CS 525: Advanced Database Organization

01: Introduction

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab

Advanced Database Organization?

- =Database Implementation
- =How to implement a database system
- … and have fun doing it ;-)

Isn't Implementing a Database System Simple?

Relations → Statements → Results

Introducing the

MEGATRON 3000

Database Management System

- The latest from Megatron Labs
- Incorporates latest relational technology
- UNIX compatible

Megatron 3000

Implementation Details

! First sign non-disclosure agreement !

Megatron 3000
Implementation Details

- Relations stored in files (ASCII)
  e.g., relation R is in /usr/db/R

```
Smith # 123 # CS
Jones # 522 # EE
    .
    .
    .
```

Megatron 3000
Implementation Details

- Directory file (ASCII) in /usr/db/directory

```
R1  #  A  #  INT  #  B  #  STR  …
R2  #  C  #  STR  #  A  #  INT  …
   ⋮
```

Megatron 3000
Sample Sessions

```
% MEGATRON3000
    Welcome to MEGATRON 3000!
&
   .
   .
   .

& quit
%
```

Megatron 3000

Sample Sessions

```
& select *
  from R #

    Relation R
   A       B    C
   SMITH  123   CS


&
```

Megatron 3000
Sample Sessions

```
& select A,B
  from R,S
  where R.A = S.A and S.C > 100 #

   A     B
  123   CAR
  522   CAT


&
```

Megatron 3000

Sample Sessions

```
& select *
  from R | LPR #
&
```

Result sent to LPR (printer).

Megatron 3000

Sample Sessions

```
& select *
  from R
  where R.A < 100 | T #
&
```

New relation T created.

Megatron 3000

- To execute "**`select * from R where`** ***`condition`***":
  - (1) Read dictionary to get R attributes
  - (2) Read R file, for each line:
    - (a) Check condition
    - (b) If OK, display

Megatron 3000

- To execute "**`select * from R`**
  `where` ***`condition`*** **`| T`**":

  (1) Process select as before

  (2) Write results to new file T

  (3) Append new line to dictionary

Megatron 3000

- To execute "`select A,B from R,S where` ***`condition`***":

```
(1) Read dictionary to get R,S attributes
(2) Read R file, for each line:
    (a) Read S file, for each line:
        (i) Create join tuple
        (ii) Check condition
        (iii) Display if OK
```

What’s wrong with the Megatron 3000 DBMS?

What’s wrong with the Megatron 3000 DBMS?

- Tuple layout on disk

e.g., - Change string from ‘Cat’ to ‘Cats’ and we have to rewrite file

- ASCII storage is expensive
- Deletions are expensive

What's wrong with the Megatron 3000 DBMS?

- Search expensive; no indexes

e.g., - Cannot find tuple with given key quickly

- Always have to read full relation

What's wrong with the Megatron 3000 DBMS?

- Brute force query processing

e.g.,
```
select *
from R,S
where R.A = S.A and S.B > 1000
```

- Do select first?
- More efficient join?

What’s wrong with the Megatron 3000 DBMS?

- No buffer manager

e.g.,   Need caching

What’s wrong with the Megatron 3000 DBMS?

- No concurrency control

What's wrong with the Megatron 3000 DBMS?

- No reliability

e.g., - Can lose data

- Can leave operations half done

What's wrong with the Megatron 3000 DBMS?

- No security

e.g., - File system insecure
- File system security is coarse

What' s wrong with the Megatron 3000 DBMS?

- No application program interface (API)

e.g., How can a payroll program get at the data?

What' s wrong with the Megatron 3000 DBMS?

- Cannot interact with other DBMSs.

What's wrong with the Megatron 3000 DBMS?

- Poor dictionary facilities

What’s wrong with the Megatron 3000 DBMS?

- No GUI

What’s wrong with the Megatron 3000 DBMS?

- Lousy salesman!!

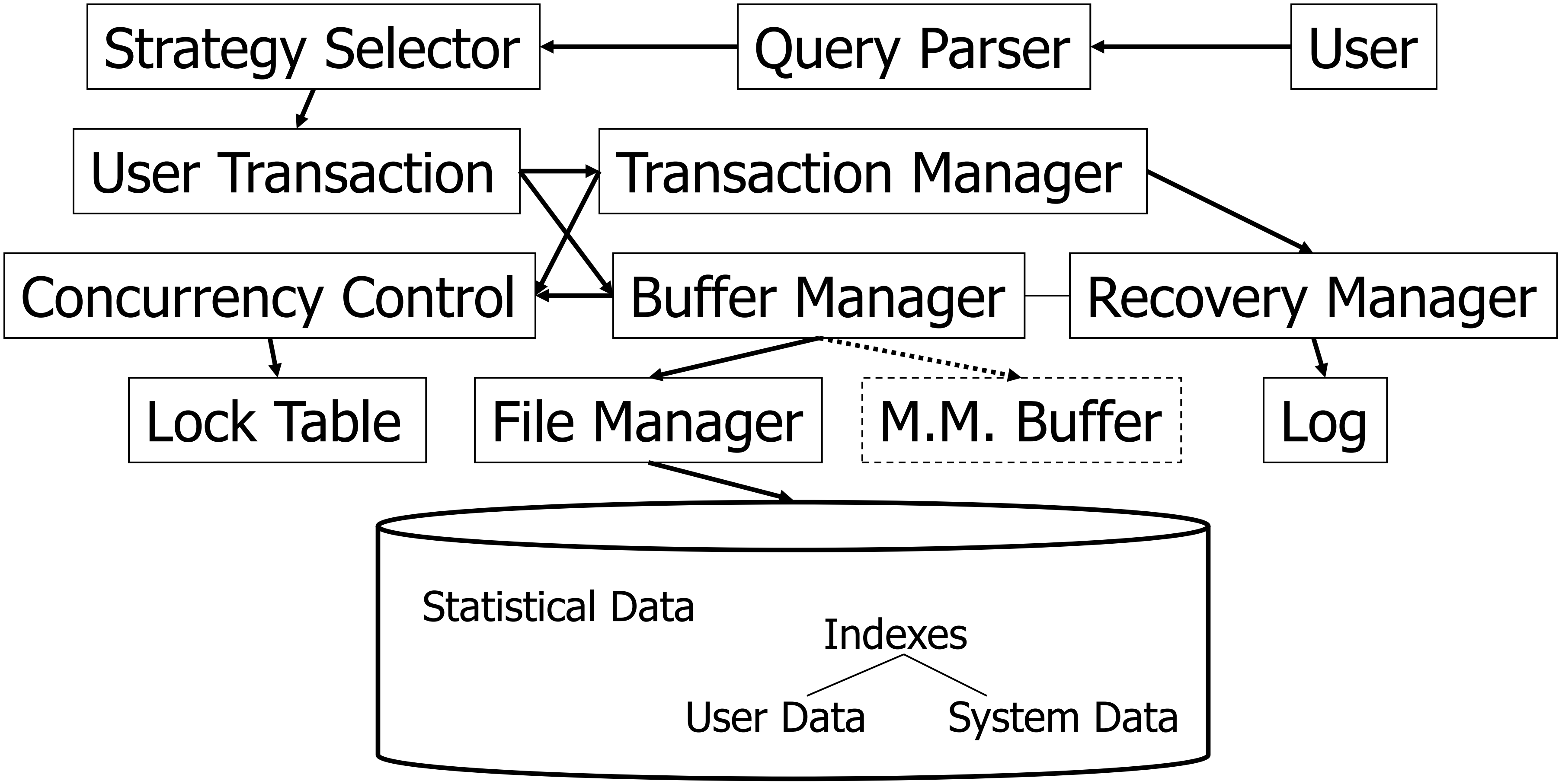
Course Overview

- File & System Structure
  - Records in blocks, dictionary, buffer management,…
- Indexing & Hashing
  - B-Trees, hashing,…
- Query Processing
  - Query costs, join strategies,…
- Crash Recovery
  - Failures, stable storage,…

Course Overview

- Concurrency Control
  Correctness, locks,…
- Transaction Processing
  Logs, deadlocks,…
- Security & Integrity
  Authorization, encryption,…
- Advanced Topics
  Distribution, More Fancy Optimizations, …

System Structure



Some Terms

- Database system
- Transaction processing system
- File access system
- Information retrieval system

Course Information

- **Webpage**: http://www.cs.iit.edu/~cs525/
- **Instructor**: Boris Glavic
  - http://www.cs.iit.edu/~glavic/
  - **DBGroup:** http://www.cs.iit.edu/~dbgroup/
  - **Office Hours: Mondays, 12pm-1pm**
  - **Office:** Stuart Building, Room 226 C
- **TA: TBA**
- **Time:** Mon + Wed 1:50pm – 3:05pm

Google Group

- https://groups.google.com/forum/#!forum/cs525-2017-spring-group
- Mailing-list for announcements
- Discussion forum
  - Student - Instructor/TA
  - Student – Student
- ->please join the group to keep up to date

Workload and Grading

- Schedule and Important Dates
  - On webpage & updated there
- Programming Assignments (50%)
  - 4 Assignments
  - Groups of 3 students
  - Plagiarism -> 0 points and administrative action
- Quizzes (10%)
- Mid Term (20%) and Final Exam (20%)

Textbooks

- Elmasri and Navathe , **Fundamentals of Database Systems**, 6th Edition , Addison-Wesley , 2003
- Garcia-Molina, Ullman, and Widom, **Database Systems: The Complete Book**, 2nd Edition, Prentice Hall, 2008
- Ramakrishnan and Gehrke , **Database Management Systems**, 3nd Edition , McGraw-Hill , 2002
- Silberschatz, Korth, and Sudarshan , **Database System Concepts**, 6th Edition , McGraw Hill , 2010

Programming Assignments

- 4 assignments one on-top of the other
- Optional 5th assignment for extra credit
- Code has to compile & run on server account
  - **Email-ID**@fourier.cs.iit.edu
  - Linux machine
  - SSH with X-forwarding
- Source code managed in **git** repository on Bitbucket.org
  - Handing in assignments = submit (push) to repository
  - One repository per student
  - You should have gotten an invitation (if not, contact me/TA)
  - Git tutorials linked on course webpage!

Next:

- Hardware

CS 525: Advanced Database Organization

02: Hardware

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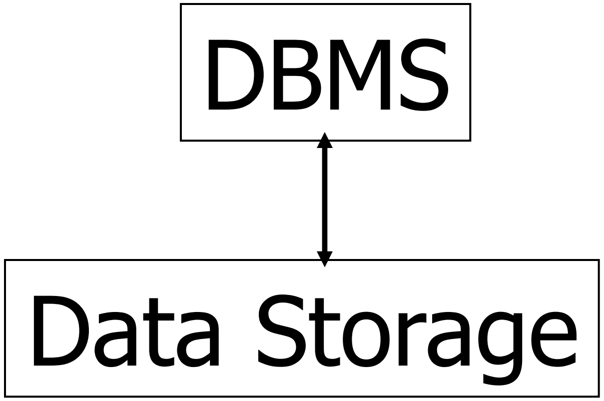
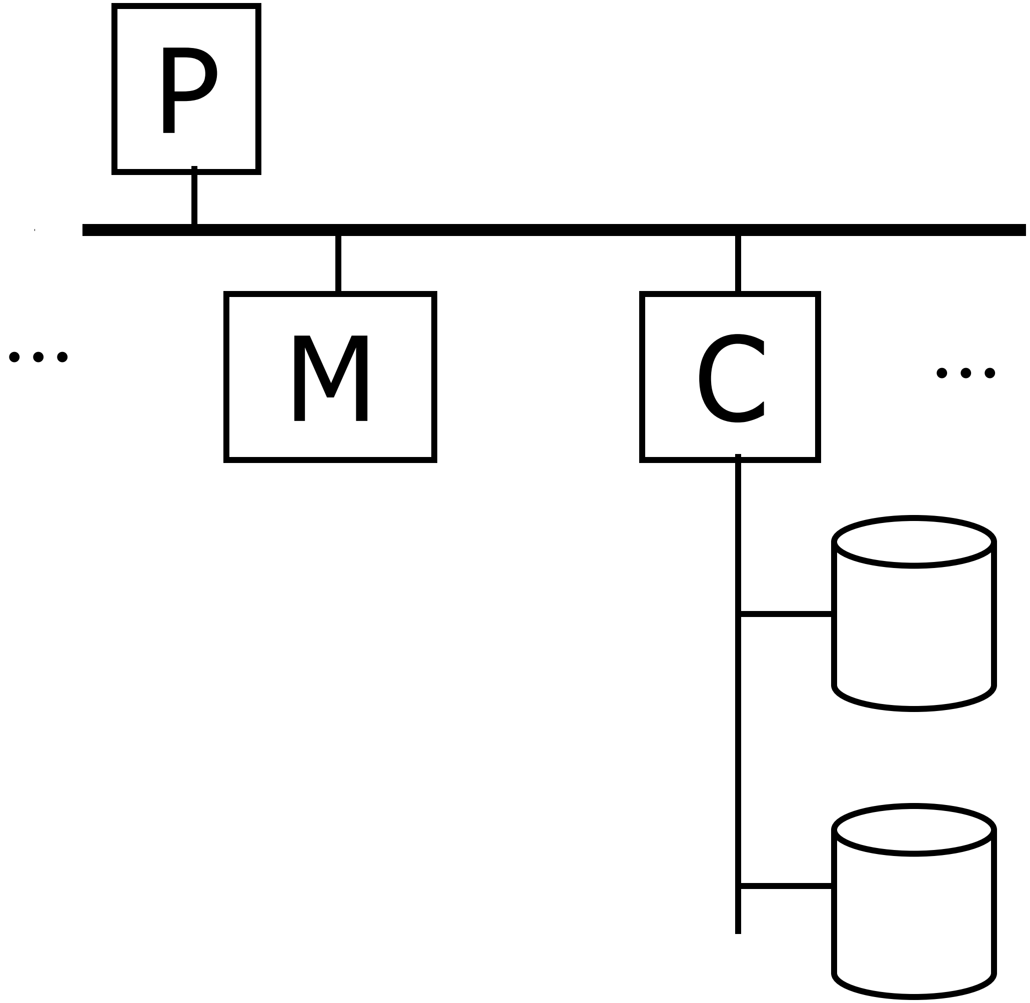
Outline

- Hardware: Disks
- Access Times
- Example - Megatron 747
- Optimizations
- Other Topics:
  - Storage costs
  - Using secondary storage
  - Disk failures

Hardware



Typical Computer



Secondary Storage

Processor

Fast, slow, reduced instruction set, with cache, pipelined…

Speed: 100 → 500 → 1000 MIPS

Memory

Fast, slow, non-volatile, read-only,…

Access time: 10^{-6} → 10^{-9} sec.

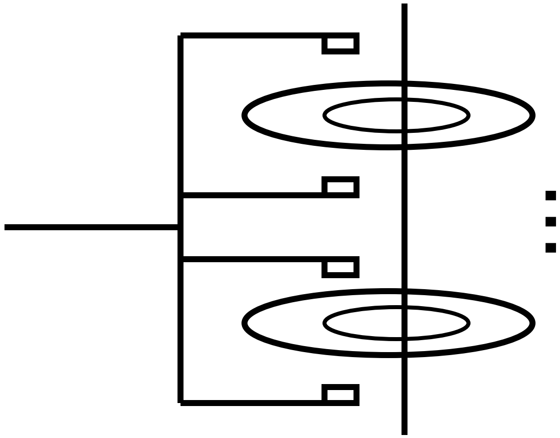
1 μs → 1 ns

Secondary storage

Many flavors:

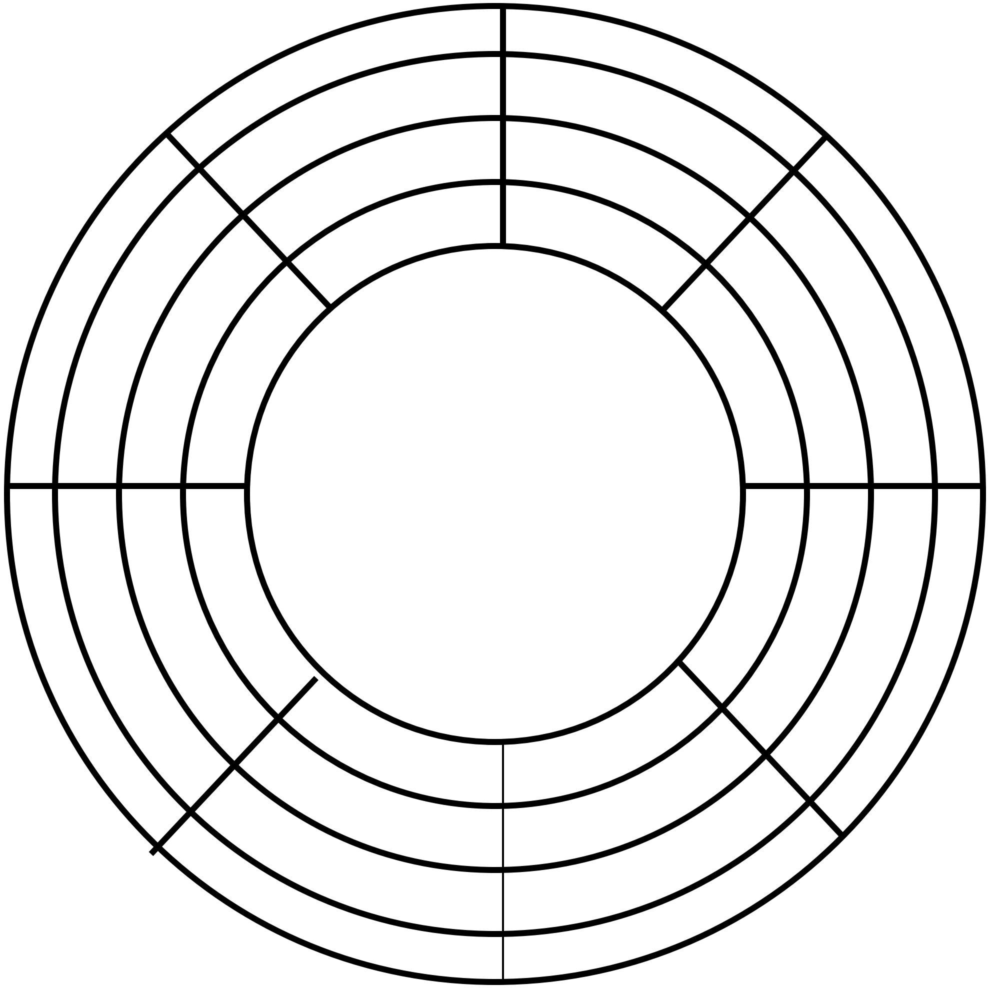
- Disk: Floppy (hard, soft)
  - Removable Packs
  - Winchester
  - Ram disks
  - Optical, CD-ROM…
  - Arrays
- Tape Reel, cartridge
  - Robots

Focus on: “Typical Disk”



Terms: Platter, Head, Actuator
Cylinder, Track
Sector (physical),
Block (logical), Gap

Top View

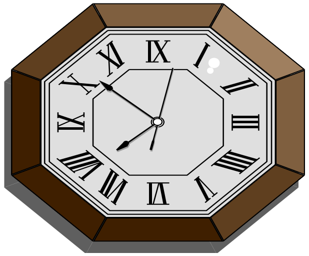


“Typical” Numbers

Diameter: 1 inch → 15 inches
Cylinders: 100 → 2000
Surfaces: 1 (CDs) →
(Tracks/cyl) 2 (floppies) → 30
Sector Size: 512B → 50K
Capacity: 360 KB (old floppy)
→ 1 TB (I use)

Disk Access Time

I want
block X

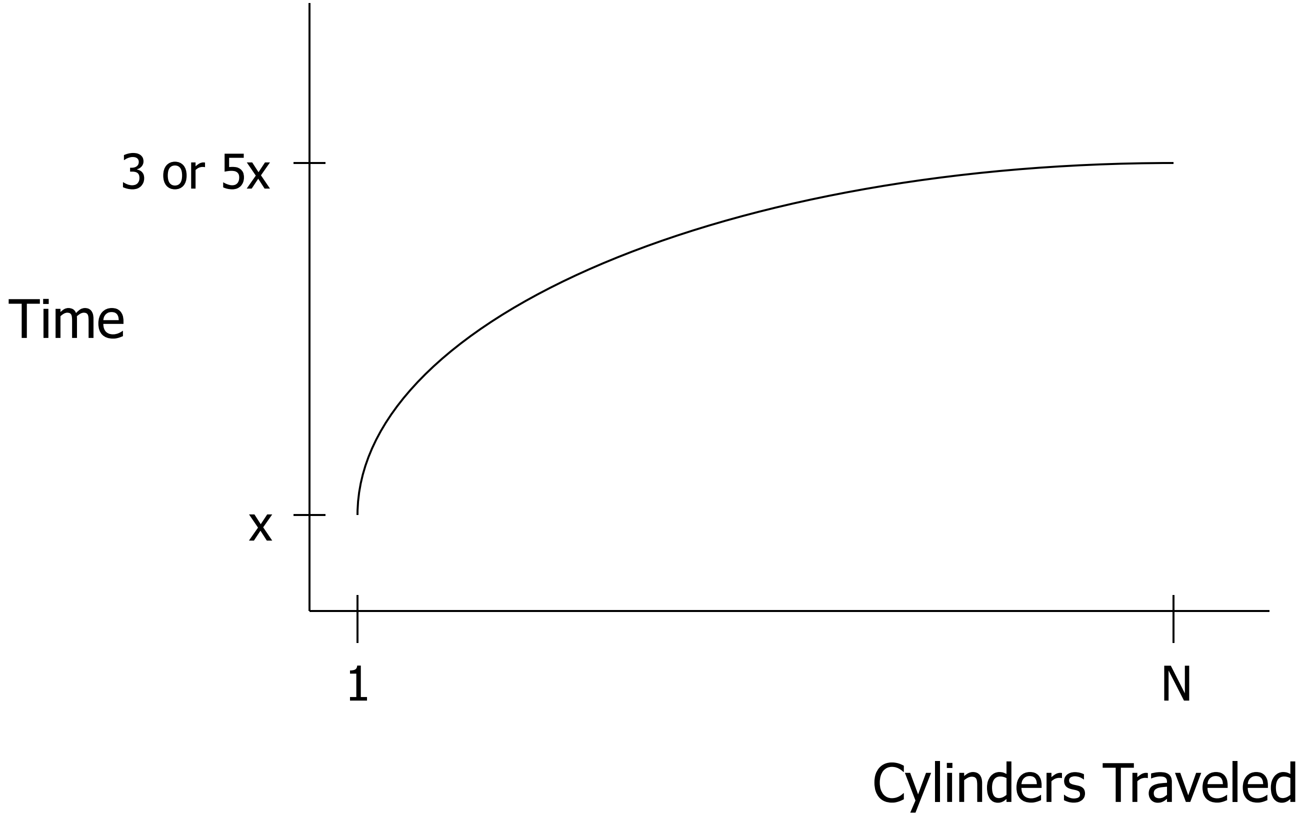


?

block x
in memory

Time = Seek Time +
Rotational Delay +
Transfer Time +
Other

Seek Time



Average Random Seek Time

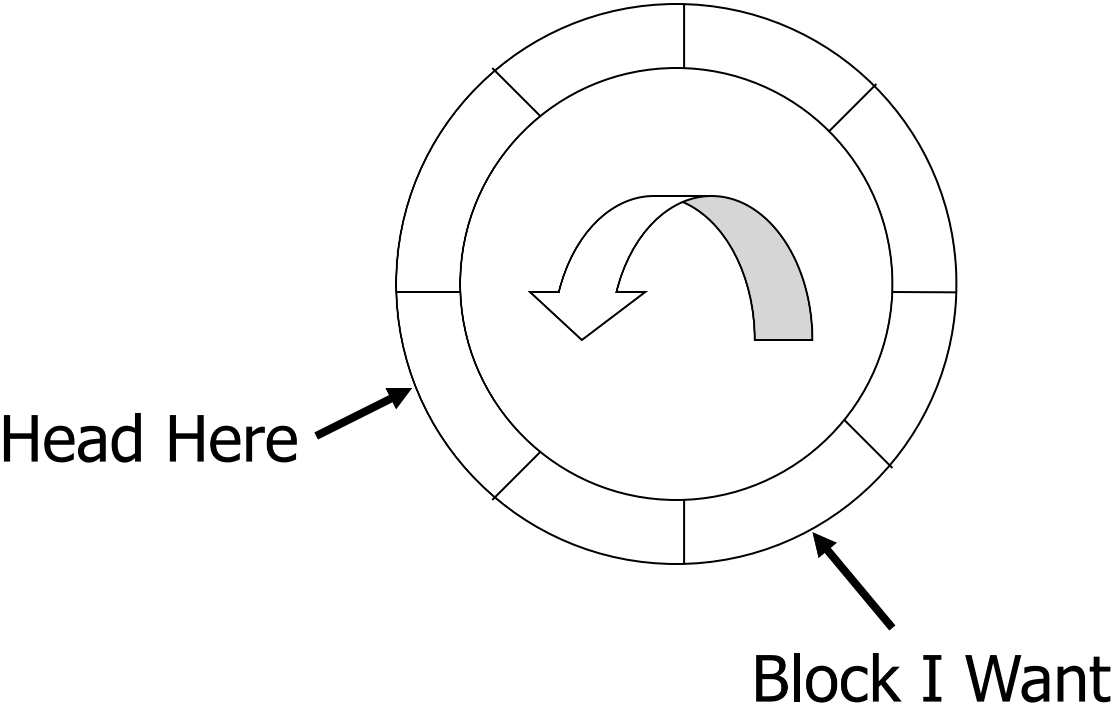
$$S = \frac{\displaystyle\sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} \text{SEEKTIME } (i \rightarrow j)}{N(N-1)}$$

Average Random Seek Time

$$S = \frac{\sum_{i=1}^{N} \sum_{\substack{j=1 \\ j \neq i}}^{N} \text{SEEKTIME } (i \rightarrow j)}{N(N-1)}$$

“Typical” S: 10 ms → 40 ms

Rotational Delay



Average Rotational Delay

R = 1/2 revolution

“typical” R = 8.33 ms (3600 RPM)

Transfer Rate: t

- "typical" t: 10's → 100's MB/second
- transfer time: $\frac{\text{block size}}{t}$

Other Delays

- CPU time to issue I/O
- Contention for controller
- Contention for bus, memory

Other Delays

- CPU time to issue I/O
- Contention for controller
- Contention for bus, memory

"Typical" Value: 0

Other Delays (now and near future)

- Increasing amount of parallelism
- Contention can become a problem
- -> need rethink approach to scale

- So far: Random Block Access
- What about: Reading “Next” block?

If we do things right (e.g., Double Buffer, Stagger Blocks…)

$$\text{Time to get block} = \frac{\text{Block Size}}{t} + \text{Negligible}$$

- skip gap
- switch track
- once in a while,
  next cylinder

Rule of Thumb	Random I/O: Expensive Sequential I/O: Much less

- Ex: 1 KB Block
  - » Random I/O: ~ 20 ms.
  - » Sequential I/O: ~ 1 ms.

Cost for Writing similar to Reading

…. unless we want to verify!

need to add (full) rotation + $\frac{\text{Block size}}{t}$

- To Modify a Block?

- To Modify a Block?

To Modify Block:

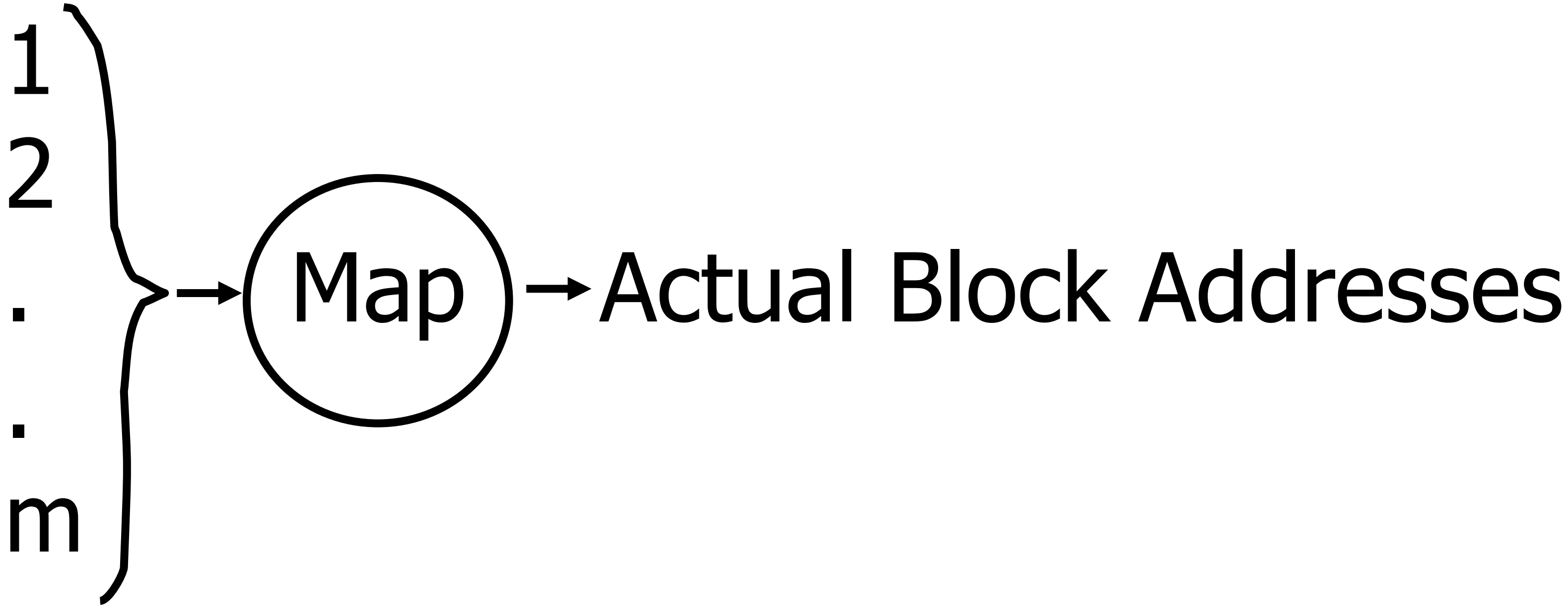
(a) Read Block
(b) Modify in Memory
(c) Write Block
[(d) Verify?]

Block Address:

- Physical Device
- Cylinder #
- Surface #
- Sector

Complication: Bad Blocks

- Messy to handle
- May map via software to integer sequence



An Example Megatron 747 Disk (old)

- 3.5 in diameter
- 3600 RPM
- 1 surface
- 16 MB usable capacity (16×2^{20})
- 128 cylinders
- seek time: average = 25 ms.

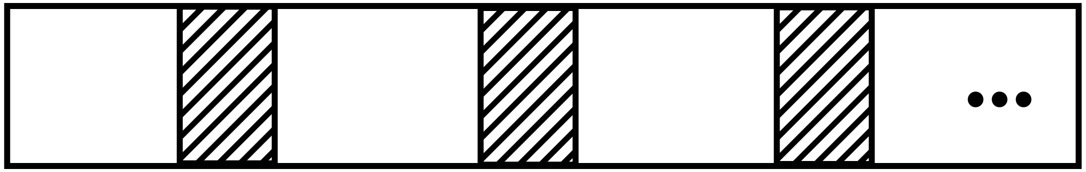
  adjacent cyl = 5 ms.

- 1 KB blocks = sectors
- 10% overhead between blocks
- capacity = 16 MB = $(2^{20})16 = 2^{24}$
- # cylinders = 128 = 2^7
- bytes/cyl = $2^{24}/2^7 = 2^{17}$ = 128 KB
- blocks/cyl = 128 KB / 1 KB = 128

3600 RPM → 60 revolutions / sec

→ 1 rev. = 16.66 msec.

One track:



3600 RPM → 60 revolutions / sec

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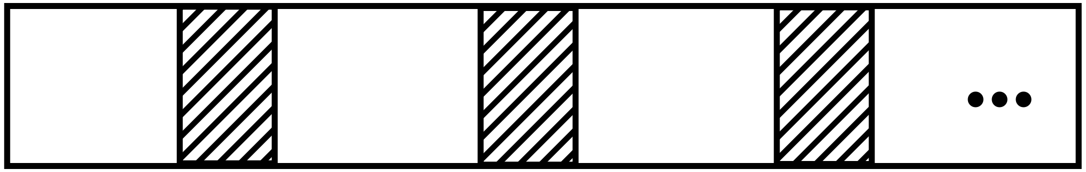
One track:



Time over useful data:(16.66)(0.9)=14.99 ms.

Time over gaps: (16.66)(0.1) = 1.66 ms.

Transfer time 1 block = 14.99/128=0.117 ms.

Trans. time 1 block+gap=16.66/128=0.13ms.

Burst Bandwith

1 KB in 0.117 ms.

BB = 1/0.117 = 8.54 KB/ms.

or

BB =8.54KB/ms x 1000 ms/1sec x 1MB/1024KB
= 8540/1024 = 8.33 MB/sec

Sustained bandwith (over track)

128 KB in 16.66 ms.

SB = 128/16.66 = 7.68 KB/ms

or

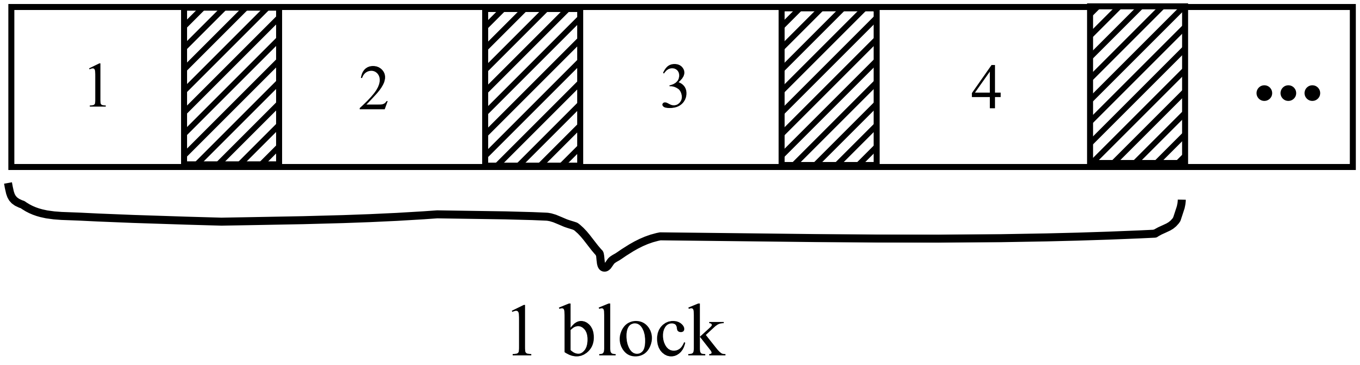
SB = 7.68 x 1000/1024 = 7.50 MB/sec.

T_1 = Time to read one random block

T_1 = seek + rotational delay + TT

$$= 25 + (16.66/2) + .117 = 33.45 \text{ ms.}$$

Suppose OS deals with 4 KB blocks



$$T_4 = 25 + (16.66/2) + (.117) \times 1$$
$$+ (.130) \times 3 = 33.83 \text{ ms}$$

[Compare to $T_1 = 33.45$ ms]

T_T = Time to read a full track
(start at any block)

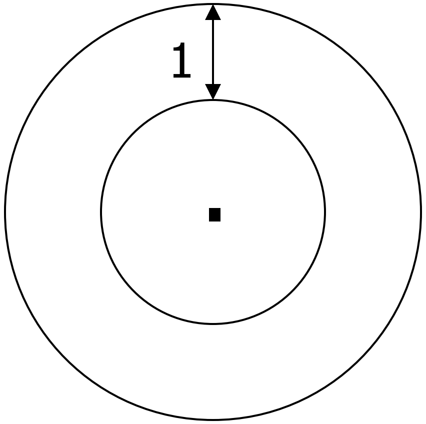
$$T_T = 25 + \underbrace{(0.130/2)}_{\text{to get to first block}} + 16.66^{*} = 41.73 \text{ ms}$$

* Actually, a bit less; do not have to read last gap.

The NEW Megatron 747

- 8 Surfaces, 3.5 Inch diameter
  - outer 1 inch used
- 2^{13} = 8192 Tracks/surface
- 256 Sectors/track
- 2^{9} = 512 Bytes/sector

- 8 GB Disk
- If all tracks have 256 sectors
  - Outermost density: 100,000 bits/inch
  - Inner density: 250,000 bits/inch



- Outer third of tracks: 320 sectors
- Middle third of tracks: 256
- Inner third of tracks: 192

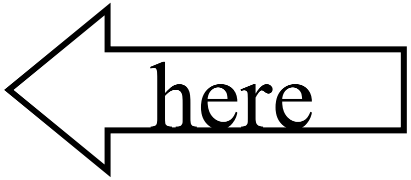
- Density: 114,000 → 182,000 bits/inch

Timing for new Megatron 747 (Ex 2.3)

- Time to read 4096-byte block:
  - MIN: 0.5 ms
  - MAX: 33.5 ms
  - AVE: 14.8 ms

Outline

- Hardware: Disks
- Access Times
- Example: Megatron 747



here

- Optimizations
- Other Topics
  - Storage Costs
  - Using Secondary Storage
  - Disk Failures

Optimizations (in controller or O.S.)

- Disk Scheduling Algorithms
  - e.g., elevator algorithm
- Track (or larger) Buffer
- Pre-fetch
- Arrays
- Mirrored Disks
- On Disk Cache

Double Buffering

Problem: Have a File

- Sequence of Blocks B1, B2

Have a Program

- Process B1
- Process B2
- Process B3

⋮

Single Buffer Solution

(1) Read B1 → Buffer

(2) Process Data in Buffer

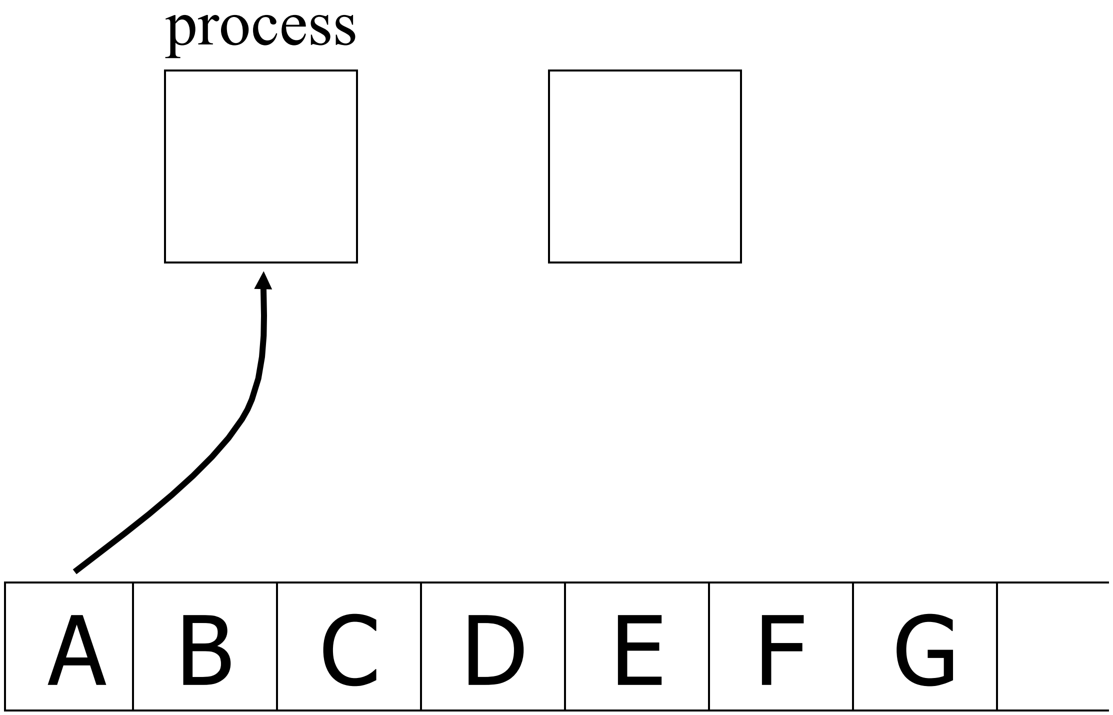
(3) Read B2 → Buffer

(4) Process Data in Buffer ...

