Introduction to DBMS Internals

DBMS Architecture

Data storage

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Reading: R & G Chapter 9

Course Overview

- Unit 1: Relational model and SQL
- Unit 2: Storage and indexing
- Unit 3: Query execution
- Unit 4: Query optimization
- Unit 5: Conceptual design
- Unit 6: Transactions
- Unit 7: Recovery
- Unit 8: NoSQL

DBMS Architecture

Architecture of a DBMS: SQL Client

- How is a SQL query executed?

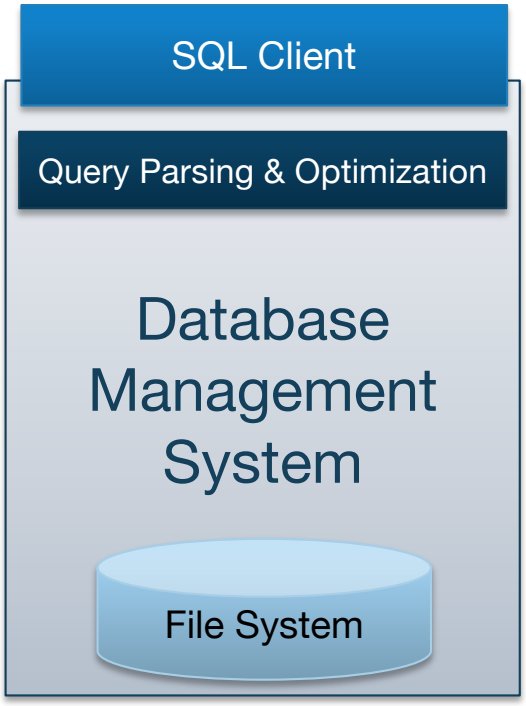
DBMS: Parsing & Optimization

Purpose:

Parse, check, and verify the SQL

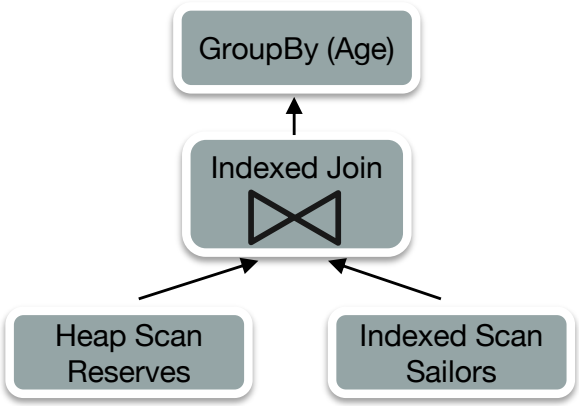
```
SELECT S.sid, S.sname, R.bid
FROM Sailors R, Reserves R
WHERE S.sid = R.sid and S.age > 30
GROUP BY age
```

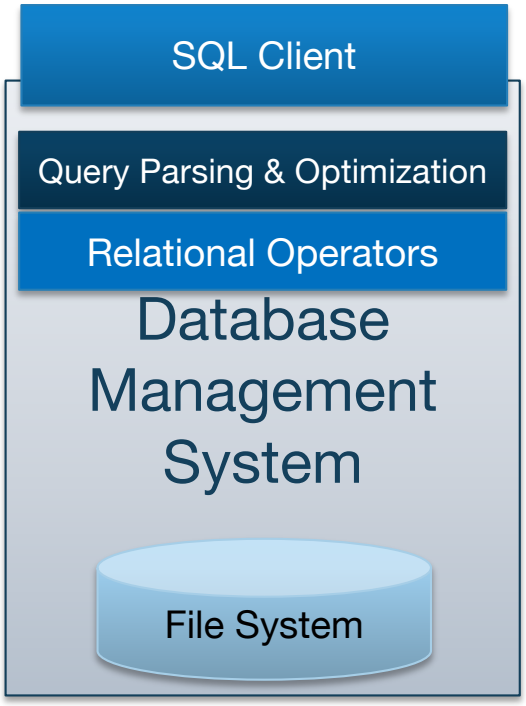
And translate into an efficient relational query plan



DBMS: Relational Operators

Purpose: Execute query plan by operating on **records** and **files**

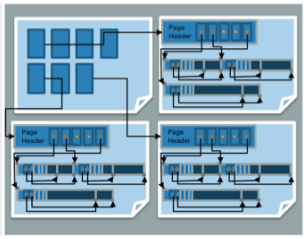


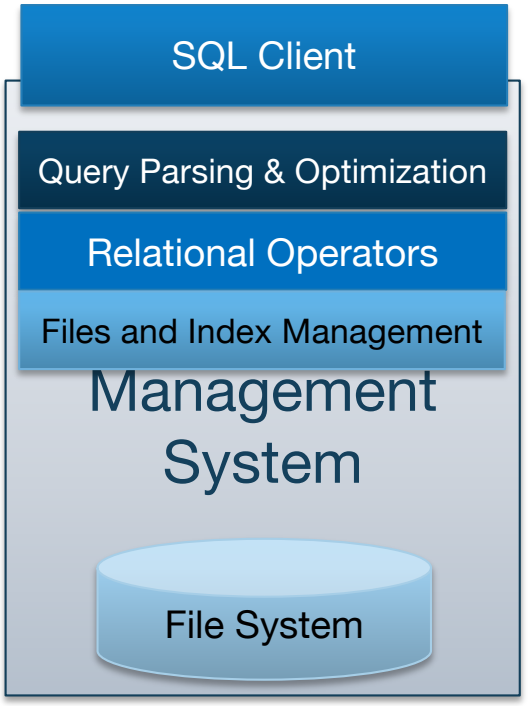


DBMS: Files and Index Management

Purpose: Organize tables and Records as groups of pages in a logical file

SSN	Last Name	First Name	Age	Salary
123	Adams	Elmo	31	$400
443	Grouch	Oscar	32	$300
244	Oz	Bert	55	$140
134	Sanders	Ernie	55	$400

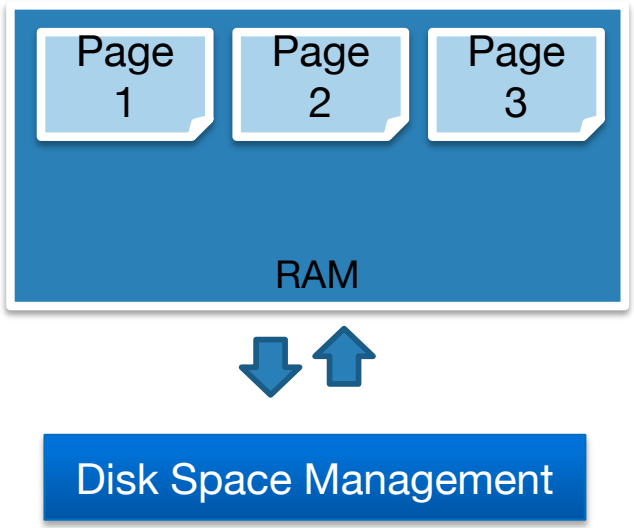


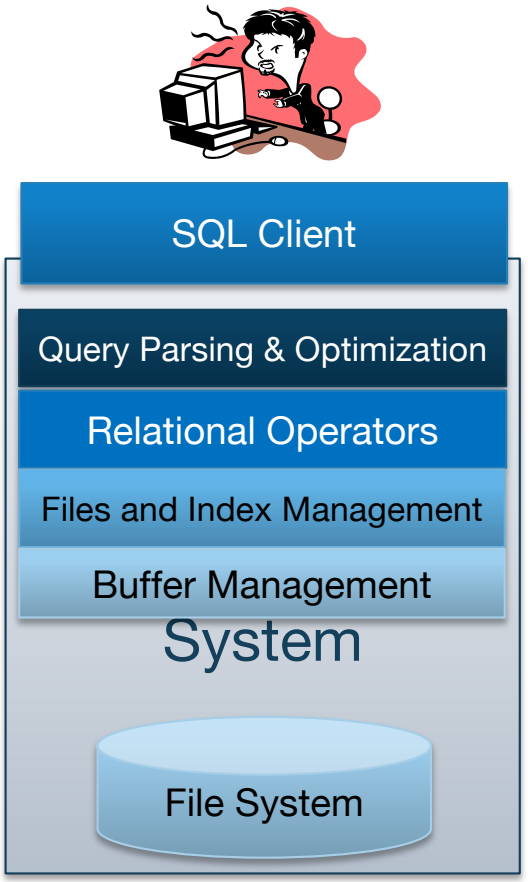


DBMS: Buffer Management

Purpose:

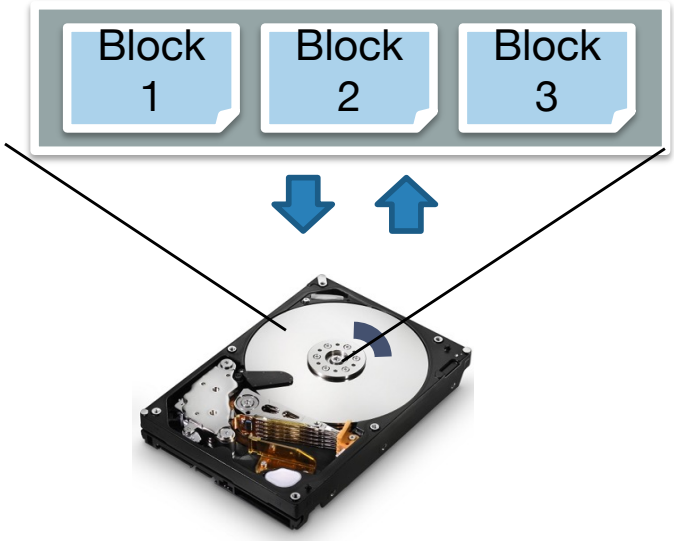
Provide the illusion of operating in memory

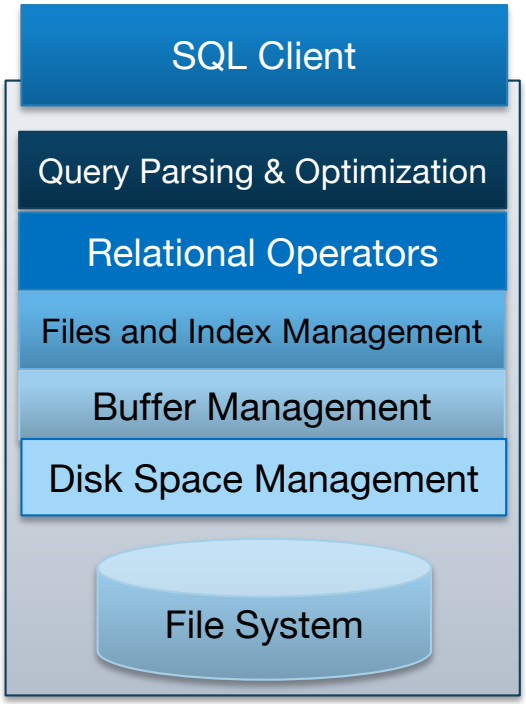




DBMS: Disk Space Management

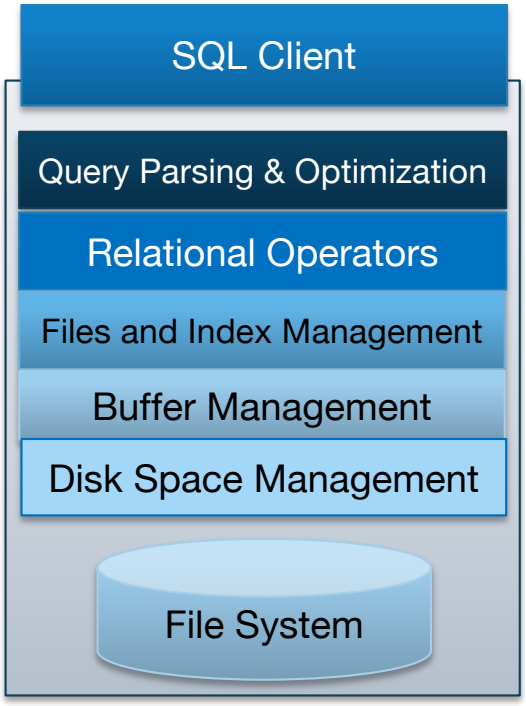
Purpose: Translate page requests into physical bytes on one or more device(s)





