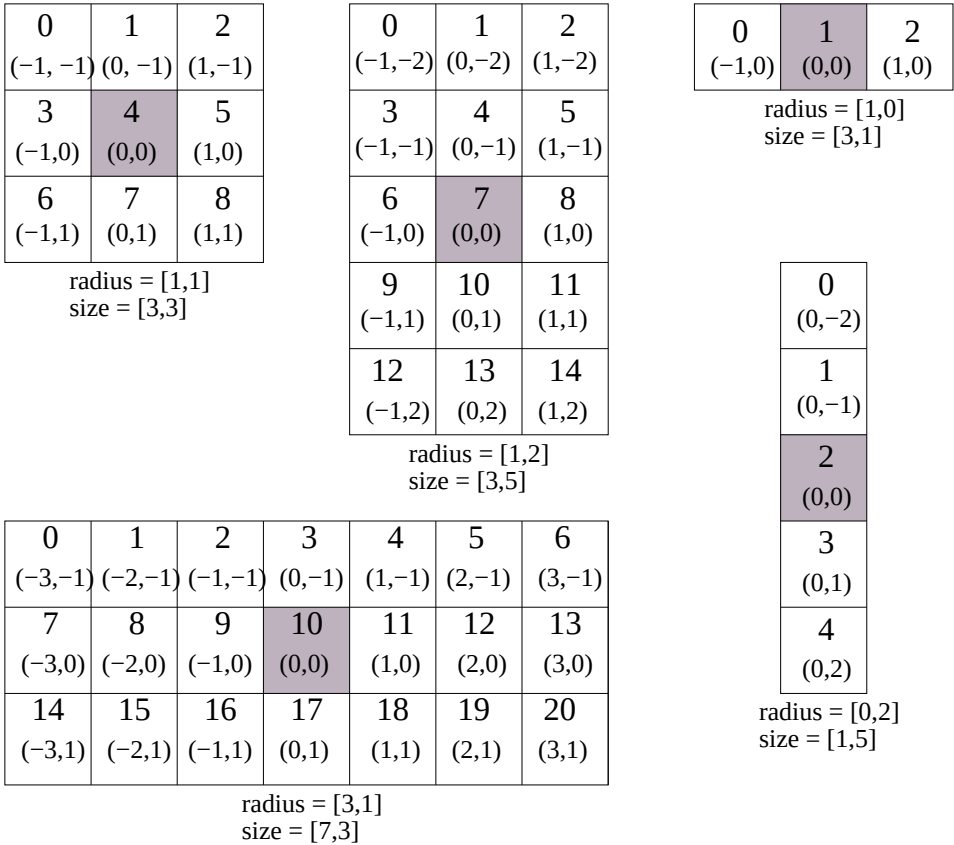


Figure 6.6: Several possible 2D neighborhood iterator shapes are shown along with their radii and sizes. A neighborhood pixel can be dereferenced by its integer index (top) or its offset from the center (bottom). The center pixel of each iterator is shaded.

The neighborhood iterator interface extends the normal ITK iterator interface for setting and getting pixel values. One way to dereference pixels is to think of the neighborhood as a linear array where each pixel has a unique integer index. The index of a pixel in the array is determined by incrementing from the upper-left-forward corner of the neighborhood along the fastest increasing image dimension: first column, then row, then slice, and so on. In Figure 6.6, the unique integer index is shown at the top of each pixel. The center pixel is always at position $n/2$, where n is the size of the array.

- **PixelType GetPixel(const unsigned int i)** Returns the value of the pixel at neighborhood position i .
- **void SetPixel(const unsigned int i, PixelType p)** Sets the value of the pixel at position i to p .

Another way to think about a pixel location in a neighborhood is as an ND offset from the neighborhood center. The upper-left-forward corner of a $3 \times 3 \times 3$ neighborhood, for example, can be described by offset $(-1, -1, -1)$. The bottom-right-back corner of the same neighborhood is at offset $(1, 1, 1)$. In Figure 6.6, the offset from center is shown at the bottom of each neighborhood pixel.

- **PixelType GetPixel(const OffsetType &o)** Get the value of the pixel at the position offset o from the neighborhood center.
- **void SetPixel(const OffsetType &o, PixelType p)** Set the value at the position offset o from the neighborhood center to the value p .

The neighborhood iterators also provide a shorthand for setting and getting the value at the center of the neighborhood.

- **PixelType GetCenterPixel()** Gets the value at the center of the neighborhood.
- **void SetCenterPixel(PixelType p)** Sets the value at the center of the neighborhood to the value p .

There is another shorthand for setting and getting values for pixels that lie some integer distance from the neighborhood center along one of the image axes.

- **PixelType GetNext(unsigned int d)** Get the value immediately adjacent to the neighborhood center in the positive direction along the d axis.
- **void SetNext(unsigned int d, PixelType p)** Set the value immediately adjacent to the neighborhood center in the positive direction along the d axis to the value p .
- **PixelType GetPrevious(unsigned int d)** Get the value immediately adjacent to the neighborhood center in the negative direction along the d axis.
- **void SetPrevious(unsigned int d, PixelType p)** Set the value immediately adjacent to the neighborhood center in the negative direction along the d axis to the value p .
- **PixelType GetNext(unsigned int d, unsigned int s)** Get the value of the pixel located s pixels from the neighborhood center in the positive direction along the d axis.
- **void SetNext(unsigned int d, unsigned int s, PixelType p)** Set the value of the pixel located s pixels from the neighborhood center in the positive direction along the d axis to value p .

- **PixelType GetPrevious(unsigned int d, unsigned int s)** Get the value of the pixel located *s* pixels from the neighborhood center in the positive direction along the *d* axis.
- **void SetPrevious(unsigned int d, unsigned int s, PixelType p)** Set the value of the pixel located *s* pixels from the neighborhood center in the positive direction along the *d* axis to value *p*.

It is also possible to extract or set all of the neighborhood values from an iterator at once using a regular ITK neighborhood object. This may be useful in algorithms that perform a particularly large number of calculations in the neighborhood and would otherwise require multiple dereferences of the same pixels.

- **NeighborhoodType GetNeighborhood()** Return a `itk::Neighborhood` of the same size and shape as the neighborhood iterator and contains all of the values at the iterator position.
- **void SetNeighborhood(NeighborhoodType &N)** Set all of the values in the neighborhood at the iterator position to those contained in Neighborhood *N*, which must be the same size and shape as the iterator.

Several methods are defined to provide information about the neighborhood.

- **IndexType GetIndex()** Return the image index of the center pixel of the neighborhood iterator.
- **IndexType GetIndex(OffsetType o)** Return the image index of the pixel at offset *o* from the neighborhood center.
- **IndexType GetIndex(unsigned int i)** Return the image index of the pixel at array position *i*.
- **OffsetType GetOffset(unsigned int i)** Return the offset from the neighborhood center of the pixel at array position *i*.
- **unsigned long GetNeighborhoodIndex(OffsetType o)** Return the array position of the pixel at offset *o* from the neighborhood center.
- **std::slice GetSlice(unsigned int n)** Return a `std::slice` through the iterator neighborhood along axis *n*.

A neighborhood-based calculation in a neighborhood close to an image boundary may require data that falls outside the boundary. The iterator in Figure 6.5, for example, is centered on a boundary pixel such that three of its neighbors actually do not exist in the image. When the extent of a neighborhood falls outside the image, pixel values for missing neighbors are supplied according to a rule, usually chosen to satisfy the numerical requirements of the algorithm. A rule for supplying out-of-bounds values is called a *boundary condition*.

ITK neighborhood iterators automatically detect out-of-bounds dereferences and will return values according to boundary conditions. The boundary condition type is specified by the second, optional template parameter of the iterator. By default, neighborhood iterators use a Neumann condition where the first derivative across the boundary is zero. The Neumann rule simply returns the closest in-bounds pixel value to the requested out-of-bounds location. Several other common boundary conditions can be found in the ITK toolkit. They include a periodic condition that returns the pixel value from the opposite side of the data set, and is useful when working with periodic data such as Fourier transforms, and a constant value condition that returns a set value *v* for all out-of-bounds pixel dereferences. The constant value condition is equivalent to padding the image with value *v*.

Bounds checking is a computationally expensive operation because it occurs each time the iterator is incremented. To increase efficiency, a neighborhood iterator automatically disables bounds checking when it detects that it is not necessary. A user may also explicitly disable or enable bounds checking. Most neighborhood based algorithms can minimize the need for bounds checking through clever definition of iteration regions. These techniques are explored in Section 6.4.1.

- **void NeedToUseBoundaryConditionOn()** Explicitly turn bounds checking on. This method should be used with caution because unnecessarily enabling bounds checking may result in a significant performance decrease. In general you should allow the iterator to automatically determine this setting.
- **void NeedToUseBoundaryConditionOff()** Explicitly disable bounds checking. This method should be used with caution because disabling bounds checking when it is needed will result in out-of-bounds reads and undefined results.
- **void OverrideBoundaryCondition(BoundaryConditionType *b)** Overrides the templated boundary condition, using boundary condition object *b* instead. Object *b* should not be deleted until it has been released by the iterator. This method can be used to change iterator behavior at run-time.
- **void ResetBoundaryCondition()** Discontinues the use of any run-time specified boundary condition and returns to using the condition specified in the template argument.
- **void SetPixel(unsigned int i, PixelType p, bool status)** Sets the value at neighborhood array position *i* to value *p*. If the position *i* is out-of-bounds, *status* is set to false, otherwise *status* is set to true.

The following sections describe the two ITK neighborhood iterator classes, `itk::NeighborhoodIterator` and `itk::ShapedNeighborhoodIterator`. Each has a const and a non-const version. The shaped iterator is a refinement of the standard `NeighborhoodIterator` that supports an arbitrarily-shaped (non-rectilinear) neighborhood.

6.4.1 NeighborhoodIterator

The standard neighborhood iterator class in ITK is the `itk::NeighborhoodIterator`. Together with its const version, `itk::ConstNeighborhoodIterator`, it implements the complete API described above. This section provides several examples to illustrate the use of `NeighborhoodIterator`.

Basic neighborhood techniques: edge detection

The source code for this section can be found in the file `NeighborhoodIterators1.cxx`.

This example uses the `itk::NeighborhoodIterator` to implement a simple Sobel edge detection algorithm [4]. The algorithm uses the neighborhood iterator to iterate through an input image and calculate a series of finite difference derivatives. Since the derivative results cannot be written back to the input image without affecting later calculations, they are written instead to a second, output image. Most neighborhood processing algorithms follow this read-only model on their inputs.

We begin by including the proper header files. The `itk::ImageRegionIterator` will be used to write the results of computations to the output image. A const version of the neighborhood iterator is used because the input image is read-only.

```
#include "itkConstNeighborhoodIterator.h"
#include "itkImageRegionIterator.h"
```

The finite difference calculations in this algorithm require floating point values. Hence, we define the image pixel type to be `float` and the file reader will automatically cast fixed-point data to `float`.

We declare the iterator types using the image type as the template parameter. The second template parameter of the neighborhood iterator, which specifies the boundary condition, has been omitted because the default condition is appropriate for this algorithm.

```
using PixelType = float;
using ImageType = itk::Image<PixelType, 2>;
using ReaderType = itk::ImageFileReader<ImageType>;

using NeighborhoodIteratorType = itk::ConstNeighborhoodIterator<ImageType>;
using IteratorType = itk::ImageRegionIterator<ImageType>;
```

The following code creates and executes the ITK image reader. The `Update` call on the reader object is surrounded by the standard `try/catch` blocks to handle any exceptions that may be thrown by the reader.

```
auto reader = ReaderType::New();
reader->SetFileName(argv[1]);
try
{
    reader->Update();
}
catch (const itk::ExceptionObject & err)
{
    std::cerr << "ExceptionObject caught !" << std::endl;
    std::cerr << err << std::endl;
    return EXIT_FAILURE;
}
```

We can now create a neighborhood iterator to range over the output of the reader. For Sobel edge-detection in 2D, we need a square iterator that extends one pixel away from the neighborhood center in every dimension.

```
NeighborhoodIteratorType::RadiusType radius;
radius.Fill(1);
NeighborhoodIteratorType it(
    radius, reader->GetOutput(), reader->GetOutput()->GetRequestedRegion());
```

The following code creates an output image and iterator.

```
auto output = ImageType::New();
output->SetRegions(reader->GetOutput()->GetRequestedRegion());
output->Allocate();

IteratorType out(output, reader->GetOutput()->GetRequestedRegion());
```

Sobel edge detection uses weighted finite difference calculations to construct an edge magnitude image. Normally the edge magnitude is the root sum of squares of partial derivatives in all directions, but for simplicity

this example only calculates the x component. The result is a derivative image biased toward maximally vertical edges.

The finite differences are computed from pixels at six locations in the neighborhood. In this example, we use the iterator `GetPixel()` method to query the values from their offsets in the neighborhood. The example in Section 6.4.1 uses convolution with a Sobel kernel instead.

Six positions in the neighborhood are necessary for the finite difference calculations. These positions are recorded in `offset1` through `offset6`.

```
NeighborhoodIteratorType::OffsetType offset1 = { { -1, -1 } };
NeighborhoodIteratorType::OffsetType offset2 = { { 1, -1 } };
NeighborhoodIteratorType::OffsetType offset3 = { { -1, 0 } };
NeighborhoodIteratorType::OffsetType offset4 = { { 1, 0 } };
NeighborhoodIteratorType::OffsetType offset5 = { { -1, 1 } };
NeighborhoodIteratorType::OffsetType offset6 = { { 1, 1 } };
```

It is equivalent to use the six corresponding integer array indices instead. For example, the offsets $(-1, -1)$ and $(1, -1)$ are equivalent to the integer indices 0 and 2, respectively.

The calculations are done in a `for` loop that moves the input and output iterators synchronously across their respective images. The `sum` variable is used to sum the results of the finite differences.

```
for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
{
    float sum;
    sum = it.GetPixel(offset2) - it.GetPixel(offset1);
    sum += 2.0 * it.GetPixel(offset4) - 2.0 * it.GetPixel(offset3);
    sum += it.GetPixel(offset6) - it.GetPixel(offset5);
    out.Set(sum);
}
```

The last step is to write the output buffer to an image file. Writing is done inside a `try/catch` block to handle any exceptions. The output is rescaled to intensity range $[0, 255]$ and cast to unsigned char so that it can be saved and visualized as a PNG image.

```
using WritePixelType = unsigned char;
using WriteImageType = itk::Image<WritePixelType, 2>;
using WriterType = itk::ImageFileWriter<WriteImageType>;

using RescaleFilterType =
    itk::RescaleIntensityImageFilter<ImageType, WriteImageType>;

auto rescaler = RescaleFilterType::New();

rescaler->SetOutputMinimum(0);
rescaler->SetOutputMaximum(255);
rescaler->SetInput(output);

auto writer = WriterType::New();
writer->SetFileName(argv[2]);
writer->SetInput(rescaler->GetOutput());
try
```

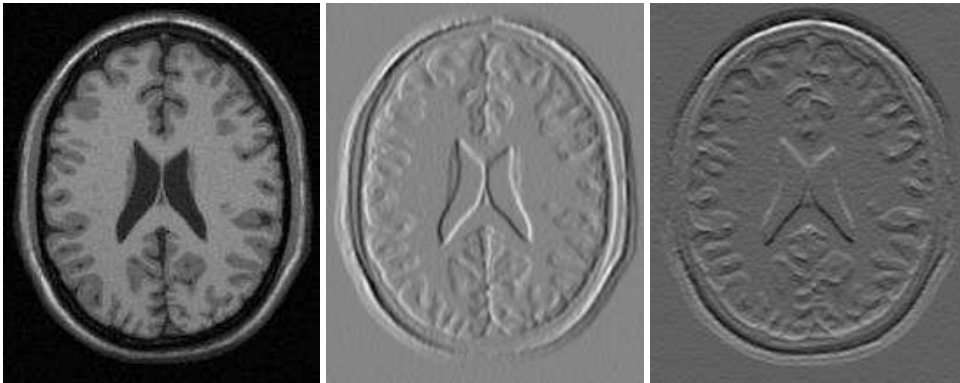


Figure 6.7: Applying the Sobel operator in different orientations to an MRI image (left) produces x (center) and y (right) derivative images.

```
{
    writer->Update();
}
catch (const itk::ExceptionObject & err)
{
    std::cerr << "ExceptionObject caught !" << std::endl;
    std::cerr << err << std::endl;
    return EXIT_FAILURE;
}
```

The center image of Figure 6.7 shows the output of the Sobel algorithm applied to `Examples/Data/BrainT1Slice.png`.

Convolution filtering: Sobel operator

The source code for this section can be found in the file `NeighborhoodIterators2.cxx`.

In this example, the Sobel edge-detection routine is rewritten using convolution filtering. Convolution filtering is a standard image processing technique that can be implemented numerically as the inner product of all image neighborhoods with a convolution kernel [4] [2]. In ITK, we use a class of objects called *neighborhood operators* as convolution kernels and a special function object called `itk::NeighborhoodInnerProduct` to calculate inner products.

The basic ITK convolution filtering routine is to step through the image with a neighborhood iterator and use `NeighborhoodInnerProduct` to find the inner product of each neighborhood with the desired kernel. The resulting values are written to an output image. This example uses a neighborhood operator called `itk::SobelOperator`, but all neighborhood operators can be convolved with images using this basic routine. Other examples of neighborhood operators include derivative kernels, Gaussian kernels, and morphological operators. `itk::NeighborhoodOperatorImageFilter` is a generalization of the code in this section to ND images and arbitrary convolution kernels.

We start writing this example by including the header files for the Sobel kernel and the inner product function.

```
#include "itkSobelOperator.h"
#include "itkNeighborhoodInnerProduct.h"
```

Refer to the previous example for a description of reading the input image and setting up the output image and iterator.

The following code creates a Sobel operator. The Sobel operator requires a direction for its partial derivatives. This direction is read from the command line. Changing the direction of the derivatives changes the bias of the edge detection, i.e. maximally vertical or maximally horizontal.

```
itk::SobelOperator<PixelType, 2> sobelOperator;
sobelOperator.SetDirection(std::stoi(argv[3]));
sobelOperator.CreateDirectional();
```

The neighborhood iterator is initialized as before, except that now it takes its radius directly from the radius of the Sobel operator. The inner product function object is templated over image type and requires no initialization.

```
NeighborhoodIteratorType::RadiusType radius = sobelOperator.GetRadius();
NeighborhoodIteratorType it(
    radius, reader->GetOutput(), reader->GetOutput()->GetRequestedRegion());

itk::NeighborhoodInnerProduct<ImageType> innerProduct;
```

Using the Sobel operator, inner product, and neighborhood iterator objects, we can now write a very simple `for` loop for performing convolution filtering. As before, out-of-bounds pixel values are supplied automatically by the iterator.

```
for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
{
    out.Set(innerProduct(it, sobelOperator));
}
```

The output is rescaled and written as in the previous example. Applying this example in the x and y directions produces the images at the center and right of Figure 6.7. Note that x -direction operator produces the same output image as in the previous example.

Optimizing iteration speed

The source code for this section can be found in the file `NeighborhoodIterators3.cxx`.

This example illustrates a technique for improving the efficiency of neighborhood calculations by eliminating unnecessary bounds checking. As described in Section 6.4, the neighborhood iterator automatically enables or disables bounds checking based on the iteration region in which it is initialized. By splitting our image into boundary and non-boundary regions, and then processing each region using a different neighborhood iterator, the algorithm will only perform bounds-checking on those pixels for which it is actually required. This trick can provide a significant speedup for simple algorithms such as our Sobel edge detection, where iteration speed is a critical.

Splitting the image into the necessary regions is an easy task when you use the `itk::NeighborhoodAlgorithm::ImageBoundaryFacesCalculator`. The face calculator is so named because it returns a list of the “faces” of the ND dataset. Faces are those regions whose pixels all lie within a distance d from the boundary, where d is the radius of the neighborhood stencil used for the numerical calculations. In other words, faces are those regions where a neighborhood iterator of radius d will always overlap the boundary of the image. The face calculator also returns the single *inner* region, in which out-of-bounds values are never required and bounds checking is not necessary.

The face calculator object is defined in `itkNeighborhoodAlgorithm.h`. We include this file in addition to those from the previous two examples.

```
#include "itkNeighborhoodAlgorithm.h"
```

First we load the input image and create the output image and inner product function as in the previous examples. The image iterators will be created in a later step. Next we create a face calculator object. An empty list is created to hold the regions that will later on be returned by the face calculator.

```
using FaceCalculatorType =
    itk::NeighborhoodAlgorithm::ImageBoundaryFacesCalculator<ImageType>;

FaceCalculatorType          faceCalculator;
FaceCalculatorType::FaceListType faceList;
```

The face calculator function is invoked by passing it an image pointer, an image region, and a neighborhood radius. The image pointer is the same image used to initialize the neighborhood iterator, and the image region is the region that the algorithm is going to process. The radius is the radius of the iterator.

Notice that in this case the image region is given as the region of the *output* image and the image pointer is given as that of the *input* image. This is important if the input and output images differ in size, i.e. the input image is larger than the output image. ITK image filters, for example, operate on data from the input image but only generate results in the RequestedRegion of the output image, which may be smaller than the full extent of the input.

```
faceList = faceCalculator(reader->GetOutput(),
                          output->GetRequestedRegion(),
                          sobelOperator.GetRadius());
```

The face calculator has returned a list of $2N + 1$ regions. The first element in the list is always the inner region, which may or may not be important depending on the application. For our purposes it does not matter because all regions are processed the same way. We use an iterator to traverse the list of faces.

```
FaceCalculatorType::FaceListType::iterator fit;
```

We now rewrite the main loop of the previous example so that each region in the list is processed by a separate iterator. The iterators `it` and `out` are reinitialized over each region in turn. Bounds checking is automatically enabled for those regions that require it, and disabled for the region that does not.

```
IteratorType          out;
NeighborhoodIteratorType it;
```

```

for (fit = faceList.begin(); fit != faceList.end(); ++fit)
{
    it = NeighborhoodIteratorType(
        sobelOperator.GetRadius(), reader->GetOutput(), *fit);
    out = IteratorType(output, *fit);

    for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
    {
        out.Set(innerProduct(it, sobelOperator));
    }
}

```

The output is written as before. Results for this example are the same as the previous example. You may not notice the speedup except on larger images. When moving to 3D and higher dimensions, the effects are greater because the volume to surface area ratio is usually larger. In other words, as the number of interior pixels increases relative to the number of face pixels, there is a corresponding increase in efficiency from disabling bounds checking on interior pixels.

Separable convolution: Gaussian filtering

The source code for this section can be found in the file `NeighborhoodIterators4.cxx`.

We now introduce a variation on convolution filtering that is useful when a convolution kernel is separable. In this example, we create a different neighborhood iterator for each axial direction of the image and then take separate inner products with a 1D discrete Gaussian kernel. The idea of using several neighborhood iterators at once has applications beyond convolution filtering and may improve efficiency when the size of the whole neighborhood relative to the portion of the neighborhood used in calculations becomes large.

The only new class necessary for this example is the Gaussian operator.

```

#include "itkGaussianOperator.h"

```

The Gaussian operator, like the Sobel operator, is instantiated with a pixel type and a dimensionality. Additionally, we set the variance of the Gaussian, which has been read from the command line as standard deviation.

```

itk::GaussianOperator<PixelType, 2> gaussianOperator;
gaussianOperator.SetVariance(std::stod(argv[3]) * std::stod(argv[3]));

```

The only further changes from the previous example are in the main loop. Once again we use the results from face calculator to construct a loop that processes boundary and non-boundary image regions separately. Separable convolution, however, requires an additional, outer loop over all the image dimensions. The direction of the Gaussian operator is reset at each iteration of the outer loop using the new dimension. The iterators change direction to match because they are initialized with the radius of the Gaussian operator.

Input and output buffers are swapped at each iteration so that the output of the previous iteration becomes the input for the current iteration. The swap is not performed on the last iteration.

```

ImageType::Pointer input = reader->GetOutput();
for (unsigned int i = 0; i < ImageType::ImageDimension; ++i)

```

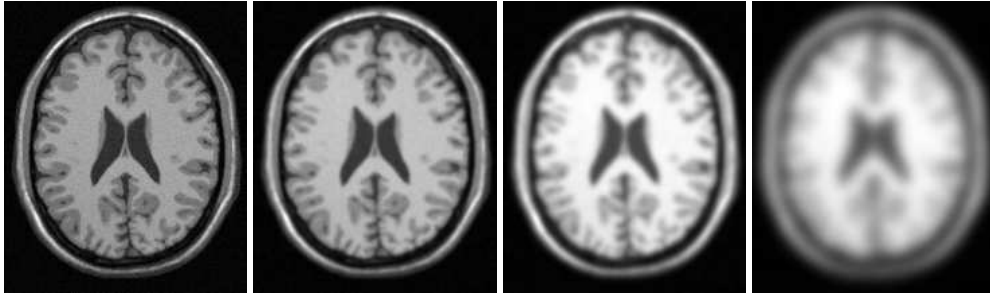


Figure 6.8: Results of convolution filtering with a Gaussian kernel of increasing standard deviation σ (from left to right, $\sigma = 0$, $\sigma = 1$, $\sigma = 2$, $\sigma = 5$). Increased blurring reduces contrast and changes the average intensity value of the image, which causes the image to appear brighter when rescaled.

```
{
    gaussianOperator.SetDirection(i);
    gaussianOperator.CreateDirectional();

    faceList = faceCalculator(
        input, output->GetRequestedRegion(), gaussianOperator.GetRadius());

    for (fit = faceList.begin(); fit != faceList.end(); ++fit)
    {
        it =
            NeighborhoodIteratorType(gaussianOperator.GetRadius(), input, *fit);

        out = IteratorType(output, *fit);

        for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
        {
            out.Set(innerProduct(it, gaussianOperator));
        }
    }

    // Swap the input and output buffers
    if (i != ImageType::ImageDimension - 1)
    {
        ImageType::Pointer tmp = input;
        input = output;
        output = tmp;
    }
}
```

The output is rescaled and written as in the previous examples. Figure 6.8 shows the results of Gaussian blurring the image `Examples/Data/BrainT1Slice.png` using increasing kernel widths.

Slicing the neighborhood

The source code for this section can be found in the file `NeighborhoodIterators5.cxx`.

This example introduces slice-based neighborhood processing. A slice, in this context, is a 1D path through an ND neighborhood. Slices are defined for generic arrays by the `std::slice` class as a start index, a step size, and an end index. Slices simplify the implementation of certain neighborhood calculations. They also provide a mechanism for taking inner products with subregions of neighborhoods.

Suppose, for example, that we want to take partial derivatives in the y direction of a neighborhood, but offset those derivatives by one pixel position along the positive x direction. For a 3×3 , 2D neighborhood iterator, we can construct an `std::slice`, (`start = 2`, `stride = 3`, `end = 8`), that represents the neighborhood offsets $(1, -1)$, $(1, 0)$, $(1, 1)$ (see Figure 6.6). If we pass this slice as an extra argument to the `itk::NeighborhoodInnerProduct` function, then the inner product is taken only along that slice. This “sliced” inner product with a 1D `itk::DerivativeOperator` gives the desired derivative.

The previous separable Gaussian filtering example can be rewritten using slices and slice-based inner products. In general, slice-based processing is most useful when doing many different calculations on the same neighborhood, where defining multiple iterators as in Section 6.4.1 becomes impractical or inefficient. Good examples of slice-based neighborhood processing can be found in any of the ND anisotropic diffusion function objects, such as `itk::CurvatureNDAnisotropicDiffusionFunction`.

The first difference between this example and the previous example is that the Gaussian operator is only initialized once. Its direction is not important because it is only a 1D array of coefficients.

```
itk::GaussianOperator<PixelType, 2> gaussianOperator;
gaussianOperator.SetDirection(0);
gaussianOperator.SetVariance(std::stod(argv[3]) * std::stod(argv[3]));
gaussianOperator.CreateDirectional();
```

Next we need to define a radius for the iterator. The radius in all directions matches that of the single extent of the Gaussian operator, defining a square neighborhood.

```
NeighborhoodIteratorType::RadiusType radius;
radius.Fill(gaussianOperator.GetRadius()[0]);
```

The inner product and face calculator are defined for the main processing loop as before, but now the iterator is reinitialized each iteration with the square `radius` instead of the radius of the operator. The inner product is taken using a slice along the axial direction corresponding to the current iteration. Note the use of `GetSlice()` to return the proper slice from the iterator itself. `GetSlice()` can only be used to return the slice along the complete extent of the axial direction of a neighborhood.

```
ImageType::Pointer input = reader->GetOutput();
faceList = faceCalculator(input, output->GetRequestedRegion(), radius);

for (unsigned int i = 0; i < ImageType::ImageDimension; ++i)
{
    for (fit = faceList.begin(); fit != faceList.end(); ++fit)
    {
        it = NeighborhoodIteratorType(radius, input, *fit);
```

```

    out = IteratorType(output, *fit);
    for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
    {
        out.Set(innerProduct(it.GetSlice(i), it, gaussianOperator));
    }
}

// Swap the input and output buffers
if (i != ImageType::ImageDimension - 1)
{
    ImageType::Pointer tmp = input;
    input = output;
    output = tmp;
}
}

```

This technique produces exactly the same results as the previous example. A little experimentation, however, will reveal that it is less efficient since the neighborhood iterator is keeping track of extra, unused pixel locations for each iteration, while the previous example only references those pixels that it needs. In cases, however, where an algorithm takes multiple derivatives or convolution products over the same neighborhood, slice-based processing can increase efficiency and simplify the implementation.

Random access iteration

The source code for this section can be found in the file `NeighborhoodIterators6.cxx`.

Some image processing routines do not need to visit every pixel in an image. Flood-fill and connected-component algorithms, for example, only visit pixels that are locally connected to one another. Algorithms such as these can be efficiently written using the random access capabilities of the neighborhood iterator.

The following example finds local minima. Given a seed point, we can search the neighborhood of that point and pick the smallest value m . While m is not at the center of our current neighborhood, we move in the direction of m and repeat the analysis. Eventually we discover a local minimum and stop. This algorithm is made trivially simple in ND using an ITK neighborhood iterator.

To illustrate the process, we create an image that descends everywhere to a single minimum: a positive distance transform to a point. The details of creating the distance transform are not relevant to the discussion of neighborhood iterators, but can be found in the source code of this example. Some noise has been added to the distance transform image for additional interest.

The variable `input` is the pointer to the distance transform image. The local minimum algorithm is initialized with a seed point read from the command line.

```

ImageType::IndexType index;
index[0] = std::stoi(argv[2]);
index[1] = std::stoi(argv[3]);

```

Next we create the neighborhood iterator and position it at the seed point.

```

NeighborhoodIteratorType::RadiusType radius;

```



```
radius.Fill(1);
NeighborhoodIteratorType it(radius, input, input->GetRequestedRegion());

it.SetLocation(index);
```

Searching for the local minimum involves finding the minimum in the current neighborhood, then shifting the neighborhood in the direction of that minimum. The `for` loop below records the `itk::Offset` of the minimum neighborhood pixel. The neighborhood iterator is then moved using that offset. When a local minimum is detected, `flag` will remain false and the `while` loop will exit. Note that this code is valid for an image of any dimensionality.

```
bool flag = true;
while (flag == true)
{
    NeighborhoodIteratorType::OffsetType nextMove;
    nextMove.Fill(0);

    flag = false;

    PixelType min = it.GetCenterPixel();
    for (unsigned int i = 0; i < it.Size(); ++i)
    {
        if (it.GetPixel(i) < min)
        {
            min = it.GetPixel(i);
            nextMove = it.GetOffset(i);
            flag = true;
        }
    }
    it.SetCenterPixel(255.0);
    it += nextMove;
}
```

Figure 6.9 shows the results of the algorithm for several seed points. The white line is the path of the iterator from the seed point to the minimum in the center of the image. The effect of the additive noise is visible as the small perturbations in the paths.

6.4.2 ShapedNeighborhoodIterator

This section describes a variation on the neighborhood iterator called a *shaped* neighborhood iterator. A shaped neighborhood is defined like a bit mask, or *stencil*, with different offsets in the rectilinear neighborhood of the normal neighborhood iterator turned off or on to create a pattern. Inactive positions (those not in the stencil) are not updated during iteration and their values cannot be read or written. The shaped iterator is implemented in the class `itk::ShapedNeighborhoodIterator`, which is a subclass of `itk::NeighborhoodIterator`. A const version, `itk::ConstShapedNeighborhoodIterator`, is also available.

Like a regular neighborhood iterator, a shaped neighborhood iterator must be initialized with an ND radius object, but the radius of the neighborhood of a shaped iterator only defines the set of *possible* neighbors. Any number of possible neighbors can then be activated or deactivated. The shaped neighborhood iterator defines an API for activating neighbors. When a neighbor location, defined relative to the center of the neighborhood,

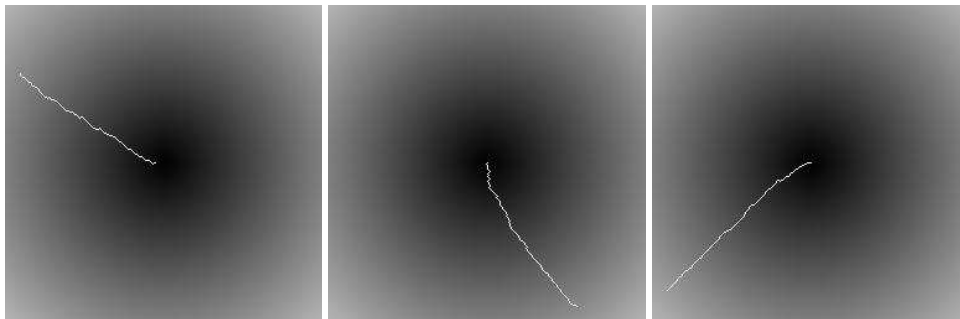


Figure 6.9: Paths traversed by the neighborhood iterator from different seed points to the local minimum. The true minimum is at the center of the image. The path of the iterator is shown in white. The effect of noise in the image is seen as small perturbations in each path.

is activated, it is placed on the *active list* and is then part of the stencil. An iterator can be “reshaped” at any time by adding or removing offsets from the active list.

- **void ActivateOffset (OffsetType &o)** Include the offset *o* in the stencil of active neighborhood positions. Offsets are relative to the neighborhood center.
- **void DeactivateOffset (OffsetType &o)** Remove the offset *o* from the stencil of active neighborhood positions. Offsets are relative to the neighborhood center.
- **void ClearActiveList ()** Deactivate all positions in the iterator stencil by clearing the active list.
- **unsigned int GetActiveIndexListSize()** Return the number of pixel locations that are currently active in the shaped iterator stencil.

Because the neighborhood is less rigidly defined in the shaped iterator, the set of pixel access methods is restricted. Only the `GetPixel()` and `SetPixel()` methods are available, and calling these methods on an inactive neighborhood offset will return undefined results.

For the common case of traversing all pixel offsets in a neighborhood, the shaped iterator class provides an iterator through the active offsets in its stencil. This *stencil iterator* can be incremented or decremented and defines `Get()` and `Set()` for reading and writing the values in the neighborhood.

- **ShapedNeighborhoodIterator::Iterator Begin()** Return a const or non-const iterator through the shaped iterator stencil that points to the first valid location in the stencil.
- **ShapedNeighborhoodIterator::Iterator End()** Return a const or non-const iterator through the shaped iterator stencil that points *one position past* the last valid location in the stencil.

The functionality and interface of the shaped neighborhood iterator is best described by example. We will use the `ShapedNeighborhoodIterator` to implement some binary image morphology algorithms (see [4], [2], et al.). The examples that follow implement erosion and dilation.

Shaped neighborhoods: morphological operations

The source code for this section can be found in the file `ShapedNeighborhoodIterators1.cxx`.

This example uses `itk::ShapedNeighborhoodIterator` to implement a binary erosion algorithm. If we think of an image I as a set of pixel indices, then erosion of I by a smaller set E , called the *structuring element*, is the set of all indices at locations x in I such that when E is positioned at x , every element in E is also contained in I .

This type of algorithm is easy to implement with shaped neighborhood iterators because we can use the iterator itself as the structuring element E and move it sequentially through all positions x . The result at x is obtained by checking values in a simple iteration loop through the neighborhood stencil.

We need two iterators, a shaped iterator for the input image and a regular image iterator for writing results to the output image.

```
#include "itkConstShapedNeighborhoodIterator.h"
#include "itkImageRegionIterator.h"
```

Since we are working with binary images in this example, an `unsigned char` pixel type will do. The image and iterator types are defined using the pixel type.

```
using PixelType = unsigned char;
using ImageType = itk::Image<PixelType, 2>;

using ShapedNeighborhoodIteratorType =
    itk::ConstShapedNeighborhoodIterator<ImageType>;

using IteratorType = itk::ImageRegionIterator<ImageType>;
```

Refer to the examples in Section 6.4.1 or the source code of this example for a description of how to read the input image and allocate a matching output image.

The size of the structuring element is read from the command line and used to define a radius for the shaped neighborhood iterator. Using the method developed in section 6.4.1 to minimize bounds checking, the iterator itself is not initialized until entering the main processing loop.

```
unsigned int element_radius = std::stoi(argv[3]);
ShapedNeighborhoodIteratorType::RadiusType radius;
radius.Fill(element_radius);
```

The face calculator object introduced in Section 6.4.1 is created and used as before.

```
using FaceCalculatorType =
    itk::NeighborhoodAlgorithm::ImageBoundaryFacesCalculator<ImageType>;

FaceCalculatorType          faceCalculator;
FaceCalculatorType::FaceListType faceList;
FaceCalculatorType::FaceListType::iterator fit;

faceList =
    faceCalculator(reader->GetOutput(), output->GetRequestedRegion(), radius);
```

Now we initialize some variables and constants.

```
IteratorType out;

constexpr PixelType background_value = 0;
constexpr PixelType foreground_value = 255;
const auto      rad = static_cast<float>(element_radius);
```

The outer loop of the algorithm is structured as in previous neighborhood iterator examples. Each region in the face list is processed in turn. As each new region is processed, the input and output iterators are initialized on that region.

The shaped iterator that ranges over the input is our structuring element and its active stencil must be created accordingly. For this example, the structuring element is shaped like a circle of radius `element_radius`. Each of the appropriate neighborhood offsets is activated in the double `for` loop.

```
for (fit = faceList.begin(); fit != faceList.end(); ++fit)
{
    ShapedNeighborhoodIteratorType it(radius, reader->GetOutput(), *fit);
    out = IteratorType(output, *fit);

    // Creates a circular structuring element by activating all the pixels
    // less than radius distance from the center of the neighborhood.

    for (float y = -rad; y <= rad; ++y)
    {
        for (float x = -rad; x <= rad; ++x)
        {
            ShapedNeighborhoodIteratorType::OffsetType off;

            float dis = std::sqrt(x * x + y * y);
            if (dis <= rad)
            {
                off[0] = static_cast<int>(x);
                off[1] = static_cast<int>(y);
                it.ActivateOffset(off);
            }
        }
    }
}
```

The inner loop, which implements the erosion algorithm, is fairly simple. The `for` loop steps the input and output iterators through their respective images. At each step, the active stencil of the shaped iterator is traversed to determine whether all pixels underneath the stencil contain the foreground value, i.e. are contained within the set I . Note the use of the stencil iterator, `ci`, in performing this check.

```
// Implements erosion
for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
{
    ShapedNeighborhoodIteratorType::ConstIterator ci;

    bool flag = true;
    for (ci = it.Begin(); ci != it.End(); ++ci)
```

```

{
    if (ci.Get() == background_value)
    {
        flag = false;
        break;
    }
}
if (flag == true)
{
    out.Set(foreground_value);
}
else
{
    out.Set(background_value);
}
}
}

```

The source code for this section can be found in the file `ShapedNeighborhoodIterators2.cxx`.

The logic of the inner loop can be rewritten to perform dilation. Dilation of the set I by E is the set of all x such that E positioned at x contains at least one element in I .

```

// Implements dilation
for (it.GoToBegin(), out.GoToBegin(); !it.IsAtEnd(); ++it, ++out)
{
    ShapedNeighborhoodIteratorType::ConstIterator ci;

    bool flag = false;
    for (ci = it.Begin(); ci != it.End(); ++ci)
    {
        if (ci.Get() != background_value)
        {
            flag = true;
            break;
        }
    }
    if (flag == true)
    {
        out.Set(foreground_value);
    }
    else
    {
        out.Set(background_value);
    }
}
}

```

The output image is written and visualized directly as a binary image of unsigned chars. Figure 6.10 illustrates some results of erosion and dilation on the image `Examples/Data/BinaryImage.png`. Applying erosion and dilation in sequence effects the morphological operations of opening and closing.



Figure 6.10: The effects of morphological operations on a binary image using a circular structuring element of size 4. From left to right are the original image, erosion, dilation, opening, and closing. The opening operation is erosion of the image followed by dilation. Closing is dilation of the image followed by erosion.

