MLDS-413 Introduction to Databases and Information Retrieval

Lecture 9
Unique Keys, Storage Hierarchy Basics

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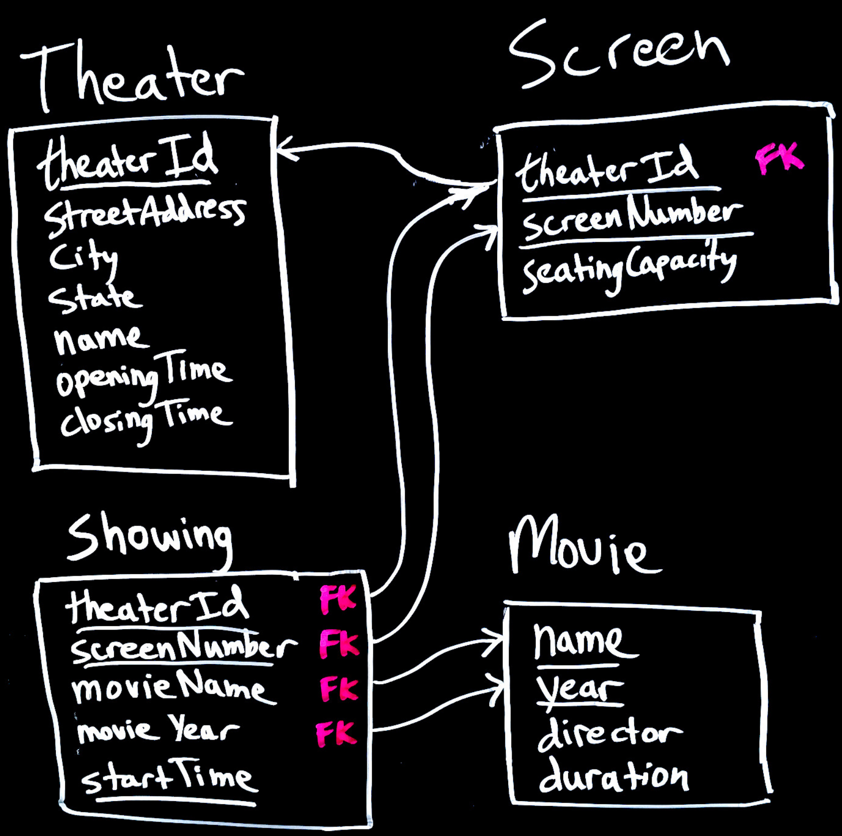
Slides adapted from Steve Tarzia

Last Lecture

- INNER JOINs
- JOINs with multiple matches
- JOINs on the same table multiple times

Movie Theater

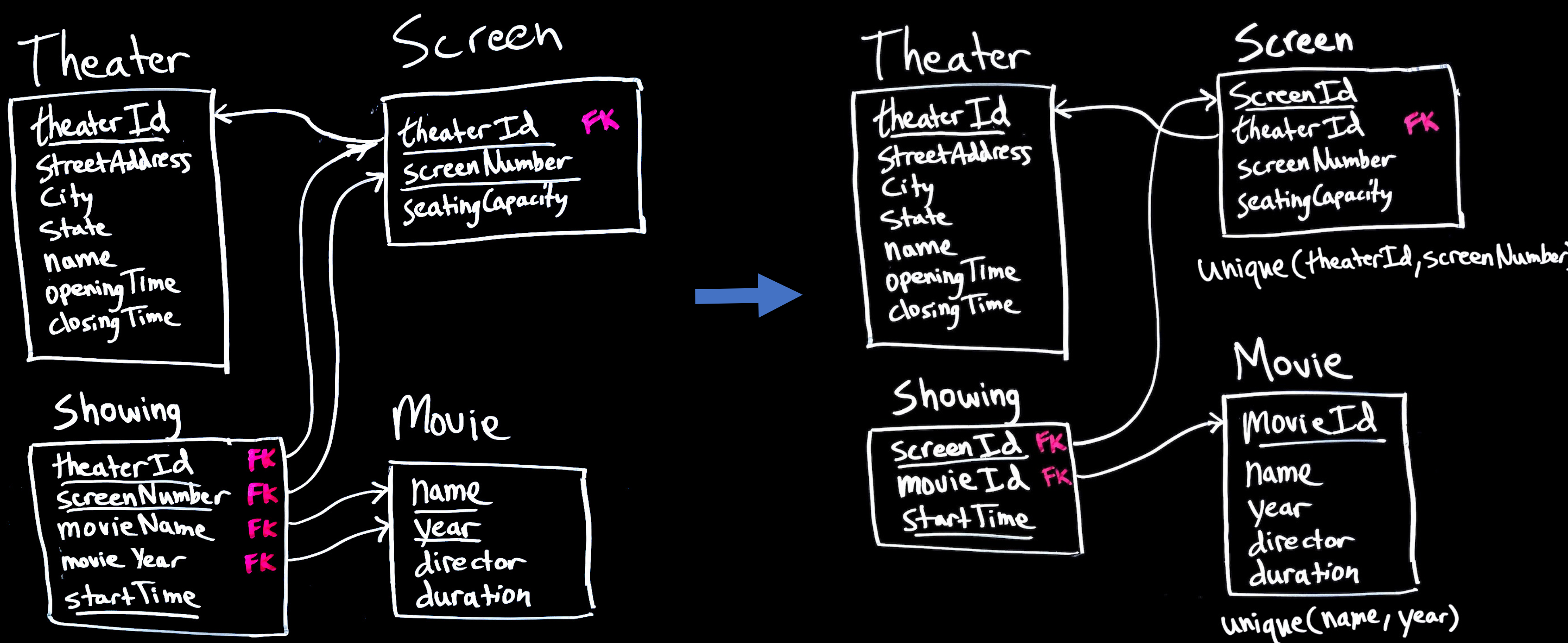


Composite Primary Keys

- Primary Keys uniquely identify rows
  - Used as ***indexes*** to find a row of interest
  - Prevent duplication
- Often we need more than one column to uniquely identify rows
  - e.g., a Screen is uniquely identified by "theaterId" *and* "screenNumber."
  - "theaterId" alone cannot be a primary key because it is OK for multiple screens to exist at the same theater, as long as they have different "screenNumber"
  - "screenNumber" alone cannot be a primary key because different theaters can use the same screen numbers (1, 2, 3 …)
- However, composite primary keys make parent-child relationships messy

