# r.terracost: Computing Least-Cost Path Surfaces for Massive Rasters

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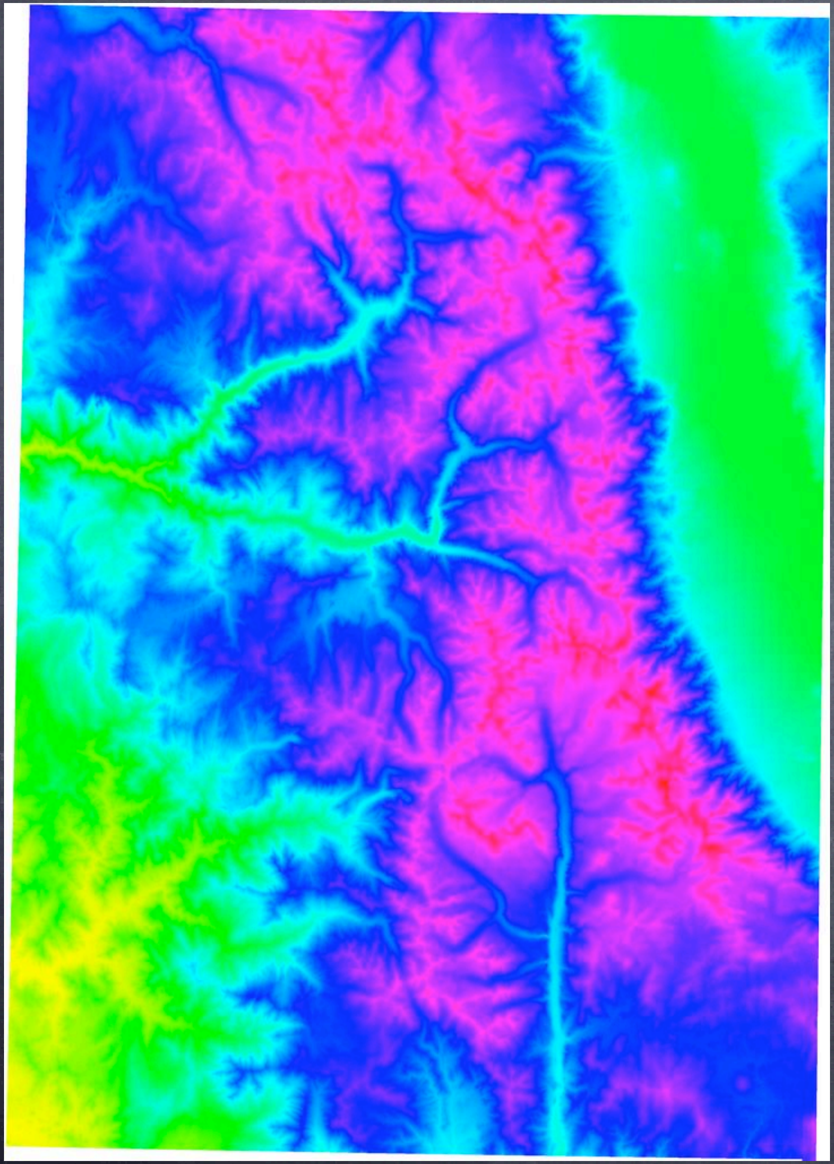
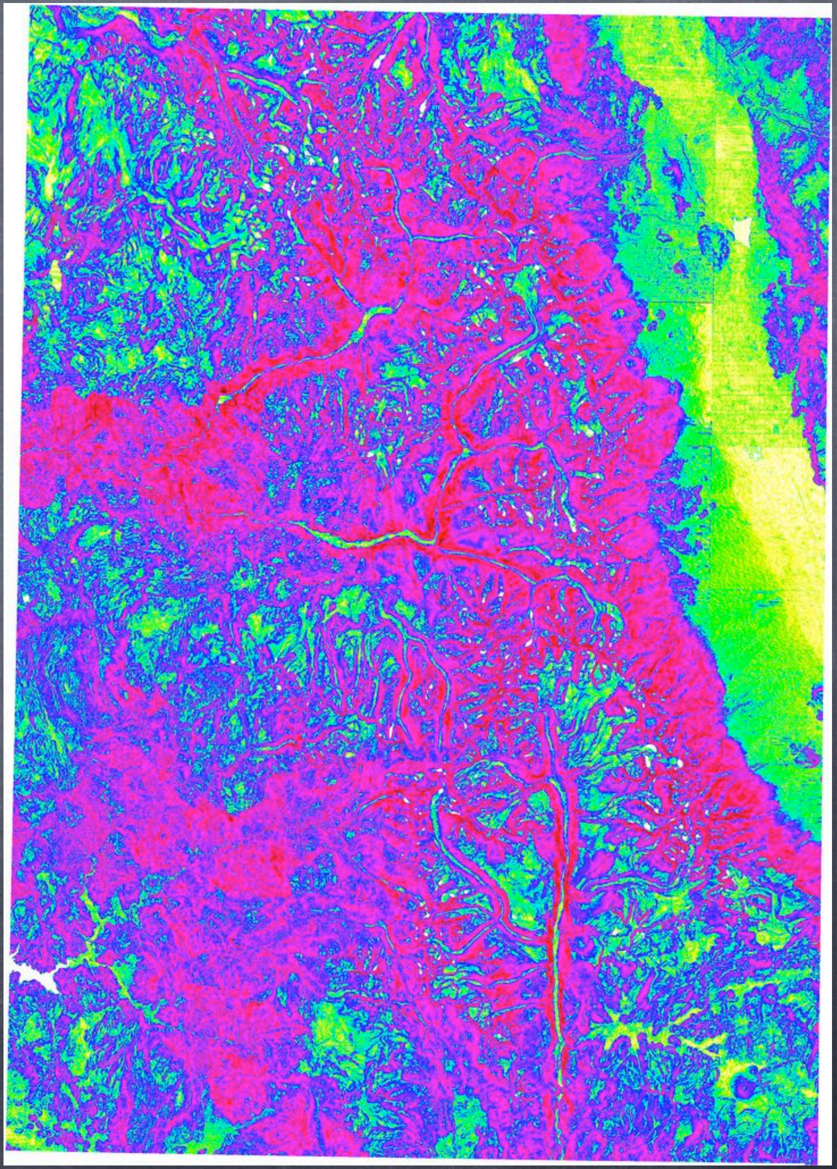
Lausanne, Switzerland

## Least-Cost Path Surfaces

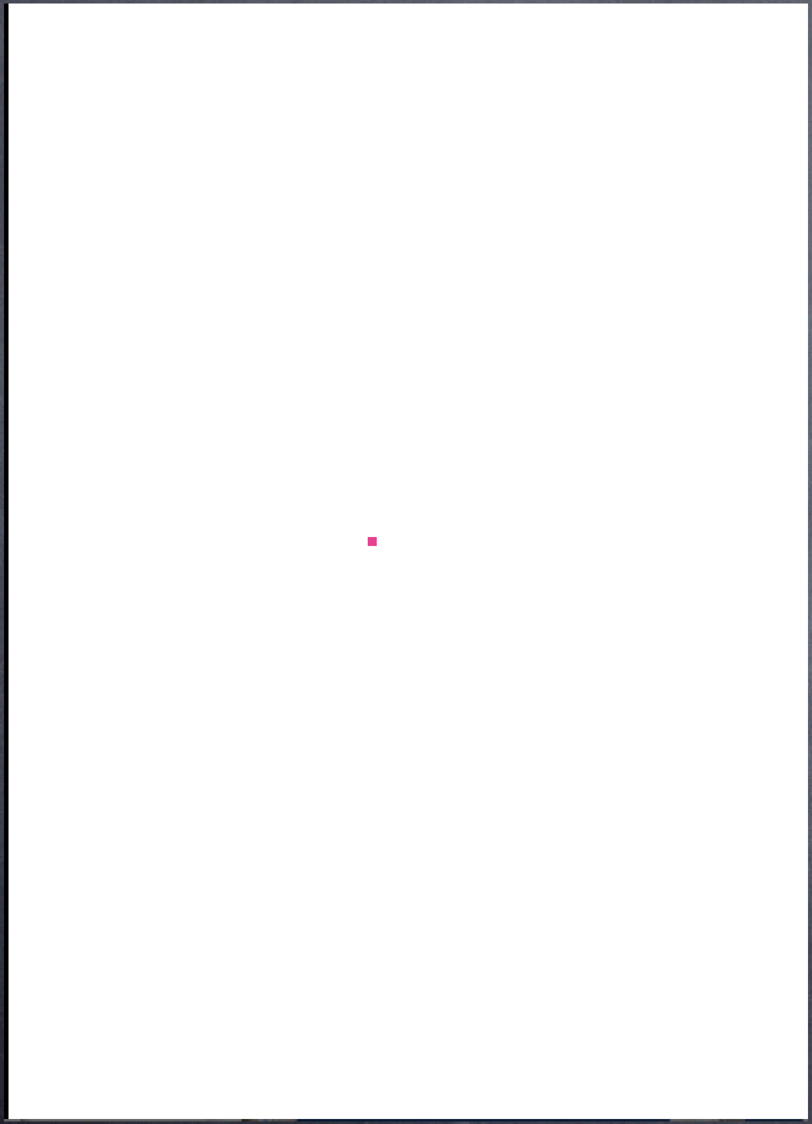
- Problem
  - Input
    - a cost surface of a terrain
    - a set of sources
  - Output
    - a least-cost path surface: each point represents the shortest distance to a source
- Cost surfaces
  - Can be correlated elevation, slope, or simply constant (uniform cost)
- Applications
  - Spread of fires from different sources
  - Distance from streams or roads
  - Cost of building pipelines or roads

