Lecture 17
Write Your Own ITK Filters, Part 2

Methods in Medical Image Analysis - Spring 2017
16-725 (CMU RI) : Bice 2630 (Pitt)
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Based in part on Damion Shelton's slides from 2006

What are “advanced” filters?

- More than one input
- Support progress methods
- Output image is a different size than input
- Multi-threaded

Details, details

- In the interests of time I’m going to gloss over some of the finer details
- I’d like to make you aware of some of the more complicated filter issues, but not scare you away
- See book 1, chapter 8 of the software guide!

Different output size

- Overload `GenerateOutputInformation()`
- This allows you to change the output image’s:
  - Largest possible region (size in pixels)
  - Origin & spacing
- By default, the output image has the same size, origin, and spacing as the input
- See `Modules/Filtering/ImageGrid/include/itkShrinkImageFilter`

Propagation of requested region size

- Remember that requested regions propagate back up the pipeline from output to input
- Therefore, it’s likely that if we are messing with the output image size, then we will also need to alter the input requested region

Changing the input requested region

- Overload `GenerateInputRequestedRegion()`
- Generate the input requested region based on:
  - The output region
  - Out algorithm’s input-padding requirements/preferences
- WARNING: Never set the input requested region larger than the input’s largest possible region!
  - If input image is too small, handle the problem gracefully
- E.g. throw an exception or degrade output at boundaries
- See:
  - `Modules/Filtering/ImageGrid/include/itkShrinkImageFilter`
  - `Modules/Filtering/Smoothing/include/BinomialBlurImageFilter`
**Multithreaded**

- Actually relatively simple
- Implement `ThreadedGenerateData()` instead of `GenerateData()`
- A few things look different...

**Multi-threaded: overview**

- The pipeline framework “chunks” the output image into regions for each thread to process
- Each thread gets its own region and thread ID
- Keep in mind that this will not (and cannot) work in all cases
  - Some filters can’t be multi-threaded

**Multi-threaded: output regions**

- The output target is now:
  ```cpp
  OutputImageRegionType & outputRegionForThread
  ```
- You iterate over this rather than over the entire output image
- Each thread can read from the *entire input image*
- Each thread can write to only its *specific output region*

**Multi-threaded: output allocation**

- `ThreadedGenerateData()` does NOT allocate the memory for its output image!
- `AllocateOutputs()` is instead responsible for allocating output memory
- The default `AllocateOutputs()` function:
  - Sets each output’s buffered region = requested region
  - Allocates memory for each buffered region

**Multi-threaded: order of operations**

- Execution of multi-threaded filters is controlled by the inherited `GenerateData()`
- `itk::ImageSource::GenerateData()` will:
  1. Call `AllocateOutputs()`
  2. If `BeforeThreadedGenerateData()` exists, call it
  3. Divide the output image into chunks, one per thread
  4. Spawn threads (usually one per CPU core)
     - Each thread executes `ThreadedGenerateData()` on its own particular output region, with its own particular thread ID
  5. If `AfterThreadedGenerateData()` exists, call it
ThreadID

- This deserves a special note...
- In the naïve case a thread would not know how many other threads were out there
- If a thread takes a non thread-safe action (e.g., file writing) it's possible other threads would do the same thing

ThreadID, cont.

- This could cause major problems!
- The software guide suggests:
  1. Don’t do “unsafe” actions in threads
  2. Only let the thread with ID 0 perform unsafe actions

Multiple inputs

- It's fairly straightforward to create filter that has multiple inputs – we will use 2 inputs as an example
- For additional reference see:
  Modules/Filtering/ImageFilterBase/include/ itkBinaryFunctorImageFilter

Step 1: Define Number of Inputs

- In the constructor, set:
  `this->SetNumberOfRequiredInputs(2);`

Step 2:

- Optional: Write named functions to set inputs 1 and 2, they look something like:

  ```cpp
  SetInputImageMask( const TInputImageMask * imageMask )
  {
    this->SetInput(0, imageMask);
  }
  ```

Step 3

- Implement `GenerateData()` or `ThreadedGenerateData()`
- Caveat: you now have to deal with input regions for both inputs, or N inputs in the arbitrary case
Multiple outputs?

