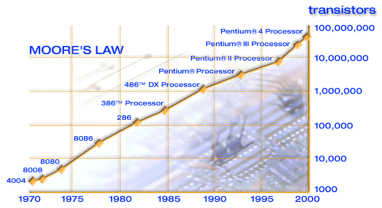
Memory Performance of Algorithms

CSE 373
Data Structures
Lecture 16

Algorithm Performance Factors

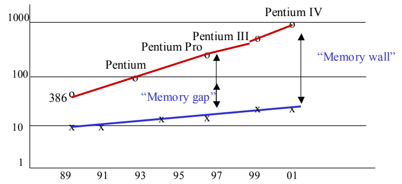
- Algorithm choices (asymptotic running time)
  - › O(n^2) or O(n log n) …
- Data structure choices
  - › Binary heap or linked list priority queue
- Language and Compiler
  - › C, C++, Java, Fortran
- Memory performance
  - › How near is the data to the processor

Moore's Law

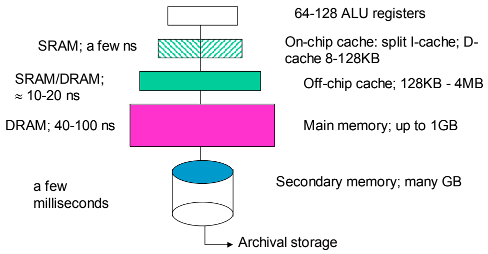


Processor-Memory Performance Gap

- x86 CPU speed (100x over 10 years)



Levels in the Memory Hierarchy



64-128 ALU registers

SRAM; a few ns

On-chip cache: split I-cache; D-cache 8-128KB

SRAM/DRAM; ≈ 10-20 ns

Off-chip cache; 128KB - 4MB

DRAM; 40-100 ns

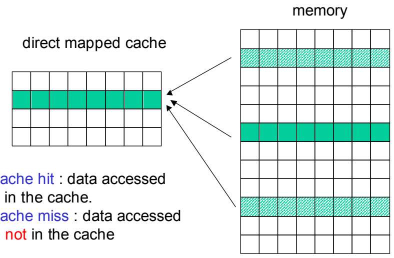
Main memory; up to 1GB

a few milliseconds

Secondary memory; many GB

Archival storage

The Cache

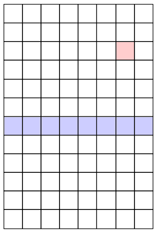


memory

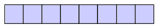
direct mapped cache

Cache hit : data accessed is in the cache.
Cache miss : data accessed Is not in the cache

Memory Blocks



🟥 Addressable unit, usually a byte



Memory block – unit of memory transferred as a whole from memory to cache. Sometimes called “cache line”. Usually, 32 64 bytes (but growing in size).

Why Memory Blocks

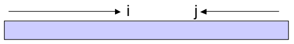
- Time to transfer x bytes is given by T(x) = a + bx. (a is latency, b ~ 1/bandwidth)
- Because a is large relative to b, it pays to transfer more than one byte at a time.
  - The hope is that bytes near the accessed byte will be accessed soon – good spatial locality.

Locality

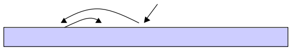
- Spatial locality : addresses near a recently accessed byte are accessed also.
- Temporal locality : the same address that was accessed recently is accessed again.

Examples of Locality

- Good spatial locality
  - Quicksort – the array is scanned

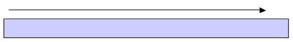


- Poor spatial locality
  - Binary search – jump around the array



Examples of locality

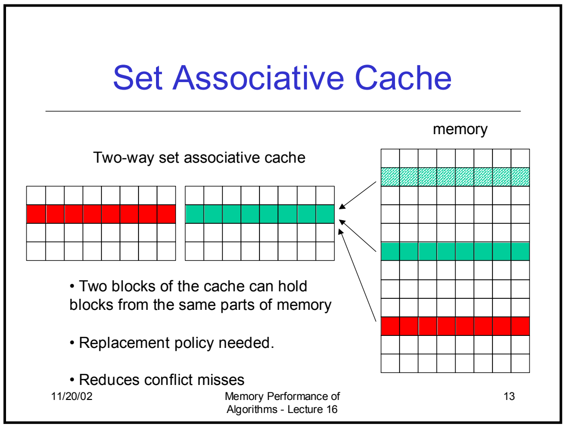
- Good temporal locality
  - For loop index i in a tight loop. for i = 1 to n do { …}
- Poor temporal locality
  - Repeated long scans that exceeds the cache size, like in iterative merge sort.



