GPU TECHNOLOGY CONFERENCE

Efficient Volume Segmentation on the GPU

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PRESENTED BY NVIDIA.

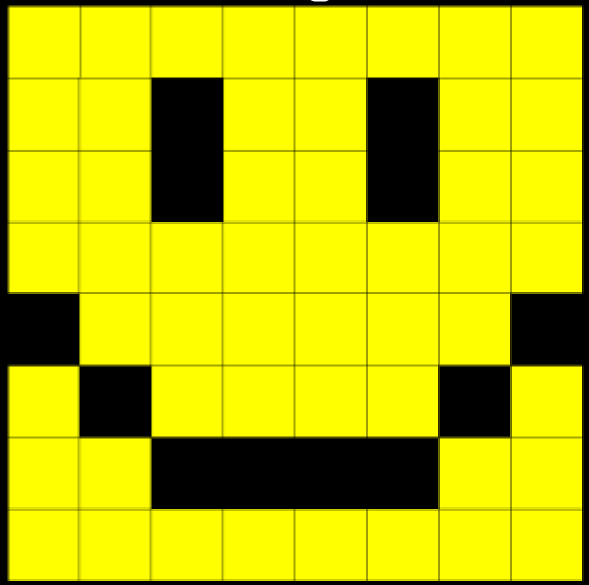
Agenda

- Introduction / Problem Task
  - Input and Expected Output, Connectivity
- Algorithm
  - Label Setup and Label Propagation
  - Acceleration concepts (Links, Master/Slave)
- Implementation
  - Algorithm mapping to CUDA C
  - Tradeoff comparison for different strategies
- Results
- Conclusion

Introduction / Problem Task

- Input
  - 2D array / 3D array of data (typical image/ volume data)
  - Connectivity Criterion (when are two elements connected?)

- Example Input
  - <u>2D RGB image</u>

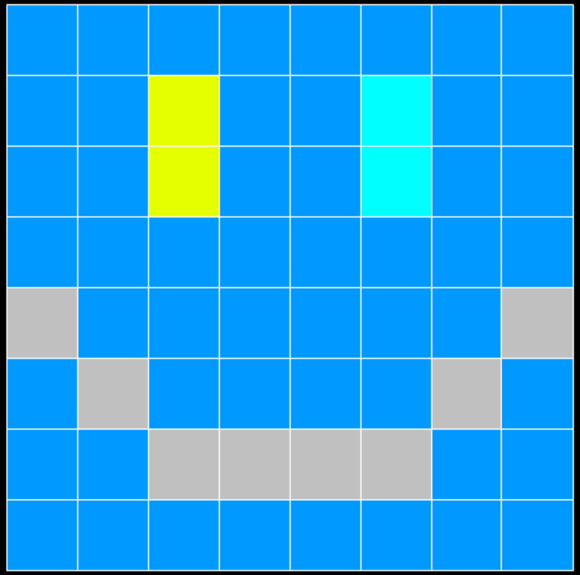


  - <u>Connectivity Criterion:</u> Equal colors, 8-connectivity

Introduction / Problem Task

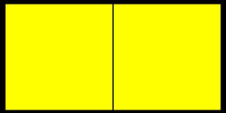
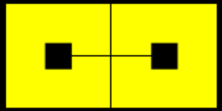
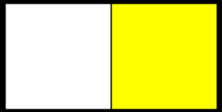
- Output
  - Uniquely labelled regions:
    2D Array / 3D Array
    with all connected regions
    having the same "label"
    (usually a 32bit integer value)

- Example
  - 2D array of labels



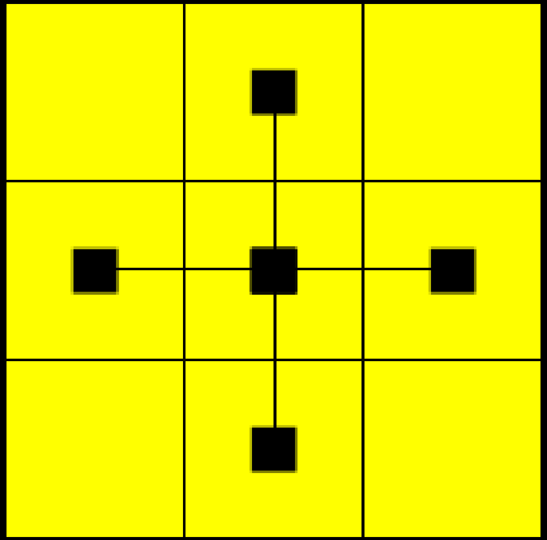
LEGEND
Labels: White outline

Connectivity Criterion

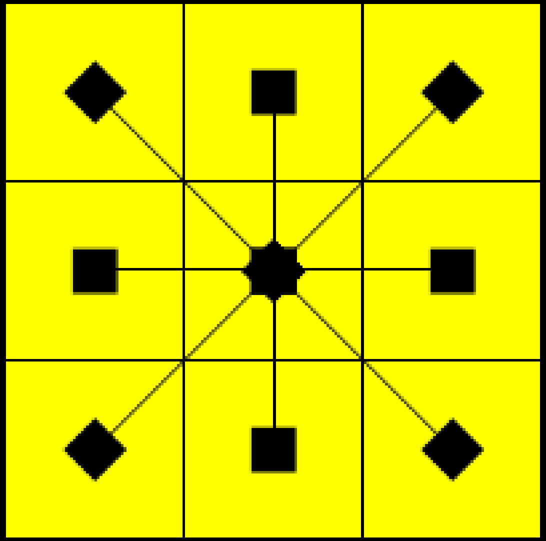
- When are neighboring cells "connected", become a region?
- Example criterion: Equal RGB values
  - Linked (= 1):  , symbolized as: 
  - Not linked (= 0): 
- More useful criterions for noisy input:
  Color gradient thresholding
  e.g. Sum(abs(p0.rgb – p1.rgb)) < 0.1
- Others: Motion data, n-edged graphs,…

2D: 4- and 8-connectivity

- Are diagonal neighbors regarded as "connected" ?



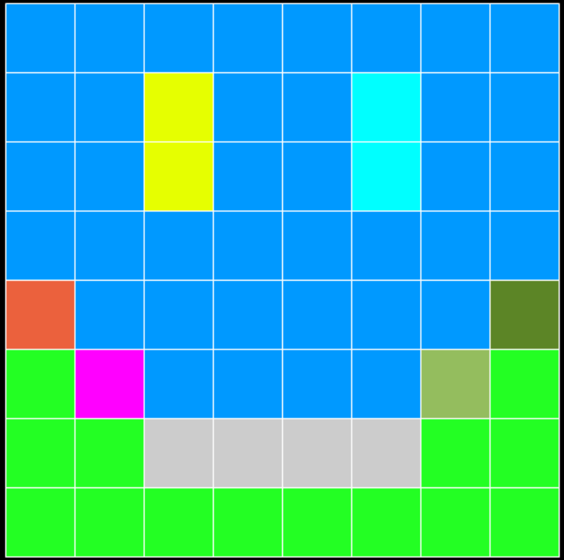
4-connectivity:
Look at vertical and
horizontal neighbors

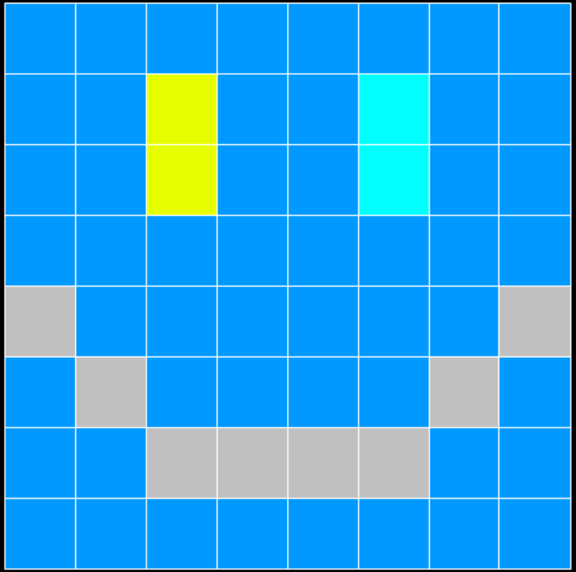


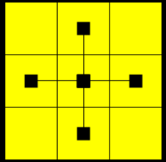
8-connectivity:
Also look at
Diagonal Neighbors

4- and 8-connectivity

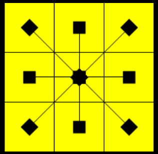
- Affects label propagation!
- Labelling results can differ substantially:







4-connectivity labelling:
Upper and lower part separate

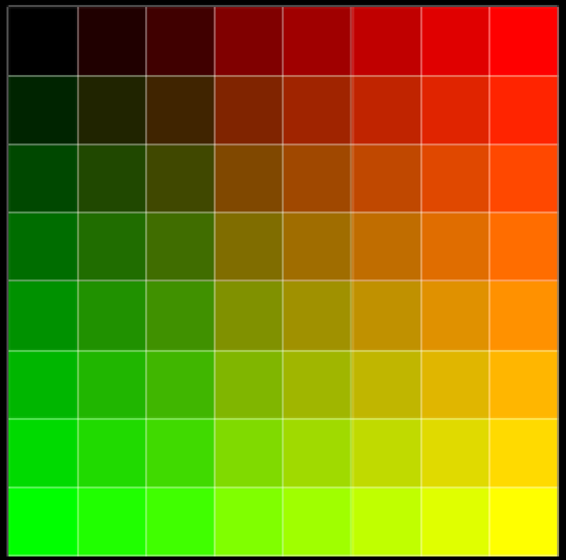


8-connectivity labelling:
Upper and lower part connected

Algorithm:
Label Setup and Propagation

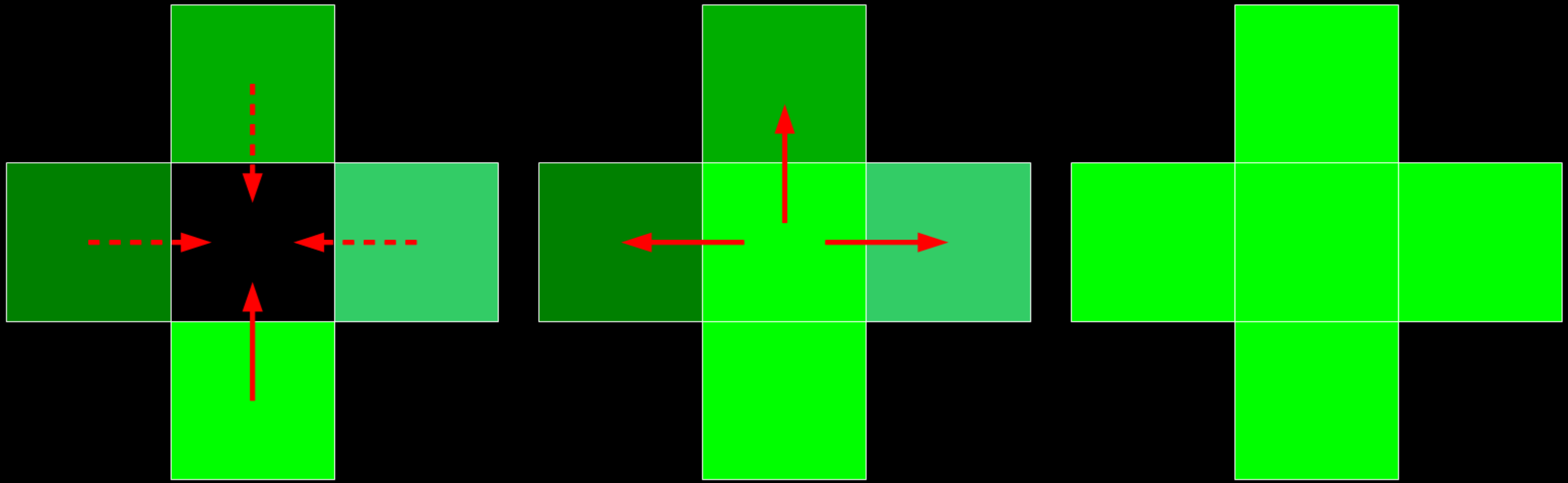
Label setup

- Each cell has its own label (p.rgb = f(p.x, p.y))
- Labels are comparable in a strict linear order, e.g. L=y*width+x
- Also, (x,y) can be recovered from label - e.g. Red=X, Green=Y



Simple Label Propagation: 1-gather

- Larger labels propagate to connected cells with smaller labels
- Cells gather from their neighbours: **1-gather**
- Completely data-parallel with double-buffering and gather



- *Finish*: When no more updates occur!

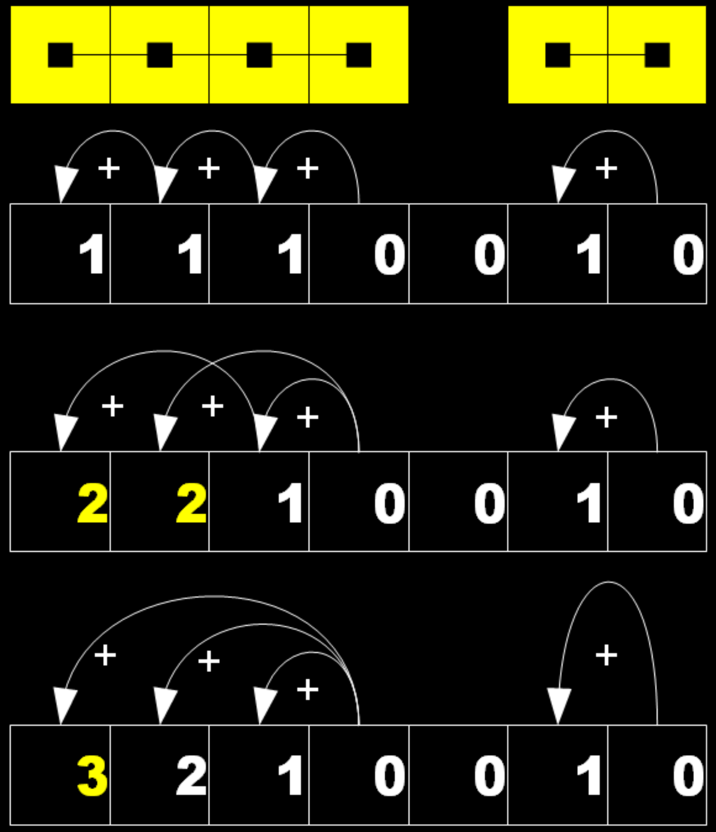
Algorithm Optimization: Links and max-gather

Links: Motivation

- Problem of 1-gather algorithm: SLOW
  (Each pass, labels propagate only one cell further)
- Can we make labels propagate faster?
- Observation: Connectivity between cells is <u>static</u>!
- Precompute the furthest connected cell along each connectivity direction (e.g. x,y,z)
- Log2(width|height|depth) steps
- (Similarities with Horn's data-parallel algorithm for prefix sum, GPU Gems 1)

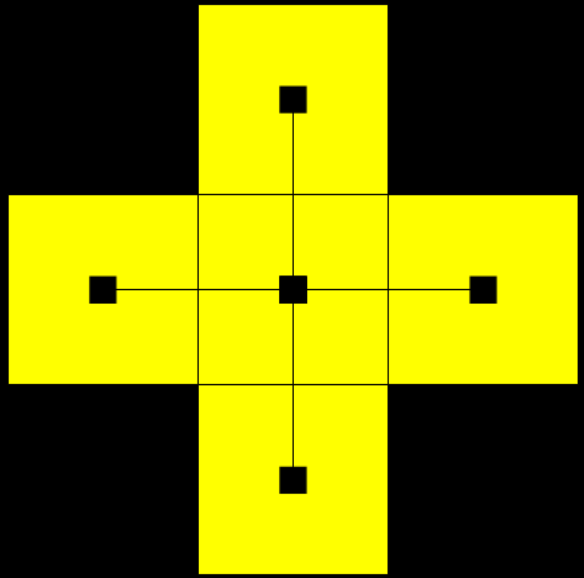
Links: Precomputation Algorithm

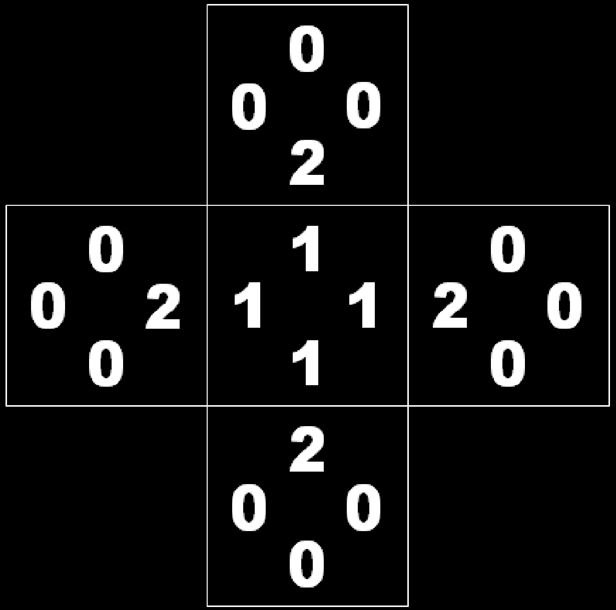
- Initialize with local connectivity.
- Repeatedly add cell value that link *points to*.
- Example shown: Computing furthest connected cell to the right



Links: Directions

- One entry for each cell and each direction
- Example: 4-connectivity links for a cross of connected cells:





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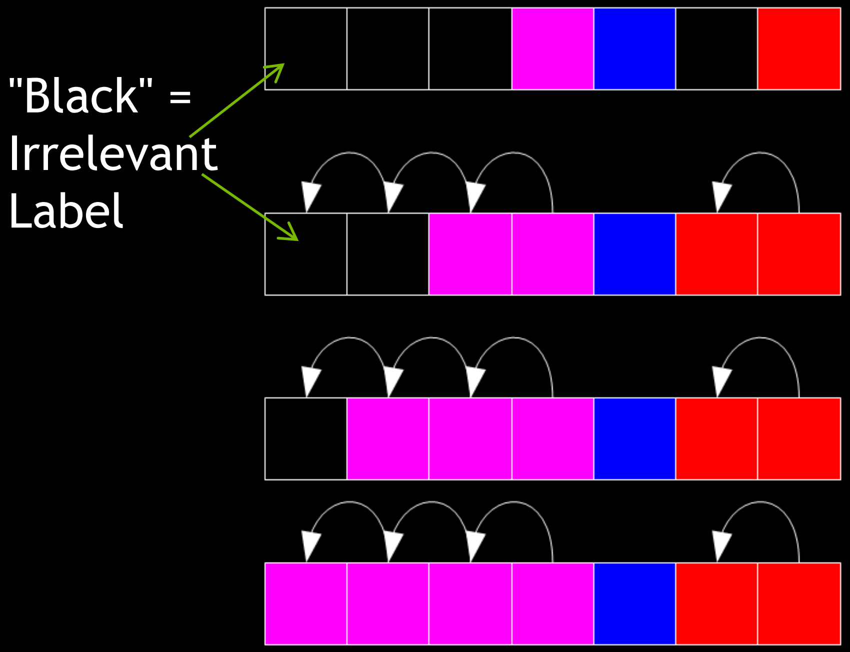
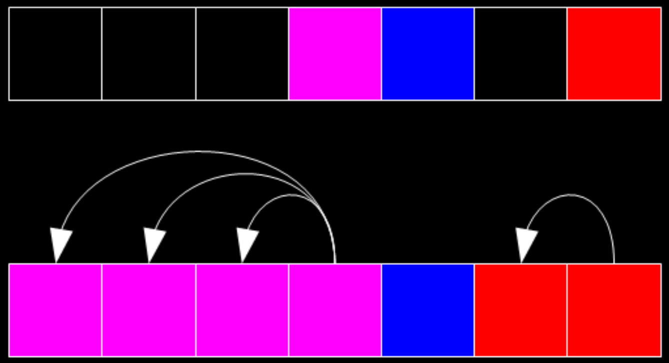
Labels: Faster Gathering

- Link Precomputation stage permits far-away label gathering

- 1-gather



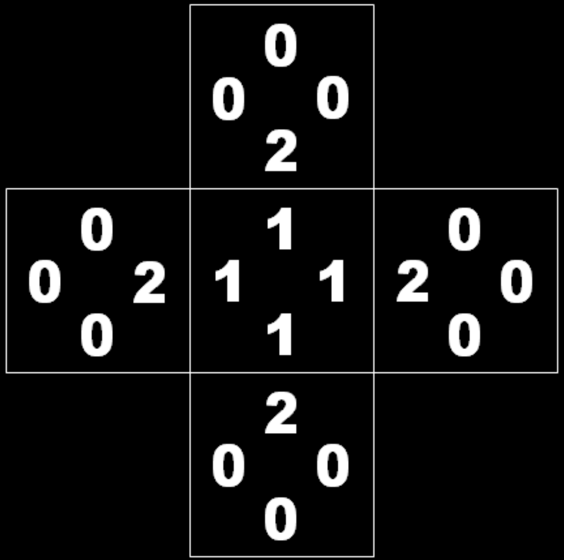
- Max-gather (via Links)



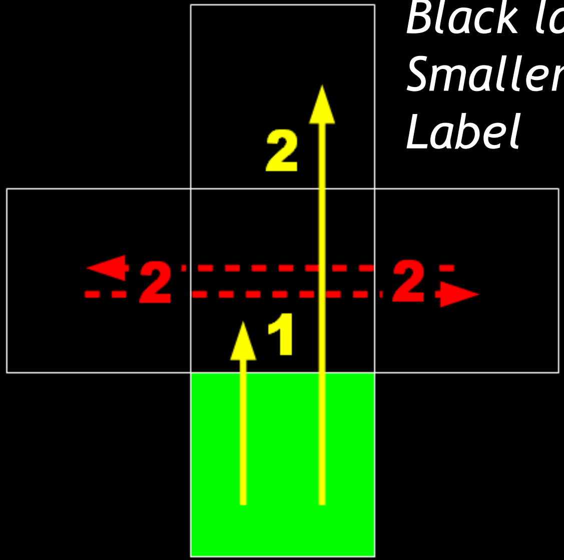
Links result in
faster label propagation

Max-gather doesn't suffice

- One might assume that 1-gather is not necessary anymore.
- BUT: there are cases where max-gather doesn't fill all cells!

