Modeling & Analyzing Massive Terrain Data Sets (STREAM Project)

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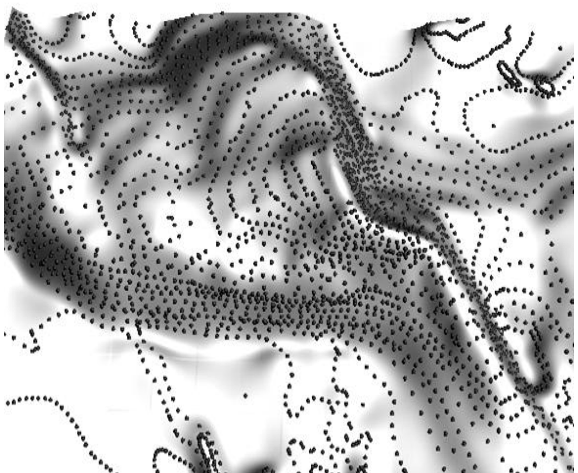
DUKE
COMPUTER SCIENCE

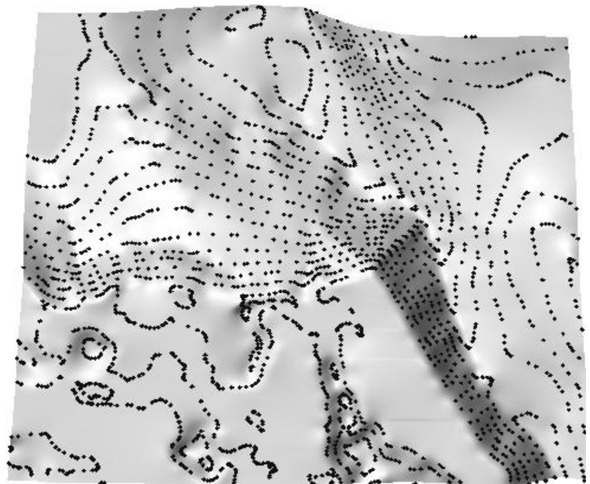
Workshop on Algorithms for Modern Massive Data Sets

Diverse elevation point data: density, distribution, accuracy

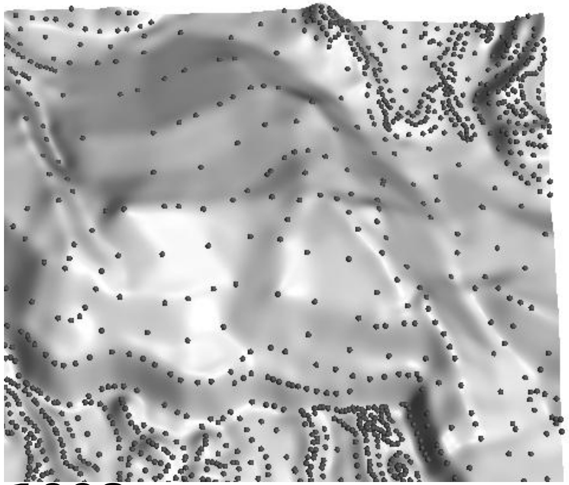
Photogrammetry 0.76m v. accuracy (5ft contours)



1974



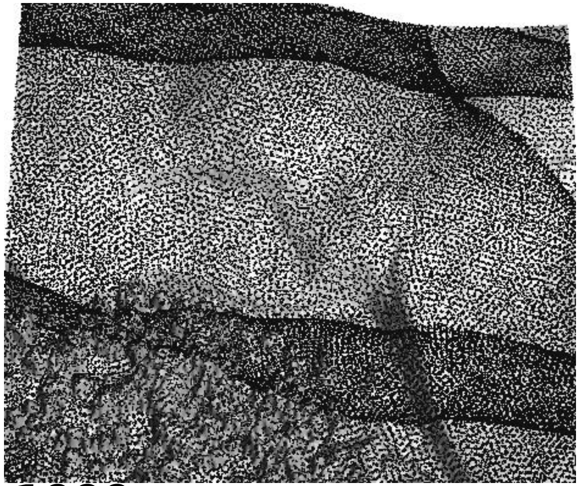
1995



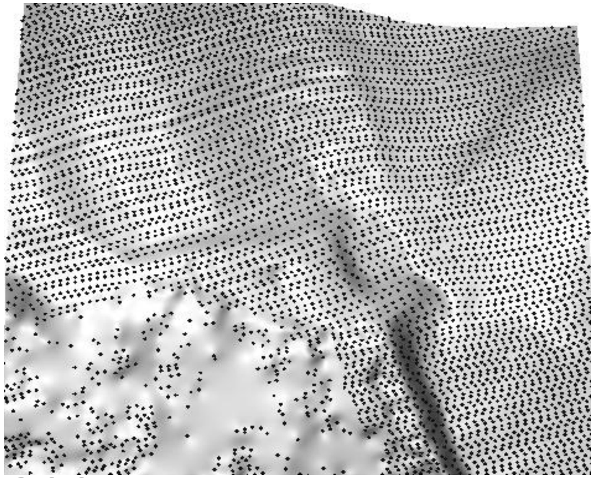
1998

Lidar 0.15m v. accuracy; altitude 700m and 2300m

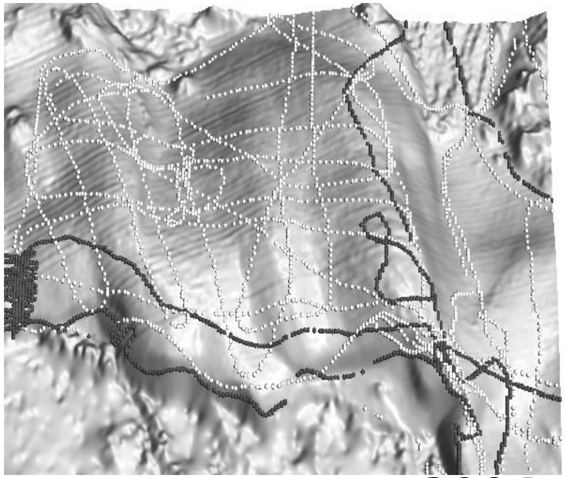
RTK-GPS 0.10m v. accuracy



1999

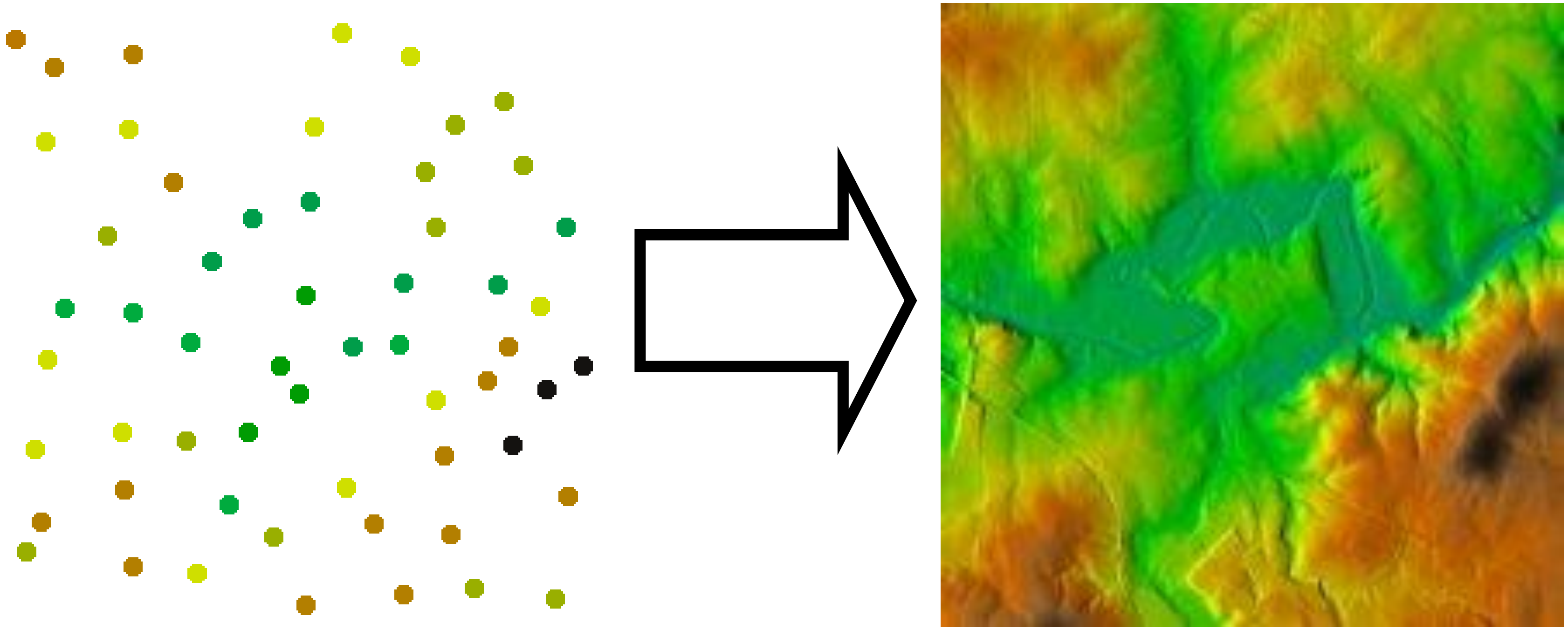


2001



2004

Constructing Digital Elevation Models



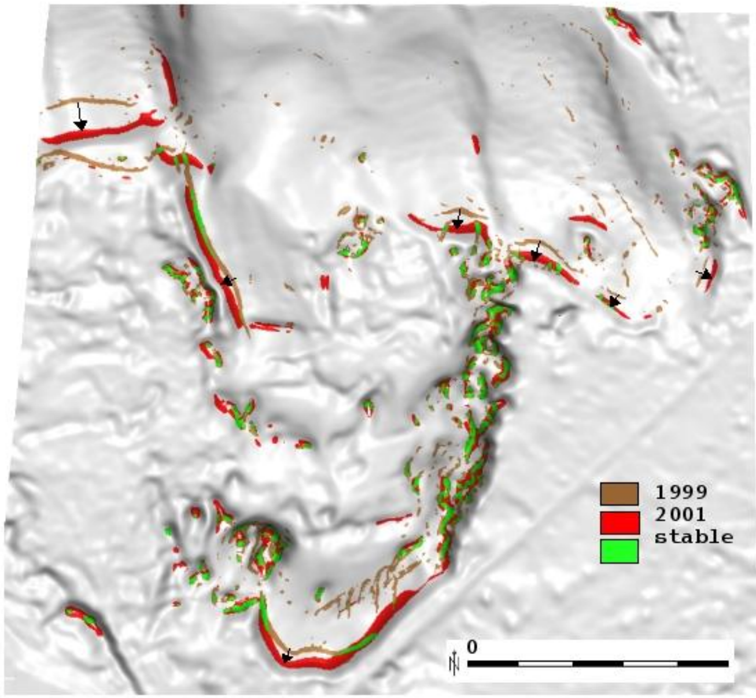
Grid DEM: Elevation stored at uniform grid points

