

Announcements

- o Welcome to CSc 460 - Database Design!
- o Class Information Sources:
 - D2L (d2l.arizona.edu/d2l/home/1186894)
 - Web (u.arizona.edu/~mccann/classes/460)
 - Piazza (piazza.com/class/l5sr9c7qjh22bi)
- o Class Modality: **In-person**. Per University policy, this class is available only in the modality in the catalog.
 - Masking is not required in class. Please respect the choices of your fellow students.
 - Lectures will be recorded (when the technology is working) and will be available via D2L (in the Content section, under Lecture Recordings).

Continues ...

Announcements (continued!)

- o Handouts: ① Summary of the Class Syllabus
② Program D#1
③ Program Style Requirements
 - We will cover these (inc. the full syllabus) today
- o Exam dates are already scheduled (see the syllabus' Topic Schedule). Please schedule your job interviews, weddings, espionage trials, etc., accordingly.
- o The Fall CS Career Fairs are coming soon:
 - Virtual: Sept 15th
 - In-person: Sept 16th

} See Arthur's Aug 16th email
- o Any questions before we get started?

Announcements

- Program #1 is now officially assigned
 - Part A is due in one week
 - If you need to fix it later, please do! (Students often discover issues w/ Part A while working on Part B.)
 - We will ‘grade’ your Part A submission, and deduct late days as appropriate, so please take the Part A due date seriously.
 - One correction so far: The State field is also a string field.

Topic 1:

Databases and Database Management Systems

Definitions of 'Database'

- “A shared collection of logically related data and its description, designed to meet the information needs of an organization.” (Connolly/Begg, 6/e)
- “... a collection of persistent data that is used by the application systems of some given enterprise” (Date, 7/e)
- “A collection of related data” (Elmasri/Navathe, 5/e)
- “[A] collection of records kept for a common purpose” (O’Neil², 2/e)
- “A collection of data, typically describing the activities of one or more related organizations” (Ramakrishnan/Gehrke, 3/e)
- “A collection of related records stored with a minimum of redundancy that many users can share simultaneously” (Shepherd)
- “[A] collection of [interrelated] data ... contain[ing] information relevant to an enterprise” (Silberschatz/Korth/Sudarshan, 4/e)

Common Definition Themes

Three very popular ideas in the definitions:

- **Collection**
- **(Inter) Related**
- **Data / Records**

Other ideas of note:

- Enterprise / Organization / Common Purpose
- Sharing
- Minimized Redundancy
- Persistence

Questions:

- Is your cell phone's contact list a database? *yes*
- Is your wallet a database? *yes*
- Where is the software?

Definitions of ‘Database Management System’

DBMS

- “A software system that enables users to define, create, maintain, and control access to the database.” (Connolly/Begg, 6/e, p. 16)
- “A computerized record–keeping system” (Date, 7/e, p. 2)
- “A collection of programs that enables users to create and maintain a database” (Elmasri/Navathe, 5/e, p. 5)
- “A program product for keeping computerized records about an enterprise” (O’Neil/O’Neil, 2/e, p. 1)
- “Software designed to assist in maintaining and utilizing large collections of data” (Ramakrishnan/Gehrke, 3/e, p. 4)
- “Cost–effective methods for storing, organizing, retrieving, and managing data” (Shepherd)
- “A collection of interrelated data and a set of programs to access those data” (Silberschatz/Korth/Sudarshan, 4/e, p. 1)

DBMS Components

1. The Database
2. Administration - Database Administrator (DBA)
 - handle maintenance, performance, security, user education, - - -
 - regular supervision is needed!
3. Application Programs
 - from text queries to web interfaces
 - there are standard programming interfaces (e.g. JDBC)
4. Hardware
 - often a dedicated cluster of servers

Why use a DBMS? (1 / 3)

① Data Sharing

- one common location vs. many individual copies
- helps maintain data consistency between copies

② Redundancy Control

- intra-file redundancy managed by Data Normalization
- Distributed DBMSes intentionally copy files to maintain accessibility

③ Centralized Control

- DBAs provide experienced & benevolent oversight
- Allows users to be users

Why use a DBMS? (2 / 3)

④ Data Integrity

- Ex: June 31st

- Most integrity info is domain-specific

- DBMSes support user-defined integrity rules

⑤ Data Security

- DBMSes can flexibly limit access to users

- Active management by DBA > user management

⑥ Views

- are automatically managed presentations of
the database

- provides clarity, convenience, & some
security

Why use a DBMS? (3 / 3)

⑦ Data Independence

- Idea: User's shouldn't know how data is organized within the DBMS
- 2 types:

a) Logical Data Independence (LDI)

- Conceptual Schema - describes the data and its relationships
- LDI allows schema to change w/o applications changing
- Difficult to achieve

b) Physical Data Independence (PDI)

- PDI allows physical storage to change w/o applications changing (eg., create index)
- More easily achieved than LDI

Disadvantages of DBMSes

- ① DB design is complex
 - matching design to desired function is not trivial
- ② Cost
 - organizational licenses are expensive
 - DBAs need to be paid
 - Servers are not cheap
- ③ Availability
 - A DBMS is a potential "single" point of failure
 - Making backups is important!
- ④ Speed v. Flexibility
 - Users want high performance, but DBMSes are designed for general purpose use.

Announcements

- Program #1 :
 - Part A is due Wednesday. We're looking for:
 - your `Prog1A.java` file that is ...
 - a good attempt at creating the binary file, with ...
 - good documentation & coding style
 - Follow the instructions in the **Hand In** section of the assignment handout to submit your code.
 - Part B is due next Wednesday.
- Our office hours are set - see Piazza and D2L for the schedule. We've started holding them today.

Data Languages

Four types of manipulation, four languages, all within SQL:

- Data Description Language (DDL)
 - turns the conceptual schema into a physical database description
- Data Manipulation Language (DML)
 - insertion / deletion of data
- Data Control Language (DCL)
 - security
- Query Language
 - read-only, to answer questions

Topic 2:

Database Management System Architectures

What is an 'Architecture' of a DBMS?

Definition: Schema

The overall description of a database
— at varying granularities

Definition: Architecture

A description of DBMS components and their interconnections.

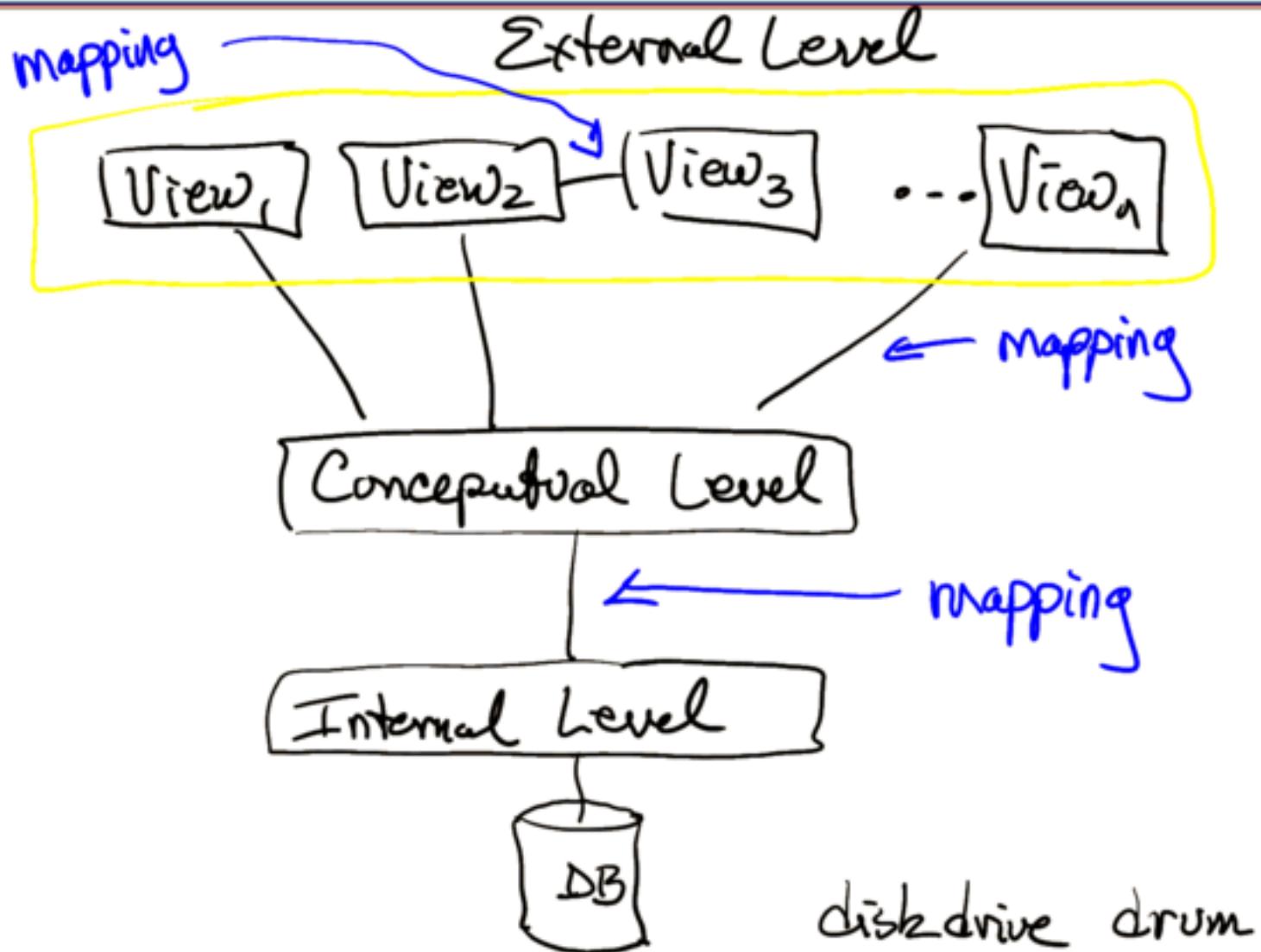
- Notes:
- the schema is part of the architecture
 - often, the terms are used interchangeably
 - I have not seen a text define "architecture"


The ANSI/SPARC Architecture (1 / 4): Background

a.k.a. Three-Level Schema

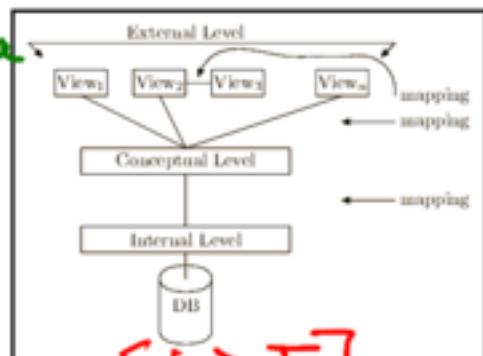
- A product of the Standards Planning and Requirements Committee (SPARC) of the American National Standards Institute (ANSI)
- Never formally adopted as an ANSI or International Standards Organization (ISO) standard, but still very influential
- Created to standardize terms and concepts surrounding DBs and DBMSes
- Goals:
 - Allow for multiple views of the data to satisfy a range of users
 - Allow for a physical (disk-level) description of the database
 - Provide an abstraction layer to separate the two

The ANSI/SPARC Architecture (2 / 4): The Diagram



The ANSI/SPARC Architecture (3 / 4): The Levels

- External Level - described by External Schema.
 - defines end-user perspective on the DB
- Conceptual Level - described by a Conceptual Schema [CDI]
 - defines field groupings, data relationships, etc.
 - abstract from physical considerations.
- Internal Level - described by an Internal Schema [PDI]
 - defines record sizes, indices, field representations, record ordering, etc.
 - hidden from applications & users



The ANSI/SPARC Architecture (4 / 4): The Mappings

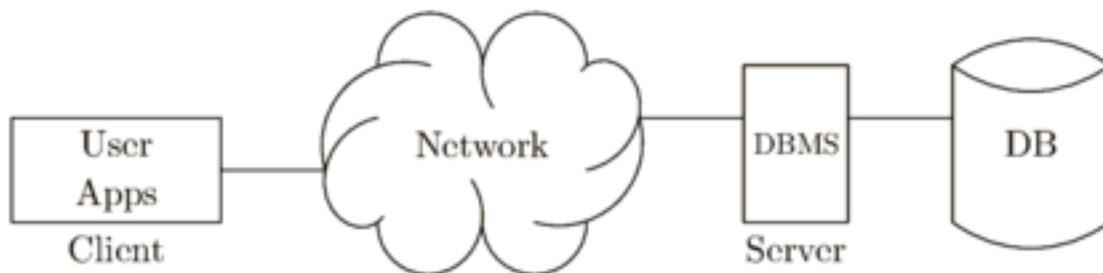
The interfaces between the levels are known as *mappings*.

- External – External Mapping
 - often easier to tweak an existing view
 - Usually more efficient to base views on Conceptual Level.
- External – Conceptual Mapping
 - Allows field renamings & arrangements for the user's benefit.
 - provides Logical Data Independence (LDI)
- Conceptual – Internal Mapping
 - Converts logical structure to physical reps.
 - provides Physical Data Indep. (PDI)

Client - Server Architectures (1 / 3): Background

- Originally: DBMSes were built with a centralized architecture.
 - All components (OS, DBMS, compilers, etc.) on one computer
 - “All or nothing” with respect to failures
 - Often a performance bottleneck
- Decentralization became feasible when:
 - Computers became less expensive and more powerful
 - Broadband networking became commonplace

Client - Server Architectures (2 / 3): Two-Tier



- One possible division of services:

① The client – presents info to user, runs applications that get data from --

② The server – fields requests from clients, runs the DBMS

- Lots of variations

– #s of clients & #s of servers

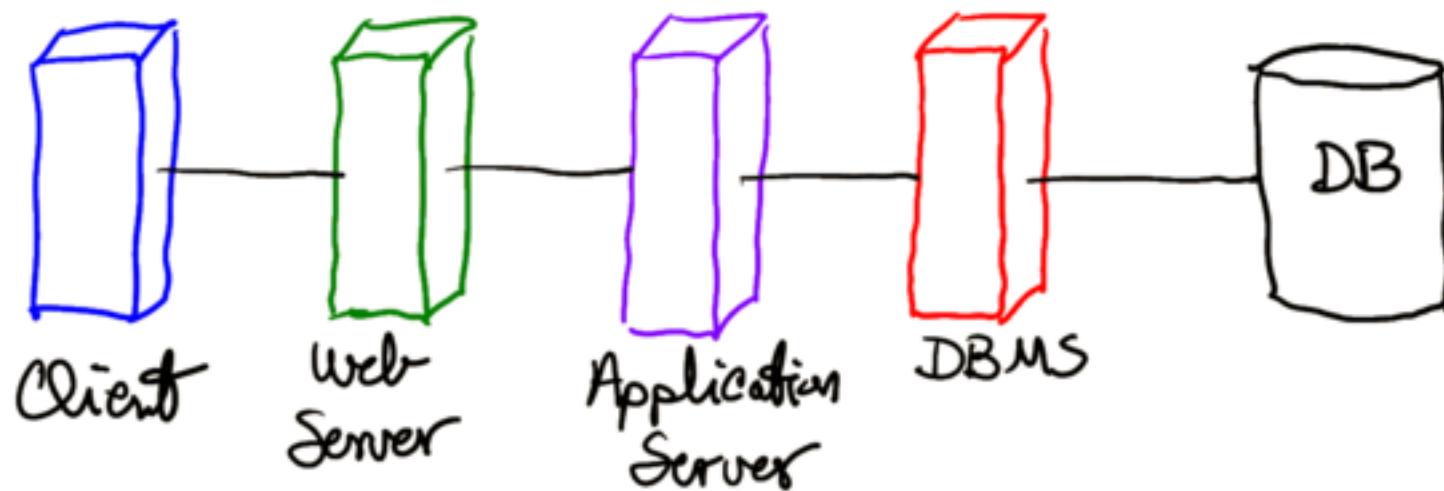
- parts of DBMS can be executed/stored by clients.

Client - Server Architectures (3 / 3): Multi-Tier

Why add more tiers?

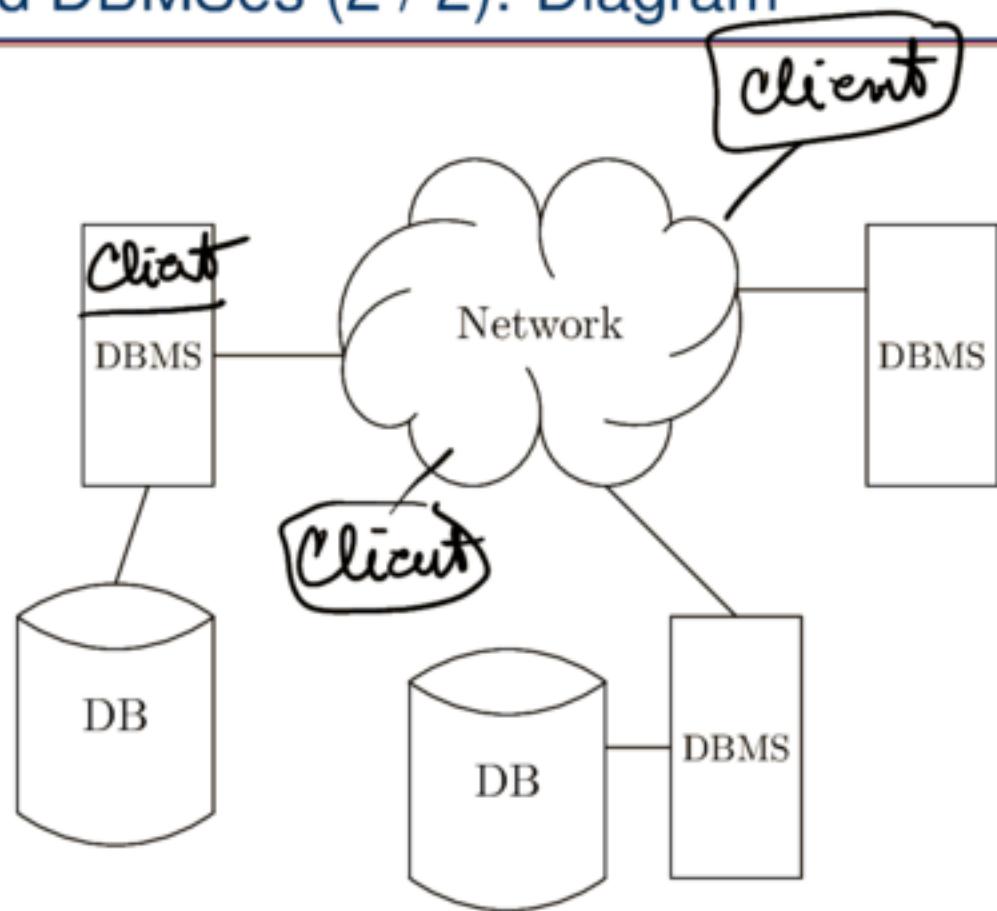
Add new capabilities, spread out old ones, ...

