# Computing Visibility on Terrains in External Memory

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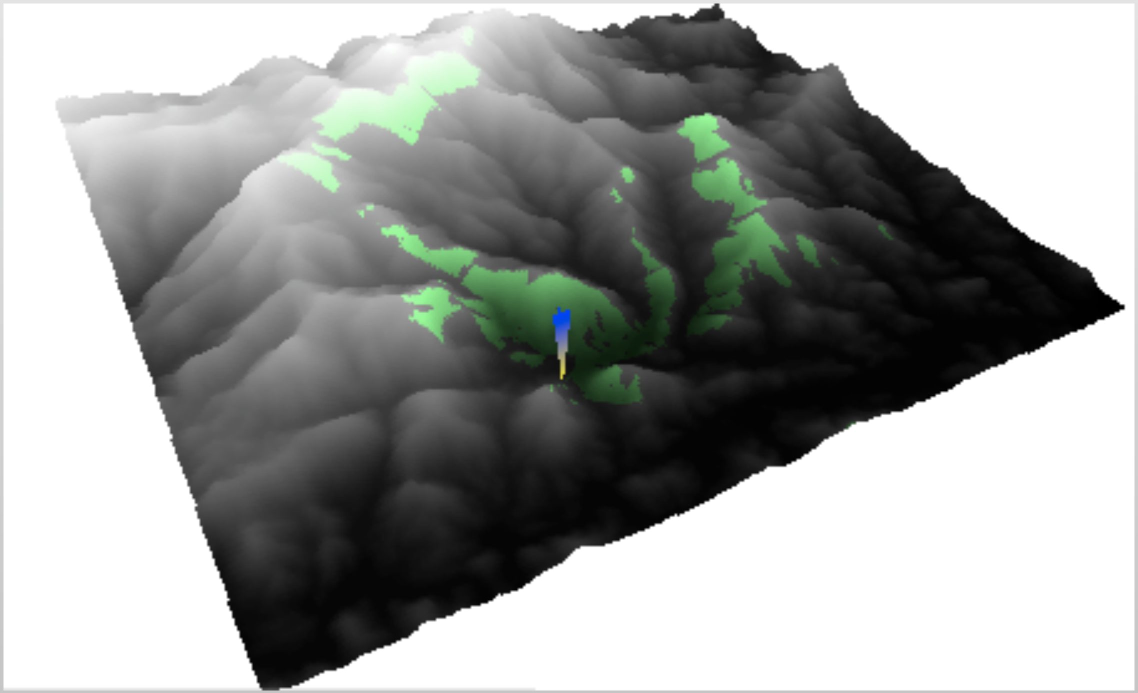
## Visibility

- Problem: visibility map (viewshed) of v
  - terrain T
  - arbitrary viewpoint v
  - the set of points in T visible from v



Sierra Nevada, 30m resolution

## Visibility

- Problem: visibility map (viewshed) of v
    - terrain T
    - arbitrary viewpoint v
    - the set of points in T visible from v

- Applications
    - graphics
    - games
    - GIS
        - military applications, path planning, navigation
        - placement of fire towers, radar sites, cell phone towers (terrain guarding)

## 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 don't scale
  - Buy more RAM?
    - Data grows faster than memory
  - Data on disk
  - Disks are MUCH slower than memory
- => I/O-bottleneck

# I/O-efficient algorithms

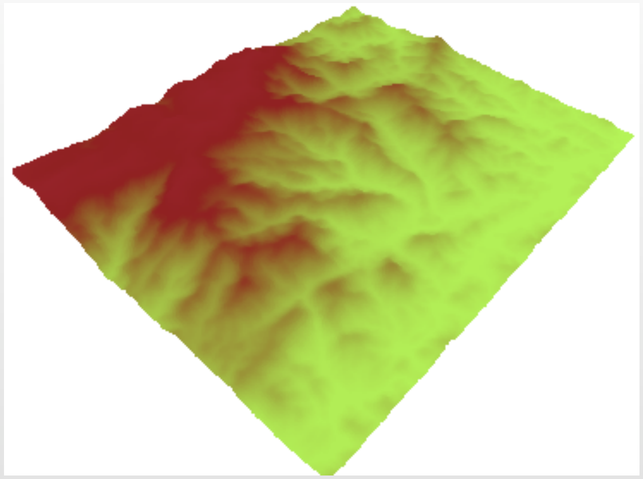
- I/O-model [AV'88]
  - Data on disk, arranged in blocks
  - I/O-operation = reading/writing one block from/to disk

| | | |
|---|---|---|
| n=grid size | M=memory size | B=block size |

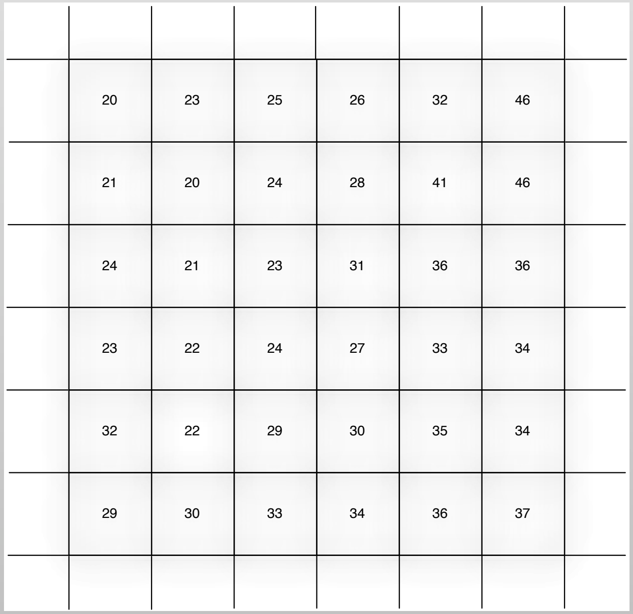
- I/O-complexity: nb. I/O-operations

- Basic I/O bounds
  - $\text{scan}(n)=n/B \quad < \quad \text{sort}(n)=n/B \log_{M/B} n/M \quad \ll \quad n$

## Terrain data

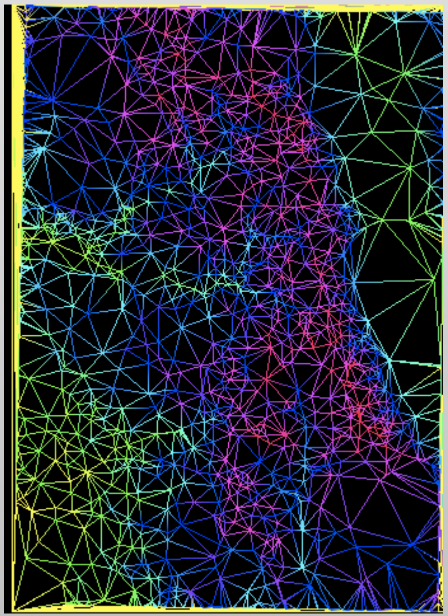


- Most often: grid terrain



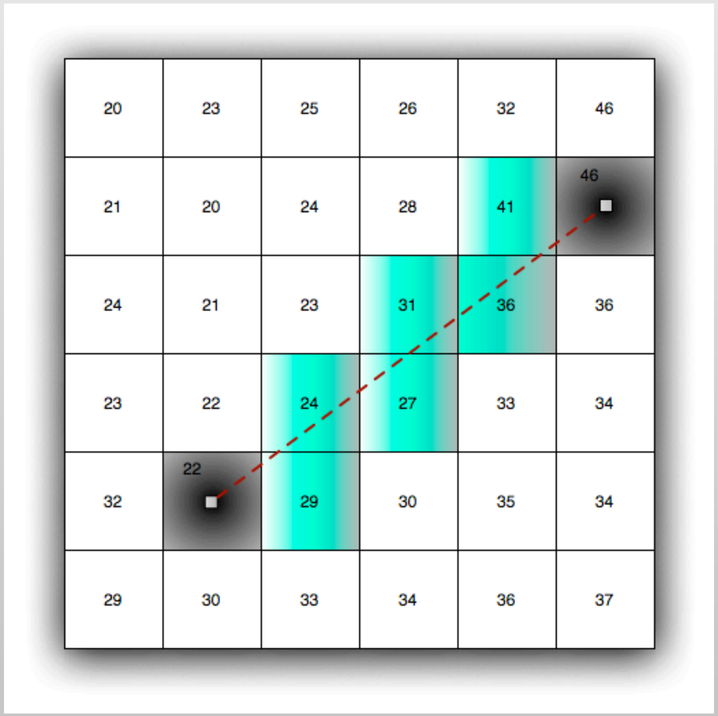
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 20 | 23 | 25 | 26 | 32 | 46 | |
| | 21 | 20 | 24 | 28 | 41 | 46 | |
| | 24 | 21 | 23 | 31 | 36 | 36 | |
| | 23 | 22 | 24 | 27 | 33 | 34 | |
| | 32 | 22 | 29 | 30 | 35 | 34 | |
| | 29 | 30 | 33 | 34 | 36 | 37 | |
| | | | | | | | |

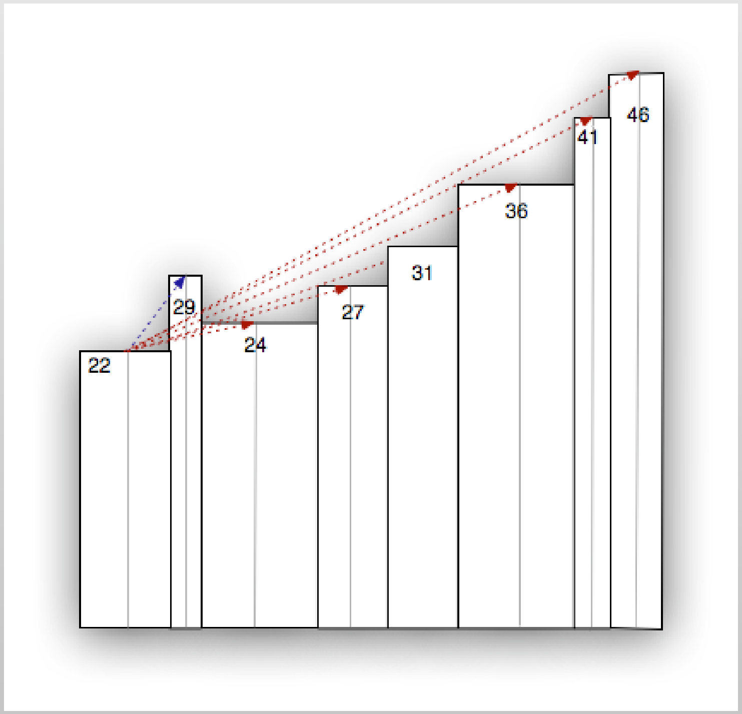
- TIN (triangulated polyhedral terrain)