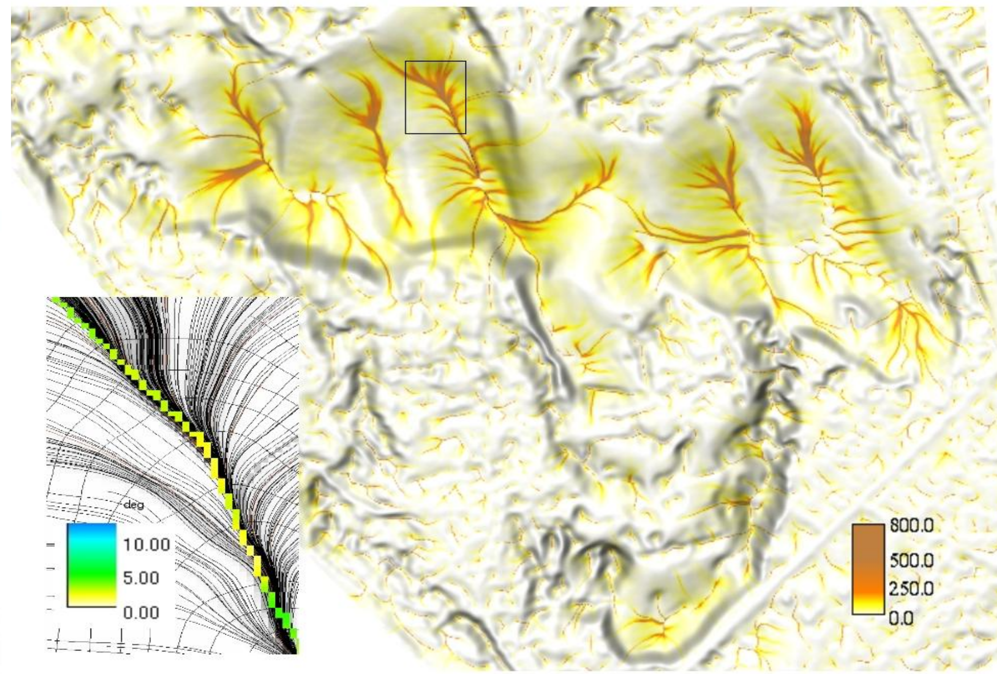
TIN: Triangulation; elevation stored at vertices

Contours Maps: Iso-contour lines at regular intervals

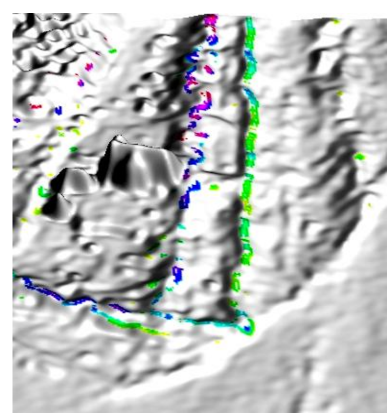
Natural feature extraction

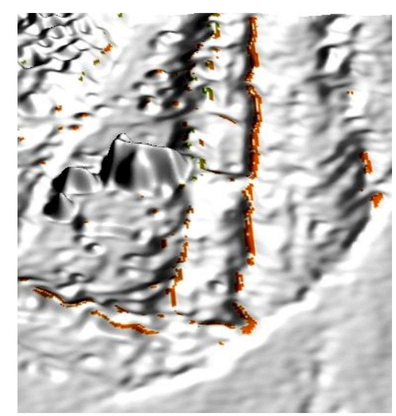
Maps of topo parameters: computed simultaneously with interpolation using partial derivatives of the RST function, terrain features: combined thresholds of topo parameters





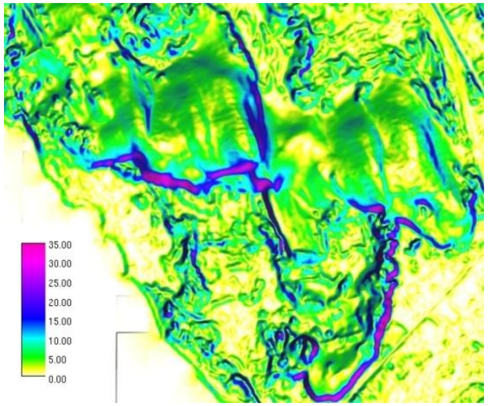
Extracted foredunes 1999-2004 using profile curvature and elevation threshold



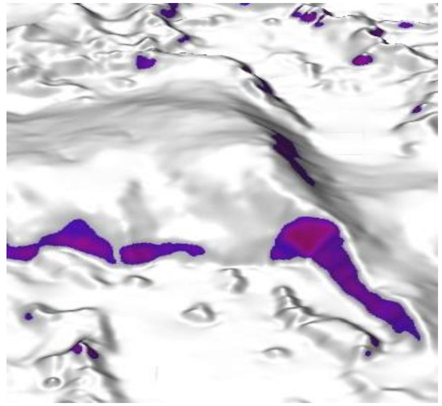


Tracking Evolving Features

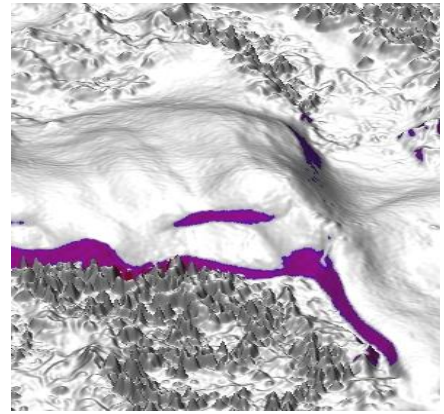
slip faces: slope > 30deg



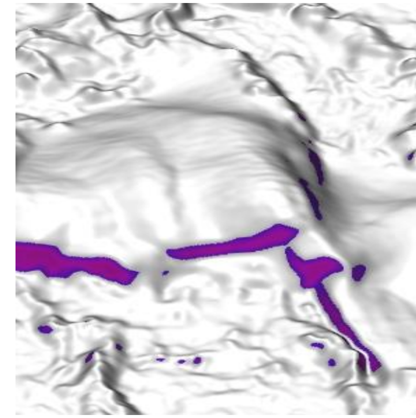
1995



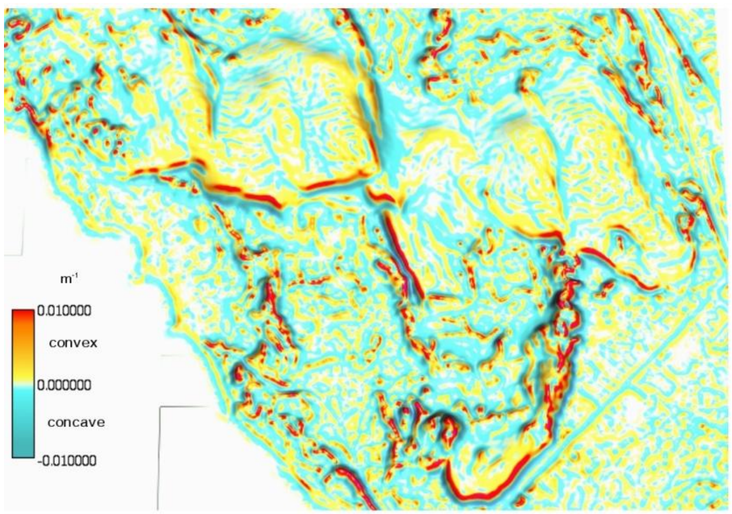
new slip face in 1999

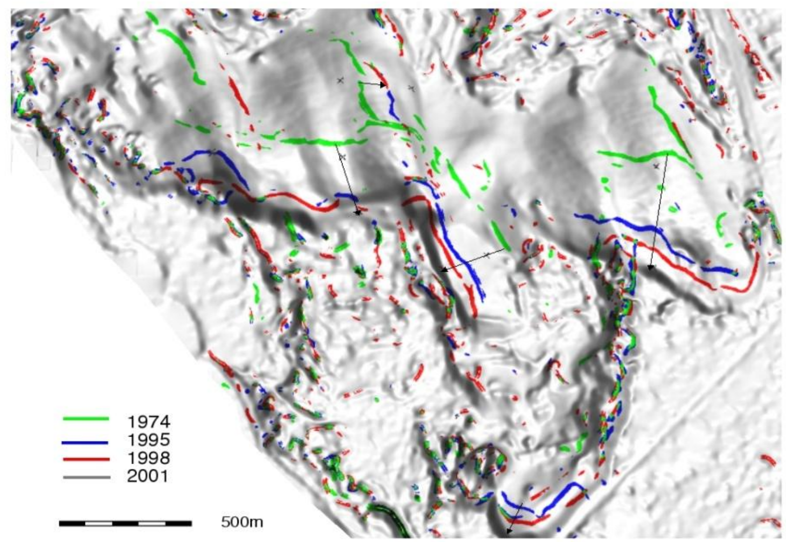


2001



dune crests: profile curvature threshold





how to automatically track features that change some of their properties over time?

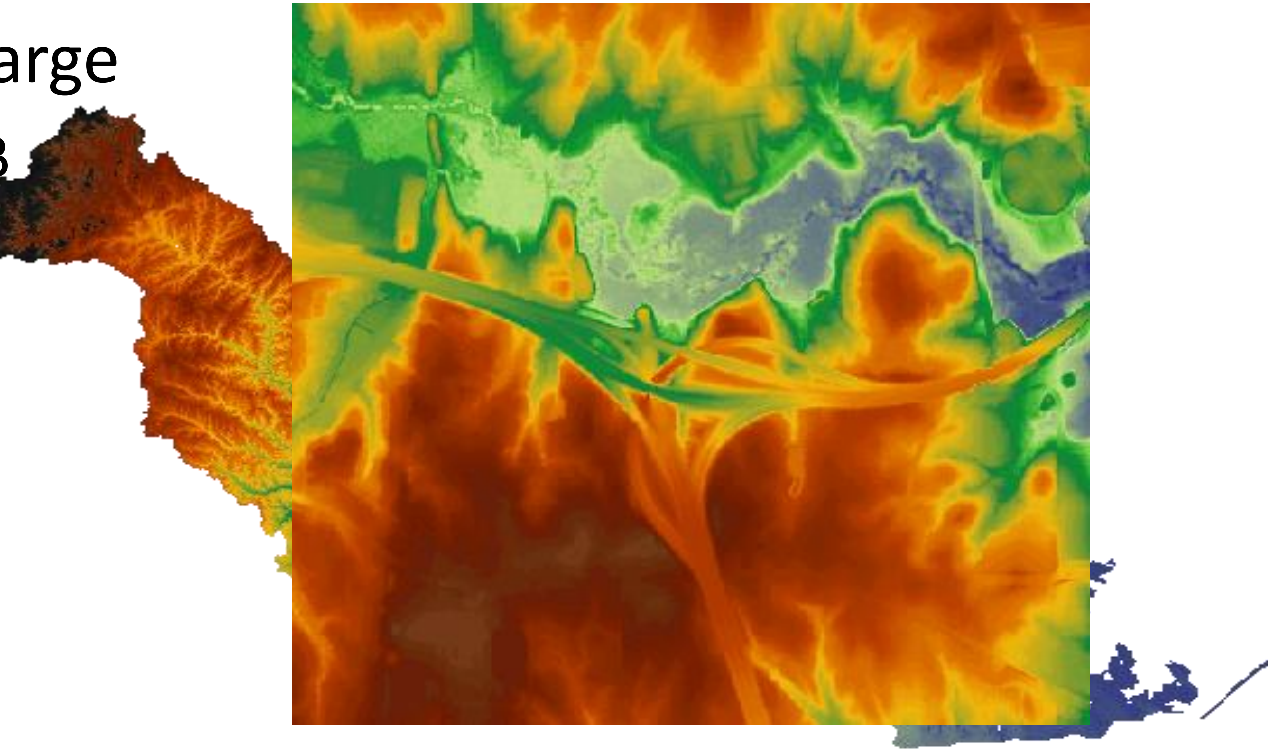
Terrain Analysis

- Flow Analysis
- Watershed hierarchy

- Visibility
- Navigation

Challenge: Massive Data Sets

- LIDAR
  - NC Coastline: 200 million points – over 7 GB
  - Neuse River basin (NC): 500 million points – over 17 GB
  - Applachian Range: 50GB-5TB
- Output is also large
  - 10ft grid: 10GB
  - 5ft grid: 40GB