Say P = time to process/block
R = time to read in 1 block
n = # blocks

Single buffer time = n(P+R)

Double Buffering



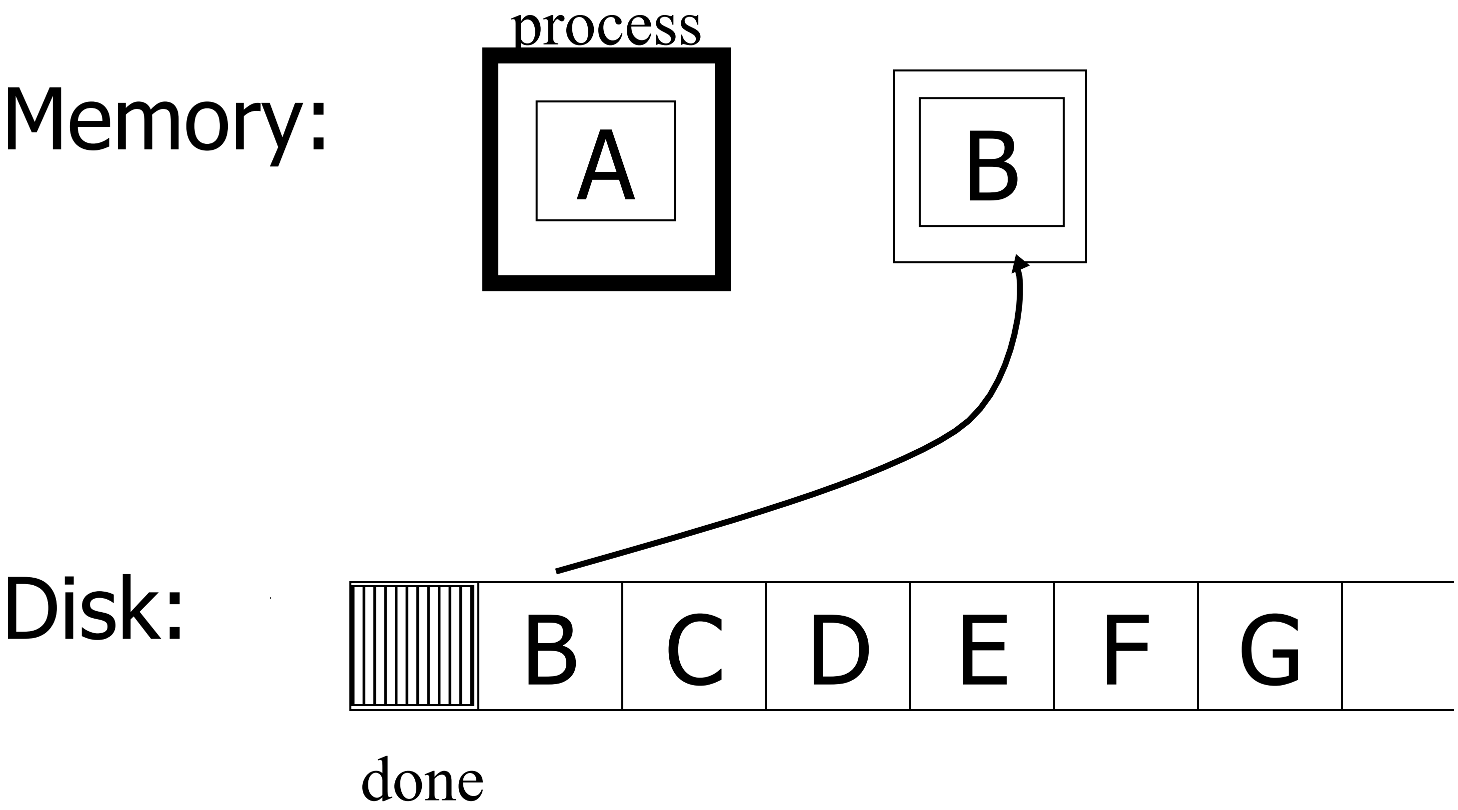
process

Memory:

Disk:

A B C D E F G

Double Buffering



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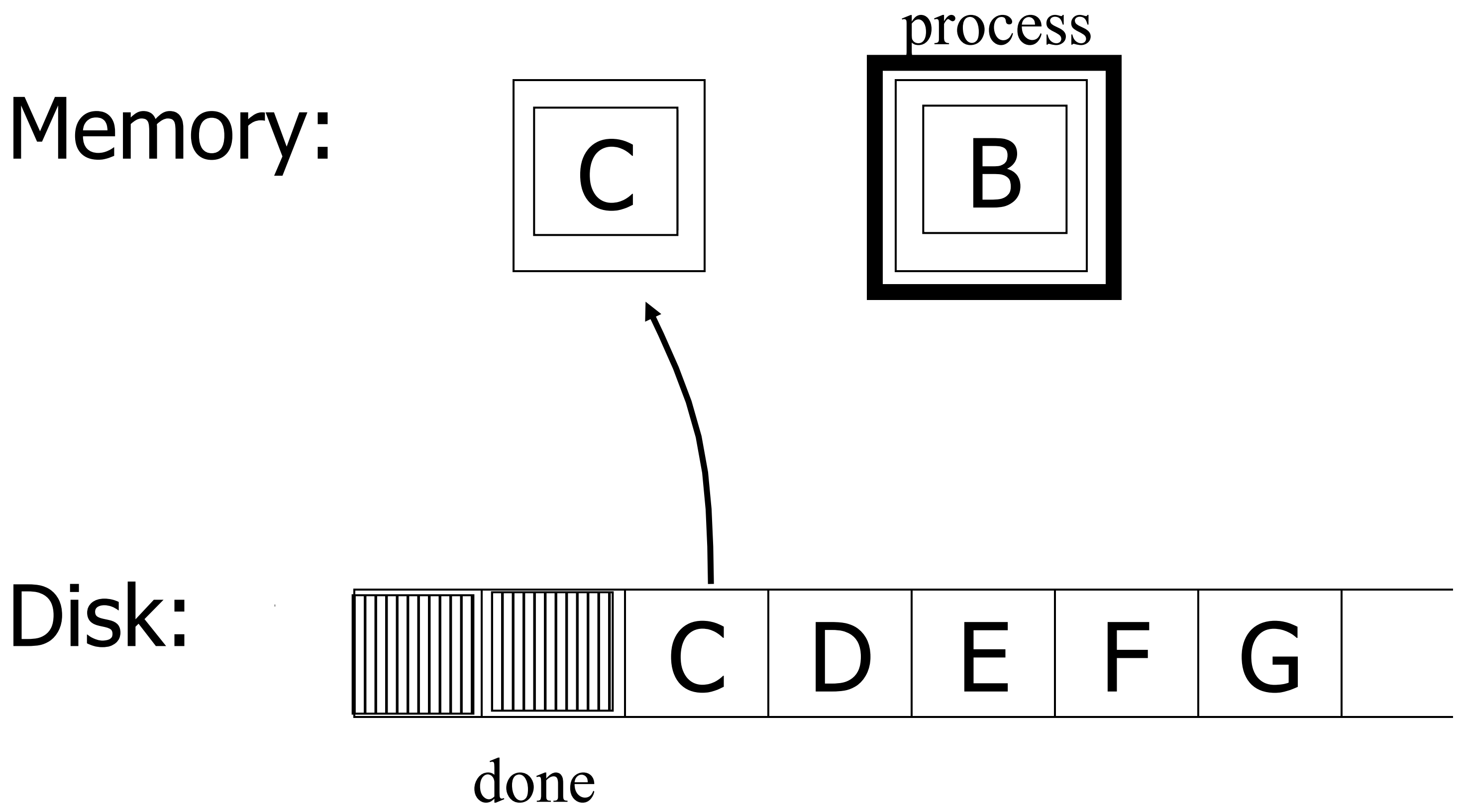

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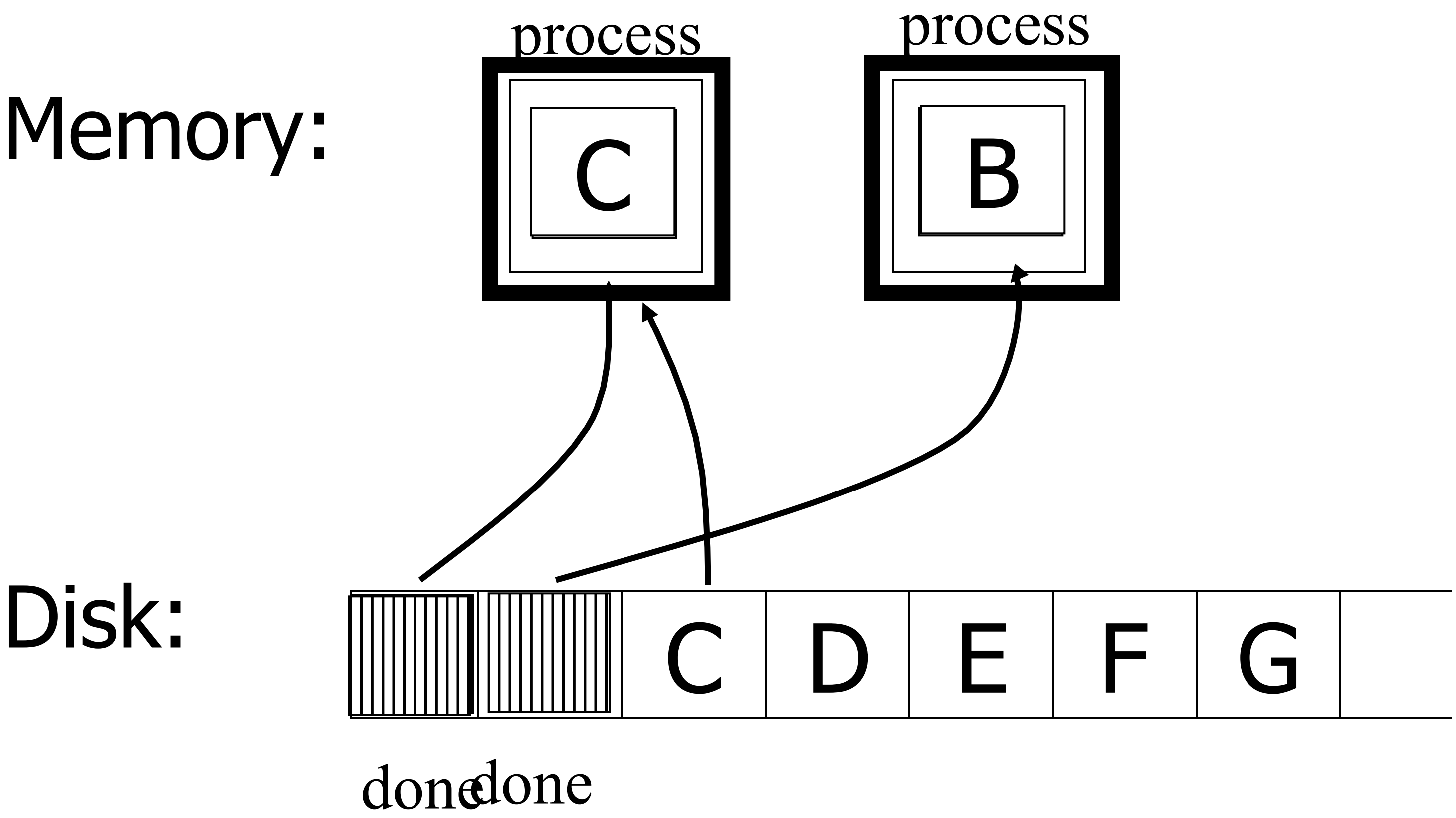


Say P ≥ R

P = Processing time/block
R = IO time/block
n = # blocks

What is processing time?

Say P ≥ R

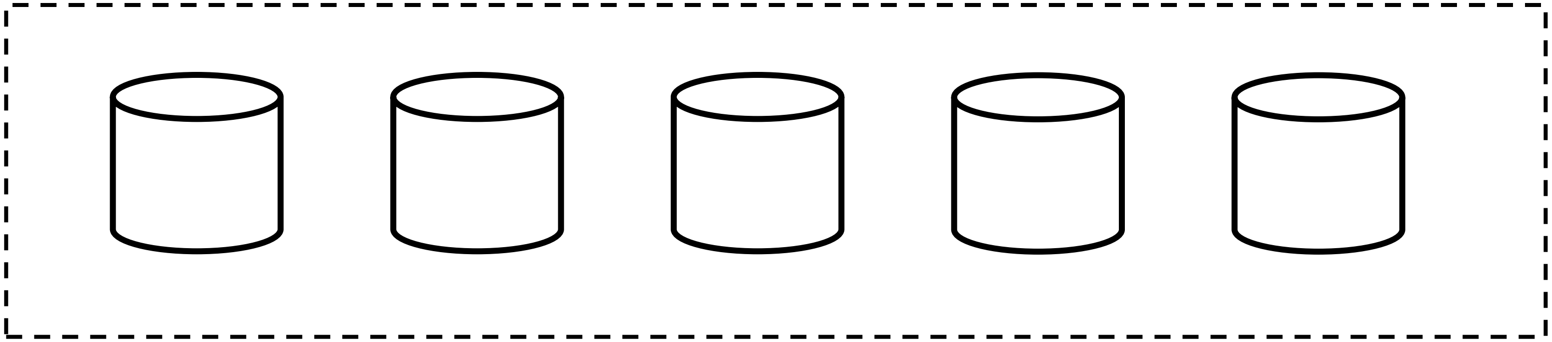
P = Processing time/block
R = IO time/block
n = # blocks

What is processing time?

- Double buffering time = R + nP
- Single buffering time = n(R+P)

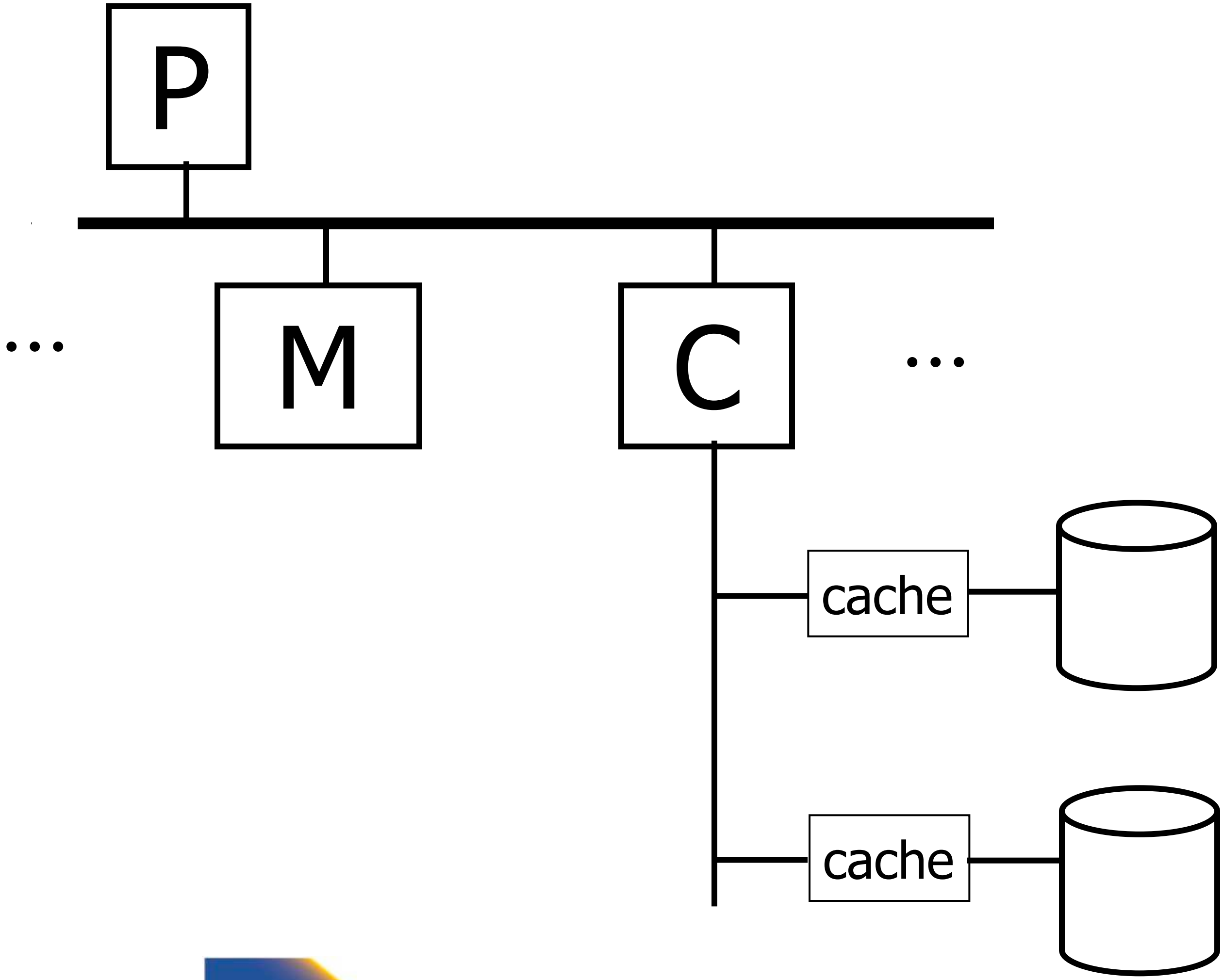
Disk Arrays

- RAIDs (various flavors)
- Block Striping
- Mirrored



logically one disk

On Disk Cache



Block Size Selection?

- Big Block → Amortize I/O Cost, Less Management Overhead

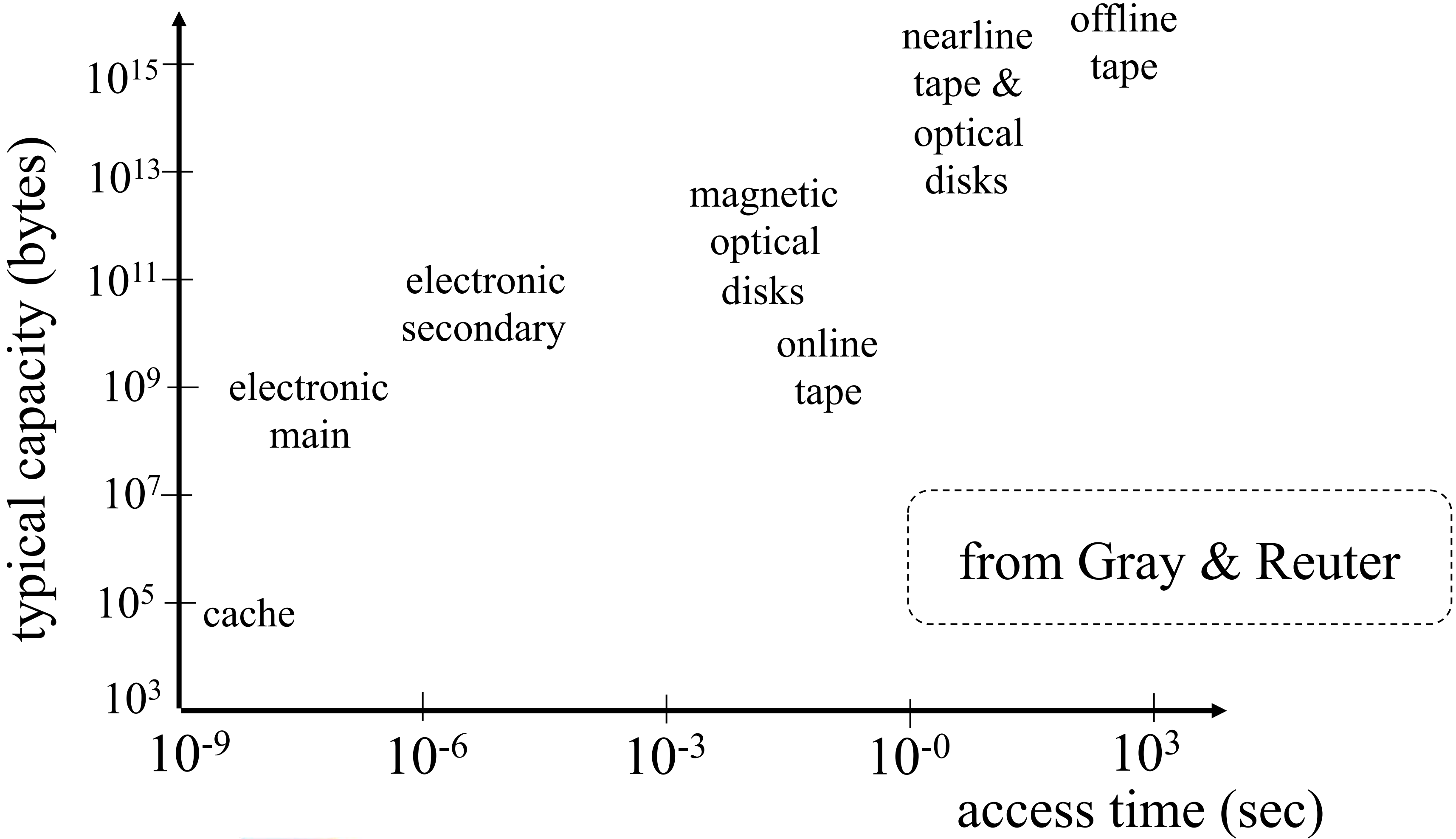
Unfortunately...

- Big Block ⇒ Read in more useless stuff!
  and takes longer to read

Trend

- As memory prices drop, blocks get bigger ...

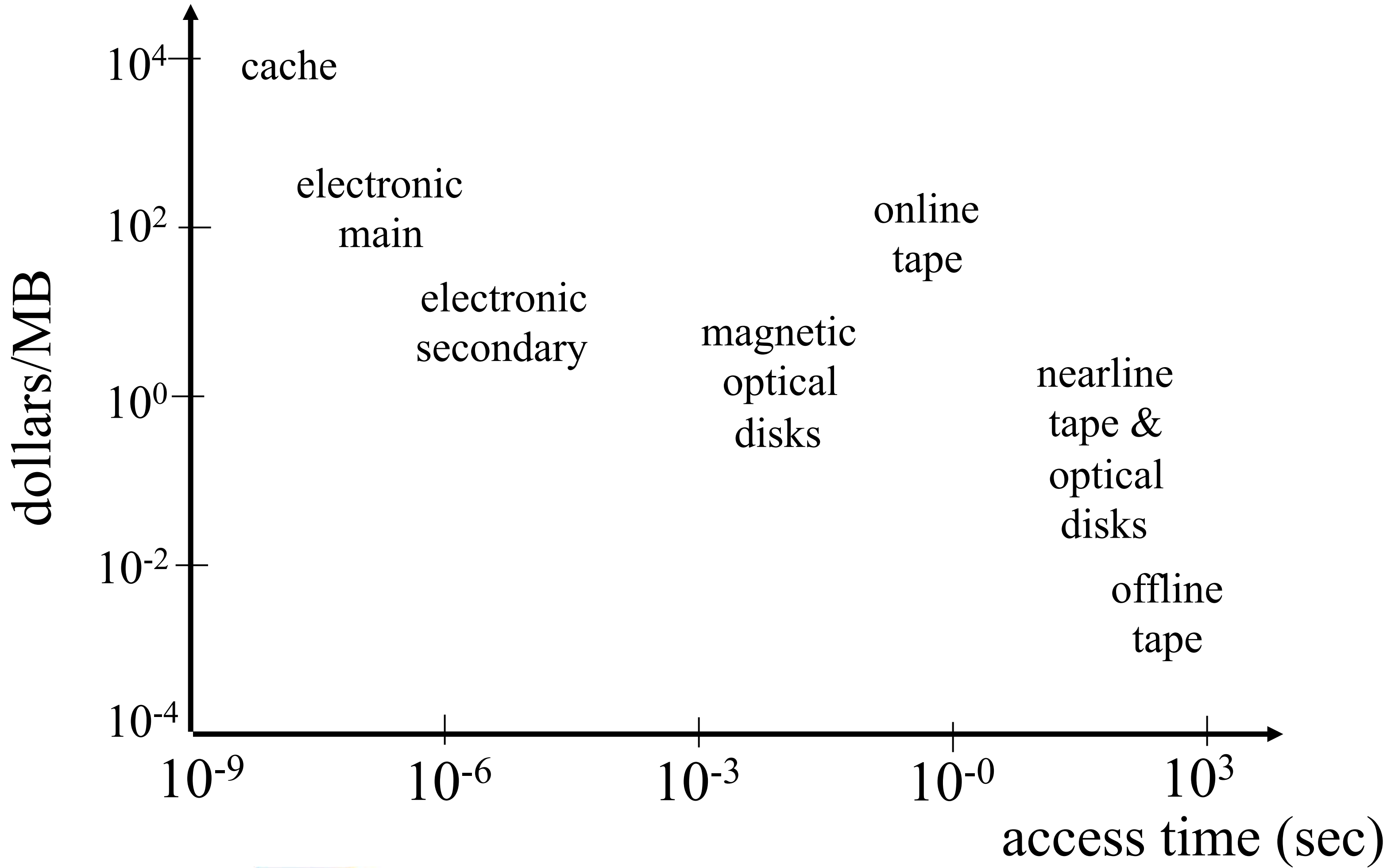
Storage Cost



from Gray & Reuter

Storage Cost

from Gray & Reuter



Using secondary storage effectively

- Example: Sorting data on disk
- Conclusion:
  - I/O costs dominate
  - Design algorithms to reduce I/O

- Also: How big should blocks be?

Five Minute Rule

- THE 5 MINUTE RULE FOR TRADING MEMORY FOR DISC ACCESSES
  Jim Gray & Franco Putzolu
  May 1985

- The Five Minute Rule, Ten Years Later
  Goetz Graefe & Jim Gray
  December 1997

Five Minute Rule

- Say a page is accessed every X seconds
- CD = cost if we keep that page on disk
  - $D = cost of disk unit
  - I = numbers IOs that unit can perform per second
  - In X seconds, unit can do XI IOs
  - So CD = $D / XI

Five Minute Rule

- Say a page is accessed every X seconds
- CM = cost if we keep that page on RAM
  - $M = cost of 1 MB of RAM
  - P = numbers of pages in 1 MB RAM
  - So CM = $M / P

Five Minute Rule

- Say a page is accessed every X seconds
- If CD is smaller than CM,
  - keep page on disk
  - else keep in memory
- Break even point when CD = CM, or

$$X = \frac{\$D \;\; P}{I \;\; \$M}$$

Using ‘97 Numbers

- P = 128 pages/MB (8KB pages)
- I = 64 accesses/sec/disk
- $D = 2000 dollars/disk (9GB + controller)
- $M = 15 dollars/MB of DRAM

- X = 266 seconds (about 5 minutes)
(did not change much from 85 to 97)

Disk Failures

- Partial → Total
- Intermittent → Permanent

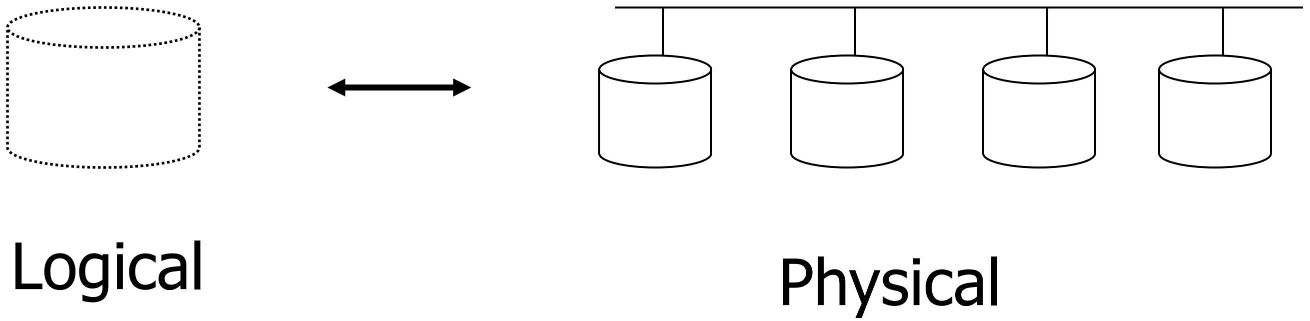
Coping with Disk Failures

- Detection
  - e.g. Checksum
- Correction

  ⇒ Redundancy

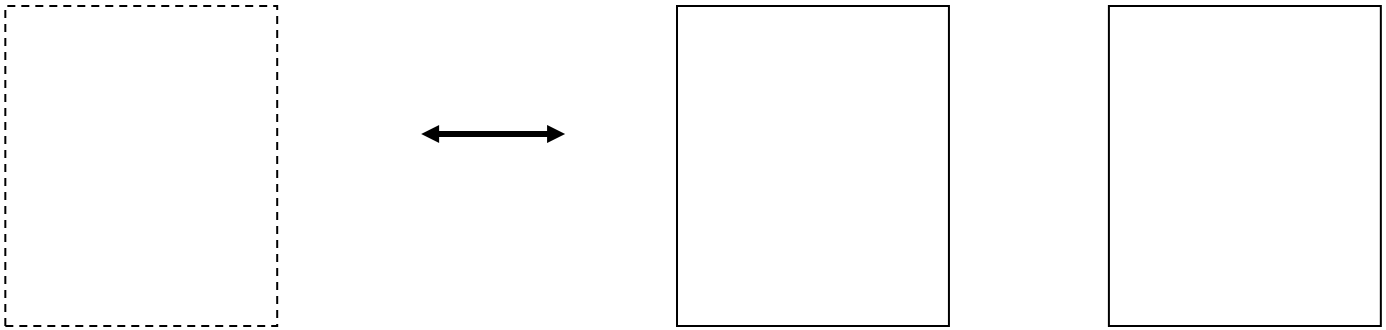
At what level do we cope?

- Single Disk
  - e.g., Error Correcting Codes
- Disk Array



→ Operating System

e.g., Stable Storage



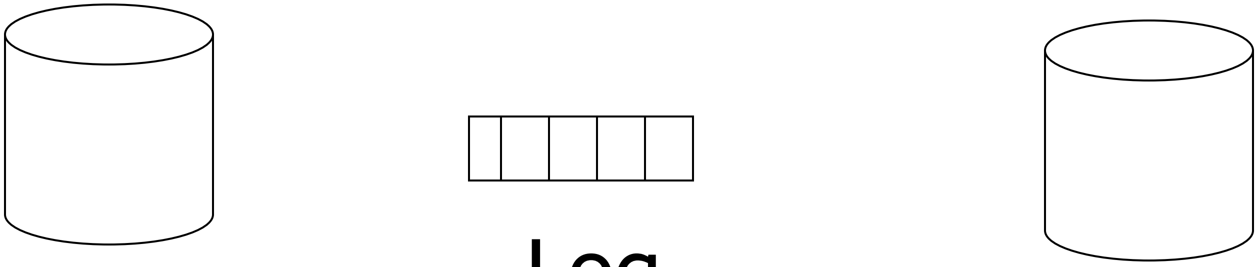
Logical Block

Copy A

Copy B

→ Database System

- e.g.,



Log

Current DB

Last week’ s DB

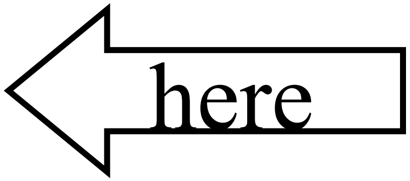
Summary

- Secondary storage, mainly disks
- I/O times + formulas
  - Sequential vs. random
- I/Os should be avoided,

  especially random ones…..
- OS optimizations
- Disk errors

Outline

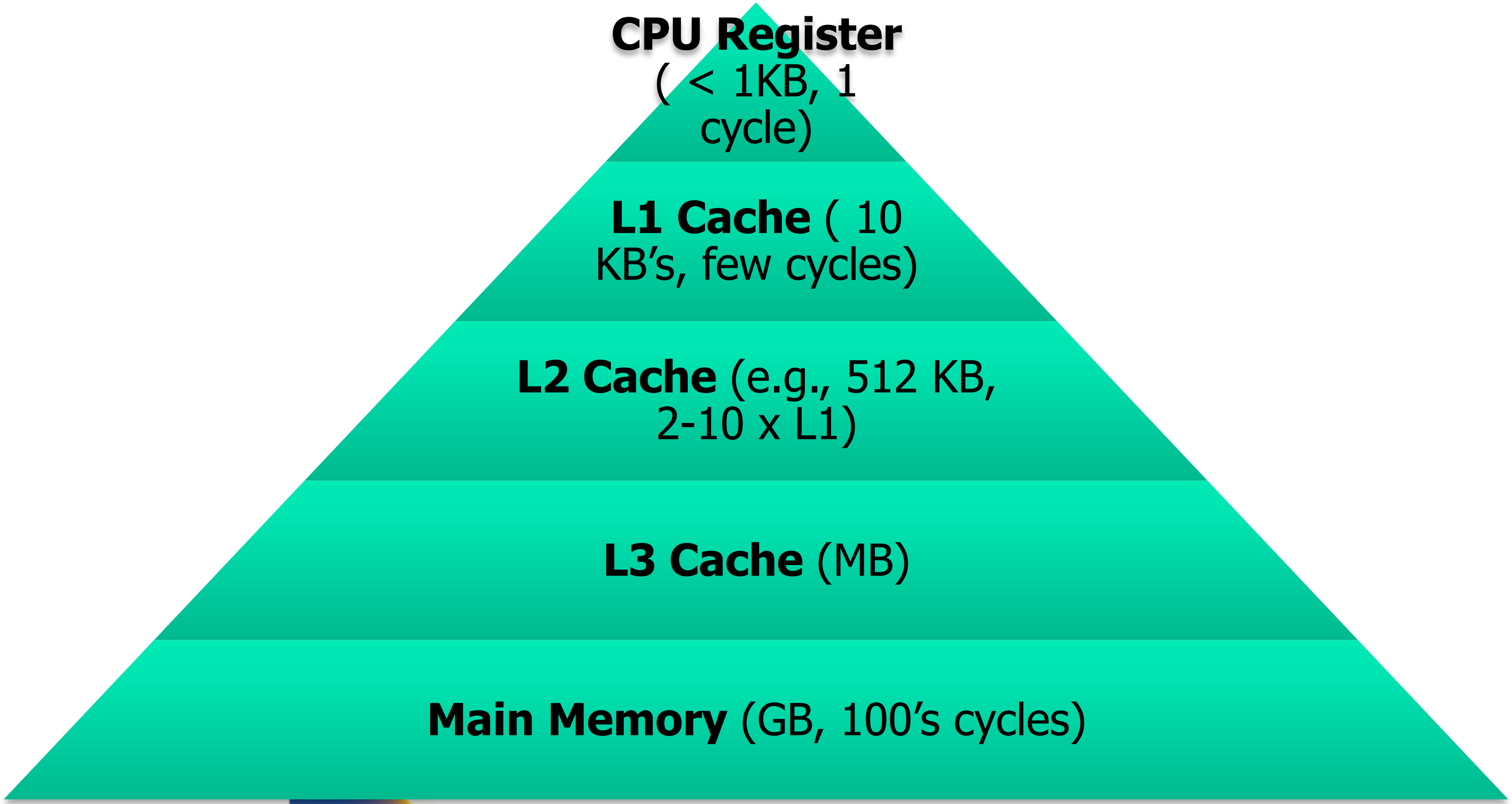
- Hardware: Disks
- Access Times
- Example: Megatron 747
- Optimizations
- Other Topics
  - Storage Costs
  - Using Secondary Storage
  - Disk Failures



Outlook - Hardware

- Disk Access is the main limiting factor
- However, to implement fast DBMS
  - need to understand other parts of the hardware
    - Memory hierarchy
    - CPU architecture: pipelining, vector instructions, OOE, …
    - SSD storage
  - need to understand how OS manages hardware
    - File access, VM, Buffering, …

Memory Hierarchy



CPU Register (< 1KB, 1 cycle)

L1 Cache (10 KB's, few cycles)

L2 Cache (e.g., 512 KB, 2-10 x L1)

L3 Cache (MB)

Main Memory (GB, 100's cycles)

Memory Hierarchy

- **Compare**: Disk vs. Main Memory
- Reduce accesses to main memory
- Cache conscious algorithms

Increasing Amount of Parallelism

- Contention on, e.g., Memory
- NUMA
- Algorithmic Challenges
  - How to parallelize algorithms?
  - Sometime: Completely different approach required
  - -> Rewrite large parts of DBMS

New Trend: Software/Hardware Co-design

- Actually, revived trend: database machines (80’s)
- New goals: power consumption
- Design specific hardware and write special software for it
- E.g., Oracle Exadata, Oracle Labs

CS 525: Advanced Database Organization

03: Disk Organization

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab

Topics for today

- How to lay out data on disk
- How to move it to/from memory

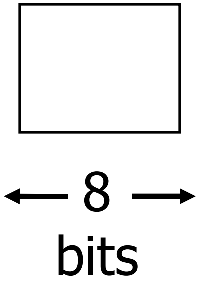
What are the data items we want to store?

- a salary
- a name
- a date
- a picture

What are the data items we want to store?

- a salary
- a name
- a date
- a picture

⇨ What we have available: Bytes



← 8 →
bits

To represent:

- Integer (short): 2 bytes

  e.g., 35 is

  00000000 00100011

  Endian! Could as well be

  00100011 00000000

- Real, floating point

  n bits for mantissa, *m* for exponent….

To represent:

- Characters

  → various coding schemes suggested,
  most popular is ASCII (1 byte encoding)

  Example:
  A: 1000001
  a: 1100001
  5: 0110101
  LF: 0001010

To represent:

- Boolean

  e.g., TRUE 1111 1111

  FALSE 0000 0000

- Application specific

  e.g., enumeration

  RED → 1 GREEN → 3

  BLUE → 2 YELLOW → 4 …

To represent:

- Boolean

  e.g., TRUE 1111 1111

  FALSE 0000 0000

- Application specific

  e.g., RED → 1 GREEN → 3

  BLUE → 2 YELLOW → 4 …

⇨ Can we use less than 1 byte/code?

Yes, but only if desperate...

To represent:

- Dates

  e.g.: - Integer, # days since Jan 1, 1900
  - 8 characters, YYYYMMDD
  - 7 characters, YYYYDDD
  (not YYMMDD! Why?)

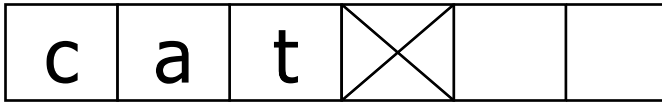
- Time

  e.g. - Integer, seconds since midnight
  - characters, HHMMSSFF

To represent:

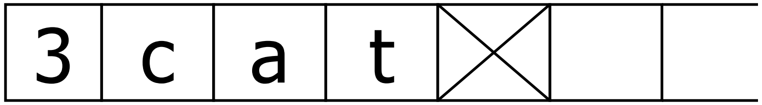
- String of characters
  - Null terminated

    e.g.,



  - Length given

    e.g.,



  - Fixed length

To represent:

- Bag of bits

Length	Bits

Key Point

- Fixed length items
- Variable length items
  - usually length given at beginning

Also

- Type of an item: Tells us how to interpret (plus size if fixed)

Overview

Data Items

↓

Records

↓

Blocks

↓

Files

⇣

Memory

Record - Collection of related data items (called FIELDS)

E.g.: Employee record:

name field,

salary field,

date-of-hire field, ...

Types of records:

- Main choices:
  - FIXED vs VARIABLE FORMAT
  - FIXED vs VARIABLE LENGTH

Fixed format

A SCHEMA (not record) contains following information

- # fields
- type of each field
- order in record
- meaning of each field

Example: fixed format and length

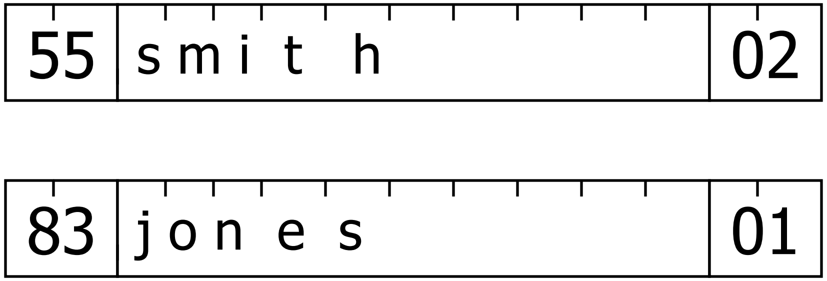
Employee record

(1) E#, 2 byte integer

(2) E.name, 10 char.

(3) Dept, 2 byte code

Schema

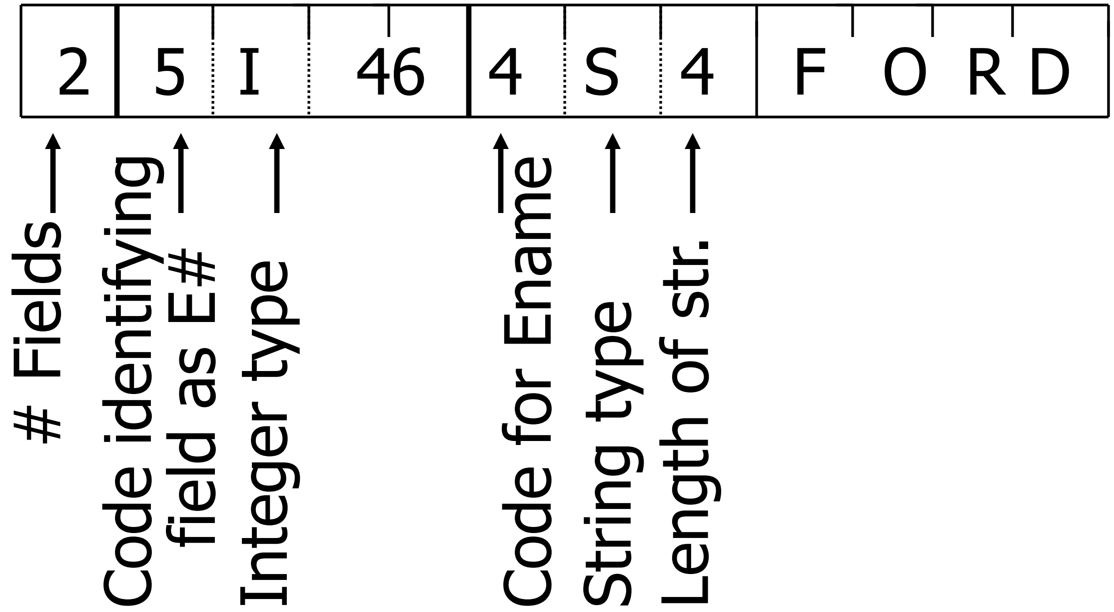


Records

Variable format

- Record itself contains format
  “Self Describing”

Example: variable format and length



Field name codes could also be strings, i.e. TAGS

Variable format useful for:

- “sparse” records
- repeating fields
- evolving formats

But may waste space...

Additional indirection…

- EXAMPLE: var format record with repeating fields

Employee → one or more → children

3	E_name: Fred	Child: Sally	Child: Tom

Note: Repeating fields does not imply

- variable format, nor
- variable size

John	Sailing	Chess	--

Note: Repeating fields does not imply

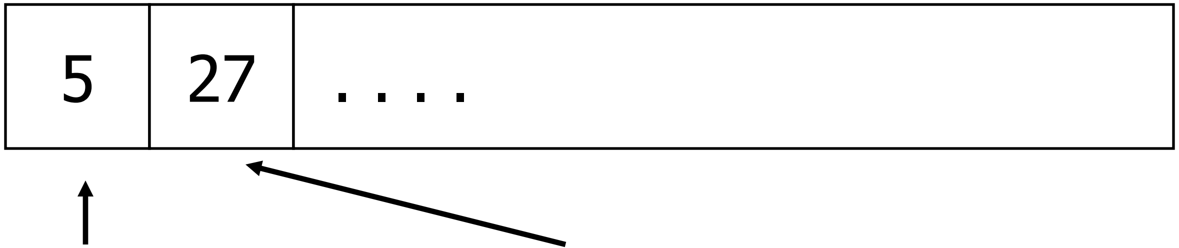
- variable format, nor
- variable size

John	Sailing	Chess	--

- Key is to allocate maximum number of repeating fields (if not used → null)

☆ Many variants between fixed - variable format:

Example: Include record type in record



5

27

. . . .

record type

tells me what

to expect

(i.e. points to schema)

record length

Record header - data at beginning that describes record

May contain:

- record type
- record length
- time stamp
- null-value bitmap
- other stuff ...

Other interesting issues:

- Compression
  - within record - e.g. code selection
  - collection of records - e.g. find common patterns
- Encryption
- Splitting of large records
  - E.g., image field, store pointer

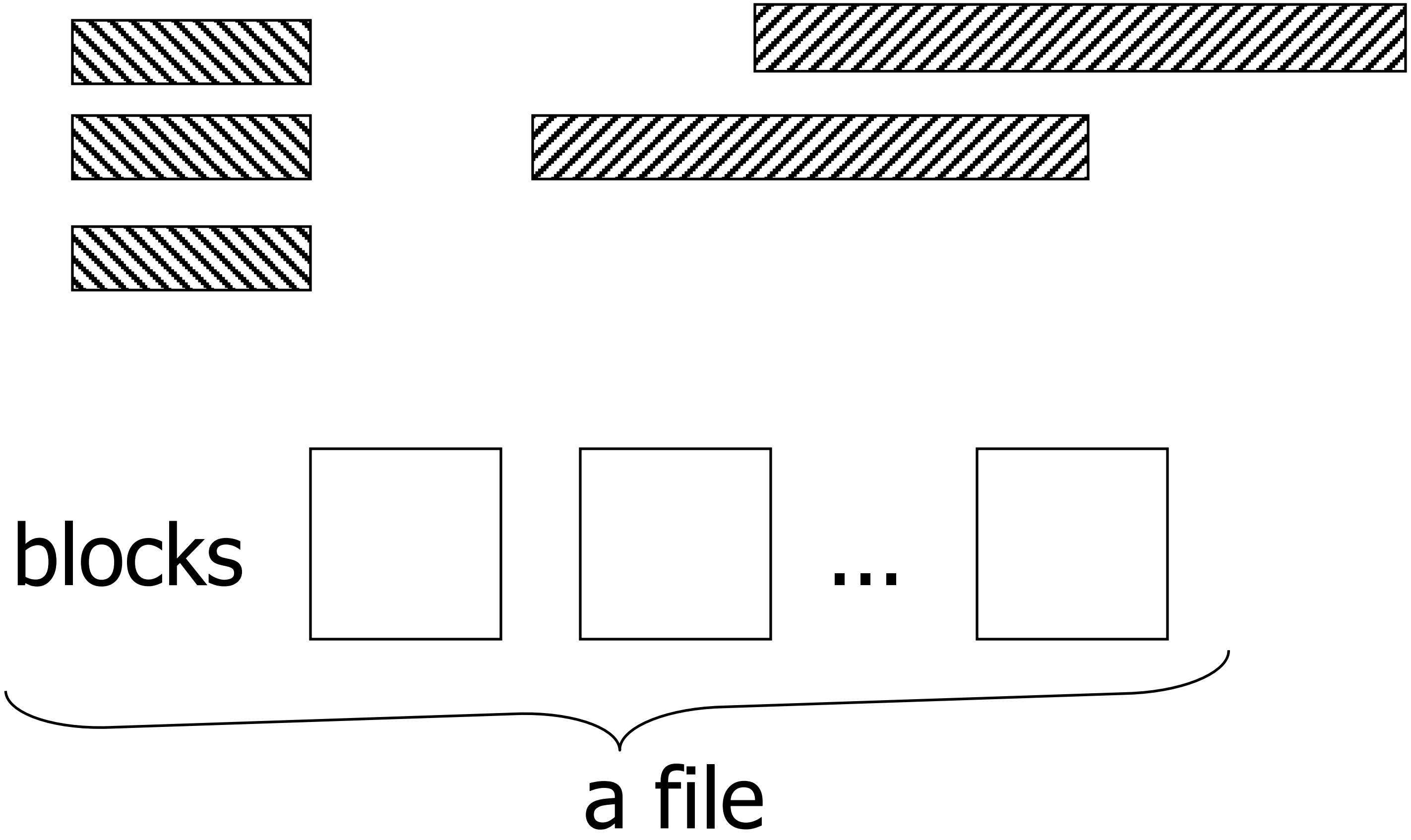
Record Header – null-map

- SQL: NULL is special value for every data type
  - Reserve one value for each data type as NULL?
- Easier solution
  - Record header has a bitmap to store whether field is NULL
  - Only store non-NULL fields in record

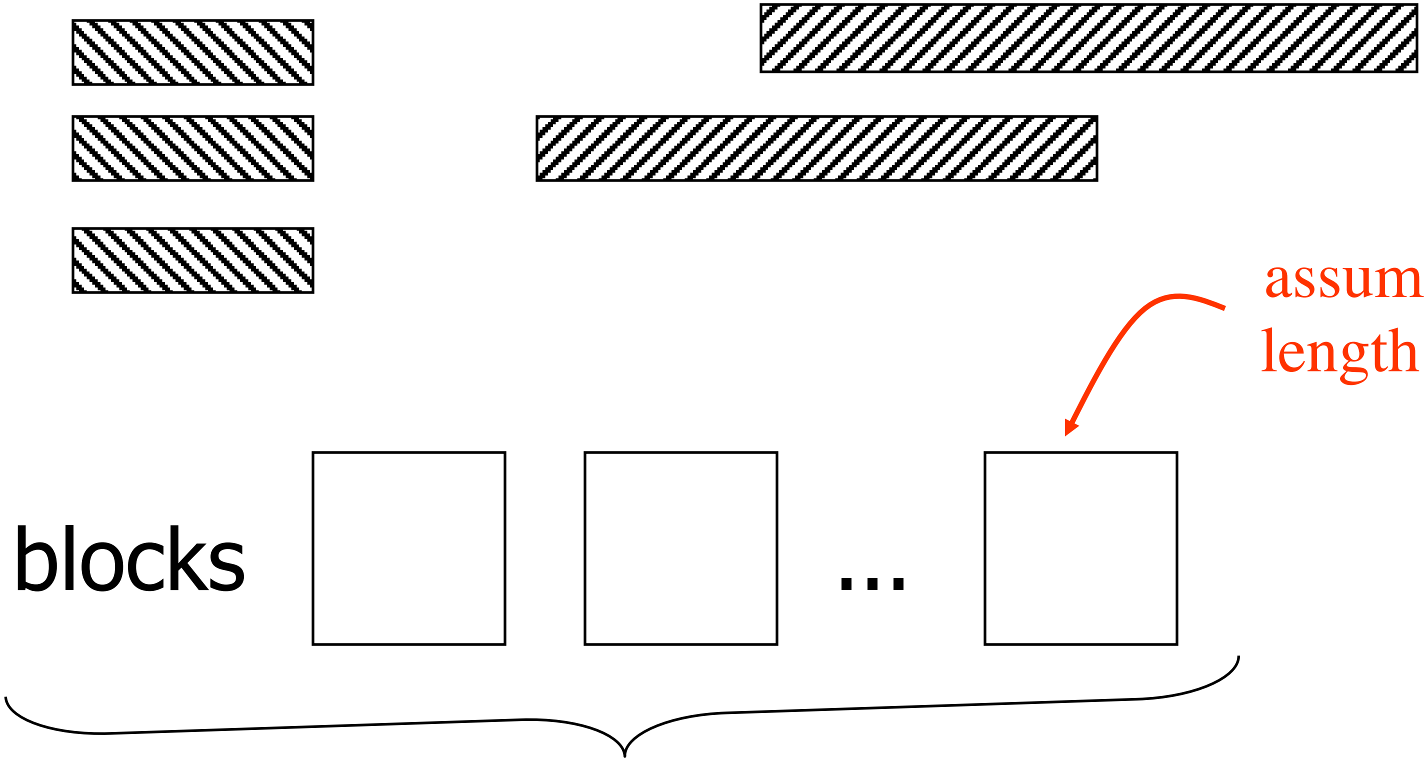
Separate Storage of Large Values

- Store fields with large values separately
  - E.g., image or binary document
  - Records have pointers to large field content
- Rationale
  - Large fields mostly not used in search conditions
  - Benefit from smaller records

Next: placing records into blocks



Next: placing records into blocks



assume fixed length blocks

blocks ...

a file ← assume a single file (for now)

Options for storing records in blocks:

(1) separating records

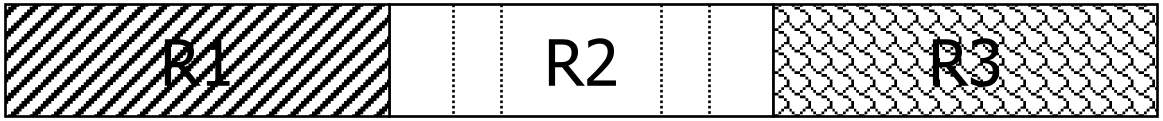
(2) spanned vs. unspanned

(3) sequencing

(4) indirection

(1) Separating records

Block



(a) no need to separate - fixed size recs.