# Visibility on grids

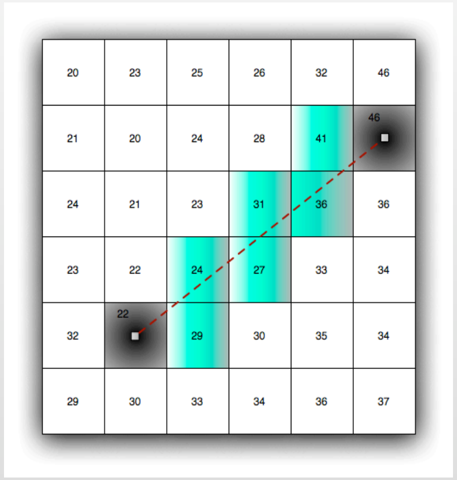
- Line-of-sight model
  - a grid cell with center q is visible from viewpoint v iff the line segment vq does not cross any cell that is above vq



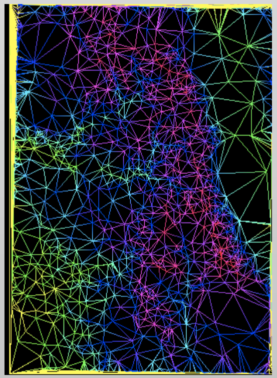


# Visibility: Related work

- Grids
  - straightforward algorithm $O(n^2)$
  - $O(n \lg n)$ by van Kreveld
  - experimental
    - Fisher [F93, F94], Franklin & Ray [FR94], Franklin [F02]
    - no worst-case guarantees



- TINs
  - surveys: de Floriani & Magillo [FM94], Cole & Sharir [CS89]
  - recently: watchtowers and terrain guarding [SoCG'05, SODA'06]



## van Kreveld’s algorithm

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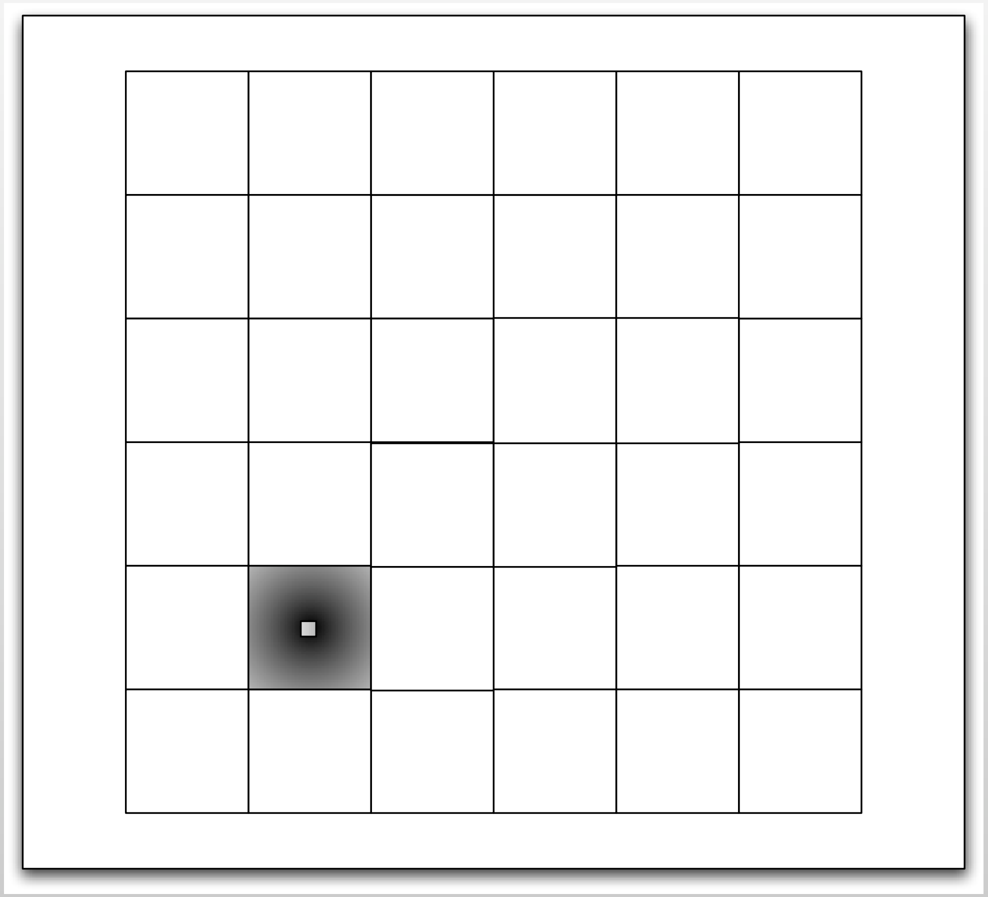

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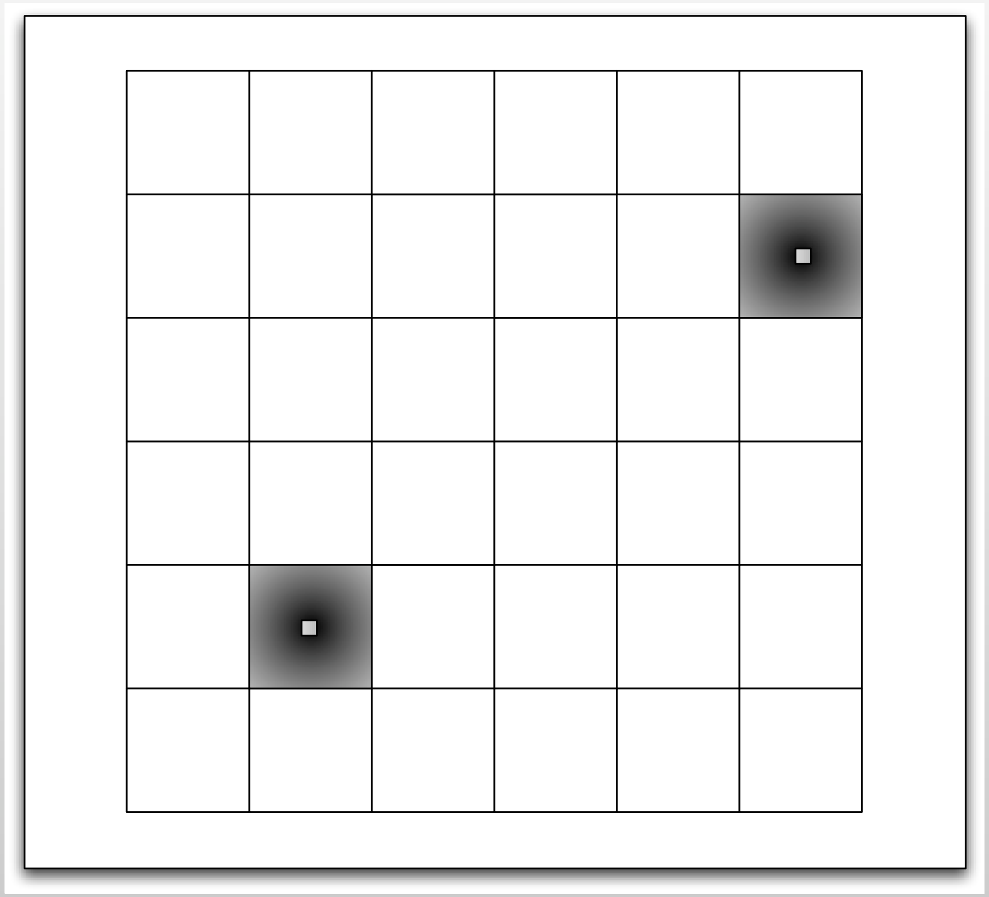

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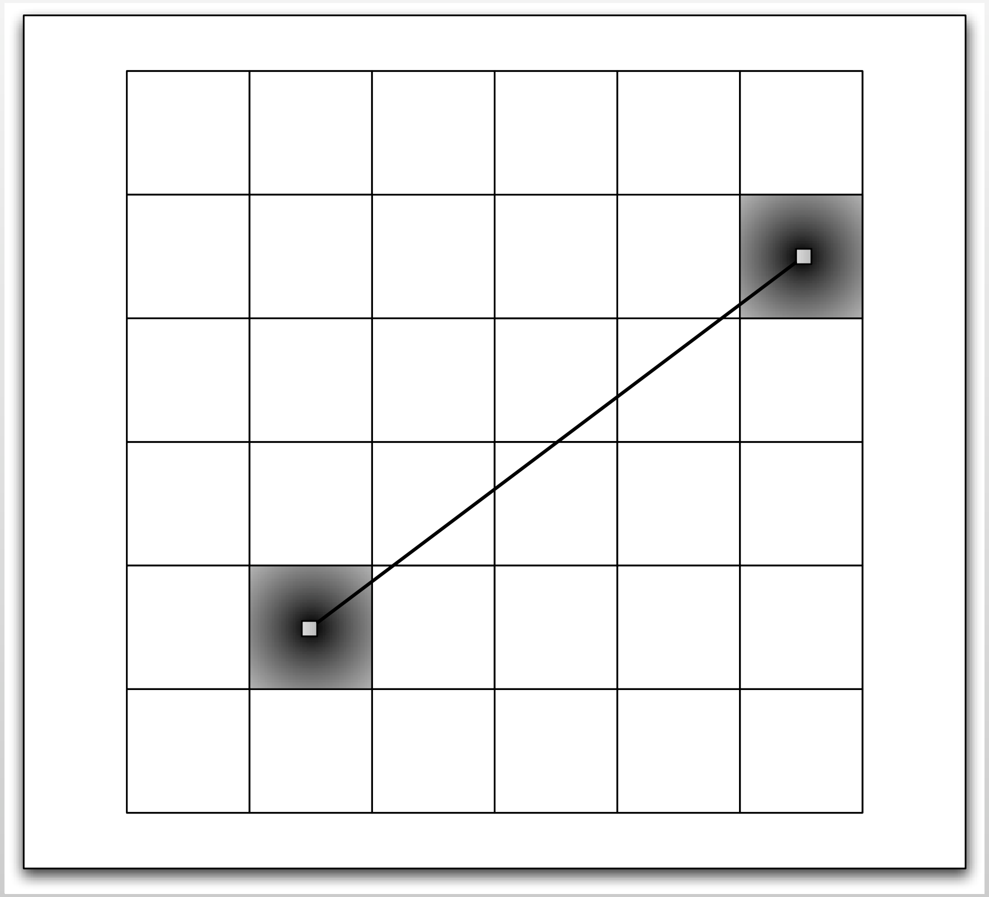