- Not many examples
  - `ImageSource` and `ImageToImageFilter` only recently gained full support for multiple outputs
  - Previously, special calls were needed to `ProcessObject`
- The constructor of the filter must:
  - Allocate the extra output, typically by calling `New()`
  - Indicate to the pipeline the # of outputs
- What if the outputs are different types?
  - More complex
    - Example: `Modules/Numerics/Eigen/include/itkEigenAnalysis2DImageFilter`
    - Also try searching online: itk multiple output filter

Progress reporting

- A useful tool for keeping track of what your filters are doing
- Initialize in `GenerateData` or `ThreadedGenerateData`:

```cpp
ProgressReporter progress(
  this,
  threadId,
  outputRegionForThread.GetNumberOfPixels()
);
```

Progress reporting, cont.

```cpp
ProgressReporter progress( 
  this,
  threadId,
  outputRegionForThread.GetNumberOfPixels()
);
```

Total pixels or steps (for iterative filters)

Querying progress from outside your filter

- How does your program query the total progress?
- Short answer is to use the inherited method: `ProcessObject::ReportProgress()`
  - All filters (including ones that you write) automatically have this function, since it is provided by `ProcessObject`

  Typically you create an external observer to both query your filter’s total progress and then update your GUI
  - In particular, you write an observer that calls your filter’s `ReportProgress()` method and then calls some other "short" function to update your GUI accordingly.

Helpful ITK features to use when writing your own filter

- Points and vectors
- VNL math
- Functions
- Conditional iterators
- Other useful ITK filters
Points and Vectors

- `itk::Point` is the representation of a point in n-d space
- `itk::Vector` is the representation of a vector in n-d space
- Both of these are derived from ITK's non-dynamic array class (meaning their length is fixed)

Interchangability

- You can convert between Points and Vectors in a logical manner:
  - `Point + Vector = Point`
  - `Vector + Vector = Vector`
  - `Point + Point = Undefined`
- This is pretty handy for maintaining clarity, since it distinguishes between the intent of different arrays

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Things to do with Points

- Get a vector from the origin to this Point
  - `GetVectorFromOrigin()`
- Get the distance to another Point
  - `EuclideanDistanceTo()`
- Set the location of this point to the midpoint of the vector between two other points
  - `SetToMidPoint()`

Things to do with Vectors

- Get the length (norm) of the vector
  - `GetNorm()`
- Normalize the vector
  - `Normalize()`
- Scale by a scalar value
  - Use the * operator

Need more complicated math?

- ITK includes a copy of the VNL numerics library
- You can get `vnl_vector` objects from both Points and Vectors by calling `Get_vnl_vector()`
  - Ex: You can build a rotation matrix by knowing basis vectors

VNL

- VNL could easily occupy an entire lecture
- Extensive documentation is available at:
  - `http://vxl.sourceforge.net/`
- Click on the the VXL book link and look at chapter 6
Things VNL can do

- Dot products
  
  ```c++
  dot_product(GL.Get_vnl_vector(),
              CL2.Get_vnl_vector());
  ```

- Create a matrix
  
  ```c++
  vnl_matrix_fixed<
      double,
      NDimensions,
      NDimensions>
      myMatrix;
  ```

More VNL tricks

- If it were just good at simple linear algebra, it wouldn't be very interesting
- VNL can solve generalized eigenproblems:
  
  ```c++
  vnl_generalized_eigensystem<
      pEigenSys = new vnl_generalized_eigensystem(
          Matrix_1, Matrix_2);
  ```

  Solves the generalized eigenproblem
  
  ```c++
  Matrix_1 * x = Matrix_2 * x
  ```

  (Matrix_2 will often be the identity matrix)

VNL take home message

- VNL can do a lot more cool stuff that you do not want to write from scratch
  - SVD
  - Quaternions
- C++ can work like Matlab!
- It’s worth spending the time to learn VNL
  - Especially true for C++ programmers!
  - But Python programmers may rather learn NumPy:
    
    ```
    http://www.scipy.org/NumPy_Tutorial
    ```

Change of topic

- Next we’ll talk about how ITK encapsulates the general idea of functions
- Generically, functions map a point in their domain to a point in their range

Functions

- ITK has a generalized function class called FunctionBase

  ```c++
  itk::FunctionBase< TInput, TOutput >
  ```

  By itself it’s pretty uninteresting, and it’s purely virtual

What good is FunctionBase?