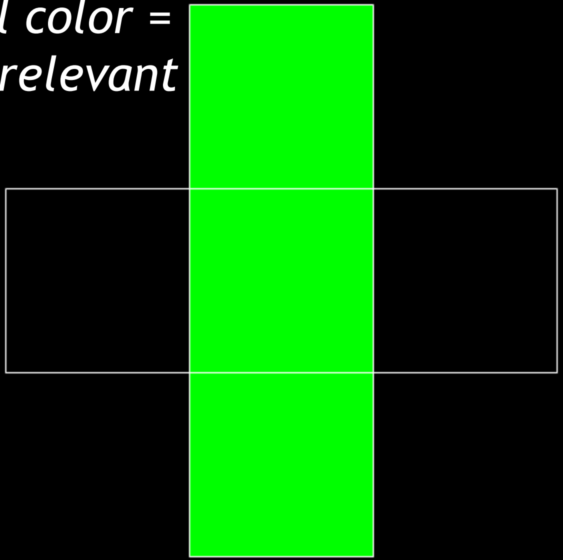


Links Data:
Cross of connected cells



Black label color = Smaller/Irrelevant Label

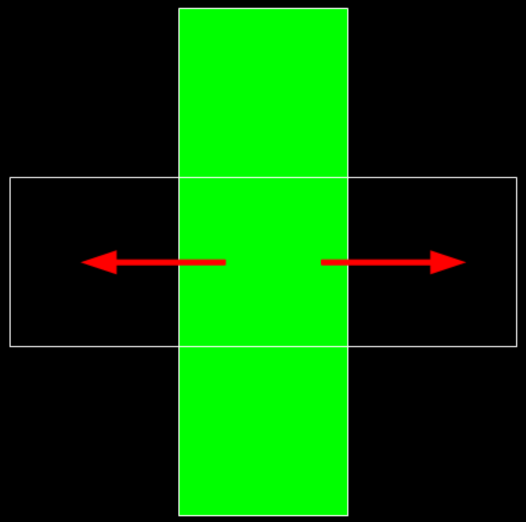
Green Label is largest -
Attempted max-gathering



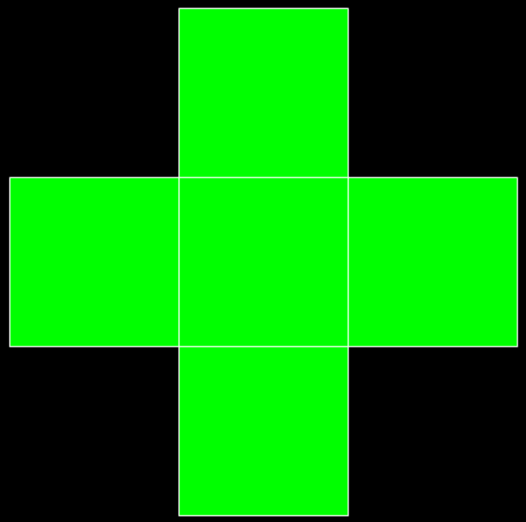
Label result (incomplete)

Max-gather doesn't suffice

- 1-gather is still necessary to fill in the unlabelled holes!



Green Label is largest -
Attempted 1-gathering

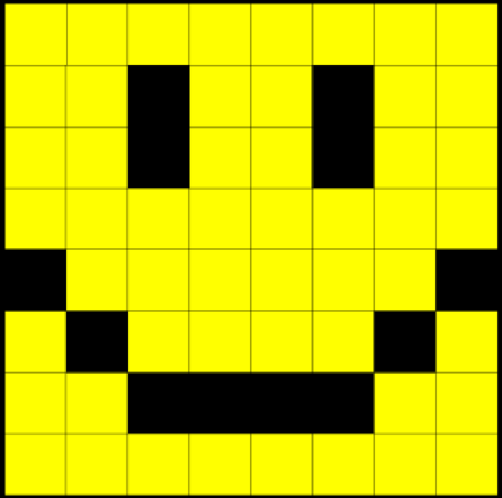


Label result (complete)

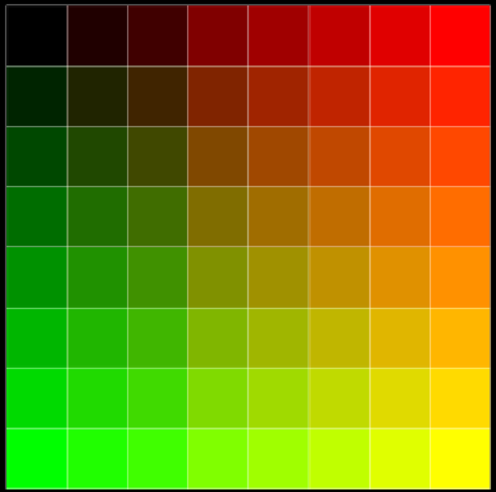
Algorithm Optimization: Master/Slave

Master cells

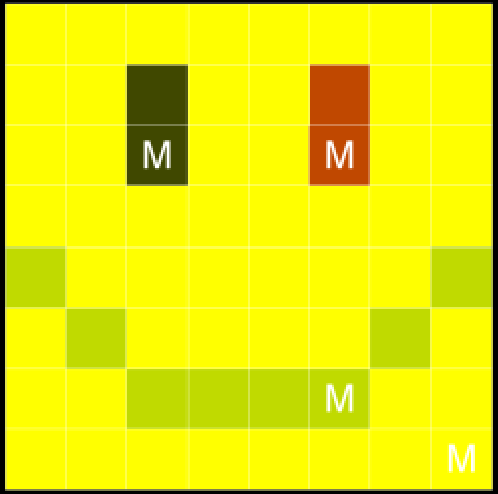
- In each region, one cell keeps its original label
- All other cells: Their label originates from this one cell
- Thus, each labelled region has a ***master cell***



Label Init: Lower/Right values are larger



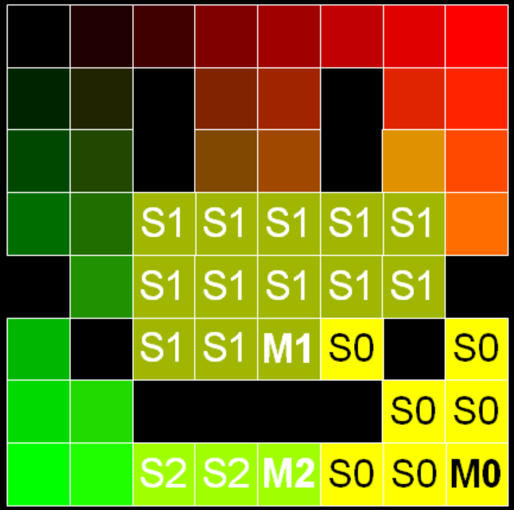
Label Init: Lower/Right values are larger



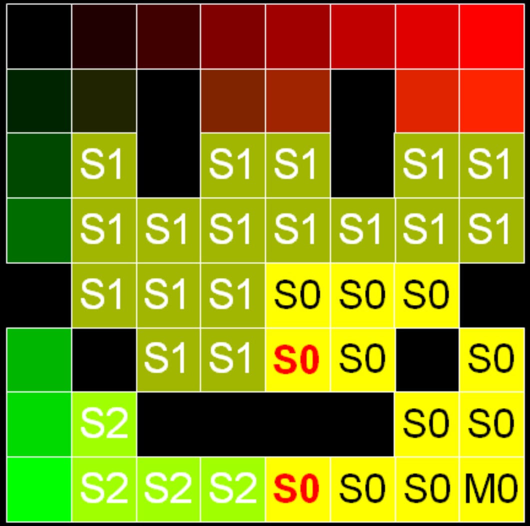
Labelled result
M = master cell

Master cells: Label propagation

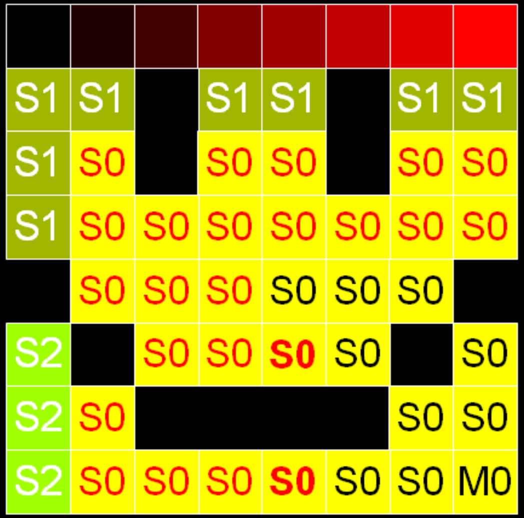
- If master cell changes label, all slave cells can change label
- Hence: Always gather current label from master cell!
- Purpose: Commonly labelled regions flip “at once”.



Pass 0: Three regions: Masters M*n*, Slaves S*n*



Pass 1: Region M0 "captures" Masters M1, M2



Pass 2: Master cell lookup makes S0's and S1's flip!

