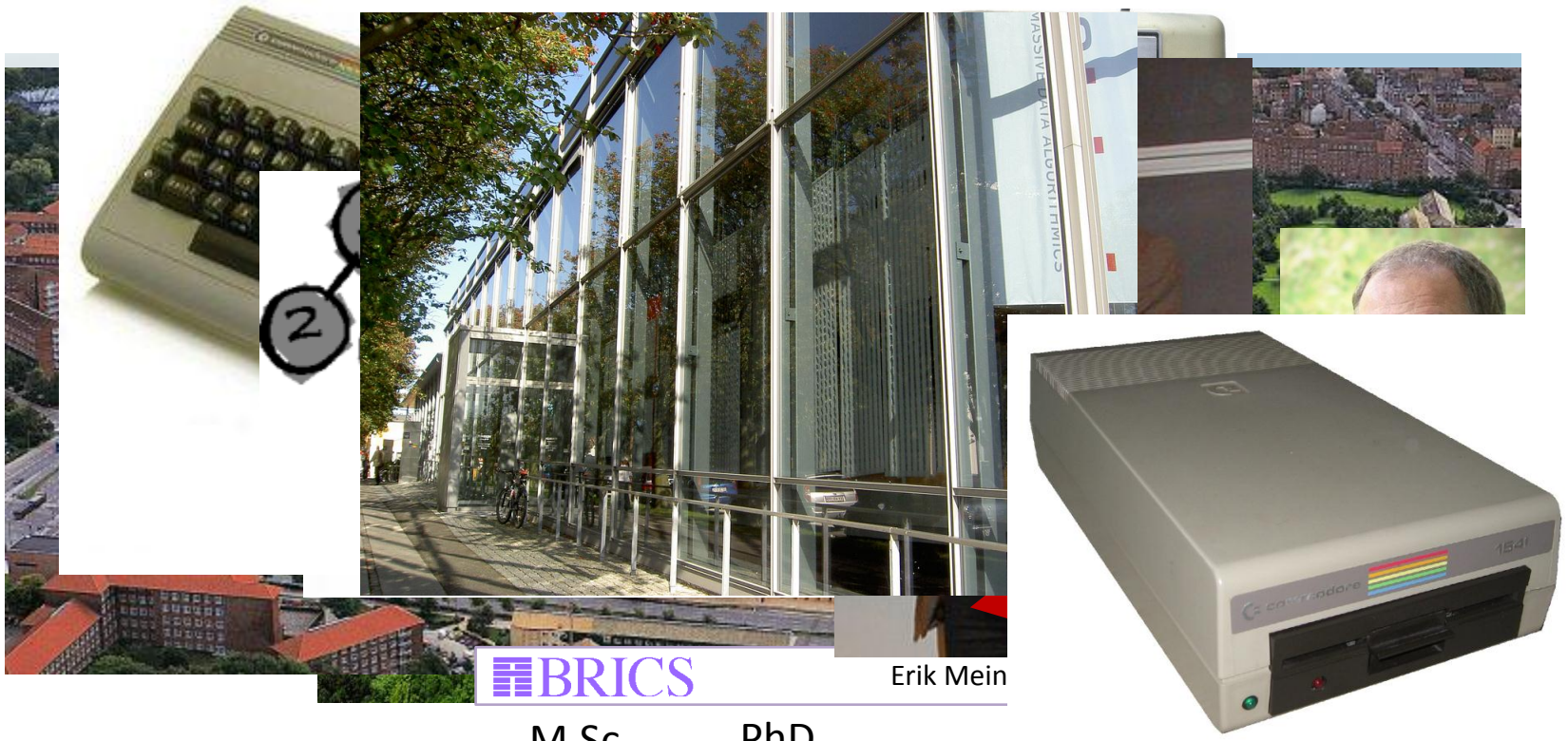
# Massive Data Algorithmics

Gerth Stølting Brodal
Aarhus University

MADALGO
CENTER FOR MASSIVE DATA ALGORITHMICS

Forskningsdag for Datamatikerlærere, Erhvervsakademiet Lillebælt, Vejle, November 2, 2010

# Gerth Stølting Brodal



# Outline of Talk

- MADALGO
  CENTER FOR MASSIVE DATA ALGORITHMICS
  - who, where, what ?
  - reseach areas
- External memory algorithmics
  - models
  - searching and sorting
- Fault-tolerant searching
- Flow simulation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MADALGO

CENTER FOR MASSIVE DATA ALGORITHMICS

# – Where?

MADALGO
CENTER FOR MASSIVE DATA ALGORITHMICS

- Center of Danmarks Grundforskningsfond Danish National Research Foundation
- **Lars Arge**, Professor, Centerleader
- Gerth S. Brodal, Associate Professor
- 5 Post Docs, 10 PhD students, 4 TAP
- Total budget for 5 years ca. 60 million DKR