Example of a Four-Tier architecture:



- A single DBMS server (with its single DB) is a single point of failure
- Solution: A DBMS can be operated by several servers.
 - Each server has all, some, or none of the DB stored locally (replication is permitted for performance and reliability)
 - DDBMS sites communicate to handle nearly all tasks
 - Goal: Be completely transparent to the users
- Again, details are beyond the scope of this course

Distributed DBMSes (2 / 2): Diagram



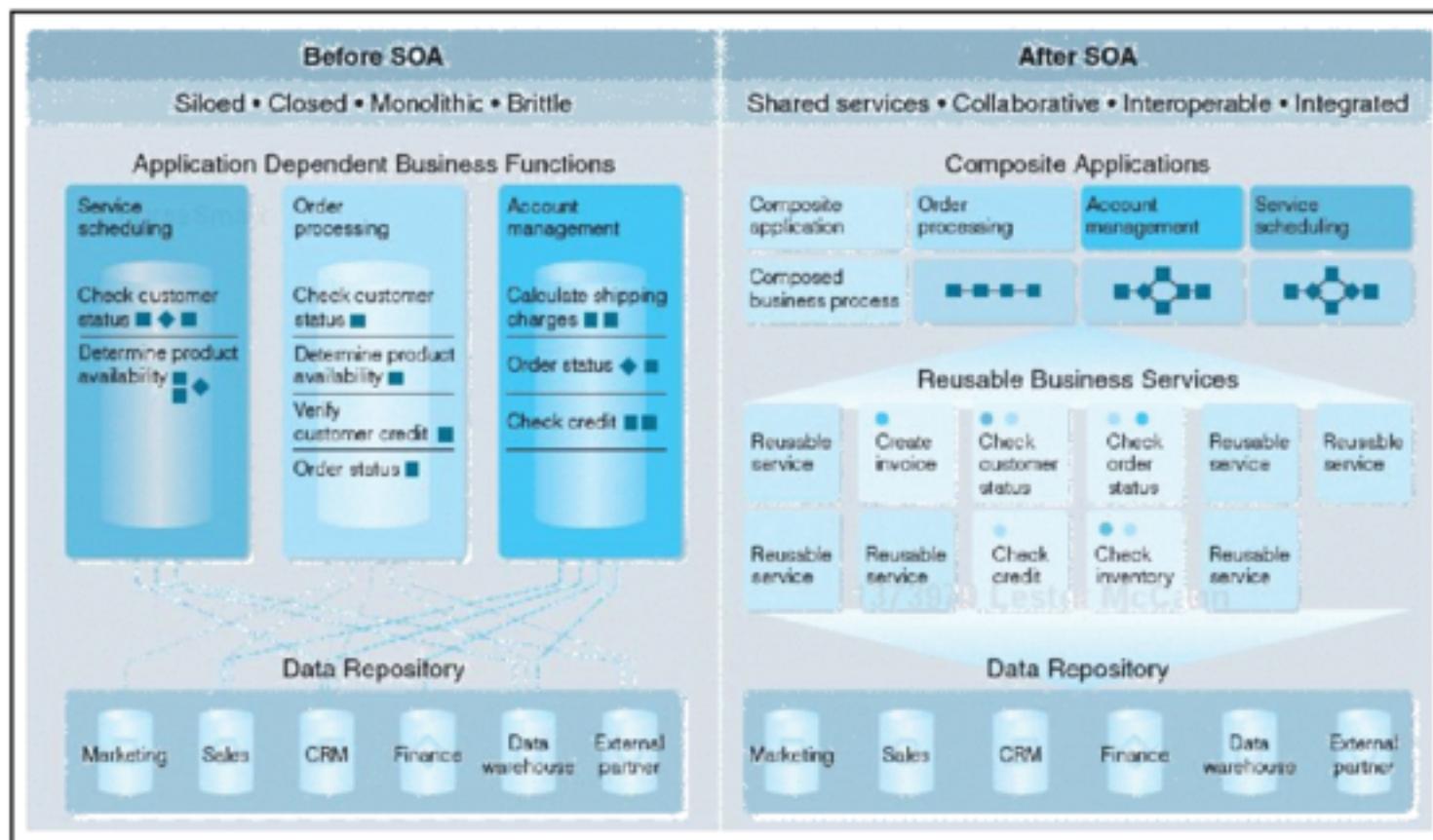
Extra Slides

The remaining slides in this topic are some that I no longer cover in class. I won't ask about them on an exam, but they could be referenced on a homework.

Service-Oriented Architectures (1 / 3): Motivation

- SOA is a software design technique:
 - Apps are built using pre-written service modules
 - E.g., a data visualization module
 - Modules are located & accessed via a common interface
- Goal is to be flexible with the adoption of new business processes
- A web service is an interface used by service modules
 - That is, it can be a component of an SOA.
- Further details are beyond the scope of this course

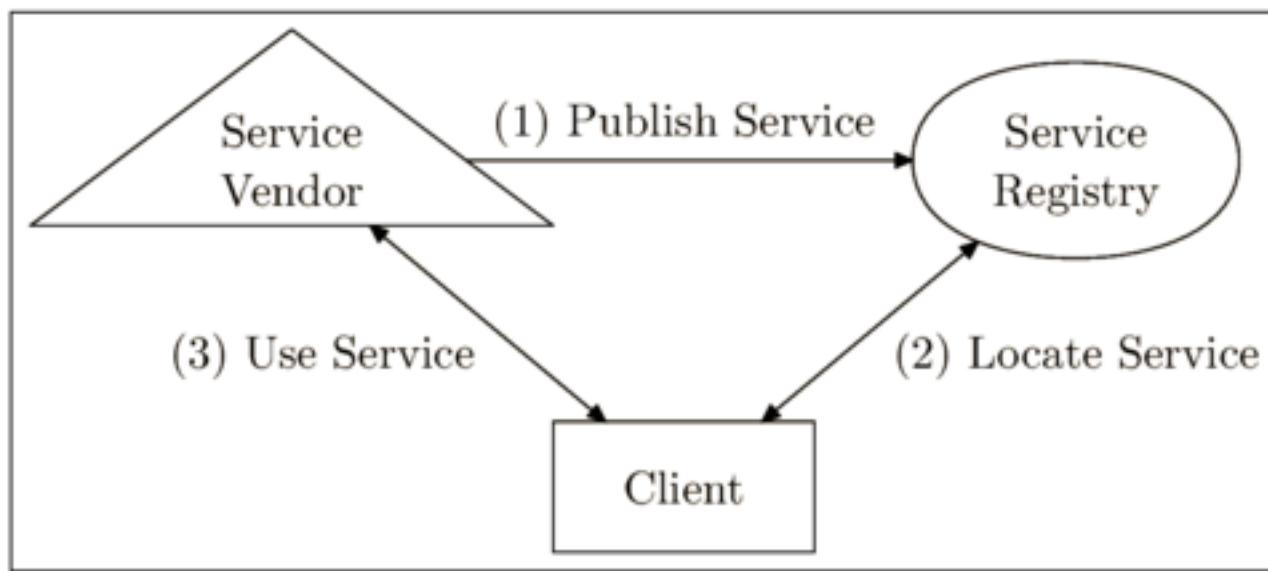
Service-Oriented Architectures (2 / 3): Before/After



Credit: Connolly/Begg, "Database Systems," 6/e, p. 72.

Service-Oriented Architectures (3 / 3): Accessing

Advertising, Finding and Using a Service:



One example: Web browser plug-ins.

(This approach is typical for web services, too.)

Additional DB–Related Architectures

- Web Services
 - Ex: Stock Quotations; Google Docs

Two types:

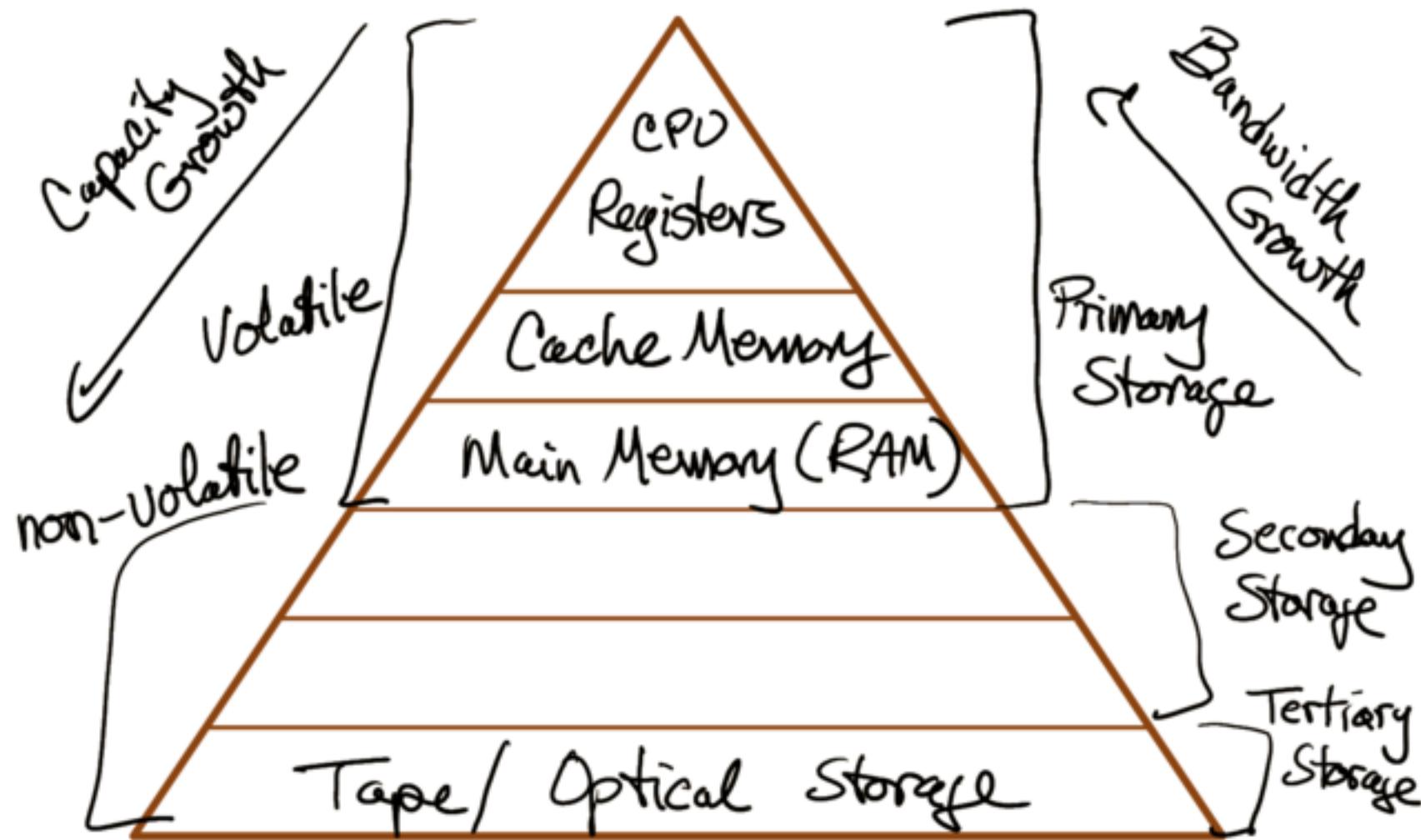
- (a) Simple Object Access Protocol (SOAP)-based
 - Typically uses XML
- (b) RESTful (Representational State Transfer) – stateless
 - Ex: HTTP

- Data Warehouses
 - Support decision-making
- Cloud Computing
 - Provides dynamic resource provisioning (of DBMSes!)

Topic 3:

Files and Indexing

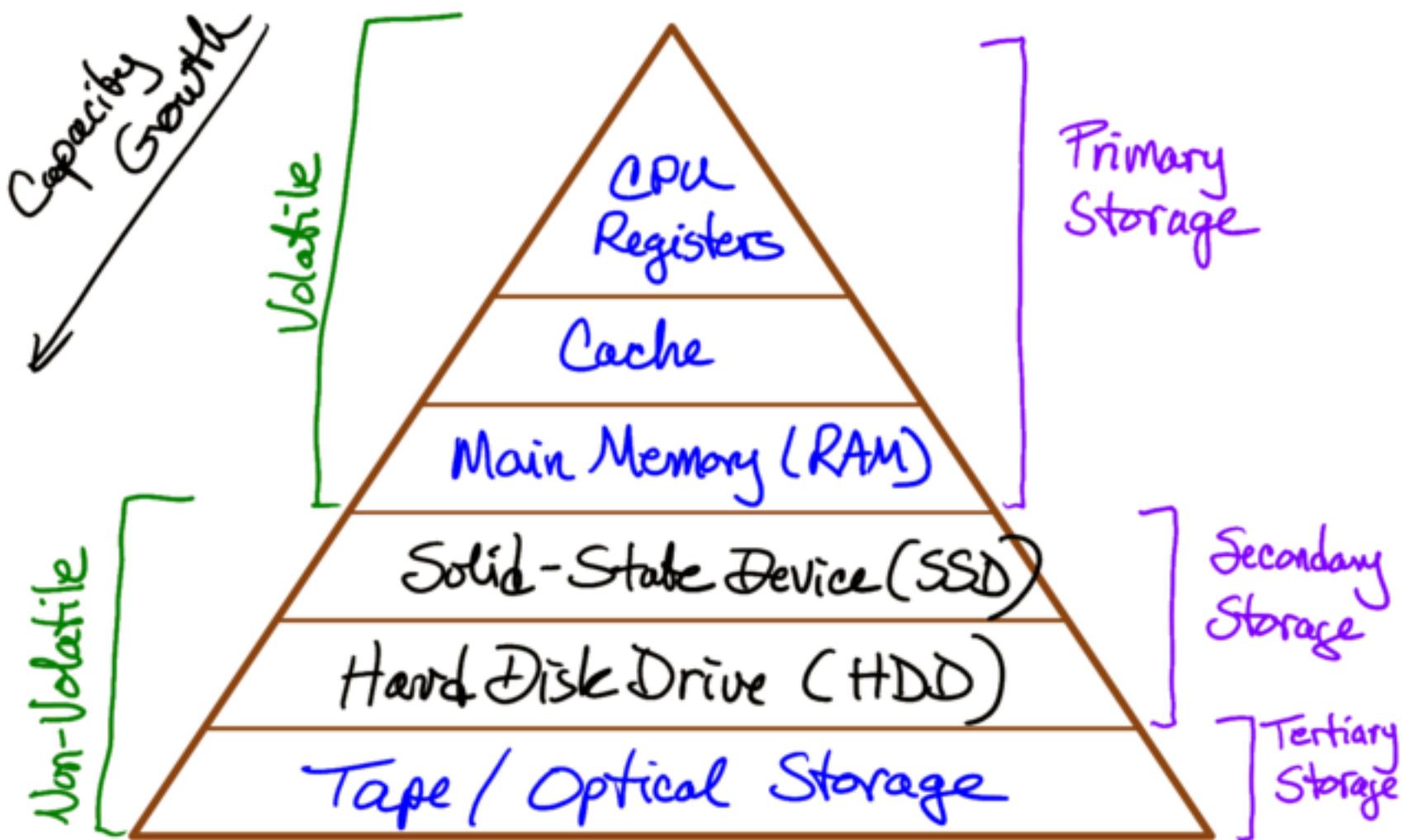
The Storage Pyramid



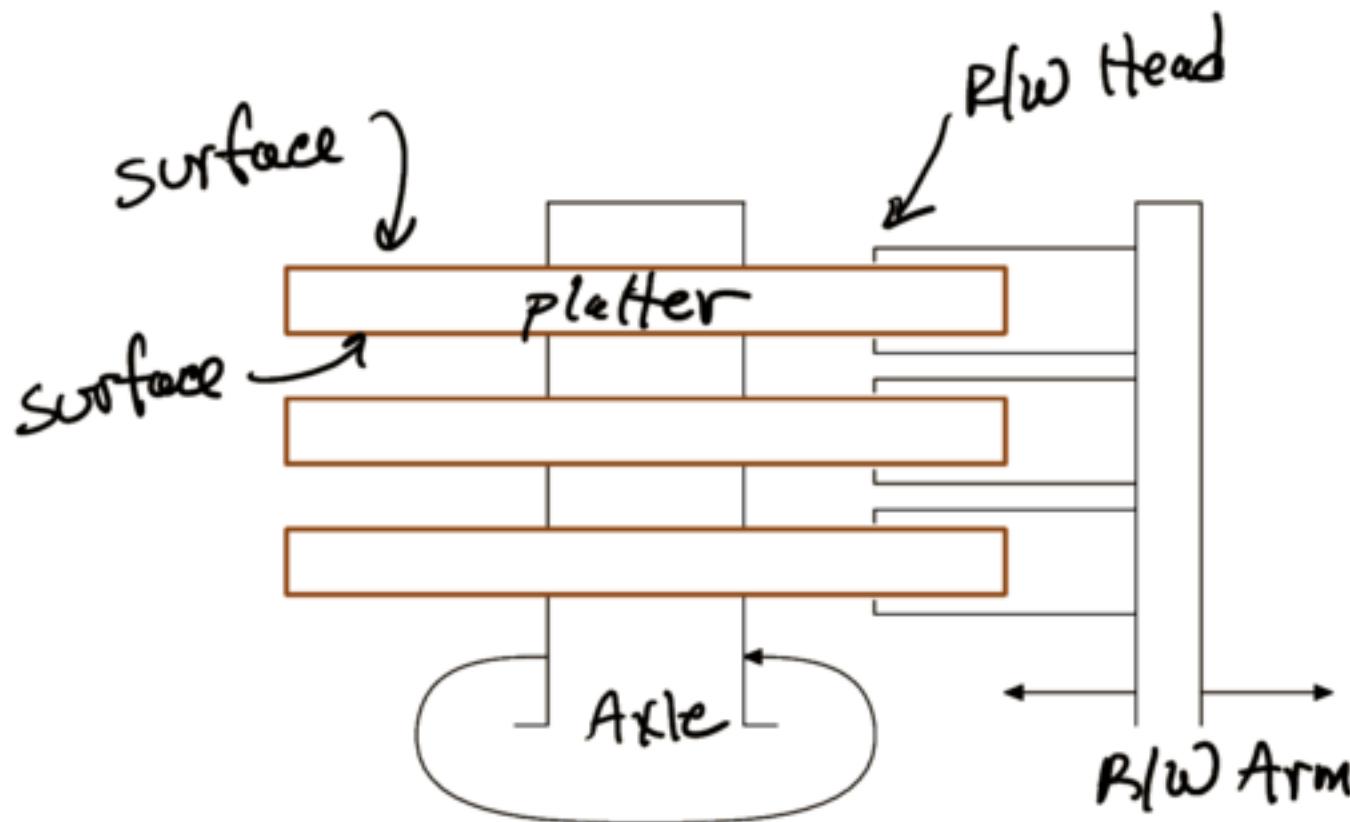
Announcements

- Program 1:
 - Part A "first draft" is due now
 - TAs will only check submission for documentation and style, not for correct operation
 - Complete assignment is due in one week
 - Submit both Part B and Part A, to be sure that they work together correctly
- Program #2 will be assigned next Wednesday
- No classes Monday - Labor Day!
 - Our only day off all semester---
- CS Tutor Center has quite a bit of coverage for 460
- "Old Storage Device Show and Tell" available w/ lecture recordings in DZL.