Architecture of a DBMS

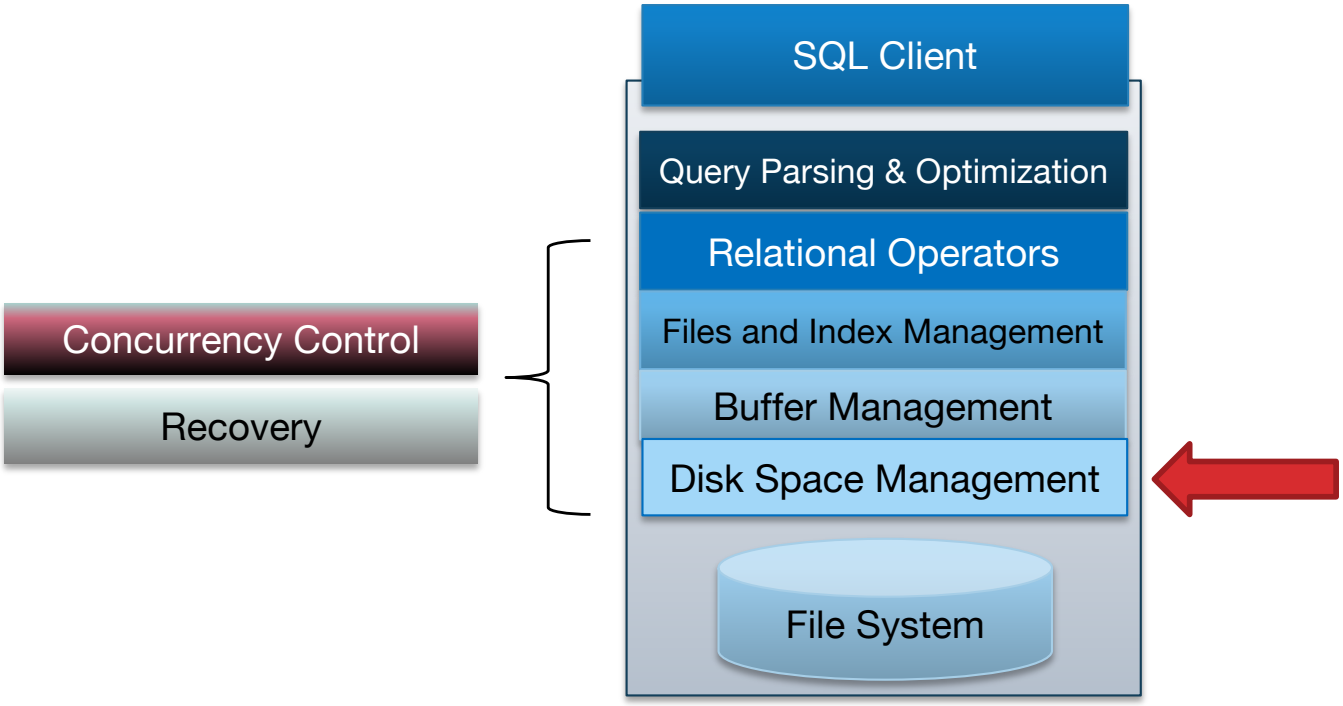
- Organized in layers
- Each layer abstracts the layer below
  - Manage complexity
  - Performance assumptions
- Example of good systems design



- Many non-relational DBMSs are structured similarly

DBMS: Concurrency & Recovery

Two cross-cutting issues related to storage and memory management:



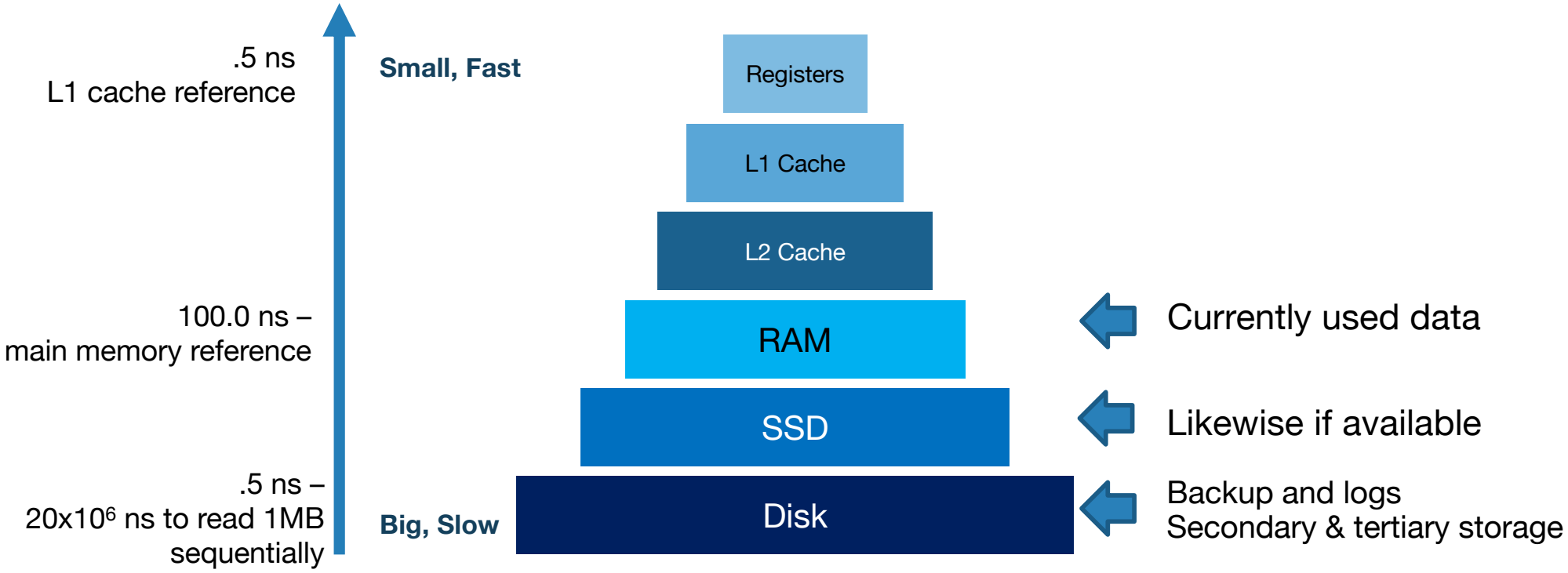
STORAGE MEDIA

Disks

- Most database systems were originally designed for magnetic “spinning” disks
  - Disk are a mechanical anachronism!
  - Instilled design ideas that apply to using solid state disks as well
- Major implications:
  - Disk API:
    - READ: transfer “page” of data from disk to RAM.
    - WRITE: transfer “page” of data from RAM to disk.
    - No random reads / writes!!
  - Both API calls are very**, very slow!**
    - Plan carefully!

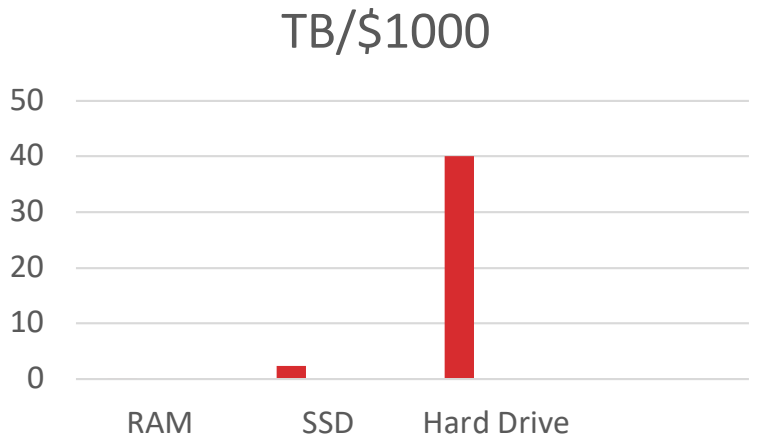
CS 162: Operating Systems and System Programming

Storage Hierarchy



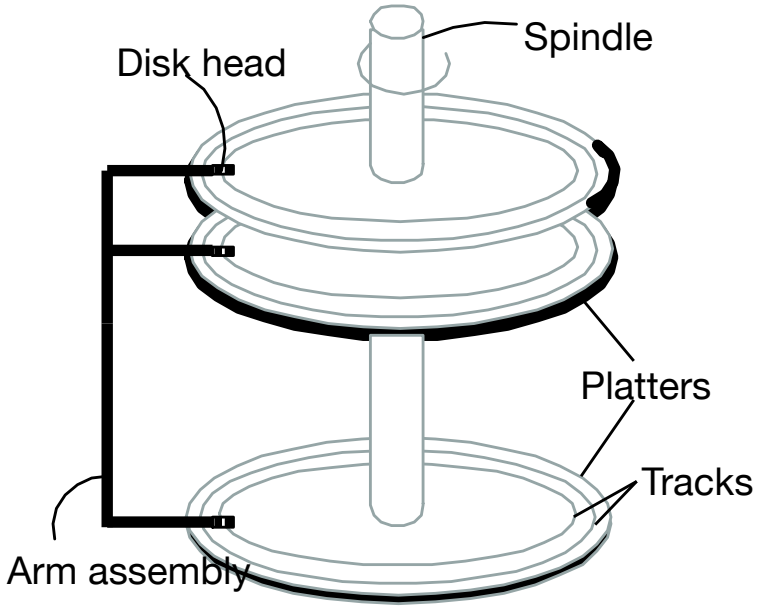
Economics

- $1000 at NewEgg 2022:
  - Mag Disk: ~40TB for $1000
  - SSD: ~2.3TB for $1000
  - RAM: 128GB for $1000



Components of a Disk

- **Platters** spin (say 15000 rpm)
- **Arm assembly** moved in or out to position a **head** on a desired **track**
  - Tracks under heads make a “cylinder”



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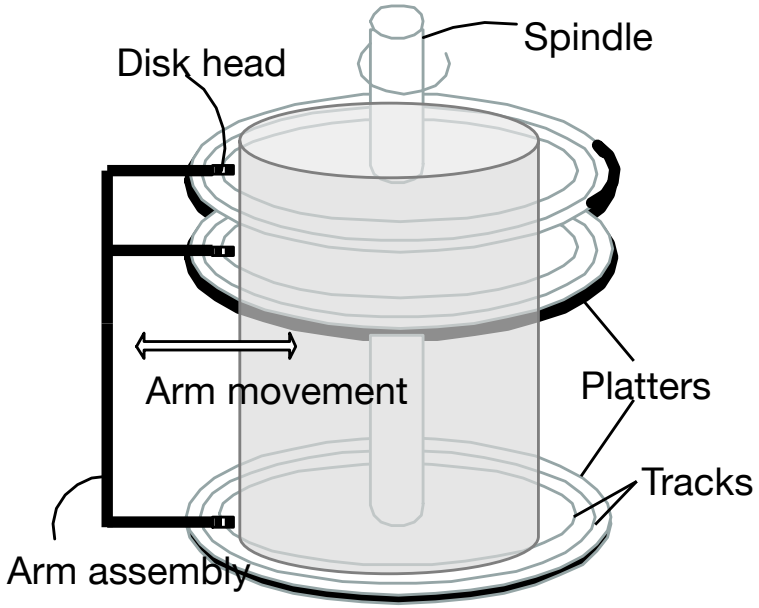
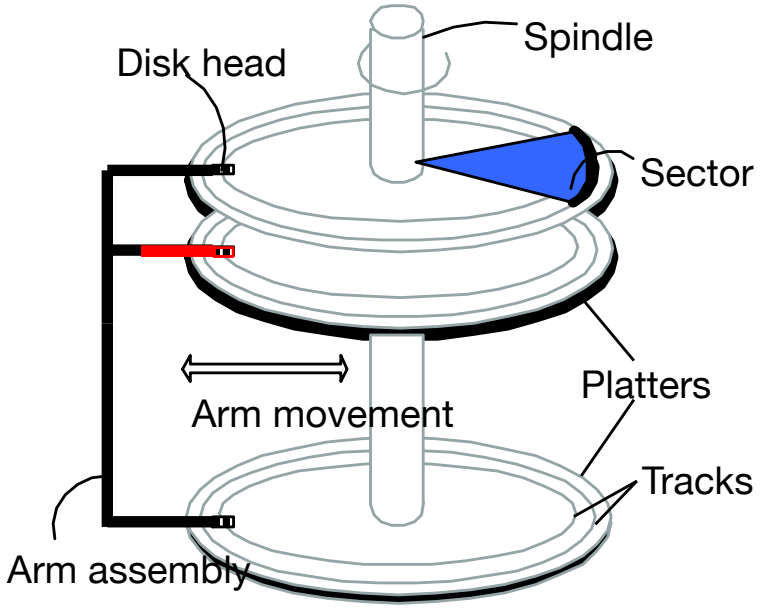


Components of a Disk

- **Platters** spin (say 15000 rpm)
- **Arm assembly** moved in or out to position a **head** on a desired **track**
  - Tracks under heads make a “cylinder”
- Only one head reads/writes at any one time
- Block/page size is a multiple of (fixed) **sector** size



An Analogy

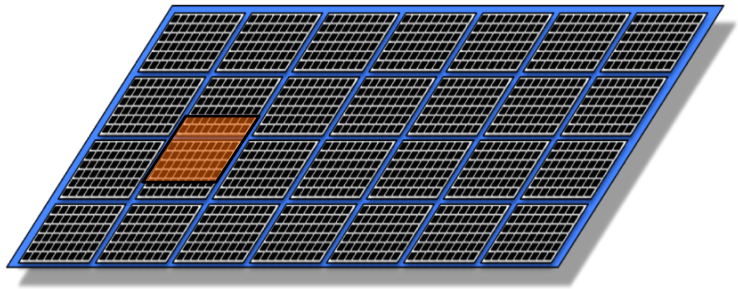
Accessing a Disk page

- Time to access (read/write) a disk block:
  - **seek time** (moving arms to position disk head on track)
    - ~2-3 ms on average
  - **rotational delay** (waiting for block to rotate under head)
    - ~0-4 ms (15000 RPM)
  - **transfer time** (actually moving data to/from disk surface)
    - ~0.25 ms per 64KB page