Adding "ScreenId" and "MovieID" simplifies the schema

Showing table becomes smaller and JOINs are simpler



Non-primary/Unique Keys

- Common to create a meaningless “ID” column for primary key @ parent, then add a non-primary composite key to enforce the integrity constraint
- Consider the movie theater example:
  - “movieId” is meaningless
    - ...but it is a convenient way for other tables to refer to movies
  - add a ***unique key*** on (name, year) to prevent two instances of the same movie
  - “Showing” table can have just a single column “movieId” as a foreign key
    - ...instead of two columns (name, year)
- Example:

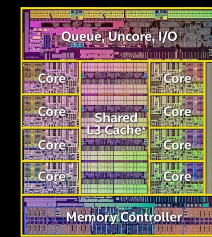
```
CREATE TABLE Movie
(MovieId PRIMARY KEY AUTOINCREMENT,
 name NVARCHAR(100),
 year DATETIME,
 UNIQUE(name, year) ON CONFLICT ABORT);
```

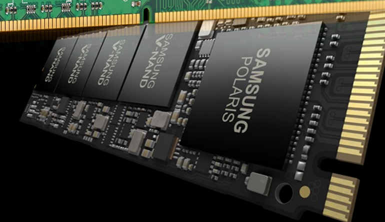
Part 2: Storage Hierarchy Basics

Computers have a hierarchy of storage

Larger, but slower

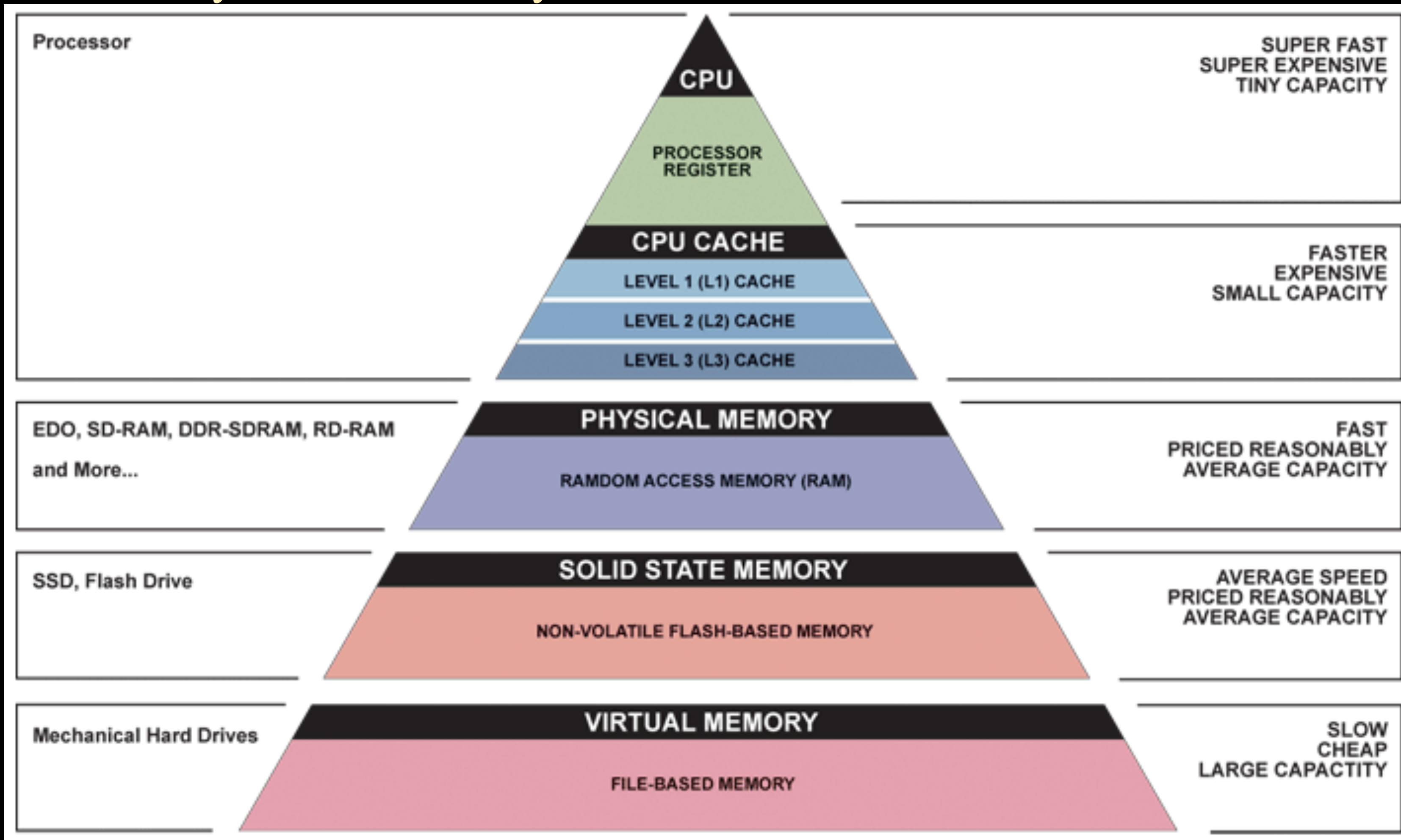
delay		*capacity*
300ps	CPU Registers	1 kB (kilobyte)
5ns	CPU Caches (L2)	16 MB
50ns	Random Access Memory (RAM)	16 GB
100µs	Flash Storage (SSD)	1 TB
5ms	Magnetic Disk	8 TB



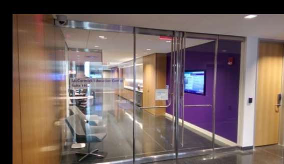


- Disk is about *ten billion* times larger than registers, but is about *ten million* times slower (latency)
- Goal is to work as much as possible in the top levels
- Large, rarely-needed data is stored at the bottom level

Memory Hierarchy



Jim Gray's Storage Analogy: How far away is the data?

