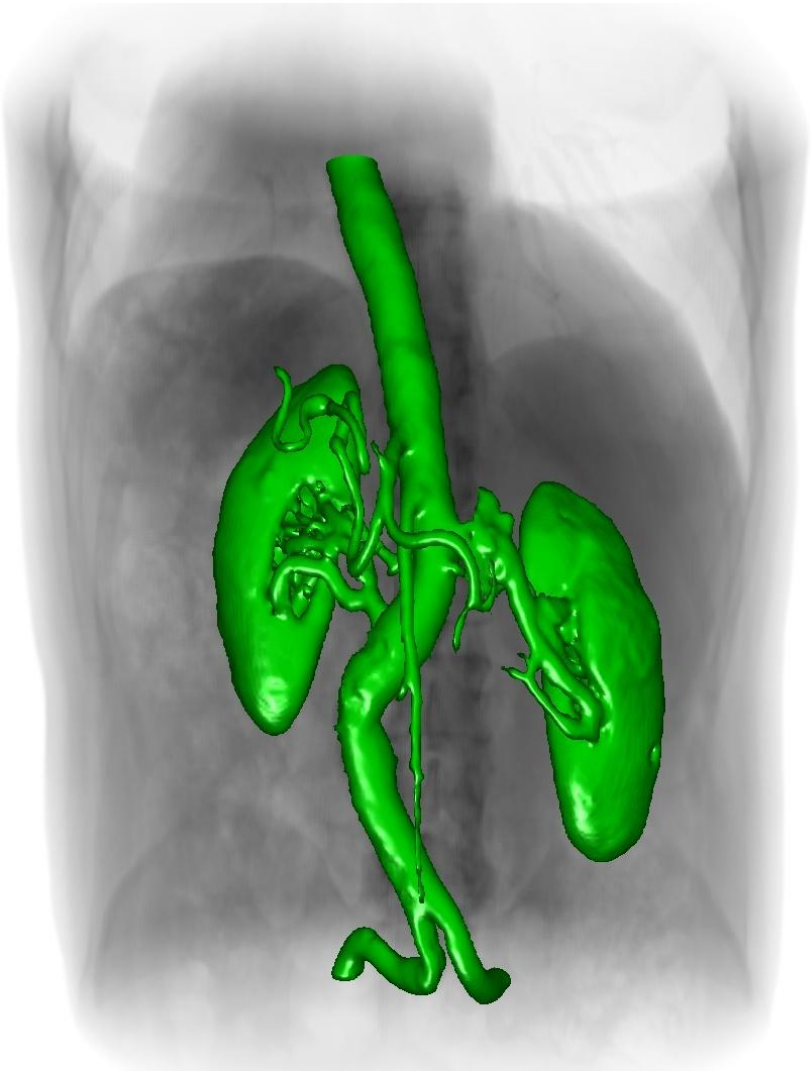
A Work-Efficient GPU Algorithm for Level Set Segmentation



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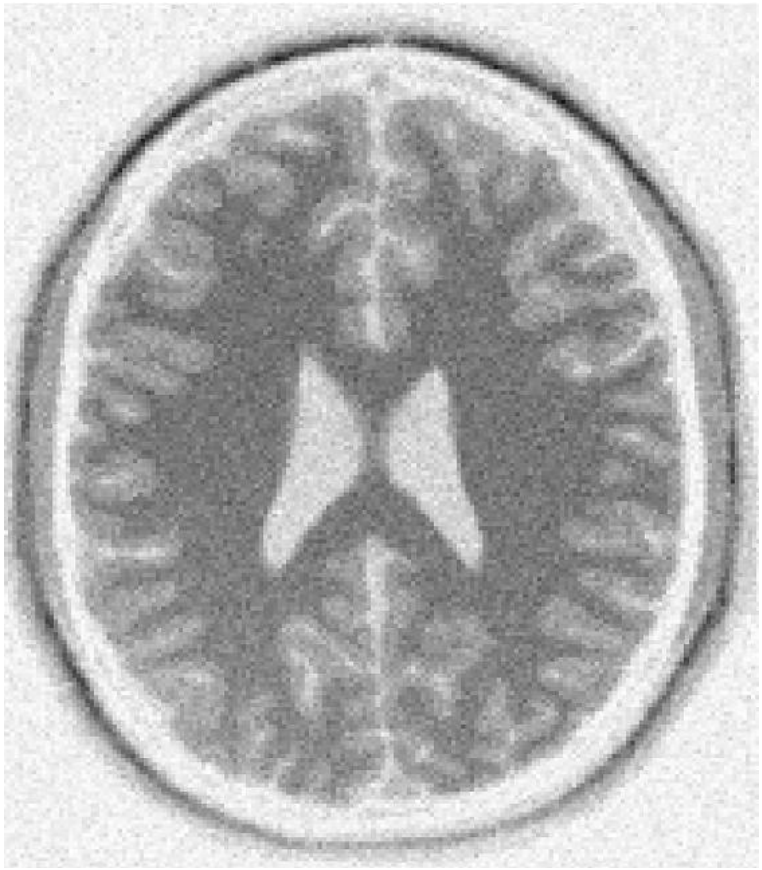
What do I mean by work-efficient?

If a parallel algorithm performs asymptotically equal *work* to the most efficient sequential algorithm, then the parallel algorithm is work-efficient.

What do I mean by segmentation?



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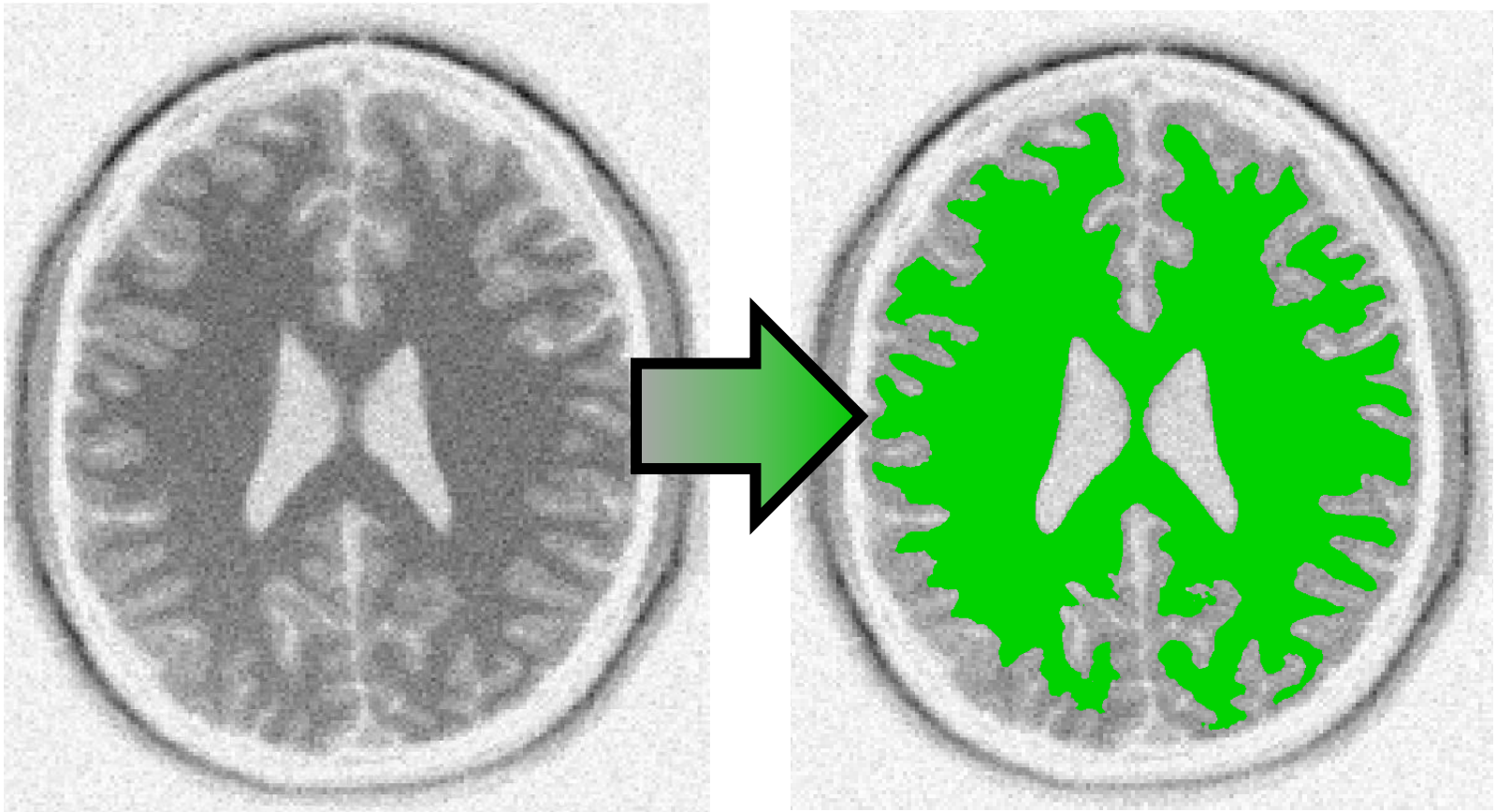

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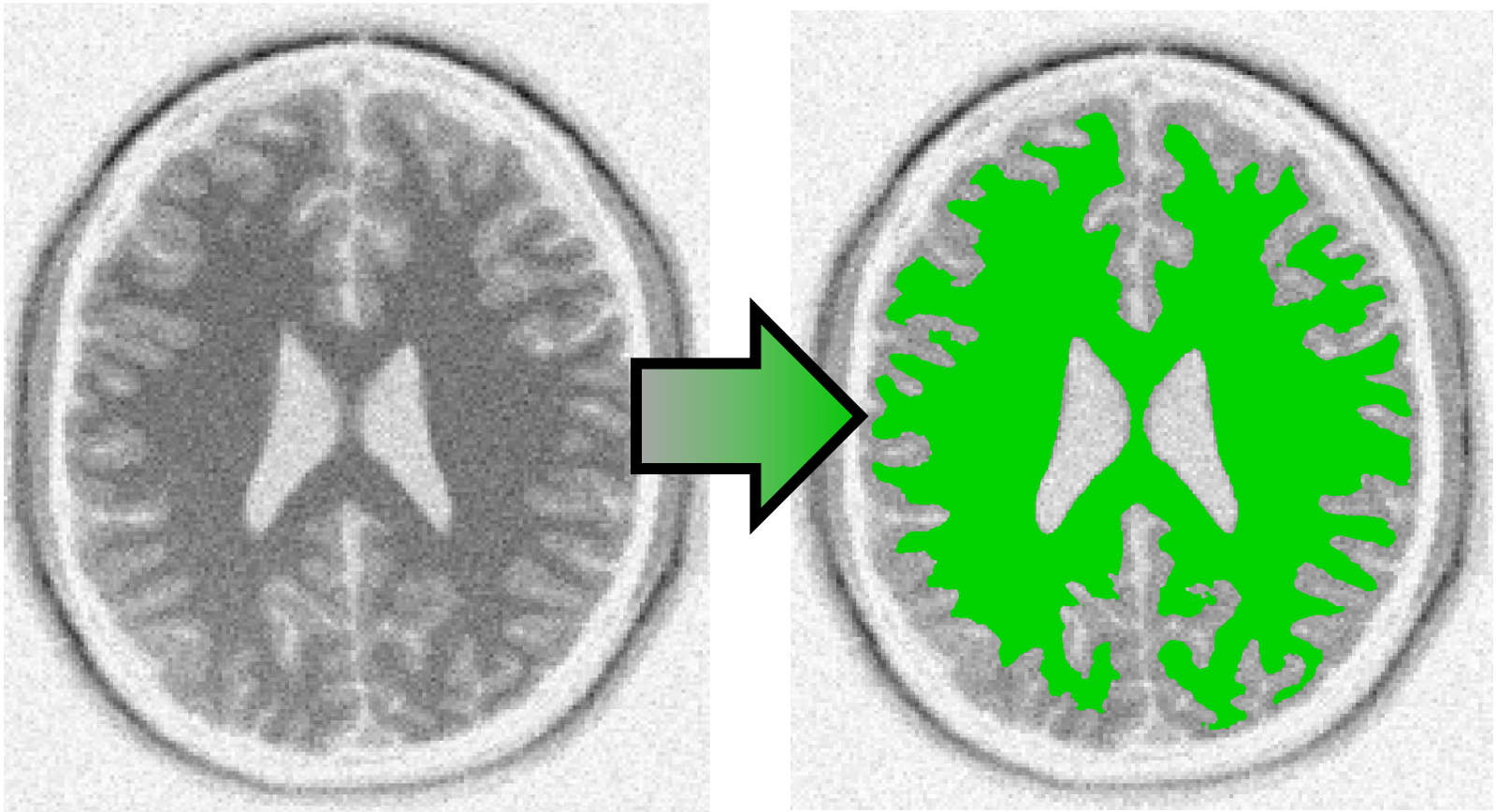

Goal: Fast, interactive, and accurate segmentations even when the data is noisy and heterogeneous

Why Level Sets?

Good: Competitive accuracy compared to manual segmentations by experts (Cates et al. 2004)

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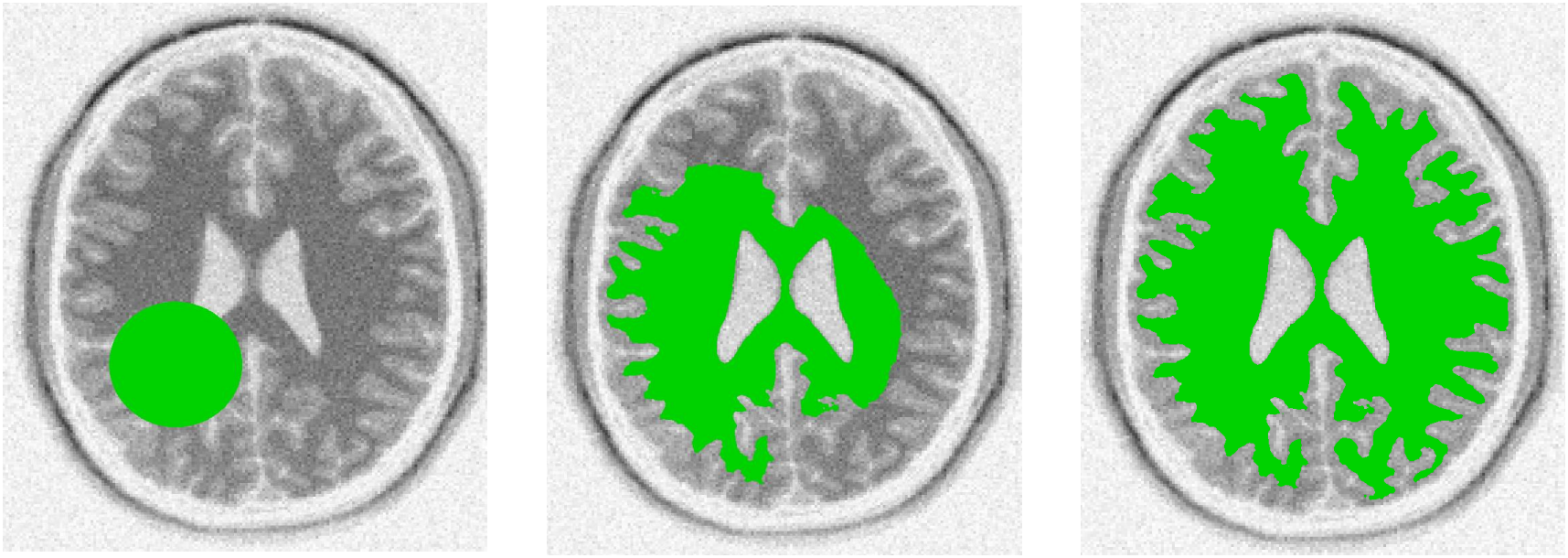
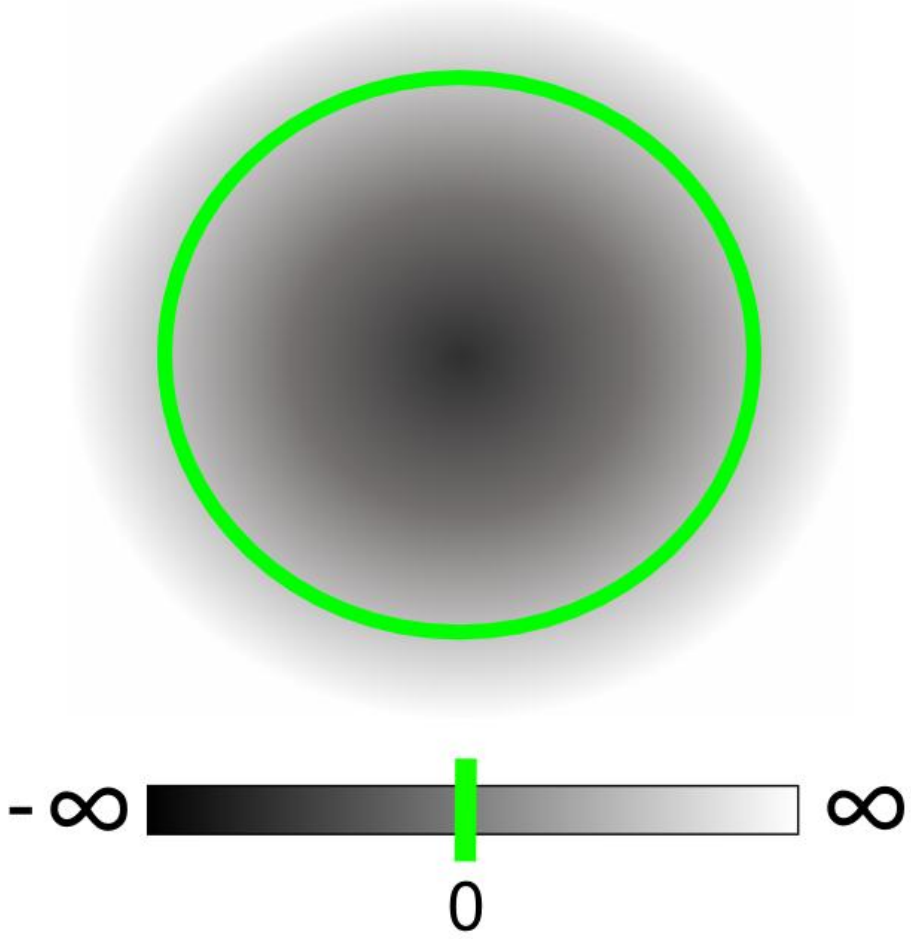
This limitation motivates our algorithm

Segmentation with Level Sets

- Embed a seed surface in an image
- Iteratively deform the surface along normal according to local properties of the surface and the underlying image

