Lecture 19
ITK Filters: How to Write Them

You should understand
- What the pipeline is and how to connect filters together to perform sequential processing
- How to move through images using iterators
- How to access specific pixels based on their location in data space or physical space

Where we are

What we’ll cover

- How to write your own filter that can fit into the pipeline
- For reference, read Chapters 6 & 8 from book 1 of the ITK Software Guide

Is it hard or easy?

- Writing filters can be really, really easy
- But, it can also be tricky at times
- Remember, don’t panic!

“Cheat” as much as possible!

- Never, ever, ever, write a filter from scratch
- Unless you’re doing something really odd, find a filter close to what you want and work from there
- Recycling the general framework will save you a lot of time and reduce errors

Much of the filter is already written

- Most of the interface for an ImageToImageFilter is already coded by the base classes
- For example, SetInput and GetOutput are not functions you have to write
- You should never have to worry about particulars of the pipeline infrastructure.
The simple case

- You can write a filter with only one function!
  - (* well, sort of)
- Overload `GenerateData` to produce output given some input
- We'll look at `BinomialBlurImageFilter` as an example
  - Located in SimpleITK-build/ITK/Modules/Filtering/Smoothing/include

More header code

- You will also see:
  - Many typedefs, some of which are particularly important:
    - `Self`
    - `Superclass`
    - `Pointer`
    - `ConstPointer`
  - Constructor and destructor prototypes
  - Member variables (in this example, only one)
- Things not typically necessary:
  - `GenerateTypeRequestedRegion()`
  - Concept checking stuff

Pay attention to...

- `#ifdef`, `#define`, `#endif` are used to enforce single inclusion of header code
- Use of `namespace itk`
- The three lines at the bottom starting with:
  ```cpp
  #ifdef ITK_MANUAL_INSTANTIATION
  control whether the .hxx file should be included with the .h file.
  #endif
  ```
- There are often three lines just before that, starting with `#if ITK_TEMPLATE_EXPLICIT`, which allow for explicitly precompiling certain combinations of template parameters.

Does this seem complex?

- That's why I suggested always starting with an existing class
- You may want to use find and replace to change the class name and edit from there
- Moving on to the .hxx file...
The constructor

- In BinomialBlurImageFilter, the constructor doesn’t do much
- Initialize the member variable

GenerateData()

- This is where most of the action occurs
- GenerateData() is called during the pipeline update process
- It’s responsible for allocating the output image (though the pointer already exists) and filling the image with interesting data

Accessing the input and output

- First, we get the pointers to the input and output images

```
InputImageConstPointer inputPtr =
    this->GetInput(0);
OutputImagePointer outputPtr =
    this->GetOutput(0);
```

Filters can have multiple inputs or outputs, in this case we only have one of each

Allocating the output image

```
outputPtr->SetBufferedRegion(
    outputPtr->GetRequestedRegion());
outputPtr->Allocate();
```

The meat of GenerateData()

- Make a temporary copy of the input image
- Repeat the desired number of times for each dimension:
  - Iterate forward through the image, averaging each pixel with its following neighbor
  - Iterate backward through the image, averaging each pixel with its preceding neighbor
- Copy the temp image’s contents to the output
- We control the number of repetitions with m_Repetitions

PrintSelf

- PrintSelf is a function present in all classes derived from itk::Object which permits easy display of the “state” of an object (i.e. all of its member variables)
- ITK’s testing framework requires that you implement this function for any class containing non-inherited member variables
  - Otherwise your code will fail the “PrintSelf test”...
  - If you try to contribute your code to ITK
- Important: users should call Print() instead of PrintSelf()
PrintSelf, cont.

• First, we call the base class implementation
  
  ```cpp
  Superclass::PrintSelf(os, indent);
  ```
  
  This is the only time you should ever call `PrintSelf()` directly!

• And second we print all of our member variables
  
  ```cpp
  os << indent << "Number of Repetitions: " << m_Repetitions << std::endl;
  ```

Questions?

• How can we make multithreaded filters?
• What if the input and output images are not the same size? E.g., convolution edge effects, subsampling, etc.
• What about requested regions?

We'll address these questions when we discuss advanced filters.

Another Question for Today

How do I deal with neighborhoods in N-Dimensions...

Such as for convolution?