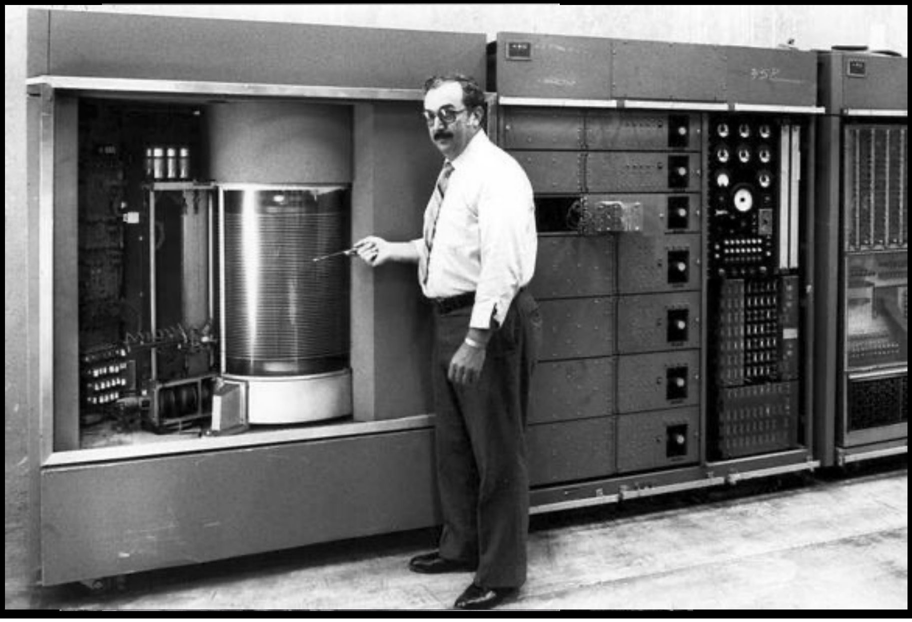
10^{10}	Tape		Andromeda	2,000 Years
10^{7}	Disk		Pluto	2 Years
100	Memory (DRAM)		Milwaukee	1.5 hr
10	On board cache		On campus	10 min
1	On chip cache		This building	2-4 min
1	Registers		My head	1 min

Disk storage

- Workhorse storage devices
  - 100-1,000x GB
  - ms to read (100,000x longer than DRAM, 10,000,000x longer than cache)

IBM 350 Disk Storage Unit
Announced Sep. 4, 1956

Size?
5 MB



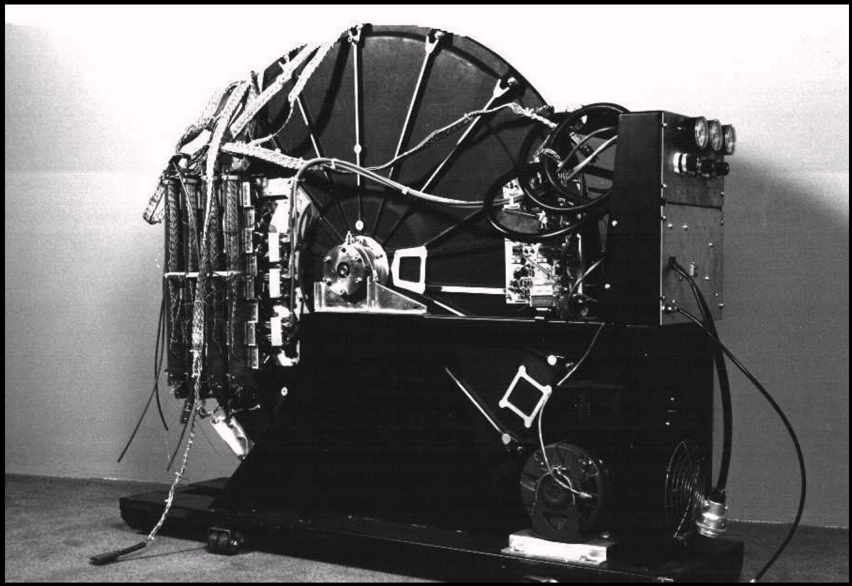
WD OptiNAND
20 TB, 2021

14.7 cm

10.16 cm

IBM Microdrive, 1999
340 MB

Disks & Files



- DBMS stores information on disks
  - In an electronic world, magnetic disks are a mechanical anachronism!
- This has major implications for DBMS design!
  - READ: transfer data from disk to main memory (DRAM)
  - WRITE: transfer data from RAM to disk
  - Both are high-cost operations, relative to in-memory operations, so must be planned carefully!

Why Not Store It All in Main Memory?

- Too expensive
  - High-end Databases today fall into the Petabyte range
  - ~ 60% of the cost of a production system is in the disks
- Main memory is volatile
  - We want data to be saved between runs (obviously!)
- Main-memory database systems do exist
  - Smaller size, performance optimized
  - Volatility is ok for some applications
- Typical DBMS hierarchy:
  - Main memory (DRAM) for currently used data
  - Disk for the main database (secondary storage)
    - Mainly for analytics / mining the data

What about Flash?

- Flash chips used for >20 years
- Flash evolved
  - USB keys

  - Storage in mobile devices
  - Consumer and enterprise flash disks (SSD)

- Flash in a DBMS
  - Main storage
  - Accelerator/enabler (Specialized cache, logging device)