Approximation Algorithms

- *Exact computation expensive*

  Many practical problems are intractable

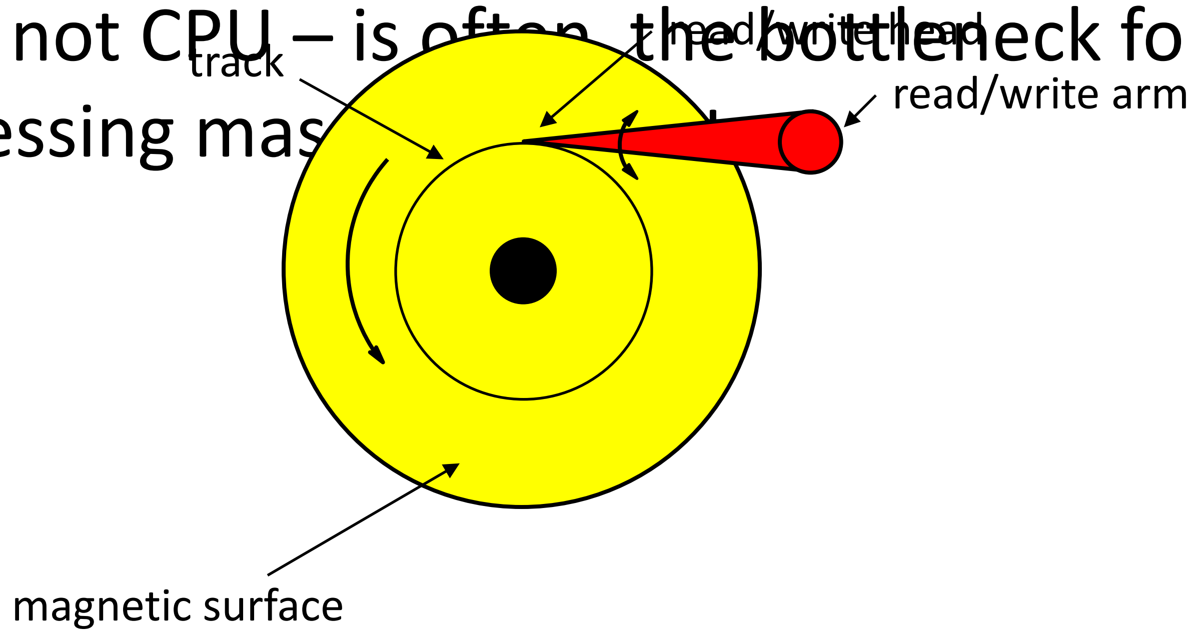
  Multiple & often conflicting optimization criteria

  Suffices to find a near-optimal solution

- *Tunable Approximation algorithms*
  - Tradeoff between accuracy and efficiency
  - User specifies tolerance

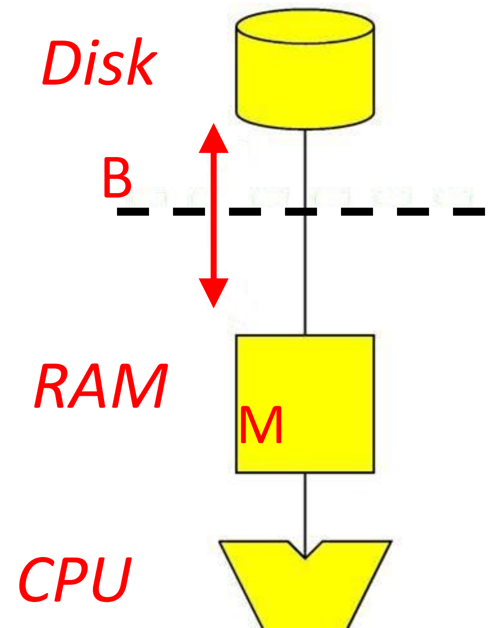
I/O-Bottleneck

- Data resides in secondary memory
- Disk access is 10^6 times slower than main memory access
  - Maximize useful data transferred with each access
  - Amortize large access time by transferring large contiguous blocks of data
- I/O – not CPU – is often the bottleneck for processing mas



I/O-efficient Algorithms [AV88]

- Traditional algorithms optimize CPU computation
  - Not sensitive to penalty of disk access
- I/O model
  - Memory is finite
  - Data is transferred in blocks (B: block size)
  - Complexity: #disk blocks transferred (#I/Os)



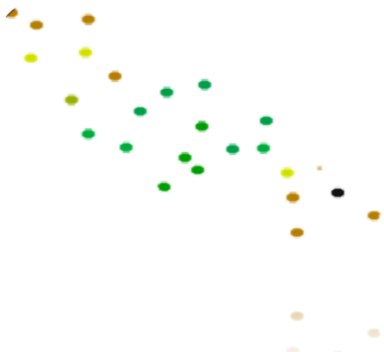
$$\text{Scan}(N) = O(N/B)$$

$$\text{Sort}(N) = O\left(\frac{N}{B} \log_{\frac{M}{B}} \frac{N}{B}\right)$$

B ~ 2K-8K

External Memory Algorithms [Vitter]

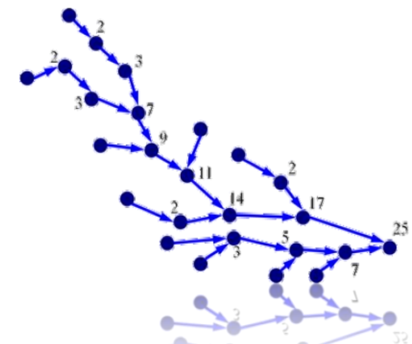
The TerraStream Modules



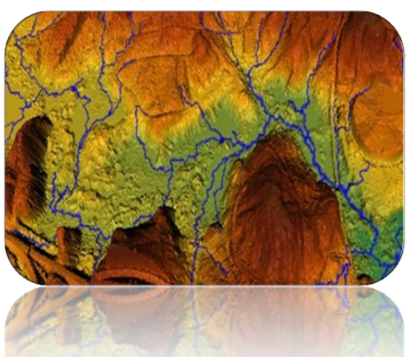
(Classification)

(DEM Construction)