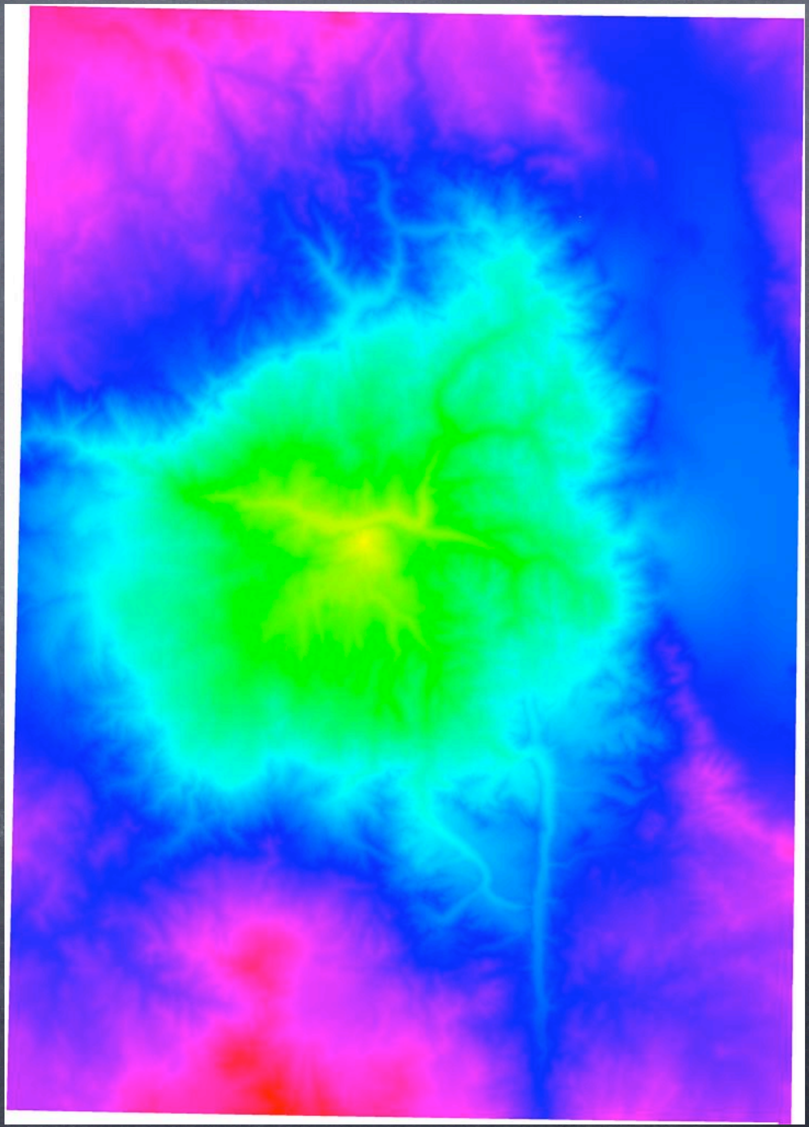
## Example


Sierra Nevada, 30m resolution

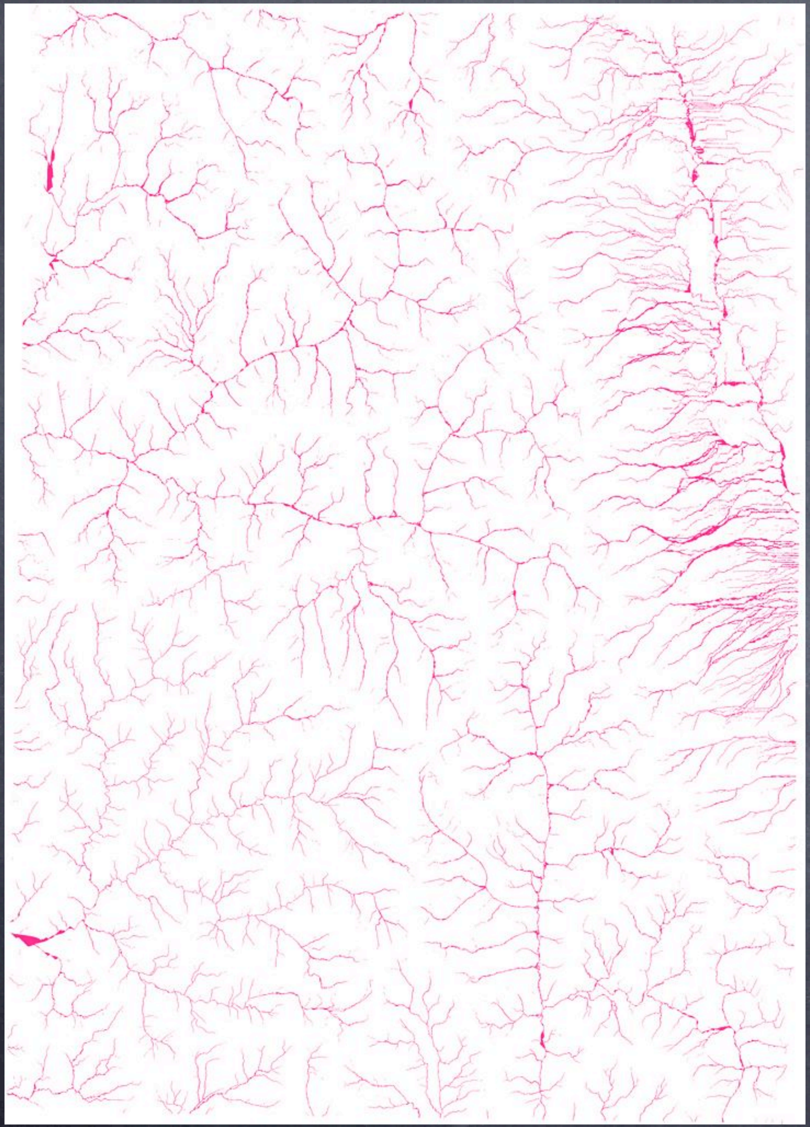

Sierra Nevada, cost surface = slope

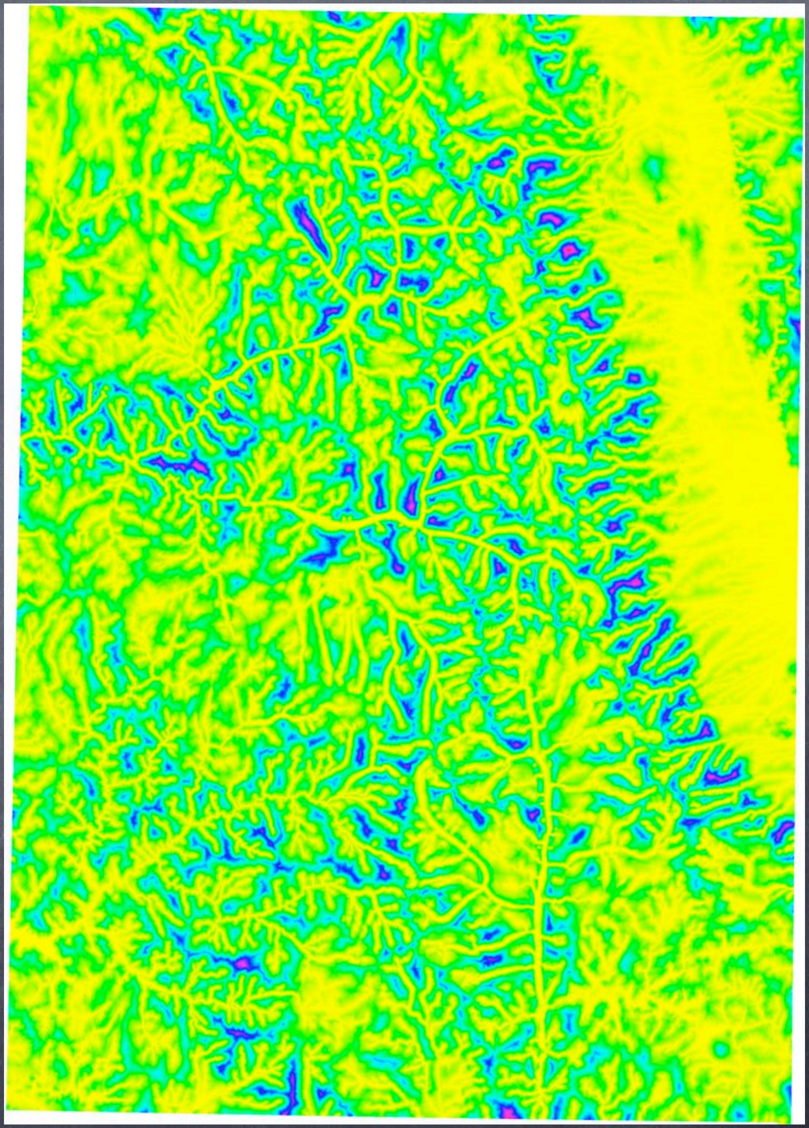
## Example (One Source)


source


Least-cost path surface

# Example (Many Sources)


Multiple sources


Least-cost path surface

## Least-Cost Surfaces in GRASS

r.cost

Description: Outputs a raster map layer showing the cumulative cost of moving between different geographic locations on an input raster map layer whose cell category values represent cost.

Usage:

```
r.cost [-vkn] input=name output=name [start_sites=name] [stop_sites=name] [start_rast=name]
[coordinate=x,y[,x,y,...]][stop_coordinate=x,y[,x,y,...]] [max_cost=cost] [null_cost=null cost]
```

Flags

| | |
|---|---|
| -v | Run verbosely |
| -k | Use the 'Knight's move'; slower, but more accurate |
| -n | Keep null values in output map |

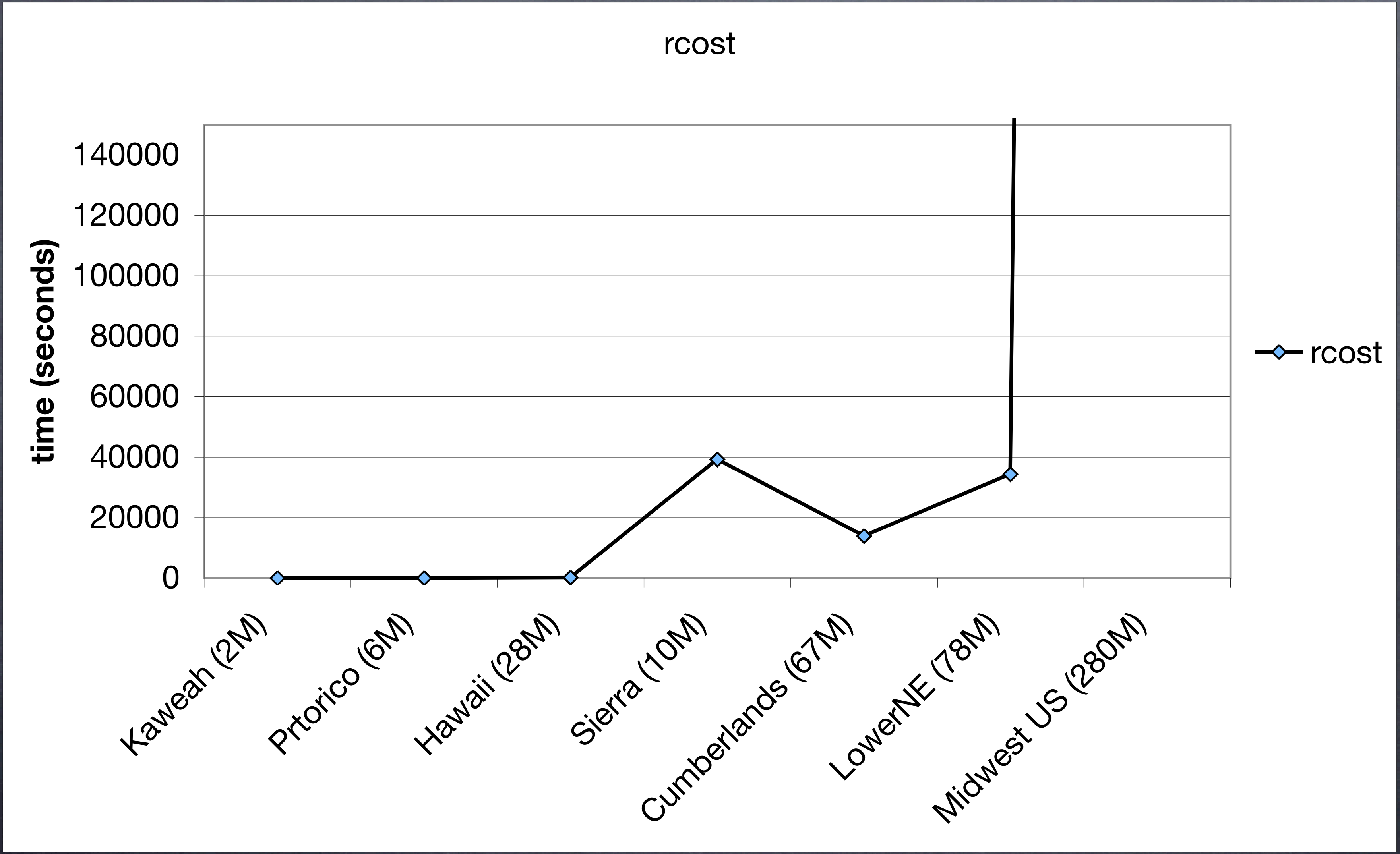
Parameters:

| | |
|---|---|
| input | Name of raster map containing grid cell cost information |
| output | Name of raster map to contain results |
| start_sites | Starting points site file |
| stop_sites | Stop points site file |
| start_rast | Starting points raster file coordinate |
| coordinate | The map E and N grid coordinates of a starting point (E,N |
| stop_coordinate | The map E and N grid coordinates of a stopping point (E,N) |
| max_cost | An optional maximum cumulative cost. default: |
| null_cost | Cost assigned to null cells. By default, null cells are excluded |

# Massive Terrains

- Why massive terrains?
  - Large amounts of data are becoming available
    - NASA SRTM project: 30m resolution over the entire globe (~10TB)
    - LIDAR data: sub-meter resolution
- Traditional algorithms designed that assume that data fits in memory and has uniform access cost don't scale
  - Buy more RAM?
    - Data grows faster than memory
  - Data does not fit in memory, sits on disk
  - Disks are MUCH slower than memory
- => I/O-bottleneck

# Performance of r.cost



GRASS users have complained it is very slow for large grids

## What To Do?

- Terminology
  - Input/output (I/O): the movement of data between main memory and disk
- Basic principle:
  - I/O is done in blocks
  - Block typical size: 8KB, 16KB, 32KB
- Design algorithms that specifically minimize I/O
  - I/O-efficient algorithms
- Idea:
  - Do not rely on virtual memory!
  - Instead, change the data access pattern of the algorithm to increase spatial locality and minimize the number of blocks transfered between main memory and disk

## This project: r.terracost

- Scalable approach to computing least-cost path surfaces on massive raster terrains
  - Based on optimal I/O-efficient algorithm
  - Versatile: Interpolate between versions optimized for I/O or CPU
- Experimental analysis on real-life data and comparison with GRASS r.cost
  - Can handle bigger grids
  - Can handle more sources
- Parallelization on a cluster

# Outline

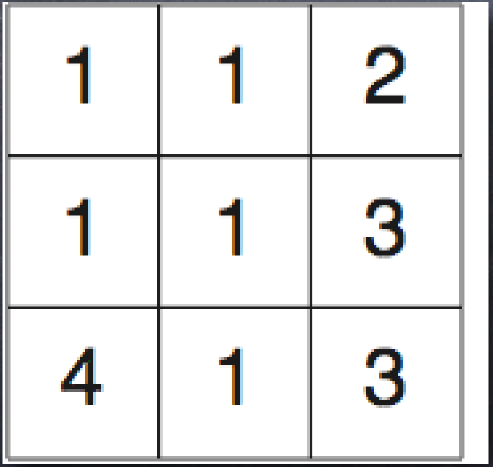
- Background
  - Least-cost path surfaces and shortest paths in graphs
  - Dijkstra's algorithm for SP
  - Dijkstra's algorithm on large grids
- r.terracost
  - Algorithm
  - Experimental results
  - Cluster implementation
- Conclusions and current/future work

# Least-Cost Path Surfaces

and

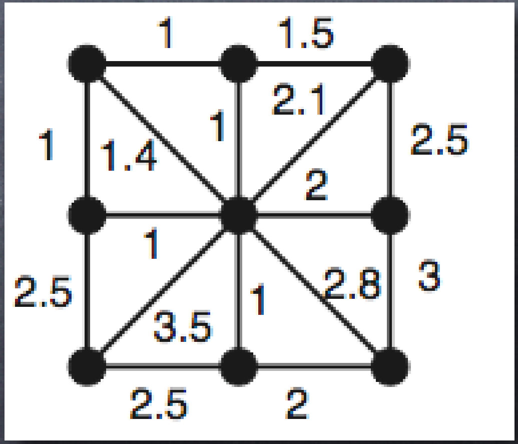
# Shortest Paths in Graphs

- Raster terrains —> graphs
- Least-cost path surfaces correspond to computing shortest paths on (raster) graphs