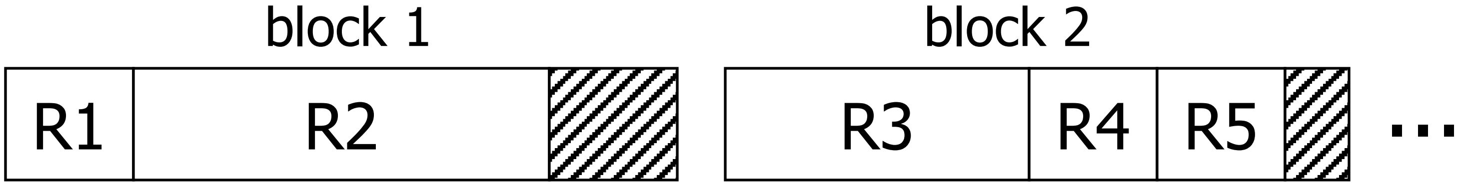
(b) special marker

(c) give record lengths (or offsets)

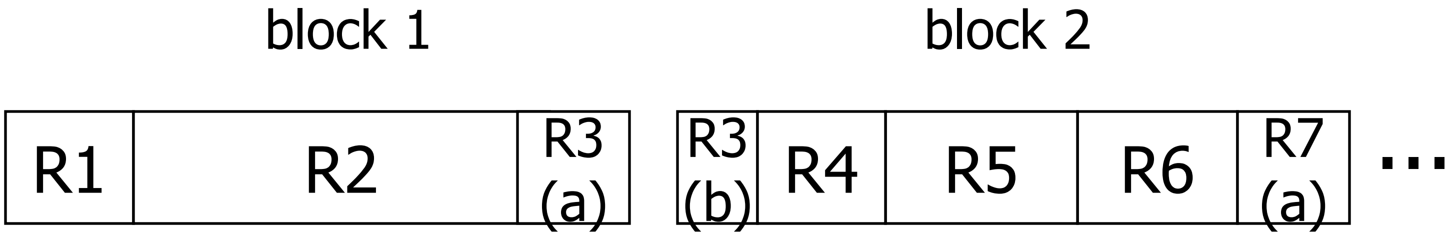
- within each record
- in block header

(2) Spanned vs. Unspanned

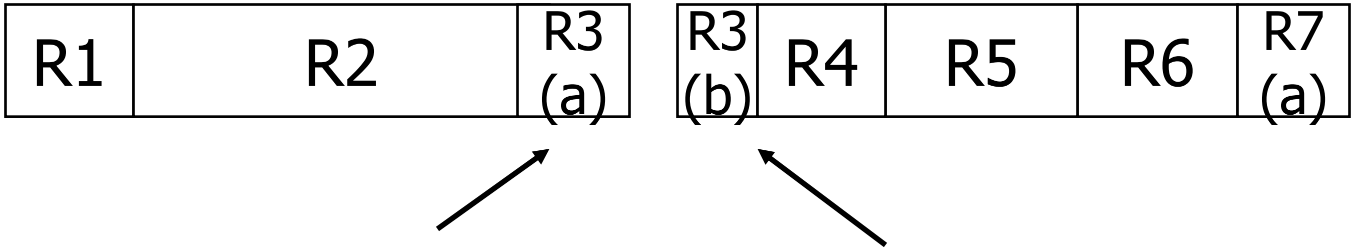
- Unspanned: records must be within one block



- Spanned



With spanned records:



need indication
of partial record
“pointer” to rest

need indication
of continuation
(+ from where?)

Spanned vs. unspanned:

- Unspanned is much simpler, but may waste space…
- Spanned essential if

  record size > block size

(3) Sequencing

- Ordering records in file (and block) by some key value

Sequential file (⇒ sequenced)

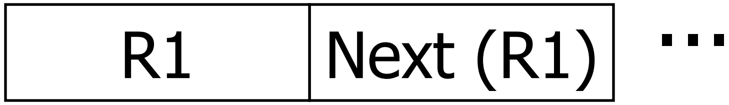
Why sequencing?

Typically to make it possible to efficiently read records in order

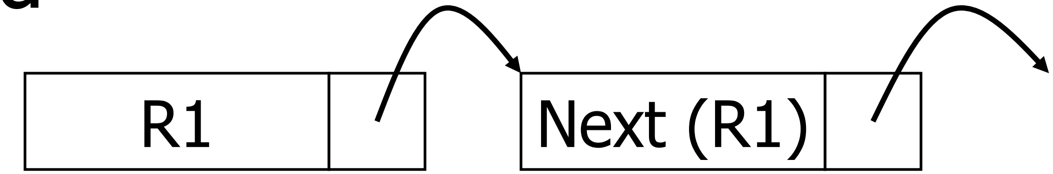
(e.g., to do a merge-join — discussed later)

Sequencing Options

(a) Next record physically contiguous



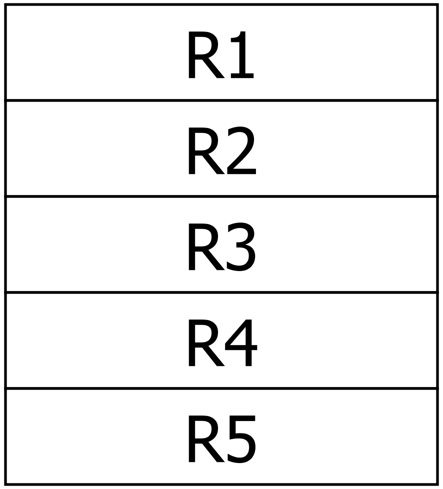
(b) Linked



Sequencing Options

(c) Overflow area

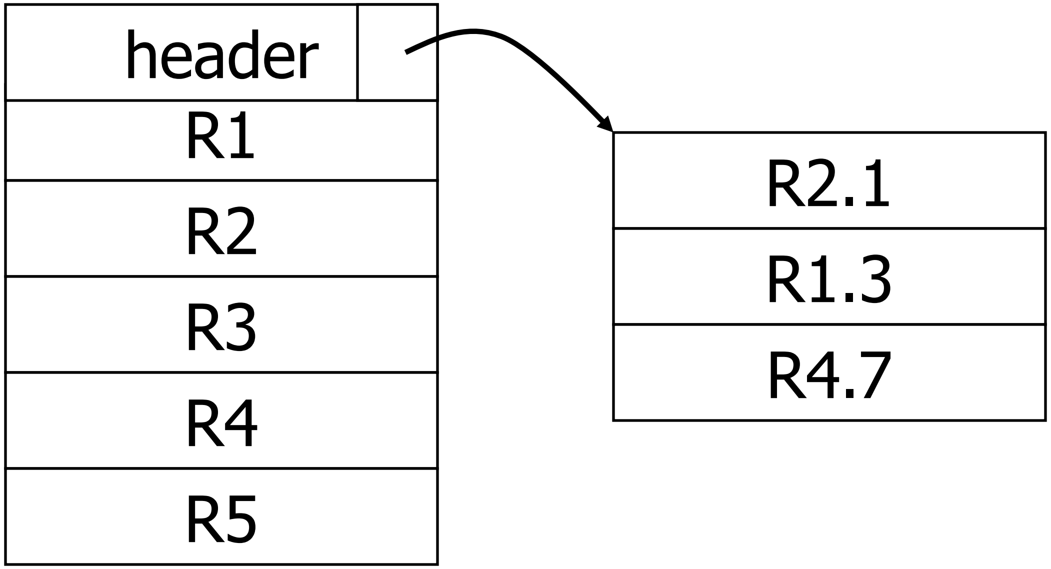
Records
in sequence



Sequencing Options

(c) Overflow area

Records
in sequence



(4) Indirection

- How does one refer to records?

(4) Indirection

- How does one refer to records?

Many options:

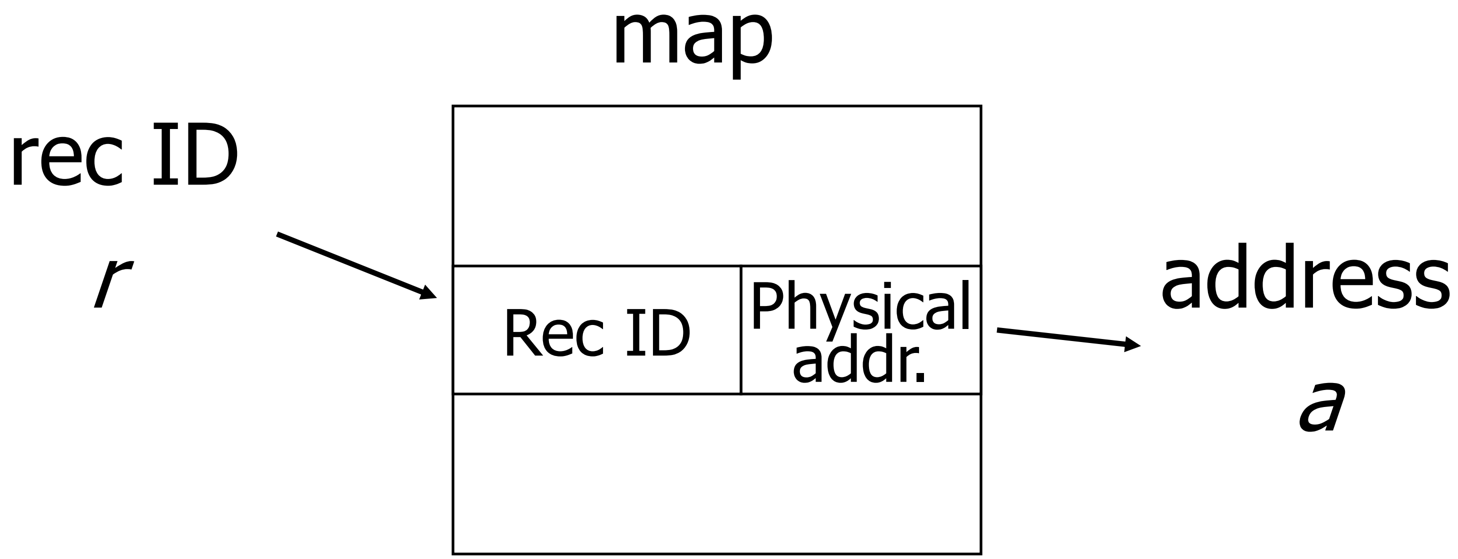
Physical ⟷ Indirect

☆ Purely Physical

$$\text{E.g., Record Address or ID} = \left\{\begin{array}{l} \left.\begin{array}{l}\text{Device ID}\\ \text{Cylinder \#}\\ \text{Track \#}\\ \text{Block \#}\end{array}\right\}\text{Block ID} \\ \text{Offset in block}\end{array}\right.$$

☆ Fully Indirect

E.g., Record ID is arbitrary bit string



Tradeoff

Flexibility ⟷ Cost

to move records of indirection

(for deletions, insertions)

Physical ⟷ Indirect

↑

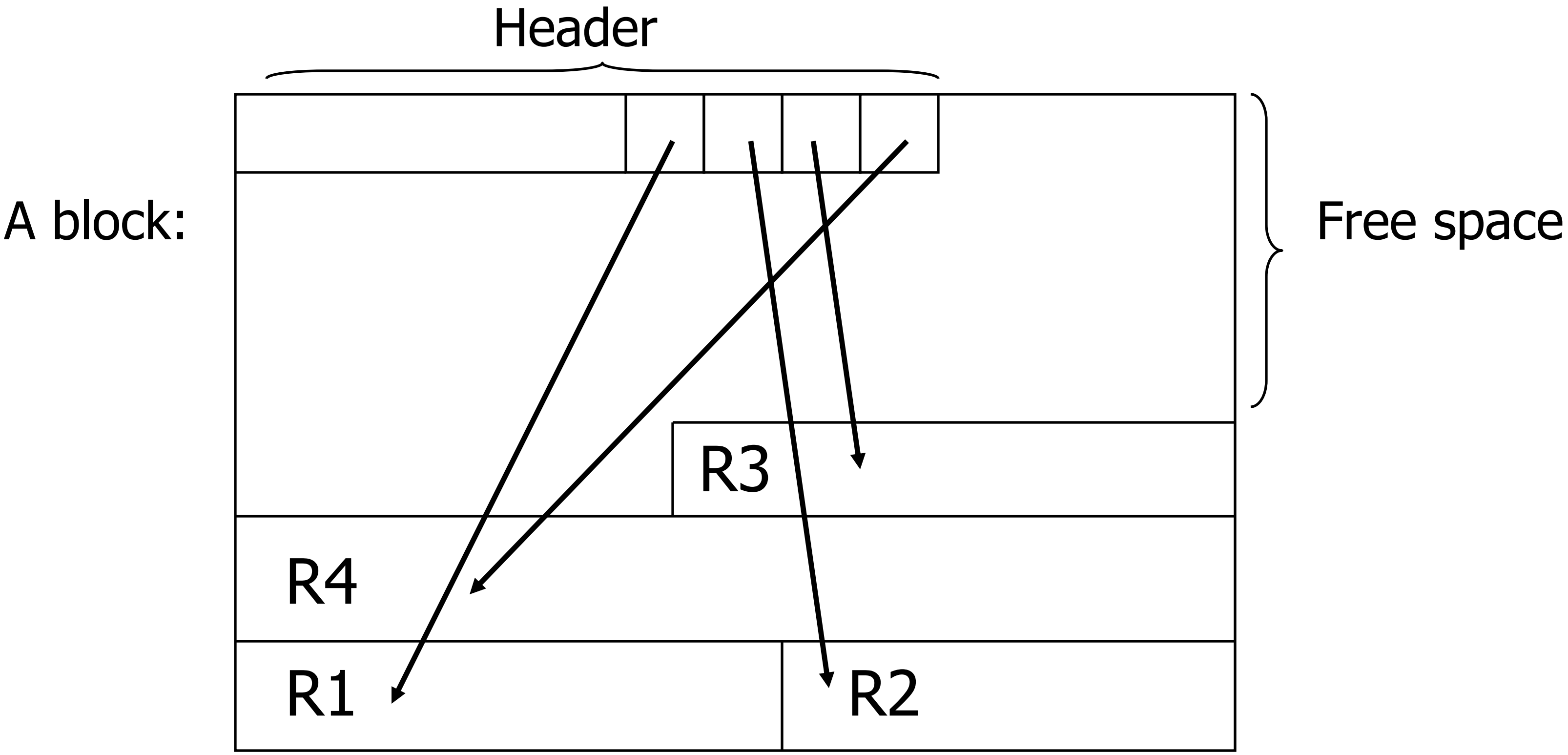
Many options
in between …

Block header - data at beginning that describes block

May contain:

- File ID (or RELATION or DB ID)
- This block ID
- Record directory
- Pointer to free space
- Type of block (e.g. contains recs type 4; is overflow, …)
- Pointer to other blocks "like it"
- Timestamp ...

Example: Indirection in block



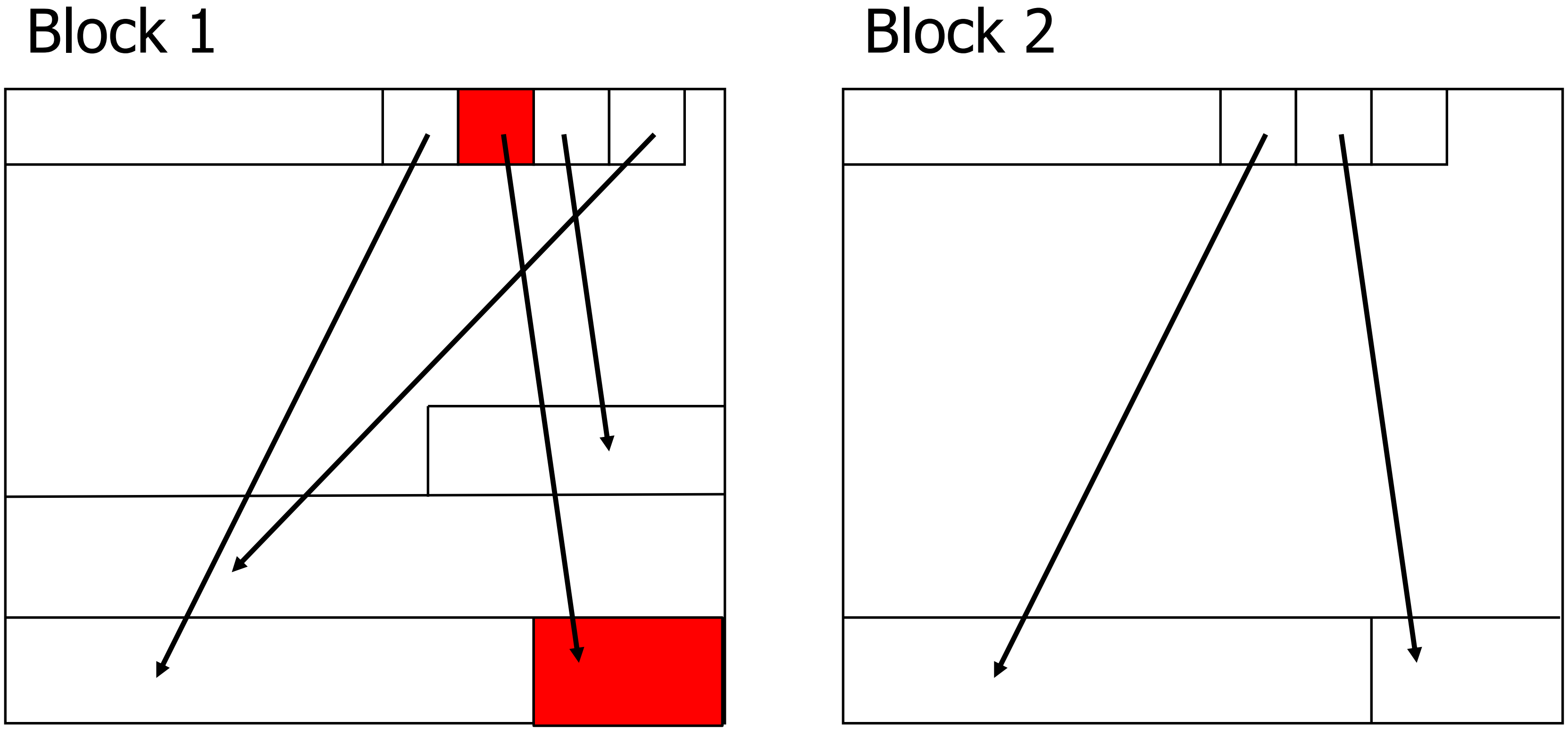
Tuple Identifier (TID)

- TID is
  - Page identifier
  - Slot number
- Slot stores either record or pointer (TID)
- TID of a record is fixed for all time

TID Operations

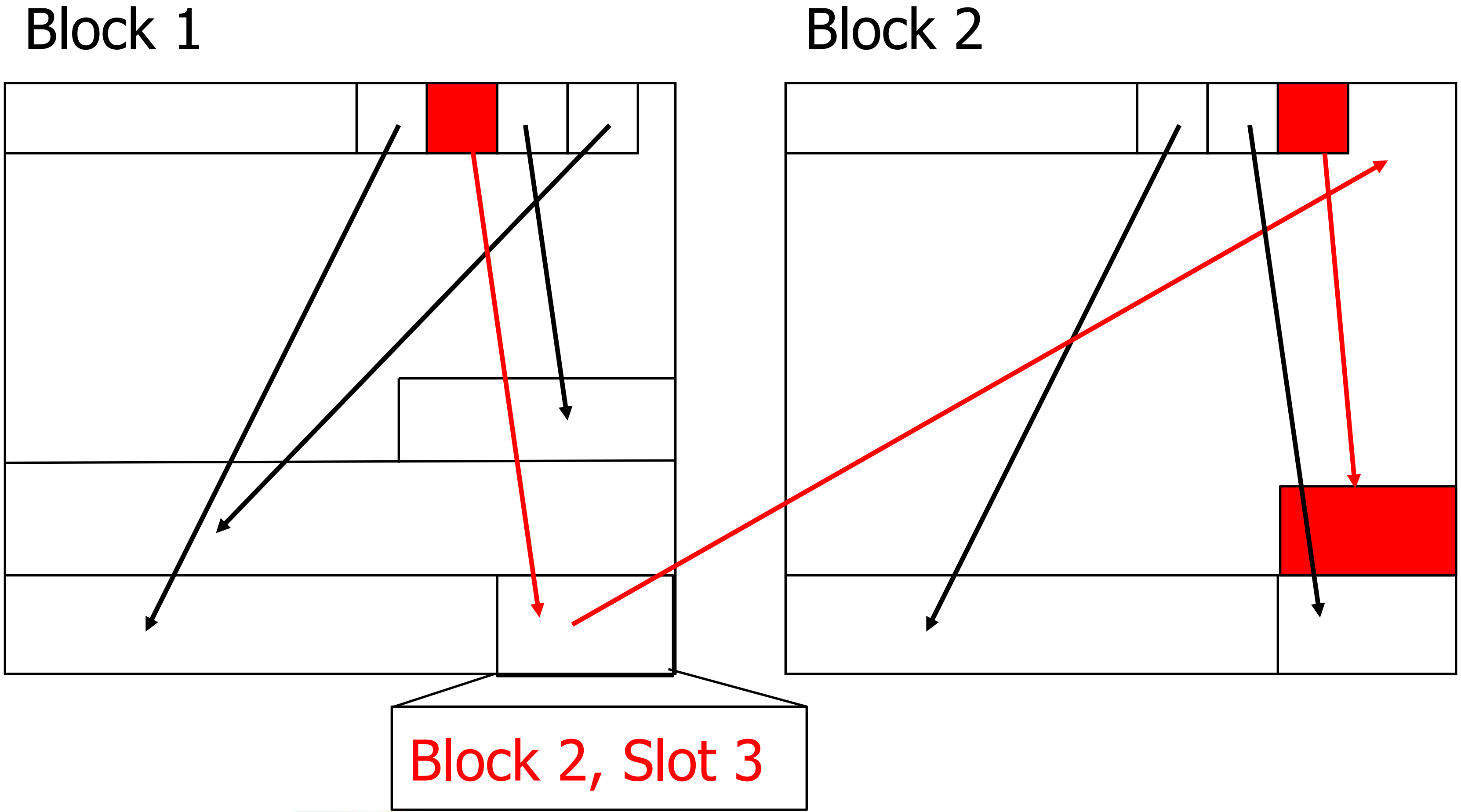
- Insertion
  - Set TID to record location (page, slot)
- Moving record
  - e.g., update variable-size or reorganization
  - Case 1: TID points to record
    - Replace record with pointer (new TID)
  - Case 2: TID points to pointer (TID)
    - Replace pointer with new pointer

TID: Block 1, Slot 2



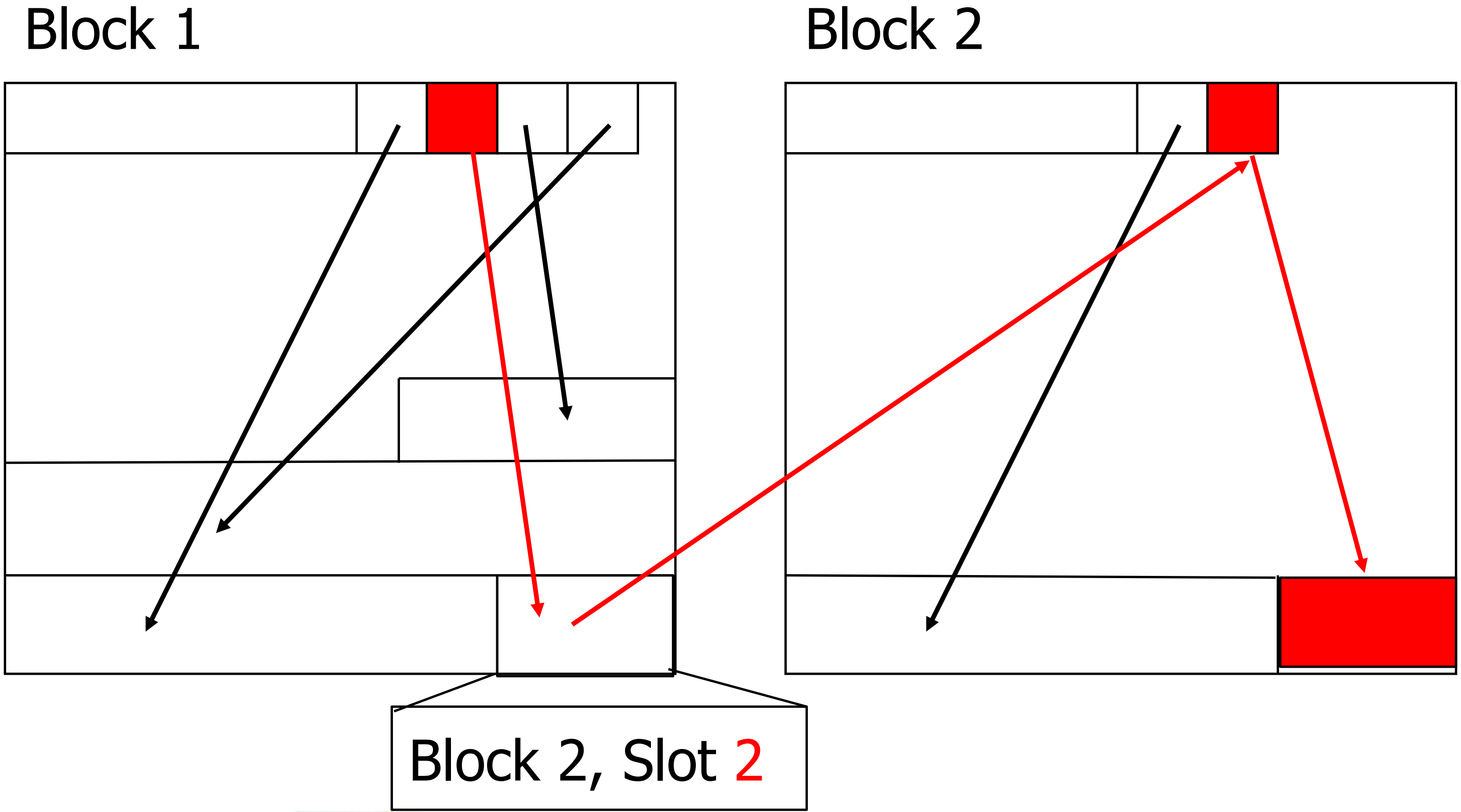
Move record to Block 2 slot 3 -> TID does not change!

TID: Block 1, Slot 2



Move record again to Block 2 slot 2
-> still one level of indirection

TID: Block 1, Slot 2



TID Properties

- TID of record never changes
  - Can be used safely as pointer to record (e.g., in index)
- At most one level of indirection
  - Relatively efficient
  - Changes to physical address - changing max 2 pages

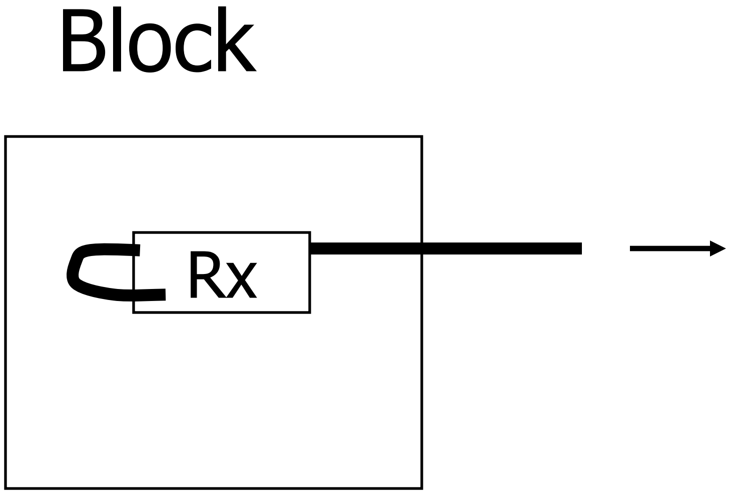
Options for storing records in blocks:

(1) separating records
(2) spanned vs. unspanned
(3) sequencing
(4) indirection

Other Topics

(1) Insertion/Deletion
(2) Buffer Management
(3) Comparison of Schemes

Deletion



Options:

(a) Immediately reclaim space

(b) Mark deleted

Options:

(a) Immediately reclaim space

(b) Mark deleted

- May need chain of deleted records

  (for re-use)

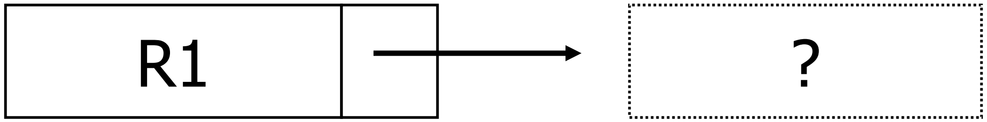
- Need a way to mark:
  - special characters
  - delete field
  - in map

☆ As usual, many tradeoffs...

- How expensive is it to move valid record to free space for immediate reclaim?
- How much space is wasted?
  - e.g., deleted records, delete fields, free space chains,...

Concern with deletions

Dangling pointers



Solution #1: Do not worry

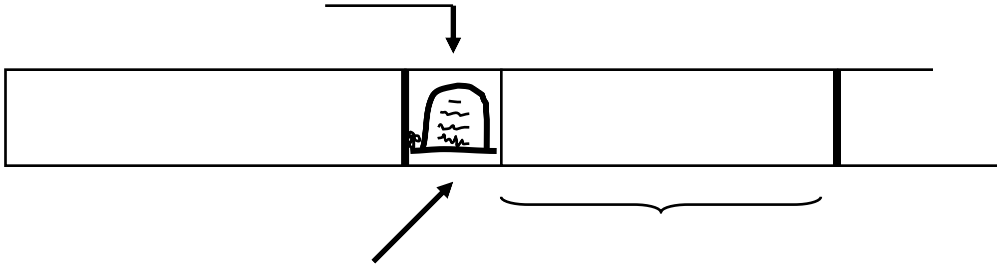
Solution #2: Tombstones

E.g., Leave "MARK" in map or old location

Solution #2: Tombstones

E.g., Leave "MARK" in map or old location

- Physical IDs



A block

This space never re-used

This space can be re-used

Solution #2: Tombstones

E.g., Leave “MARK” in map or old location

- Logical IDs

map

ID	LOC
7788	

Never reuse ID 7788 nor space in map...

Insert

Easy case: records not in sequence

→ Insert new record at end of file or in deleted slot

→ If records are variable size, not as easy...

Insert

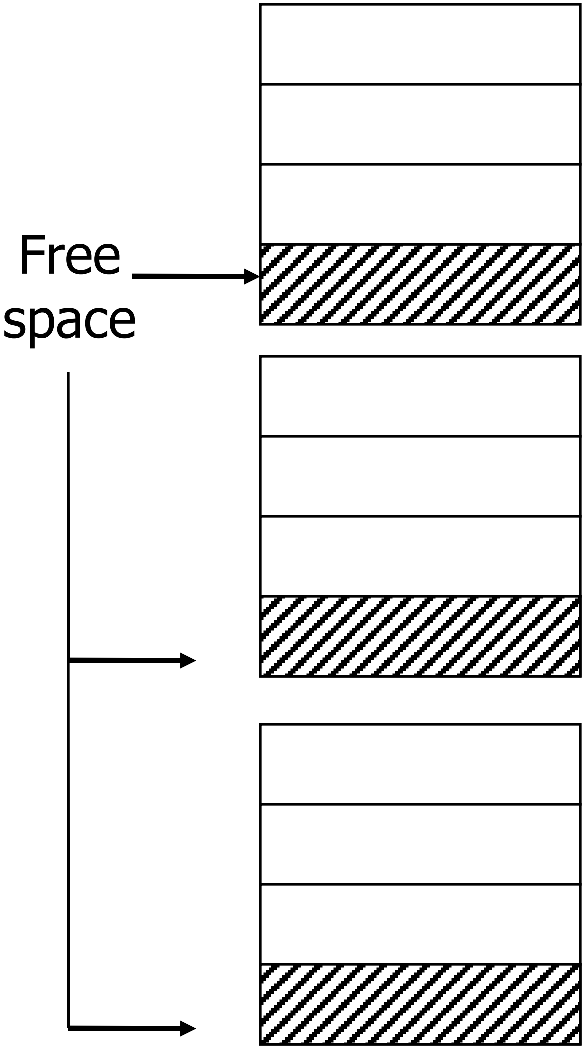
<u>Hard case:</u> records in sequence

→ If free space “close by”, not too bad...

→ Or use overflow idea...

Interesting problems:

- How much free space to leave in each block, track, cylinder?
- How often do I reorganize file + overflow?


Free space

Buffer Management

- For Caching of Disk Blocks
- Buffer Replacement Strategies
  - E.g., LRU, clock
- Pinned blocks
- Forced output ------------→ in Notes02
- Double buffering
- Swizzling

Buffer Manager

- Manages blocks cached from disk in main memory
- Usually -> fixed size buffer (M pages)
- DB requests page from Buffer Manager
  - Case 1: page is in memory -> return address
  - Case 2: page is on disk -> load into memory, return address

Goals

- Reduce the amount of I/O
- Maximize the *hit rate*
  - Ratio of number of page accesses that are fulfilled without reading from disk
- -> Need strategy to decide when to

Buffer Manager Organization

- Bookkeeping
  - Need to map (hash table) page-ids to locations in buffer (**page frames**)
  - Per page store *fix count, dirty bit, …*
  - Manage free space
- Replacement strategy
  - If page is requested but buffer is full
  - Which page to emit remove from buffer

FIFO

- **F**irst **I**n, **F**irst **O**ut
- Replace page that has been in the buffer for the longest time
- Implementation: E.g., pointer to oldest page (circular buffer)
  - Pointer->next = Pointer++ % M
- Simple, but not prioritizing frequently accessed pages

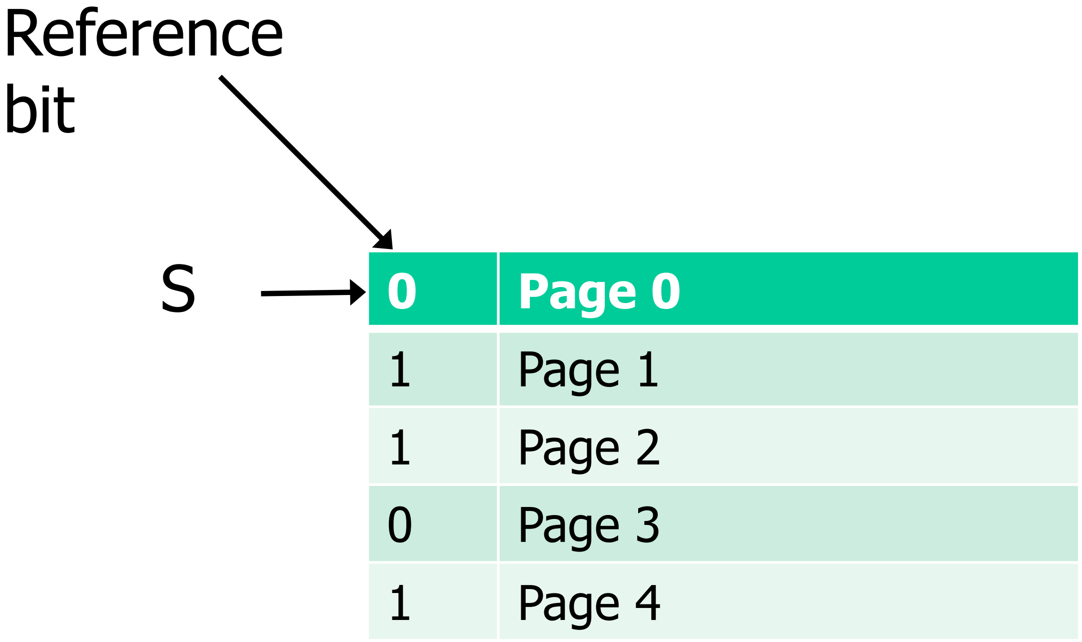
LRU

- Least Recently Used
- Replace page that has not been accessed for the longest time
- Implementation:
  - List, ordered by LRU
  - Access a page, move it to list tail
- Widely applied and reasonable performance

Clock

- Frames are organized clock-wise
- Pointer S to current frame
- Each frame has a reference bit
  - Page is loaded or accessed -> bit = 1
- Find page to replace (advance pointer)
  - Return first frame with bit = 0
  - On the way set all bits to 0

Clock Example

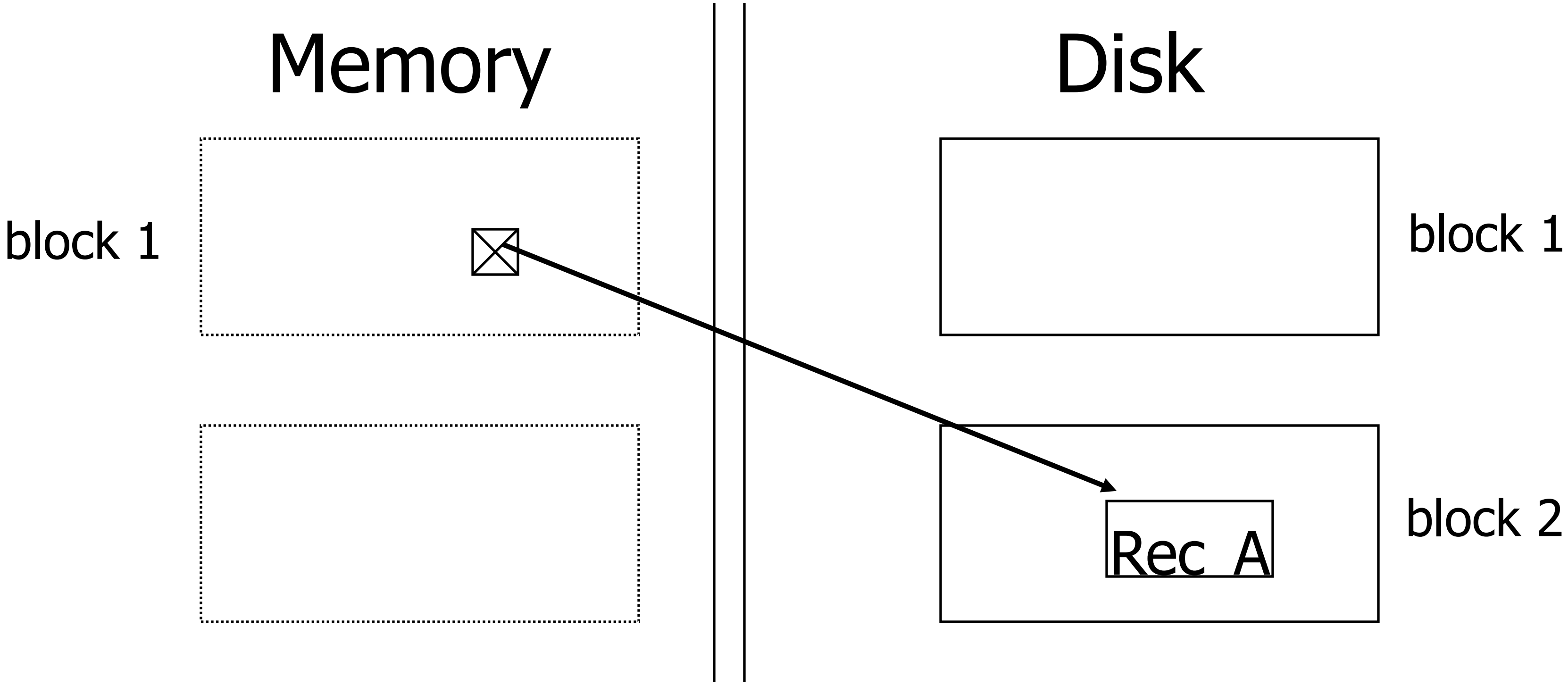


0	**Page 0**
1	Page 1
1	Page 2
0	Page 3
1	Page 4

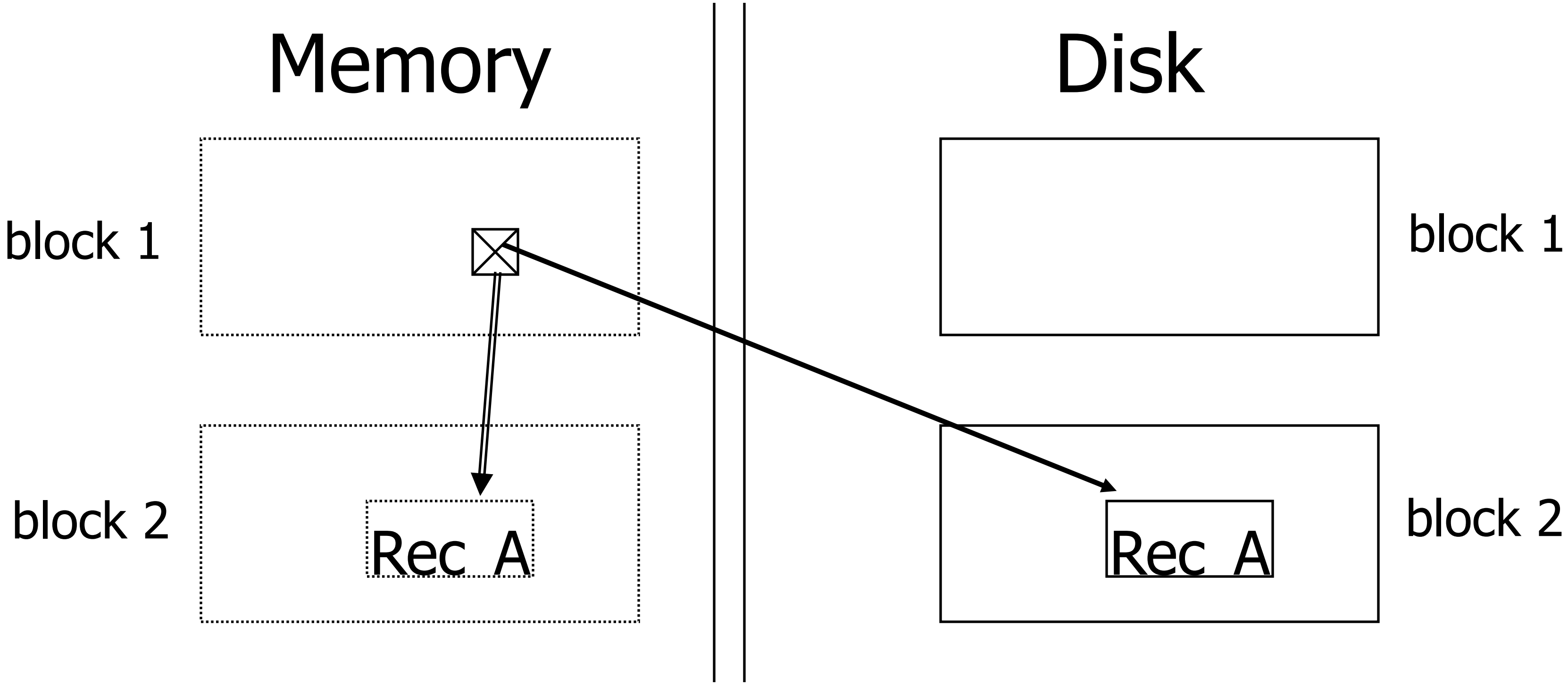
Other Replacement Strategies

- LRU-K
- GCLOCK
- Clock-Pro
- ARC
- LFU

Swizzling



Swizzling



Row vs Column Store

- So far we assumed that fields of a record are stored contiguously (row store)...
- Another option is to store all values of a field together (column store)