AU

Arge

Brodal

MIT

Demaine

Indyk

MPII

Mehlhorn

Frankfurt

Meyer

# MADALGO

CENTER FOR MASSIVE DATA ALGORITHMICS

**Faculty**

Lars Arge

Gerth Stølting Brodal

**Researchers**

Henrik Blunck

Brody Sandel

Nodari Sitchinava

Elad Verbin

Qin Zhang

**PhD Students**

Lasse Kosetski Deleuran

Freek van Walderveen

Casper Kejlberg-Rasmussen

Kasper Dalgaard Larsen

Jesper Erenskjold Moeslund

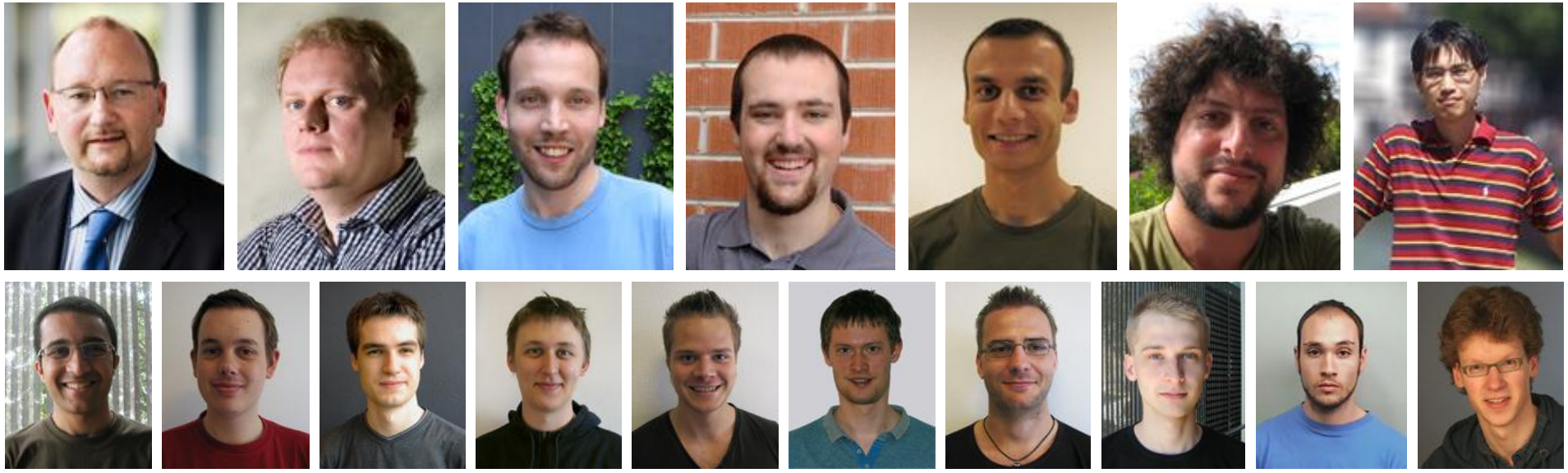
Jakob Truelsen

Kostas Tsakalidis

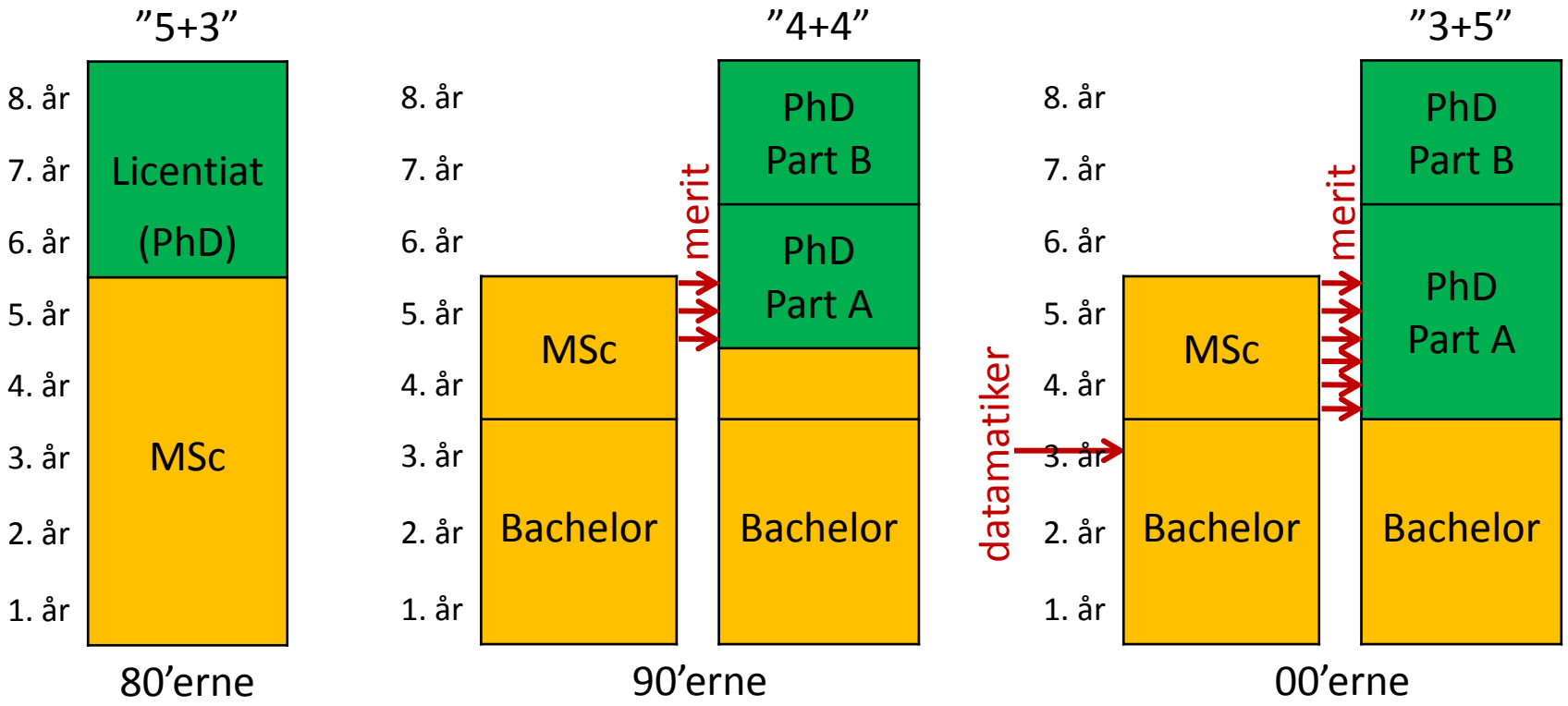
Mark Greve

Morten Revsbæk

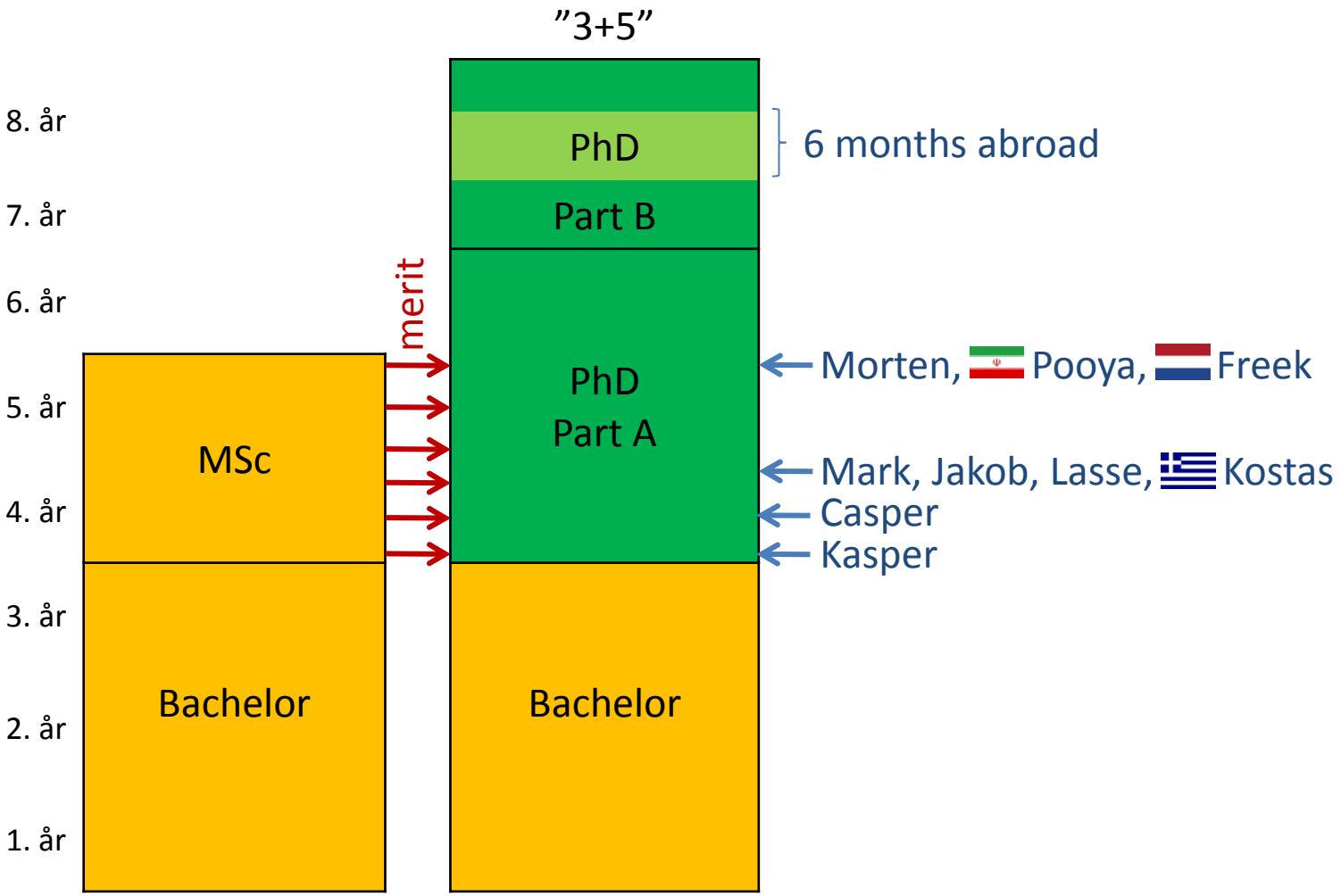
Pooya Davoodi



# PhD Education @ AU



# PhD Education @ MADALGO




snowbird

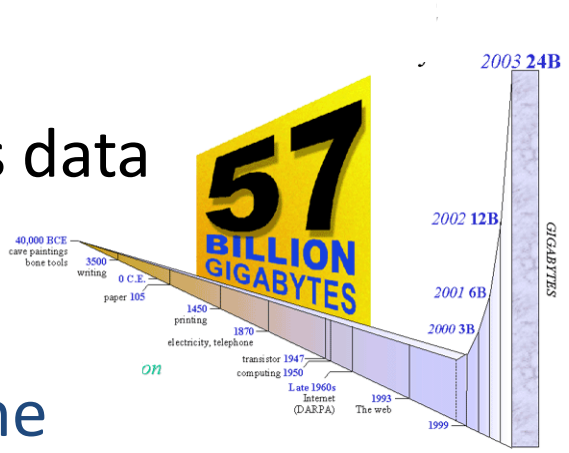

MASSIVE 2010
Summer School 2010
SoCG 2009
Retreat 2009
Massive Data Algorithmics
Retreat 2008
MASSIVE 2009
Summer School 2008
Retreat 2007
Summer School 2007
Inauguration 2007

MADALGO
CENTER FOR MASSIVE DATA ALGORITHMICS

- *High level objectives*
  - Advance algorithmic knowledge in “massive data” processing area
  - Train researchers in world-leading international environment
  - Be catalyst for multidisciplinary/industry collaboration
- *Building on*
  - Strong international team
  - Vibrant international environment (focus on people)

# Massive Data

- Pervasive use of computers and sensors
- Increased ability to acquire/store/process data
  → Massive data collected everywhere
- Society increasingly "data driven"
  → Access/process data anywhere any time




Nature special issues

- 2/06: "2020 – Future of computing"
- 9/08: "BIG DATA



- Scientific data size growing exponentially, while quality and availability improving
- Paradigm shift: *Science will be about mining data*
  → Computer science paramount in all sciences

# Massive Data

- Pervasive use of computers and sensors
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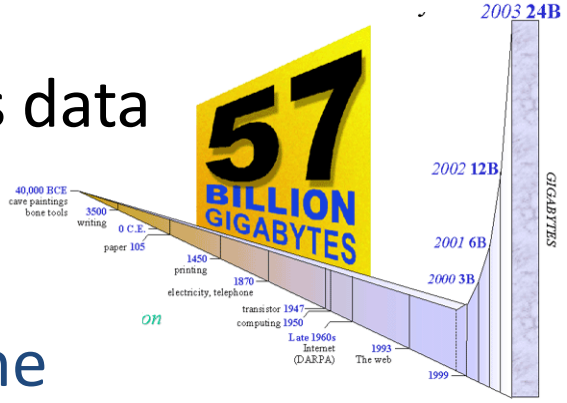
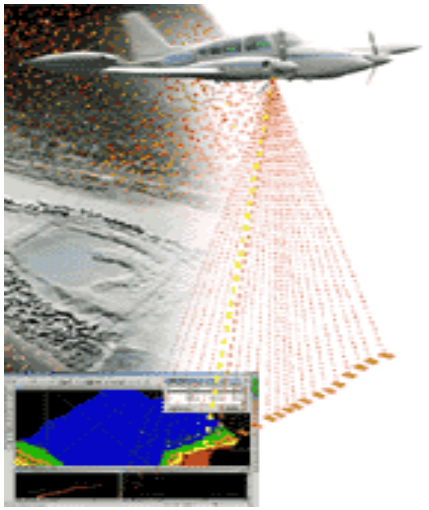


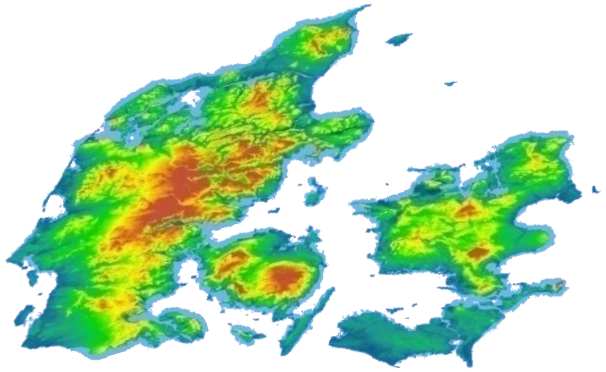

Obviously not only in sciences:

- Economist 02/10:
  - From 150 Billion Gigabytes five years ago to 1200 Billion today
  - Managing data deluge difficult; doing so will transform business/public life

# Example: Massive Terrain Data

- New technologies: Much easier/cheaper to collect detailed data
  - Previous 'manual' or radar based methods
    - Often 30 meter between data points
    - Sometimes 10 meter data available
  - New laser scanning methods (LIDAR)
    - Less than 1 meter between data points
    - Centimeter accuracy (previous meter)





Denmark

~2 million points at 30 meter (<1GB)

~18 billion points at 1 meter (>1TB)

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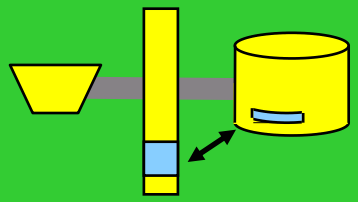
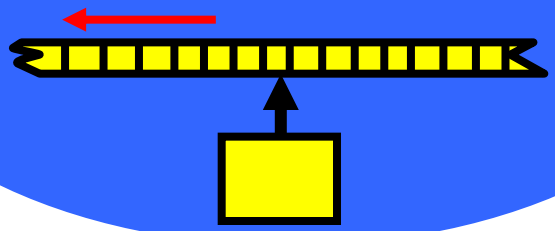
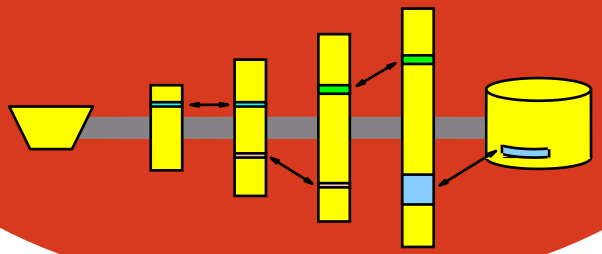
## I/O Efficient Algorithms