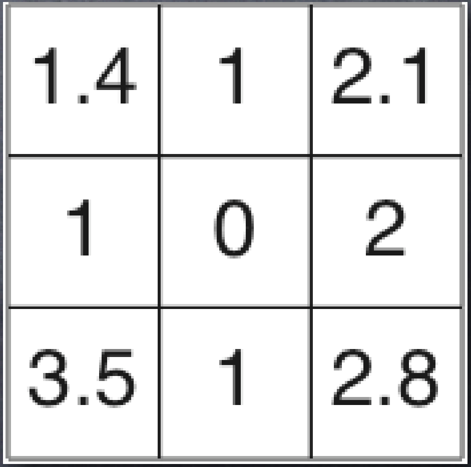


| | | |
|---|---|---|
| 1 | 1 | 2 |
| 1 | 1 | 3 |
| 4 | 1 | 3 |

Cost raster



Corresponding graph

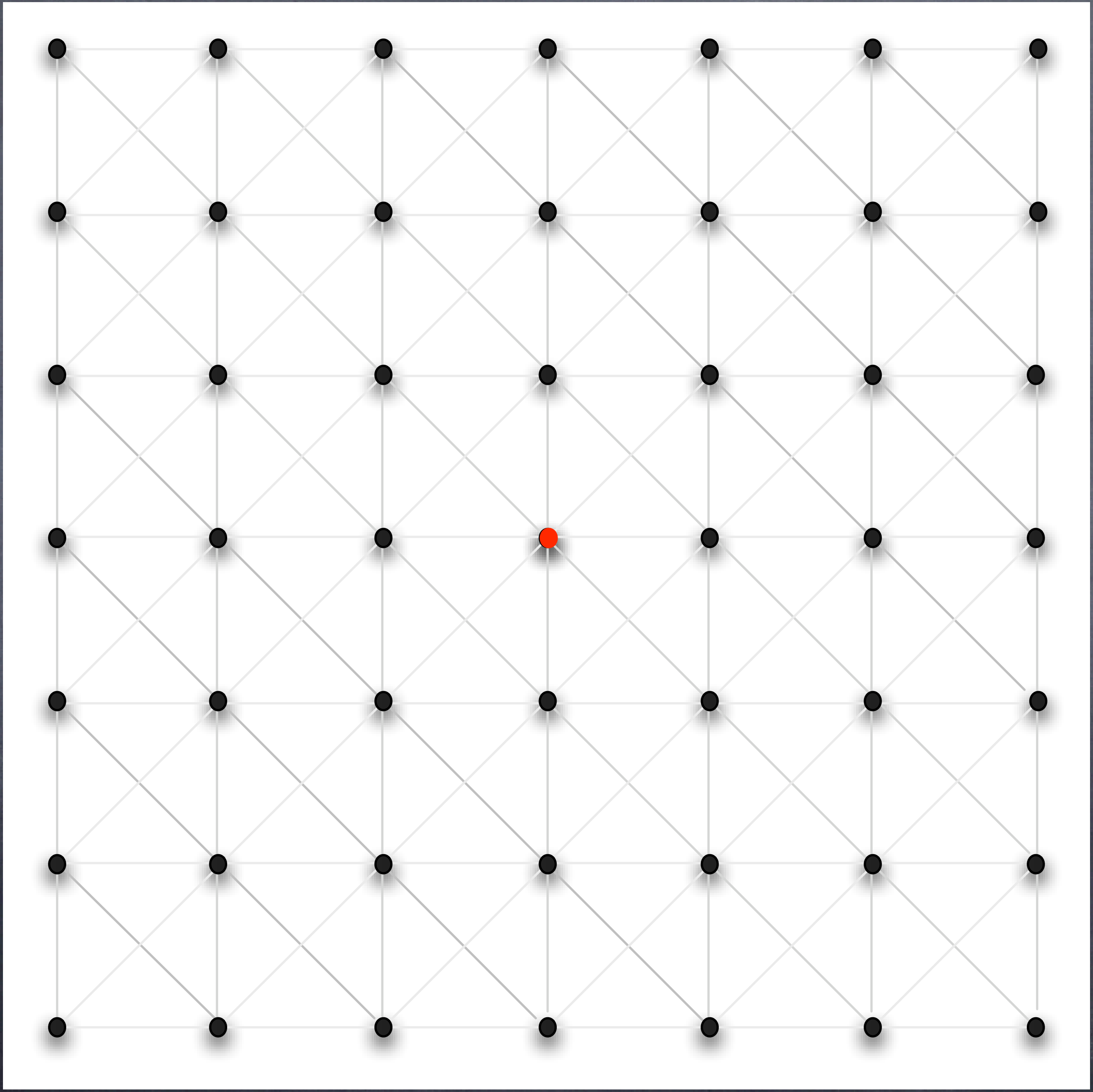


| | | |
|---|---|---|
| 1.4 | 1 | 2.1 |
| 1 | 0 | 2 |
| 3.5 | 1 | 2.8 |

Shortest-distance from center point

## Dijkstra’S SP Algorithm

# Dijkstra's SP Algorithm



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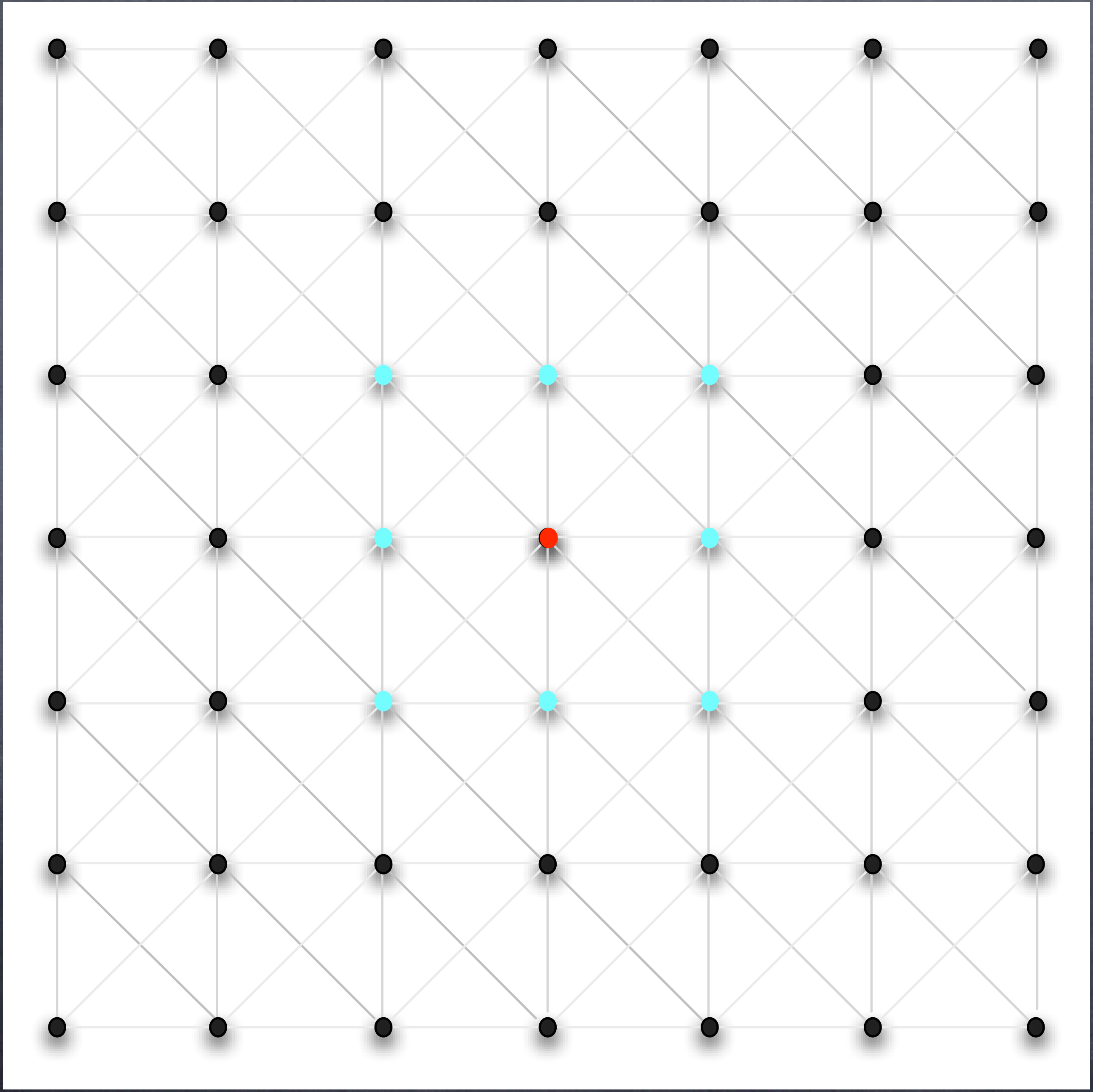

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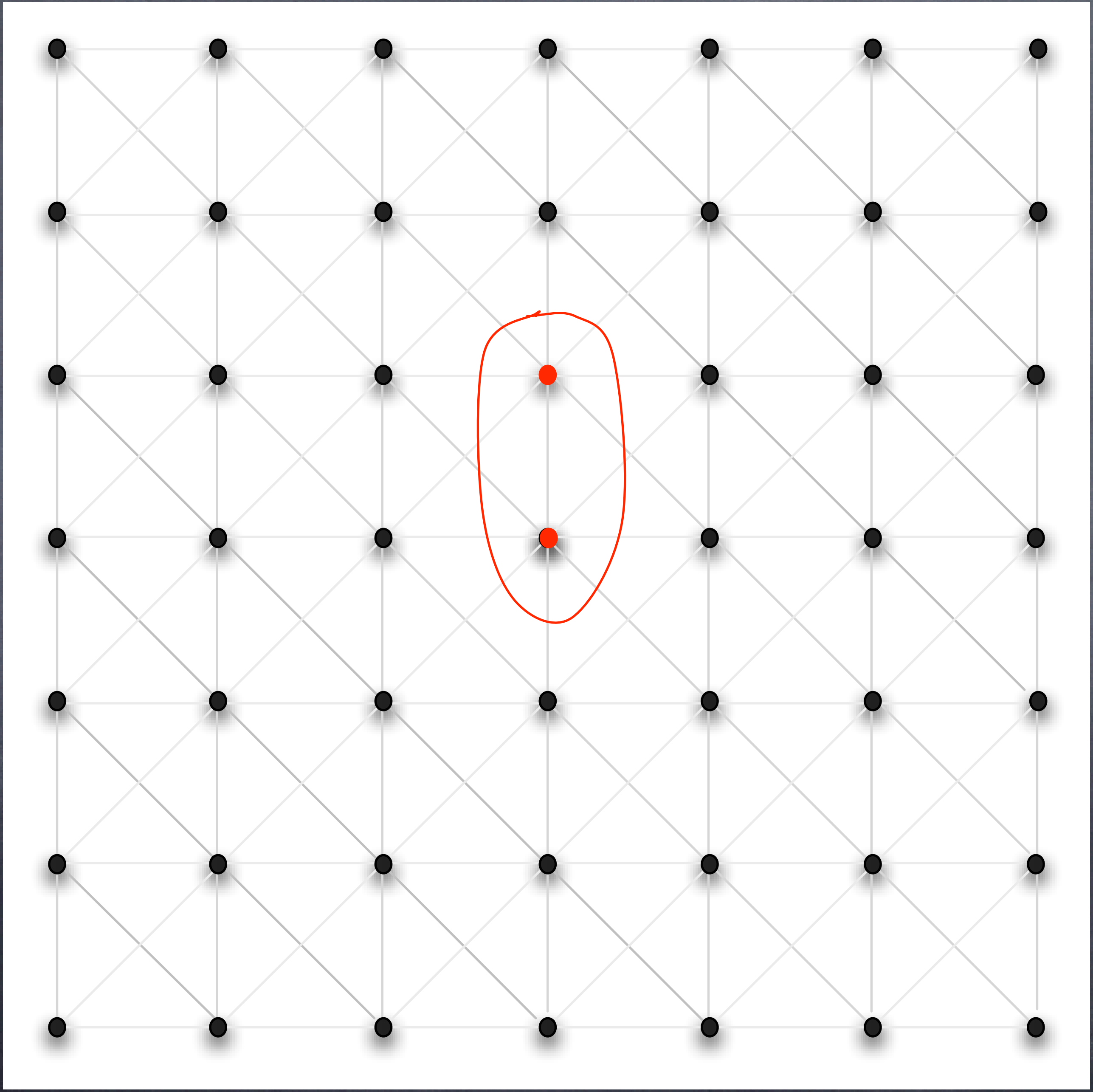