Row Store

- Example: Order consists of
  - id, cust, prod, store, price, date, qty

id1	cust1	prod1	store1	price1	date1	qty1
id2	cust2	prod2	store2	price2	date2	qty2
id3	cust3	prod3	store3	price3	date3	qty3

Column Store

- Example: Order consists of
  - id, cust, prod, store, price, date, qty

id1	cust1
id2	cust2
id3	cust3
id4	cust4
...	...

id1	prod1
id2	prod2
id3	prod3
id4	prod4
...	...

id1	price1	qty1
id2	price2	qty2
id3	price3	qty3
id4	price4	qty4
...	...	...

ids may or may not be stored explicitly

Row vs Column Store

- Advantages of Column Store
  - more compact storage (fields need not start at byte boundaries)
  - Efficient compression, e.g., RLE
  - efficient reads on data mining operations
- Advantages of Row Store
  - writes (multiple fields of one record)more efficient
  - efficient reads for record access (OLTP)

Compression

- When should I compress
  - **Compression reduces storage size**
    - Less space on disk
    - More "content" can be read/written with less I/O
  - **(De-)Compression takes time**
    - CPU occupied with compressing de-compressing data -> not available for other operations

The Laws of Compression ;-)

- If I/O is the performance bottleneck then compression improves performance
- If CPU is the bottleneck then compression may hurt performance

Types of compression

- Dictionary compression
- Run-length encoding (more later)
- Deltacoding (more later)
- Bitpacking
- …

Scope of compression

- Global
  - Global dictionary encoding for strings
    - Replace individual strings with integers using a invertible map
- Per table / column
  - Run-length encode the values of a column
- Per page (group of pages)
  - Compress pages before writing to disk

Processing compressed data

- Can we evaluate operations directly over compressed data?
- In some cases yes
- Example: dictionary compressed strings
  - **WHERE** name = ‘Peter’
  - => **WHERE** name = 1

String	Code
Peter	1
Bob	2
Alice	3

Example: Apache Parquet

- Parquet is a columnar/compressed storage format developed in the context of the Hadoop ecosystem
- Supported by many big data systems like Spark or MR
- Support nested relational data (we ignore this here)

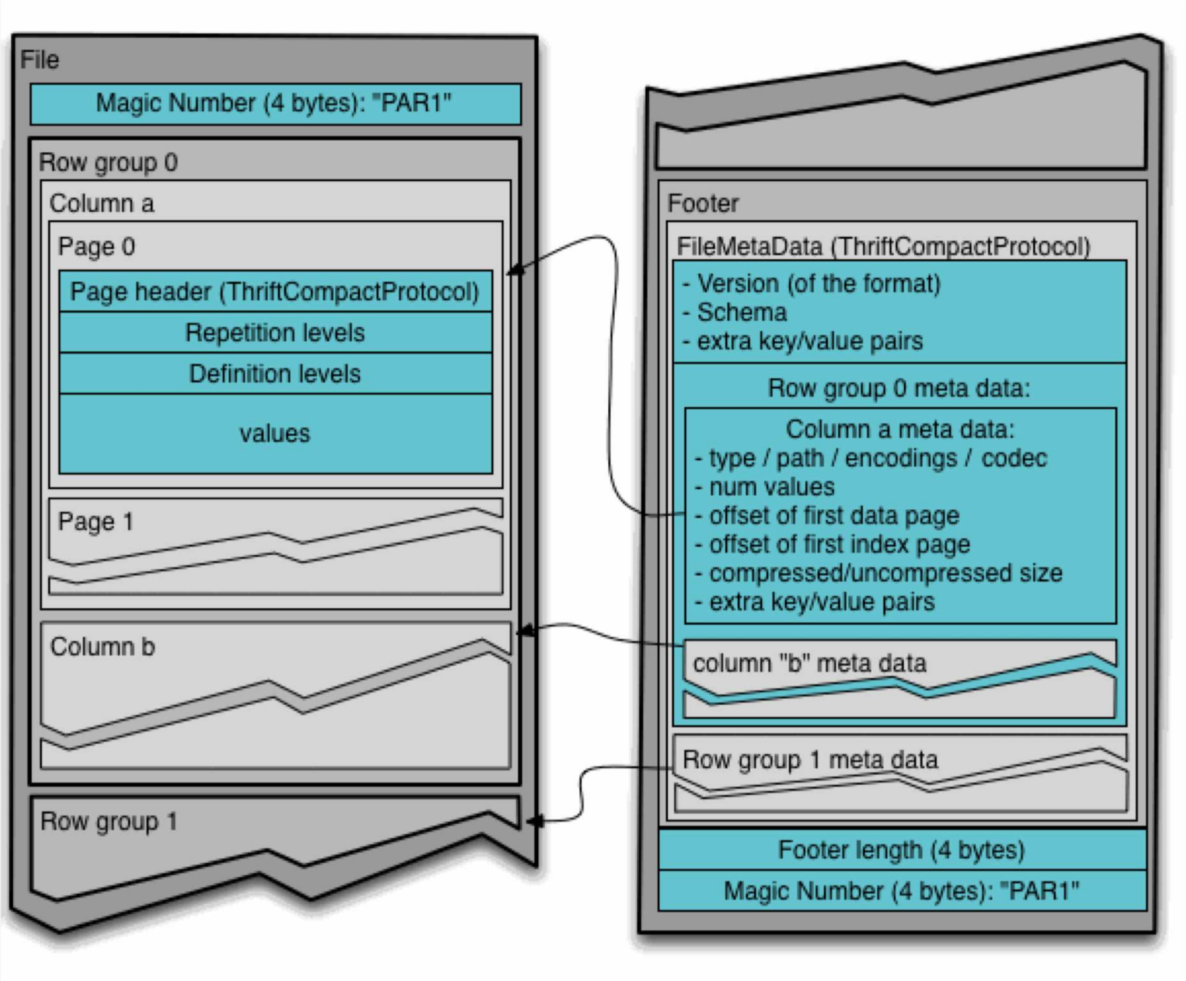
Parquet - Structure

- **Row group:** A logical horizontal partitioning of the data into rows
- **Column chunk**: A chunk of the data for a particular column.
  - Guaranteed to be contiguous in the file
- **Page**: Column chunks are divided up into pages, indivisible units for compression and coding

Parquet - Structure

- **Row group:** GBs in size
- **Column chunk**: typically 100s of MBs
- **Page**: recommended 8KB
  - Pages are compressed and maybe RLE

Parquet - Structure



Parquet - Analysis

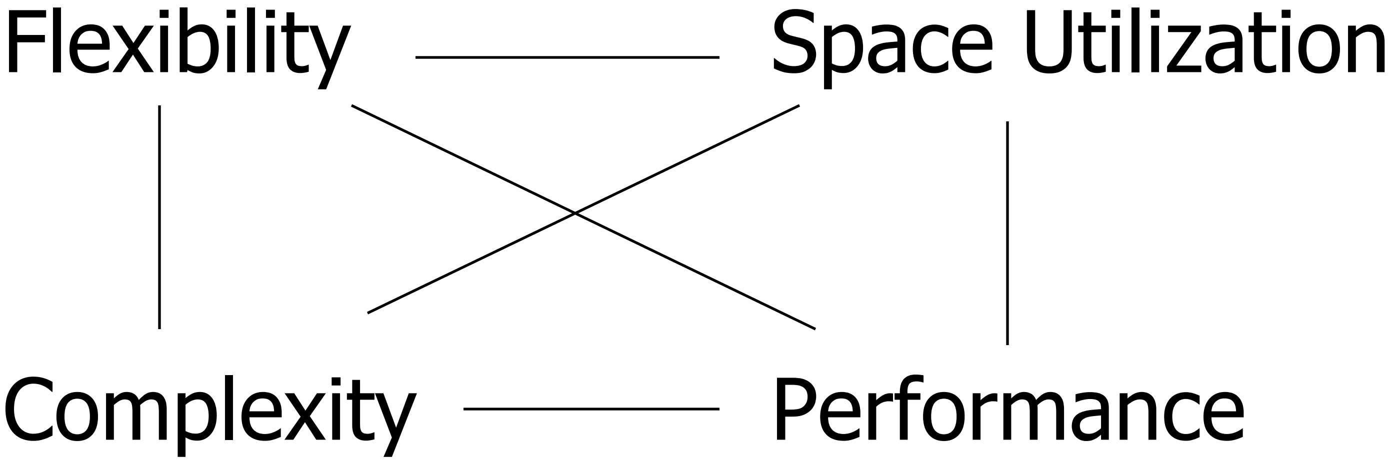
- Columnar
- Hierarchical organization
- Metadata separable from data
- I/O granularity (chunks) different from compression/lookup granularity (pages)

Comparison

- There are 10,000,000 ways to organize my data on disk…

Which is right for me?

Issues:



☆ To evaluate a given strategy, compute following parameters:

-> space used for expected data

-> expected time to

- fetch record given key
- fetch record with next key
- insert record
- append record
- delete record
- update record
- read complete file
- reorganize file

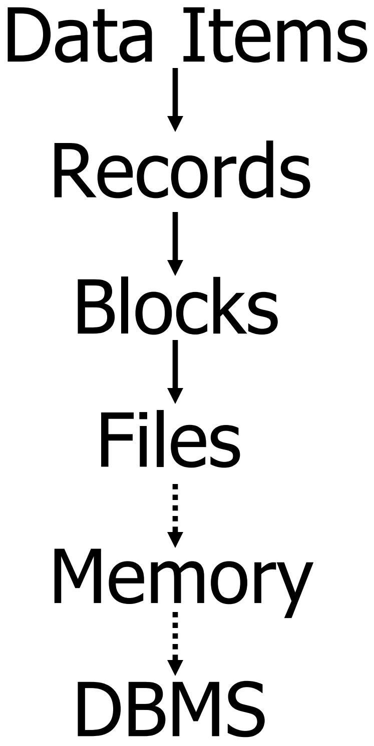
Example

How would you design Megatron 3000 storage system? (for a relational DB, low end)

- Variable length records?
- Spanned?
- What data types?
- Fixed format?
- Record IDs ?
- Sequencing?
- How to handle deletions?

Summary

- How to lay out data on disk



Data Items

Records

Blocks

Files

Memory

DBMS

Next

How to find a record quickly,
given a key

CS 525: Advanced Database Organization

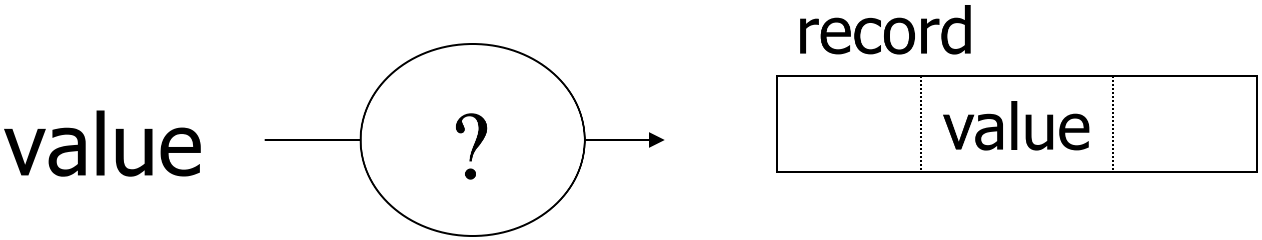
04: Indexing

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab

Part 04

Indexing & Hashing


value

?

record

value

Query Types:

- **Point queries**:
  - *Input:* value **v** of attribute **A**
  - *Output:* all objects (tuples) with that value in attribute **A**
- **Range queries**:
  - *Input:* value interval **[low,high]** of attr **A**
  - Output: all tuples with a value

    low <= v < high in attribute **A**

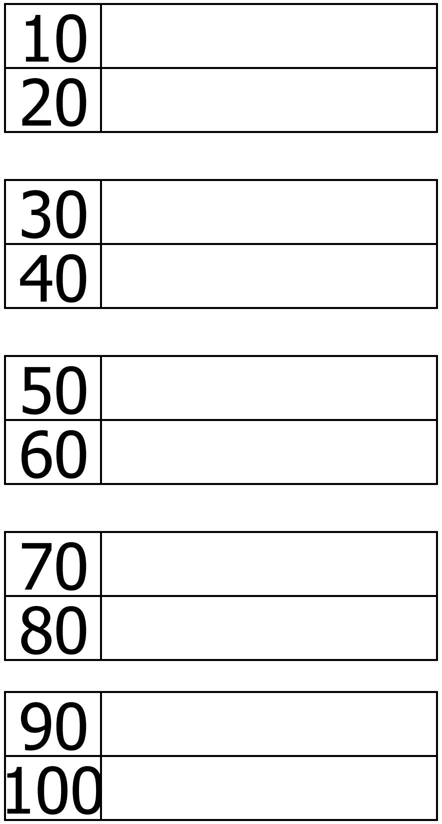
Index Considerations:

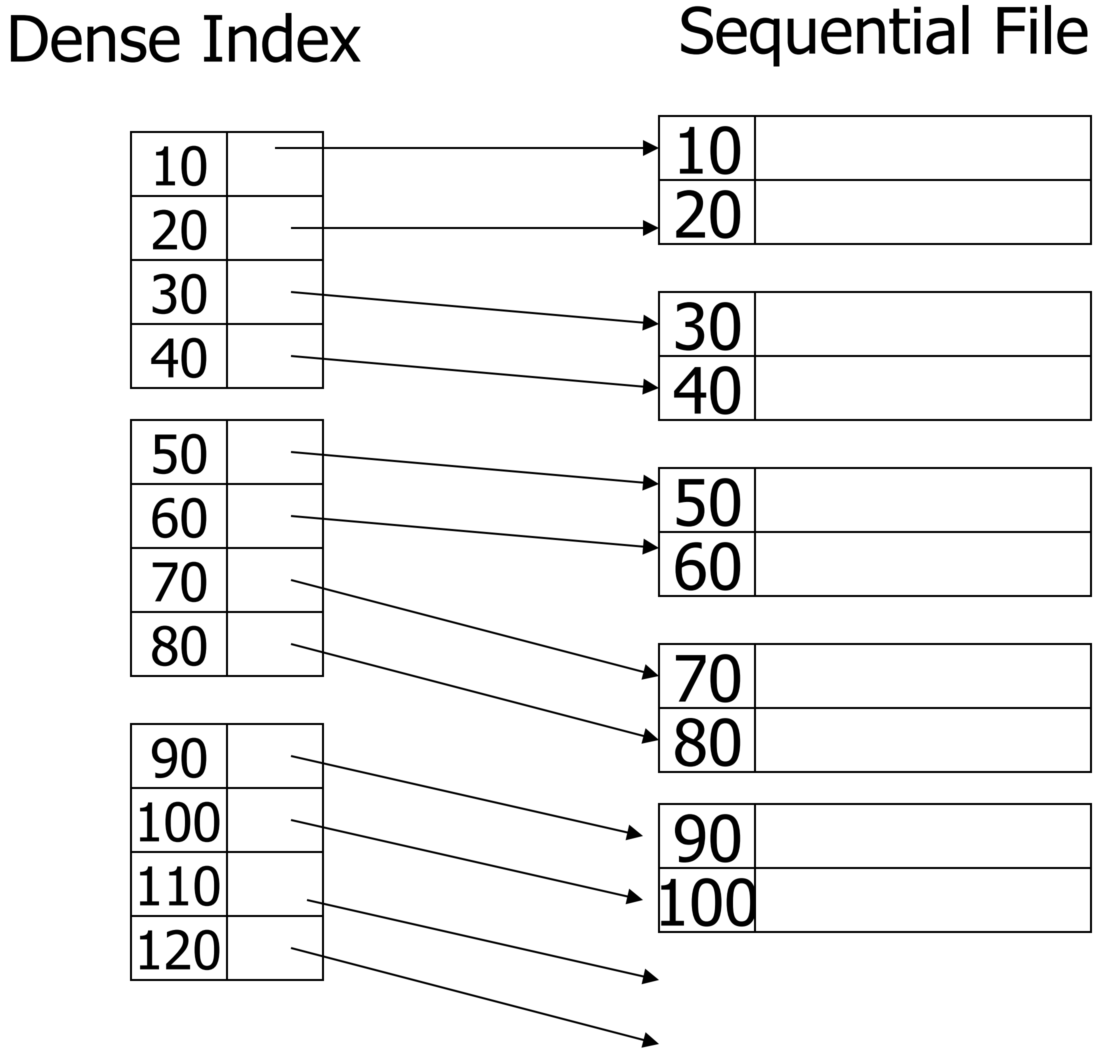
- Supported Query Types
- Secondary-storage capable
- Storage size
  - Index Size / Data Size
- Complexity of Operations
  - E.g., insert is O(log(n)) worst-case
- Efficient Concurrent Operations?

Topics

- Conventional indexes
- B-trees
- Hashing schemes
- Advanced Index Techniques

Sequential File



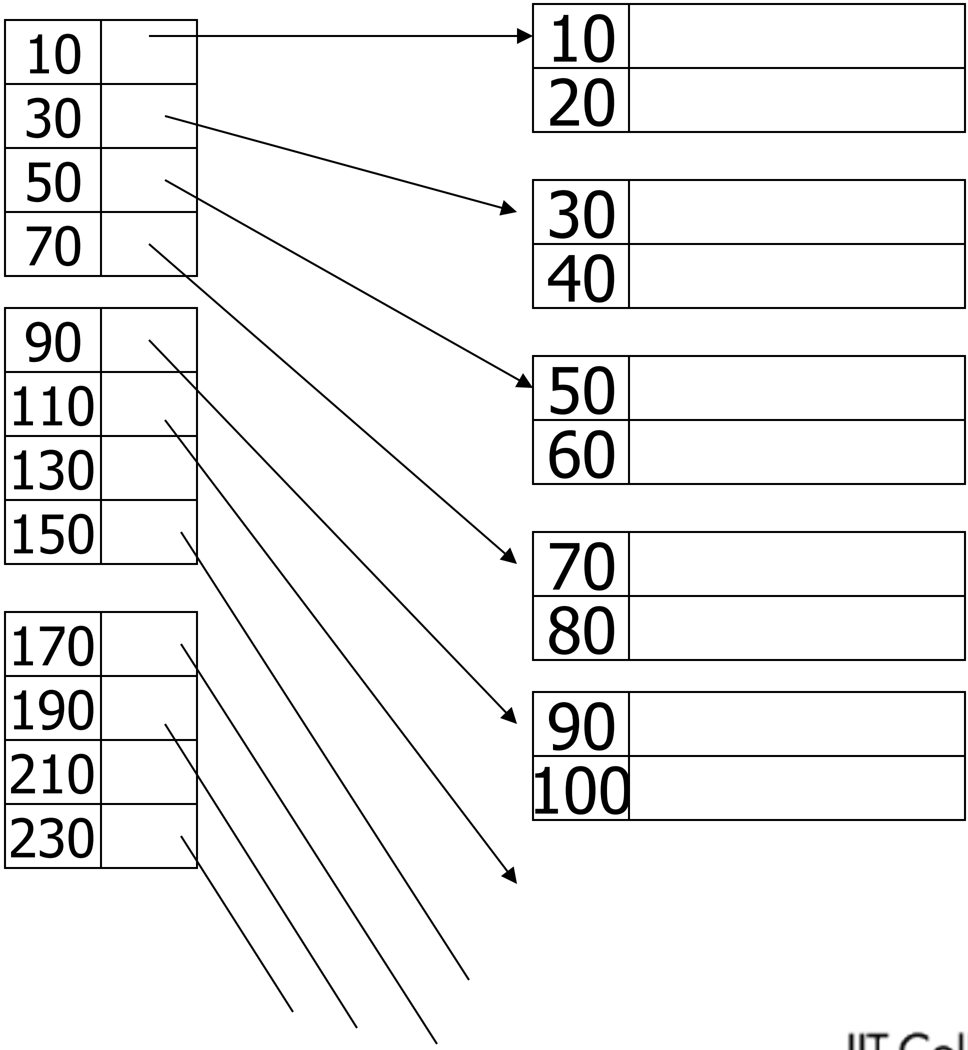


Dense Index

Sequential File

10
20
30
40
50
60
70
80
90
100
110
120

10
20
30
40
50
60
70
80
90
100

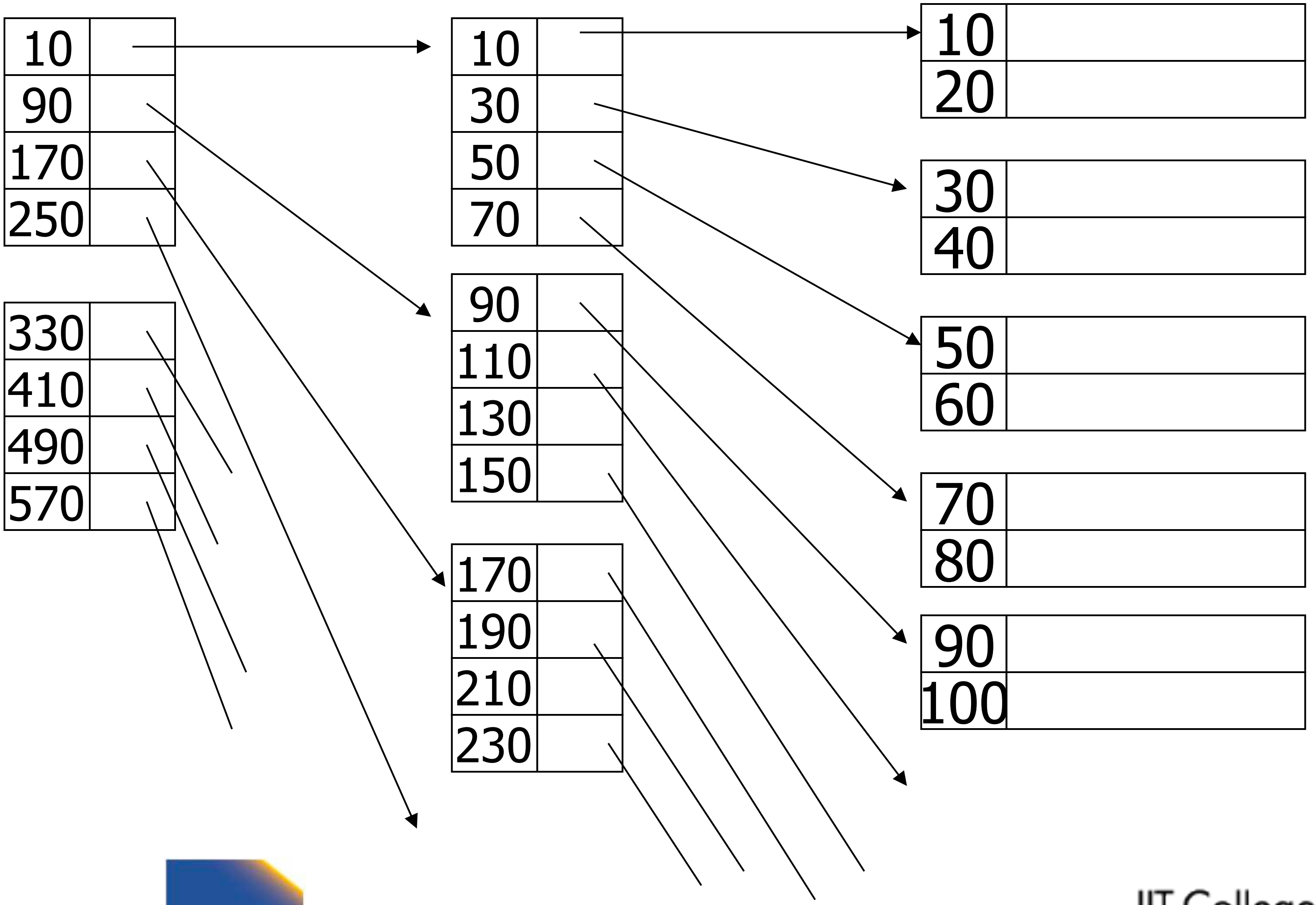


Sparse Index

Sequential File

Sparse 2nd level

Sequential File


10
90
170
250

330
410
490
570

10
30
50
70

90
110
130
150

170
190
210
230

10
20

30
40

50
60

70
80

90
100

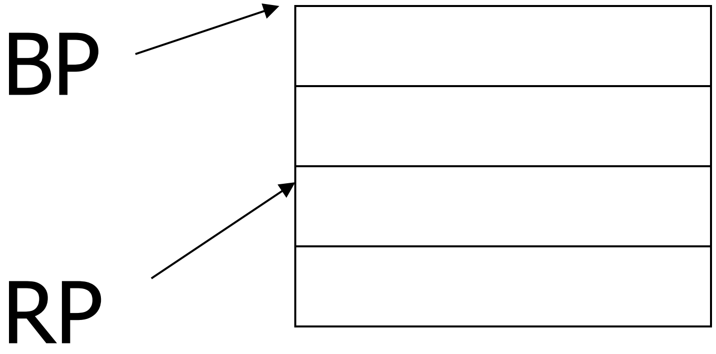
- Comment:
  {FILE,INDEX} may be contiguous
  or not (blocks chained)

Question:

- Can we build a dense, 2nd level index for a dense index?

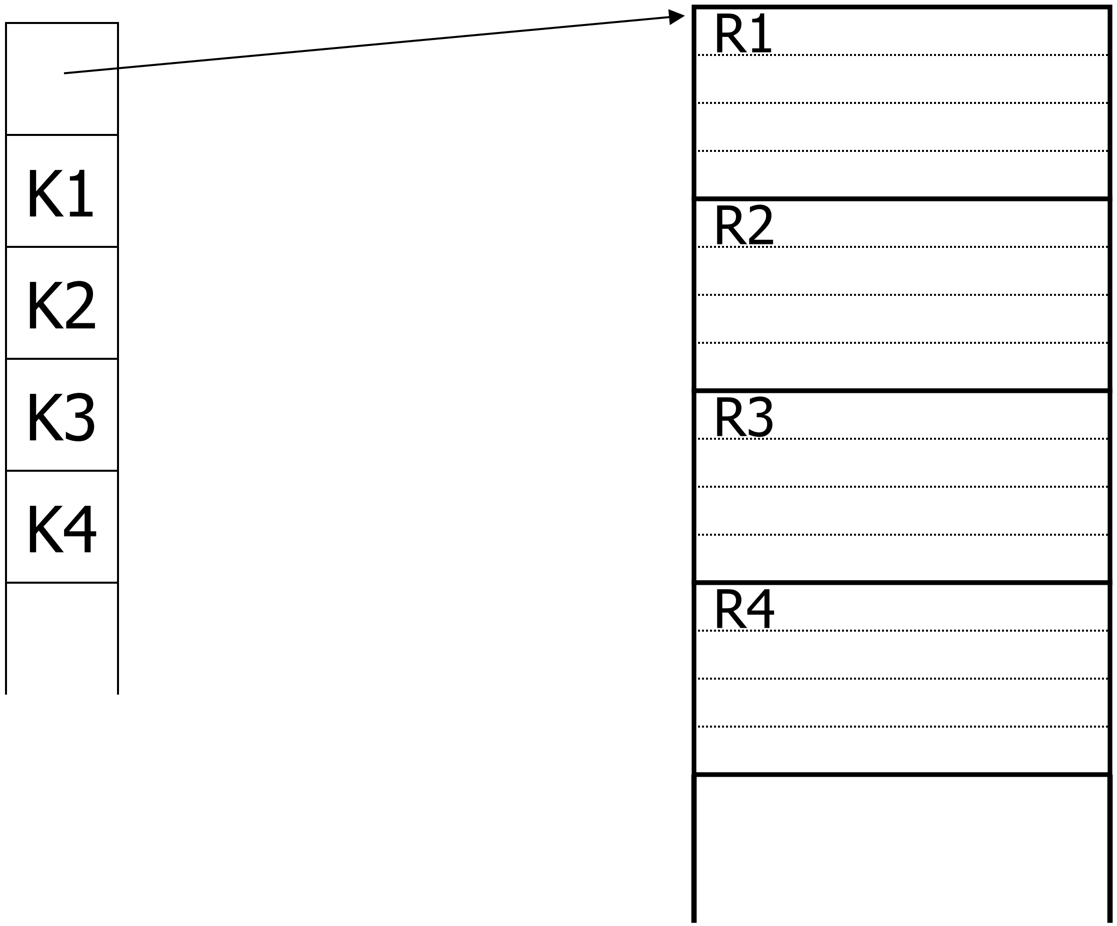
Notes on pointers:

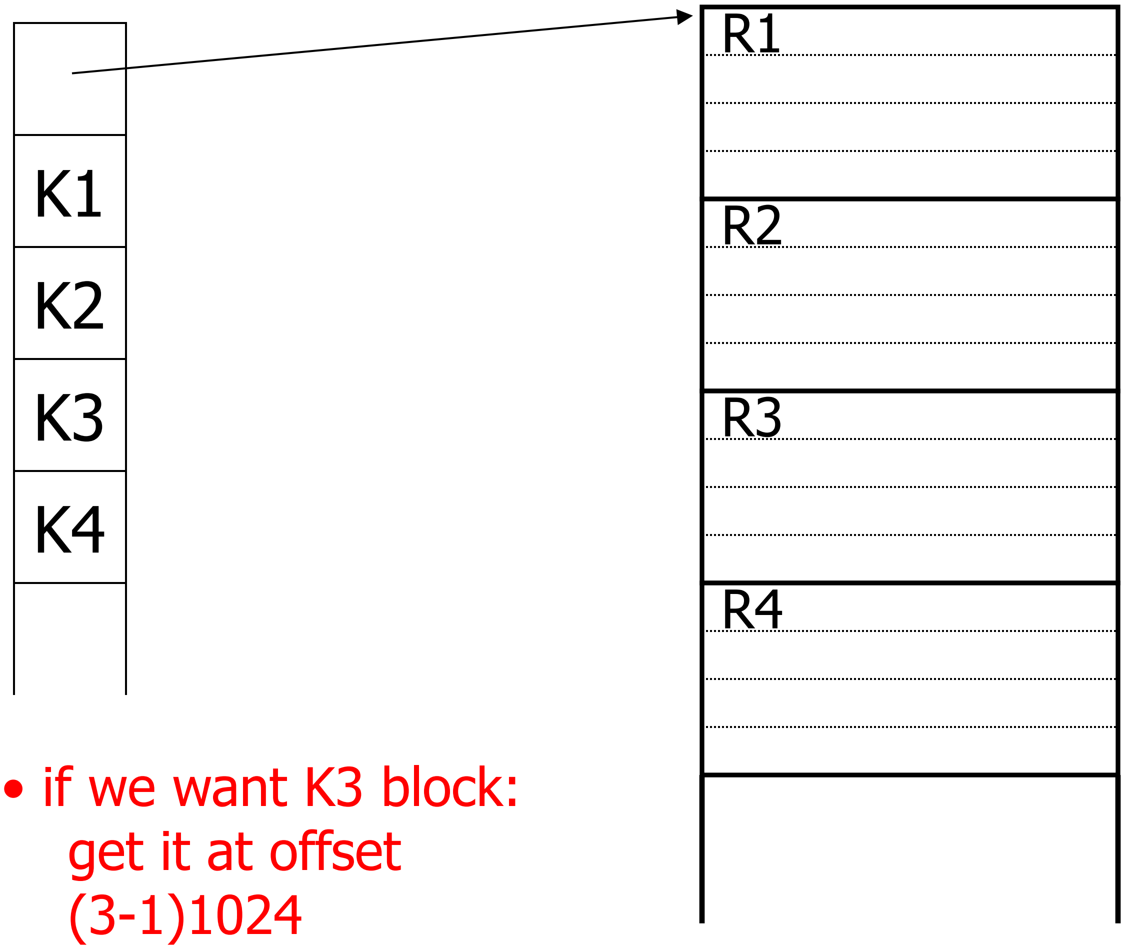
(1) Block pointer (sparse index) can be smaller than record pointer



Notes on pointers:

(2) If file is contiguous, then we can omit pointers (i.e., compute them)


K1
K2
K3
K4
R1
R2
R3
R4



say:
1024 B
per block

- if we want K3 block:
  get it at offset
  (3-1)1024
  = 2048 bytes

Sparse vs. Dense Tradeoff

- Sparse: Less index space per record
  can keep more of index
  in memory
- Dense: Can tell if any record exists
  without accessing file

(Later:

- sparse better for insertions
- dense needed for secondary indexes)

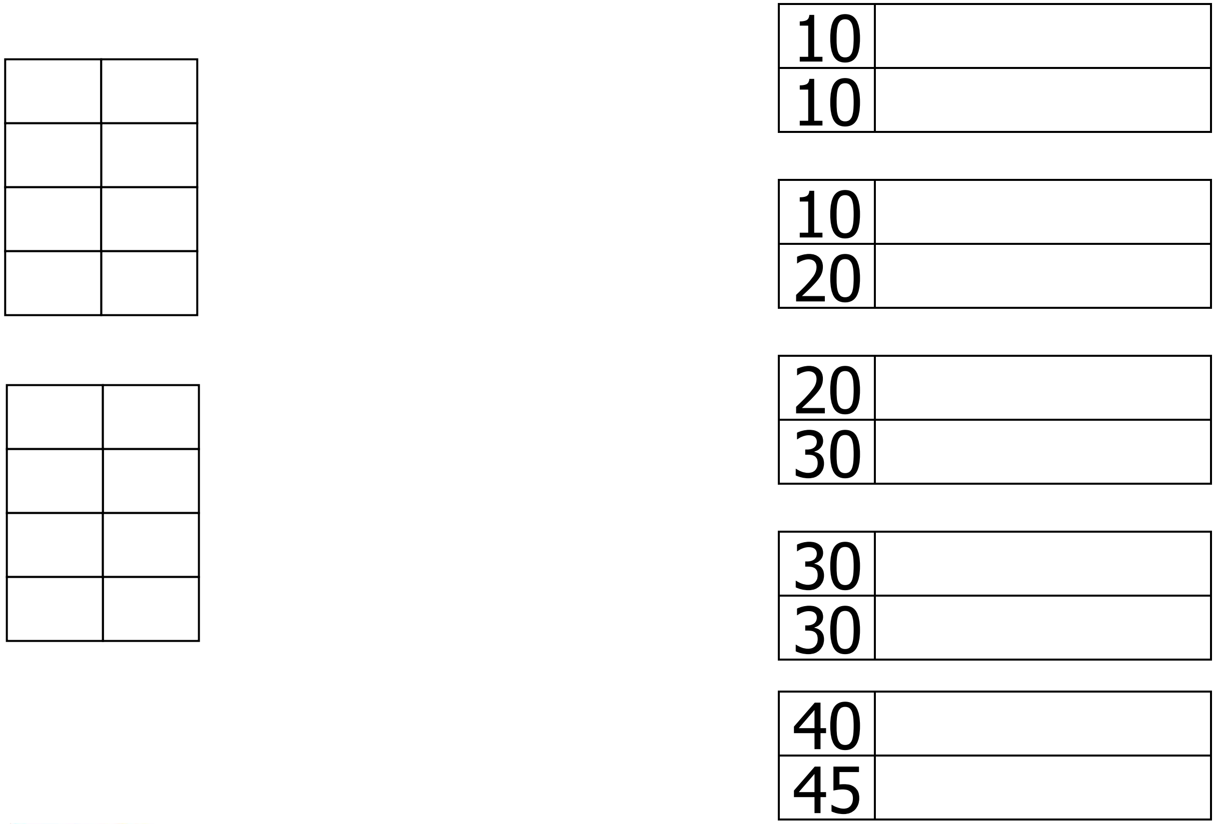
Terms

- Index sequential file
- Search key (≠ primary key)
- Primary index (on Sequencing field)
- Secondary index
- Dense index (all Search Key values in)
- Sparse index
- Multi-level index

Next:

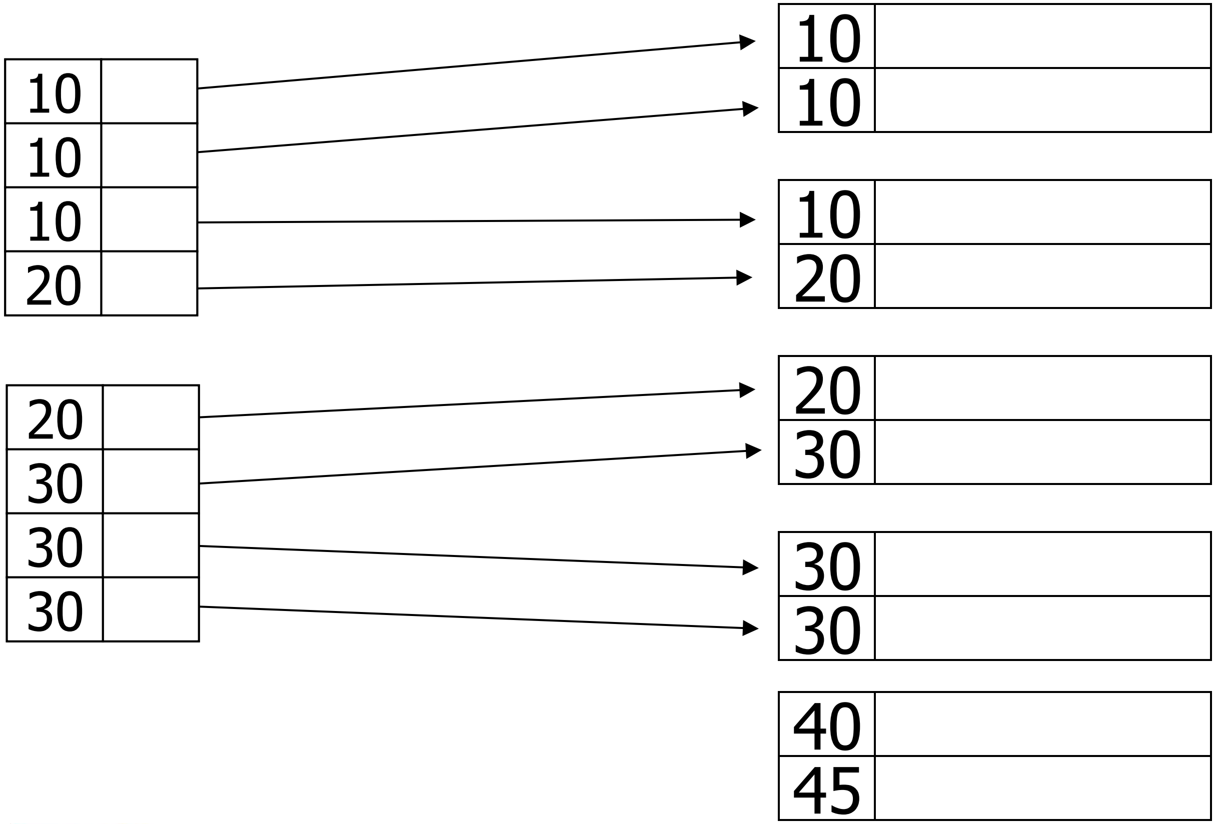
- Duplicate keys
- Deletion/Insertion
- Secondary indexes

Duplicate keys



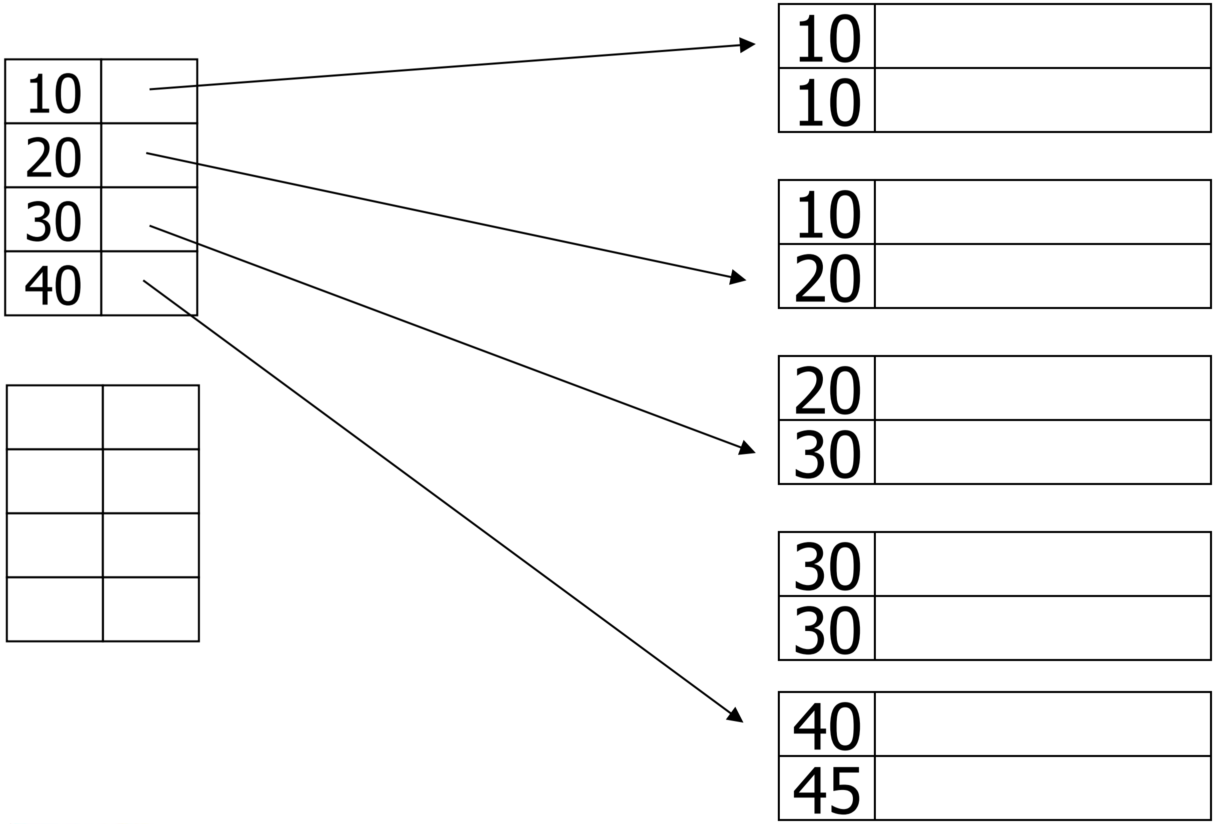
Duplicate keys

Dense index, one way to implement?