🟥 cache size

Classifying Cache Misses

- Compulsory misses – first time a block is accessed
  - Can never be avoided
- Capacity misses – data structure does not fit in cache
  - Can be avoided by algorithmic design.
- Conflict misses – several accessed blocks map to the same location in cache
  - Conflict misses are not much of a problem because modern caches are set associative.

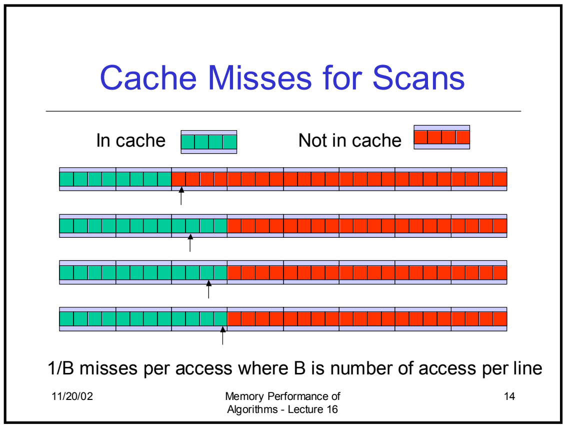


Set Associative Cache

Two-way set associative cache

memory

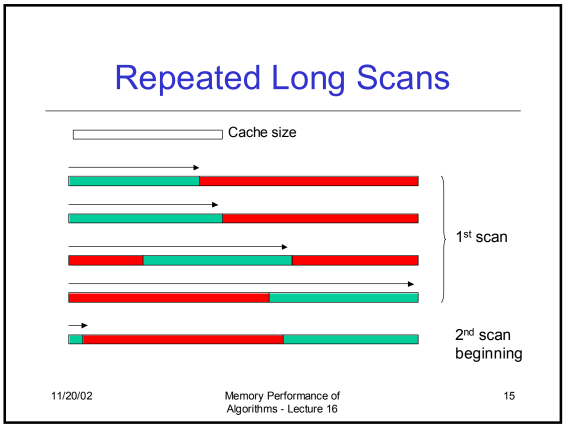
- Two blocks of the cache can hold blocks from the same parts of memory
- Replacement policy needed.
- Reduces conflict misses



Cache Misses for Scans

In cache 🟩 Not in cache 🟥

1/B misses per access where B is number of access per line

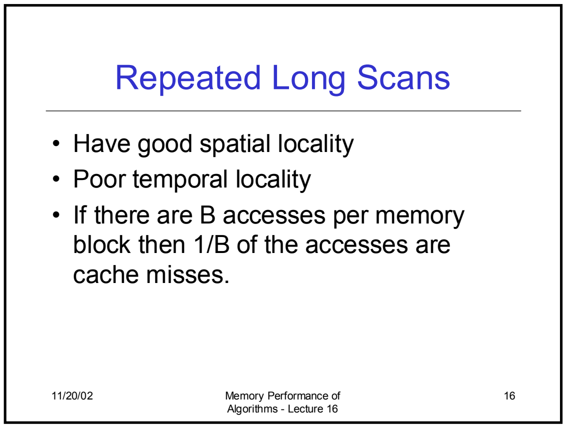


Repeated Long Scans

Cache size

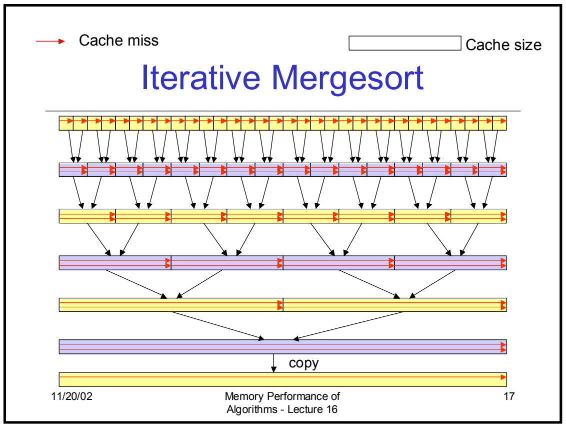
1st scan

2nd scan beginning



Repeated Long Scans

- Have good spatial locality
- Poor temporal locality
- If there are B accesses per memory block then 1/B of the accesses are cache misses.