Pseudo-Code: Simple Algorithm

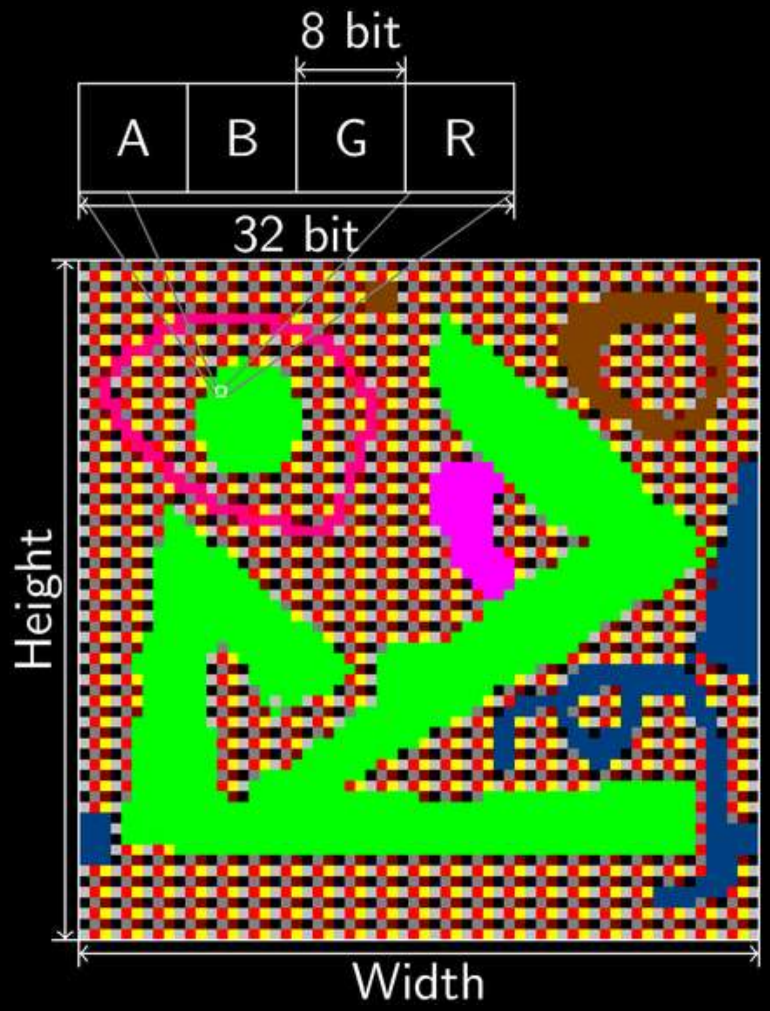
```
// Step I - Label Init
for (all pixels) {
  pixel.label = encodeLabel(pixel.x, pixel.y);
}

// Step II - Propagate Labels
while (AnyLabelChanges) {
  for (all pixels) {
     for (all directions) {
       neighborLabel = gather(neighbor, direction);
       pixel.label = max(pixel.label, neighborLabel);
     }
  }
}
```

Pseudo-Code: Optimized Algorithm

```
// Step I - Label Init
for (all pixels)
  pixel.label = encodeLabel(pixel.x, pixel.y);
// Precalculate links
precomputeLinks();
// Step II - Propagate Labels
while (AnyLabelChanges) {
  for (all pixels) {
     for (all directions) {
       // Use max-gather
       neighborLabel1 = gather(neighbor, direction);
       neighborLabelMax = gather(neighbor, pixel.maxgather(direction));
       pixel.label = max(pixel.label, neighborLabel1, neighborLabelMax);
       // Master/Slave
       if (pixel.label != pixel.originalLabel) {
         masterRef = decodeLabel(pixel.label);
         pixel.label = max(pixel.label, masterRef.label); }}}}
```