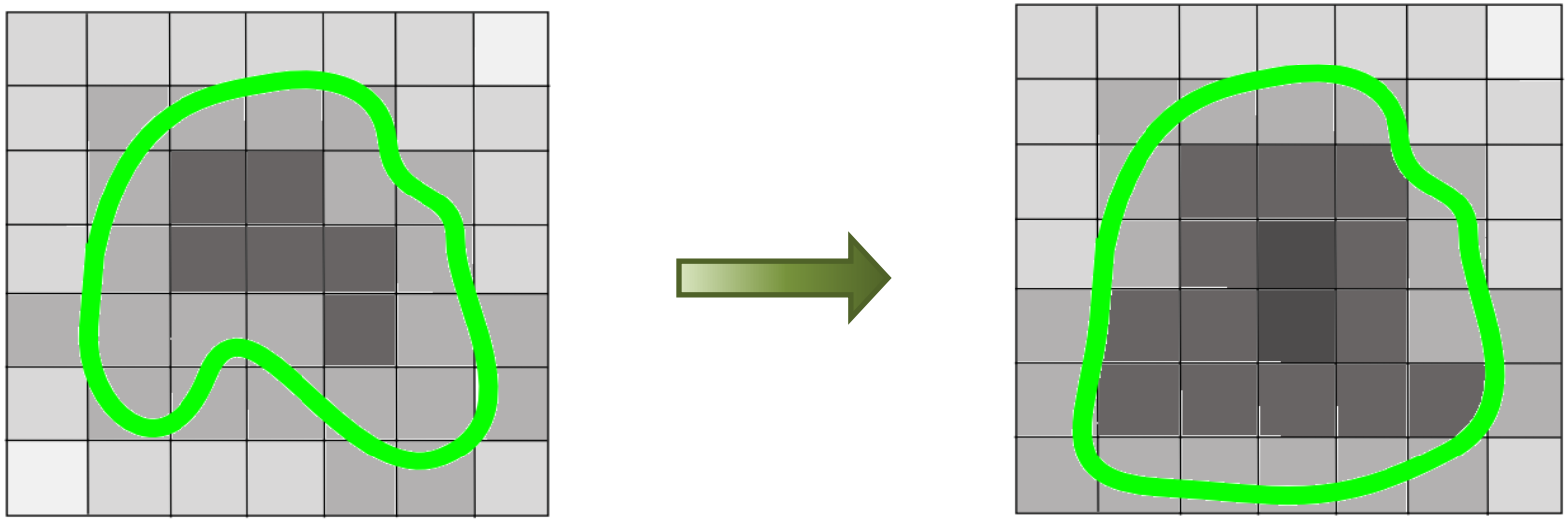


Segmentation with Level Sets



Represent the level set surface as the zero isosurface of an implicit field

Segmentation with Level Sets



- Deformation occurs by updating fixed elements in the implicit field
- Surface splitting and merging events are handled implicitly
- Requires many small iterations for surface to converge on a region of interest

Previous Work

- CPU
  - Narrow Band (Adalsteinson and Sethian 1995)
  - Sparse Field (Whitaker 1998, Peng et al. 1999)
  - Sparse Block Grid (Bridson 2003)
  - Dynamic Tubular Grid (Nielson and Museth 2006)
  - Heirarchical Run-Length-Encoded (Houston et al. 2006)
  - Above algorithms:
    - leverage spatial coherence by only processing elements near level set surface
    - require at least linear time to update the level set field
- GPU
  - GPU Narrow Band (Lefohn et al. 2003, 2004; Jeong et al. 2009)
  - Requires a linear number of steps to update the level set field
  - Saves memory by only storing a sparse representation of the level set field

Our Approach

Leverage spatial and temporal coherence in the level set simulation to reduce GPU work

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Contributions:

1. Novel algorithm that limits computation by examining the temporal and spatial derivatives of the level set field
2. Work-efficient mapping to many-core GPU hardware that updates the level set field in a logarithmic number of steps

Leveraging Temporal Coherence

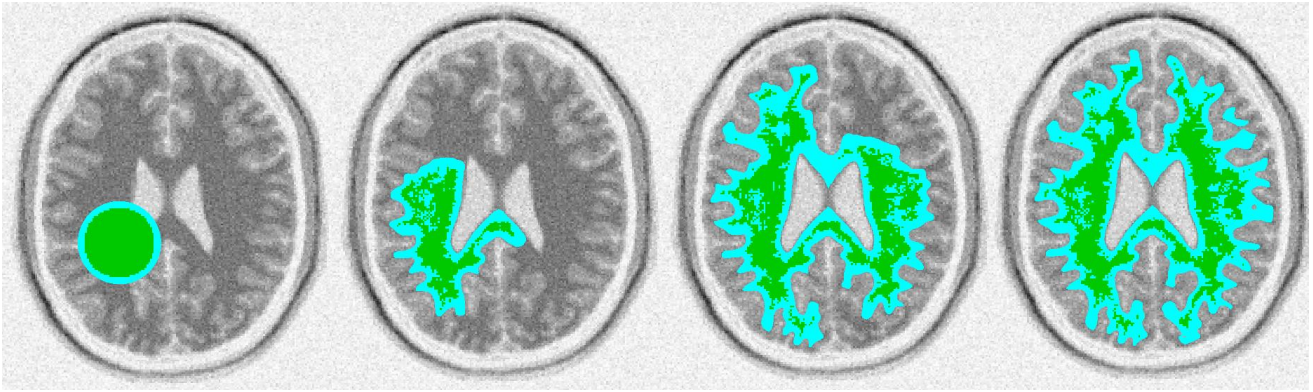
We only want to spend time updating the voxels that are actually changing

Leveraging Temporal Coherence

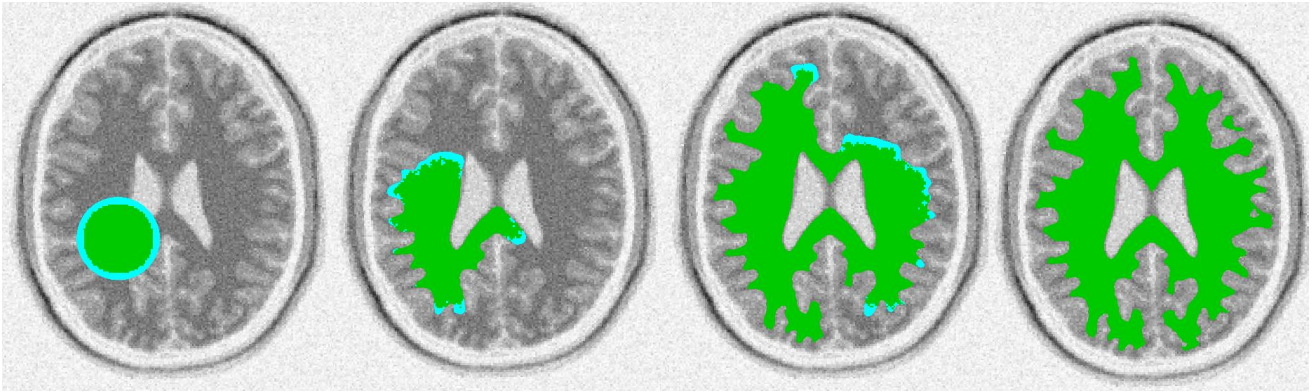
Necessary conditions for voxels to be in the active computational domain:

1. **Are we close to the surface border?** (Lefohn et al. 2003)
2. **Is the field neighborhood changing over time?**

Leveraging Temporal Coherence



"Are we close to the surface border?"



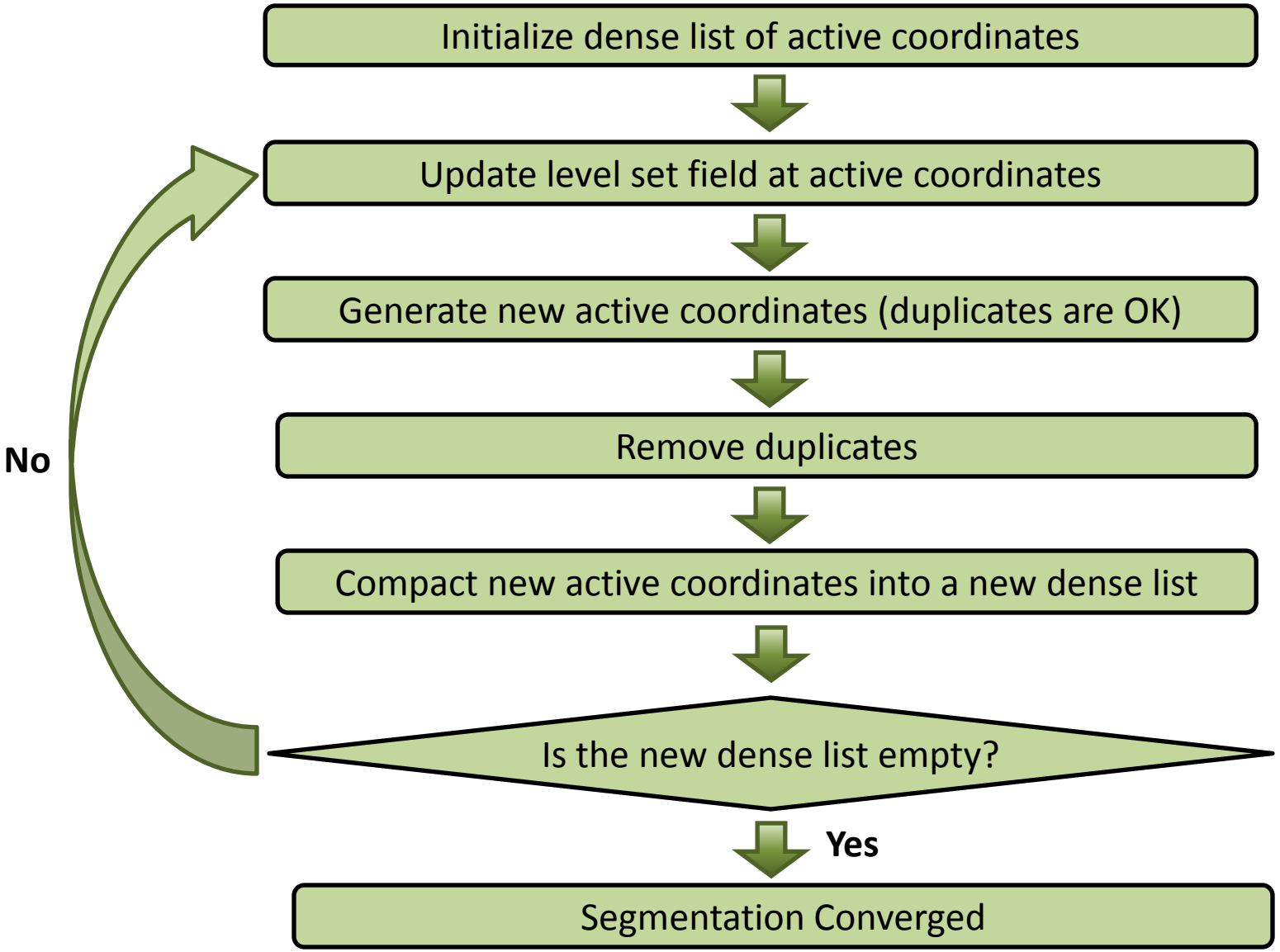
"Are we close to the surface border?" **AND** "Is the field neighborhood changing over time?"

currently active computational domain

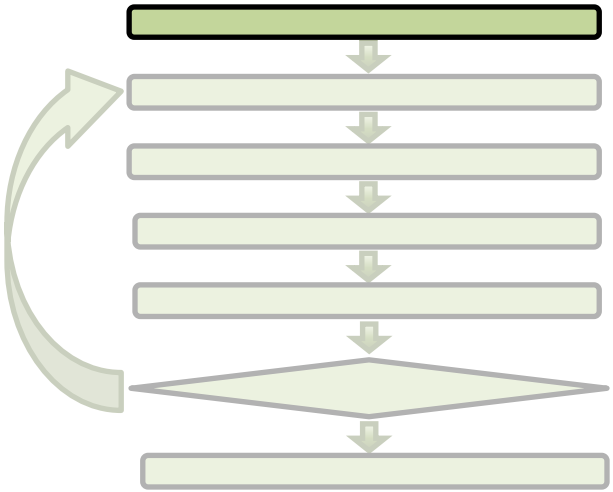
segmented region

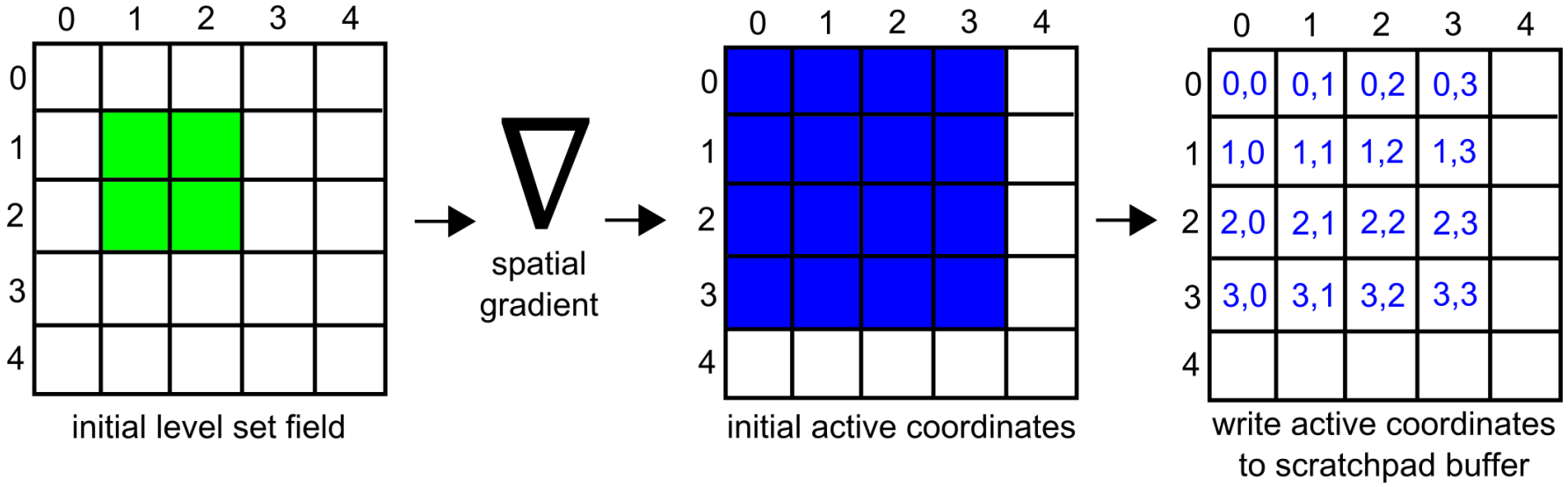
Live Demo

Our Work-Efficient GPU Pipeline

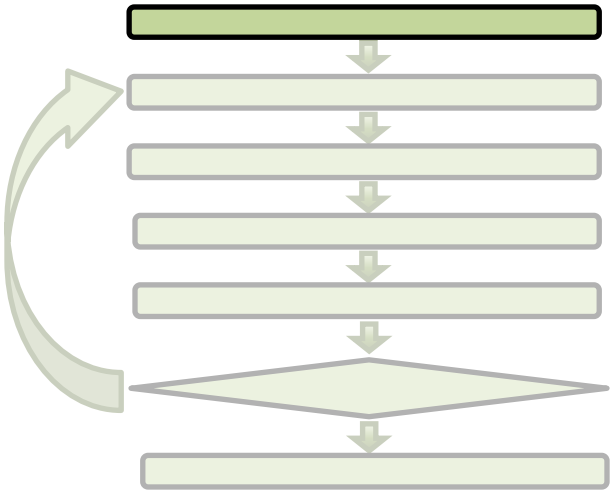


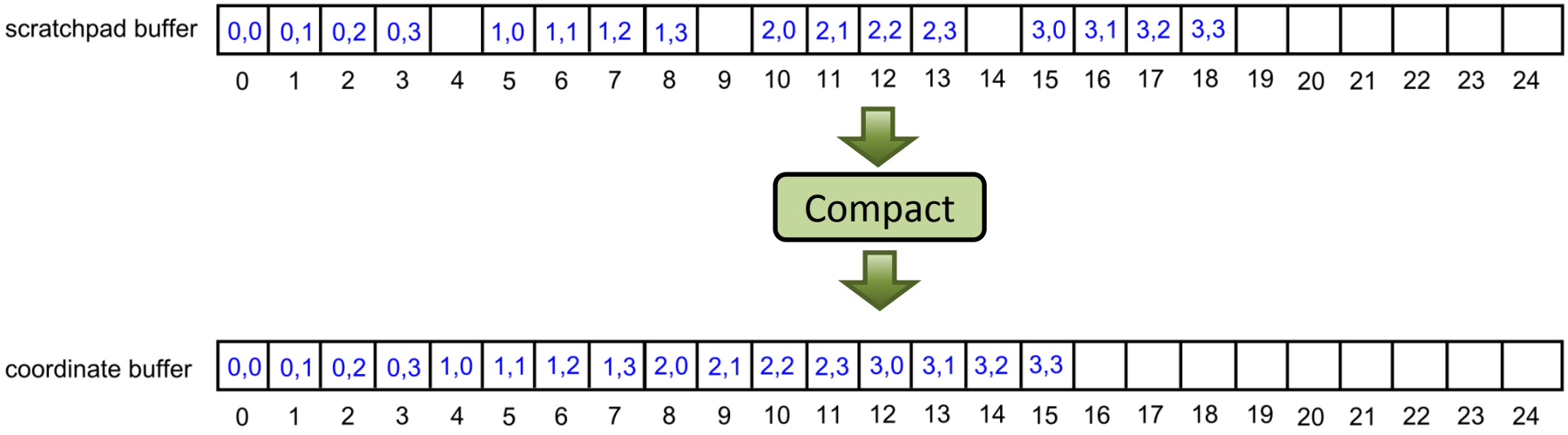
Initializing a scratchpad buffer with active coordinates





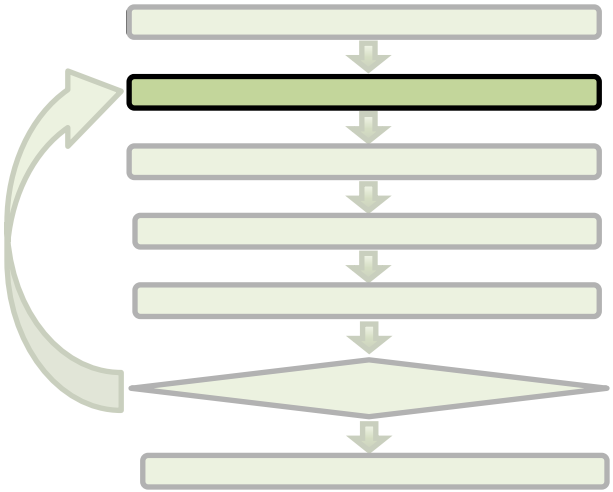
Compacting the scratchpad buffer to produce a dense list

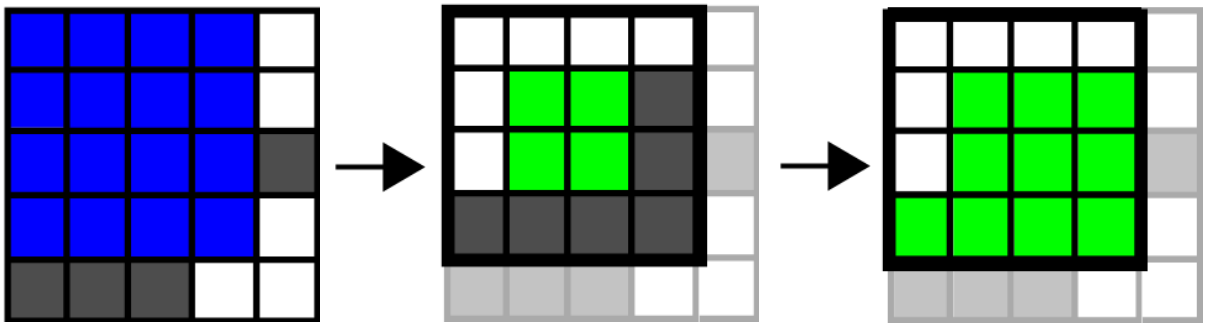




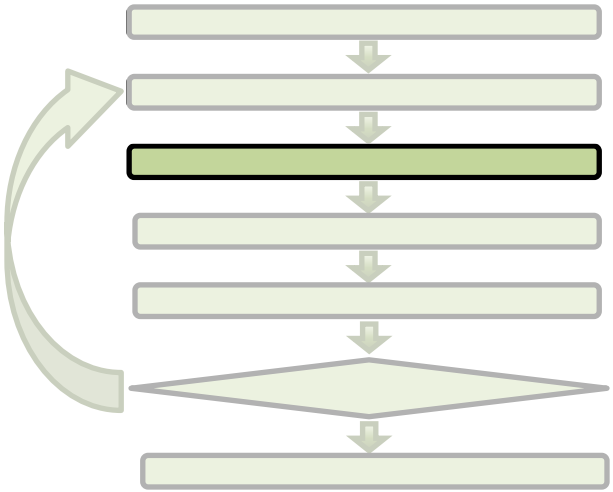
For more details see Harris et al. 2007; Sengupta et al. 2007, 2008