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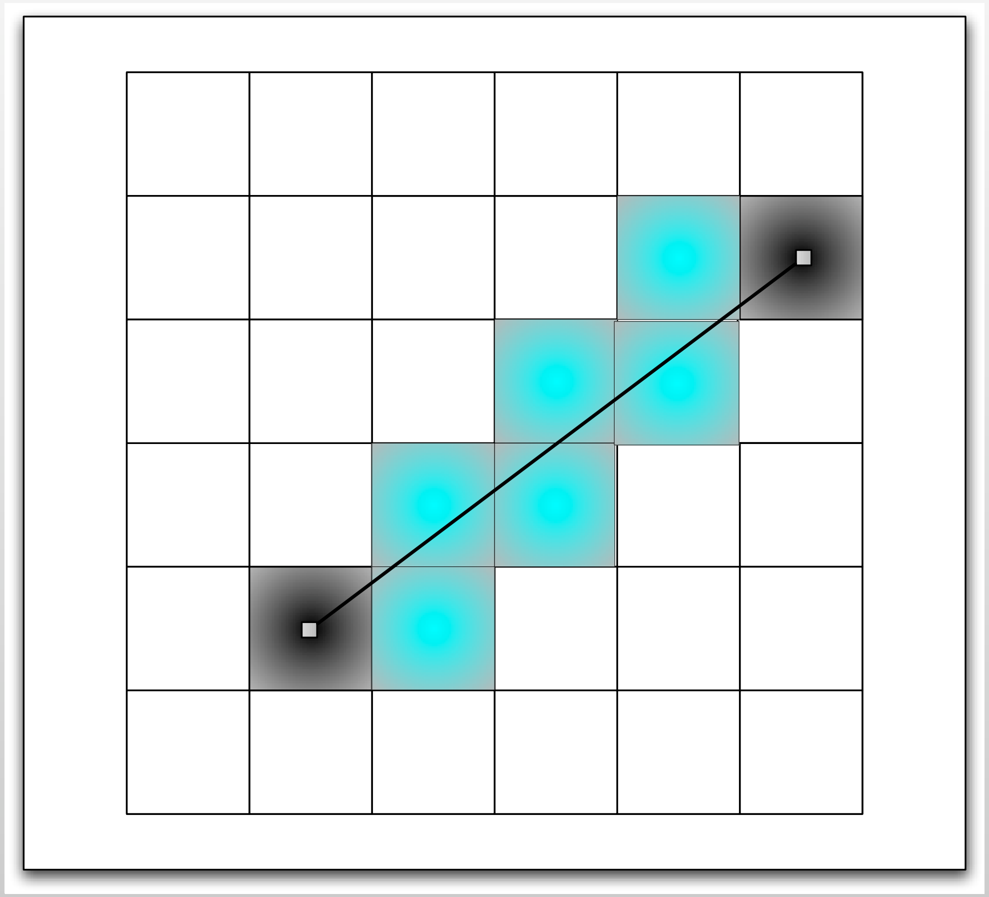

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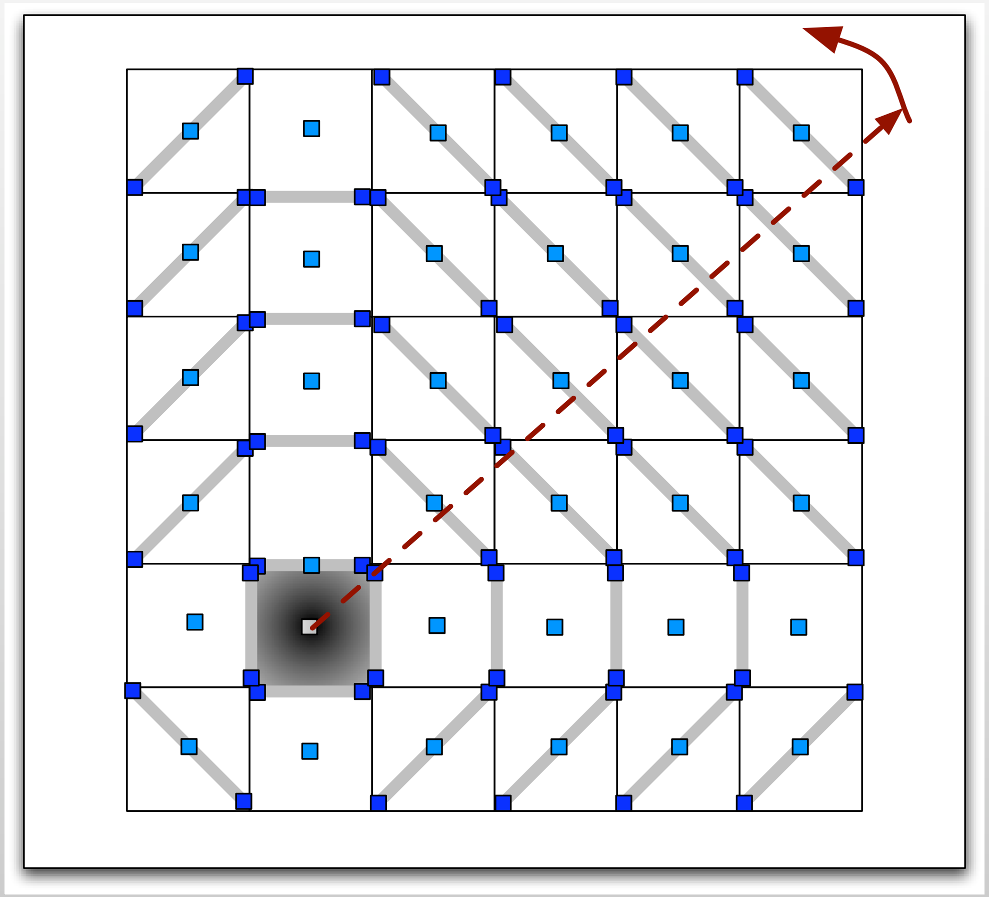

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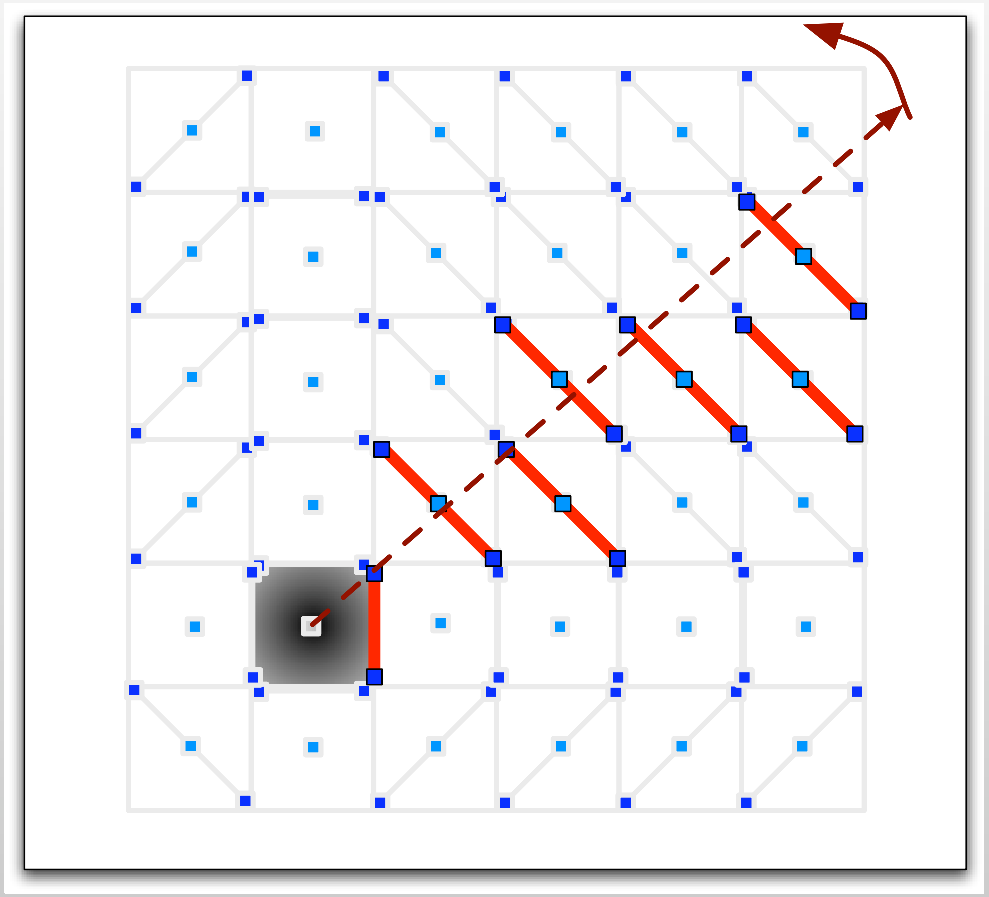

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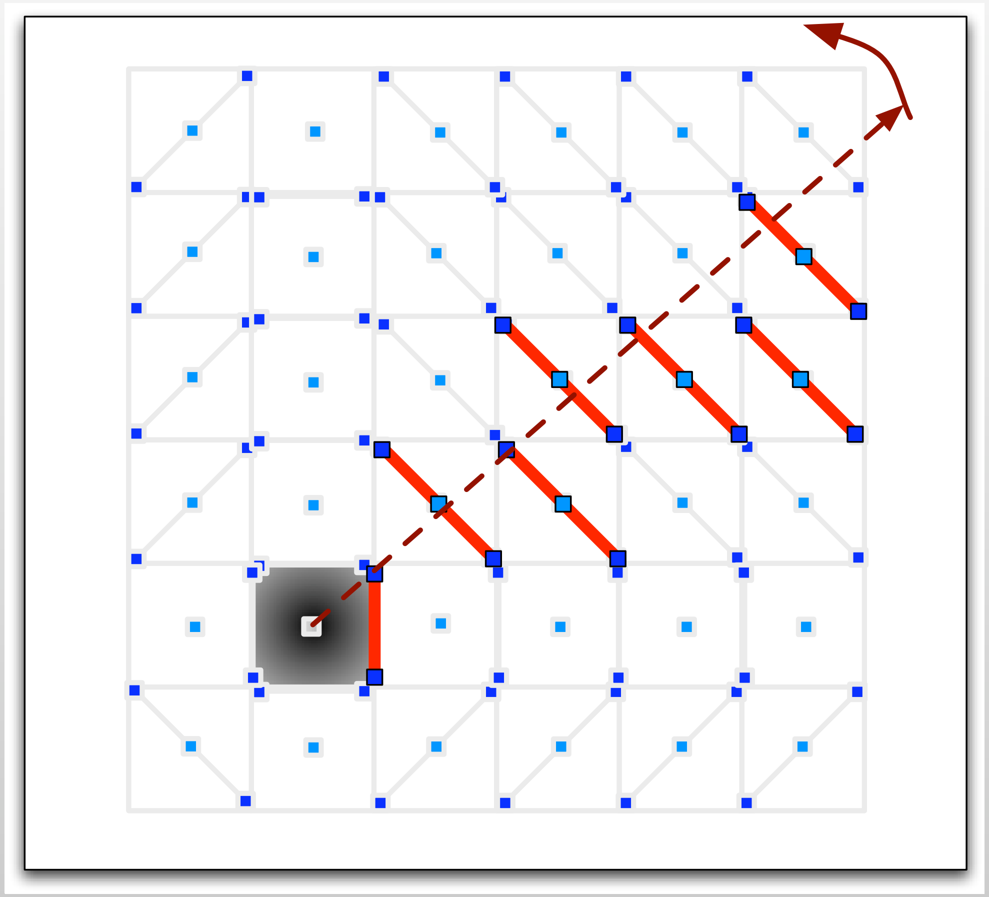