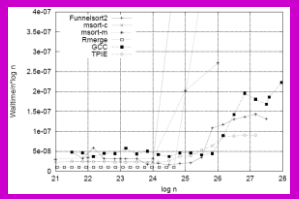
## Streaming Algorithms

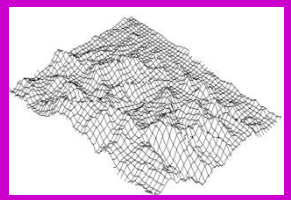


## Cache Oblivious Algorithms

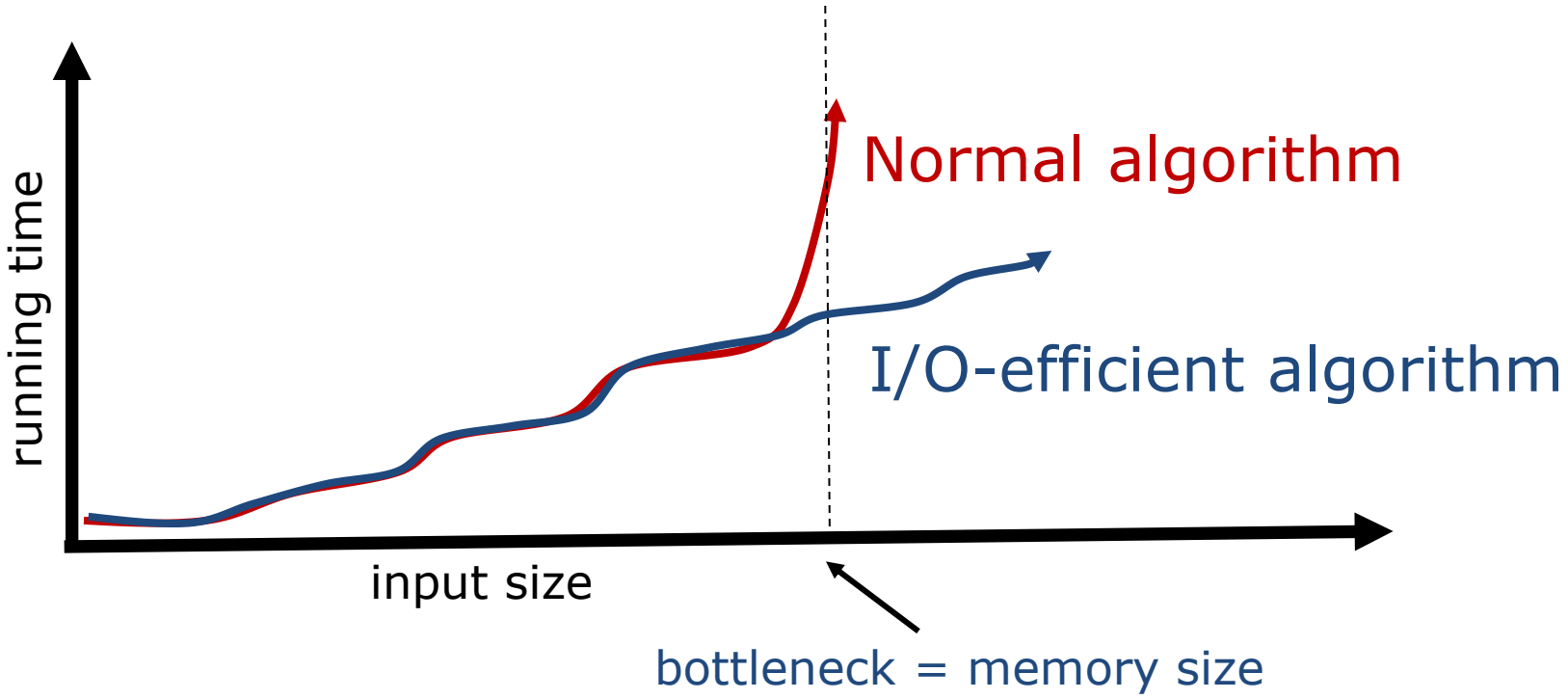


## Algorithm Engineering

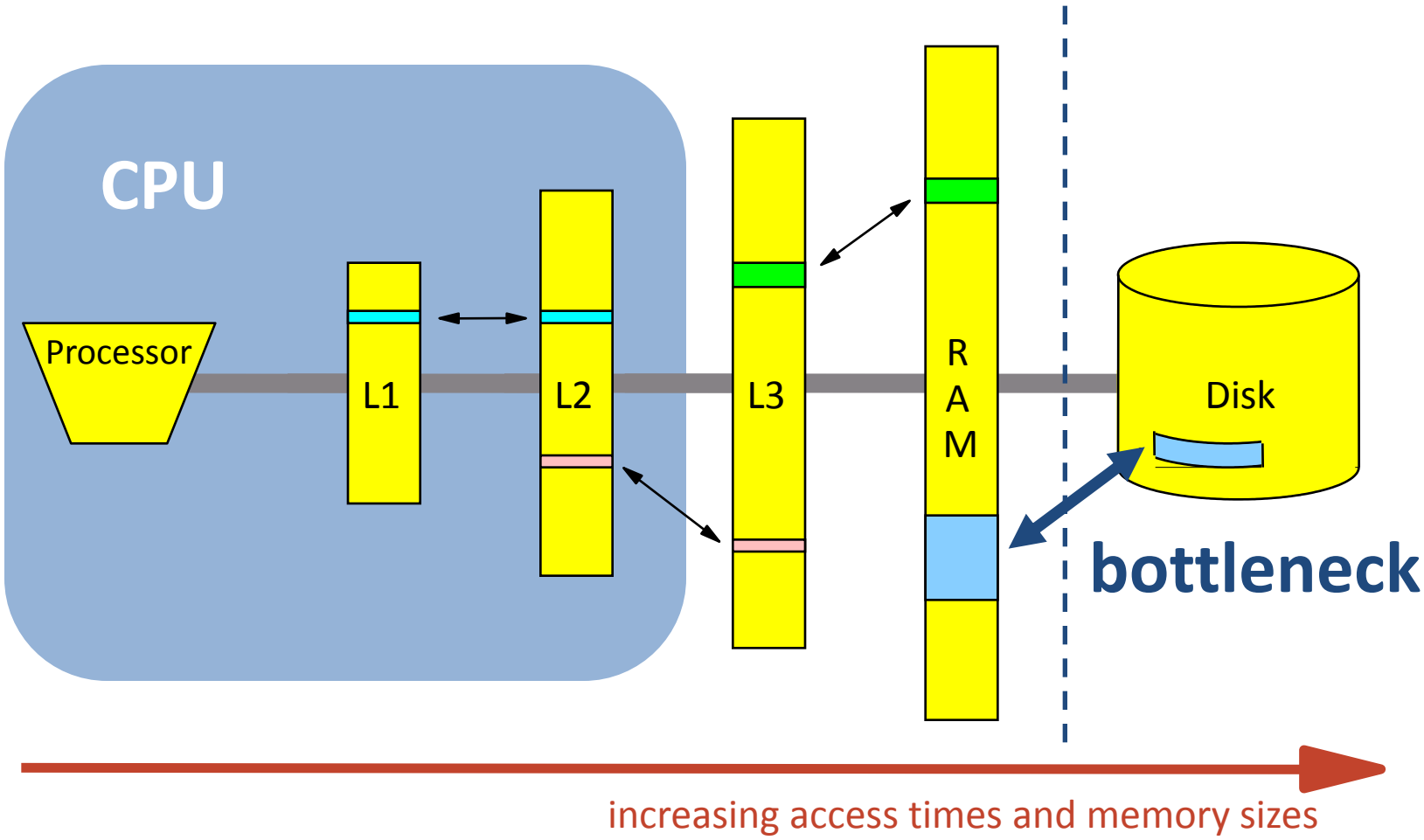


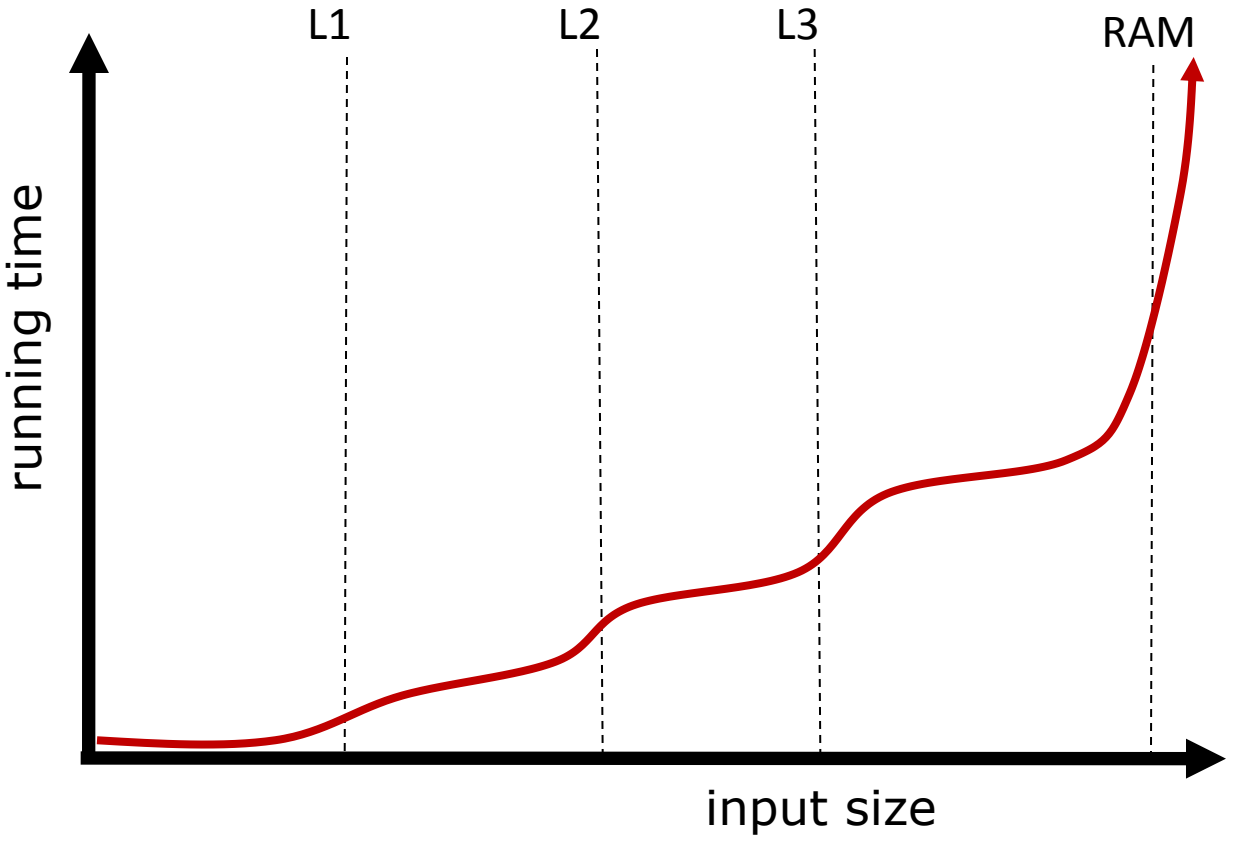
# The problem...