Updating the level set field at active coordinates





Generating new active coordinates into a series of auxiliary buffers (duplicates are OK)



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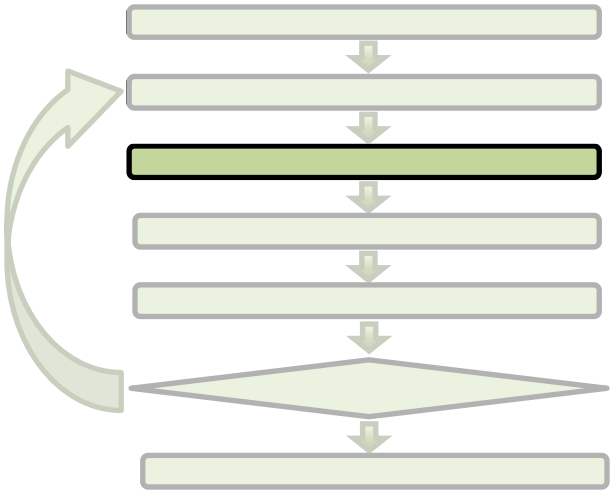

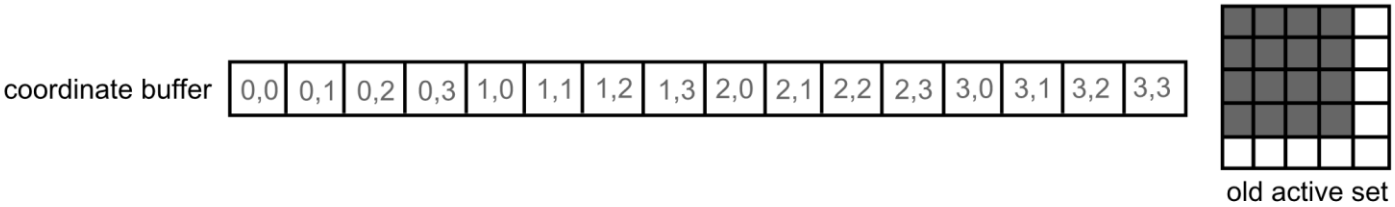

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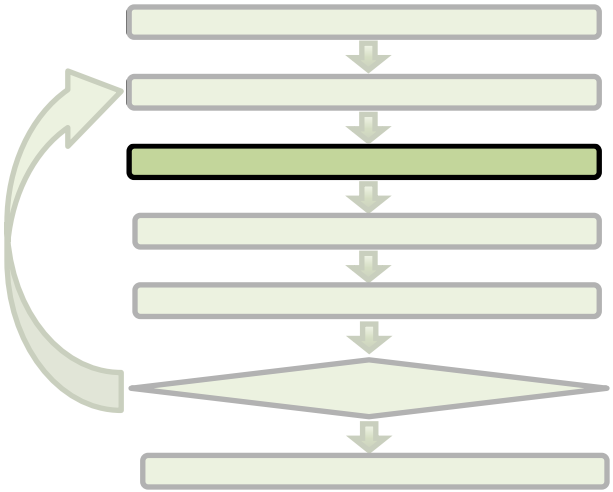

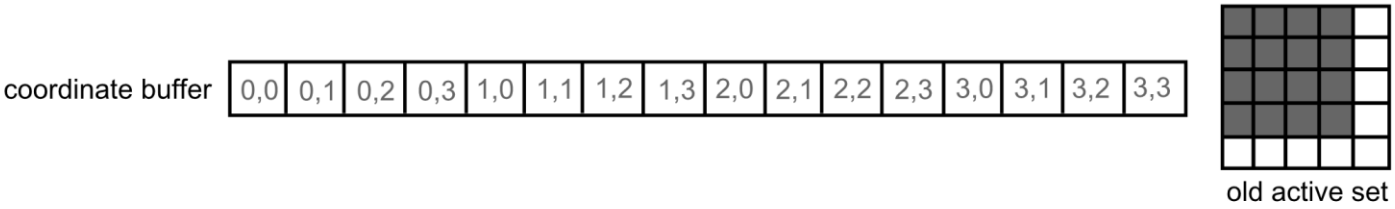

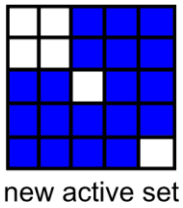

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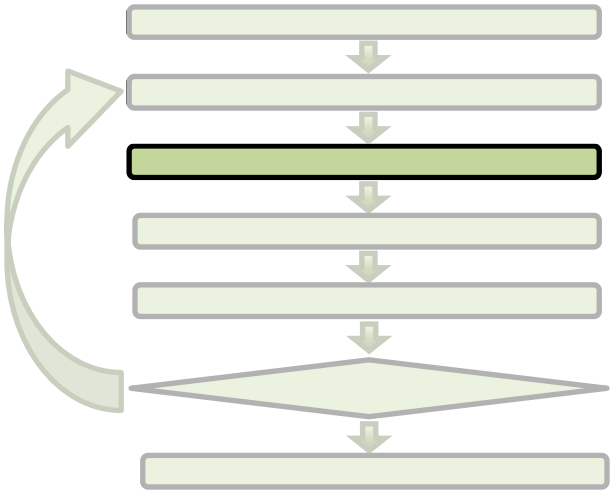
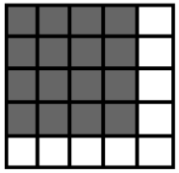


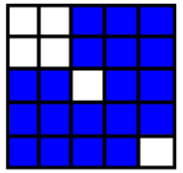
coordinate buffer

0,0	0,1	0,2	0,3	1,0	1,1	1,2	1,3	2,0	2,1	2,2	2,3	3,0	3,1	3,2	3,3



old active set

auxiliary buffers $\{ B^{\bullet}, B^{\rightarrow}, B^{\uparrow}, B^{\leftarrow}, B^{\downarrow} \}$



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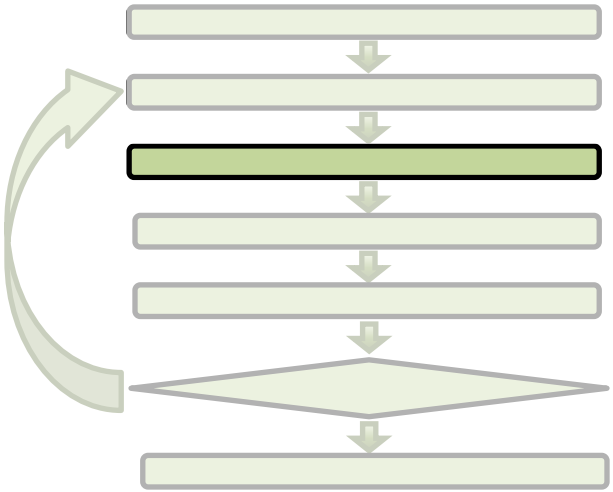
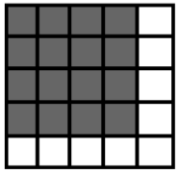


threads

coordinate buffer

0,0	0,1	0,2	0,3	1,0	1,1	1,2	1,3	2,0	2,1	2,2	2,3	3,0	3,1	3,2	3,3



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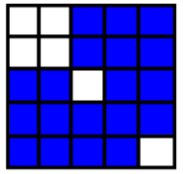
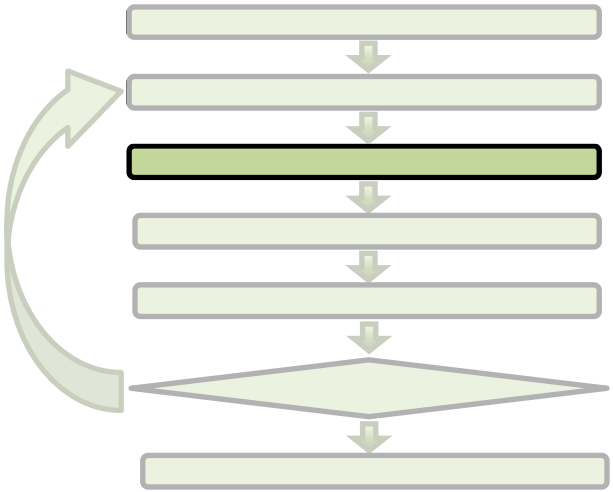


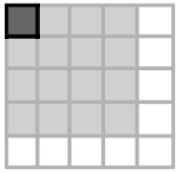
new active set

Generating new active coordinates into a series of auxiliary buffers (duplicates are OK)



threads

coordinate buffer | 0,0 | 0,1 | 0,2 | 0,3 | 1,0 | 1,1 | 1,2 | 1,3 | 2,0 | 2,1 | 2,2 | 2,3 | 3,0 | 3,1 | 3,2 | 3,3 |



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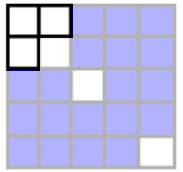

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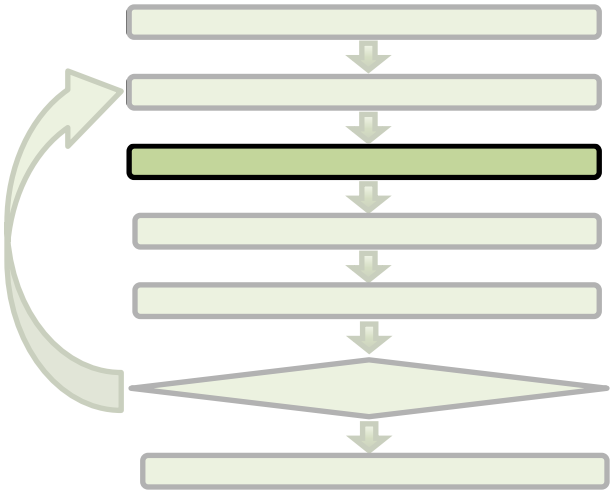

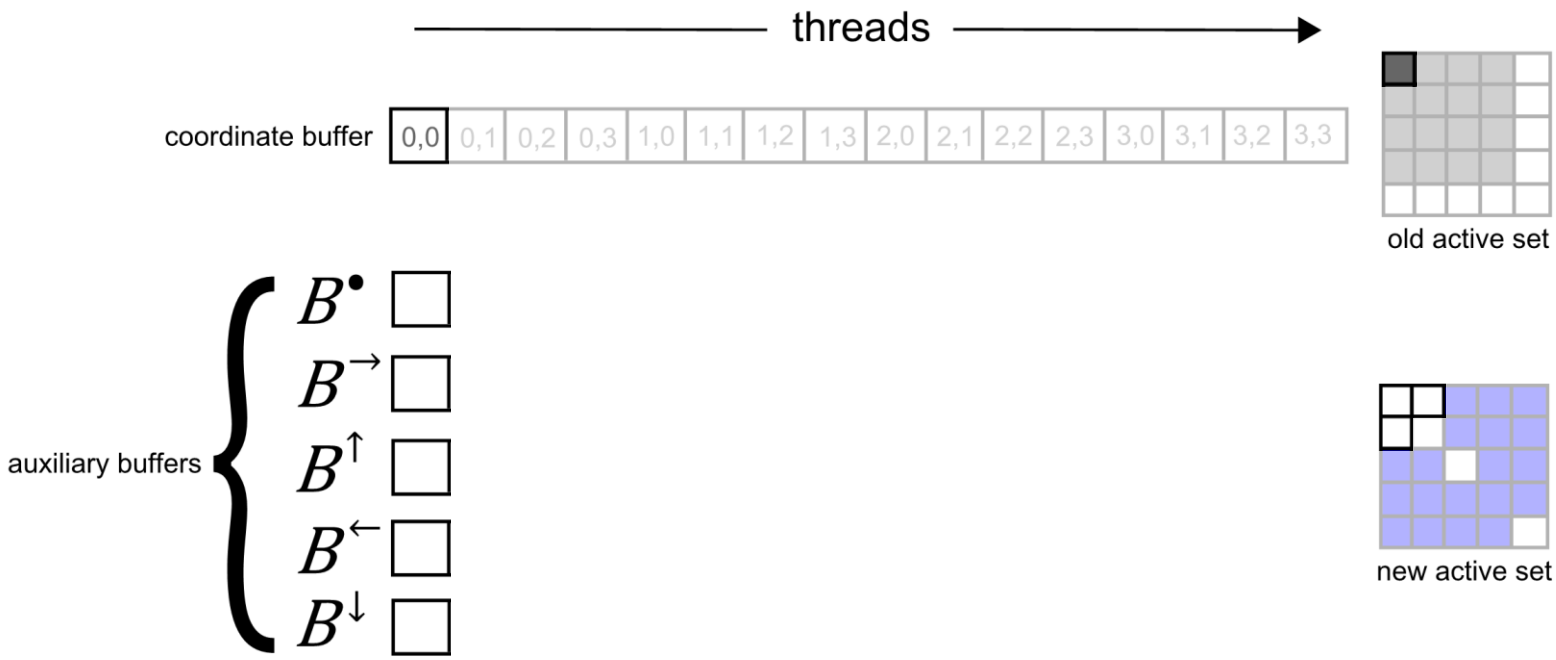

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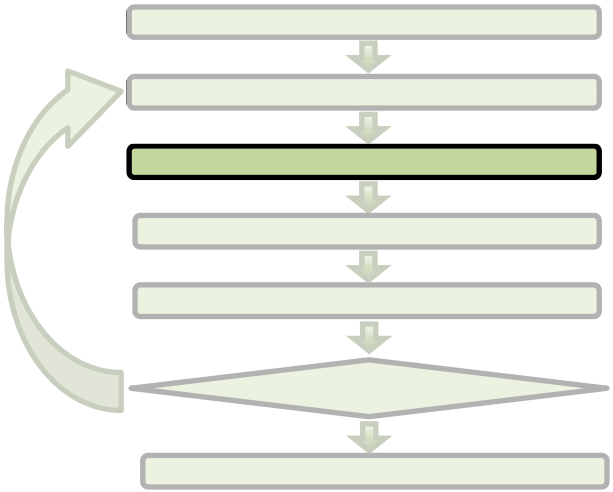

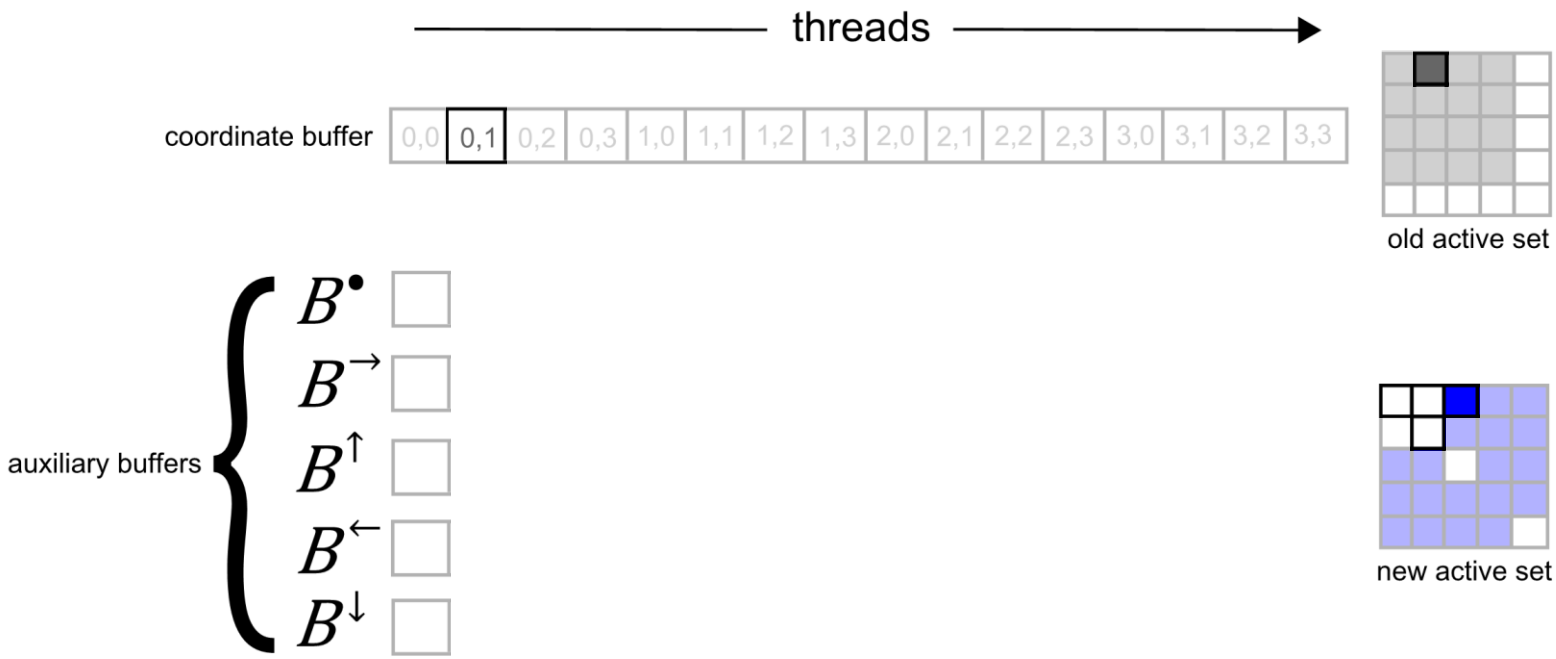

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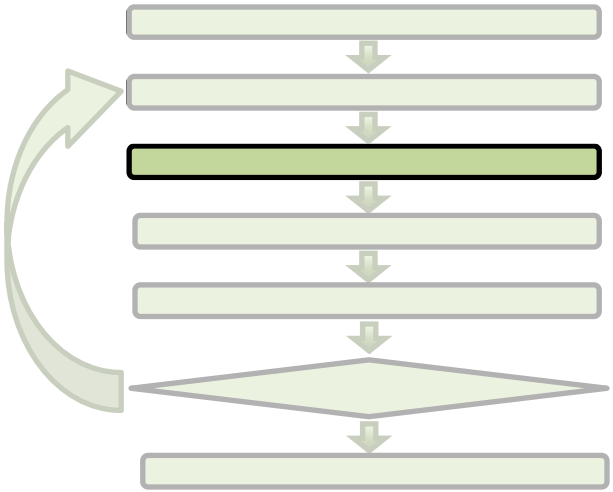