- Key to lower I/O cost: reduce seek/rotational delays

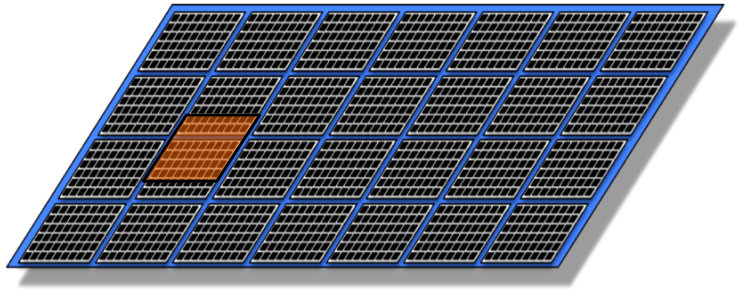
Flash (SSD)

- Organized into “cells”
- Current generation (NAND)
  - Random reads and writes, but:
  - Fine-grain reads (4-8K reads), coarse-grain writes (1-2MB writes)



Flash (SSD), Pt. 2

- So… read is fast and predictable
  - 4KB random reads: ~500MB/sec
- But write is not!
  - 4KB random writes: ~120 MB/sec
  - Why? Only 2k-3k erasures before failure
    - so keep moving write units around (“wear leveling”)



DISK SPACE MANAGEMENT

Block Level Storage

- Read and Write **large chunks of sequential bytes**
- *Sequentially*: “Next” disk block is fastest
- Maximize usage of data per Read/Write
  - “Amortize” seek delays (HDDs) and writes (SSDs):
    if you’re going all the way to Pluto, pack the spaceship full!
- Predict future behavior
  - Cache popular blocks
  - Pre-fetch likely-to-be-accessed blocks
  - Buffer writes to sequential blocks
  - More on these as we go

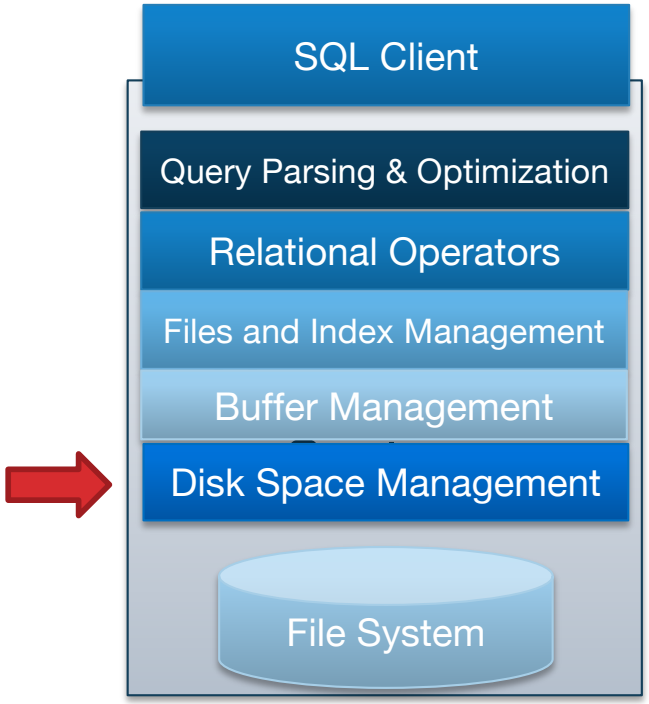
A Note on Terminology

- Block = Unit of transfer for disk read/write
  - 64KB – 128KB is a good number today
  - Book says 4KB
  - We'll use this unit for all storage devices
- Page: a common synonym for "block"
  - In some texts, "page" = a block-sized chunk of RAM

- We'll treat "block" and "page" as synonyms

Disk Space Management

- Lowest layer of DBMS, manages space on disk
- Purpose:
  - Map pages to locations on disk
  - Load pages from disk to memory
  - Save pages back to disk & ensuring writes
- Higher levels call upon this layer to:
  - Read/write a page
  - Allocate/de-allocate logical pages