running time
input size
Normal algorithm
I/O-efficient algorithm
bottleneck = memory size

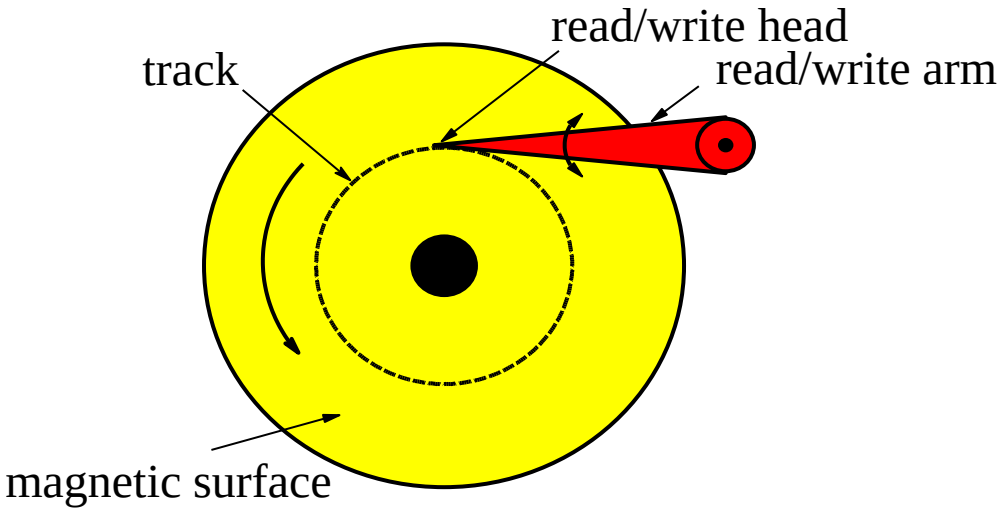
# Memory Hierarchies



# Memory Hierarkies vs. Running Time

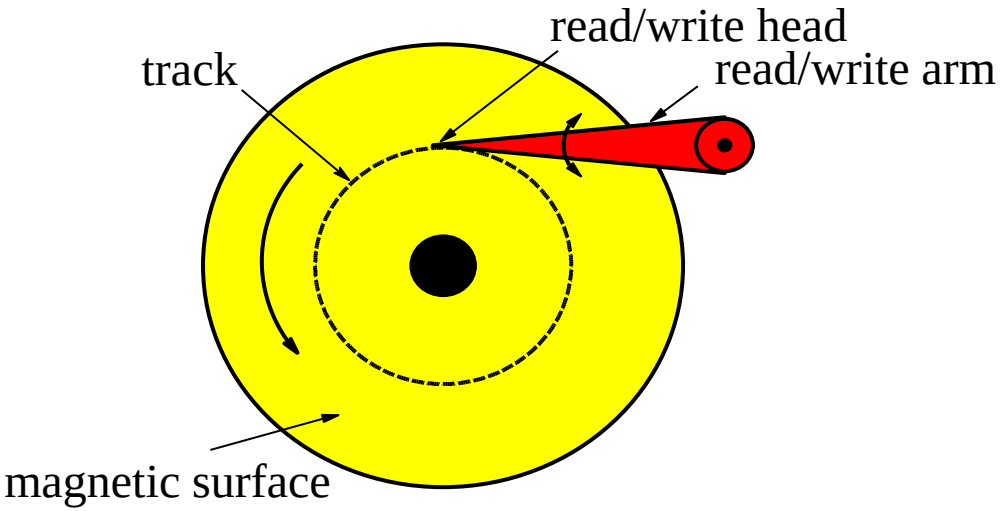


# Disk Mechanics




*"The difference in speed between modern CPU and disk technologies is analogous to the difference in speed in sharpening a pencil using a sharpener on one's desk or by taking an airplane to the other side of the world and using a sharpener on someone else's desk."* (D. Comer)

# Disk Mechanics



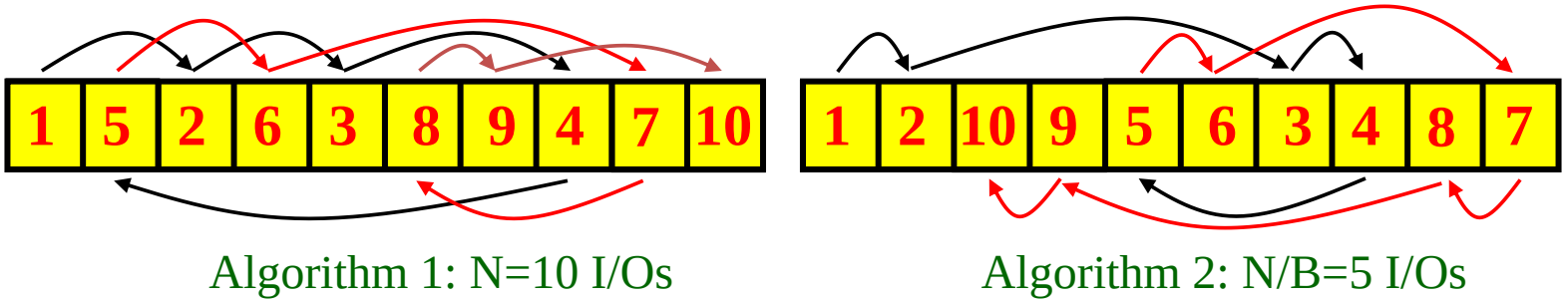

- I/O is often bottleneck when handling massive datasets
- Disk access is $10^7$ times slower than main memory access!
- Disk systems try to amortize large access time transferring large contiguous blocks of data
- Need to store and access data to take advantage of blocks !

# Memory Access Times

| | Latency | Relative to CPU |
|---|---|---|
| Register | 0.5 ns | 1 |
| L1 cache | 0.5 ns | 1-2 |
| L2 cache | 3 ns | 2-7 |
| DRAM | 150 ns | 80-200 |
| TLB | 500+ ns | 200-2000 |
| Disk | 10 ms | $10^7$ |

# I/O-Efficient Algorithms Matter

- Example: Traversing linked list (List ranking)
  - Array size $N$ = 10 elements
  - Disk block size $B$ = 2 elements
  - Main memory size $M$ = 4 elements (2 blocks)




Algorithm 1: N=10 I/Os

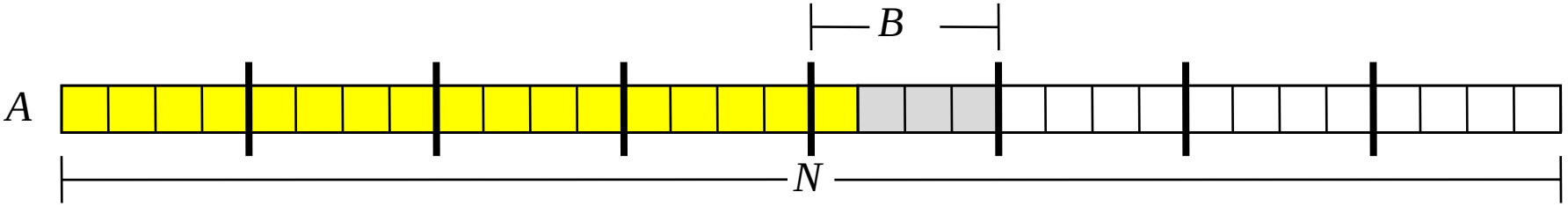
Algorithm 2: N/B=5 I/Os

- Difference between $N$ and $N/B$ large since block size is large
  - Example: $N = 256 \times 10^6$, $B = 8000$ , $1ms$ disk access time

    $\Rightarrow$ $N$ I/Os take $256 \times 10^3$ $sec = 4266$ $min = 71$ $hr$

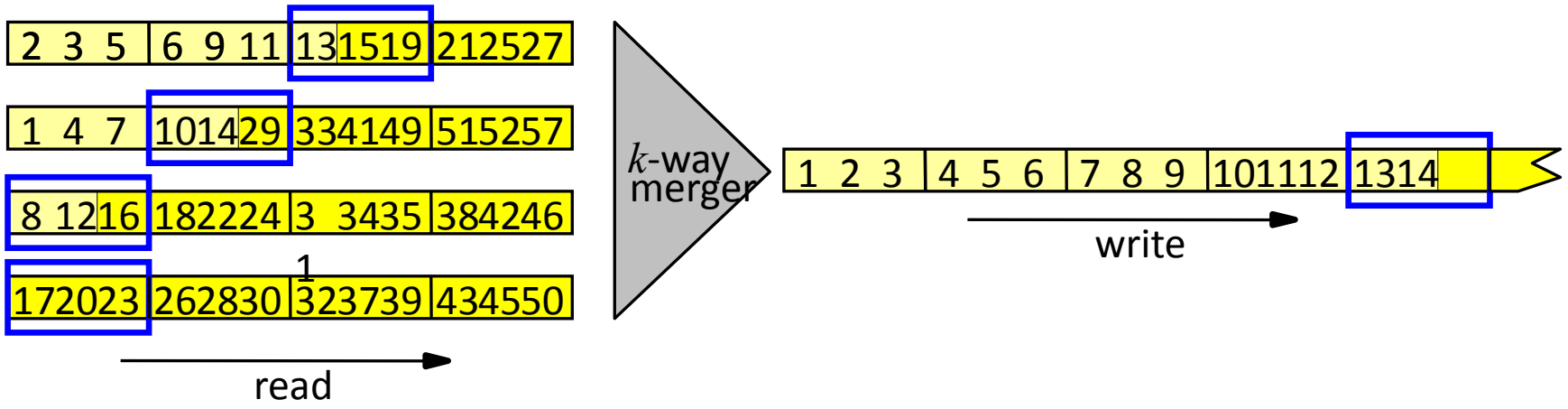
    $\Rightarrow$ $N/B$ I/Os take $256/8$ $sec = 32$ $sec$