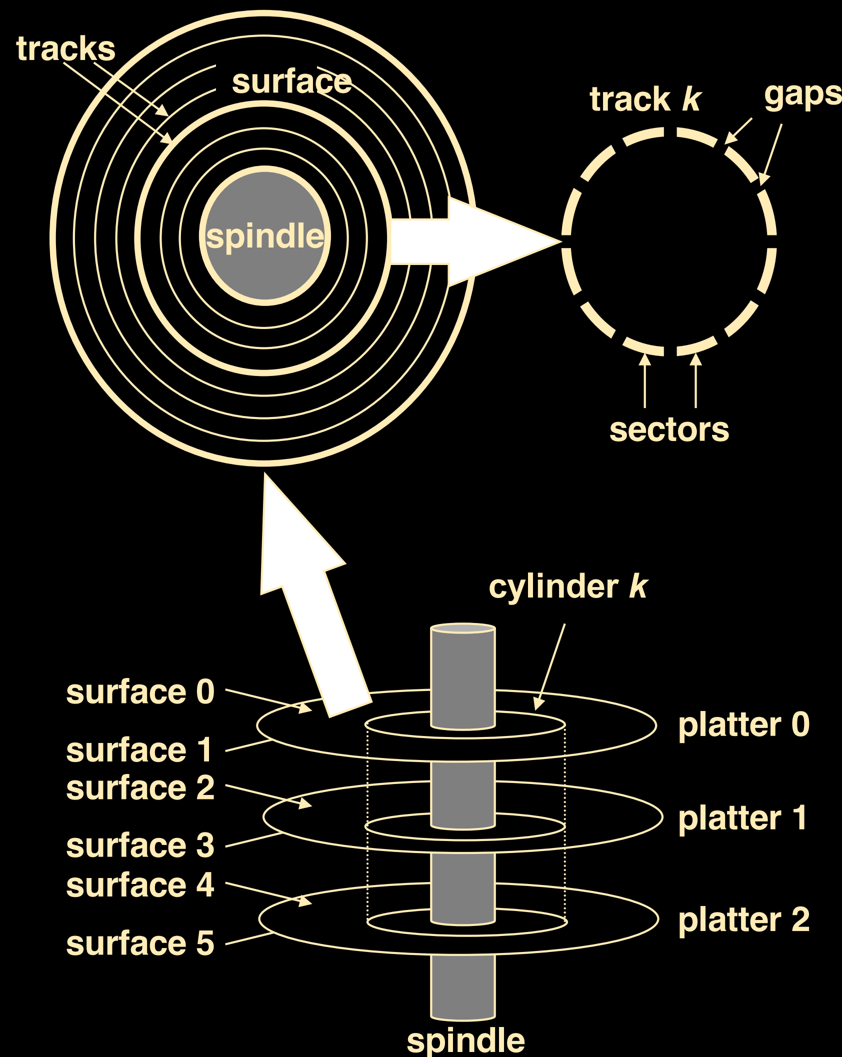
Disks

- Secondary storage device of choice
- Main advantage over tapes:

  random access vs. *sequential*
- Data is stored and retrieved in units called disk blocks or disk pages
- Unlike DRAM, time to retrieve a disk block varies
  - Depending on location on disk
  - Relative placement of blocks on disk has major impact on DBMS performance!

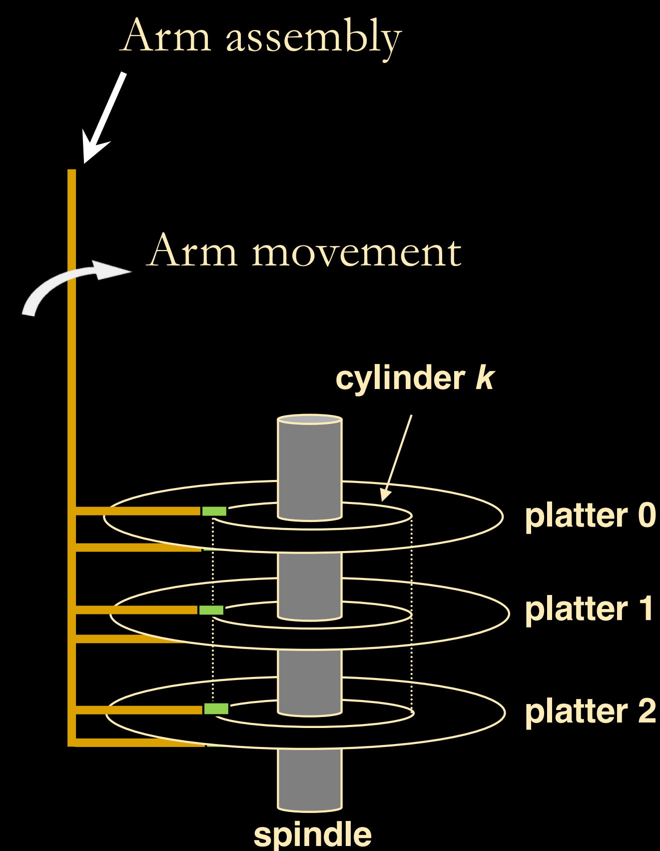
Disk geometry

- Disks consist of platters, each with two surfaces
- Each surface consists of concentric rings called tracks
- Each track consists of sectors separated by gaps
- Sectors contain equal # of data bits (typically 512B)
- Aligned tracks across surfaces/platters form a cylinder



Anatomy of a Disk

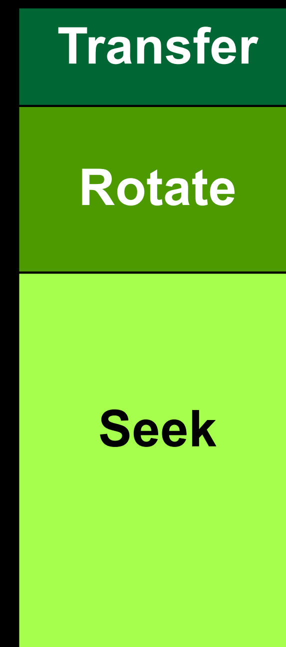
- The platters spin (5-15 KRPM)
- The arm assembly is moved in or out to position a head on a desired track.
- Tracks under heads make a cylinder (imaginary!)
- Only one head reads/writes at any one time
- Block size is a multiple of the fixed sector size
- Newer disks have several "zones", with more data on outer tracks



Accessing a Disk Page

Time to access (read/write) a disk block:

- seek time (moving arms to position disk head on track)
- rotational delay (waiting for block to rotate under head)
- transfer time (moving data to/from disk surface)



- Seek time varies from about 1 to 20 ms
- Rotational delay varies from 0 to 10 ms
- Transfer rate is < 1ms per 4KB page
- Key to lower I/O cost: **reduce seek/rotation delays**
  - Sequential accesses to data