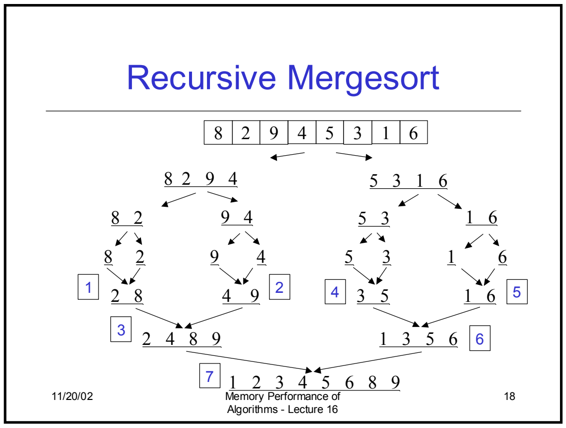


Cache miss

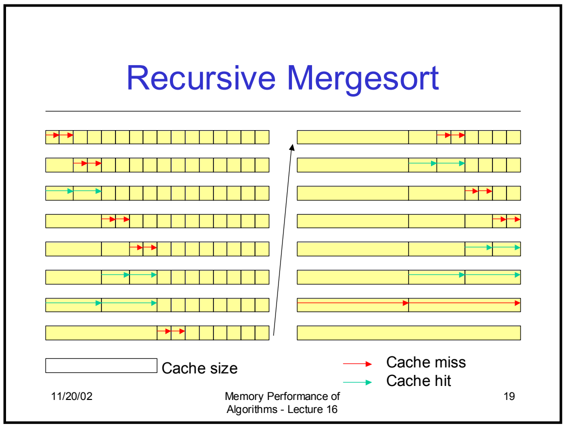
Cache size

Iterative Mergesort

copy



Recursive Mergesort

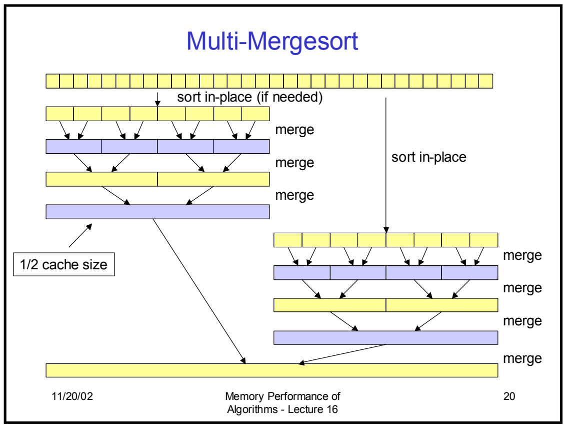


Recursive Mergesort

Cache size

Cache miss

Cache hit



Multi-Mergesort

sort in-place (if needed)

merge

merge

merge

sort in-place

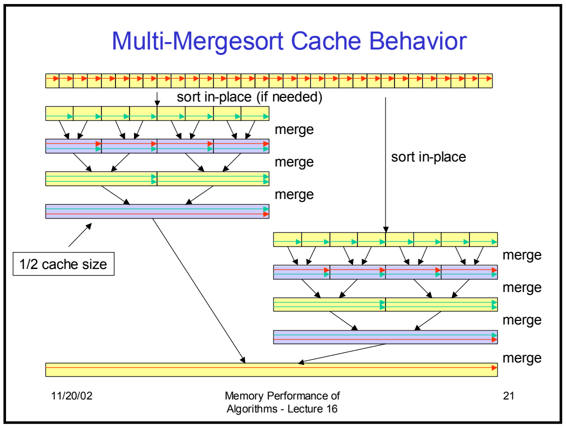
1/2 cache size

merge

merge

merge

merge



Multi-Mergesort Cache Behavior

sort in-place (if needed)