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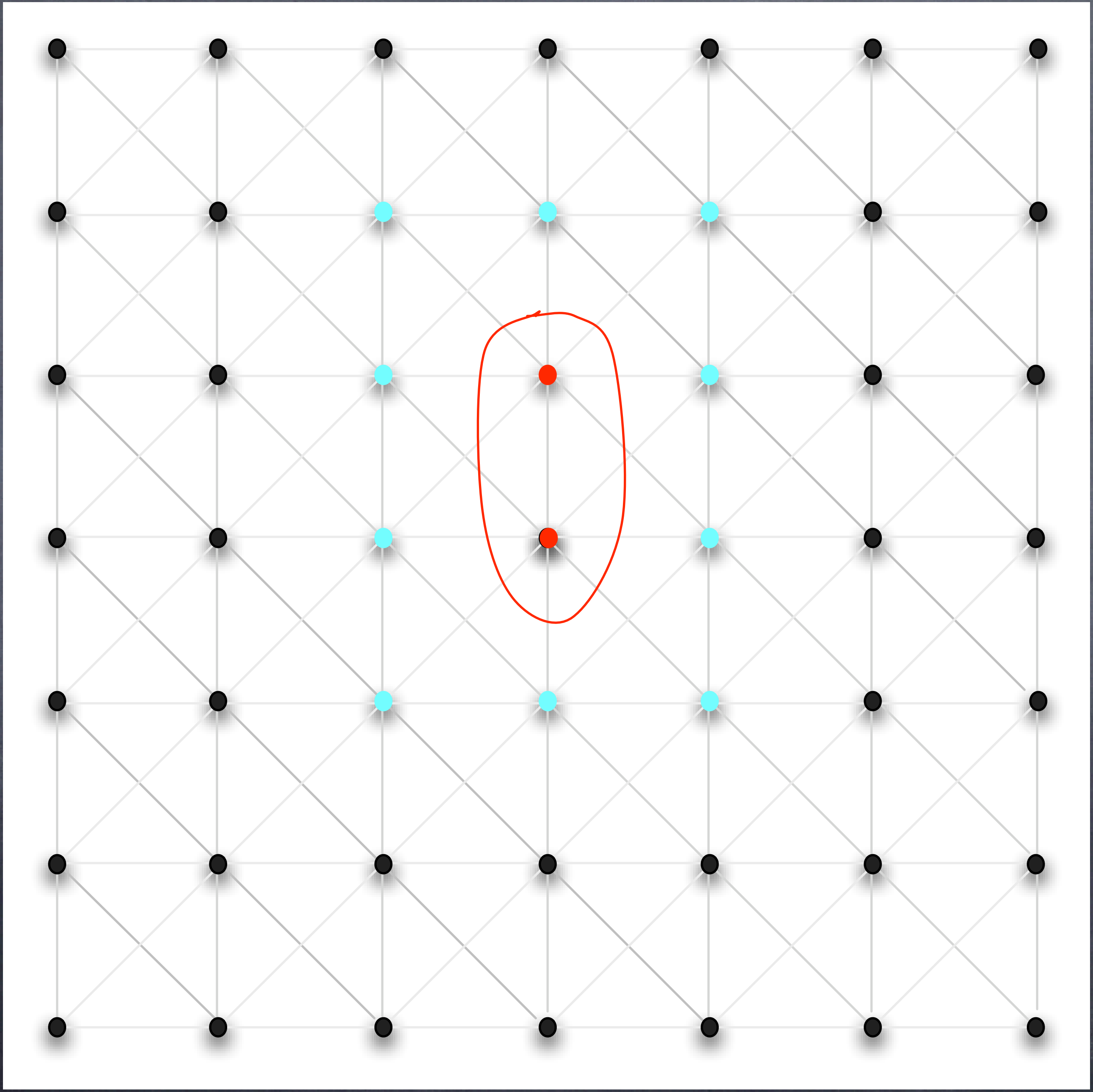

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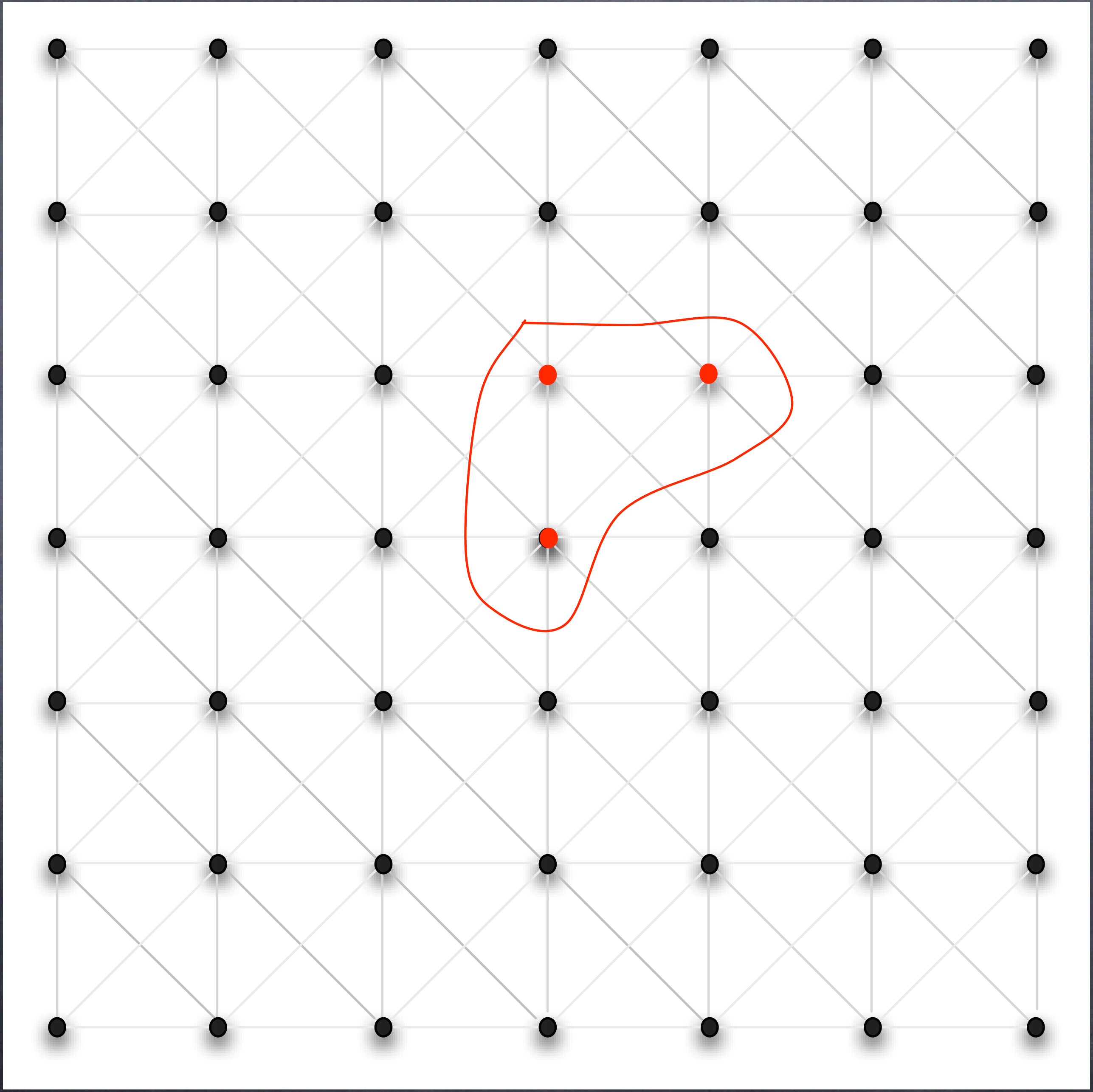

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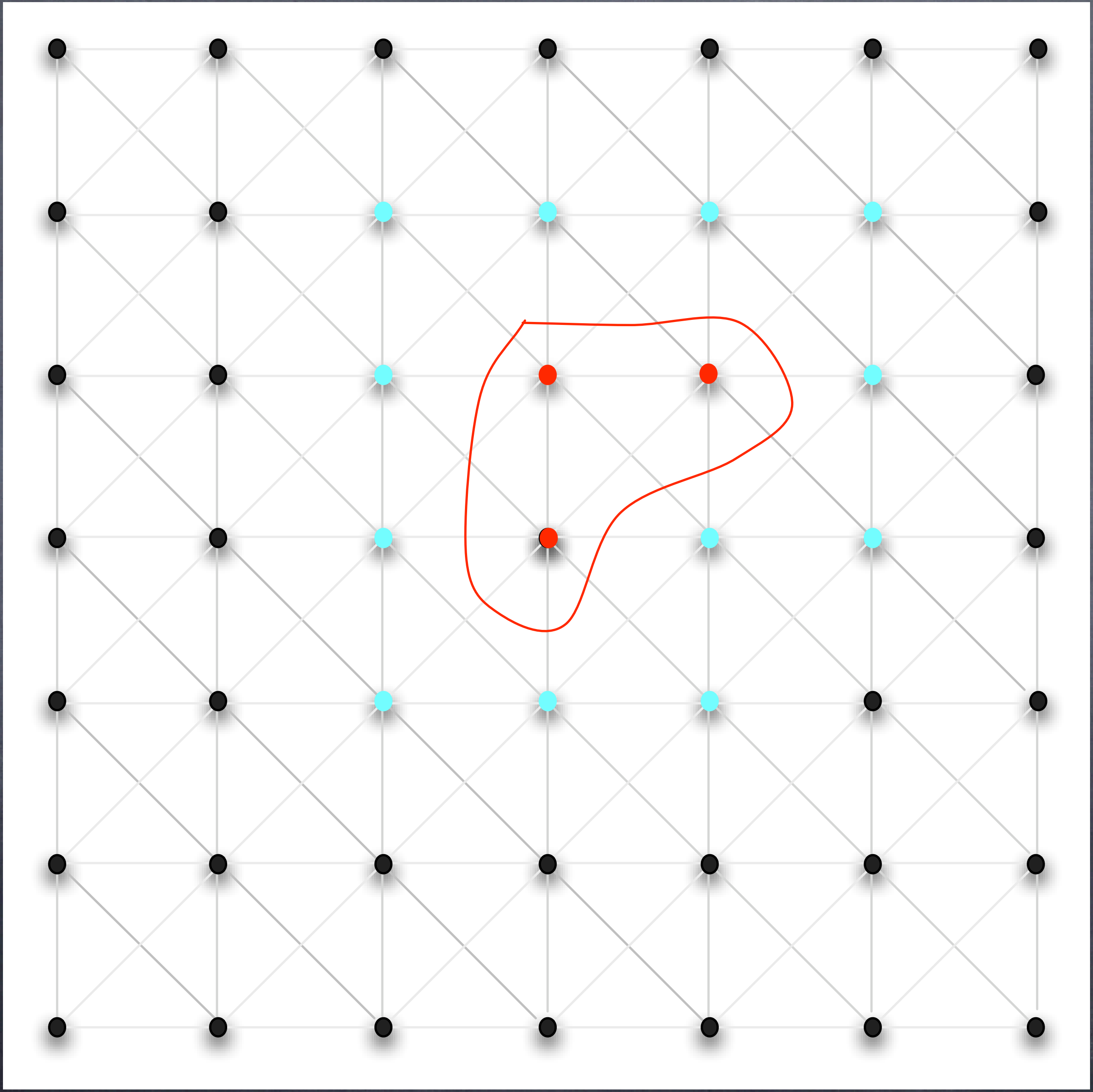

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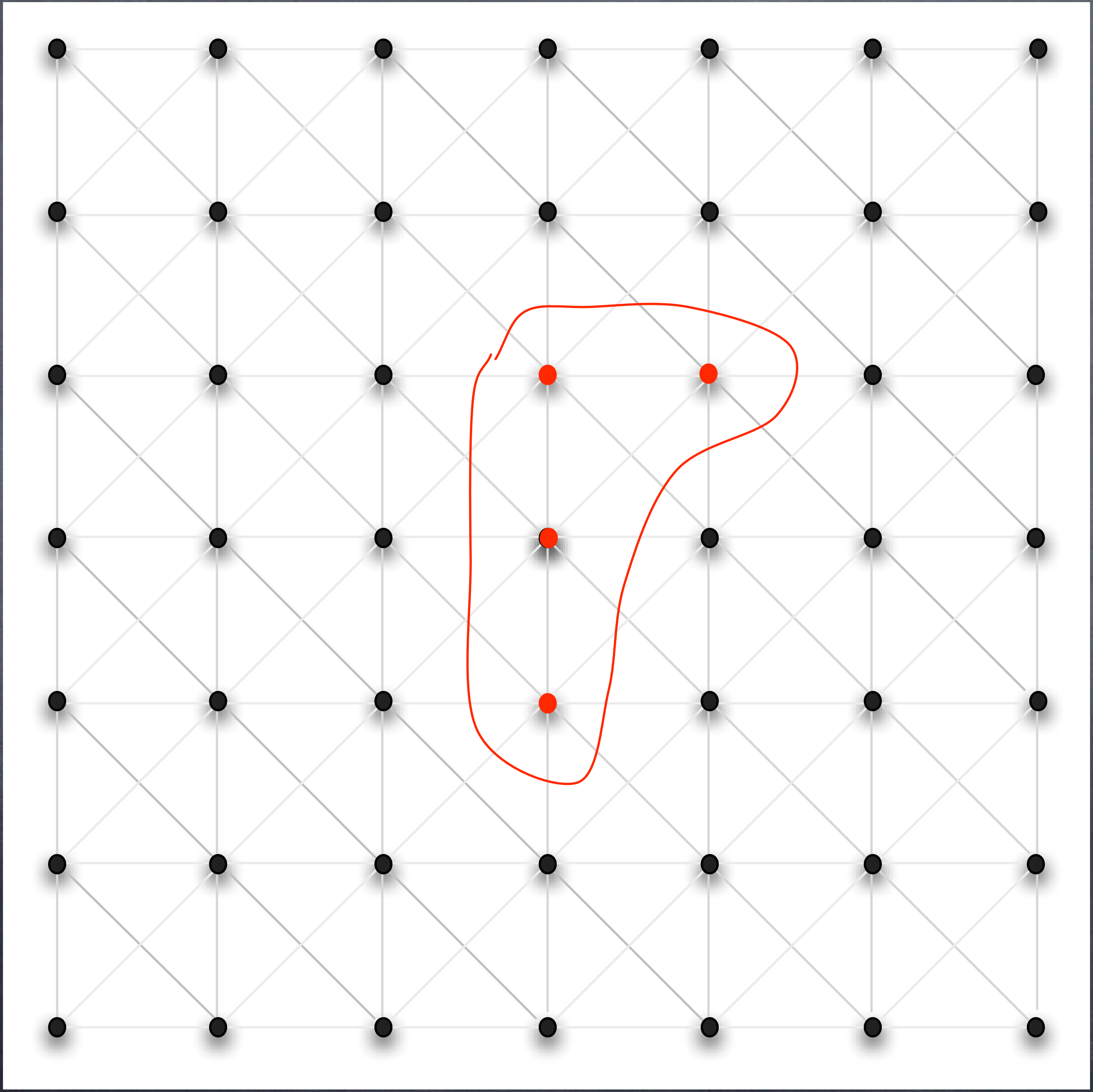