The Storage Pyramid

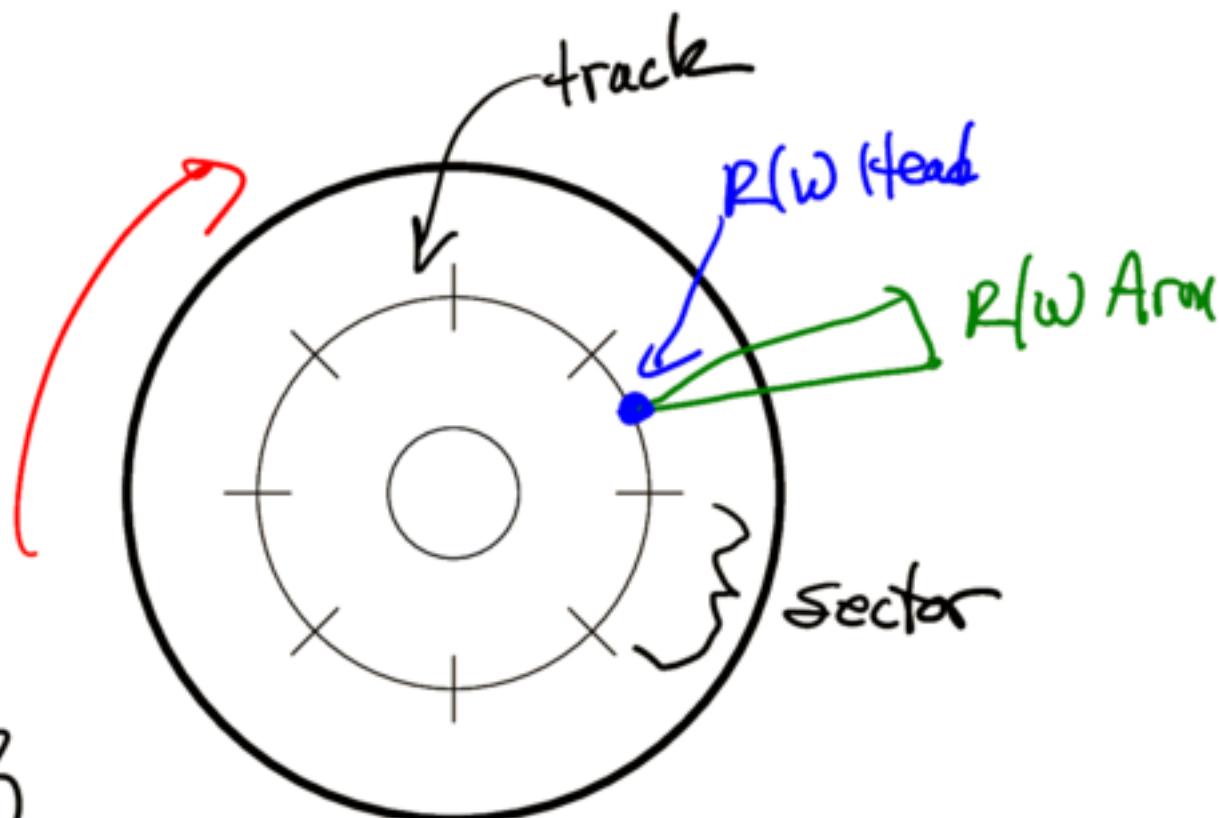


Hard Drive Physical Characteristics (1 / 2)



Side View

Hard Drive Physical Characteristics (2 / 2)



A block is
a group of
sectors
⇒ The basic
unit of HDD storage

Top View (one surface)

Sources of Read / Write Delay

The three major sources of delay (in descending order):

① Seek Time

- move R/W head to appropriate track

② (Rotational) Latency

- wait for block to rotate to R/W Head

③ Transfer Time

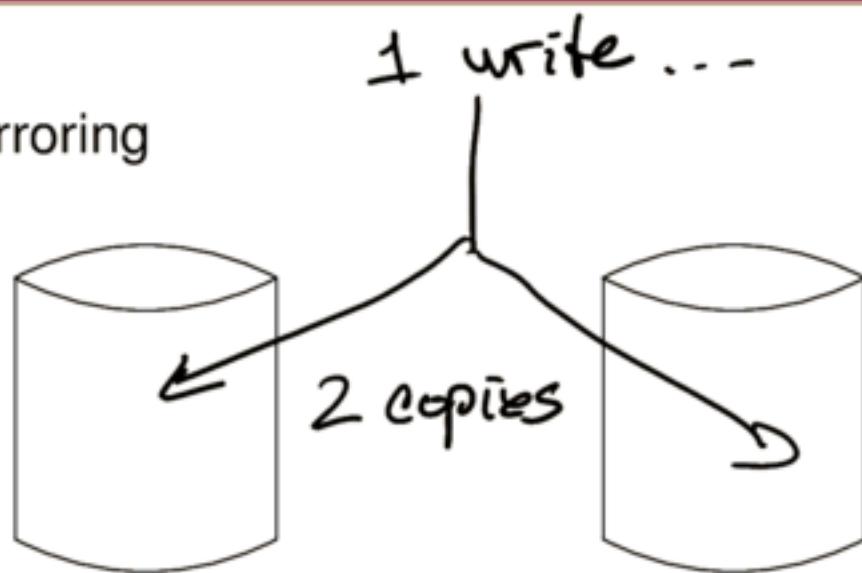
- read/write data from/to surface.

Western Digital 3.5" Hard Drive Specs

	WD450AA (9/2000)	WD1001FALS (7/2009)	WD4003FZEX (7/2015)	DC HC550 (8/2020)
Size (GB)	45	1,000	4,000	18,000
Platters & Heads	3 & 6	3 & 6	5 & 10	9 & 18
Bytes per Sector	512	512	512	512 / 4096
Sectors per Surface	14,655,144	325,587,528	781,403,717	??
Rotations (RPM)	5400	7200	7200	7200
R/W Seek (ms)	9.5 / 13.4	?? / ??	?? / ??	?? / ??
Latency (ms)	5.4	4.2	??	4.16
Cache (MB)	2	32	64	512
Buffer to Host (MB/s max.)	66.6	3000.0	6000.0	600.0
[Power]				
Read / Write (W)	6.2	8.4	9.5	6.5
Idle (W)	6.2	7.8	8.1	5.6
Standby / Sleep (W)	~1.1	1.0	1.3	??

RAID Background (1 / 3): Disk Mirroring

(a) Disk Mirroring



Advantage(s): Can operate w/ a failure of a HDD
Can read in parallel

Disadvantage(s): Cost (2x the drives)
Power

RAID Background (2 / 3): Disk Striping

(b) Disk Striping - striping units are distributed across multiple disks.

Example(s):

4 drives (# 0, 1, 2, 3). A file of 5 blocks
Store block 6 on drive 6 % 4.

Advantage(s): Performance (parallel reads/writes)

Disadvantage(s): Increased prob. of disk system failure
No data replication

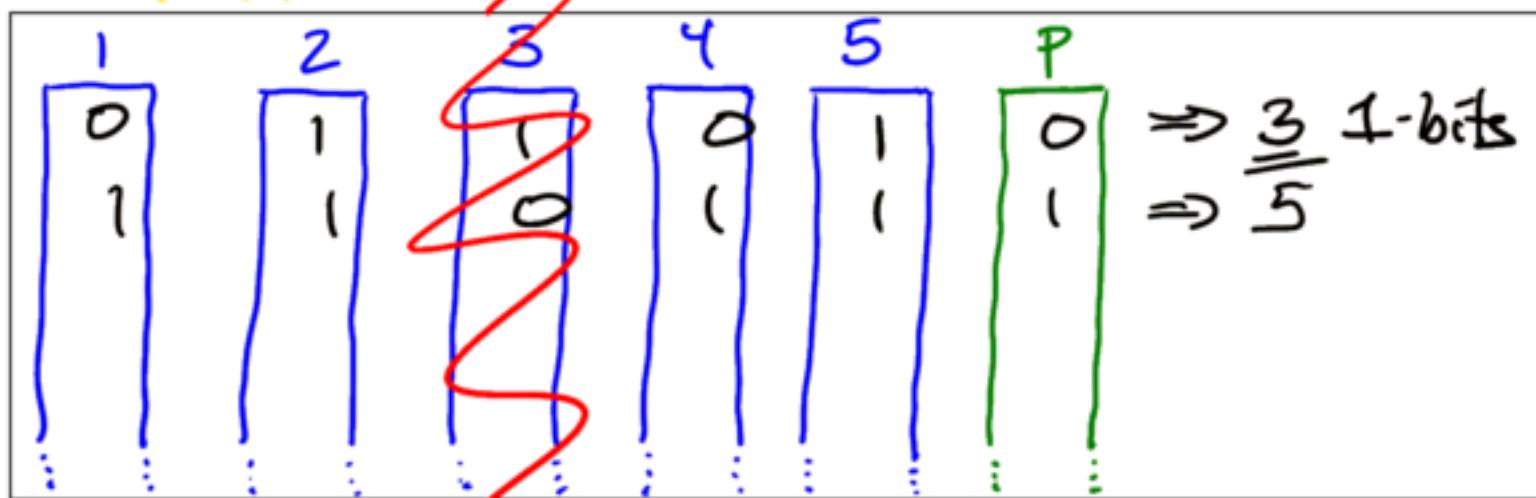
RAID Background (3 / 3): Parity Bits

(others: even, mark, none)

(c) Parity Schemes

odd parity (for this example)
of 1-bits to be odd

Example(s):



Advantage(s): Can recover 1 failed drive

Disadvantage(s): Buy the parity drive (cost)
Parity drive is popular
only good for 1 failure

Detour: Independent Event Probabilities (1 / 3)

First, some set and probability review!

1. DeMorgan's Laws for Sets:

$$\begin{aligned}\overline{A \cup B} &= \overline{A} \cap \overline{B} \\ \overline{A \cap B} &= \overline{A} \cup \overline{B}\end{aligned}$$

2. For a sample space S and an event $E \in S$,
the probability of E 's occurrence is:

$$P(E) = \frac{|E|}{|S|}$$

3. $\sum_{e \in S} p(e) = 1$

Detour: Independent Event Probabilities (2 / 3)

Next, Independent Events:

4. Events A and B are *independent* when ...

$$P(A \cap B) = P(A) \cdot P(B) \quad \frac{1}{2} \cdot \frac{1}{2} = \underline{\frac{1}{4}}$$

Ex: Flip a coin twice

$$P(H \cap H) = \underline{\frac{1}{4}} \quad P(\text{H on } \overset{\text{st flip}}{1\text{st flip}}) = \frac{1}{2}$$

$\dots \dots 2^n \dots \dots = \frac{1}{2}$

5. Recall: Principle of Inclusion/Exclusion for 2 Sets is:

$$|M \cup N| = |M| + |N| - |M \cap N|$$

Applied to probabilities:

$$P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

Detour: Independent Event Probabilities (3 / 3)

Probabilities for Independent Events (cont.):

Recall:

$$4. \underline{p(A \cap B)} = p(A) \cdot p(B)$$

$$5. p(A \cup B) = p(A) + p(B) - \underline{p(A \cap B)}$$

6. Combining (4) and (5):

$$p(A \cup B) = p(A) + p(B) - p(A) \cdot p(B)$$

7. And thanks to DeMorgan's Laws and (4):

$$P(\overline{A \cup B}) = P(\overline{A} \cap \overline{B}) = P(\overline{A}) \cdot P(\overline{B})$$

Probability of Hard Disk Drive Failures (1 / 4)

Factors contributing to HDD failures:

Temperature, manufacturer, age,
qty of scan errors, qty of sector
remappings

How often does a 'young' (1-3 years old) HDD fail?

Annualized Failure Rate (AFR) = 70 % devices
failing in a year

Refs: http://research.google.com/archive/disk_failures.pdf

~~<https://www.backblaze.com/blog/best-hard-drive/>~~

~~backblaze-drive-stats-for-q2-2022/~~

Announcements

- Program #1 is due now!
 - Can use late days if you wish
 - TAs will have grades for you before the due date of ...
- Handout: Program #2 - Linear Hashing Lite
 - I will provide a separate video to help clarify the expectations for the linear hashing index.
- Today: Finish RAID, jump ahead to hash-based indexing, discuss Program #2, then jump back.

Probability of Hard Disk Drive Failures (2 / 4)

What is the p_f for a striped 2-disk system?

⇒ Remember, the system fails when either drive fails!

(Let $D\#_f$ be the event of Disk # failing.)

$$\begin{aligned} p_f &= p(D1_f \cup D2_f) && \text{Either or both!} \\ &= p(D1_f) + p(D2_f) - p(D1_f) \cdot p(D2_f) && \text{Princ. Inc./Ex. \&} \\ &= 0.02 + 0.02 - (0.02)^2 && \dots \text{Indep. events} \\ &= 0.0396 (3.96\%) \end{aligned}$$

Probability of Hard Disk Drive Failures (3 / 4)

New point of view: Be an optimist!

The probability that Disk D# does not fail:

$$p(D\#_{nf}) = 1 - p(D\#_f) = 1 - 0.02 = 0.98$$

What is the p_{nf} for a striped 2-disk system?

$$\begin{aligned} p_{nf} &= p(\overline{D1_f \cup D2_f}) && [\text{Neither fails!}] \\ &= p(\overline{D1_f} \cap \overline{D2_f}) && [\text{De Morgan's}] \\ &= p(D1_{nf} \cap D2_{nf}) && [\overline{D\#_f} = D\#_{nf}] \\ &= p(D1_{nf}) \cdot p(D2_{nf}) && [\text{Independent events assumed}] \\ &= p(D\#_{nf})^2 && [\text{Foreshadowing ...}] \\ &= (0.98)^2 && [\text{From above}] \\ &= 0.9604 \text{ (96.04\%)} && [= 1 - 0.0396] \end{aligned}$$

Probability of Hard Disk Drive Failures (4 / 4)

What if we have *dozens* of HDDs? Say, three dozen?

No problem; being optimistic scales nicely!

$$\begin{aligned} p_{nf} &= p(\overline{D1}_f \cup \dots \cup \overline{D36}_f) && [\text{None fail!}] \\ &= p(\overline{D1}_f \cap \dots \cap \overline{D36}_f) && [\text{Massive De Morgan's}] \\ &= p(D1_{nf} \cap \dots \cap D36_{nf}) && [\overline{D\#}_f = D\#_{nf}] \\ &= p(D1_{nf}) \cdot \dots \cdot p(D36_{nf}) && [\text{Independent events assumed}] \\ &= (0.98)^{36} && [\text{From last slide}] \\ &= 0.4832\dots (48.32\%) && [p_f = 1 - p_{nf} = 0.5168] \end{aligned}$$

Remember: Assuming independence is convenient, not realistic!

RAID: Redundant Arrays of Independent* Disks (1 / 2)

* Originally "Inexpensive"

Level 0: Striped Volume (N data disks)

⇒ Striping only!

- Good write performance
- Cannot recover from a drive failure
(Even if we're making backups.)

Level 1: Mirrored (N data disks + N mirror disks)

⇒ Mirroring only!

- Opportunity for parallel reads
- Cost: 2x the # of drives!

RAID: Redundant Arrays of Independent Disks (2 / 2)

Level 5: Block-Interleaved Distributed Parity ($N+1$ disks)

- striping unit is 1 block
- parity blocks are distributed across disks
- controller design is kinda complex

Level 6: "Double Parity" ($N+2$ disks)

- Level 5 w/ 2 parity schemes
- Can recover from 2 concurrent failures
- Same read perf. as Level 5, but slower write perf.

SSDs: Solid-State Device (Flash) Storage

NVRAM

- NAND-based non-volatile RAM
- Not a new idea: Used to have “RAM drives”
(Even though the 1981 IBM PC had 256 KB RAM – max!)

Advantage(s): No mechanical delays or failures
Excellent read perf.
Consumes little physical space

Disadvantage(s): Write speed lags (erase then write)
erasures \approx 100K - 1000K
more expensive than HDDs

Review of Internal Hashing

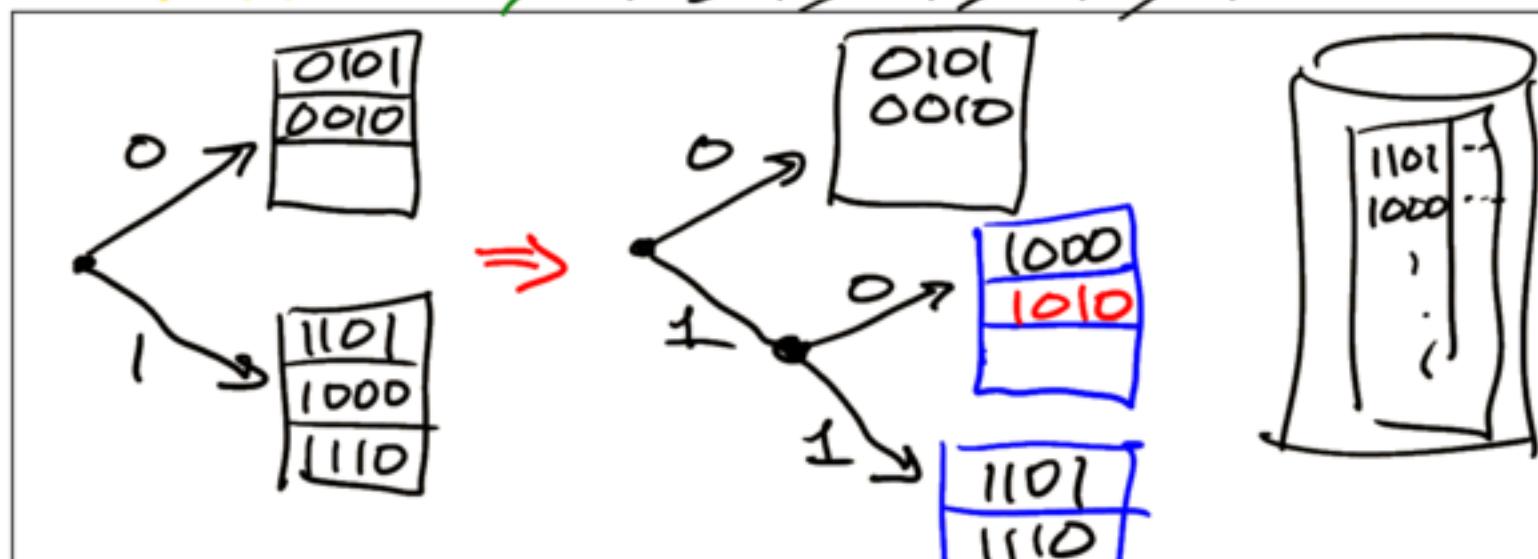
- Goal: $O(1)$ search performance
- Key → Hash Coding → Compression Mapping → Hash Table Index
- Collision Resolution: Chaining v. Open Addressing
- Problem: How can we do hashing on secondary storage?

Dynamic Hashing

Two components:

- A tree-structured directory
- Leaves are disk blocks holding the index entries.

Example(s): Insert ~~1101, 1000, 0101, 0010, 1110, and 1010~~:



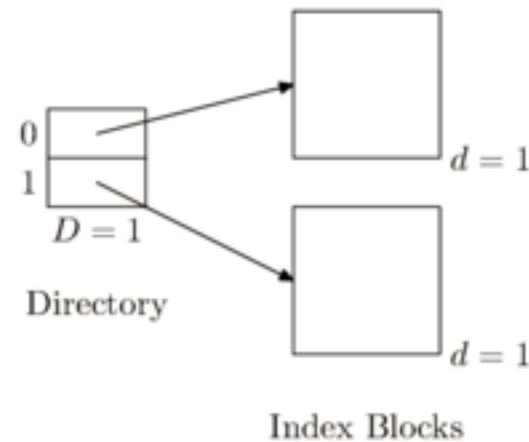
3 entries / block

Problem: How do I store the directory on disk?

