Lecture 19
Write Your Own ITK Filters, Part2

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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`

An aside: base class implementations

- In general, when overloading base class functionality you should first call the base class function
- You do this with a line like this:

```
Superclass::GenerateInputRequestedRegion();
```

- This ensures that the important framework stuff still happens

Multi-threaded

- 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 can not) work in all cases
  - Some filters can't be multi-threaded

Multi-threaded: output regions

- The output target is now:

```
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

   -or-

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:

```
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`**:

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

Progress reporting cont.

Pointer to the filter

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

ThreadID, or 0 for ST

Total pixels or steps (for iterative filters)

Progress reporting, cont.

- To update progress, each time you successfully complete operations on one pixel (or one iteration), call:

```
progress.CompletedPixel();
```

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

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

```
dot_product(G1.Get_vnl_vector(),
              C12.Get_vnl_vector() )
```

- Create a matrix

```
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:

```
vnl_generalized_eigensystem*
pEigenSys = new
vnl_generalized_eigensystem(
Matrix_1, Matrix_2);
```

Solves the generalized eigenproblem
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

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

Domain (TInput) Range (TOutput)

- By itself it's pretty uninteresting, and it's purely virtual

What good is FunctionBase?

- It enforces an interface...

```
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`** let's 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-dimension 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:

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

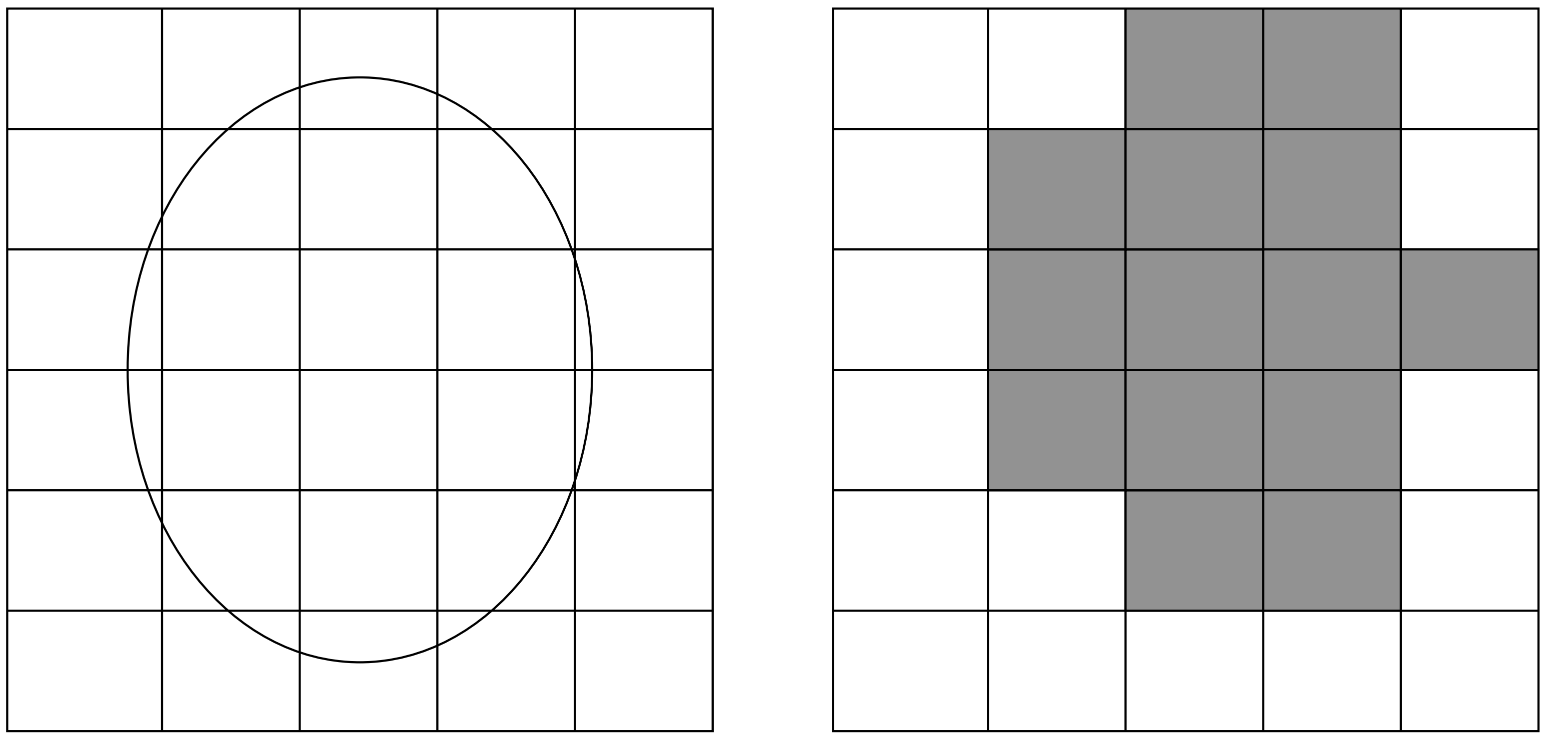
- This code sets all pixels “inside” the function to 255