# I/O Efficient Scanning



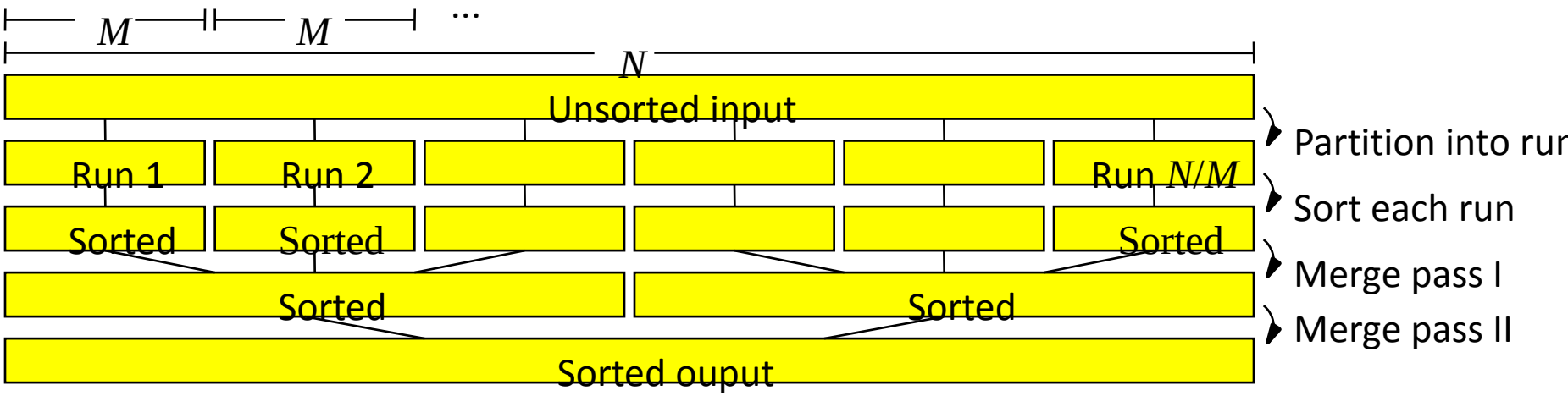

$O(N/B)$ I/Os

# External-Memory Merging



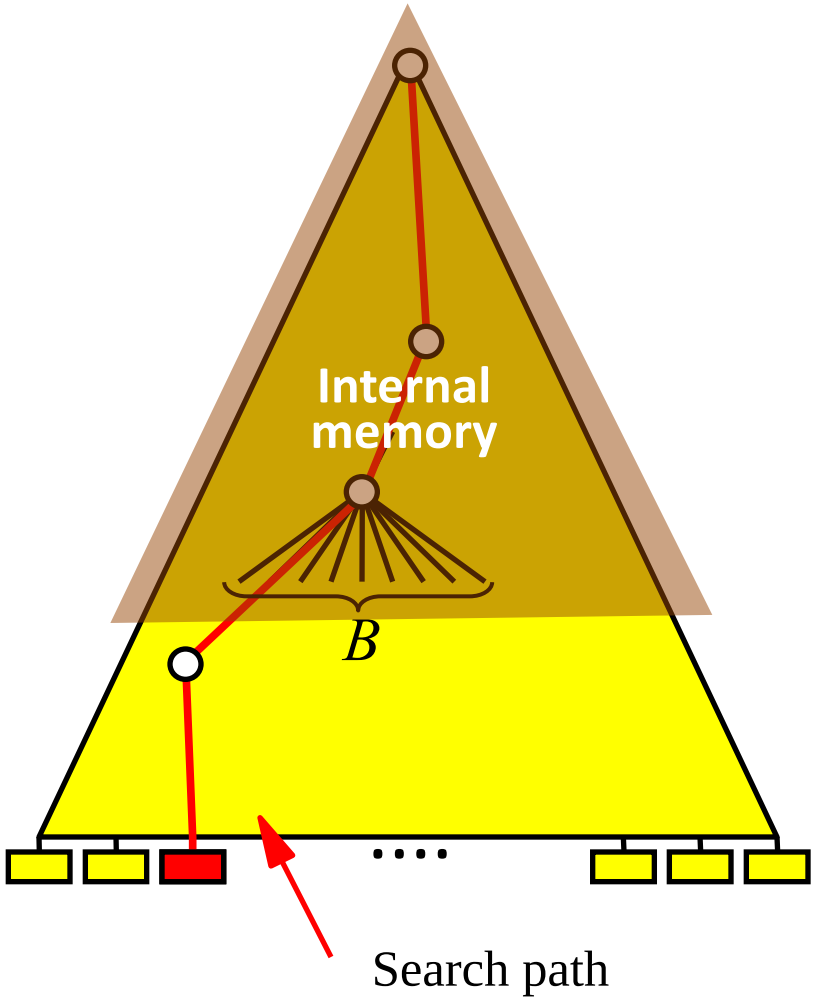

Merging $k$ sequences with $N$ elements requires $O(N/B)$ IOs (provided $k \leq M/B - 1$)

# External-Memory Sorting




- MergeSort uses $O(N/B \cdot \log_{M/B}(N/B))$ I/Os
- Practice number I/Os: 4-6 x scanning input

# B-trees -
# The Basic Searching Structure



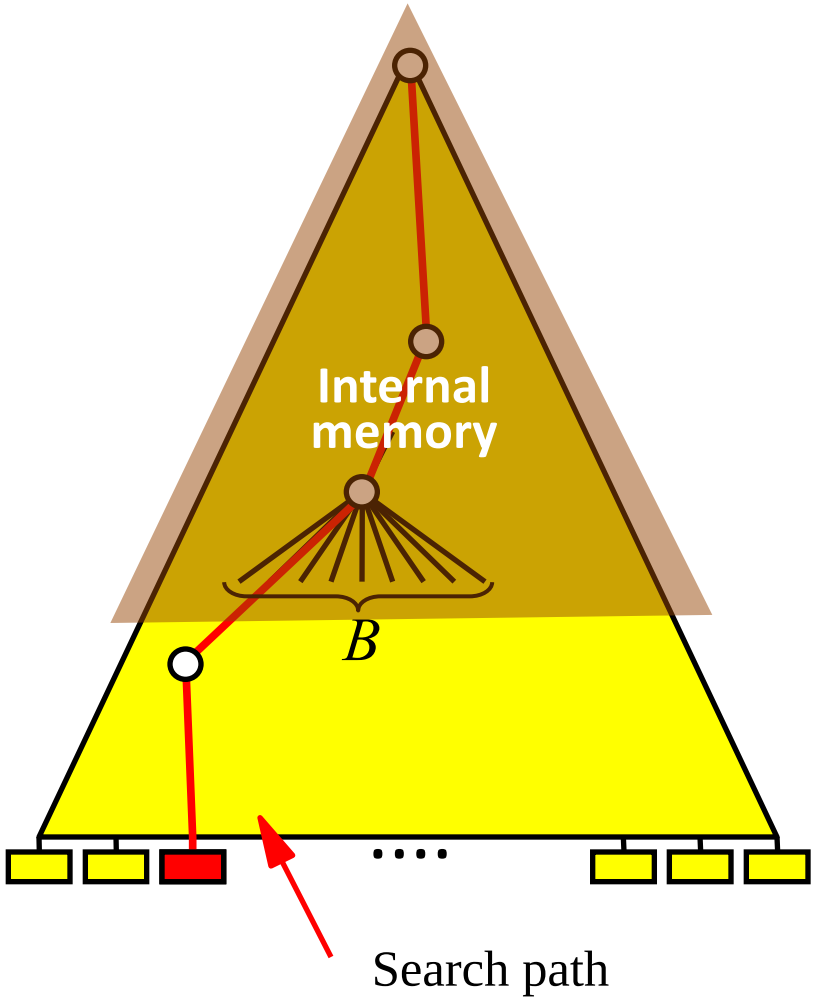

- **Searches**

  **Practice: 4-5 I/Os**

- **Repeated searching**

  **Practice: 1-2 I/Os**

# B-trees

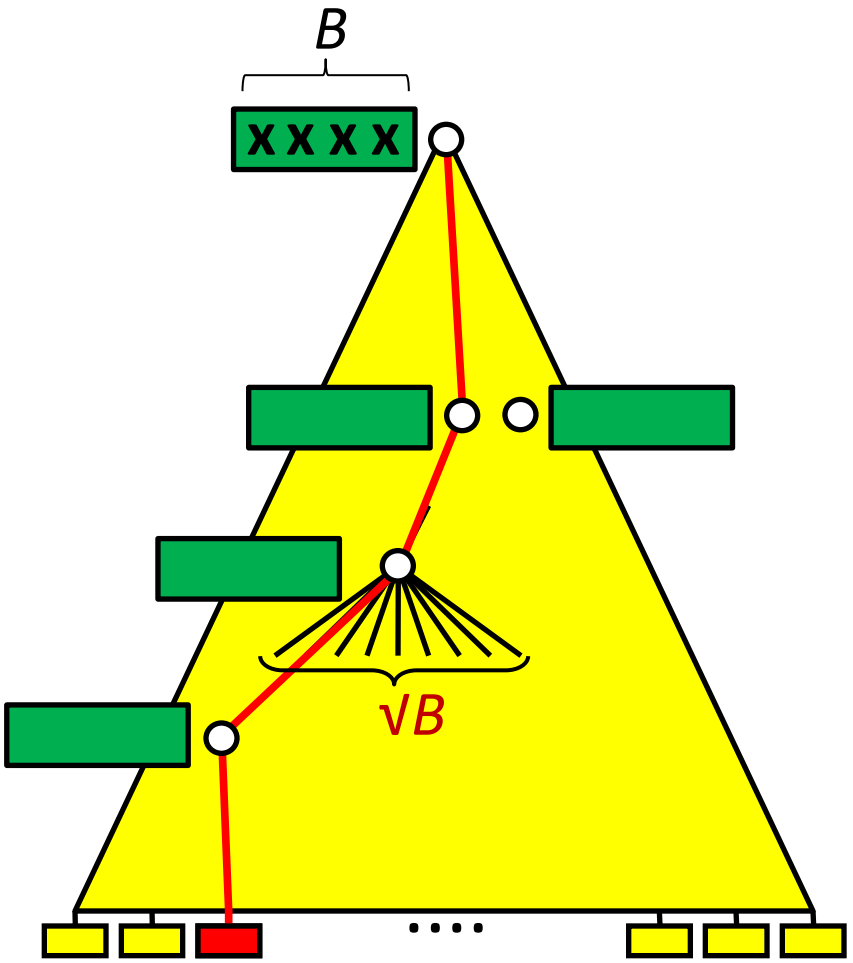



Best possible

- **Searches** $O(\log_B N)$ I/Os
- **Updates** $O(\log_B N)$ I/Os

?