Rules of thumb…

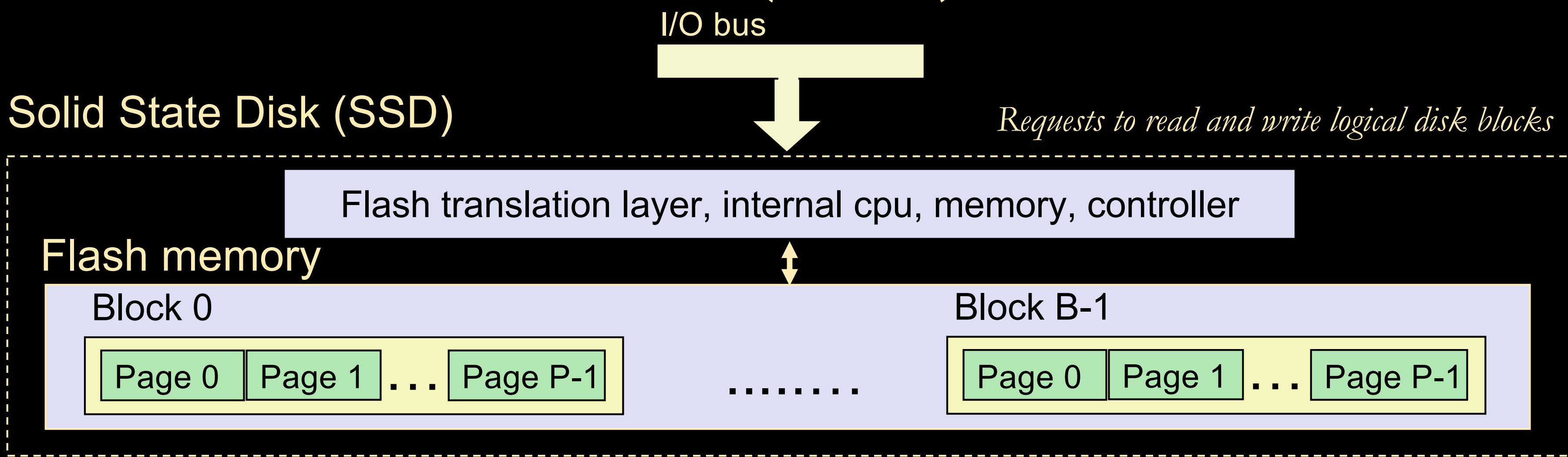
1. Memory access <u>much</u> faster than disk I/O (~ **100,000x**)

2. “Sequential” I/O faster than “random” I/O (~ **10x**)

Flash Solid State Disks (SSDs)

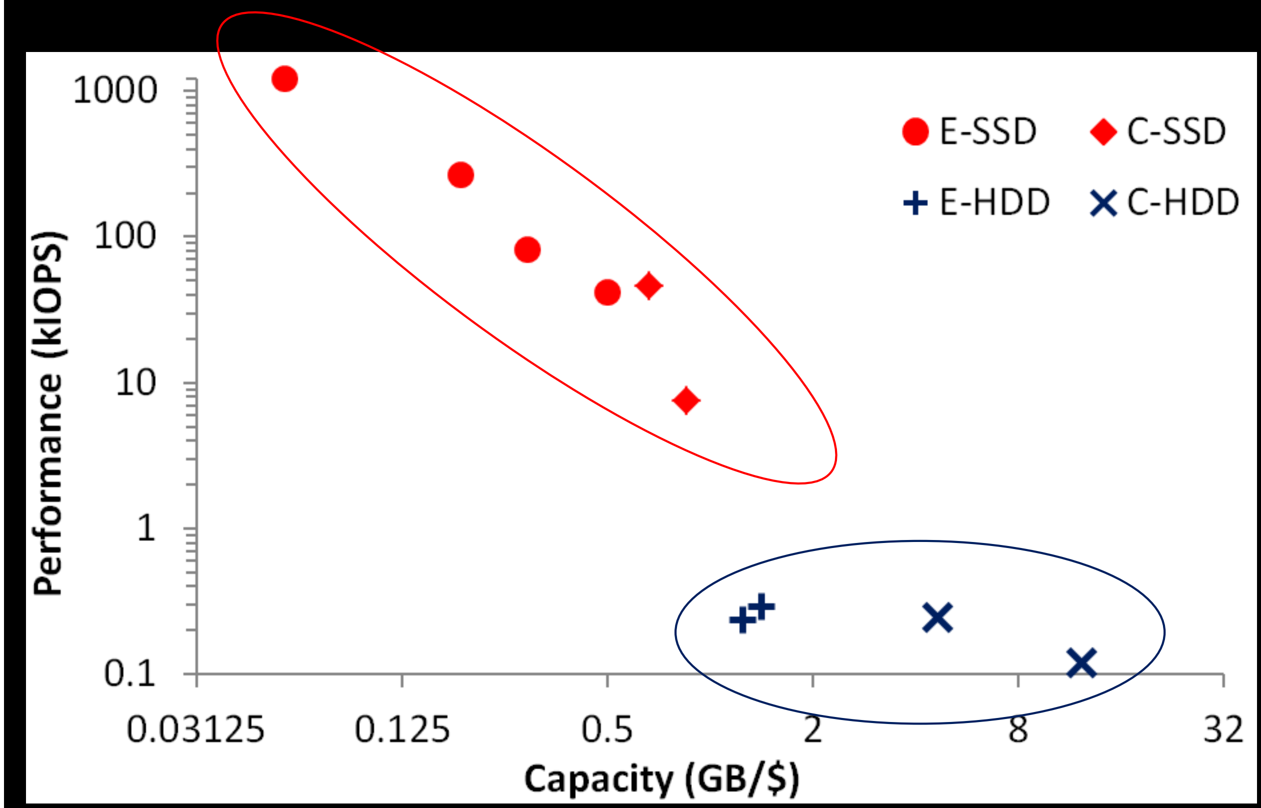
- Secondary storage *or* caching layer
- Main advantage over disks:
  random reads as fast as ***sequential*** reads
- But slow random writes
- Data organized in **pages** (similarly to disks)
- Pages organized in **flash blocks**
- Like DRAM (main memory), time to retrieve a disk page is **independent** of the location on flash disk

Flash Solid State Disks (SSDs)



- Pages: 512KB to 4KB, Blocks: 32 to 128 pages
- Data read/written in units of pages
- Page can be written only after its block has been erased
- A block wears out after ~1M repeated writes (SLC NAND, Micron/Sun, 2008)
  - May sound a lot, but it isn't. 1M seconds ≈ 12 days
  - Thermal annealing may push this to 100M writes (Macronix, 2013)

Flash disks vs. HDD



HDD

- ✓ Large – cheap capacity
- x Inefficient random reads
- ✓ Slow wear-out

SSD (Flash) disks

- x Small – expensive capacity
- ✓ Very efficient random reads
- x Slow writes (throughput)
- x Fast wear-out

