Conflict of Interest

- Dr. Supratik Moulik does not have a significant financial stake in any company, nor does he receive financial support or grants from any corporate or government entity.
Overview

- Introduction
- Traditional Region Growth Algorithms
- Simple GPU based Region Growth
- Enhanced Threshold Based Techniques
- Conclusions
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The Presenter

- **Who am I**
  - Fellowship trained cardiovascular radiologist.
  - Background in engineering and physics
  - CUDA developer since ~2007 (v1.0)

- **What kind of work do I do**
  - 50% clinical
  - 50% programming

- **What to expect from the talk**
  - GPU specific region growth and vessel tracking algorithms

- **What not to expect**
  - Optimized algorithm with perfectly coalesced memory access
  - Comprehensive analysis of traditional CPU algorithms
General Principles

- General Philosophical Principles
  - Code should be adaptive to input
  - All algorithms fail in the situations where it is actually needed
- Importance of Error Checking
  - Primary Goal - Not showing incorrect result
  - Secondary Goal - Showing correct result

Focus of talk
- Various region growth and segmentation algorithms
- Application to medical imaging.
- Novel GPU vessel tracking techniques
Overview

- Introduction
- **Traditional Region Growth Algorithms**
  - Simple GPU based Region Growth
  - Enhanced Threshold Based Techniques
- Conclusions
Who is Jason Walsh?

- Full time student Studying CS
- Plans for BS and MS
- Informatics work at Hospital of the University of Pennsylvania (HUP)
  - Creating a secure online patient record system
- Interested in research opportunities in medical imaging or GPU Development
General Principles

- **Simple image segmentation process**
  - Assign points to groups based on set of criteria
  - All point determined to be “in” or “out” of the region
  - Points in region “connected” spatially and by membership criteria

- **Utilizes an initial seed point(s)**
  - Seed points are provided either manually or auto generated
  - Serve as starting point for region
  - Provide parameters for initial region membership criteria

- **Boundaries determined by processes such as thresholding**
  - Based on differences in specific pixel properties
  - Can be used with RGB or BW images
Target Lesion with Various Red Values
Initial Growth Threshold Set Narrow

Initial region growth threshold
- set narrowing/specific
- only deepest red values
Progressively Widen Threshold

Widened threshold
-includes more of the lesion
Progressively Widen Threshold
Progressively Widen Threshold
Region Growth in Medical Imaging

- Used for partitioning volumetric data
  - Identify individual organs
  - Remove extraneous data

- Segmenting Thin Section or Volumetric Studies
  - CT Angiograms
  - Cardiac MRI
  - Multiphase CT scans

- Region Growth Often Combined with Volume Rendering
  - Provides information regarding region volume
  - Aids in visualizing spatial relationships
Major Uses in medical imaging

- Vessel Segmentation
- Bone Segmentation
- Targeted Lesion Segmentation
Vessel Segmentation

- **Isolation of the vessels**
  - Aorta and major 1\textsuperscript{st} and 2\textsuperscript{nd} order branches
  - Dependant on degree of vascular contrast
- **Aids treatment planning by providing accurate 3 dimensional path length of vessels.**

- **Airway Segmentation**
  - Similar to vessel tracking in terms of algorithms
  - Virtual Bronchoscopy for identifying tumors
Vascular Stent

Aortic Stent

Treatment Length
Virtual Bronchoscopy
Major uses in medical imaging

- Vessel Segmentation
- **Bone Segmentation**
- Targeted Lesion Segmentation
Bone Segmentation

- Primary use:
  - Modeling fractures for operative planning
  - Excluding bone points to aid in the accuracy of vessel tracking
  - Individual bone segmentation for lesion localization

- Bone has overlap of density values with numerous other structures
  - Vascular calcium
  - Densely enhanced vessels
  - Enteric contrast
  - Small metallic structures
Region Growth of the Pelvis
Individual Bone Growth

- Sacrum
- Iliac
- Femur
Not all that is white is bone
Major Uses in medical imaging

- Vessel Segmentation
- Bone Segmentation
- Targeted Lesion Segmentation
Target Lesion Segmentation

- The most critical role of region growth in medical imaging is in the isolation of target lesions
  - Measure size of primary and metastatic tumors
  - Change of lesion size and morphology over time
- Critical to incorporate edge detection data as well as dynamic thresholds
Primary Development Workstation
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Translating Region Growth to the GPU

- **Calculate Gradients**
  - Well suited in general for GPU implementation.
  - 2D or 3D gradients

- **Region Growth Loop**
  - Major difference between CPU and GPU implementation.
  - Result of i-th iteration
    - depends on result of iteration (i-1)
    - results from earlier threads
    - Race condition can cause variability in results when number of iterations is limited.