IMAGE ADAPTORS

The purpose of an *image adaptor* is to make one image appear like another image, possibly of a different pixel type. A typical example is to take an image of pixel type `unsigned char` and present it as an image of pixel type `float`. The motivation for using image adaptors in this case is to avoid the extra memory resources required by using a casting filter. When we use the `itk::CastImageFilter` for the conversion, the filter creates a memory buffer large enough to store the `float` image. The `float` image requires four times the memory of the original image and contains no useful additional information. Image adaptors, on the other hand, do not require the extra memory as pixels are converted only when they are read using image iterators (see Chapter 6).

Image adaptors are particularly useful when there is infrequent pixel access, since the actual conversion occurs on the fly during the access operation. In such cases the use of image adaptors may reduce overall computation time as well as reduce memory usage. The use of image adaptors, however, can be disadvantageous in some situations. For example, when the downstream filter is executed multiple times, a `CastImageFilter` will cache its output after the first execution and will not re-execute when the filter downstream is updated. Conversely, an image adaptor will compute the cast every time.

Another application for image adaptors is to perform lightweight pixel-wise operations replacing the need for a filter. In the toolkit, adaptors are defined for many single valued and single parameter functions such as trigonometric, exponential and logarithmic functions. For example,

- `itk::ExpImageAdaptor`
- `itk::SinImageAdaptor`
- `itk::CosImageAdaptor`

The following examples illustrate common applications of image adaptors.

7.1 Image Casting

The source code for this section can be found in the file `ImageAdaptor1.cxx`.

This example illustrates how the `itk::ImageAdaptor` can be used to cast an image from one pixel type to

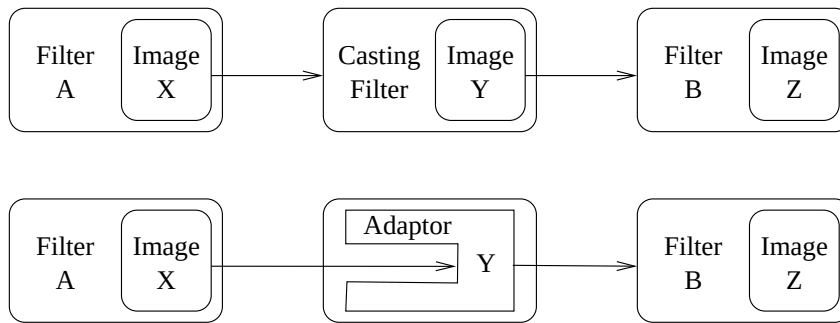


Figure 7.1: The difference between using a `CastImageFilter` and an `ImageAdaptor`. `ImageAdaptors` convert pixel values when they are accessed by iterators. Thus, they do not produce an intermediate image. In the example illustrated by this figure, the *Image Y* is not created by the `ImageAdaptor`; instead, the image is simulated on the fly each time an iterator from the filter downstream attempts to access the image data.

another. In particular, we will *adapt* an `unsigned char` image to make it appear as an image of pixel type `float`.

We begin by including the relevant headers.

```
#include "itkImageAdaptor.h"
```

First, we need to define a *pixel accessor* class that does the actual conversion. Note that in general, the only valid operations for pixel accessors are those that only require the value of the input pixel. As such, neighborhood type operations are not possible. A pixel accessor must provide methods `Set()` and `Get()`, and define the types of `InternalPixelType` and `ExternalPixelType`. The `InternalPixelType` corresponds to the pixel type of the image to be adapted (`unsigned char` in this example). The `ExternalPixelType` corresponds to the pixel type we wish to emulate with the `ImageAdaptor` (`float` in this case).

```
class CastPixelAccessor
{
public:
    using InternalType = unsigned char;
    using ExternalType = float;

    static void
    Set(InternalType & output, const ExternalType & input)
    {
        output = static_cast<InternalType>(input);
    }

    static ExternalType
    Get(const InternalType & input)
    {
        return static_cast<ExternalType>(input);
    }
};
```


The `CastPixelAccessor` class simply applies a `static_cast` to the pixel values. We now use this pixel accessor to define the image adaptor type and create an instance using the standard `New()` method.

```
using InputPixelType = unsigned char;
constexpr unsigned int Dimension = 2;
using ImageType = itk::Image<InputPixelType, Dimension>;

using ImageAdaptorType = itk::ImageAdaptor<ImageType, CastPixelAccessor>;
auto adaptor = ImageAdaptorType::New();
```

We also create an image reader templated over the input image type and read the input image from file.

```
using ReaderType = itk::ImageFileReader<ImageType>;
auto reader = ReaderType::New();
```

The output of the reader is then connected as the input to the image adaptor.

```
adaptor->SetImage(reader->GetOutput());
```

In the following code, we visit the image using an iterator instantiated using the adapted image type and compute the sum of the pixel values.

```
using IteratorType = itk::ImageRegionIteratorWithIndex<ImageAdaptorType>;
IteratorType it(adaptor, adaptor->GetBufferedRegion());

double sum = 0.0;
it.GoToBegin();
while (!it.IsAtEnd())
{
    float value = it.Get();
    sum += value;
    ++it;
}
```

Although in this example, we are just performing a simple summation, the key concept is that access to pixels is performed as if the pixel is of type `float`. Additionally, it should be noted that the adaptor is used as if it was an actual image and not as a filter. ImageAdaptors conform to the same API as the `itk::Image` class.

7.2 Adapting RGB Images

The source code for this section can be found in the file `ImageAdaptor2.cxx`.

This example illustrates how to use the `itk::ImageAdaptor` to access the individual components of an RGB image. In this case, we create an `ImageAdaptor` that will accept a RGB image as input and presents it as a scalar image. The pixel data will be taken directly from the red channel of the original image.

As with the previous example, the bulk of the effort in creating the image adaptor is associated with the definition of the pixel accessor class. In this case, the accessor converts a RGB vector to a scalar containing the red channel component. Note that in the following, we do not need to define the `Set()` method since we only expect the adaptor to be used for reading data from the image.

```

class RedChannelPixelAccessor
{
public:
    using InternalType = itk::RGBPixel<float>;
    using ExternalType = float;

    static ExternalType
    Get(const InternalType & input)
    {
        return static_cast<ExternalType>(input.GetRed());
    }
};

```

The `Get()` method simply calls the `GetRed()` method defined in the `itk::RGBPixel` class.

Now we use the internal pixel type of the pixel accessor to define the input image type, and then proceed to instantiate the `ImageAdaptor` type.

```

using InputPixelType = RedChannelPixelAccessor::InternalType;
constexpr unsigned int Dimension = 2;
using ImageType = itk::Image<InputPixelType, Dimension>;

using ImageAdaptorType =
    itk::ImageAdaptor<ImageType, RedChannelPixelAccessor>;

auto adaptor = ImageAdaptorType::New();

```

We create an image reader and connect the output to the adaptor as before.

```

using ReaderType = itk::ImageFileReader<ImageType>;
auto reader = ReaderType::New();

```

```

adaptor->SetImage(reader->GetOutput());

```

We create an `itk::RescaleIntensityImageFilter` and an `itk::ImageFileWriter` to rescale the dynamic range of the pixel values and send the extracted channel to an image file. Note that the image type used for the rescaling filter is the `ImageAdaptorType` itself. That is, the adaptor type is used in the same context as an image type.

```

using OutputImageType = itk::Image<unsigned char, Dimension>;
using RescalerType =
    itk::RescaleIntensityImageFilter<ImageAdaptorType, OutputImageType>;

auto rescaler = RescalerType::New();
using WriterType = itk::ImageFileWriter<OutputImageType>;
auto writer = WriterType::New();

```

Now we connect the adaptor as the input to the rescaler and set the parameters for the intensity rescaling.

```

rescaler->SetOutputMinimum(0);
rescaler->SetOutputMaximum(255);

rescaler->SetInput(adaptor);
writer->SetInput(rescaler->GetOutput());

```

Finally, we invoke the `Update()` method on the writer and take precautions to catch any exception that may be thrown during the execution of the pipeline.

```
try
{
    writer->Update();
}
catch (const itk::ExceptionObject & excp)
{
    std::cerr << "Exception caught " << excp << std::endl;
    return EXIT_FAILURE;
}
```

ImageAdaptors for the green and blue channels can easily be implemented by modifying the pixel accessor of the red channel and then using the new pixel accessor for instantiating the type of an image adaptor. The following define a green channel pixel accessor.

```
class GreenChannelPixelAccessor
{
public:
    using InternalType = itk::RGBPixel<float>;
    using ExternalType = float;

    static ExternalType
    Get(const InternalType & input)
    {
        return static_cast<ExternalType>(input.GetGreen());
    }
};
```

A blue channel pixel accessor is similarly defined.

```
class BlueChannelPixelAccessor
{
public:
    using InternalType = itk::RGBPixel<float>;
    using ExternalType = float;

    static ExternalType
    Get(const InternalType & input)
    {
        return static_cast<ExternalType>(input.GetBlue());
    }
};
```

Figure 7.2 shows the result of extracting the red, green and blue components from a region of the Visible Woman cryogenic data set.

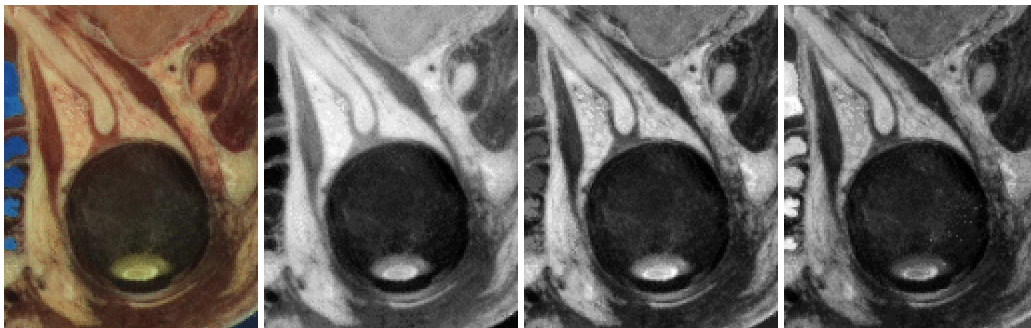


Figure 7.2: Using ImageAdaptor to extract the components of an RGB image. The image on the left is a subregion of the Visible Woman cryogenic data set. The red, green and blue components are shown from left to right as scalar images extracted with an ImageAdaptor.

7.3 Adapting Vector Images

The source code for this section can be found in the file `ImageAdaptor3.cxx`.

This example illustrates the use of `itk::ImageAdaptor` to obtain access to the components of a vector image. Specifically, it shows how to manage pixel accessors containing internal parameters. In this example we create an image of vectors by using a gradient filter. Then, we use an image adaptor to extract one of the components of the vector image. The vector type used by the gradient filter is the `itk::CovariantVector` class.

We start by including the relevant headers.

```
#include "itkGradientRecursiveGaussianImageFilter.h"
```

A pixel accessors class may have internal parameters that affect the operations performed on input pixel data. Image adaptors support parameters in their internal pixel accessor by using the assignment operator. Any pixel accessor which has internal parameters must therefore implement the assignment operator. The following defines a pixel accessor for extracting components from a vector pixel. The `m_Index` member variable is used to select the vector component to be returned.

```
class VectorPixelAccessor
{
public:
    using InternalType = itk::CovariantVector<float, 2>;
    using ExternalType = float;

    VectorPixelAccessor() = default;

    VectorPixelAccessor &
    operator=(const VectorPixelAccessor & vpa) = default;
    ExternalType
    Get(const InternalType & input) const
    {
```

```

    return static_cast<ExternalType>(input[m_Index]);
}
void
SetIndex(unsigned int index)
{
    m_Index = index;
}

private:
    unsigned int m_Index{ 0 };
};

```

The `Get()` method simply returns the i -th component of the vector as indicated by the index. The assignment operator transfers the value of the index member variable from one instance of the pixel accessor to another.

In order to test the pixel accessor, we generate an image of vectors using the `itk::GradientRecursiveGaussianImageFilter`. This filter produces an output image of `itk::CovariantVector` pixel type. Covariant vectors are the natural representation for gradients since they are the equivalent of normals to iso-values manifolds.

```

using InputPixelType = unsigned char;
constexpr unsigned int Dimension = 2;
using InputImageType = itk::Image<InputPixelType, Dimension>;
using VectorPixelType = itk::CovariantVector<float, Dimension>;
using VectorImageType = itk::Image<VectorPixelType, Dimension>;
using GradientFilterType =
    itk::GradientRecursiveGaussianImageFilter<InputImageType,
                                              VectorImageType>;

auto gradient = GradientFilterType::New();

```

We instantiate the `ImageAdaptor` using the vector image type as the first template parameter and the pixel accessor as the second template parameter.

```

using ImageAdaptorType =
    itk::ImageAdaptor<VectorImageType, itk::VectorPixelAccessor>;

auto adaptor = ImageAdaptorType::New();

```

The index of the component to be extracted is specified from the command line. In the following, we create the accessor, set the index and connect the accessor to the image adaptor using the `SetPixelAccessor()` method.

```

itk::VectorPixelAccessor accessor;
accessor.SetIndex(std::stoi(argv[3]));
adaptor->SetPixelAccessor(accessor);

```

We create a reader to load the image specified from the command line and pass its output as the input to the gradient filter.

```

using ReaderType = itk::ImageFileReader<InputImageType>;
auto reader = ReaderType::New();
gradient->SetInput(reader->GetOutput());

```

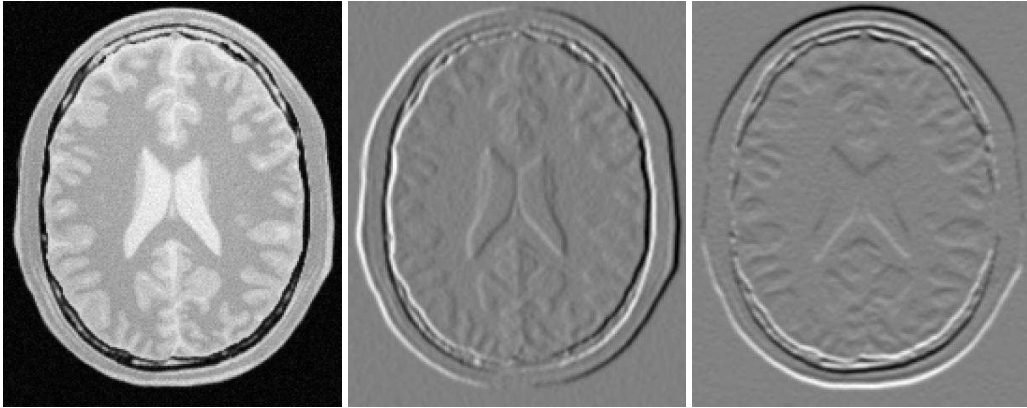


Figure 7.3: Using ImageAdaptor to access components of a vector image. The input image on the left was passed through a gradient image filter and the two components of the resulting vector image were extracted using an image adaptor.

```
reader->SetFileName(argv[1]);
gradient->Update();
```

We now connect the output of the gradient filter as input to the image adaptor. The adaptor emulates a scalar image whose pixel values are taken from the selected component of the vector image.

```
adaptor->SetImage(gradient->GetOutput());
```

As in the previous example, we rescale the scalar image before writing the image out to file. Figure 7.3 shows the result of applying the example code for extracting both components of a two dimensional gradient.

7.4 Adaptors for Simple Computation

The source code for this section can be found in the file `ImageAdaptor4.cxx`.

Image adaptors can also be used to perform simple pixel-wise computations on image data. The following example illustrates how to use the `itk::ImageAdaptor` for image thresholding.

A pixel accessor for image thresholding requires that the accessor maintain the threshold value. Therefore, it must also implement the assignment operator to set this internal parameter.

```
class ThresholdingPixelAccessor
{
public:
    using InternalType = unsigned char;
    using ExternalType = unsigned char;
```

```

ThresholdingPixelAccessor() = default;

ExternalType
Get(const InternalType & input) const
{
    return (input > m_Threshold) ? 1 : 0;
}
void
SetThreshold(const InternalType threshold)
{
    m_Threshold = threshold;
}

ThresholdingPixelAccessor &
operator=(const ThresholdingPixelAccessor & vpa) = default;

private:
    InternalType m_Threshold{ 0 };
};
} // namespace itk

```

The `Get()` method returns one if the input pixel is above the threshold and zero otherwise. The assignment operator transfers the value of the threshold member variable from one instance of the pixel accessor to another.

To create an image adaptor, we first instantiate an image type whose pixel type is the same as the internal pixel type of the pixel accessor.

```

using PixelType = itk::ThresholdingPixelAccessor::InternalType;
constexpr unsigned int Dimension = 2;
using ImageType = itk::Image<PixelType, Dimension>;

```

We instantiate the `ImageAdaptor` using the image type as the first template parameter and the pixel accessor as the second template parameter.

```

using ImageAdaptorType =
    itk::ImageAdaptor<ImageType, itk::ThresholdingPixelAccessor>;

auto adaptor = ImageAdaptorType::New();

```

The threshold value is set from the command line. A threshold pixel accessor is created and connected to the image adaptor in the same manner as in the previous example.

```

itk::ThresholdingPixelAccessor accessor;
accessor.SetThreshold(std::stoi(argv[3]));
adaptor->SetPixelAccessor(accessor);

```

We create a reader to load the input image and connect the output of the reader as the input to the adaptor.

```

using ReaderType = itk::ImageFileReader<ImageType>;
auto reader = ReaderType::New();

```

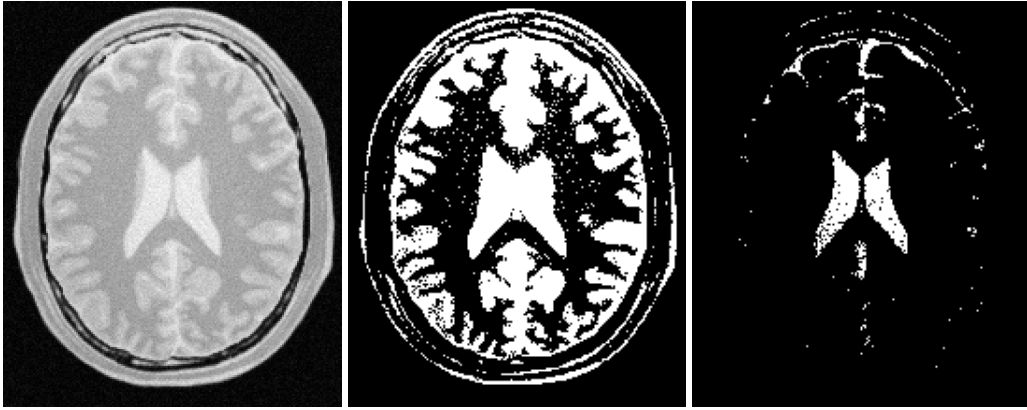


Figure 7.4: Using ImageAdaptor to perform a simple image computation. An ImageAdaptor is used to perform binary thresholding on the input image on the left. The center image was created using a threshold of 180, while the image on the right corresponds to a threshold of 220.

```
reader->SetFileName(argv[1]);  
reader->Update();  
  
adaptor->SetImage(reader->GetOutput());
```

As before, we rescale the emulated scalar image before writing it out to file. Figure 7.4 illustrates the result of applying the thresholding adaptor to a typical gray scale image using two different threshold values. Note that the same effect could have been achieved by using the `itk::BinaryThresholdImageFilter` but at the price of holding an extra copy of the image in memory.

7.5 Adaptors and Writers

Image adaptors will not behave correctly when connected directly to a writer. The reason is that writers tend to get direct access to the image buffer from their input, since image adaptors do not have a real buffer their behavior in this circumstances is incorrect. You should avoid instantiating the `ImageFileWriter` or the `ImageSeriesWriter` over an image adaptor type.

Part III

Development Guidelines

HOW TO WRITE A FILTER

This purpose of this chapter is help developers create their own filter (process object). This chapter is divided into four major parts. An initial definition of terms is followed by an overview of the filter creation process. Next, data streaming is discussed. The way data is streamed in ITK must be understood in order to write correct filters. Finally, a section on multi-threading describes what you must do in order to take advantage of shared memory parallel processing.

8.1 Terminology

The following is some basic terminology for the discussion that follows. Chapter 3 provides additional background information.

- The **data processing pipeline** is a directed graph of **process** and **data objects**. The pipeline inputs, operators on, and outputs data.
- A **filter**, or **process object**, has one or more inputs, and one or more outputs.
- A **source**, or source process object, initiates the data processing pipeline, and has one or more outputs.
- A **mapper**, or mapper process object, terminates the data processing pipeline. The mapper has one or more outputs, and may write data to disk, interface with a display system, or interface to any other system.
- A **data object** represents and provides access to data. In ITK, the data object (ITK class `itk::DataObject`) is typically of type `itk::Image` or `itk::Mesh`.
- A **region** (ITK class `itk::Region`) represents a piece, or subset of the entire data set.
- An **image region** (ITK class `itk::ImageRegion`) represents a structured portion of data. ImageRegion is implemented using the `itk::Index` and `itk::Size` classes
- A **mesh region** (ITK class `itk::MeshRegion`) represents an unstructured portion of data.
- The **LargestPossibleRegion** is the theoretical single, largest piece (region) that could represent the entire dataset. The LargestPossibleRegion is used in the system as the measure of the largest possible data size.

- The **BufferedRegion** is a contiguous block of memory that is less than or equal in size to the LargestPossibleRegion. The buffered region is what has actually been allocated by a filter to hold its output.
- The **RequestedRegion** is the piece of the dataset that a filter is required to produce. The RequestedRegion is less than or equal in size to the BufferedRegion. The RequestedRegion may differ in size from the BufferedRegion due to performance reasons. The RequestedRegion may be set by a user, or by an application that needs just a portion of the data.
- The **modified time** (represented by ITK class `itk::TimeStamp`) is a monotonically increasing integer value that characterizes a point in time when an object was last modified.
- **Downstream** is the direction of dataflow, from sources to mappers.
- **Upstream** is the opposite of downstream, from mappers to sources.
- The **pipeline modified time** for a particular data object is the maximum modified time of all upstream data objects and process objects.
- The term **information** refers to metadata that characterizes data. For example, index and dimensions are information characterizing an image region.

8.2 Overview of Filter Creation

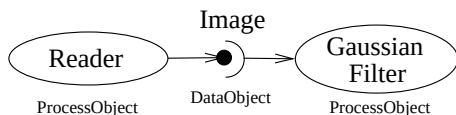


Figure 8.1: Relationship between DataObject and ProcessObject.

Filters are defined with respect to the type of data they input (if any), and the type of data they output (if any). The key to writing a ITK filter is to identify the number and types of input and output. Having done so, there are often superclasses that simplify this task via class derivation. For example, most filters in ITK take a single image as input, and produce a single image on output. The superclass `itk::ImageToImageFilter` is a convenience class

that provide most of the functionality needed for such a filter.

Some common base classes for new filters include:

- **ImageToImageFilter**: the most common filter base for segmentation algorithms. Takes an image and produces a new image, by default of the same dimensions. Override `GenerateOutputInformation` to produce a different size.
- **UnaryFunctorImageFilter**: used when defining a filter that applies a function to an image.
- **BinaryFunctorImageFilter**: used when defining a filter that applies an operation to two images.
- **ImageFunction**: a functor that can be applied to an image, evaluating $f(x)$ at each point in the image.
- **MeshToMeshFilter**: a filter that transforms meshes, such as tessellation, polygon reduction, and so on.
- **LightObject**: abstract base for filters that don't fit well anywhere else in the class hierarchy. Also useful for "calculator" filters; i.e. a sink filter that takes an input and calculates a result which is retrieved using a `Get()` method.

Once the appropriate superclass is identified, the filter writer implements the class defining the methods required by most all ITK objects: `New()`, `PrintSelf()`, and protected constructor, copy constructor, delete, and operator=, and so on. Also, don't forget standard type aliases like `Self`, `Superclass`, `Pointer`, and `ConstPointer`. Then the filter writer can focus on the most important parts of the implementation: defining the API, data members, and other implementation details of the algorithm. In particular, the filter writer will have to implement either a `GenerateData()` (non-threaded) or `ThreadedGenerateData()` and `DynamicThreadedGenerateData()` methods. (See Section 3.2.7 for an overview of multi-threading in ITK.)

An important note: the `GenerateData()` method is required to allocate memory for the output. The `ThreadedGenerateData()` method is not. In default implementation (see `itk::ImageSource`, a superclass of `itk::ImageToImageFilter`) `GenerateData()` allocates memory and then invokes `DynamicThreadedGenerateData()` or `ThreadedGenerateData()`.

One of the most important decisions that the developer must make is whether the filter can stream data; that is, process just a portion of the input to produce a portion of the output. Often superclass behavior works well: if the filter processes the input using single pixel access, then the default behavior is adequate. If not, then the user may have to a) find a more specialized superclass to derive from, or b) override one or more methods that control how the filter operates during pipeline execution. The next section describes these methods.

8.3 Streaming Large Data

The data associated with multi-dimensional images is large and becoming larger. This trend is due to advances in scanning resolution, as well as increases in computing capability. Any practical segmentation and registration software system must address this fact in order to be useful in application. ITK addresses this problem via its data streaming facility.

In ITK, streaming is the process of dividing data into pieces, or regions, and then processing this data through the data pipeline. Recall that the pipeline consists of process objects that generate data objects, connected into a pipeline topology. The input to a process object is a data object (unless the process initiates the pipeline and then it is a source process object). These data objects in turn are consumed by other process objects, and so on, until a directed graph of data flow is constructed. Eventually the pipeline is terminated by one or more mappers, that may write data to storage, or interface with a graphics or other system. This is illustrated in figures 8.1 and 8.2.

A significant benefit of this architecture is that the relatively complex process of managing pipeline execution is designed into the system. This means that keeping the pipeline up to date, executing only those portions of the pipeline that have changed, multi-threading execution, managing memory allocation, and streaming is all built into the architecture. However, these features do introduce complexity into the system, the bulk of which is seen by class developers. The purpose of this chapter is to describe the pipeline execution process in detail, with a focus on data streaming.

8.3.1 Overview of Pipeline Execution

The pipeline execution process performs several important functions.

1. It determines which filters, in a pipeline of filters, need to execute. This prevents redundant execution and minimizes overall execution time.

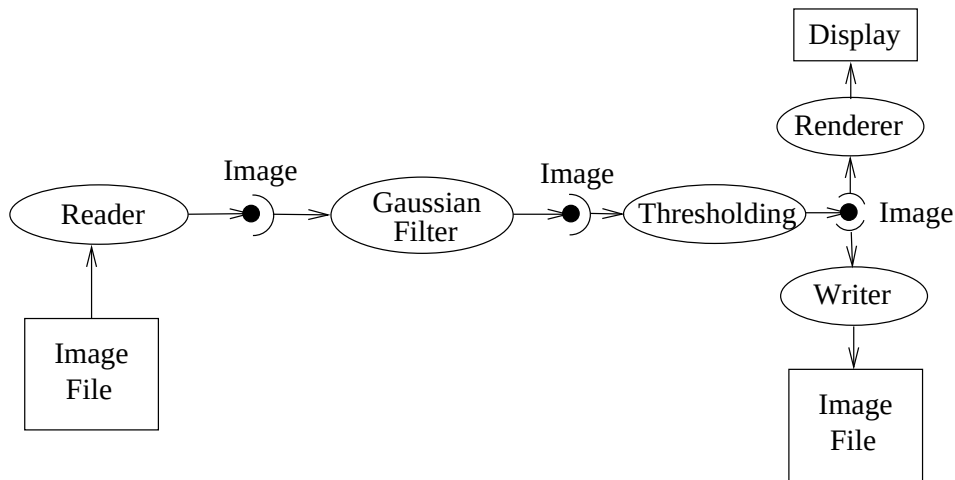


Figure 8.2: The Data Pipeline

2. It initializes the (filter's) output data objects, preparing them for new data. In addition, it determines how much memory each filter must allocate for its output, and allocates it.
3. The execution process determines how much data a filter must process in order to produce an output of sufficient size for downstream filters; it also takes into account any limits on memory or special filter requirements. Other factors include the size of data processing kernels, that affect how much data input data (extra padding) is required.
4. It subdivides data into subpieces for multi-threading. (Note that the division of data into subpieces is exactly same problem as dividing data into pieces for streaming; hence multi-threading comes for free as part of the streaming architecture.)
5. It may free (or release) output data if filters no longer need it to compute, and the user requests that data is to be released. (Note: a filter's output data object may be considered a "cache". If the cache is allowed to remain (`ReleaseDataFlagOff()`) between pipeline execution, and the filter, or the input to the filter, never changes, then process objects downstream of the filter just reuse the filter's cache to re-execute.)

To perform these functions, the execution process negotiates with the filters that define the pipeline. Only each filter can know how much data is required on input to produce a particular output. For example, a shrink filter with a shrink factor of two requires an image twice as large (in terms of its x-y dimensions) on input to produce a particular size output. An image convolution filter would require extra input (boundary padding) depending on the size of the convolution kernel. Some filters require the entire input to produce an output (for example, a histogram), and have the option of requesting the entire input. (In this case streaming does not work unless the developer creates a filter that can request multiple pieces, caching state between each piece to assemble the final output.)

Ultimately the negotiation process is controlled by the request for data of a particular size (i.e., region). It may be that the user asks to process a region of interest within a large image, or that memory limitations result in processing the data in several pieces. For example, an application may compute the memory required by a pipeline, and then use `itk::StreamingImageFilter` to break the data processing into several pieces. The

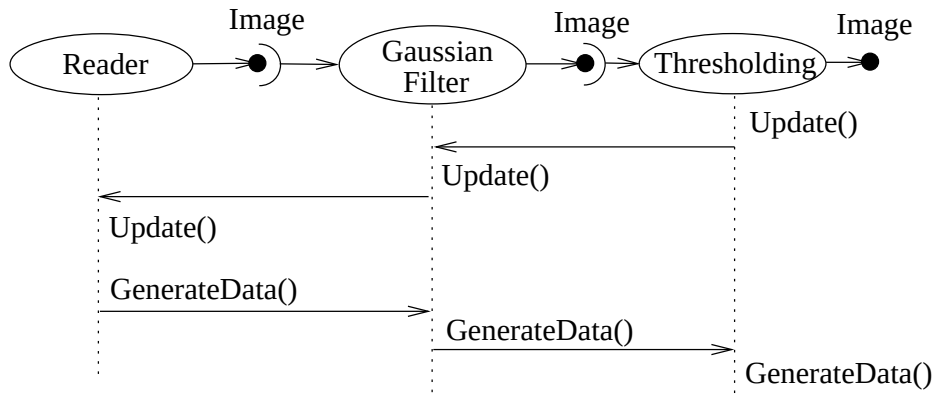


Figure 8.3: Sequence of the Data Pipeline updating mechanism

data request is propagated through the pipeline in the upstream direction, and the negotiation process configures each filter to produce output data of a particular size.

The secret to creating a streaming filter is to understand how this negotiation process works, and how to override its default behavior by using the appropriate virtual functions defined in `itk::ProcessObject`. The next section describes the specifics of these methods, and when to override them. Examples are provided along the way to illustrate concepts.

8.3.2 Details of Pipeline Execution

Typically pipeline execution is initiated when a process object receives the `ProcessObject::Update()` method invocation. This method is simply delegated to the output of the filter, invoking the `DataObject::Update()` method. Note that this behavior is typical of the interaction between `ProcessObject` and `DataObject`: a method invoked on one is eventually delegated to the other. In this way the data request from the pipeline is propagated upstream, initiating data flow that returns downstream.

The `DataObject::Update()` method in turn invokes three other methods:

- `DataObject::UpdateOutputInformation()`
- `DataObject::PropagateRequestedRegion()`
- `DataObject::UpdateOutputData()`

UpdateOutputInformation()

The `UpdateOutputInformation()` method first calls the `VerifyPreconditions` to check that all required inputs are set and all parameters are valid and consistent. This enables quick failure of a filter when not configured correctly. The default implementation checks that all required pipeline inputs are set.

Next the pipeline modified time is determined. The `RequestedRegion` is set to process all the data, i.e., the `LargestPossibleRegion`, if neither `UpdateLargestPossibleRegion` was called nor `RequestedRegion` has not been set. The `UpdateOutputInformation()` propagates upstream through the entire pipeline and terminates at the sources.

After the upstream inputs have completed their `UpdateOutputInformation` the metadata of inputs are available. The `VerifyInputInformation` is then called. The default implementation in `ImageToImageFilter` checks that all input images occupy the same physical space. This may need to be overridden if the filter does not require the image's voxels occupy the same physical space.

During `UpdateOutputInformation()`, filters have a chance to override the `ProcessObject::GenerateOutputInformation()` method (`GenerateOutputInformation()` is invoked by `UpdateOutputInformation()`). The default behavior is for the `GenerateOutputInformation()` to copy the metadata describing the input to the output (via `DataObject::CopyInformation()`). Remember, information is metadata describing the output, such as the origin, spacing, and `LargestPossibleRegion` (i.e., largest possible size) of an image.

A good example of this behavior is `itk::ShrinkImageFilter`. This filter takes an input image and shrinks it by some integral value. The result is that the spacing and `LargestPossibleRegion` of the output will be different to that of the input. Thus, `GenerateOutputInformation()` is overloaded.

PropagateRequestedRegion()

The `PropagateRequestedRegion()` call propagates upstream to satisfy a data request. In typical application this data request is usually the `LargestPossibleRegion`, but if streaming is necessary, or the user is interested in updating just a portion of the data, the `RequestedRegion` may be any valid region within the `LargestPossibleRegion`.

The function of `PropagateRequestedRegion()` is, given a request for data (the amount is specified by `RequestedRegion`), propagate upstream configuring the filter's input and output process object's to the correct size. Eventually, this means configuring the `BufferedRegion`, that is the amount of data actually allocated.

The reason for the buffered region is this: the output of a filter may be consumed by more than one downstream filter. If these consumers each request different amounts of input (say due to kernel requirements or other padding needs), then the upstream, generating filter produces the data to satisfy both consumers, that may mean it produces more data than one of the consumers needs.

The `ProcessObject::PropagateRequestedRegion()` method invokes three methods that the filter developer may choose to overload.

- `EnlargeOutputRequestedRegion(DataObject *output)` gives the (filter) subclass a chance to indicate that it will provide more data than required for the output. This can happen, for example, when a source can only produce the whole output (i.e., the `LargestPossibleRegion`).
- `GenerateOutputRequestedRegion(DataObject *output)` gives the subclass a chance to define how to set the requested regions for each of its outputs, given this output's requested region. The default implementation is to make all the output requested regions the same. A subclass may need to override this method if each output is a different resolution. This method is only overridden if a filter has multiple outputs.
- `GenerateInputRequestedRegion()` gives the subclass a chance to request a larger requested region on

the inputs. This is necessary when, for example, a filter requires more data at the “internal” boundaries to produce the boundary values - due to kernel operations or other region boundary effects.

`itk::RGBGibbsPriorFilter` is an example of a filter that needs to invoke `EnlargeOutputRequestedRegion()`. The designer of this filter decided that the filter should operate on all the data. Note that a subtle interplay between this method and `GenerateInputRequestedRegion()` is occurring here. The default behavior of `GenerateInputRequestedRegion()` (at least for `itk::ImageToImageFilter`) is to set the input `RequestedRegion` to the output’s `RequestedRegion`. Hence, by overriding the method `EnlargeOutputRequestedRegion()` to set the output to the `LargestPossibleRegion`, effectively sets the input to this filter to the `LargestPossibleRegion` (and probably causing all upstream filters to process their `LargestPossibleRegion` as well. This means that the filter, and therefore the pipeline, does not stream. This could be fixed by reimplementing the filter with the notion of streaming built in to the algorithm.)

`itk::GradientMagnitudeImageFilter` is an example of a filter that needs to invoke `GenerateInputRequestedRegion()`. It needs a larger input requested region because a kernel is required to compute the gradient at a pixel. Hence the input needs to be “padded out” so the filter has enough data to compute the gradient at each output pixel.

UpdateOutputData()

`UpdateOutputData()` is the third and final method as a result of the `Update()` method. The purpose of this method is to determine whether a particular filter needs to execute in order to bring its output up to date. (A filter executes when its `GenerateData()` method is invoked.) Filter execution occurs when a) the filter is modified as a result of modifying an instance variable; b) the input to the filter changes; c) the input data has been released; or d) an invalid `RequestedRegion` was set previously and the filter did not produce data. Filters execute in order in the downstream direction. Once a filter executes, all filters downstream of it must also execute.

`DataObject::UpdateOutputData()` is delegated to the `DataObject`’s source (i.e., the `ProcessObject` that generated it) only if the `DataObject` needs to be updated. A comparison of modified time, pipeline time, release data flag, and valid requested region is made. If any one of these conditions indicate that the data needs regeneration, then the source’s `ProcessObject::UpdateOutputData()` is invoked. These calls are made recursively up the pipeline until a source filter object is encountered, or the pipeline is determined to be up to date and valid. At this point, the recursion unrolls, and the execution of the filter proceeds. (This means that the output data is initialized, `StartEvent` is invoked, the filters `GenerateData()` is called, `EndEvent` is invoked, and input data to this filter may be released, if requested. In addition, this filter’s `InformationTime` is updated to the current time.)

The developer will never override `UpdateOutputData()`. The developer need only write the `GenerateData()` method (non-threaded) or `DynamicThreadedGenerateData()` method. A discussion on threading follows in the next section.

8.4 Threaded Filter Execution

Filters that can process data in pieces can typically multi-process using the data parallel, shared memory implementation built into the pipeline execution process. To create a multi-threaded filter, simply define and

implement a `DynamicThreadedGenerateData()`. For example, a `itk::ImageToImageFilter` would create the method:

```
void
DynamicThreadedGenerateData(
    const OutputImageRegionType & outputRegionForThread) override;
```

The key to threading is to generate output for the output region given as the parameter. In ITK, this is simple to do because an output iterator can be created using the region provided. Hence the output can be iterated over, accessing the corresponding input pixels as necessary to compute the value of the output pixel.

Multi-threading requires caution when performing I/O (including using `cout` or `cerr`) or invoking events. A safe practice is to allow only the invoking thread to perform I/O or generate events. If more than one thread tries to write to the same place at the same time, the program can behave badly, and possibly even deadlock or crash.

`DynamicThreadedGenerateData` signature allows number of pieces (output regions) to be processed to be different, usually bigger than the number of real threads executing the work. In turn, this allows load balancing. The number of work units controls filter parallelism, and the name ‘threads’ is reserved for real threads as exposed by `itk::MultiThreaderBase` and its descendants.

8.5 Filter Conventions

In order to fully participate in the ITK pipeline, filters are expected to follow certain conventions, and provide certain interfaces. This section describes the minimum requirements for a filter to integrate into the ITK framework.

A filter should define public types for the class itself (`Self`) and its Superclass, and `const` and non-`const` smart pointers, thus:

```
using Self = ExampleImageFilter;
using Superclass = ImageToImageFilter<TImage, TImage>;
using Pointer = SmartPointer<Self>;
using ConstPointer = SmartPointer<const Self>;
```

The `Pointer` type is particularly useful, as it is a smart pointer that will be used by all client code to hold a reference-counted instantiation of the filter.

Once the above types have been defined, you can use the following convenience macros, which permit your filter to participate in the object factory mechanism, and to be created using the canonical `::New()`:

```
/** Method for creation through the object factory. */
itkNewMacro(Self);
```

```
/** Run-time type information (and related methods). */
itkOverrideGetNameOfClassMacro(ExampleImageFilter);
```

The default constructor should be protected, and provide sensible defaults (usually zero) for all parameters. The copy constructor and assignment operator should not be implemented in order to prevent instantiating the filter without the factory methods (above). They should be declared in the public section using the `ITK_DISALLOW_COPY_AND_ASSIGN` macro (see Section C.18 on page 356).

Finally, the template implementation code (in the `.hxx` file) should be included, bracketed by a test for manual instantiation, thus:

```
#ifndef ITK_MANUAL_INSTANTIATION
# include "itkExampleFilter.hxx"
#endif
```

8.5.1 Optional

A filter can be printed to an `std::ostream` (such as `std::cout`) by implementing the following method:

```
void
PrintSelf(std::ostream & os, Indent indent) const;
```

and writing the name-value pairs of the filter parameters to the supplied output stream. This is particularly useful for debugging.

8.5.2 Useful Macros

Many convenience macros are provided by ITK, to simplify filter coding. Some of these are described below:

itkStaticConstMacro Declares a static variable of the given type, with the specified initial value.

itkGetMacro Defines an accessor method for the specified scalar data member. The convention is for data members to have a prefix of `m_`.

itkSetMacro Defines a mutator method for the specified scalar data member, of the supplied type. This will automatically set the `Modified` flag, so the filter stage will be executed on the next `Update()`.

itkBooleanMacro Defines a pair of `OnFlag` and `OffFlag` methods for a boolean variable `m_Flag`.