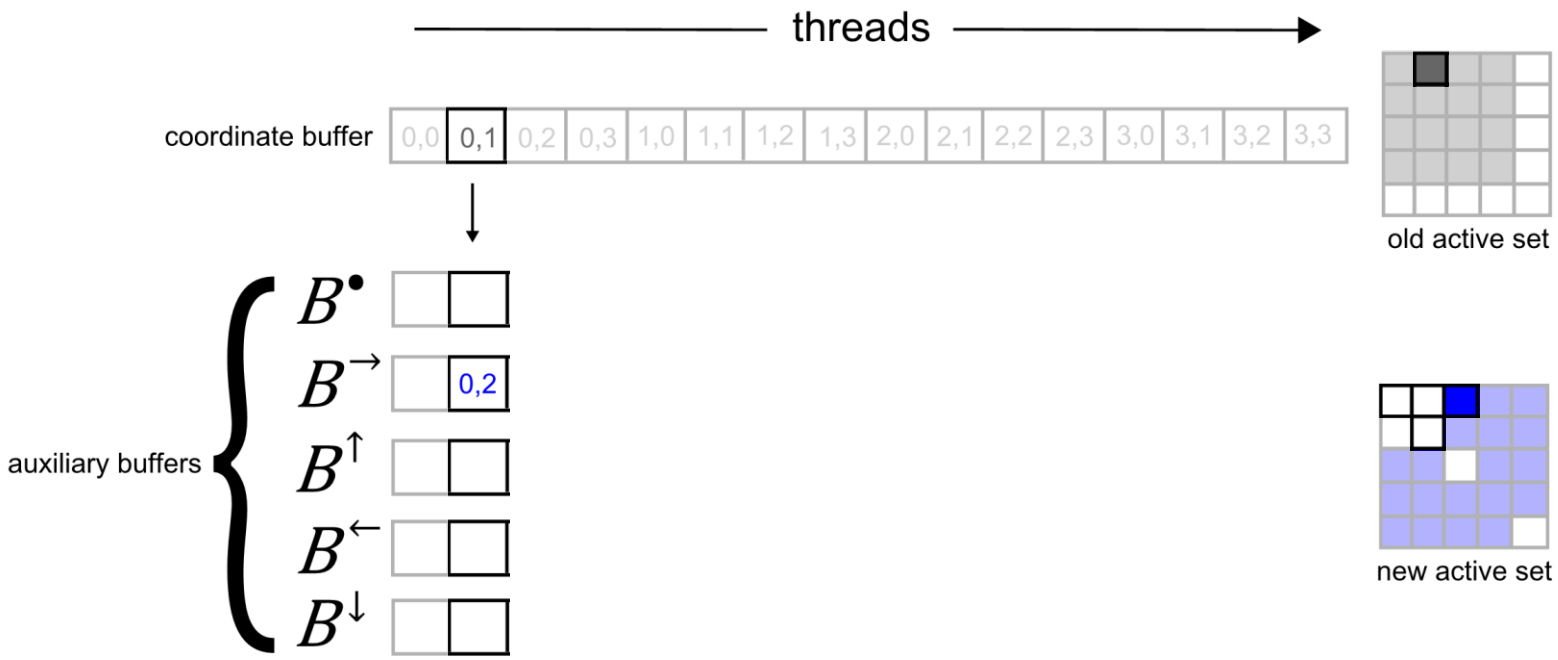

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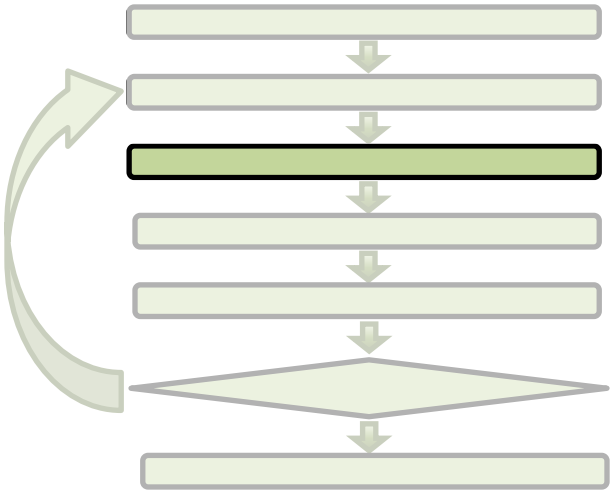

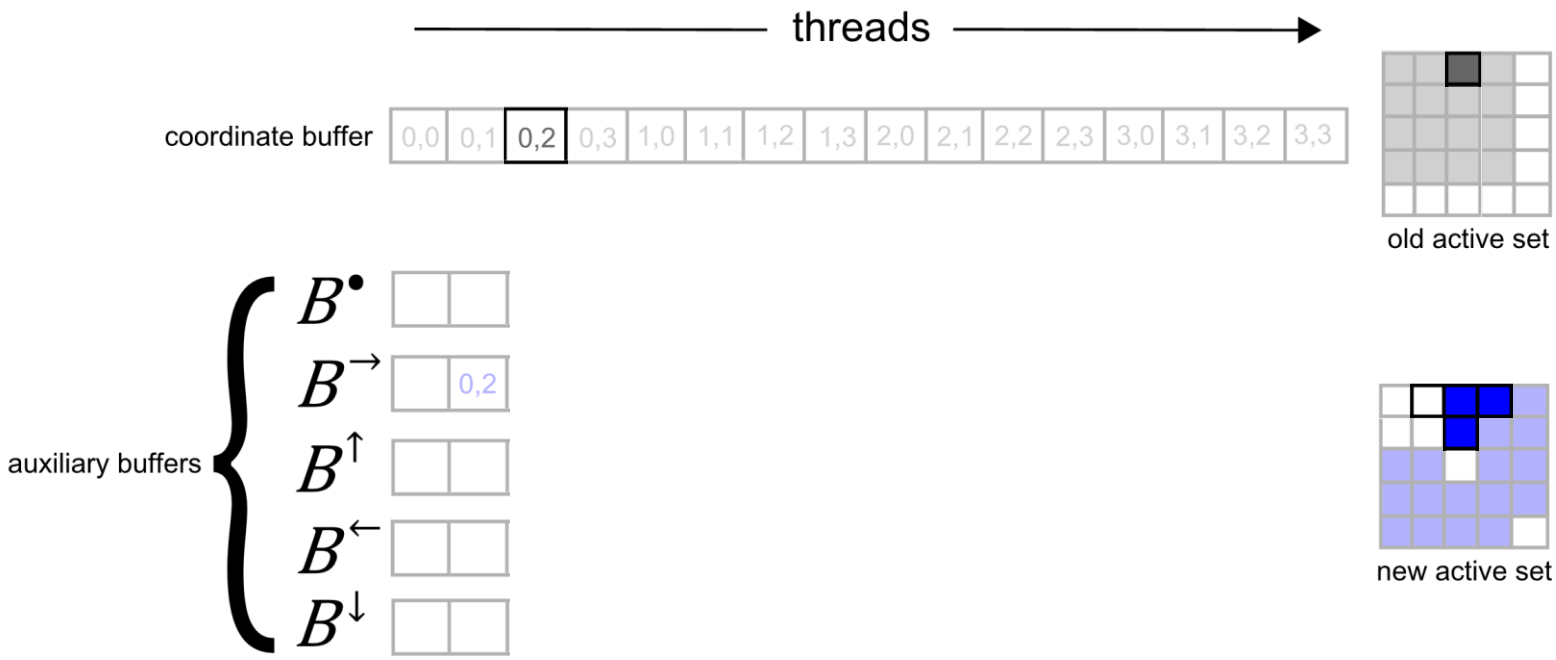

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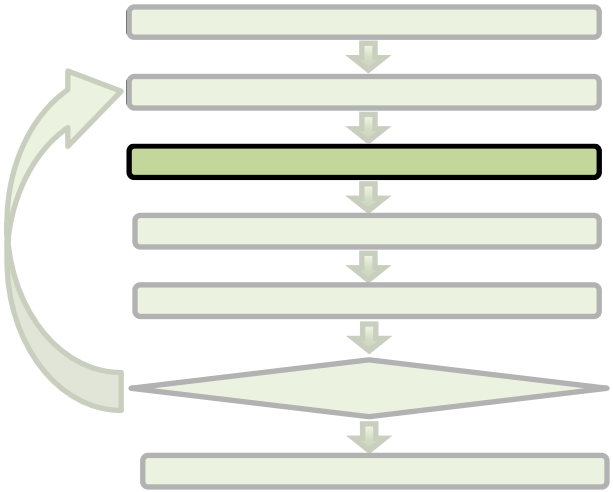

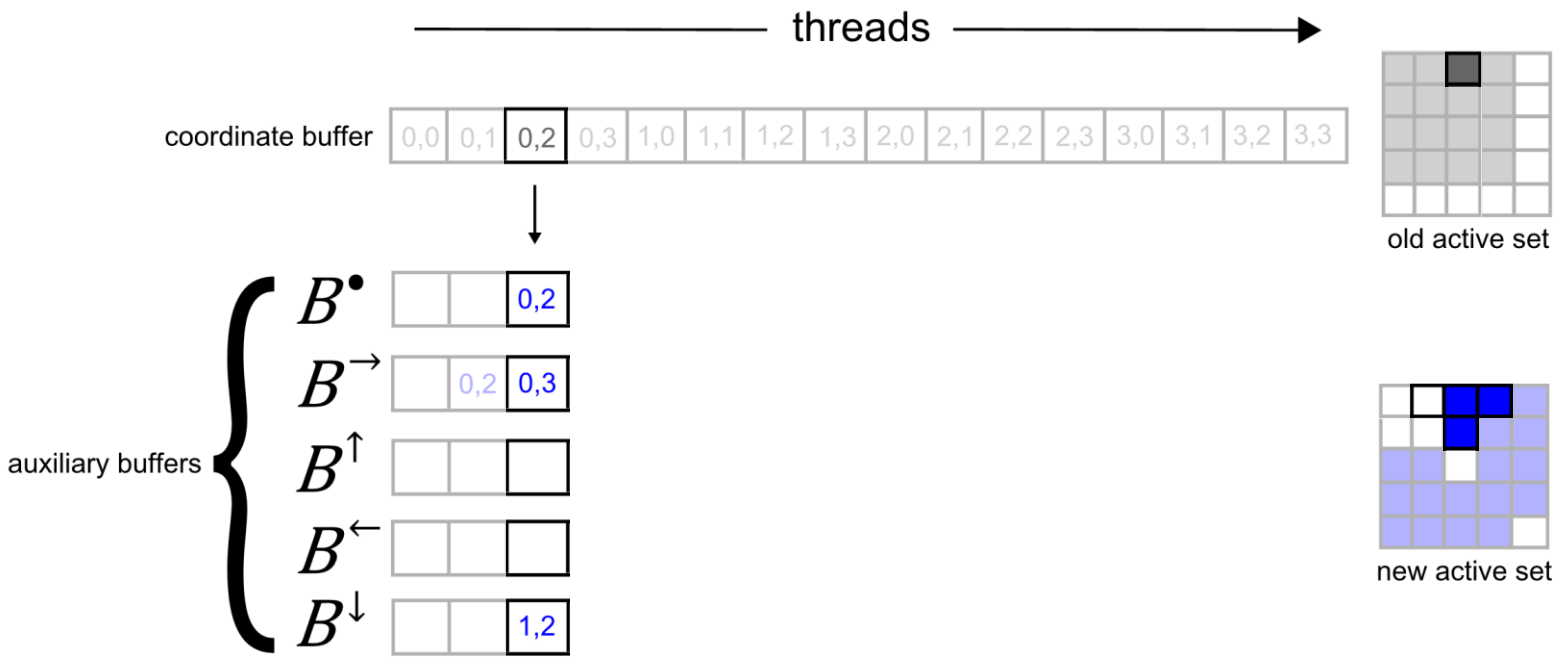

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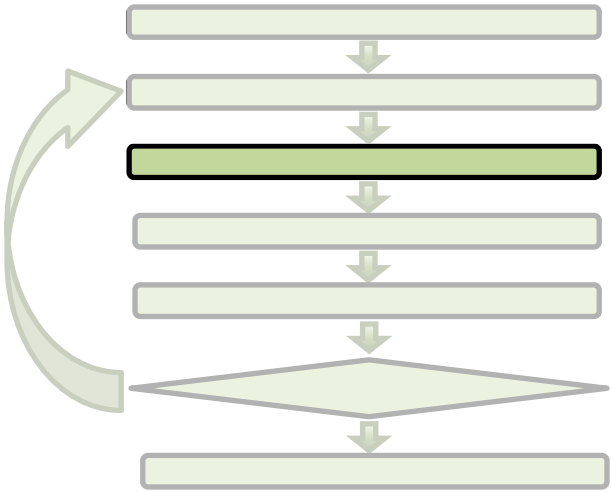

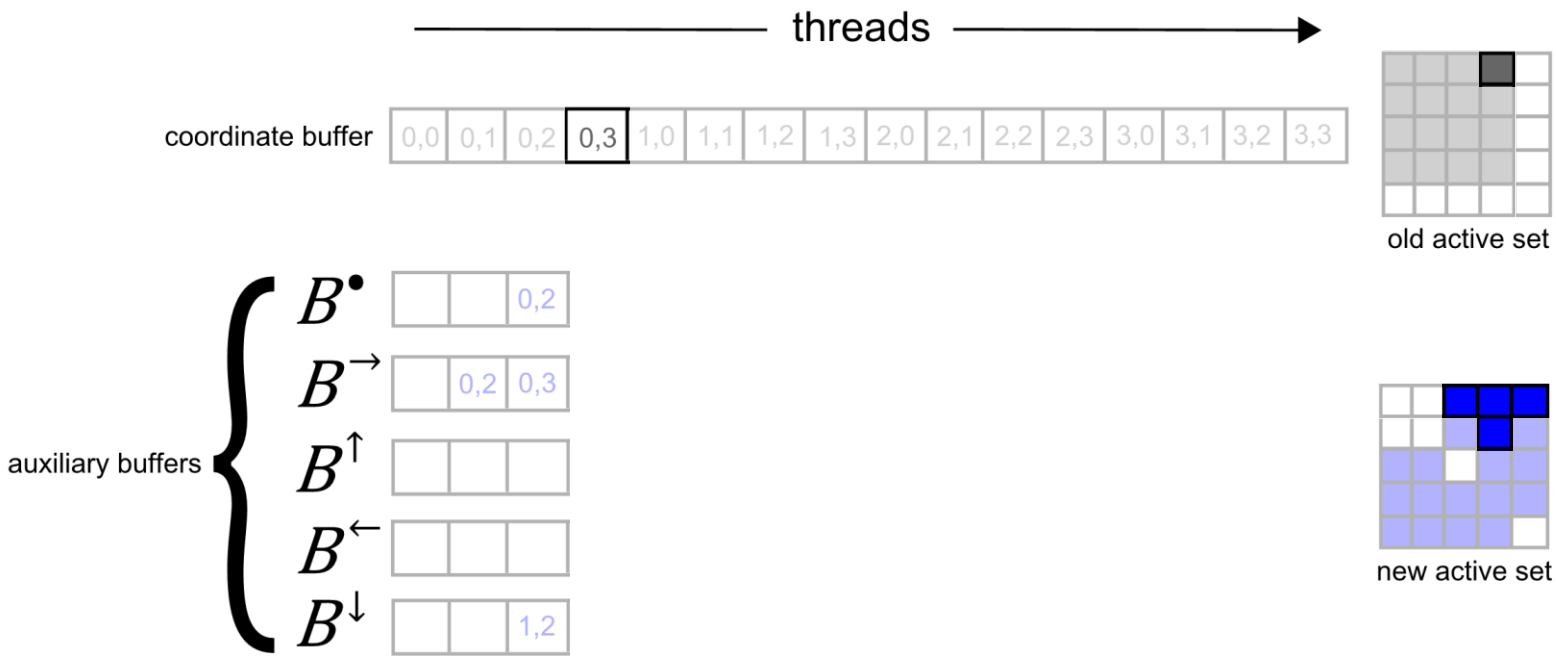

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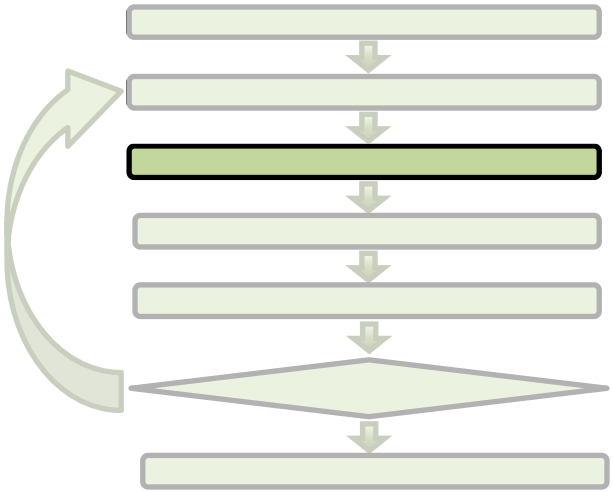

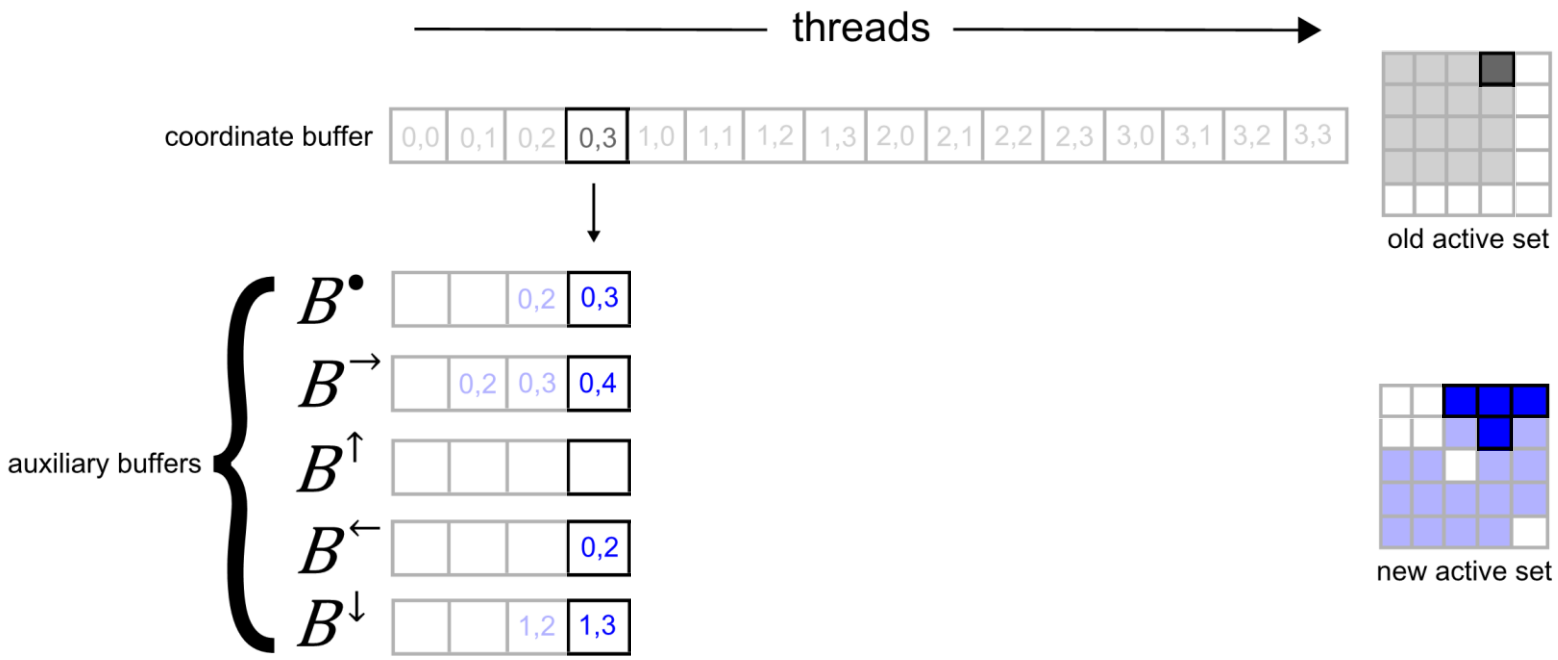

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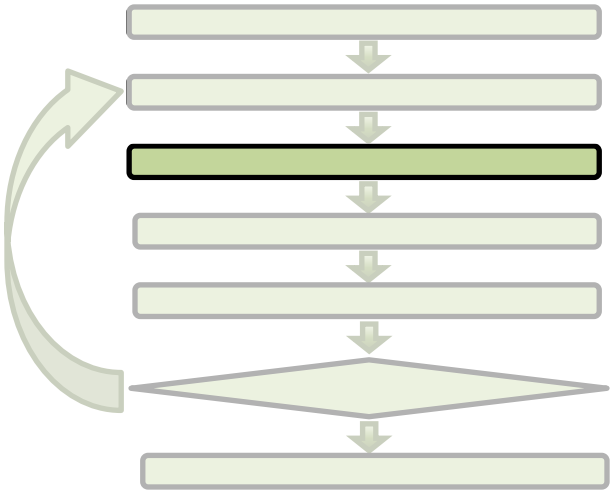