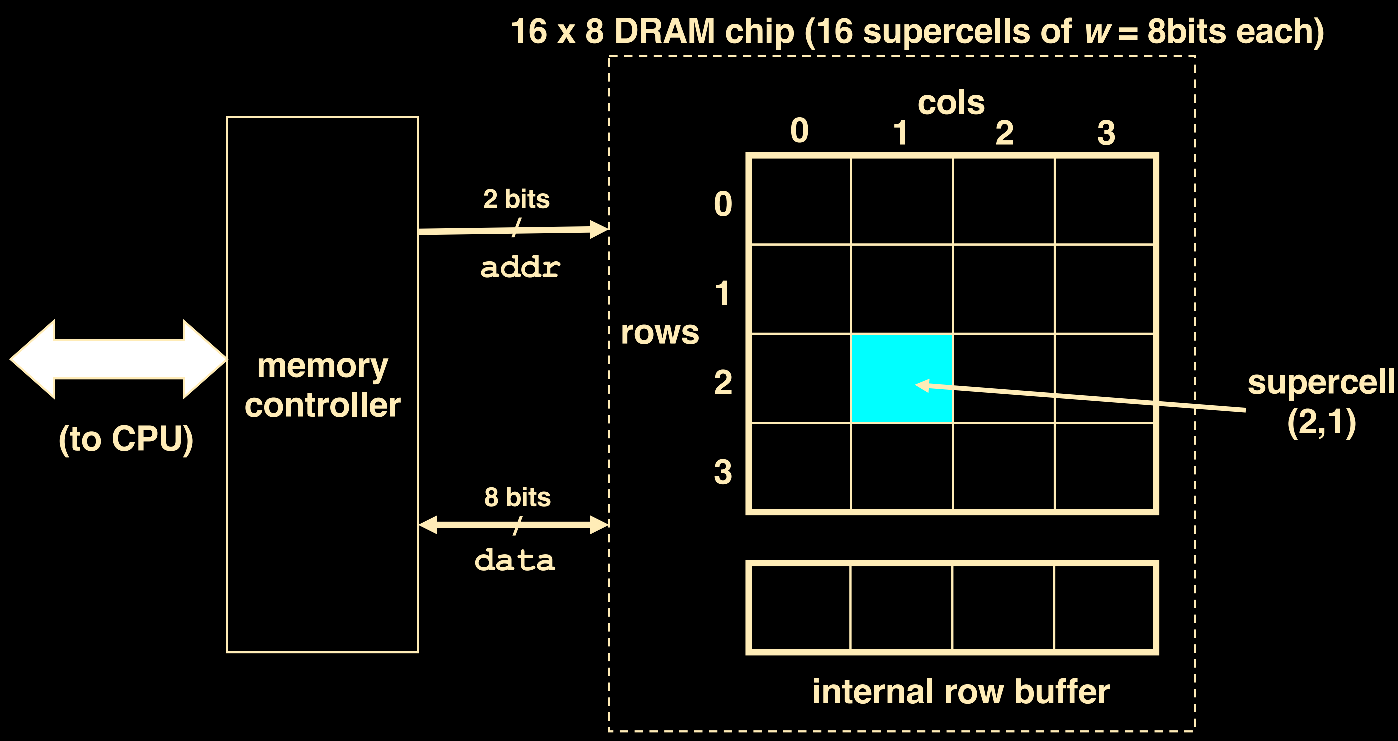
Dynamic Random Access Memory (DRAM)

- Similar to "array of bytes", each bit stored in a "cell"
- Dynamic RAM (DRAM)
  - Each cell stores a bit as a charge in a capacitor
  - Capacitors lose charge; each cell must be refreshed every 10-100 ms
  - More sensitive to disturbances (EMI, radiation, …) than SRAM
  - *Slower* than SRAM, but *cheaper and denser*
- Static RAM (SRAM)
  - Each cell stores a bit in a bi-stable circuit, typically a six-transistor circuit
  - Static – no need for periodic refreshing; keeps data while powered
  - Relatively insensitive to disturbances such as electrical noise
    - Energetic particles (alpha particles, cosmic rays) can flip stored bits

	Transistors/bit	Access time	Refresh?	Sensitive?	Cost	Applications
SRAM	6	1X	No	Yes (but less so)	100X	Cache memory
DRAM	1	10X	Yes	Yes	1X	Main memory, frame buffers

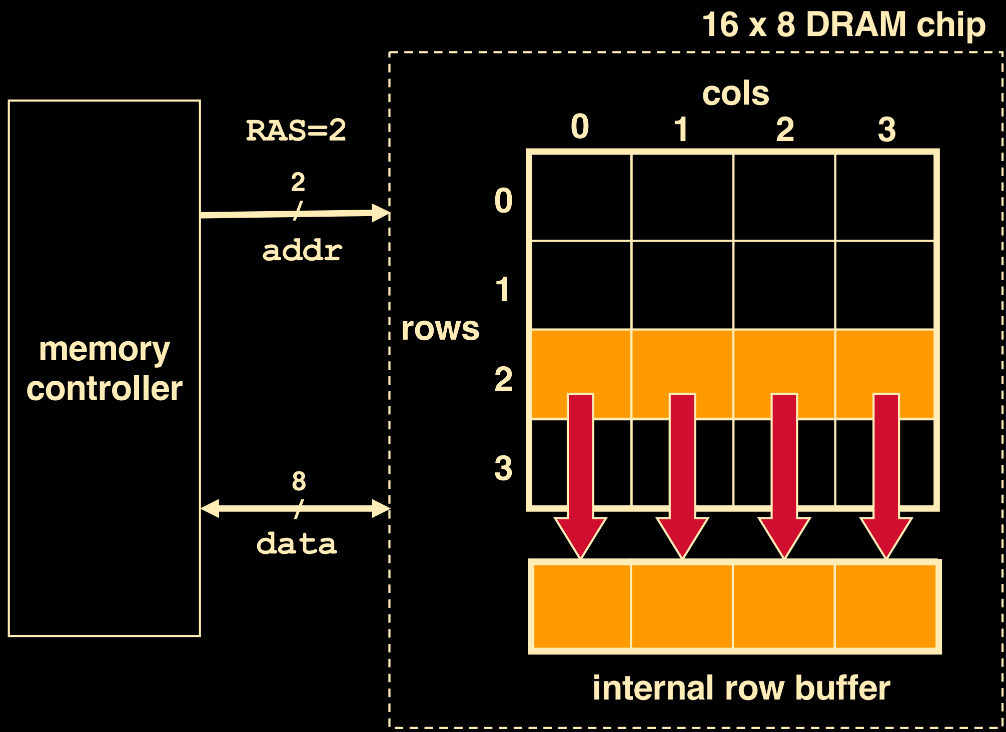
Conventional DRAM organization

- DRAM chip partitioned into supercells
  - Each supercell consists of w DRAM cells
  - Supercells organized as arrays of r rows and c cols ($r*c=d$)
  - A $(d \times w)$ DRAM stores $(d*w)$ bits