Neighborhoods in ITK

• An ITK neighborhood can be any collection of pixels that have a fixed relationship to the “center” based on offsets in data space.
  • Not limited to the max- or min-connected immediately neighboring pixels!
  • See 6.4 in the ITK Software Guide, book 1

Neighborhoods in ITK, cont.

• In general, the neighborhood is not completely arbitrary
  • Neighborhoods are rectangular, defined by a “radius” in N-dimensions
  • Shaped Neighborhoods are more arbitrary, defined by a list of offsets from the center

• The first form is most useful for mathematical morphology kinds of operations, convolution, etc.

Neighborhood iterators

• The cool & useful thing about neighborhoods is that they can be used with neighborhood iterators to allow efficient access to pixels “around” a target pixel in an image
Neighborhood iterators

- Remember that I said access via pixel indices was slow?
  - Get current index = i
  - Upper left pixel index $I_{UL} = i-(1,1)$
  - Get pixel at index $I_{UL}$
- Neighborhood iterators solve this problem by doing pointer arithmetic based on offsets.

Remember that I said access via pixel indices was slow?

Get current index = i

Upper left pixel index $I_{UL} = i-(1,1)$

Get pixel at index $I_{UL}$

Neighborhood iterators solve this problem by doing pointer arithmetic based on offsets.

Neighborhood layout

- Neighborhoods have one primary vector parameter, their “radius” in N-dimensions
- The side length along a particular dimension $i$ is $2 \times \text{radius}_i + 1$
- Note that the side length is always odd because the center pixel always exists.

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A 3x5 neighborhood in 2D

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Stride

- Neighborhoods have another parameter called stride which is the spacing (in data space) along a particular axis between adjacent pixels in the neighborhood
- In the previous numbering scheme, stride in Y is amount then index value changes when you move in Y
- In our example, $\text{Stride}_x = 1$, $\text{Stride}_y = 5$

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Neighborhood pixel access

- The lexicographic numbering on the previous diagram is important!
  - It’s ND
  - It’s how you index (access) that particular pixel when using a neighborhood iterator
  - This will be clarified in a few slides...

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Neighborhood iterator access

- Neighborhood iterators are created using:
  - The radius of the neighborhood
  - The image that will be traversed
  - The region of the image to be traversed
  - Their syntax largely follows that of other iterators (++, IsAtEnd(), etc.)

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Neighborhood pixel access, cont.

Let's say there's some region of an image that has the following pixel values:

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Pixel access, cont.

Now assume that we place the neighborhood iterator over this region and start accessing pixels:

What happens?

Pixel access, cont.

Get the length & stride length of the iterator:

myNeigh.GetPixel(7) returns 0.7
so does myNeigh.GetCenterPixel()

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Let's assume that the neighborhood iterator is placed over this region, and we start accessing pixels.

Pixel access, cont.

myNeigh.GetPixel(0) returns 1.8
myNeigh.GetPixel(0-1) returns 1.1

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Now, assume that we place the neighborhood iterator over this region and start accessing pixels.

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Let's assume that the neighborhood iterator is placed over this region, and we start accessing pixels.
The ++ method

- In Image-Region Iterators, the ++ method moves the focus of the iterator on a per pixel basis.
- In Neighborhood Iterators, the ++ method moves the center pixel of the neighborhood and therefore implicitly shifts the entire neighborhood.

An aside: “regular” iterators

- Regular ITK Iterators are also lexicographic.
  - That is how they too are ND.
- The stride parameters are for the entire image.
- Conceptual parallel between:
  - ITK mapping a neighborhood to an image pixel in an image.
  - Lexicographically unwinding a kernel for an image.
- The linear pointer arithmetic is very fast!
  - Remember, all images are stored linearly in RAM.

Convolution (ahem, correlation)!

To do correlation we need 3 things:

1. A kernel
2. A way to access a region of an image the same size as the kernel
3. A way to compute the inner product between the kernel and the image region

Item 1 - the kernel

- A NeighborhoodOperator is a set of pixel values that can be applied to a Neighborhood to perform a user-defined operation (i.e. convolution kernel, morphological structuring element).
  - NeighborhoodOperator is derived from Neighborhood.

Item 2 - image access method

- We already showed that this is possible using the neighborhood iterator.
  - Just be careful setting it up so that it's the same size as your kernel.

Item 3 - inner product method

- The NeighborhoodInnerProduct computes the inner product between two neighborhoods.
  - Since NeighborhoodOperator is derived from Neighborhood we can compute the IP of the kernel and the image region.
Good to go?