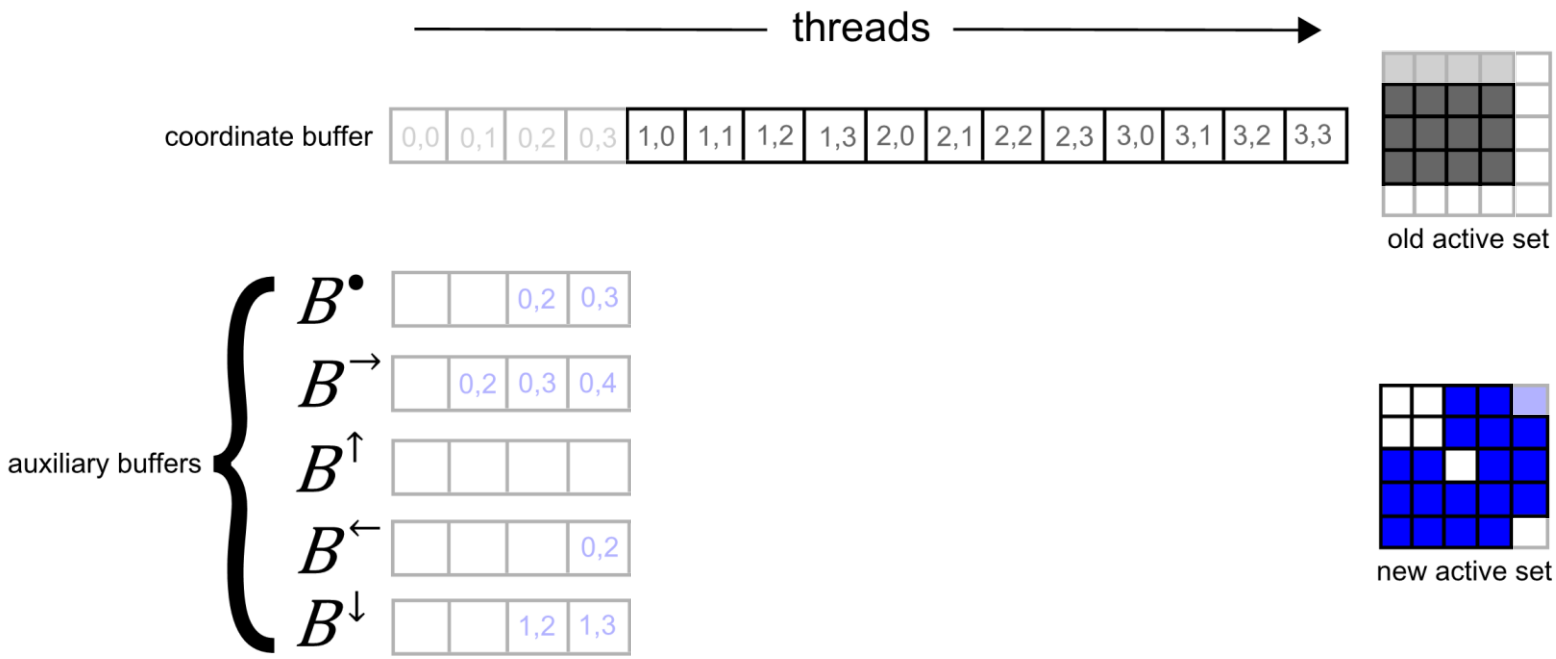

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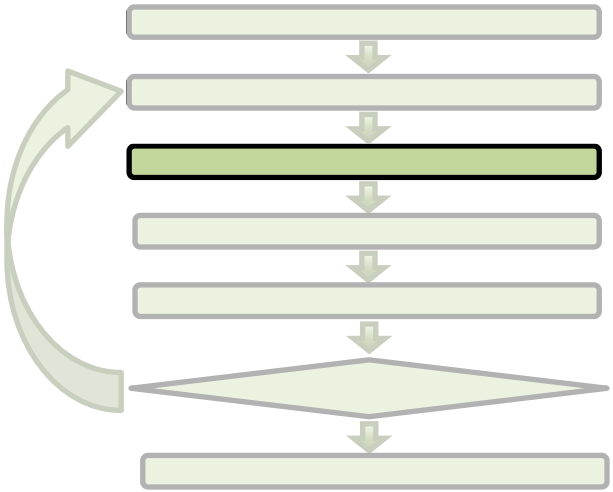
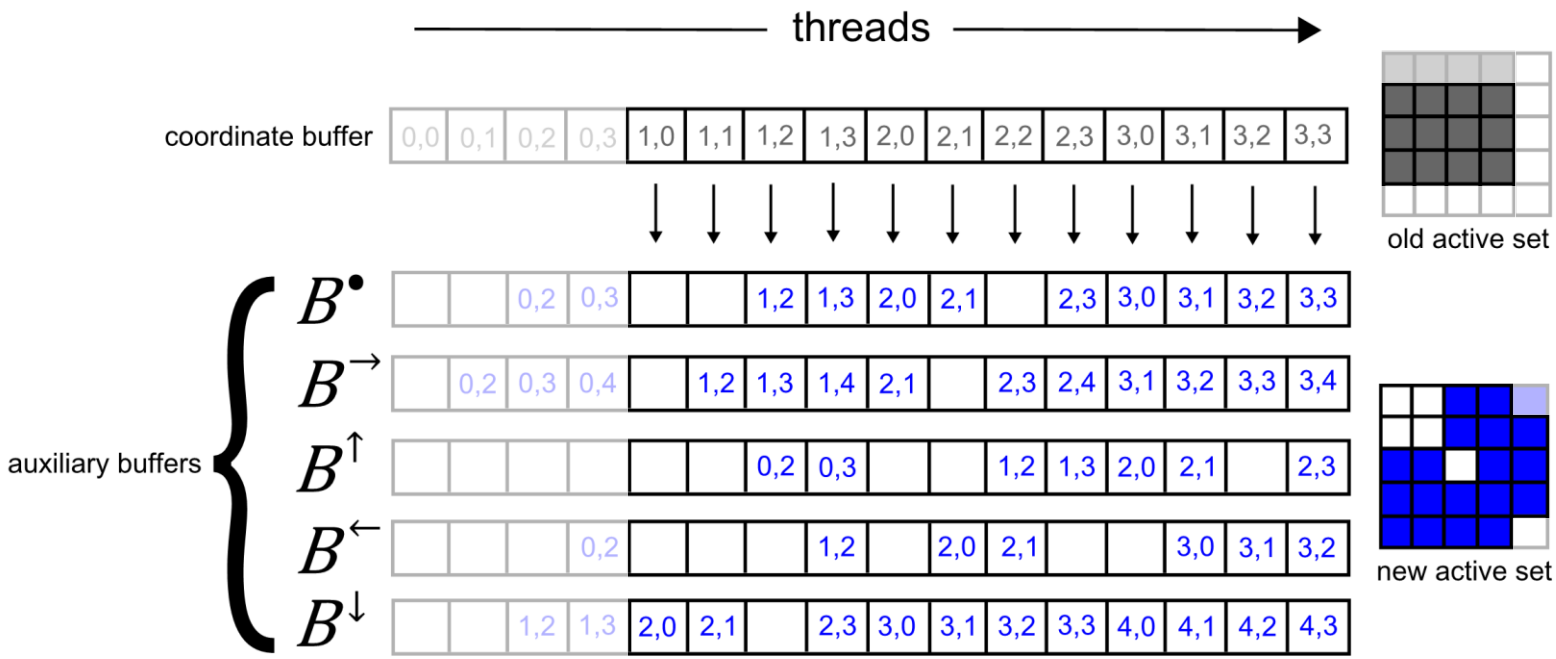
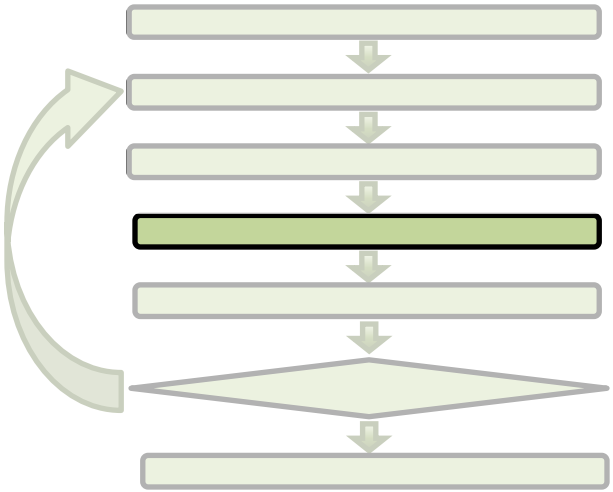
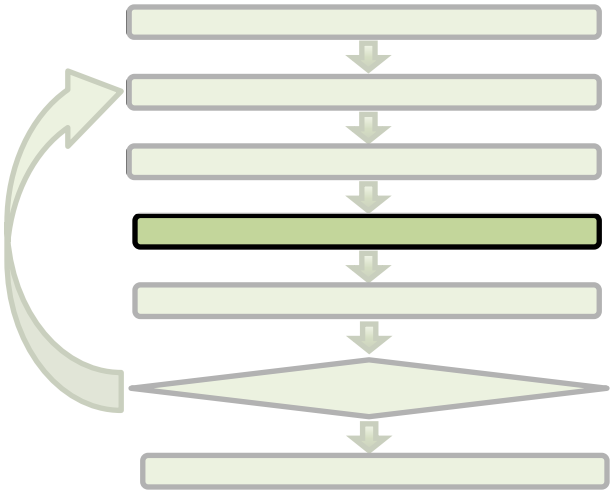


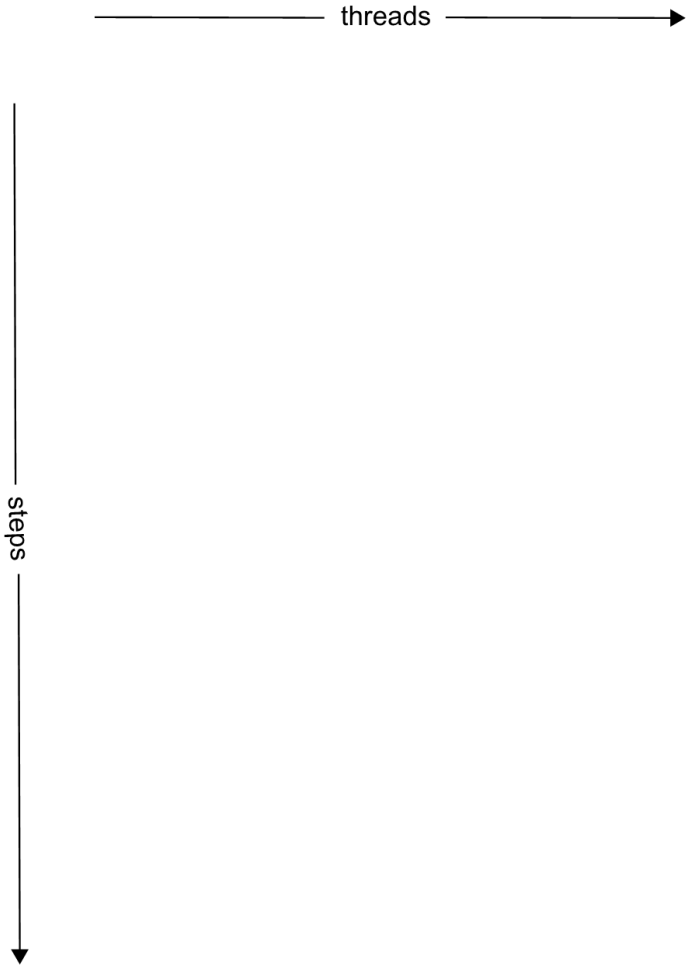


Removing duplicate active coordinates from the auxiliary buffers

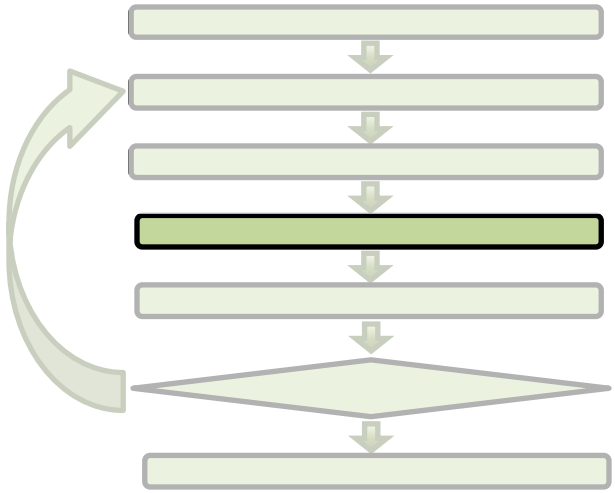


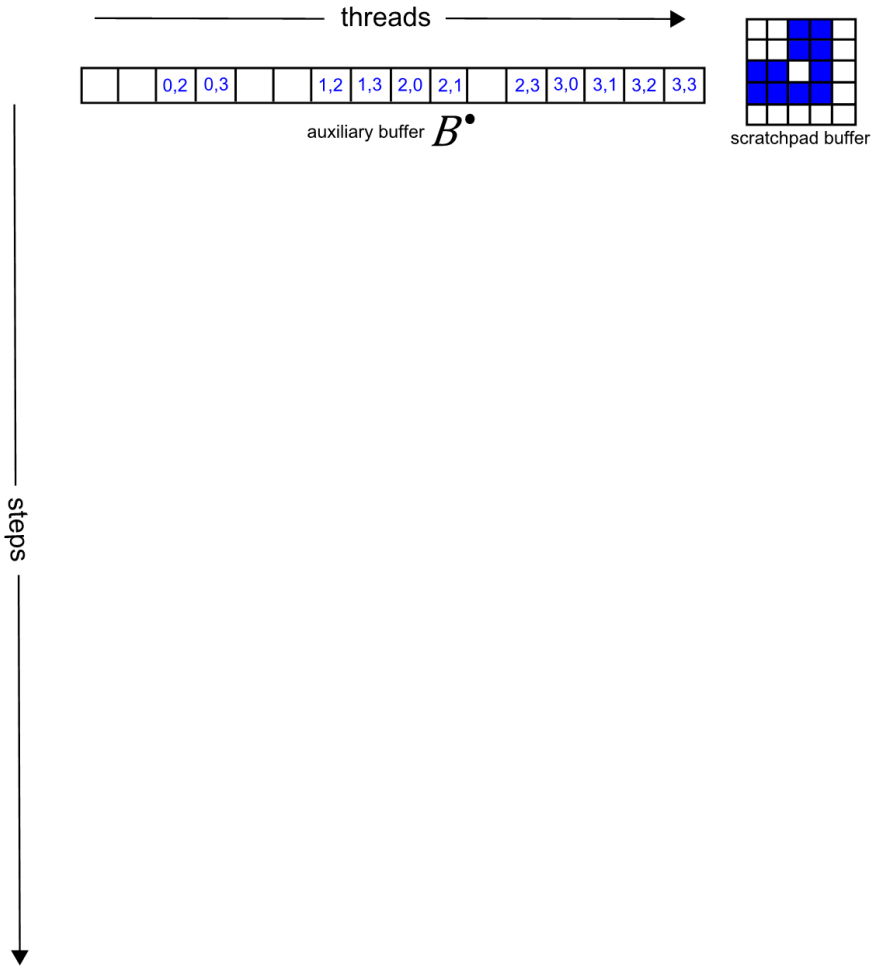
Removing duplicate active coordinates from the auxiliary buffers



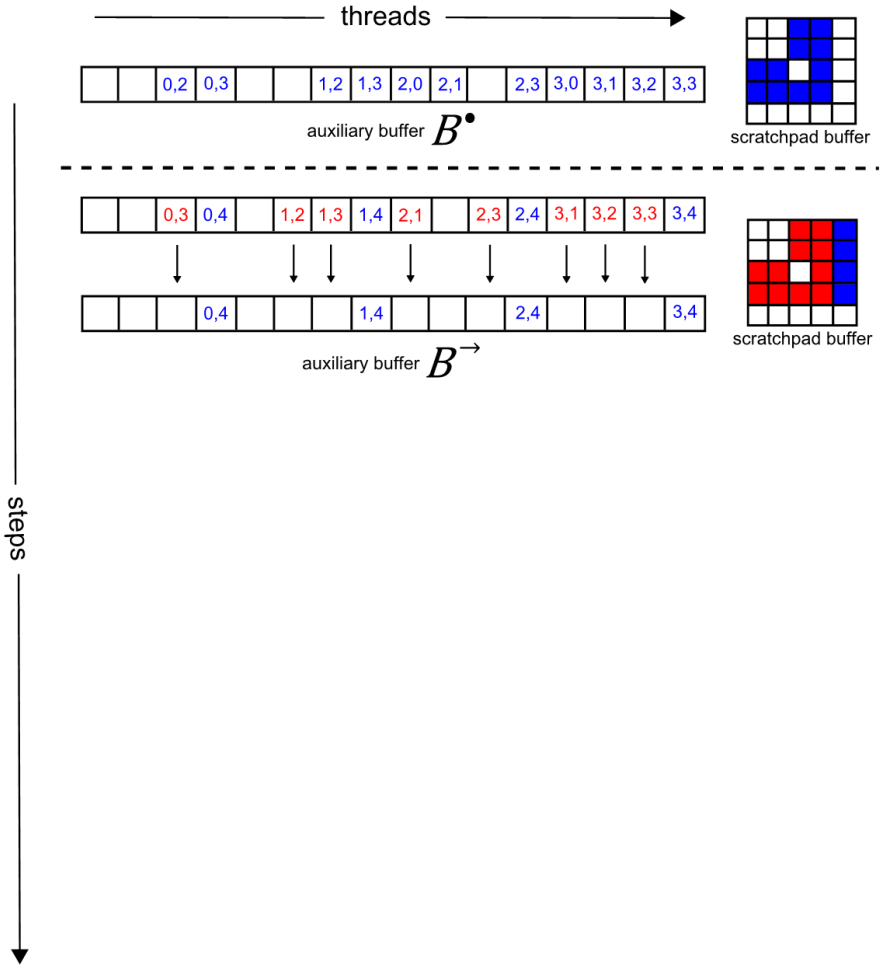


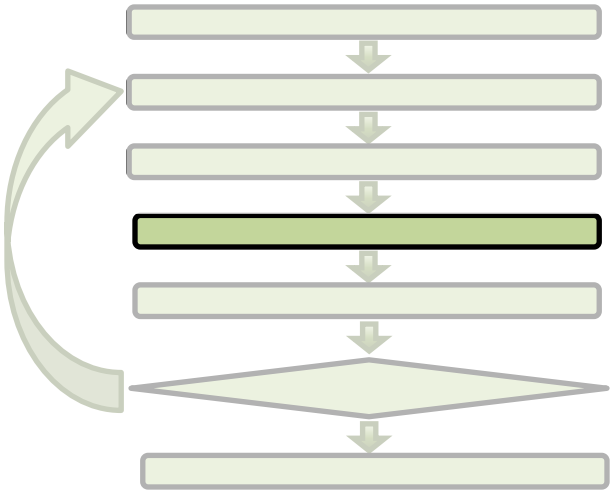
Removing duplicate active coordinates from the auxiliary buffers