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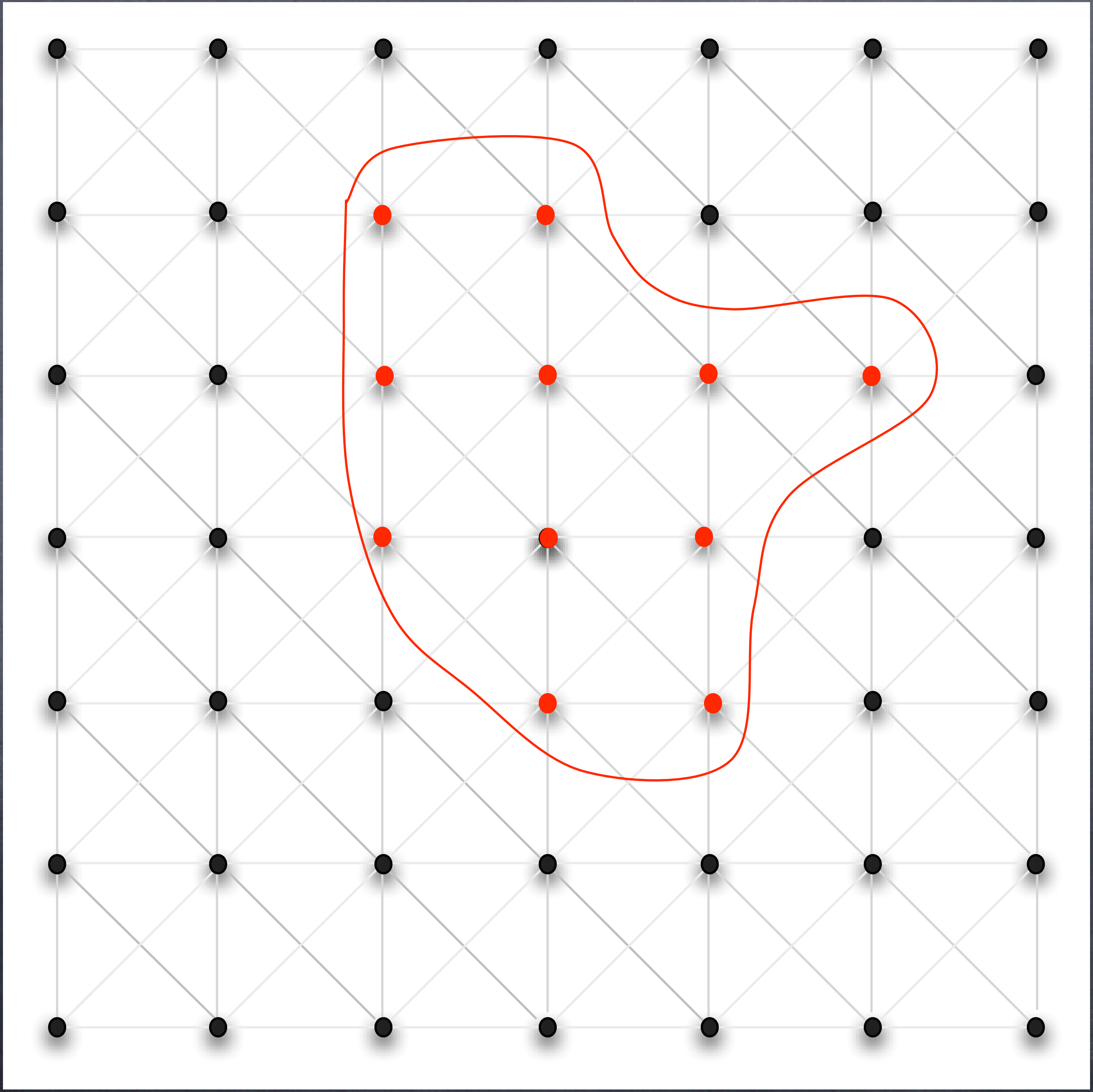
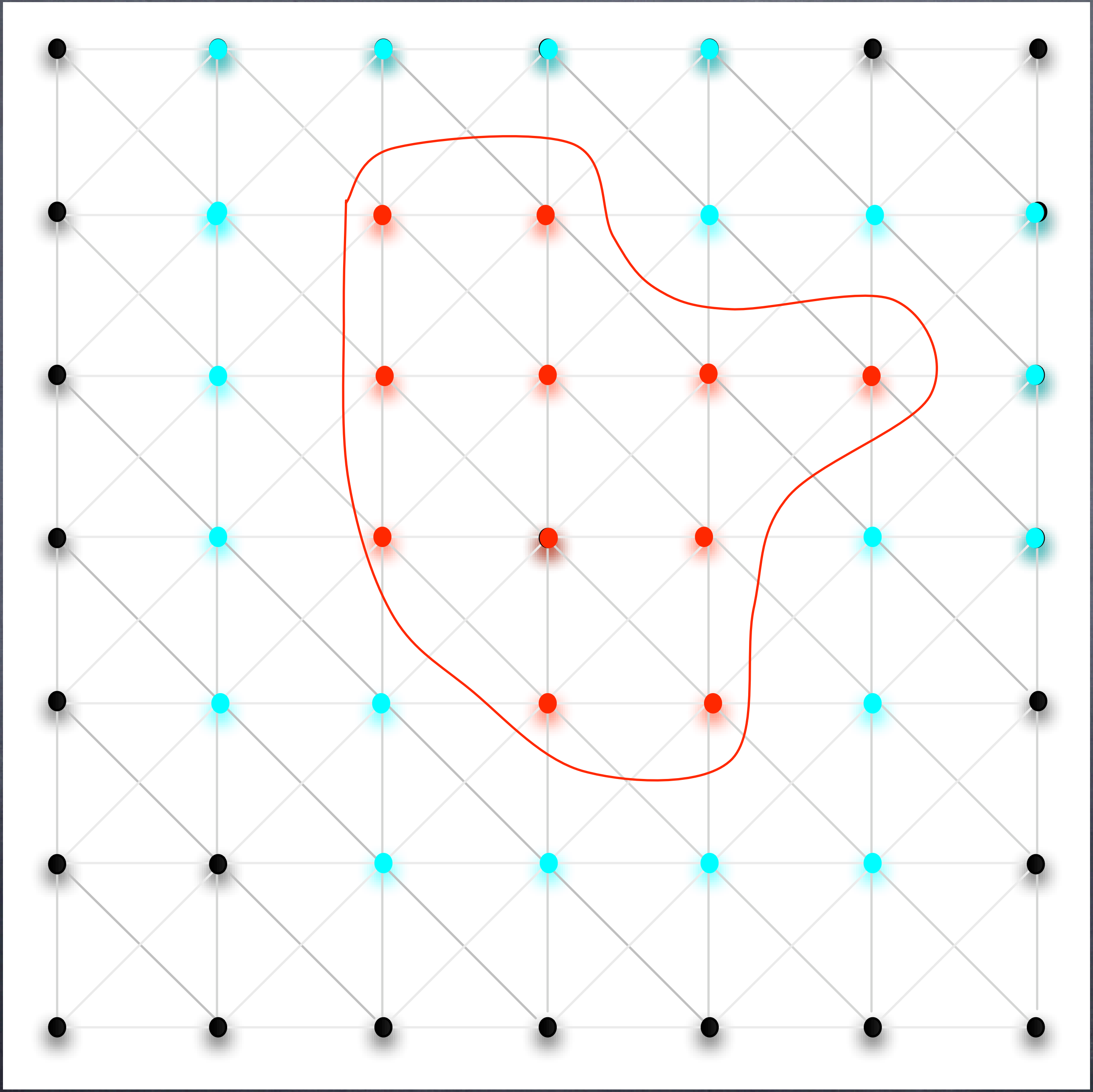
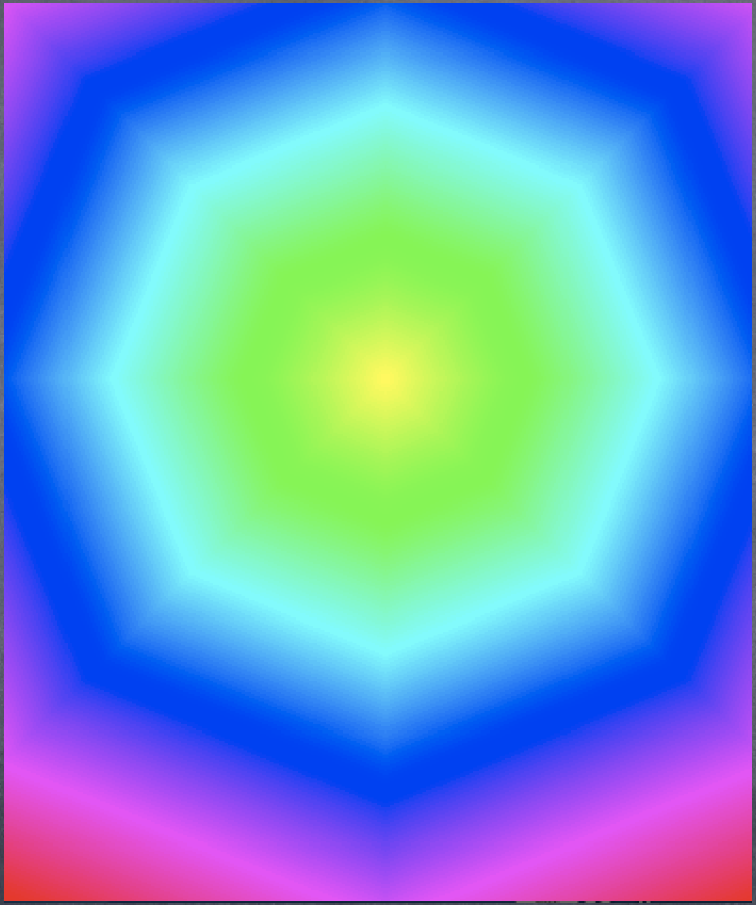


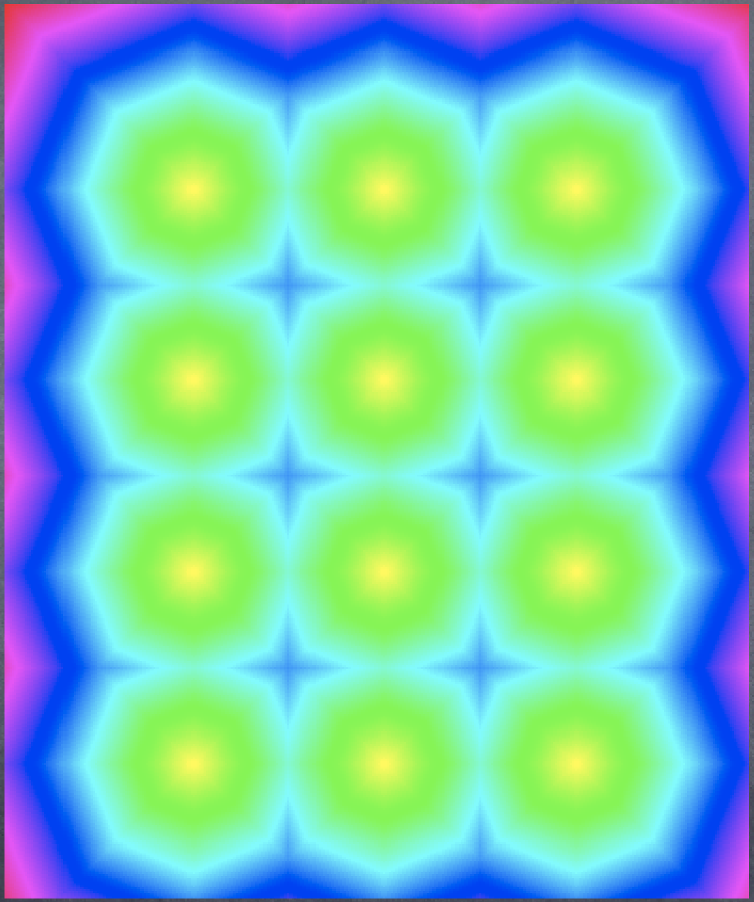
# Dijkstra's SP Algorithm



# SP (one source)



## SP (many sources)



## Dijkstra's SP Algorithm

- Priority queue PQ:
  - stores black vertices not yet settled (=reached by front)
  - each vertex u in PQ has priority d(u)

```
Insert sources in PQ
While PQ is not empty
        u = PQ.DeleteMin() gives vertex with least cost from PQ
        Relax all edges incident  to u and update PQ
```

## Related Work on Shortest Paths

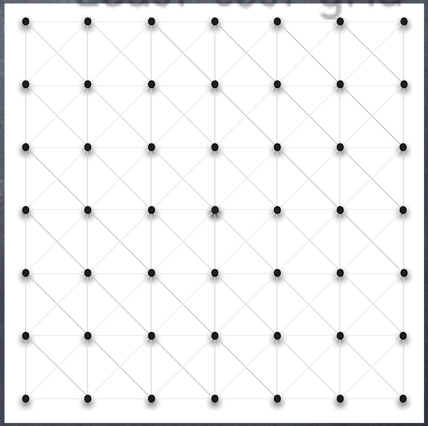
- Dijkstra's Algorithm
  - Best known for SSSP/MSSP on general graphs, non-negative weights
- Recent variations on the SP algorithm
  - Goldberg et al SODA 2000, WAE 2005
  - Kohler, Mohring, Schilling WEA 2005
  - Gutman WEA 2004
  - Lauther 2004
- Different setting
  - Point-to-point SP
    - E.g. Route planning, navigation systems
  - Exploit geometric characteristics of graph to narrow down search

# Dijkstra's Algorithm on Large Grids

Cost grid

- Dijkstra's algorithm requires 3 data structures:
  - 1: Cost grid
  - 2: Least-cost grid
  - 3: Priority queue
- If grids do not fit in main memory ==> stored on disk
- For each vertex that we settle, we must do a lookup in both grids.
  - These lookups can cost one I/O each in the worst case
- ==> One I/O per element in the grid