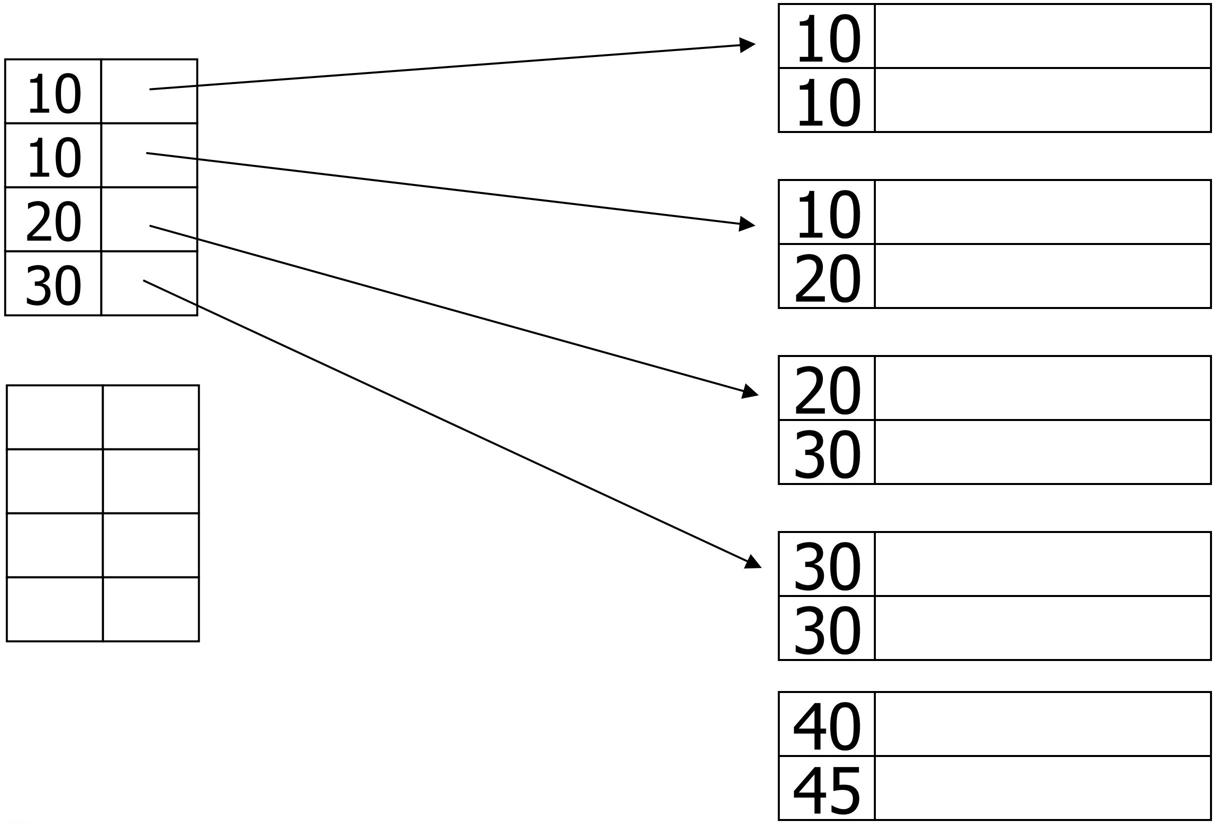
Duplicate keys

Dense index, better way?



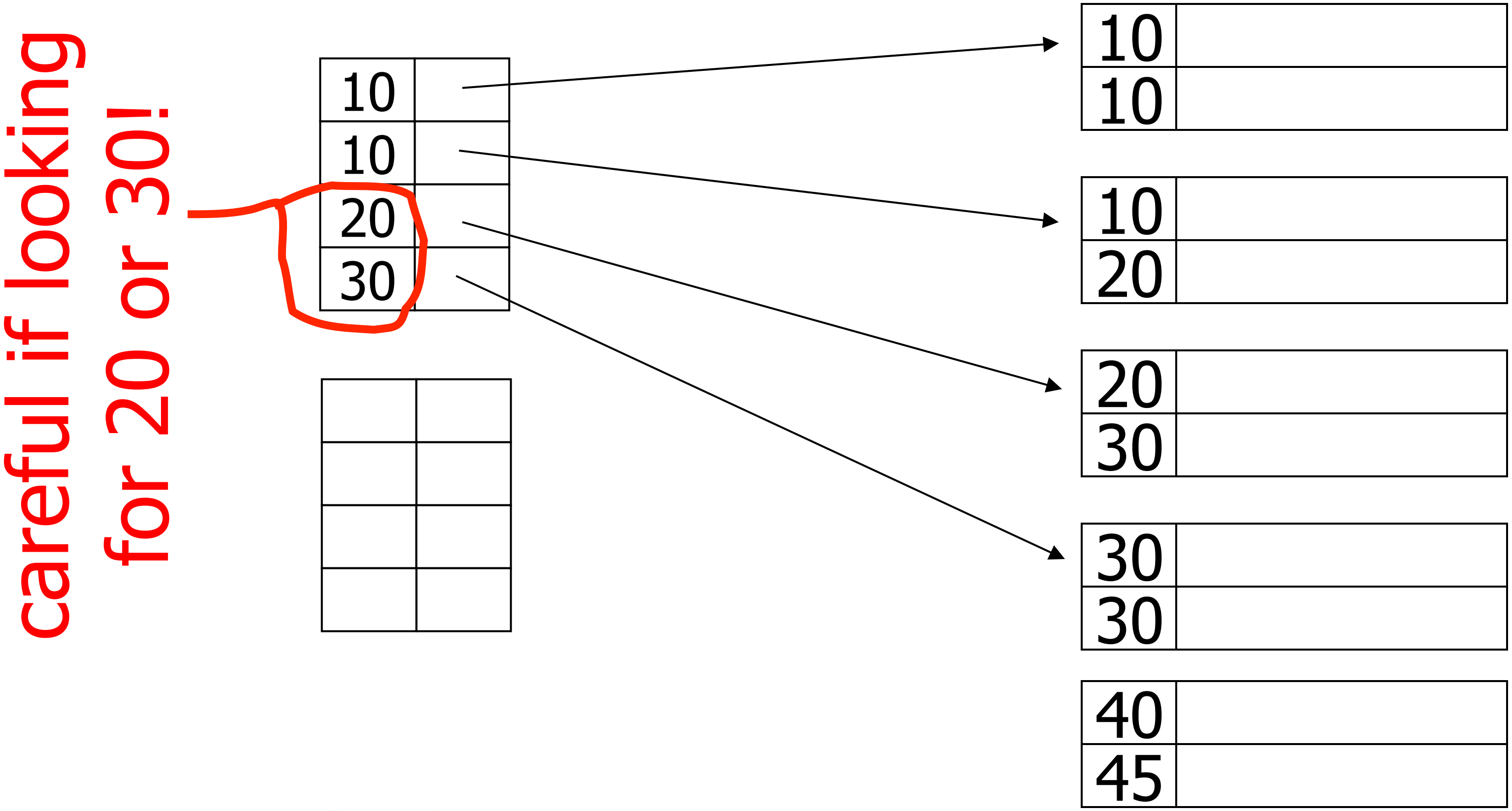
Duplicate keys

Sparse index, one way?



Duplicate keys

Sparse index, one way?

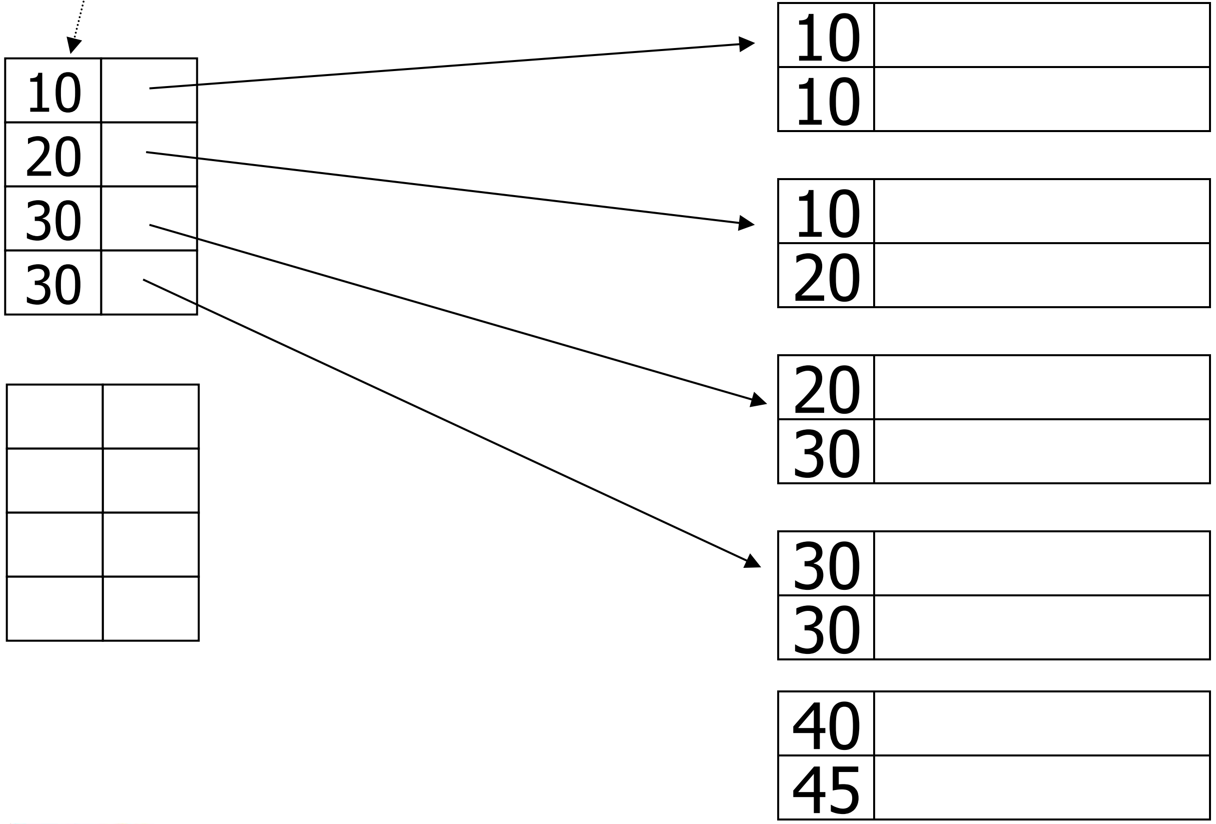


careful if looking for 20 or 30!

Duplicate keys

Sparse index, another way?

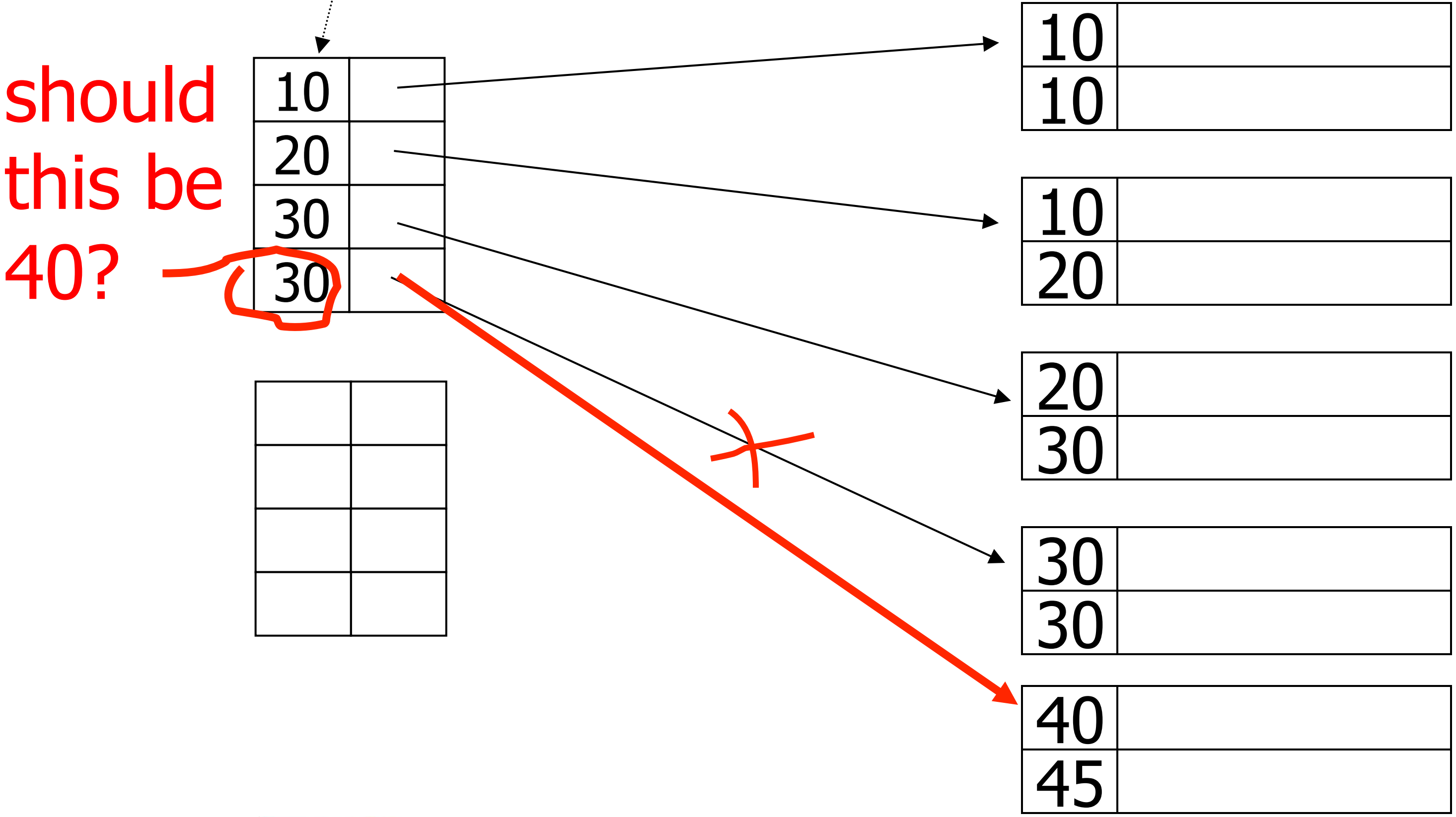
- place first new key from block



Duplicate keys

Sparse index, another way?