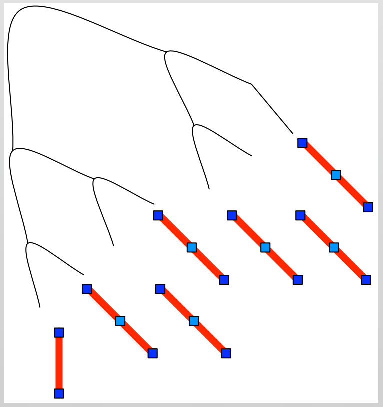

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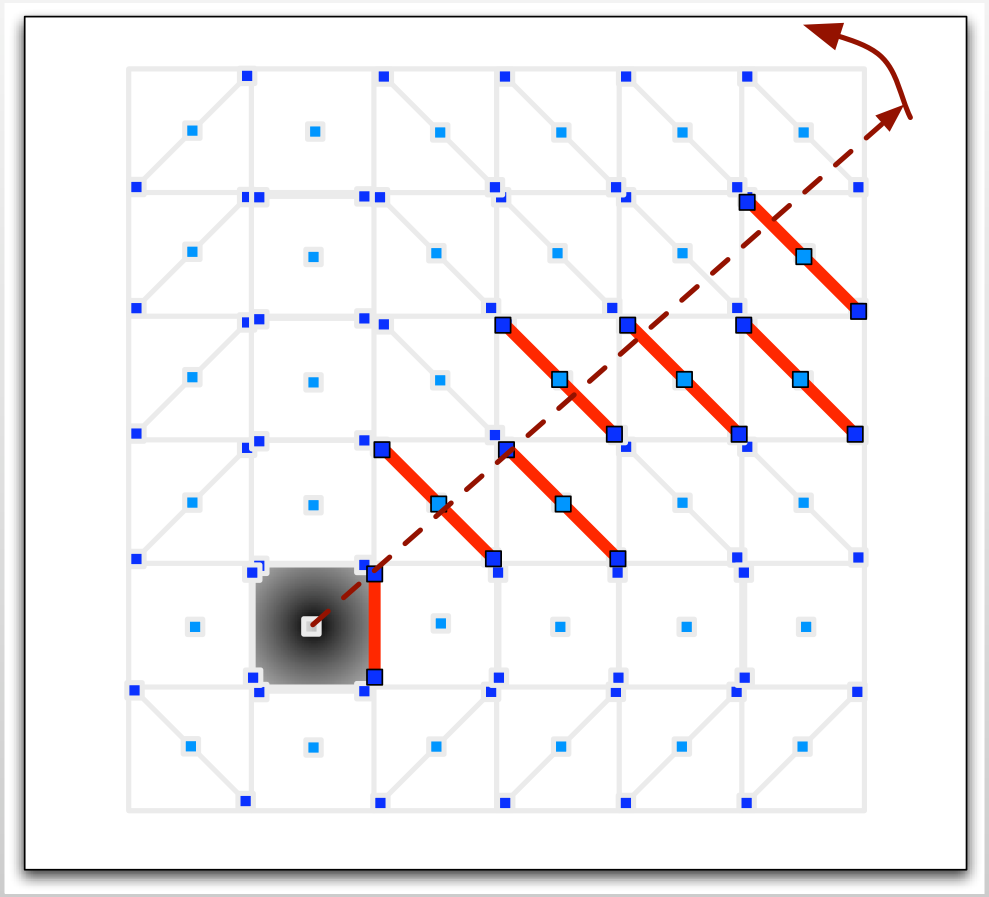

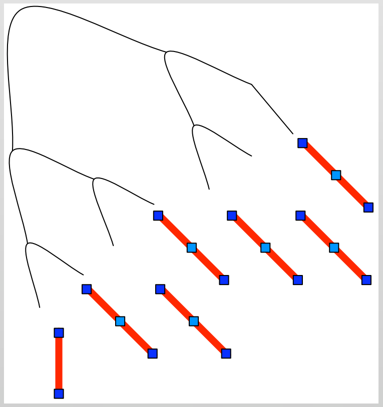

- 3n events, O(lg n) per event --> O(n lg n)   CPU time

# van Kreveld's algorithm

## -in external memory-

- Requires 4 structures in memory
    - input elevation grid, output visibility grid
        - stored in row-major order, read in sweep order
    - event list
    - status structure

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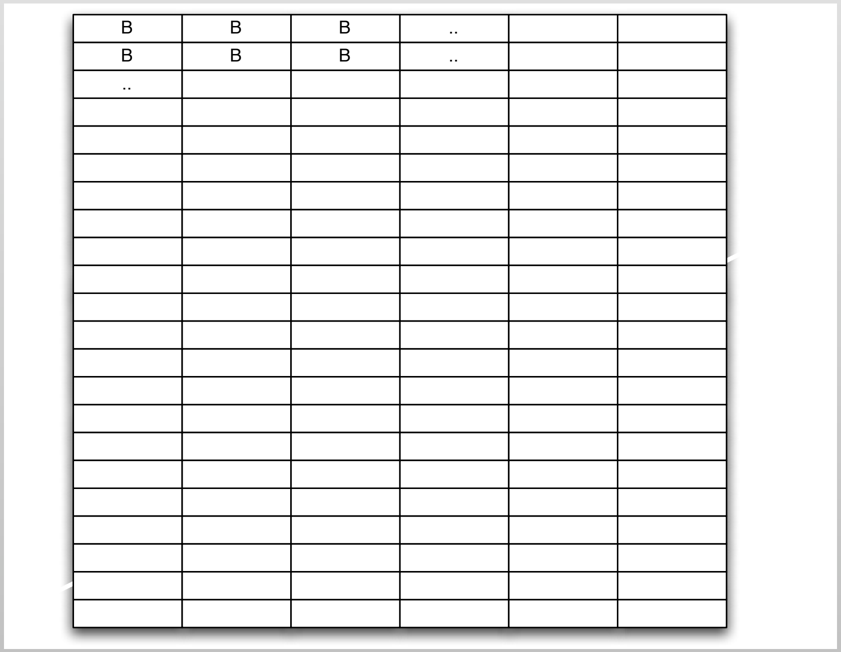

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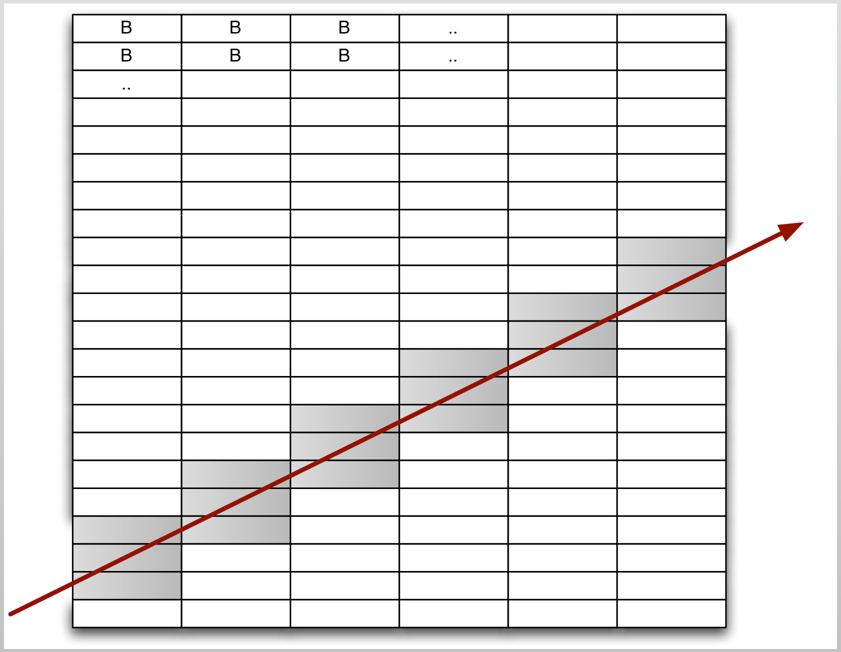

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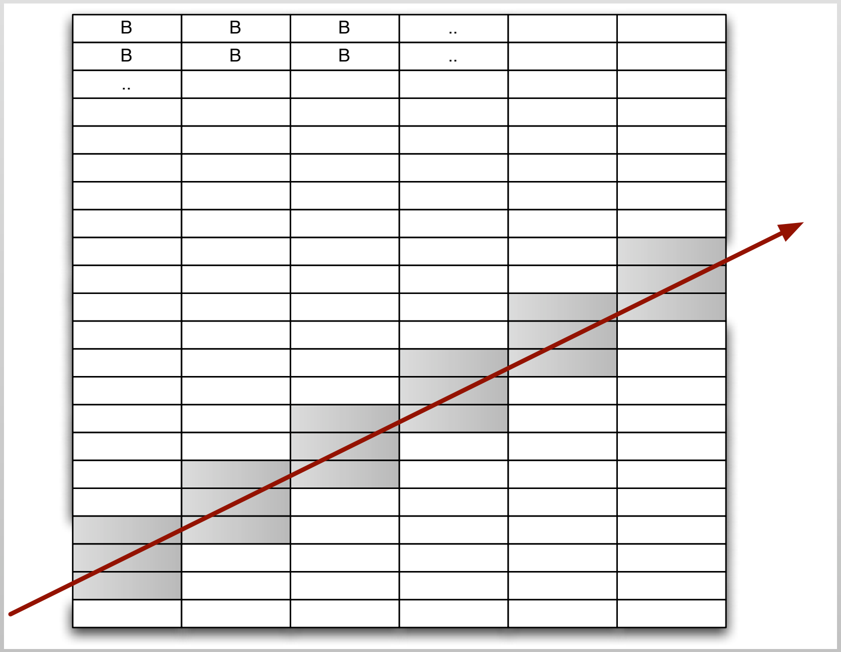
## -in external memory-

