ITK Filters: How to Write Them, etc.

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16-725 (CMU RI) : BioE 2630 (Pitt)
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Based in part on Damion Shelton's slides from 2006

Where we are

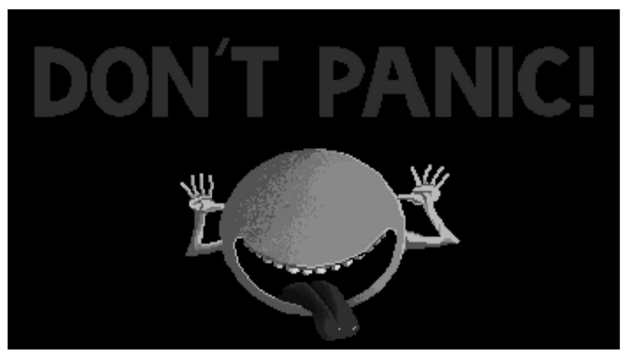
- You should understand
  - What the pipeline is and how to connect filters together to perform sequential processing
  - How to move through images using iterators
  - How to access specific pixels based on their location in data space or physical space

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(void)`** to produce output given some input
- We'll look at **`BinomialBlurImageFilter`** as an example
  - Located in SimpleITK-build/ITK/Modules/Filtering/Smoothing/include

The header - stuff that's "always there"

- **`itkNewMacro`** sets up the object factory (for reference counted smart pointers)
- **`itkTypeMacro`** allows you to use run time type information
- **`itkGetConstMacro`** and **`itkSetMacro`** are used to access private member variables

The header cont.

- Prototypes for functions you will overload:

```
void PrintSelf(std::ostream& os,
Indent indent) const;

void GenerateData(void);
```

- For multi-threaded filters, the latter will instead be:

```
ThreadedGenerateData(void);
```

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:
  - **`GenerateInputRequestedRegion()`**
  - 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:

  `#ifndef ITK_MANUAL_INSTANTIATION`

  control whether the .hxx file should be included with the .h file.
- 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

```
Superclass::PrintSelf(os,indent);
```

This is the only time you should ever call **`PrintSelf()`** directly!

- And second we print all of our member variables

```
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
  - *ShapedNeighborhoods* 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

Neighborhood layout

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

A 3x5 neighborhood in 2D

0	1	2	3	4
5	6	7	8	9
10	11	12	13	14

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, $Stride_x = 1$, $Stride_y = 5$

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...

NeighborhoodIterator 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.)

Neighborhood pixel access, cont.

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

1.2	1.3	1.8	1.4	1.1
1.8	1.1	0.7	1.0	1.0
2.1	1.9	1.7	1.4	2.0

Pixel access, cont.

- Now assume that we place the neighborhood iterator over this region and start accessing pixels
- What happens?

Pixel access, cont.

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

1.2 0	1.3 1	1.8 2	1.4 3	1.1 4
1.8 5	1.1 6	0.7 7	1.0 8	1.0 9
2.1 10	1.9 11	1.7 12	1.4 13	2.0 14

Intensity of currently underlying pixel in the image

lexicographic index within neighborhood

Pixel access, cont.

Get the length & stride length of the iterator:

`Size()` returns the #pixels in the neighborhood

Ex: find the center pixel's index:

```
unsigned int c = iterator.Size() / 2;
```

`GetStride()` returns the stride of dimension N:

```
unsigned int s = iterator.GetStride(1);
```

Pixel access, cont.

`myNeigh.GetPixel(c)` returns 0.7

`myNeigh.GetPixel(c-1)` returns 1.1

1.2 0	1.3 1	1.8 2	1.4 3	1.1 4
1.8 5	1.1 6	0.7 7	1.0 8	1.0 9
2.1 10	1.9 11	1.7 12	1.4 13	2.0 14

Pixel access, cont.

`myNeigh.GetPixel(c-s)` returns 1.8

`myNeigh.GetPixel(c-s-1)` returns 1.3

1.2 0	1.3 1	1.8 2	1.4 3	1.1 4
1.8 5	1.1 6	0.7 7	1.0 8	1.0 9
2.1 10	1.9 11	1.7 12	1.4 13	2.0 14

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

```
itk::NeighborhoodInnerProduct<ImageType> IP;

itk::DerivativeOperator<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.

```
iterator.SetToBegin();
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...

- **`NeighborhoodOperatorImageFilter`** 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`**
    - **`NeighborhoodOperatorImageFilter`**

What at the types of Pixels?

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.

itk::NumericTraits

- NumericTraits is class that is specialized to provide information about pixel types
- Examples include:
  - Min and max, epsilon and infinity values
  - Definitions of Zero and One
    - (I.e., Additive and multiplicative identities)
  - **`IsPositive()`**, **`IsNegative()`** functions
- See also:
  - Modules/ThirdParty/VNL/src/vxl/vcl/emulation/vcl_limits.h
  - http://www.itk.org/Doxygen/html/classitk_1_1NumericTraits.html
  - http://www.itk.org/Wiki/ITK/Examples/SimpleOperations/NumericTraits

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<PixelType>::max()**

Get used to coding like this!

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

```
#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 << "Zero: " << itk::NumericTraits< float >::ZeroValue() << std::endl;
std::cout << "Is -1 negative? " << itk::NumericTraits< float >::IsNegative(-1)
          << std::endl;
std::cout << "Is 1 negative? " << 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;
// ...
```

Some Helpful Filters:

Useful "utility" filters to process images, etc.

Useful ITK filters

- These are filters that solve particularly common problems that arise in image processing
- You can use these filters at least 2 ways:
  - In addition to your own filters
  - Inside of your own filters
- Don’t re-invent the wheel!
- This list is not comprehensive (obviously)
- Specific filter documentation is an EFTR

Padding an image

- Problem: you need to add extra pixels outside of an image (e.g., prior to running a filter)
- Solution: `PadImageFilter` and its derived classes

Cropping an image

- Problem: trimming image data from the outside edges of an image (the inverse of padding)

- Solution: **`CropImageFilter`**

Rescaling image intensity

- Problem: you need to translate between two different pixel types, or need to shrink or expand the dynamic range of a particular pixel type

- Solutions:
  - **`RescaleIntensityImageFilter`**
  - **`IntensityWindowingImageFilter`**

Computing image derivatives

- Problem: you need to compute the derivative at each pixel in an image
- Solution: **`DerivativeImageFilter`**, which is a wrapper for the neighborhood tools discussed in a previous lecture
- See also **`LaplacianImageFilter`**

Compute the mirror image

- Problem: you want to mirror an image about a particular axis or axes
- Solution: `FlipImageFilter` - you specify flipping on a per-axis basis

Rearrange the axes in an image

- Problem: the coordinate system of your image isn't what you want; the x axis should be z, and so on

- Solution: **`PermuteAxesImageFilter`** - you specify which input axis maps to which output axis

Resampling an image

- Problem: you want to apply an arbitrary coordinate transformation to an image, with the output being a new image
- Solution: `ResampleImageFilter` - you control the transform and interpolation technique
  - (This is used when doing registration)

Getting a lower dimension image

- Problem: you have read time-series volume data as a single 4D image, and want a 3D “slice” of this data (one frame in time), or want a 2D slice of a 3D image, etc.

- Solution: **`ExtractImageFilter`** - you specify the region to extract and the “index” within the parent image of the extraction region