# B-trees with Buffered Updates




- **Searches cost**

  $O(\log_B N)$ I/Os

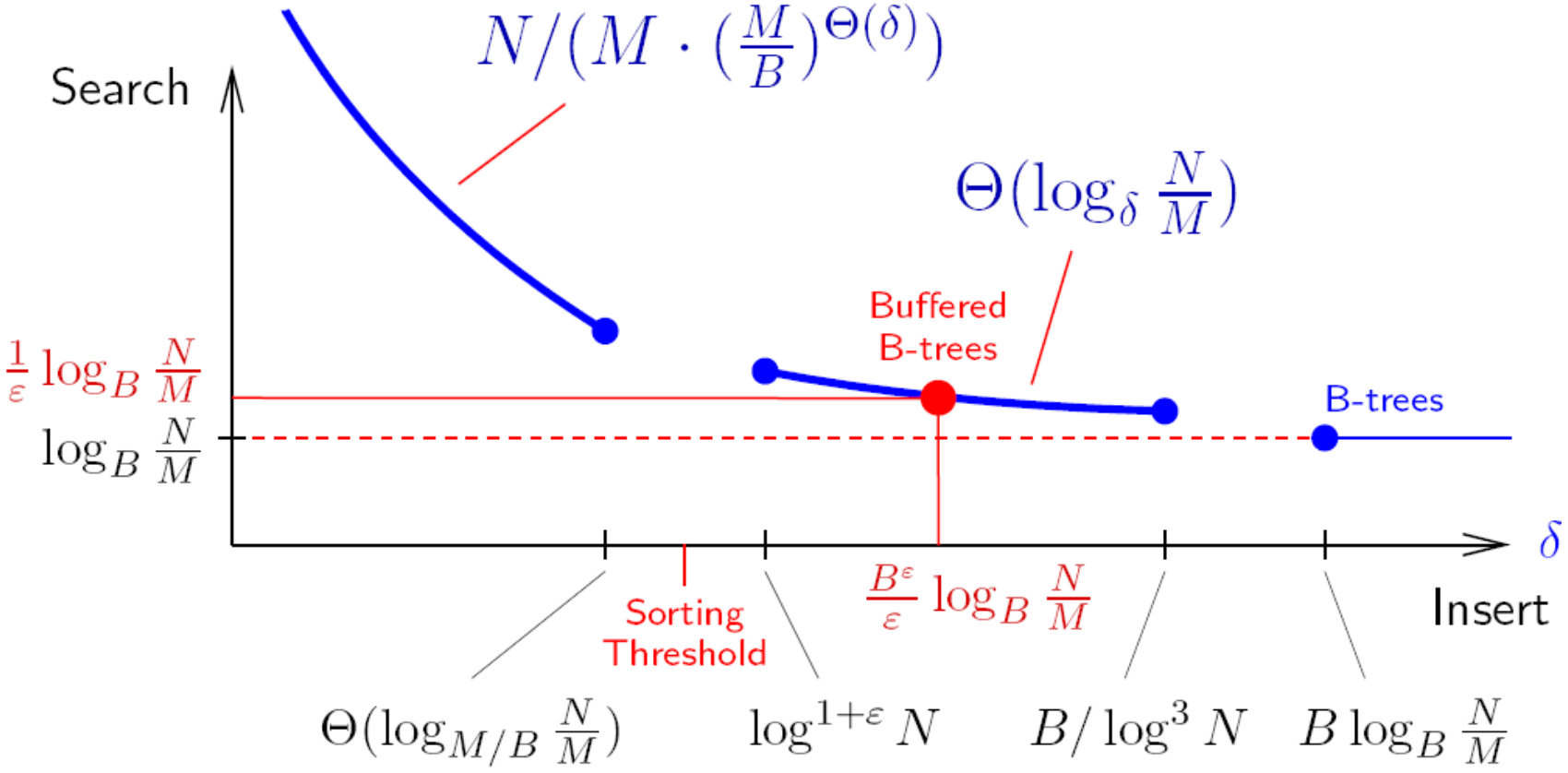
- ***N* updates cost**

  $O(N/\sqrt{B} \cdot \log_B N)$ I/Os

**Trade-off between search and update times – optimal *!***

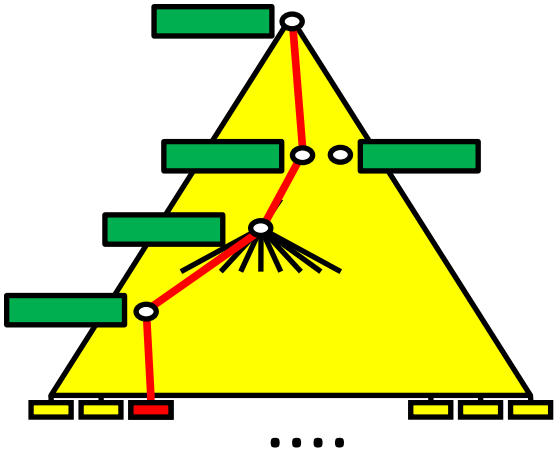
Brodal and Fagerberg (2003)

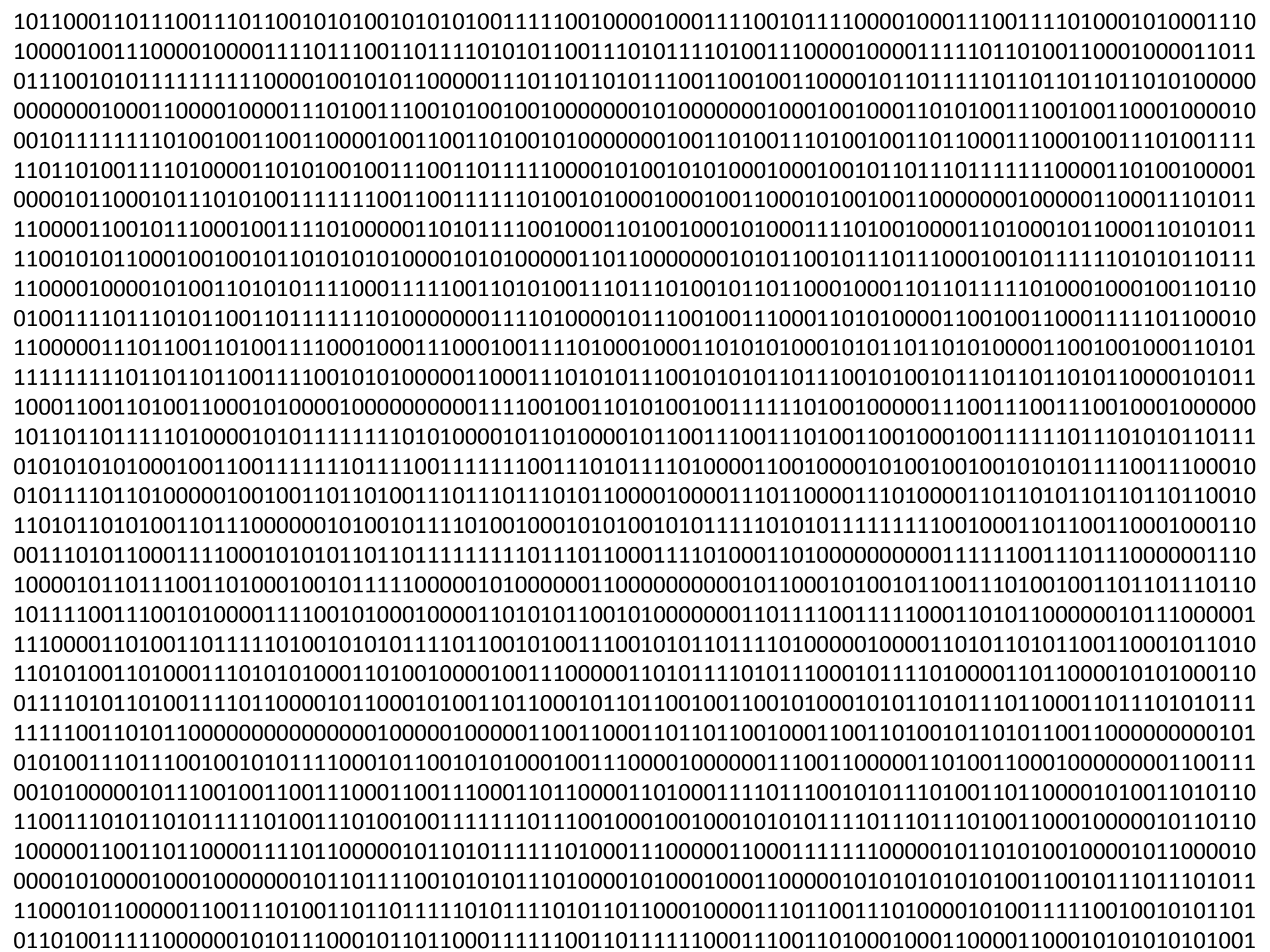
# B-trees with Buffered Updates

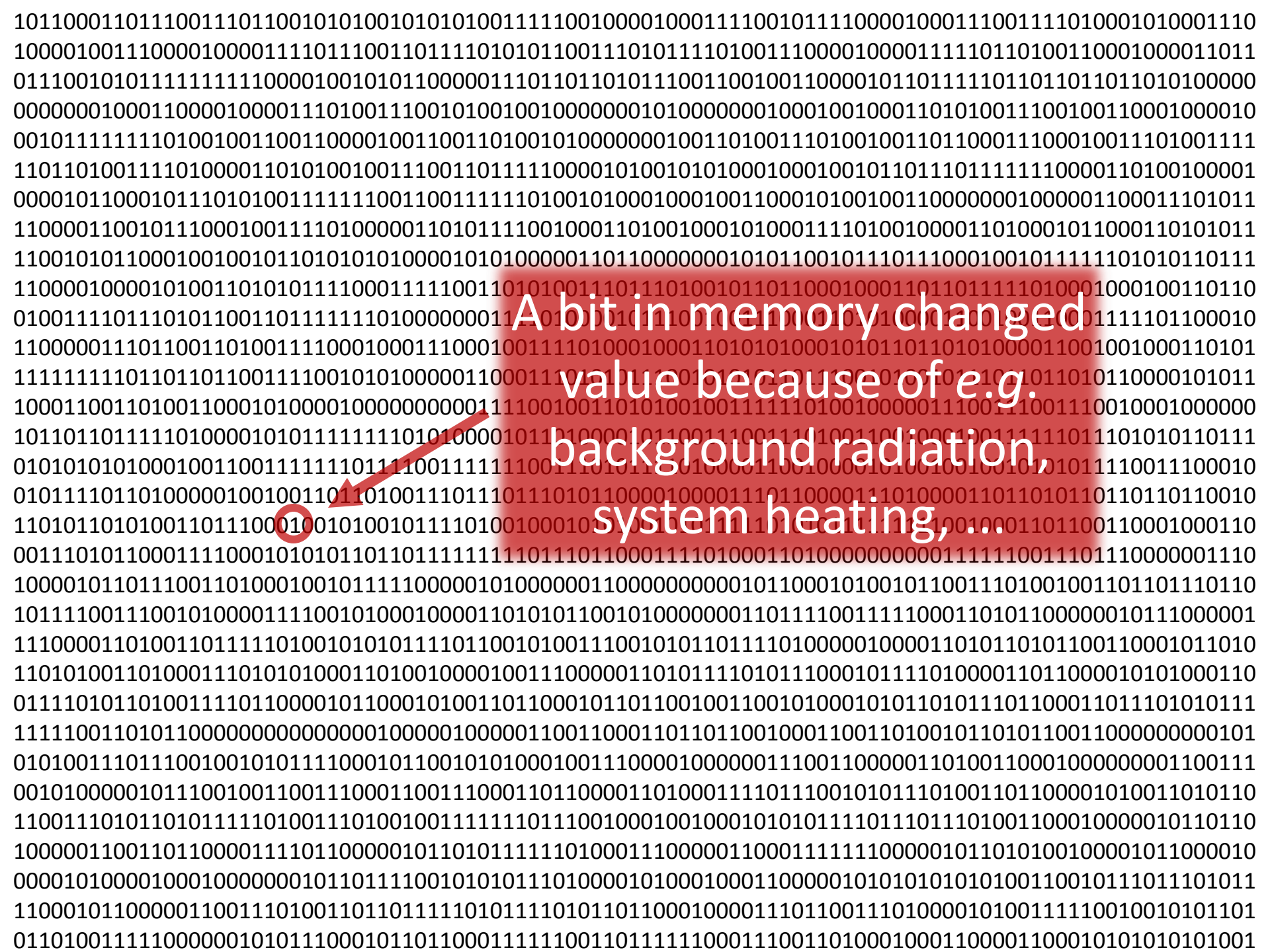


# B-trees with Buffered Updates Experimental Study

- 100.000.000 elements
- Search time basically unchanged with buffers
- Updates 100 times faster