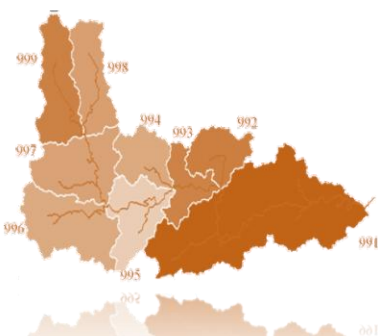
Conditioning



Flow Routing

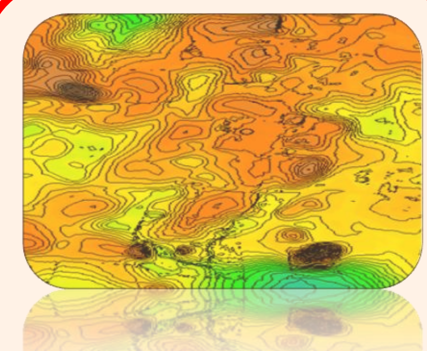


Flow Accumulation



Watershed Hierarchies

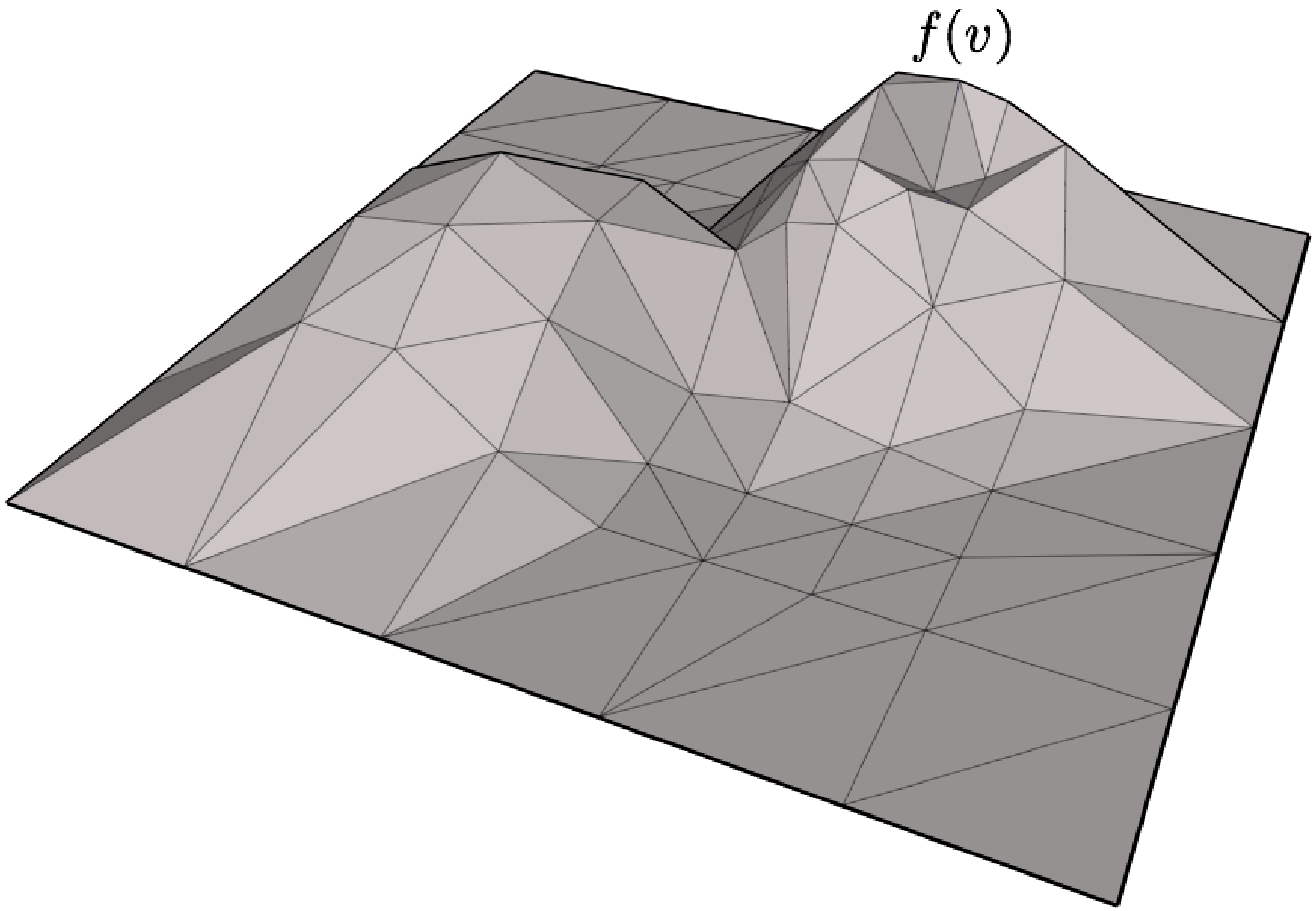
Quality Metrics



Contour Lines

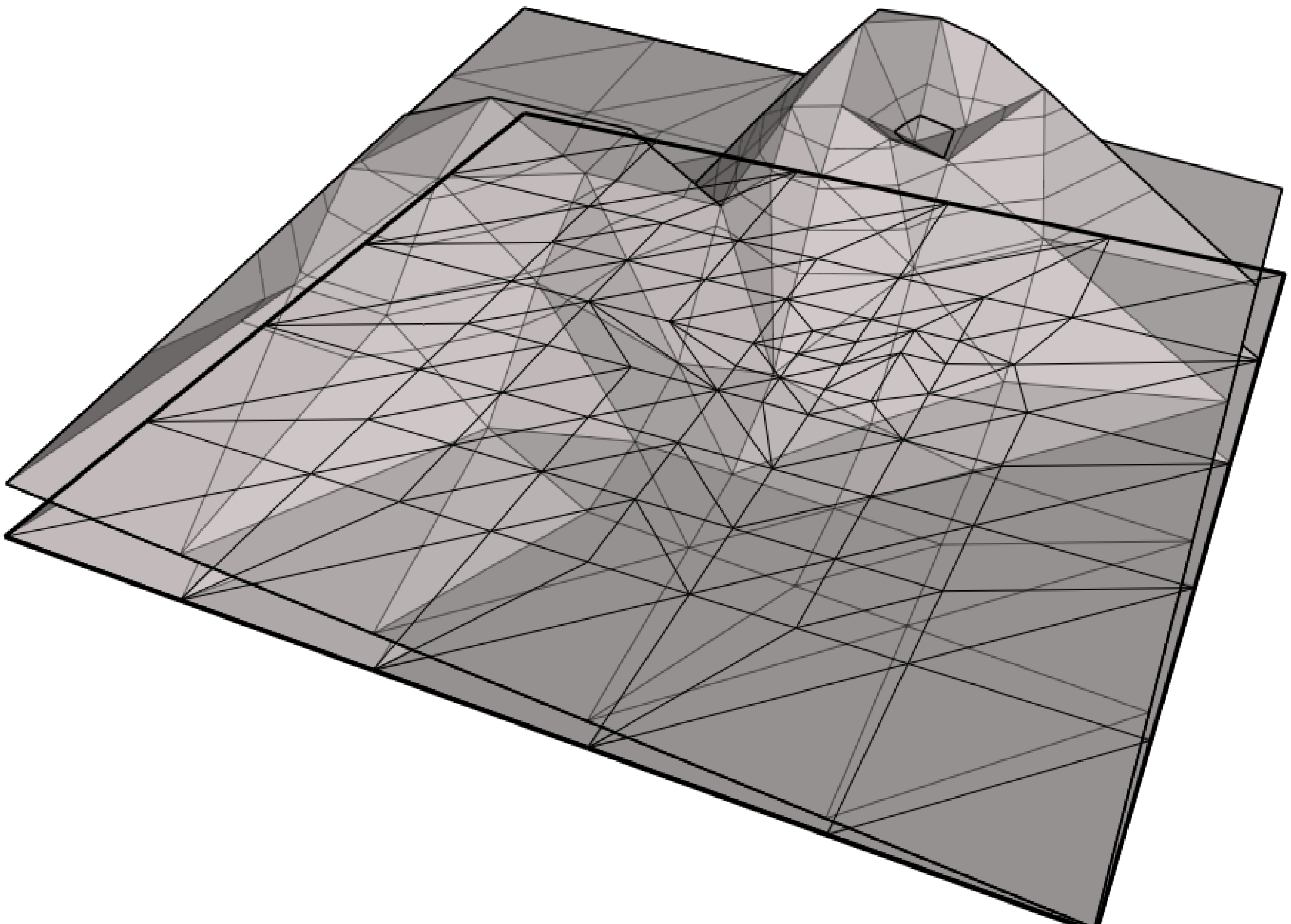
TIN DEM

Given a plane triangulation Σ with with a height $f(v)$ for each vertex v, one can linearly interpolate f in the interior of every face of Σ.



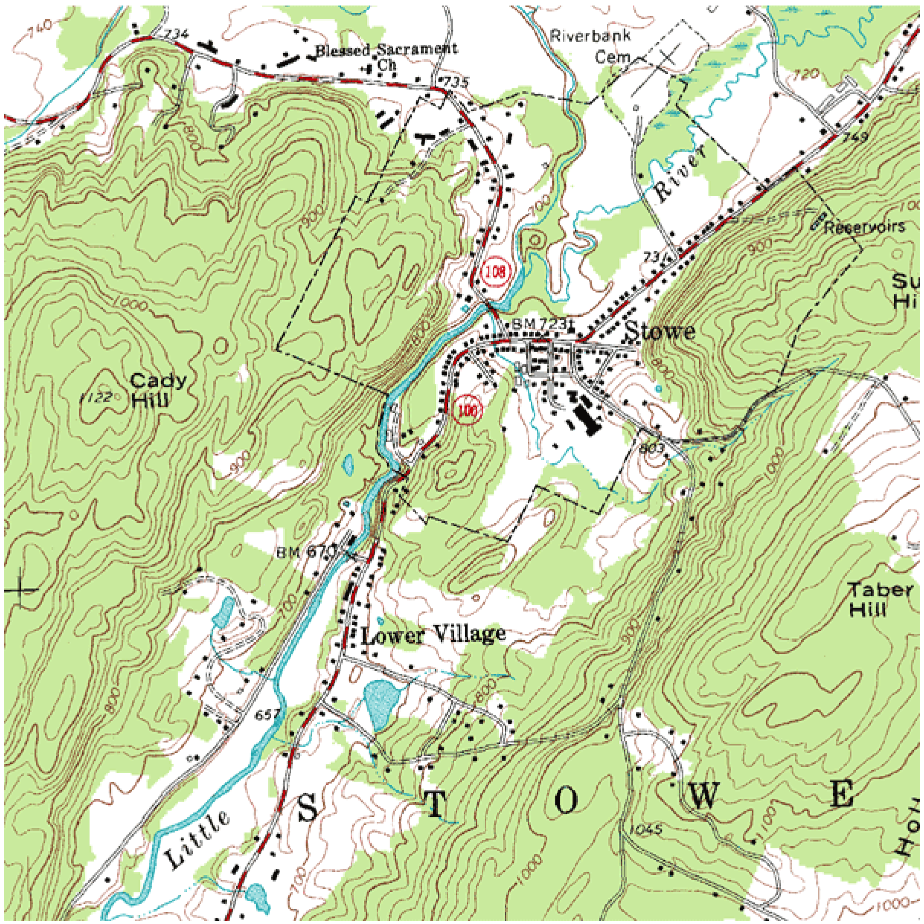
Level Sets, Contours

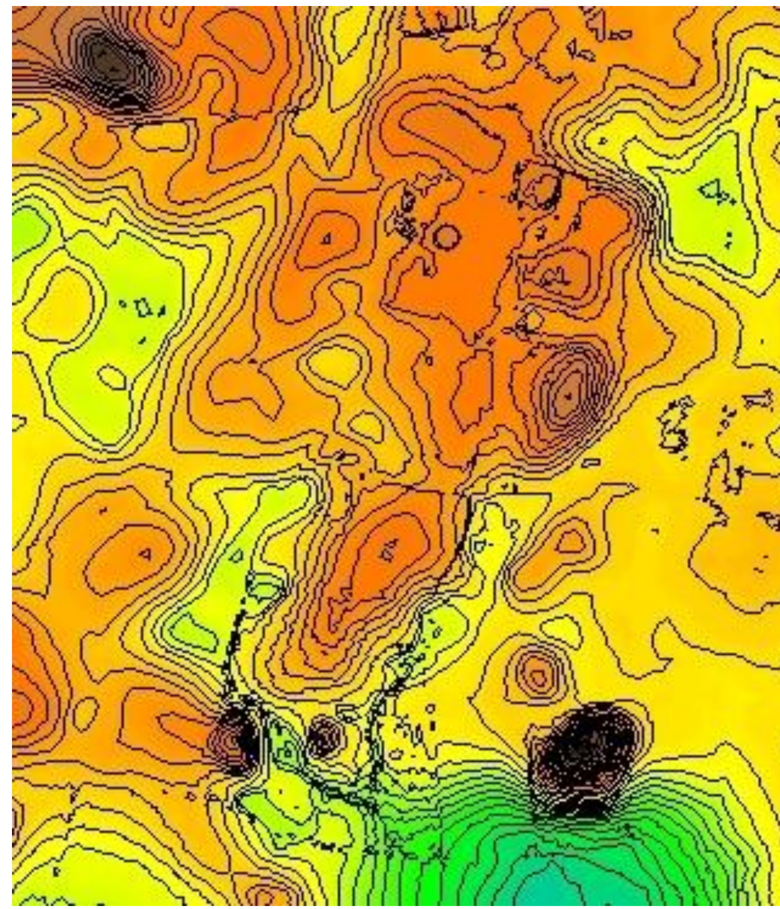
The level-set at height l is $f^{-1}(l)$.
Each connected component of a level set is called a contour.
Given levels $L = \{l_1, \ldots, l_k\}$, the contour map is $f^{-1}(L)$.



Contour Maps

Given a set of levels $L = \{l_1, \ldots, l_k\}$, compute the contour map $f^{-1}(L)$ such that each contour is reported separately and in sorted (circular) order.