- **Speed**
  - Maintain a single data set that is modified and changes during a single kernel execution
  - RAW (result from one thread effect other thread in warp or block)
  - WAR (missed opportunity for region growth)

- **Reproducibility**
  - Main data set and Result data

- **Determining Completion**
  - Typically achieved when all points are classified
  - Not always a straightforward task with large 3D data sets
How We Think it Happens

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**Legend:**
- **Pink**: Initial state
- **Red**: Change occurred
- **Black**: Double change occurred
- **Blue**: Tertiary change occurred
What Really Happens
Code Path

User Input
P (x,y,z)

Process Image
- Gradient Calculation
- Initial Threshold

Establish Region Criteria

Apply Selection Criteria to Boundary Elements

Apply Result

Region Growth Loop
Host Code

Initial Region Assignment And Propagation

Region Growth Loops
Device Code

Check for seed point

Check Criteria for Immediately Surrounding Points

Memory Access Not Globally Convergent
Initial Seed Points
Results

- The quality of a region growth algorithm judged by:
  - Speed of completion
    - Number of seed points
    - Limit iterations on non-edge points
  - Sensitivity
  - Specificity
  - Reproducibility
    - In general only possible with the use of memory result buffer

- How to determine failure
  - Non-target organs included in region
  - Large sections of bone omitted.
Pelvic Subsegmentation By Contextual Analysis
Image Through Lower Chest
Growth Error Including Hypogastrics
Closer look at boundary problems
Distinct Structures, But How Do You Know?
Context Clearly Matters More than Density
Cooling A Hexa-GPU System After Hours
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Methods for Guiding Region Growth

- **General Edge/Gradient based**
  - Established method for constraining growth
  - Perform an initial edge detection
  - Use derivative in N directions for edges/bounding
  - Work poorly for noisy or low contrast images

- **Problem Specific**
  - Geometric
    - Features of structures used to guide region growth.
    - Avoid overly rigid geometries that prevent accommodating variations in anatomy
    - Not generally useful in structures that have significant variations.
  - Several key geometries are useful in the human body
    - Spherical Symmetry
    - Cylindrical Symmetry
    - Model based geometry
    - Other
Guided Methods

- Spherical Symmetry for Small Vessel Tracking
- Cylindrical Symmetry for Large Vessel Tracking
- Variable Threshold for Small Vessel Tracking
Guided Methods

- Spherical Symmetry for Small Vessel Tracking
- Cylindrical Symmetry for Large Vessel Tracking
- Variable Threshold for Small Vessel Tracking
Spherical Coordinate in Vessel Tracking

- Very simply coordinate system to manipulate
  - Provides an intrinsic symmetry when analyzing structures which would otherwise require multiple coordinate transformations
  - Auto compensates for rotation about long axis

- Well Suited for specific tasks
  - Identifying Initial segments of vessels
  - Maintaining luminal axis
Vessel Tracking With Spherical Symmetry

- What is most important
  - Continuity is one of the hallmarks of vessels
  - Relative density is important
  - Exploiting spherical symmetry requires appropriately positioned seed point

- To track vessels you can use concentric spheres
  - Isolate potential points for region growth
  - Vastly improves subsequent growth by limiting extraneous analysis
Applying Concentric Sphere Model
Device Code

Calculate Point on Sphere Surface

Global Memory Access

Determine if Point Meets Criteria
Device Code (2)

Global Memory Access to Retrieve Sphere Points on Adjacent Shells

Restrict to Points that Passed Previous Stage

Check Point Between Shells

Record Results
Limitations

- Vessels that deviate significantly from spherical symmetry
  - Lumen follows contour of sphere shell
  - Significant obliquity of course
- No straight forward way to limit inclusion of non-vascular points
  - Only an initial/ pre-processing step for more guided region growth
- Requires appropriate positioning of initial seed point
  - Typically near the origin of vessel
  - Works best for short segments of small straight-ish vessels
Guided Methods

- Spherical Symmetry for Small Vessel Tracking
- **Cylindrical Symmetry for Large Vessel Tracking**
- Variable Threshold for Small Vessel Tracking
Principles of Large Vessel Tracking

- Numerous structures in human body have intrinsic cylindrical symmetry
  - Scale on which the symmetry is maintained varies
  - Aorta is not a “true” cylinders