Least-cost grid



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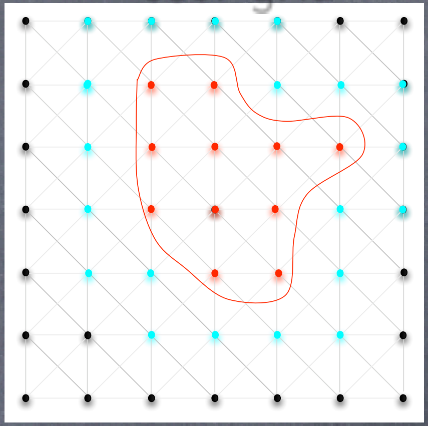
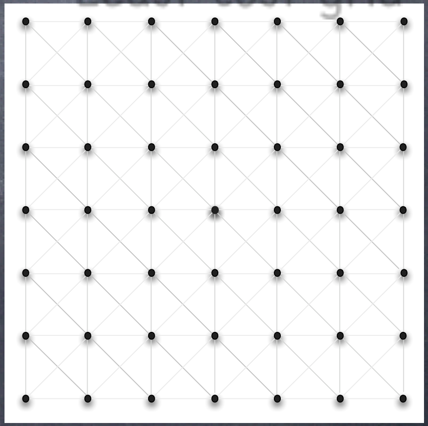
Cost grid



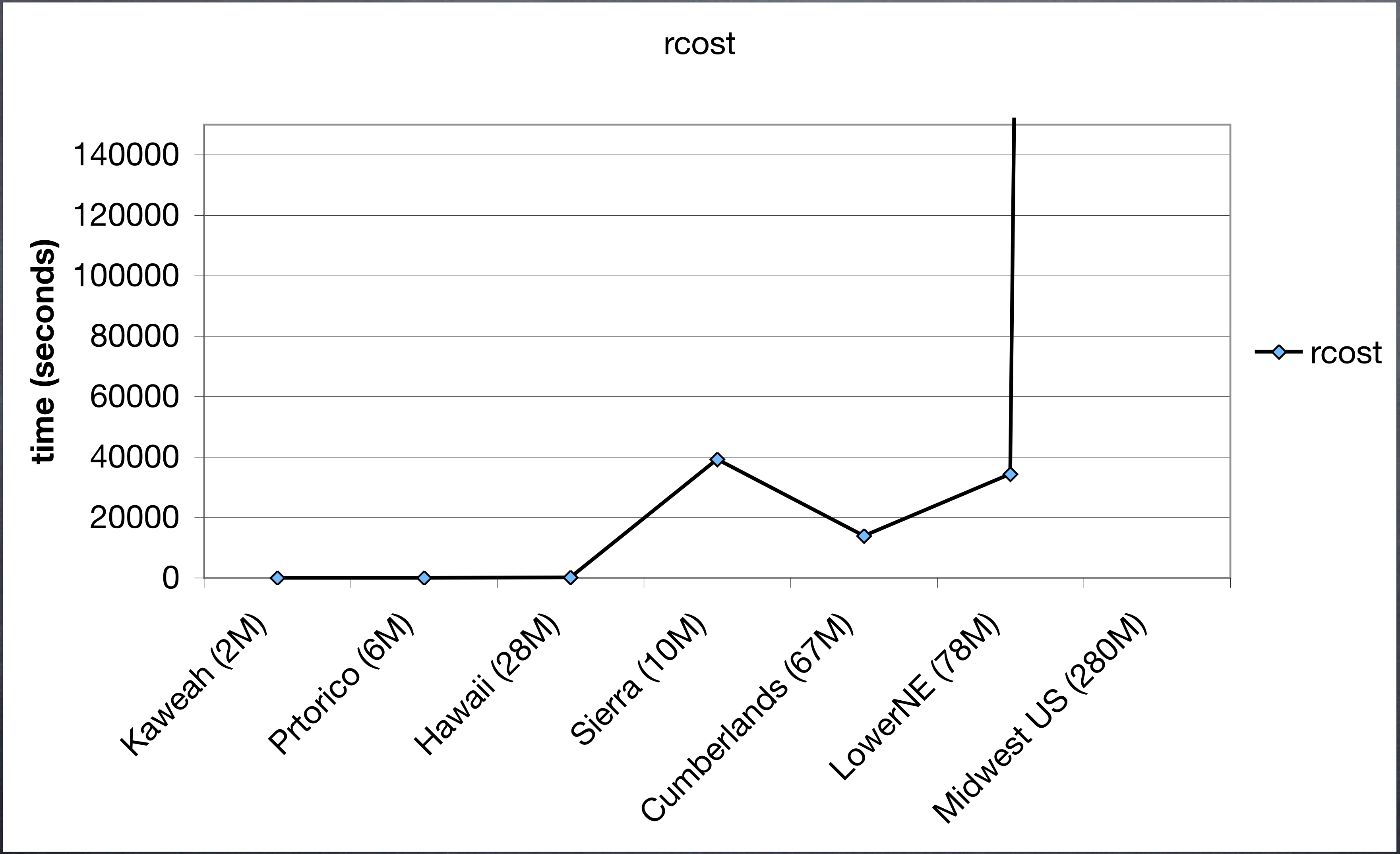
Least-cost grid



# GRASS Segment Library

- If data does not fit in memory
  - default: use the virtual memory system (VMS)
    - program may abort because of malloc() fail
  - use GRASS segment library
    - bypass the VMS
    - manage data allocation and de-allocation in segments on disk
    - program will always run
    - but.... may be slow
- GRASS segment library cannot change the data access pattern of the algorithm, and thus cannot optimize block transfer

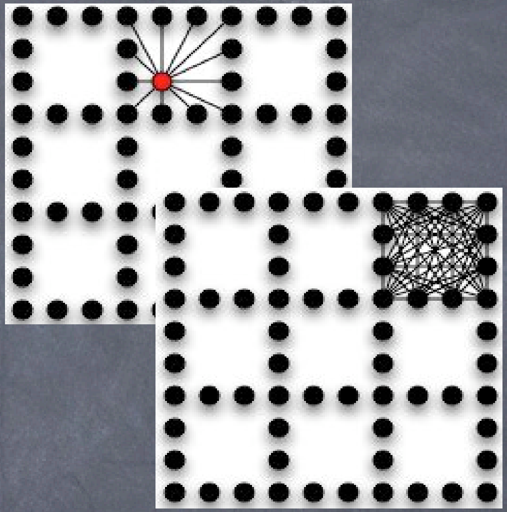
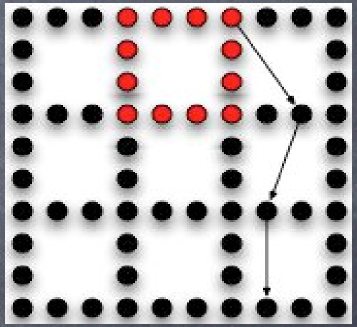
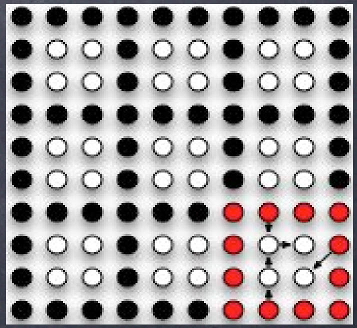
# Performance of r.cost



uses segment library

## r.terracost

- Step 1 (intra-tile Dijkstra)
  - Divide grid G into tiles. of size R
  - Compute boundary-to-boundary graph: Replace each tile with a complete graph on its boundary
- Step 2 (Inter-tile Dijkstra)
  - Dijkstra on boundary-to-boundary graph
  - Gives SP for all boundary vertices in G
- Step 3 (Final-Dijkstra)
  - Dijkstra inside each tile
  - Gives SP to vertices inside tiles

## r.terracost

- Optimized for internal or external memory by setting numtiles
    - numtiles=1
        - r.terracost runs Dijkstra in memory
    - numtiles = xxx
        - Use xxx tiles
    - if numtiles is not specified
        - Default value is set to size of grid/10000, which is experimentally optimal
- Has same functionality as r.cost in GRASS

# r.terracost

```
GRASS:~ > r.terracost -h
    Synopsis:
     r.terracost computes a least-cost surface for a given cost grid and a set of start points. See
    "Terracost: a versatile and scalable approach for computing shortest paths on massive terrains" by
    Hazel, Toma, Vahrenhold and Wickremesinghe (2005)

    Usage:
     r.terracost [-hqdi0123] [cost=name] [start_raster=name] [distance=name] [memory=value]
    [STREAM_DIR=name] [VTMPDIR=name] [numtiles=value]
    Flags:
      -h   Help
      -q   Quiet (suppress messages)
      -d   Debug (for developer use)
      -i   Info (prints useful information and exits)

    Parameters:
            cost   Input cost grid
            start_raster   Input raster of source points
            distance   Output distance grid
            memory   Main memory size (in MB) default: 400)
            STREAM_DIR   Location of temporary STREAM default: /var/tmp
            VTMPDIR   Location of intermediate STREAM  default: /var/tmp/ltoma
            numtiles   Number of tiles (-h for info) default: -1
```

## Example

```
GRASS:~ > r.terracost  cost=elev start_rast=accu1000  dist=lcs numtiles=1

        STREAM temporary files in /var/tmp (THESE INTERMEDIATE STREAMS WILL NOT BE DELETED IN
        CASE OF ABNORMAL TERMINATION OF THE PROGRAM. TO SAVE SPACE PLEASE DELETE THESE
        FILES MANUALLY!)
        intermediate files in /var/tmp/ltoma
        region size is 472 x 391
        file set1-stats.out exists - renaming.
        memory size: 400.00M (419430400) bytes
        Memory manager registering memory in MM_WARN_ON_MEMORY_EXCEEDED mode.
        Using normal Dijkstra
        Using normal Dijkstra
          99%
        Opened raster file lcs for writing!

        cleaning up...
        r.terracost done
GRASS:~ >
```

## Example

```
GRASS:~/nfs-gis > r.terracost  cost=elev start_rast=accu1000  dist=lcs numtiles=10
    STREAM temporary files in /var/tmp (THESE INTERMEDIATE STREAMS WILL NOT BE DELETED IN
    CASE OF ABNORMAL TERMINATION OF THE PROGRAM. TO SAVE SPACE PLEASE DELETE THESE
    FILES MANUALLY!)
    intermediate files in /var/tmp/ltoma
    region size is 472 x 391
    memory size: 400.00M (419430400) bytes
    STEP 0: Memory Available: 400.00M (419429559)
    ----------------------------------------
    STEP 0:  COMPUTE SUBSTITUTE GRAPH
    Grid size is: 184552 Tile size is: 18360  TF #Tiles: 12
    ----------------------------------------
    STEP 1
    TileFactory: Sorting internalstr...
    ----------------------------------------
    STEP 2
    Sorting b2b stream
    ----------------------------------------
    STEP 3
    ----------------------------------------
    INTER TILE DIJKSTRA
    ----------------------------------------
    IN-TILE FINAL DIJKSTRA
    r.terracost done
```

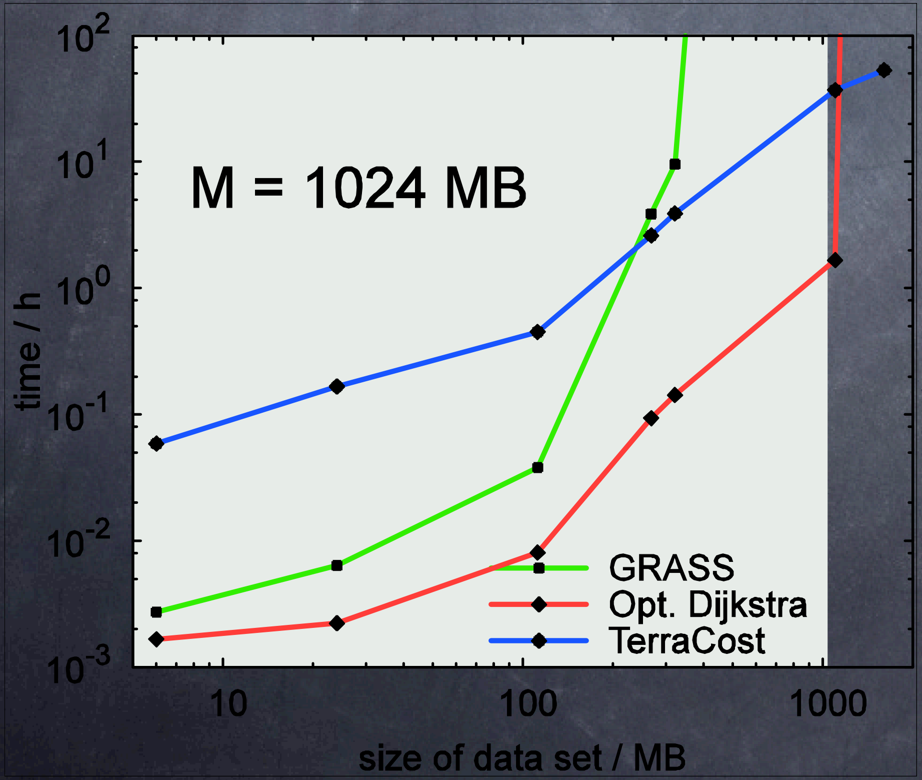
## Experimental Results

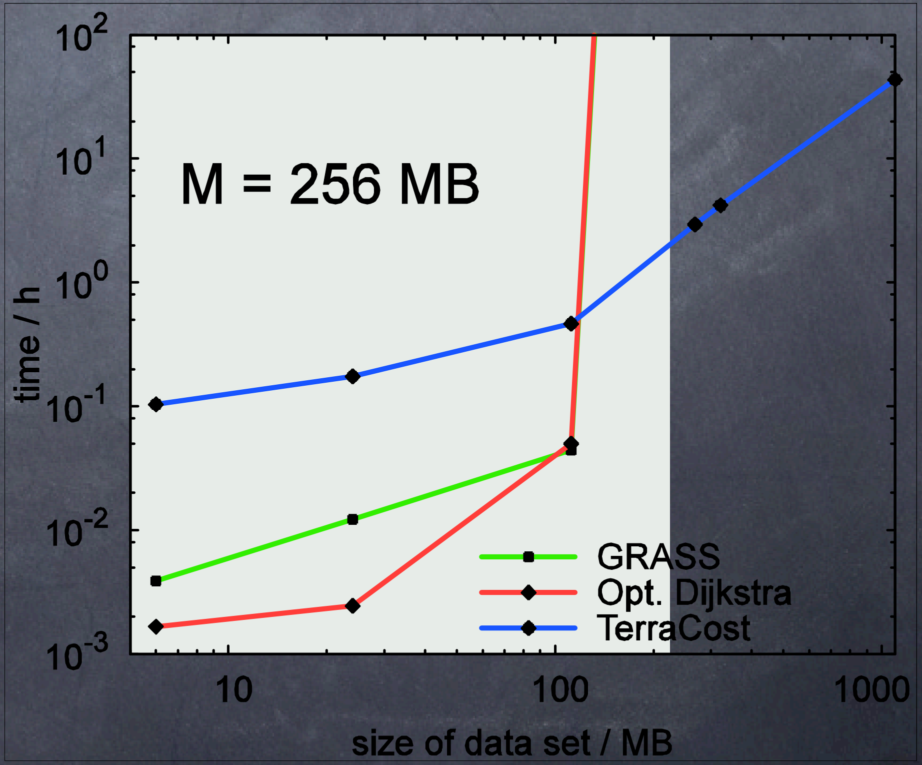
- Experimental Platform
  - Apple Power Macintosh G5
  - Dual 2.5 GHz processors
  - 512 KB L2 cache
  - 1 GB RAM