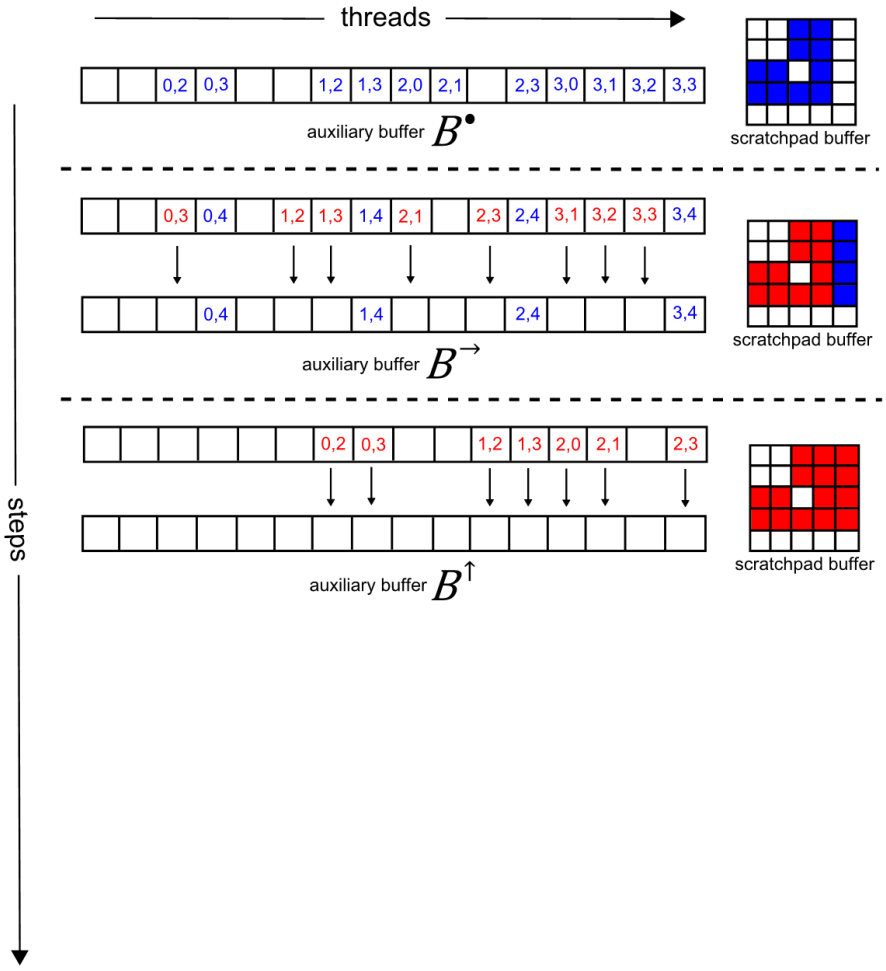


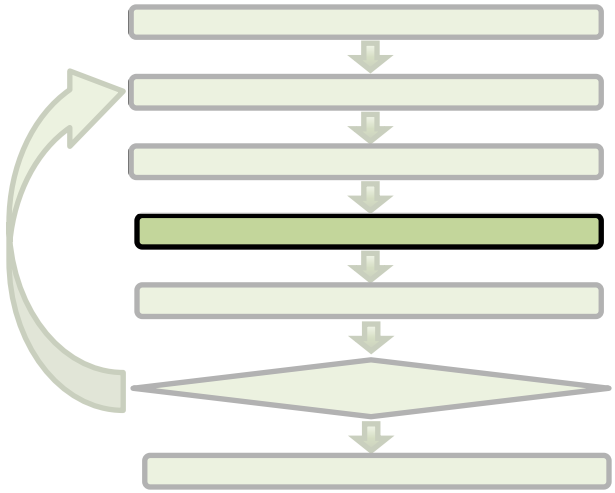
Removing duplicate active coordinates from the auxiliary buffers



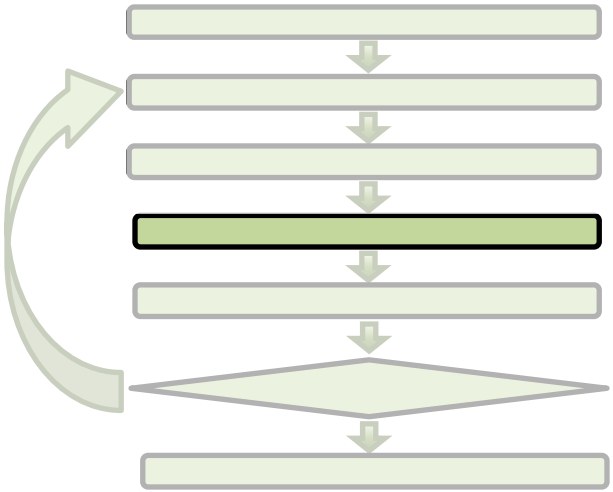


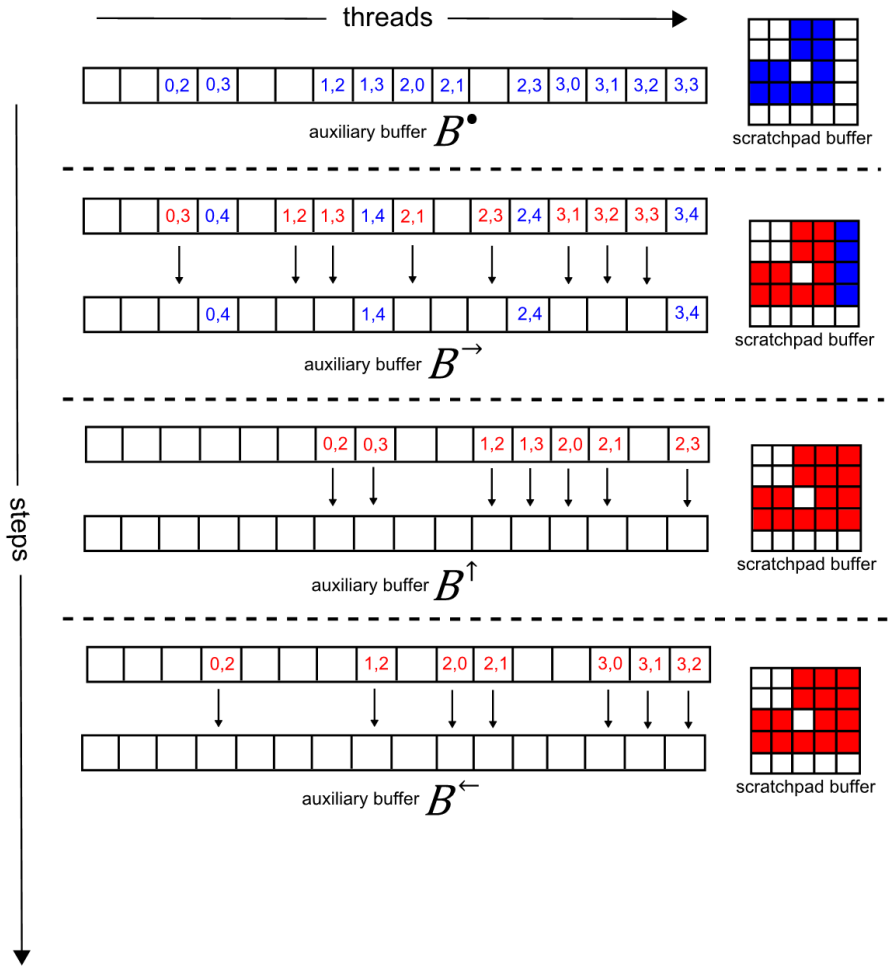
Removing duplicate active coordinates from the auxiliary buffers



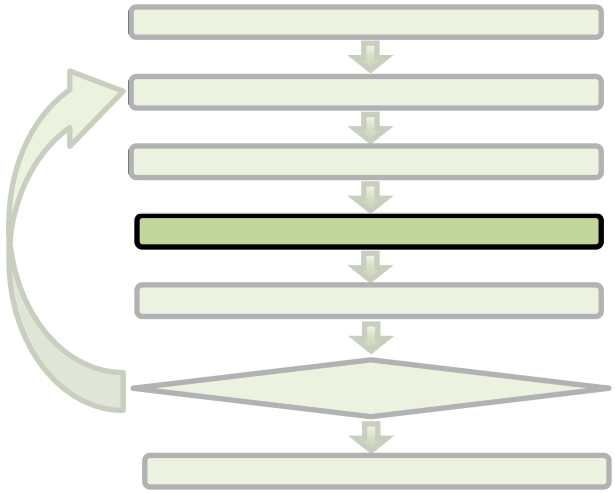


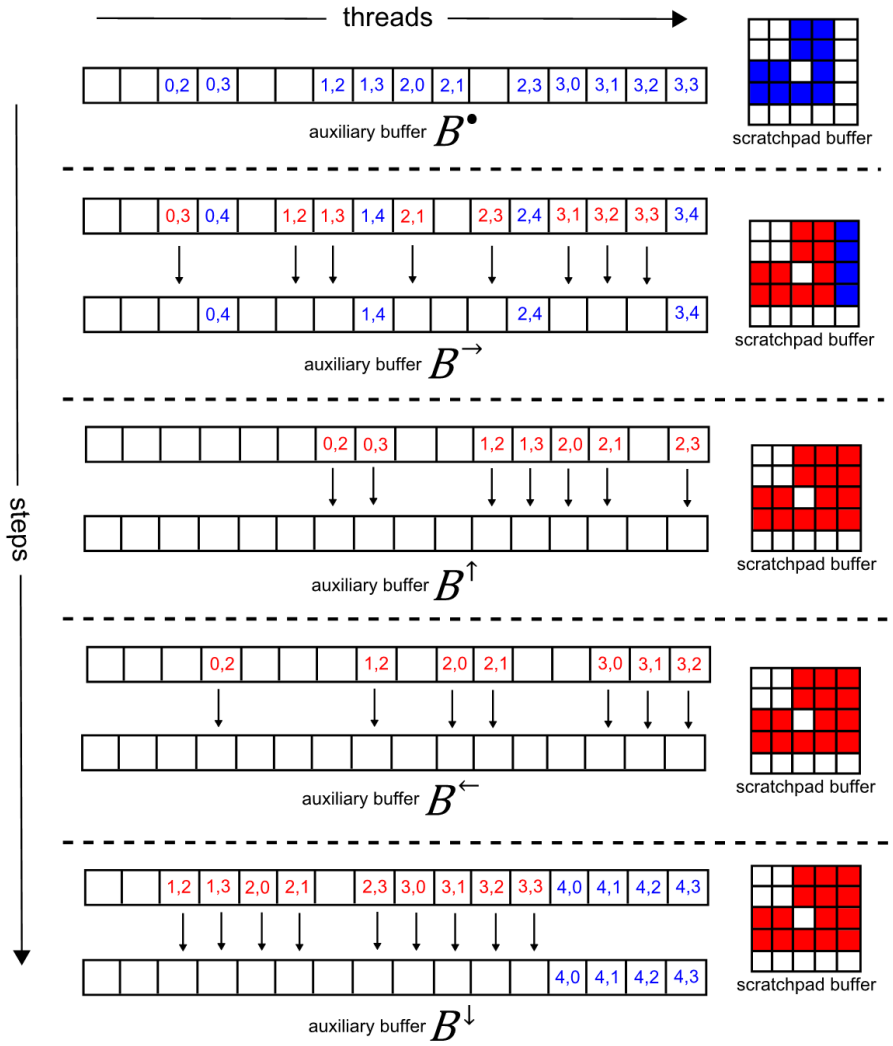
Removing duplicate active coordinates from the auxiliary buffers



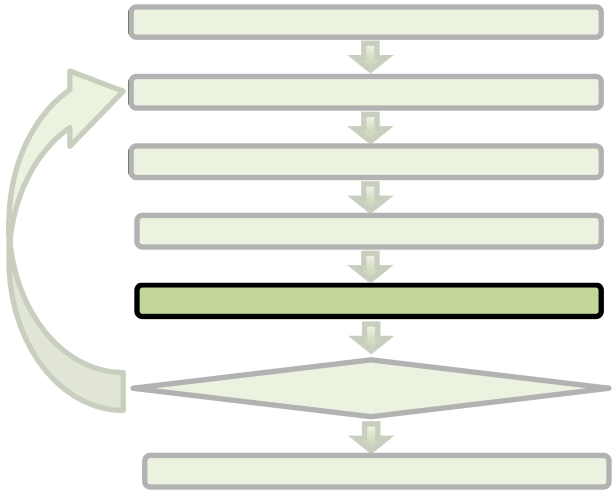


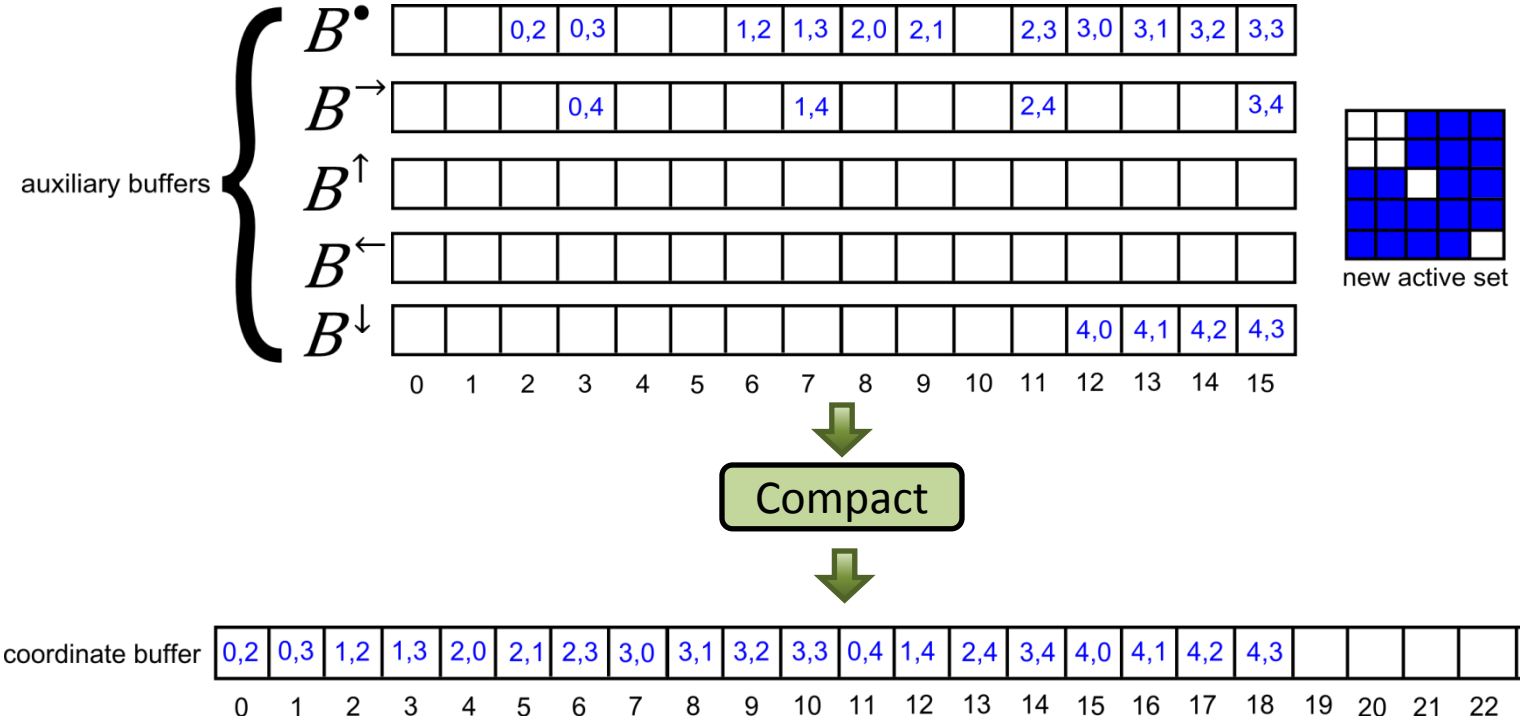
Removing duplicate active coordinates from the auxiliary buffers





Compacting the auxiliary buffers to produce a new dense list of active coordinates





Algorithmic Complexity

- Compact (Harris et al. 2007; Sengupta et al. 2007, 2008)
  - $O(\log n)$ steps
  - $O(n)$ work

- Rest of our algorithm
  - $O(1)$ steps
  - $O(n)$ work

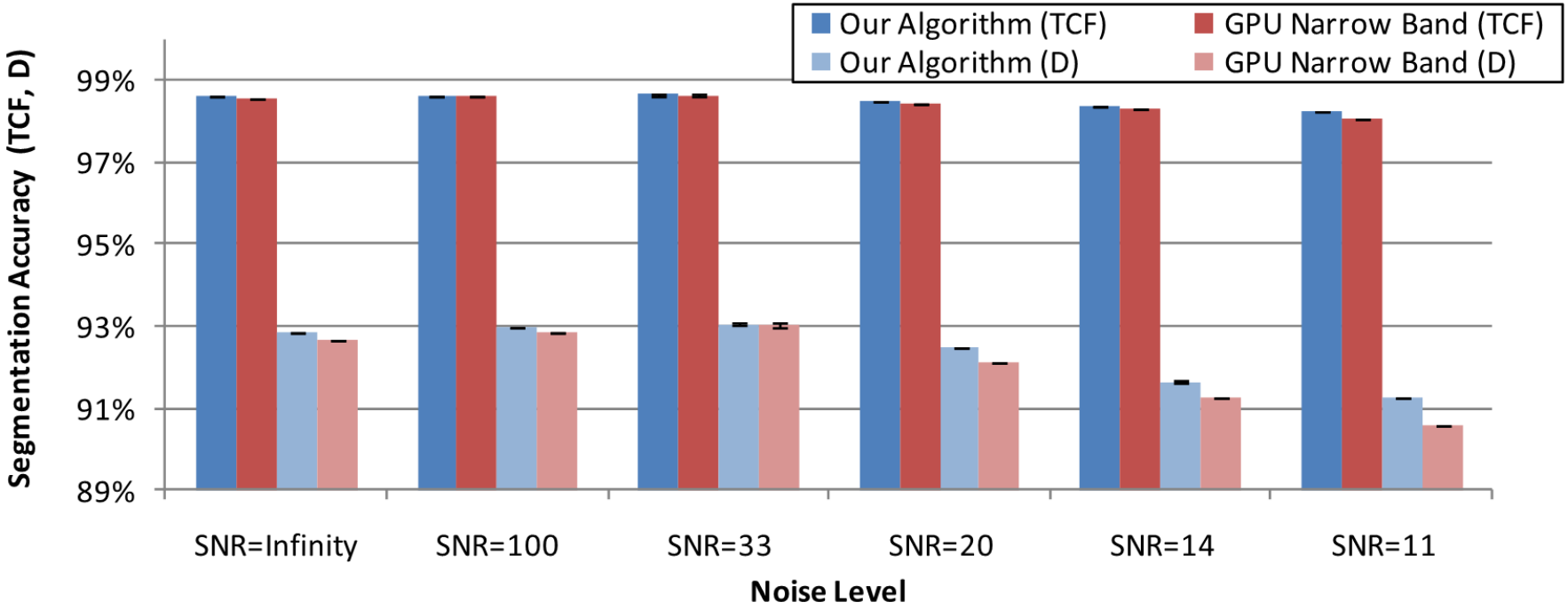
Good: Our algorithm is work-efficient and requires a logarithmic number of steps to update the level set field

Bad: Our algorithm requires memory proportional to the size of the level set field