- The cool part: the function can be arbitrarily complex - we don’t care!

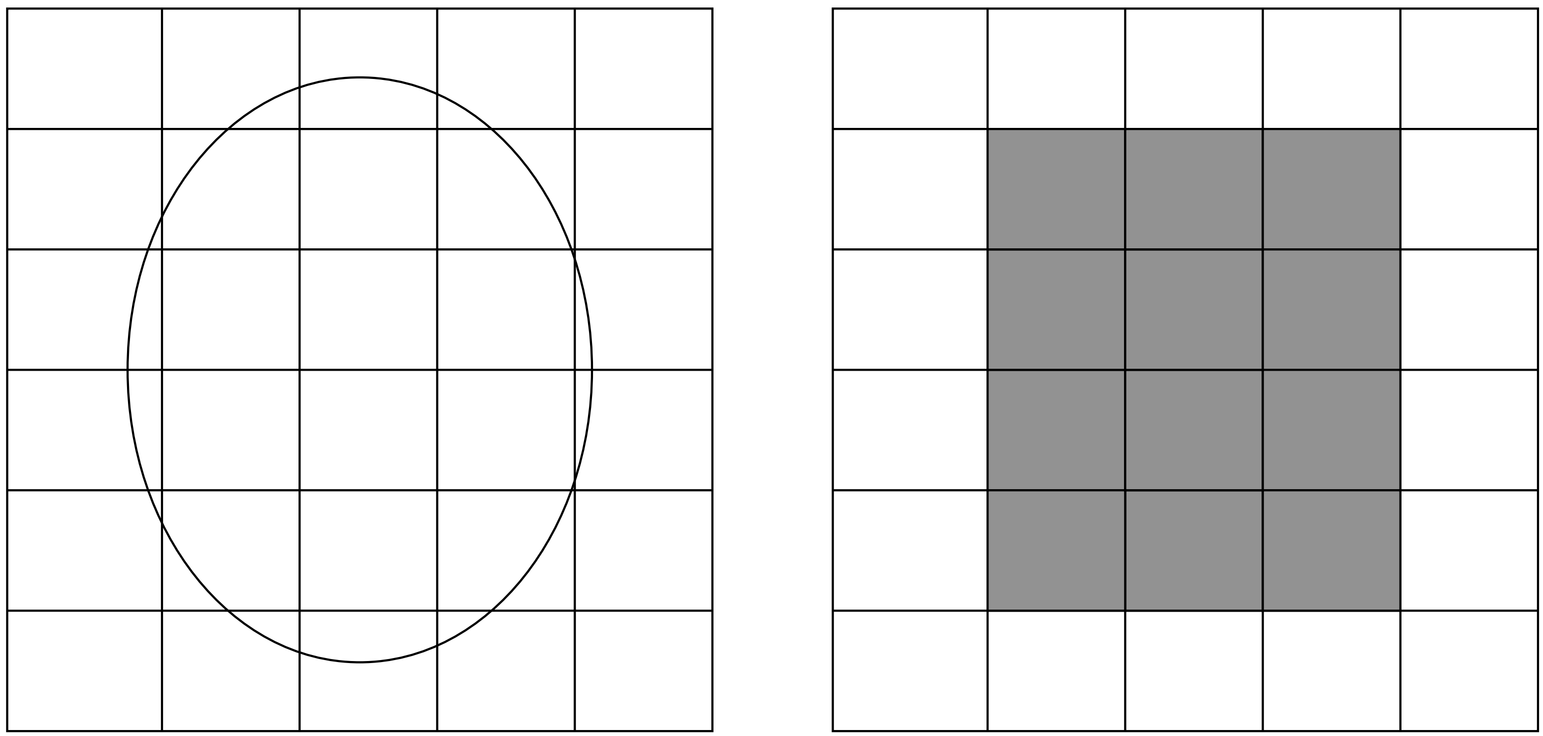
Flood filled spatial function example

- 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"