Disk Space Management: Requesting Pages


- ```
  page = getFirstPage("Sailors");
  while (!done) {
    process(page);
    page = page.nextPage();
  }
  ```
- Physical details hidden from higher levels of system
- Higher levels may "safely" assume `nextPage` is fast
  - Hence sequential runs of pages are quick to scan
  ```

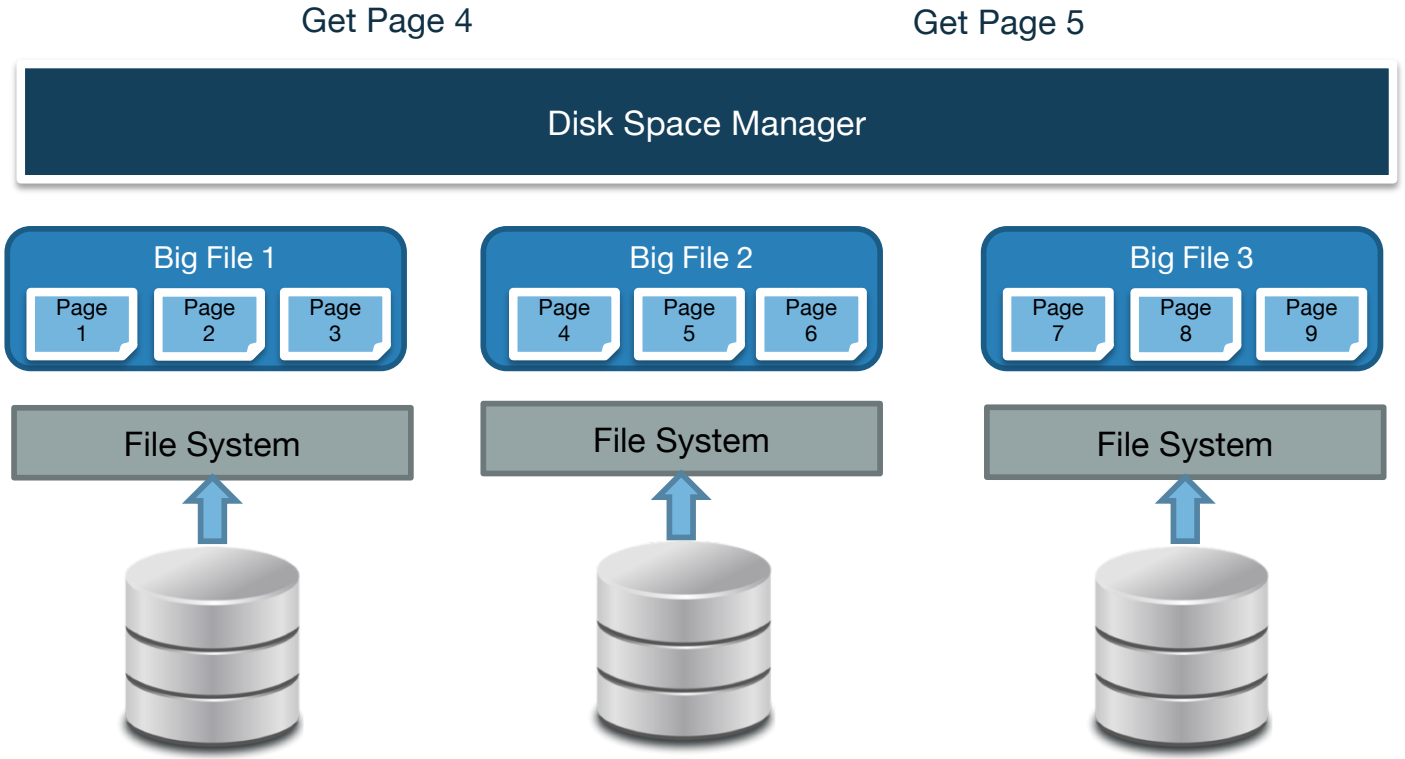
Disk Space Management: Implementation

- **Proposal 1:** Talk to the storage device directly
  - Could be very fast if you knew the device well
  - Hard to program when each device has its own API
  - What happens when devices change?

Disk Space Management: Implementation

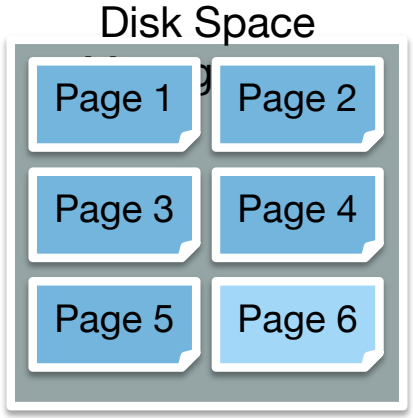
- **Proposal 2**: Run our own over filesystem (FS)
  - Bypass the OS, allocate single large “contiguous” file on an empty disk
    - assume sequential/nearby byte access are fast
  - Most FS optimize disk layout for sequential access
    - Gives us what we want if we start with an empty disk
  - DBMS “file” may span multiple FS files on multiple disks/machines

Using Local Filesystem



Summary: Disk Space Management

- Provide API to read and write pages to device
- Pages: block level organization of bytes on disk
- Provides “next” locality and abstracts FS/device details



Disks and Files: Summary

- Magnetic (hard) disks and SSDs
  - Basic HDD and SSD mechanics
  - Concept of “near” pages and how it relates to cost of access

  - Relative cost of
    - Random vs. sequential disk access (10x)
    - Disk (Pluto) vs RAM (Sacramento) vs. registers (your head)
      - Big, big differences!

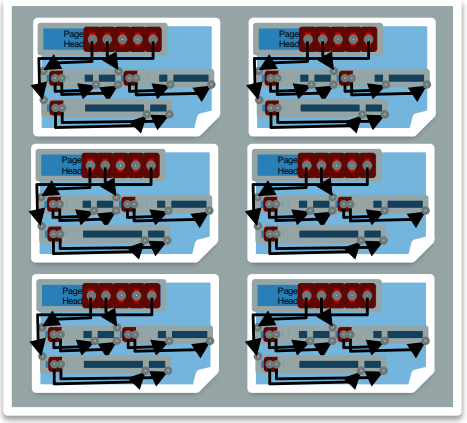
Files: Summary

- DB File storage
  - Typically over FS file(s)
- Disk space manager loads and stores pages
  - Block level reasoning
  - Abstracts device and file system; provides fast “next page”

Disk Representations:
Files, Pages, Records

Overview: Files of Pages of Records

- It's all about abstractions!
  - Each table is stored in one or more OS files
  - Each file contains many pages
  - Each page contains contains many records
- Pages are the common currency understood by multiple layers:
  - Managed on disk by the disk space manager: pages read/written to physical disk/files
  - Managed in memory by the buffer manager: higher levels of DBMS only operate in memory



Files of Pages of Records

- Let's talk about a single table for now
- **DB FILE:** A collection of pages, each containing a collection of records.
- API for higher layers of the DBMS:
  - Reads:
    - Fetch a particular record by ***record id*** …
      - Record id is a pointer encoding pair of (**pageID, location on page**)
    - Scan all records