- Requires 4 structures in memory
  - input elevation grid, output visibility grid
    - stored in row-major order, read in sweep order
  - event list
  - status structure
- If n > M: O(1) I/O per element, O(n) I/Os total



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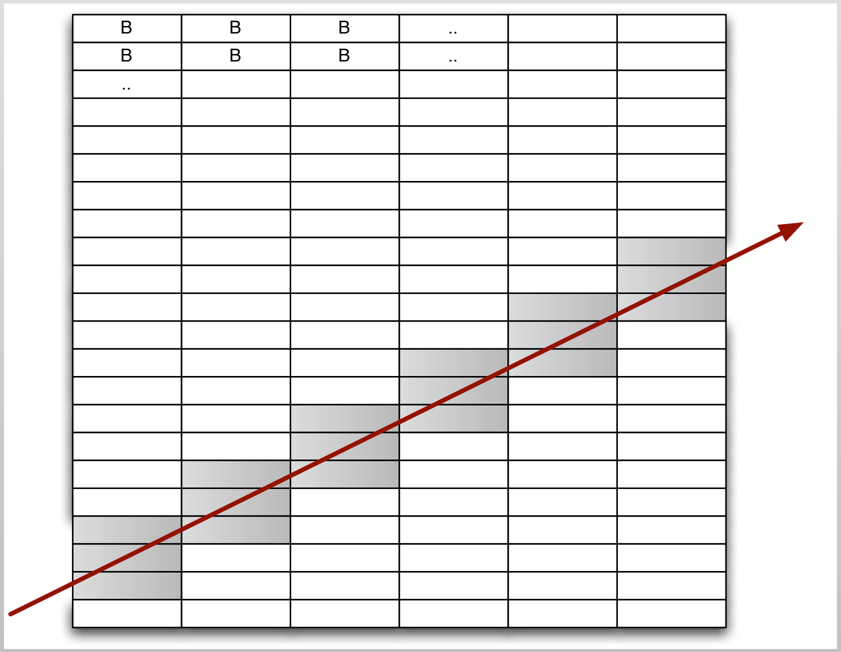
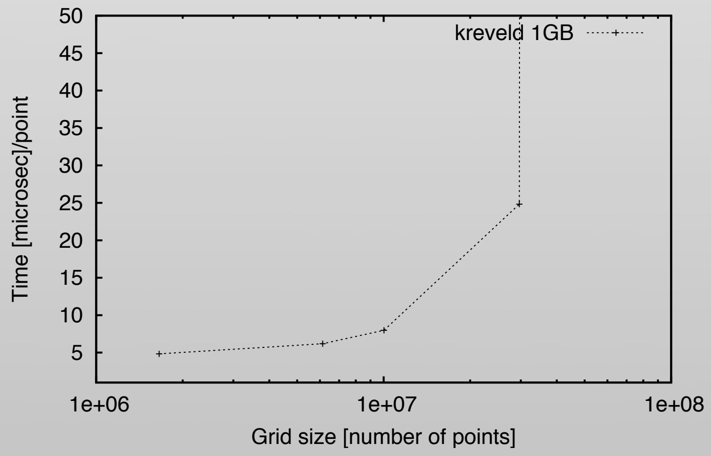




## Our results

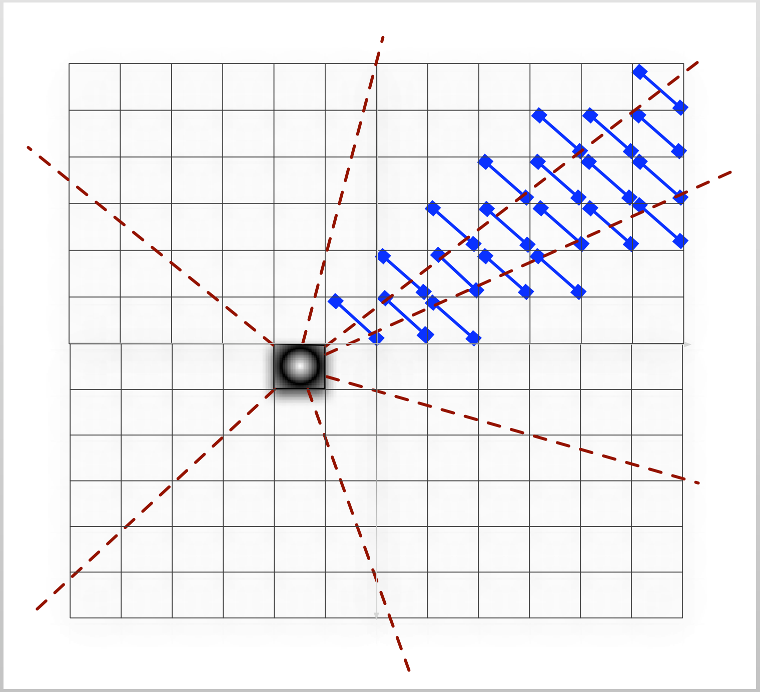
n = grid size      M=memory      size B=block size

- The visibility grid of an arbitrary viewpoint on a grid of size n can be computed with O(n) space and O(sort(n)) I/Os

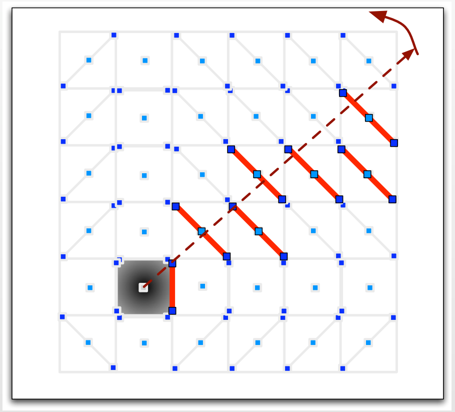
- Experimental evaluation
  - ioviewshed
  - standard algorithm (Kreveld)
  - visibility algorithm in GRASS GIS

# Computing visibility in external memory

- Distribution sweeping [GTVV FOCS93]
  - divide input in M/B sectors each containing an equal nb. of points
  - solve each sector recursively
  - handle sector interactions



## The base case

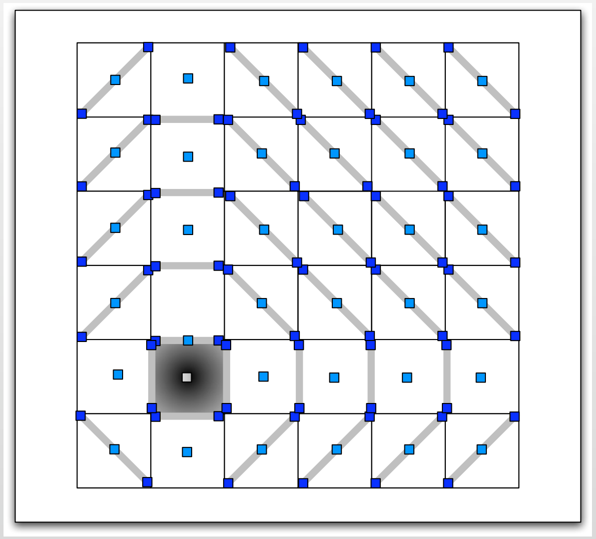


- Usually, stop recursion when n < M
- Our idea: stop when status structure fits in memory

- Run modified Kreveld
    - elevation grid: encode elevation in event
    - event list: store events in a sorted stream on disk
    - visibility grid: when determining visibility of a cell, write it to a stream. Sort the stream at the end to get visibility grid

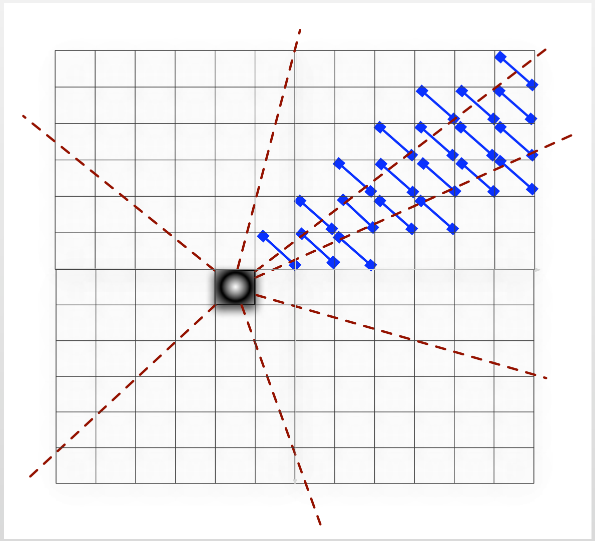
- Total: O(sort(n)) I/Os

## The recursion



- cell <--> {start, end, query}
- 3n events

## The recursion

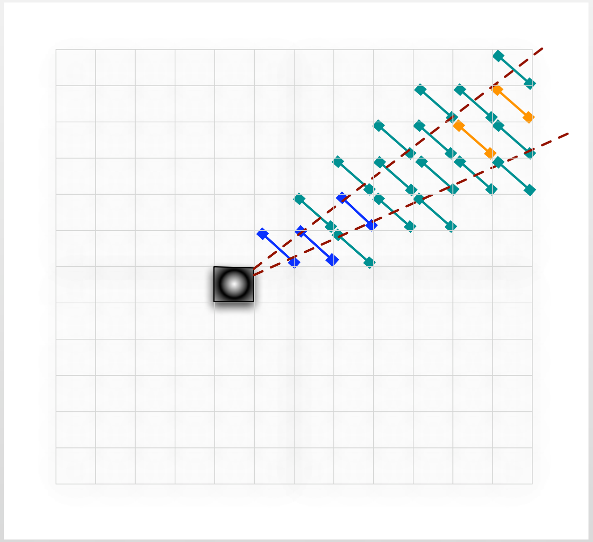


- Divide events into O(M/B) sectors of equal size
- $O(\log_{M/B} n)$ recursion levels

- If O(scan(n)) per recursion level
- --> overall $\text{scan}(n) \cdot O(\log_{M/B} n) = O(\text{sort}(n))$

# The recursion:

## Distributing events to sectors

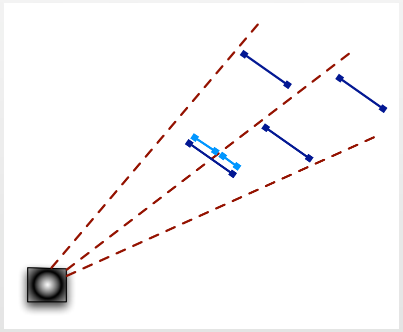


- query points
- narrow cells: crossing at most one sector boundary
- wide cells: crossing at least two sector boundaries