- It enforces an interface...

  ```c++
  virtual OutputType Evaluate ( const InputType &input ) const = 0
  ```

  The evaluate call is common to all derived classes; pass it an object in the domain and you get an object in the range
Spatial functions

- Spatial functions are functions where the domain is the set of N-d points in continuous space
- The base class is `itk::SpatialFunction`
- Note that the range (TOutput) is still templated

Spatial function example

- `GaussianSpatialFunction` evaluates an N-d Gaussian
- It forms the basis for `GaussianImageSource`, which evaluates the function at all of the pixels in an image and stores the value

Interior-exterior spatial functions

- These are a further specialization of spatial functions, where the range is enforced to be of type `bool`
- Semantically, the output value is taken to mean “inside” the function if true and “outside” the function if false

IE spatial function example

- `itk::ConicShellInteriorExteriorSpatialFunction` lets you determine whether or not a point lies within the volume of a truncated cone
- `itk::SphereSpatialFunction` does the same thing for a N-d sphere (circle, sphere, hypersphere...) - note a naming inconsistency here

Image functions

- Image functions are functions where the domain is the pixels within an image
- The function evaluates based on the value of a pixel accessed by its position in:
  - Physical space (via `Evaluate`)
  - Discrete data space (via `EvaluateAtIndex`)
  - Continuous data space (via `EvaluateAtContinuousIndex`)

Image function examples

- `itk::BinaryThresholdImageFunction` returns true if the value being accessed lies within the bounds of a lower and upper threshold
- `itk::InterpolateImageFunction` is the base class for image functions that allow you to access subpixel interpolated values
Hey - this is messy...

- You might be wondering why there are so many levels in this hierarchy.
- The goal is to enforce conceptual similarity in order to better organize the toolkit.
- In particular, the interior-exterior functions have a specific reason for existence.

Change of topic

- You may have observed that we have (at least) two ways of determining whether or not a point/pixel is “included” in some set:
  - Within the bounds of a spatial function
  - Within a threshold defined by an image function
- Useful for, e.g., connected component labeling.

Conditional iterators

- One way to think about iterators is that they return all of the objects within a certain set.
- With `ImageRegionIterators`, the set is all pixels within a particular image region.
- What about more complicated sets?

The “condition”

- The condition in a `ConditionalIterator` is the test that you apply to determine whether or not a pixel is included within the set of interest.
- Examples:
  - Is the pixel inside a spatial function?
  - Is the pixel within a certain threshold?

Using the condition - brute force

- If the pixel passes the test, it can be accessed by the iterator.
- Otherwise, it’s not part of the set.
- The brute force implementation is to visit all pixels in an image, apply the test, and return the pixel if it passes.

Conditional iterators - UI

- The interface to conditional iterators is consistent with the other iterators:
  - `++` means get the next pixel
  - `GetIndex()` returns the index of the current pixel
  - `IsAtEnd()` returns true if there are no more pixels to access.
## Conditional iterators - guts

- What’s happening “underneath” may be quite complex, in general:
  1. Start at some pixel
  2. Find the next pixel
  3. Next pixel exists? Return it, otherwise we’re finished and `IsAtEnd()` returns true.
  4. Go to 2.

## Special case - connected regions

- For small regions within large, high-dimensional images, applying this test everywhere is needlessly expensive.
- Moreover, the brute-force method can’t handle region growing, where the “condition” is based on neighbor inclusion (in an iterative sense).

## Flood filled iterators

- Flood filled iterators get around these limitations by performing an N-d flood fill of a connected region where all of the pixels meet the “condition”
  
  ```
  FloodFilledSpatialFunctionConditionalIterator
  FloodFilledImageFunctionConditionalIterator
  ```

## How they work

- Create the iterator and specify an appropriate function
- You need a seed pixel(s) to start the flood - set these a priori or find them automatically with `FindSeedPixel(s)`
- Start using the iterator as you normally would

## “Drawing” geometric objects

- Given an image, spatial function, and seed position:

  ```c++
  TItType sfi = TItType(outputImage, spatialFunc, seedPos);
  for( ; !( sfi.IsAtEnd() ); ++sfi)
  {
    sfi.Set(255);
  }
  ```

  - This code sets all pixels “inside” the function to 255
  - The cool part: the function can be arbitrarily complex - we don’t care!

## Flood filled spatial function example

- Here we’ll look at some C++ code:
  ```
  itkFloodFilledSpatialFunctionExample.cxx
  ```
  found in the InsightApplications downloadable archive of examples.
- This code illustrates a subtlety of spatial function iterators - determining pixel inclusion by vertex/corner/center inclusion
- Inclusion is determined by the “inclusion strategy”
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

- 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)
• 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