1. Create an interesting operator to form a kernel
2. Move a neighborhood through an image
3. Compute the IP of the operator and the neighborhood at each pixel in the image

Voila – correlation in N-dimensions

Inner product example

```cpp
itk::NeighborhoodInnerProduct<ImageType> IP;
itk::Derivative Operator<TPixel, ImageType::ImageDimension> operator;
operator->SetOrder(1);
operator->SetDirection(0);
operator->CreateDirectional();

itk::NeighborhoodIterator<ImageType> iterator;
operator->GetRadius(), myImage, myImage->GetRequestedRegion();
```

Inner product example, cont.

```cpp
while (! iterator.IsAtEnd())
{
    std::cout << "Derivative at index " << iterator.GetIndex() << " is " << IP(iterator, operator) << std::endl;
    ++iterator;
}
```

Note

- No explicit reference to dimensionality in neighborhood iterator
- Therefore easy to make N-d

This suggests a filter...

- `NeighborhodOperatorImageFilter` wraps this procedure into a filter that operates on an input image
- So, if the main challenge is coming up with an interesting neighborhood operator, ITK can do the rest

Your arch-nemesis...

- image boundaries
  - One obvious problem with inner product techniques is what to do when you reach the edge of your image
  - Is the operation undefined?
  - Does the image wrap?
  - Should we assume the rest of the world is empty/full/something else?
**ImageBoundaryCondition**

- Subclasses of ImageBoundaryCondition can be used to tell neighborhood iterators what to do if part of the neighborhood is not in the image.

**ConstantBoundaryCondition**

- The rest of the world is filled with some constant value of your choice.
- The default is 0.
- Be careful with the value you choose - you can (for example) detect edges that aren’t really there.

**PeriodicBoundaryCondition**

- The image wraps, so that if I exceed the length of a particular axis, I wrap back to 0 and start over again.
- If you enjoy headaches, imagine this in 3D.
- This isn’t a bad idea, but most medical images are not actually periodic.

**ZeroFluxNeumannBoundaryCondition**

- This is the default boundary condition.
- Simply returns the closest in-bounds pixel value to the requested out-of-bounds location.
- Important result: the first derivative across the boundary is zero.
- Thermodynamic motivation.
- Useful for solving certain classes of diff eq.

**Using boundary conditions**

- NeighborhoodIterator automatically determines whether or not it needs to enable bounds checking when it is created (i.e. constructed).
- SetNeedToUseBoundaryCondition (true/false)
  - Manually forces or disables bounds checking.
- OverrideBoundaryCondition()
  - Changes which boundary condition is used.
  - Can be called on both:
    - NeighborhoodIterator
    - NeighborhoodOperatorMapFilter

**Last Major Question**

(for today, anyway)

How do I do math with different pixel types...
Answer: numeric traits

- Provide various bits of numerical information about arbitrary pixel types.
- Usage scenario:
  - "What is the max value of the current pixel type?"
- Need to know these things at compile time, but templated pixel types make this hard.
- Numeric traits provide answers that are “filled in” at compilation for our pixel type.

using traits

- What's the maximum value that can be represented by an unsigned char?
  - `itk::NumericTraits<unsigned char>::max()`
- What about for our pixel type?
  - `itk::NumericTraits<T>::max()`

Excerpt from

http://www.itk.org/Wiki/ITK/Examples/SimpleOperations/NumericTraits

```cpp
#include "itkNumericTraits.h"

//...

std::cout << "Min: ": itk::NumericTraits<float>::min() << std::endl;

std::cout << "Max: ": itk::NumericTraits<float>::max() << std::endl;

std::cout << "Zero: ": itk::NumericTraits<float>::Zero << std::endl;

std::cout << "ZeroValue: ": itk::NumericTraits<float>::ZeroValue() << std::endl;

std::cout << "IsNegative(-1): ": itk::NumericTraits<float>::IsNegative(-1) << std::endl;

std::cout << "IsNegative(1): ": itk::NumericTraits<float>::IsNegative(1) << std::endl;

std::cout << "One: ": itk::NumericTraits<float>::One << std::endl;

std::cout << "Epsilon: ": itk::NumericTraits<float>::epsilon() << std::endl;

std::cout << "Infinity: ": itk::NumericTraits<float>::infinity() << std::endl;

//..."