## The recursion:

### Distributing events to sectors

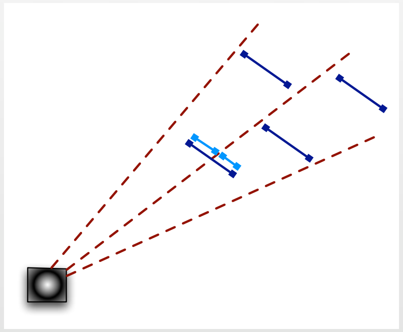
- narrow cells
    - cut and insert in both sectors

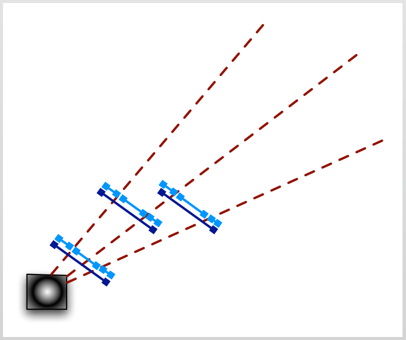


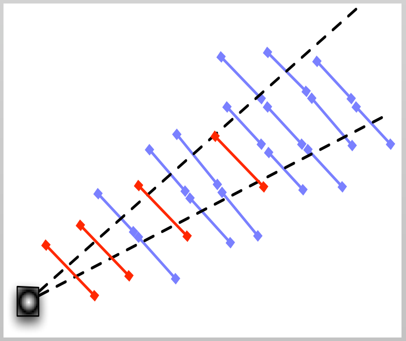
# The recursion:

## Distributing events to sectors

- narrow cells
    - cut and insert in both sectors
- wide cells
    - cannot insert cell in each sector spanned (space blow-up)
    - the visibility of a cell is determined by
        - the highest of all wide cells that span the sector and are closer to the viewpoint
        - all narrow cells in the sector that are closer to the viewpoint
    - for each sector, process wide cells spanning the sector interleaved with query points and narrow cells in the sector,  in increasing order of their distance form viewpoint

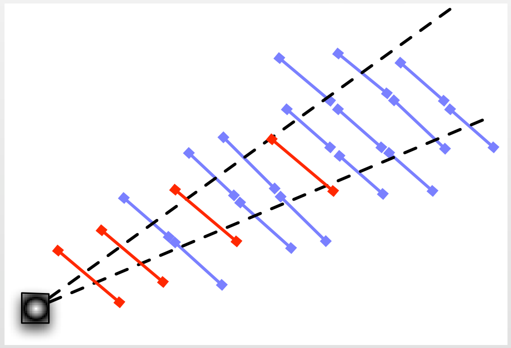






# The recursion

- Input: event list in concentric order $E_c$ and in radial order $E_r$
- Radial sweep: scan $E_r$
    - find sector boundaries
    - compute a list $E_r$ of events in each sector
- Concentric sweep: scan $E_c$
    - for each sector
        - keep a block of events in memory
        - maintain the currently highest wide cell spanning the sector, $High_S$
    - if next event in $E_c$ is
        - wide cell: for each sector spanned, update $High_S$ for that sector.
        - narrow cell: if it is not occluded by $High_S$, insert in the buffer of sector. Otherwise skip it.
        - query point: if it is not occluded by $High_S$, insert it in the buffer of sector. Otherwise, mark it as invisible and output it.
- Recurse on each sector



O(scan(n)) per recursion level -> O(sort(n)) total

## Experimental results

- kreveld
  - C
  - uses virtual memory system
- ioviewshed
  - C++
  - uses an I/O core derived from TPIE library
- GRASS visibility module
  - $O(n^2)$ straightforward algorithm
  - GRASS segment library for virtual memory management
  - bypass the VMS, manage data allocation and de-allocation in segments on disk
  - program will always run (no malloc() fails) but ... slow

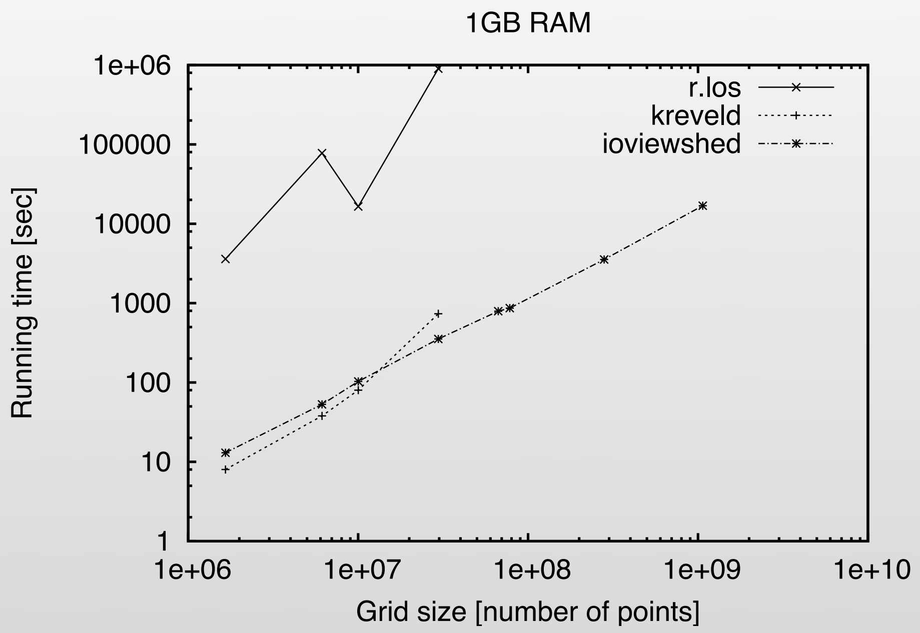
# Experimental results

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

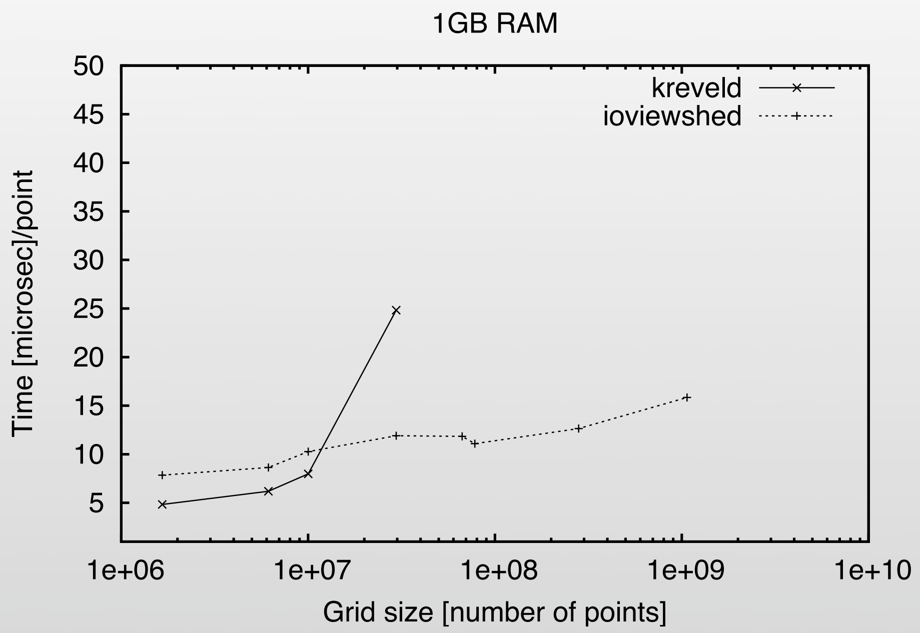
| Dataset | Grid Size (million elements) | MB (Grid Only) | Valid size |
|---|---|---|---|
| Kaweah | 1.6 | 6 | 56% |
| Puerto Rico | 5.9 | 24 | 19% |
| Sierra Nevada | 9.5 | 38 | 96% |
| Hawaii | 28.2 | 112 | 7% |
| Cumberlands | 67 | 268 | 27% |
| Lower New England | 77.8 | 312 | 36% |
| Midwest USA | 280 | 1100 | 86% |
| Washington | 1066 | 4264 | 95% |

# 1GB RAM

## total time (seconds)



## microseconds per grid point



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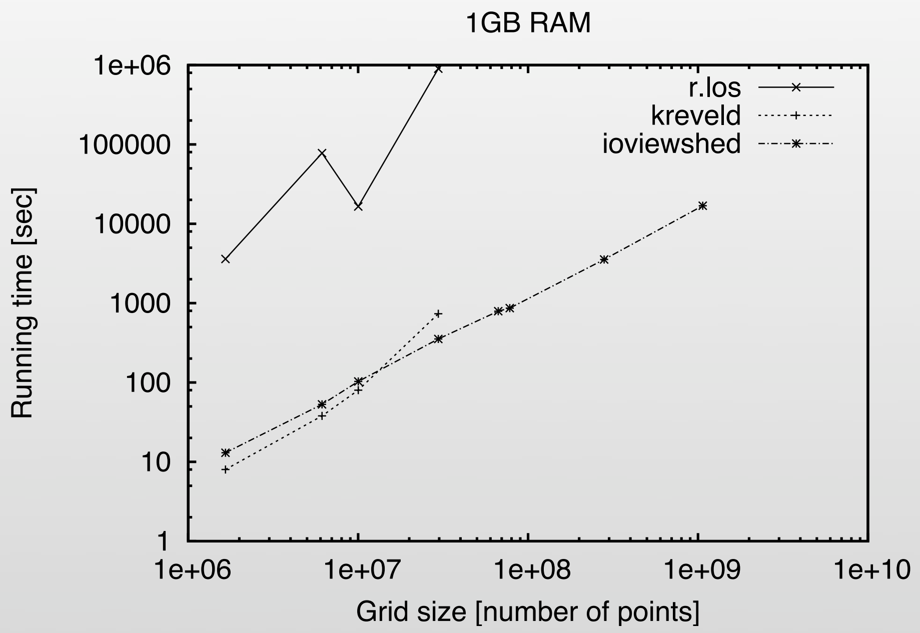