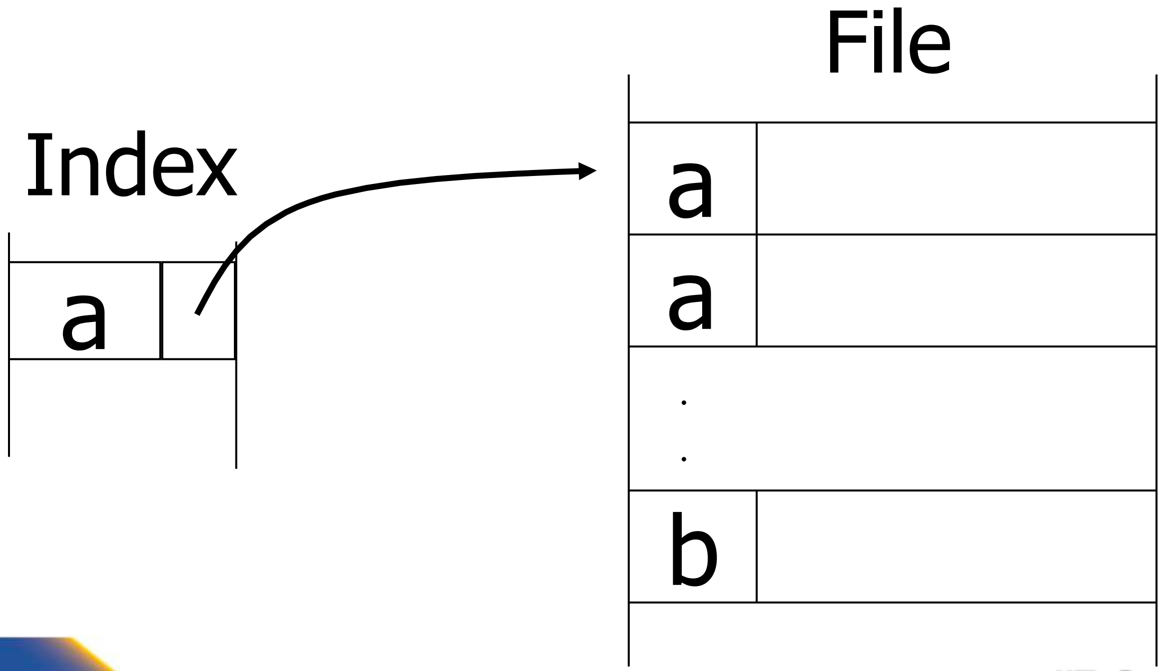
- place first new key from block



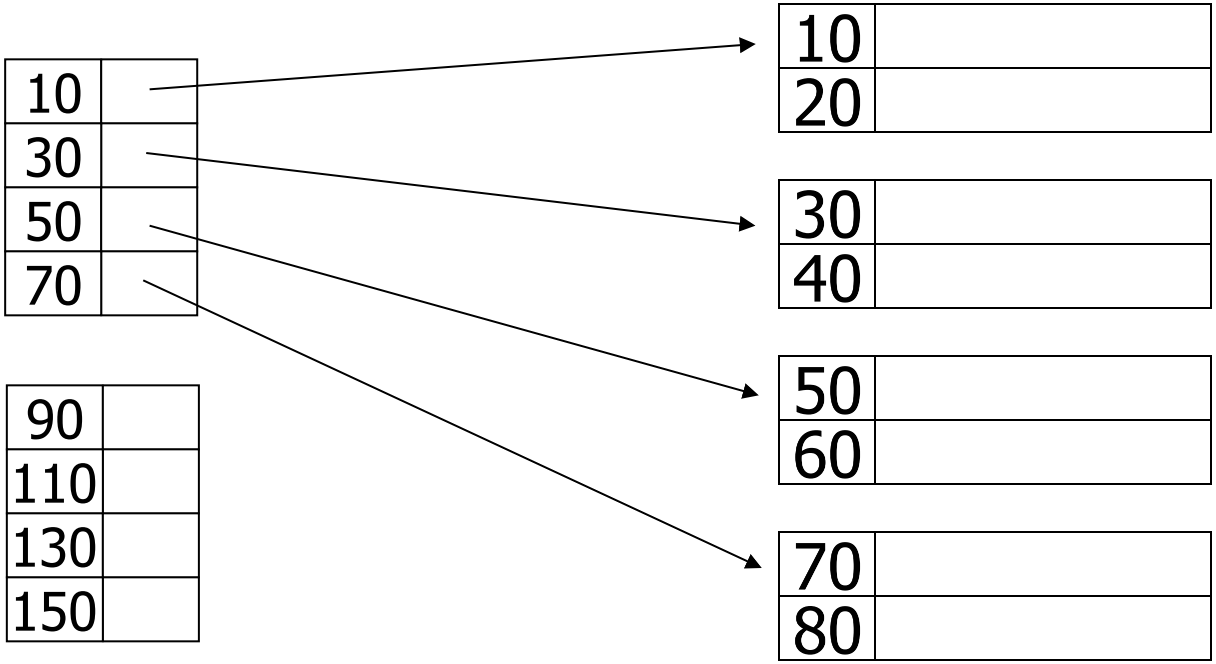
Summary

Duplicate values, primary index

- Index may point to <u>first</u> instance of each value only

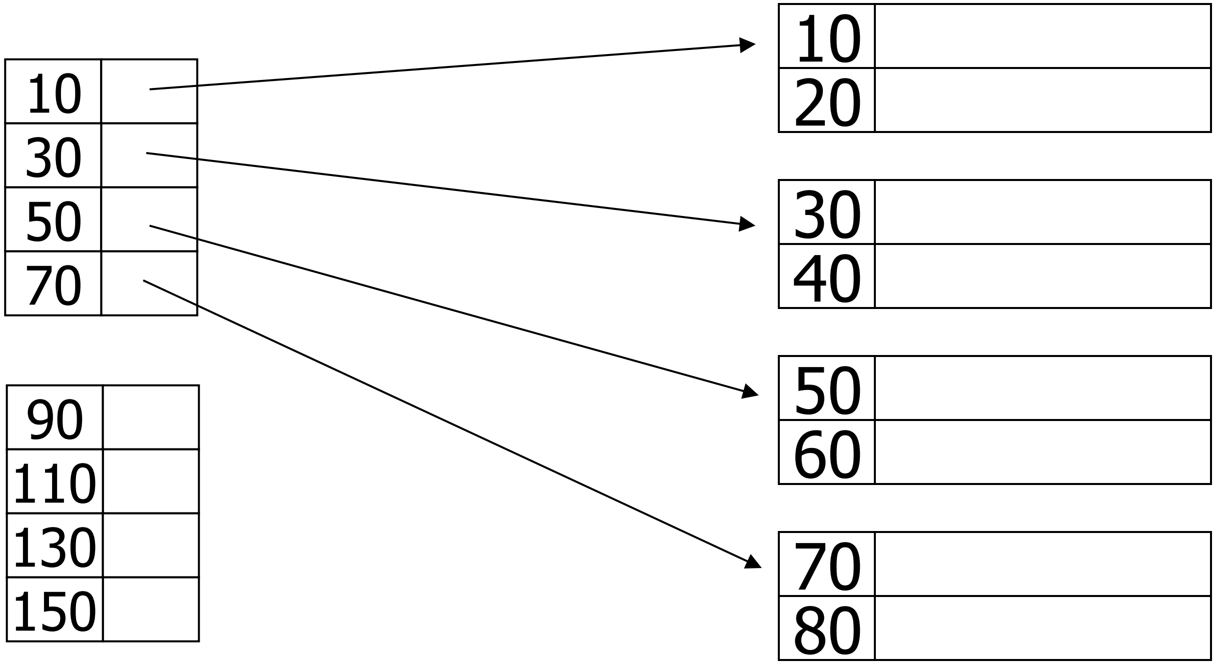


Deletion from sparse index



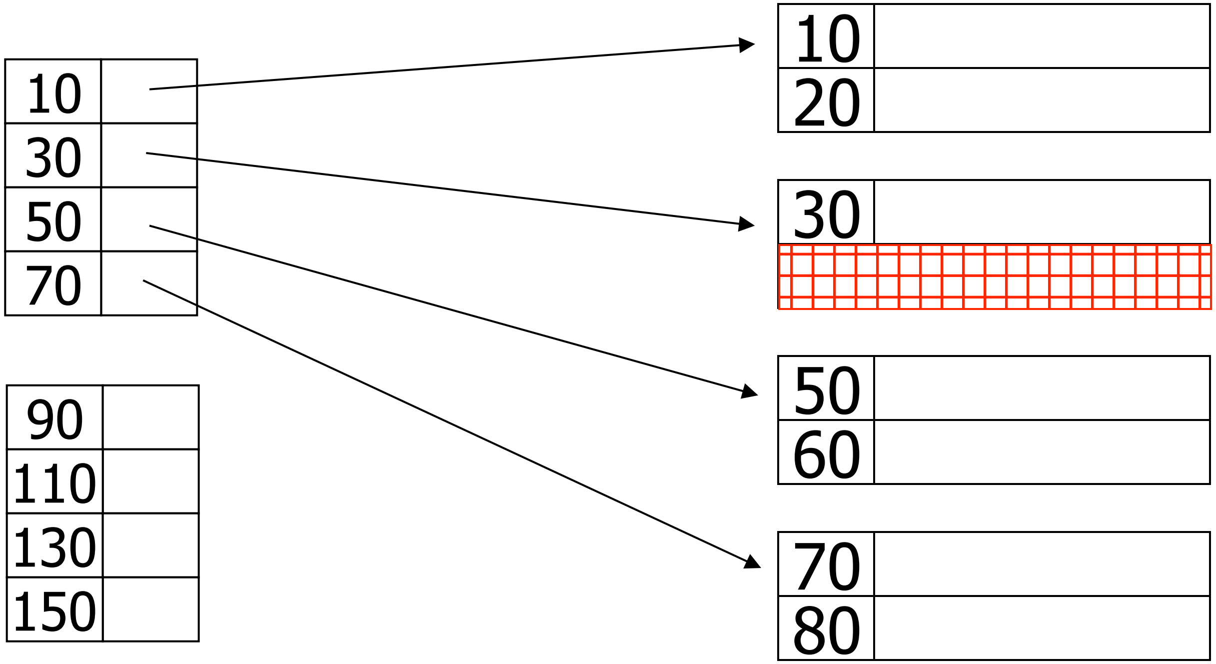
Deletion from sparse index

- delete record 40



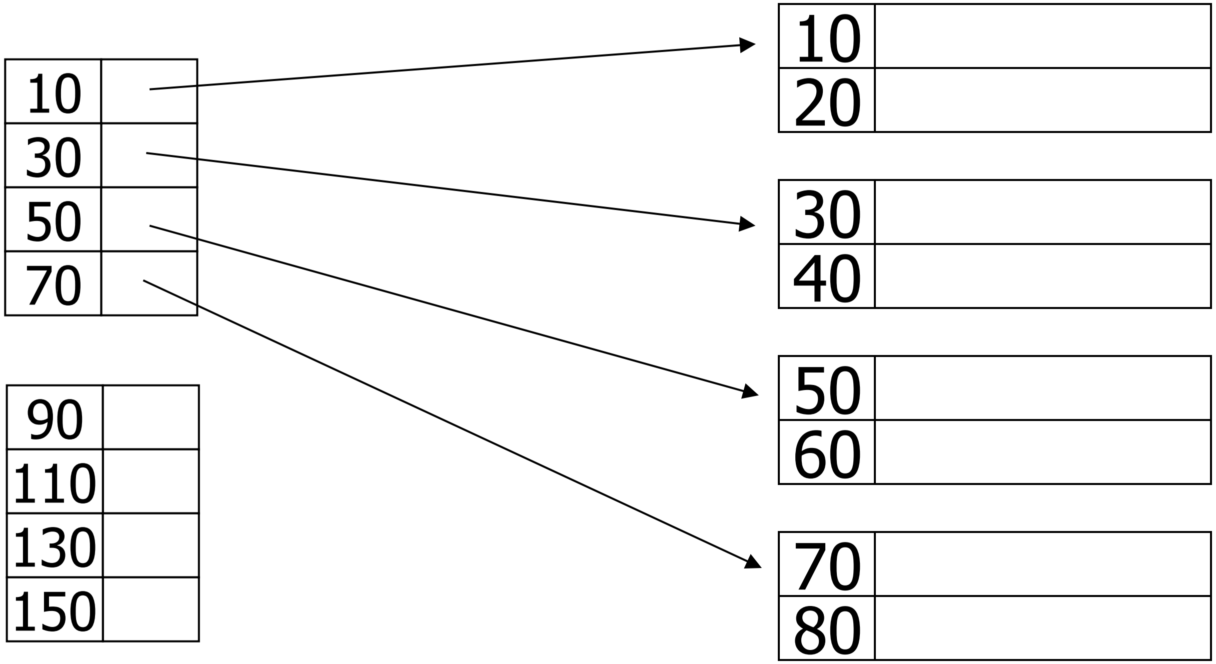
Deletion from sparse index

– delete record 40



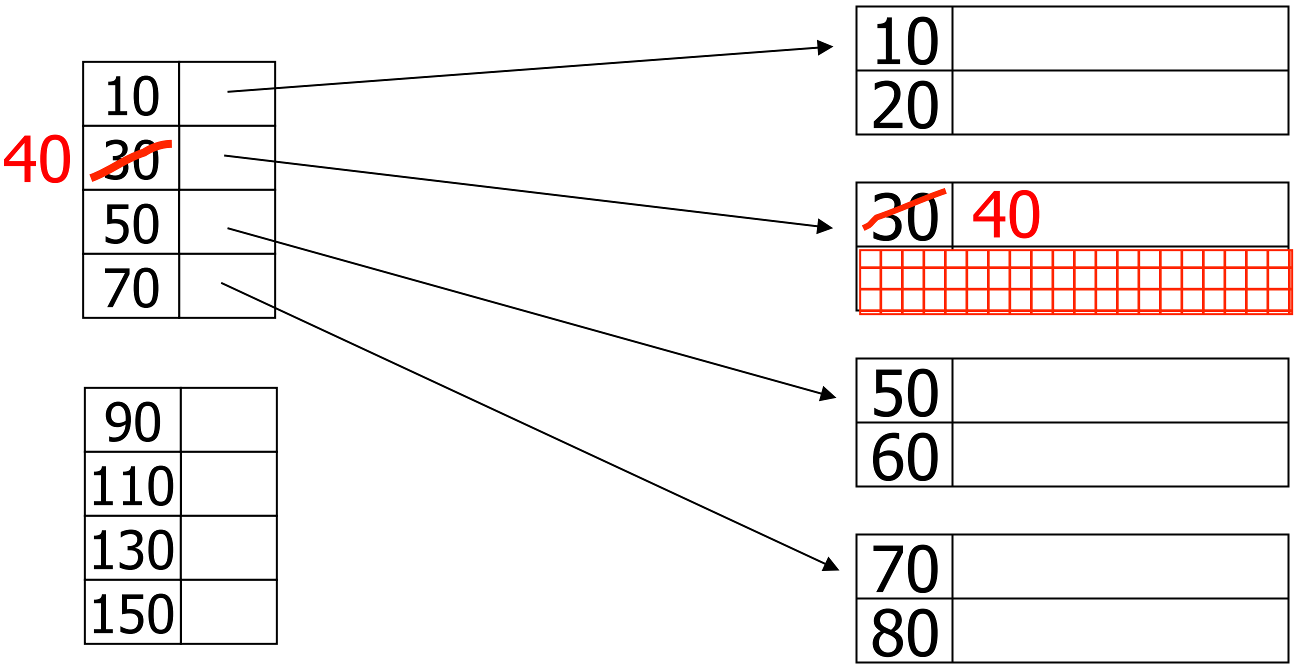
Deletion from sparse index

- delete record 30



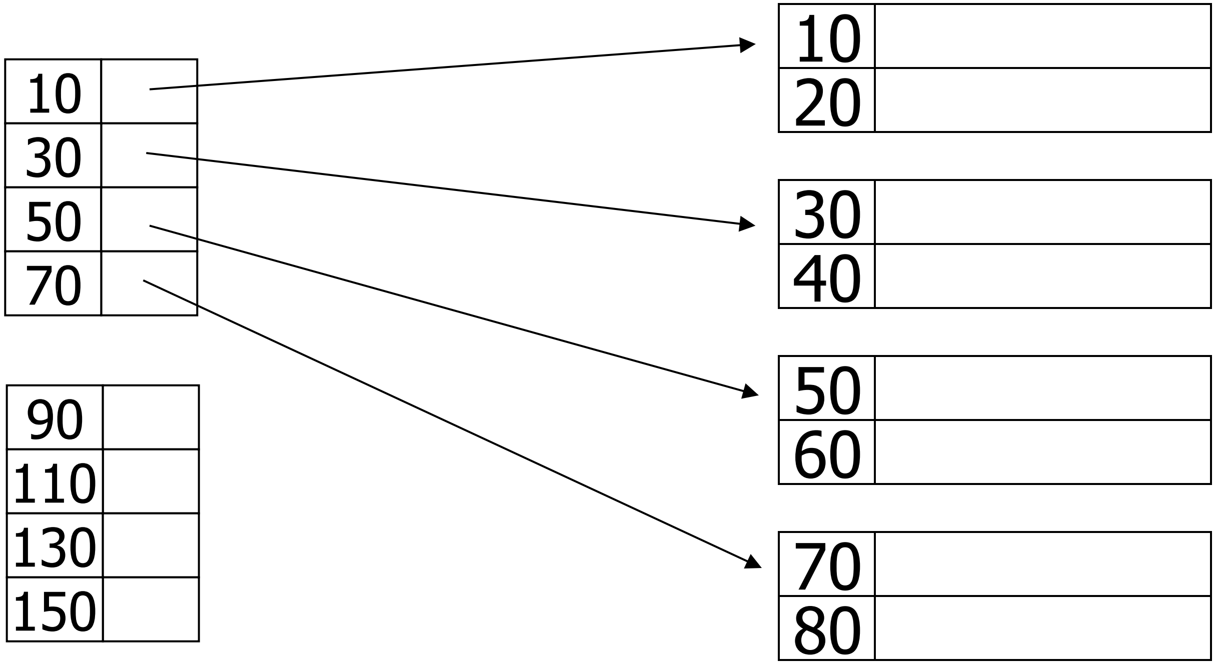
Deletion from sparse index

- delete record 30



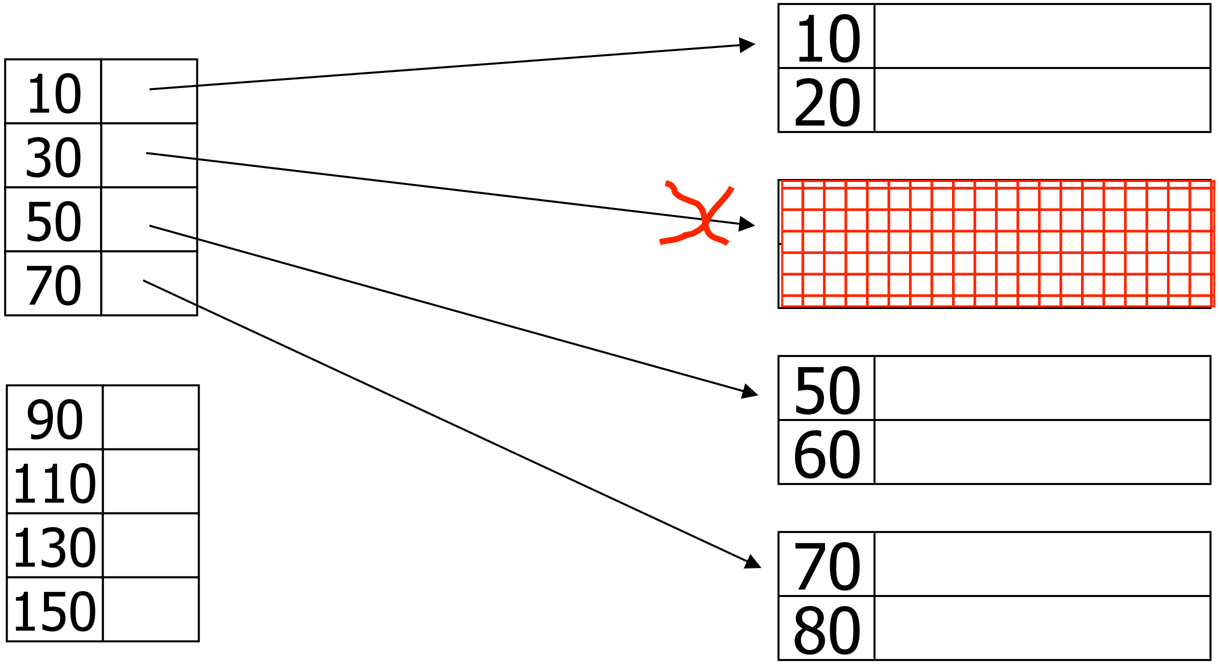
Deletion from sparse index

– delete records 30 & 40



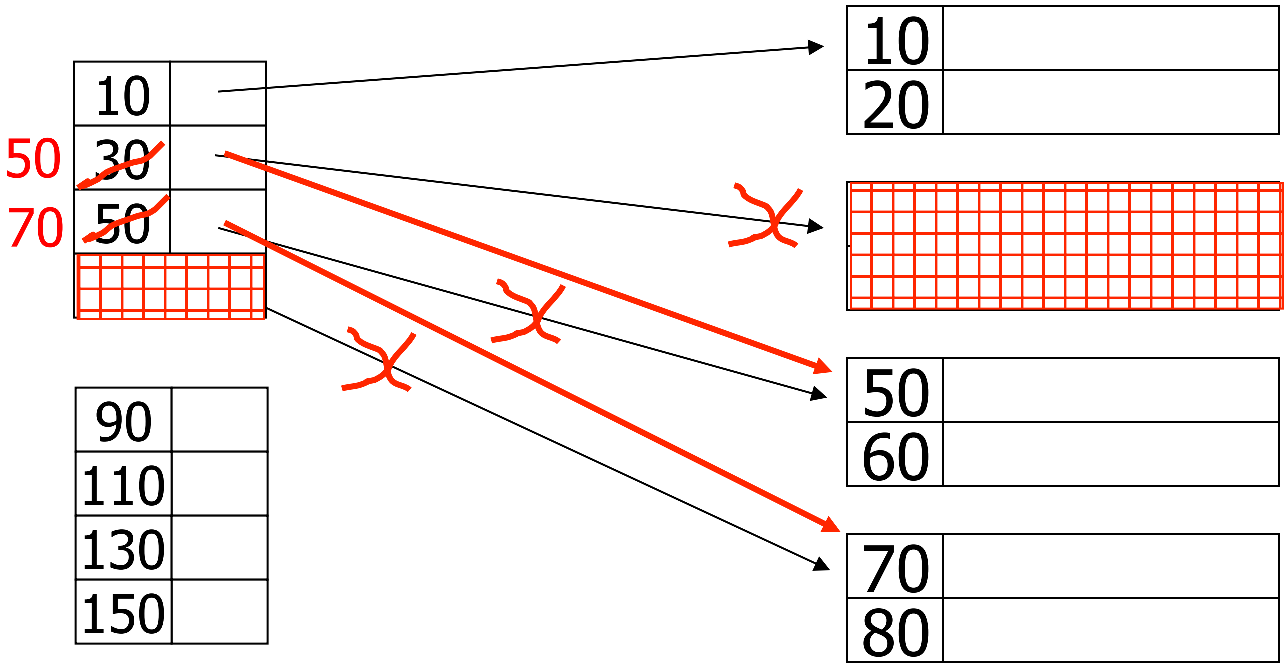
Deletion from sparse index

– delete records 30 & 40

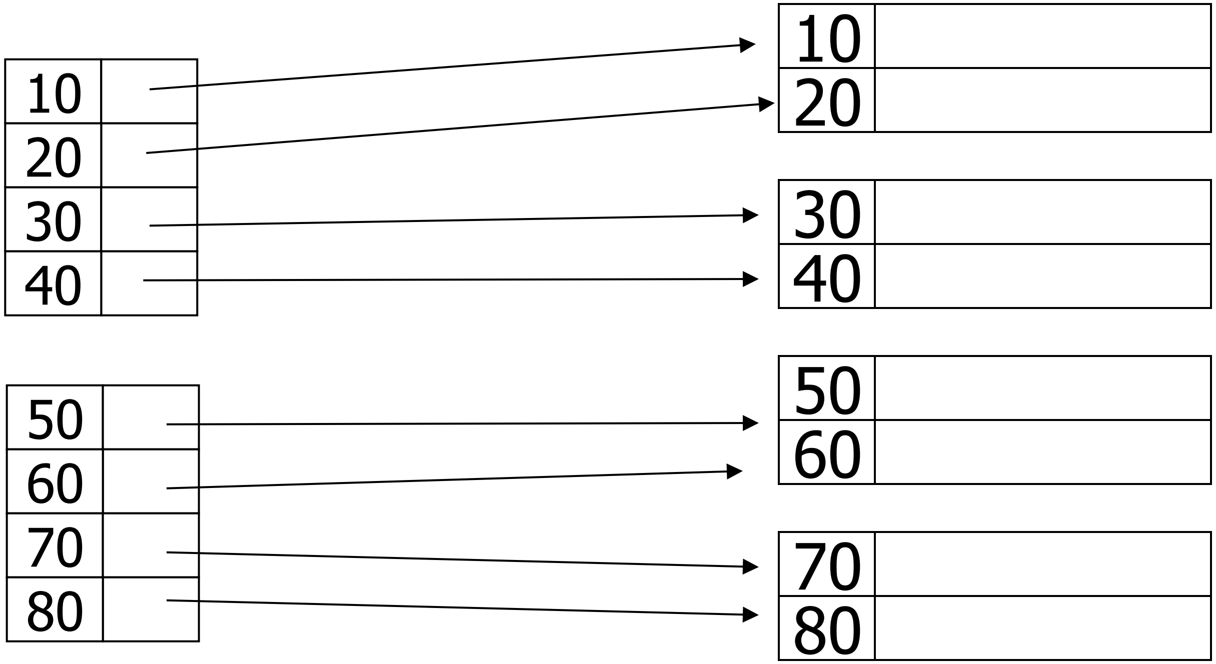


Deletion from sparse index

– delete records 30 & 40

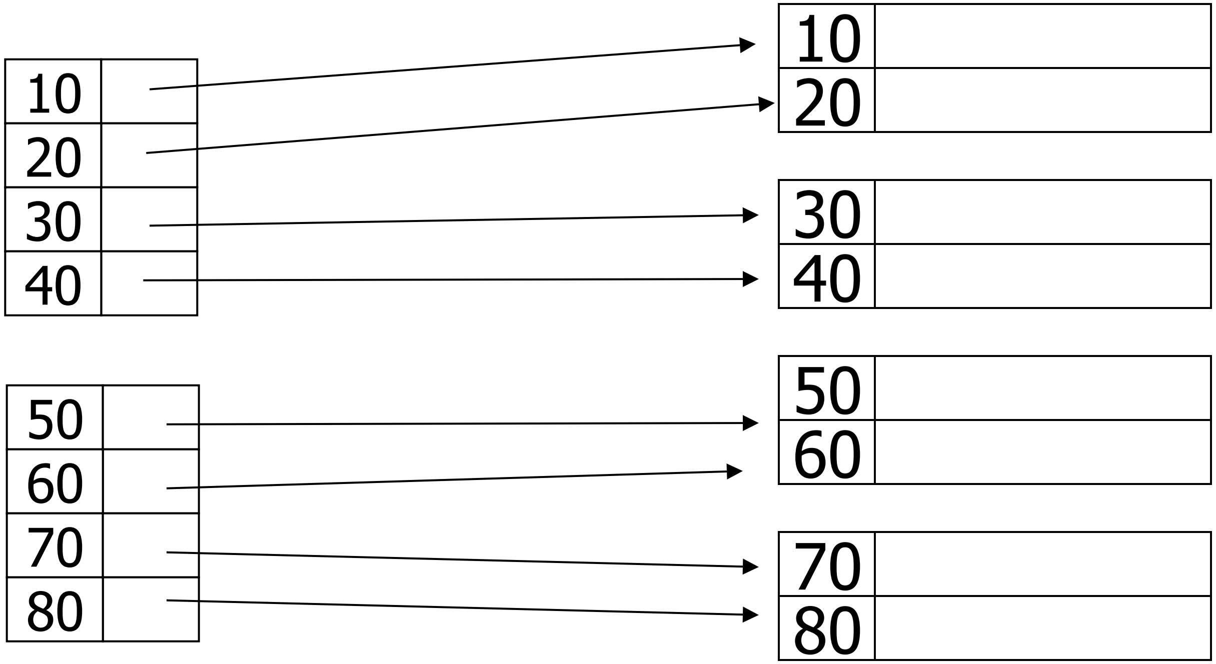


Deletion from dense index



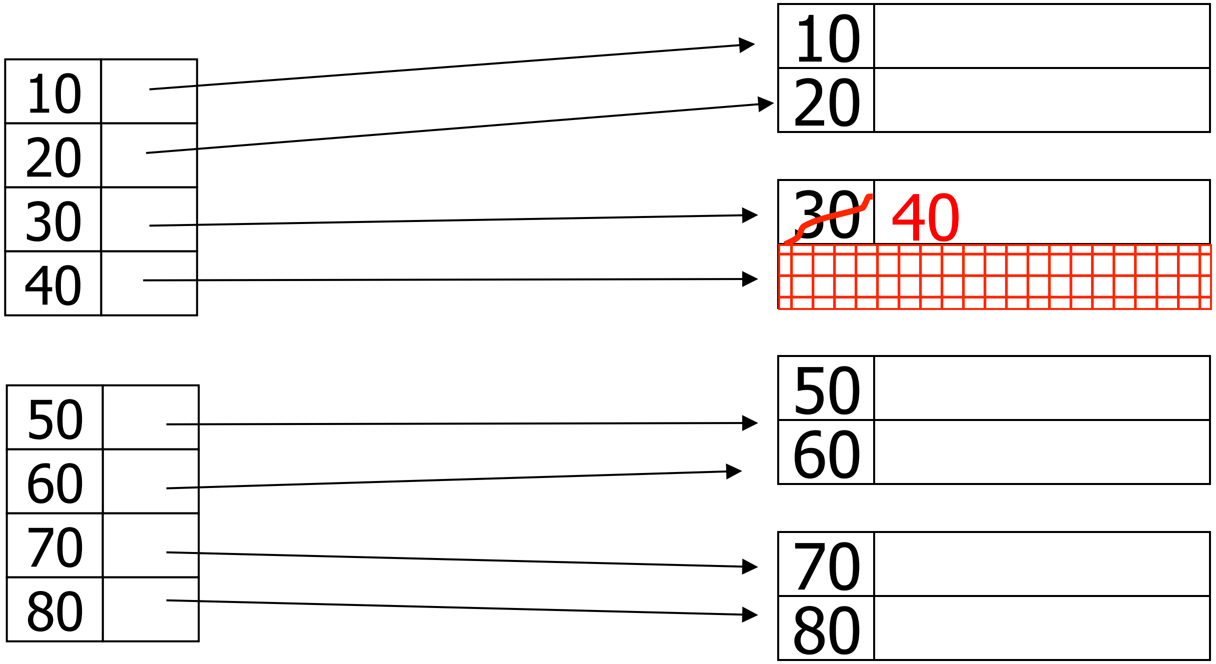
Deletion from dense index

- delete record 30



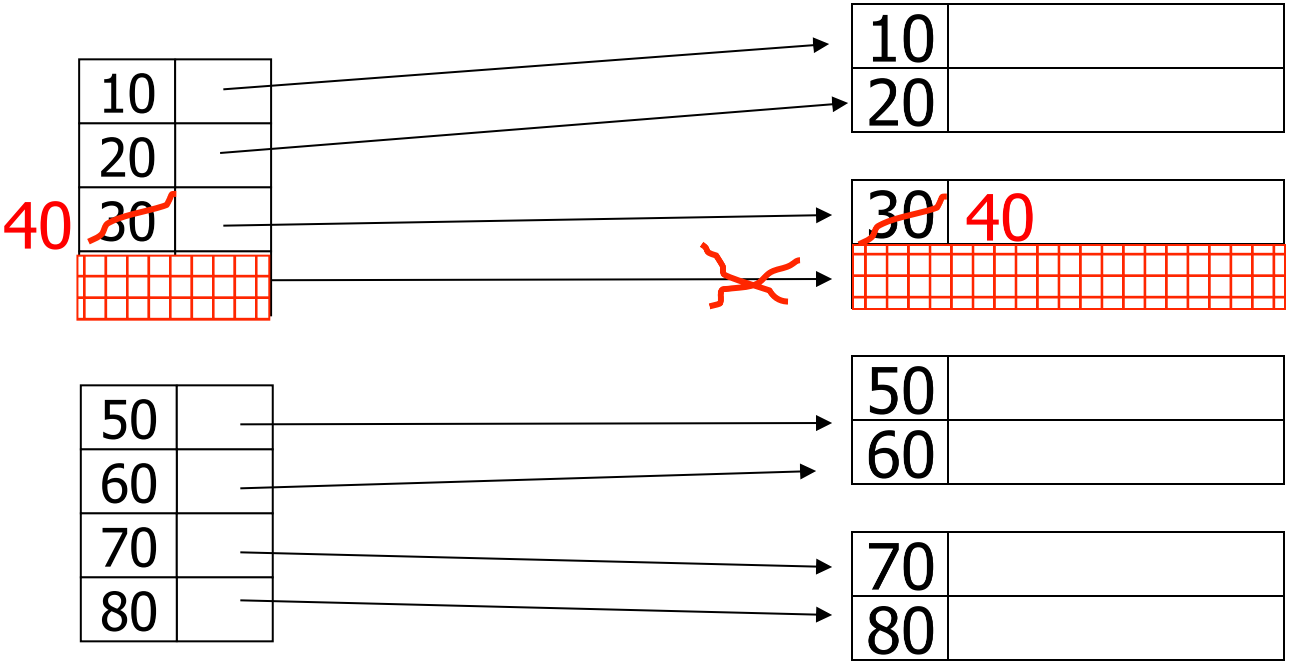
Deletion from dense index

– delete record 30

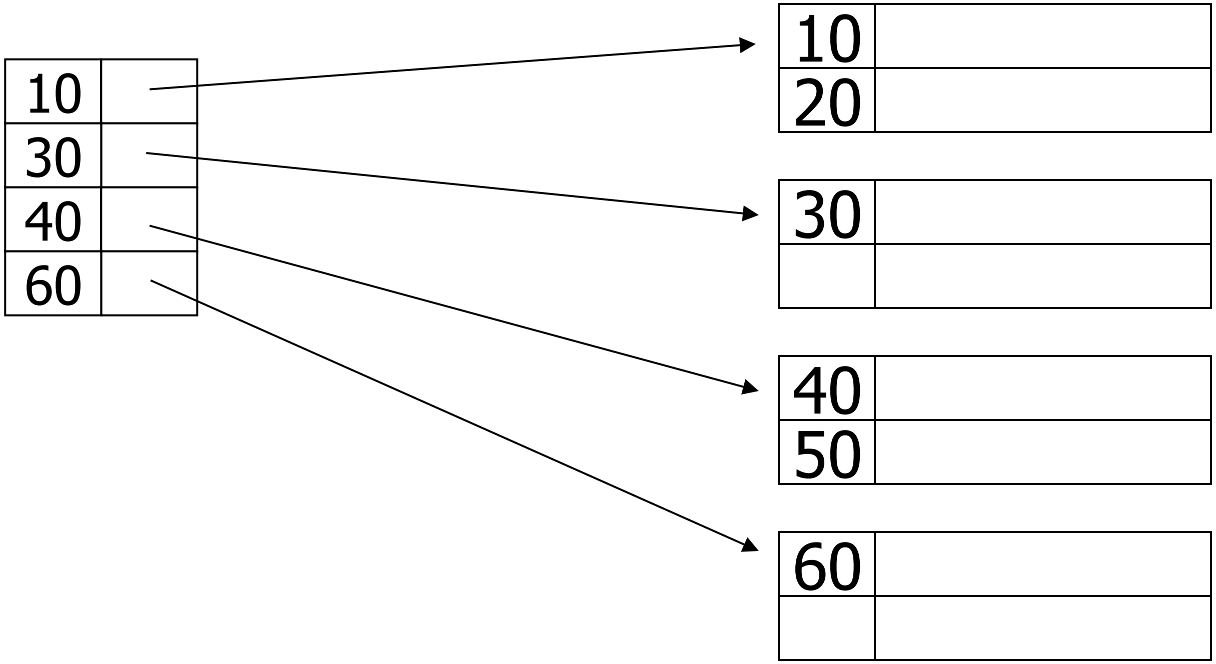


Deletion from dense index

- delete record 30

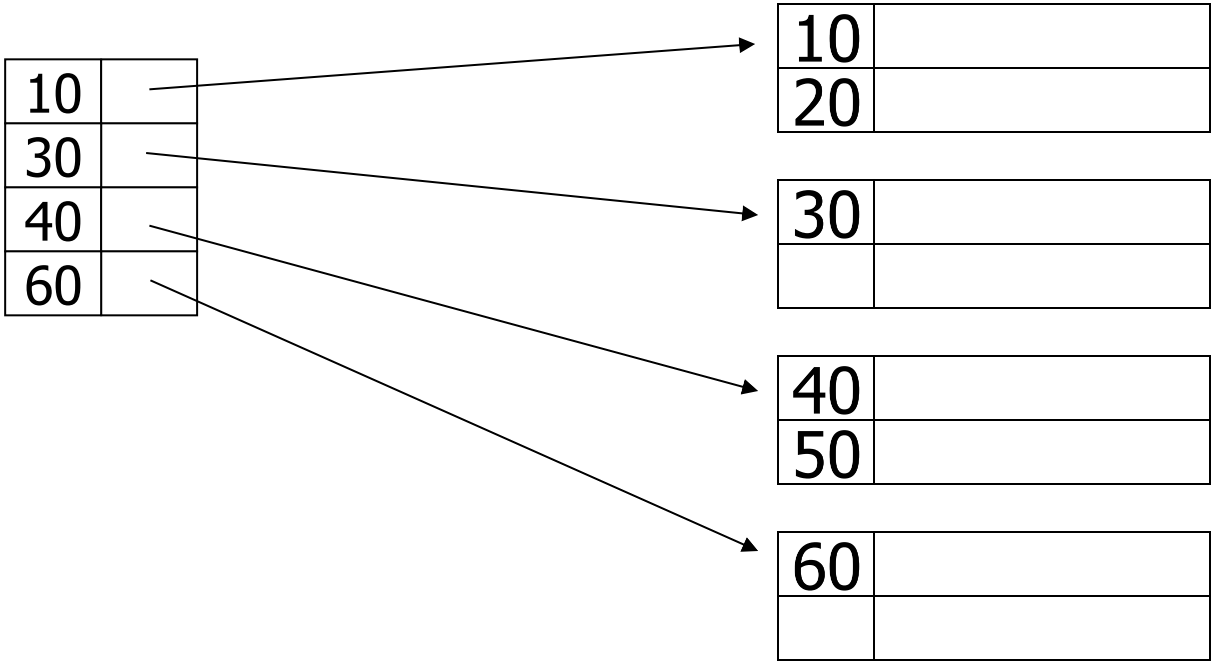


Insertion, sparse index case



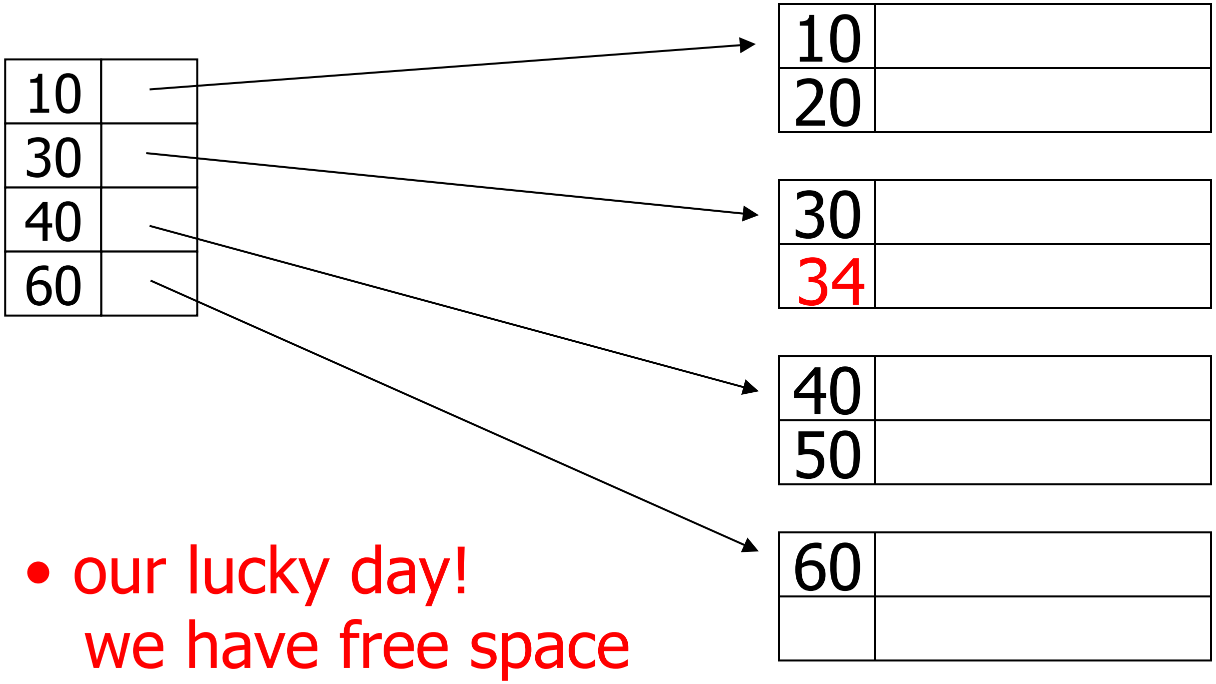
Insertion, sparse index case

- insert record 34



Insertion, sparse index case

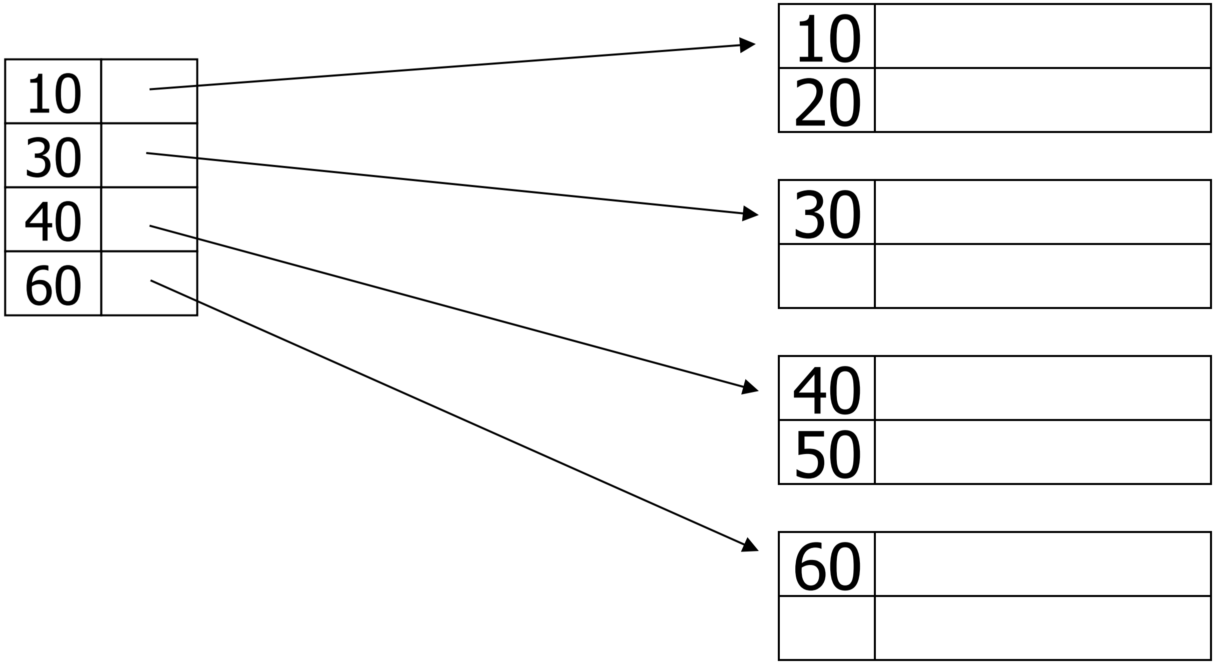
– insert record 34



- our lucky day!
  we have free space
  where we need it!

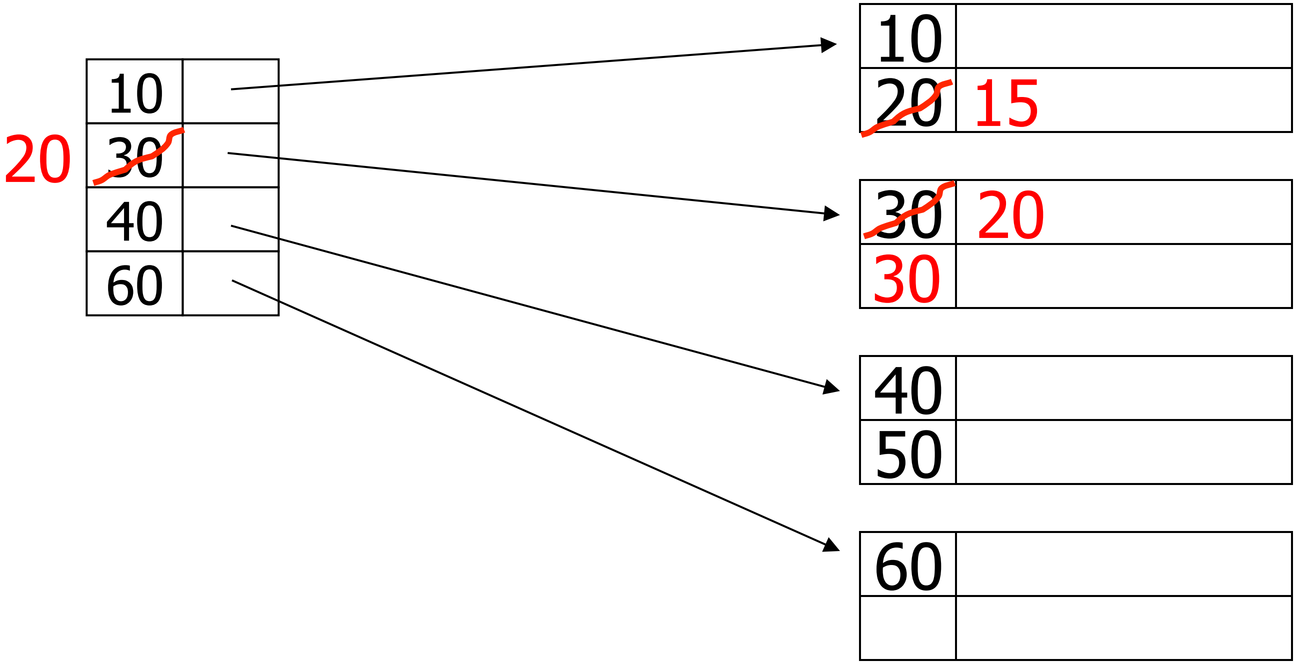
Insertion, sparse index case

– insert record 15



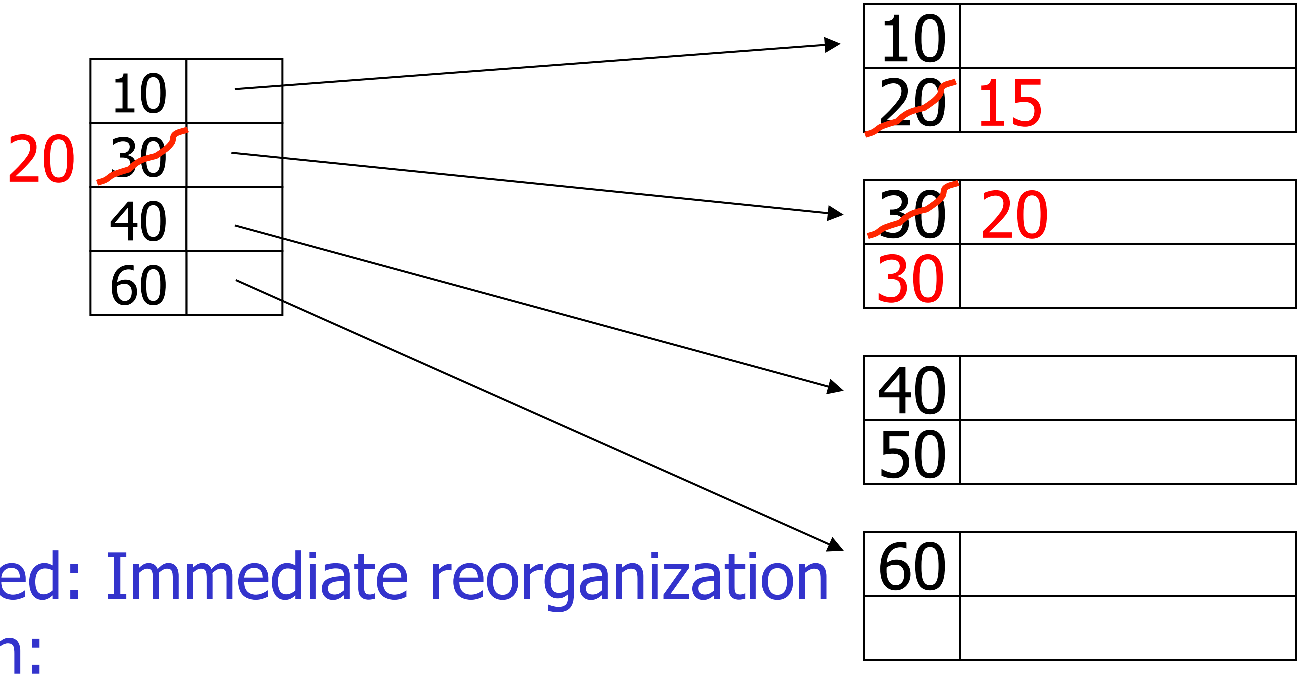
Insertion, sparse index case

– insert record 15



Insertion, sparse index case

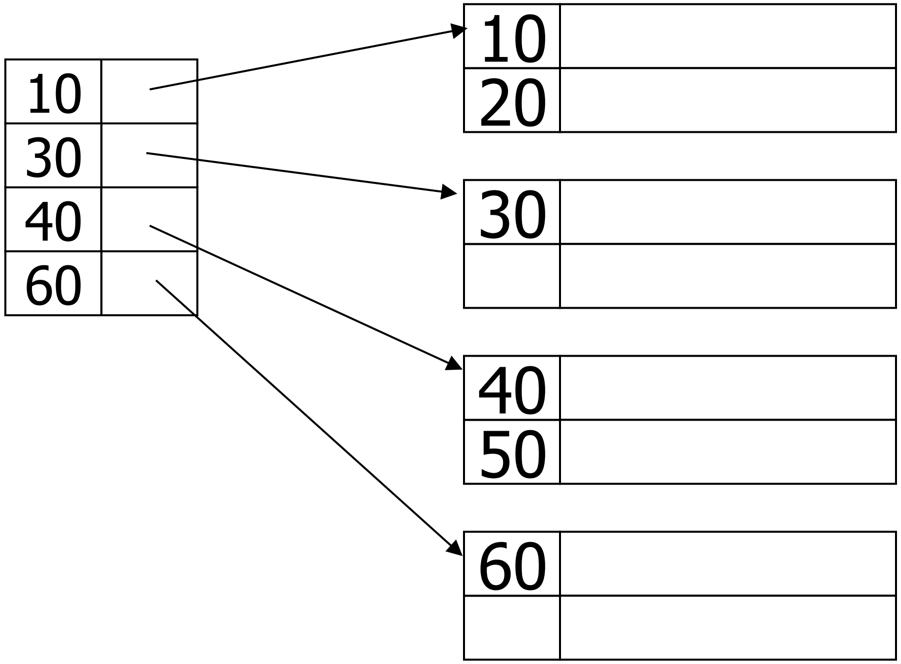
– insert record 15



- Illustrated: Immediate reorganization
- Variation:
  - insert new block (chained file)
  - update index

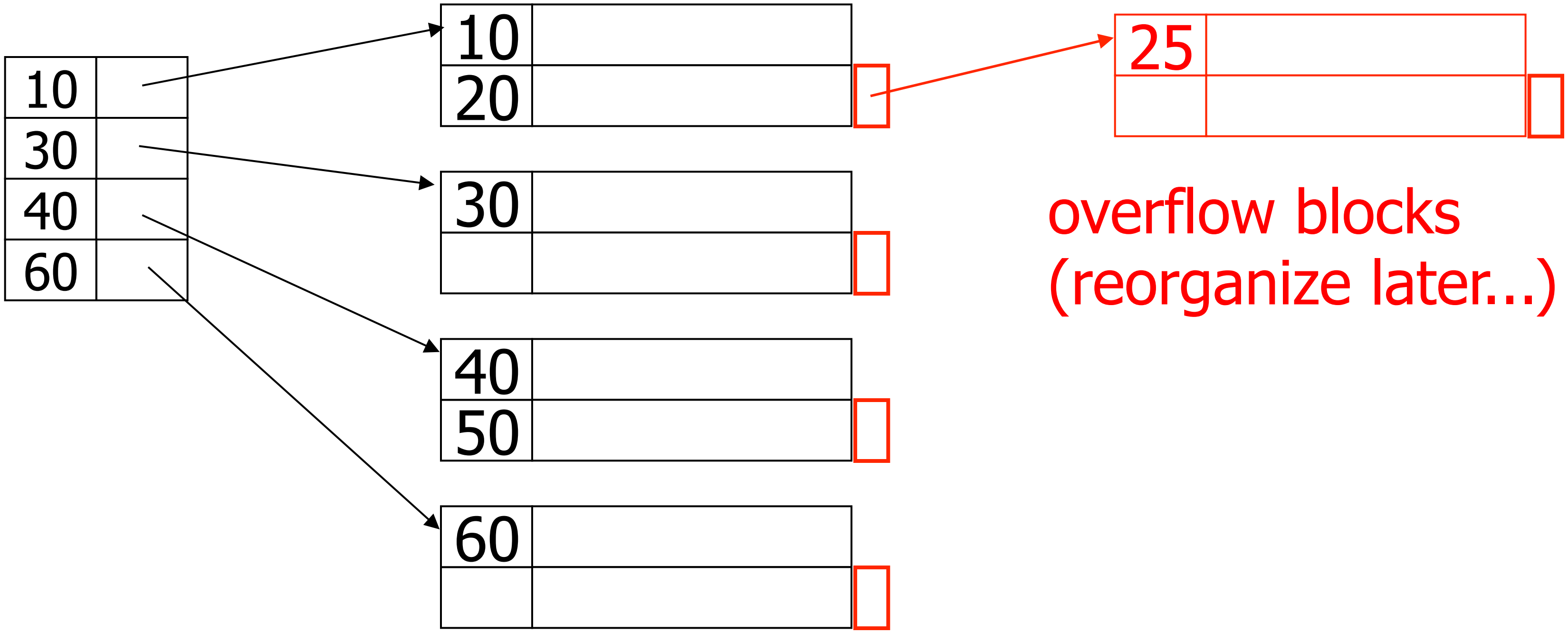
Insertion, sparse index case

- insert record 25



Insertion, sparse index case

– insert record 25

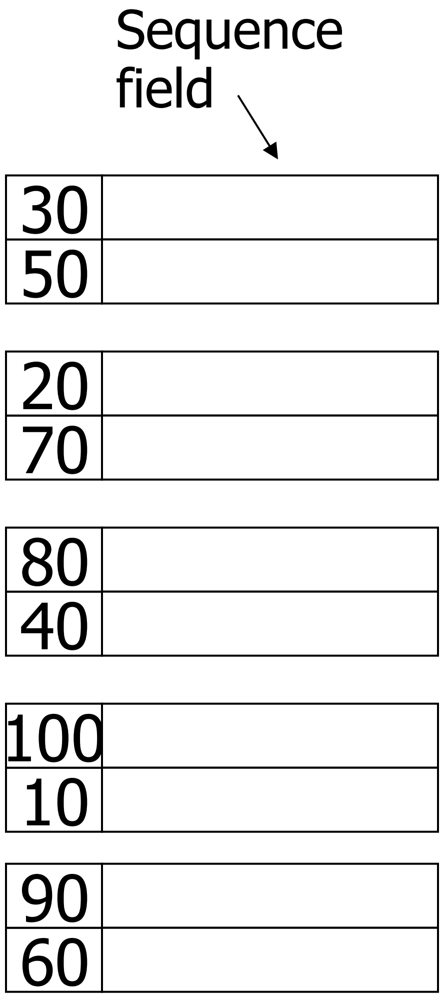


overflow blocks
(reorganize later...)

Insertion, dense index case

- Similar
- Often more expensive . . .

Secondary indexes



Sequence field

30
50

20
70

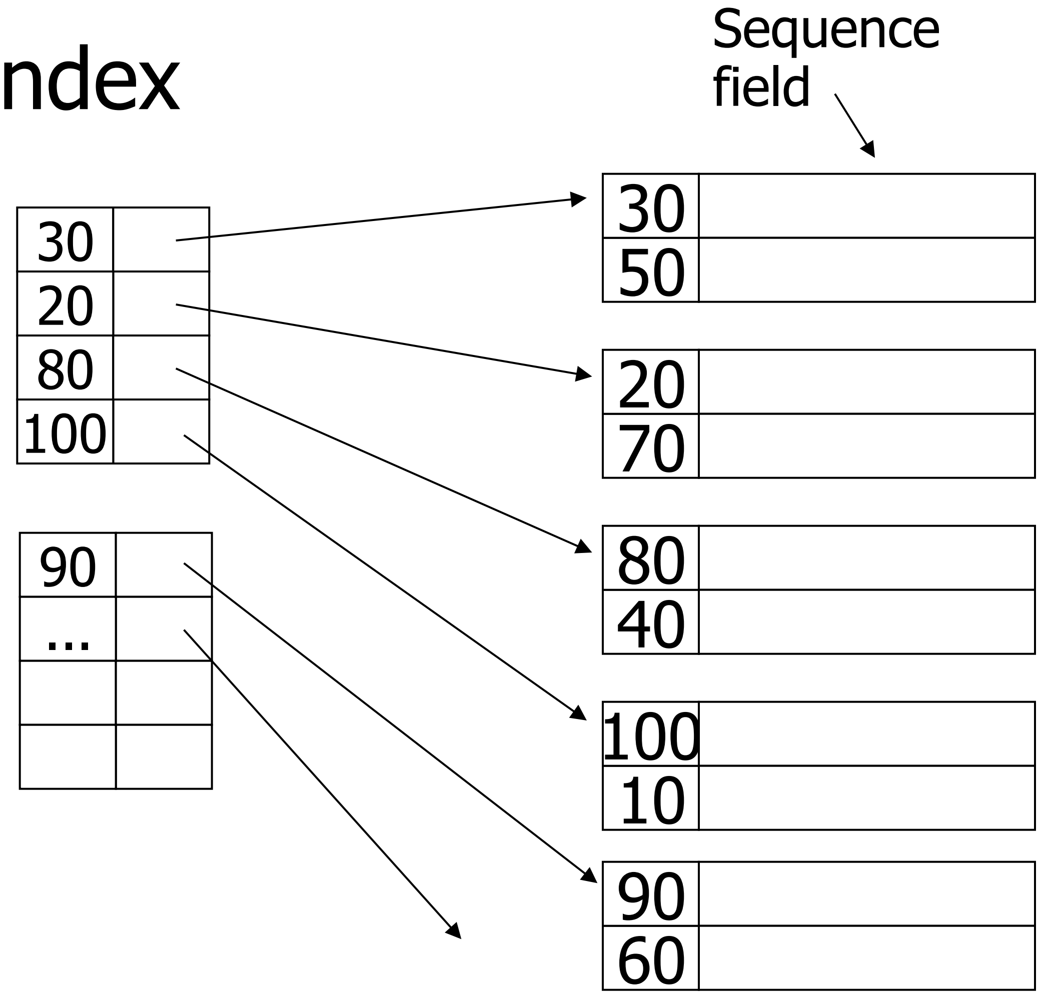
80
40

100
10

90
60

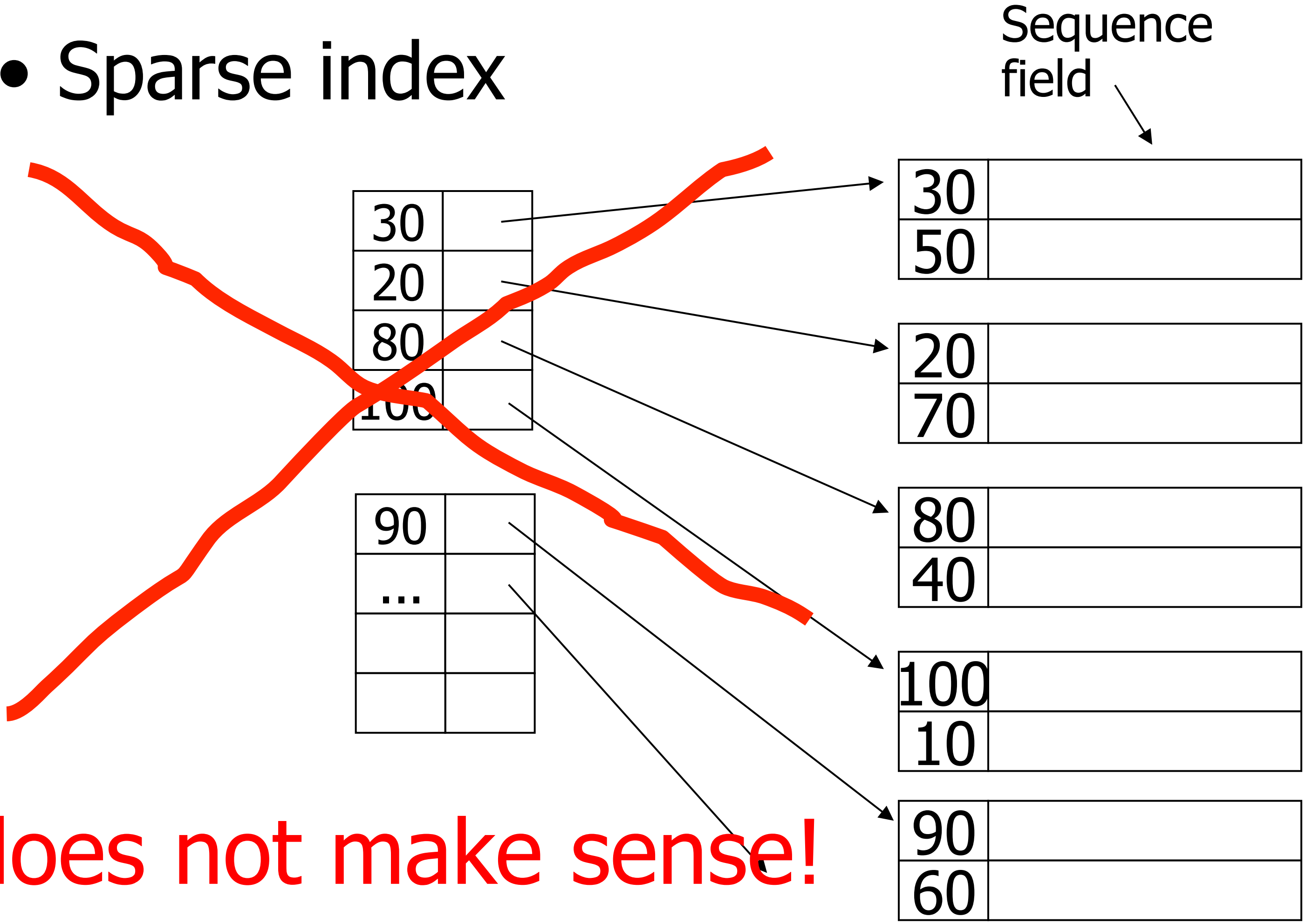
Secondary indexes

- Sparse index



Secondary indexes

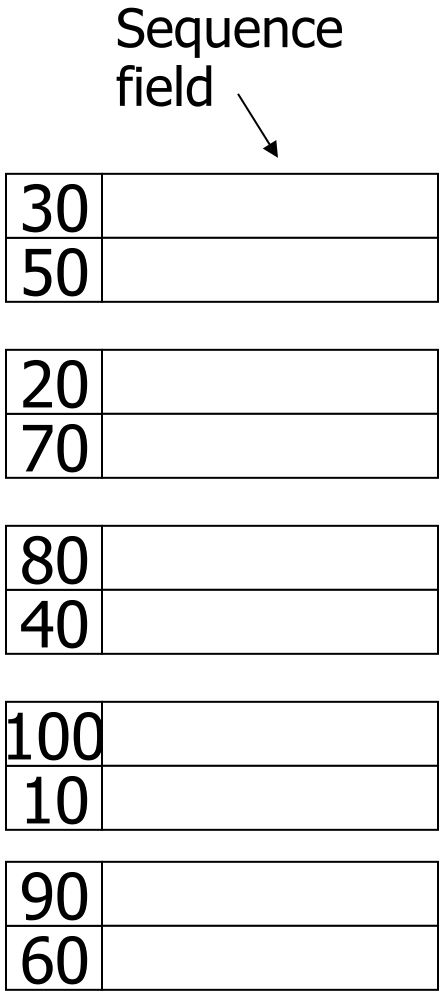
- Sparse index



does not make sense!

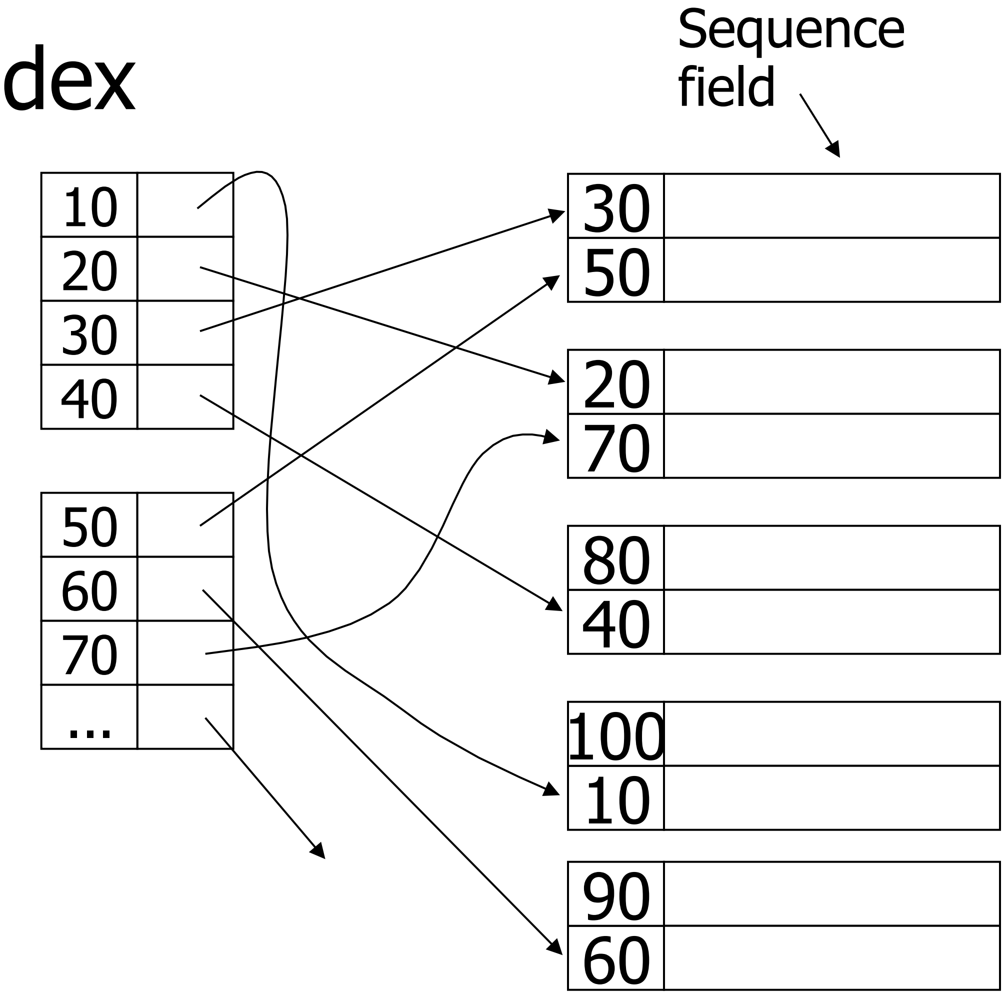
Secondary indexes

- Dense index



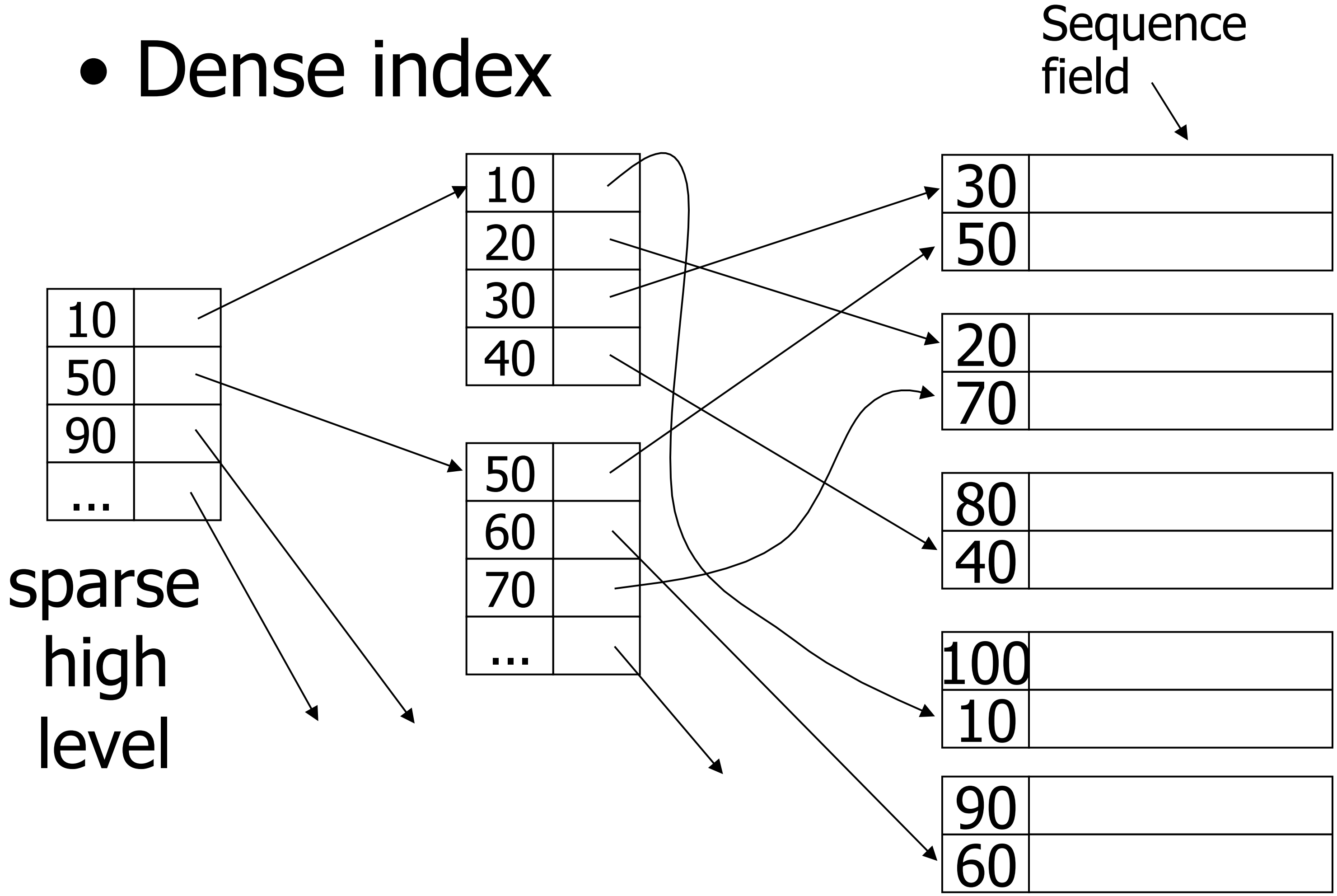
Secondary indexes

- Dense index



Secondary indexes

- Dense index



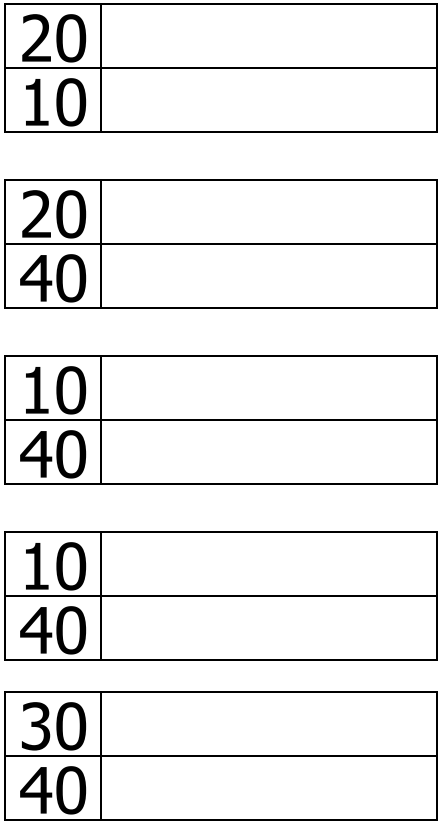
With secondary indexes:

- Lowest level is dense
- Other levels are sparse

Also: Pointers are record pointers

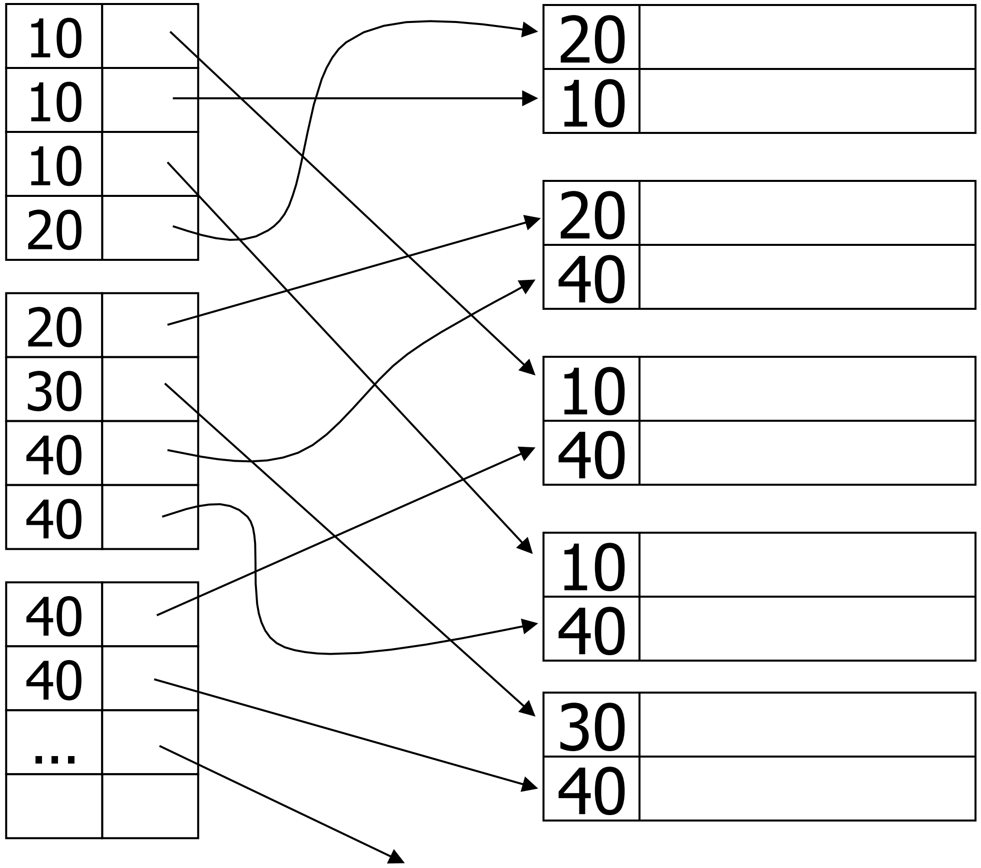
(not block pointers; not computed)

Duplicate values & secondary indexes



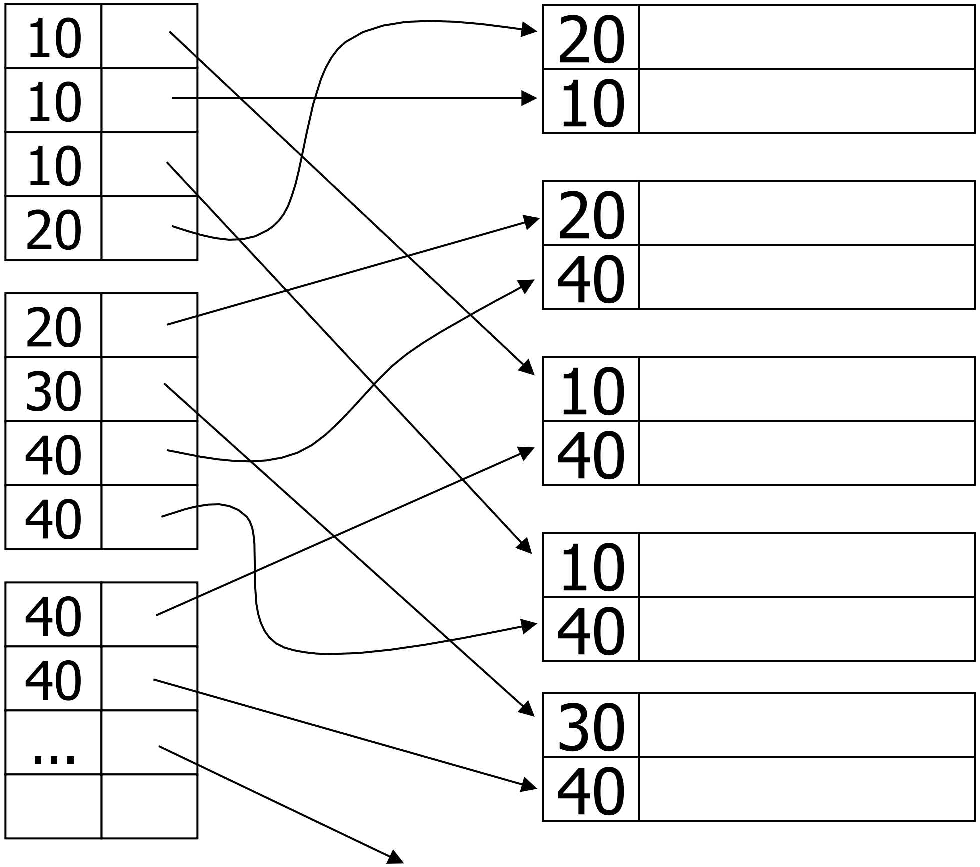
Duplicate values & secondary indexes

one option...