      - Possibly with some conditions on the records to be retrieved
  - Updates: Insert/delete/modify record
- This abstraction could span multiple OS files and even machines

Many DB File Structures

Information is stored in files in multiple different ways

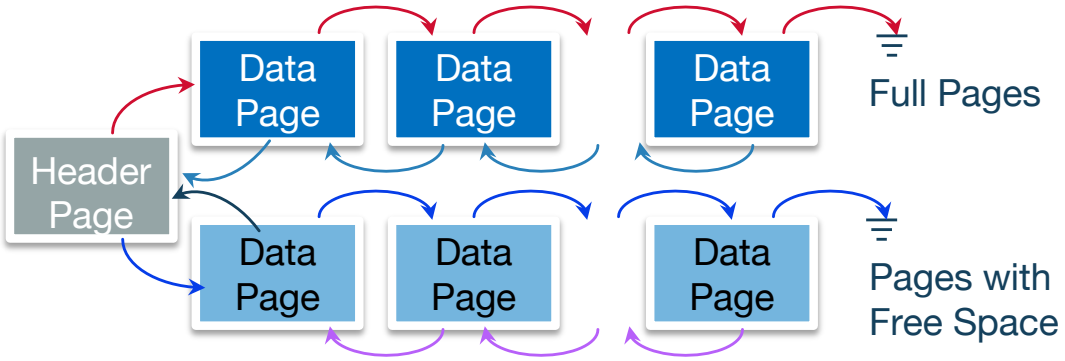
- Unordered Heap Files
  - Records placed arbitrarily across pages
- Clustered Heap Files
  - Records and pages are grouped in some meaningful way
- Sorted Files
  - Pages and records are in strict sorted order
- Index Files
  - B+ Trees, Linear Hashing, …
  - May contain records or point to records in other files
- Focus on Unordered Heap Files for now…

Unordered Heap Files

- Collection of records in no particular order
  - Not to be confused with “heap” data-structure: efficient max/min
- As file shrinks/grows, pages (de)allocated
- To support record level operations, we must
  - Keep track of the pages in a file
  - Keep track of free space on pages
  - Keep track of the records on a page

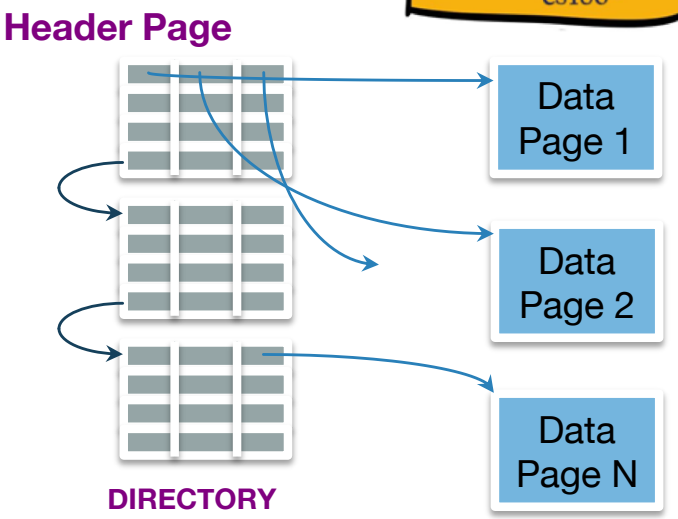
Take 1: Heap File as List

- Heap file has one special “Header page”
  - Location of the heap file and the header page saved e.g., in catalog
- Each page contains 2 “pointers” plus **free space** and **data**
- What is wrong with this?
  - Find a page with enough space for a 20 byte record?
  - A: Might need to access many pages (w/ free space) to check



Take 2: Use a Page Directory

- Directory, with multiple Header Pages, each encoding:
  - A pointer to page
  - Number of free bytes on the page } 8 bytes
- There can be multiple such header pages
- Header pages accessed often → likely in cache
- Finding a page to fit a record required far fewer page loads than linked list. Why?
  - One header page load reveals free space of many pages
- We can optimize the page directory further:
  - E.g., compressing header page, keeping header page in sorted order based on free space, etc.
  - But diminishing returns?



Summary

- Table encoded as files which are collections of pages
- Page directory provides locations of pages and free space

SSNz	Last Name	First Name	Age	Salary
123	Adams	Elmo	31	$400
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244	Oz	Bert	55	$140
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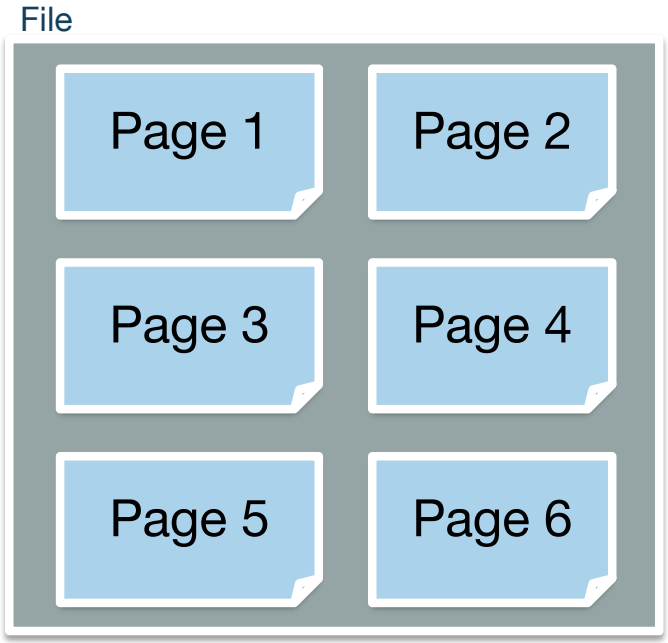
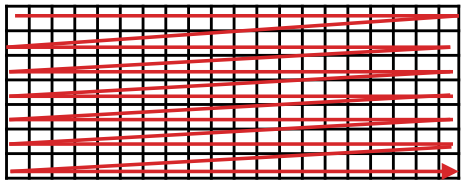


PAGE LAYOUT

A Note On Imagery

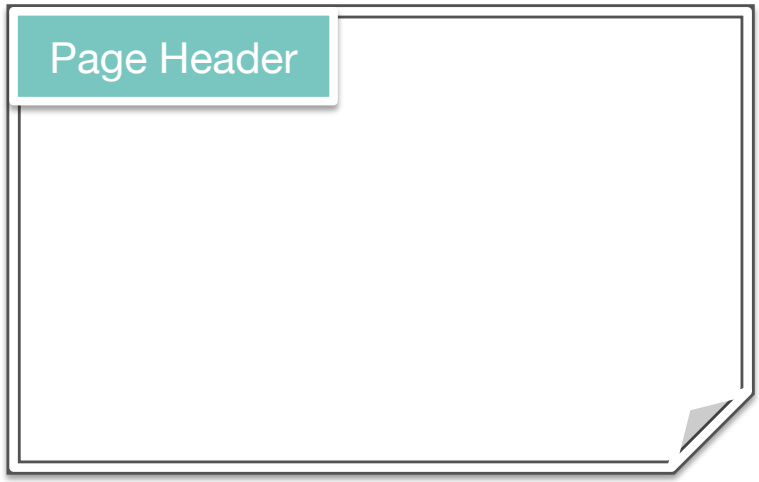
- Data (in memory or disk) is stored in linear order

- This doesn't fit nicely on screen
  - So we will "wrap around" the linear order into a rectangle

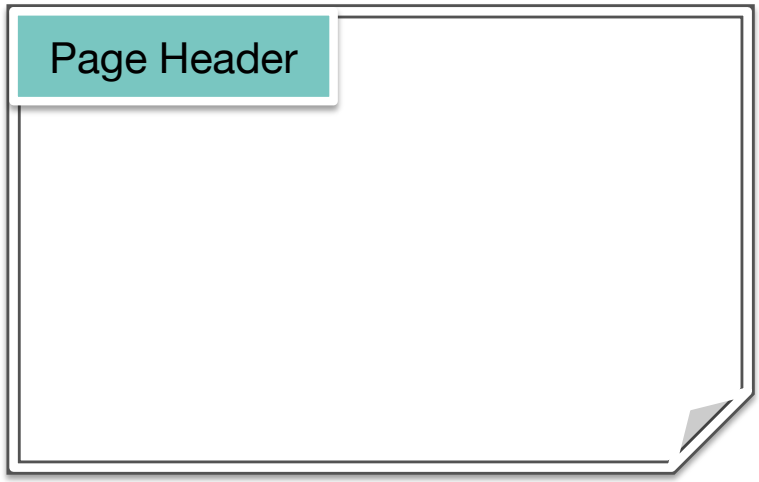


Page Basics: The Header