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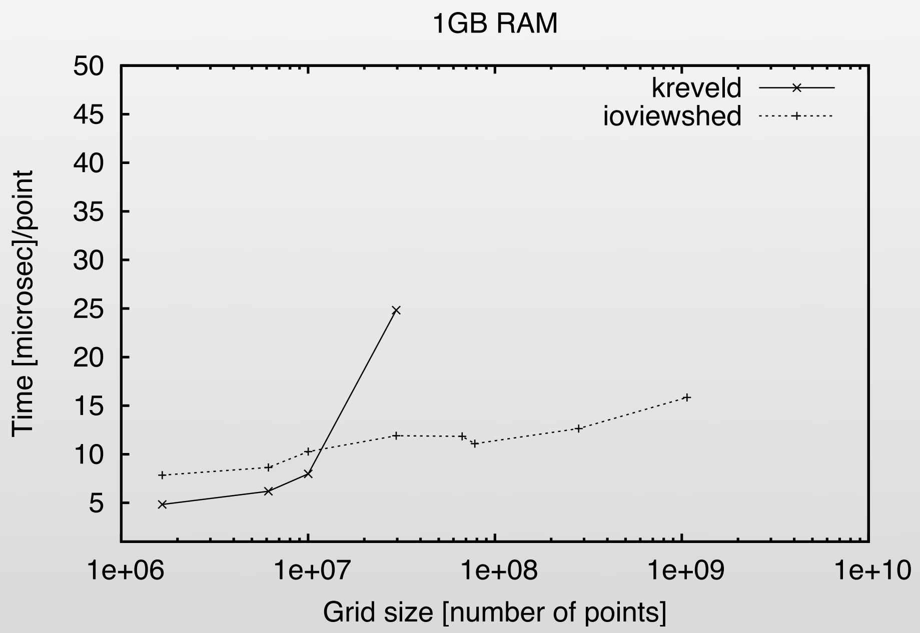

- GRASS
  - program always runs (no malloc() failures) but is very slow
- kreveld
  - starts thrashing on Hawaii (39% CPU, 739 seconds)
  - malloc() fails on Cumberlands
- ioviewshed
  - finishes Washington in 4.5 hours
  - in practice status structure fits in memory, never enters recursion

## 1GB RAM

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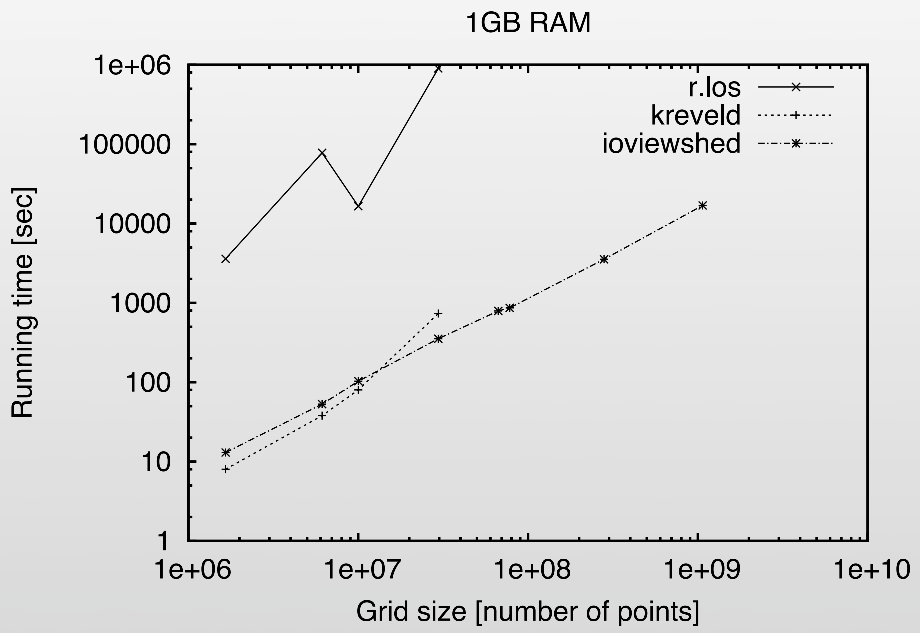

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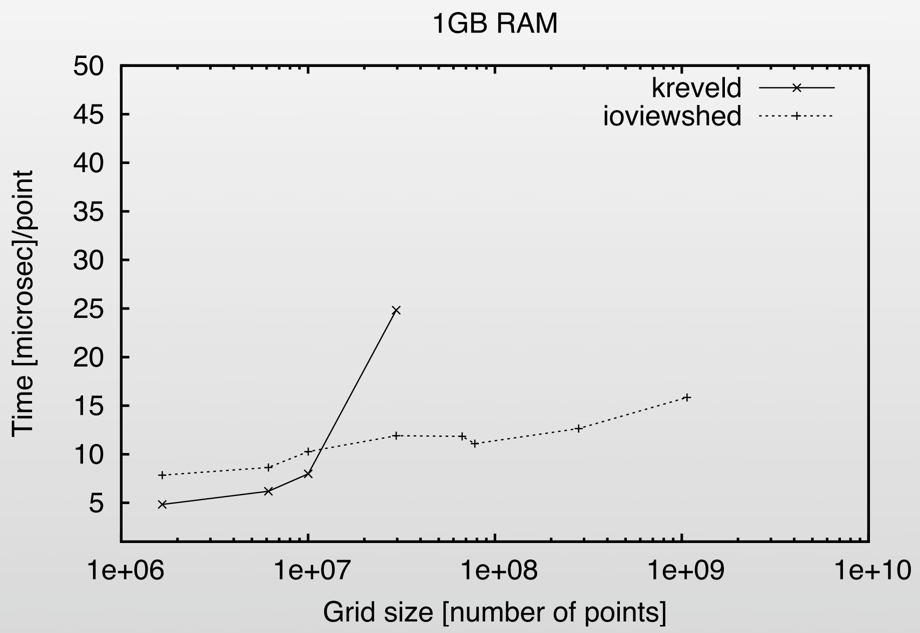
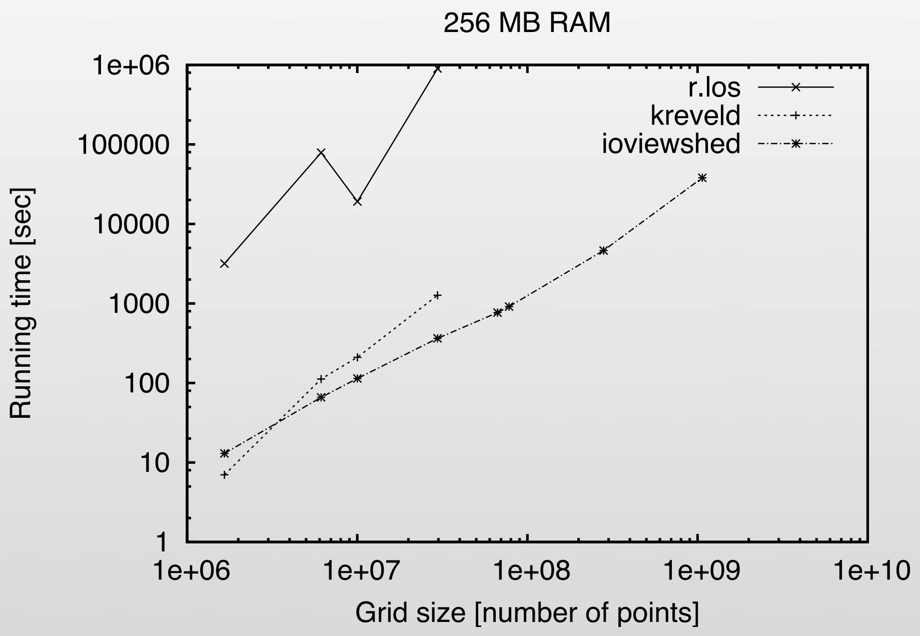


| Data set | r.los | kreveld | ioviewshed |
|---|---|---|---|
| Kaweah | 2 928 | 8 (100 %) | 13 (84 %) |
| Puerto Rico | 78 778 | 38 (100 %) | 53 (78 %) |
| Sierra Nevada | 16 493 | 80 (95 %) | 102 (67 %) |
| Hawaii | >1 200 000 | 736 (39 %) | 353 (63 %) |
| Cumberlands | | malloc fails | 791 (63 %) |
| LowerNE | | | 865 (64 %) |
| Midwest USA | | | 3 546 (64 %) |
| Washington | | | 16 895 (68 %) |

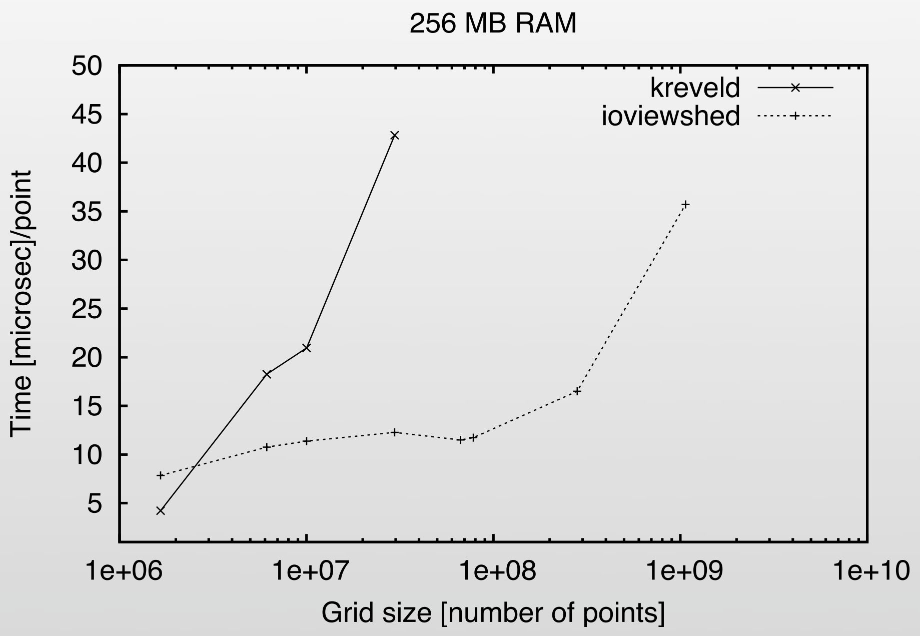
Table 3: Running times (seconds) and CPU-utilization (in parentheses) at 1 GB RAM.