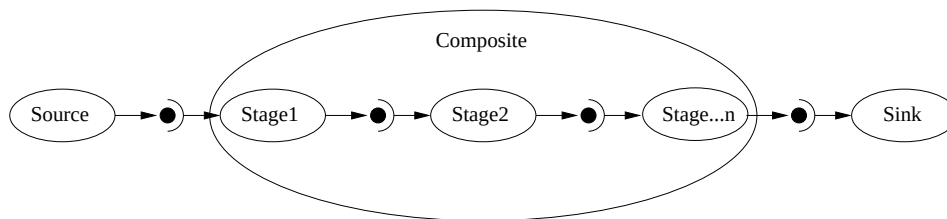


Figure 8.4: A Composite filter encapsulates a number of other filters.

itkGetConstObjectMacro, itkSetObjectMacro Defines an accessor and mutator for an ITK object. The Get form returns a smart pointer to the object.

Much more useful information can be learned from browsing the source in `Code/Common/itkMacro.h` and for the `itk::Object` and `itk::LightObject` classes.

8.6 How To Write A Composite Filter

In general, most ITK filters implement one particular algorithm, whether it be image filtering, an information metric, or a segmentation algorithm. In the previous section, we saw how to write new filters from scratch. However, it is often very useful to be able to make a new filter by combining two or more existing filters, which can then be used as a building block in a complex pipeline. This approach follows the Composite pattern [3], whereby the composite filter itself behaves just as a regular filter, providing its own (potentially higher level) interface and using other filters (whose detail is hidden to users of the class) for the implementation. This composite structure is shown in Figure 8.4, where the various Stage-*n* filters are combined into one by the Composite filter. The Source and Sink filters only see the interface published by the Composite. Using the Composite pattern, a composite filter can encapsulate a pipeline of arbitrary complexity. These can in turn be nested inside other pipelines.

8.6.1 Implementing a Composite Filter

There are a few considerations to take into account when implementing a composite filter. All the usual requirements for filters apply (as discussed above), but the following guidelines should be considered:

1. The template arguments it takes must be sufficient to instantiate all of the component filters. Each component filter needs a type supplied by either the implementor or the enclosing class. For example, an `ImageToImageFilter` normally takes an input and output image type (which may be the same). But if the output of the composite filter is a classified image, we need to

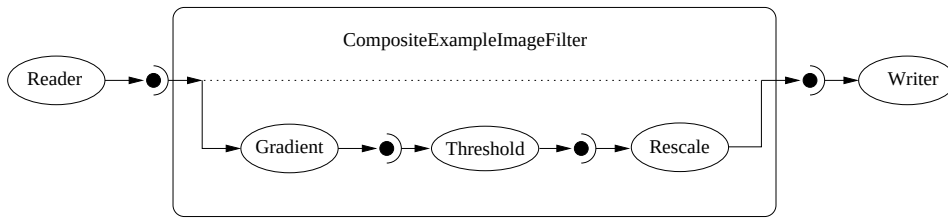


Figure 8.5: Example of a typical composite filter. Note that the output of the last filter in the internal pipeline must be grafted into the output of the composite filter.

either decide on the output type inside the composite filter, or restrict the choices of the user when she/he instantiates the filter.

2. The types of the component filters should be declared in the header, preferably with `protected` visibility. This is because the internal structure normally should not be visible to users of the class, but should be to descendent classes that may need to modify or customize the behavior.
3. The component filters should be private data members of the composite class, as in `FilterType::Pointer`.
4. The default constructor should build the pipeline by creating the stages and connect them together, along with any default parameter settings, as appropriate.
5. The input and output of the composite filter need to be grafted on to the head and tail (respectively) of the component filters.

This grafting process is illustrated in Figure 8.5.

8.6.2 A Simple Example

The source code for this section can be found in the file `CompositeFilterExample.cxx`.

The composite filter we will build combines three filters: a gradient magnitude operator, which will calculate the first-order derivative of the image; a thresholding step to select edges over a given strength; and finally a rescaling filter, to ensure the resulting image data is visible by scaling the intensity to the full spectrum of the output image type.

Since this filter takes an image and produces another image (of identical type), we will specialize the `ImageToImageFilter`:

Next we include headers for the component filters:

```
#include "itkGradientMagnitudeImageFilter.h"
#include "itkThresholdImageFilter.h"
#include "itkRescaleIntensityImageFilter.h"
```

Now we can declare the filter itself. It is within the ITK namespace, and we decide to make it use the same image type for both input and output, so that the template declaration needs only one parameter. Deriving from `ImageToImageFilter` provides default behavior for several important aspects, notably allocating the output image (and making it the same dimensions as the input).

```
namespace itk
{
    template <typename TImage>
    class CompositeExampleImageFilter : public ImageToImageFilter<TImage, TImage>
    {
    public:
        ITK_DISALLOW_COPY_AND_MOVE(CompositeExampleImageFilter);
```

Next we have the standard declarations, used for object creation with the object factory:

```
using Self = CompositeExampleImageFilter;
using Superclass = ImageToImageFilter<TImage, TImage>;
using Pointer = SmartPointer<Self>;
using ConstPointer = SmartPointer<const Self>;
```

Here we declare an alias (to save typing) for the image's pixel type, which determines the type of the threshold value. We then use the convenience macros to define the Get and Set methods for this parameter.

```
using ImageType = TImage;
using PixelType = typename ImageType::PixelType;

itkGetMacro(Threshold, PixelType);
itkSetMacro(Threshold, PixelType);
```

Now we can declare the component filter types, templated over the enclosing image type:

```
protected:
    using ThresholdType = ThresholdImageFilter<ImageType>;
    using GradientType = GradientMagnitudeImageFilter<ImageType, ImageType>;
    using RescalerType = RescaleIntensityImageFilter<ImageType, ImageType>;
```

The component filters are declared as data members, all using the smart pointer types.

```

typename GradientType::Pointer m_GradientFilter;
typename ThresholdType::Pointer m_ThresholdFilter;
typename RescalerType::Pointer m_RescaleFilter;

PixelType m_Threshold;
};

} // end namespace itk

```

The constructor sets up the pipeline, which involves creating the stages, connecting them together, and setting default parameters.

```

template <typename TImage>
CompositeExampleImageFilter<TImage>::CompositeExampleImageFilter()
{
    m_Threshold = 1;
    m_GradientFilter = GradientType::New();
    m_ThresholdFilter = ThresholdType::New();
    m_ThresholdFilter->SetInput(m_GradientFilter->GetOutput());
    m_RescaleFilter = RescalerType::New();
    m_RescaleFilter->SetInput(m_ThresholdFilter->GetOutput());
    m_RescaleFilter->SetOutputMinimum(
        NumericTraits<PixelType>::NonpositiveMin());
    m_RescaleFilter->SetOutputMaximum(NumericTraits<PixelType>::max());
}

```

The `GenerateData()` is where the composite magic happens.

First, connect the first component filter to the inputs of the composite filter (the actual input, supplied by the upstream stage). At a filter's `GenerateData()` stage, the input image's information and pixel buffer content have been updated by the pipeline. To prevent the mini-pipeline update from propagating upstream, the input image is disconnected from the pipeline by grafting its contents to a new `itk::Image` pointer.

This implies that the composite filter must implement pipeline methods that indicate the `itk::ImageRegion`'s it requires and generates, like `GenerateInputRequestedRegion()`, `GenerateOutputRequestedRegion()`, `GenerateOutputInformation()` and `EnlargeOutputRequestedRegion()`, according to the behavior of its component filters.

Next, graft the output of the last stage onto the output of the composite, which ensures the requested region is updated and the last stage populates the output buffer allocated by the composite filter. We force the composite pipeline to be processed by calling `Update()` on the final stage. Then, graft the output back onto the output of the enclosing filter, so it has the result available to the downstream filter.

```

template <typename TImage>
void
CompositeExampleImageFilter<TImage>::GenerateData()
{

```

```

    auto input = ImageType::New();
    input->Graft(const_cast<ImageType *>(this->GetInput()));
    m_GradientFilter->SetInput(input);

    m_ThresholdFilter->ThresholdBelow(this->m_Threshold);

    m_RescaleFilter->GraftOutput(this->GetOutput());
    m_RescaleFilter->Update();
    this->GraftOutput(m_RescaleFilter->GetOutput());
}

```

Finally we define the `PrintSelf` method, which (by convention) prints the filter parameters. Note how it invokes the superclass to print itself first, and also how the indentation prefixes each line.

```

template <typename TImage>
void
CompositeExampleImageFilter<TImage>::PrintSelf(std::ostream & os,
                                              Indent indent) const
{
    Superclass::PrintSelf(os, indent);

    os << indent << "Threshold: " << m_Threshold << std::endl;
}

} // end namespace itk

```

It is important to note that in the above example, none of the internal details of the pipeline were exposed to users of the class. The interface consisted of the `Threshold` parameter (which happened to change the value in the component filter) and the regular `ImageToImageFilter` interface. This example pipeline is illustrated in Figure 8.5.

HOW TO CREATE A MODULE

The Insight Toolkit is organized into logical units of coherent functionality called modules. These modules are self-contained in a directory, whose components are organized into subdirectories with standardized names. A module usually has dependencies on other modules, which it declares. A module is defined with CMake scripts that inform the build system of its contents and dependencies.

The modularization effort significantly improves the extensibility of the toolkit and lowers the barrier to contribution.

Modules are organized into:

- The **top level** directory.
- The **include** directory.
- The **src** directory.
- The **test** directory.
- The **wrapping** directory.

This chapter describes how to create a new module. The following sections are organized by the different directory components of the module. The chapter concludes with a section on how to add a third-party library dependency to a module.

Note that the Insight Toolkit community has adopted a Coding Style guideline for the sake of consistency and readability of the code. Such guideline is described in [Chapter C](#).

9.1 Name and dependencies

The top level directory of a module is used to define a module's name and its dependencies. Two files are required:

1. CMakeLists.txt
2. itk-module.cmake

The information described in these files is used to populate `<ModuleName>.cmake` files in the ITK module registry. The module registry is located at `<ITK build directory>/lib/cmake/5.4/Modules/` in a build tree or `<CMAKE_INSTALL_PREFIX>/lib/cmake/5.4/Modules/` in an install tree. These module files declare information about the module and what is required to use it. This includes its module dependencies, C++ include directories required to build against it, the libraries to link against, and CMake code required to use it in a CMake configured project.

9.1.1 CMakeLists.txt

When CMake starts processing a module, it begins with the top level `CMakeLists.txt` file. At a minimum, the `CMakeLists.txt` should contain

```
cmake_minimum_required(VERSION 3.10.2 FATAL_ERROR)
cmake_policy(VERSION 3.10.2)

project(MyModule)

set(MyModule_LIBRARIES MyModule)

if(NOT ITK_SOURCE_DIR)
    find_package(ITK REQUIRED)
    list(APPEND CMAKE_MODULE_PATH ${ITK_CMAKE_DIR})
    include(ITKModuleExternal)
else()
    itk_module_impl()
endif()
```

where `MyModule` is the name of the module.

The CMake variable `<module-name>_LIBRARIES` should be set to the names of the libraries, if any, that clients of the module need to link. This will be the same name as the library generated with the `add_library` command in a module's `src` directory, described in further detail in the Libraries Section 9.3.

The path `if(NOT ITK_SOURCE_DIR)` is used when developing a module outside of the ITK source tree, i.e. an External module. An External module can be made available to the community by adding it to `Modules/Remote/*.remote.cmake` Remote module index in the ITK repository per Section 10.1.

The CMake macro `itk_module_impl` is defined in the file `CMake/ITKModuleMacros.cmake`. It will initiate processing of the remainder of a module's CMake scripts. The script `ITKModuleExternal` calls `itk_module_impl` internally.

9.1.2 itk-module.cmake

The `itk-module.cmake` is also a required CMake script at the top level of a module, but this file is used to declare

1. The module name.
2. Dependencies on other modules.
3. Modules properties.
4. A description of the module.

In this file, first set a CMake variable with the module's description followed by a call to the `itk_module` macro, which is already defined by the time the script is read. For example, `itk-module.cmake` for the `ITKCommon` module is

```
set(DOCUMENTATION "This module contains the central classes of the ITK
toolkit. They include, basic data structures \ (such as Points, Vectors,
Images, Regions\ ) the core of the process objects \ (such as base
classes for image filters\ ) the pipeline infrastructure classes, the support
for multi-threading, and a collection of classes that isolate ITK from
platform specific features. It is anticipated that most other ITK modules will
depend on this one.")

itk_module(ITKCommon
  ENABLE_SHARED
  PRIVATE_DEPENDS
    ITKDoubleConversion
  COMPILE_DEPENDS
    ITKKWSys
    ITKVNLInstantiation
  TEST_DEPENDS
    ITKTestKernel
    ITKMesh
    ITKImageIntensity
    ITKIOImageBase
  DESCRIPTION
    "${DOCUMENTATION}"
)
```

The description for the module should be escaped as a CMake string, and it should be formatted with Doxygen markup. This description is added to ITK's generated Doxygen documentation when the module is added to the Remote module index. The description should describe the purpose and content of the module and reference an Insight Journal article for further information.

A module name is the only required positional argument to the `itk_module` macro. Named options that take one or argument are:

DEPENDS Modules that will be publicly linked to this module. The header's used are added to `include/*.{h,hxx}` files.

PRIVATE_DEPENDS Modules that will be privately linked to this module. The header's used are only added to `src/*.cxx` files.

COMPILE_DEPENDS Modules that are needed at compile time by this module. The header's used are added to `include/*{h,hxx}` files but there is not a library to link against.

TEST_DEPENDS Modules that are needed by this modules testing executables. The header's used are added to `test/*.cxx` files.

DESCRIPTION Free text description of the module.

Public dependencies are added to the module's `INTERFACE_LINK_LIBRARIES`, which is a list of transitive link dependencies. When this module is linked to by another target, the libraries listed (and recursively, their link interface libraries) will be provided to the target also. Private dependencies are linked to by this module, but not added to `INTERFACE_LINK_LIBRARIES`.

Compile Dependencies are added to CMake's list of dependencies for the current module, ensuring that they are built before the current module, but they will not be linked either publicly or privately. They are only used to support the building of the current module.

The following additional options take no arguments:

EXCLUDE_FROM_DEFAULT Exclude this module from collection of modules enabled with the `ITK_BUILD_DEFAULT_MODULES` CMake option.

ENABLE_SHARED Build this module as a shared library if the `BUILD_SHARED_LIBS` CMake option is set.

All External and Remote modules should set the `EXCLUDE_FROM_DEFAULT` option.

9.2 Headers

Headers for the module, both `*.h` declaration headers and `*.hxx` template definition headers, should be added to the `include` directory. No other explicit CMake configuration is required.

This path will automatically be added to the build include directory paths for libraries (9.3) and tests (9.4) in the module and when another module declares this module as a dependency.

When a module is installed, headers are installed into a single directory common to all ITK header files.

When `BUILD_TESTING` is enabled, a header test is automatically created. This test simply builds a simple executable that `#includes` all header files in the `include` directory. This ensures that all included headers can be found, which tests the module's dependency specification per Section 9.1.

9.3 Libraries

Libraries generated by a module are created from source files with the `.cxx` extension in a module's `src` directory. Some modules are header-only, and they will not generate any libraries; in this case, the `src` directory is omitted. When present, the `src` directory should contain a `CMakeLists.txt` file that describes how to build the library. A minimal `CMakeLists.txt` file is as follows.

```
set(AModuleName_SRCs
    itkFooClass.cxx
    itkBarClass.cxx
)

itk_module_add_library(AModuleName ${AModuleName_SRCs})
```

The `itk_module_add_library` macro will create a library with the given sources. The macro will also link the library to the libraries defined by the module dependency specification per Section 9.1. Additionally, the macro will set CMake target properties associated with the current module to the given target.

If the `ENABLE_SHARED` option is set on a module, a shared library will be generated when the CMake option `BUILD_SHARED_LIBS` is enabled. A library symbol export specification header is also generated for the module. For a module with the name `AModuleName`, the generated header will have the name `AModuleNameExport.h`. Include the export header in the module source headers, and add the export specification macro to the contained classes. The macro name in this case would be called `AModuleName_EXPORT`. For example, the file `itkFooClass.h` would contain

```
#include "AModuleNameExport.h"

namespace itk
{
    class AModuleName_EXPORT FooClass
    {
        ...
    }
```

Modules that do not build a library in their `src` directory or do not have export specifications on their class declarations should not set `ENABLE_SHARED`.

9.4 Tests

Regression tests for a module are placed in the `test` directory. This directory will contain a `CMakeLists.txt` with the CMake configuration, test sources, and optional `Input` and `Baseline` directories, which contain test input and baseline image datasets, respectively. Placement of the input and baseline image datasets within a given module directory is preferred over placement in

the general `Testing/Data` directory; this ensures that a module's data is only downloaded when the module is enabled. An exception to this rule may be widely used input datasets, such as the `cthead1.png` image.

An example CMake configuration for a test directory is shown below.

```
itk_module_test()

set(ModuleTemplateTests
  itkMinimalStandardRandomVariateGeneratorTest.cxx
  itkLogNormalDistributionImageSourceTest.cxx
)

CreateTestDriver(ModuleTemplate "${ModuleTemplate-Test_LIBRARIES}" "${ModuleTemplateTests}")

itk_add_test(NAME itkMinimalStandardRandomVariateGeneratorTest
  COMMAND ModuleTemplateTestDriver itkMinimalStandardRandomVariateGeneratorTest
)

itk_add_test(NAME itkLogNormalDistributionImageSourceTest
  COMMAND ModuleTemplateTestDriver --without-threads
  --compare
  ${ITK_TEST_OUTPUT_DIR}/itkLogNormalDistributionImageSourceTestOutput.mha
  DATA{Baseline/itkLogNormalDistributionImageSourceTestOutput.mha}
  itkLogNormalDistributionImageSourceTest
  ${ITK_TEST_OUTPUT_DIR}/itkLogNormalDistributionImageSourceTestOutput.mha
)
```

The `CMakeLists.txt` file should start with a call to the `itk_module_test` macro. Next, the test sources are listed. The naming convention for unit test files is `itk<ClassName>Test.cxx`. Each test file should be written like a command line executable, but the name of the main function should be replaced with the name of the test. The function should accept `int argc, char * argv[]` as arguments. To reduce the time required for linking and to provide baseline comparison functionality, all tests are linked to into a single test driver executable. To generate the executable, call the `CreateTestDriver` macro.

Tests are defined with the `itk_add_test` macro. This is a wrapper around the CMake `add_test` command that will resolve content links in the `DATA` macro. Testing data paths are given inside the `DATA` macro. Content link files, stored in the source code directory, are replaced by actual content files in the build directory when CMake downloads the `ITKData` target at build time. A content link file has the same name as its target, but a `.sha512` extension is added, and the `.sha512` file's contents are only the SHA512 hash of its target. Content links for data files in a Git distributed version control repository prevent repository bloat. To obtain content links, register an account at <https://data.kitware.com>. Upload images to your account's `My folders/Public` folder. Once the image has been uploaded, click on the item's link, then click the `Show info` icon. A `Download key file` icon will be available to download the content link. Place this file in the repository tree where referenced by the `DATA` macro.

When a test requires a new (or modified) input or baseline image dataset, the corresponding content

link files have to be provided as well. Image datasets provided should be kept as small as possible. As a rule of thumb, their size should be under 50 *kB*.

Test commands should call the test driver executable, followed by options for the test, followed by the test function name, followed by arguments that are passed to the test. The test driver accepts options like `--compare` (or `--compare-MD5` when using the MD5SUM hash) to compare output images to baselines or options that modify tolerances on comparisons. An exhaustive list of options is displayed in `itkTestDriverInclude.h`.

A few rules must be acknowledged to actually write a units test file `itk<ClassName>Test.cxx` for a given ITK class:

1. All class methods must be exercised.
2. Test cases with values for member variables different from the default ones should be provided. The usefulness of this rule is especially manifest for boolean members, whose value usually determines whether a large portion of code is exercised or not.
3. Test cases to reach the exception cases within the class should be provided.
4. Regression tests must be included for methods returning a value.
5. When a test detects a failure condition it must return the `EXIT_FAILURE` value; if a test exits normally, it must return the `EXIT_SUCCESS` value.

In any case, ITK provides with a number of classes and macros that ease the process of writing tests and checking the expected results. The following is an exhaustive list of such tools:

- `itkTestingMacros.h`: it contains a number of macros that allow testing of basic object properties:
 - `ITK_EXERCISE_BASIC_OBJECT_METHODS()`: verifies whether the class and superclass names provided match the RTTI, and exercises the `PrintSelf()` method. Since the `PrintSelf()` method prints all class member variables, this macro, when exercised, can identify uninitialized member variables.
 - `ITK_TEST_SET_GET_VALUE()`: once a member variable value has been set using the corresponding `Set` macro, this macro verifies that the value provided to the `Set()` method was effectively assigned to the member variable by comparing it to the value returned by the `Get()` value.
 - `ITK_TEST_SET_GET_BOOLEAN()`: exercises the `Set()/Get()`, and `On()/Off()` methods of class applied to a boolean member variable.
- `ITK_TRY_EXPECT_NO_EXCEPTION()`: exercises a method which is expected to return with no errors. It is only required for methods that are known to throw exceptions, such as I/O operations, filter updates, etc.

- `ITK_TRY_EXPECT_EXCEPTION()`: exercises a method in the hope of detecting an exception. This macro allows a test to continue its execution when setting test cases bound to hit a class' exception cases. It is only required for methods that are known to throw exceptions, such as I/O operations, filter updates, etc.
- `itkMath.h`: contains a series of static methods used for basic type comparison. Methods are available to perform fuzzy floating point equality comparison, e.g. `itk::Math::FloatAlmostEquals()`, to handle expected cross-platform differences.

A test may have some input arguments. When a test does not need any input argument (e.g., it generates a synthetic input image), the main argument names may either be omitted (`int itk<ClassName>Test( int, char* [] )`), or the `itkNotUsed` macro can be used (`int itk<ClassName>Test( int itkNotUsed( argc ), char *itkNotUsed( argv ) [] )`), to avoid compiler warnings about unused variables.

The number of input arguments provided must be checked at the beginning of the test. If a test requires a fixed number of input arguments, then the argument number check should verify the exact number of arguments.

It is essential that a test is made quantitative, i.e., the methods' returned values and the test's output must be compared to a known ground-truth. As mentioned, ITK contains a series of methods to compare basic types. ITK also provide a powerful regression tool for a test that checks the validity of a process over an image, which is the most common case in ITK. To this end, the test is expected to write its output to a file. The first time the test is run, the output is expected to be manually placed within the test module's `Baseline` folder. Hence, when `CTest` is executed, the distance between the test's output and the expected output (i.e., the baseline) is computed. If the distance is below a configurable tolerance, the regression test is marked as a success.

9.5 Wrapping

Wrapping for programming languages like Python can be added to a module through a simple configuration in the module's `wrapping` directory. While wrapping is almost entirely automatic, configuration is necessary to add two pieces of information,

1. The types with which to instantiate templated classes.
2. Class dependencies which must be wrapped before a given class.

When wrapping a class, dependencies, like the base class and other types used in the wrapped class's interface, should also be wrapped. The wrapping system will emit a warning when a base class or other required type is not already wrapped to ensure proper wrapping coverage. Since module dependencies are wrapped by the build system before the current module, class wrapping build order is already correct module-wise. However, it may be required to wrap classes within a module in a specific order; this order can be specified in the `wrapping/CMakeLists.txt` file.

Many ITK classes are templated, which allows an algorithm to be written once yet compiled into optimized binary code for numerous pixel types and spatial dimensions. When wrapping these templated classes, the template instantiations to wrap must be chosen at build time. The template that should be used are configured in a module's *.wrap files. Wrapping is configured by calling CMake macros defined in the `ITK/Wrapping/TypedefMacros.cmake` file.

9.5.1 CMakeLists.txt

The `wrapping/CMakeLists.txt` file calls three macros, and optionally set a variable, `WRAPPER__SUBMODULE_ORDER`. The following example is from the `ITKImageFilterBase` module:

```
itk_wrap_module(ITKImageFilterBase)

set(WRAPPER__SUBMODULE_ORDER
    itkRecursiveSeparableImageFilter
    itkFlatStructuringElement
    itkKernelImageFilter
    itkMovingHistogramImageFilterBase
)
itk_auto_load_submodules()
itk_end_wrap_module()
```

The `itk_wrap_module` macro takes the current module name as an argument. In some cases, classes defined in the *.wrap files within a module may depend each other. The `WRAPPER__SUBMODULE_ORDER` variable is used to declare which submodules should be wrapped first and the order they should be wrapped.

9.5.2 Class wrap files

Wrapping specification for classes is written in the module's *.wrap CMake script files. These files call wrapping CMake macros, and they specify which classes to wrap, whether smart pointer's should be wrapped for the the class, and which template instantiations to wrap for a class.

Overall toolkit class template instantiations are parameterized by the CMake build configuration variables shown in Table 9.1. The wrapping configuration refers to these settings with the shorthand values listed in the second column.

Class wrap files call sets of wrapping macros for the class to be wrapped. The macros are often called in loops over the wrapping variables to instantiate the desired types. The following example demonstrates wrapping the `itk::ImportImageFilter` class, taken from the `ITK/Modules/Core/Common/wrapping/itkImportImageFilter.wrap` file.

```
itk_wrap_class("itk::ImportImageFilter" POINTER)

foreach(d ${ITK_WRAP_IMAGE_DIMS})
```

CMake variable	Wrapping shorthand value
ITK_WRAP_IMAGE_DIMS	List of unsigned integers
ITK_WRAP_VECTOR_COMPONENTS	List of unsigned integers
ITK_WRAP_double	D
ITK_WRAP_float	F
ITK_WRAP_complex_double	CD
ITK_WRAP_complex_float	CF
ITK_WRAP_vector_double	VD
ITK_WRAP_vector_float	VF
ITK_WRAP_covariate_vector_double	CVD
ITK_WRAP_covariate_vector_float	CVF
ITK_WRAP_signed_char	SC
ITK_WRAP_signed_short	SS
ITK_WRAP_signed_long	SL
ITK_WRAP_unsigned_char	UC
ITK_WRAP_unsigned_short	US
ITK_WRAP_unsigned_long	UL
ITK_WRAP_rgb_unsigned_char	RGBUC
ITK_WRAP_rgb_unsigned_short	RGBUS
ITK_WRAP_rgba_unsigned_char	RGBAUC
ITK_WRAP_rgba_unsigned_short	RGBAUS

Table 9.1: CMake wrapping type configuration variables and their shorthand value in the wrapping configuration.

```
foreach(t ${WRAP_ITK_SCALAR})  
  itk_wrap_template("${ITKM_${t}}${d}" "${ITKT_${t}},${d}")  
endforeach()  
endforeach()  
  
itk_end_wrap_class()
```

Wrapping Variables

Instantiations for classes are determined by looping over CMake lists that collect sets of shorthand wrapping values, namely,

- ITK_WRAP_IMAGE_DIMS
- ITK_WRAP_IMAGE_DIMS_INCREMENTED
- ITK_WRAP_IMAGE_VECTOR_COMPONENTS
- ITK_WRAP_IMAGE_VECTOR_COMPONENTS_INCREMENTED
- WRAP_ITK_USIGN_INT
- WRAP_ITK_SIGN_INT
- WRAP_ITK_INT
- WRAP_ITK_REAL
- WRAP_ITK_COMPLEX_REAL
- WRAP_ITK_SCALAR
- WRAP_ITK_VECTOR_REAL
- WRAP_ITK_COV_VECTOR_REAL
- WRAP_ITK_VECTOR
- WRAP_ITK_RGB
- WRAP_ITK_RGBA

- `WRAP_ITK_COLOR`
- `WRAP_ITK_ALL_TYPES`

Templated classes are wrapped as type aliases for particular instantiations. The type aliases are named with a name mangling scheme for the template parameter types. The mangling of common types are stored in CMake variables listed in Table 9.2, Table 9.3, and Table 9.4. Mangling variables start with the prefix `ITKM_` and their corresponding C++ type variables start with the prefix `ITKT_`.

Wrapping Enumerations

Enumeration classes need to be wrapped through the class they are declared in using the `itk_wrap_simple_class`, e.g.:

```
itk_wrap_simple_class("itk::MathematicalMorphologyEnums")
```

which results in access to the class in Python as `itk.MathematicalMorphologyEnum`, its Algorithm enumeration class being accessible as `itk.MathematicalMorphologyEnums.Algorithm`, and its enum-list being accessed as `itk.MathematicalMorphologyEnums.Algorithm_BASIC`, `itk.MathematicalMorphologyEnums.Algorithm_HISTO`, etc.

Wrapping Macros

There are a number of wrapping macros called in the `wrapping/*.wrap` files. Macros are specialized for classes that use `itk::SmartPointers` and templated classes.

For non-templated classes, the `itk_wrap_simple_class` is used. This macro takes fully qualified name of the class as an argument. Lastly, the macro takes an optional argument that can have the values `POINTER`, `POINTER_WITH_CONST_POINTER`, or `POINTER_WITH_SUPERCLASS`. If this argument is passed, then the type alias `classname::Pointer`, `classname::ConstPointer`, or `classname::Superclass::Pointer` are wrapped. Thus, the wrapping configuration for `itk::Object` is

```
itk_wrap_simple_class("itk::Object" POINTER)
```

When wrapping templated classes, three or more macro calls are required. First, `itk_wrap_class` is called. Again, its arguments are the fully qualified followed by an option argument that can have the value `POINTER`, `POINTER_WITH_CONST_POINTER`, `POINTER_WITH_SUPERCLASS`, `POINTER_WITH_2_SUPERCLASSES`, `EXPLICIT_SPECIALIZATION`, `POINTER_WITH_EXPLICIT_SPECIALIZATION`, `ENUM`, or `AUTOPOINTER`. Next, a series of calls are made to macros that declare which templates to instantiate. Finally, the `itk_end_wrap_class` macro is called, which has no arguments.

	CMake Variable	Value
Mangling	ITKM_B	B
C++ Type	ITKT_B	bool
Mangling	ITKM_UC	UC
C++ Type	ITKT_UC	unsigned char
Mangling	ITKM_US	US
C++ Type	ITKT_US	unsigned short
Mangling	ITKM_UI	UI
C++ Type	ITKT_UI	unsigned integer
Mangling	ITKM_UL	UL
C++ Type	ITKT_UL	unsigned long
Mangling	ITKM_ULL	ULL
C++ Type	ITKT_ULL	unsigned long long
Mangling	ITKM_SC	SC
C++ Type	ITKT_SC	signed char
Mangling	ITKM_SS	SS
C++ Type	ITKT_SS	signed short
Mangling	ITKM_SI	SI
C++ Type	ITKT_SI	signed integer
Mangling	ITKM_SL	SL
C++ Type	ITKT_SL	signed long
Mangling	ITKM_SLL	SLL
C++ Type	ITKT_SLL	signed long long
Mangling	ITKM_F	F
C++ Type	ITKT_F	float
Mangling	ITKM_D	D
C++ Type	ITKT_D	double

Table 9.2: CMake wrapping mangling variables, their values, and the corresponding CMake C++ type variables and their values for plain old datatypes (PODS).

	CMake Variable	Value
Mangling	ITKM_C\${type}	C\${type}
C++ Type	ITKT_C\${type}	std::complex<\${type}>
Mangling	ITKM_AS\${type}	A\${type}
C++ Type	ITKT_AS\${type}	itk::Array<\${type}>
Mangling	ITKM_FA\${ITKM_- \${type}}\${dim}	FA\${ITKM_\${type}}\${dim}
C++ Type	ITKT_FA\${ITKM_- \${type}}\${dim}	itk::FixedArray<\${ITKT_\${type}}, \${dim}>
Mangling	ITKM_RGB\${dim}	RGB\${dim}
C++ Type	ITKT_RGB\${dim}	itk::RGBPixel<\${dim}>
Mangling	ITKM_RGBA\${dim}	RGBA\${dim}
C++ Type	ITKT_RGBA\${dim}	itk::RGBAPixel<\${dim}>
Mangling	ITKM_VS\${ITKM_- \${type}}\${dim}	VS\${ITKM_\${type}}\${dim}
C++ Type	ITKT_VS\${ITKM_- \${type}}\${dim}	itk::Vector<\${ITKT_\${type}}, \${dim}>
Mangling	ITKM_CV\${ITKM_- \${type}}\${dim}	CV\${ITKM_\${type}}\${dim}
C++ Type	ITKT_CV\${ITKM_- \${type}}\${dim}	itk::CovariantVector<\${ITKT_\${type}}, \${dim}>
Mangling	ITKM_VLV\${ITKM_- \${type}}\${dim}	VLV\${ITKM_\${type}}\${dim}
C++ Type	ITKT_VLV\${ITKM_- \${type}}\${dim}	itk::VariableLengthVector<\${ITKT_\${type}}, \${dim}>
Mangling	ITKM_SSRT\${ITKM_- \${type}}\${dim}	SSRT\${ITKM_\${type}}\${dim}
C++ Type	ITKT_SSRT\${ITKM_- \${type}}\${dim}	itk::SymmetricSecondRankTensor<\${ITKT_- \${type}}, \${dim}>

Table 9.3: CMake wrapping mangling variables, their values, and the corresponding CMake C++ type variables and their values for other ITK pixel types.

	CMake Variable	Value
Mangling	ITKM_OS\${dim}	OS\${dim}
C++ Type	ITKT_OS\${dim}	itk::Offset<\${dim} >
Mangling	ITKM_CIS{ITKM_ \${type}}\${dim}	CIS{ITKM_\${type}}\${dim}
C++ Type	ITKT_CIS{ITKM_ \${type}}\${dim}	itk::ContinuousIndex<\${ITKT_\${type}}, \${dim} >
Mangling	ITKM_PS{ITKM_ \${type}}\${dim}	PS{ITKM_\${type}}\${dim}
C++ Type	ITKT_PS{ITKM_ \${type}}\${dim}	itk::Point<\${ITKT_\${type}}, \${dim} >
Mangling	ITKM_IS{ITKM_ \${type}}\${dim}	IS{ITKM_\${type}}\${dim}
C++ Type	ITKT_IS{ITKM_ \${type}}\${dim}	itk::Image<\${ITKT_\${type}}, \${dim} >
Mangling	ITKM_VIS{ITKM_ \${type}}\${dim}	VIS{ITKM_\${type}}\${dim}
C++ Type	ITKT_VIS{ITKM_ \${type}}\${dim}	itk::VectorImage<\${ITKT_\${type}}, \${dim} >
Mangling	ITKM_SO\${dim}	SO\${dim}
C++ Type	ITKT_SO\${dim}	itk::SpatialObject<\${dim} >
Mangling	ITKM_SE\${dim}	SE\${dim}
C++ Type	ITKT_SE\${dim}	itk::FlatStructuringElement<\${dim} >
Mangling	ITKM_HS{ITKM_\${type}}	HS{ITKM_\${type}}
C++ Type	ITKT_HS{ITKM_\${type}}	itk::Statistics::Histogram<\${ITKT\${type}} >
Mangling	ITKM_ST	Depends on platform
C++ Type	ITKT_ST	itk::SizeValueType
Mangling	ITKM_IT	Depends on platform
C++ Type	ITKT_IT	itk::IdentifierType
Mangling	ITKM_OT	Depends on platform
C++ Type	ITKT_OT	itk::OffsetValueType

Table 9.4: CMake wrapping mangling variables, their values, and the corresponding CMake C++ type variables and their values for basic ITK types.

The most general template wrapping macro is **itk_wrap_template**. Two arguments are required. The first argument is a mangled suffix to be added to the class name, which uniquely identifies the instantiation. This argument is usually specified at least partially with `ITKM_` mangling variables. The second argument is the template instantiation in C++ form. This argument is usually specified at least partially with `ITKT_` C++ type variables. For example, wrapping for `itk::ImageSpatialObject`, which templated a dimension and pixel type, is configured as

```
itk_wrap_class("itk::ImageSpatialObject" POINTER)
# unsigned char required for the ImageMaskSpatialObject
UNIQUE(types "UC;${WRAP_ITK_SCALAR}")

foreach(d ${ITK_WRAP_IMAGE_DIMS})
  foreach(t ${types})
    itk_wrap_template("${d}${ITKM_${t}}" "${d},${ITKT_${t}}")
  endforeach()
endforeach()
itk_end_wrap_class()
```

In addition to `itk_wrap_template`, there are template wrapping macros specialized for wrapping image filters. The highest level macro is **itk_wrap_image_filter**, which is used for wrapping image filters that need one or more image parameters of the same type. This macro has two required arguments. The first argument is a semicolon delimited CMake list of pixel types. The second argument is the number of image template arguments for the filter. An optional third argument is a dimensionality condition to restrict the dimensions that the filter can be instantiated. The dimensionality condition can be a number indicating the dimension allowed, a semicolon delimited CMake list of dimensions, or a string of the form `n+`, where `n` is a number, to indicate that instantiations are allowed for dimension `n` and above. The wrapping specification for `itk::ThresholdMaximumConnectedComponentsImageFilter` is

```
itk_wrap_class("itk::ThresholdMaximumConnectedComponentsImageFilter" POINTER)
  itk_wrap_image_filter("${WRAP_ITK_INT}" 1 2+)
itk_end_wrap_class()
```

If it is desirable or required to instantiate an image filter with different image types, the **itk_wrap_image_filter_combinations** macro is applicable. This macro takes a variable number of parameters, where each parameter is a list of the possible image pixel types for the corresponding filter template parameters. A condition to restrict dimensionality may again be optionally passed as the last argument. For example, wrapping for `itk::VectorMagnitudeImageFilter` is specified with

```
itk_wrap_class("itk::VectorMagnitudeImageFilter" POINTER_WITH_SUPERCLASS)
  itk_wrap_image_filter_combinations("${WRAP_ITK_COV_VECTOR_REAL}" "${WRAP_ITK_SCALAR}")
itk_end_wrap_class()
```

The final template wrapping macro is **itk_wrap_image_filter_types**. This macro takes a variable number of arguments that should correspond to the image pixel types in the filter's template parameter list. Again, an optional dimensionality condition can be specified as the last argument. For example, wrapping for `itk::RGBToLuminanceImageFilter` is specified with


```

itk_wrap_class("itk::RGBToLuminanceImageFilter" POINTER_WITH_SUPERCLASS)
  if(ITK_WRAP_rgb_unsigned_char AND ITK_WRAP_unsigned_char)
    itk_wrap_image_filter_types(RGBUC UC)
  endif(ITK_WRAP_rgb_unsigned_char AND ITK_WRAP_unsigned_char)

  if(ITK_WRAP_rgb_unsigned_short AND ITK_WRAP_unsigned_short)
    itk_wrap_image_filter_types(RGBUS US)
  endif(ITK_WRAP_rgb_unsigned_short AND ITK_WRAP_unsigned_short)

  if(ITK_WRAP_rgba_unsigned_char AND ITK_WRAP_unsigned_char)
    itk_wrap_image_filter_types(RGBAUC UC)
  endif(ITK_WRAP_rgba_unsigned_char AND ITK_WRAP_unsigned_char)

  if(ITK_WRAP_rgba_unsigned_short AND ITK_WRAP_unsigned_short)
    itk_wrap_image_filter_types(RGBAUS US)
  endif(ITK_WRAP_rgba_unsigned_short AND ITK_WRAP_unsigned_short)
itk_end_wrap_class()

```

In some cases, it necessary to specify the headers required to build wrapping sources for a class. To specify additional headers to included in the generated wrapping C++ source, use the **itk_wrap_include** macro. This macro takes the name of the header to include, and it can be called multiple times.

By default, the class wrapping macros include a header whose filename corresponds to the name of the class to be wrapped according to ITK naming conventions. To override the default behavior, set the CMake variable `WRAPPER_AUTO_INCLUDE_HEADERS` to `OFF` before calling `itk_wrap_class`. For example,

```

set(WRAPPER_AUTO_INCLUDE_HEADERS OFF)
itk_wrap_include("itkTransformFileReader.h")
itk_wrap_class("itk::TransformFileReaderTemplate" POINTER)
  foreach(t ${WRAP_ITK_REAL})
    itk_wrap_template("${ITKM_${t}}" "${ITKT_${t}}")
  endforeach()
itk_end_wrap_class()

```

There are a number of convenience CMake macros available to manipulate lists of template parameters. These macros take the variable name to populate with their output as the first argument followed by input arguments. The **itk_wrap_filter_dims** macro will process the dimensionality condition previously described for the filter template wrapping macros. **DECREMENT**, **INCREMENT** are macros that operate on dimensions. The **INTERSECTION** macro finds the intersection of two list arguments. Finally, the **UNIQUE** macro removes duplicates from the given list.