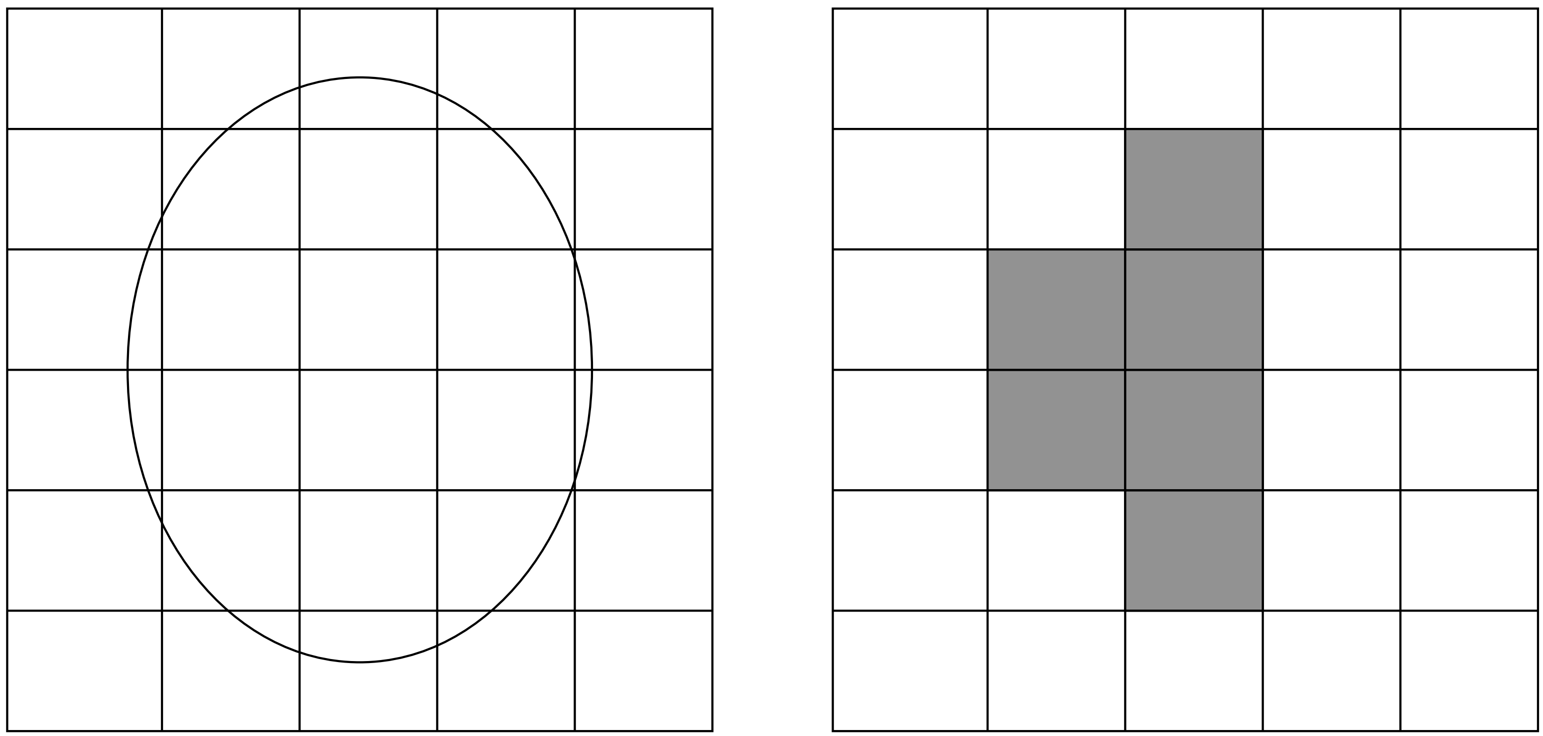
Origin Strategy



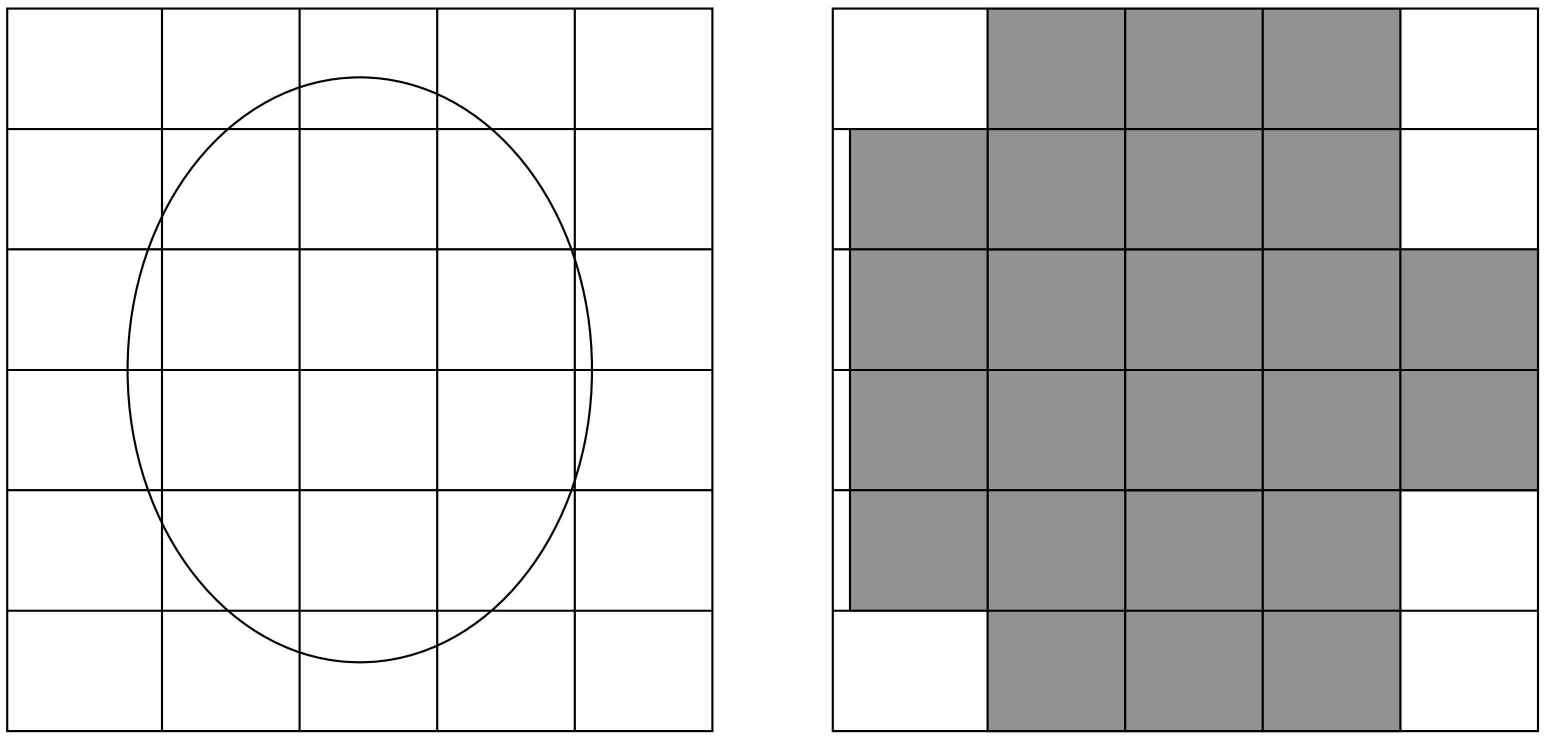
Center Strategy



Complete Strategy



Intersect Strategy



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