# 256MB RAM

## total time (seconds)



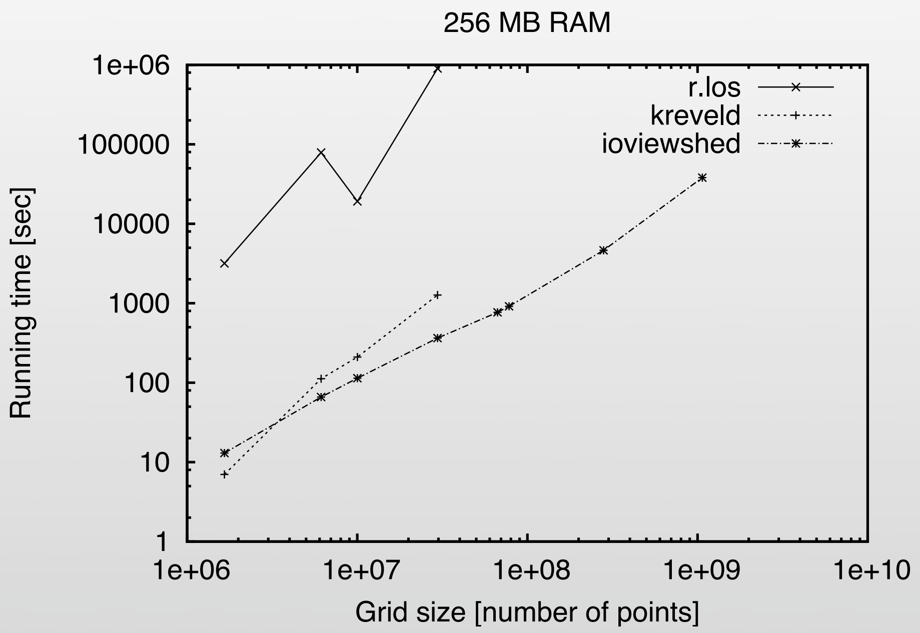
## microseconds per grid point



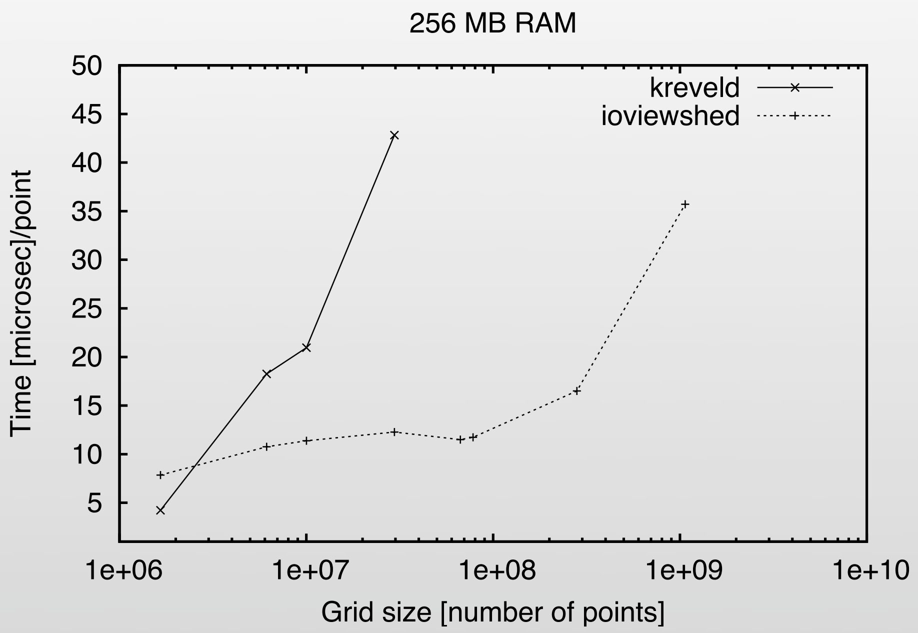
- kreveld starts thrashing earlier (Puerto Rico, 38% CPU)
- ioviewshed slowdown on Washington dataset
    - due 90% to sorting
    - can be improved using customized I/O sorting [TPIE, STXXL]

## 256MB RAM

### total time (seconds)



### microseconds per grid point



| Data set | r.los | kreveld | ioviewshed |
|---|---|---|---|
| Kaweah | 2 984 | 7 (100 %) | 13 (77 %) |
| Puerto Rico | 78 941 | 112 (38 %) | 66 (60 %) |
| Sierra Nevada | 19 140 | 211 (29 %) | 115 (57 %) |
| Hawaii | >1 200 000 | 1270 (27 %) | 364 (63 %) |
| Cumberlands | | malloc fails | 768 (62 %) |
| LowerNE | | | 916 (62 %) |
| Midwest USA | | | 4 631 (52 %) |
| Washington | | | 40 734 (30 %) |

Table 4: Running times (seconds) and CPU-utilization (in parentheses) at 256 MB RAM.

# 1GB vs. 256MB RAM kreveld

| | | | |
|---|---|---|---|
| Kaweah | 1.6 | 6 | 56% |
| Puerto Rico | 5.9 | 24 | 19% |
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| Cumberlands | 67 | 268 | 27% |
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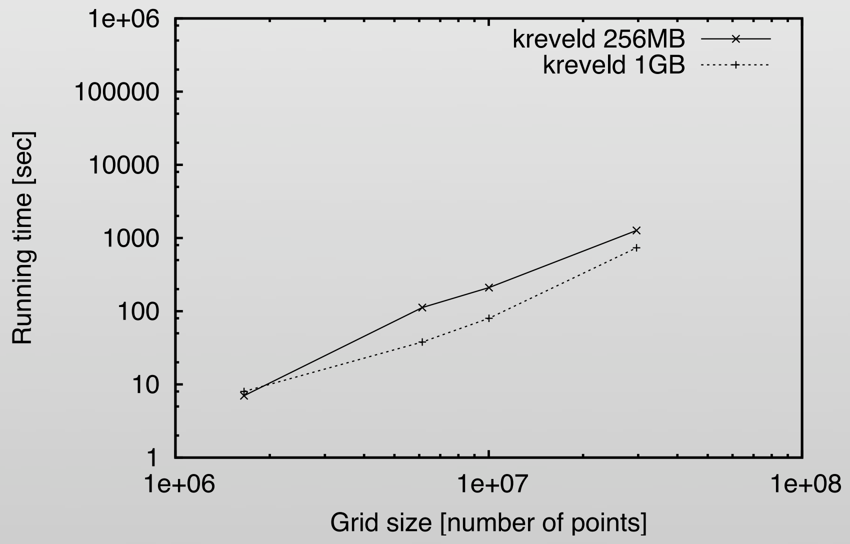

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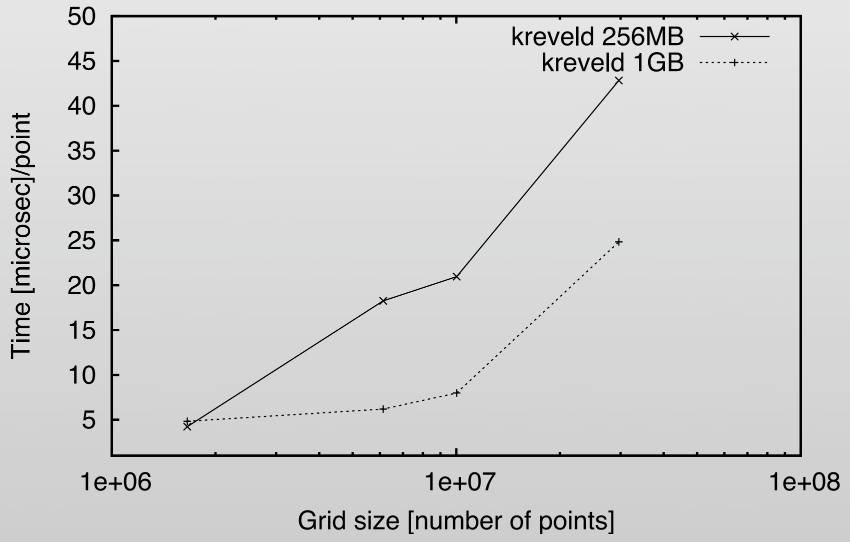

- starts thrashing earlier
  - 1GB: Hawai, 39% CPU
  - 256MB: Puerto Rico 38% CPU

| | | | |
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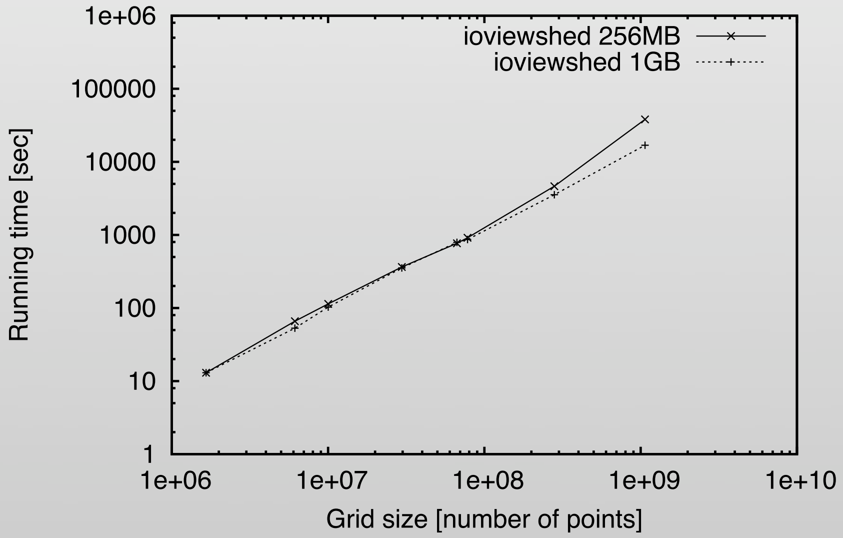
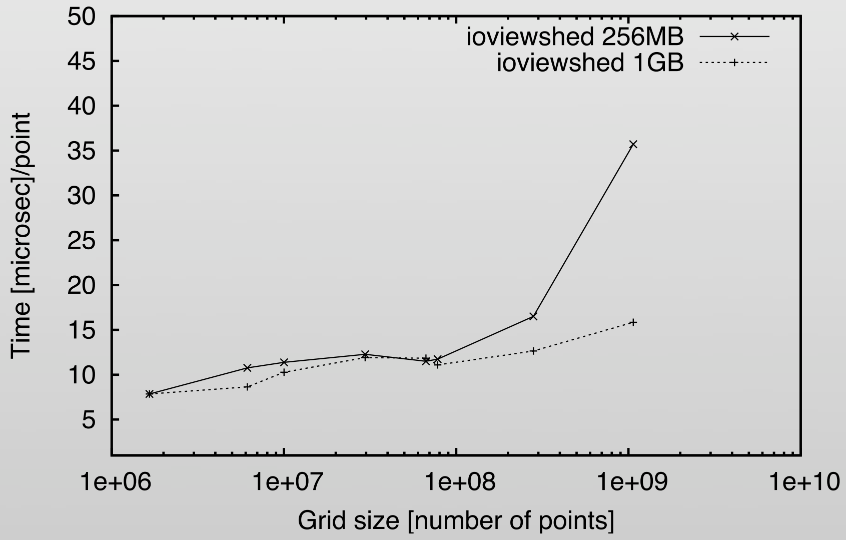
# 1GB vs. 256MB RAM ioviewshed

## total time (seconds)



## microseconds per grid point



- slowdown on Washington dataset
- due 90% to sorting
- can be improved using a customized I/O sorting [TPIE, STXXL]

## Conclusion

- I/O-efficient visibility computation
  - Theoretically worst-case optimal algorithm
  - In practice status structure fits in memory
    - with extended base case it never enters recursion
  - Scalable
    - Can process grids that are out of scope with traditional algorithm

Thank you.