Wrapping Tests

Wrapped classes need to be accompanied with their own test files to ensure that the classes can be instantiated correctly. Similar to regular C++ tests, the tests for wrapped classes

dwell in a `CMakeLists.txt` file inside the `wrapping/test` directory of the module of interest, e.g. `Modules/<ModuleName>/<SubModuleName>/wrapping/test/CMakeLists.txt`. The following is an example of how such file would look like for the wrapping corresponding to the `itk::ExtrapolateImageFunction` and `itk::WindowedSincInterpolateImageFunction` classes:

```
itk_python_expression_add_test(NAME itkExtrapolateImageFunctionPythonTest
    EXPRESSION "instance = itk.ExtrapolateImageFunction.New()")
itk_python_expression_add_test(NAME itkWindowedSincInterpolateImageFunctionPythonTest
    EXPRESSION "instance = itk.WindowedSincInterpolateImageFunction.New()")
```

9.5.3 Debugging Strategies

ITK wrappings allow users to make use of ITK classes in other languages for various purposes, such as relying on ITK Python wrappings to sidestep C++ compilation steps for rapid prototyping. However, this often introduces additional complexity in the process of identifying and localizing issues in C++ classes or even in the wrapping process itself. Fortunately, language-specific tools are available to assist in the debugging process. In this section we focus on strategies for investigating ITK Python code generated with SWIG.

Swig Python Architecture

ITK 5.x uses SWIG (Simplified Wrapper and Interface Generator) to distill ITK C++ classes into Python modules. This largely takes place in four distinct stages:

- `.wrap` CMake files, included in the ITK source tree in the `Wrapping` folder for each module to define class template instantiations to be wrapped. These are discussed in Section 9.5.2.
- SWIG `.cpp` source files generated at compile time at `Wrapping/Modules` under the ITK build tree. These C++ files explicitly implement the class and template instantiations defined in the class `.wrap` files in the source tree. Debug symbols will be generated for these files.
- SWIG compiled code. For Python wrappings these are generated as Python `.pyd` (Windows) or `.so` (Linux or macOS) binaries and Python `.py` modules at `Wrapping/Generators/Python/itk` in the ITK build tree.
- Additional Python configuration files are generated in the `Wrapping/Generators/Python` directory and its subdirectories. `WrapITK.pth` provides the path for a Python environment to find the ITK module, while `__init__.py` allows the module under development to be loaded correctly at runtime. `<module_name>Config.py` defines module dependencies and class template definitions, while `<module_name>_snake_case.py` maps C++-style filter pipeline executions to Pythonic snake case functions.

ITK Python pre-compiled wheels may be obtained from the PyPI package index and contain pre-compiled binaries without debugging symbols. To debug the native binaries a local build must be created as in Section 2.2 with a `Debug` or `RelWithDebInfo` CMake build configuration as described below.

```
python -m pip install itk
```

Python Runtime Tracing

ITK Python contains glue behavior to make ITK classes behave in a Pythonic manner, such as querying object attributes, joining class names to template instantiations, and more. Python-specific behavior in ITK Python may be investigated with the Python Debugger module, `pdb`.

Tracing can be performed on a function call with `pdb.run`, or by editing ITK Python files to add a `pdb.set_trace()` statement inline. In the following code snippet an image is loaded and the debugger is set up to trace through an image cast operation.

```
(venv-itk) > python
>>> import itk
>>> import pdb
>>> image = itk.imread(r'myimage.mha', pixel_type=itk.F)
>>> pdb.runeval('itk.cast_image_filter(image, ttype=[type(image), itk.Image[itk.UC, 2]])')
> <string>(1) <module>()
(Pdb)
```

At this point the debugger can step into and through Python code for translating ITK type names and getting the correct template instantiations to run the cast operation. More information on Python debugger commands can be found at <https://docs.python.org/3/library/pdb.html>.

While the Python debugger is useful, it does not allow us to examine implementation details of ITK classes in the native binary. A deeper investigation may be necessary for localizing errors in ITK classes.

C++ Runtime Tracing

As discussed in Section 9.5.3, SWIG wrapping generates C++ source files and manages the interface and ownership semantics between Python objects and C++ objects during ITK compilation. When binary debug symbols are available, a running Python process may be attached to step through ITK or ITK SWIG sources at runtime. Several steps are required to set up and execute debugging:

1. The ITK build must be configured so that debug symbols are generated. Python wrapping must also be enabled. This is accomplished by setting the CMake variables

```
CMAKE_BUILD_TYPE:STRING="RelWithDebInfo" and ITK_WRAP_PYTHON:BOOL="On".
```

Note that the "RelWithDebInfo" build type is strongly encouraged over a "Debug" build as

the former will build against a standard Python distribution. See Section 2.2 for a detailed explanation of how to build ITK locally with CMake.

2. A Python virtual environment must be appropriately configured with `WrapITK.pth` so that the ITK debug build can be imported. See Section 3.7 for further explanation.
3. The ITK modules to be debugged must be loaded in a new Python session initialized from the given virtual environment. Given that ITK Python uses lazy loading, it is pragmatic to use `itk.force_load()` to ensure that all possible debug symbols are made available. The `os` module can be used to identify the PID of the given session.

```
(venv-itk) > python
>>> import itk
>>> itk.force_load()
>>> import os
>>> os.getpid()
99999
```

4. The Python session may be attached to a debugger using the returned PID.

- On a Windows operating system, Microsoft Visual Studio 2019 or a similar platform can be used for attaching to a running process for debugging. Select "Attach To Process" from the Debug menu, choose "Native" code, and then search for the process PID. If debug symbols were generated correctly then ITK modules will appear under the list of loaded modules.

In Visual Studio, debugging can be enabled right from the start if the Python script is loaded into Visual Studio as part of a "Python Project". Mixed mode debugging needs to be enabled, as per Visual Studio documentation¹. Starting a project like this is an order of magnitude slower, as many debug symbols need to be loaded and examined.

- On a Linux operating system the GNU Project Debugger `gdb` can be used for attaching to a running Python process, reading symbol files, and setting breakpoints. The following example attaches to a running process and sets a breakpoint inside an `itk.Image` Python object. It may be necessary to elevate user permissions to allow `gdb` to attach to the running process.

```
(venv-itk) > gdb
(gdb) > attach 99999
Reading symbols from
/path/to/ITK-build/Wrapping/Generators/Python/itk/_ITKPyBasePython.so...
Reading symbols from
/path/to/ITK-build/Wrapping/Generators/Python/itk/_ITKCommonPython.so...
(gdb) > break /path/to/ITK-build/Wrapping/Modules/ITKCommon/itkImagePython.cpp:<ln>
Breakpoint 1 at ...:
file /path/to/ITK-build/Wrapping/Modules/ITKCommon/itkImagePython.cpp, line <ln>.
(gdb) > break /path/to/ITK-source/Core/Common/include/itkImage.hxx:<ln>
Breakpoint 2 at ...:
/path/to/ITK-source/Modules/Core/Common/include/itkImage.hxx:<ln>
```

¹<https://docs.microsoft.com/en-us/visualstudio/python/debugging-mixed-mode-c-cpp-python-in-visual-studio>

```
(gdb) > c
... continue in Python session until breakpoint is hit ...
```

- On a macOS operating system the LLDB debugger can be used for attaching to a Python process in much the same way as GDB on Linux, with a few extra security requirements and slightly different command syntax. The following example attaches to a running process and sets a breakpoint inside an `itk.Image` Python object.

```
(venv-itk) > lldb
(lldb) process attach -- pid 99999
Process 99999 stopped
* thread #1, queue = 'com.apple.main-thread', stop reason = signal SIGSTOP
  frame #0: 0x00007fff203ec656 libsystem_kernel.dylib`__select:
libsystem_kernel.dylib`__select:
-> 0x7fff203ec656 <+10>: jae      0x7fff203ec660          ; <+20>
    0x7fff203ec658 <+12>: movq    %rax, %rdi
    0x7fff203ec65b <+15>: jmp     0x7fff203e56bd          ; cerror
    0x7fff203ec660 <+20>: retq
Target 0: (Python) stopped.

Executable module set to
"/Library/Frameworks/Python.framework/Versions/3.9/
Resources/Python.app/Contents/MacOS/Python".
Architecture set to: x86_64h-apple-macosx-.

(lldb) breakpoint set
-f /path/to/ITK/Modules/Core/Common/include/itkImage.hxx
--line <ln>
Breakpoint 1: 172 locations.
(lldb) continue
... continue in Python session until breakpoint is hit ...
```

LLDB command syntax is documented at <https://lldb.llvm.org/index.html>.

Developers may find it necessary to examine the follow security concepts and requirements in order to permit lldb to attach to Python:

- The Python process must be authorized for debugging. MacOS relies on the process of “hardened” runtimes to mitigate security concerns, which reduces the ability of debuggers such as lldb and other processes to attach to and intercept the functions of other programs. Python distributions are intentionally “hardened” in this way, but additional settings can be enabled to allow just-in-time debugging.
- It may be necessary to enter developer mode to allow Python debugging. This is accomplished with the following command in the developer console:

```
DevToolsSecurity -enable
```

- It may be necessary to add entitlements to the Python executable so that lldb can attach to the hardened process. This may be accomplished by updating a .plist entitlements file and setting the executable entitlements.

```
codesign -d --entitlements :-
"/path/to/python" >> "/tmp/path/to/python_entitlements.plist"
```

```

/usr/libexec/PlistBuddy -c
  "Add :com.apple.security.get-task-allow bool true"
  "/tmp/path/to/python_entitlements.plist"
/usr/libexec/PlistBuddy -c
  "Add :com.apple.security.cs.allow-jit bool true"
  "/tmp/path/to/python_entitlements.plist"
codesign --force --options runtime --sign -
  --entitlements "/tmp/path/to/python_entitlements.plist"
  "/path/to/python"

```

- If attaching to the process continues to fail, log files can be dumped with `log collect` and opened in the Console application. `lldb` error messages will be listed as `debugserver` entries.

With these steps completed the respective debugger can be used to set breakpoints and step through C++ source code for a respective ITK Python execution.

The debugger can also be used for examining runtime failures and crashes either at the time the error occurs or posthumously with a dump file.

- On Windows, Microsoft Visual Studio will catch process aborts to allow the attached process to be examined before exit. Stacks, threads, and variables are made available to the user for backtracing via the Debug toolbar menu. Dump files in the minidump format may also be manually saved and reloaded later for investigation².
- On Linux, `gdb` will catch process aborts at runtime to allow a developer to examine the program state before it exits. If allowed, core dumps can also be generated on program failures to allow posthumous debugging. The following sample configures a Linux system to remove the default limit of 0 for allowable coredump size and to write out coredump files to the `/tmp/` directory.

```

> ulimit -c unlimited
> sudo bash -c 'echo "/tmp/coredump-%e.%p" > /proc/sys/kernel/core_pattern'

```

More information is available in Python documentation³.

- On MacOS, `lldb` will catch process aborts at runtime and may also be used to examine core dumps. The following sample configures a MacOS system to write out core dump files to the `/cores/` directory and then runs `lldb` to inspect a core dump.

```

(venv-itk) > ulimit -c unlimited

... Run process and generate a core dump ...

(venv-itk) > lldb
(lldb) target create "python3" --core "/cores/core.1007"
Core file '/cores/core.1007' (x86_64) was loaded.

```

²<https://docs.microsoft.com/en-us/visualstudio/debugger/using-dump-files?view=vs-2022>

³https://pythondevs.readthedocs.io/debug_tools.html#create-a-core-dump-file

9.6 Third-Party Dependencies

When an ITK module depends on another ITK module, it simply lists its dependencies as described in Section 9.1. A module can also depend on non-ITK third-party libraries. This third-party library can be encapsulated in an ITK module – see examples in the `ITK/Modules/ThirdParty` directory. Or, the dependency can be built or installed on the system and found with CMake. This section describes how to add the CMake configuration to a module for it to find and use a third-party library dependency.

9.6.1 itk-module-init.cmake

The `itk-module-init.cmake` file, if present, is found in the top level directory of the module next to the `itk-module.cmake` file. This file informs CMake of the build configuration and location of the third-party dependency. To inform CMake about the OpenCV library, use the `find_package` command,

```
find_package(OpenCV REQUIRED)
```

9.6.2 CMakeList.txt

A few additions are required to the top level `CMakeLists.txt` of the module.

First, the `itk-module-init.cmake` file should be explicitly included when building the module externally against an existing ITK build tree.

```
if(NOT ITK_SOURCE_DIR)
    include(itk-module-init.cmake)
endif()
project(ITKVideoBridgeOpenCV)
```

Optionally, the dependency libraries are added to the `<module-name>_LIBRARIES` variable. Alternatively, if the module creates a library, publicly link to the dependency libraries. Our `ITKVideoBridgeOpenCV` module example creates its own library, named `ITKVideoBridgeOpenCV`, and publicly link to the OpenCV libraries.

`CMakeLists.txt`:

```
set(ITKVideoBridgeOpenCV_LIBRARIES ITKVideoBridgeOpenCV)
```

`src/CMakeLists.txt`:

```
target_link_libraries(ITKVideoBridgeOpenCV LINK_PUBLIC ${OpenCV_LIBS})
```

Next, CMake export code is created. This code is loaded by CMake when another project uses this module. The export code stores where the dependency was located when the module was built, and how CMake should find it. Two versions are required for the build tree and for the install tree.

```
# When this module is loaded by an app, load OpenCV too.
set(ITKVideoBridgeOpenCV_EXPORT_CODE_INSTALL "
set(OpenCV_DIR "${OpenCV_DIR}")
find_package(OpenCV REQUIRED)
")
set(ITKVideoBridgeOpenCV_EXPORT_CODE_BUILD "
if(NOT ITK_BINARY_DIR)
  set(OpenCV_DIR "${OpenCV_DIR}")
  find_package(OpenCV REQUIRED)
endif()
")
```

Finally, set the `<module-name>_SYSTEM_INCLUDE_DIRS` and `<module-name>_SYSTEM_LIBRARY_DIRS`, if required, to append compilation header directories and library linking directories for this module.

```
set(ITKVideoBridgeOpenCV_SYSTEM_INCLUDE_DIRS ${OpenCV_INCLUDE_DIRS})
set(ITKVideoBridgeOpenCV_SYSTEM_LIBRARY_DIRS ${OpenCV_LIB_DIRS})
```

9.7 Contributing with a Remote Module

For most ITK community members, the modularization of the toolkit is relatively transparent. The default configuration includes all the (default) modules into the ITK library, which is used to build their own ITK applications.

For ITK developers and code contributors, the modular structure imposes rules for organizing the source code, building the library and contributing to the ITK source code repository.

A Module may be developed outside the main ITK repository, but it may be made available in the ITK repository as a Remote Module. The Remote Module infrastructure enables fast dissemination of research code through ITK without increasing the size of the main repository. The Insight Journal (<https://www.insight-journal.org/>) adds support for ITK module submissions with automatic dashboard testing (see Section 10.2 on page 228 for further details).

The source code of a Remote Module can be downloaded by CMake (with a CMake variable switch) at ITK CMake configuration time, making it a convenient way to distribute modular source code.

9.7.1 Policy for Adding and Removing Remote Modules

A module can be added to the list of remotes if it satisfies the following criteria:

- There is a peer-reviewed article in an online, open access journal (such as the Insight Journal) describing the theory behind and usage of the module.
- There is a nightly build against ITK master on the CDash dashboard that builds and passes tests successfully.
- A name and contact email exists for the dashboard build. The maintainer of the dashboard build does not necessarily need to be the original author of the Insight Journal article.
- The license should be compatible with the rest of the toolkit. That is it should be an Open Source Initiative-approved license⁴ without copyleft or non-commercial restrictions. Ideally, it should be an Apache 2.0 license assigned to NumFOCUS as found in the rest of the toolkit. Note that the module should contain neither patented code, nor algorithms, nor methods.

At the beginning of the release candidate phase of a release, maintainers of failing module dashboard builds will be contacted. If a module's dashboard submission is still failing at the last release candidate tagging, it will be removed before the final release.

Module names must be **unique**.

At no time in the future should a module in the main repository depend on a Remote Module.

9.7.2 Procedure for Adding a Remote Module

The repository

<https://github.com/InsightSoftwareConsortium/ITKModuleTemplate>

provides a useful template to be used as a starting point for a new ITK module.

The procedure to publish a new module in ITK is summarized as follows:

1. Publish an open access article describing the module in an online, open access journal like The Insight Journal.
2. Push a topic to the ITK GitHub repository (see Section 10.1 on page 227 that adds a file named `Modules/Remote/<module name>.remote.cmake`. This file must have the following:
 - (a) Dashboard maintainer name and email in the comments.
 - (b) A call to the `itk_fetch_module` CMake function (documented in `CMake/ITKModuleRemote.cmake`) whose arguments are:
 - i. The name of the remote module. Note that in each `<remote module name>.remote.cmake`, the first argument of the function `itk_fetch_module()`

⁴<https://opensource.org/licenses>

is the name of the remote module, and it has to be consistent with the module name defined in the corresponding `<remote module name>.remote.cmake`. To better distinguish the remote modules from the internal ITK modules, the names of the remote modules should **NOT** contain the “ITK” string prefix.

- ii. A short description of the module with the handle to the open access article.
- iii. URLs describing the location and version of the code to download. The version should be a specific hash.

After the Remote Module has experienced sufficient testing, and community members express broad interest in the contribution, the submitter can then move the contribution into the ITK repository via GitHub code review.

It is possible but not recommended to directly push a module to GitHub for review without submitting to Insight Journal first.

SOFTWARE PROCESS

An outstanding feature of ITK is the software process used to develop, maintain and test the toolkit. The Insight Toolkit software continues to evolve rapidly due to the efforts of developers and users located around the world, so the software process is essential to maintaining its quality. If you are planning to contribute to ITK, or use the Git source code repository, you need to know something about this process (see 2.1 on page 10 to learn more about obtaining ITK using Git). This information will help you know when and how to update and work with the software as it changes. The following sections describe key elements of the process.

10.1 Git Source Code Repository

Git¹<https://git-scm.com/> is a tool for version control. It is a valuable resource for software projects involving multiple developers. The primary purpose of Git is to keep track of changes to software. Git date and version stamps every addition to files in the repository. Additionally, a user may set a tag to mark a particular of the whole software. Thus, it is possible to return to a particular state or point of time whenever desired. The differences between any two points is represented by a “diff” file, that is a compact, incremental representation of change. Git supports concurrent development so that two developers can edit the same file at the same time, that are then (usually) merged together without incident (and marked if there is a conflict). In addition, branches off of the main development trunk provide parallel development of software.

Developers and users can check out the software from the Git repository. When developers introduce changes in the system, Git facilitates to update the local copies of other developers and users by downloading only the differences between their local copy and the version on the repository. This is an important advantage for those who are interested in keeping up to date with the leading edge of the toolkit. Bug fixes can be obtained in this way as soon as they have been checked into the system.

ITK source code, data, and examples are maintained in a Git repository. The principal advantage of a system like Git is that it frees developers to try new ideas and introduce changes without fear of

¹[\unskip\protect\penalty\@M\vrulewidth\z@height\z@depth\dpff](https://git-scm.com/)

losing a previous working version of the software. It also provides a simple way to incrementally update code as new features are added to the repository.

The ITK community use Git, and the social coding web platform, GitHub (<https://github.com/InsightSoftwareConsortium>), to facilitate a structured, orderly method for developers to contribute new code and bug fixes to ITK. The GitHub review process allows anyone to submit a proposed change to ITK, after which it will be reviewed by other developers before being approved and merged into ITK. For more information on how to contribute, please visit <https://github.com/InsightSoftwareConsortium/ITK/blob/master/CONTRIBUTING.md>. For information about the Git-based development workflow adopted by ITK, see the Appendix B on page 259.

10.2 CDash Regression Testing System

One of the unique features of the ITK software process is its use of the CDash regression testing system (<https://www.cdash.org>). In a nutshell, what CDash does is to provide quantifiable feedback to developers as they check in new code and make changes. The feedback consists of the results of a variety of tests, and the results are posted on a publicly-accessible Web page (to which we refer as a *dashboard*) as shown in Figure 10.1. The most recent dashboard is accessible from <https://www.itk.org/ITK/resources/testing.html>). Since all users and developers of ITK can view the Web page, the CDash dashboard serves as a vehicle for developer communication, especially when new additions to the software is found to be faulty. The dashboard should be consulted before considering updating software via Git.

Note that CDash is independent of ITK and can be used to manage quality control for any software project. It is itself an open-source package and can be obtained from

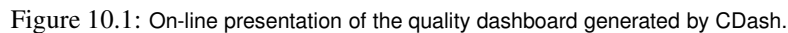
<https://www.cdash.org>

CDash supports a variety of test types. These include the following.

Compilation. All source and test code is compiled and linked. Any resulting errors and warnings are reported on the dashboard.

Regression. Some ITK tests produce images as output. Testing requires comparing each test's output against a valid baseline image. If the images match then the test passes. The comparison must be performed carefully since many 3D graphics systems (e.g., OpenGL) produce slightly different results on different platforms.

Memory. Problems relating to memory such as leaks, uninitialized memory reads, and reads/ writes beyond allocated space can cause unexpected results and program crashes. ITK checks runtime memory access and management using Purify, a commercial package produced by Rational. (Other memory checking programs will be added in the future.)



Coverage. There is a saying among ITK developers: *If it isn't covered, then it's broke*. What this means is that code that is not executed during testing is likely to be wrong. The coverage tests identify lines that are not executed in the Insight Toolkit test suite, reporting a total percentage covered at the end of the test. While it is nearly impossible to bring the coverage to 100% because of error handling code and similar constructs that are rarely encountered in practice, the coverage numbers should be 75% or higher. Code that is not covered well enough requires additional tests.

When a user or developer decides to update ITK source code from Git it is important to first verify that the current dashboard is in good shape. This can be rapidly judged by the general coloration of the dashboard. A green state means that the software is building correctly and it is a good day to

start with ITK or to get an upgrade. A red state, on the other hand, is an indication of instability on the system and hence users should refrain from checking out or upgrading the source code.

Another nice feature of CDash is that it maintains a history of changes to the source code (by coordinating with Git) and summarizes the changes as part of the dashboard. This is useful for tracking problems and keeping up to date with new additions to ITK.

10.2.1 Developing tests

As highlighted, testing is an essential part of ITK. Regression testing on a regular basis allows ITK to meet high code quality standards, and to enable reproducible research. Code coverage reported daily in CDash allows us to systematically measure the degree to which the ITK source code is reliable. Therefore, writing tests, and improving current tests and the testing infrastructure is crucial to ITK.

There are a number of scenarios when writing tests:

- **Modifying existing classes.** When modifying an existing class (either due to a bug or a performance improvement), it must be checked that existing tests exercise the new code. Otherwise, either the existing tests should be modified to include the appropriate cases for the new code to be exercised (without harm to existing cases), or a new test file may be required.
- **Contributing new classes.** When contributing a new class, a unit test or a few unit tests should be provided to check that the class is working as expected. The unit tests are expected to exercise all of the members of the new class.

In either case, the tips and tools described in Section 9.4 were developed to improve and facilitate the process.

10.3 Working The Process

The ITK software process functions across three cycles—the continuous cycle, the daily cycle, and the release cycle.

The continuous cycle revolves around the actions of developers as they check code into Git. When changed or new code is checked into Git, the CDash continuous testing process kicks in. A small number of tests are performed (including compilation), and if something breaks, email is sent to all developers who checked code in during the continuous cycle. Developers are expected to fix the problem immediately.

The daily cycle occurs over a 24-hour period. Changes to the source base made during the day are extensively tested by the nightly CDash regression testing sequence. These tests occur on different combinations of computers and operating systems located around the world, and the results are

posted every day to the CDash dashboard. Developers who checked in code are expected to visit the dashboard and ensure their changes are acceptable—that is, they do not introduce compilation errors or warnings, or break any other tests including regression, memory, `PrintSelf`, and `Set/Get`. Again, developers are expected to fix problems immediately.

The release cycle occurs a small number of times a year. This requires tagging and branching the Git repository, updating documentation, and producing new release packages. Although additional testing is performed to insure the consistency of the package, keeping the daily Git build error free minimizes the work required to cut a release.

ITK users typically work with releases, since they are the most stable. Developers work with the Git repository, or sometimes with periodic release snapshots, in order to take advantage of newly-added features. It is extremely important that developers watch the dashboard carefully, and *update their software only when the dashboard is in good condition (i.e., is “green”)*. Failure to do so can cause significant disruption if a particular day’s software release is unstable.

10.4 The Effectiveness of the Process

The effectiveness of this process is profound. By providing immediate feedback to developers through email and Web pages (e.g., the dashboard), the quality of ITK is exceptionally high, especially considering the complexity of the algorithms and system. Errors, when accidentally introduced, are caught quickly, as compared to catching them at the point of release. To wait to the point of release is to wait too long, since the causal relationship between a code change or addition and a bug is lost. The process is so powerful that it routinely catches errors in vendor’s graphics drivers (e.g., OpenGL drivers) or changes to external subsystems such as the VXL/VNL numerics library. All of these tools that make up the process (CMake, Git, and CDash) are open-source. Many large and small systems such as VTK (The Visualization Toolkit <https://www.vtk.org>) use the same process with similar results. We encourage the adoption of the process in your environment.

Appendices

LICENSES

A.1 Insight Toolkit License

Apache License
Version 2.0, January 2004
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A.2 Third Party Licenses

The Insight Toolkit bundles a number of third party libraries that are used internally. The licenses of these libraries are as follows.

A.2.1 DICOM Parser

```
/*=====
```

```
Program:  DICOMParser
Module:   Copyright.txt
Language: C++
```

```
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```

```
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```

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A.2.4 GDCM

```
/*=====
```

```
Program: GDCM (Grassroots DICOM). A DICOM library
```

```
Copyright (c) 2006-2016 Mathieu Malaterre
```

```
Copyright (c) 1993-2005 CREATIS
```

```
(CREATIS = Centre de Recherche et d'Applications en Traitement de l'Image)
```

```
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```

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=====*/

A.2.5 GIFTI

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Author: Richard Reynolds, SSCC, DIRP, NIMH, National Institutes of Health
May 13, 2008 (release version 1.0.0)

<http://www.nitrc.org/projects/gifti>

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A.2.9 MetaIO

MetaIO - Medical Image I/O

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/*=====

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```
=====*/
/*=====
```

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A.2.11 NIFTI

Niftilib has been developed by members of the NIFTI DFWG and volunteers in the neuroimaging community and serves as a reference implementation of the nifti-1 file format.

<http://nifti.nimh.nih.gov/>

Nifticlib code is released into the public domain, developers are encouraged to incorporate niftilib code into their applications, and, to contribute changes and enhancements to niftilib.

A.2.12 NrrdIO

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** above applies to only the source files in the NrrdIO distribution, and not
** to Teem.

NrrdIO is a modified and highly abbreviated version of the Teem. NrrdIO contains only the source files (or portions thereof) required for creating and destroying nrrds, and for getting them into and out of files. The NrrdIO sources are created from the Teem sources by using GNU Make (pre-GNUMakefile in the NrrdIO distribution).

NrrdIO makes it very easy to add support for the NRRD file format to your program, which is a good thing considering the design and flexibility of the NRRD file format, and the existence of the "unu" command-line tool for operating on nrrds. Using NrrdIO requires exactly one header file, "NrrdIO.h", and exactly one library, libNrrdIO.

Currently, the API presented by NrrdIO is a strict subset of the Teem API. There is no additional encapsulation or abstraction. This could be annoying in the sense that you still have to deal with the biff (for error messages) and the air (for utilities) library function calls. Or it could be good and sane in the sense that code which uses NrrdIO can be painlessly "upgraded" to use more of Teem. Also, the API documentation for the same functionality in Teem will apply directly to NrrdIO.

NrrdIO was originally created with the help of Josh Cates in order to add support for the NRRD file format to the Insight Toolkit (ITK).

NrrdIO API crash course -----

Please read <<http://teem.sourceforge.net/nrrd/lib.html>>. The functions that are explained in detail are all present in NrrdIO. Be aware, however, that NrrdIO currently supports ONLY the NRRD file format, and not: PNG, PNM, VTK, or EPS.

The functionality in Teem's nrrd library which is NOT in NrrdIO is basically all those non-trivial manipulations of the values in the nrrd, or their ordering in memory. Still, NrrdIO can do a fair amount, namely all the functions listed in these sections of the "Overview of rest of API" in the above web page:

- Basic "methods"
- Manipulation of per-axis meta-information
- Utility functions
- Comments in nrrd

- Key/value pairs
- Endianness (byte ordering)
- Getting/Setting values (crude!)
- Input from, Output to files

Files comprising NrrdIO -----

NrrdIO.h: The single header file that declares all the functions and variables that NrrdIO provides.

sampleIO.c: Tiny little command-line program demonstrating the basic NrrdIO API. Read this for examples of how NrrdIO is used to read and write NRRD files.

CMakeLists.txt: to build NrrdIO with CMake

pre-GNUMakefile: how NrrdIO sources are created from the Teem sources. Requires that TEEM_SRC_ROOT be set, and uses the following two files.

tail.pl, unteem.pl: used to make small modifications to the source files to convert them from Teem to NrrdIO sources

mangle.pl: used to generate a #include file for name-mangling the external symbols in the NrrdIO library, to avoid possible problems with programs that link with both NrrdIO and the rest of Teem.

preamble.c: the preamble describing the non-copyleft licensing of NrrdIO.

qnanhibit.c: discover a variable which, like endianness, is architecture dependent and which is required for building NrrdIO (as well as Teem), but unlike endianness, is completely obscure and unheard of.

encodingBzip2.c, formatEPS.c, formatPNG.c, formatPNM.c, formatText.c, formatVTK.c: These files create stubs for functionality which is fully present in Teem, but which has been removed from NrrdIO in the interest of simplicity. The filenames are in fact unfortunately misleading, but they should be understood as listing the functionality that is MISSING in NrrdIO.

All other files: copied/modified from the air, biff, and nrrd libraries of Teem.

A.2.13 OpenJPEG

```
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 */
```

A.2.14 PNG

A.2.15 TIFF

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A.2.16 VNL

```
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#define vxl_copyright_h_
```

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// STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE)
// ARISING IN ANY WAY OUT OF THE USE OF THIS SOFTWARE, EVEN IF ADVISED
// OF THE POSSIBILITY OF SUCH DAMAGE.

#endif // vx1_copyright_h_
```

A.2.17 ZLIB

Acknowledgments:

The deflate format used by zlib was defined by Phil Katz. The deflate and zlib specifications were written by L. Peter Deutsch. Thanks to all the people who reported problems and suggested various improvements in zlib; they are too numerous to cite here.

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If you use the zlib library in a product, we would appreciate *not* receiving lengthy legal documents to sign. The sources are provided for free but without warranty of any kind. The library has been entirely written by Jean-loup Gailly and Mark Adler; it does not include third-party code.

If you redistribute modified sources, we would appreciate that you include in the file ChangeLog history information documenting your changes. Please read the FAQ for more information on the distribution of modified source versions.

ITK GIT WORKFLOW

This chapter describes the workflow adopted by the ITK community to develop the software. The adopted Git-based **branchy workflow** is an efficient and flexible model to develop modern software.

B.1 Git Setup

Visit the main [Git download site](#), and depending on your operating system, follow the guidelines.

B.1.1 Windows

Git comes in two flavors on Windows:

- A Windows native application installer
- A Cygwin package

Choose one and stick with it. They do not get along well in a given work tree on disk (the repository formats are compatible but the “stat cache” of the work tree is not unless `core.filemode` is false).

Git for Windows

Download the “git for windows” executable from the [git for windows](#) site. You want to download the file that is named something like

```
Git-2.14.2.2-64-bit.exe
```

Note that the filename changes as new versions are released.

Run the installer. When prompted, choose to not modify the `PATH` and choose the `core.autocrlf=true` option. Launch the Git Bash tool to get a command line shell with Git.

Cygwin

Install the following packages:

- **git**: Git command-line tool
- **gitk**: Graphical history browser
- **git-completion**: Bash shell completion rules

Launch a Cygwin command prompt to get a command line shell with Git.

B.1.2 macOS

Xcode 4

If you have Xcode 4 installed, you already have git installed.

Verify with:

```
which git
/usr/bin/git
```

```
git --version
git version 1.7.4.4
```

OS X Installer

Download an installer from code.google.com.

MacPorts

Enter these commands:

```
sudo port selfupdate
sudo port install git-core +doc
```

B.1.3 Linux

Popular Linux distributions already come with packages for Git. Typically the packages are called:

- **git-core**: Git command-line tool
- **git-doc**: Git documentation
- **gitk**: Graphical history browser

B.2 Workflow

B.2.1 A Primer

This primer details a possible workflow for using Git and ITK. There are many ways to use Git and it is a very flexible tool. This page details my particular way of working with Git, and is certainly not the last word. It is also rambling collection of tips and experiences that I’ve picked up in the last few years of using Git.

It is worth trying to explain some high-level Git concepts. A [feature](#) (or a [bug](#)) that sets Git apart from Subversion is its distributed nature. In practice, that means that ITK needs to “bless” a repository for it to be the “official” source of ITK. This has already been done at the [ITK GitHub repository](#).

Another Git concept is that of a **commit**. Git uses a [SHA1 hash](#) to uniquely identify a change set. The hash is (almost) guaranteed to be unique across your project, and even across all projects everywhere and for all time.

Quoting from the excellent Pro Git book¹:

A lot of people become concerned at some point that they will, by random happenstance, have two objects in their repository that hash to the same SHA-1 value. What then?

If you do happen to commit an object that hashes to the same SHA-1 value as a previous object in your repository, Git will see the previous object already in your Git database and assume it was already written. If you try to check out that object again at some point, you’ll always get the data of the first object.

However, you should be aware of how ridiculously unlikely this scenario is. The SHA-1 digest is 20 bytes or 160 bits. The number of randomly hashed objects needed to ensure a 50% probability of a single collision is about 2^{80} (the formula for determining collision probability is $p = (n(n-1)/2) * (1/2^{160})$). 2^{80} is 1.2×10^{24} or 1 million billion billion. That’s 1,200 times the number of grains of sand on the earth.

¹<https://git-scm.com/book/en/v2>

Here's an example to give you an idea of what it would take to get a SHA-1 collision. If all 6.5 billion humans on Earth were programming, and every second, each one was producing code that was the equivalent of the entire Linux kernel history (1 million Git objects) and pushing it into one enormous Git repository, it would take 5 years until that repository contained enough objects to have a 50% probability of a single SHA-1 object collision. A higher probability exists that every member of your programming team will be attacked and killed by wolves in unrelated incidents on the same night.

B.2.2 A Topic

This workflow is based on the branchy development workflow documented by [Git help workflows](#).

Motivation

The primary goal of this workflow is to make release preparation and maintenance easier. We set the following requirements, of which some are themselves worthwhile goals:

- Amortize the effort of release preparation throughout development.
- Support granular selection of features for release.
- Allow immature features to be published without delaying release.
- **Keep unrelated development paths (topics) independent of one another.**
- Maintain a clean shape of history (see Section [B.2.2](#) on page [273](#)).

Design

The design of this workflow is based on the observation that meeting the highlighted goal makes the other goals easy. It is based on branchy development in which each branch has a well-defined purpose.

We define two branch types:

- **Topic Branch**
 - Commits represent **changes** (real work)
 - Distinguished by **feature** (one topic per feature or fix)
 - Named locally by each developer (describe purpose of work)
 - Heads not published (no named branch on server)
- **Integration Branch**

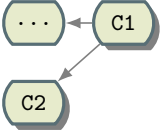
Meaning	Symbol
Branch name	
Current branch	
Commit with parent in same branch	
Commit with two parents (merge)	

Table B.1: Git graphs notation.

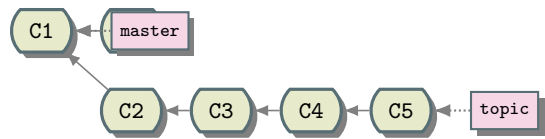


Figure B.1: Topic branch.

- Commits represent **merges** (merge topics together)
- Distinguished by **stability** (release maintenance, release preparation, development edge)
- Named everywhere
- Heads published on server

Notation

This chapter uses Git Directed Acyclic Graphs (DAG) to depict commit history:

Topic branches generally consist of a linear sequence of commits forked off an integration branch:

Integration branches generally consist of a sequence of merge commits:

Published Branches

We publish an *integration* branch for each stage of development:

- **release**: Release maintenance (high stability). Only bug fixes should be published here. Only the release manager can push here.

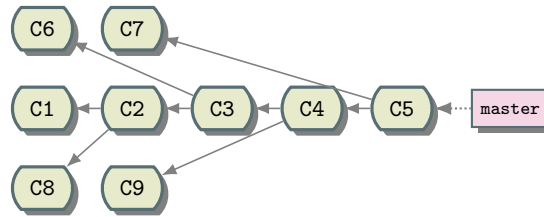


Figure B.2: Merge commits into the `master` branch.

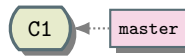


Figure B.3: Locate at `master`.

- **master**: Release preparation (medium stability). Only mature features and bug fixes should be published here.

Topic branches are not published directly; their names exist only in each developer's local repositories.

Development

We cover below the steps to take during each phase of development.

Initial Setup These instructions generally provide all arguments to `git push` commands. Some people prefer to use `git push` with no additional arguments to push the current tracking branch. Run the command

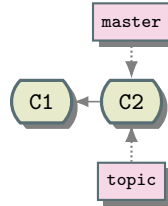
```
git config --global push.default tracking
```

to establish this behavior. See the [git config](#) man-page for details.

New Topic Create a new topic branch for each separate feature or bug fix. Always start the topic from a stable integration branch, usually **master**. If the topic fixes a bug in the current release, use **release**. In the following section we review the steps and commands to create, develop, and publish a topic branch based on **master**.

Update master to base work on the most recently integrated features.

```
git checkout master
```


Figure B.4: Bring most recent changes to `master`.Figure B.5: Create a local `topic` branch.

```
git pull
```

Create the local topic branch. Use a meaningful name for *topic* (see Section B.2.2 on page 276).

```
git checkout -b topic
```

This is where the real work happens. Edit, stage, and commit files repeatedly as needed for your work.

During this step, avoid the B.2.2 from an integration branch. Keep your commits focused on the topic at hand.

```
edit files
git add -- files
git commit
```

```
edit files
git add -- files
git commit
```

When the topic is ready for publication it must be merged into **master**. It should be the current local branch when you merge.

Switch to **master** and update it.

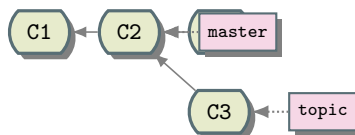


Figure B.6: Commit changes.

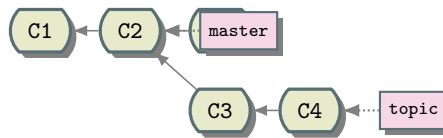
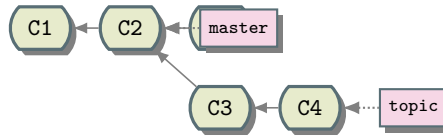


Figure B.7: Commit last changes.

Figure B.8: Checkout *master* and pull changes.

```
git checkout master
git pull
```

Merge the topic and test it.

```
git merge topic
```

See Section B.2.2 on page 287 to resolve any conflict that may arise when merging.

Finally, publish the change.

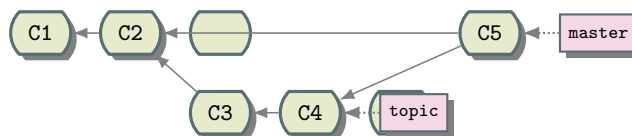
```
git push origin master
```

See Section B.2.2 on page 277 and Section B.2.2 on page 278 to resolve any conflict that may arise when publishing the change.

Mature Topic When a topic is ready for inclusion in the next release, we merge it into **master**.

Update **master** to get the latest work by others. We will merge the *topic* branch into it.