Contour Maps

- Usage of contour lines (also called iso-contours, isogons, etc) goes back to at least 17^{th} century

P

of the ſame relative altitude: by ſo doing, I obtained a

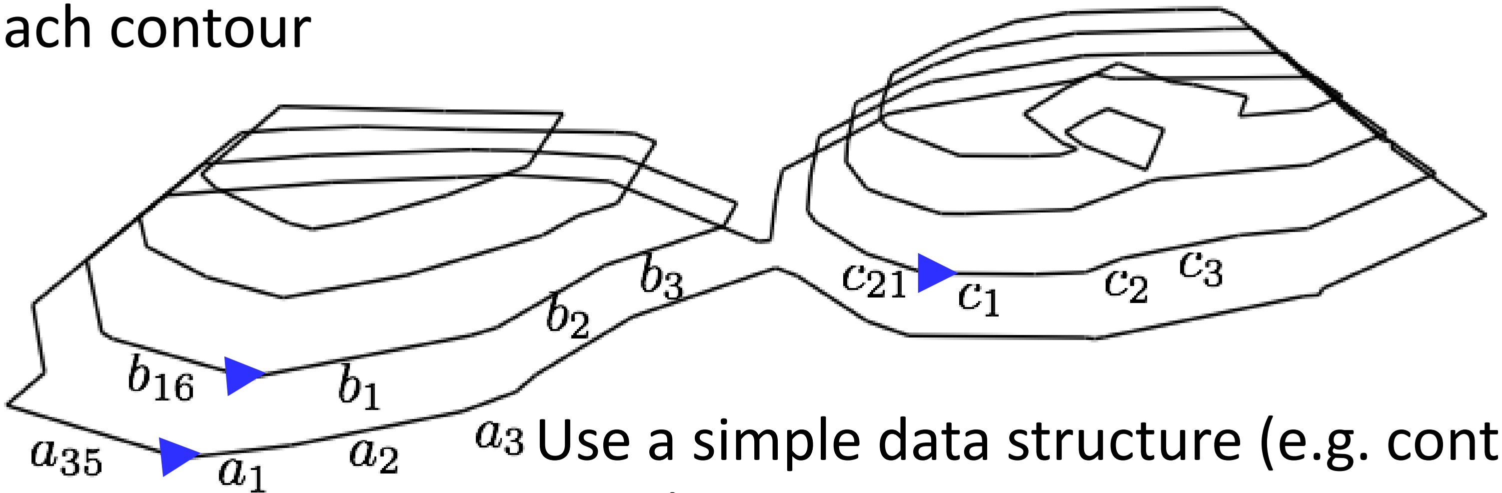
number of irregular polygons lying within and

XXXIII. *An Account of the Calculations made from the Survey and Meaſures taken at* Schehallien, *in order to aſcertain the mean Denſity of the Earth.* *By* Charles Hutton, *Eſq. F. R. S.*

ſeveral of them paſſing through it, I was thereby able to determine the altitude belonging to each ſpace with much eaſe and accuracy. In this eſtimation I could ge-

Computing Contour Map: Internal Memory Algorithm

Find a *seed* point on each contour and traverse the triangulation to trace each contour



Use a simple data structure (e.g. contour trees) to compute seed points

Query time: O(log N + T) T: #contour edges

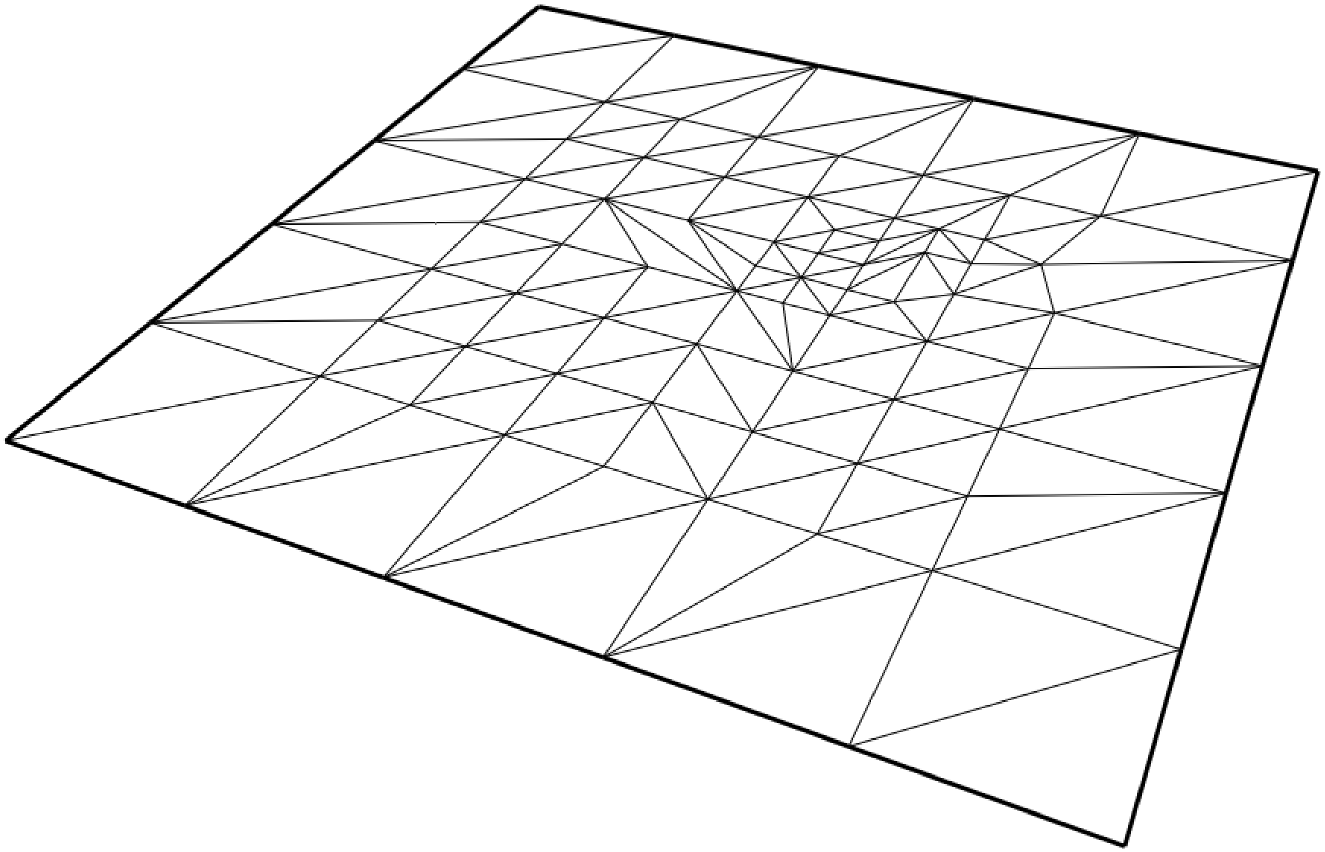
Contour map: O(Nlog N +T) T: #contour map edges

For massive terrains

I/O efficiency is bad: O(N+T) instead of O((N+T)/B)

Storing a TIN on a disk so that it can be traversed with as few I/Os possible

Is there a good ordering of the triangles?



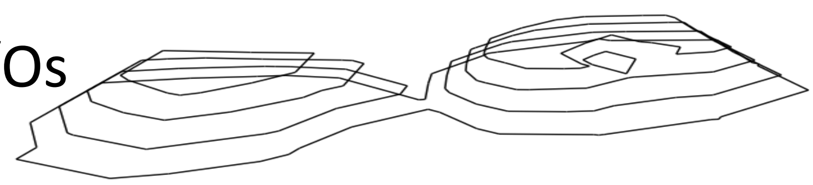
Our results

Ordering Theorem: *A total ordering, called **C-ordering**, of triangles can be computed in O(Sort(N)) I/Os s.t. the subsequence of triangles intersecting a contour appears along the contour and contours in a level set are broken in nested order.*

$$a_1 a_2 - - b_1 - - - c_1 c_2 c_3 - - - - b_2 b_3 - d_1 d_2 - - b_4 - - a_3 a_4 a_5$$

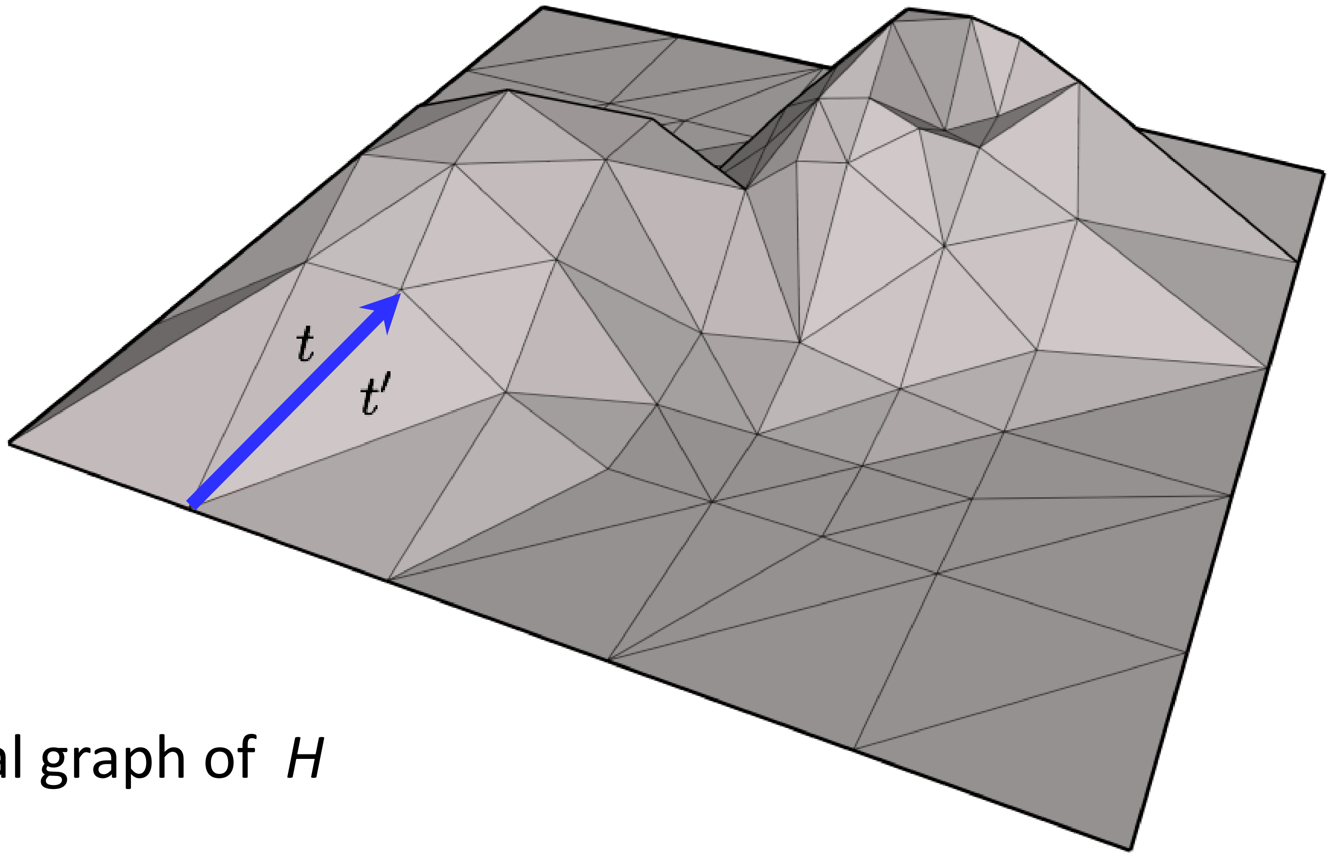
Individual contours can be retrieved in O(T/B)I/Os from this ordering