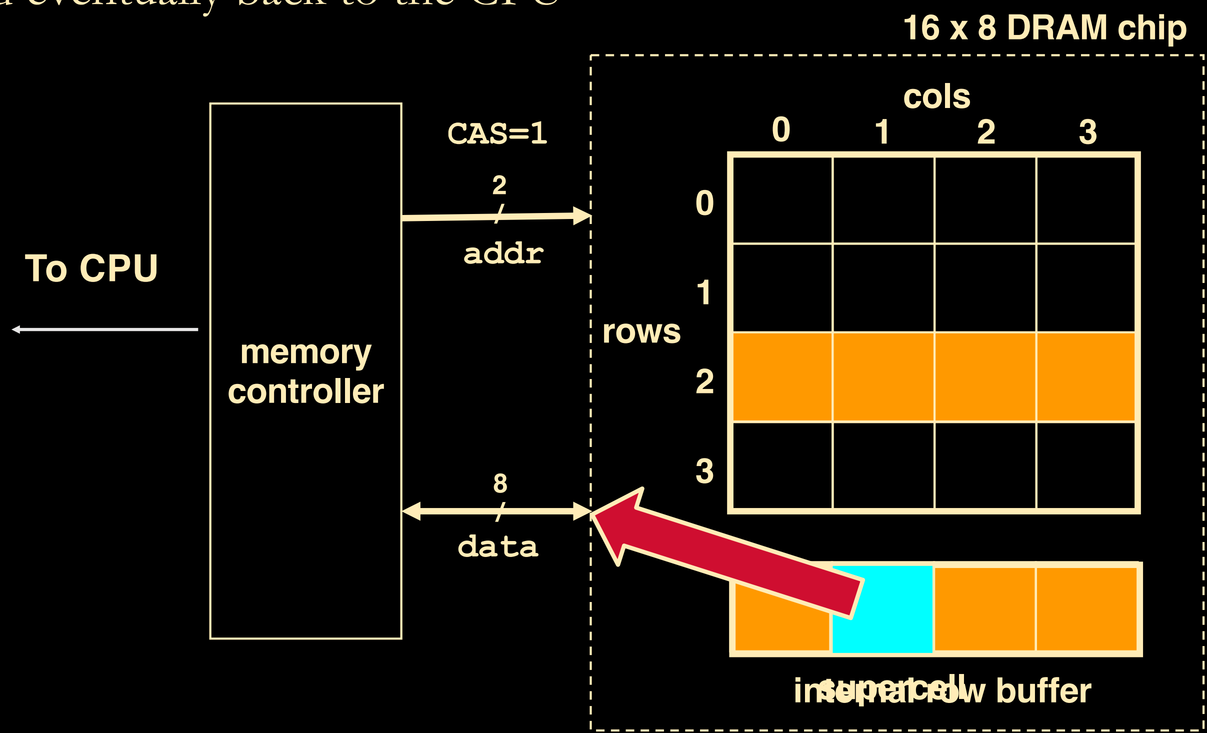
Reading DRAM supercell (2,1)

- Access done in two steps
  - Step 1(a): Row access strobe (**RAS**) selects row 2
  - Step 1(b): Row copied from DRAM array to row buffer



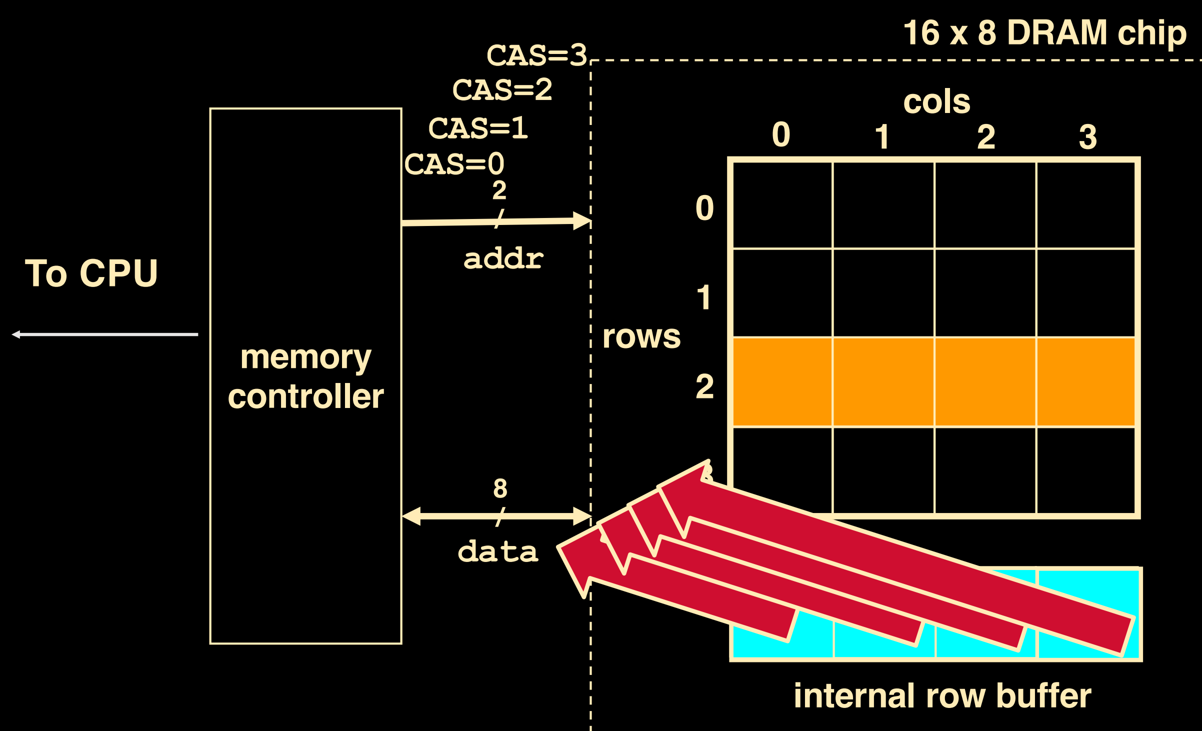
Reading DRAM supercell (2,1)

- …
  - Step 2(a): Column access strobe (**CAS**) selects column 1
  - Step 2(b): Copy supercell (2,1) from row buffer to data lines, and eventually back to the CPU