```
git checkout master
```

Figure B.9: Merge *topic* branch into *master*.

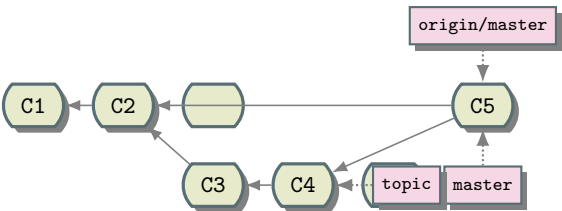


Figure B.10: Publish the change.

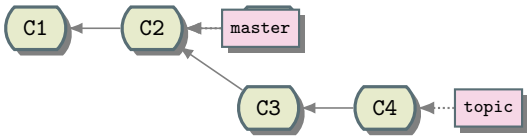


Figure B.11: Checkout master.

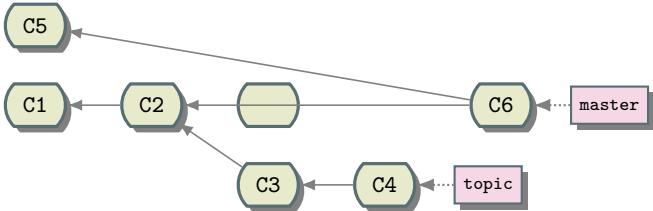
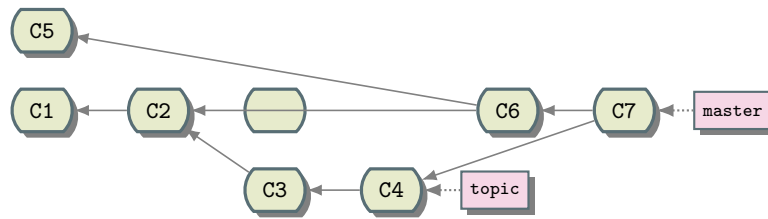
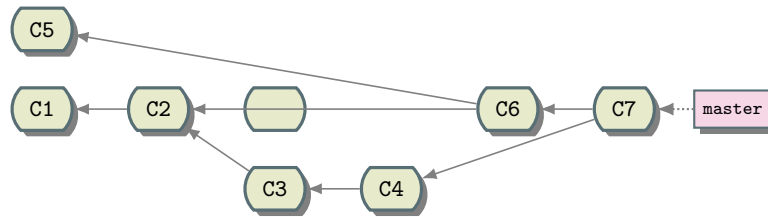


Figure B.12: Pull latest changes into master.

Figure B.13: Merge the `topic` branch into `master`.Figure B.14: Delete the local `topic` branch.

```
git pull
```

Merge the topic and test it.

```
git merge topic
```

See Section [B.2.2](#) on page [287](#) to resolve any conflict that may arise when merging the branch.

Delete the local branch.

```
git branch -d topic
```

Finally, publish the change.

```
git push origin master
```

See Section [B.2.2](#) on page [277](#) and Section [B.2.2](#) on page [278](#) to resolve any conflict that may arise when publishing the change.

Old Topic Sometimes we need to continue work on an old topic that has already been merged to an integration branch and for which we no longer have a local topic branch. To revive an old topic, we create a local branch based on the last commit from the topic (this is not one of the merges into an integration branch).

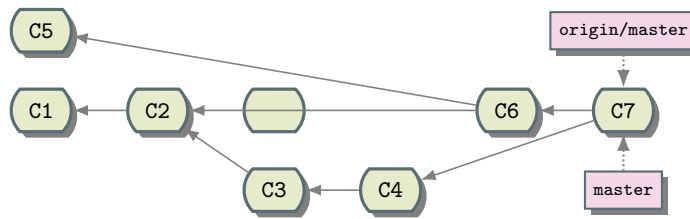
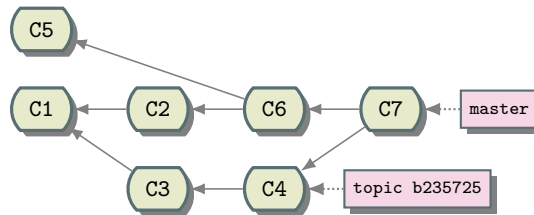


Figure B.15: Publish the change.

Figure B.16: Local *topic* branch started from a given commit and switch to it.

First we need to identify the commit by its hash. It is an ancestor of the integration branch into which it was once merged, say **master**. Run `git log` with the `--first-parent` option to view the integration history:

```

git log --first-parent master
commit 9057863...
Merge: 2948732 a348901
...
Merge branch topicA

commit 2948732...
Merge: 1094687 b235725
...
Merge branch topicB

commit 1094687...
Merge: 8267263 c715789
...
Merge branch topicC

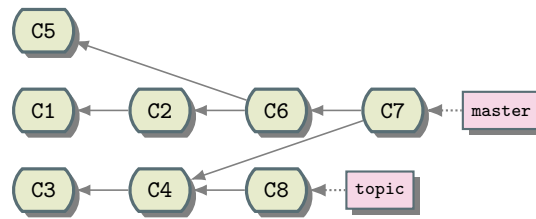
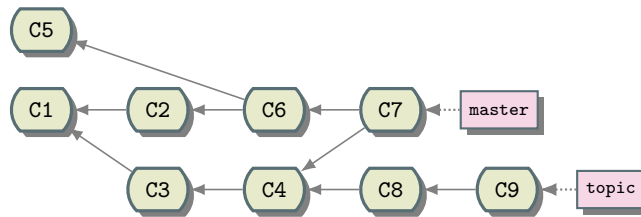
```

Locate the merge commit for the topic of interest, say *topicB*. Its second parent is the commit from which we will restart work (*b235725* in this example).

Create a local topic branch starting from the commit identified above.

```
git checkout -b topic b235725
```

Continue development on the topic.

Figure B.17: Commit files to *topic*.Figure B.18: Further continue developing and commit files to *topic*.

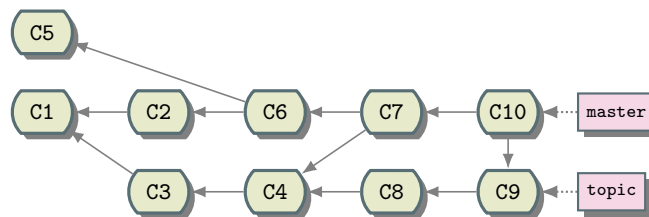
```
edit files
git add -- files
git commit
```

```
edit files
git add -- files
git commit
```

When the new portion of the topic is ready, merge it into **master** and test.

```
git checkout master
git pull
git merge topic
```

Publish **master**.

Figure B.19: Merge into *master*.

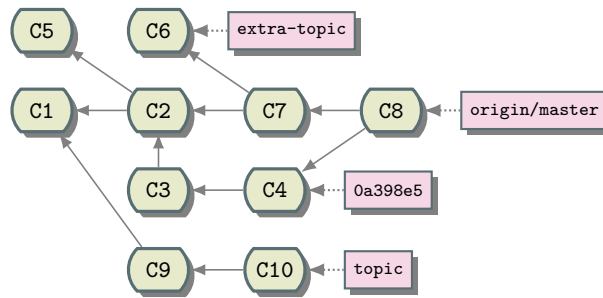


Figure B.20: Fetch the upstream integration branch *other-topic*.

```
git push origin master
```

Dependent Topic Occasionally you may realize that you need the work from another topic to complete work on your topic. In this case your topic depends on the other topic, so merging the other topics into yours is legitimate (see Section B.2.2 on page 277). Do not merge an integration branch that has the *other-topic* branch name. Use the instructions below to merge only the *other-topic* branch without getting everything else.

Fetch the upstream integration branch that has the *other-topic* branch, say **master**.

```
git fetch origin
```

Use `git log --first-parent origin/master` to find the commit that merges *other-topic*. The commit message gives you the name of the other topic branch (we use *other-topic* here as a placeholder). The second parent of the commit (0a398e5 in this example) is the end of the *other-topic* branch. Create a local branch from that commit.

```
git branch other-topic 0a398e5
```

Merge the *other-topic* branch into your topic.

```
git merge other-topic
git branch -d other-topic
```

(It is also possible to run `git merge 0a398e5` and then use `git commit --amend` to write a nice commit message.)

The *topic* branch now looks like this:

Note that after the merge, the *other-topic* is reachable from your topic but the *extra-topic* has not been included. By not merging from the integration branch we avoided bringing in an unnecessary

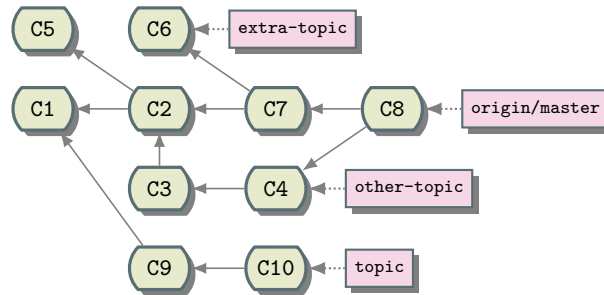


Figure B.21: Create a local branch *other-topic* from commit *0a398e5*.

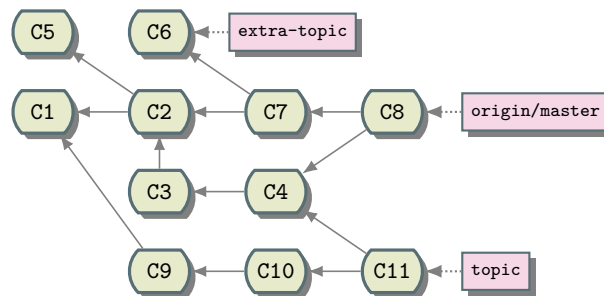


Figure B.22: Merge *other-branch* into *topic* branch.

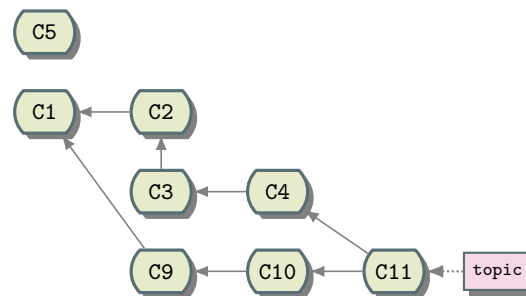
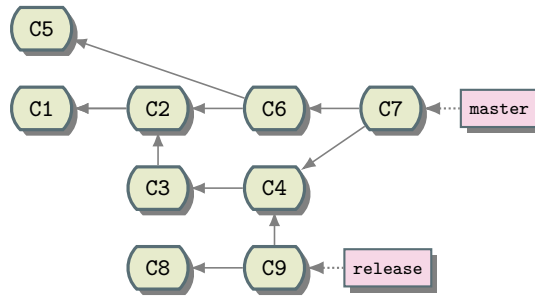


Figure B.23: *topic* branch shape.

Figure B.24: Update *master* and *release*.

dependency on the *extra-topic*. Furthermore, the message “Merge branch ‘other-topic’ into topic” is very informative about the purpose of the merge. Merging the whole integration branch would not be so clear.

Merge Integration Branches Each published integration branch (see Section B.2.2 on page 263) has a defined level of stability. Express this relationship by merging more-stable branches into less-stable branches to ensure that they do not diverge. After merging a mature topic to **master**, we merge **master** into **release**:

Update **master** and then **release**:

```
git checkout master
git pull
git checkout release
git pull
```

Merge **master** into **release**:

```
git merge master
```

Finally, publish the change.

```
git push origin release
```

See Section B.2.2 on page 277 and Section B.2.2 on page 278 to resolve any conflict that may arise when publishing the change.

Discussion

History Shape The history graphs produced by this workflow may look complex compared to the fully linear history produced by a rebase workflow (used by CVS and Subversion):

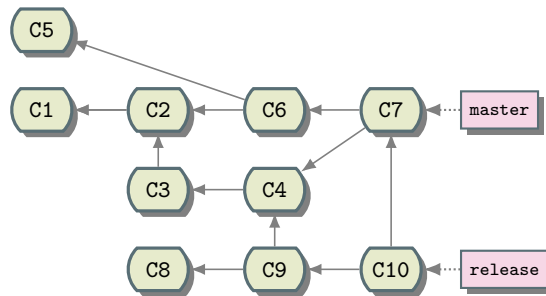
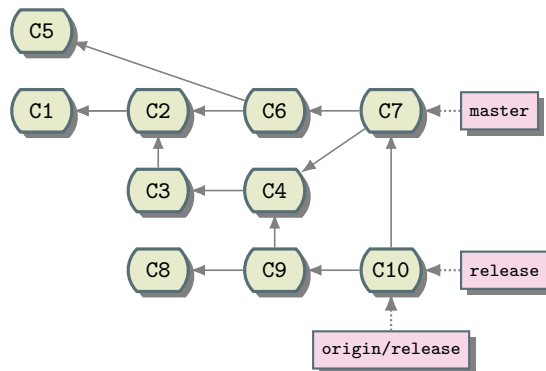
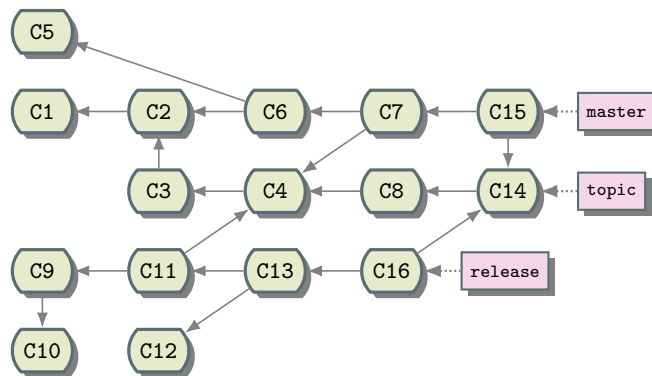
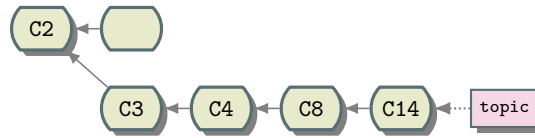
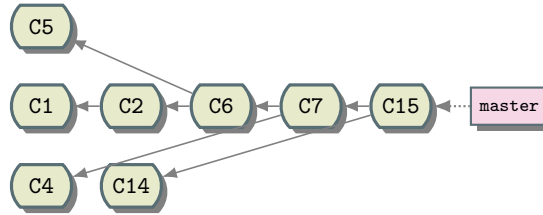
Figure B.25: Merge `master` into `release`.Figure B.26: Publish to `release`.

Figure B.27: Complex history graph in Git.

Figure B.28: Parent commit in *topic* branch.Figure B.29: Parent commit in *master* branch.

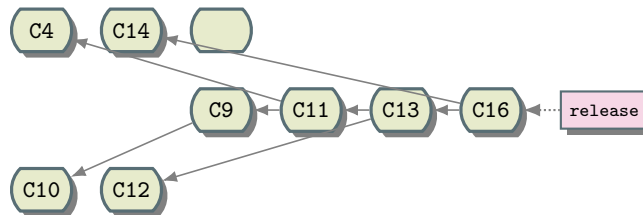
However, consider the shape of history along each branch. We can view it using Git's *--first-parent* option. It traverses history by following only the first parent of each merge. The first parent is the commit that was currently checked out when the `git merge` command was invoked to create the merge commit. By following only the first parent, we see commits that logically belong to a specific branch.

```
git log --first-parent topic
```

```
git log --first-parent master
```

```
git log --first-parent release
```

Each branch by itself looks linear and has only commits with a specific purpose. The history behind each commit is unique to that purpose. Topic branches are independent, containing only commits for their specific feature or fix. Integration branches consist of merge commits that integrate topics together.

Figure B.30: Parent commit in *release* branch.

Note that achieving the nice separation of branches requires understanding of the above development procedure and strict adherence to it.

Naming Topics This section uses the placeholder *topic* in place of a real topic name. In practice, substitute for a meaningful name. Name topics like you might name functions: concise but precise. A reader should have a general idea of the feature or fix to be developed given just the branch name.

Note that topic names are not published as branch heads on the server, so no one will ever see a branch by your topic name unless they create it themselves. However, the names do appear in the default merge commit message:

```
git checkout master
git merge topic
git show
...
Merge branch 'topic' into master
...
```

These merge commits appear on the integration branches and should therefore describe the changes they integrate. Running `git log --first-parent` as described in Section B.2.2 will show only these merge commits, so their messages should be descriptive of the changes made on their topics. If you did not choose a good branch name, or feel that the merge needs more explanation than the branch name provides, amend the commit to update the message by hand:

```
git commit --amend
Merge branch 'topic' into master
(edit the message)
```

Urge to Merge Avoid the “urge to merge” from an integration branch into your topic. Keep commits on your topic focused on the feature or fix under development.

Habitual Merges Merge your work with others when you are finished with it by merging into an integration branch as documented above. Avoid habitual merges from an integration branch; doing so introduces unnecessary dependencies and complicates the shape of history (see Section B.2.2 on page 273).

Many developers coming from centralized version control systems have trained themselves to regularly update their work tree from the central repository (e.g. “cvs update”). With those version control systems this was a good habit because they did not allow you to commit without first integrating your work with the latest from the server. When integrating the local and remote changes resulted in conflicts, developers were forced to resolve the conflicts before they could commit. A mistake during conflict resolution could result in loss of work because the local changes might have been lost. By regularly updating from the server, developers hoped to avoid this loss of work by resolving conflicts incrementally.

Developers using Git do not face this problem. Instead, one should follow a simple motto: “commit first, integrate later”. There is no risk that your work will be lost during conflict resolution because all your changes have been safely committed before attempting to merge. If you make a mistake while merging, you always have the option to throw away the merge attempt and start over with a clean tree.

Legitimate Merges One reason to merge other work into your topic is when you realize that your topic depends on it. See Section [B.2.2](#) on page [271](#) for help with this case.

Occasionally one may merge directly from **master** if there is a good reason. This is rare, so bring up the reason on your project discussion forum first. Never merge **release** into a topic under any circumstances!!!

Troubleshooting

Here we document problems one might encounter while following the workflow instructions above. This is not a general Git troubleshooting page.

Trouble Merging

Trouble Pushing

Remote End Hung up Unexpectedly Pushing may fail with this error:

```
git push
fatal: The remote end hung up unexpectedly
```

This likely means that you have set a *push URL* for the remote repository. You can see the URL to which it tries to push using `-v`:

```
git push -v
Pushing to git://public.kitware.com/Project.git
fatal: The remote end hung up unexpectedly
```

The `git://` repository URL may not be used for pushing; it is meant for efficient read-only anonymous access only. Instead you need to configure a SSH-protocol URL for pushing:

```
git config remote.origin.pushurl git@public.kitware.com:Project.git
```

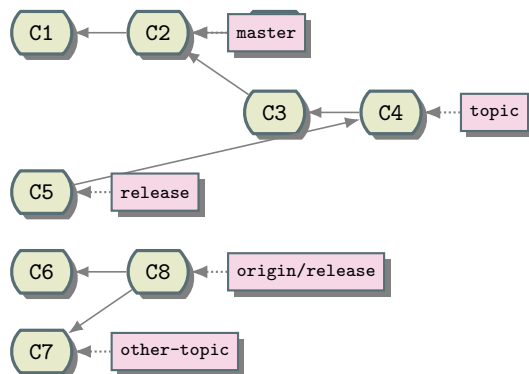


Figure B.31: Unreachable *origin/release* branch.

(Note that `pushurl` requires Git $\geq$ 1.6.4. Use just `url` for Git $\geq$ 1.6.4.). The URL in the above example is a placeholder. In practice, use the push URL documented for your repository.

The above assumes that you want to push to the same repository that you originally cloned. To push elsewhere, see help for [git push](#) and [git remote](#).

Non-Fast-Forward When trying to publish new merge commits on an integration branch, perhaps **release**, the final push may fail:

```
git push origin release
To ...
! [rejected]        release -> release (non-fast-forward)
error: failed to push some refs to '...'
To prevent you from losing history, non-fast-forward updates were rejected
Merge the remote changes before pushing again. See the 'Note about
fast-forwards' section of 'git push --help' for details.
```

This means that the server's **release** refers to a commit that is not reachable from the **release** you are trying to push:

This is the Git equivalent to when `cvs commit` complains that your file is not up-to-date, but now it applies to the whole project and not just one file. Git is telling you that it cannot update **release** on the server to point at your merge commit because that would throw away someone else's work (such as *other-topic*). There are a few possible causes, all of which mean you have not yet integrated your work with the latest from *upstream*:

- You forgot to run `git pull` before `git merge` so you did not have everything from *upstream*.
- Someone else managed to merge and push something into **release** since you last ran `git pull`.

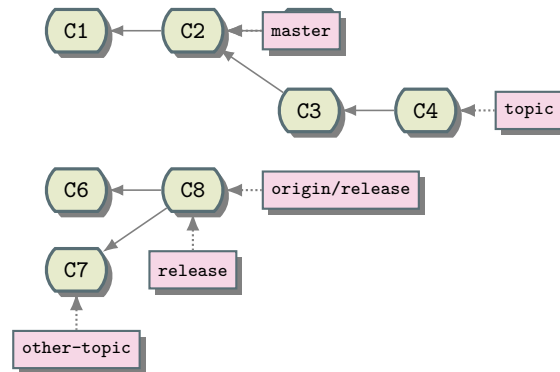
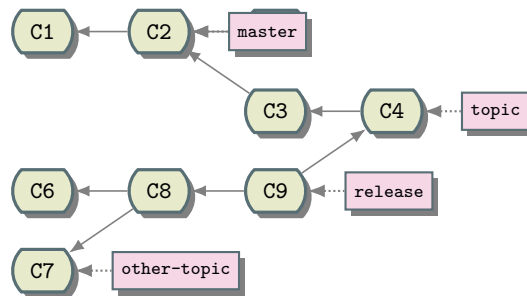


Figure B.32: Start from latest upstream commit.

Figure B.33: Merge the *topic* branch into the local *release* branch.

Some Git guides may tell you to just `git pull` again to merge *upstream* work into yours. That approach is not compatible with the goals of this workflow. We want to preserve a clean shape of history (see Section B.2.2 on page 273).

The solution is to throw away your previous merge and try again, but this time start from the latest *upstream* work:

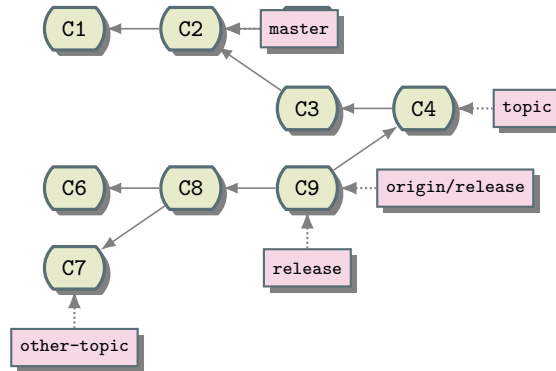
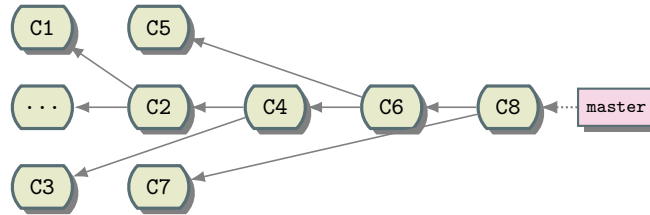
```
git reset --hard origin/release
```

```
git merge topic
```

Now your **release** can reach the upstream work as well as yours. Publish it.

```
git push origin release
```

See [git rerere](#) to help avoid resolving the same conflicts on each merge attempt.

Figure B.34: Publish the *release* branch.Figure B.35: Traversal of the *master* integration branch.

First-Parent Sequence Not Preserved One goal of this workflow is to preserve a clean shape of history (see Section B.2.2 on page 273). This means that a `--first-parent` traversal of an integration branch, such as **master**, should see only the merge commits that integrate topics into the branch:

The commits on the individual topic branches are not included in the traversal. This provides a medium-level overview of the development of the project.

We enforce the shape of history on the server's integration branches using an update hook at push-time. Each update must point its branch at a new commit from which a `first-parent` traversal reaches the old head of the branch:

A first-parent traversal of **master** from *before* the update (`master@1`) sees A B C D:

A first-parent traversal of **master** from *after* the update sees M A B C D:

The above assumes correct history shape. Now, consider what happens if merge M is incorrectly made on the topic branch:

Now a first-parent traversal of **master** from after the update sees M' T U B C D:

This not only shows details of the topic branch, but skips over A altogether! Our update hooks will reject the push in this case because the new **master** cannot see the old one in a first-parent traversal.

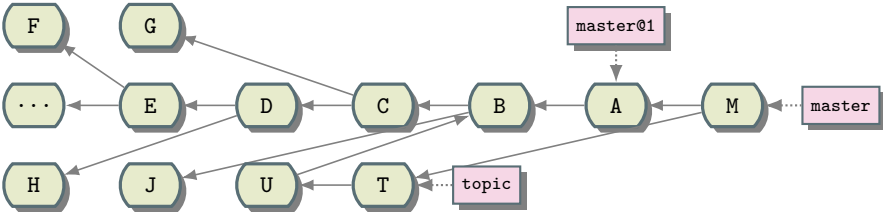


Figure B.36: Server's integration branch history shape.

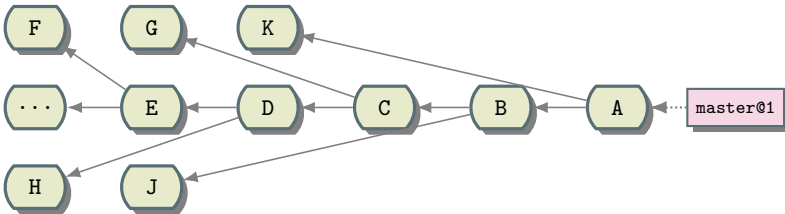


Figure B.37: First parent traversal of *master* before update.

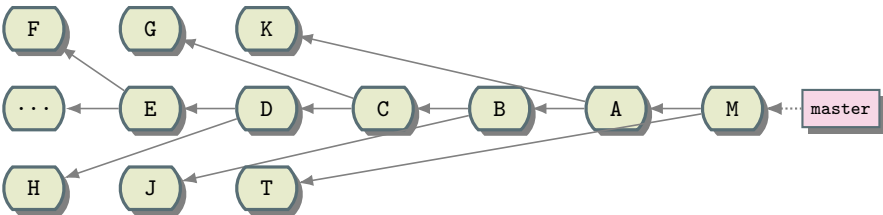


Figure B.38: First parent traversal of *master* after update.

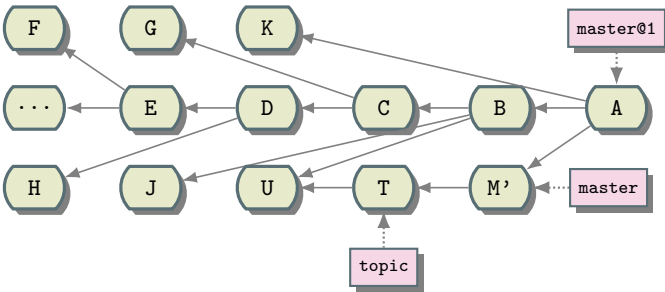


Figure B.39: Incorrect merge of *M* on branch *topic*.

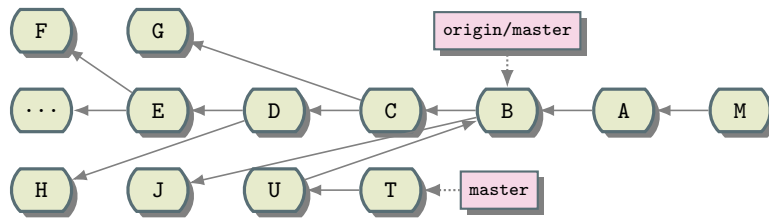
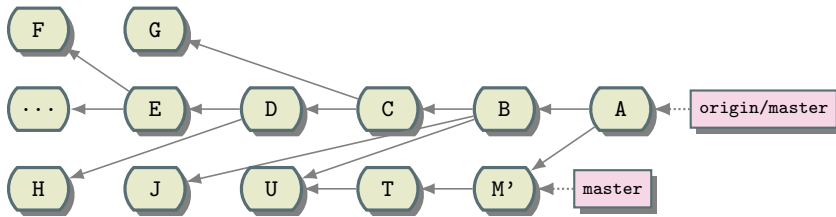
Figure B.43: Additional commit on *master* branch.

Figure B.44: Pull from upstream.

```
wrong$ git add files
wrong$ git commit
```

```
wrong$ git push origin master
```

Rejected as *non-fast-forward* (see Section B.2.2 on page 278).

```
wrong$ git pull
```

```
wrong$ git push origin master
```

Rejected with the *first parent sequence not preserved* error (see Section B.2.2 on page 280).

The solution in this case is to recreate the merge on the proper branch.

First, create a nicely-named topic branch starting from the first-parent of the incorrect merge.

```
git branch topic 'master^1'
```

Then reset your local master to that from upstream.

```
git reset --hard origin/master
```

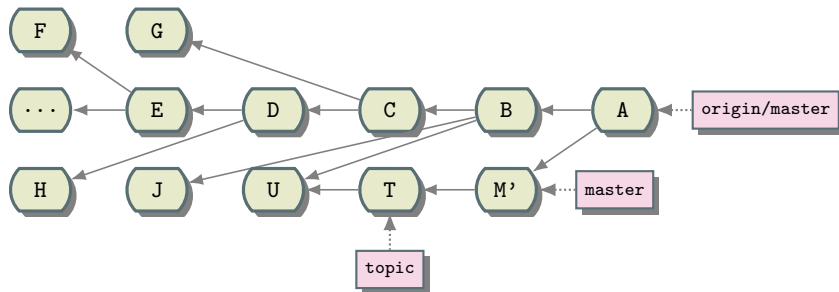


Figure B.45: Create a *topic* branch starting from the first-parent of the incorrect merge.

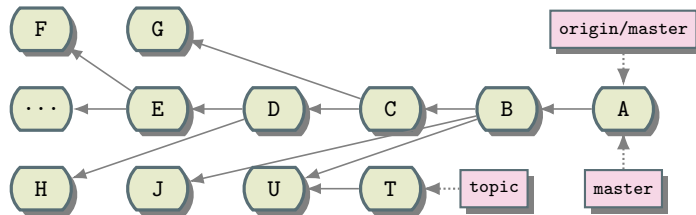


Figure B.46: Reset the local *master* branch to upstream *master*.

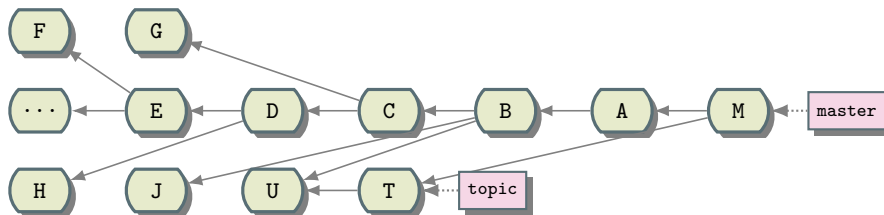


Figure B.47: Merge the *topic* branch.

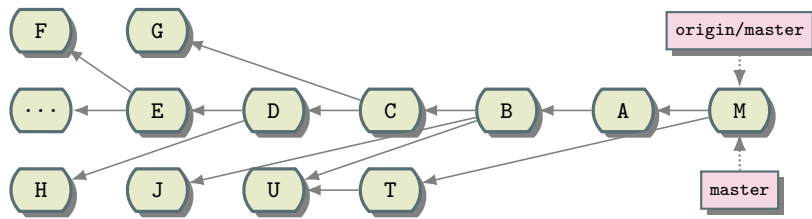
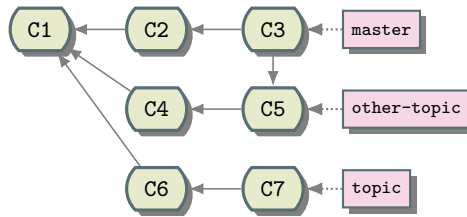
Figure B.48: Delete the local *topic* branch.

Figure B.49: Conflicting topic branches.

Now create the correct merge commit as described in the workflow instructions above.

```
git merge topic
```

```
git push origin master
git branch -d topic
```

Topics Must Be Merged

Conflicts

This section documents conflict resolution in a topic-based branchy workflow.

Whenever two paths of development make different changes to the same initial content conflicts may occur when merging the branches.

Single Integration Branch Consider two conflicting topic branches, *topic* and *other-topic*, with the latter already merged to **master**:

An attempt to merge *topic* into *master* will fail with conflicts. One may use the following approaches to resolve the situation:

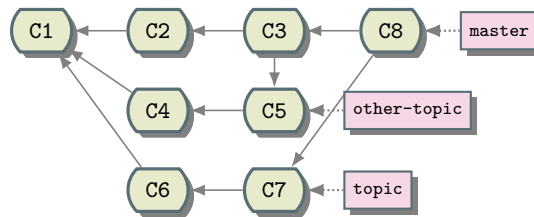


Figure B.50: Topic-to-single branch resolution approach.

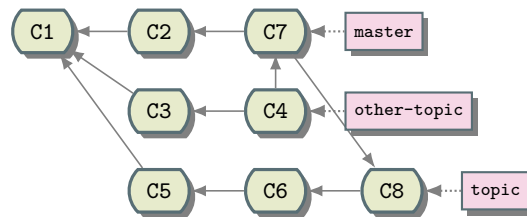


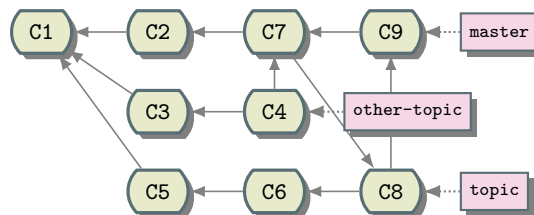
Figure B.51: Branch-to-Topic resolution approach.

- Merge the topic to the branch
- Merge the branch to the topic

Topic-to-Single-Branch If one performs the merge in a local work tree it is possible to simply resolve the conflicts and complete the merge:

Branch-to-Topic Since a developer works on a topic branch locally one may simply merge the conflicting integration branch into the topic and resolve the conflicts:

In order to maintain a good shape of history one may then merge the topic into the integration branch without allowing a *fast-forward* (`merge --no-ff`):

Figure B.52: Merge disallowing fast-forward (`--no-ff`).

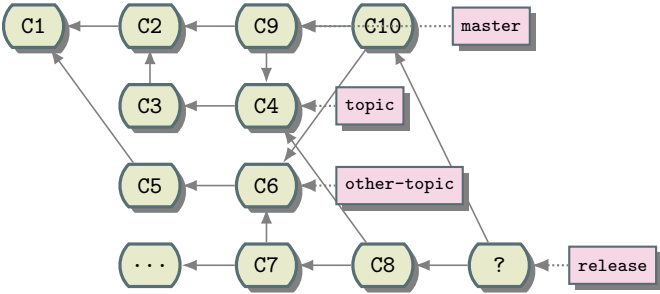


Figure B.57: **master** not merging cleanly into **release** if conflicts have not been resolved.

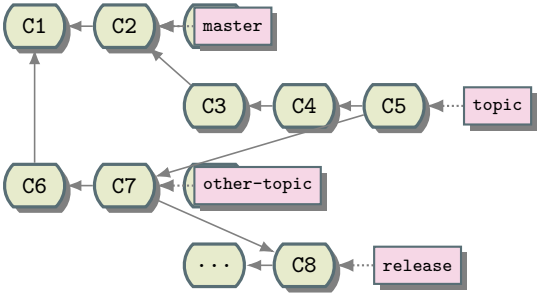


Figure B.58: Manually merge *other-topic* into *topic*.

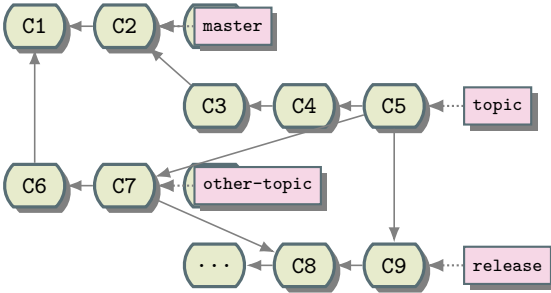
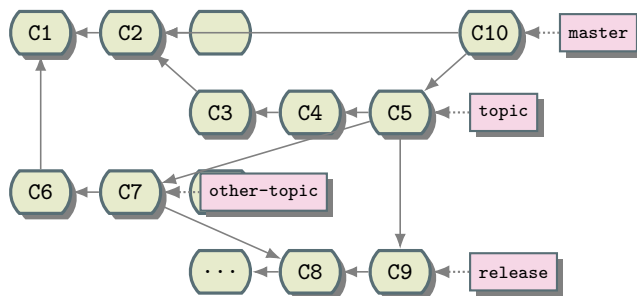
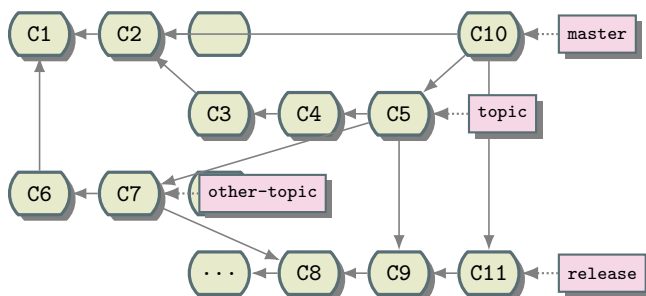


Figure B.59: Merge into *release*.

Figure B.60: Merge into *master*.Figure B.61: Merge *master* into *release*.

has already been merged):

Finally, **master** may be merged cleanly into **release**:

Note that this produces an artificial topic dependency (see Section B.2.2 on page 271) introduced by the conflict resolution commit. See the B.2.2 approach to avoid this problem.

Resolution Topic The B.2.2 approach introduces an artificial topic dependency because it asymmetrically favors one topic over another. Instead one may use a third topic to resolve the conflicts.

One may start a new *resolve/topic/other-topic* branch from *topic*, merge *other-topic* into it, and resolve the conflicts:

The resolution topic will merge cleanly into **release** to bring in the changes from topic through the conflict resolution commit:

Since *topic* and *other-topic* are still independent either may be merged to **master** first. Assume *topic* is merged first:

As in the B.2.2 approach, an attempt to merge *other-topic* directly into **master** will fail with the original conflicts but now we have a topic containing the resolution commit independent of next. One may merge the resolution topic to **master** to bring in the changes from *other-topic* and the

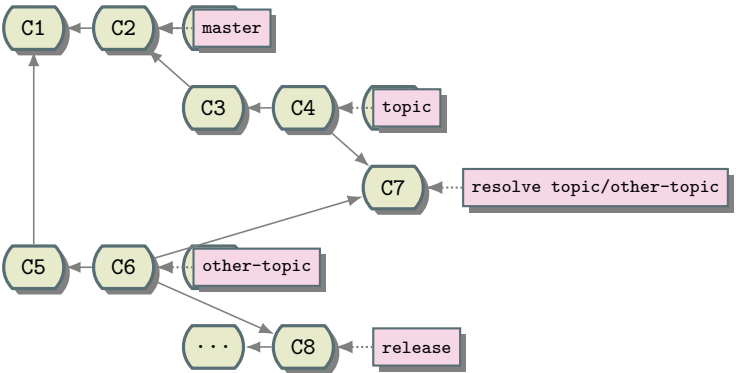


Figure B.62: Start conflict resolution branch.

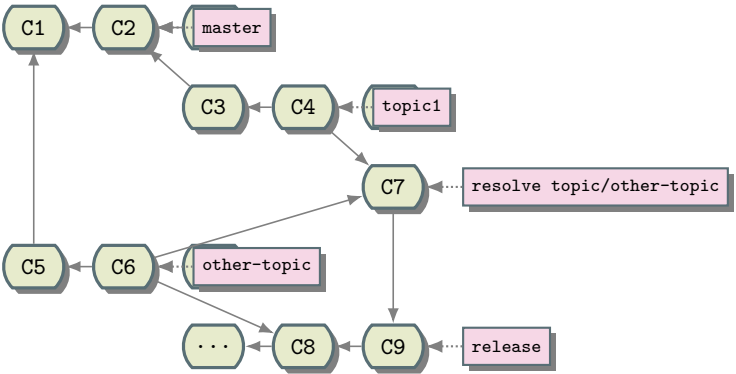


Figure B.63: Merge into *release*.

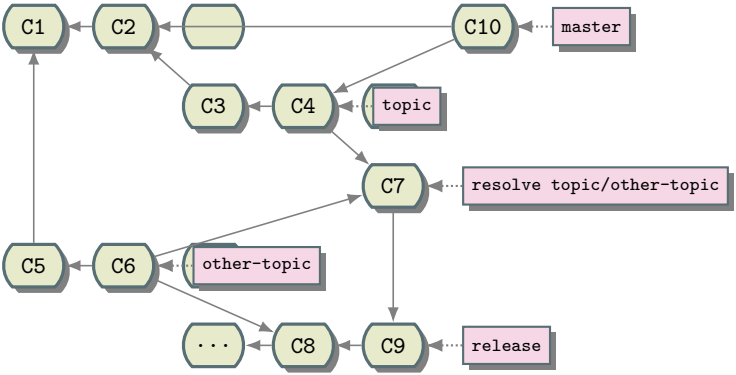
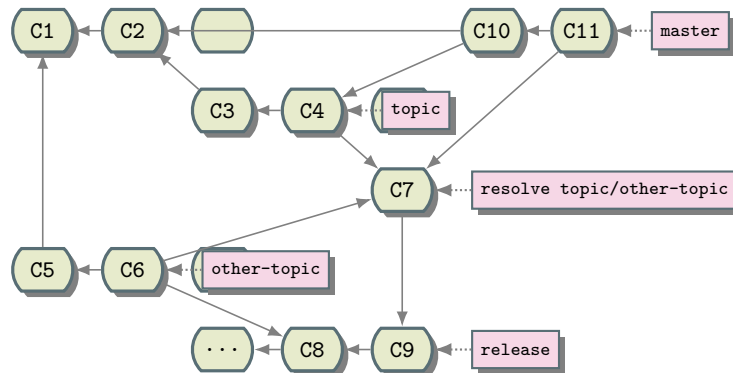
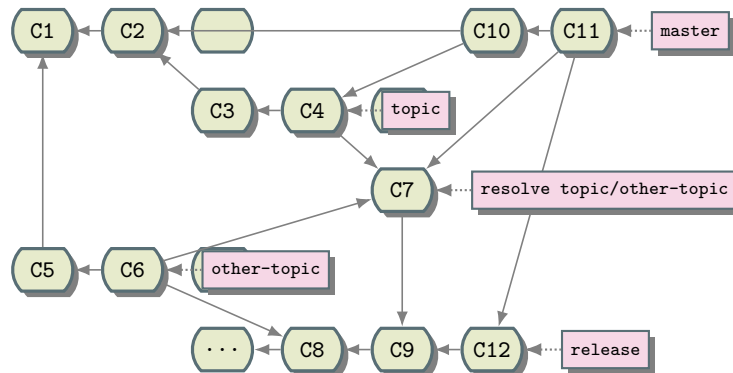


Figure B.64: Merge *topic* branch.

Figure B.65: Merge conflict resolution branch into *master*.Figure B.66: Merge into *release*.

conflict resolution:

Finally, **master** may be merged cleanly into **release**:

B.2.3 Publish

Push Access

Authorized developers may publish work directly to a repository using Git's SSH protocol.

Note that we may not grant all contributors push access to any given repository. The distributed nature of Git allows contributors to retain authorship credit even if they do not publish changes directly.

Authentication All publishers share the `git@public.kitware.com` account but each uses a unique SSH key for authentication. If you do not have a public/private SSH key pair, generate one:

```
ssh-keygen -C 'you@yourdomain.com'
Generating public/private rsa key pair.
Enter file in which to save the key (\$HOME/.ssh/id_rsa):
Enter passphrase (empty for no passphrase): (use-a-passphrase!!)
Enter same passphrase again: (use-same-passphrase!!)
Your identification has been saved in \$HOME/.ssh/id_rsa.
Your public key has been saved in \$HOME/.ssh/id_rsa.pub.
```

To request access, fill out the [Kitware Password](#) form. Include your SSH public key, `id_rsa.pub`, and a reference to someone our administrators may contact to verify your privileges.

SSH on Windows If you are familiar with generating an SSH key on Linux or macOS, you can follow the same procedure on Windows in a Git Bash prompt. There is an `ssh-keygen` program installed with Git for Windows to help you set up an SSH identity on a Windows machine. By default it puts the `.ssh` directory in the `HOME` directory, which is typically `C:`

Users

Username.

Alternatively, you can also set up a “normal” Windows command prompt shell such that it will work with Git for Windows (see Section [B.1.1](#)) on page 259, without ever invoking the Git Bash prompt if you like. If you install Git for Windows and accept all its default options, “git” will not be in the `PATH`. However, if you add `C:`

Program Files (x86)

Git

`cmd` to your `PATH`, then only the two commands `git` and `gitk` are available to use via `*.cmd` script wrappers installed by Git for Windows. Or, if you add `C:`

Program Files (x86)

Git

`bin` to your `PATH`, then all of the command line tools that git installs are available.

The full PuTTY² suite of tools includes an application called PuTTYgen. If you already have a private key created with PuTTYgen, you may export it to an OpenSSH identity file. Open the key using PuTTYgen and choose *Conversions ; Export OpenSSH key* from the menu bar. That will allow you to save an `id_rsa` file for use in the `.ssh` directory. You can also copy and paste the public key portion of the key from the PuTTYgen text field to save into an `id_rsa.pub` file if you like. Or email it to whoever needs the public side of your key pair.

If you routinely set up your own command prompt environment on Windows, using Git for Windows from that environment is a cinch: just add the full path to either Git

`cmd` or Git

`bin` to your `PATH`. (Or, write your own `git.cmd` wrapper that is in your `PATH` that simply calls the

²<https://www.chiark.greenend.org.uk/~sgtatham/putty/>

`git.cmd` installed with `msysGit`.) And make sure you have a `HOME` environment variable that points to the place where the `.ssh` directory is.

AuthenticationTest When your SSH public key has been installed for `git@public.kitware.com`, you may test your SSH key setup by running

```
ssh git@public.kitware.com info
```

If your key is correctly configured you should see a message reporting your email address followed by a list of access permissions. If you get something like *Permission denied* then add `-v` options to your ssh command line to diagnose the problem:

```
ssh -v git@public.kitware.com info
```

Do not attempt to `git push` until the ssh-only test succeeds.

Pushing Git automatically configures a new clone to refer to its *origin* through a *remote* called `origin`. Initially one may `fetch` or `pull` changes from `origin`, but may not push changes to it.

In order to publish new commits in a repository, developers must configure a push URL for the origin. Use `git config` to specify an SSH-protocol URL:

```
git config remote.origin.pushurl git@public.kitware.com:repo.git
```

The actual URL will vary from project to project. (Note that `pushurl` requires Git $\geq$ 1.6.4. Use just `url` for Git $\leq$ 1.6.4.)

Failing to do so with result in the error message *fatal: The remote end hung up unexpectedly*.

Once your push URL is configured and your key is installed for `git@public.kitware.com` then you can try pushing changes. Note that many repositories use an `update hook` to check commit as documented in Section B.2.4 on page 296.

Patches

Git allows anyone to be a first-class developer on any published project. One can clone a public repository, commit locally, and publish these commits for inclusion upstream. One method of sending commits upstream is to supply them as patches.

See these links for more help:

- Pro Git Book, Chapter 5: Distributed Git³

³<https://git-scm.com/book/en/v2>

- Everyday Git: Integrator⁴

Creating Patches Construct your commits on a local topic branch, typically started from the *upstream master*:

```
git checkout -b my-cool-feature origin/master
edit files
git add -- files
git commit
```

Begin each commit message with a short one-line summary of its change, suitable for use as an email subject line. Then leave a blank line and describe the change in detail as one might write in an email body.

When the patch(es) are ready for publication to upstream developers, use the `git format-patch` command to construct the patch files:

```
git format-patch -M origin/master
```

Git will write out one patch file per commit. Each patch file is formatted like a raw email message and includes enough information to reconstruct the commit message and author.

Sending Patches The patch files created in the preceding step will be named with the form

```
NNNN-Subject-line-of-commit-message.patch
```

where `NNNN` is an index for the patch within the series. These files may be attached in bug trackers or attached to email messages.

A patch series may also be sent directly as email. Use `git config --global` to set `sendemail.*` configuration entries that tell Git how to send email from your computer (one-time setup per user per machine). Then use the `git send-email` command:

```
git send-email *.patch --to='Some One <someone@somewhere.com>' --cc='Someone Else <someoneelse@somewhereelse.com>'
```

Applying Patches One may receive patches as attachments in a bug tracker or as attachments to email messages. Save these files to your local disk. One may also receive patches inlined in email messages. In this case, save the whole message to your local disk (typically as `.eml` files). (If your local mail client uses `maildir` format mailboxes each message is already its own file.)

Create a local topic branch on which to replay the patch series:

⁴<https://git-scm.com/docs/giteveryday>

```
git checkout -b cool-feature origin/master
```

Now use `git am` to apply the patch series as local commits:

```
git am --whitespace=fix /path/to/*.patch
```

Review the changes using

```
git log -p origin/master..
```

or the method of your choice. Note that the author of each commit is the contributor rather than yourself. Build, test, and publish the changes normally.

If the `git am` command fails with a message like

```
Patch format detection failed.
```

this means that the patch was not generated with `git format-patch` and transmitted correctly. Either ask the contributor to try again using the above patch creation instructions, or apply each patch separately using `git apply`:

```
git apply --whitespace=fix /path/to/0001-First-change.patch
git commit --author='Contributor Name <contributor@theirdomain.com>'
```

B.2.4 Hooks

Setup

The `git commit` command creates local commits. A separate `git push` step is needed to publish commits to a repository. The server enforces some rules (see Section B.2.4 on page 299) on the commits it accepts and will reject non-conforming commits. In order to push rejected commits, one must edit history locally to repair them before publishing.

Since it is possible to create many commits locally and push them all at once, we provide local Git *hooks* to help developers keep their individual commits clean. Git provides no way to enable such hooks by default, giving developers maximum control over their local repositories. We recommend enabling our hooks manually in all clones.

Git looks for hooks in the `.git/hooks` directory within the work tree of a local repository. Create a new local repository in this directory to manage the hooks:

```
cd .git/hooks
git init
cd ../../
```

Choose one of the following methods to install or update the hooks. The hooks will then run in the outer repository to enforce some rules on commits.

Local Pull Many repositories provide a `hooks` branch. It will have already been fetched into your local clone. Pull it from there:

```
git fetch origin
cd .git/hooks
git pull .. remotes/origin/hooks
cd ../../
```

Direct Pull If you did not clone from a repository you may not have a `hooks` branch. Pull it from :

```
cd .git/hooks
git pull git://public.kitware.com/<repo>.git hooks
cd ../../
```

where `<repo>.git` is the name of your project repository.

Local

The above sequences maintain the following local `hooks` in your repository. See Git help on <https://git-scm.com/docs/githooks> for more details.

pre-commit This runs during `git commit`. It checks identity and content of changes:

- Git `user.name` and `user.email` are set to something reasonable.
- Git's standard whitespace checks (see help on `git diff --check`).
- The staged changes do not introduce any leading tabs in source files (we indent with spaces)
- File modes look reasonable (no executable `.cxx` files, scripts with shebang lines are executable).
- File size is not too large (do not commit big data files; prints limit and instructions on rejection).
- Submodule updates are staged alone or explicitly allowed (prints instructions on rejection).

One of Git's standard whitespace checks is to reject trailing whitespace on lines that were added or modified. Many people consider extra space characters at the end of a line to be an unprofessional style (including Git's own developers), but some don't care. Text editors typically have a mode to highlight trailing whitespace:

- **Emacs**

```
(custom-set-variables '(show-trailing-whitespace t))
```

- **Vim**

```
:highlight ExtraWhitespace ctermbg=red guibg=red
:match ExtraWhitespace /\s\+$/
```

- **Microsoft Visual Studio** To toggle viewing of white space characters, with a source file document active, choose the menu item:

```
Edit > Advanced > View White Space

(2-stroke keyboard shortcut: Ctrl+R, Ctrl+W)
```

- **Notepad++ (v7.5.1)** To eliminate trailing white space, choose the menu item:

```
Edit > Blank Operations > Trim Trailing Space
```

To toggle viewing of white space characters, choose from the menu items:

```
View > Show Symbol > (multiple items, choose one...)
```

If you really don't want to keep your code clean of trailing whitespace, you can disable this part of Git's checks locally:

```
git config core.whitespace "-blank-at-eol"
```

`commit-msg` This runs during `git commit`. It checks the commit message format:

- The first line must be between 8 and 78 characters long. If you were writing an email to describe the change, this would be the *Subject line*. Use the pre-defined prefixes (e.g. `ENH:` or `BUG:`); they are valuable to allow the user get a fast understanding of the change.
- The first line must not have leading or trailing whitespace.
- The second line must be blank, if present.
- The third line and below may be free-form. Usually, a summary of the commit changes is written. Try to keep paragraph text formatted in 72 columns (this is not enforced).

GUI and text-based tools that help view history typically use the first line (*Subject line*) from the commit message to give a one-line summary of each commit. This allows a medium-level view of history, but works well only if developers write good *Subject lines* for their commits.

Examples of improper commit messages:

```
Fixed
```

This is too short and not informative at all.

```
I did a really complicated change and I am trying to describe the entire thing
with a big message entered on the command line.
```

Some good tips on why good commit messages matter can be found in the post *How to Write a Git Commit Message*⁵.

Many CVS users develop the habit of using the `-m` commit option to specify the whole message on the command line. This is probably because in CVS it is hard to abort a commit if it already brought up the message editor. In Git this is trivial. Just leave the message blank and the whole commit will be aborted. Furthermore, since commits are not published automatically it is easy to allow the commit to complete and then fix it with `git commit --amend`.

Server

Many public.kitware.com repositories have server-side hooks.

Update The update hook runs when someone tries to update a ref on the server by pushing. The hook checks all commits included in the push:

- Commit author and committer must have valid email address domains (DNS lookup succeeds).
- Commit message does not start with `WIP:.` (Use the prefix locally for work-in-progress that must be rewritten before publishing.)
- Changes to paths updated by robots (such as `Utilities/kwsys`) are not allowed.
- No “large” blobs may be pushed. The limit is set on a per-repository basis and is typically 1 MB or so.
- No CRLF newlines may be added in the repository (see `core.autocrlf` in `git help config`).
- Submodules (if any) must be pushed before the references to them are pushed.

B.2.5 TipsAndTricks

Editor support

Emacs users: if you put this line in your `.emacs` file:

⁵<https://chris.beams.io/posts/git-commit/>

```
(setq auto-mode-alist (cons ' ("COMMIT_EDITMSG" . auto-fill-mode) auto-mode-alist))
```

Git will automatically wrap your commit messages, which is what good Git etiquette requires.

Shell Customization

Bash Completion Bash users: Git comes with a set of completion options that are very useful. The location of the file varies depending on your system:

```
# Mac with git installed by Mac Ports
source /opt/local/share/doc/git-core/contrib/completion/git-completion.bash
# Linux
source /usr/share/bash-completion/git
# Linux debian/gentoo
source /etc/bash_completion.d/git
```

Bash Prompt If you are using the bash shell, you can customize the prompt to show which Git branch is active. Here are the commands for your `/.bashrc` file:

```
# Use the appropriate path from the above section
source /etc/bash_completion.d/git
export GIT_PS1_SHOWDIRTYSTATE=1
export GIT_PS1_SHOWUNTRACKEDFILES=1
export GIT_PS1_SHOWUPSTREAM="verbose"
export PS1="\[\e[01;34m\]\W\[\e[31m\]\${_\git_ps1 " (%s)" }\[\e[00m\]\[\e[00m\]
```

For more information on the options, see the comments in the top of the bash completion script.

Renaming Git does not explicitly track renames. The command

```
git mv old new
```

is equivalent to

```
mv old new
git add new
git rm old
```

Neither approach records the rename outright. However, Git’s philosophy is “dumb add, smart view”. It uses heuristics to detect renames when viewing history after-the-fact. It even works when the content of a renamed file changes slightly.

In order to help Git efficiently detect the rename, it is important to remove the old file and add the new one in one commit, perhaps by using `git mv` or the above 3-step procedure. If the new file

were added in one commit and the old file removed in the next, Git would report this as a copy followed by a removal. Its copy-detection heuristics are more computationally intensive and must be explicitly enabled with the `-C` option to relevant operations (such as `git blame`).

CODING STYLE GUIDE

This chapter describes the ITK Coding Style. Developers must follow these conventions when submitting contributions to the toolkit.

The following coding-style guidelines have been adopted by the ITK community. To a large extent these guidelines are a result of the fundamental architectural and implementation decisions made early in the project. For example, the decision was made to implement ITK with a C++ core using principles of generic programming, so the rules are oriented towards this style of implementation. All guidelines are strictly enforced, including whitespace indentation levels and style. Careful consideration and considerable discussion occurred in an attempt to find coding styles consistent with accepted practices in the active community. The primary goal is to adhere to a common style to assist community members of the future to learn, use, maintain, and extend ITK. Given the fact that code is read many more times than it is written, a strong emphasis is placed on generating a common style that improves readability.

Please do your best to be an outstanding member of the ITK community. The rules described here have been developed with the community as a whole in mind. Any contributor's code is subject to style review, and it will likely not be accepted until it is consistent with these guidelines.

C.1 Purpose

The following document is a description of the accepted coding style for the NLM Insight Segmentation and Registration Toolkit (ITK). Developers who wish to contribute code to ITK should read and adhere to the standards described here.

C.2 Overview

This chapter is organized into the following sections:

- **System Overview & Philosophy:** coding methodologies and motivation for the resulting style.
- **Copyright:** the copyright header to be included in all files and other copyright issues.
- **Citations:** guidelines to be followed when citing others' work in the documentation.
- **Naming Conventions:** patterns used to name classes, variables, template parameters, and instance variables.
- **Namespaces:** the use of namespaces.
- **Aliasing Template Parameter Typenames:** guidelines on aliasing template parameter type-names in a class.
- **The auto Keyword:** when and when not to use the `auto` keyword.
- **Pipelines:** useful tips when writing pipelines in ITK.
- **Initialization and Assignment:** accepted standards for variable initialization and assignment.
- **Accessing Members:** patterns to be used when accessing class members.
- **Code Layout and Indentation:** accepted standards for arranging code including indentation style.
- **Empty Arguments in Methods:** guidelines for specifying empty argument lists.
- **Ternary Operator:** accepted standards for using the ternary operator.
- **Using Standard Macros** (`itkMacro.h`): use of standard macros in header files.
- **Exception Handling:** how to add exception handling to the system.
- **Messages:** accepted guidelines to output messages to the error and standard outputs.
- **Concept Checking:** specifics on the use of concept checking in ITK.
- **Printing Variables:** guidelines to print member variable values.
- **Checking for Null:** accepted standards for checking `null` values.
- **Writing Tests:** additional rules specific to writing tests in ITK.
- **Doxygen Documentation System:** basic Doxygen formatting instructions.
- **CMake Style:** guidelines to write CMake files.
- **Documentation Style:** a brief section describing the documentation philosophy adopted by the Insight Software Consortium.

This style guide is an evolving chapter.

Please discuss with the ITK community members if you wish to add, modify, or delete the rules described in these guidelines.

See <https://www.itk.org/ITK/help/mailing.html> for more information about joining the ITK community members discussion. This forum is one of the best venues in which to propose changes to these style guidelines.

C.3 System Overview & Philosophy

The following implementation strategies have been adopted by the ITK community. These directly and indirectly affect the resulting code style. Understanding these aspects motivates the reasons for many of the style guidelines described in this chapter.

The principle is that code is read many more times than it is written, and readability is far more important than writability.

- **Readability:** the code is intended to be read by humans. Most of the time of debugging code is spent reading code.
- **Consistency:** systematically following these guidelines will make the code more robust, and easier to read, which will at term save time to community members.
- **Conciseness:** class, method and variable names should be concise, but self-contained. Extraordinarily long names and redundancies should be avoided.
- **Language:** proper English must be used when writing the code and the documentation.
- **Documentation:** document the code. Approximately one third of the code should be documentation.

Note as well that ITK follows American English spelling and norms.

C.3.1 Clang Style

ITK has adopted a `.clang-format` coding style configuration file so that a number of coding style rules are applied to all C++ code with the `clang-format` binary. A consistent coding style is critical for readability and collaborative development.

ITK has a pre-commit hook to automatically reformat any changed C++ ITK code to adhere to the style defined in the `.clang-format`.

C.3.2 Kitware Style

Kitware Style ([KWStyle](#)) pre-commit hooks enforce a number of policies on any given patch set submitted to ITK.

C.3.3 Implementation Language

The core implementation language is C++. C++ was chosen for its flexibility, performance, and familiarity to consortium members. ITK uses the full spectrum of C++ features including const and volatile correctness, namespaces, partial template specialization, operator overloading, traits, and iterators.

Currently, C++11 and C++14 features are used in the code whenever they are available.

A growing number of ITK classes offer a Python wrapping. Note that these are wrappers on the C++ counterparts. ITK's Python wrappers can be easily installed. See [Section 9.5](#) on page 208 for further details. Users requiring a Python interface for ITK classes may refer to SimpleITK (<https://www.simpleitk.org/>).

Additionally, SimpleITK offers interpreted language bindings for Java, C#, R, Tcl, and Ruby.

C.3.4 Constants

ITK does not define constants with `#define` in header files, hence do not declare constants using

```
#define CONST_VALUE_NAME 3
```

Use instead

```
constexpr unsigned int ConstValueName = 3;
```

or

```
const typename OperatorType::ConstIterator opEnd = op.End();
```

Add the `const` qualifier to arguments which set the pipeline inputs and state functions, e.g.

```
/** Set the marker image */
void
SetMaskImage(const MaskImageType * input)
{
    // Process object is not const-correct so the const casting is required.
    this->SetNthInput(1, const_cast<MaskImage *>(input));
}
```

C.3.5 Generic Programming and the STL

Compile-time binding using methods of generic programming and template instantiation is the preferred implementation style. This approach has demonstrated its ability to create efficient, flexible code. Use of the STL (Standard Template Library) is encouraged. STL is typically used by a class, rather than as serving as a base class for derivation of ITK classes. Other STL influences are iterators and traits. ITK defines a large set of iterators; however, the ITK iterator style differs in many cases from STL because STL iterators follow a linear traversal model; ITK iterators are often designed for 2D, 3D, and even n-D traversal (see Section 6 on page 137 for further details on iterators).

Traits are used heavily by ITK. ITK naming conventions supersede STL naming conventions; this difference is useful in that it indicates to the community member something of a boundary between ITK and STL.

C.3.6 Portability

ITK is designed to build and is systematically tested on a set of target operating system/compiler combinations and results are reported continuously to the dashboards using [CDash](#). These combinations include Linux, macOS, and Windows operating systems, and various versions of compilers for each. This ensures that the code complies with the particular requirements on each of these environments. See Section 10.2 on page 228 for further details.

When sufficient demand or need is detected, ITK maintainers add machines to the dashboard. Note that since the dashboard is open to submissions from remote locations, other user configurations can be tested dynamically. For a detailed and updated view, visit the [ITK dashboard](#).

Since some of these compilers do not support all C++ features, the ITK community has had to back off some important C++ features (such as partial specialization) because of limitations in compilers (e.g., MSVC 6.0).

ITK's open source philosophy, as well as its design, and heavy use of templates has made it possible to improve the support of many of these compilers over time. Indeed, ITK has been incorporated to the Microsoft Visual Studio and Intel C++ Compiler (ICC) build validation suites as of April 2017. This means that ITK is being used by these teams in their benchmarks and validation cycles before a version of their compiler is released to the market.

C.3.7 Multi-Layer Architecture

ITK is designed with a multi-layer architecture in mind. That is, three layers: a templated layer, a run-time layer, and an application layer. The templated (or generic) layer is written in C++ and requires significant programming skills and domain knowledge. The run-time layer is generated automatically using the Swig-based wrapping system to produce language bindings to Python. The interpreted layer is easier to use than the templated layer, and can be used for prototyping and

smaller-sized application development. Finally, the application layer is not directly addressed by ITK other than providing simple examples of applications.

C.3.8 CMake Build Environment

The ITK build environment is CMake. CMake is an open-source, advanced cross-platform build system that enables community members to write simple makefiles (named `CMakeLists.txt`) that are processed to generate native build tools for a particular operating system/compiler combination. See the CMake web pages at <https://www.cmake.org> for more information.

See Section 2.2 on page 11 for specifics about the use of CMake in ITK.

Section C.27 on page 373 provides a reference to the recommended style of makefiles in ITK.

C.3.9 Doxygen Documentation System

The Doxygen open-source system is used to generate on-line documentation. Doxygen requires the embedding of simple comments in the code which is in turn extracted and formatted into documentation.

Note that ITK prefers the backslash (`\`) style versus the at-sign (`@`) style to write the documentation commands (e.g. `\class`).

For more information about Doxygen, please visit <https://www.doxygen.nl/index.html>.

C.3.10 vnl Math Library

ITK has adopted the vnl – visual numerics library. Vnl is a portion of the vxI image understanding environment. See <http://vxl.sourceforge.net/> for more information about vxI and vnl.

C.3.11 Reference Counting

ITK has adopted reference counting via so-called `itk::SmartPointer` to manage object references. While alternative approaches such as automatic garbage collection were considered, their overhead due to memory requirements, performance, and lack of control as to when to delete memory, precluded these methods. SmartPointers manage the reference to objects, automatically incrementing and deleting an instance's reference count, deleting the object when the count goes to zero.

An important note about SmartPointers refers to their destruction: the `Delete()` method on an ITK smart pointer must never be called directly; if a `SmartPointer` object `itkSmartPtr` needs to be deleted:

```
itkSmartPtr = nullptr;
```

must be done instead. The ITK smart pointer will determine whether the object should be destroyed. See Section 3.2.4 on page 28 for further details.

C.4 Copyright

ITK has adopted a standard copyright. This copyright should be placed at the head of every source code file. The current copyright header and license reads as follows:

```
/*=====
 *
 * Copyright NumFOCUS
 *
 * Licensed under the Apache License, Version 2.0 (the "License");
 * you may not use this file except in compliance with the License.
 * You may obtain a copy of the License at
 *
 *     https://www.apache.org/licenses/LICENSE-2.0.txt
 *
 * Unless required by applicable law or agreed to in writing, software
 * distributed under the License is distributed on an "AS IS" BASIS,
 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
 * See the License for the specific language governing permissions and
 * limitations under the License.
 *
 *=====*/
```

See Chapter A.1 for further details on the ITK license.

C.5 Citations

Give credit to others' work. If when writing some piece of code (whether it is a class, group of classes or algorithm in a method) the theory, framework or implementation are based on some scientific work, cite the work. In general, a citation to the peer-reviewed scientific publication, including its Digital Object Identifier (DOI), is preferred. This helps avoiding issues with web links. In absence of such a reference, it is recommended that the link to the URL is written as it is (i.e. even if the maximum line width is exceeded). Do not use URL shortening services.

When documenting a class header, if citations are required, use the Doxygen `\par References` command to list the references in a separate and clearly visible paragraph.

For instance,

```
namespace itk
```

```

{
/** \class DiffusionTensor3DReconstructionImageFilter
 * \brief This class takes as input one or more reference image (acquired in the
 * absence of diffusion sensitizing gradients) and 'n' diffusion
 * weighted images and their gradient directions and computes an image of
 * tensors. (with DiffusionTensor3D as the pixel type). Once that is done, you
 * can apply filters on this tensor image to compute FA, ADC, RGB weighted
 * maps, etc.
 *
 * ...
 *
 * \par References
 * \li<a href="http://lmi.bwh.harvard.edu/papers/pdfs/2002/westinMEDIA02.pdf">[1]
 * </a>
 * Carl-Fredrik Westin, Stephan E. Maier, Hatsuho Mamata, Arya Nabavi, Ferenc
 * Andras Jolesz, and Ron Kikinis. "Processing and visualization for Diffusion
 * tensor MRI. Medical Image Analysis, 6(2):93-108, 2002
 * \li<a href="splweb.bwh.harvard.edu:8000/pages/papers/westin/ISMRM2002.pdf">[2]
 * </a>
 * Carl-Fredrik Westin, and Stephan E. Maier. A Dual Tensor Basis Solution to the
 * Stejskal-Tanner Equations for DT-MRI. Proceedings of the 10th International
 * Society of Magnetic Resonance In Medicine (ISMRM) Scientific Meeting \&
 * Exhibition, Honolulu (HW, USA), 2002.
 *
 * ...
 *
 * \sa DiffusionTensor3D SymmetricSecondRankTensor
 * \ingroup MultiThreaded TensorObjects
 * \ingroup ITKDiffusionTensorImage
 */

template <typename TReferenceImagePixelType,
          typename TGradientImagePixelType = TReferenceImagePixelType,
          typename TTensorPixelType = double,
          typename TMaskImageType = Image<unsigned char, 3>>
class ITK_TEMPLATE_EXPORT DiffusionTensor3DReconstructionImageFilter
: public ImageToImageFilter<Image<TReferenceImagePixelType, 3>,
                           Image<DiffusionTensor3D<TTensorPixelType>, 3>>
{
    ...
};

} // end namespace itk

```

The recommended bibliography style for citations is the L^AT_EXplain style.

Or in a method body,

```

template <unsigned int VDimension>
void
Solver<VDimension>::ApplyBC(int dimension, unsigned int matrix)
{
    ...
}

```

```
// Store the appropriate value in bc correction vector (-K12*u2)
//
// See
// http://titan.colorado.edu/courses.d/IFEM.d/IFEM.Ch04.d/IFEM.Ch04.pdf
// chapter 4.1.3 (Matrix Forms of DBC Application Methods) for more
// info.
m_LinearSystem->AddVectorValue(*cc, -d * fixedvalue, 1);
}
```

C.6 Naming Conventions

In general, names are constructed by using case change to indicate separate words, as in `TimeStamp`.

Other general rules that must be followed in naming ITK constructs are:

- Underscores are not used (with the sole exception of enums and member variables).
- Variable names are chosen carefully with the intention to convey the meaning behind the code.
- Names are generally spelled out; use of abbreviations is discouraged. While this does result in long names, it self-documents the code (e.g. use `Dimension`, `point`, `size`, or `vector`, instead of `D`, `pt`, `sz`, or `vec`, respectively). Abbreviations are allowable when in common use, and should be in uppercase as in `RGB`, or `ID` for “identifier”).

The above general conventions must be followed in all cases. Depending on whether the name is a

- **class**
- **file**
- **variable**
- **other name**

variations on this theme result as explained in the following subsections.

C.6.1 ITK

The acronym for the NLM Insight Segmentation and Registration Toolkit must always be written in capitals, i.e. `ITK`, when referring to it, e.g. in class documentation.

C.6.2 Naming Namespaces

Namespaces must be written in lowercase, e.g.

```
namespace itk
{
...
} // end namespace itk
```

C.6.3 Naming Classes

Classes are:

- Named beginning with a capital letter.
- Placed in the appropriate namespace, typically `itk::` (see Section C.7 on page 326).
- Named according to the following general rule:

```
class name = <algorithm><input><concept>
```

In this formula, the name of the algorithm or process (possibly with an associated adjective or adverb) comes first, followed by an input type (if the class is a filter), and completed by a concept name.

A concept is an informal classification describing what a class does. There are many concepts in ITK, the more common or important being:

- **Accessor:** Access and convert between types.
- **Adaptor:** Provide access to a portion of a complex pixel type.
- **Boundary:** The boundary of a cell.
- **Calculator:** Compute information.
- **Classifier:** Classify a pixel.
- **Container:** A container of objects such as points or cells.
- **Estimator:** Estimate a value or condition.
- **Factory:** Object factories are used to create instances.
- **Filter:** A class that participates in the data processing pipeline. Filters typically take one or more inputs and produce one or more outputs.
- **Function:** Evaluate a function at a given position.
- **Identifier:** A unique ID for accessing points, cells, or other entities.

- **Interface:** Classes that specify an abstract interface.
- **Interpolator:** Interpolate data values, for example at non-pixel values.
- **Iterator:** Traverse data in various ways (e.g., forward, backward, within a region, etc.)
- **Mapper:** Transform data from one form into another.
- **Metric:** Compute similarity between two objects.
- **Operator:** A class that applies a user-specified function to a region.
- **Optimizer:** A class that performs numerical optimization.
- **Pointer:** A `itk::SmartPointer` to an instance of a class. Almost all instances in ITK are referred to via SmartPointers.
- **Reader:** A class that reads a single data object (e.g., image or mesh).
- **Reference:** A type that refers to another object.
- **Region:** A subset of a data object, such as an image region.
- **Source:** A filter that initiates the data processing pipeline such as a reader or a procedural data generator.
- **Threader:** A class that manages multi-threading.
- **Traits:** A collection of template parameters used to control the instantiation of other classes.
- **Transform:** Various types of transformations including affine, procedural, and so on.
- **Writer:** A filter that terminates the data processing pipeline by writing data to disk or to a communications port.

The naming of classes is an art form; please review existing names to catch the spirit of the naming convention.

Conventions adopted in ITK for naming classes include:

- The “To” convention (such as in `itk::ImageToImageFilter`) is generally used for base classes, and when a filter converts from one data type to another. Derived classes do not continue the “To” convention. Classes like `itk::HistogramToTextureFeaturesFilter`, or `itk::ImageToHistogram` do not produce an image as outputs, but change the data type or produce a set of features. The expectation of an ITK filter name is that it maintains the same type (even when changing the dimensionality as when changing from an `itk::Image` to a `itk::VectorImage`) unless it has the “To” naming conventions.
- Adding the `Base` appendix to a base class name is generally discouraged.

Example names include:

- ShrinkImageFilter
- TriangleCell
- ScalarImageRegionIterator
- NeighborhoodIterator
- MapContainer
- BackwardDifferenceOperator

C.6.4 Naming Files

Files should have the same name as the class, with an “itk” prepended.

Header files are named `.h`, while implementation files are named either `.cxx` or `.hxx`, depending on whether they are implementations of templated classes.

For example, the class `itk::Image`

- is declared in the file `itkImage.h` and
- is defined in the file `itkImage.hxx` (because `itk::Image` is templated).

The class `itk::Object`

- is declared in the file `itkObject.h` and
- is defined in the file `itkObject.cxx`.

Naming Tests

Following the `TestDriver` philosophy, see Section 9.4 on page 205, test files must be named with the same name used to name the `main` method contained in the test file (`.cxx`). This name should generally be indicative of the class tested, e.g.

```
int  
itkTobogganImageFilterTest(int argc, char * argv[])
```

for a test that checks the `itk::TobogganImageFilter` class, and contained in the test file named `itkTobogganImageFilterTest.cxx`.

Note that all test files should start with the lowercase `itk` prefix. Hence, the `main` method name in a test is the sole exception to the method naming convention of starting all method names with capitals (see C.6.6).

A test's input argument number should always be named `argc`, and the input arguments `argv` for the sake of consistency.

If due to some constraint (e.g. nature of input images, number of input images, dimensionality) a class has multiple test files with minor changes in its content, the test files should be named following the convention

```
test filename = <filename><variation>
```

In this formula, the filename comes first, and is completed by the variation tested, conveying the meaning behind the test, e.g.

```
itkSimpleImageRegistrationTest.cxx
itkSimpleImageRegistrationTestWithMaskAndSampling.cxx
```

When the same test file is used by multiple tests in the corresponding `CMakeLists.txt`, for example, with different parameters, these different tests should be named following the convention

```
test name = <filename><variation>
```

In this formula, the filename comes first, and is completed by the variation tested, conveying the meaning behind the test, e.g.

```
itk_add_test(NAME itkHConcaveImageFilterTestFullyConnectedOff
  COMMAND ITKMathematicalMorphologyTestDriver
  --compare-MD5
  ${ITK_TEST_OUTPUT_DIR}/itkHConcaveImageFilterTestFullyConnectedOff.png
  bdlb5ab47f54cd97b5c6b454beel30e2
  itkHConcaveImageFilterTest DATA(${ITK_DATA_ROOT}/Input/Input-RA-Short.nrrd)
  ${ITK_TEST_OUTPUT_DIR}/itkHConcaveImageFilterTestFullyConnectedOff.png 2000
  0)
itk_add_test(NAME itkHConcaveImageFilterTestFullyConnectedOn
  COMMAND ITKMathematicalMorphologyTestDriver
  --compare-MD5
  ${ITK_TEST_OUTPUT_DIR}/itkHConcaveImageFilterTestFullyConnectedOn.png
  c7116406ded975955965226f6a69e28d
  itkHConcaveImageFilterTest DATA(${ITK_DATA_ROOT}/Input/Input-RA-Short.nrrd)
  ${ITK_TEST_OUTPUT_DIR}/itkHConcaveImageFilterTestFullyConnectedOn.png 2000 1)
```

If the test checks features that span multiple classes or other general features, the filename should adhere to the general convention of conveying the meaning behind the code, e.g.

```
int
itkSingleLevelSetWhitakerImage2DWithCurvatureTest(int argc, char * argv[])
```

means that the `itk::WhitakerSparseLevelSetImage` class is tested on two dimensions, using the `itk::LevelSetEquationCurvatureTerm` class to represent the curvature term in the level-set evolution PDE.

However, in these last cases, readability of the test name is important, and too long test names are discouraged.

See Section 9.4 on page 205 for further details about the ITK testing framework.

C.6.5 Examples

C.6.6 Naming Methods and Functions

Global functions and class methods, either static or class members, are named beginning with a capital letter. The biggest challenge when naming methods and functions is to be consistent with existing names. For example, given the choice between `ComputeBoundingBox()` and `CalculateBoundingBox()`, the choice is `ComputeBoundingBox()` because “Compute” is used elsewhere in the system in similar settings (i.e. the concepts described in Section C.6.3 should be used whenever possible).

Note that in the above example `CalcBoundingBox()` is not allowed because it is not spelled out.

Method argument names should be included in their declaration.

When declaring class methods, it is generally recommended to follow a logical order, not alphabetical, and group them by blocks separated by empty lines for the sake of readability.

The definition of the methods should follow this same order.

C.6.7 Naming Class Data Members

Class data members are prepended with `m_` as in `m_Size`. This clearly indicates the origin of data members, and differentiates them from all other variables. Furthermore, it is a key requirement for the correct application of the ITK macros (such as the `Get##name` and `Set##name` methods).

```
RadiusType m_Radius;
```

When declaring class data members, it is generally recommended to follow a logical order, not alphabetical, and group them by blocks separated by empty lines for the sake of readability.

C.6.8 Naming Enumerations

ITK uses strongly-typed enumerations through the `enum class` keyword. Enumerations in ITK need to be declared within a dedicated class and be declared as `public`. The class name must be appended with the `Enums` label (even when the class contains a single strongly-typed enumeration). Enumeration classes must declare their identifier before the `enum-list` is specified, it must start with capitals and be written with case change, and it shall not bear the `Type` appendix. The type of the enumeration must be defined explicitly. The streaming operator `<<` must be overloaded to define enumerations are printed. The `enum-list` must be specified in capitals. The documentation or comments added for each `enum-list` entry, if necessary, need not to be aligned.

For example,

```
/**  
 * \class MathematicalMorphologyEnums
```

```

*/ \brief Mathematical Morphology enum classes.
*/ \ingroup ITKMathematicalMorphology
*/

class MathematicalMorphologyEnums
{
public:
    /**\class Algorithm
     * \brief Algorithm or implementation used in the dilation/erosion operations.
     * \ingroup ITKMathematicalMorphology
     */
    enum class Algorithm : uint8_t
    {
        BASIC = 0,
        HISTO = 1,
        ANCHOR = 2,
        VHGW = 3
    };
};

/** Define how to print enumeration values. */
extern ITKMathematicalMorphology_EXPORT std::ostream &
operator<<(std::ostream & out,
           const MathematicalMorphologyEnums::Algorithm value);

```

The enumeration streaming method needs to be defined the implementation file, e.g.:

```

std::ostream &
operator<<(std::ostream & out,
           const MathematicalMorphologyEnums::Algorithm value)
{
    return out << [value] {
        switch (value)
        {
            case MathematicalMorphologyEnums::Algorithm::BASIC:
                return "itk::MathematicalMorphologyEnums::Algorithm::BASIC";
            case MathematicalMorphologyEnums::Algorithm::HISTO:
                return "itk::MathematicalMorphologyEnums::Algorithm::HISTO";
            case MathematicalMorphologyEnums::Algorithm::ANCHOR:
                return "itk::MathematicalMorphologyEnums::Algorithm::ANCHOR";
            case MathematicalMorphologyEnums::Algorithm::VHGW:
                return "itk::MathematicalMorphologyEnums::Algorithm::VHGW";
            default:
                return "INVALID VALUE FOR "
                    "itk::MathematicalMorphologyEnums::Algorithm";
        }
    } ();
}

```

Enumeration classes do not need to have their corresponding integral value specified, although it may be allowed (i.e. BASIC = 0,).

For the sake of brevity aliases can be defined for an enum class. These shall be appended with the Enum label, e.g.

```
using AlgorithmEnum = MathematicalMorphologyEnums::Algorithm;
```

When calling an enum class entry from within a class, it may not be called with the `Self::` class alias, e.g.

```
if (algo == AlgorithmEnum::BASIC)
{
    m_BasicFilter->SetKernel(this->GetKernel());
}
else if (algo == AlgorithmEnum::HISTO)
{
    m_HistogramFilter->SetKernel(this->GetKernel());
}
else if (flatKernel != nullptr && flatKernel->GetDecomposable() &&
        algo == AlgorithmEnum::ANCHOR)
{
    m_AnchorFilter->SetKernel(*flatKernel);
}
else if (flatKernel != nullptr && flatKernel->GetDecomposable() &&
        algo == AlgorithmEnum::VHGW)
{
    m_VHGWFilter->SetKernel(*flatKernel);
}
else
{
    itkExceptionMacro(<< "Invalid algorithm");
}
```

C.6.9 Naming Local Variables

Local variables begin in lowercase. There is more flexibility in the naming of local variables, but they should adhere to the general convention of conveying the meaning behind the code.

Please remember that others will review, maintain, fix, study and extend your code. Any bread crumbs that you can drop in the way of explanatory variable names and comments will go a long way towards helping other community members.

Temporary Variable Naming

Every effort should be made to properly name temporary variables of any type that may be used in a reduced part of a method, such as in

```
...
// Resize the schedules
ScheduleType schedule(m_NumberOfLevels, ImageDimension);
schedule.Fill(0);
m_Schedule = schedule;
...
```

For such temporary variables whose naming would be overly wordy to express their meaning or may be misleading, or may be re-used at multiple stages within a method (e.g. using the name `output` for intermediate results), the name `tmp` can be used.