Duplicate values & secondary indexes

one option...



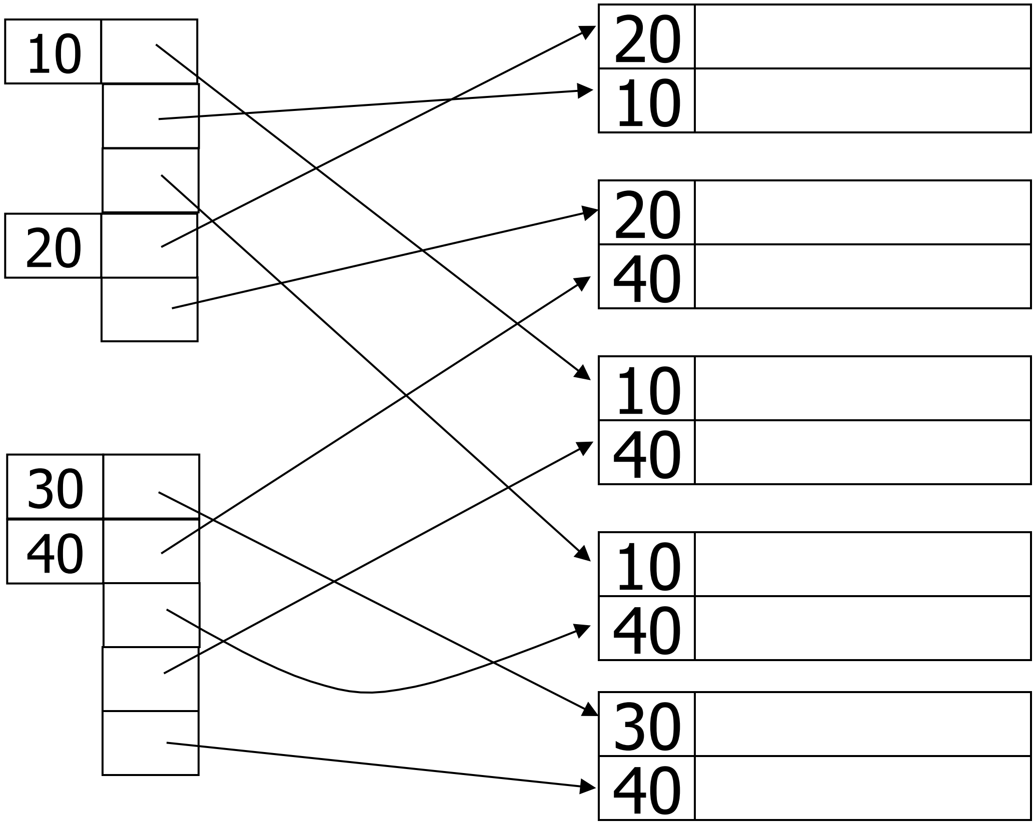
Problem:

excess overhead!

- disk space
- search time

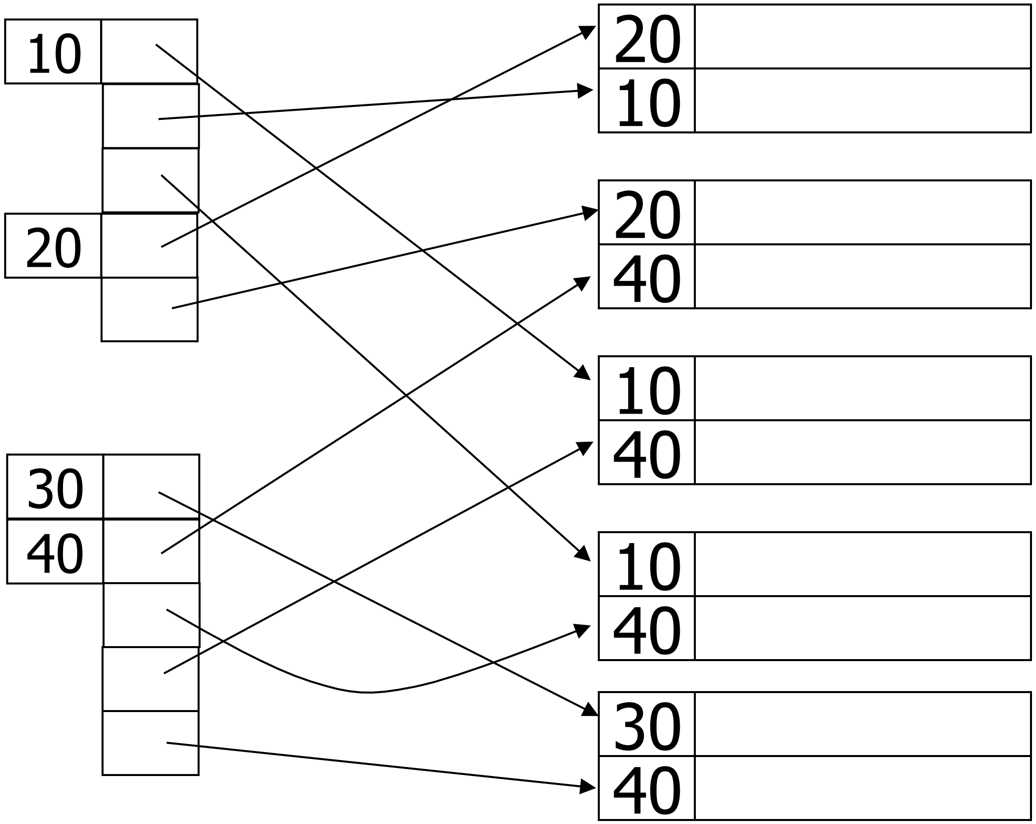
Duplicate values & secondary indexes

another option...



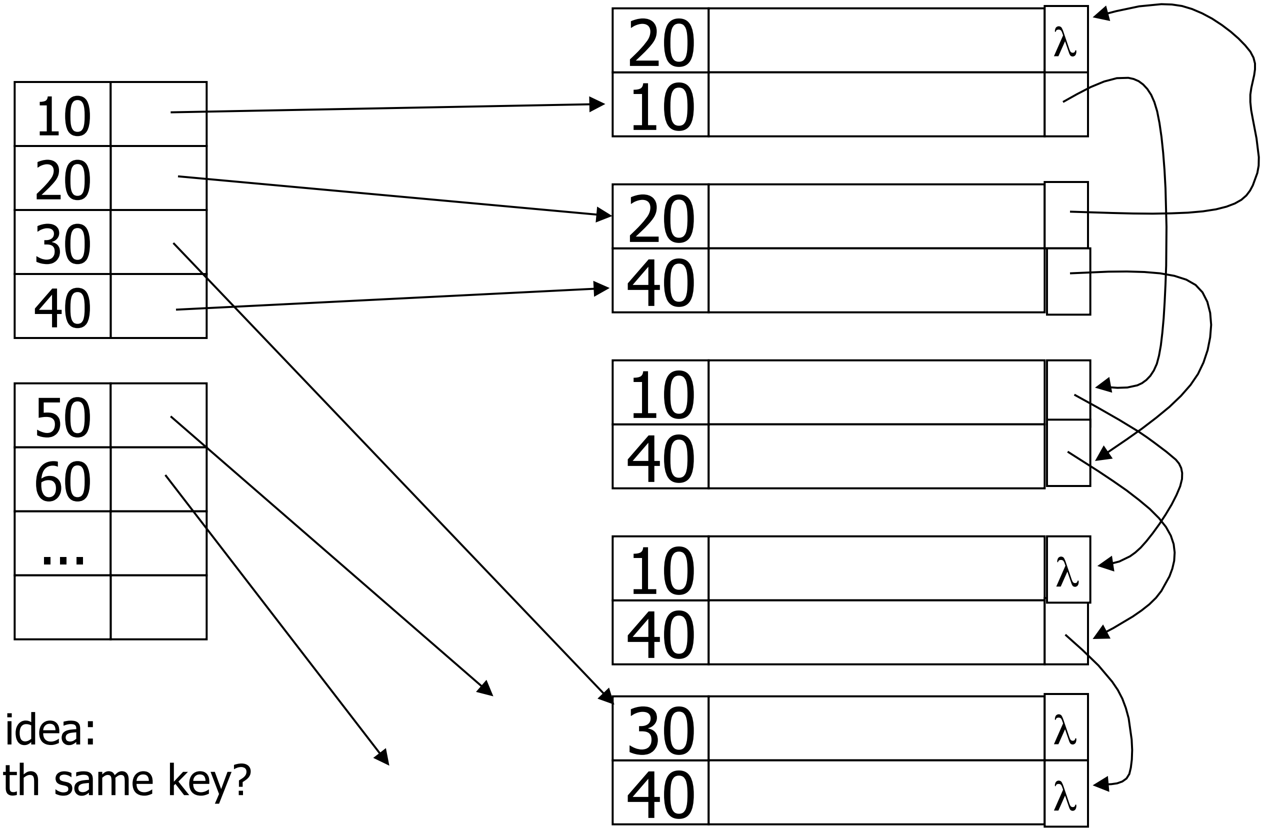
Duplicate values & secondary indexes

another option...



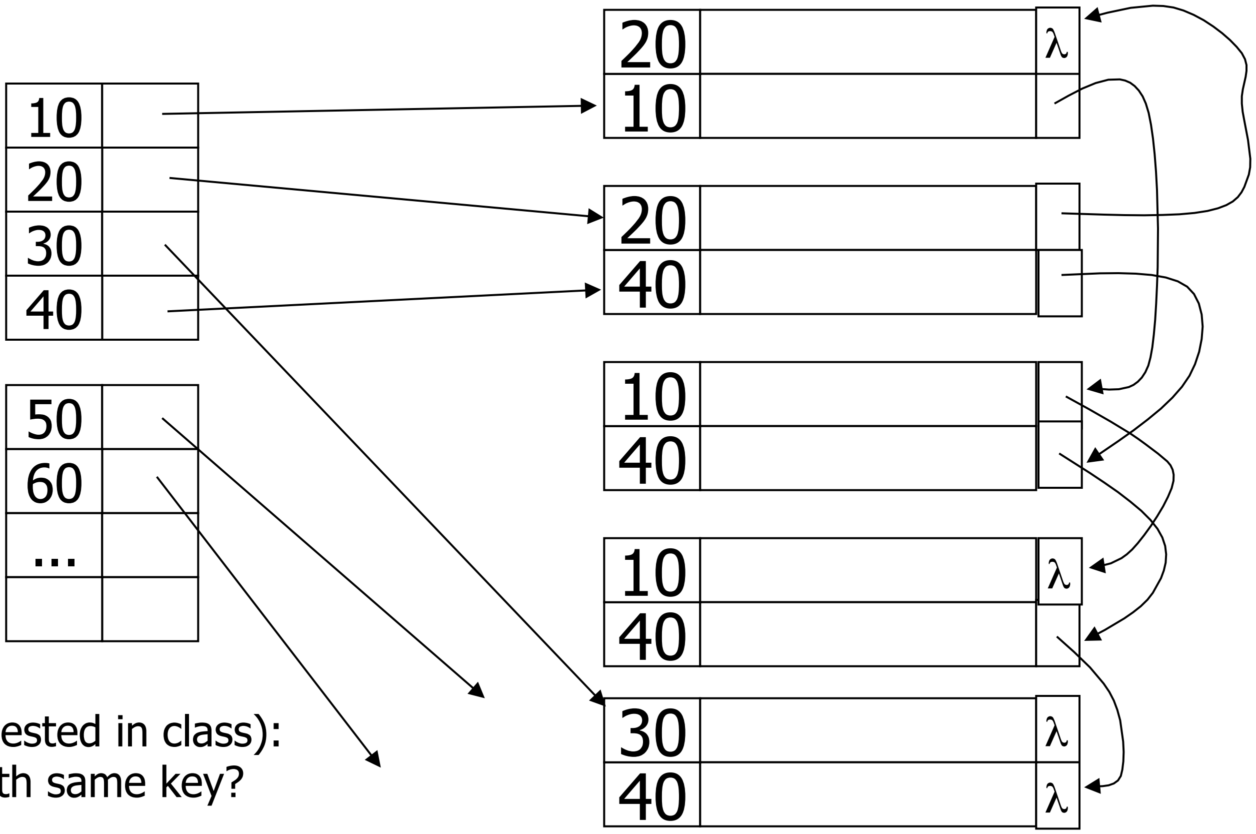
Problem: variable size records in index!

Duplicate values & secondary indexes



Another idea:
Chain records with same key?

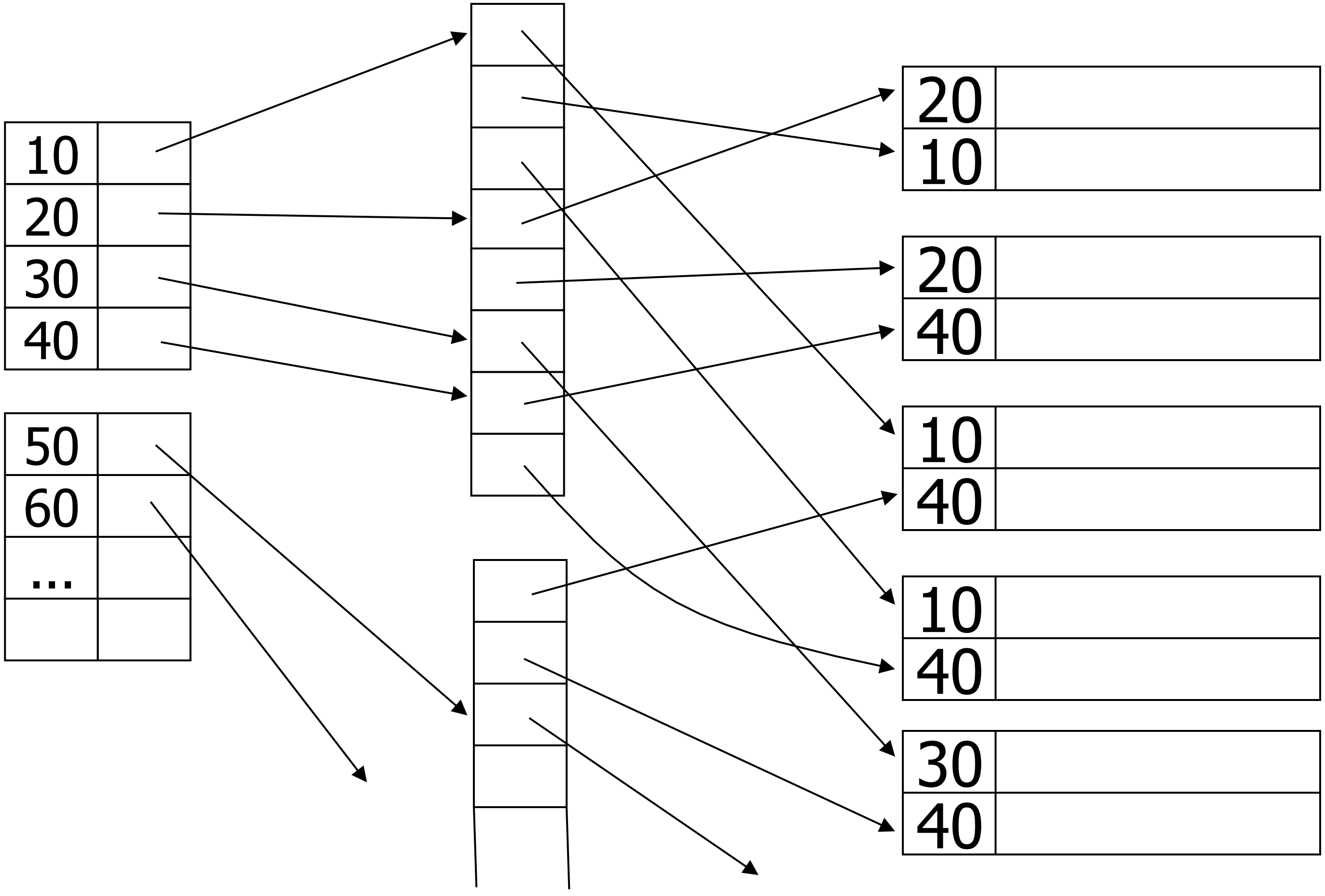
Duplicate values & secondary indexes



Another idea (suggested in class):
Chain records with same key?

Problems:
- Need to add fields to records
- Need to follow chain to know records

Duplicate values & secondary indexes

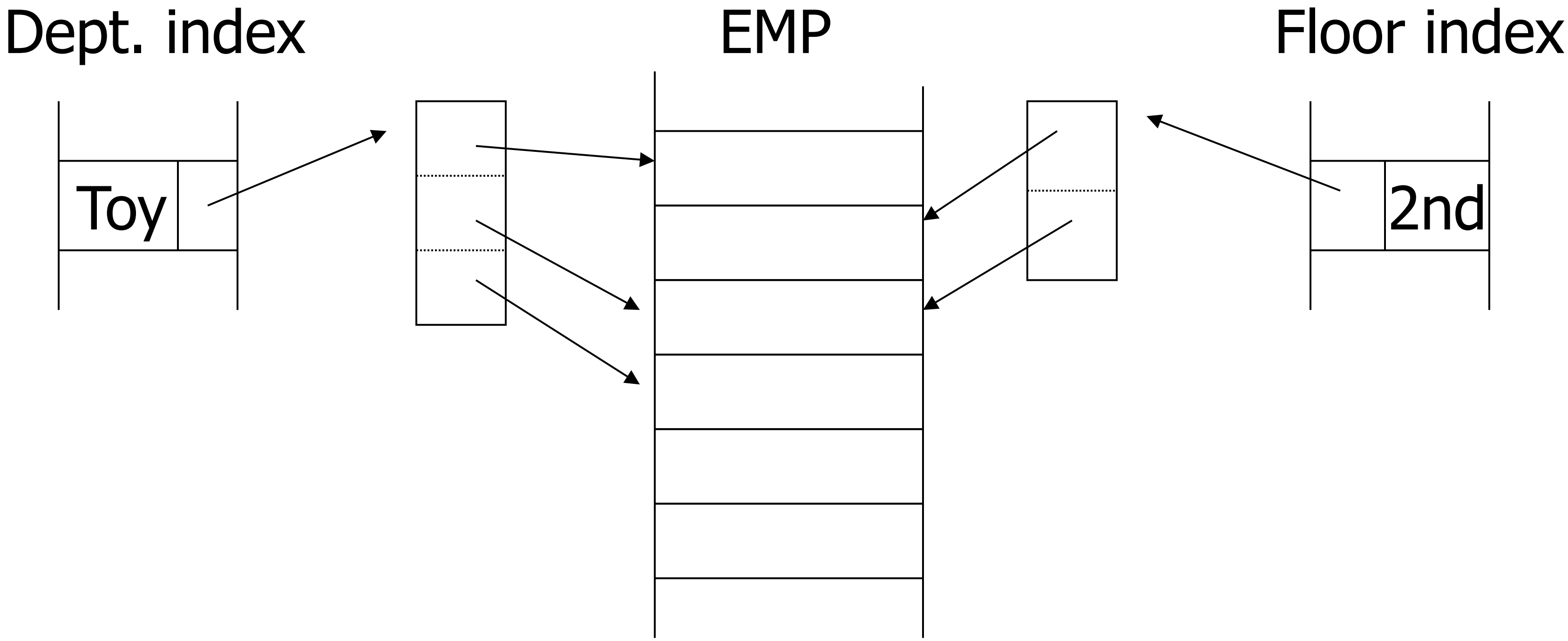


buckets

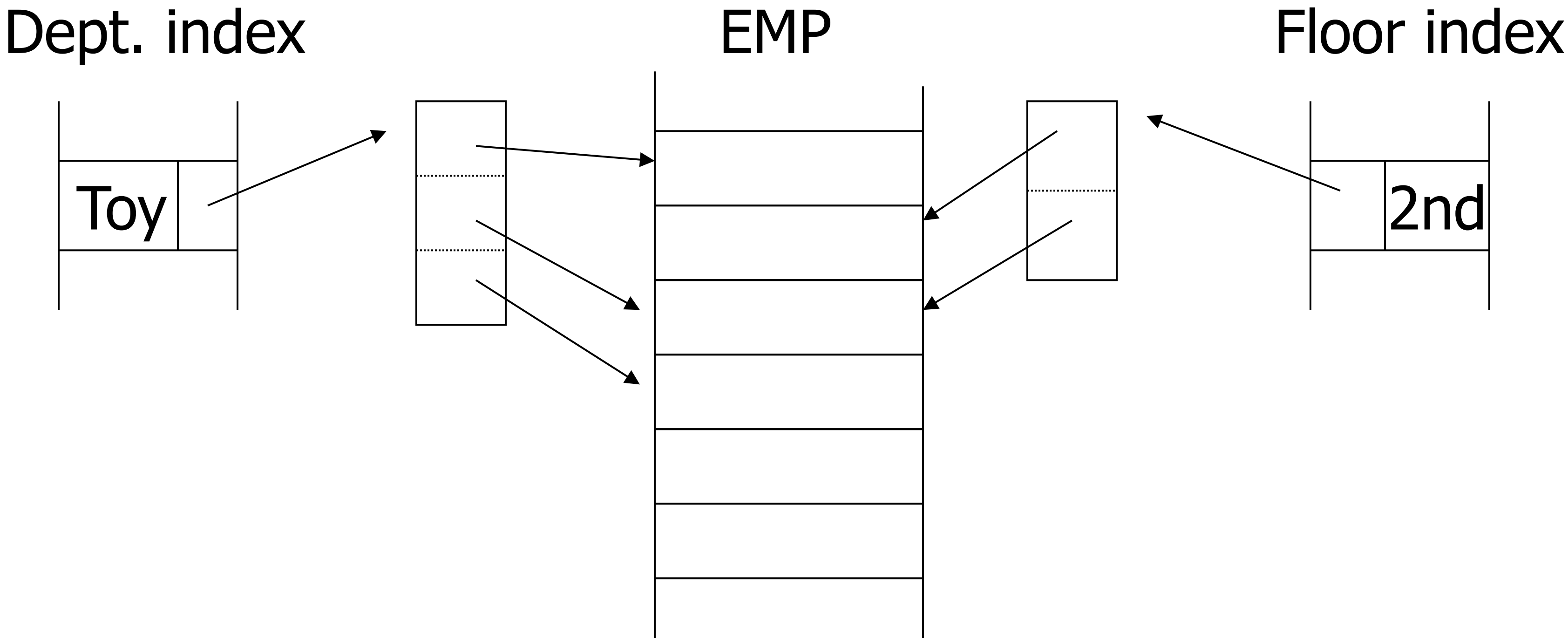
Why "bucket" idea is useful

Indexes	Records
Name: primary	EMP (name,dept,floor,...)
Dept: secondary	
Floor: secondary	

Query: Get employees in (Toy Dept) $\wedge$ (2nd floor)



Query: Get employees in (Toy Dept) $\wedge$ (2nd floor)



→ Intersect toy bucket and 2nd Floor bucket to get set of matching EMP's

This idea used in
text information retrieval

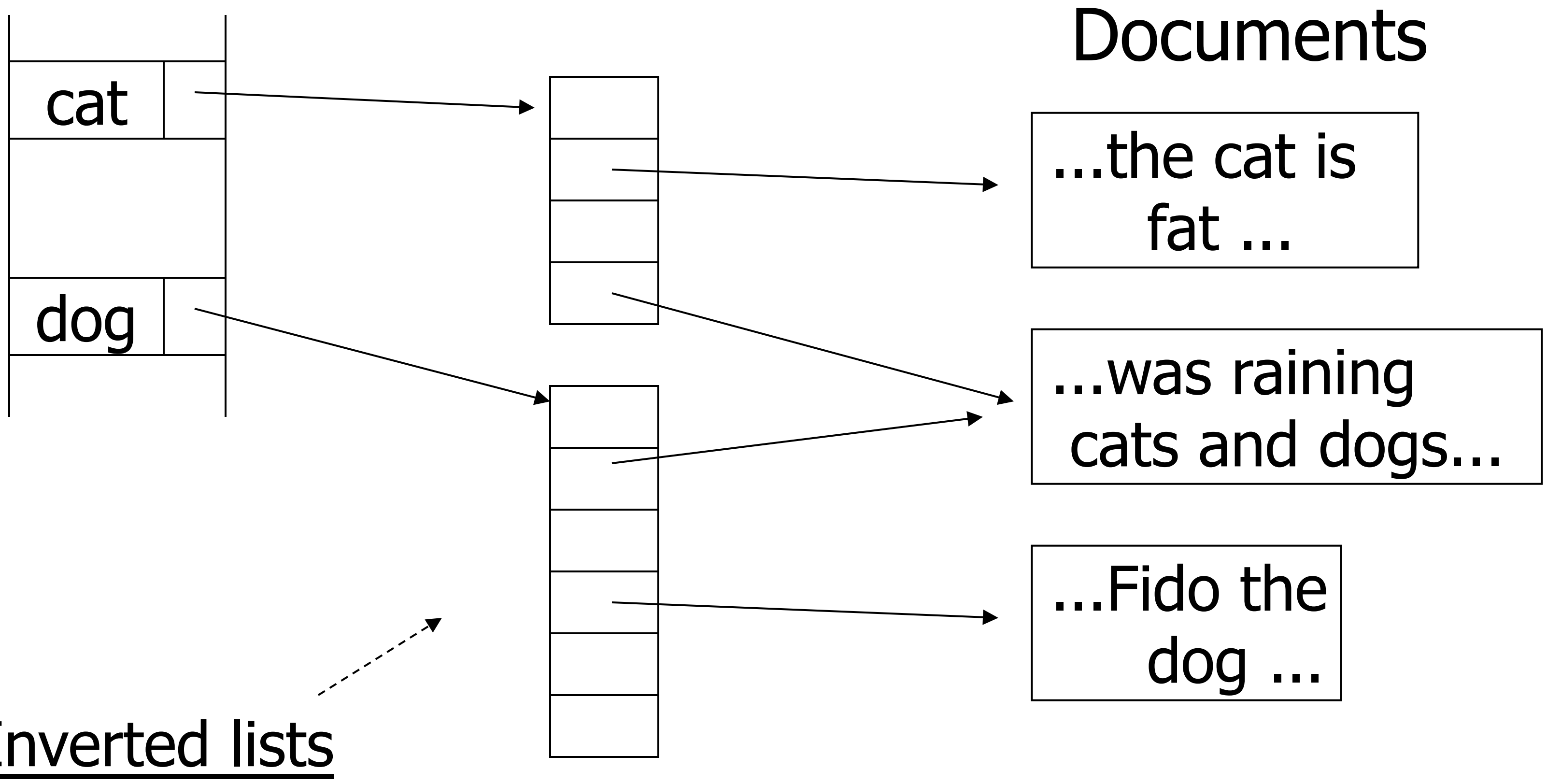
Documents

...the cat is fat ...

...was raining cats and dogs...

...Fido the dog ...

This idea used in
<u>text information retrieval</u>



IR QUERIES

- Find articles with “cat” and “dog”
- Find articles with “cat” or “dog”
- Find articles with “cat” and not “dog”

Summary so far

- Conventional index
  - Basic Ideas: sparse, dense, multi-level…
  - Duplicate Keys
  - Deletion/Insertion
  - Secondary indexes
    - Buckets of Postings List

Conventional indexes

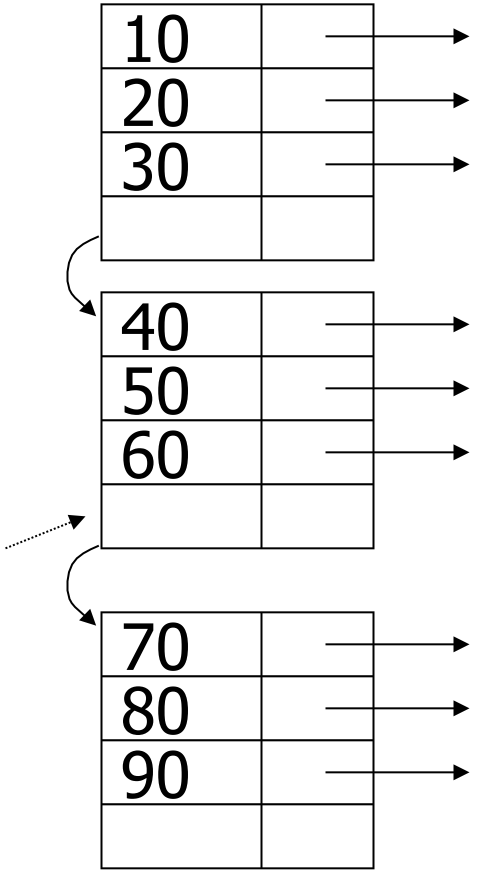
Advantage:

- Simple
- Index is sequential file
  good for scans

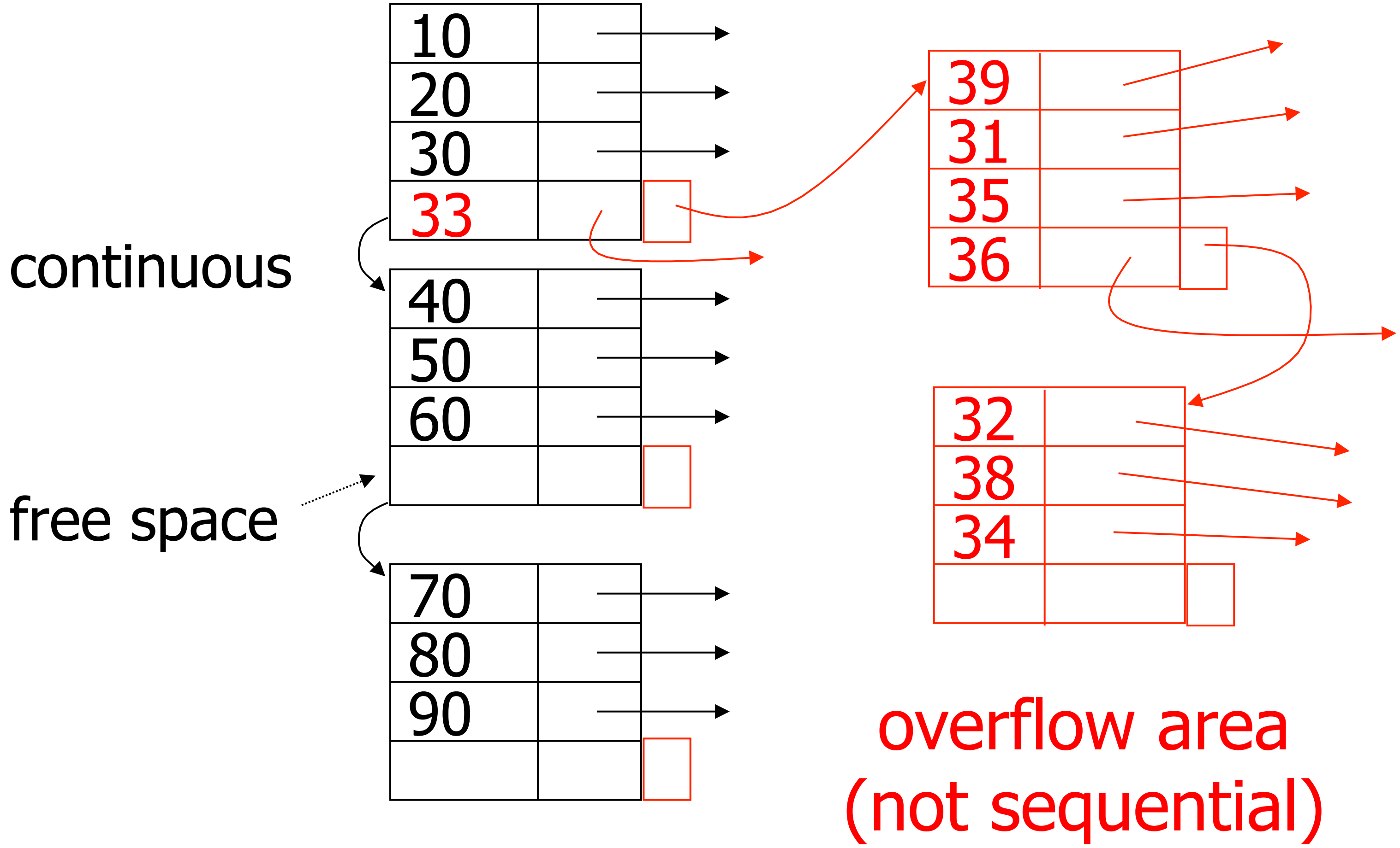
Disadvantage:

- Inserts expensive, and/or
- Lose sequentiality & balance

Example Index (sequential)



Example Index (sequential)



Outline:

- Conventional indexes
- B-Trees ⇒ NEXT
- Hashing schemes
- Advanced Index Techniques

- NEXT: Another type of index
  - Give up on sequentiality of index
  - Try to get “balance”

B+-tree Motivation

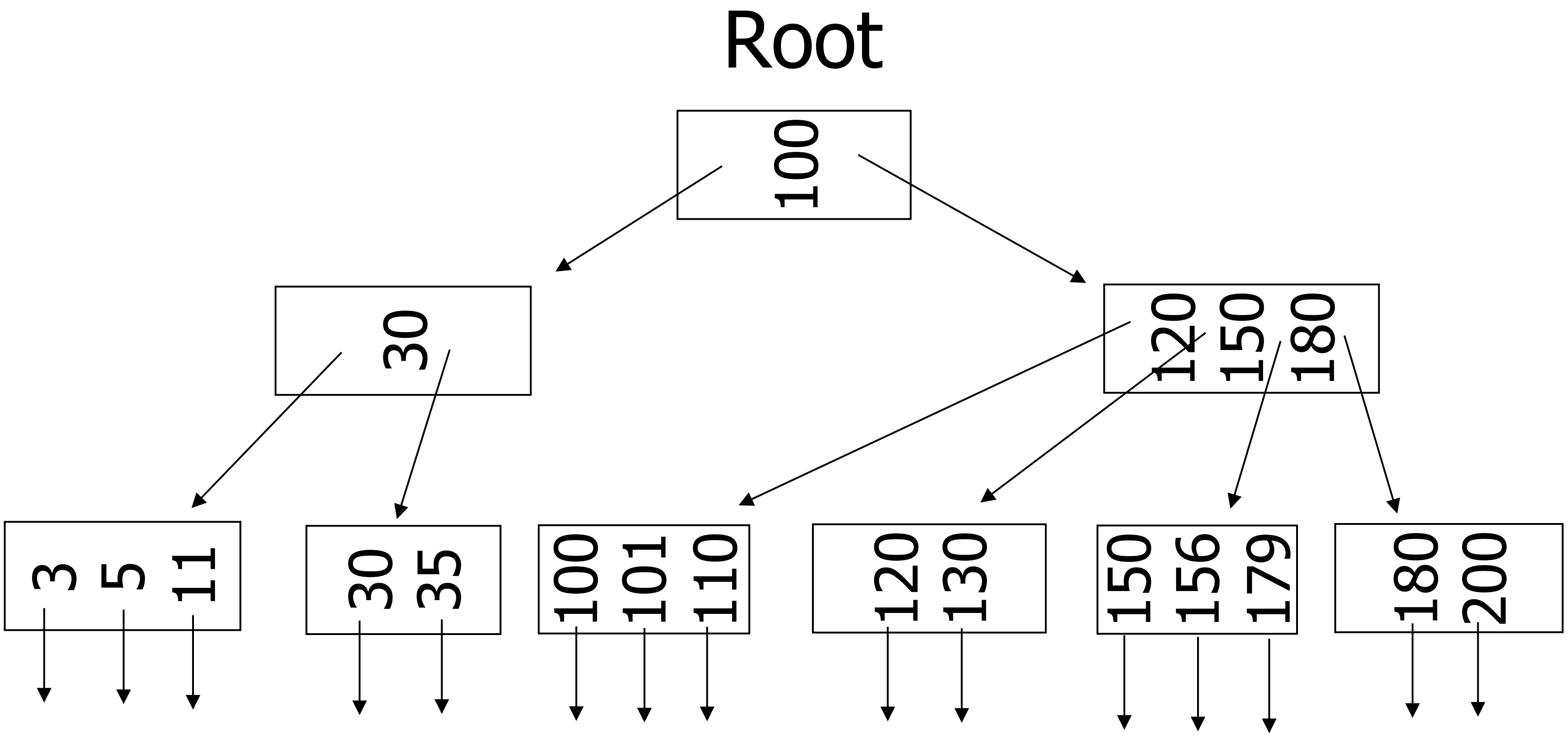
- Tree indices are pretty efficient
  - E.g., binary search tree
    - Average case O(log(n)) lookup
- However
  - Unclear how to map to disk (index larger than main memory, loading partial index)
  - Worst-case O(n) lookup

B+-tree Properties

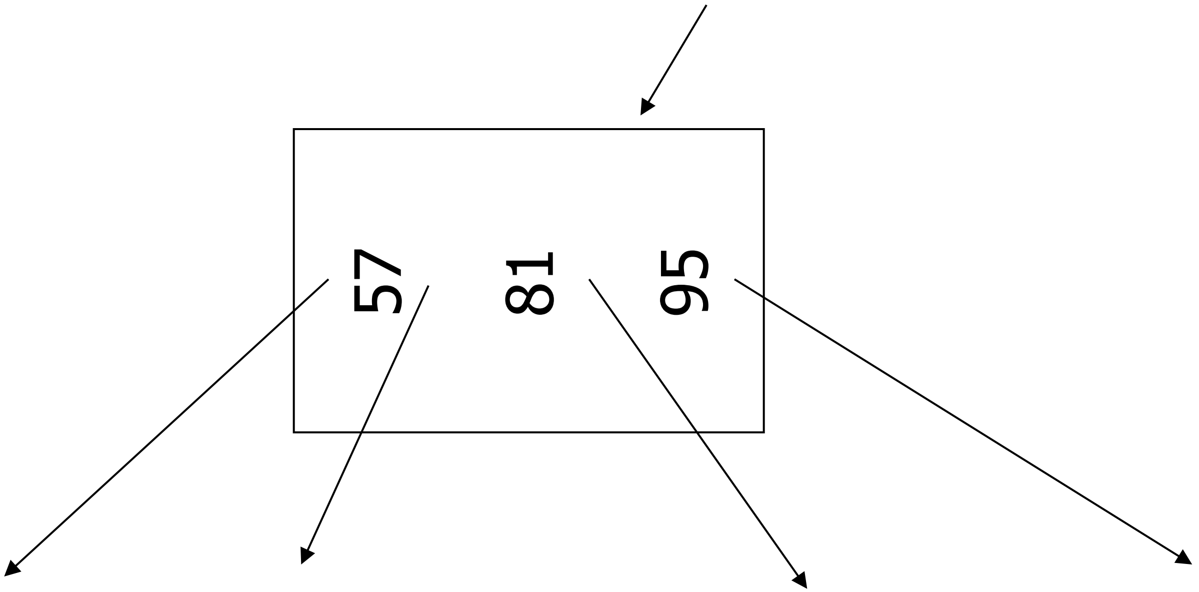
- Large nodes:
  - Node size is multiple of block size
    - -> small number of levels
    - -> simple way to map index to disk
    - -> many keys per node
- Balance:
  - Require all nodes to be more than X% full
  - -> for n records guaranteed only logarithmically many levels
  - -> log(n) worst-case performance