- Computing contour maps: *O*(Sort(N)+T/B) I/Os
- Answering contour queries
  - Preprocessing Time: *O*(Sort(N)) I/Os
  - Space: *O*(N/B) disk blocks
  - Query: $O(\log_B N + T/B)$



Height Graph

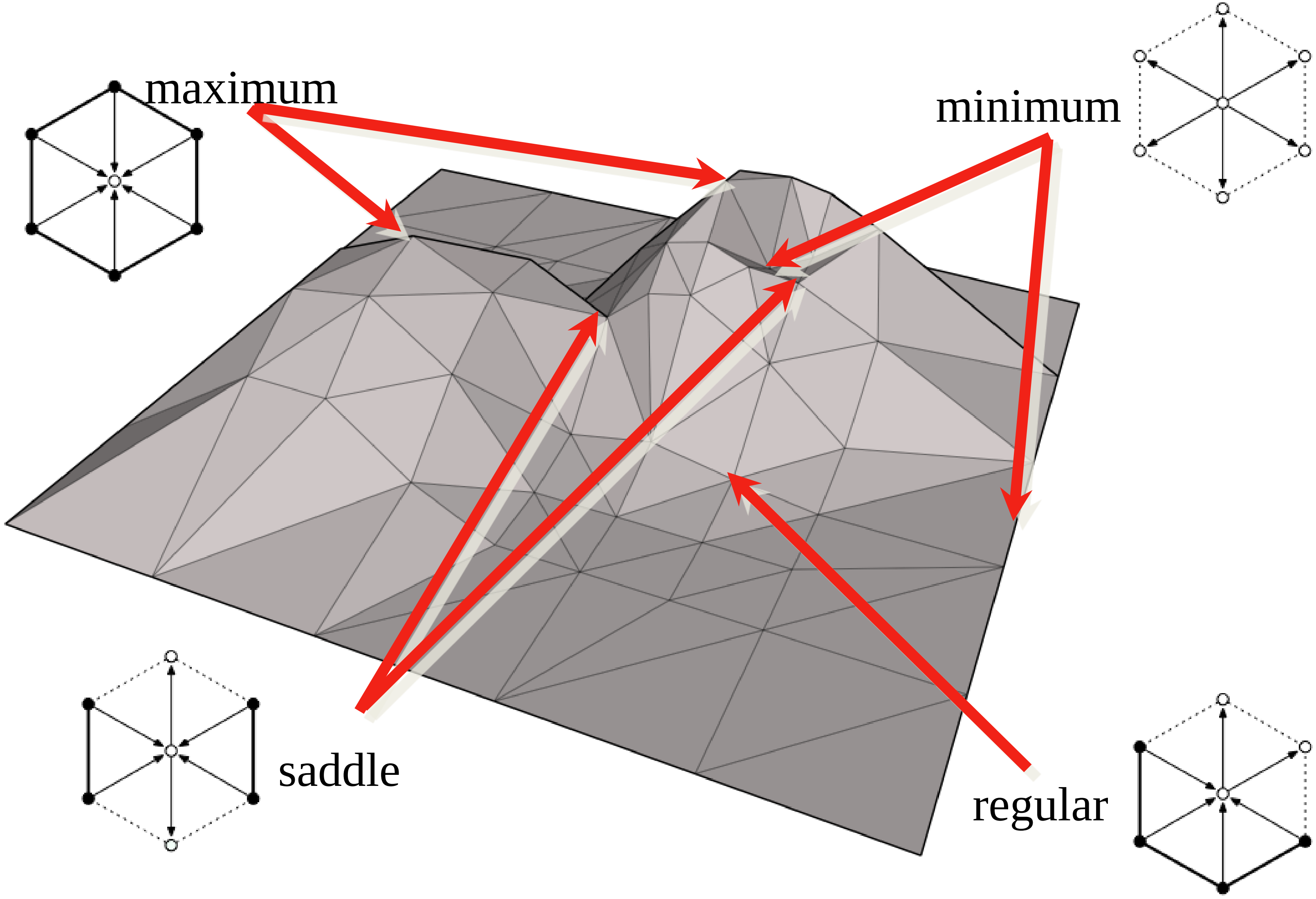
$$H = (V(\Sigma), \{u \rightarrow v : uv \in E(\Sigma), f(u) < f(v)\})$$



*H**: Dual graph of *H*

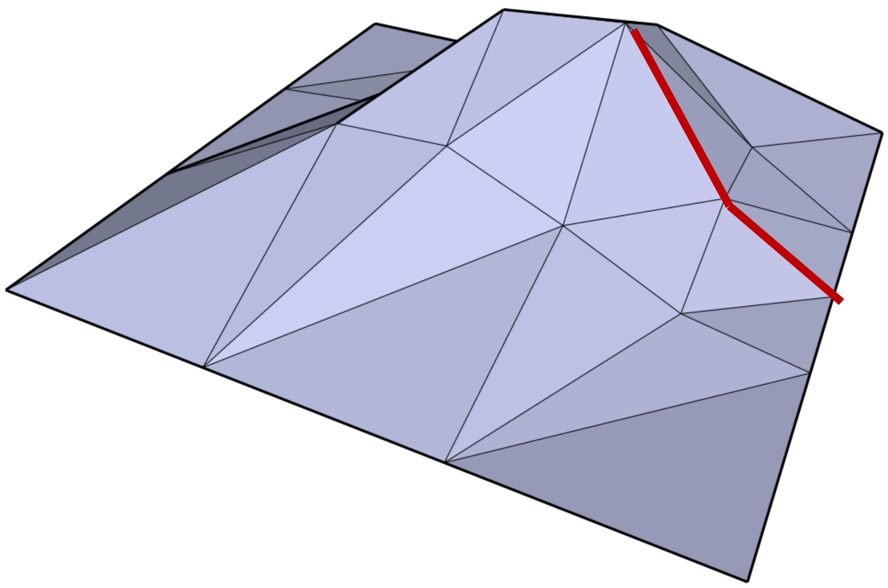
$$t \prec t' \quad \text{iff} \quad t^* \rightarrow t'^* \text{ in } H^*.$$

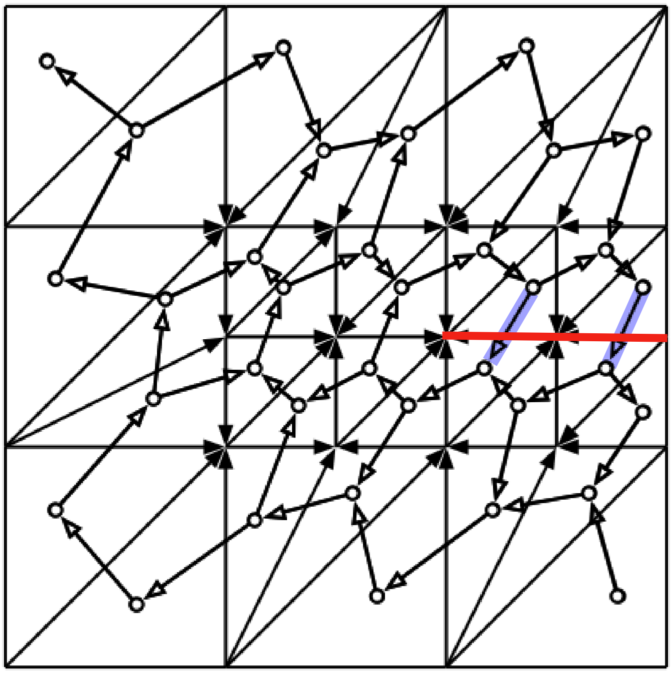
Critical Points



Simple Terrains

A simple terrain is one with no saddles; thus 1 max and 1 min (boundary). Take a min (bd) to max path P and delete its dual from H^*.

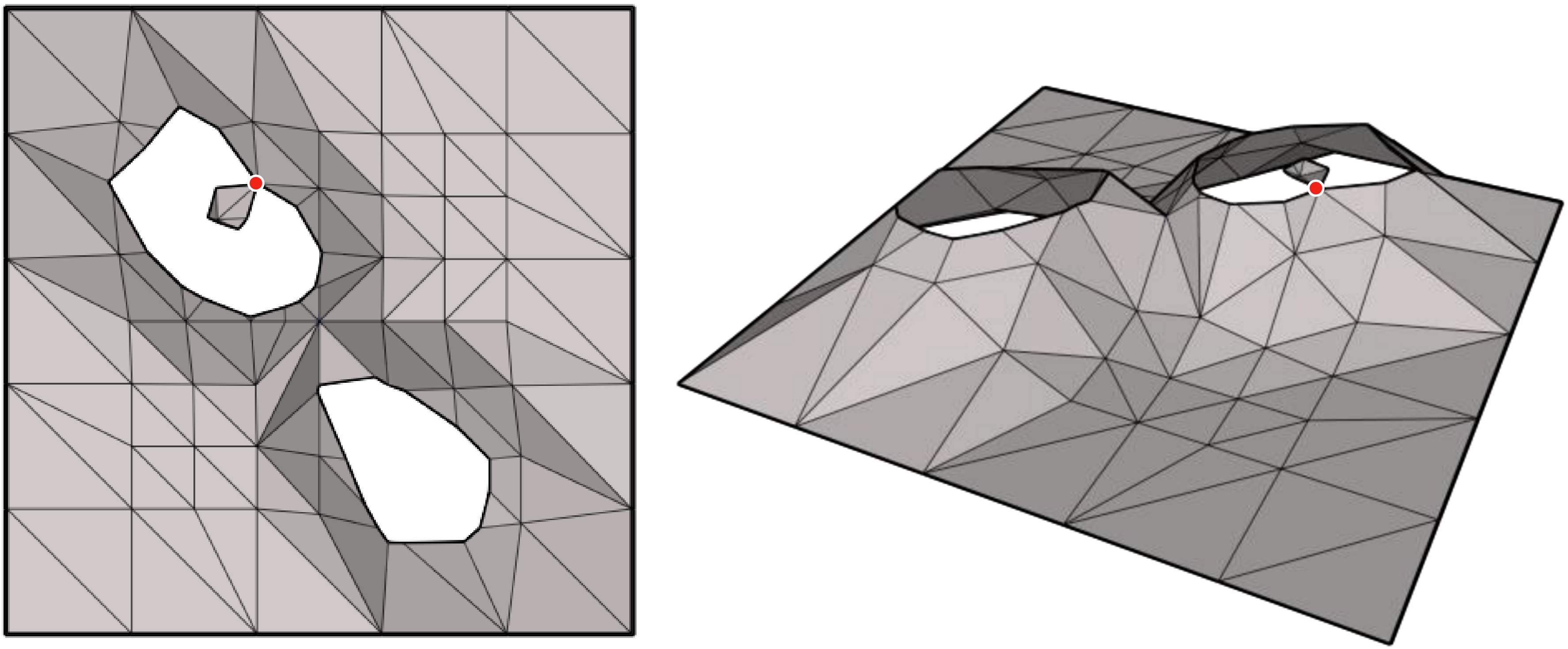




Once the dual graph becomes acyclic, the induced relation "$\prec$" becomes a partial order which can then be topologically sorted into a total order.