```
...
ValueType dimension = static_cast<ValueType>(ImageDimension);

NormalVectorFilterType normalVectorFilter = NormalVectorFilterType::New();
...
normalVectorFilter->SetIsoLevelLow(-m_CurvatureBandWidth - dimension);
normalVectorFilter->SetIsoLevelHigh(m_CurvatureBandWidth + dimension);
...

// Move the pixel container and image information of the image we are working
// on into a temporary image to use as the input to the mini-pipeline. This
// avoids a complete copy of the image.
typename OutputImageType::Pointer output = this->GetOutput();
auto tmp = OutputImageType::New();
tmp->SetRequestedRegion(output->GetRequestedRegion());
tmp->SetBufferedRegion(output->GetBufferedRegion());
tmp->SetLargestPossibleRegion(output->GetLargestPossibleRegion());
tmp->SetPixelContainer(output->GetPixelContainer());
tmp->CopyInformation(output);

typename SparseImageType::Pointer sparseNormalImage =
    normalVectorFilter->GetOutput();
this->ComputeCurvatureTarget(tmp, sparseNormalImage);
m_LevelSetFunction->SetSparseTargetImage(sparseNormalImage);
```

Variable Initialization

A basic type variable declared and not being assigned immediately within a method should be initialized to its zero value.

Note the `weight` variable in the following example:

```
template <typename TInputImage>
double
WarpHarmonicEnergyCalculator<TInputImage>::EvaluateAtNeighborhood(
    ConstNeighborhoodIteratorType & it) const
{
    vnl_matrix_fixed<double, ImageDimension, VectorDimension> J;

    PixelType next, prev;

    double weight = 0;

    for (unsigned int i = 0; i < ImageDimension; ++i)
    {
        next = it.GetNext(i);
        prev = it.GetPrevious(i);
```

```

weight = 0.5 * m_DerivativeWeights[i];

for (unsigned int j = 0; j < VectorDimension; ++j)
{
    J[i][j] = weight *
        (static_cast<double>(next[j]) - static_cast<double>(prev[j]));
}

const double norm = J.fro_norm();
return norm * norm;
}

```

Take into account that many ITK variables, such as `itk::ImageRegion` class instances initialize themselves to zero, so they do not need to be initialized unless required. The following declaration would create a matrix with all zero by default:

```

// Define the dimension of the images
constexpr unsigned int ImageDimension = 2;

...

// Declare the type of the size
using SizeType = itk::Size<ImageDimension>;

SizeType size;
size[0] = 100;
size[1] = 100;

// Declare the type of the index to access images
using IndexType = itk::Index<ImageDimension>;

IndexType start;
start[0] = 0;
start[1] = 0;

// Declare the type of the Region
using RegionType = itk::ImageRegion<ImageDimension>;

RegionType region;
region.SetIndex(start);
region.SetSize(size);

```

Control Statement Variable Naming

Control statement variables names should be clear and concise. For simple counters over arrays, lists, maps elements or matrices, the `i`, `j`, `k` order is preferred, i.e. when requiring to walking over multiple dimensions, over, for example `ii`.

If more than three nested control statements are required, there is probably a better design that can be implemented.

For iterators, `inIt` and `outIt` are recommended if both input and output structures are involved. Otherwise, `it` can be used.

Variable Scope

Control statement variables should have a local scope. Hence, instead of declaring a method-scope variable and re-using it,

```
unsigned int i;
for (i = 0; i < ImageDimension; ++i)
{
    Something();
}
...
for (i = 0; i < ImageDimension; ++i)
{
    SomethingElse();
}
```

it is recommended to limit the scope of the variables to the control statements in which they are required:

```
unsigned int i = 0;
for (unsigned int i = 0; i < ImageDimension; ++i)
{
    Something();
}
...
for (unsigned int i = 0; i < ImageDimension; ++i)
{
    SomethingElse();
}
```

C.6.10 Naming Template Parameters

Template parameters follow the usual rules with naming except that they should start with either the capital letter “T” or “V”. Type parameters (such as the pixel type) begin with the letter “T” while value template parameters (such as the dimensionality) begin with the letter “V”.

```
template <typename TPixel, unsigned int VImageDimension = 2>
class ITK_TEMPLATE_EXPORT Image : public ImageBase<VImageDimension>
```

For template parameters the use of `typename` is preferred over `class`. Very early C++ compilers did not have a `typename` keyword, and `class` was purposed for declaring template parameters. It was later discovered that this led to ambiguity in some valid code constructs, and the `typename` key word was added. It is often agreed (<https://blogs.msdn.com/b/slippman/archive/2004/08/11/212768.aspx>) that `typename` is marginally more expressive in its intent and ITK should consistently use `typename` instead of `class`.

C.6.11 Naming Typedefs

Type aliases are absolutely essential in generic programming. They significantly improve the readability of code, and facilitate the declaration of complex syntactic combinations. Unfortunately, creation of type aliases is tantamount to creating another programming language. Hence type aliases must be used in a consistent fashion. The general rule for type alias names is that they end in the word “Type”. For example,

```
using PixelType = TPixel;
```

However, there are many exceptions to this rule that recognize that ITK has several important concepts that are expressed partially in the names used to implement the concept. An iterator is a concept, as is a container or pointer. These concepts are used in preference to `Type` at the end of a type alias as appropriate. For example,

```
using PixelContainer = typename ImageTraits::PixelContainer;
```

Here “Container” is a concept used in place of “Type”. ITK currently identifies the following concepts used when naming type aliases:

- **Self** as in

```
using Self = Image;
```

All classes should define this type alias.

- **Superclass** as in

```
using Superclass = ImageBase<VImageDimension>;
```

All classes should define the `Superclass` type alias.

- **Pointer** as in a smart pointer to an object as in

```
using Pointer = SmartPointer<Self>;
```

All classes should define the `Pointer` type alias.

- **Container** is a type of container class.
- **Iterator** an iterator over some container class.
- **Identifier** or id such as a point or cell identifier.

C.6.12 Naming Constants

Constants must start with capital letters, e.g.

```
constexpr unsigned int CodeAxisField = 14;
```

C.6.13 Using Operators to Pointers

The indirection unary operator (*) must be placed next to the variable, e.g.

```
int
itkTransformFileReaderTest(int argc, char * argv[])
```

or

```
const InputImageType * inputPtr = this->GetInput();
```

The reference or address unary operator (&) must be placed next to the variable, e.g.

```
const typename FixedImageType::RegionType & fixedRegion =
    m_FixedImage->GetLargestPossibleRegion();
```

or

```
::PrintSelf(std::ostream & os, Indent indent) const
```

C.6.14 Using Operators to Arrays

The subscript operator ([]) must be placed next to the variable, e.g.

```
int
itkGaborKernelFunctionTest(int argc, char * argv[])
```

or

```
unsigned int
GetSplitInternal(unsigned int dim,
                 unsigned int i,
                 unsigned int numberOfPieces,
                 IndexValueType regionIndex[],
                 SizeValueType regionSize[]) const override;
```

C.6.15 Using Underscores

Do not use underscores. The only exception is when defining preprocessor variables and macros (which are discouraged). In this case, underscores are allowed to separate words.

C.6.16 Include Guards

An include guard's case must mimic the one used for a file, with the file extension separated by an underscore

```
#ifndef itkImage_h
#define itkImage_h

// Class declaration code

#endif
```

and

```
#ifndef itkImage_hxx
#define itkImage_hxx

// Template class implementation code

#endif
```

Note that include guards in implementation files are to be used only for templated classes.

C.6.17 Preprocessor Directives

Some of the worst code contains many preprocessor directives and macros such as

```
#if defined(__APPLE__) && (__clang_major__ == 3) && \
    (__clang_minor__ == 0) && defined(NDEBUG) && defined(__x86_64__)
cc = -1.0 * itk::Math::sqr(1.0 / (cc + itk::Math::eps));
#else
cc = -1.0 * itk::Math::sqr(1.0 / cc);
#endif
```

Do not use them except in a very limited sense (to support minor differences in compilers or operating systems). If a class makes extensive use of preprocessor directives, it is a candidate for separation into multiple sub-classes.

However, if such directives are to be used, they should start in column one, regardless of the required indentation level of the code they contain.

C.6.18 Header Includes

Headers in ITK must be included using quotes (“ ”)

```
#include "itkImageRegion.h"
```

Only the required headers should be included. If an included header already includes a header for a class also used in the current file, the header for that class should not be included.

Header includes are preferred over forward declarations. Forward declarations are only used to prevent circular dependencies.

C.6.19 Const Correctness

As a general rule, the `const` type qualifier must be used for:

- Arguments which set the pipeline inputs, e.g.

```
/** Set the marker image. */
void
SetMaskImage(const MaskImageType * input)
{
    // Process object is not const-correct so the const casting is required.
    this->SetNthInput(1, const_cast<MaskImage *>(input));
}

/** Set the input image. */
void
SetInput1(const InputImageType * input)
{
    this->SetInput(input);
}

/** Set the marker image. */
void
SetInput2(const MaskImageType * input)
{
    this->SetMaskImage(input);
}
```

- Accessor / state functions, e.g.

```
bool
GetUseVectorBasedAlgorithm() const
{
    return HistogramType::UseVectorBasedAlgorithm();
}
```

C.6.20 Integer Type Specifiers

Throughout the code base, the built-in type `unsigned int` is spelled exactly like that: “unsigned int” (rather than just “unsigned”). Other built-in integer types should in general be specified by their shortest form. For example, “short”, “long”, and “long long” are preferred to “signed short int”, “signed long int”, and “signed long long int”.

Within the `itk` namespace, integer type aliases from C++ Standard headers for C library facilities (like `<cstdlib>` and `<cstdint>`) should generally be used without a `std::` prefix. For example, “`size_t`”, “`int8_t`”, and “`uintmax_t`” are preferred to “`std::size_t`”, “`std::int8_t`”, and “`std::uintmax_t`”. When using any of those type aliases, the ITK header file “`itkIntTypes.h`” may need to be `#included`, to ensure that those types are declared within the `itk` namespace.

C.7 Namespaces

All classes should be placed in the `itk::` namespace. Additional sub-namespaces are being designed to support special functionality, e.g.

```
namespace itk
{
  namespace fem
  {
    ...
  } // end namespace fem
} // end namespace itk
```

Please see current documentation to determine if there is a sub-namespace relevant to a specific situation. Normally sub-namespaces are used for helper ITK classes.

Code should not use `using namespace`. This is to avoid namespace conflicts, but, more importantly, to improve readability.

When declaring or defining members of the `itk::` namespace, for example, the `itk::` namespace prefix should not be added. That is, code within `namespace itk { ... }` should not use `itk::`.

The `::` global namespace should be used when referring to a global function, e.g.

```
// Execute the filter
clock_t start = ::clock();
m_Filter->UpdateLargestPossibleRegion();
clock_t stop = ::clock();
```

It helps clarifying exactly which method is exactly being invoked and where it originates.

Note that `itk::` should only be used outside the `itk::` namespace.

C.8 Aliasing Template Parameter Typenames

The public class typename's should be limited to the types that are required to be available by other classes. The typename's can clutter a class API and can restrict future refactoring that changes the types when unnecessary.

For instance,

```
template <typename TPixel, unsigned int VImageDimension = 2>
class ITK_TEMPLATE_EXPORT Image : public ImageBase<VImageDimension>
{
public:
  ITK_DISALLOW_COPY_AND_MOVE(Image);
```

```

/** Standard class type alias. */
using Self = Image;
using Superclass = ImageBase<VImageDimension>;
using Pointer = SmartPointer<Self>;
using ConstPointer = SmartPointer<const Self>;
using ConstWeakPointer = WeakPointer<const Self>;

...

/** Pixel type alias support. Used to declare pixel type in filters
 * or other operations. */
using PixelType = TPixel;
...

```

or

```

template <typename TImage>
class ITK_TEMPLATE_EXPORT ImageRegionIterator
: public ImageRegionConstIterator<TImage>
{
public:
    /** Standard class type alias. */
    using Self = ImageRegionIterator;
    using Superclass = ImageRegionConstIterator<TImage>;

    /** Types inherited from the Superclass */
    using IndexType = typename Superclass::IndexType;
    using SizeType = typename Superclass::SizeType;

    ...

```

C.9 Pipelines

The following is a set of useful tips that must be taken into account when developing ITK code:

- Do call `Update()` before using the pipeline output.
- Do call `UpdateLargestPossibleRegion()` when reusing a reader.

When reusing a reader you must call:

```
reader->UpdateLargestPossibleRegion()
```

instead of the usual:

```
reader->Update()
```

Otherwise the extent of the previous image is kept, and in some cases lead to Exceptions being thrown if the second image is smaller than the first one.

- Do not assume `inputImage->SetRequestedRegion(smallRegion)` will make the filter faster! The filter might run on the entire input image regardless. To make it run on a smaller block, get a new `itk::RegionOfInterestImageFilter`, say `ROIfilter`, and do:

```
ROIfilter->SetInput(inputImage);  
ROIfilter->SetRegionOfInterest(smallRegion);  
CCfilter->SetInput(ROIfilter->GetOutput());
```

- On a newly-manually-created image, do initialize the pixel values if you expect them to be so! ITK does not initialize the image buffer when you call `Allocate()`. It is your responsibility to initialize the pixel values, either by calling `Allocate(true)` or filling the image buffer as in:

```
image->FillBuffer(0); // Initialize it to all dark.
```

C.10 The auto Keyword

Available since C++11, the `auto` keyword specifies that a variable's type is automatically deduced from its initializer.

The `auto` keyword should be used to specify a type in the following cases:

- The type is duplicated on the left side of an initialization when it is mandated on the right side, e.g. when there is an explicit cast or initializing with `new` or ITK's `::New()`.
- When obtaining container elements, when the element type is obvious from the type of the container.
- When the type does not matter because it is not being used for anything other than equality comparison.
- When declaring iterators in a `for` loop.
- When a trailing return type is used in a function declaration.
- When creating lambda functions.

All other cases should not use `auto`, but a semantic type name should be used that conveys meaning, as described in Section [C.6](#) and Section [C.6.11](#) on page [322](#).

Application or example code that uses ITK, as opposed to the toolkit itself, may use `auto` more liberally.

C.11 Initialization and Assignment

C.11.1 Initialization of member variables

All member variables must be initialized when they are declared. For such purpose, brace initializers, e.g.

```
private:
    double    m_InnerRadius{ 1.0 };
    double    m_Thickness{ 1.0 };
    bool      m_Normalize{ false };
    bool      m_BrightCenter{ false };
    PixelType m_InteriorValue{};
    PixelType m_AnnulusValue{ NumericTraits<PixelType>::OneValue() };
    PixelType m_ExteriorValue{};
    SpacingType m_Spacing{ 1.0 };
```

and brace list initialization, e.g.

```
private:
    IndexType m_Index = { { 0 } };
    SizeType  m_Size  = { { 0 } };
```

are preferred over initialization lists in the method constructor, e.g.

```
template <typename TInputImage, typename TOutputImage>
SpecializedFilter<TInputImage, TOutputImage>::SpecializedFilter()
    : m_BackgroundValue{}
    , m_ForegroundValue(NumericTraits<OutputImagePixelType>::OneValue())
{
    ...
}
```

or assignment:

```
template <typename TInputImage, typename TOutputImage>
SpecializedFilter<TInputImage, TOutputImage>::SpecializedFilter()
{
    m_BackgroundValue = {};
    m_ForegroundValue = NumericTraits<OutputImagePixelType>::OneValue();

    ...
}
```

Exceptions to this guideline:

Private data members that are just there to add padding bytes between other (member) variables (typically to avoid false sharing in the context of multi-threading) should not be initialized. Such a padding data member is typically declared as a C-style array of a (possibly unsigned) character type.

A data member that is declared as `std::unique_ptr<T>` or `itk::SmartPointer<T>` should not have an empty `{}` initializer at its declaration, at least for now, because of a GCC issue (prior to GCC release 9.2), which would cause compilation errors when the type `T` is an incomplete (forward declared) class type.

Another exception is made for low level utility classes for which data member initialization would cause a significant performance penalty. This is why for example `FixedArray::m_InternalArray` and `Index::m_InternalArray` do not have a default member initializer.

C.11.2 Initializing variables of fixed size array types

ITK has various fixed size array types, including template instantiations of `Index`, `Size`, `FixedArray`, `Point`, and `Vector`.

A variable of such a fixed size array type can be zero-initialized by an empty initializer list, `.` This is usually the preferred way to initialize the variable, when it should initially be filled with zeroes. For example:

```
// Declare an index at position (0, 0).
Index<2> index{};

// Declare a point whose coordinates are all 0.0 (the origin).
PointType origin{};
```

`Index` and `Size` both have a static `Filled(fillValue)` member function, to allow creating a variable that is filled with an arbitrary value. For these types, this is usually the preferred way to initialize the variable, when it should initially be filled with a value that may be non-zero. For example:

```
// Declare the index {1, 1, 1}.
auto index = Index<3>::Filled(1);

// Declare the size of an 256 x 256 image.
auto imageSize = Size<2>::Filled(256);
```

For other fixed size array types, the function `itk::MakeFilled<T>(fillValue)` is preferable, when the array should initially be filled with a value that may be non-zero. For example:

```
// Declare a spacing filled with the value 0.5 (for each direction).
// SpacingType is typically defined as Vector<double, Dimension>.
auto spacing = MakeFilled<SpacingType>(0.5);
```

C.12 Accessing Members

The C++ keyword `this` must be used when calling a class' own methods:

```

template <typename TInputImage, typename TOutputImage>
void
ExpandImageFilter<TInputImage, TOutputImage>::GenerateInputRequestedRegion()
{
    // Call the superclass' implementation of this method
    Superclass::GenerateInputRequestedRegion();

    // Get pointers to the input and output
    InputImageType * inputPtr = const_cast<InputImageType *>(this->GetInput());
    const OutputImageType * outputPtr = this->GetOutput();

    ...
}

```

The use of the explicit `this->` pointer helps clarifying which method is exactly being invoked and where it originates.

The value of a member variables or data within a class must be retrieved calling the variable name directly, i.e. the use of its getter method (i.e. `GetMyVariable()`) is discouraged for such purpose. Similarly, the use of the `this` keyword when calling self data members is discouraged, i.e.

```

template <typename TInputImage, typename TOutputImage>
void
InterpolateImageFilter<InputImage, TOutputImage>::PrintSelf(
    std::ostream & os,
    Indent        indent) const
{
    Superclass::PrintSelf(os, indent);

    os << indent << "Distance: " << m_Distance << std::endl;
    ...
}

```

is preferred over

```

template <typename TInputImage, typename TOutputImage>
void
InterpolateImageFilter<TInputImage, TOutputImage>::PrintSelf(
    std::ostream & os,
    Indent        indent) const
{
    Superclass::PrintSelf(os, indent);

    os << indent << "Distance: " << m_Distance << std::endl;
    ...
}

```

C.13 Code Layout and Indentation

The following are the accepted ITK code layout rules and indentation style. After reading this section, you may wish to visit many of the source files found in ITK. This will help crystallize the

rules described here.

C.13.1 General Layout

- Each line of code should take no more than 200 characters.
- Break the code across multiple lines as necessary.
- Use lots of white space to separate logical blocks of code, intermixed with comments.
- To a large extent the structure of code directly expresses its implementation.
- The appropriate indentation level is **two spaces** for each level of indentation.
- **Do not use tabs**; set up your editor to insert spaces. Using tabs may look good in your editor but will wreak havoc in others.
- The declaration of variables within classes, methods, and functions should be one declaration per line:

```
int    i = 0;
int    j = 0;
char * stringName;
```

A short code snippet in ITK might look like:

```
if (condition)
{
    unsigned int numberOfIterations = 100;
    filter->SetNumberOfIterations(numberOfIterations);
    filter->Update();
    filter->Print(std::cout);
}
```

The body of a method must always be indented, starting with an indentation of two white spaces, and indenting the rest of the body as described in this section.

C.13.2 Class Layout

Classes are declared (.h) using the following guidelines:

- Begin with the Copyright notice.
- Follow with include guards (e.g `#ifndef itkBoxImageFilter_h`).
- Follow with the necessary includes. Include only what is necessary to avoid dependency problems.

- Place the class in the correct namespace.
- public methods come first.
- protected methods follow.
- private members come last.
- public data members are **forbidden**.
- End the namespaces.
- Templated classes require a special preprocessor directive to control the manual instantiation of templates. See the example below and look for ITK_MANUAL_INSTANTIATION.
- Close the include guards.

The class layout looks something like this:

```

/*=====
 *
 * Copyright NumFOCUS
 *
 * Licensed under the Apache License, Version 2.0 (the "License");
 * you may not use this file except in compliance with the License.
 * You may obtain a copy of the License at
 *
 *     https://www.apache.org/licenses/LICENSE-2.0.txt
 *
 * Unless required by applicable law or agreed to in writing, software
 * distributed under the License is distributed on an "AS IS" BASIS,
 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
 * See the License for the specific language governing permissions and
 * limitations under the License.
 *=====*/

#ifndef itkImage_h
#define itkImage_h

#include "itkImageRegion.h"
#include "itkImportImageContainer.h"
#include "itkDefaultPixelAccessor.h"
#include "itkDefaultPixelAccessorFunctor.h"
#include "itkPoint.h"
#include "itkFixedArray.h"
#include "itkWeakPointer.h"
#include "itkNeighborhoodAccessorFunctor.h"

#include <type_traits>

namespace itk
{

```

```

/** \class Image
 * \brief Templated N-dimensional image class.
 *
 * Detailed documentation...
 */

template <typename TPixel, unsigned int VImageDimension = 2>
class ITK_TEMPLATE_EXPORT Image : public ImageBase<VImageDimension>
{
public:
    ...

protected:
    ...

private:
    ...
};

} // end namespace itk

#ifdef ITK_MANUAL_INSTANTIATION
# include "itkImage.hxx"
#endif

#endif // itkImage_h

```

Many of the guidelines for the class declaration file are applied to the class definition (.hxx, .cxx) file:

- Begin with the Copyright notice.
- Follow with include guards in case of templated classes (e.g. `#ifndef itkBoxImageFilter_hxx`).
- Follow with the necessary includes. Include only what is necessary to avoid dependency problems.
- Place the class in the correct namespace.
- The constructor come first.
- The destructor follows.
- The `PrintSelf` member come last.
- End the namespaces.
- Close the include guards if present.

The class definition layout looks something like this:

```

/*=====
 *
 * Copyright NumFOCUS
 *
 * Licensed under the Apache License, Version 2.0 (the "License");
 * you may not use this file except in compliance with the License.
 * You may obtain a copy of the License at
 *
 *     https://www.apache.org/licenses/LICENSE-2.0.txt
 *
 * Unless required by applicable law or agreed to in writing, software
 * distributed under the License is distributed on an "AS IS" BASIS,
 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
 * See the License for the specific language governing permissions and
 * limitations under the License.
 *
 *=====*/
/*=====
 *
 * Portions of this file are subject to the VTK Toolkit Version 3 copyright.
 *
 * Copyright (c) Ken Martin, Will Schroeder, Bill Lorensen
 *
 * For complete copyright, license and disclaimer of warranty information
 * please refer to the NOTICE file at the top of the ITK source tree.
 *
 *=====*/

#ifndef itkImage_hxx
#define itkImage_hxx

#include "itkProcessObject.h"

#include <algorithm>

namespace itk
{
template <typename TPixel, unsigned int VImageDimension>
Image<TPixel, VImageDimension>::Image()
{
    m_Buffer = PixelContainer::New();
}

...

template <typename TPixel, unsigned int VImageDimension>
void
Image<TPixel, VImageDimension>::PrintSelf(std::ostream & os,
                                         Indent      indent) const
{
    Superclass::PrintSelf(os, indent);

    os << indent << "PixelContainer: " << std::endl;
}

```

```
m_Buffer->Print(os, indent.GetNextIndent());  
}  
  
} // end namespace itk  
#endif
```

Note that ITK headers are included first, and system or third party libraries follow.

C.13.3 Method Definition

Methods are defined across multiple lines. This is to accommodate the extremely long definitions possible when using templates. The starting and ending brace should be in column one, and the following order must be followed:

- The first line is the template declaration.
- The second line is the method return type.
- The third line is the class qualifier and the name of the method.

e.g.

```
template <typename TPixel, unsigned int VImageDimension>  
unsigned int  
Image<TPixel, VImageDimension>::GetNumberOfComponentsPerPixel() const  
{  
    ...  
}
```

The same rules apply for non-templated classes:

```
void  
Bruker2DSEQImageIO::PrintSelf(std::ostream & os, Indent indent) const  
{  
    ...  
}
```

If the line length exceed the threshold set by the automatic style enforcement tool, they will be automatically be formatted.

Due to different line length rules in this text book, the name of the method may be split into a separate line.

C.13.4 Use of Braces

Braces in Control Sequences

Braces must be used to delimit the scope of an `if`, `for`, `while`, `switch`, or other control structure.

```
for (unsigned int i = 0; i < ImageDimension; ++i)
{
    ...
}
```

or when using an `if`:

```
if (condition)
{
    ...
}
else if (otherCondition)
{
    ...
}
else
{
    ...
}
```

In `switch` statement cases, the constant-expression statement bodies should not be enclosed with braces:

```
switch (m_OperationQ.front())
{
    case Self::SET_PRIORITY_LEVEL:
        m_PriorityLevel = m_LevelQ.front();
        m_LevelQ.pop();
        break;
    case Self::SET_LEVEL_FOR_FLUSHING:
        m_LevelForFlushing = m_LevelQ.front();
        m_LevelQ.pop();
        break;
    ...
    default:
        break;
}
```

In `do-while` statements the opening/closing braces must lie on a line of their own:

```
do
{
    k += 1;
    p *= rand->GetVariate();
} while (p > L);
```

Braces in Arrays

When initializing an array, no space shall be left between the first value and the opening brace, and the last argument and closing brace:

```
// Define the image size in image coordinates, and origin and spacing in
// physical coordinates.
SizeType size = { { 20, 20, 20 } };
double origin[3] = { 0.0, 0.0, 0.0 };
double spacing[3] = { 1, 1, 1 };
```

C.13.5 Indentation and Tabs

The ITK style bans the use of tabs. Contributors should configure their editors to use white spaces instead of tabs. The size of the indent in ITK is fixed to **two white spaces**.

```
template <typename TInputImage, typename TOutputImage = TInputImage>
class ITK_TEMPLATE_EXPORT SpecializedFilter
: public ImageToImageFilter<TInputImage, TOutputImage>
{
public:
    using Self = SpecializedFilter;
    using Superclass = ImageToImageFilter<TInputImage, TOutputImage>;
    using Pointer = SmartPointer<Self>;
    using ConstPointer = SmartPointer<const Self>;

    /** Method for creation through the object factory. */
    itkNewMacro(Self);

    /** Run-time type information (and related methods) */
    itkOverrideGetNameOfClassMacro(SpecializedFilter);

    ...
};
```

or for the implementation of a given method:

```
template <typename TInputImage, typename TOutputImage>
void
SpecializedFilter<TInputImage, TOutputImage>::GenerateData() const
{
    // Allocate the outputs.
    this->AllocateOutputs();

    // Create a process accumulator for tracking the progress of this
    // minipipeline.
    auto progress = ProgressAccumulator::New();
    progress->SetMiniPipelineFilter(this);

    ...
}
```

ITK uses the Allman indentation style, with the braces associated with a control statement on the next line, indented to the same level as the control statement. Thus, source code in the body of the brackets must be indented.

```
while (x == y)
{
    Something();
}
```

C.13.6 White Spaces

As a general rule, a single white space should be used to separate every word.

However, no white space shall be added between type names, keywords, and method names and the following marks:

- An opening angle bracket (<) and the `template` keyword.
- An opening round bracket (() and its preceding word (e.g. in method declarations and definitions).
- An opening/closing brace ({/}) and its subsequent/preceding word (e.g. when initializing an array).
- An opening or closing square bracket ([,]) and its contents (e.g. when specifying the index of an array).
- The constant expression termination colon in a `switch` statement (e.g. `case Self::SET_PRIORITY_LEVEL:`).
- Semicolons (;) and their preceding word (e.g. end of a statement, etc.).

To the contrary, a single white space should be added between

- An opening angle bracket (<) and the subsequent template, variable or keyword.
- A closing angle bracket (>) and the preceding and subsequent words (such as in type aliases).
- An opening/closing round bracket (/) and its subsequent/preceding word (e.g. in method argument lists).
- Individual members in a list separated by commas (e.g. `SizeType size = 20, 20, 20, or data[i, j]`). The comma must be always placed next to a given element, and be followed by the single white space.
- Operators(i.e. `+`, `-`, `=`, `==`, `+=`, `<<`, etc.) and the left-hand and right-hand arguments.

- The ternary operators (`?`, `:`) and the left-hand condition, and right-hand values.
- Control statements (i.e. `if`, `for`, `while`, `switch`, etc.) and their conditional statements or arguments.
- The different parts of a `for` control statement.

```
for (unsigned int i = 0; i < ImageDimension; ++i)
{
    ...
}
```

- A method call parentheses and its content

```
this->SomeMethod(param, a + b);
```

Thus, for a class declaration we would write

```
template <typename TInputImage, typename TOutputImage = TInputImage>
class ITK_TEMPLATE_EXPORT SpecializedFilter
: public ImageToImageFilter<TInputImage, TOutputImage>
{
public:
    using Self = SpecializedFilter;
    using Superclass = ImageToImageFilter<TInputImage, TOutputImage>;
    using Pointer = SmartPointer<Self>;
    using ConstPointer = SmartPointer<const Self>;

    /** Method for creation through the object factory. */
    itkNewMacro(Self);

    /** Run-time type information (and related methods) */
    itkOverrideGetNameOfClassMacro(SpecializedFilter);

    // ...
};
```

And for a class constructor we would write

```
template <typename TInputImage, typename TOutputImage>
SpecializedFilter<TInputImage, TOutputImage>::SpecializedFilter()
{
    // The filter requires two inputs
    this->SetNumberOfRequiredInputs(2);
}
```

Trailing white spaces are not allowed in ITK.

C.13.7 Grouping

Unnecessary parentheses for grouping hinder reading the code. The C++ precedence and associativity (the order in which the operands are evaluated) of operators must be taken into account to avoid using unnecessary parentheses.

As a general principle, these apply to condition expressions, and statements where mathematical, logical or bitwise operations are performed.

Conditional Expressions

In conditional expressions contained in control statements (e.g. `if`, `for`, `while`, etc.) composed by multiple operands (e.g. joined using the logical operators), assignments and other constructs where such expressions are involved, the use of excessive parentheses is discouraged.

For example, the style below:

```
if (modelFile == "tri3-q.meta" && (s == 2 || s == 1))
{
    ...
}
else
{
    ...
}
```

is recommended over:

```
if ((modelFile == "tri3-q.meta") && ((s == 2) || (s == 1)))
{
    ...
}
else
{
    ...
}
```

Assignments

In assignments, the operator precedence and associativity rules apply to help keeping the code readable and void of operators in-excess. In assignments that do not involve long expressions that would otherwise be hard and time-consuming to interpret, the use of parentheses should be avoided.

For example, in

```
sum[dim] += (component * weight);
```

grouping is not necessary, as only a single operator exists in the right-hand operand. Hence, instead of writing the above code, community members should rather write:

```
sum[dim] += component * weight;
```

Return Statements

In return statements, using parentheses should be avoided when they are not strictly necessary for the evaluation of the returned term. For example, when returning variables or method calls, as in:

```
OutputType
Evaluate(const PointType & point) const override
{
    ContinuousIndexType index;

    this->GetInputImage()->TransformPhysicalPointToContinuousIndex(point,
                                                                    index);

    // No thread info passed in, so call method that doesn't need thread
    // identifier.
    return this->EvaluateDerivativeAtContinuousIndex(index);
}
```

The same principle applies when returning the result of an algebraic, logical or bitwise operation that does not require using parentheses to specify evaluation preference, such as in:

```
template <typename TPoint>
double
SimpleSignedDistance(const TPoint & p)
{
    ...
    return accum - radius;
}
```

instead of writing `return (accum - radius);`.

Or in:

```
bool
RealTimeStamp::operator>(const Self & other) const
{
    if (this->m_Seconds > other.m_Seconds)
    {
        return true;
    }

    if (this->m_Seconds < other.m_Seconds)
    {
        return false;
    }
}
```

```
return this->m_MicroSeconds > other.m_MicroSeconds;
}
```

Or in:

```
IntegerType mixBits(const IntegerType & u, const IntegerType & v) const
{
    return hiBit(u) | loBits(v);
}
```

C.13.8 Alignment

In every ITK file, the following code parts always start in column one:

- Copyright notice.
- Namespace opening/closing braces.
- Include guards.

The following specific parts of a class declaration always start in column one:

- Class documentation.
- Template declaration.
- Class declaration, including its opening/closing braces.
- Manual instantiation preprocessor directives.
- Access modifiers.

For instance,

```
/*=====
 *
 * Copyright NumFOCUS
 *
 * Licensed under the Apache License, Version 2.0 (the "License");
 * you may not use this file except in compliance with the License.
 * You may obtain a copy of the License at
 *
 *     https://www.apache.org/licenses/LICENSE-2.0.txt
 *
 * Unless required by applicable law or agreed to in writing, software
 * distributed under the License is distributed on an "AS IS" BASIS,
 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
 * See the License for the specific language governing permissions and
 * limitations under the License.
 */
```

```

*
*=====*/

#ifndef itkImage_h
#define itkImage_h

#include "itkImageBase.h"

namespace itk
{

/** \class Image
 * \brief Templated N-dimensional image class.
 *
 * Detailed documentation...
 */

template <typename TPixel, unsigned int VImageDimension = 2>
class ITK_TEMPLATE_EXPORT Image : public ImageBase<VImageDimension>
{
public:
    ...

protected:
    ...

private:
    ...
};

} // end namespace itk

#ifndef ITK_MANUAL_INSTANTIATION
# include "itkImage.hxx"
#endif

#endif // itkImage_h

```

In a class implementation, the following code parts always start in column one:

- Method definition,
- Method opening/closing braces.

For instance,

```

template <typename TPixel, unsigned int VImageDimension>
unsigned int
Image<TPixel, VImageDimension>::GetNumberOfComponentsPerPixel() const
{
    ...
}

```


Member data declarations should also be aligned when they are declared in consecutive lines.

```
std::string          m_FileName;
ConstTransformListType m_TransformList;
bool                m_AppendMode{ false };

bool                m_UseCompression{ false };
typename TransformIOType::Pointer m_TransformIO;
```

By virtue of the principles in Section , method calls on consecutive lines should not align their parentheses, i.e. use:

```
normalVectorFilter->SetIsoLevelLow(-m_CurvatureBandWidth - dimension);
normalVectorFilter->SetIsoLevelHigh(m_CurvatureBandWidth + dimension);
normalVectorFilter->SetMaxIteration(m_MaxNormalIteration);
normalVectorFilter->SetUnsharpMaskingFlag(m_NormalProcessUnsharpFlag);
normalVectorFilter->SetUnsharpMaskingWeight(m_NormalProcessUnsharpWeight);
```

avoiding:

```
normalVectorFilter->SetIsoLevelLow      (-m_CurvatureBandWidth - dimension);
normalVectorFilter->SetIsoLevelHigh     (m_CurvatureBandWidth + dimension);
normalVectorFilter->SetMaxIteration     (m_MaxNormalIteration);
normalVectorFilter->SetUnsharpMaskingFlag (m_NormalProcessUnsharpFlag);
normalVectorFilter->SetUnsharpMaskingWeight (m_NormalProcessUnsharpWeight);
```

The same principle applies to consecutive statements involving any type of operator. Prefer:

```
double weight = 0.;
double distance = 0.;
```

over

```
double weight  = 0.;
double distance = 0.;
```

Lines exceeding the recommended line length in ITK that are split in several lines must be consecutive, and must be aligned with two-space indentation:

```
if (coeff.size() > m_MaximumKernelWidth)
{
    itkWarningMacro(
        "Kernel size has exceeded the specified maximum width of "
        << m_MaximumKernelWidth << " and has been truncated to "
        << static_cast<unsigned long>(coeff.size())
        << " elements. You can raise "
        "the maximum width using the SetMaximumKernelWidth method.");
    break;
}
```

is preferred over

```

if (coeff.size() > m_MaximumKernelWidth)
{
    itkWarningMacro("Kernel size has exceeded the specified maximum width of "
        << m_MaximumKernelWidth << " and has been truncated to "
        << static_cast<unsigned long>(coeff.size()) << " elements. You can raise "
        "the maximum width using the SetMaximumKernelWidth method.");
    break;
}

```

The same principle applies to method declarations:

```

unsigned int
GetSplitInternal(unsigned int dim,
    unsigned int i,
    unsigned int numberOfPieces,
    IndexValueType regionIndex[],
    SizeValueType regionSize[]) const override;

```

is preferred over

```

unsigned int GetSplitInternal( unsigned int dim,
    unsigned int i,
    unsigned int numberOfPieces,
    IndexValueType regionIndex[],
    SizeValueType regionSize[] ) const override;

```

C.13.9 Line Splitting Policy

Lines exceeding the recommended line length in ITK must be split in the necessary amount of lines. This policy is enforced by the KWStyle pre-commit hooks (see [Section C.3.2](#) on page 306).

If a line has to be split, the following preference order is established in ITK:

- Split the right-hand operand in an assignment =, e.g.

```

const typename FixedImageType::RegionType & fixedRegion =
    m_FixedImage->GetLargestPossibleRegion();

```

- Split after the comma separator (,) in a list, e.g.

```

using FilterType = AddImageFilter<BiasFieldControlPointLatticeType,
    BiasFieldControlPointLatticeType,
    BiasFieldControlPointLatticeType>

```

- Split before the math operator (+, *, ||, &&, etc.) in an arithmetic or logical operation:, e.g.