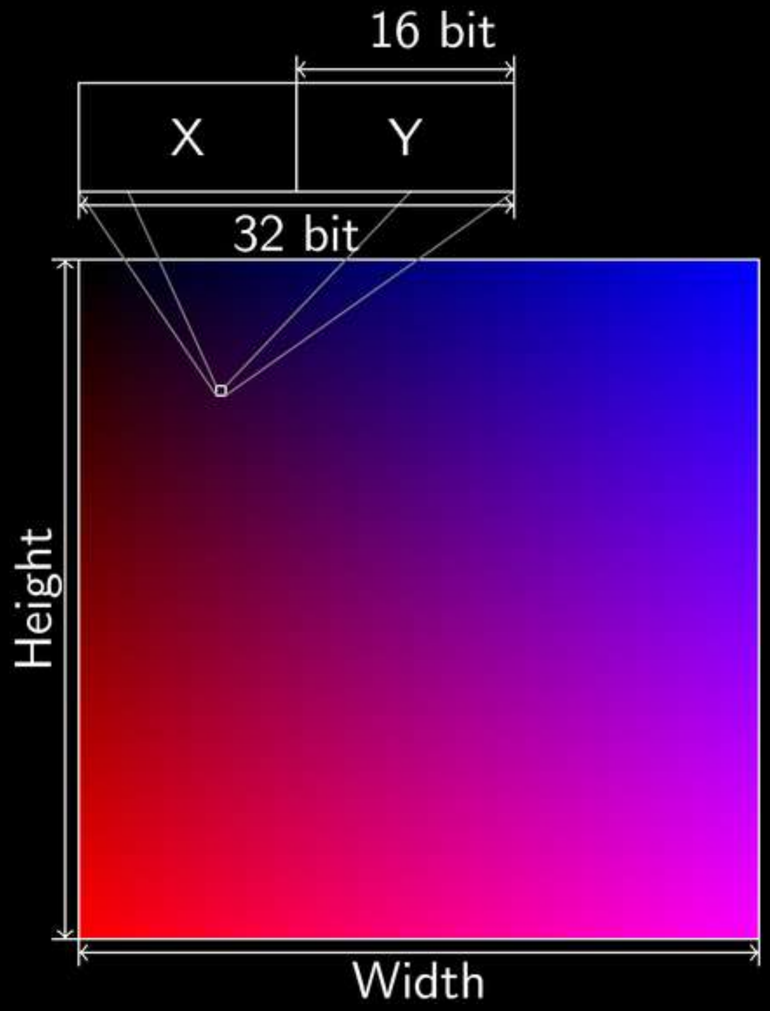
Implementation

Implementation: Image Storage



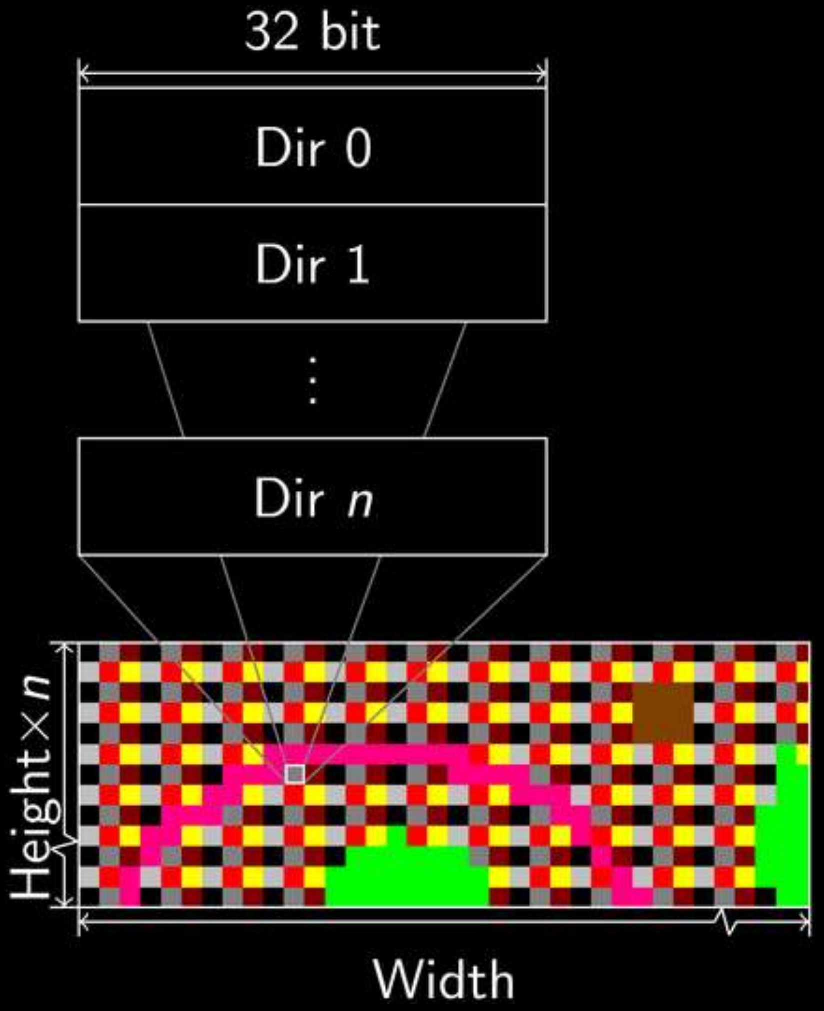
- Input: RGBA, 8 bit

Implementation: Label Storage



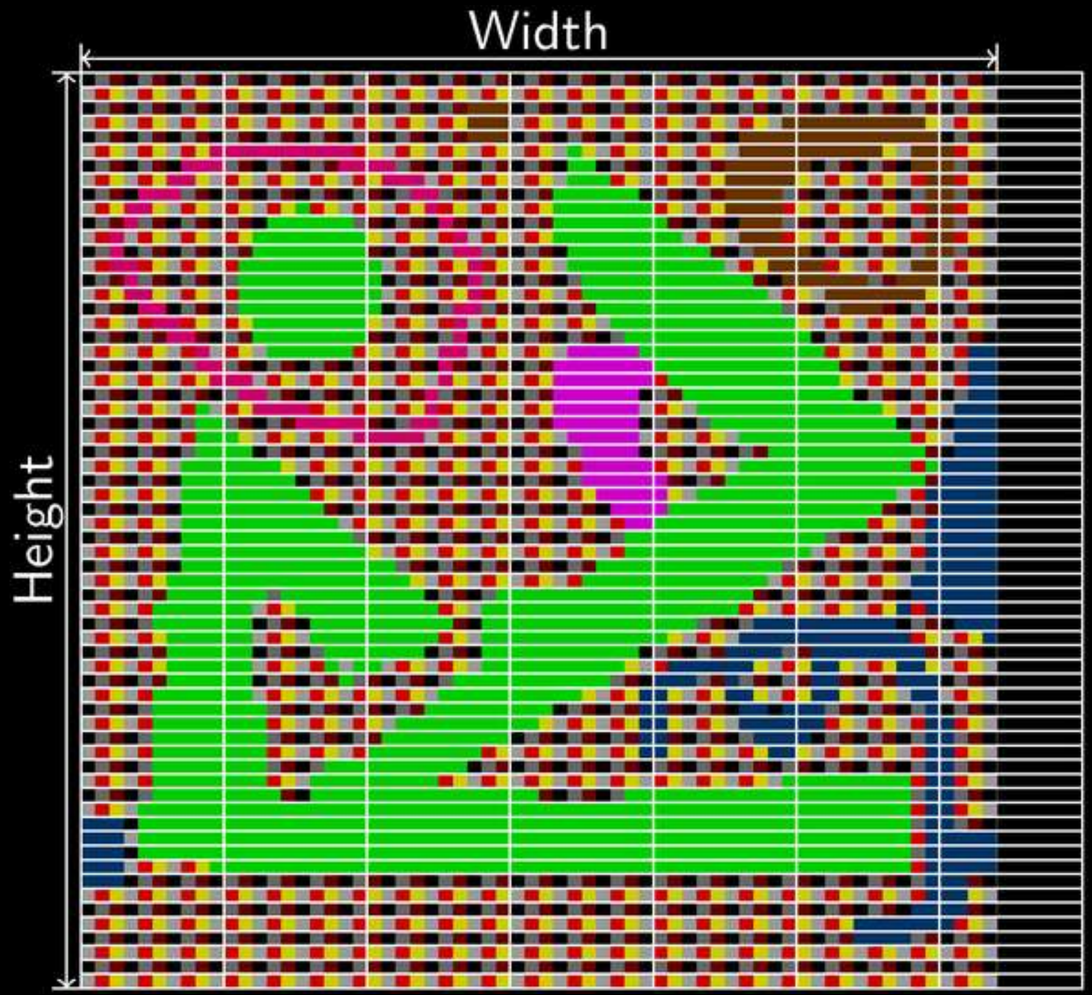
- 32 bit for x and y
- Max width: 65535
- Max height: 65535
- Label ordering: upper left << lower right
- L=x*width+y (!)
- 3D version: 8/10 bit for x, y and z

Implementation: Links Storage



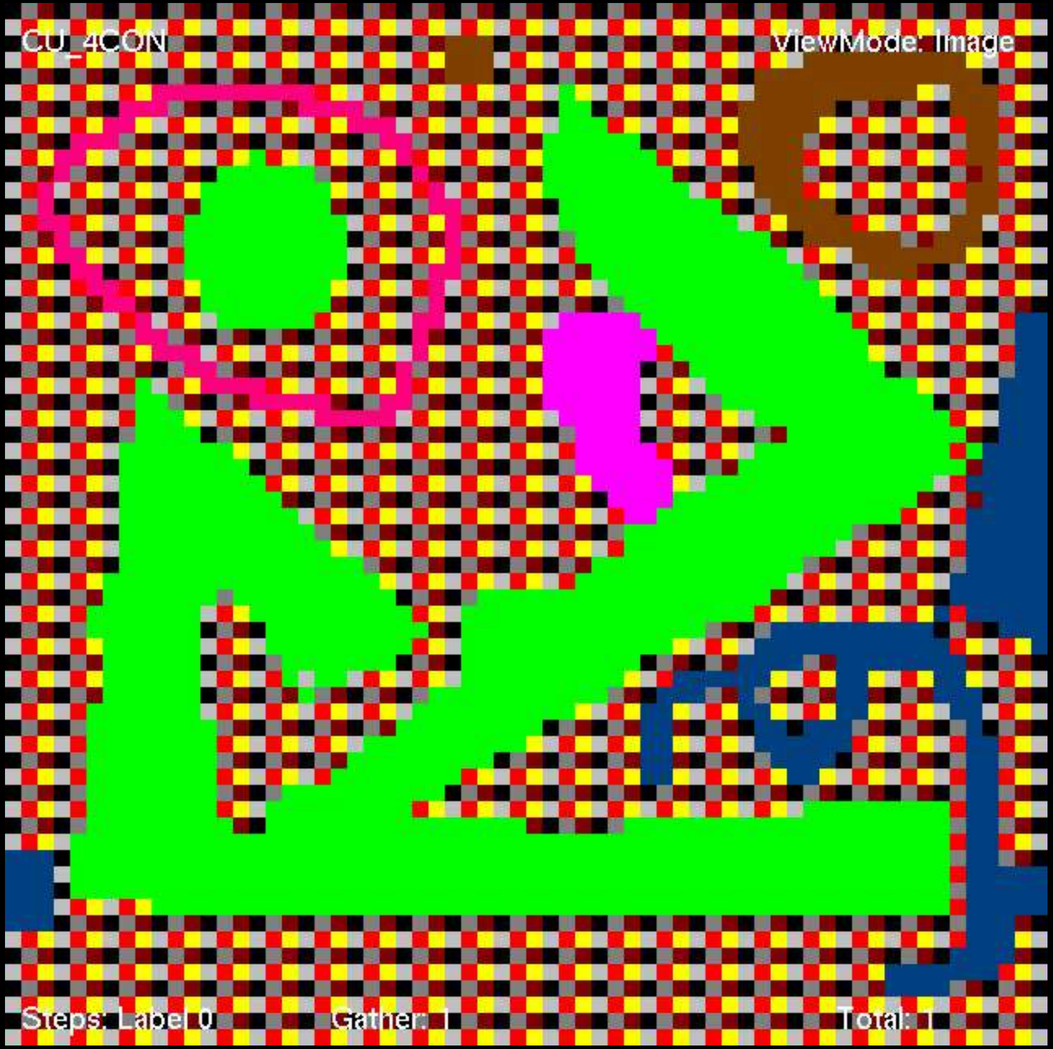
- All directions stored in global memory
- Line-interleaving ensures memory coalescing during links precomputation & label propagation

Implementation: Execution Configuration



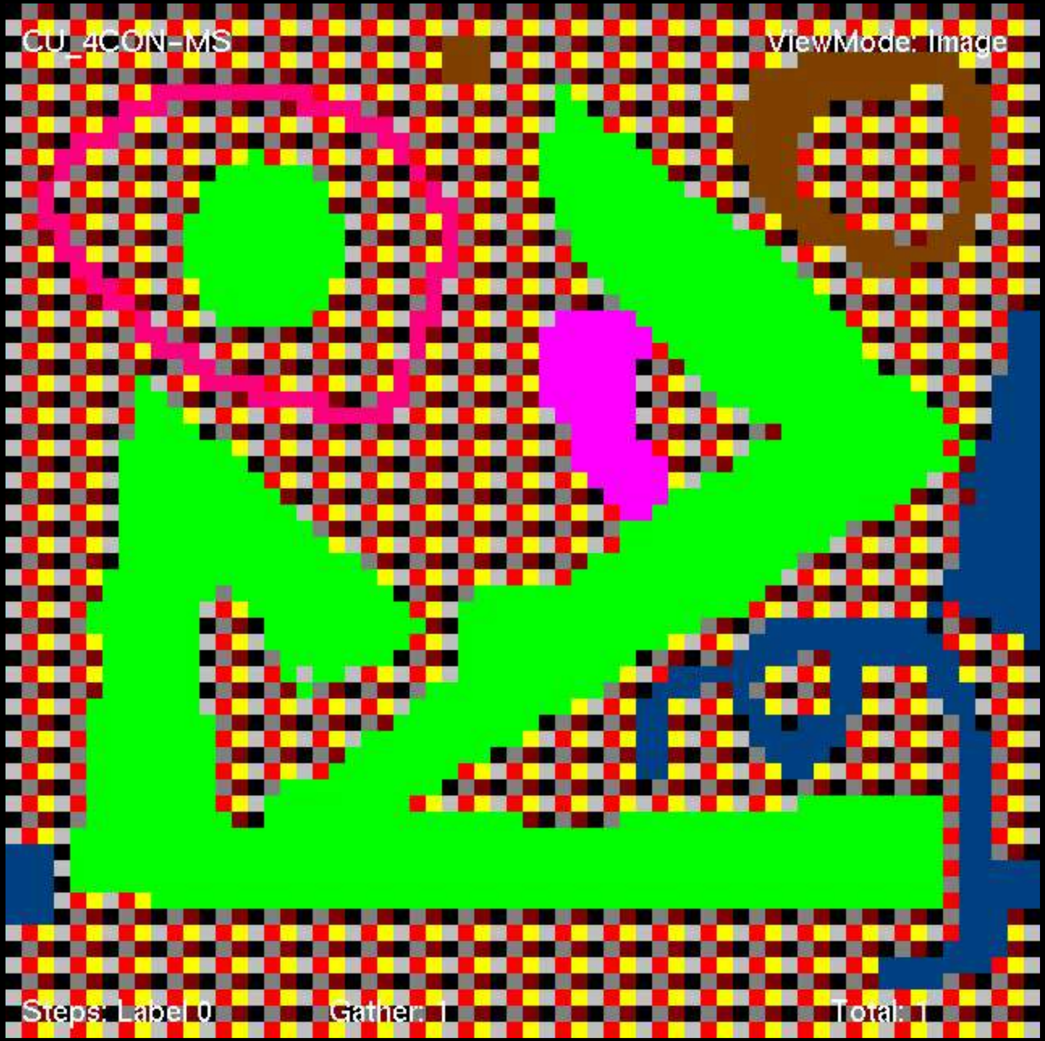
- Block Size = (multiple of 32, 1)
- Extra horizontal block for odd-width images
- Exact number of vertical blocks
- Thread config fits image, label and links processing