- Header may contain “metadata” about the page, e.g.
  - Number of records
  - Free space
  - Maybe a next/last pointer to other pages
  - Bitmaps, Slot Table
  - (We’ll talk about why all of these later)



Things to Address



Some options:

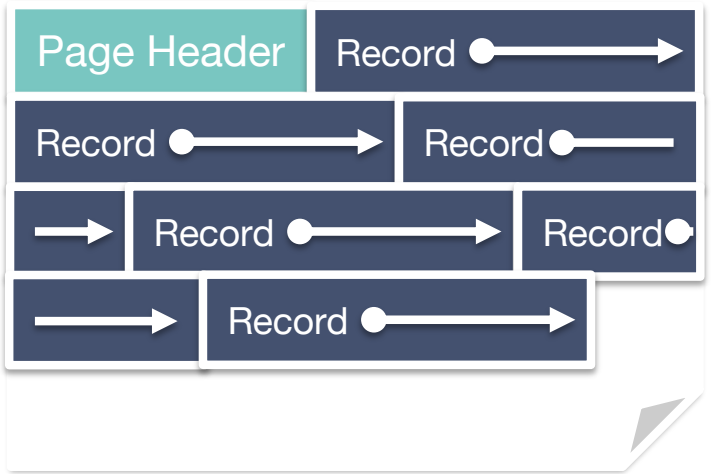
- Record length? **Fixed** or Variable
- Page layout? **Packed** or Unpacked

Some questions:

- Find records by record id?
  - Record id = (Page, Location in Page)
- How do we add and delete records?

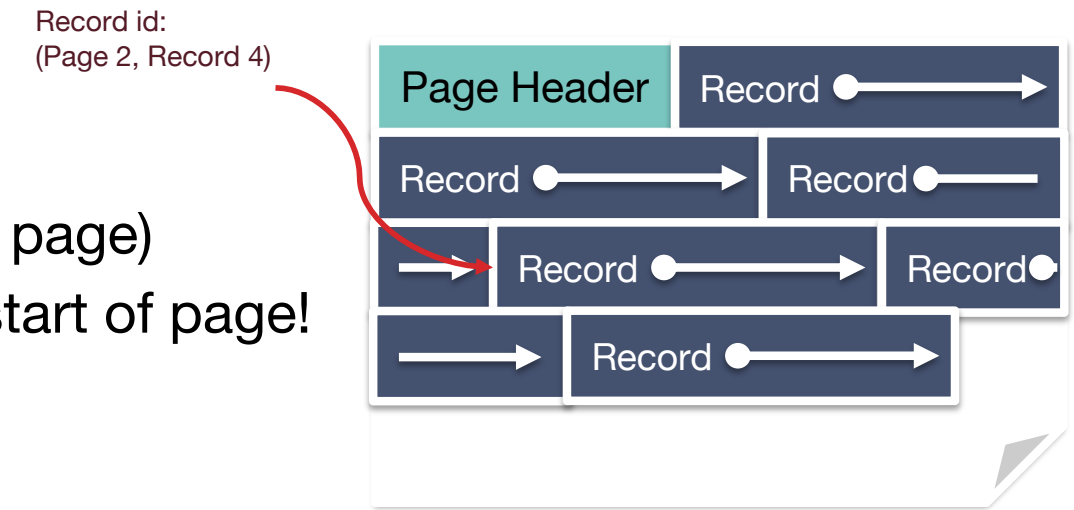
Fixed Length Records, Packed

- Pack records densely
- Record id?
  - (pageId, record number in page)
  - We know the offset from start of page!
    - Offset = header + (record size) x (n-1)
- Add a record: just append
- Delete?



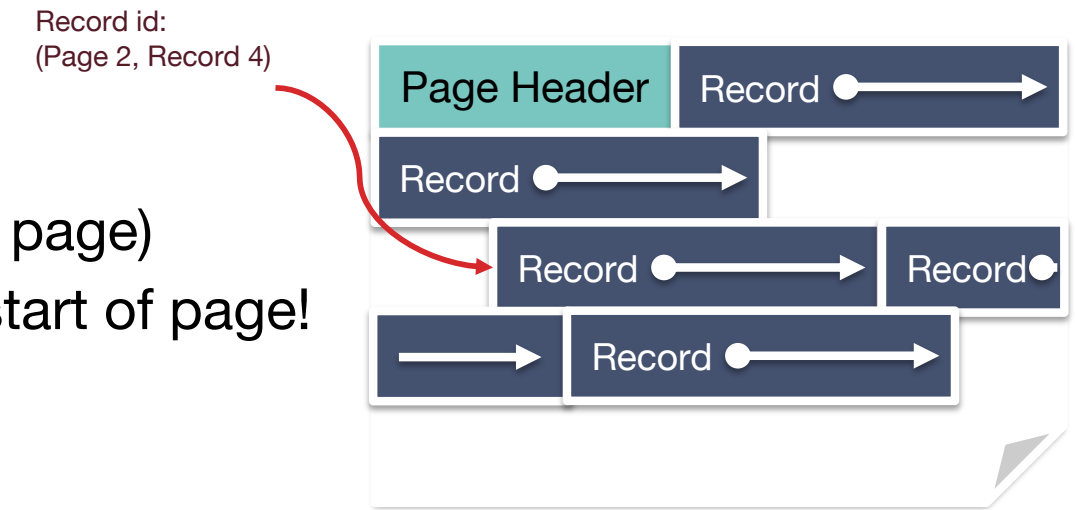
Fixed Length Records, Packed, Pt 2.

- Pack records densely
- Record id?
  - (pageId, record number in page)
  - We know the offset from start of page!
- Add a record: just append
- Delete?
  - Say we delete (Page 2, Record 3)



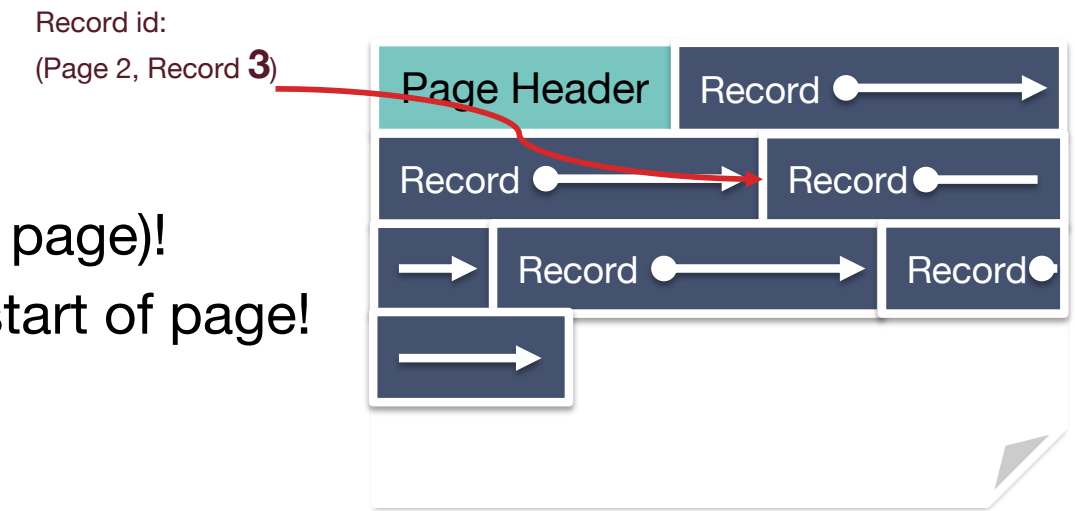
Fixed Length Records: Packed, Pt 3.

- Pack records densely
- Record id?
  - (pageId, record number in page)
  - We know the offset from start of page!
- Add a record: just append
- Delete?
  - Say we delete (Page 2, Record 3)
  - Now free space… need to reorg

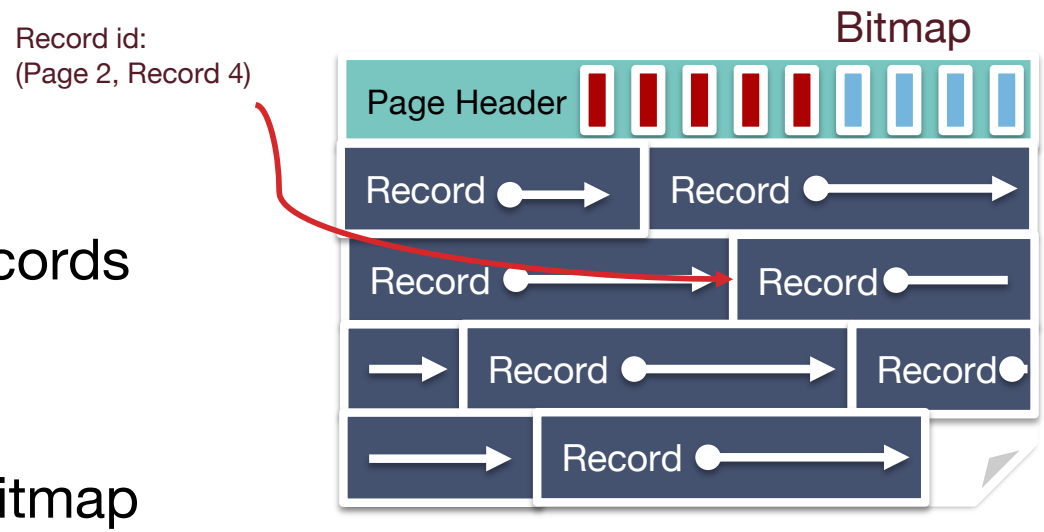


Fixed Length Records: Packed, Pt. 5

- Pack records densely
- Record id?
  - (pageId, record number in page)!
  - We know the offset from start of page!
- Add a record: just append
- Delete?
  - Packed implies re-arrange!
  - “record id” - (Page 2, Record 4) now need to be updated to (Page 2, Record 3)
  - Record Ids need to be updated!
    - Could be expensive if they’re in other files.

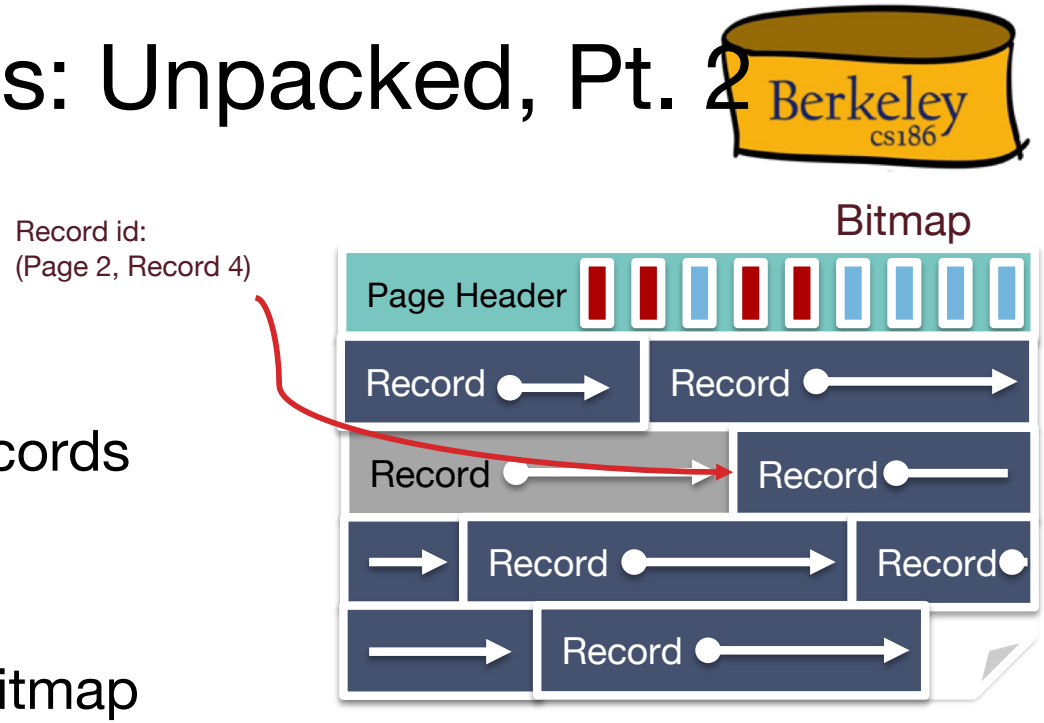


Fixed Length Records: Unpacked



- Bitmap denotes “slots” with records
- Record id?
  - (pageId, slotId)
- **Insert**: find first empty slot in bitmap
- **Delete**: ?

Fixed Length Records: Unpacked, Pt. 2

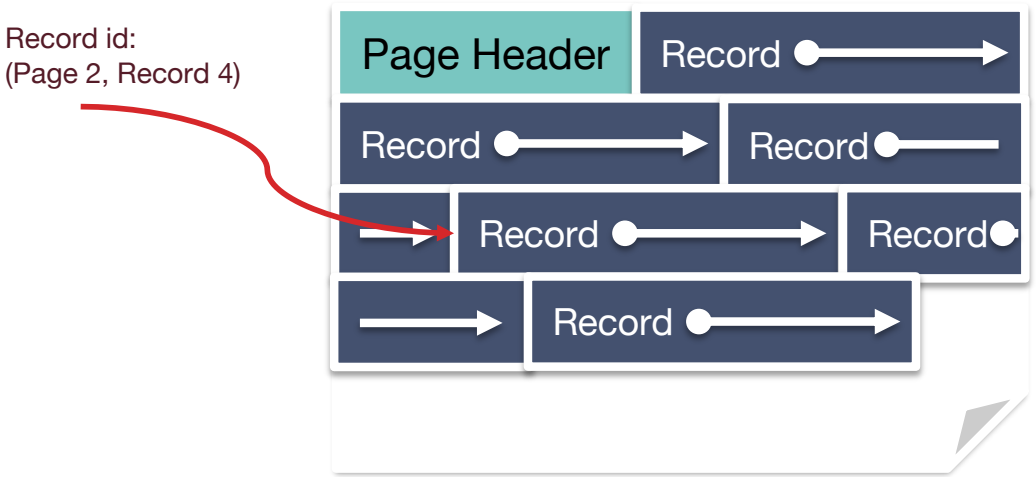


- Bitmap denotes “slots” with records
- Record id?
  - (pageId, slotId)
- **Insert**: find first empty slot in bitmap
- **Delete**: clear bit
  - No reorganization needed!
  - Small cost of a bitmap, which can be very compact

Variable Length Records

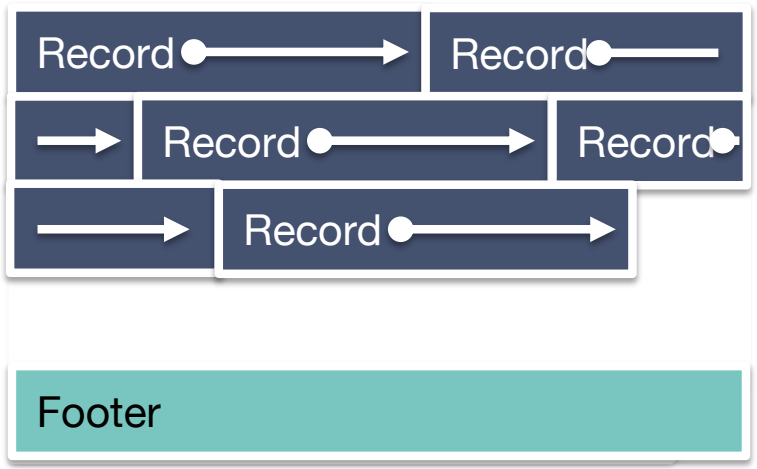
- We've already seen that packed isn't the best idea, so let's consider the unpacked case

- How do we know where each record begins (mapping record id to location)?
- What happens when we add and delete records?



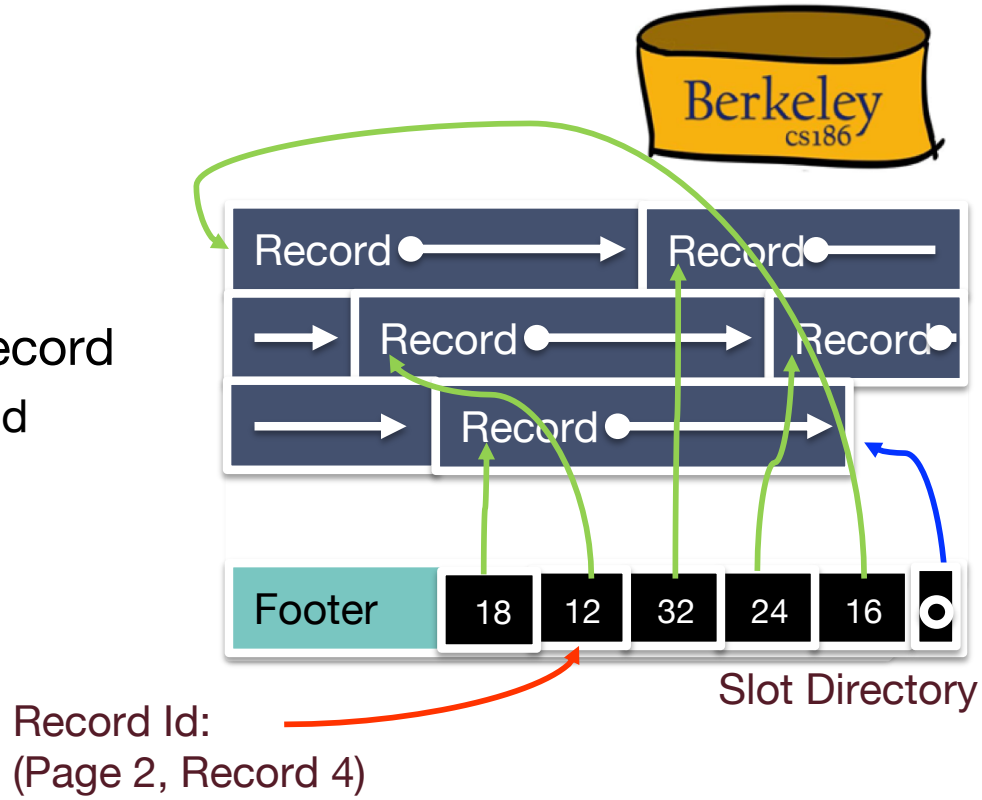
First: Relocate metadata to footer