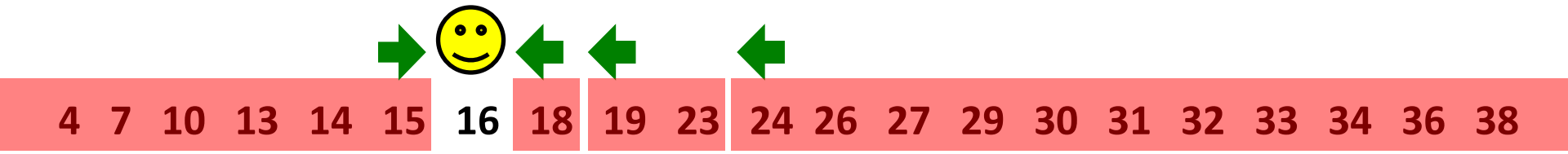



A bit in memory changed value because of *e.g.* background radiation, system heating, ...

*"You have to provide reliability on a software level. If you're running 10,000 machines, something is going to die every day."*

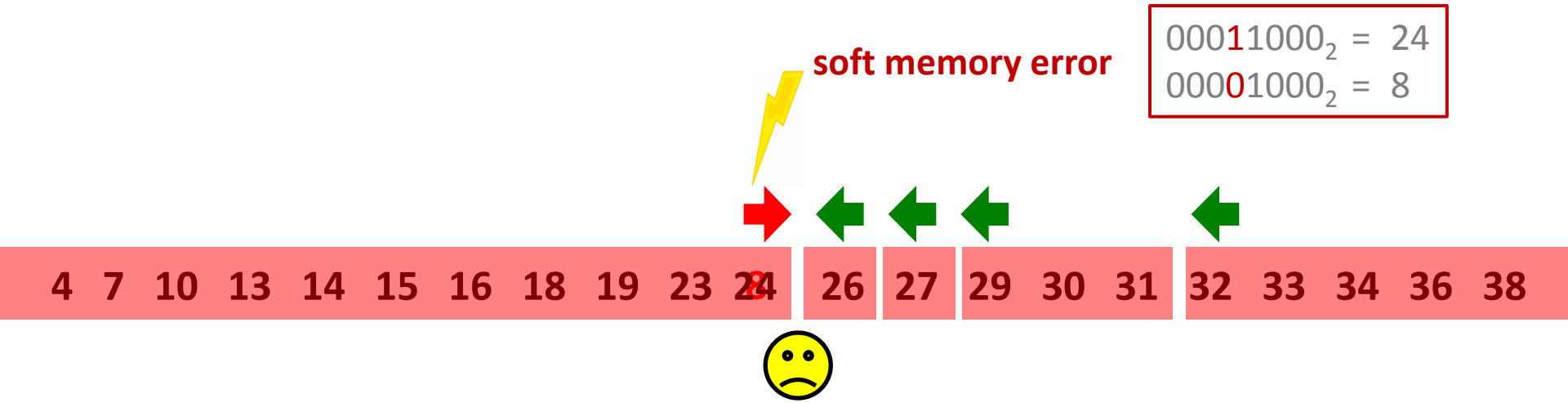
— Google fellow Jeff Dean

# Binary Search for 16




$O(\log N)$ comparisons

# Binary Search for 16




**Requirement**: If the search key ocours in the array as an uncorrupted value, then we should report a match *!*

# Where is Michael ?

# Where is Michael ?

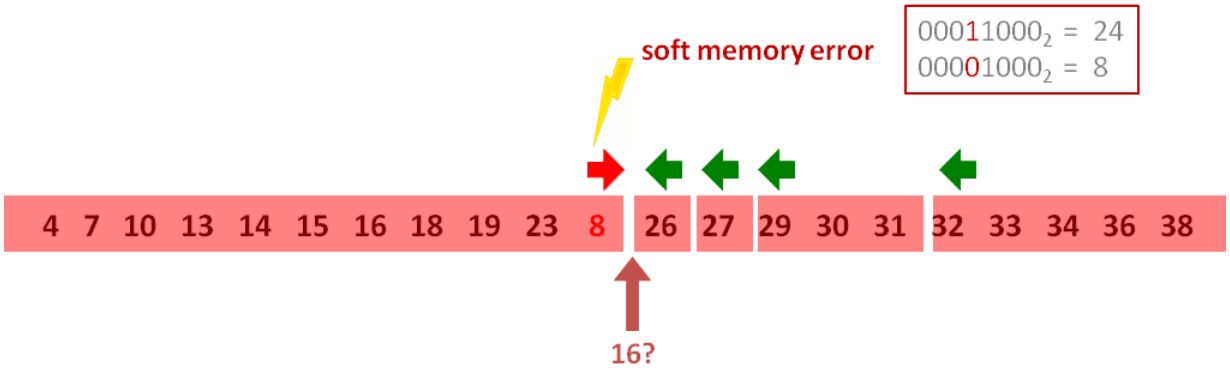
# Where is Michael ?

If at most 4 faulty answers then Jens is somewhere here

# Faulty-Memory RAM Model

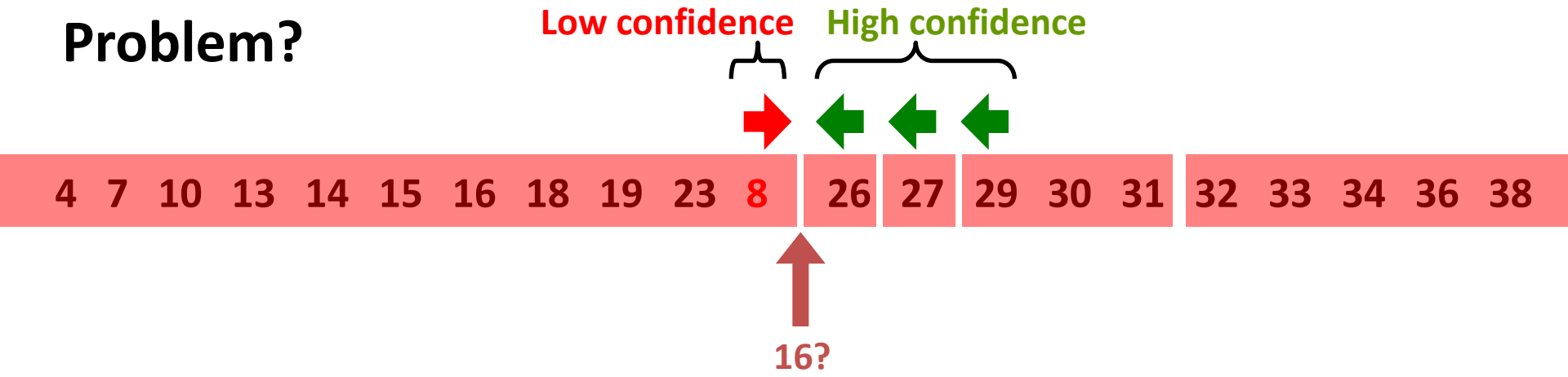
**Finocchi and Italiano, STOC'04**

- Content of memory cells can get corrupted
- Corrupted and uncorrupted content cannot be distinguished
- $O(1)$ safe registers
- **Assumption**: At most $\delta$ corruptions



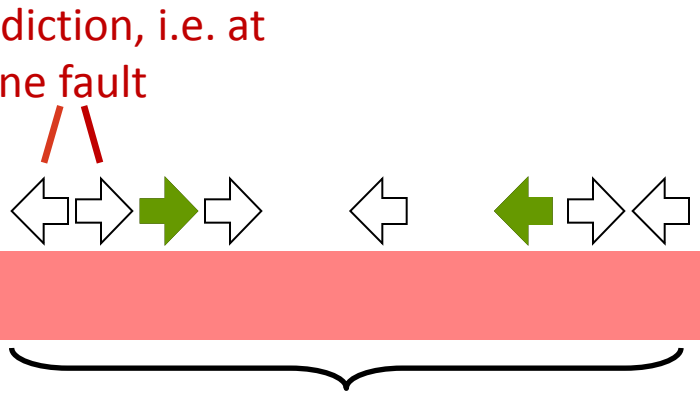
# Faulty-Memory RAM: Searching

**Problem?**



# Faulty-Memory RAM: Searching

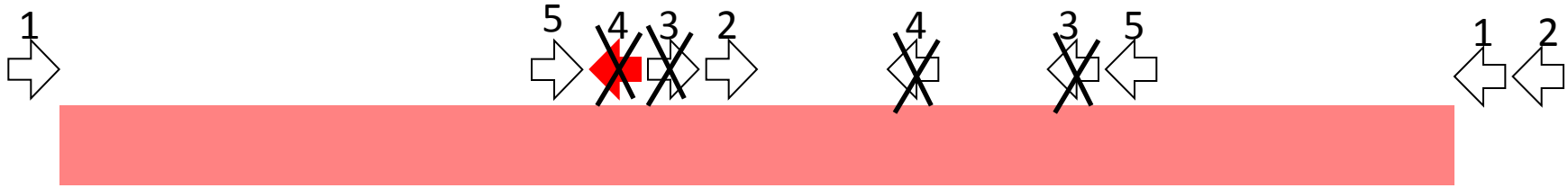
**When are we done (δ=3)?**




If range contains at least δ+1 ⇨ and δ+1 ⇦ then there is at least one uncorrupted ➡ and ⬅, i.e. *x* must be contained in the range

# Faulty-Memory RAM: Θ(log $N$ + $\delta$) Searching

Brodal, Fagerberg, Finocchi, Grandoni, Italiano, Jørgensen, Moruz, Mølhave, ESA'07




If verification fails

→ contradiction, i.e. ≥1 memory-fault

→ ignore 4 last comparisons

→ backtrack one level of search

# Flood Prediction Important

- Prediction areas susceptible to floods
  - Due to e.g raising sea level or heavy rainfall
- Example: Hurricane Floyd Sep. 15, 1999