Results: Simple 1-gather



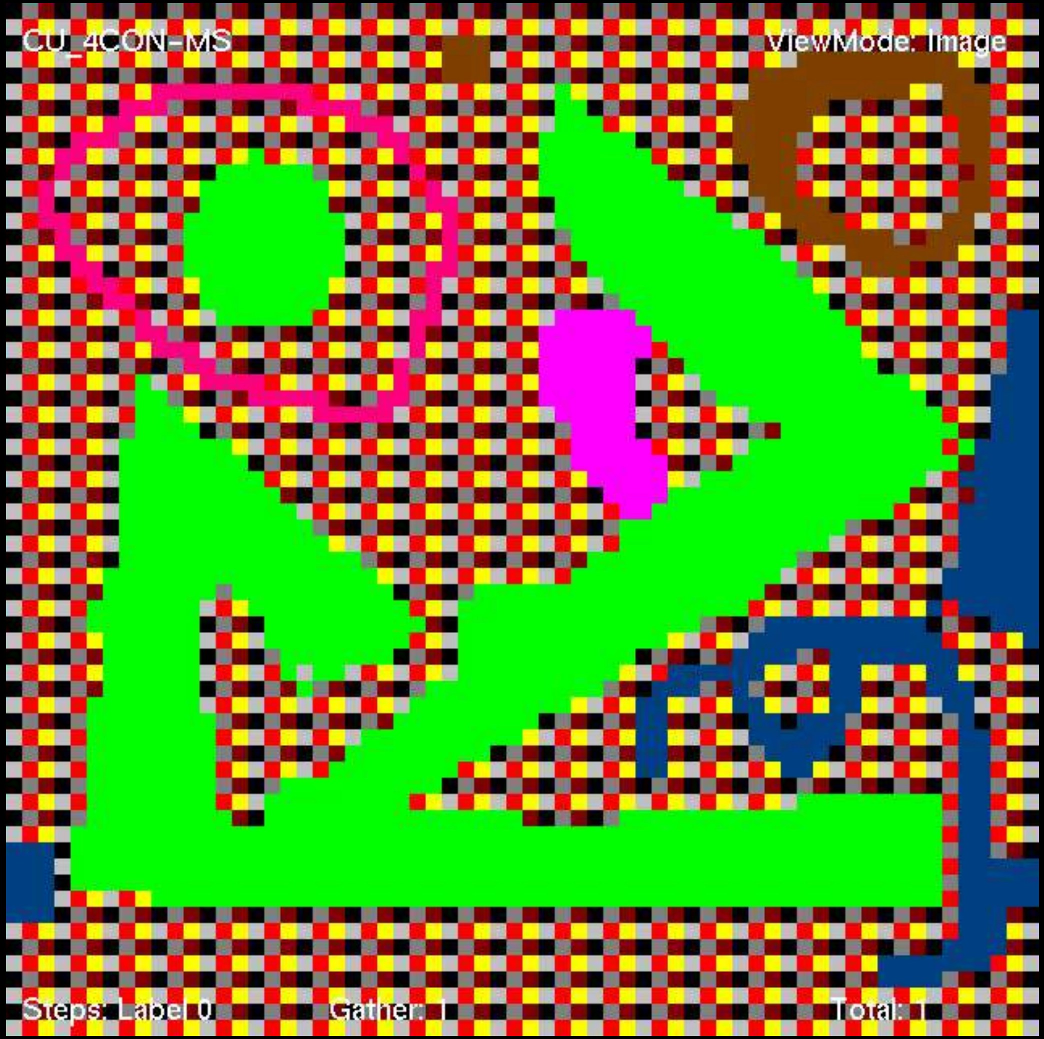
- Only 1-gather
- Simple and works, but: SLOW!
- Interesting: "Tug-of-war" in lower part of image, until a much larger label from right (large x component) comes along

Results: Master/Slave Principle



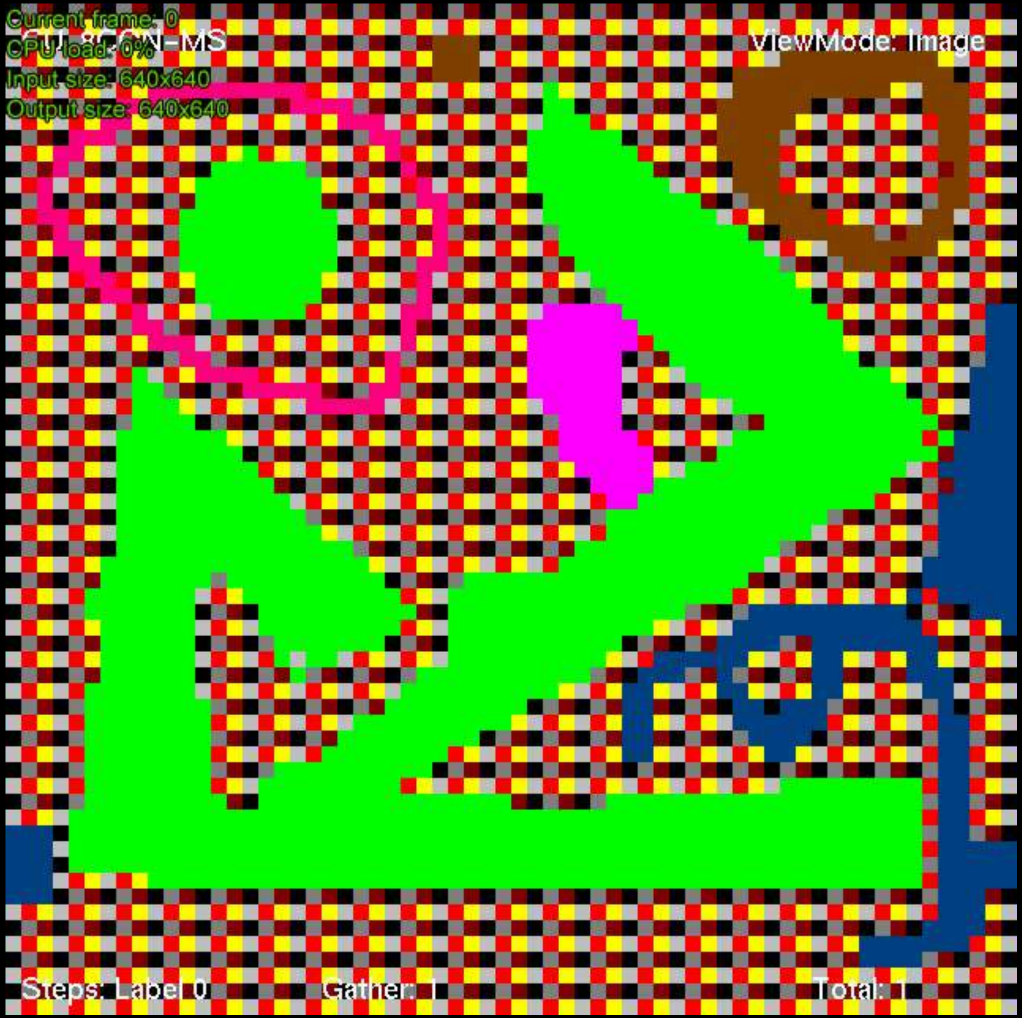
- Already-connected regions switch at once, see e.g. video's ending

Results: Links & Master/Slave



- Pre-linked regions switch a lot faster

Example of 8-connectivity



- 8-connectivity:
  Links in 8 directions are generated and used.

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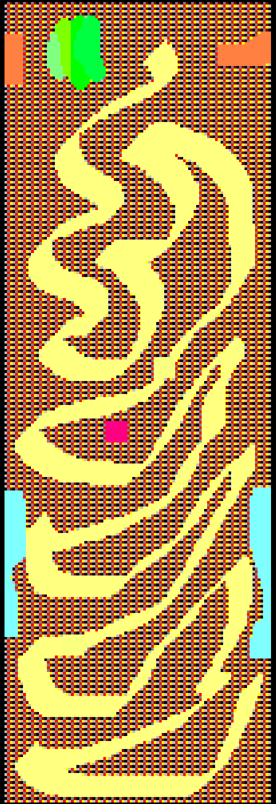
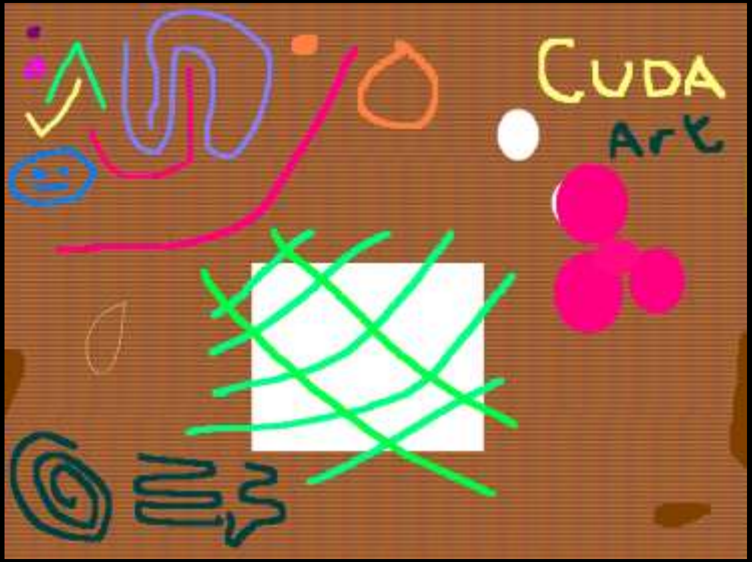
Results: Input Images