- We'll see why this is handy shortly…



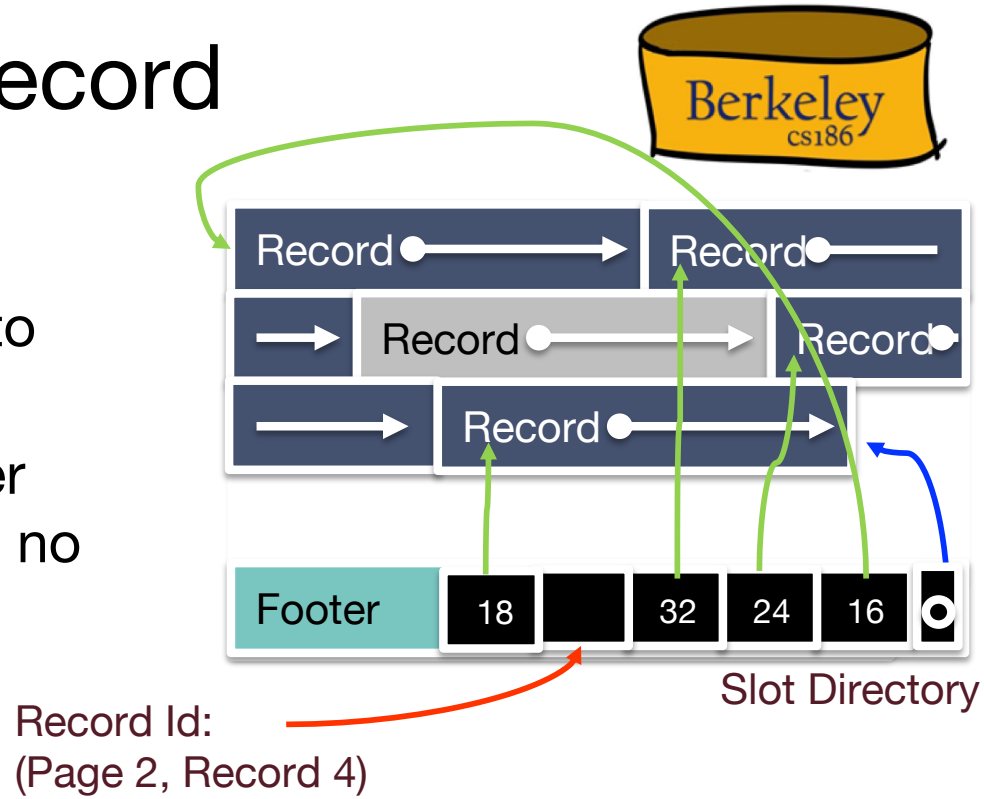
Slotted Page

- Introduce slot directory in footer
  - Pointer to free space
  - Length + Pointer to beginning of record
    - Slots are filled starting from the end
- Record ID = location in slot table
  - from right
- Delete?
  - e.g., 4th record on the page



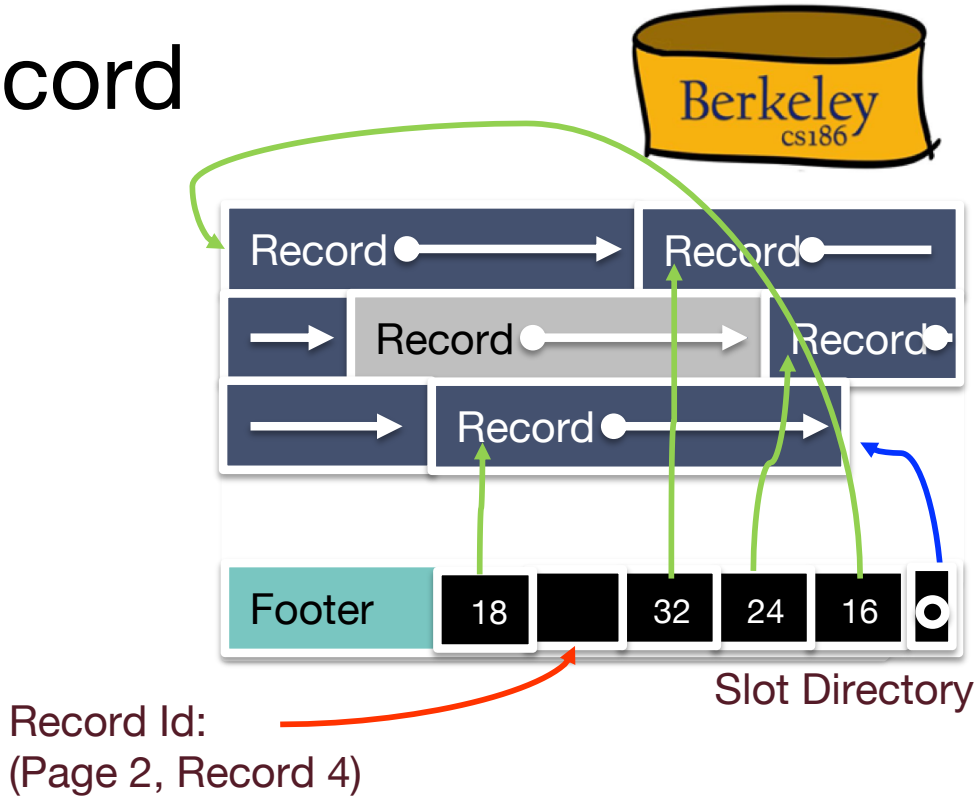
Slotted Page: Delete Record

- Delete record (Page 2, Record 4):
  - Set 4th slot directory pointer to null
  - Doesn't affect pointers to other records (no internal reorg, and no updating of external pointers)



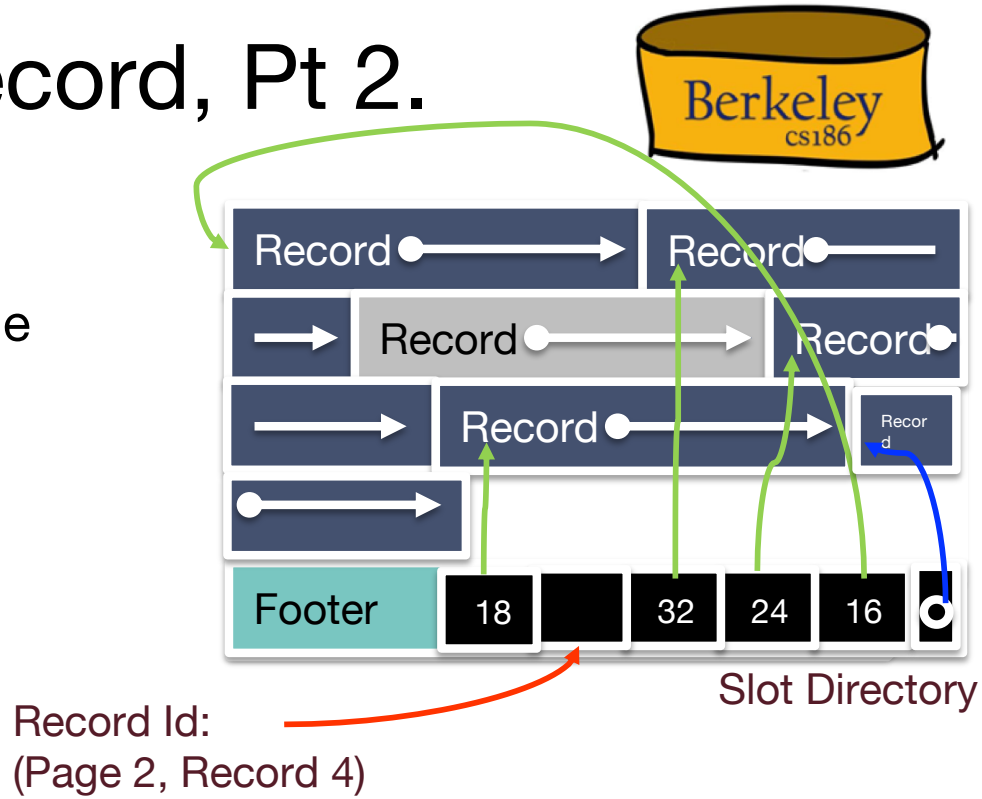
Slotted Page: Insert Record

- Insert:



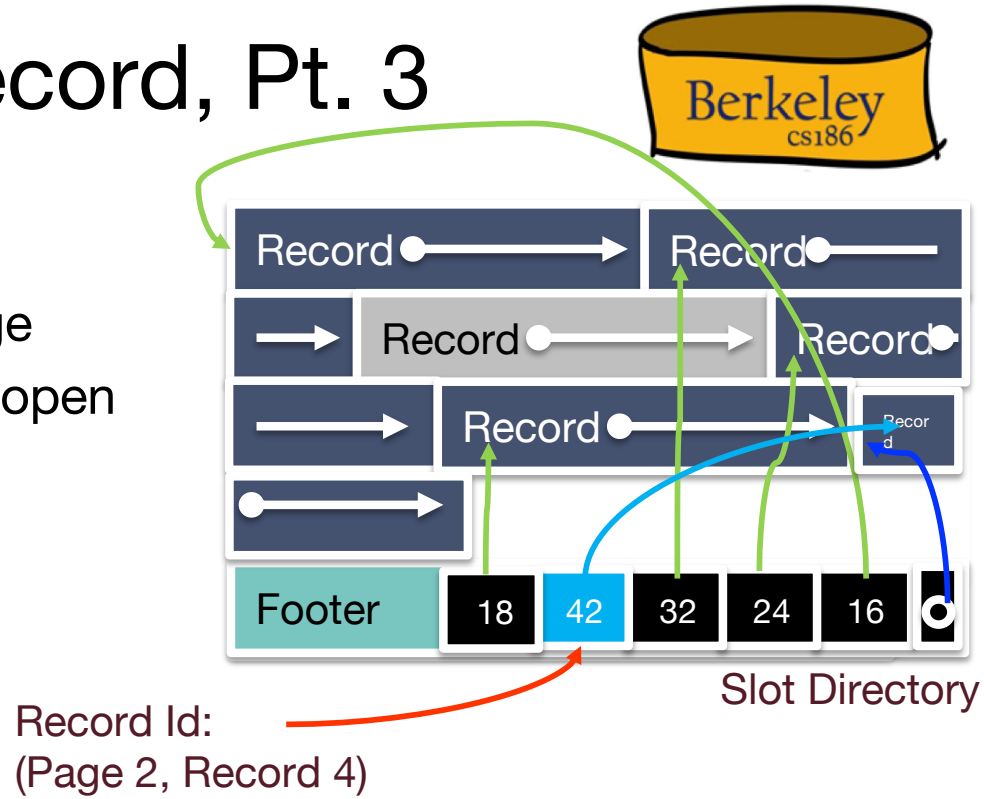
Slotted Page: Insert Record, Pt 2.

- Insert:
  - Place record in free space on page



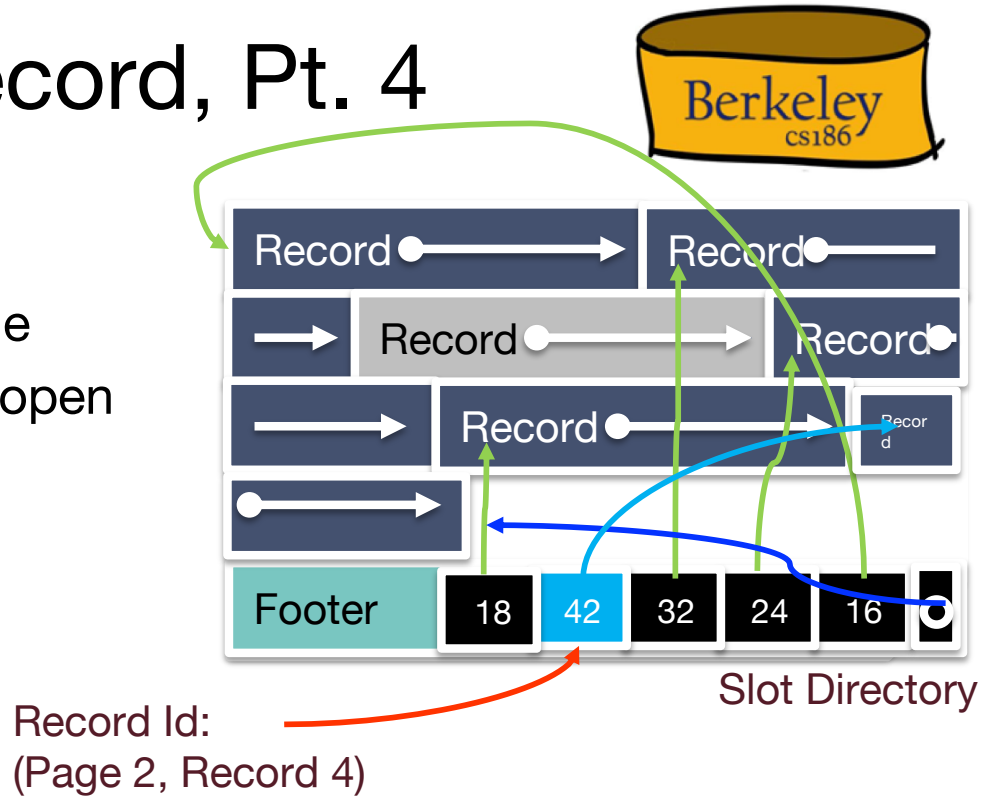
Slotted Page: Insert Record, Pt. 3

- Insert:
  - Place record in free space on page
  - Create pointer/length pair in next open slot in slot directory



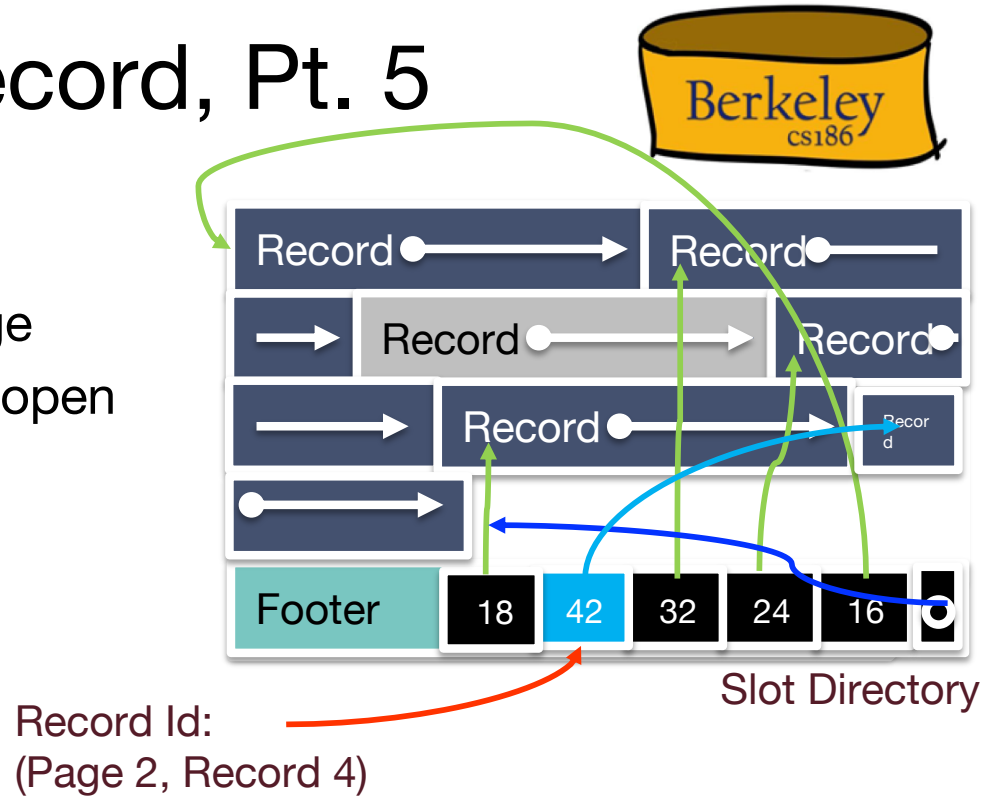
Slotted Page: Insert Record, Pt. 4

- Insert:
  - Place record in free space on page
  - Create pointer/length pair in next open slot in slot directory
  - Update the free space pointer



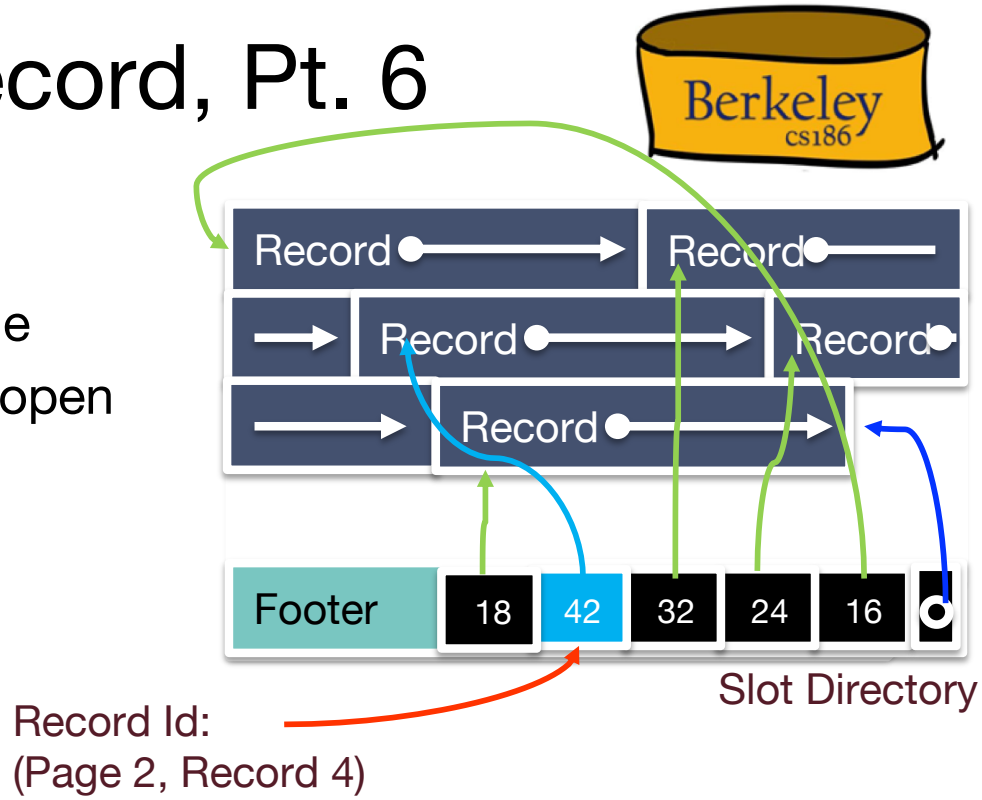
Slotted Page: Insert Record, Pt. 5

- Insert:
  - Place record in free space on page
  - Create pointer/length pair in next open slot in slot directory
  - Update the free space pointer
  - Fragmentation?



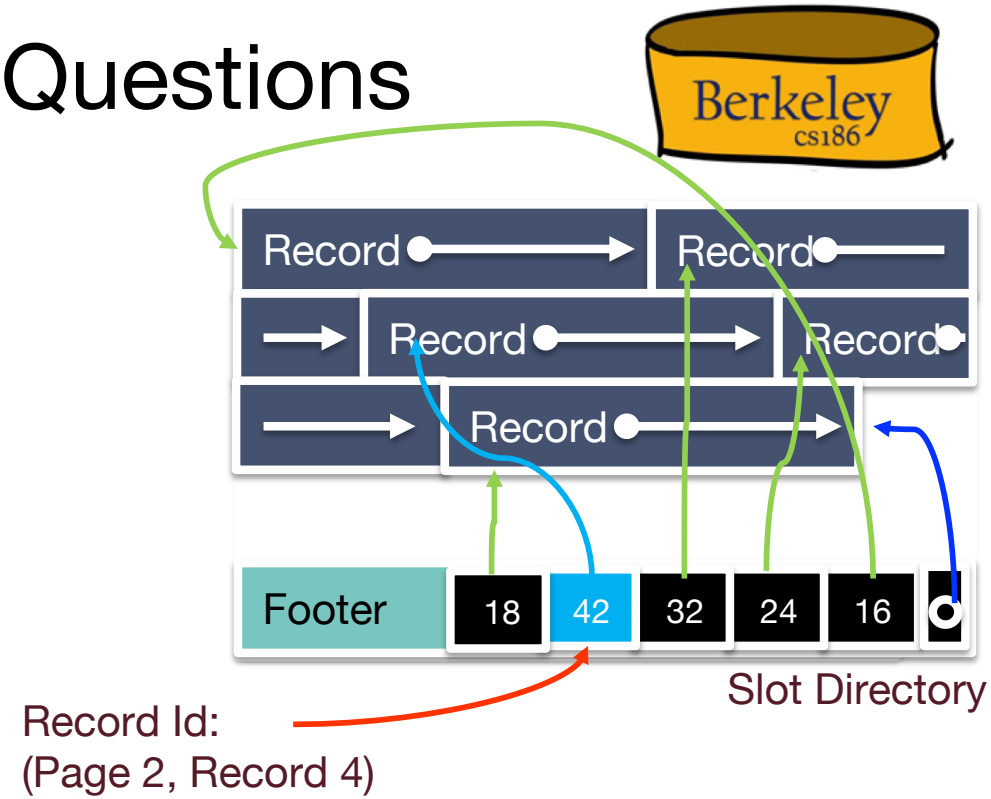
Slotted Page: Insert Record, Pt. 6

- Insert:
  - Place record in free space on page
  - Create pointer/length pair in next open slot in slot directory
  - Update the free space pointer
  - Fragmentation?
    - Reorganize data on page!



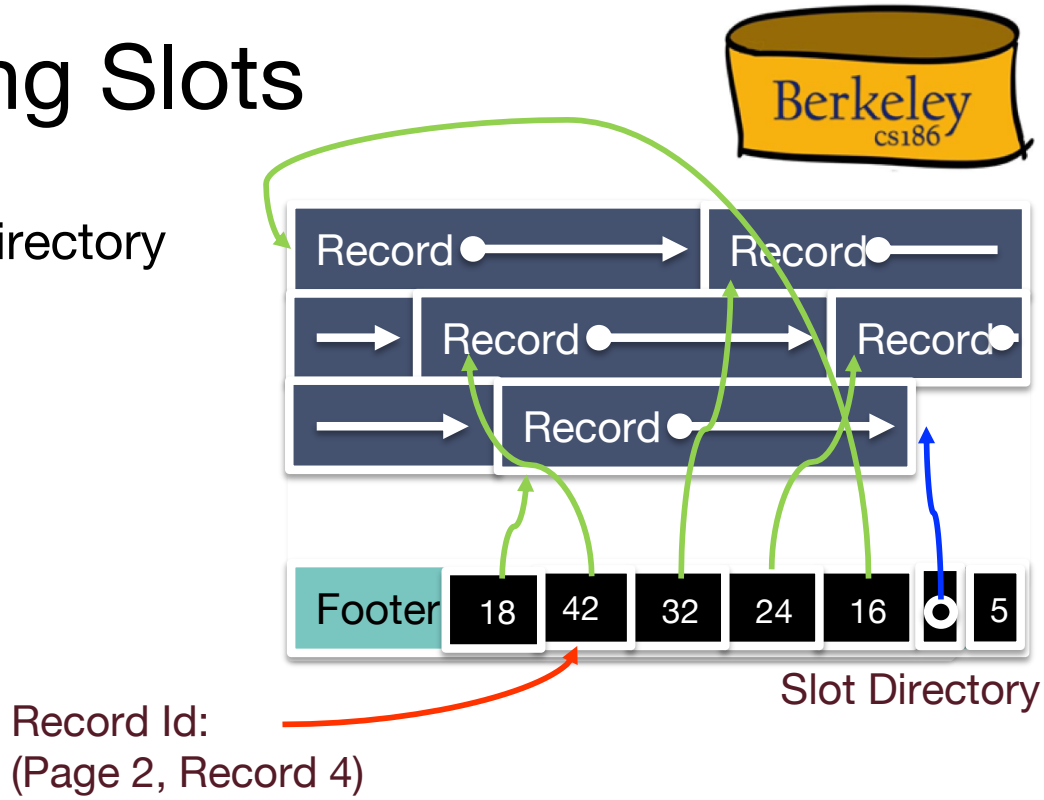
Slotted Page: Leading Questions

- Reorganize data on page
  - Is this safe?
    - Yes this is safe because records ids don't change. Record ids refer to slots
- When should I reorganize?
  - We could re-organize on delete
  - Or wait until fragmentation blocks record addition and then reorganize.
  - Often pays to be a little sloppy if page never gets more records.
- What if we need more slots?
  - Let's see…



Slotted Page: Growing Slots

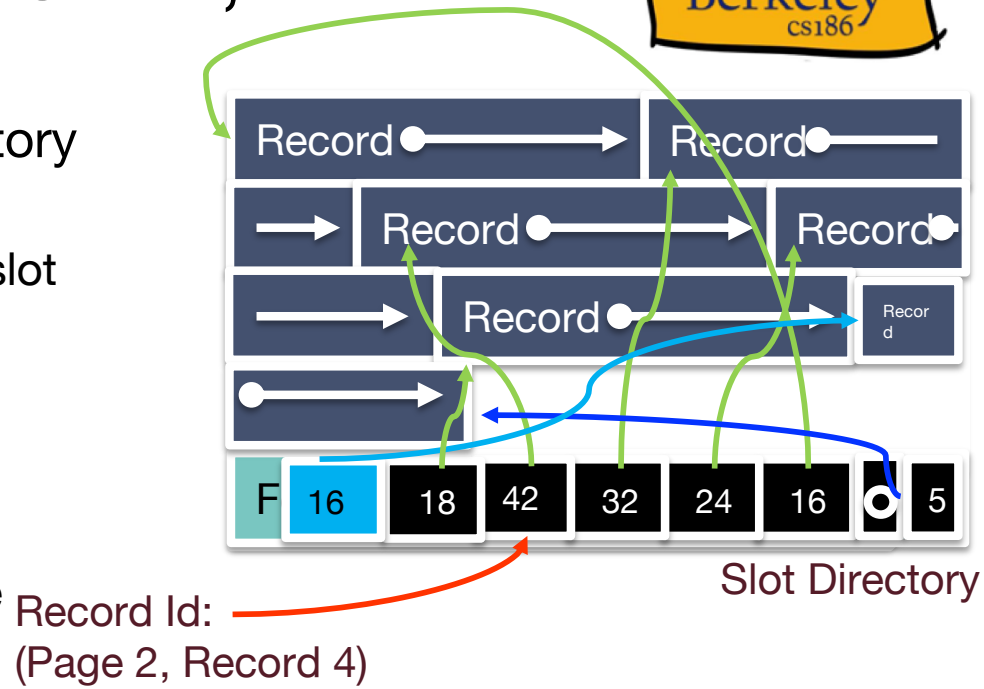
- Tracking number of slots in slot directory
  - Empty or full



Slotted Page: Growing Slots, Pt. 2

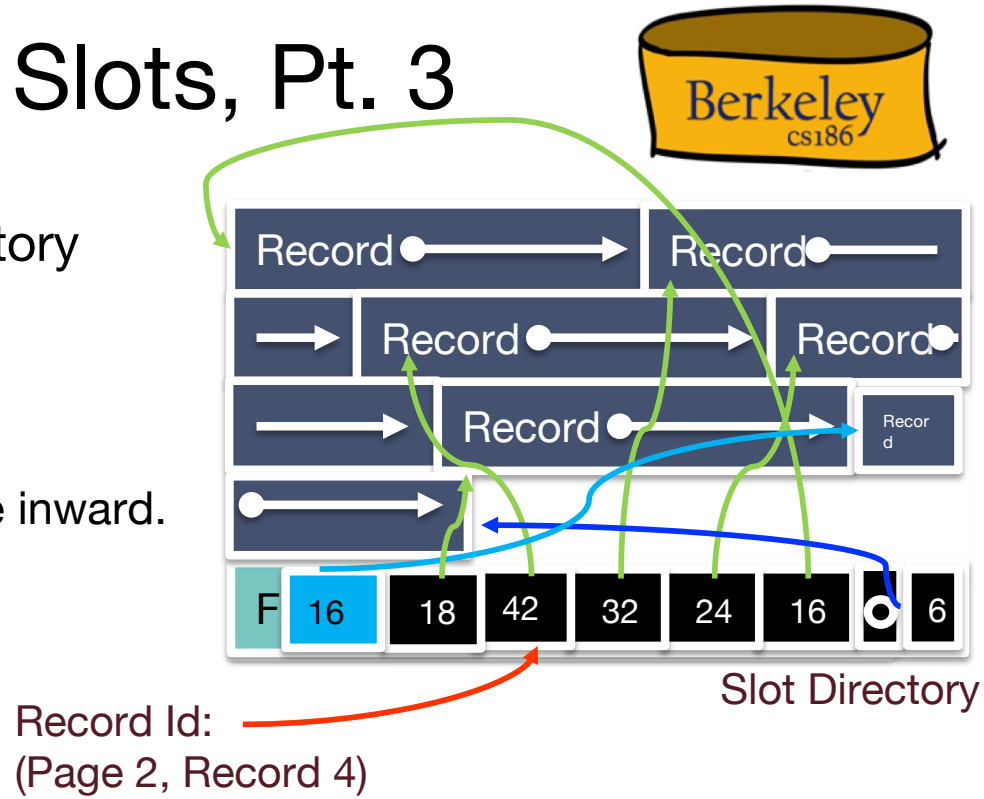
- Tracking number of slots in slot directory
  - Empty or full
- If full slots = number of slots, then extend slot directory

- To extend slot directory
  - Slots grow from end of page inward
  - Records grow from beginning of page inward.