Extendible Hashing: Basics

Improvement over Dynamic Hashing:

Directory is an array \Rightarrow



- Each index block has a local depth (d), $d \geq 1$
- The directory has a global depth (D), $D \geq \max(d_i)$
- Directory has k^D pointers, where k is the cardinality of the alphabet set.
 - Ex: When keys are binary, $k=2$

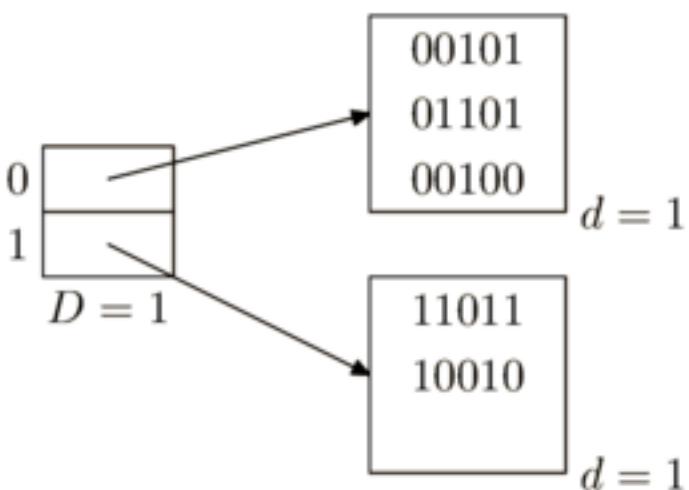
Extendible Hashing: Insertion (1 / 2)

When a key is inserted into a full index block:

- The block becomes k blocks
- The depth of each is one more than the original's
- Existing content is distributed to the new blocks
- If any $d > D$, split ('double') the directory:
 - increase global depth by one
 - create new directory of k^D pointers
 - copy existing block pointers
 - add pointers to new blocks

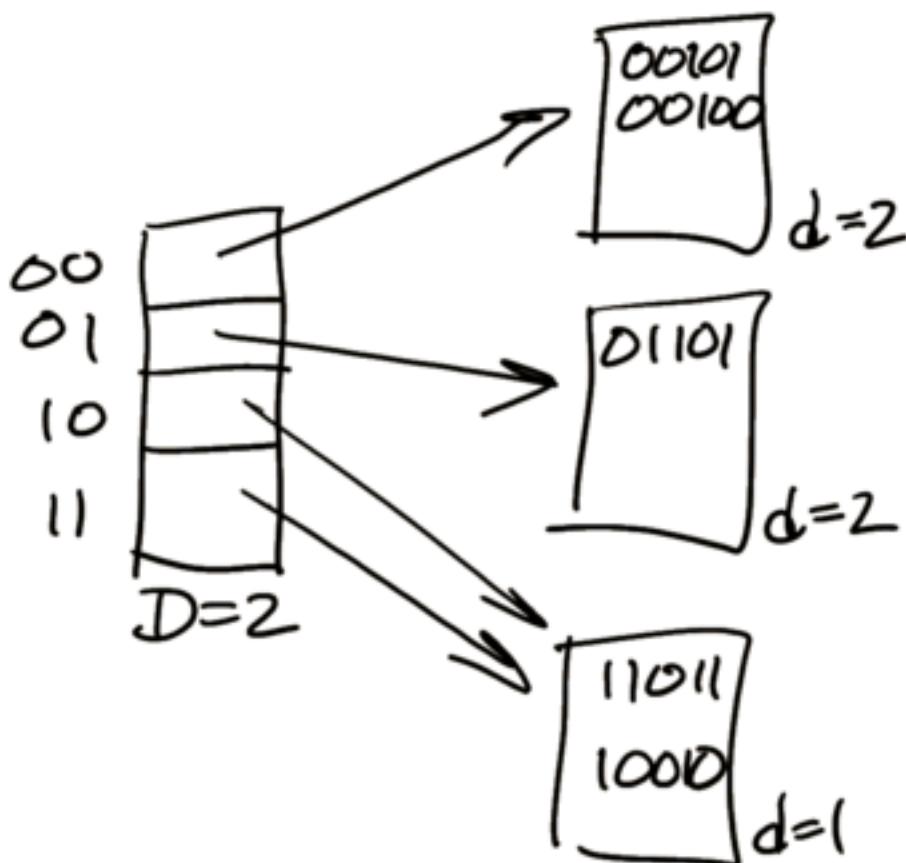
Extendible Hashing: Insertion (2 / 2)

After Inserting 11011,
00101, 01101, 10010,
and 00100:



(Assume max. 3 keys/node)

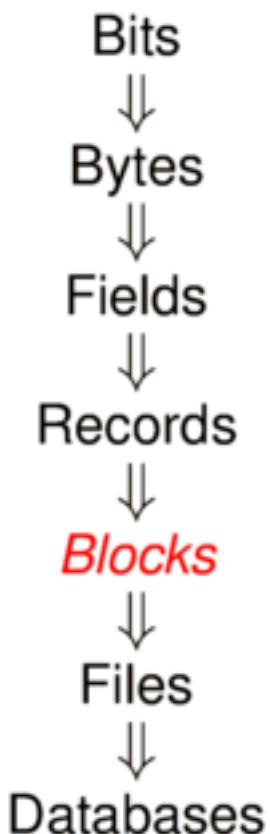
After Inserting 01110:



Announcements

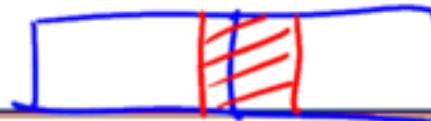
- Program #2 is due a week from Wednesday.
 - The video that shows how to get started is available in D2L.
 - Any questions?
- Today:
 - Finish last slide on Extendible Hashing
 - Jump back to key indexing ideas
 - (Maybe) Start B-Trees
- CS Career Fairs are this week !

File Granularity Hierarchy



File Blocking (1 / 2)

$\frac{1000}{300}$



Definition: Blocking Factor (bf)

The # of records that can be stored in a block

$$bf = \left\lfloor \frac{\text{block size}}{\text{record size}} \right\rfloor$$

(assuming records are not split between blocks)

Definition: Internal Fragmentation

Unallocatable storage within a block.

8192

Example(s): Block size = 8K bytes; Record size = 55 bytes.

$$bf = \left\lfloor \frac{8192}{55} \right\rfloor = 148 \text{ recs/block}$$

$$8192 - 148 * 55 = 52 \text{ bytes of internal frag.}$$

File Blocking (2 / 2)

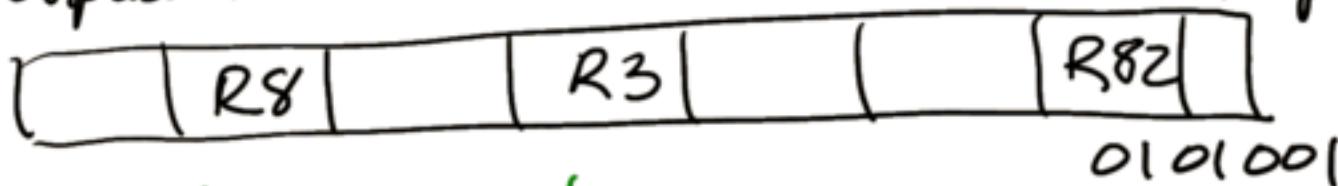
Locating records within blocks:

① Fixed-length records

(a) Packed (Contiguous) Allocation

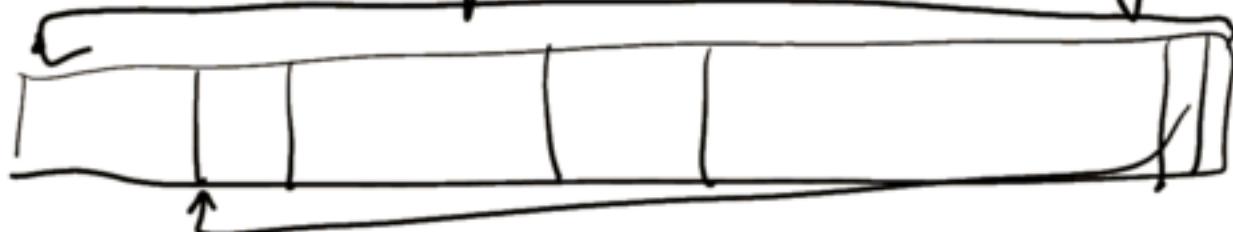


(b) Unpacked Allocation



② Variable-length records

Replace the bitmap with a slot directory

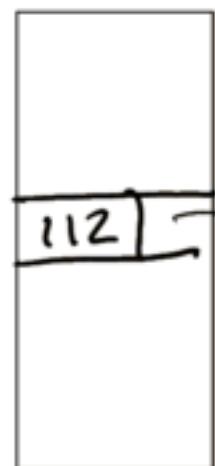


Indexing

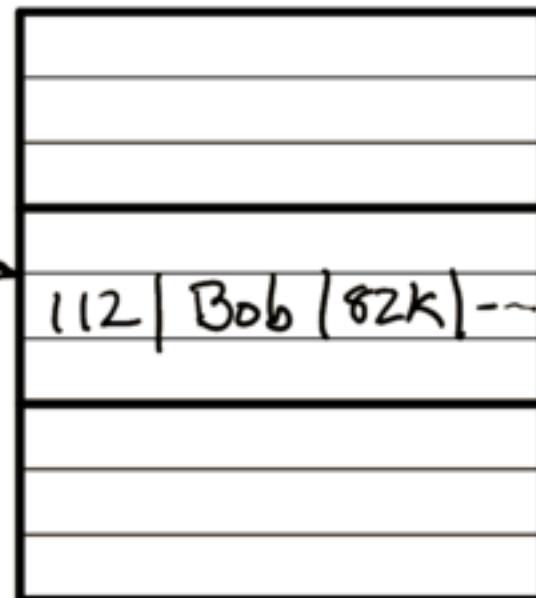
Definition: Index

A file containing structured references to records of another file.

Key
112



Index
File



Database File

A Few Words about Keys

Some of the types of keys:

- Candidate Key - A key able to uniquely identify a record!
Ex: StudID, NetID, ~~SSN~~
- Primary Key - The CK chosen to be the identifier.
- Secondary Key - Any non-CK
Ex: SSN, Name, birthday, ---
- Sort Key - The key used to order the records of a file.
- Search Key - --

One Classification of Indices

(1) Ordered

(a) Single-level

Ex: Sorted file of index records

(b) Multi-level

Ex: B^+ -Tree

(2) Unordered Index

- Typically hash-based

Ex: Extendible Hashing

Primary Index (1 / 2)

Characteristics:

- The indexed field is a candidate key.
- The index records are sorted on the key.
- The DB file records are sorted on the key.

Notes

- Can have at most one per file
- The term "primary index" has many definitions.

Primary Index (2 / 2)

Example(s):

University	RID	University	Founded
Eau Claire	—	Eau Claire	1916
Green Bay	—	Green Bay	1968
La Crosse	—	La Crosse	1909
Madison	—	Madison	1848
Milwaukee	—	Milwaukee	1885
Oshkosh	—	Oshkosh	1871
Parkside	—	Parkside	1968
Platteville	—	Platteville	1866
River Falls	—	River Falls	1874
Stevens Point	—	Stevens Point	1894
Stout	—	Stout	1891
Superior	—	Superior	1893
Whitewater	—	Whitewater	1868

PRIMARY INDEX

Clustered Index (1 / 2)

Characteristics:

- The indexed field is a secondary key. Not a CK!
- The index records are sorted on the key.
- The DB file records are sorted on the key.

Notes :

- per ^{DB}\file, the # of primary indices plus the # of clustered indices can be no greater than one.
- some see primary indices as a special case of clustered.

Clustered Index (2 / 2)

Example(s):

Founded	RID	University	Founded
1848	—	Madison	1848
1866	—	Platteville	1866
1868	—	Whitewater	1868
1871	—	Oshkosh	1871
1874	—	River Falls	1874
1885	—	Milwaukee	1885
1891	—	Stout	1891
1893	—	Superior	1893
1894	—	Stevens Point	1894
1909	—	La Crosse	1909
1916	—	Eau Claire	1916
1968	—	Green Bay	1968
1968	—	Parkside	1968

CLUSTERED INDEX

Secondary Index (1 / 2)

Characteristics:

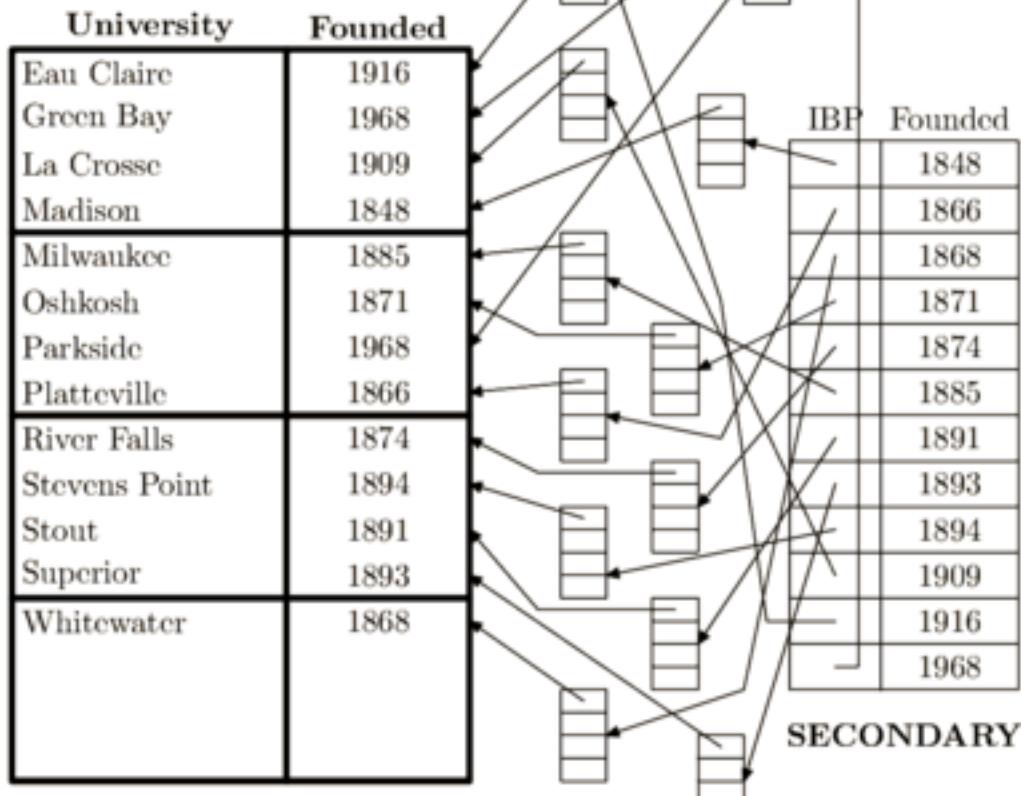
- The indexed field is any field!.
- The index records are sorted on the key.
- The DB file records are not sorted on the key.

Notes

- can have as many of these as you want
- special index construction is needed.

Secondary Index (2 / 2)

Example(s):



Extendible Hashing: Deletion

Question: Do you have lots of disk space available?

If so: Just delete the entry
(leave the space for future insertions)

If not: Collapse the sibling nodes
and shrink the directory if
necessary/possible

Announcements

- Program #2 (Linear Hashing Lite) is due in a week (Wed, Sept. 21)
 - you'll need your .bin file that Program 1 (Part A) created
- Next assignment will be Homework #1, to be assigned next Wed., and due a week later
- Exam #1 is in 3 weeks.

Another Index Categorization: Dense vs. Sparse (1 / 2)

Dense Indices:

- Hold one index record for every file record
(excepting perhaps dup. keys)
- Permits existence queries using just the index

Sparse Indices:

- Index has a subset of the field values of the key
- Smaller, \therefore faster to search

Notes:

- All of the examples of ordered indices from Monday are dense.
- Any ordered index type can be either dense or sparse.

Another Index Categorization: Dense vs. Sparse (2 / 2)

Example(s):

University	Founded	BID	University
Eau Claire	1916		Eau Claire
Green Bay	1968		Milwaukee
La Crosse	1909		River Falls
Madison	1848		Whitewater
Milwaukee	1885		
Oshkosh	1871		
Parkside	1968		
Platteville	1866		
River Falls	1874		
Stevens Point	1894		
Stout	1891		
Superior	1893		
Whitewater	1868		

SPARSE PRIMARY

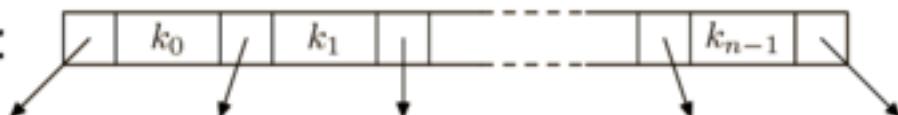
B-Trees: Structure

But first: Know that “B” does not stand for “binary”!

“Bayer”? (Rudolf Bayer & Edward McCreight, '72)

“Balanced”? (It is!) “Boeing”? (McCreight's employer?)

Structure of a B-Tree node:



- A node holding n keys holds $n + 1$ pointers
- Each key is stored in the index exactly once (\therefore dense)
- A node's keys are stored in (ascending) sorted order
- Pointer 0's subtree has all keys $<$ key k_0
- Pointer i 's subtree has all keys $>$ k_{i-1} and $<$ k_i
- Pointer n 's subtree has all keys $>$ k_{n-1}

B-Trees: Definition

Definition: B-Tree of Order M (a la D. Comer[§])

- Each node contains at most $2M$ keys
 $(\therefore 2M+1$ pointers)
- Each node (except the root) must contain at least M keys.
- A non-leaf node node has at least 2 children
- All leaf nodes are at the same level
- A non-leaf node with n keys has exactly $n+1$ children.

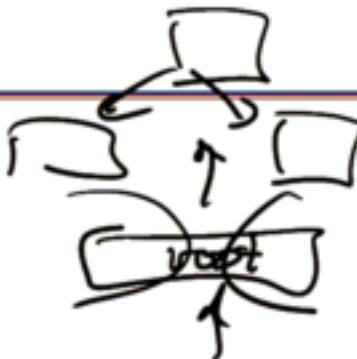
[§] Comer, D. "The Ubiquitous B-Tree," ACM Computing Surveys 11(2), June 1979, pp. 121-137.

B-Tree: Insertion (1 / 2)

- Find the leaf node that should contain the new key value
- If leaf has capacity, insert the key into it.