| Dataset | Grid Size (million elements) | MB (Grid Only) |
|---|---|---|
| Kaweah | 1.6 | 6 |
| Puerto Rico | 5.9 | 24 |
| Hawaii | 28.2 | 112 |
| Sierra Nevada | 9.5 | 38 |
| Cumberlands | 67 | 268 |
| Lower New England | 77.8 | 312 |
| Midwest USA | 280 | 1100 |

# Experimental Results

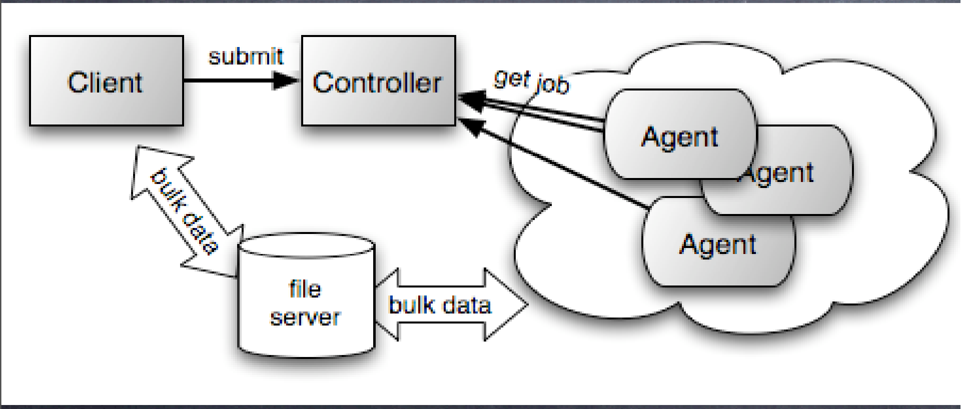
- r.cost
- Opt Dijkstra (r.terracost numtiles=1: internal memory version of Terracost)
- TerraCost (r.terracost numtiles=optimal: I/O-efficient version of Terracost)

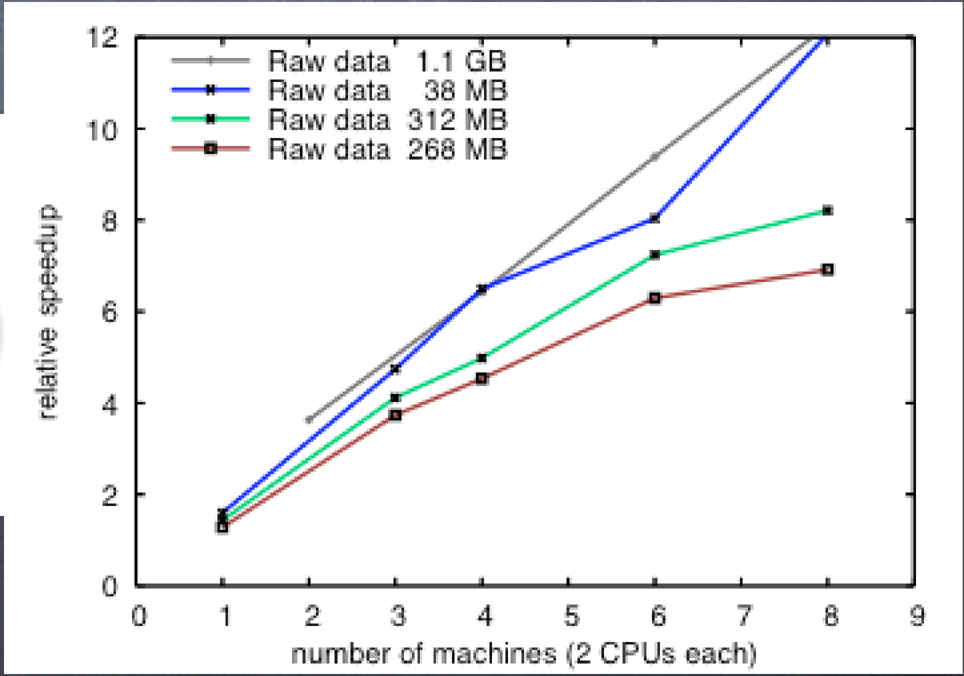




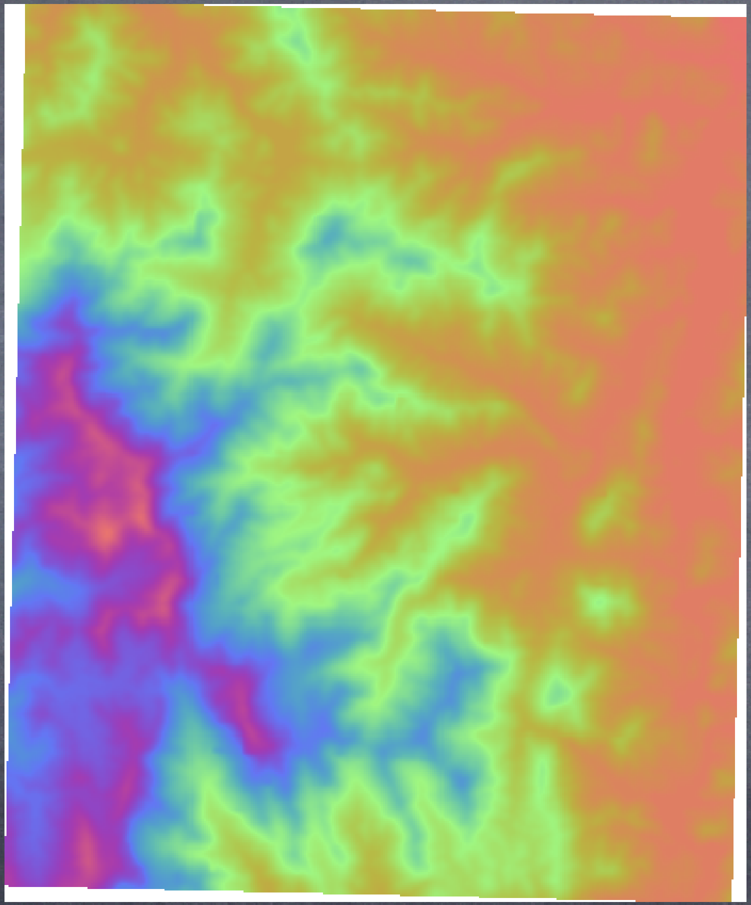
# r.terracost on Clusters

- We parallelized the most CPU-intensive part (Step 1)
- Hgrid: Cluster management tool
  - Clients submit requests (run jobs, query status); agents get jobs and run them
  - Near-linear speedup