Experimental Methodology

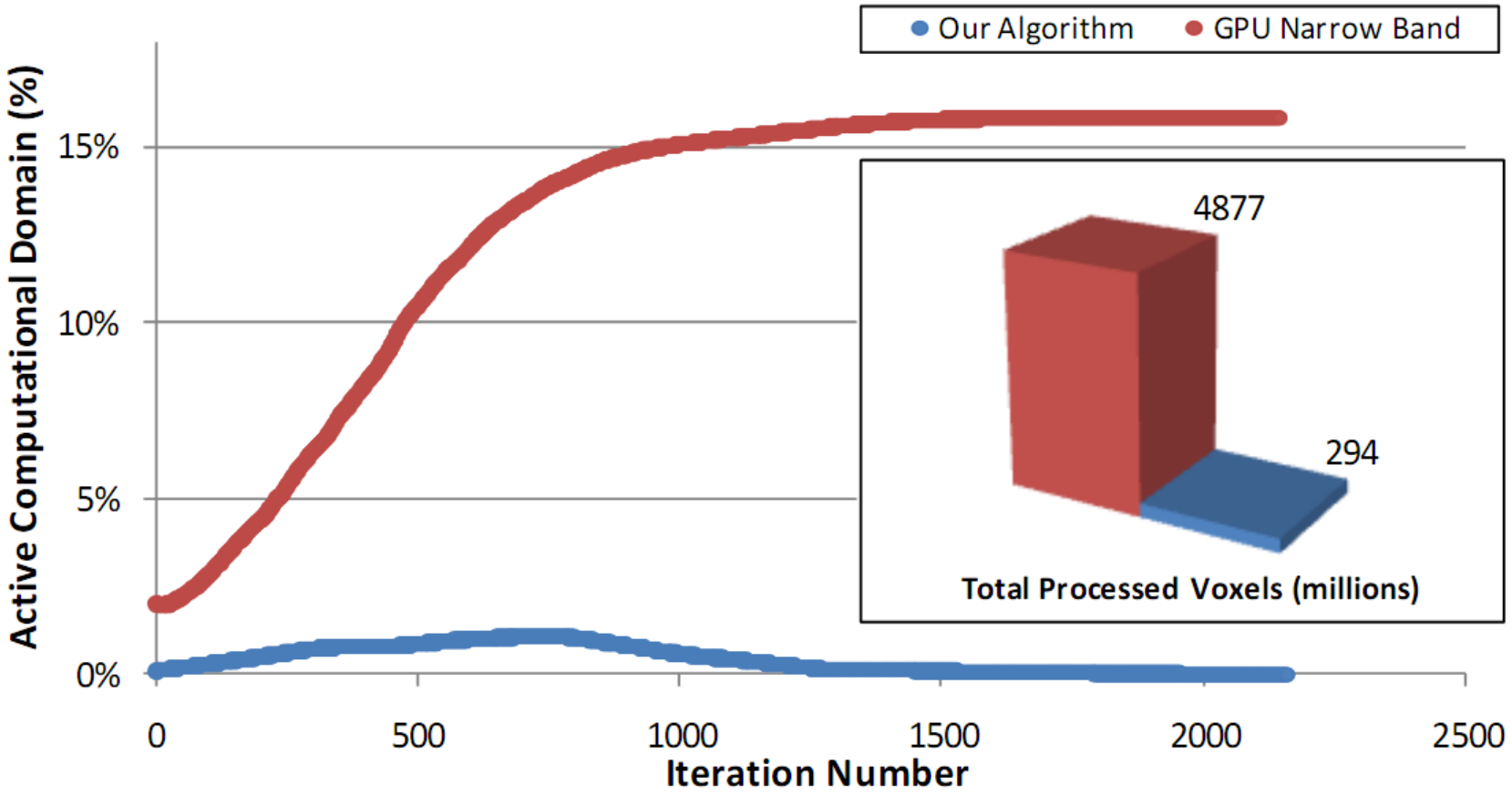
- 256x256x256 human head MRI (ground truth from expert)
- Segmented white and grey matter
- Variety of noise levels
- 10 repeated segmentations per noise level
- Nvidia GTX 280
- Measured computational domain size, speed, accuracy
- Repeated using our algorithm and the GPU narrow band algorithm (Lefohn et al. 2004)

Accuracy

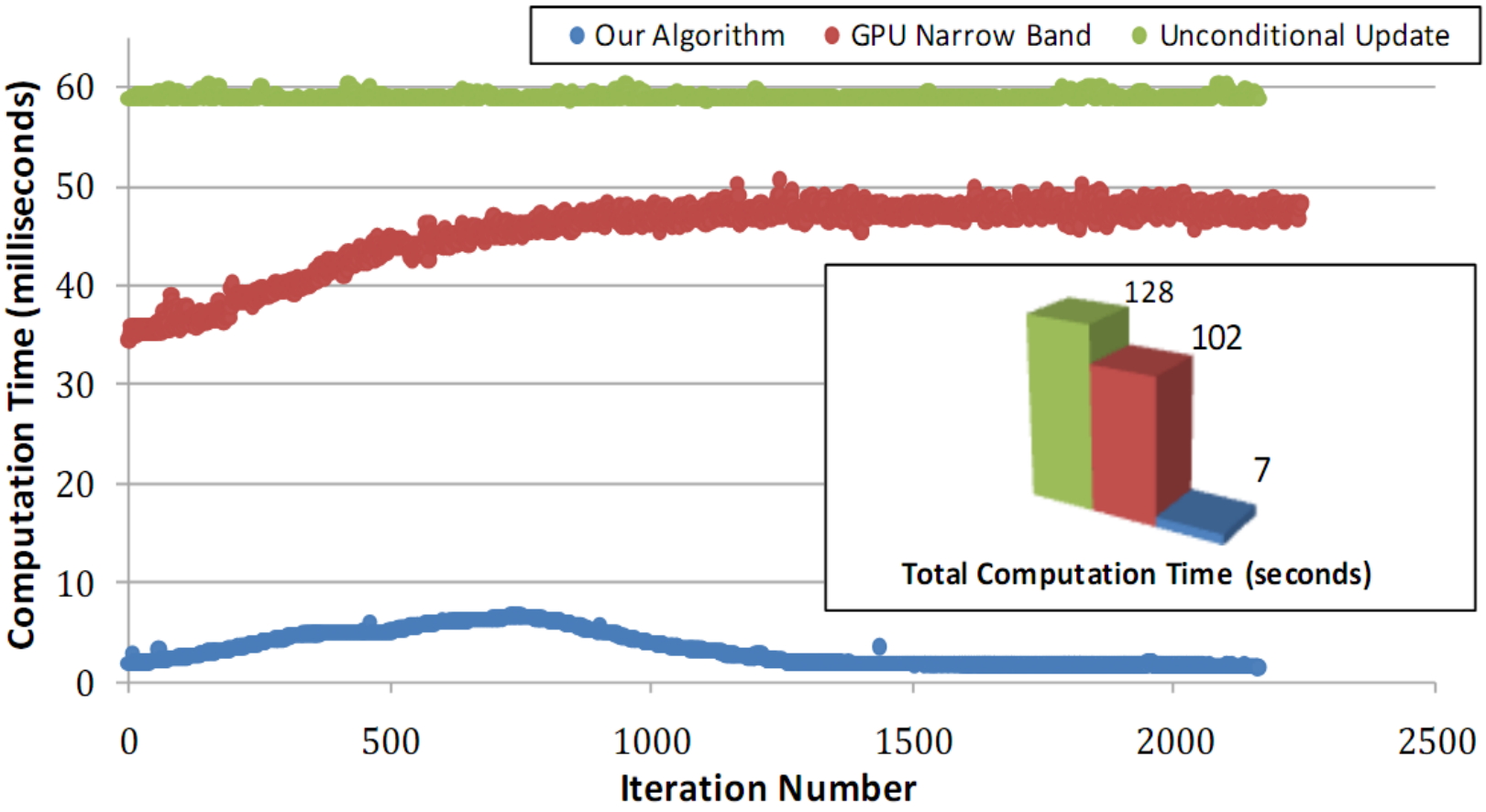


SNR = Signal-to-noise Ratio
D = Dice Coefficient
TCF = Total Correct Fraction of Labeled Voxels

Computational Domain Size



Speed

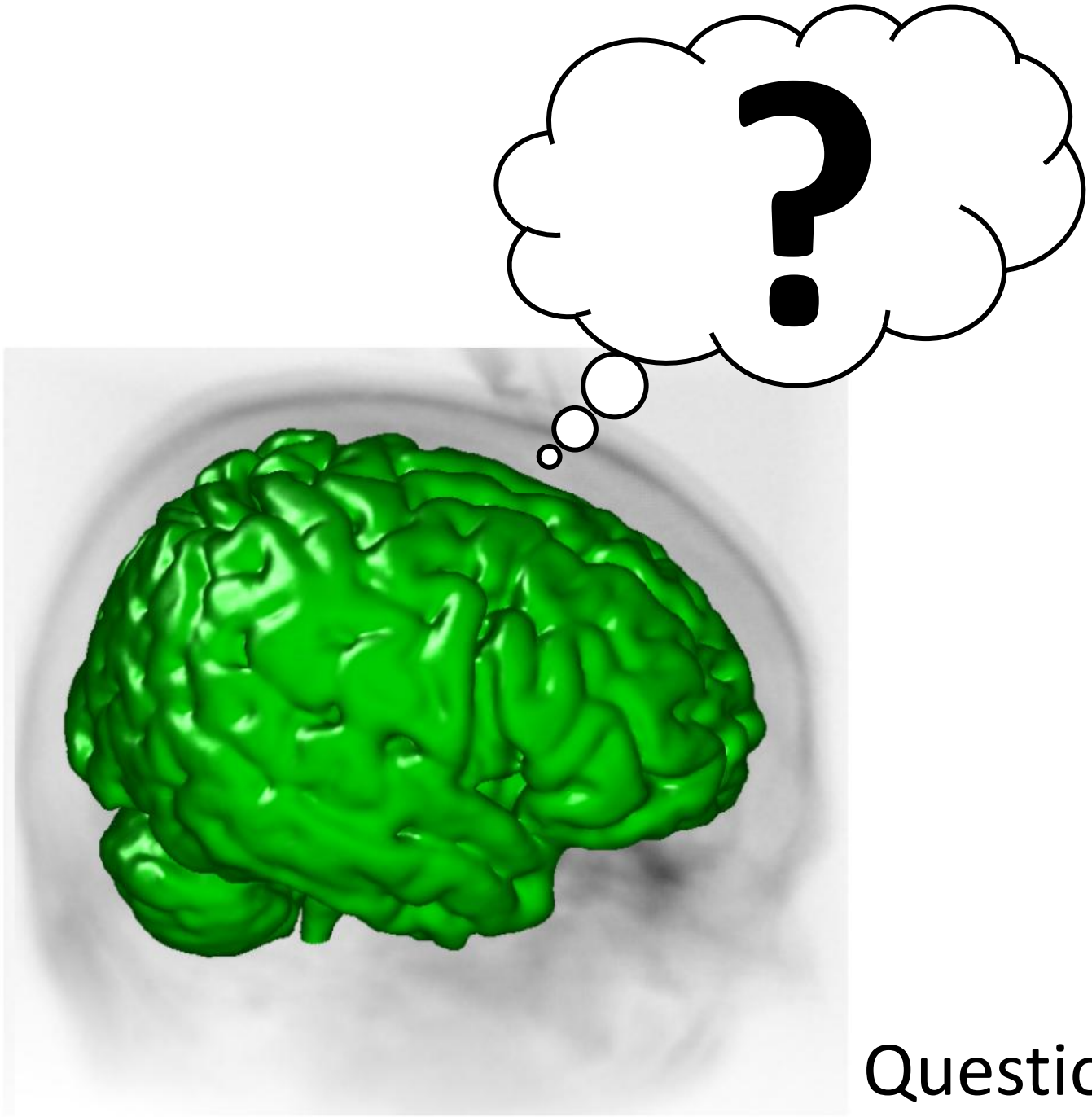

Our Algorithm
GPU Narrow Band
Unconditional Update
Computation Time (milliseconds)
0
10
20
30
40
50
60
0
500
1000
1500
2000
2500
Iteration Number
128
102
7
Total Computation Time (seconds)

Limitations

- Requires a large amount of GPU memory
  - About 500 MB for a 256x256x256 data set
- Scaling to high order neighborhoods increases memory requirements
  - Need extra auxiliary buffers
  - Increases redundant work per thread

Future Work

- Reduce the memory requirements
  - Implement sparse representation of the level set field and other buffers (i.e. hierarchical run-length-encoded level sets) on the GPU
- Applicable to other level set problems in computer graphics?
  - Fluid simulation, surface reconstruction, image restoration, etc
- Are there other applications for the duplicate removal algorithm?

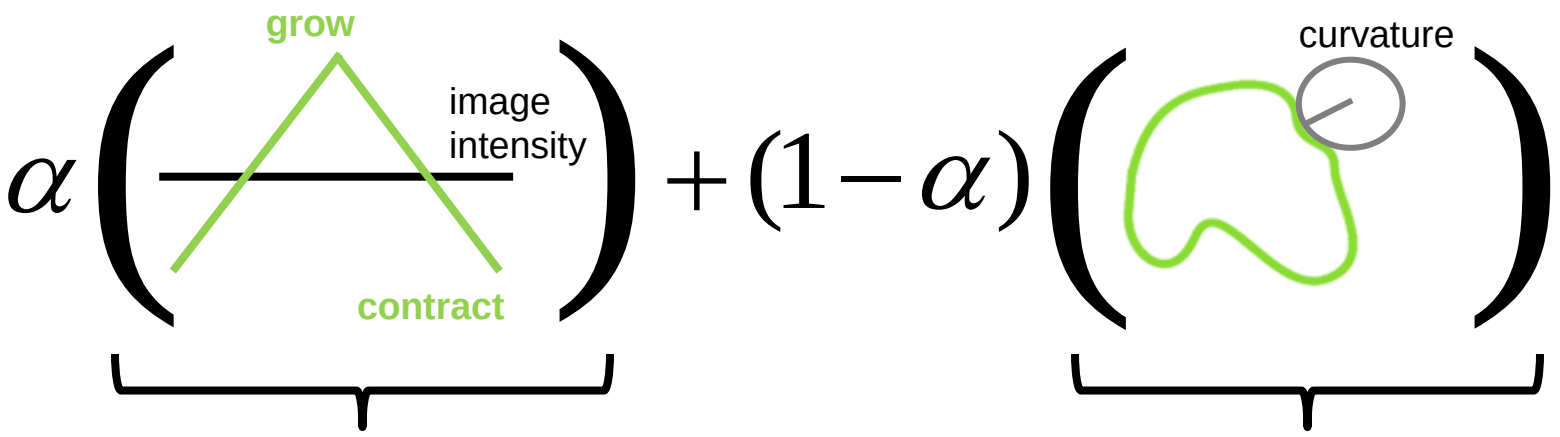


Questions?

Bonus Slides

Speed Function

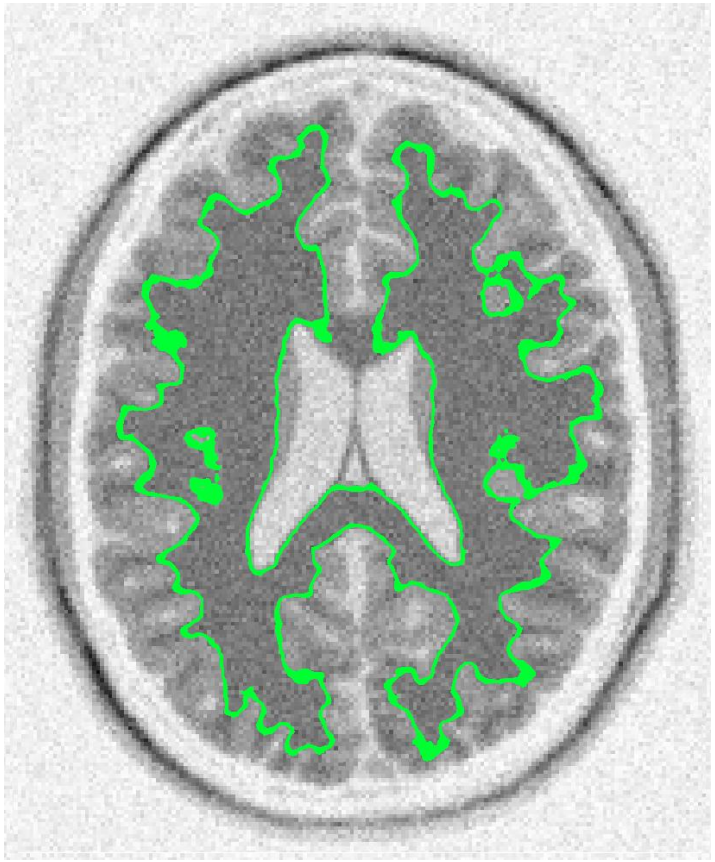
Speed function proposed by Lefohn et al. 2003, 2004



α controls the smoothness of the segmentation

Speed Function

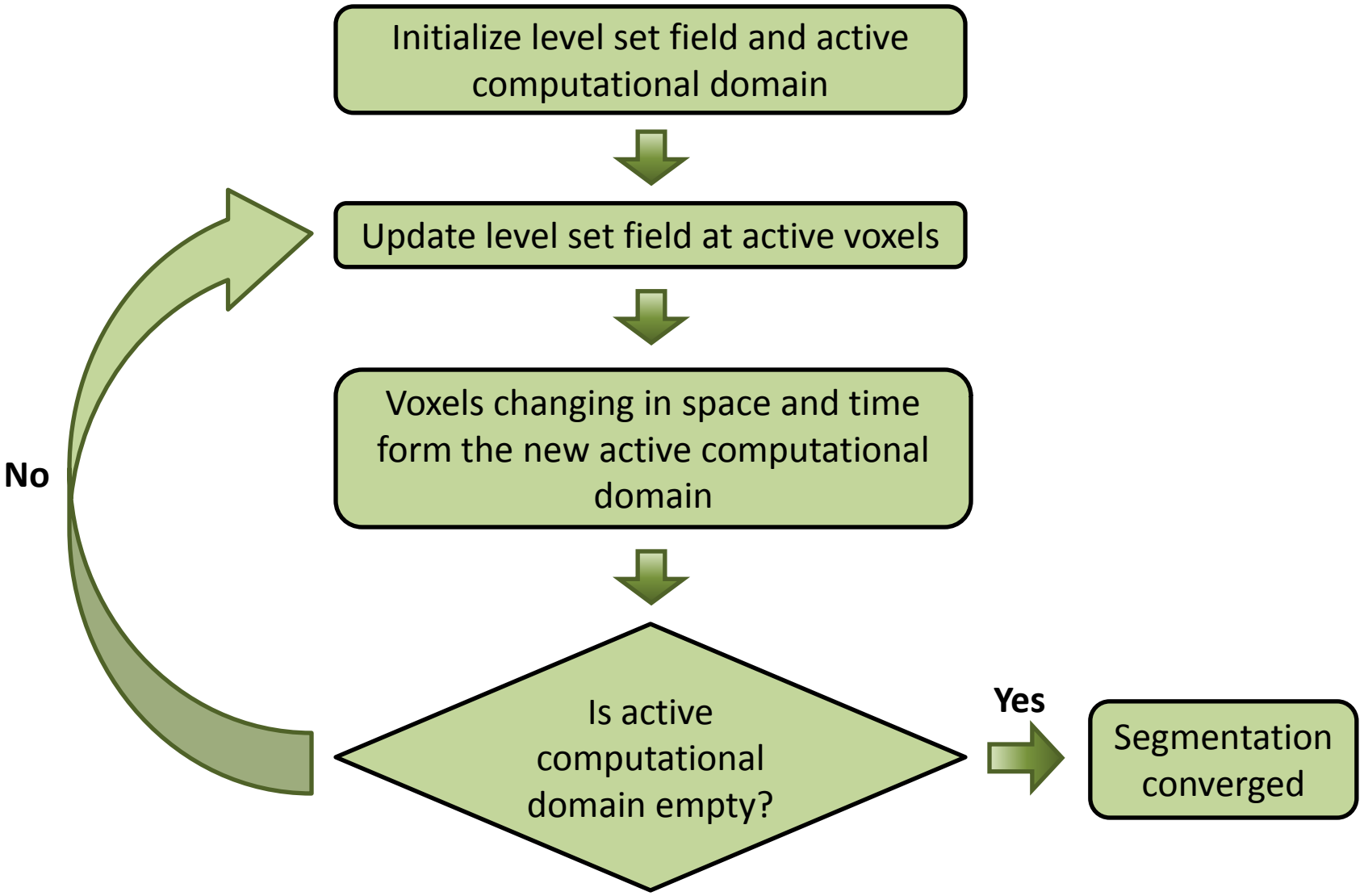
The curvature term enforces a smooth segmentation and prevents leaking