Otherwise: (when leaf node has $2M$ keys)

- Form a set of the leaf's keys plus the insertion key
- Promote the set's median value to the parent
- Create two nodes to hold the key values that are $<$ and $>$ the median, respectively.
- Attach nodes as children on either side of the median



$2M+1$
keys

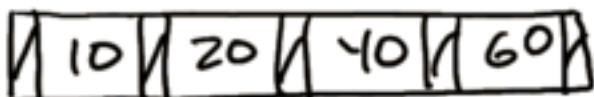


B-Tree: Insertion (2 / 2)

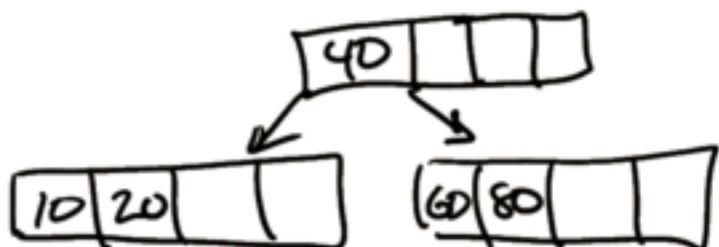
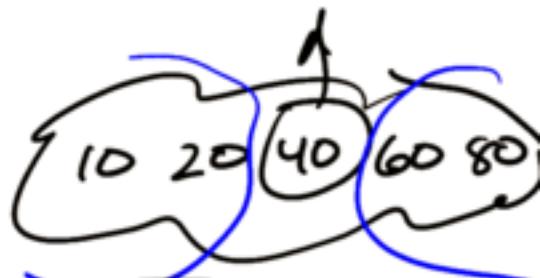
Example: Insert 40, 20, 60, 10, 80, 5, 15, and 25

into a B-Tree of Order 2:

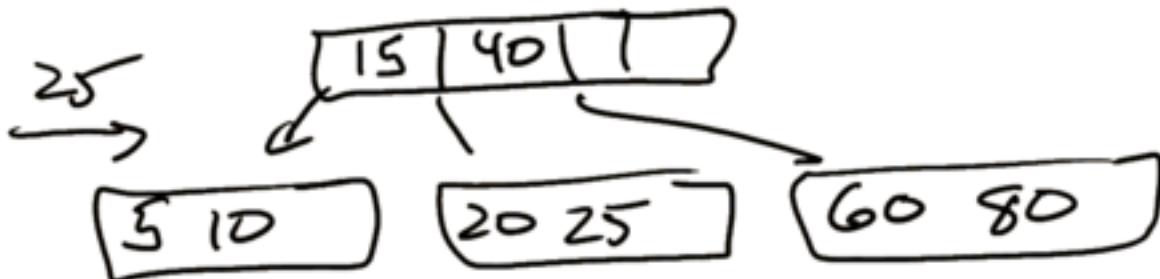
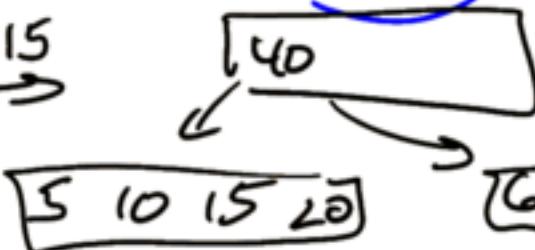
40, 20, 60, 10 →



→ 80



→ 5, 15



B-Tree: Deletion (1 / 2)

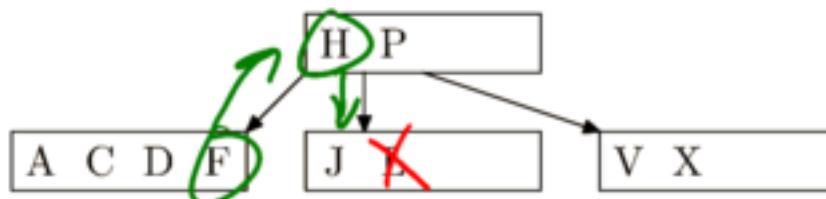
When a deletion leaves a node under-full:

- If the under-full node is a leaf node:
 - If a neighboring sibling has above-minimum occupancy, borrow:
 - Move separating value from parent to under-full node
 - Move appropriate value (smallest / largest) from neighbor to parent
 - Otherwise, concatenate:
 - Merge node, a neighboring sibling, and the parent's separating value into one node
 - (Note that this can leave the parent under-full, so recurse!)
- Otherwise, the under-full node is an internal node:
 - Replace deleted key with its inorder predecessor or successor
 - Recurse if necessary

B-Tree: Deletion (2 / 2)

Example(s): Still assuming M = 2

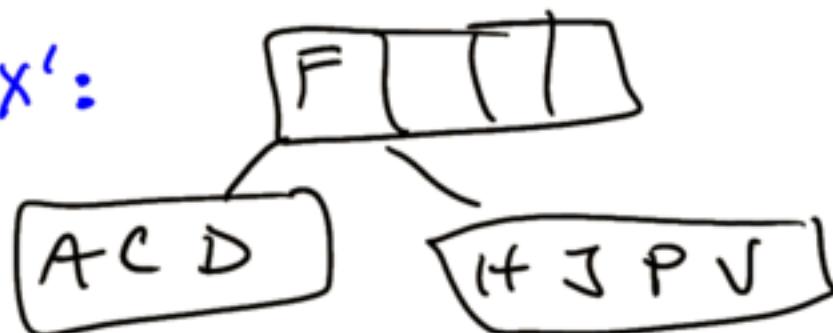
Initially



Delete 'L':



Delete 'X':



B-Tree: Capacity

What is the key capacity of a B-Tree of Order M?

Example(s): Order 128

First Level (the Root): 256 keys

Second Level: $257 \text{ nodes} * 256 \text{ keys}$
 $= 65,792 \text{ keys}$

Third Level: $257^2 \text{ nodes} * 256$
 $= 16,908,544 \text{ keys}$

Total = 16,974,592 keys.

B-Tree: Order Determination

The Idea: Select order to best fit disk block capacity

Remember: A node of a B-Tree of Order M can hold

$2M$ keys and $2M + 1$ pointers
8192

Example(s): Assume 8K bytes/block, keys of 12 bytes, ptrs of 8 bytes

The amount of storage required by a node, in terms of M :

$$(2M)(12) + (2M+1)(8) \leq 8192$$

$$M \leq 204.6$$

So $M = 204$

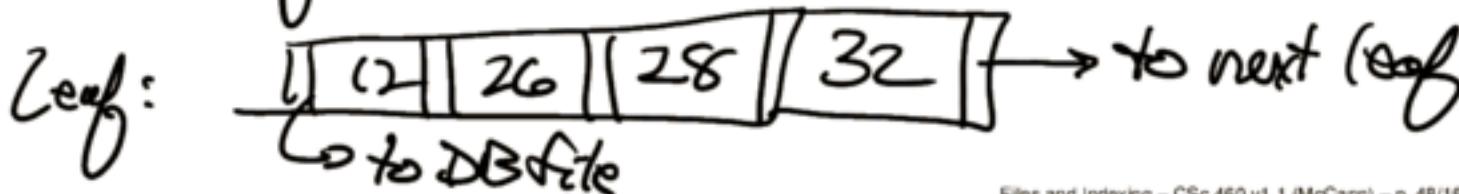
Announcements

- Program #2 is due Wednesday @ the start of class
 - Submit your code via **turnin** to the **CS460p2** folder
- Up next: **Homework #1**
 - Assigned Wednesday, due next Wednesday
- Program #1 was graded & scores emailed to you over the weekend.
 - Have grading concerns? Start by directing your questions to Priya & Aayush. If you reach an impasse, come talk with me about it.

B⁺-Tree: A B-Tree for Indexing

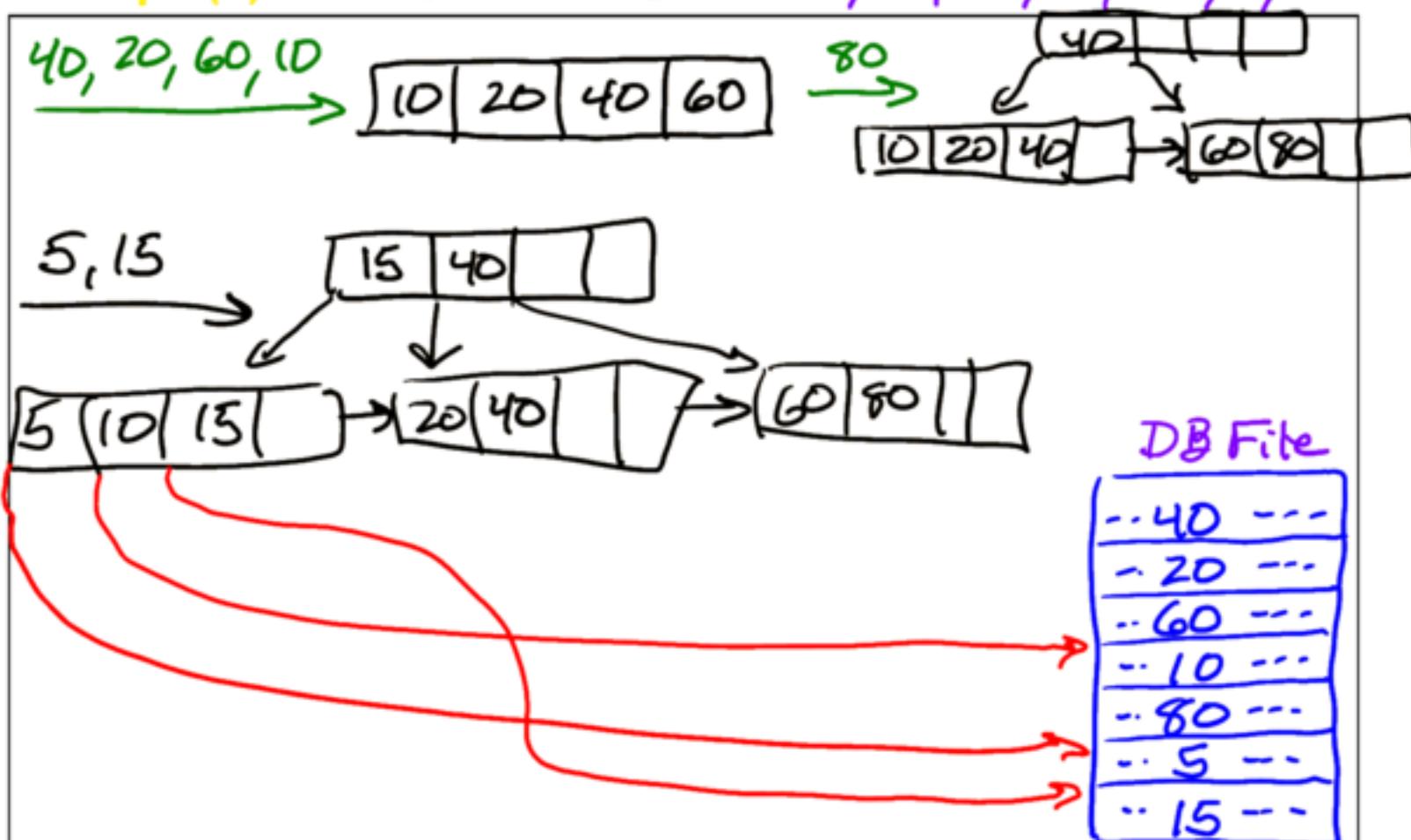
Like a B-Tree, but:

- All of the keys are stored in leaf nodes
- Copies of some keys occupy internal nodes
(to maintain the tree structure)
- Leaf nodes are linked sequentially ($L \rightarrow R$) to form the sequence set
 - facilitated linear searching
 - requires no additional pointers



B⁺-Tree: Insertion

Example(s): Order 2. Insert 40, 20, 60, 10, 80, 5, and 15.



B⁺-Tree: Advantages and Disadvantages over B-Trees

Advantage(s):

- Has built-in disk pointer space in leaf nodes
- Supports exact-match ("find 26") and range ("Find 20-60") queries.

Disadvantage(s):

- "waste" of storage in internal nodes (but a tiny amount)
- insertions / deletions are a little more complex.

Topic 4:

E-R

DB Design and the Entity–Relationship Model

Review of File Schemata

- Recall: Fields \Rightarrow Records (\Rightarrow Blocks) \Rightarrow Files
- A record represents a real-world item or concept
 - Example: A student record in a grading program
- A basic DB file's records all have the same construction
 - (Same fields, same types, same order)
- Identification:
 - Fields: By assigned name
 - Records: By primary key
- Together, these items define the file's schema

Date's Supplier-Part-Project Schema

Also see the SPJ Schema handout!

Used by C. J. Date in his papers and textbooks.

Consists of four files:

Supplier (S)	<table border="1"><tr><td><u>S#</u></td><td>Sname</td><td>Status</td><td>City</td></tr></table>	<u>S#</u>	Sname	Status	City	
<u>S#</u>	Sname	Status	City			
Part (P)	<table border="1"><tr><td><u>P#</u></td><td>Pname</td><td>Color</td><td>Weight</td><td>City</td></tr></table>	<u>P#</u>	Pname	Color	Weight	City
<u>P#</u>	Pname	Color	Weight	City		
Project (J)	<table border="1"><tr><td><u>J#</u></td><td>Jname</td><td>City</td></tr></table>	<u>J#</u>	Jname	City		
<u>J#</u>	Jname	City				
SPJ	<table border="1"><tr><td><u>S#</u></td><td><u>P#</u></td><td><u>J#</u></td><td>Qty</td></tr></table>	<u>S#</u>	<u>P#</u>	<u>J#</u>	Qty	
<u>S#</u>	<u>P#</u>	<u>J#</u>	Qty			

Notes:

- We underline the PKs
- All fields of a composite key are underlined.

Three Tangents

- These are topics of importance to the creation of file schemas.
- They need to be introduced sometime; might as well be now!
- They are:
 - Nulls
 - Foreign Keys
 - A Few Types of Data Integrity

Nulls

Definition: Null

A null is a marker that indicates that a field does not have a value.

Notes:

- The phrase "null value" is contradictory here.
- Nulls are useful when values are not known.
 - Ex: Students w/o a local address
- Nulls are somewhat controversial
 - Relational Model is based on logic
 - But they are useful!

Foreign Keys

Definition: Foreign Key

A field in one file whose values are drawn from the PK field of (usually another) file.

Notes:

- Unlike PKs, FKs may be null.
- Every FK value must also be a PK value
- Ex: In SPJ schema, the SPJ table holds 3 FK fields.

A Few Types of Data Integrity

Foreign keys are essential to three types of data integrity:

1. Key Constraint

- PKs and FKs are designed into a DB.

2. Entity Integrity

- No PK field may be null (b/c PKs are record IDs)

3. Referential Integrity

- This is the name for the idea that an FK value must refer to an existing PK value

⇒ All take effort to enforce.

DB Design: Overview

- Very similar to software development processes
- Everyone has his/her own n step design process
 - The one we'll present is rather generic
- Some ideas to keep in mind:
 - Any design process is iterative
 - Processes can be categorized as being either ...
 - top-down vs. bottom-up, or
 - data-driven vs. function-driven, or
 - ...

DB Design: Phases 1 & 2

Phase 1:

Requirements Analysis - Learn what the customer needs!

... by asking lots of questions!

Phase 2:

Conceptual Design - Create the conceptual schema

- the high-level description of the DB's structure
- includes data requirements, data relationships, data constraints,
- does not include implementation details
- example modeling tool: The E-R Model

DB Design: Phases 3 & 4

Phase 3:

Logical Design - convert conceptual design into a DBMS' implementation data model
(See Topic 5)

- Ex: The Relational Model

- Conversion includes data normalization

Phase 4:

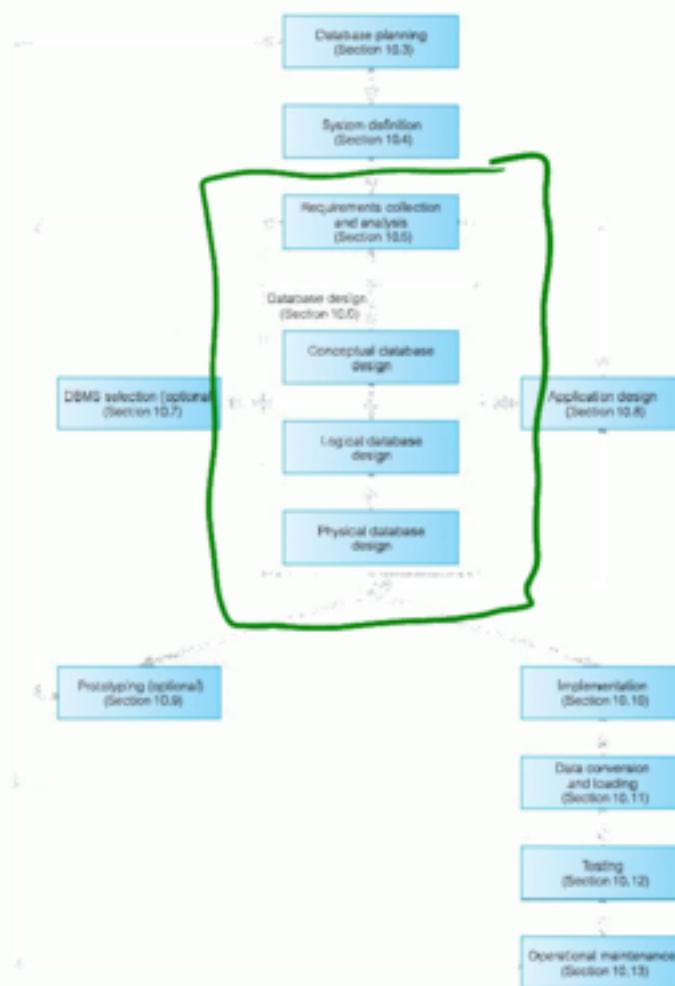
Physical Design - specify the DB's storage requirements

- such as: indices, record order, data types

- all based on expected usage of the DB.

(Learned in Phase 1.)

DB Design: In Context



Credit:
Connolly/Begg, 6/e,
Figure 10.1, p. 300.

Announcements

- o Program #2 is due now!
 - Submit files using **turnin** to **cs460p2** folder.
- o Handout: Homework #1 ← Note: **#9's (13.7's) topic will be covered Monday.**
 - Pay heed to the directions:
 - Submissions must be PDFs (yes, you can write answers by hand & scan to PDF)
 - Upload your PDF to **Gradescope**.
 - you can use at most 1 late day on homeworks because ...
 - we will be making solutions available 24 hours after the due date/time, to help you study for ...
- o Exam #1 is two weeks from today (Oct. 5th).

What are 'Entities'?

Definition: Entity

An entity is an instance of a general classification

DBs store representations of entities

Example(s):

Each of you is an instances of the class 'human'!

Lincoln's Gettysberg Address is a speech instance.

What are 'Relationships'?



Credit: "Mother Goose and Grimm" by Mike Peters, 2009– 02–12

Definition: Relationship

A is an association between sets of entities.

Example(s):

Instructors teach classes.

Companies visit career fairs

One-to-One Relationships

Definition: One-to-One Relationship

In a relationship between two entity sets A and B, an entity from A is associated with at most one entity from B, and an entity from B is associated with at most one entity from A.

Symmetric

Example(s):

Employee manages Department
Patient – Vaccine Syringe

One-to-Many Relationships

Not Symmetrical!

(a.k.a. Many-to-One Relationships)

Definition: One-to-Many Relationship

In a , one entity from A is associated with 0 or more entities from B, but each from B is associated with at most one from A.

Example(s):

Professor - Department (if multiple apps are not possible)

Barber - Client

(Biological) Father - Child

Many-to-Many Relationships

Definition: Many-to-Many Relationship

(M-to-N)

A is a pair of 1-to-N relationships.

(Back to symmetry)

Example(s):

Employee - Project

Patient - Doctor

Other Varieties of Relationships

This list is by no means exhaustive! Some others:

- 1:1, 1:N, M:N with Varied Multiplicities

Ex: Zero or One vs exactly one

- Ternary (a.k.a. 3-Way, Degree 3)

Ex: SPJ Schema

Ex: Course - Time - Room

- Recursive (a.k.a. Cyclic)

Ex: Supervise : Employee - Employee

— there are more! —

The E-R Model: Origins

- First proposed by Pin-Shan (Peter) Chen in a 1976 paper
 - Extended many times since
 - Example: Enhanced E-R (E-E-R) Model
 - Has an annual conference devoted to it
 - (Int'l Conf. on Conceptual Modeling)
- Easily the most popular conceptual model in use today
- Many of its ideas appear in the Unified Modeling Language (UML)
- Diagrammatic variants abound

An E-R Example (1 / 6): A Bank Database

Description:

Consider a (very) simple database for a bank. We need to store information about the bank's customers. Of course, the customers have accounts with the bank, and they perform transactions on those accounts.

Question: What are the entity sets for our database?

Customer
Account
Transaction

Hint: Use singular names!

Bank as an entity set? **No**

An E-R Example (2 / 6): Fields

Question: Which pieces of information do we need for each entity set?

Customer: Name, SSN, CID, Address, - - -

Account: Acct#, Balance

Transaction: Date, TID, Type, Amount, - - -

Notes:

- A weak entity set is one whose existence depends upon another entity set. Ex: Transaction
 - symbol: Dashed underline is a partial key
- Customer & Account are strong entity sets (have good primary keys)

An E-R Example (3 / 6): Relationships

Question: Which relationships connect these entity sets?