Positive & Negative Saddles

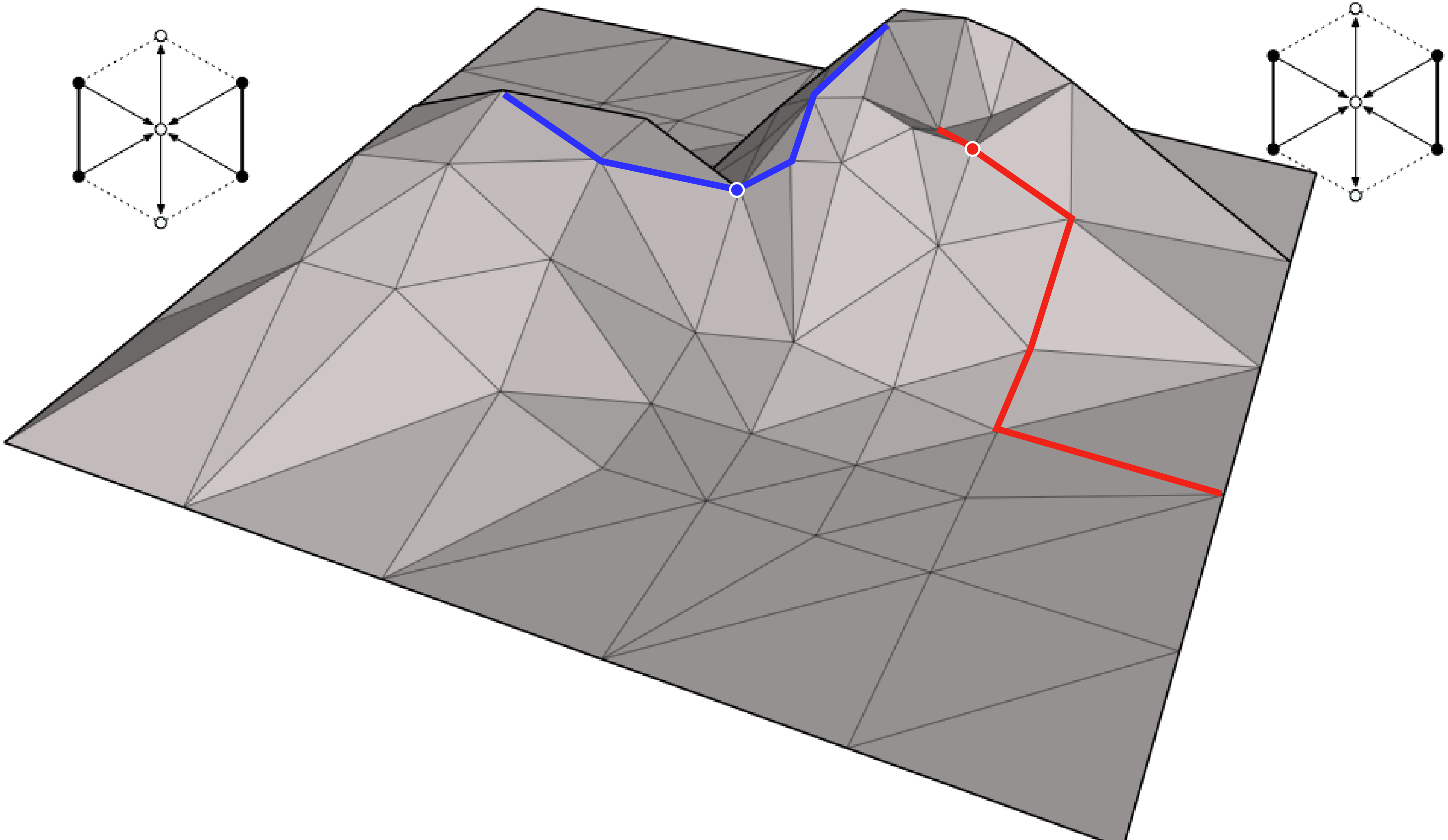
A saddle is negative if it joins two disjoint connected components of its sublevel-set and positive otherwise.



If we replace f with $-f$, the two types switch roles.

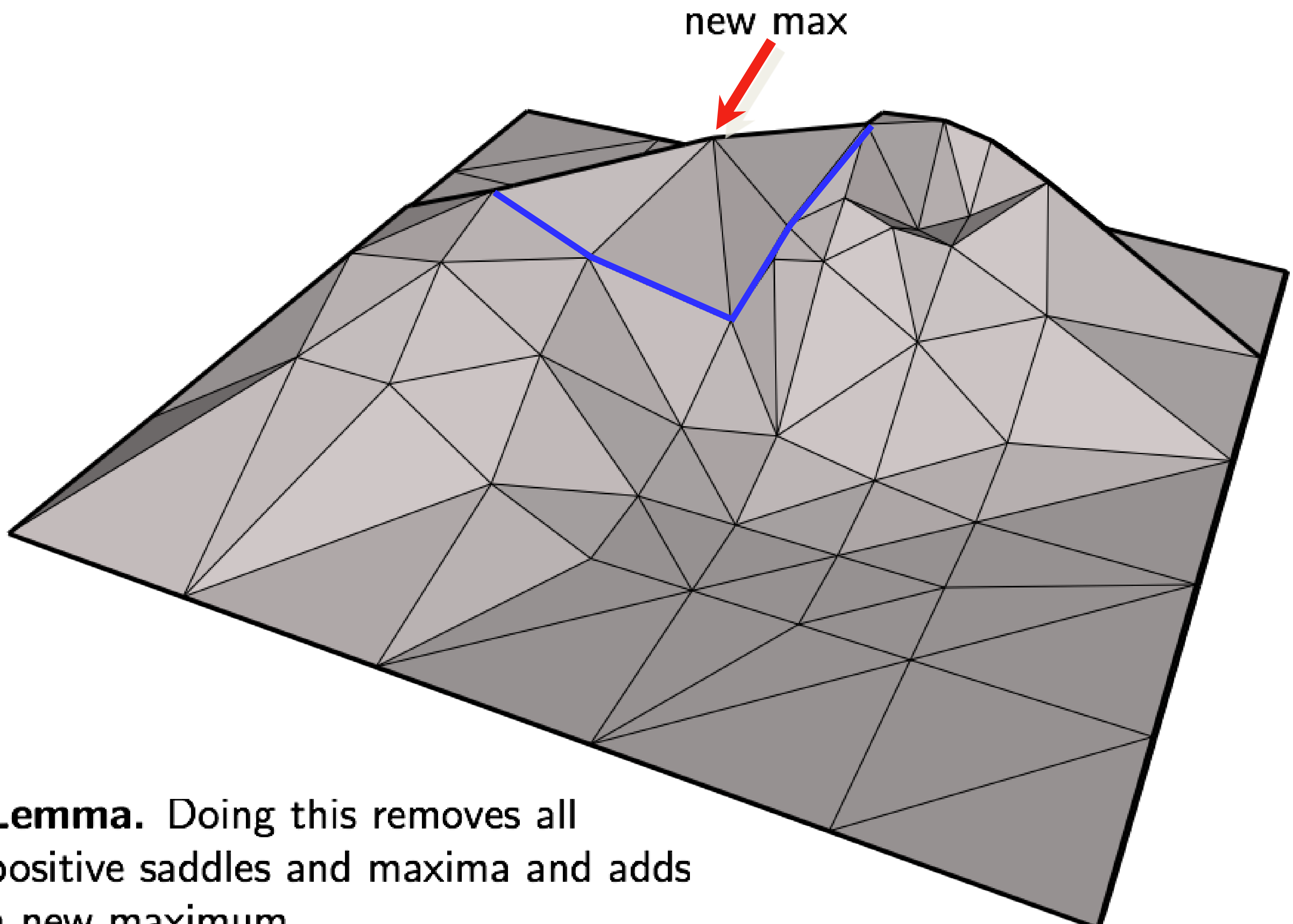
Cut Trees

Positive Cut-Tree: follow an ascending path in every connected component of the upper link of every positive saddle, joining paths when they collide.



Lemma. The result is a tree (not just forest) that reaches every maximum.