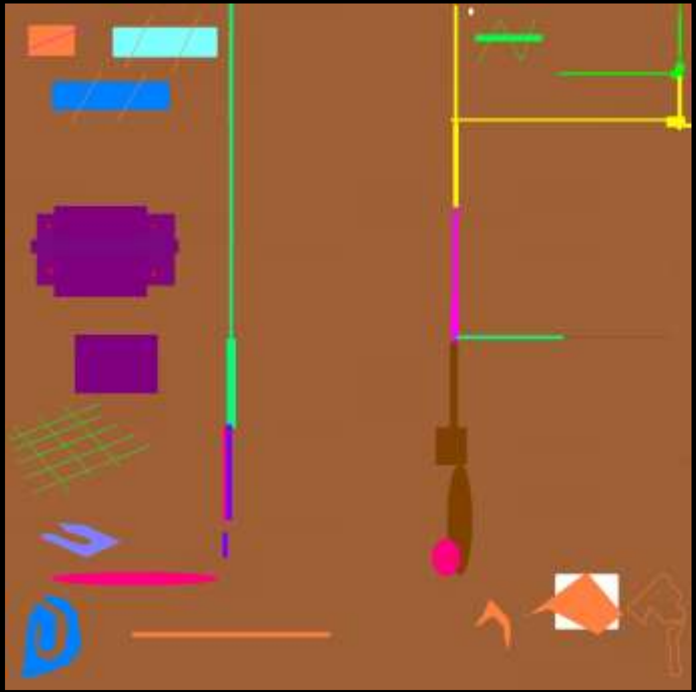
- Used in CUDA TopCoder challenge



100by300

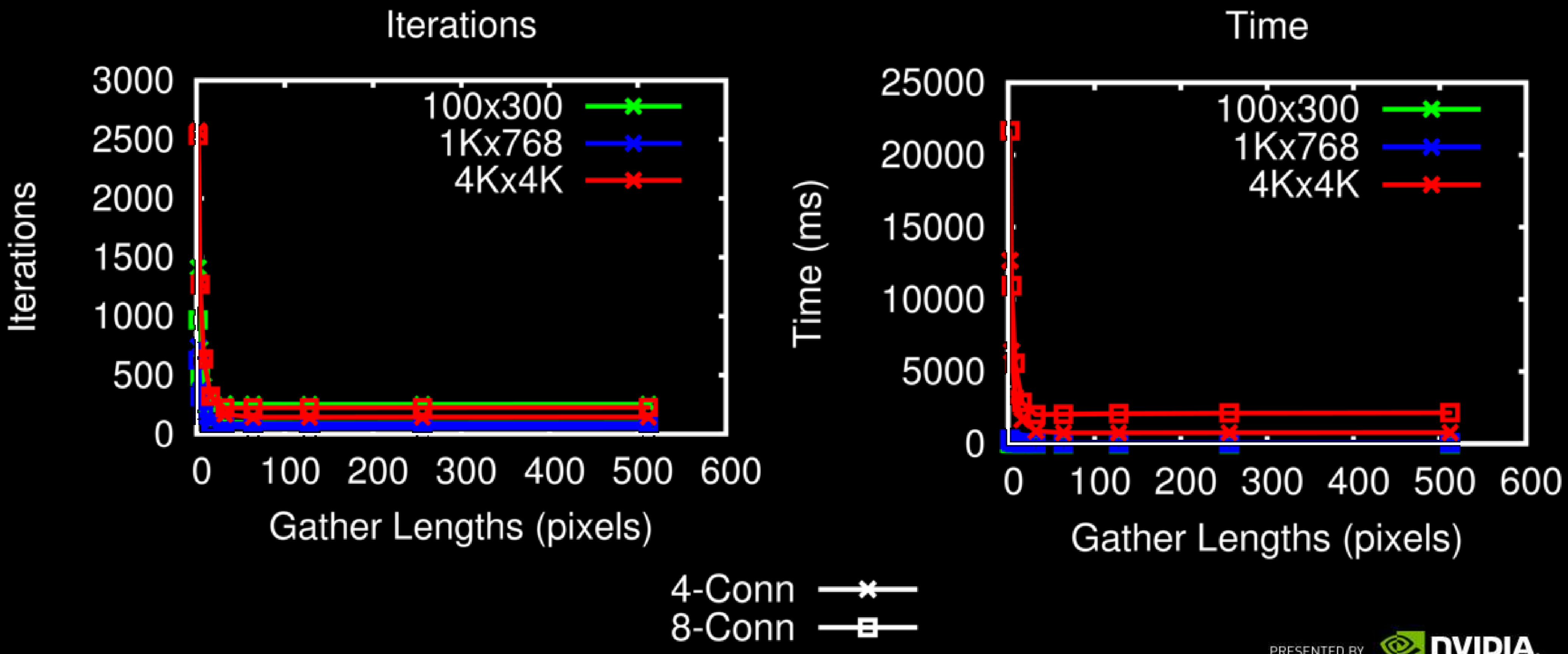


1Kby768

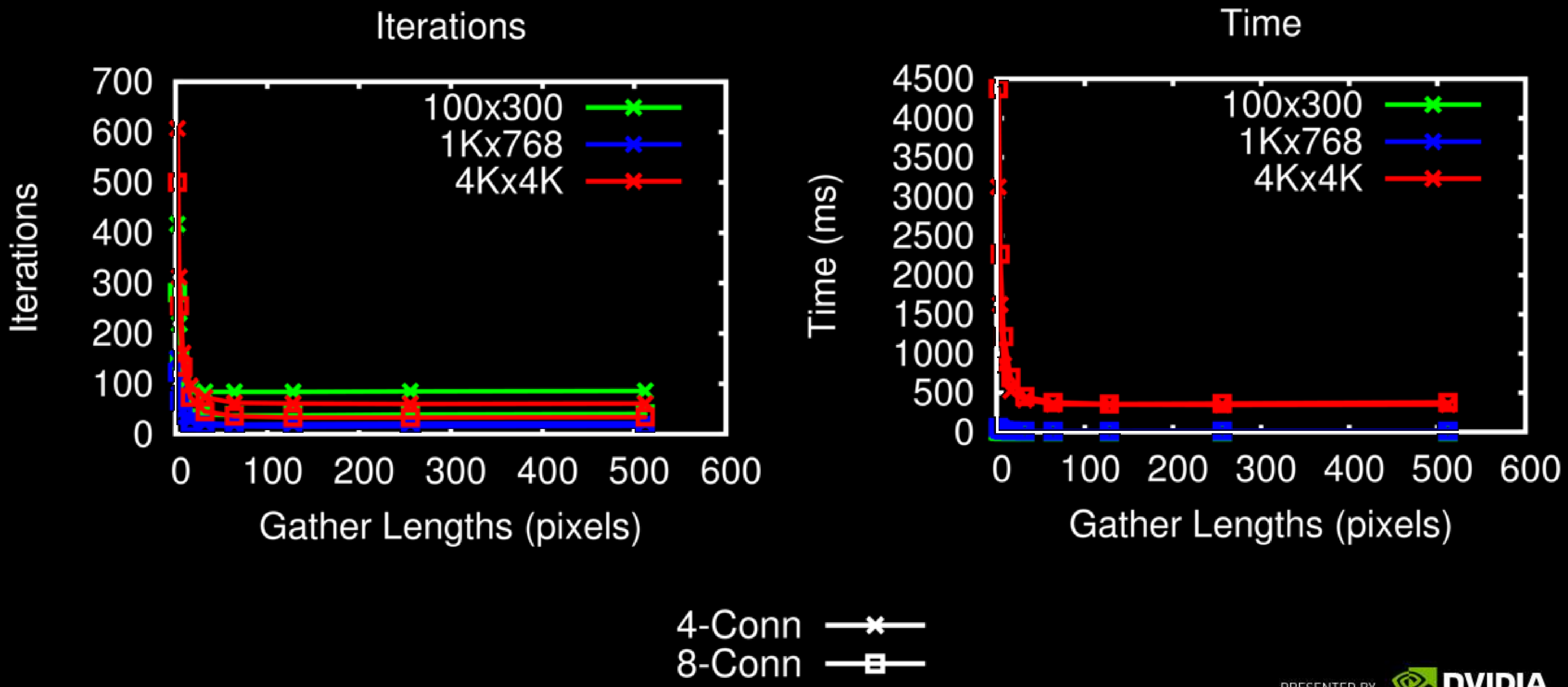


4Kby4K

Impact of Links & max-gather

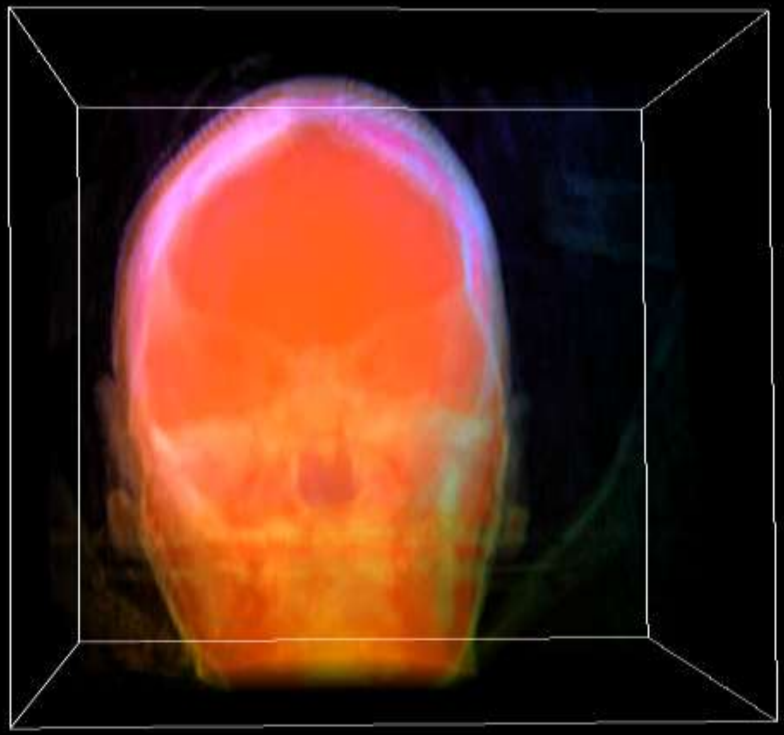


Impact of Master/Slave



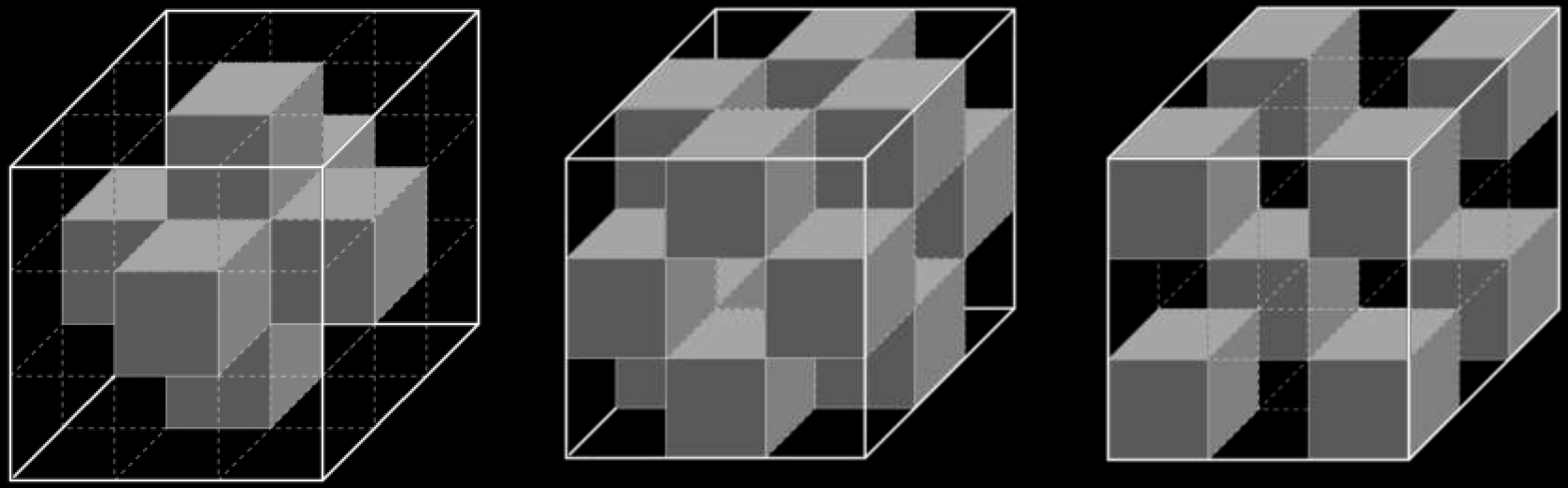
Extension to 3D

- Extend algorithm to 3D (cells = voxels)
- Choice of connectivity scheme
- Labels are now a function of x,y,z
- Labels can be converted to and from 3D coordinates
- 8bit x,y,z -> RGB 8bit