① Customer - Account (CostAcct)

Cardinality: M:N

Attribute: Date of Creation

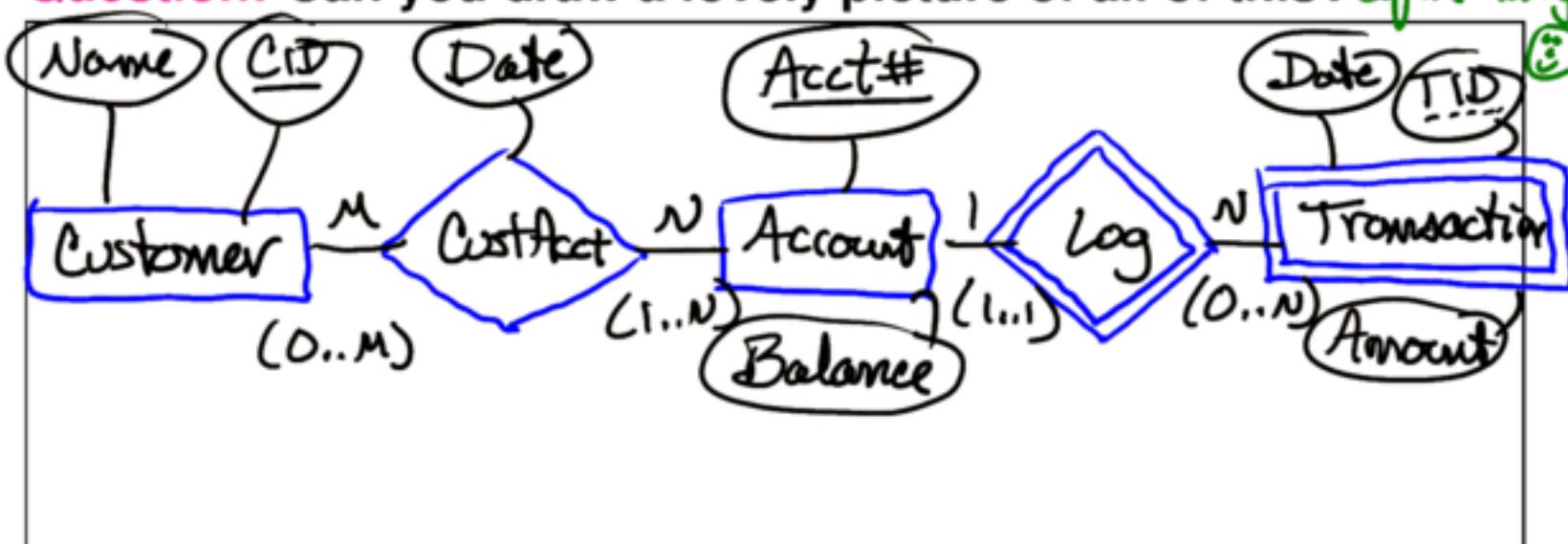
② Account - Transaction (Log)

Cardinality: 1:M

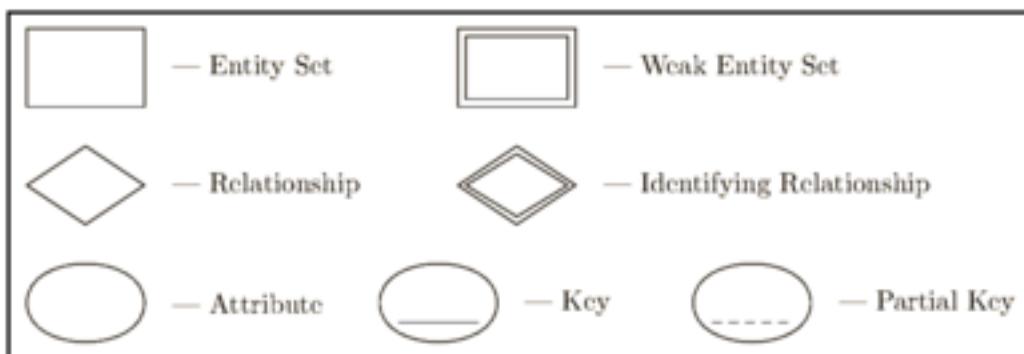
⇒ The relationship supporting a weak entity set is called an identifying relationship.

An E-R Example (4 / 6): Diagram (Chen's Notation)

Question: Can you draw a lovely picture of all of this? *depends; define "lovely"*



Legend:

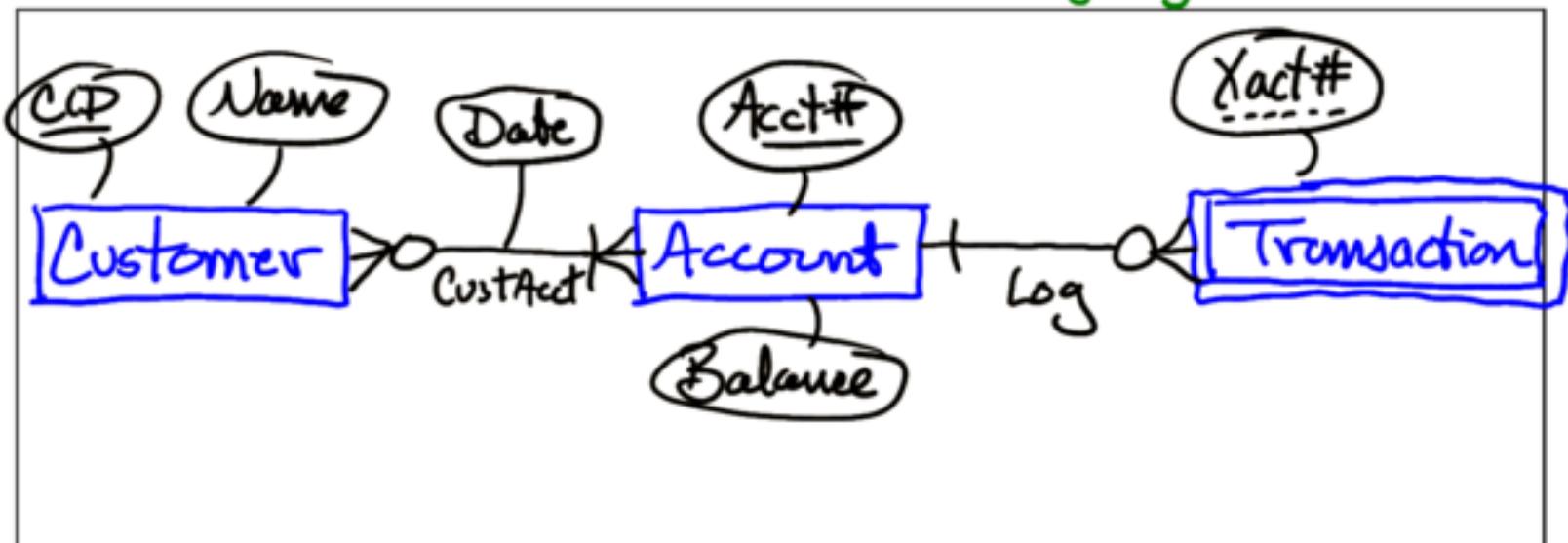


Announcements

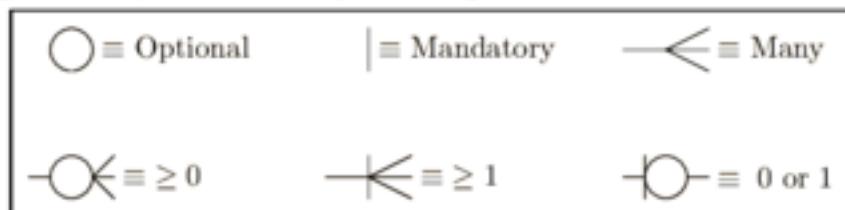
- Homework #1 is due @ the start of class on Wednesday.
 - Remember, submit your highly-legible PDF to Gradescope!
 - You can use a late day, but only one.
 - Answers will be posted after 3:30pm Thursday
- Exam #1 is Wednesday, Oct 5th.
 - Topics: 1-5 (hopefully!)
 - Sorry, no sample exam & no review session.
(We're confident that you know how to study for exams by now!)
- We are behind pace, which isn't unusual, but is a problem...

An E-R Example (5 / 6): Diagram (Crow's Feet Notation)

Question: Is there another notation? Sure; why not?

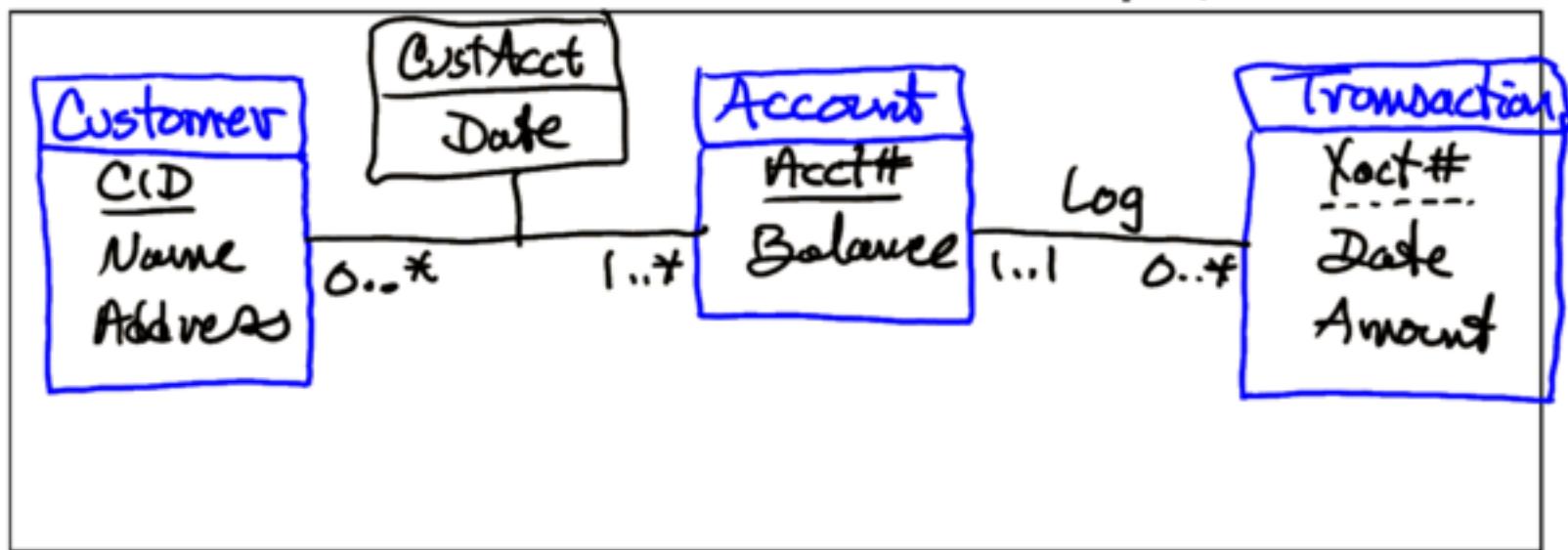


Legend (not completely standardized . . .):



An E-R Example (6 / 6): Diagram (UML Notation)

Question: Doesn't UML include these concepts, too? Yup!



Notes People mix and match from these styles
Lots of other notation options on each of these.

Another E-R Example: Faculty

Try it!

Description:

University faculty members teach classes that are offered by departments. Faculty are members of departments. Each department has a chairperson.

Question: What are the entity sets and relationships?

E-R Modeling Rules of Thumb

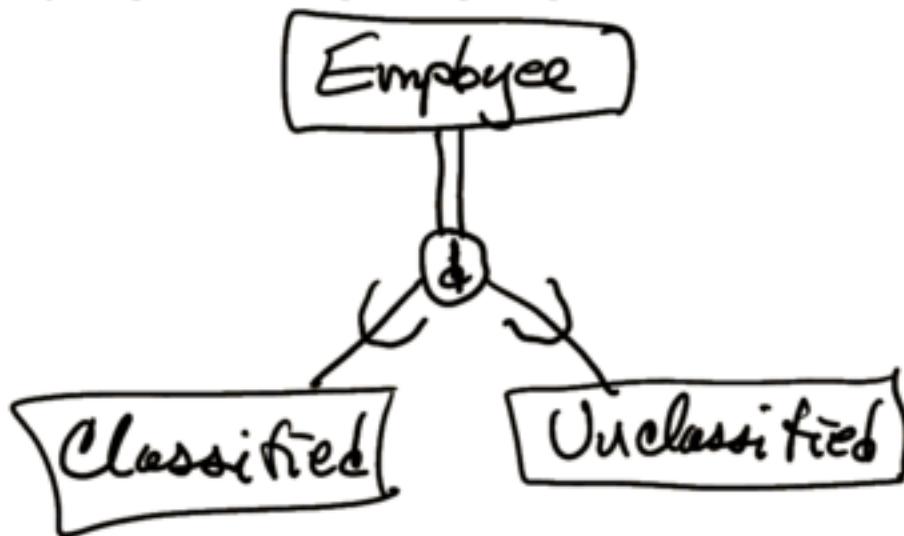
- Choose singular (v. plural) names for entity sets
- Naming relationships can be a challenge; concatenation of the names of participating entity sets is an option
- If you can't find a candidate key, perhaps the entity set is weak
 - If so, remember that the relationship is *identifying*.
- Mixing & matching notation is common
- Make your model as informative as possible

Enhanced E-R Model: Motivation

- The basic E-R Model was designed for ‘business data’
 - Basically, text and numeric fields
- Now that computers are more common, more capable, and used for a wider variety of purposes, additional representational power is required to model user concepts.
- Generally, this is called *semantic modeling*.
- Some semantic modeling suggestions have been added to E-R modeling

EER: Specialization / Generalization ("is-a")

Consider inheritance in an O-O programming language ...



$\text{Manager} \subset \text{Employee}$

 means "total specialization" means "partial ..."

d means 'disjoint', o means 'overlap is Ok', u means 'union'

EER: Aggregation (“has-a”)

Several types:

1. An entity is formed from a collection of attribute values

Ex: A person “has-a” name, id#, ...

2. An entity formed from other entities

Ex: A car is engine, tires, doors, ...

3. An entity formed from a relationship to a relationship

Ex: A job interview (relationship between Company and Applicant) resulting in a job offer

Notation is often just a line between relationship diamonds.

Topic 5:

Implementation Data Models

A Wee Bit O' History

There are four data models of note:

1. Hierarchical (early 1960s, IBM)
2. Network (early 1970s, CODASYL/DBTG)
3. Relational (early 1970s, Codd @ IBM)
4. Object (????)

Notes: All need "tricks" to handle M-to-N refs.
A data model has (a) data structure
and (b) operations
⇒ like an ADT.

Hierarchical Model: Background and Ideas

Background:

- John F. Kennedy, May 25, 1961: '... man on the moon ...'
- Rockwell needed to organize parts for the Apollo CM & SM
- IBM created IMS (Information Management System) in 1968
 - original name: ICS/DL/I; thankfully renamed in '69
 - both used and introduced the Hierarchical Model
 - still sold today!

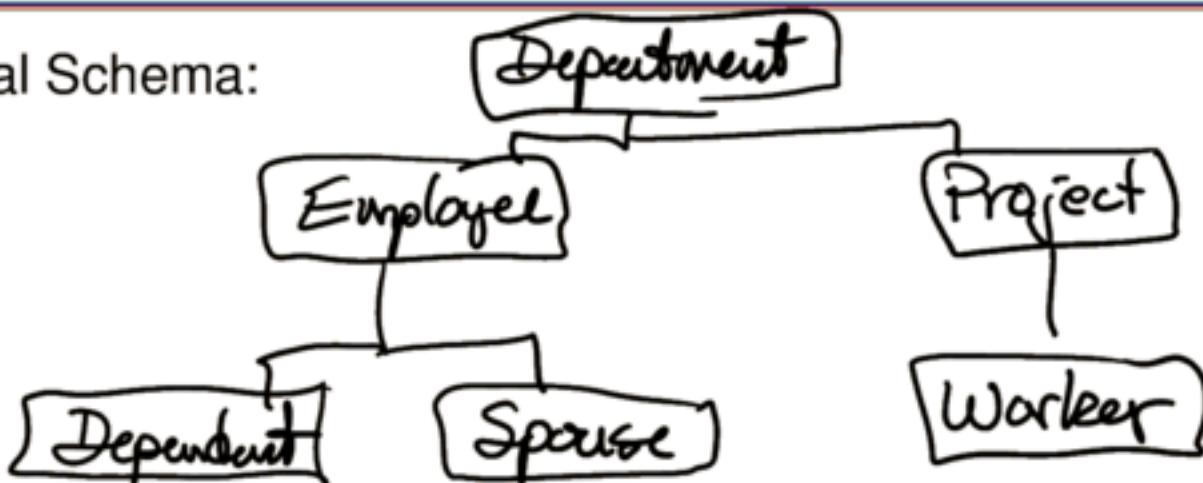
Ideas:

Schema is tree structured

only 1-N relationships are directly supported
- 1 parent, many children.

Hierarchical Model: Terminology

Sample Logical Schema:

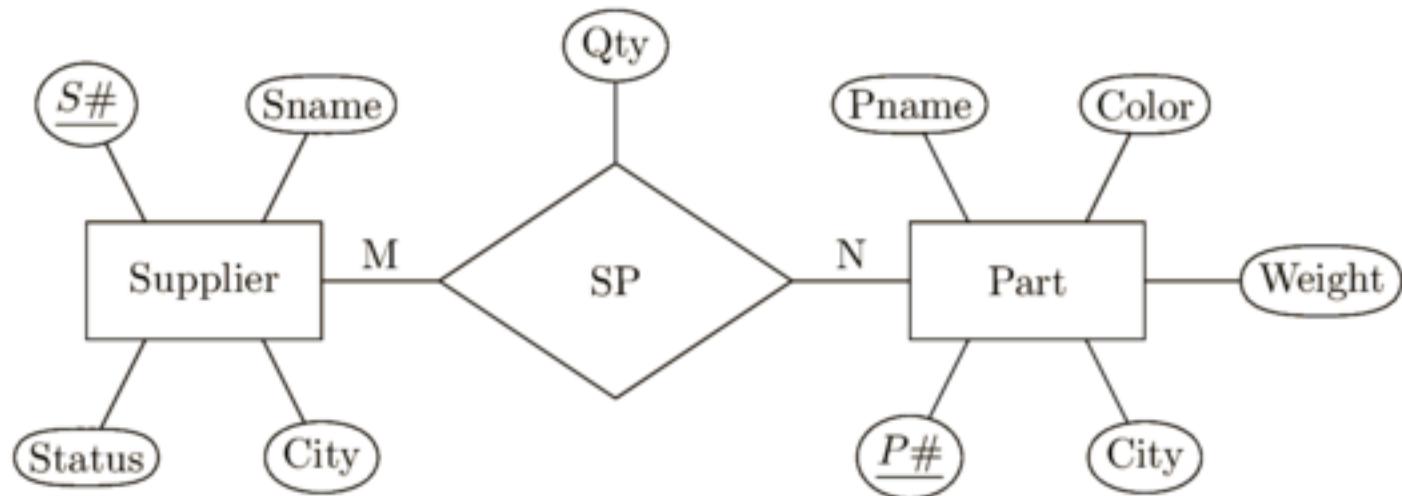


Terminology:

E-R Model	≡	Hierarchical Model
Entity Set	≡	Segment Type
Entity	≡	Segment Occurrence (or Instance)
Attributes	≡	Fields or Data Items
Relationships	≡	PCRs - Parent-Child Relationships

Hierarchical Model: Supplier–Part Schema

Consider this subset of Codd's SPJ schema:

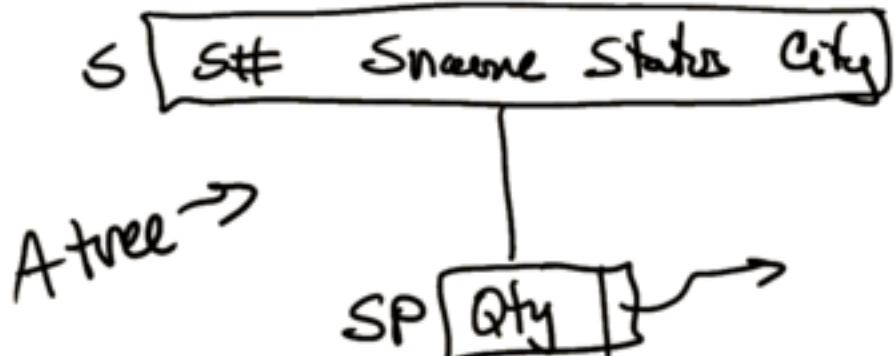


- Don't need Project here.