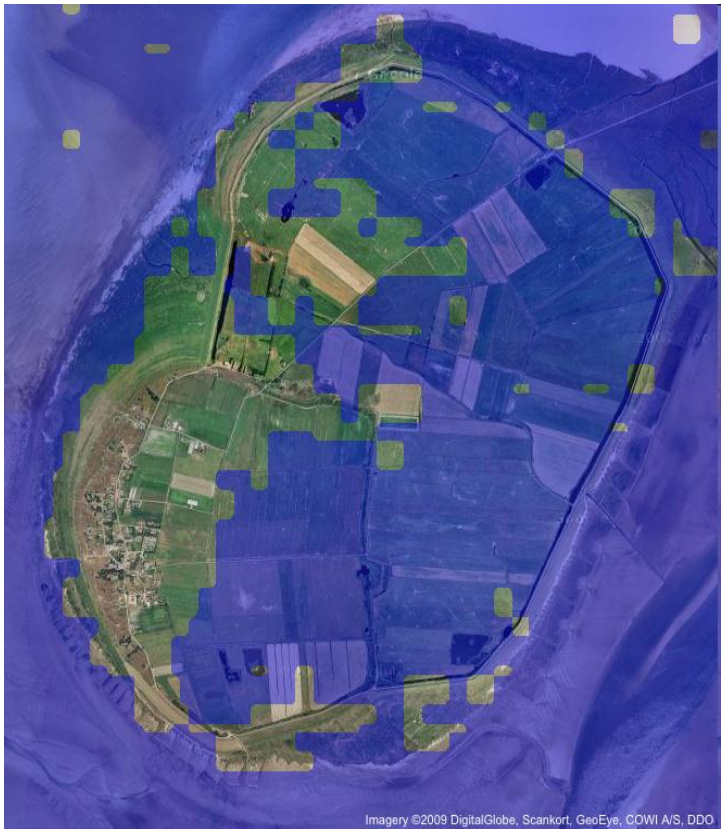


7 am


3pm

# Detailed Terrain Data Essential

Mandø with 2 meter sea-level raise

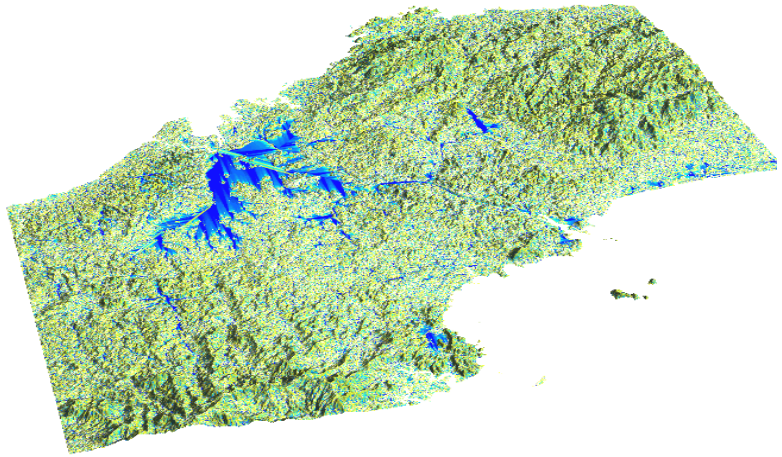



80 meter terrain model


2 meter terrain model

# Surface Flow Modeling



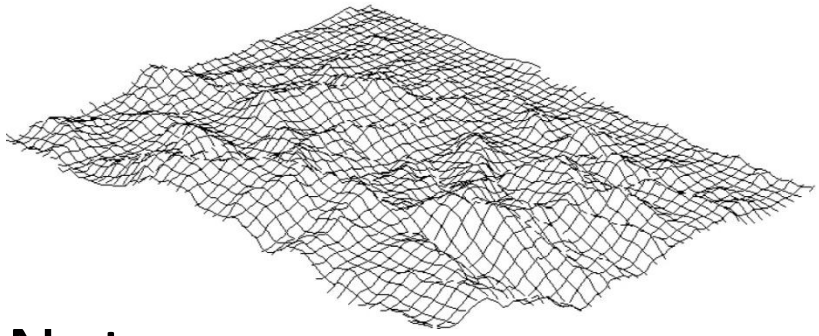



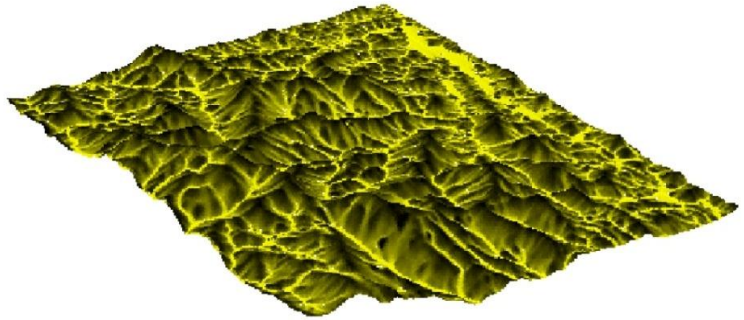
Hurricane Floyd (September 15, 1999)

- Conceptually flow is modeled using two basic attributes
  - Flow direction: The direction water flows at a point
  - Flow accumulation: Amount of water flowing through a point

# Flow Accumulation

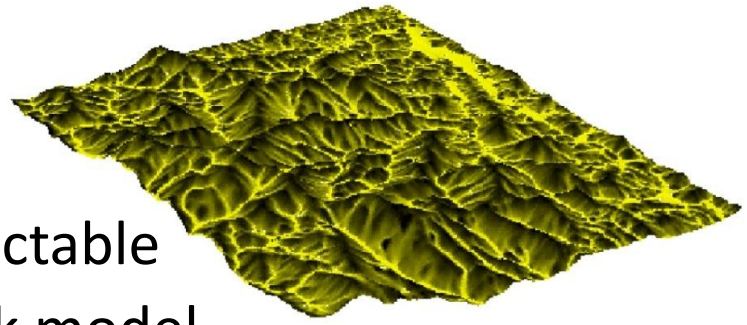
- Flow accumulation on grid terrain model:
  - Initially one unit of water in each grid cell
  - Water (initial and received) distributed from each cell to lowest lower neighbor cell (if existing)
  - Flow accumulation of cell is total flow through it





- Note:
  - Flow accumulation of cell = size of “upstream area”
  - Drainage network = cells with high flow accumulation

# Massive Data Problems



- Commercial systems:
  - Often *very* slow
  - Performance somewhat unpredictable
  - Cannot handle 2-meter Denmark model
- Collaboration environmental researchers in late 90'ties
  - US Appalachian mountains dataset
    - 800x800km at 100m resolution ⇒ a few Gigabytes 14 days!!
    - Customized software on ½ GB machine:
- Appalachian dataset would be Terabytes sized at 1m resolution!

# Flood Modeling

- Not all terrain below height *h* is flooded when water rise to *h* meters!

- Theoretically not too hard to compute area flooded when rise to *h* meters
  - But no software can do it for Denmark at 2-meter resolution

- Use of I/O-efficient algorithms
  $\Rightarrow$ Denmark in a few days

- Even compute new terrain where terrain below *h* is flooded when water rise to *h*

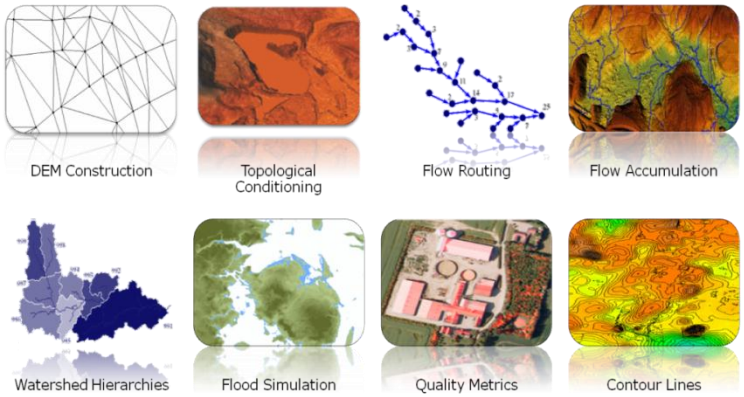
# Interdisciplinary Collaboration

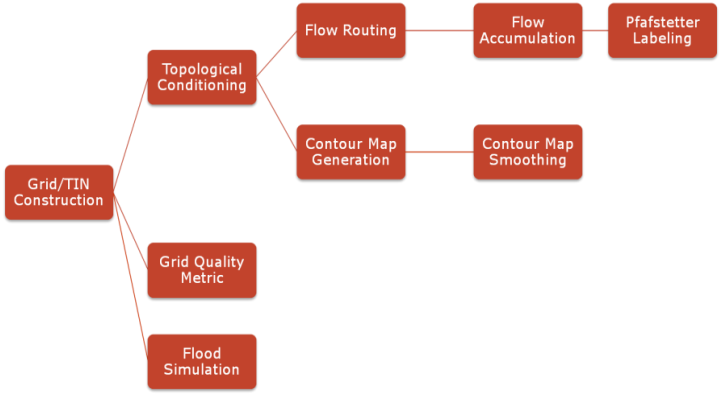
- Flow/flooding work example of center interdisciplinary collaboration
  - Flood modeling and efficient algorithms in biodiversity modeling
  - Allow for used of global and/or detailed geographic data

- Brings together researchers from
  - Biodiversity
  - Ecoinformatics
  - Algorithms
  - Datamining
  - …

# TerraSTREAM

- Flow/flooding work part of comprehensive software package
  - TerraSTREAM: Whole pipeline of terrain data processing software




- TerraSTREAM used on full 2 meter Denmark model (~25 billion points, ~1.5 TB)
  - Terrain model (grid) from LIDAR point data
  - Surface flow modeling: Flow directions and flow accumulation
  - Flood modeling

# Summary

- Basic research center in Aarhus
  - Organization
  - PhD education
- Examples of research
  - Theoretical external memory algorithmics
  - Practical (flow simulation)

MADALGO
CENTER FOR MASSIVE DATA ALGORITHMICS

Tau · Jërë-jëf · Tashakkur · S.aHHa · Sag olun
Giihtu · Djakujo · Dâkujem vám · Thank you
Tesekkür ederim · To-siä · Merci · Tashakur
Taing · Dankon · Efharistó · Shukriya · Kiitos
Dhanyabad · Rakhmat · Trugarez · Asante
Köszönöm · Blagodarya · Dziekuje · Eskerrik asko
Grazie · Tak · Bayarlaa · Miigwech · Dank u
Spasibo · Dêkuji vám · Ngiyabonga · Dziakuj
Obrigado · Gracias · A dank aych · Salamat
Takk · Arigatou · Tack · Tänan · Aciu
Korp kun kah · Multumesk · Terima kasih · Danke
Rahmat · Gratias · Mahalo · Dhanyavaad
Paldies · Faleminderit · Diolch · Hvala
Kam-sa-ham-ni-da · Xìe xìe · Mèrcie · Dankie

# Thank You

**Gerth Stølting Brodal**
**gerth@cs.au.dk**