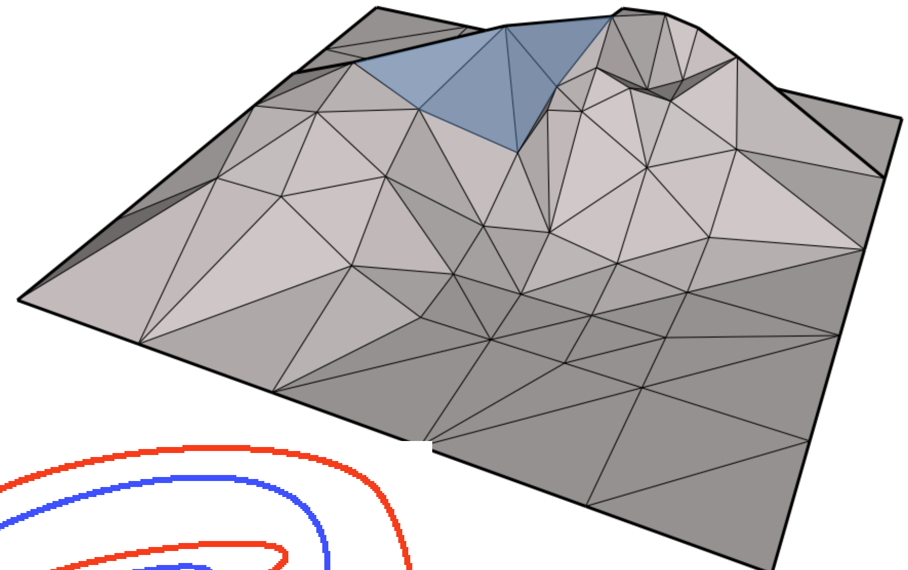
Surgery on Terrain



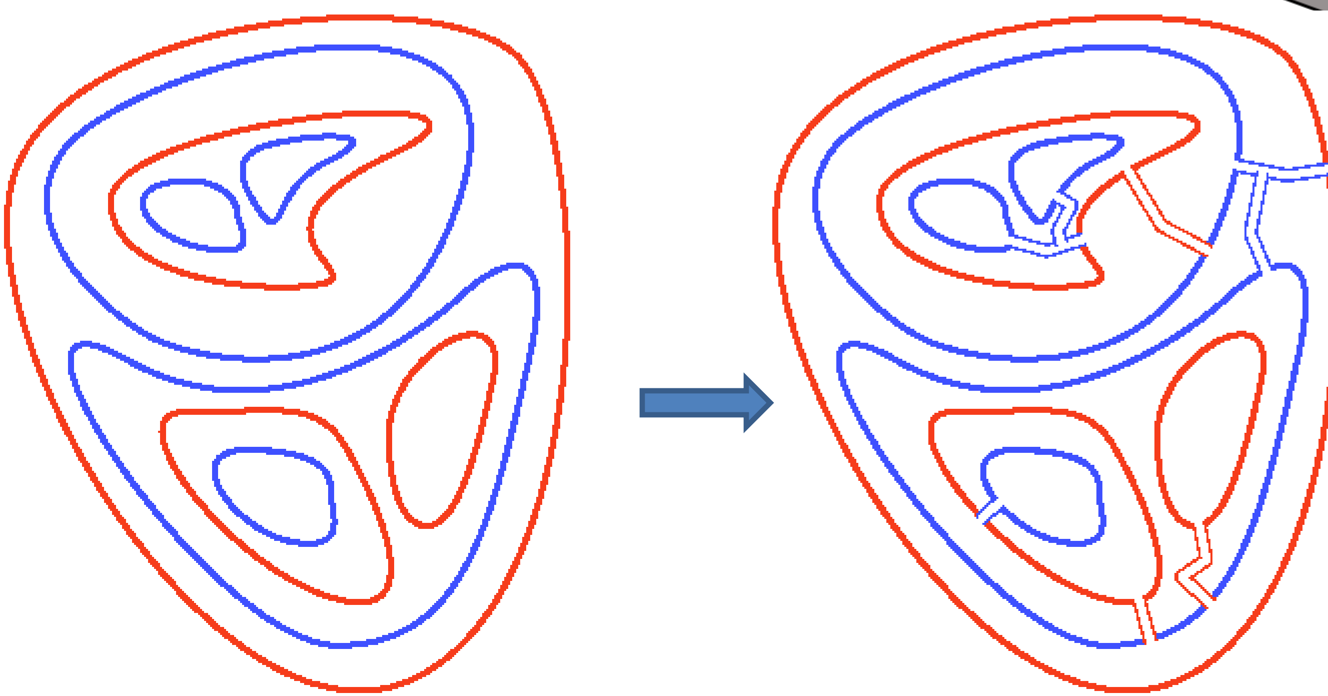
Lemma. Doing this removes all positive saddles and maxima and adds a new maximum.

Surgery & Contours

The simplified terrain T' has all the triangles of the original terrain T plus a number of auxiliary triangles.



All contours of a level set of T are combined in a single contour in T'



Nesting of Contours

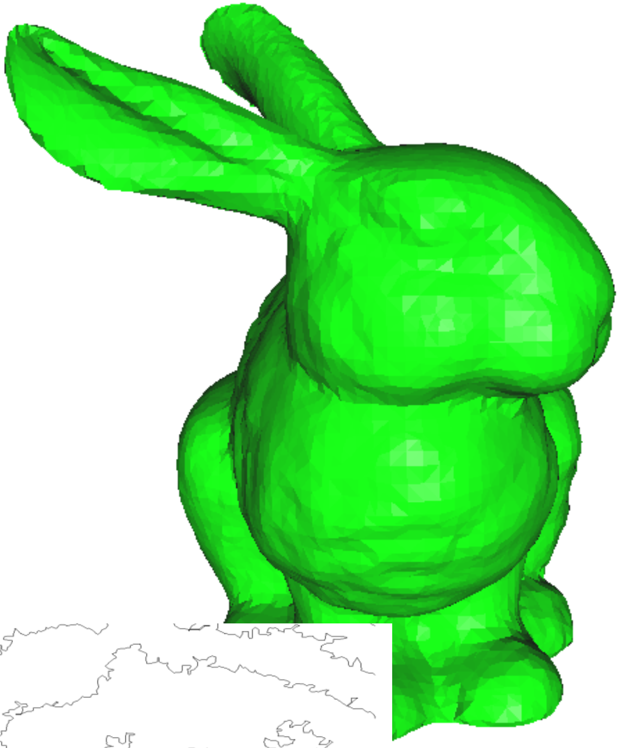
Theorem. In any contour of T', contours of T are broken (by segments from auxiliary triangles) in a nested (parenthesized) manner.

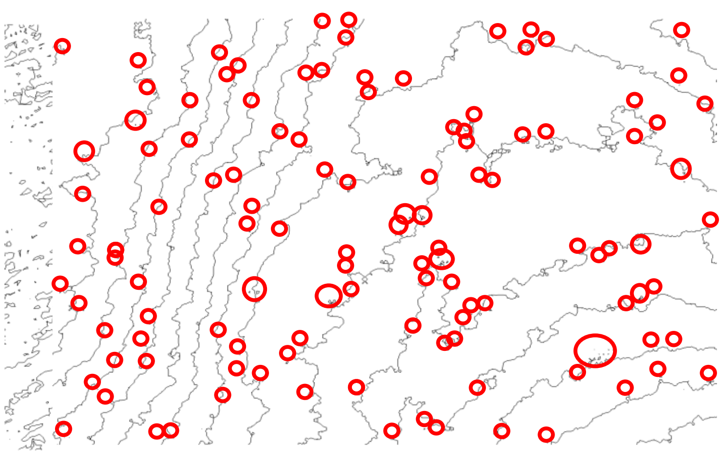
$$[\ a_1 a_2 - -[b_1 - - -[\ c_1 c_2 c_3\ ]- - - -b_2 b_3 -[d_1 d_2\ ]- -b_4\ ]- -a_3 a_4 a_5\ ]$$

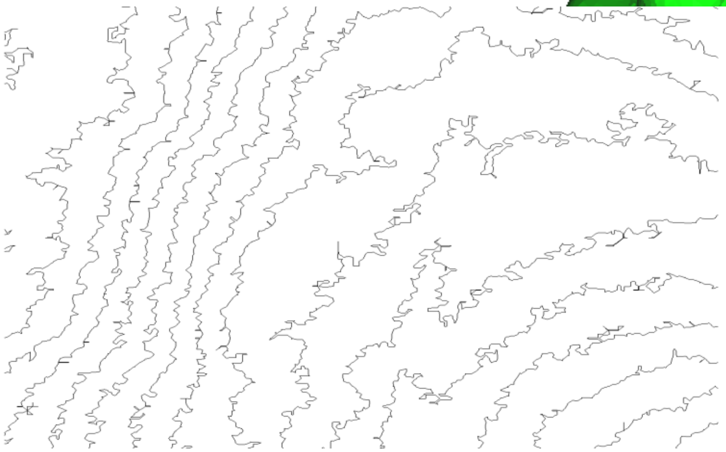
This results a simple stack algorithm that separates tracks belonging to individual contours in $O(T/B)$ I/Os.

Ongoing Work

- Compute C-ordering for general manifolds
- Maintain C-ordering for hierarchical representation of terrains
- Denoising contours







Collaborators

Lars Arge

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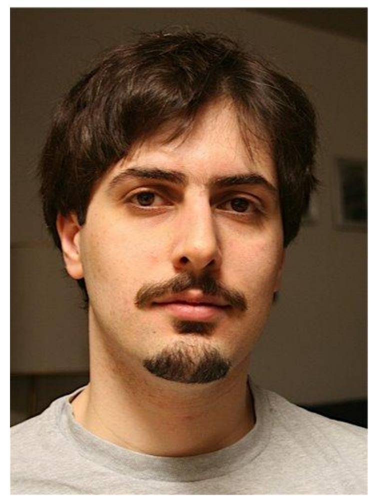
Andy Danner

Thomas Molhave



Bardia Sadri

Ke Yi

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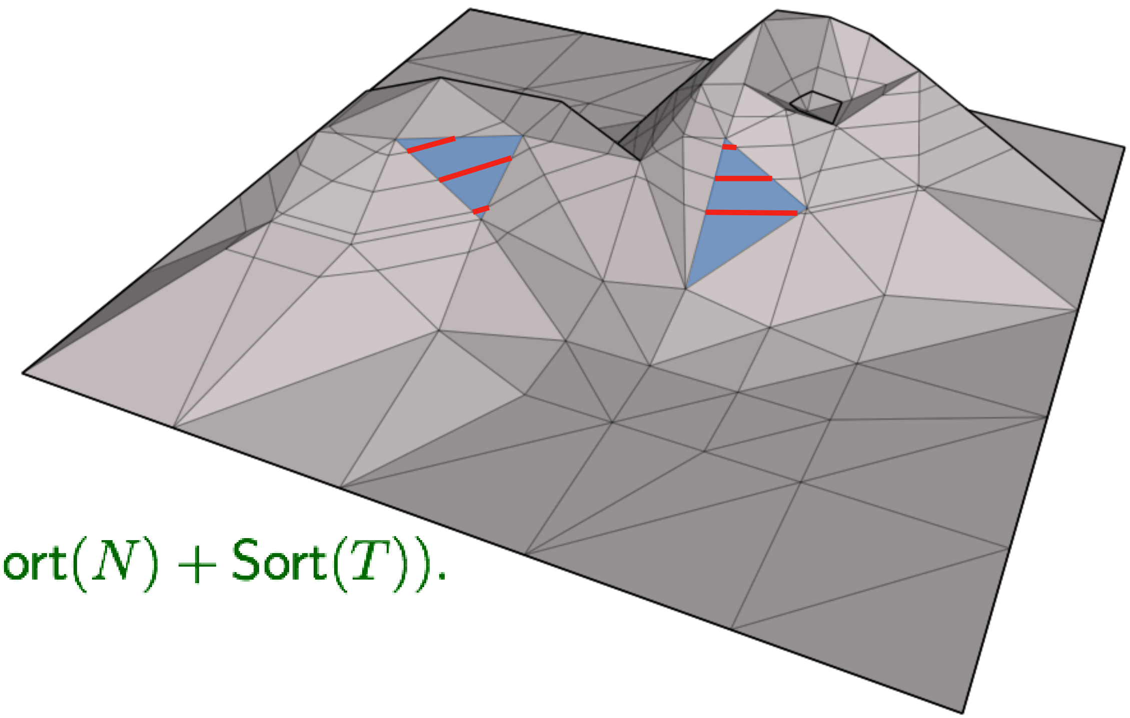
I/O-Efficient Algorithms

Scan the triangles (in the order laid out on the disk) and generate all segments. Then sort the output.



I/O Complexity:

$$O(\mathsf{Sort}(N) + \mathsf{Sort}(T)).$$

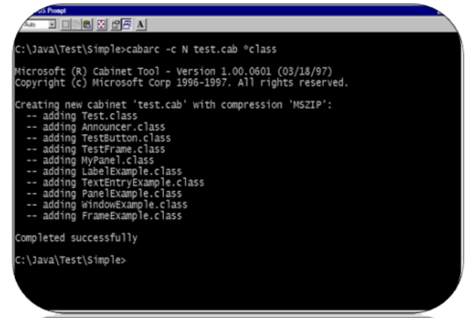
Answering a contour query:

Preprocessing $O(N\log_B N)$, Space: $O(N/B)$ blocks Query: $O(\log_B N + T/B)$

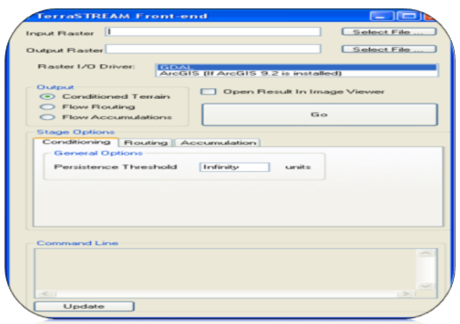
Front-ends

ArcGIS Extension

GRASS Extension



Command Line Tools



Front-End GUI

MapInfo