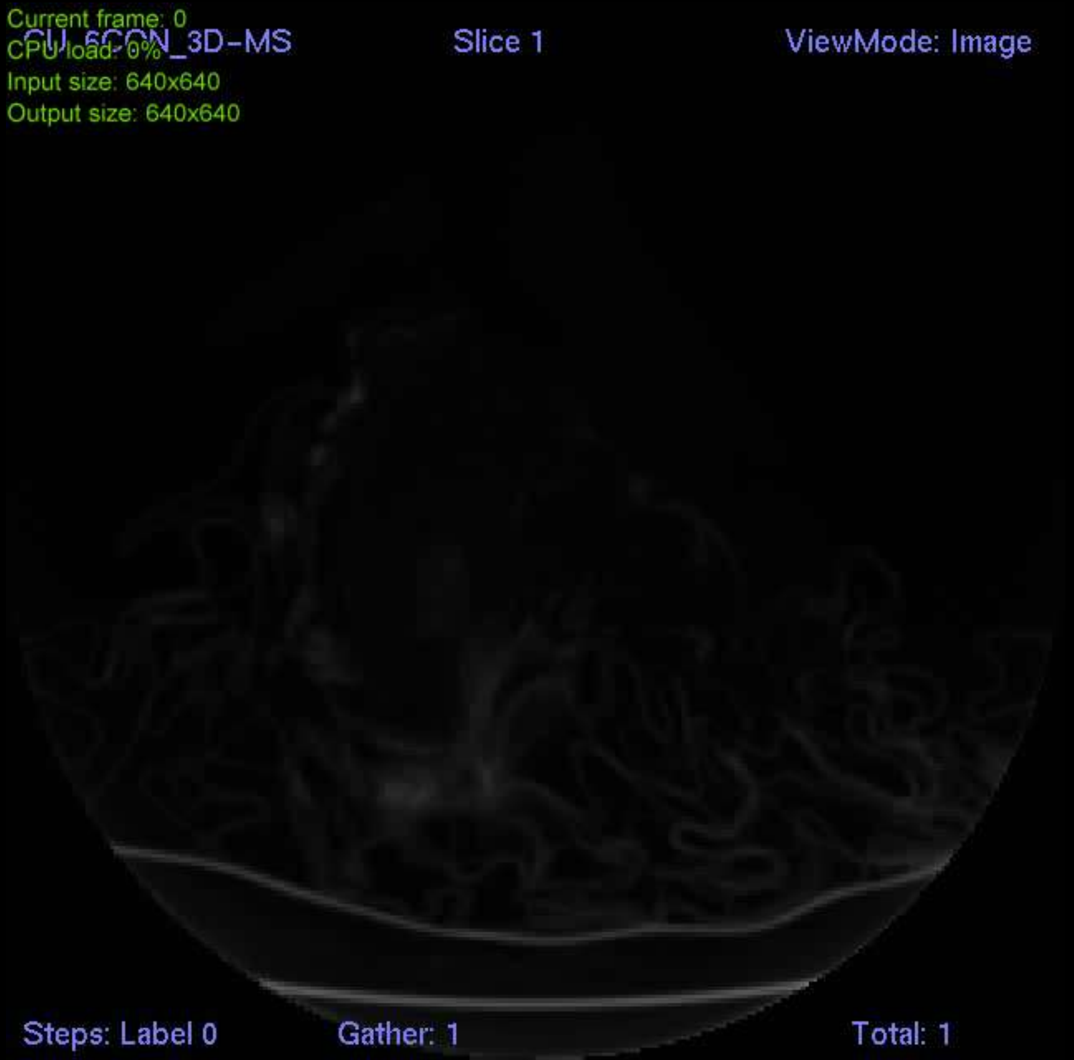
3D Connectivity

- Choice of connectivity scheme from three building blocks:



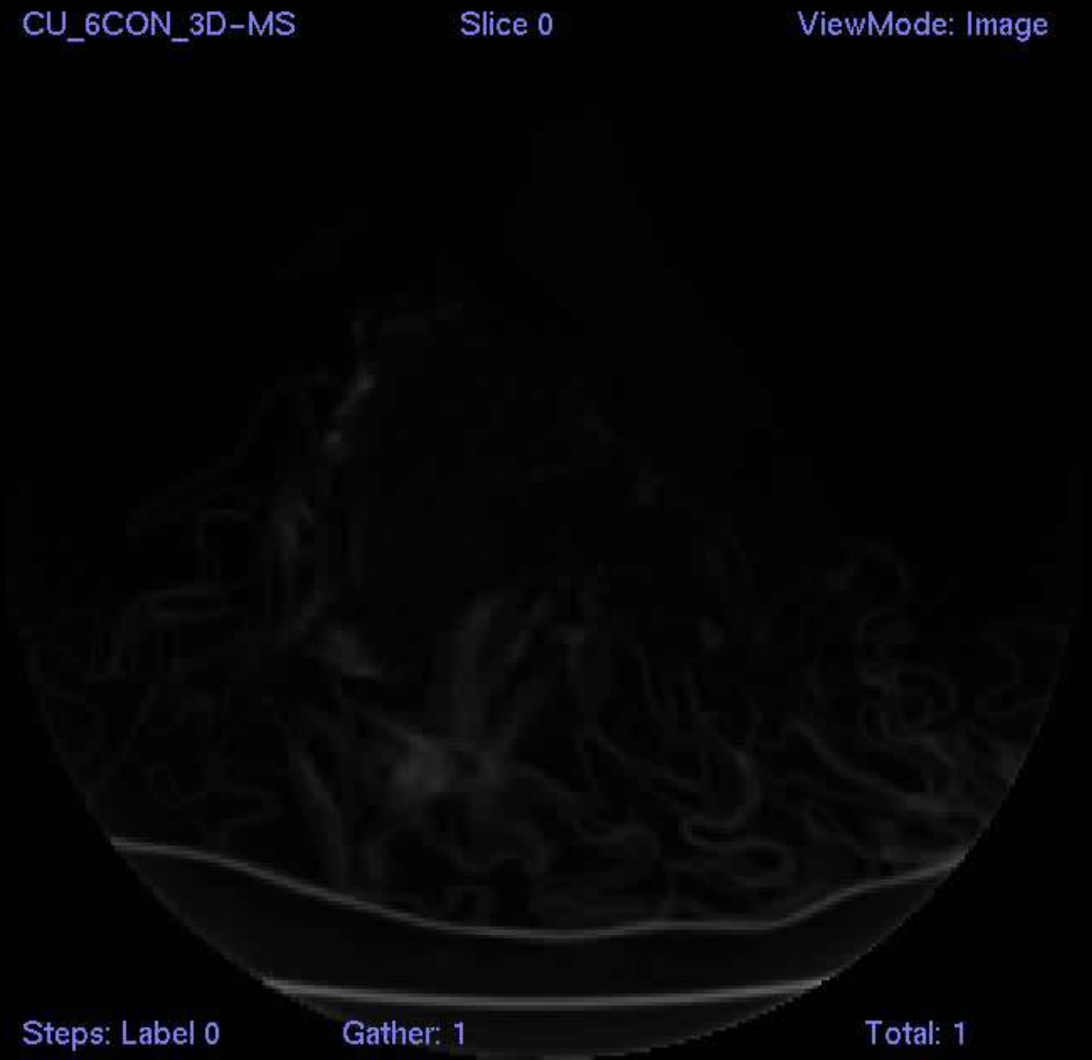
Results: 3D volume (256x256x100)

1-Gather &
Master/Slave



Results: 3D volume (256x256x100)

Max-Gather



Results: Typical execution times

Image	Kernel	Gather	Time (ms)
100by300	CU_4CON	32	4.04
100by300	CU_8CON	64	2.44
1Kby768	CU_4CON	64	7.48
1Kby768	CU_8CON	128	10.78
4Kby4K	CU_4CON	256	343.84
4Kby4K	CU_8CON	128	356.43
ctHead	CU_6CON_3D	128	1499.43

Run on Tesla C2050, includes GPU memory transfers

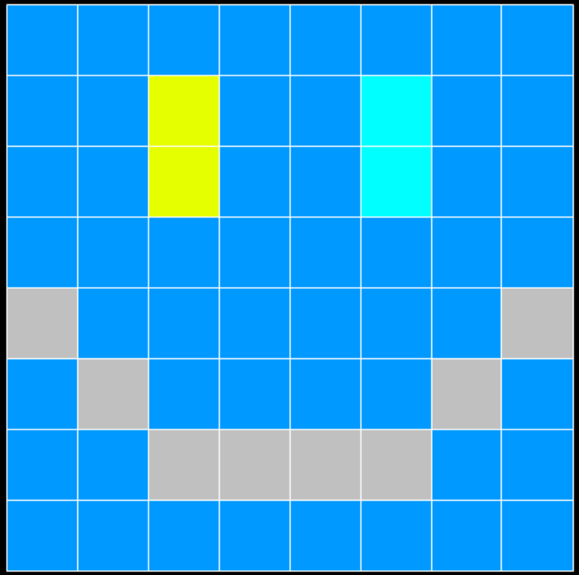
- Fast enough for video processing!
- 3D volume of
  - 256x256x100: 1500 ms
- Fast enough for interactive connectivity experiments
- Shmem not yet utilized!

Summary

- Links Precomputation from static connectivity is highly beneficial for label propagation.
  - Surprise: Less than maximal gather lengths are just as usable!
- Completely data-parallel algorithm (parallelization over all pixels, no atomic operations)
- Current implementation (gmem-based) already has real-time 2D performance

Future Work

- Efficient usage of shared memory (prototypes exist)
- Label List generation (based on data compaction)
- Distance Field computation might also benefit from Links



Thank you !

Additional Material

Label lists (Sketch)

- *Q: How can I extract a list of all discovered regions?*
- Step 1: Each region has one master cell.
  Isolate all cells that have retained their own label!
- Step 2: With list of master cells and their labels, each region's cells can be extracted by filtering for that label.
- Both steps can be solved by Data Compaction!
  (e.g. HistoPyramids, or Scan)
- Future Work!