  - Easy!

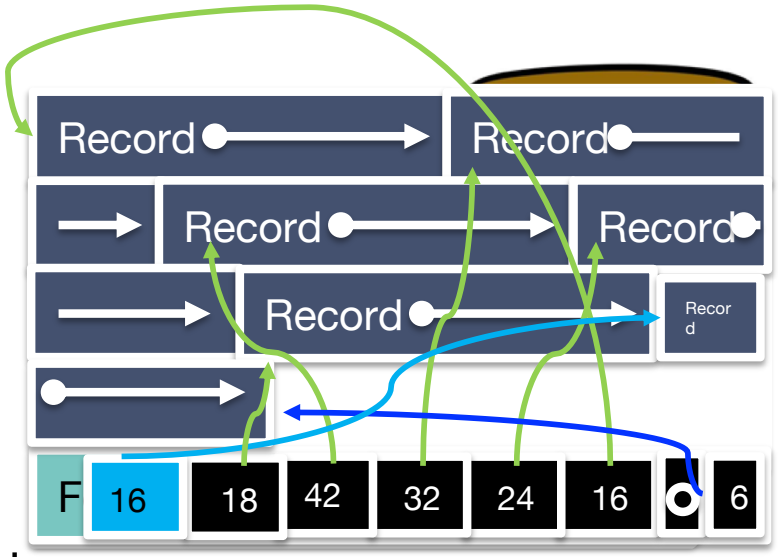


Slotted Page: Growing Slots, Pt. 3

- Tracking number of slots in slot directory
  - Empty or full
- Extend slot directory
  - Slots grow from end of page inward
  - Records grow from beginning of page inward.
  - Easy!
- And update count



Slotted Page: Summary



- Typically use Slotted Page
  - Good for variable and fixed length records
- Not bad for fixed length records too.
  - Why?
  - Fixed length records also have NULL fields
  - NULL values can be “squashed” and indicated using a flag, avoiding full attribute length storage
  - But, if we have only non-NULL fields, can be worth the optimization of fixed-length format

RECORD LAYOUT

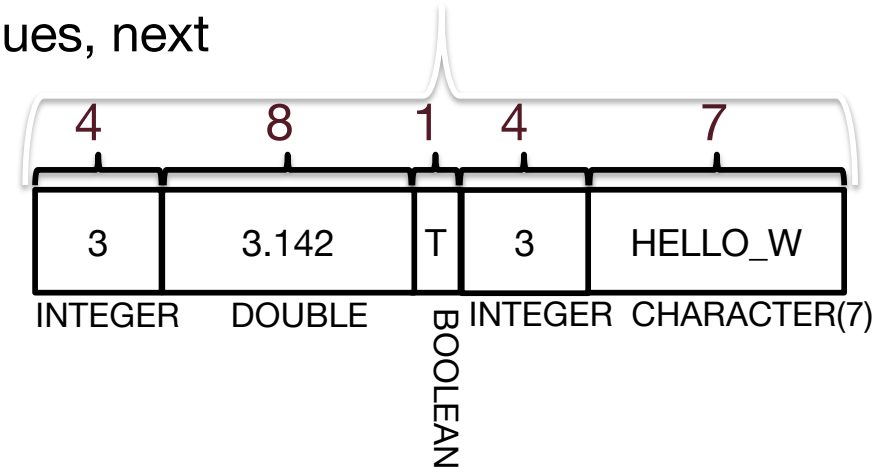
Record Formats

- Each record in a table/relation has a fixed combo of types
- Relational databases use same page format for data on disk or in memory
  - Save cost of conversion (known as serialization/deserialization)
- Assume System Catalog stores the Schema
  - No need to store type information with records (save space!)
  - Catalog is just another table
- Goals:
  - Fast access to fields (why?)
  - Records should be compact

- Easy Case: Fixed Length Fields
- Interesting Case: Variable Length Fields

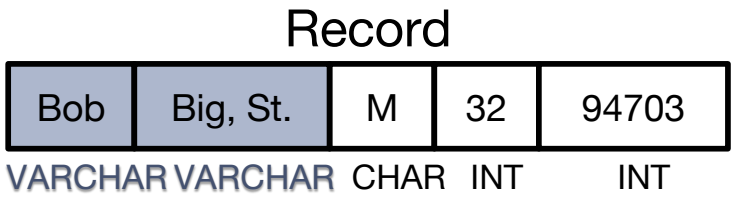
Record Formats: Fixed Length

- Finding i'th field?
  - done via arithmetic (fast)
- Making it more compact?
  - If all fields are not-null, no good way of compacting
  - Else apply variable length techniques, next

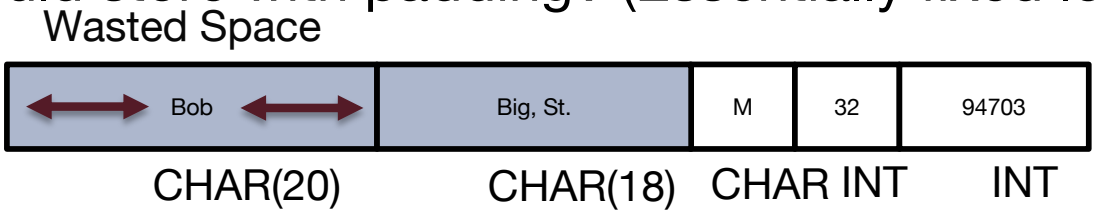


Record Formats: Variable Length

What happens if fields are variable length?



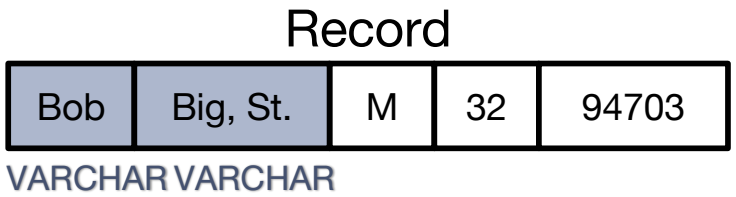
Could store with padding? (Essentially fixed length)

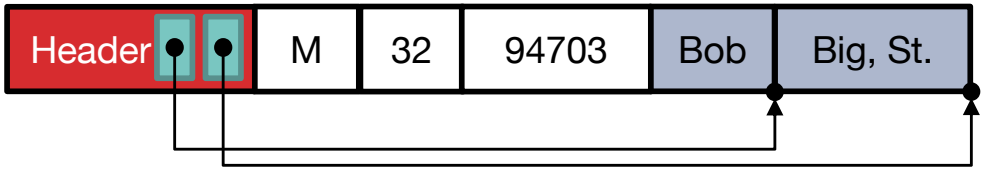


- Must account for largest possible string (wasteful) or rearrange as soon as a larger string comes (inefficient).
- Could store with delimiters (e.g., commas)?
  - Hard to find fields and strings with commas

Record Formats: Variable Length

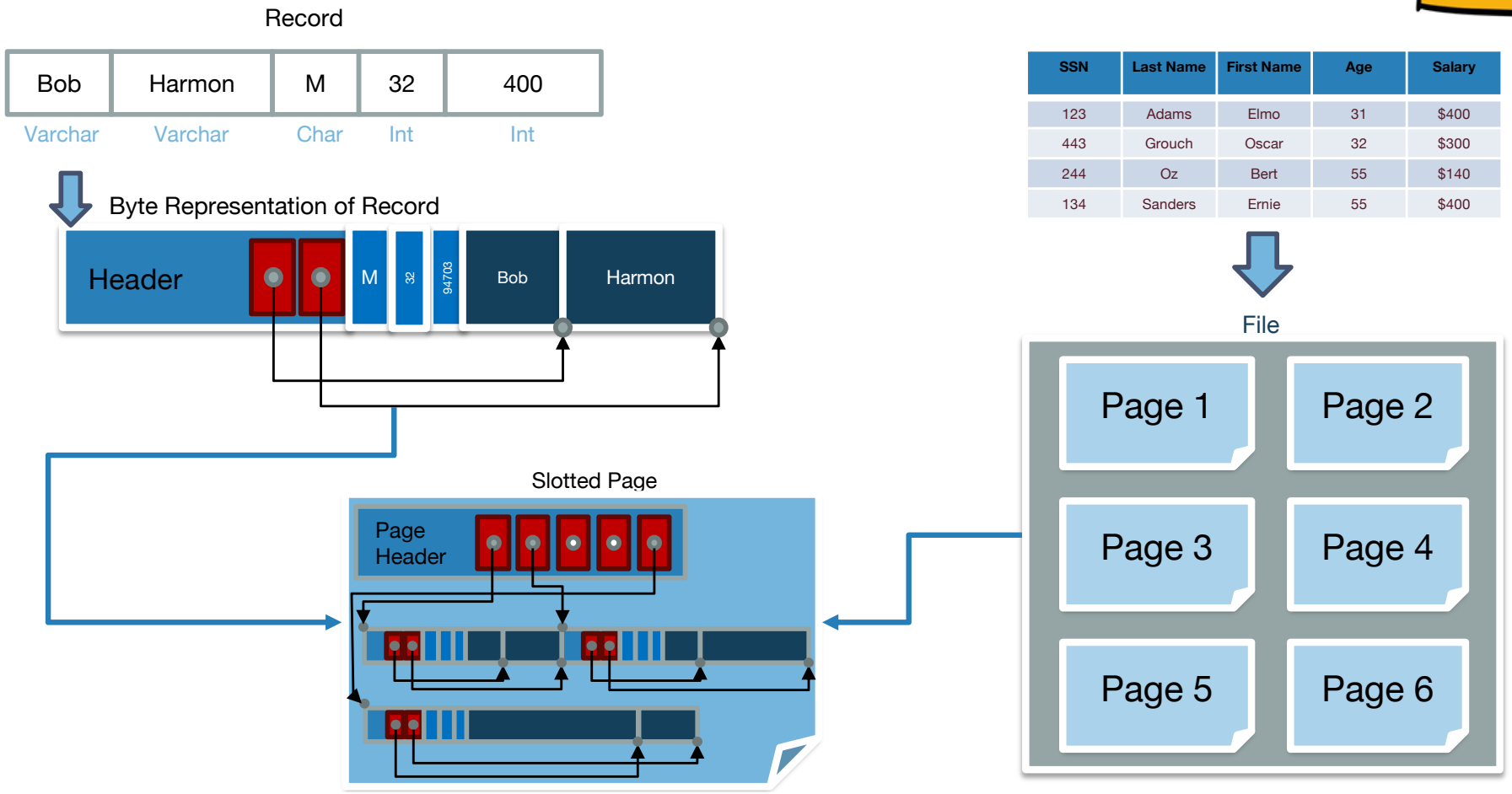
- What happens if fields are variable length?





- Solution: introduce a record header
- Easy access to fields, and almost as compact as can be (modulo header)
  - Same approach can be used to squash fixed length null fields w. many nulls

Overview: Representations



Files: Summary

- DBMS “File” contains pages, and records within pages
  - Heap files: unordered records organized with directories
- Page layouts
  - Fixed-length packed and unpacked
  - Variable length records in slotted pages, with intra-page reorg
- Variable length record format
  - Direct access to i’th field and null values