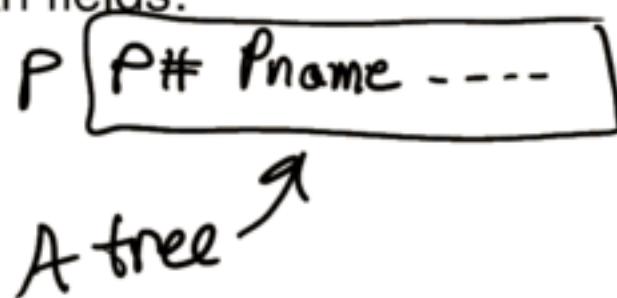
Hierarchical Model: M:N Relationships (1 / 3)

Physical

~~Logical Schema~~, but augmented with fields:



A tree →



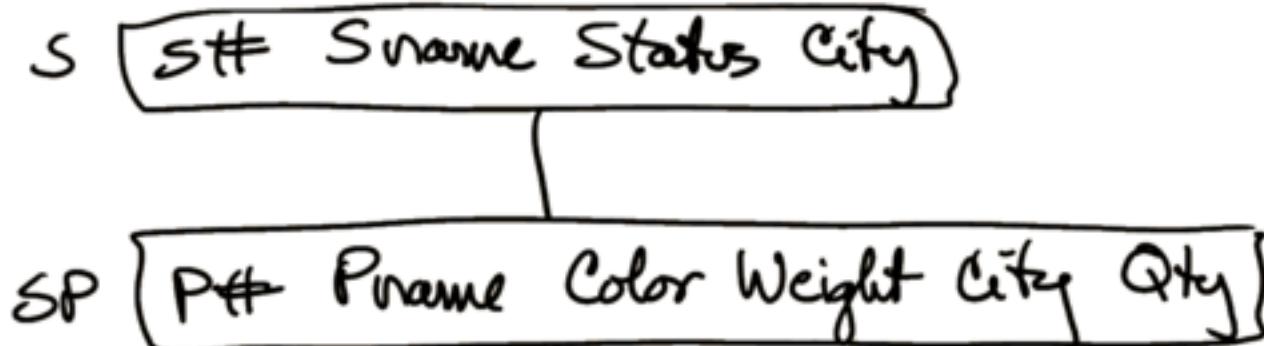
A tree →

Notes: 2 separate trees.

The pointers from SP Segment Occurrences will point to seg. occurrences of P

Hierarchical Model: M:N Relationships (2 / 3)

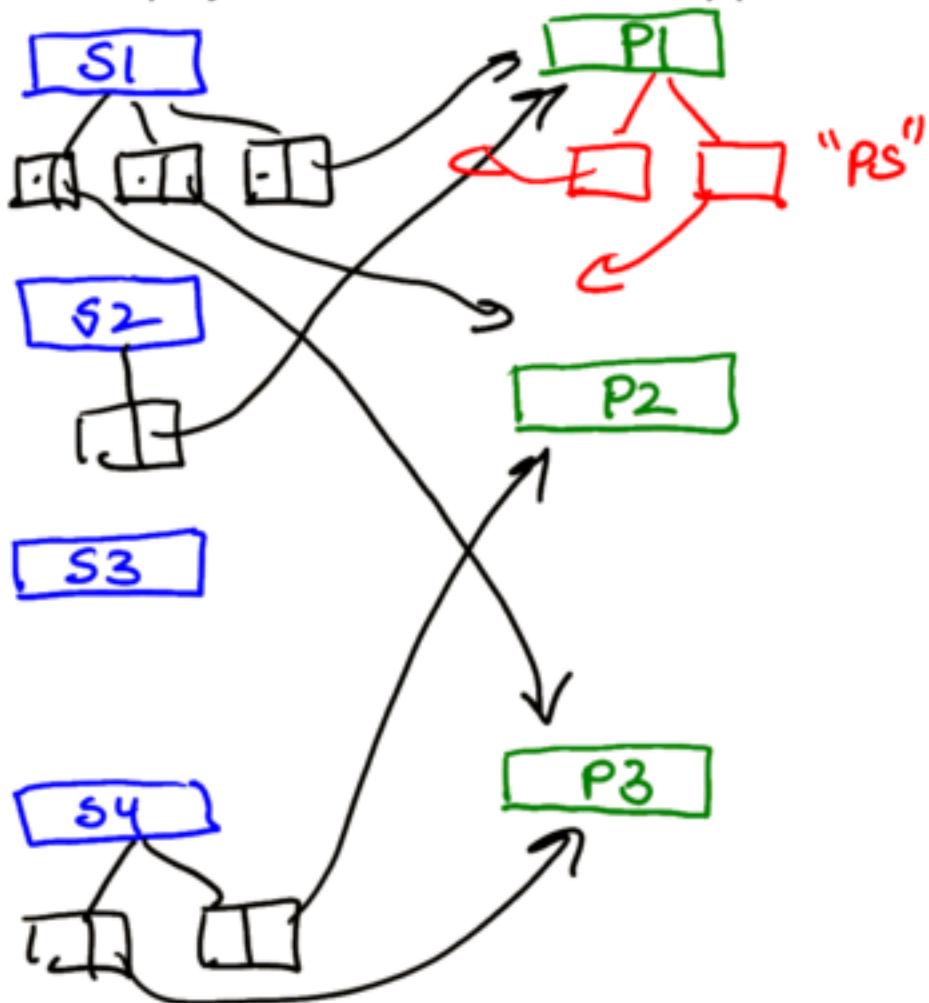
Logical
~~Physical~~ Schema:



Notes: SP is the merger of the SP & P fields
It appears that if a supplier supplies a part, we will need n copies of that part.

Hierarchical Model: M:N Relationships (3 / 3)

The physical schema for Supplier–Part w/ sample data:



Questions:

- ① Which parts can S1 supply?
- ② Which suppliers can supply P3?

Network Model: Background and Ideas

- Created in the early 1970s by CODASYL's
(Conference/Committee on Data Systems Languages)
DBTG (Database Task Group)
- Goal: A standard theory of DB systems.
Origin of the ideas of DML and DDL
- Became an ISO standard in 1987 (ISO 8907:1987)
(And was withdrawn in 1998!)
- Graph-based instead of tree-based

Network Model: Terminology

A Sample Logical Schema:

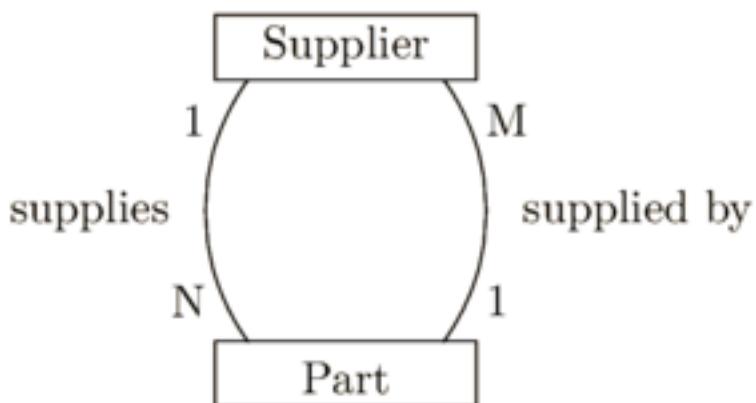


Terminology:

E-R Model	Network Model
Entity Set	<i>Record Type</i>
Entity	<i>Record Occurrence</i>
Attributes	<i>Date Items</i>
Relationships	<i>Set or Link Type (orig. 'DBTG sets')</i>

Network Model: M:N Relationships (1 / 2)

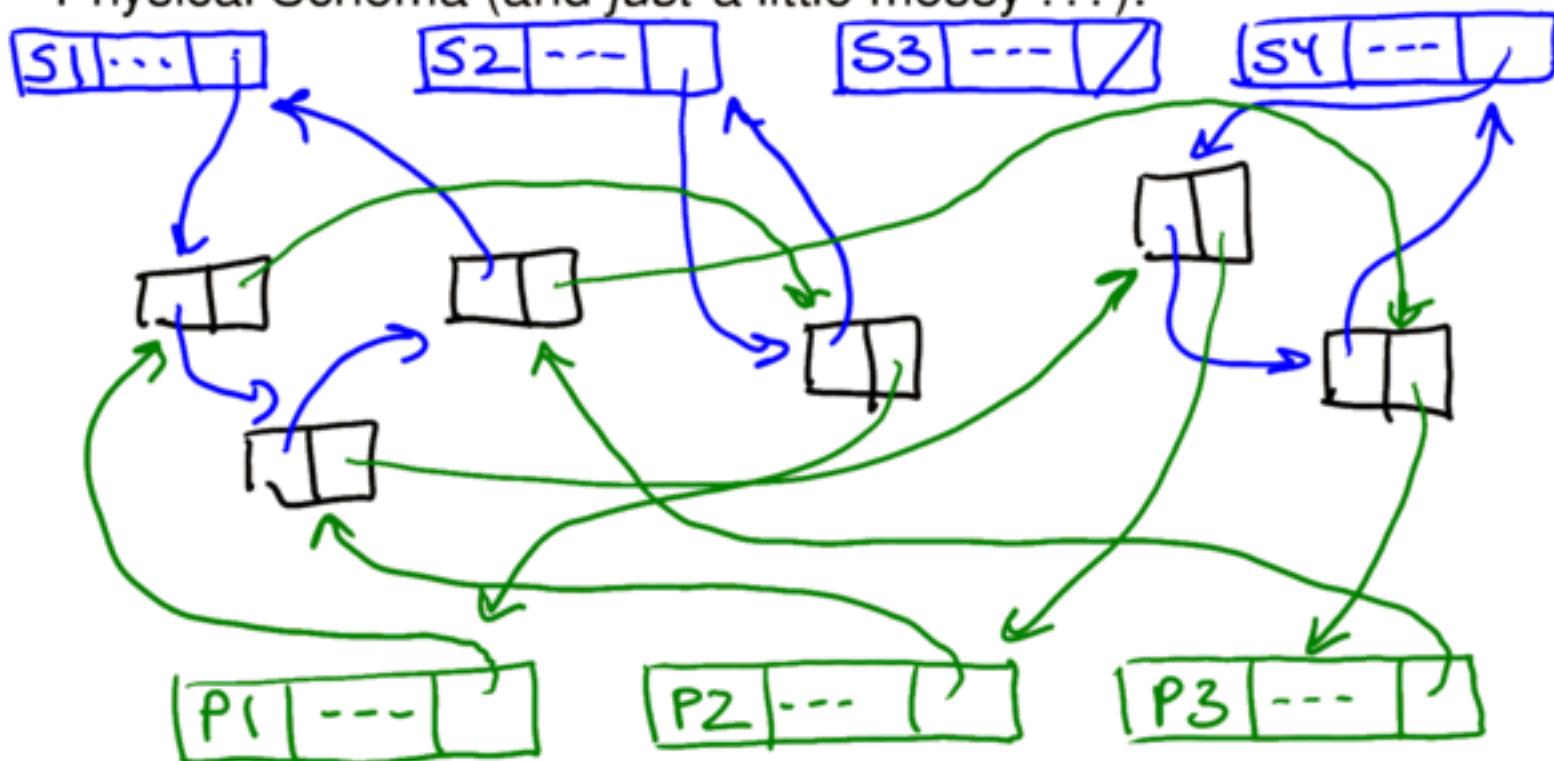
Logical Schema (of the M:N Supplier - Part relationship):



Note: An undirected graph – can travel either way.

Network Model: M:N Relationships (2 / 2)

Physical Schema (and just a little messy ...):



Imagine the quantities are part of the Link Record Occurrences

- ① Which parts can S1 supply?
- ② Which suppliers can supply P3?

Relational Model: Background and Ideas

- Created by Edgar F. Codd. Famous paper:
“A relational model of data for large shared data banks,” 1970.
- Theoretical foundation: Set Theory
- Uses foreign keys instead of pointers
- No distinction between logical and physical schemas

Relational Model: DMLs

Codd proposed two types of DMLs:

- ① Relational Calculus (non-procedural)
- ② Relational Algebra (procedural)

SQL has elements of each

Watch for video!

Announcements

- Homework #1 is due now.
 - Late submissions can use at most one late day
 - Solutions will be posted sometime after 3:30pm tomorrow.
- Exam #1 is one week from today! (Oct 5th)
 - Topics: 1 - 5
- The video covering Topic 6 (Relational Calculus) is available in D2L (under Content / Lect. Recordings)
 - Today, we'll finish Topic 5 and will start Topic 7 (Relational Algebra).
- Homework #2 will be assigned Monday, due 9 days later.

Relational Model: DMLs

Partial Review

Codd proposed two types of DMLs:

- ① Relational Calculus (non-procedural; "declarative")
(Lecture Topic 6 - see video for coverage!)
- ② Relational Algebra (procedural)
(Lecture Topic 7)

Notes: Neither is suitable for practical use.

Codd's RC is now called Tuple RC,
the later version is Domain RC.

Relational Model: Terminology (1 / 2)

Sample Supplier - Part Schema:

S	S#	Sname	Status	City
	S1	Acme	10	Omro
	S2	Fubar	10	Fisk
	S3	Snafu	20	Ring

P	P#	Pname	Color	Weight	City
	P1	Nut	Pink	0.2	Anton
	P2	Bolt	Blue	0.9	Borea

Terminology:

E-R Model

Relational Model

Entity Set

≡

Relation (or table)

Entity

≡

Tuple (pronounce: TOO-ples)

Attributes

≡

Fields

Relationships

≡

Relationships!

Relational Model: Terminology (2 / 2)

Sample Department – Employee Schema:

DEPARTMENT				
	<u>DeptNum</u>	DeptName	ManagerID	ManagerStartDate
1	Shipping	364	2001-04-01	
2	Payroll	NULL	NULL	
3	Billing	298	2000-11-17	

PK

EMPLOYEE	Surname	GivenName	<u>EmpNum</u>	DeptID	Salary
Spade	Sam	786	1	48000	
Trune	Joe	410	2	49500	
Smith	Megan	364	1	75000	
Maher	Mary	298	3	72000	

FK

- Cardinality = # of tuples
- degree (or arity) = # of attributes
- unary relation = A relation of Degree 1
- n-ary relation = A relation of Degree N

Relational Model: Misc. Notes

logically!

- Order of tuples in a relation is irrelevant (Why?)

Relations are sets of tuples!

- Fields are single-valued by default (vs. set-valued)

This is frequently violated in practice.

- Relationships are supported by foreign keys

May be stored in separate relations.
(stay tuned!)

Relational Model: 1:N Relationships

We've already seen how to do this! (Just two slides ago!)

PK

DEPARTMENT	<u>DeptNum</u>	DeptName	ManagerID	ManagerStartDate
	1	Shipping	364	2001-04-01
	2	Payroll	NULL	NULL
	3	Billing	298	2000-11-17

FK

EMPLOYEE	Surname	GivenName	<u>EmpNum</u>	DeptID	Salary
	Spade	Sam	786	1	48000
	Trune	Joe	410	2	49500
	Smith	Megan	364	1	75000
	Maher	Mary	298	3	72000

Notes:

A dept can have many employees; each employee has 1 dept.

Relational Model: 1:1 Relationships

- Just a restriction of 1:N relationships:
 - We still store a FK in the 'many' relation
 - Must constrain the field's values to be unique; two options:
 - ① Insist that the FK be a Candidate key.
 - ② Create a unique index on the FK
(the DBMS enforces the uniqueness of the attr's content)

Relational Model: M:N Relationships

PK

S	S#	Sname	Status	City
S1	Acme	10	Omro	
S2	Fubar	10	Fisk	
S3	Snafu	20	Ring	

PK

P	P#	Pname	Color	Weight	City
P1	Nut	Pink	0.2	Anton	
P2	Bolt	Blue	0.9	Borea	

FK

FK

SP

S#	P#	Qty
S1	P1	50
S1	P2	150
S2	P2	25
S3	P1	300

attr. of the
relationship

Notes:

- called a relationship relation
 - necessary because won't work to store both FKs in source relations (try it!)

Object Model: Ideas

- OO programming languages have existed since Simula in 1967
- We'd like to be able to store objects in a DBMS
 - provides object persistence
 - can do it by mapping object instance fields to relational tuples, but that's clunky
- The Object Data Management Group (ODMG) defined an object-based DBMS standard
 - finished ODMG 3.0 in 2001 (and then disbanded!)

Object Model: Object DBMS Types

Two major varieties:

1. Object Oriented DBMS (OODBMS)
 - Marriage of an OOPL and a DBMS
2. Object Relational DBMS (ORDBMS)
 - A relational DBMS with added objects



Most popular

— get to leverage existing customer base.

Topic 6:

Relational Calculi

Meanings of 'Calculus'

- Calculus refers to any method or system of calculation
- 'Calculus' is derived from the Latin word for pebble
- Modern uses of the word include:
 - Differential Calculus: rates of change
 - Integral Calculus: limits of sums
 - Lambda Calculus: functional abstraction & application
 - Predicate Calculus: reasoning about symbolic logic

Why? Because FOPC \Rightarrow Relational Calculus \Rightarrow SQL

FOPC (a.k.a. First-Order Logic):

- uses predicates (e.g., $P(x)$)
 - predicate*
 - subject*
- Subjects may be values; they may not be predicates.
- FOPC can formalize all of set theory.

Supplied Primitives:

Variables, Logical operators, Quantifiers

Constructs of our creation:

Constants, Predicates, Functions

Example(s):

$\text{Feathers}(x)$: x has feathers, $x \in \text{Animal}$

$\text{Bird}(x)$: x is a bird, $x \in \text{Animal}$

$\text{Feathers}(\text{Eagle}) \rightarrow \text{Bird}(\text{Eagle})$

$\forall x [\text{Feathers}(x) \rightarrow \text{Bird}(x)], x \in \text{Animal}$

$\exists x [\text{Bird}(x) \wedge \neg \text{Fly}(x)], x \in \text{Animal}$

Relational Calculi: Ideas

Relational Calculi are “what, not how” languages



There are two forms:

Tuple Relational Calculus (TRC)
Domain " " (DRC)

Tuple Relational Calculus (TRC): Background

- Proposed by Codd in 1972
- So named because the variables in TRC represent tuples
- TRC queries have this basic form:

$$\{ t \mid \text{predicate}(t) \}$$

where:

t is a free (unbound) tuple variable

predicate is a wff

TRC: Query #1

Question: What is the content of the Employee Relation?

$$\{ e \mid \text{Employee}(e) \}$$

Recall these schemas:

DEPARTMENT	DeptNum	DeptName	ManagerID	ManagerStartDate	
EMPLOYEE	Surname	GivenName	EmpNum	DeptID	Salary

TRC: Query #2

Question: What are the names and salaries of the people in department #5?

$$\{ e.\text{givenname}, e.\text{surname}, e.\text{salary} \mid \text{Employee}(e) \\ \wedge e.\text{deptid} = 5 \}$$

DEPARTMENT	DeptNum	DeptName	ManagerID	ManagerStartDate
EMPLOYEE	Surname	GivenName	EmpNum	DeptID
				5

TRC: Query #3

Question: What are the names of the parts that can be supplied by individual suppliers in quantity > 200?

$$\{ p.pname \mid P(p) \wedge \exists(g) (SP(g) \wedge g.P\# = p.P\# \wedge g.Qty > 200) \}$$

S	S#	Sname	Status	City	
P	P#	Pname	Color	Weight	City
SP	S#	P#	Qty	= 200	

TRC: Query #4

Question: What are the names of the active suppliers of nuts?

$$\{ \exists s. \text{sname}(S(s)) \wedge s.\text{status} > 0 \wedge \\ \exists q. (\text{SP}(q) \wedge q.\text{S\#} = s.\text{S\#}) \wedge \\ \exists p. (\text{PC}(p) \wedge p.\text{P\#} = q.\text{P\#}) \wedge \\ p.\text{pname} = 'Nut')) \}$$

↗
S → P → SP

S	S#	Sname	Status	City	
P	P#	Pname	Color	Weight	City
SP	S#	P#	Qty		

Aside: Expression Safety

Definition: Expression Safety

An expression is safe if the expression's domain is the source of all resulting values.