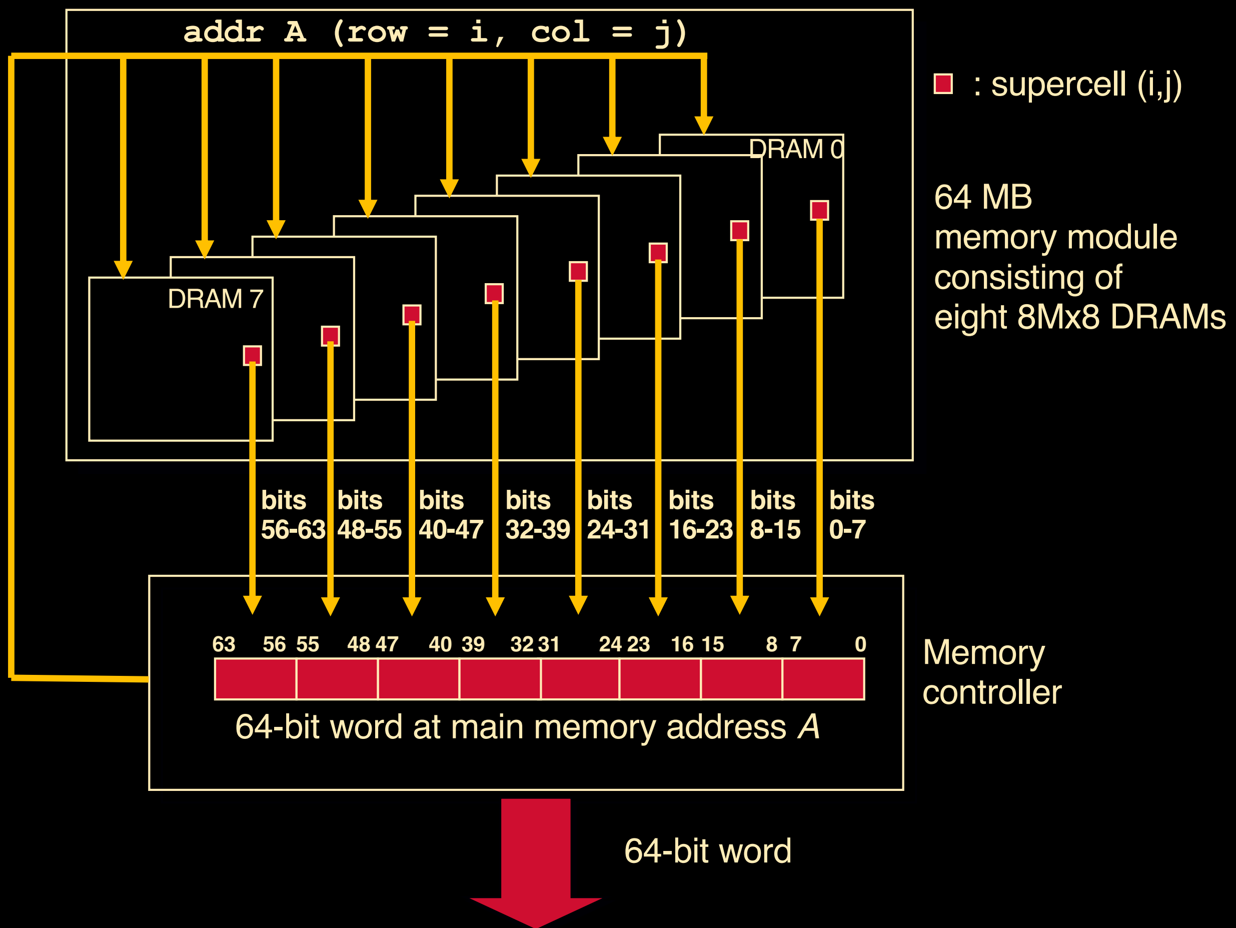


Fast Page Mode: Reading (2,0)(2,1)(2,2)(2,3)

- …
  - Consecutive **CAS** select consecutive columns of the same row
  - Direct row buffer access, no precharge → VERY fast memory access



Memory module basic idea



Caches

- ***<u>Cache:</u>*** A smaller, faster storage device that keeps a copy of a subset of the data from a larger, slower device

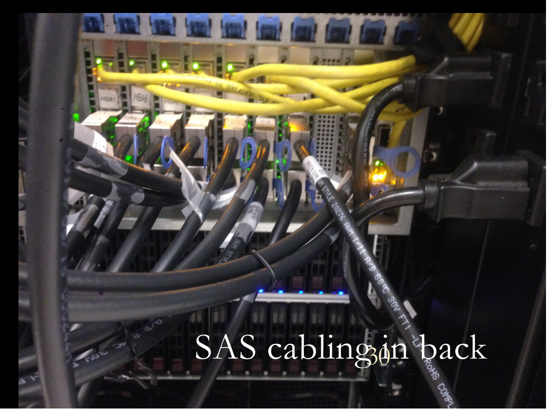
- Fundamental idea of a memory hierarchy:
  - For each *k*, the faster, smaller device at level *k* serves as a cache for the larger, slower device at level *k+1*
  - Each level stores some of the most frequently accessed data
  - The closer the cache is to the processor, the hotter the cached data

- Why do memory hierarchies work?
  - Programs tend to access data at level *k* more often than they access data at level *k+1*
  - Thus, the storage at level *k+1* can be slower, and thus larger and cheaper per bit
  - *Net effect: A **large pool of memory** that **costs as much as the cheap** storage near the bottom, but that serves data to programs at a rate close to the **rate of the fast** storage near the top*

A Database Server @ NU

- 264 fast (10k RPM) magnetic disks (for production)
- 56 slow (7200 RPM) magnetic disks (for backup)
- ~150 TB storage capacity
- Comprises 6 physical chassis (boxes) in one big cabinet, about the size of a coat closet

Front view



SAS cabling in back

Stack Overflow database

- Questions and Answers from a popular programming help website
  - 150 GB of data
  - 29M posts
  - 55M comments
- Reading through all the data takes about 1,000 seconds (17 minutes)
- We do not want to wait 17 minutes for an answer
- We need a way to quickly find the data of interest

How to work with very large datasets fast?

Indexing

- When working with large amounts of data we have to know where to find an item of interest
- In the paper analogy, we do not want to request every box from the warehouse and scan through every page to find what we're looking for
- *Sorting* the data can help tremendously, because it allows *binary search*