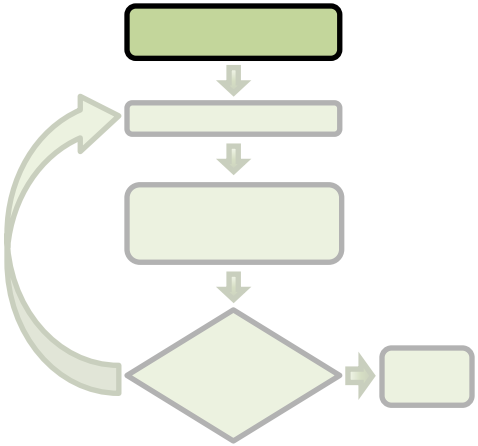
with curvature influence

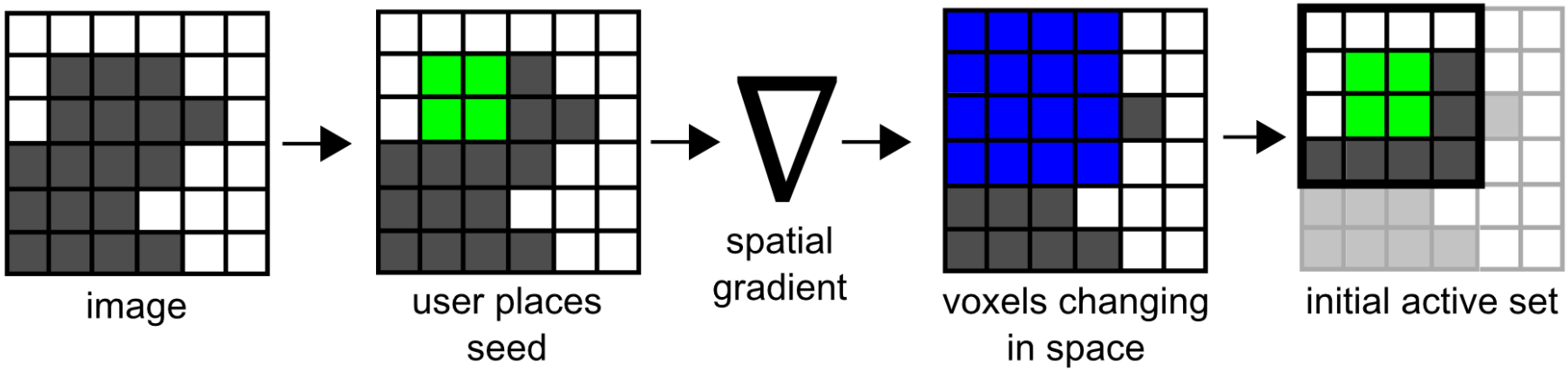
without curvature influence

Temporally Coherent Algorithm

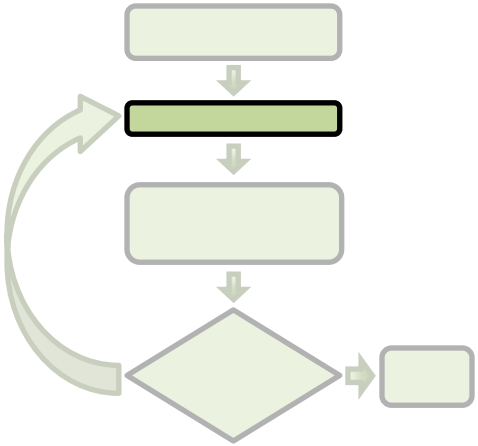


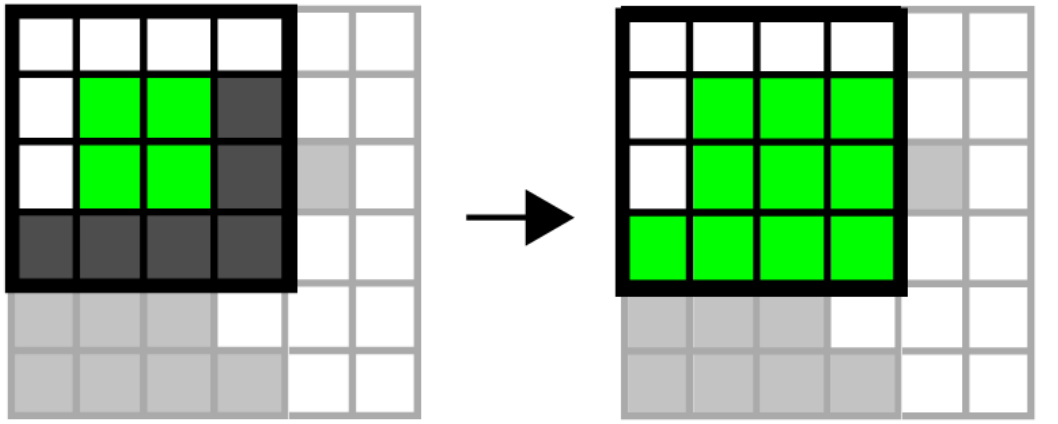
Initializing the level set field and the active computational domain



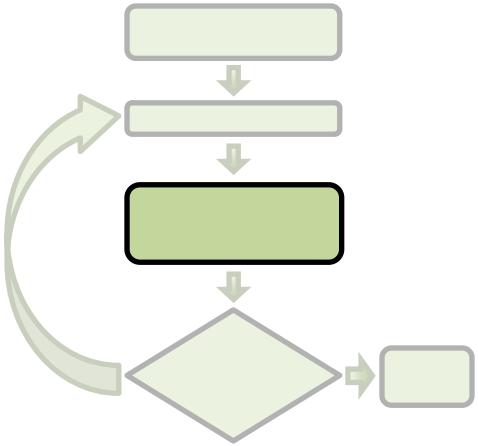


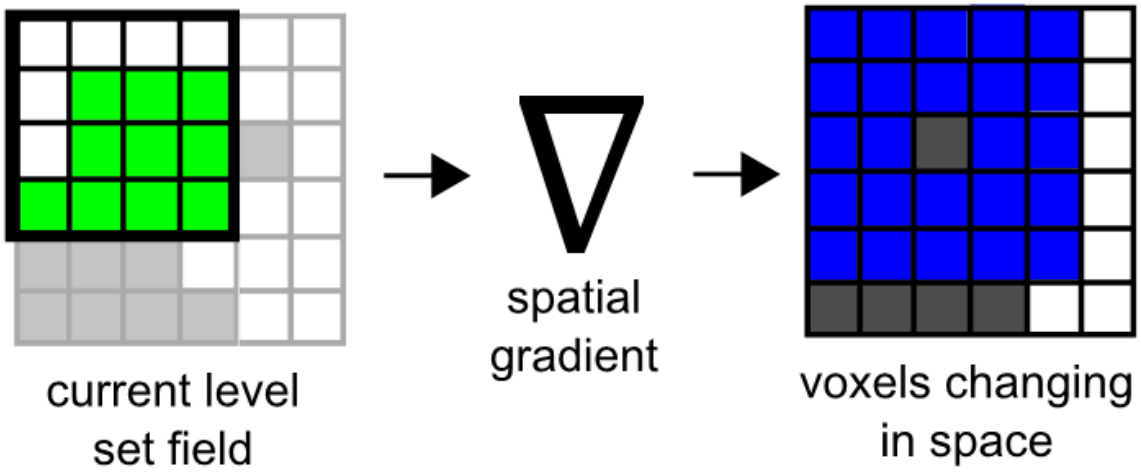
Updating the level set field at active voxels



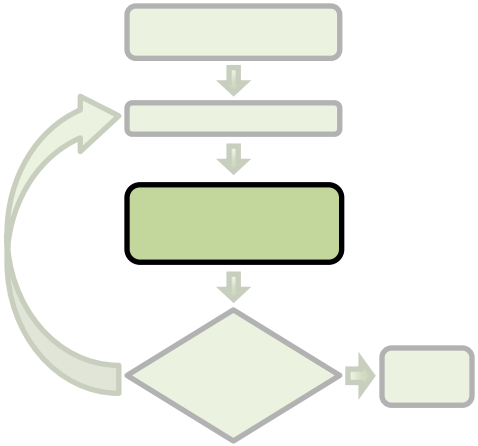


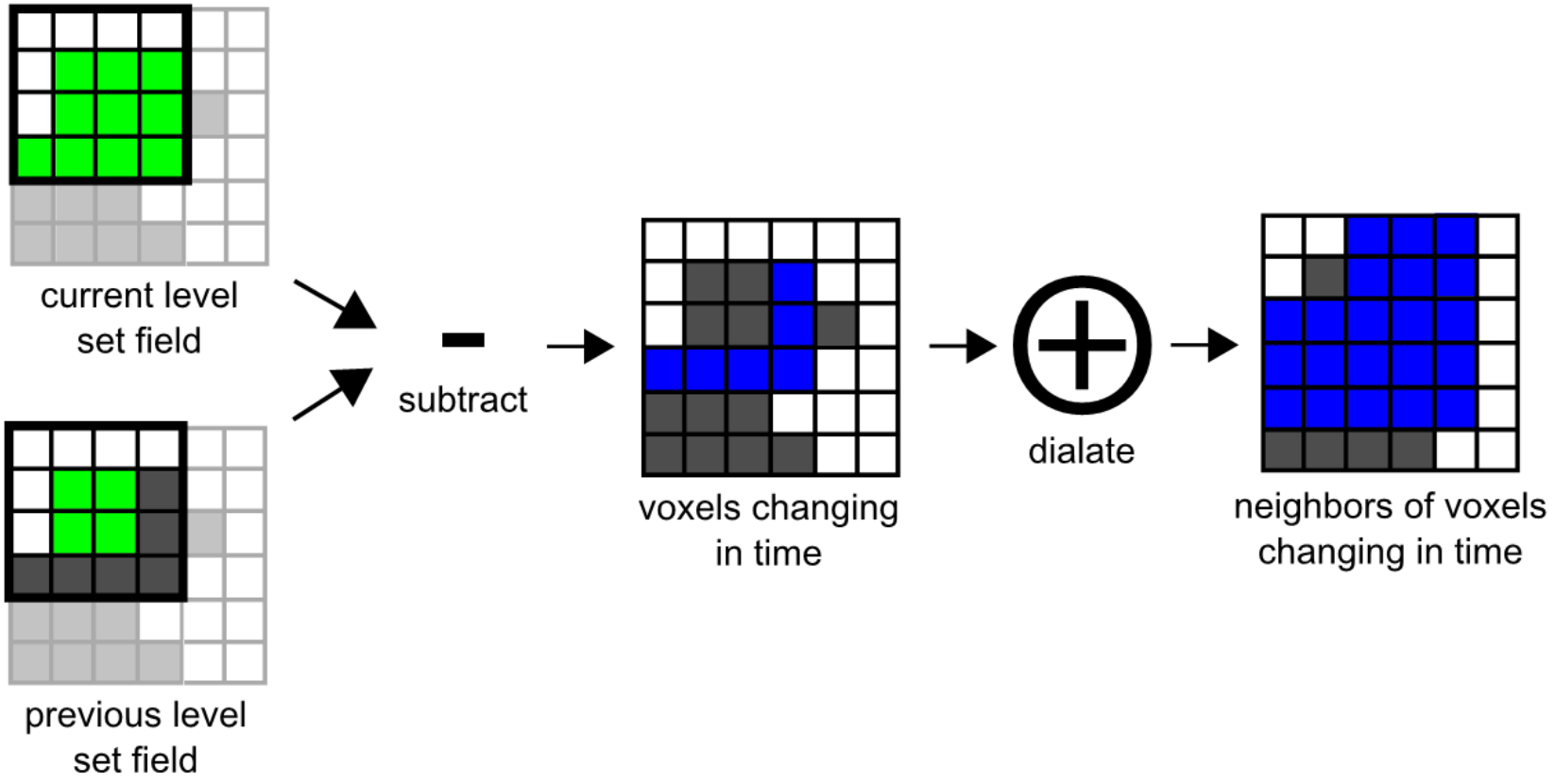
Finding the voxels that are changing in *space*



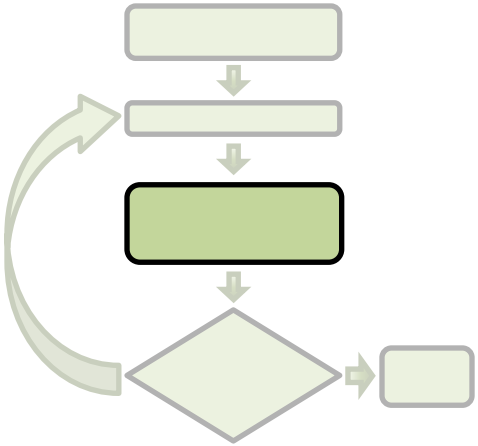


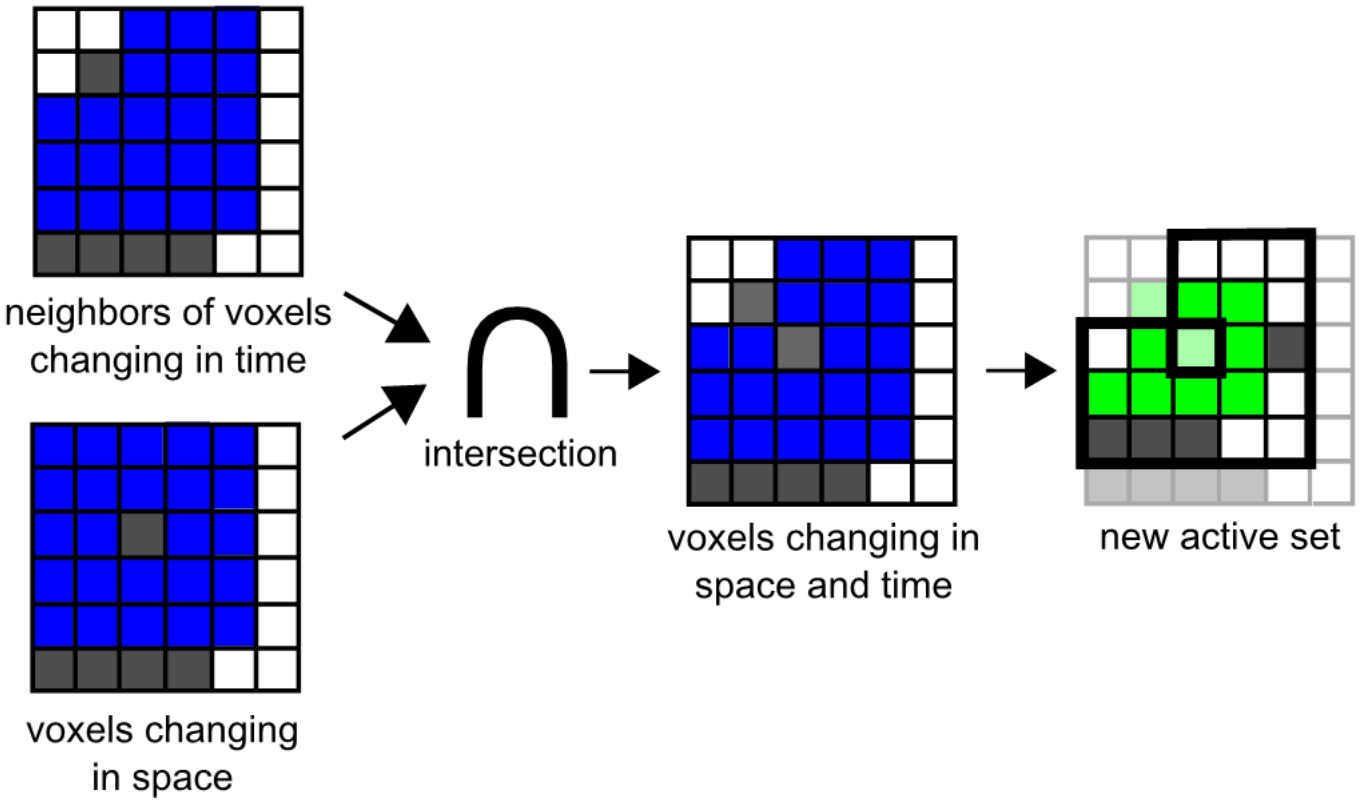
Finding the voxels that are changing in *time*



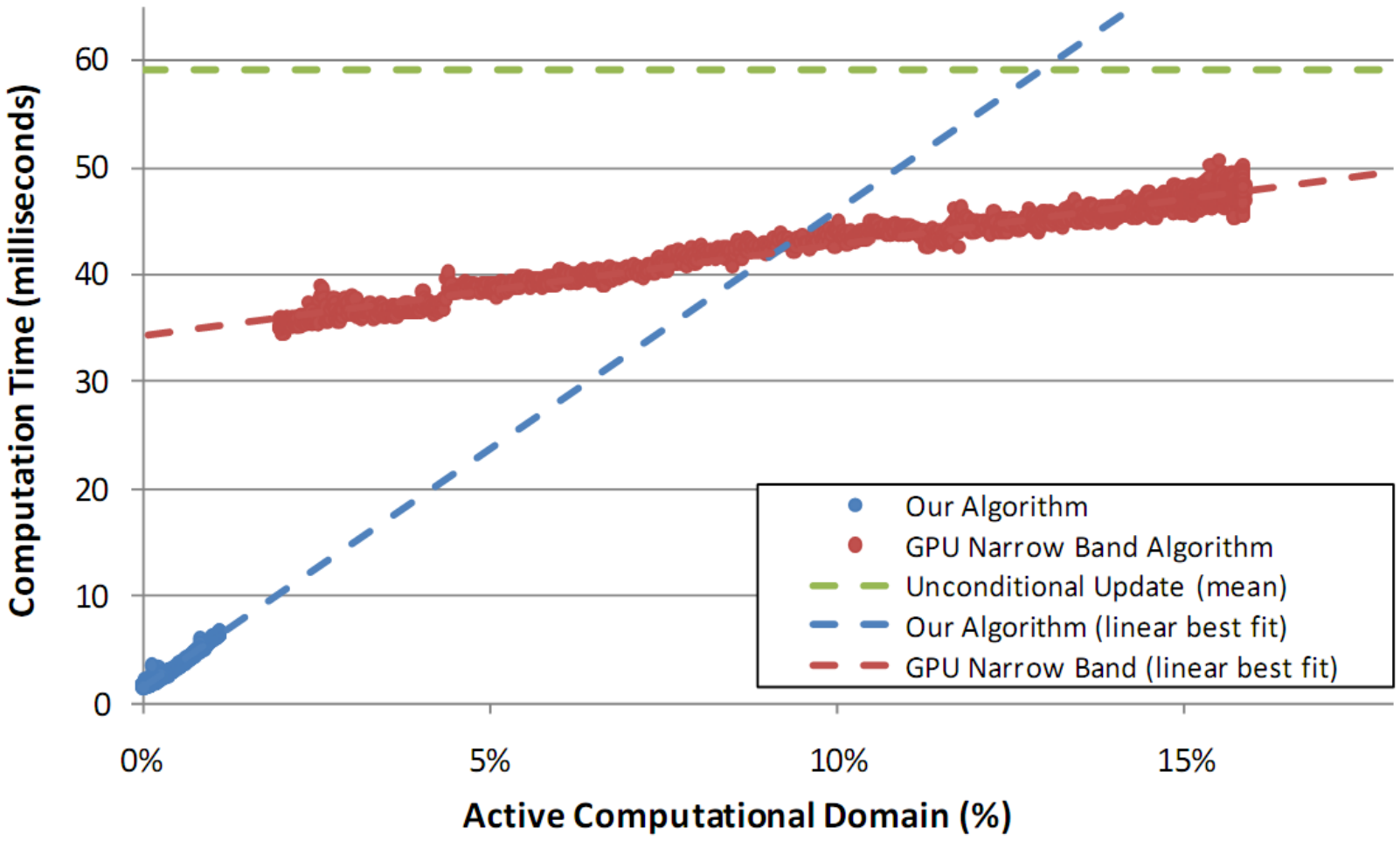


Finding the voxels that are changing in *space and time*





Speed *vs.* Computational Domain Size



Speed per Subroutine