Example(s):

Safe: $\{e \mid \text{Employee}(e)\}$

Unsafe: $\{e \mid \neg \text{Employee}(e)\}$

No way to prevent unsafe queries.

Domain Relational Calculus (DRC): Bkgd.

- Proposed by Lacroix and Pirotte in 1977 to supply a formalism for IBM's Query By Example (QBE) product.
- In DRC, a variable represents just one field of a tuple
- DRC queries have this basic form:

$$\{ \underline{\langle abcd \dots \rangle} \mid \text{condition } (\underline{\langle abcd \dots \rangle}) \}$$

where:

$\langle abcd \dots \rangle$ is a set of ≥ 1 unbound domain variables, one per field of the relation
condition is a DRC w.f.f.

DRC Query #1

Question: What is the content of the Employee Relation?

$$\{ \langle e f g h i \rangle \mid \langle e f g h i \rangle \in \text{Employee} \}$$

Note the helpful field labels!



	a	b	c	d	
DEPARTMENT	DeptNum	DeptName	ManagerID	ManagerStartDate	
	e	f	g	h	i
EMPLOYEE	Surname	GivenName	EmpNum	DeptID	Salary

DRC Query #2

Question: What are the names and salaries of the people in department #5?

$$\{ \langle f e i \rangle \mid (\exists h)(\langle e f g h i \rangle \in \text{Employee} \wedge h = 5) \}$$

	a	b	c	d
DEPARTMENT	DeptNum	DeptName	ManagerID	ManagerStartDate
EMPLOYEE	e	f	g	h
	Surname	GivenName	EmpNum	DeptID
				Salary

DRC Query #3

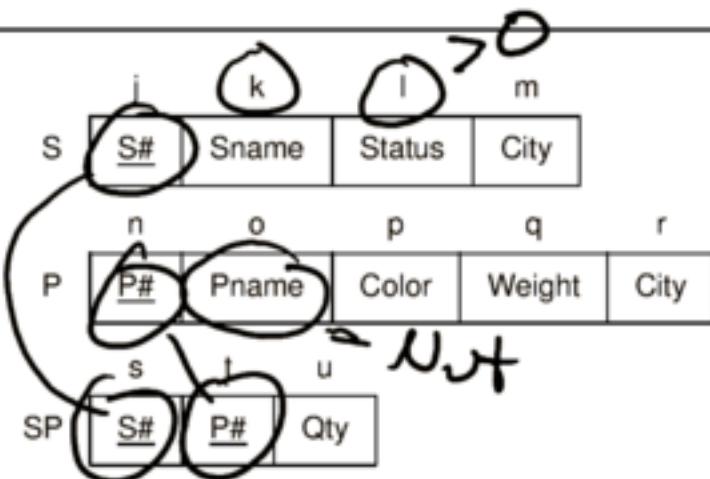
Question: What are the names of the parts that can be supplied by individual suppliers in quantity > 200?

$$\{ \langle o \rangle | (\exists n) (\langle n \rangle \in P \wedge (\exists t_a) (\langle s t_a \rangle \in SP \wedge n = t \wedge u > 200)) \}$$

S	j	k	l	m	
	S#	Sname	Status	City	
P	n	o	p	q	r
	P#	Pname	Color	Weight	City
SP	s	t	u	> 200	
	S#	P#	Qty	> 200	

DRC Query #4 (1 / 2)

Question: What are the names of the active suppliers of nuts?

$$\{ \langle k \rangle | (\exists j l) (\langle j k l m \rangle \in S \wedge l > 0 \wedge (\exists s t) (\langle j t u \rangle \in SP \wedge j = s \wedge (\exists n o) (\langle t o p q r \rangle \in P \wedge n = t \wedge o = 'NUT')))) \}$$


Shortcut is optional.

Topic 7:

Relational Algebra

Looking for Topic 6 (Relational Calculus)? See:

- Video covering it (in D2L)
 - Slides are in a separate file in the completed slides area of the class web-page.
- yes, Relational Calculus will be on Exam #2 and the Final Exam.

Background

- Introduced by Codd (along with the Tuple Relational Calculus)
- Relational Algebra . . . :
 - Is procedural, like most programming languages
 - we need to supply an ordering of operations
 - Would not be a good replacement for SQL in a DBMS
 - Is a good introduction to the operators provided by SQL

Relational Operators (1 / 2)

Relations are *closed* under Relational Algebra operators

- That is, they accept relations as operands, and produce relations as results.
- Example: Integers are closed under + and -.

The eight basic Relational Algebra operators are:

\times	Cartesian Product	\bowtie	Join
$-$	Difference	π	Project
\div	Division	σ	Select
\cap	Intersection	\cup	Union

Relational Operators (2 / 2)

The eight Relational Algebra operators can be grouped in two ways:

1. Set vs. Relational:

- Set: \cup , \cap , $-$, \times , \div
- Relational: σ , π , \bowtie

2. Fundamental vs. Derived:

- Fundamental: σ , π , \times , \cup , $-$
- Derived: \cap , \bowtie , \div

The Fundamental Operators

- Select (σ)
- Project (π)
- Cartesian Product (\times)
- Union (\cup)
- Difference ($-$)

Select (σ , sigma) (1 / 2)

- A unary (single argument) operator
- Chooses full tuples from a relation based on a condition
- Form: $\sigma_{\text{condition}} (\text{relation})$

Example(s):

List all information of the employees in department #5:

$$\sigma_{\text{dept\#} = 5} (\text{Employee})$$

Who are the active suppliers in Paris?

$$\sigma_{\text{city} = \text{'Paris'} \wedge \text{status} > 0} (S)$$

Select (σ , sigma) (2 / 2)

Notes:

- Conditions may be as complex as is necessary
- Select is commutative:

$$\sigma_A(\sigma_B(r)) \equiv \sigma_B(\sigma_A(r))$$

- Cascades of selects \equiv conjunction in a single select:

$$\sigma_A(\sigma_B(\sigma_C(r))) \equiv \sigma_{A \wedge B \wedge C}(r)$$

Project (π , pi) (1 / 2)

Pronunciation: PRO-ject (not pro-JECT, not PRAH-ject)

- Also a unary operator
- Chooses named columns from a relation
 - Resulting group of tuples may include duplicates . . .
 - . . . which we drop to preserve entity integrity
- Form:

$$\pi_{\text{list of attrs}} (\text{relation})$$

↑
comma-separated

Project (π , pi) (2 / 2)

Example(s):

Find the names & salaries of the employees in department 5:

$\pi_{\text{givenname, surname, salary}} (\sigma_{\text{dept\#}=5} (\text{Employee}))$

Alternatively:

$\text{temp} \leftarrow \sigma_{\text{dept\#}=5} (\text{Employee})$

$\pi_{\text{givenname, surname, salary}} (\text{temp})$

Cartesian Product (\times) (1 / 2) $\{ (x,y), (x,z) \ldots \}$

- A binary operator (form: $R \times S$)
- ‘Marries’ all pairings of tuples from the given relations
 - resulting cardinality = $\text{card}(R) \cdot \text{card}(S)$
 - resulting degree = $\text{degree}(R) + \text{degree}(S)$

Example(s):

A	m	n
2	i	
3	iv	
7	x	

B	o	p
3	β	
7	α	

$A \times B$

m	n	o	p
2	i	3	β
2	i	7	α
3	iv	3	β
3	iv	7	α
7	x	3	β
7	x	7	α

Cartesian Product (\times) (2 / 2)

Example(s):

What are the names of the active suppliers of nuts?

The complete query:

$$\pi_{\text{Sname}}(\sigma_{\text{Status} > 0 \wedge \text{Pname} = \text{'Nut'}}(\sigma_{\text{S.S\#} = \text{SP.S\#}}(\sigma_{\text{SP.P\#} = \text{P.P\#}}(S \times (SP \times P)))))$$

For a visualization of this query step-by-step with sample data, see the handout:

“Examples of the Relation Algebra Operations σ , π , and \times ”

Announcements

- Exam #1 is Wednesday, in G-S 906.
 - Topics: 1-5 (DBs & DBMSes; Architectures; Files & Indexing; DB Design & ER Model; Implementation Data Models)
 - Expect short-answer (1-3 sentences) and problem-solving questions, mostly.
 - You'll have the full 75 minutes.
- Handout: Homework #2 (Relational Algebra)

Union (\cup) (1 / 2)

- Another binary operator (form: $R \cup S$)
- Result contains all tuples of both relations w/o duplicates

Example(s):

“Create a table of the Phoenix and Tucson employee data.”

$PtxEmps \leftarrow \Gamma_{loc='Ptx'}(Employee)$

$TusEmps \leftarrow \Gamma_{loc='Tus'}(Employee)$

$AZEmps \leftarrow PtxEmps \cup TusEmps$

Union (\cup) (2 / 2)

To perform $R \cup S$, R and S must be union compatible.

Definition: Union Compatible

Two relations that have the same degree and the same domains on corresponding pairs of attributes are union compatible.

Example(s):

Can we legally union $R(ssn, name)$ and $S(age, hometown)$?
yes, but --- why?

Difference (−) (1 / 2)

- Do you remember this one from basic sets?

$$\{a, b, c, d, e, f\} - \{b, d, f, h\} = \{a, c, e\}$$

- Yet another binary operator (form: R − S)
- Result is a relation of tuples from R that are not also in S
- Note that R and S must be union compatible

Difference ($-$) (2 / 2)

Example(s):

X	s	t
a	12	
m	4	
e	6	

Y	u	v
e	6	
a	16	
f	4	

$X - Y$

	s	t
m	4	
a	12	

$Y - X$

	u	v
a	16	
f	4	

not commutative!

The Derived Operators

- Intersection (\cap)
- Join (\bowtie)
- Division (\div)

Intersection (\cap) (1 / 2)

- YABO — Yet Another Binary Operator! (form: $R \cap S$)
- Resulting relation has the tuples that appear in both operand relations
- As with difference, R and S must be union compatible

Definition of \cap : $R \cap S \equiv R - (R - S)$

Intersection (\cap) (2 / 2)

Example(s):

X	s	t
a	12	
m	4	
e	6	

Y	u	v
e	6	
a	16	
f	4	

X \cap Y	s	t
e	6	

$$X - Y = \begin{array}{cc} s & t \\ \boxed{a\ 12} \\ m\ 4 \end{array}$$

$$X - (X - Y) = \boxed{s\ t \\ e\ 6}$$

Join (\bowtie) (1 / 3)

- YABO! (form: $R \bowtie_{\text{condition}} S$)
- Join is used to exploit PK–FK connections
(using it with other attributes is unwise!)

Definition : $R \bowtie_{\theta} S \equiv \sigma_{\theta}(R \times S)$

Join (\bowtie) (2 / 3)

Example(s):

pname
P

What are the names of the parts that can be supplied
by individual suppliers in quantity > 200? qty SP

Without \bowtie : $\pi_{pname}(\sigma_{qty>200}(\sigma_{SP.P\#=P.P\#}(SP \times P)))$

With \bowtie : $\pi_{pname}(\sigma_{qty>200}(SP \bowtie_{SP.P\#=P.P\#} P))$

$\bowtie_{P\#=P\#}$

$\bowtie_{P\#}$

Join (\bowtie) (3 / 3)

Three join variations:

1. Theta Join: $r \bowtie_{\theta} s$

where θ is any PK-FK comparison (so, \leq , $>$, etc.)

2. Equijoin: $r \bowtie_{\theta} s$

where θ is an equality PK-FK comparison

3. Natural Join: $r \bowtie s \equiv \pi_{R \cup S}(r \bowtie_{r.a_1=s.a_1 \wedge r.a_2=s.a_2 \wedge \dots} s)$

where R and S are the attribute sets of r and s, respectively

Division (\div) (1 / 9)

Let α and β be relations, where $A - B$ is the set difference of the attributes of α & β

Definition of Relational Division:

$$\alpha \div \beta = \pi_{A-B}(\alpha) - \pi_{A-B}\left(\left(\pi_{A-B}(\alpha) \times \beta\right) - \alpha\right)$$

Notes:

- Famously hard to understand
- But you can't avoid it.

Division (\div) (2 / 9)

Let's review multiplication and division of integers:

Ex: $4 * 6 = 24$, so $24/6 = 4$ and $24/4 = 6$.

Now, consider Cartesian Product and Division with relations:

M	c
	4
	8

N	d
	3
	1
	7

$$M \times N = O$$

c	d
4	3
4	1
4	7
8	3
8	1
8	7

$$O \div N = \boxed{\frac{c}{4 \\ 8}}$$

$$O \div M = N$$

Division (\div) (3 / 9)

What purpose does Division serve?

Division answers the "find X that are matched with all Y " queries.

Example(s):

Recall:

S	<u>S#</u>	Sname	Status	City
---	-----------	-------	--------	------

P	<u>P#</u>	Pname	Color	Weight	City
---	-----------	-------	-------	--------	------

X

SP	<u>S#</u>	<u>P#</u>	Qty
----	-----------	-----------	-----

Find the S#s of the suppliers that supply all parts of weight = 17.

Y

Division (\div) (4 / 9)

$$\alpha \div \beta = \pi_{A \cdot B}(\alpha) - \pi_{A \cdot B}((\pi_{A \cdot B}(\alpha) \times \beta) - \alpha)$$

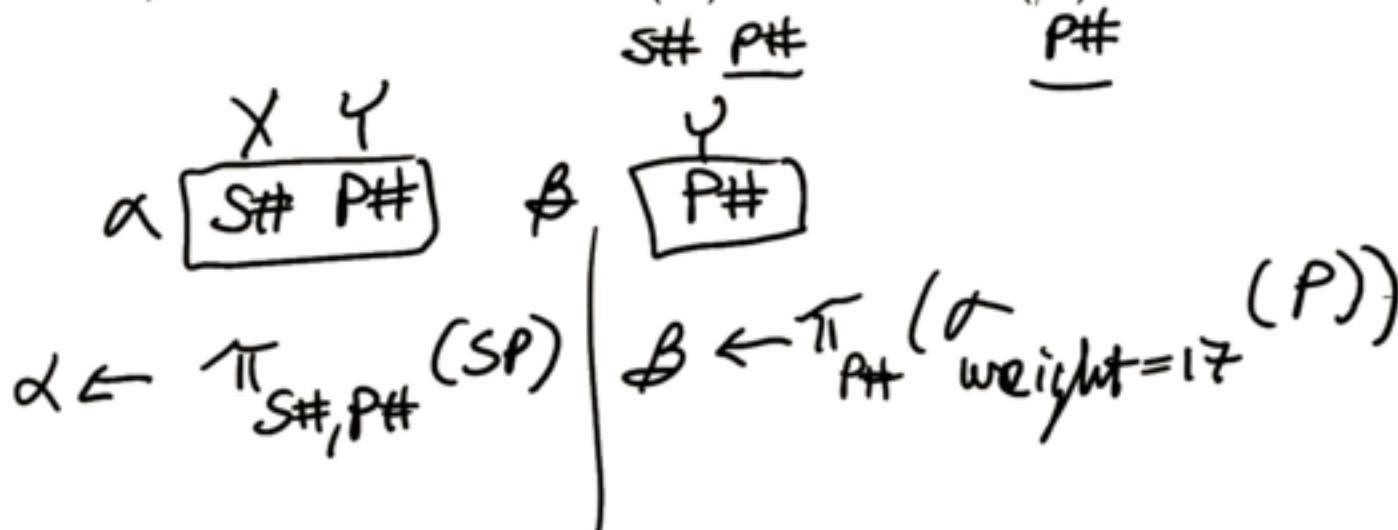
Example(s): (continued)

(Find the S#s of the suppliers
that supply all parts of weight = 17)

“Find the X ...” \leftarrow X is S# (the matches we want)

“... matched w/ all Y” \leftarrow Y is the set of weight 17 P#s

Next, create the dividend (α) and divisor (β) relations:



Division (\div) (5 / 9)

Example(s): (continued)

The content of α and β :

α	S#	P#	
	S1	P1	
	S2	P3	
	S2	P5	
	S3	P3	
	S3	P4	
	S4	P6	
	S5	P1	
<td>S5</td> <td>P2</td> <td>P3</td>	S5	P2	P3
	S5	P3	
	S5	P4	
	S5	P5	
	S5	P6	

β	P#
	P2
	P3

Do any suppliers supply ALL
of β 's parts?

S5

Division (\div) (6 / 9)

Let's examine the definition in detail:

$$\alpha \div \beta = \pi_{S^{\#}}(\alpha) - \pi_{S^{\#}}((\pi_{S^{\#}}(\alpha) \times \beta) - \alpha)$$

Suppliers that do not
 supply all parts that we want
 ↗
 all possible
 answer pairs

↗
 contains
 actual
 answer pairs

Suppliers that do supply
 all parts we want

Division (\div) (7 / 9)

Looking at the data should help, too:

$$\pi_{S\#}(\alpha) \times \beta$$

S#	P#
S1	P2
S1	P3
S2	P2
S2	P3
S3	P2
S3	P3
S4	P2
S4	P3
S5	P2
S5	P3

$$\alpha$$

S#	P#
S1	P1
S2	P3
S2	P5
S3	P3
S3	P4
S4	P6
S5	P1
S5	P2
S5	P3
S5	P4
S5	P5
S5	P6

$$(\pi_{S\#}(\alpha) \times \beta) - \alpha$$

S#	P#
S1	P2
S1	P3
S2	P2
S3	P2
S4	P2
S4	P3

Division (\div) (8 / 9)

And so, finally, we have our answer:

$\pi_{S\#}(\alpha)$	S#
	S1
	S2
	S3
	S4
	S5

$$\pi_{S\#}((\pi_{S\#}(\alpha) \times \beta) - \alpha)$$

S#
S1
S2
S3
S4

$$\alpha \div \beta = \pi_{S\#}(\alpha) - \pi_{S\#}((\pi_{S\#}(\alpha) \times \beta) - \alpha) =$$

S#
S5

Supplier S5 supplies all parts of weight 17 (P2 and P3).

Division (\div) (9 / 9)

Is there a short-cut to avoid that mess? **NO!**

Consider this very similar query:

Find the S#s of the suppliers that supply
all parts of weight = **19**.

The only weight = 19 part is P6, which this simple
expression produces: $\pi_{S\#}(\alpha \bowtie_{P\#} \beta)$ (\rightarrow S4 and S5)

But, when weight = 17, that query gives S2, S3, and S5!