merge

merge

merge

sort in-place

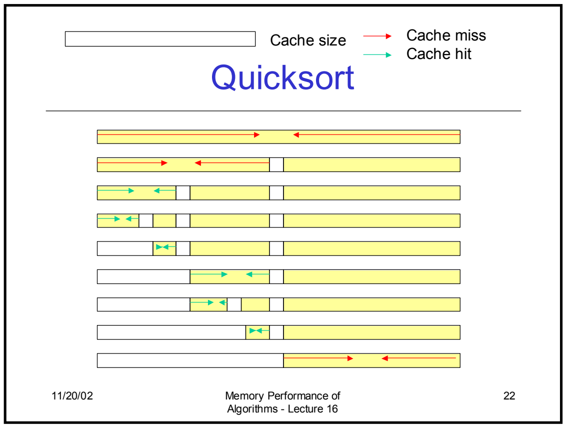
1/2 cache size

merge

merge

merge

merge

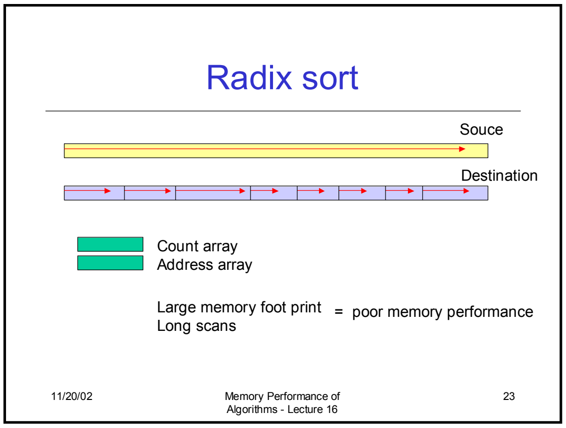


Cache size

Cache miss

Cache hit

Quicksort



Radix sort

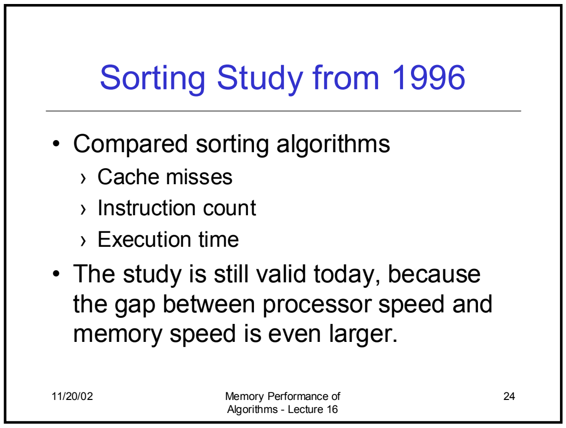
Souce

Destination

Count array

Address array

Large memory foot print
Long scans = poor memory performance



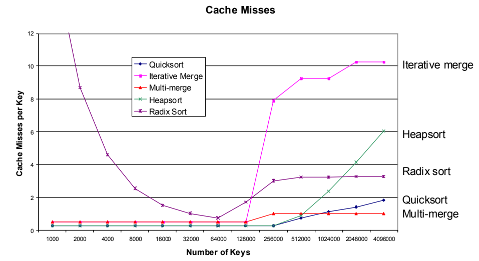
Sorting Study from 1996

- Compared sorting algorithms
  - › Cache misses
  - › Instruction count
  - › Execution time
- The study is still valid today, because the gap between processor speed and memory speed is even larger.

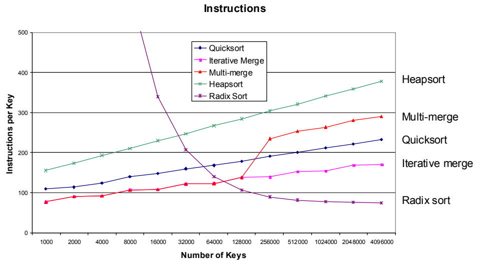
Algorithms

- Iterative mergesort
- Multi-mergesort
- Quicksort
- Heapsort
- Radix sort
  - › Parameters chosen for large data set.
  - › 4 passes for 64 bit integers.

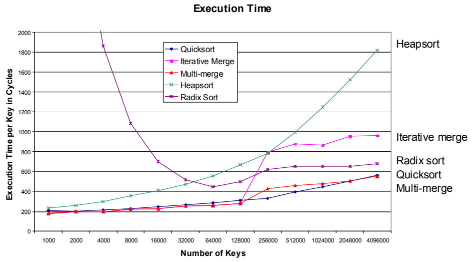
Cache Misses



Instructions



Execution Time



Notes on Memory Performance

- Memory performance may matter.
- Tips
  - › Sacrifice instructions to get better cache performance.
  - › Smaller memory footprint is good.
  - › Divide and conquer is good.
  - › Processing data into cache sized pieces is good.
  - › Fully utilize memory blocks if possible
    - Short scans are good.
    - Multiway trees are good.