```

while (m_ElapsedIterations++ < m_MaximumNumberOfIterations[m_CurrentLevel]
    && m_CurrentConvergenceMeasurement > m_ConvergenceThreshold)

```

or

```
centerFixedIndex[k] =  
    static_cast<ContinuousIndexValueType>(fixedIndex[k])  
    + static_cast<ContinuousIndexValueType>(fixedSize[k] - 1) / 2.0;
```

C.13.10 Empty Lines

As a general rule, empty lines should be used to separate code blocks that semantically belong to separate operations, or when a portion of code is too long. In the latter case, adding documentation lines contributes to the readability of the code.

However, no empty lines shall be added between:

- The accessor type (`public`, `protected`, `private`) and the declaration that immediately follows it.
- An opening/closing brace (`{/}`) and its subsequent/preceding line (e.g. nested namespace braces, method definition and its body, control statements, etc).

However, an empty line should exist in a header file (`.h`)

- Between the Copyright notice and the include guards (e.g. `#ifndef itkBoxImageFilter_`
`h`).
- Between the pre-processor directives and the header includes.
- Between the header includes and the ITK namespace (i.e. `namespace itk`).
- Between the ITK namespace brace and the class documentation.
- Between the class documentation and the class declaration.
- Between the access modifier and its preceding declaration, unless for the first declaration of `public`.
- Between method declarations (including their corresponding documentation block).
- Between a member method declaration and any member variable declaration that immediately follows.
- Between the ITK namespace end brace `}// end namespace itk` and further pre-processor directives `#ifndef ITK_MANUAL_INSTANTIATION`.
- Between the closing pre-processor directives and include guards `#endif`.

For instance,

```

/*=====
 *
 * Copyright NumFOCUS
 *
 * Licensed under the Apache License, Version 2.0 (the "License");
 * you may not use this file except in compliance with the License.
 * You may obtain a copy of the License at
 *
 *     https://www.apache.org/licenses/LICENSE-2.0.txt
 *
 * Unless required by applicable law or agreed to in writing, software
 * distributed under the License is distributed on an "AS IS" BASIS,
 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
 * See the License for the specific language governing permissions and
 * limitations under the License.
 *
 *=====*/

#ifndef itkBoxImageFilter_h
#define itkBoxImageFilter_h

#include "itkImageToImageFilter.h"
#include "itkCastImageFilter.h"

namespace itk
{
/** \class BoxImageFilter
 * \brief A base class for all the filters working on a box neighborhood.
 *
 * This filter provides the code to store the radius information about the
 * neighborhood used in the subclasses.
 * It also conveniently reimplement the GenerateInputRequestedRegion() so
 * that region is well defined for the provided radius.
 *
 * \author Gaetan Lehmann. Biologie du Developpement et de la Reproduction,
 * INRA de Jouy-en-Josas, France.
 * \ingroup ITKImageFilterBase
 */

template <typename TInputImage, typename TOutputImage>
class ITK_TEMPLATE_EXPORT BoxImageFilter
: public ImageToImageFilter<TInputImage, TOutputImage>
{
public:
    ITK_DISALLOW_COPY_AND_ASSIGN(BoxImageFilter);

    /** Standard class type alias. */
    using Self = BoxImageFilter;
    using Superclass = ImageToImageFilter<TInputImage, TOutputImage>;

    ...

protected:
    BoxImageFilter();

```

```

~BoxImageFilter() override = default;

void
GenerateInputRequestedRegion() override;

void
PrintSelf(std::ostream & os, Indent indent) const override;
private:
    RadiusType m_Radius;
};

} // end namespace itk

#ifdef ITK_MANUAL_INSTANTIATION
# include "itkBoxImageFilter.hxx"
#endif

#endif // itkBoxImageFilter_h

```

An empty line should exist in an implementation file (.cxx, .hxx):

- Between the Copyright notice and the include guard (e.g. `#ifndef itkBoxImageFilter_hxx`).
- Between the pre-processor directives and the header includes.
- Between the header includes and the class implementation.
- Between the ITK namespace end brace `}// end namespace itk` and closing include guard `#endif`.

Two empty lines are recommended between method definitions for the sake of readability. For instance,

```

/*=====
 *
 * Copyright NumFOCUS
 *
 * Licensed under the Apache License, Version 2.0 (the "License");
 * you may not use this file except in compliance with the License.
 * You may obtain a copy of the License at
 *
 *     https://www.apache.org/licenses/LICENSE-2.0.txt
 *
 * Unless required by applicable law or agreed to in writing, software
 * distributed under the License is distributed on an "AS IS" BASIS,
 * WITHOUT WARRANTIES OR CONDITIONS OF ANY KIND, either express or implied.
 * See the License for the specific language governing permissions and
 * limitations under the License.
 *
 */

```

```

===== */

#ifndef itkSpecializedImageFilter_hxx
#define itkSpecializedImageFilter_hxx

#include "itkProgressAccumulator.h"

namespace itk
{

template <typename TInputImage, typename TOutputImage>
SpecializedImageFilter<TInputImage, TOutputImage>::SpecializedImageFilter()
{
    this->DynamicMultiThreadingOn();
}

template <typename TInputImage, typename TOutputImage>
void
SpecializedImageFilter<TInputImage, TOutputImage>::SetRadius(
    const RadiusType & radius)
{
    if (m_Radius != radius)
    {
        m_Radius = radius;
        this->Modified();
    }
}

template <typename TInputImage, typename TOutputImage>
void
SpecializedImageFilter<TInputImage, TOutputImage>::PrintSelf(
    std::ostream & os,
    Indent      indent) const
{
    Superclass::PrintSelf(os, indent);

    os << indent << "Radius: " << m_Radius << std::endl;
}

} // end namespace itk

#endif // itkSpecializedImageFilter_hxx

```

Logical code blocks that must dwell in the same method but which may not be tightly related can be separated by two empty lines at most, e.g.

```

int
itkHMinimaImageFilterTest(int argc, char * argv[])
{
    ...

    hMinimaFilter->SetInput(reader->GetOutput());
}

```

```

// Run the filter
ITK_TRY_EXPECT_NO_EXCEPTION(hMinimaFilter->Update());

// Write the output
using WriterType = itk::ImageFileWriter<OutputImageType>;
auto writer = WriterType::New();
writer->SetFileName(argv[2]);
writer->SetInput(hMinimaFilter->GetOutput());

ITK_TRY_EXPECT_NO_EXCEPTION(writer->Update());

std::cout << "Test finished." << std::endl;
return EXIT_SUCCESS;
}

```

However, it is preferable to use a single empty line and use a comment block using the `//` character to describe the part of the code at issue, as in:

```

int
itkHMinimaImageFilterTest(int argc, char * argv[])
{
    if (argc != 5)
    {
        std::cerr << "Missing parameters." << std::endl;
        std::cerr << "Usage: " << itkNameOfTestExecutableMacro(argv);
        std::cerr << "  inputImageFile"
                  << "  outputImageFile"
                  << "  height"
                  << "  fullyConnected" << std::endl;
        return EXIT_FAILURE;
    }

    // Define the input and output pixel types and their associated image types.
    constexpr unsigned int Dimension = 2;

    using InputPixelType = short;
    using OutputPixelType = unsigned char;

    ...
}

```

or just have an empty line before and after the comment, such as in:

```

template <typename TInputImage, typename TMaskImage, typename TOutputImage>
void
N4BiasFieldCorrectionImageFilter<TInputImage, TMaskImage, TOutputImage>::
    SharpenImage(const RealImageType * unsharpenedImage,
                 RealImageType * sharpenedImage) const
{
    const auto maskImageBufferRange =

```

```

    MakeImageBufferRange(this->GetMaskImage());
    const auto confidenceImageBufferRange =
        MakeImageBufferRange(this->GetConfidenceImage());
    const MaskPixelType maskLabel = this->GetMaskLabel();
    const bool useMaskLabel = this->GetUseMaskLabel();

    // Build the histogram for the uncorrected image. Store copy
    // in a vnl_vector to utilize vnl FFT routines. Note that variables
    // in real space are denoted by a single uppercase letter whereas their
    // frequency counterparts are indicated by a trailing lowercase 'f'.

    RealType binMaximum = NumericTraits<RealType>::NonpositiveMin();
    RealType binMinimum = NumericTraits<RealType>::max();

    ImageRegionConstIterator<RealImageType> itU(
        unsharpenedImage, unsharpenedImage->GetLargestPossibleRegion());

    ...
}

```

Empty lines are not allowed to contain white spaces in ITK.

Logical blocks may be separated by a single-line comment (`// Comment`) if necessary in the implementation file (`.h`). No comment line or any other separation string (e.g. `/*****`) must be placed between the definition of two methods in the implementation file (`.cxx`, `.hxx`).

C.13.11 New Line Character

Use `std::endl` to introduce a new line instead of `\n` in string literals, e.g.

```

template <typename TInputImage>
void
MinimumMaximumImageCalculator<TInputImage>::PrintSelf(std::ostream & os,
                                                         Indent indent) const
{
    Superclass::PrintSelf(os, indent);

    os << indent << "Minimum: "
        << static_cast<typename NumericTraits<PixelType>::PrintType>(m_Minimum)
        << std::endl;
    os << indent << "Maximum: "
        << static_cast<typename NumericTraits<PixelType>::PrintType>(m_Maximum)
        << std::endl;
    os << indent << "IndexOfMinimum: " << m_IndexOfMinimum << std::endl;
    os << indent << "IndexOfMaximum: " << m_IndexOfMaximum << std::endl;
    itkPrintSelfObjectMacro(Image);
    os << indent << "Region: " << std::endl;
    m_Region.Print(os, indent.GetNextIndent());
    os << indent << "RegionSetByUser: " << m_RegionSetByUser << std::endl;
}

```


C.13.12 End Of File Character

The file must be terminated by a (preferably single) blank line. This policy is enforced by the KWStyle pre-commit hooks (see Section [C.3.2](#) on page [306](#)).

C.14 Increment/decrement Operators

Systematically use the pre-increment(decrement) syntax, instead of the post-increment(decrement) syntax:

```
for (unsigned int i = 0; i < ImageDimension; ++i)
{
    ...
}
```

Although the advantage can be very little when using it with a standard type, in the case of iterators over potentially large structures, the optimization performed by modern compilers may involve a significant advantage:

```
while (it != m_Container.end())
{
    ...
    ++it;
}
```

C.15 Trailing Return Types

Whenever choosing between a trailing return type (as introduced with C++11) and the old form of having the return type before the function name (as was already supported by C++98), prefer the form that is the shortest, and the simplest.

In the following example, the old form is preferred over a trailing return type:

```
// Preferred:
template <typename T1, typename T2>
bool
AlmostEquals(T1 x1, T2 x2)

// Rather than:
template <typename T1, typename T2>
auto
AlmostEquals(T1 x1, T2 x2) -> bool
```

In the following example, a trailing return type is preferred over the old form:

```
// Preferred:
template <typename TValue, unsigned int VLength>
auto
FixedArray<TValue, VLength>::Size() const -> SizeType

// Rather than:
template <typename TValue, unsigned int VLength>
typename FixedArray<TValue, VLength>::SizeType
FixedArray<TValue, VLength>::Size() const
```

C.16 Empty Arguments in Methods

The use of the `void` keyword is discouraged for methods not requiring input arguments. Hence, they are declared and called with an empty opening/closing parenthesis pair:

```
/** Method doc. */
void
methodName();
```

and

```
this->methodName();
```

C.17 Ternary Operator

The use of the ternary operator

```
for (unsigned int i = 0; i < m_NumOfThreads; ++i)
{
    for (unsigned int j = (i == 0 ? 0 : m_Boundary[i - 1] + 1);
        j <= m_Boundary[i];
        ++j)
    {
        m_GlobalZHistogram[j] = m_Data[i].m_ZHistogram[j];
    }
}
```

is generally discouraged in ITK, especially in cases where complicated statements have any part of the ternary operator.

Thus, the above should be expanded to

```
for (unsigned int i = 0; i < m_NumOfThreads; ++i)
{
    if (i == 0)
```

```

{
    for (unsigned int j = 0; j <= m_Boundary[i]; ++j)
    {
        m_GlobalZHistogram[j] = m_Data[i].m_ZHistogram[j];
    }
}
else
{
    for (unsigned int j = m_Boundary[i - 1] + 1; j <= m_Boundary[i]; ++j)
    {
        m_GlobalZHistogram[j] = m_Data[i].m_ZHistogram[j];
    }
}
}

```

or, performing a code refactoring:

```

for (unsigned int j = 0; j <= m_Boundary[i]; ++j)
{
    m_GlobalZHistogram[j] = m_Data[0].m_ZHistogram[j];
}
for (unsigned int i = 1; i < m_NumOfThreads; ++i)
{
    for (unsigned int j = m_Boundary[i - 1] + 1; j <= m_Boundary[i]; ++j)
    {
        m_GlobalZHistogram[j] = m_Data[i].m_ZHistogram[j];
    }
}

```

However, in simple constructs, such as when initializing a variable that could be const, e.g.

```

for (unsigned int i = 0; i < ImageDimension; ++i)
{
    const elementSign = (m_Step[i] > 0) ? 1.0 : -1.0;
    flipMatrix[i][i] = elementSign;
}

```

a ternary operator can have significant advantage in terms of the reading speed over the alternative if-else statement with duplicated syntax:

```

for (unsigned int i = 0; i < ImageDimension; ++i)
{
    if (m_Step[i] > 0)
    {
        elementSign = 1.0;
    }
    else
    {
        elementSign = -1.0;
    }
    flipMatrix[i][i] = elementSign;
}

```

And hence, the ternary operator is accepted in such cases.

C.18 Using Standard Macros

There are several macros defined in the file `itkMacro.h`. These macros should be used because they perform several important operations that if not done correctly can cause serious, hard to debug problems in the system.

These operations are:

- Object modified time is properly managed.
- Debug information is printed.
- Reference counting is handled properly.
- Disallow copy semantics by deleting copy constructor and assignment operator.

Some of the more important object macros are:

- `itkNewMacro(T)`: Creates the static class method `New()` that interacts with the object factory to instantiate objects. The method returns a `SmartPointer<T>` properly reference counted.
- `itkOverrideGetNameOfClassMacro(thisClass)`: Adds an override of the `GetNameOfClass()` method to the class.
- `ITK_DISALLOW_COPY_AND_ASSIGN(TypeName)`: Disallow copying by declaring copy constructor and assignment operator deleted. This must be declared in the **public** section.
- `ITK_DEFAULT_COPY_AND_MOVE(TypeName)`: Enables copying and moving by explicitly defaulting the copy constructor, copy assignment operator, move constructor, and move assignment operator of a class. Especially useful for classes that have a user-defined destructor. Intended to be placed in the **public** section of a class.
- `itkDebugMacro(x)`: If debug is set on a subclass of `itk::Object`, prints debug information to the appropriate output stream.
- `itkStaticConstMacro(name, type, value)`: Creates a static const member of type `type` and sets it to the value `value`.
- `itkSetMacro(name, type)`: Creates a method `SetName()` that takes an argument of type `type`.
- `itkGetMacro(name, type)`: Creates a method `GetName()` that returns a non-const value of type `type`.
- `itkGetConstMacro(name, type)`: Creates a method `GetName()` that returns a const value of type `type`.

- `itkSetStringMacro(name)`: Creates a method `SetName()` that takes an argument of type `const char*`.
- `itkGetStringMacro(name)`: Creates a method `GetName()` that returns an argument of type `const char*`.
- `itkBooleanMacro(name)`: Creates two methods named `NameOn` and `NameOff` that set `true/false` boolean values.
- `itkSetObjectMacro(name, type)`: Creates a method `SetName()` that takes argument type `type *`. For ITK objects, `itkSetObjectMacro` must be used in lieu of `itkSetMacro`.
- `itkGetConstObjectMacro(name, type)`: Creates a method named `GetName()` that returns a `itk::SmartPointer` to a type `type`.
- `itkSetConstObjectMacro(name, type)`: Creates a method `SetName()` that takes an argument of type `const type *`.
- `itkGetConstObjectMacro(name, type)`: Creates a method named `GetName()` that returns a `const itk::SmartPointer` to a type `type`.
- `itkSetClampMacro(name, type, min, max)`: Creates a method named `SetName()` that takes an argument of type `type` constraining it to the `[min, max]` closed interval.

Furthermore, the ITK symbol visibility is governed by some macros using the following rules:

- `$ModuleName_EXPORT`: export for non-templated classes.
- `ITK_TEMPLATE_EXPORT`: export for templated classes.
- `ITK_FORWARD_EXPORT`: export for forward declarations.

This supports the all the combinations of:

- macOS, Linux and Windows operating systems,
- the shared `BUILD_SHARED_LIBS` ON and OFF static linking modes,
- explicit and implicit template instantiation,
- the CMake `CMAKE_CXX_VISIBILITY_PRESET` flag set to hidden (i.e. `-fvisibility=hidden`),
- the CMake flag `CMAKE_WINDOWS_EXPORT_ALL_SYMBOLS:BOOL=ON`.

Please review this file and become familiar with these macros.

All classes must declare the basic macros for object creation and run-time type information (RTTI):

```

/** Method for creation through the object factory. */
itkNewMacro(Self);

/** Run-time type information (and related methods). */
itkOverrideGetNameOfClassMacro(Image);

```

Basic types (e.g. `int`, `double`, etc.) must be returned by value using the method defined through the `itkGetMacro` macro; member data pointers that must not be modified should be returned using the method defined through the `itkGetConstMacro`.

When using a macro that accepts a statement, a semi-colon (`;`) is not required for the argument, e.g.

```
ITK_TRY_EXPECT_NO_EXCEPTION(writer->Update());
```

C.19 Exception Handling

ITK exceptions are defined in `itkExceptionObject.h`. Derived exception classes include:

- `itkImageFileReaderException.h` for exceptions thrown while trying to read image files (i.e. DICOM files, JPEG files, metainage files, etc.).
- `itkMeshFileReaderException.h` for exceptions thrown while trying to read mesh files.
- `itkMeshFileWriterException.h` for exceptions thrown while trying to write mesh files.

Methods throwing exceptions must indicate so in their declaration as in:

```

/** Initialize the components related to supporting multiple threads. */
virtual void
MultiThreadingInitialize() throw(ExceptionObject);

```

When a code block is liable to throw an exception, a `try/catch` block must be used to deal with the exception. The following rules apply to such blocks

- The exception object should generally be redirected to the error output `std::cerr` and be trailed with a line break `std::endl`.
- In classes that have a member to store the error messages (e.g. `m_ExceptionMessage`), the exception description must be obtained using `GetDescription()` and be assigned to the exception message member.
- Otherwise, the error shall be re-thrown to the caller.

For instance,

```

try
{
    // Code liable to throw an exception
}
catch (const ExceptionObject & exc)
{
    std::cerr << exc << std::endl;
}
catch (const std::exception & exc)
{
    std::cerr << exc.what() << std::endl;
}

```

For instance,

```

try
{
    m_ExceptionMessage = "";
    this->TestFileExistenceAndReadability();
}
catch (const ExceptionObject & exc)
{
    m_ExceptionMessage = exc.GetDescription();
}

```

For instance,

```

// Do the optimization
try
{
    m_Optimizer->StartOptimization();
}
catch (const ExceptionObject & exc)
{
    // An error has occurred in the optimization.
    // Update the parameters.
    m_LastTransformParameters = m_Optimizer->GetCurrentPosition();

    // Pass the exception to the caller
    throw exc;
}

```

Exceptions can also be thrown outside try/catch blocks, when there is sufficient evidence for that, e.g. a filename to be read is empty. In such cases, depending on the exception class the following information should be included:

- the file
- the line
- the error message

of the related exception, e.g.

```
if (m_FileName == "")
{
    throw MeshFileReaderException(
        __FILE__, __LINE__, "FileName must be specified", ITK_LOCATION);
}
```

See Section 3.2.5 on page 29 for details about error handling in ITK.

C.19.1 Errors in Pipelines

When in a function an element must have a given value, a check must ensure that such condition is met. The condition is generally being non-null (e.g. for I/O images), or different from zero (e.g. for sizes, etc.).

When the I/O objects are not set, the ITK `itkAssertInDebugAndIgnoreInReleaseMacro` macro is used: the ITK processing framework should handle this situation and throw the appropriate exception (e.g. the `itk::ProcessObject` class), such macro assertion is preferred over an exception, e.g.

```
template <typename TInputImage, typename TOutputImage>
void
BinShrinkImageFilter<TInputImage,
    TOutputImage>::GenerateInputRequestedRegion()
{
    // Call the superclass' implementation of this method.
    Superclass::GenerateInputRequestedRegion();

    // Get pointers to the input and output.
    InputImageType * inputPtr = const_cast<InputImageType *>(this->GetInput());
    const OutputImageType * outputPtr = this->GetOutput();

    itkAssertInDebugAndIgnoreInReleaseMacro(inputPtr != nullptr);
    itkAssertInDebugAndIgnoreInReleaseMacro(outputPtr);

    ...
}
```

e.g

```
template <typename TInputImage, typename TOutputImage>
void
PatchBasedDenoisingBaseImageFilter<TInputImage, TOutputImage>::
    SetPatchWeights(const PatchWeightsType & weights)
{
    itkAssertOrThrowMacro(
        this->GetPatchLengthInVoxels() == weights.GetSize(),
        "Unexpected patch size encountered while setting patch weights");
}
```



```
...  
}
```

The `itkAssertInDebugAndIgnoreInReleaseMacro` macro is useful for logic checks in performance sections that should never be violated. `itkAssertOrThrowMacro` is fine for non-performance critical sections where it would be helpful to also add an error message.

C.20 Messages

C.20.1 Messages in Macros

Messages written for debugging purposes which are deemed to be appropriate to remain in the code, and those reported when raising exceptions should be using the output stream operator (`<<`) to add the message to any previous string in the buffer. Messages should start with capitals and should not finish with a period. Self-contained sentences must be streamed.

```
itkDebugMacro(<< "Computing Bayes Rule");
```

or

```
itkExceptionMacro(<< "The size of the mask differs from the input image");
```

C.20.2 Messages in Tests

ITK tests are run automatically, and hence, results are not read by humans. Although at times it may be beneficial (e.g. when a large number of regressions are done in a test, checking different image types, or using different approaches), tests should not generally contain messages sent to the standard output.

One of the general exceptions is a message at the end of the test signaling that the test has ended:

```
...  
std::cout << "Test finished." << std::endl;  
return EXIT_SUCCESS;
```

In case of test failure, this allows ITK maintainers to know whether the issue came from the test execution or from a potential regression against a baseline.

When failures are to be reported in a test (i.e. if an insufficient number of test arguments are provided or a regression fails), messages must be redirected to the error output.

When an insufficient number of parameters are found, the test arguments should be written in medial capitals, starting with lower cases.

```

if (argc != 3)
{
    std::cerr << "Missing parameters." << std::endl;
    std::cerr << "Usage: " << itkNameOfTestExecutableMacro(argv);
    std::cerr << " inputImage outputImage" << std::endl;
    return EXIT_FAILURE;
}

```

If the length of the message is longer than 200 characters, the argument list must be split in its individual components, leaving a white space at the beginning of each line, and the `std::cerr` redirection should only exist on the first line. A final line break must be always added. Optional arguments must be enclosed in square brackets `[]`.

```

if (argc < 3)
{
    std::cerr << "Missing parameters." << std::endl;
    std::cerr << "Usage: " << itkNameOfTestExecutableMacro(argv);
    std::cerr << " inputImage"
                << " outputImage"
                << " [foregroundValue]"
                << " [backgroundValue]" << std::endl;
    return EXIT_FAILURE;
}

```

When a regression fails in a check, it must be clearly stated that the test failed, and details about the method that failed to return the correct value, as well as the expected and returned values, must be provided:

```

bool tf = colors->SetColor(0, 0, 0, 0, name);
if (tf != true)
{
    std::cerr << "Test failed!" << std::endl;
    std::cerr << "Error in itk::ColorTable::SetColor" << std::endl;
    std::cerr << "Expected: " << true << ", but got: " << tf << std::endl;
    return EXIT_FAILURE;
}

```

If any index is involved (i.e. the test failure stems from a given index position when checking the values of a list, image, etc.), the index at issue must be specified in the message:

```

// Check the content of the result image
const OutputImageType::PixelType expectedValue =
    static_cast<OutputImageType::PixelType>(valueA * valueB);
const OutputImageType::PixelType epsilon = 1e-6;
while (!oIt.IsAtEnd())
{
    if (!itk::Math::FloatAlmostEqual(oIt.Get(), expectedValue, 10, epsilon))
    {
        std::cerr.precision(
            static_cast<int>(itk::Math::abs(std::log10(epsilon))));
        std::cerr << "Test failed!" << std::endl;
    }
}

```

```

std::cerr << "Error in pixel value at index [" << oIt.GetIndex() << "]"
    << std::endl;
std::cerr << "Expected value " << expectedValue << std::endl;
std::cerr << " differs from " << oIt.Get();
std::cerr << " by more than " << epsilon << std::endl;
return EXIT_FAILURE;
}
++oIt;
}

```

C.21 Concept Checking

C.22 Printing Variables

All member variables, regardless of whether they are publicly exposed or not, must be printed in a class' `PrintSelf` method. Besides being an important sanity check that allows to identify uninitialized variables, it allows to know the state of a class instance at any stage.

The basic conventions for printing member variables are:

- Each variable must be printed on a new line and be indented.
- The name of the variable must immediately follow to the indentation.
- The Superclass must always be printed.

Thus, the general layout for printing member variables is:

```

Superclass::PrintSelf(os, indent);

os << indent << "<MemberVariableName>" << <MemberVariableValue> << std::endl;

```

The following additional conventions apply to printing member variables:

- When printing constructs such as matrices, double indentation should be used to print its contents using `itk::Indent::GetNextIndent()`.
- Objects that can be null (such as `itk::SmartPointer`) must be printed using the `itkPrintSelfObjectMacro` macro.
- Without harm to the previous convention, constructs such as images can be printed using the `Print` method.
- Objects that have been declared as a type alias must be casted statically using the `NumericTraits<Type>::PrintType` helper formatting.

- The order of the variables should be the same used in their declaration.

For instance,

```
template <typename TInputImage>
void
MinimumMaximumImageCalculator<TInputImage>::PrintSelf(std::ostream & os,
                                                         Indent indent) const
{
    Superclass::PrintSelf(os, indent);

    os << indent << "Minimum: "
      << static_cast<typename NumericTraits<PixelType>::PrintType>(m_Minimum)
      << std::endl;
    os << indent << "Maximum: "
      << static_cast<typename NumericTraits<PixelType>::PrintType>(m_Maximum)
      << std::endl;
    os << indent << "IndexOfMinimum: " << m_IndexOfMinimum << std::endl;
    os << indent << "IndexOfMaximum: " << m_IndexOfMaximum << std::endl;
    itkPrintSelfObjectMacro(Image);
    os << indent << "Region: " << std::endl;
    m_Region.Print(os, indent.GetNextIndent());
    os << indent << "RegionSetByUser: " << m_RegionSetByUser << std::endl;
}
```

C.23 Checking for Null

ITK's `itk::SmartPointer` constructs can be checked against the null pointer using either the syntax

```
itkSmartPtr.IsNull();
```

or

```
itkSmartPtr == nullptr;
```

The latter, being more explicit, is preferred over the former.

C.24 Writing Tests

The following section provides additional rules that apply to writing tests in ITK.

C.24.1 Code Layout in Tests

The following general layout is recommended for ITK unit tests:

- Input argument number check.
- Input image read (or generation).
- `foo` class instantiation and basic object checks (e.g. `ITK_EXERCISE_BASIC_OBJECT_METHODS`).
- `foo` class properties' input argument read and test (e.g. using the macros in `itkTestingMacro.h`, such as `ITK_TEST_SET_GET_VALUE`, etc.).
- `foo` class `Update()`.
- Regression checks.
- Output image write.

Note that constant declarations (e.g. image dimensions, etc.) and type alias declarations (e.g. pixel and image types, etc.) should be local to where they are used for the sake of readability. If the test main body uses them, they should be put after the input argument number check section.

C.24.2 Regressions in Tests

Tests should run as long as possible to report as much failures as possible before returning

```
int
itkAbsImageFilterAndAdaptorTest(int, char *[])
{
    int testStatus = EXIT_SUCCESS;

    ...

    // Check the content of the result image.
    const OutputImageType::PixelType epsilon = 1e-6;
    ot.GoToBegin();
    it.GoToBegin();
    while (!ot.IsAtEnd())
    {
        std::cout.precision(
            static_cast<int>(itk::Math::abs(std::log10(epsilon))));
        std::cout << ot.Get() << " = ";
        std::cout << itk::Math::abs(it.Get()) << std::endl;
        const InputImageType::PixelType input = it.Get();
        const OutputImageType::PixelType output = ot.Get();
        const OutputImageType::PixelType absolute = itk::Math::abs(input);
        if (!itk::Math::FloatAlmostEqual(absolute, output, 10, epsilon))
        {
            std::cerr.precision(
                static_cast<int>(itk::Math::abs(std::log10(epsilon))));
            std::cerr << "Test failed!" << std::endl;
            std::cerr << "Error in pixel value at index [" << oIt.GetIndex() << "]"
```

```

        << std::endl;
    std::cerr << "Expected value "
        << "abs(" << input << ") = " << absolute << std::endl;
    std::cerr << " differs from " << output();
    std::cerr << " by more than " << epsilon << std::endl;
    testStatus = EXIT_FAILURE;
}
++ot;
++it;
}

//
// Test AbsImageAdaptor
//

...

// Check the content of the diff image.
std::cout << "Comparing the results with those of an Adaptor" << std::endl;
std::cout << "Verification of the output " << std::endl;

// Create an iterator for going through the image output.
OutputIteratorType dt(diffImage, diffImage->GetRequestedRegion());

dt.GoToBegin();
while (!dt.IsAtEnd())
{
    std::cout.precision(
        static_cast<int>(itk::Math::abs(std::log10(epsilon))));
    const OutputImageType::PixelType diff = dt.Get();
    if (!itk::Math::FloatAlmostEqual(
        diff, (OutputImageType::PixelType)0, 10, epsilon))
    {
        std::cerr.precision(
            static_cast<int>(itk::Math::abs(std::log10(epsilon))));
        std::cerr << "Test failed!" << std::endl;
        std::cerr << "Error in pixel value at index [" << dt.GetIndex() << "]"
            << std::endl;
        std::cerr << "Expected difference " << diff << std::endl;
        std::cerr << " differs from 0 ";
        std::cerr << " by more than " << epsilon << std::endl;
        testStatus = EXIT_FAILURE;
    }
    ++dt;
}

std::cout << "Test finished." << std::endl;
return testStatus;
}

```

Note that when dealing with real numbers, a tolerance parameter must be specified in order to avoid precision issues. Furthermore, setting the output message precision with `std::cerr.precision(int n);` is recommended to allow for easy identification of the magnitude of the error.

When the magnitude of the error needs to be reported, as in the above examples, the error message should be split into different lines, all starting with the error output redirection `std::cerr << "`";. Care must be taken to appropriately add white space for a correct formatting of the message.

C.24.3 Arguments in Tests

Tests generally require input arguments, whether the filename of an input image, the output image filename for regression purposes, or a variety of other parameters to be set to a filter instance. However, some tests are self-contained and do not need any input parameter.

In such cases, the test's main method argument variables do not need to be specified. The generally accepted syntax for these cases is:

```
int
itkVersionTest(int, char *[])
```

Otherwise, it may happen that some test may or may not accept arguments, depending on the implementation. In such cases, the `itkNotUsed` ITK macro must be used to avoid compiler warnings:

```
int
itkGaborKernelFunctionTest(int itkNotUsed(argc), char * itkNotUsed(argv))
```

When a test requires input arguments, a basic sanity check on the presence of the required arguments must be made. If the test does not have optional arguments, the exact match for the input arguments must be checked:

```
if (argc != 3)
{
    std::cerr << "Missing parameters." << std::endl;
    std::cerr << "Usage: " << itkNameOfTestExecutableMacro(argv);
    std::cerr << " inputImage outputImage " << std::endl;
    return EXIT_FAILURE;
}
```

If the test does have optional arguments, the presence of the set of compulsory arguments must be checked:

```
if (argc < 3)
{
    std::cerr << "Missing parameters." << std::endl;
    std::cerr << "Usage: " << itkNameOfTestExecutableMacro(argv);
    std::cerr << " inputImage"
                << " outputImage"
                << " [foregroundValue]"
                << " [backgroundValue]" << std::endl;
    return EXIT_FAILURE;
}
```

C.24.4 Testing Enumeration Streaming

The enumeration class streaming operator overload needs to be tested, e.g.

```
// Test streaming enumeration for MathematicalMorphologyEnums::Algorithm
// elements
const std::set<itk::MathematicalMorphologyEnums::Algorithm> allAlgorithm{
    itk::MathematicalMorphologyEnums::Algorithm::BASIC,
    itk::MathematicalMorphologyEnums::Algorithm::HISTO,
    itk::MathematicalMorphologyEnums::Algorithm::ANCHOR,
    itk::MathematicalMorphologyEnums::Algorithm::VHGW
};
for (const auto & ee : allAlgorithm)
{
    std::cout << "STREAMED ENUM VALUE MathematicalMorphologyEnums::Algorithm: "
                << ee << std::endl;
}
```

C.24.5 Test Return Value

Tests must always return a value of type `int`, even if `bool` is tempting:

```
int
itkVersionTest(int, char *[])
```

Thus, if a test requires a variable to store its exit value due to the need of multiple regressions, an `int` variable must be declared:

```
int
itkAbsImageFilterAndAdaptorTest(int, char *[])
{
    int testStatus = EXIT_SUCCESS;

    ...

    return testStatus;
```

Tests must exit gracefully using the values `EXIT_SUCCESS` (in case of success) or `EXIT_FAILURE` (in case of failure) defined in the `stdlib.h` library values. Other ways of exiting tests such as `exit(1);`, `exit(255);`, or `exit(EXIT_FAILURE);` are not allowed in ITK.

C.25 Writing Examples

Many ITK examples are used in this software guide to demonstrate ITK's architecture and development.

Thanks to scripting work, parts of the `*.cxx` example files within special placeholders are included in this software guide. The $\LaTeX$ placeholders available to the code for such purpose are:

- **Software Guide : BeginLatex** and **Software Guide : EndLatex**: the text within these placeholders is included in this software guide for text explanations, e.g.

```
// Software Guide : BeginLatex
//
// Noise present in the image can reduce the capacity of this filter to grow
// large regions. When faced with noisy images, it is usually convenient to
// pre-process the image by using an edge-preserving smoothing filter. Any of
// the filters discussed in Section~\ref{sec:EdgePreservingSmoothingFilters}
// could be used to this end. In this particular example we use the
// \doxygen{CurvatureFlowImageFilter}, so we need to include its header
// file.
//
// Software Guide : EndLatex
```

- **Software Guide : BeginCodeSnippet** and **Software Guide : EndCodeSnippet**: the text within these placeholders is included in this software guide for verbatim code snippets, e.g.

```
// Software Guide : BeginCodeSnippet
#include "itkCurvatureFlowImageFilter.h"
// Software Guide : EndCodeSnippet
```

Note that anything inside these gets inserted into the document; avoid blank lines or too much whitespace. Make sure any L^AT_EX comments included in the code are correct in terms of grammar, spelling, and are complete sentences.

Note that **the code should not exceed 79 columns** or it will go out of margins in the final document. It is recommended that the L^AT_EX comment blocks are aligned to the code for the sake of readability.

C.26 Doxygen Documentation System

Doxygen is an open-source, powerful system for automatically generating documentation from source code. To use Doxygen effectively, the developer must insert comments, delimited in a special way, that Doxygen extracts to produce the documentation. While there are a large number of options to Doxygen, ITK community members are required at a minimum to insert Doxygen commands listed in this section.

See more at <https://www.stack.nl/~dimitri/doxygen/>

C.26.1 General Principles

ITK uses a subset of C-style Doxygen markdown. No other markdown style (e.g. Qt, Javadoc) shall be used.

In ITK, documentation is placed before the documented construct (i.e. a class, a method, a variable, etc.).

Although not the general rule, if a comment is too short or applies to a single line so that it is a clear candidate to dwell on that line, it can be placed on the same line using the `//` comment style, and leaving a single space before the statement-ending `;` and the comment itself, e.g.

```
template <typename TInputImage, typename TOutputImage>
void
SpecializedImageFilter<TInputImage, TOutputImage>::SpecializedMethod()
{
    ...

    OutputVectorRealType lambda11 = -(x1 * v1) / ((x - x1) * v1); // upper left
    OutputVectorRealType lambda12 = -(x1 * v2) / ((x - x1) * v2); // upper right
    OutputVectorRealType lambda21 = -(x2 * v1) / ((x - x2) * v1); // lower left
    OutputVectorRealType lambda22 = -(x2 * v2) / ((x - x2) * v2); // lower right

    ...
}
```

Correct English and complete, grammatically correct sentences must be used when documenting. Finish the sentences with a period (`.`).

C.26.2 Documenting Classes

Classes must be documented using the `\class`, `\brief`, and `\ingroup` Doxygen commands, followed by the detailed class description. The comment starts with `/**`, each subsequent line has an aligned `*`, and the comment block terminates with a `*/` on a line of its own. A single white space should exist between these keywords/characters and the documentation body, e.g.

```
/** \class Object
 * \brief Base class for most ITK classes.
 *
 * Object is the second-highest level base class for most itk objects.
 * It extends the base object functionality of LightObject by
 * implementing debug flags/methods and modification time tracking.
 *
 * \ingroup Module
 */
```

The `\ingroup` and other additional Doxygen keywords must be separated from their preceding and following lines by an empty comment `*` line.

Doxygen keywords that may most commonly apply to complete a class documentation are

- `\note`
- `\sa`

Math formulas in class documentation are formatted following the $\text{\LaTeX}$ guidelines. For more information, please visit <https://www.stack.nl/~dimitri/doxygen/manual/formulas.html>.

Every class must be documented.

C.26.3 Documenting Methods

The method Doxygen documentation must be placed in the header file (.h).

A single white space should separate the comment characters (/**, *, or */) and the comment itself. The starting (/**) and ending (*/) comment characters must be placed on the same lines as the comment text, and the lines with the asterisk (*) character should be aligned, e.g.

```
/** Provides opportunity for the data object to insure internal
 * consistency before access. Also causes owning source/filter (if
 * any) to update itself. The Update() method is composed of
 * UpdateOutputInformation(), PropagateRequestedRegion(), and
 * UpdateOutputData(). This method may call methods that throw an
 * InvalidRequestedRegionError exception. This exception will leave
 * the pipeline in an inconsistent state. You will need to call
 * ResetPipeline() on the last ProcessObject in your pipeline in
 * order to restore the pipeline to a state where you can call
 * Update() again. */
virtual void
Update();
```

The base class virtual method documentation is automatically applied for such methods in derived class unless they are overridden. Virtual methods whose meaning or set of instructions differs from their base class need to be documented in the derived classes. If the base class method documentation applies, they need not to be documented in derived classes (e.g. the `PrintSelf` method).

Intra-method documentation must be done where necessary using single-line comment style, and must be repeated for every line. A single white space should separate the comment character `//` and the comment itself, e.g.

```
// We wish to copy whole lines, otherwise just use the basic implementation.
// Check that the number of internal components match.
if (inRegion.GetSize()[0] != outRegion.GetSize()[0] ||
    NumberOfInternalComponents !=
    ImageAlgorithm::PixelSize<OutputImageType>::Get(outImage))
{
    ImageAlgorithm::DispatchedCopy<InputImageType, OutputImageType>(
        inImage, outImage, inRegion, outRegion);
    return;
}
```

Self-contained, complete sentences must end with a period.

Every method must be documented.

C.26.4 Documenting Data Members

Class member variables should be documented through their corresponding `Get##name/Set##name` methods, using a comment block style shown in the following example:

```
public:
    /** Set/Get the standard deviation of the Gaussian used for smoothing. */
    itkSetMacro(Sigma, SigmaArrayType);
    itkGetConstMacro(Sigma, SigmaArrayType);

private:
    SigmaArrayType m_Sigma;
```

The documentation block must be aligned to the `Get##name/Set##name` method indentation.

For `bool` type variables, the recommended way of documenting its default value is using “On” for true and “Off” for false:

```
/** Set/Get direction along the gradient to search.
 * Set to true to use the direction that the gradient is pointing;
 * set to false for the opposite direction. */
itkGetConstMacro(Polarity, bool);
itkSetMacro(Polarity, bool);
itkBooleanMacro(Polarity);
```

Member variables that do not have either a `Get##name` or a `Set##name` method should also be documented following the above guidelines.

Data members that should share the same documentation description should be embedded in the Doxygen grouping commands by means of the comments `/** @ITKStartGrouping */` and `/** @ITKEndGrouping */`:

```
public:
    /** Set/Get the standard deviation of the Gaussian used for smoothing. */
    /** @ITKStartGrouping */
    itkSetMacro(Sigma, SigmaArrayType);
    itkGetConstMacro(Sigma, SigmaArrayType);
    /** @ITKEndGrouping */
```

C.26.5 Documenting Macros

The documentation block in a macro should start in column one, and should be placed immediately before the macro definition, and will use `/*` as the starting character, immediately followed by the body of the documentation, which shall be split into different lines starting with asterisks (`*`), aligned to the preceding asterisk character, with a single white space indentation for the text, and will end with the `*/` character. The macro definition should have a double indentation, e.g.

```

/** This macro is used to print debug (or other information). They are
 * also used to catch errors, etc. Example usage looks like:
 * itkDebugMacro(<< "this is debug info" << this->SomeVariable); */
#if defined(NDEBUG)
# define itkDebugMacro(x)
# define itkDebugStatement(x)
#else
# define itkDebugMacro(x)
    do
    {
        if (this->GetDebug() && ::itk::Object::GetGlobalWarningDisplay())
        {
            std::ostringstream itkmsg;
            itkmsg << "Debug: In " __FILE__ ", line " << __LINE__ << "\n"
                << this->GetClassName() << " (" << this << "): " x
                << "\n\n";
            ::itk::OutputWindowDisplayDebugText(itkmsg.str().c_str());
        }
    } while (0)

```

C.26.6 Documenting Tests

Generally, an ITK test does not need to have a documentation block stating its purpose if this is restricted to testing a single class. However, for tests that check multiple classes or complex pipelines, documenting its motivation and purpose, as well as its general schema, is recommended.

The documentation block should start in column one, and should be placed immediately before the main method, and will use `/*` as the starting character, immediately followed by the body of the documentation, which shall be split into different lines starting with asterisks (`*`), aligned to the preceding asterisk character, with a single white space indentation for the text, and will end with the `*/` character, e.g.

```

/* Test the SetMetricSamplingPercentage and SetMetricSamplingPercentagePerLevel.
 * We only need to explicitly run the SetMetricSamplingPercentage method because
 * it invokes the SetMetricSamplingPercentagePerLevel method. */
int
itkImageRegistrationSamplingTest(int, char *[])

```

It is recommended to document the body of the test with single-line comment style where appropriate.

C.27 CMake Style

For writing CMake scripts, the community member is referred to the standard CMake style.

C.28 Documentation Style

The Insight Software Consortium has adopted the following guidelines for producing supplemental documentation (documentation not produced by Doxygen):

- The common denominator for documentation is either PDF or HTML. All documents in the system should be available in these formats, even if they are mastered by another system.
- Presentations are acceptable in Microsoft PowerPoint format.
- Administrative and planning documents are acceptable in Microsoft Word format (either .docx or .rtf).
- Larger documents, such as the user's or developer's guide, are written in $\text{\LaTeX}$.

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