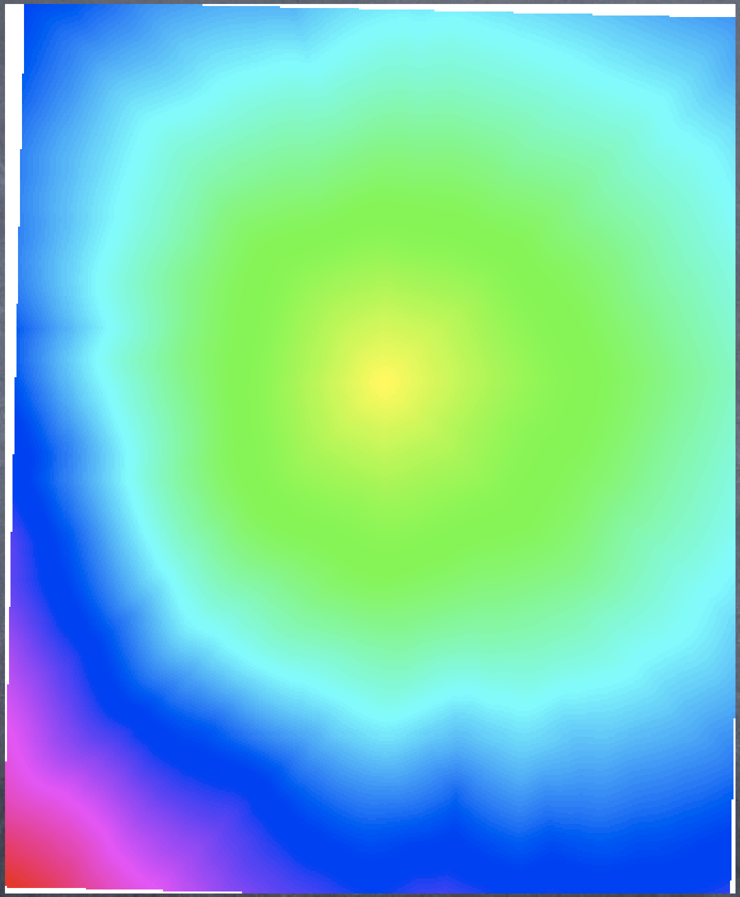




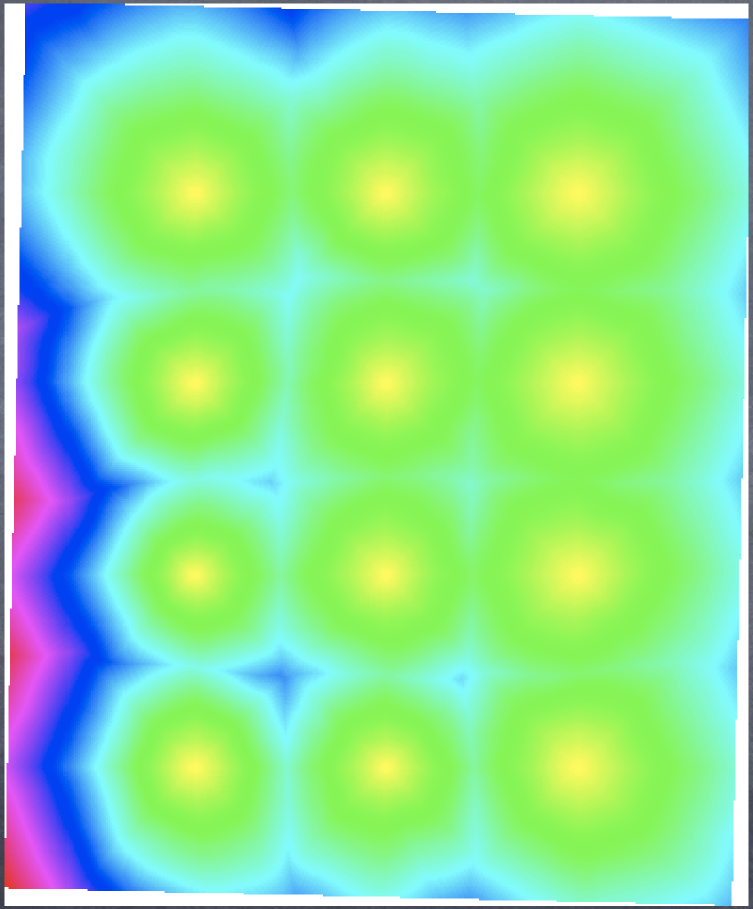
## Results



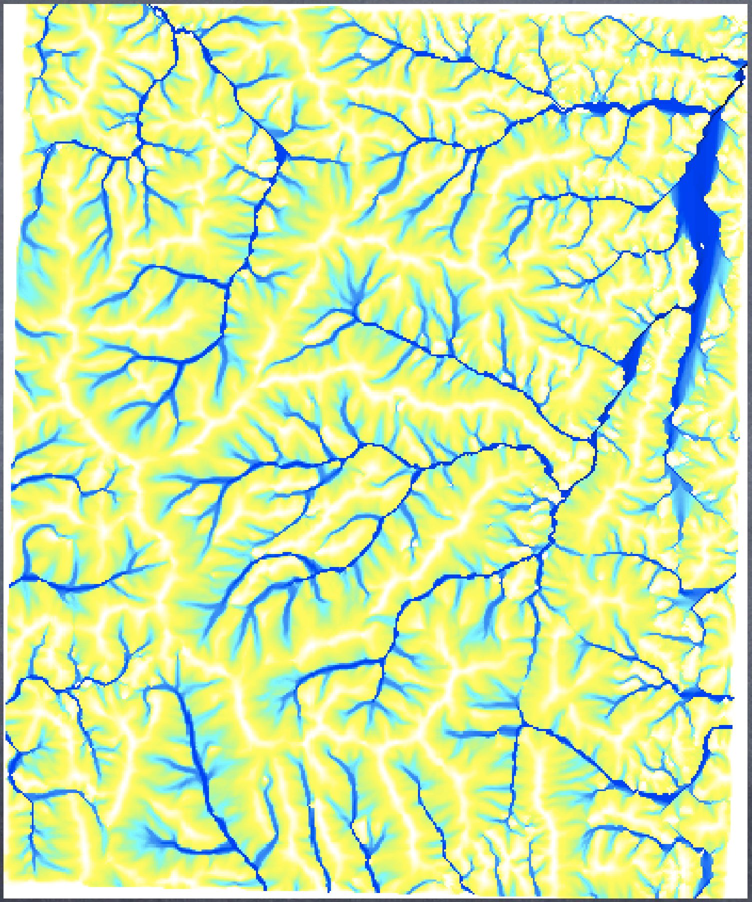
elevation



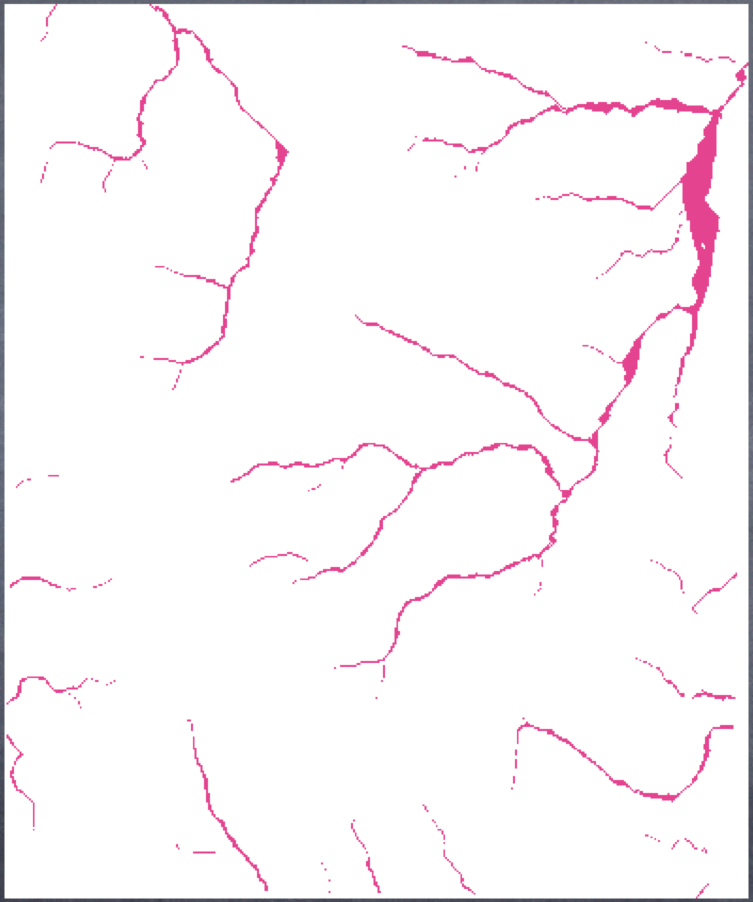
cost=elevation, 1 source



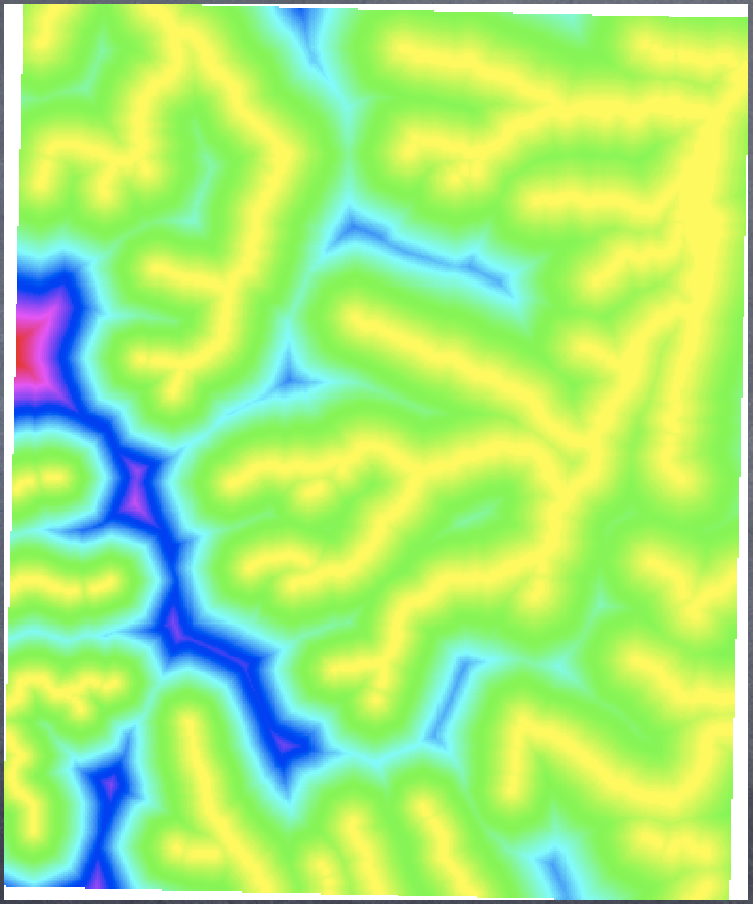
cost=elevation, many src



flow accumulation



```
if(flowaccumulation>1000, 1, null())
```



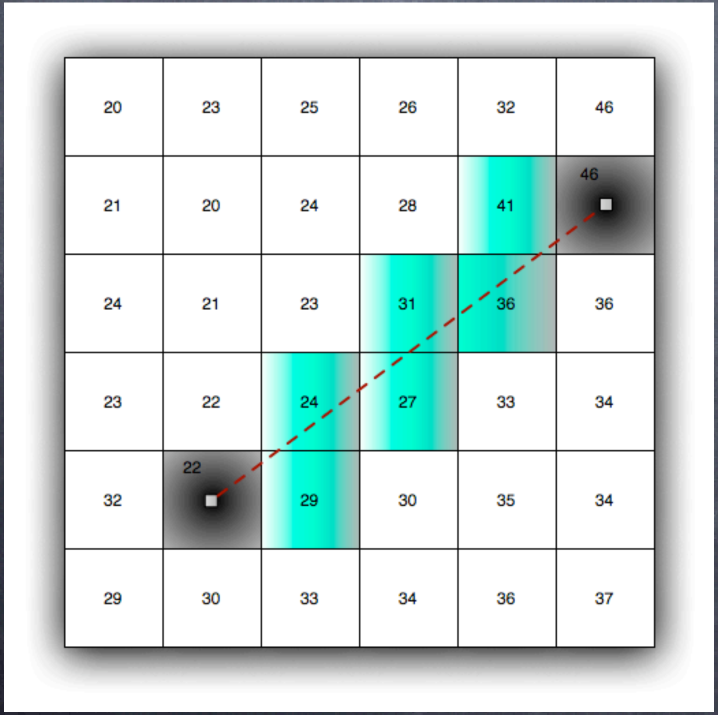
cost=elevation, sources=flowaccu>1000

## Conclusion

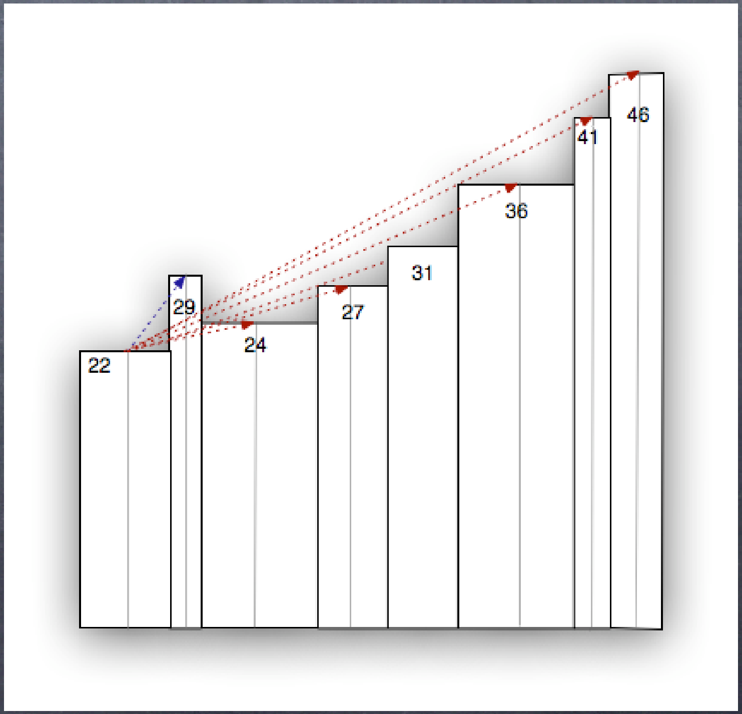
- Key Points
  - r.terracost is a scalable version of r.cost
  - r.terracost restructures the input grid to run I/O-efficiently
  - Tiling naturally allows for parallelization

# Current/Future Work

- Scalable viewshed computation
  - GRASS: r.los
  - New: r.viewshed

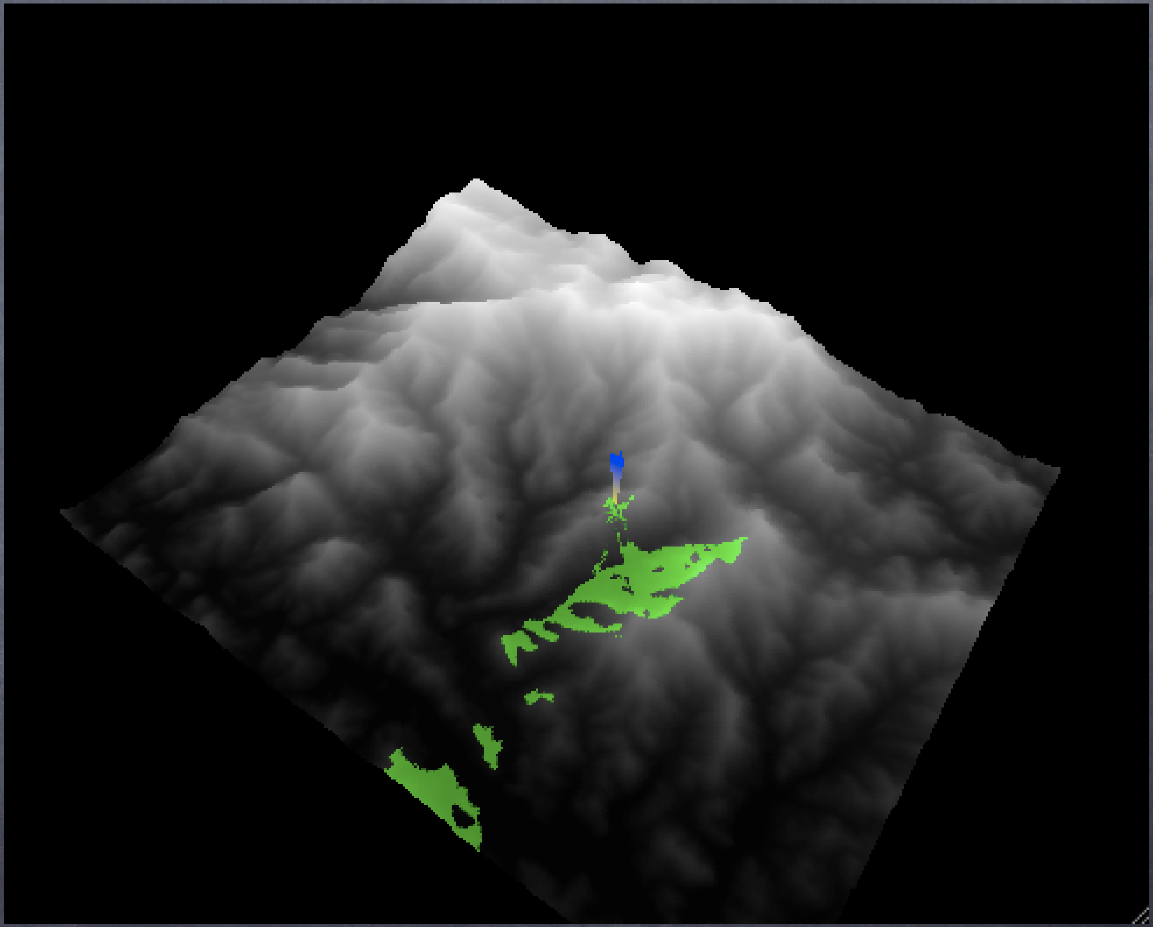


| | | | | | |
|---|---|---|---|---|---|
| 20 | 23 | 25 | 26 | 32 | 46 |
| 21 | 20 | 24 | 28 | 41 | 46 |
| 24 | 21 | 23 | 31 | 36 | 36 |
| 23 | 22 | 24 | 27 | 33 | 34 |
| 32 | 22 | 29 | 30 | 35 | 34 |
| 29 | 30 | 33 | 34 | 36 | 37 |



# r.viewshed

- (.1M)
  - r.los: 3 sec
  - r.viewshed: 1 sec
- Sierra (10M)
  - r.los: 4.5 hours
  - r.viewshed: 1 min
- Washington (1000M)
  - r.viewshed: 4.5 hours



## Thank you.

Laura Toma
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http://www.bowdoin.edu/~ltoma/