- Coordinate system matters
  - Aorta tends toward a specific direction
  - Starts near midline and ends near midline
  - Not necessarily predictable in between

- Massively threaded code allows for cooperative behavior
  - One thread can motivate but not restrict other threads.
  - Numerous paths exist which satisfy a set of conditions
  - The tendency is for true paths to outnumber stray paths
Defying Density with Brute GPU force
- Highly computationally intensive algorithm
  - Initial slice search grid (256 * 256)
  - Distal slice target points (64 * 64)
  - Distance between slices (128)
- Total ~ 270 million combinations (128 points sampled per combination)
- Longer path length
  - Increases specificity.
  - Decreases sensitivity
- Location matters
  - Regardless of path length, IVC contamination is always an issue
  - Spine needs to be avoided
Host Code

- MemCopy
- Run kernel
- Statistical Analysis of Results
Device Code

Thread and Block Indexing

Use Shared Memory

Convert thd/blk index to spatial positioning

Global Memory Access

Converge Shared Data

Compare Result to Existing Max
Limitations

- Vessels which vary significantly in directionality
  - Very common, though not on scales typically used by algorithm
  - Surgical aorta poses additional problems
- Significant variations in contrast density over length of vessel analysis
  - Fortunately uncommon
- Significant variants in vessel size
  - Common and important to recognize
- Discontinuity of vessel
  - Uncommon though important to recognize
- Extra-vascular contrast
  - Uncommon though important to recognize
Roots in ray tracing

- This algorithm inspired by ray tracing
- Typical Ray tracing provides structures with attributes
  - Reflection, refraction, and shadow
- Acceleration structures
  - Way to efficiently traverse static scene
  - GPU implementation exist (OptiX)
- Vessel tracking implementation
  - Continuous medium
  - Acceleration structure dynamically changing
  - Fractional transmission rather than refraction
Ray Tracing/Mean Free Path

- Each ray made up of multiple points
  - Various density values
  - Separate average and standard deviation

Potential Fate of Rays

- Reflection/Refraction
  - Not a possible outcome in this algorithm
- True absorbed rays
  - Average or standard deviation outside range
  - Significant acute drop in density (edge)
- Partial transmission
  - Results from fluctuations in density (e.g. image noise, metal artifact, heart failure)
  - Excluded unless no other choice
- Successful rays
  - All points meet criteria
  - Low variance in density with average within range
  - Limited fluctuations (>95% transmission)
Guided Methods

- Spherical Symmetry for Small Vessel Tracking
- Cylindrical Symmetry for Large Vessel Tracking
- **Variable Threshold for Small Vessel Tracking**
Variable Threshold for Small Vessels

- **Small vessel tracking**
  - Significantly more challenging than aortic tracking
  - No reasonable expectation of linearity
  - Vessel width varies greatly inter and intra scan

- **Quality of contrast enhancement**
  - Varies greatly between scans.
  - Scanner can outrun the contrast bolus

- **Minimizing the density window is desirable**
  - Artery / vein differentiation often relies on very small differences
  - Artery/ bone differentiation relies critically on boundary point which have intermediate values
Points that fall in window (150-400 HU)
- Arteries
- Veins
- Organs
Intra vessel variations in average HU
Dynamic Variable Threshold

- Requires partitioning a region into sub-regions
- Sub-regions have their own parameters
- Overall constraint on parameters dynamically computed
- Connection with overall region not necessarily more computationally intensive
- Avoid unnecessary computations
- Easier to identify aberrant paths.

- Each thread block defines separate sub-region
- Cooperative interaction within sub-region analysis keeps threshold and window appropriately narrow
- Global memory for communication between sub-regions prevents backtracking
- Allows low level coordination and communication

Entire Vessel is Region

Sub-region 1
- Level 1
- Width 1

Sub-region 2
- Level 2
- Width 2
Host Code

MemCopy

Run kernel

Check Results
Device Code

Thread and Block Indexing

Adjust Level

Perform Adjacent Point Analysis

Converge Shared Data and Check Bounds

Write Results to Global Memory
First Server Running Alpha Build of Software
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Conclusions

- Basic Principles of Region Growth
- Utilization of Region Growth in Medical Imaging
- Basic GPU Implementation of Region Growth Algorithm
  - Direct translation of CPU code problematic
  - Doesn’t utilize full potential of massively parallel GPU
- Guiding region growth
  - Large vessel tracking with modified ray tracing
- Small vessel tracking
  - Spherical
  - Variable threshold
QUESTIONS