B+Tree Example

n=3



Sample non-leaf



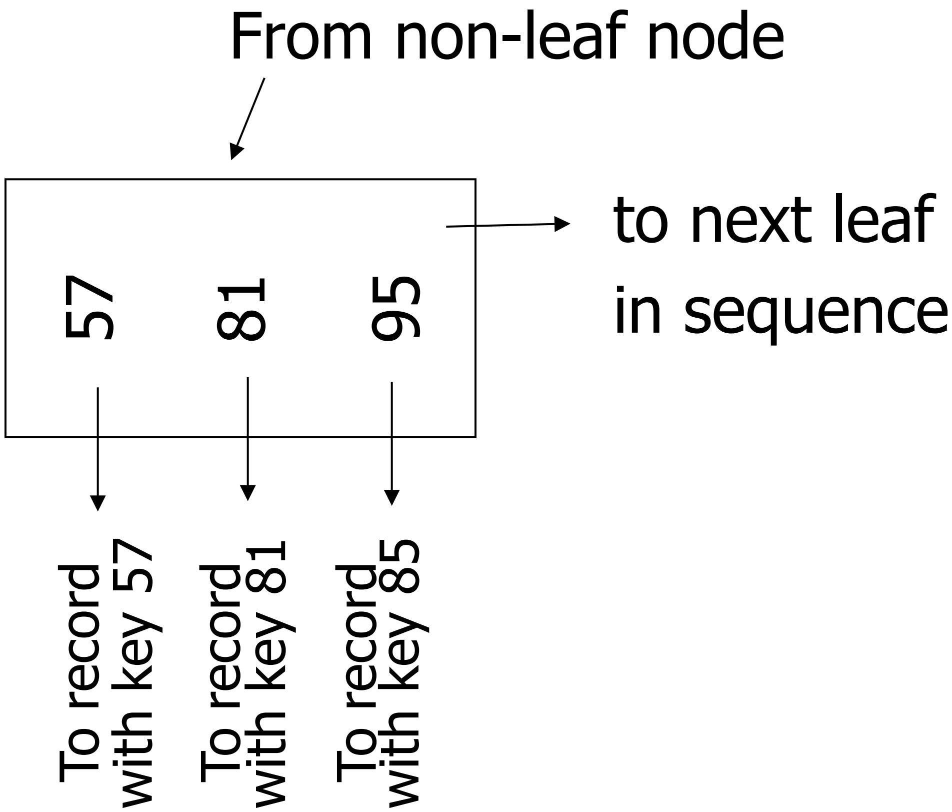
to keys
< 57

to keys
57≤ k<81

to keys
81≤k<95

to keys
≥95

Sample leaf node:



From non-leaf node

to next leaf in sequence

57

81

95

To record with key 57

To record with key 81

To record with key 85

In textbook' s notation n=3

Leaf:

Non-leaf:

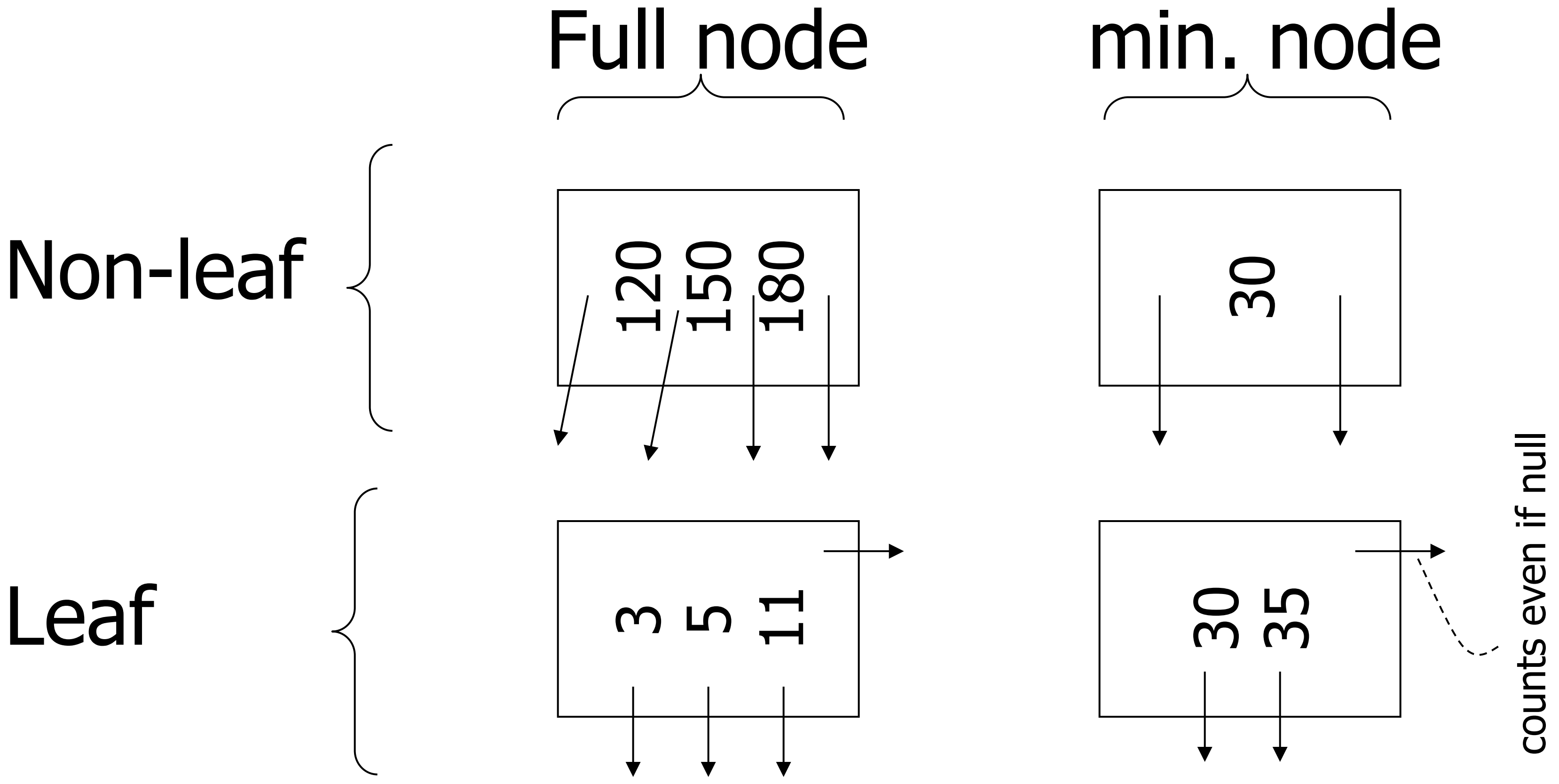
Size of nodes: $\left\{ \begin{array}{l} \text{n+1 pointers} \\ \text{n keys} \end{array} \right.$ <u>(fixed)</u>

Don't want nodes to be too empty

- Use at least (balance)

Non-leaf: $\lceil (n+1)/2 \rceil$ pointers

Leaf: $\lfloor (n+1)/2 \rfloor$ pointers to data n=3


Full node
min. node
Non-leaf
Leaf
120
150
180
30
3
5
11
30
35
counts even if null

B+tree rules tree of order *n*

(1)All leaves at same lowest level (balanced tree)

-> guaranteed worst-case complexity for operations on the index

(2) Pointers in leaves point to records except for “sequence pointer”

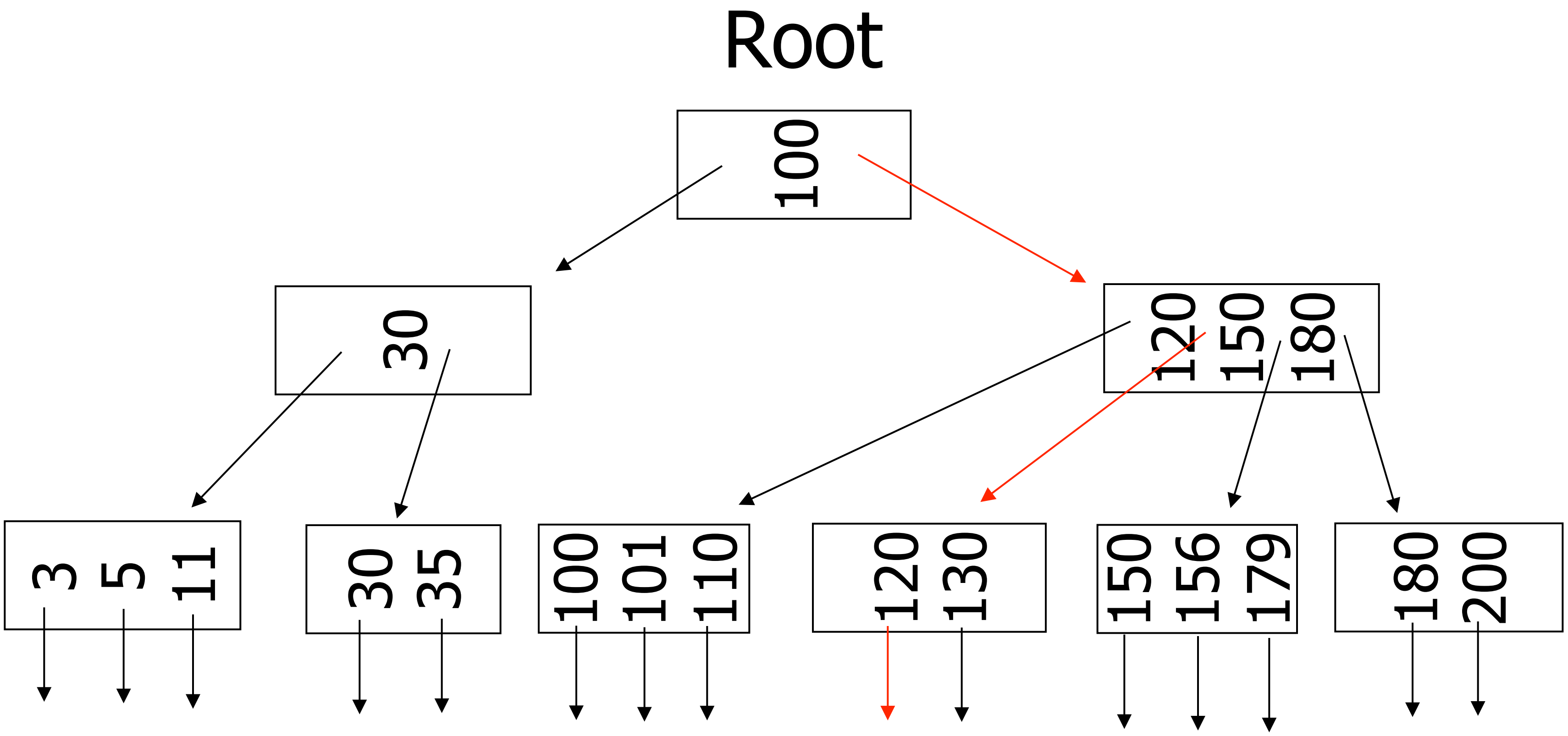
(3) Number of pointers/keys for B+tree

	Max ptrs	Max keys	Min ptrs→data	Min keys
Non-leaf (non-root)	n+1	n	$\lceil (n+1)/2 \rceil$	$\lceil (n+1)/2 \rceil - 1$
Leaf (non-root)	n+1	n	$\lfloor (n+1)/2 \rfloor$	$\lfloor (n+1)/2 \rfloor$
Root	n+1	n	1	1

Search Algorithm

- Search for key **k**
- Start from root until leaf is reached
- For current node find i so that
  - Key[i] <= **k** < Key[i + 1]
  - Follow i+1th pointer
- If current node is leaf return pointer to record or fail (no such record in tree)

Search Example **k= 120** n=3



Remarks Search

- If **n** is large, e.g., 500
- Keys inside node are sorted
- -> use binary search to find **I**
- Performance considerations
  - Linear search O(n)
  - Binary search $O(\log_2(n))$

Insert into B+tree

(a) simple case
  - space available in leaf

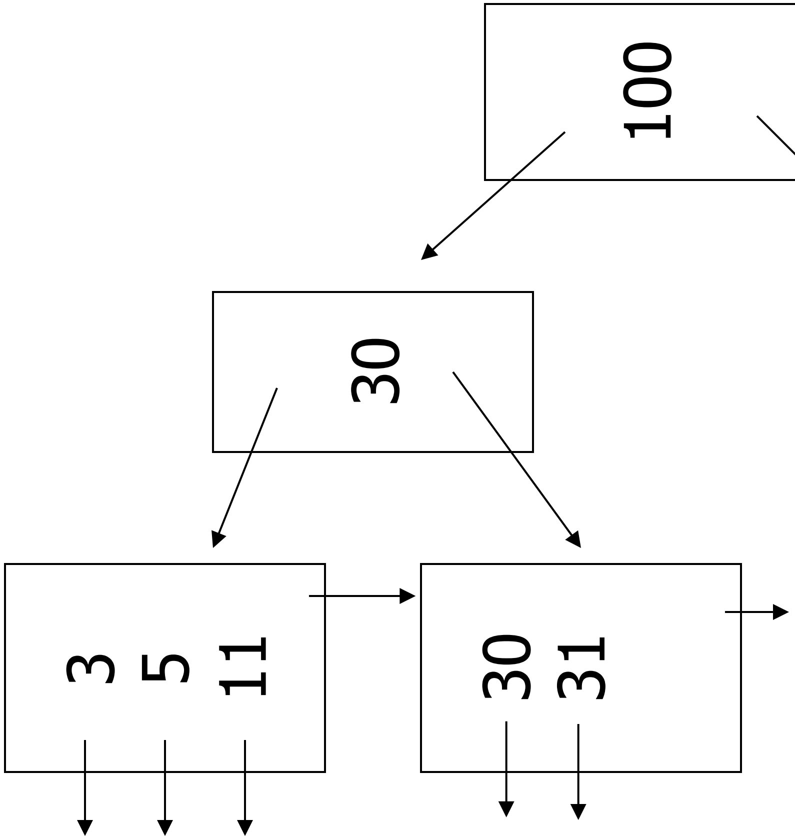
(b) leaf overflow

(c) non-leaf overflow

(d) new root

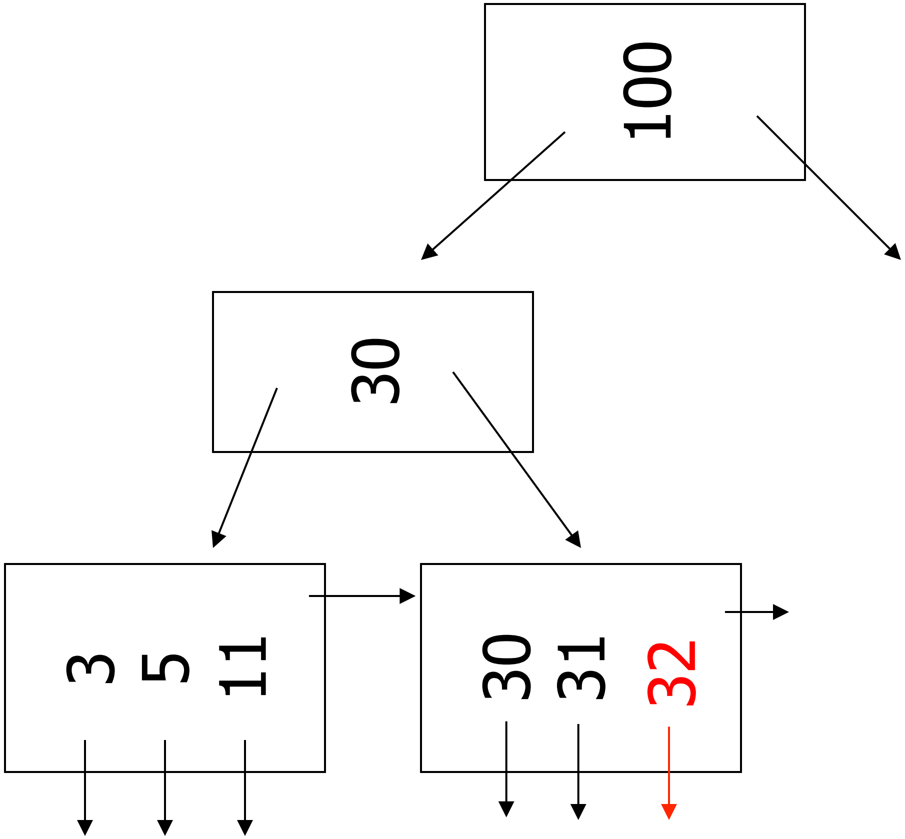
(a) Insert key = 32

n=3



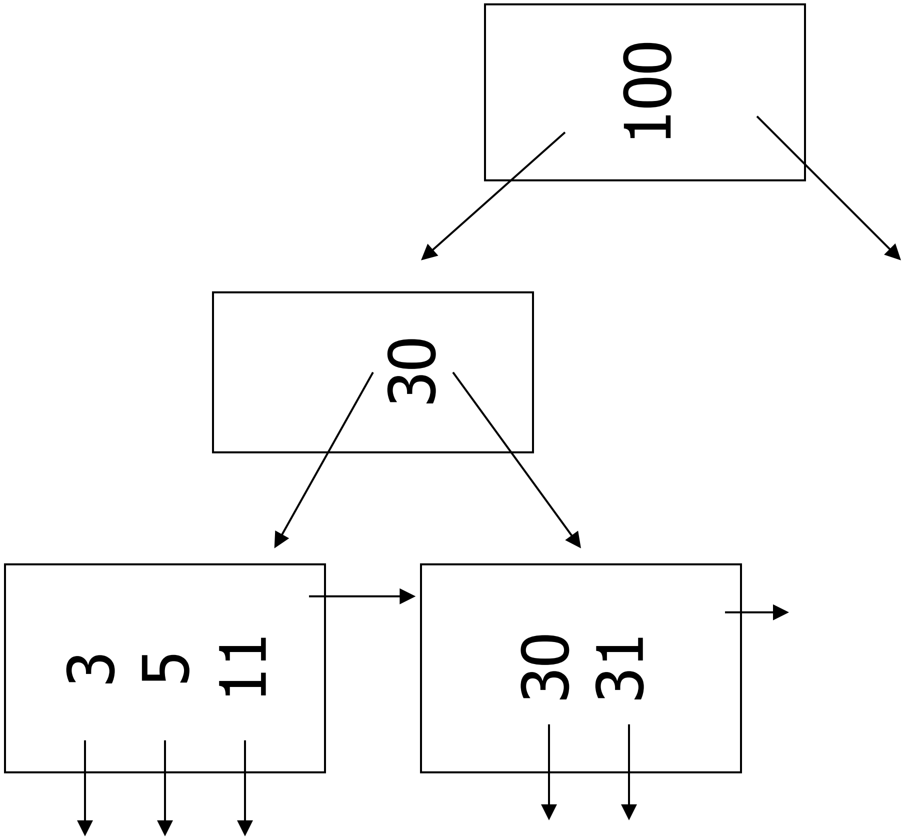
(a) Insert key = 32

n=3



(a) Insert key = 7

n=3



(a) Insert key = 7

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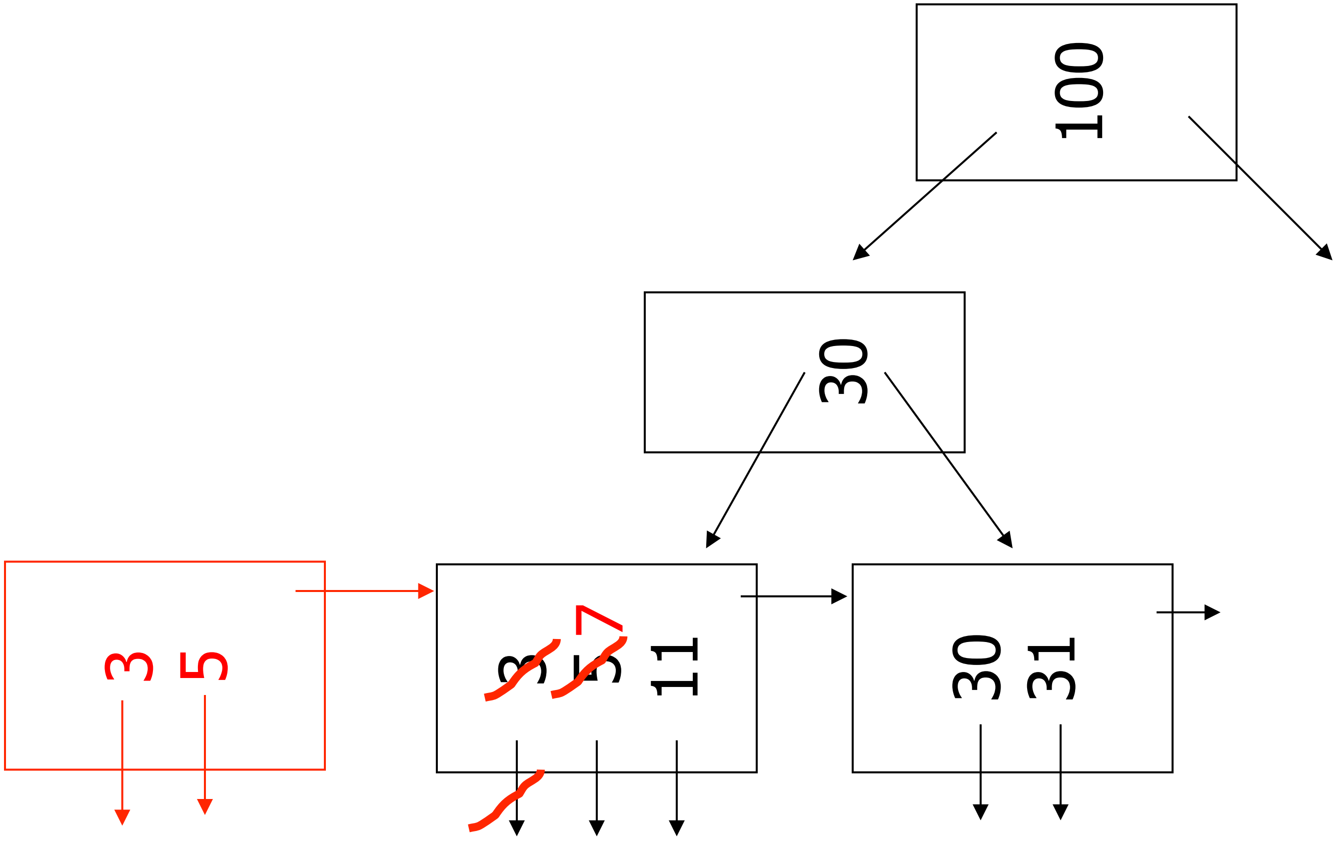
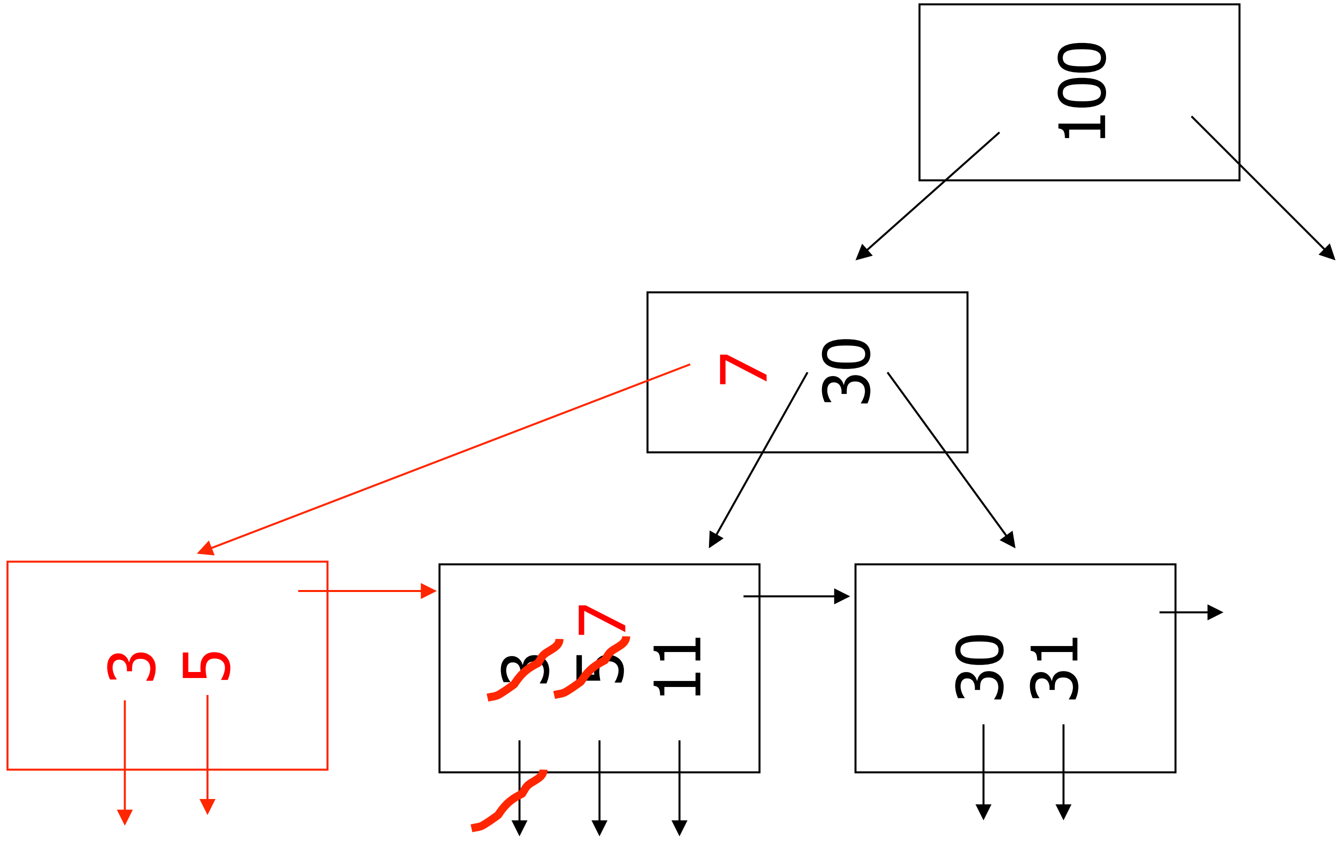


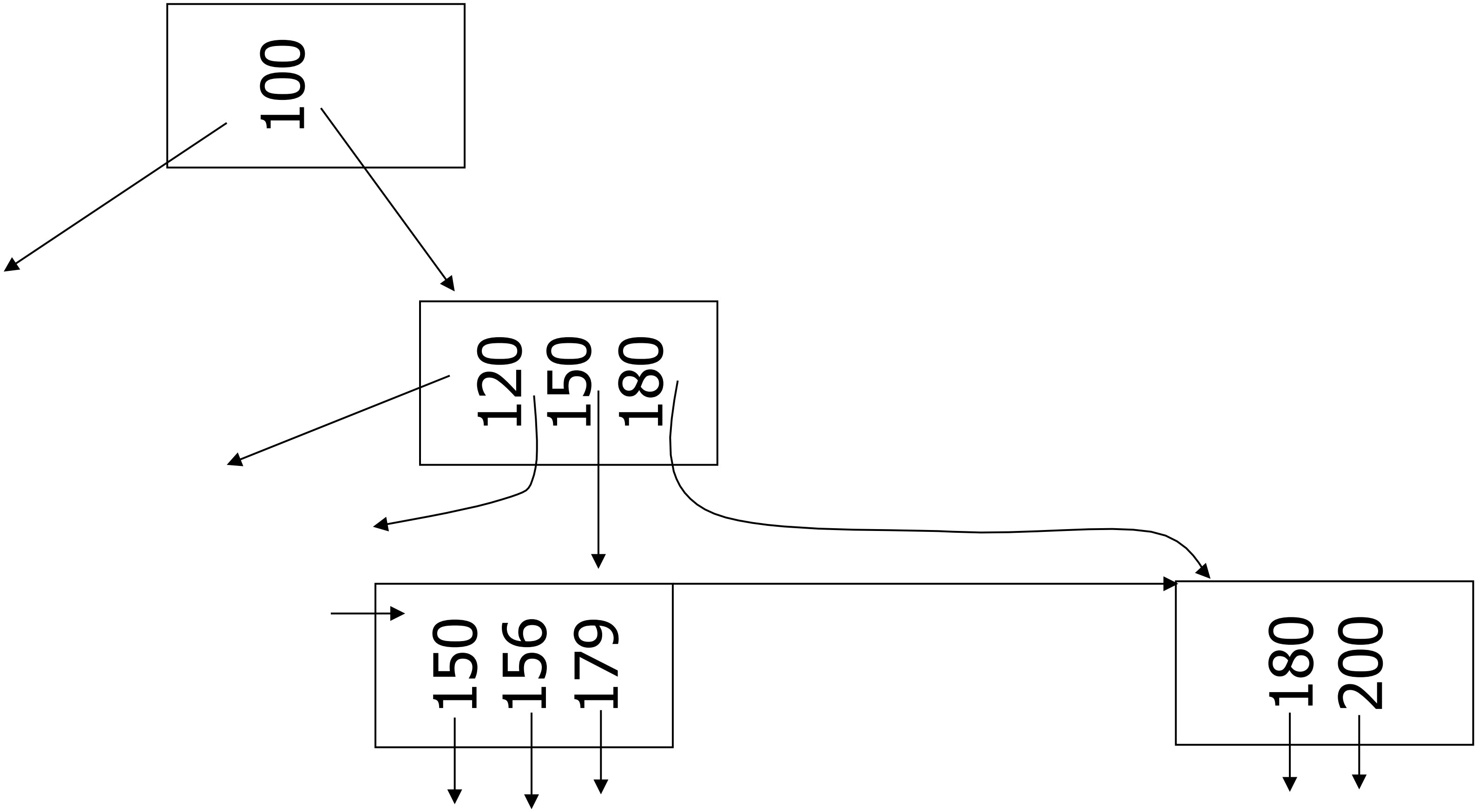
(a) Insert key = 7

n=3



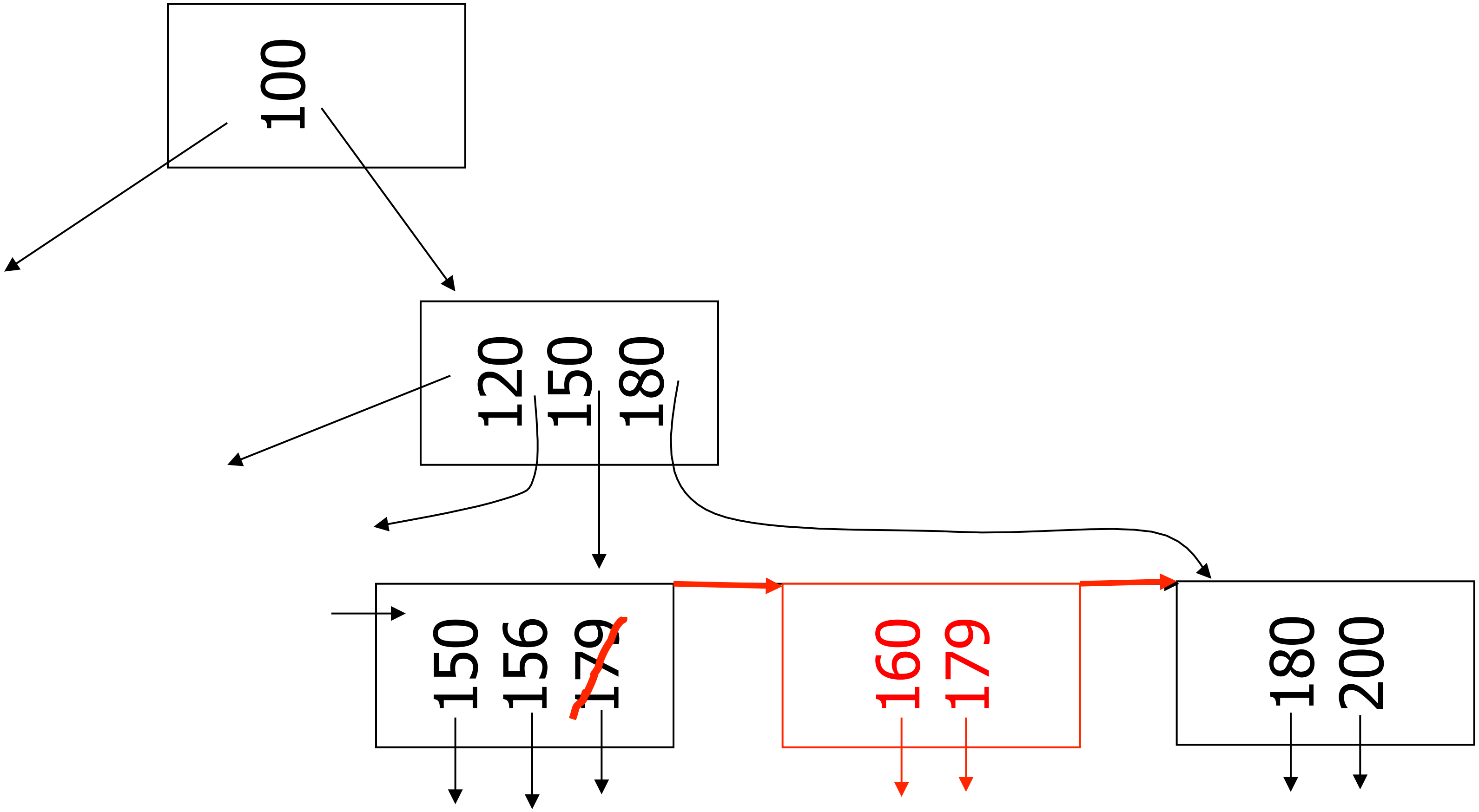
(c) Insert key = 160

n=3



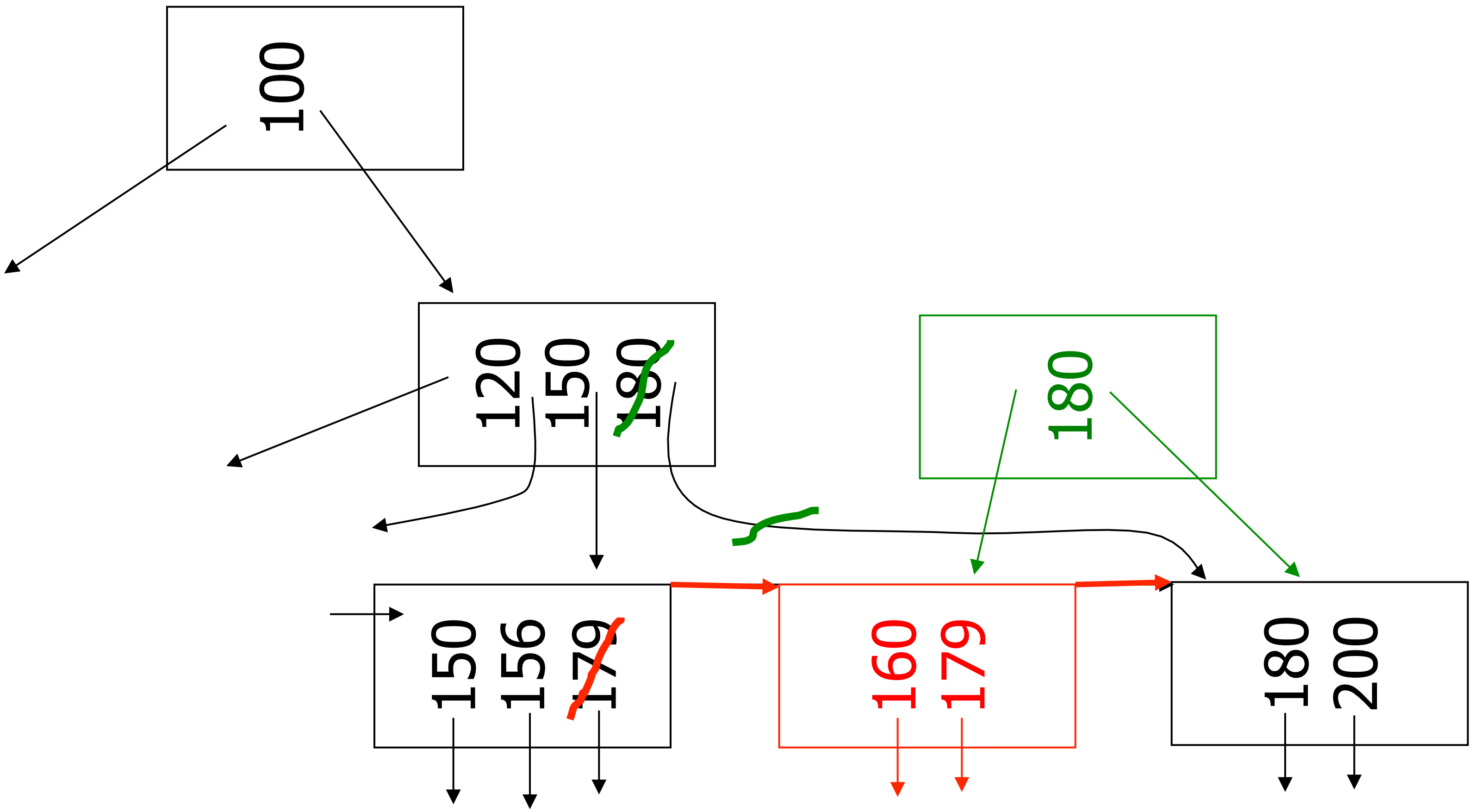
(c) Insert key = 160

n=3



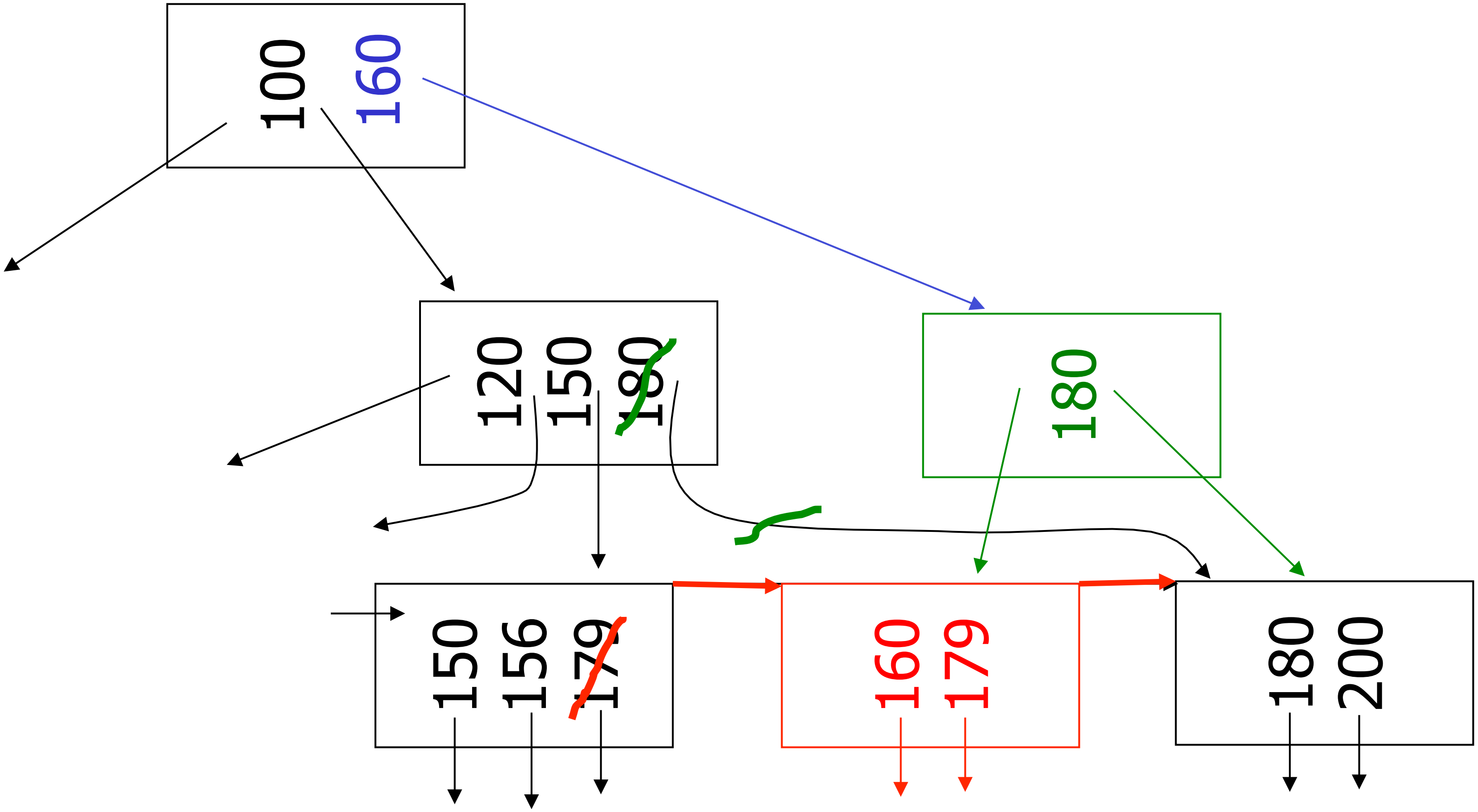
(c) Insert key = 160

n=3



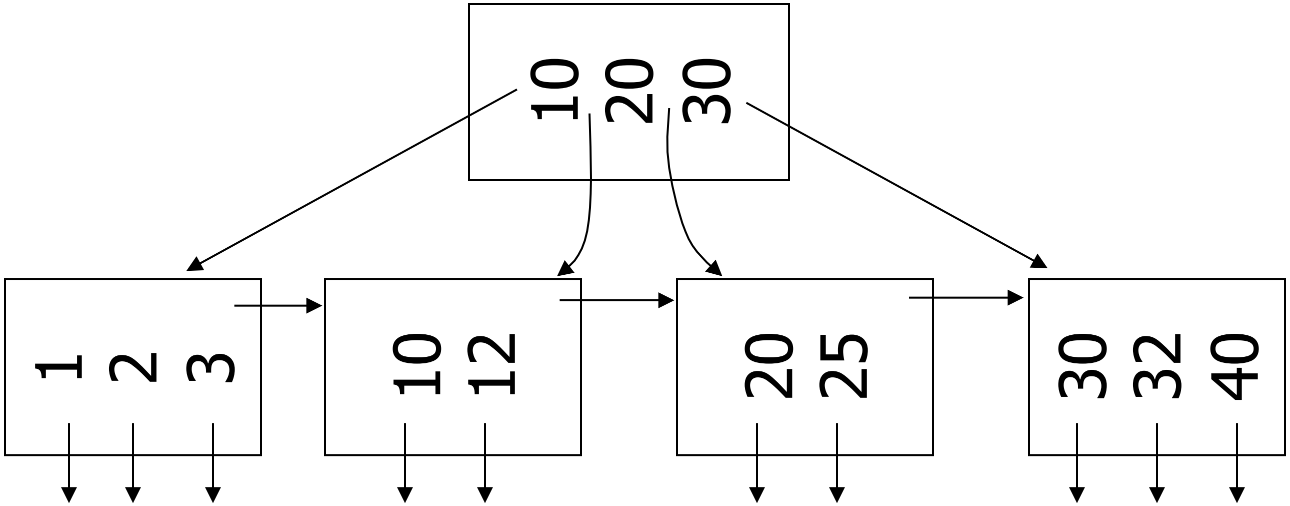
(c) Insert key = 160

n=3



(d) New root, insert 45

n=3



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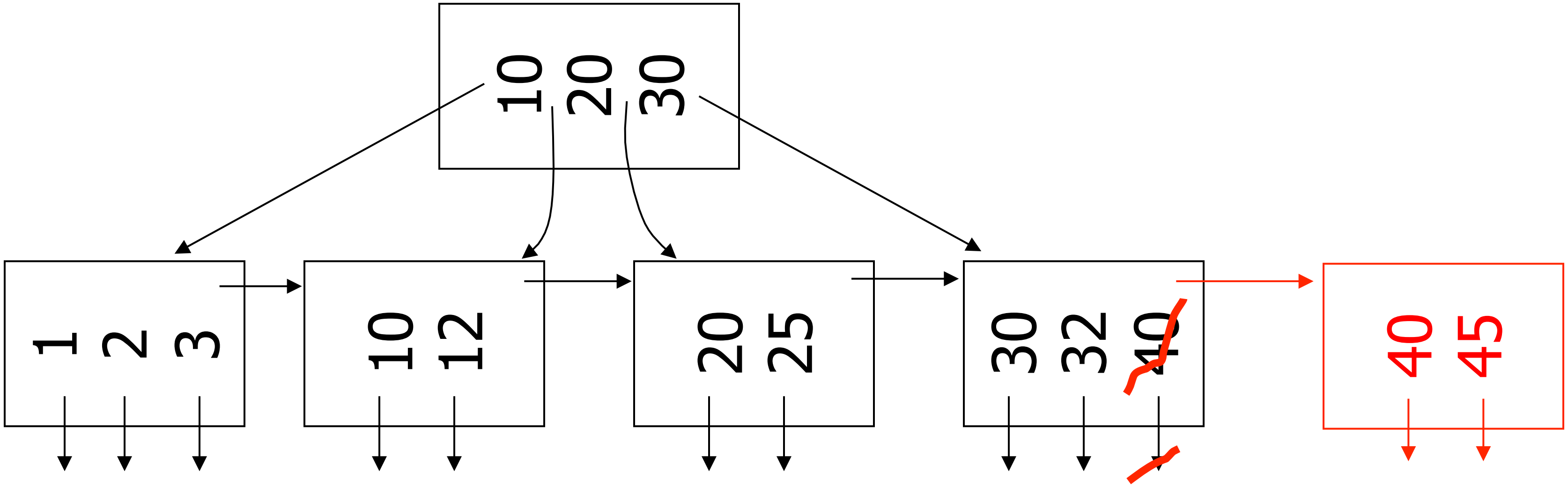
n=3



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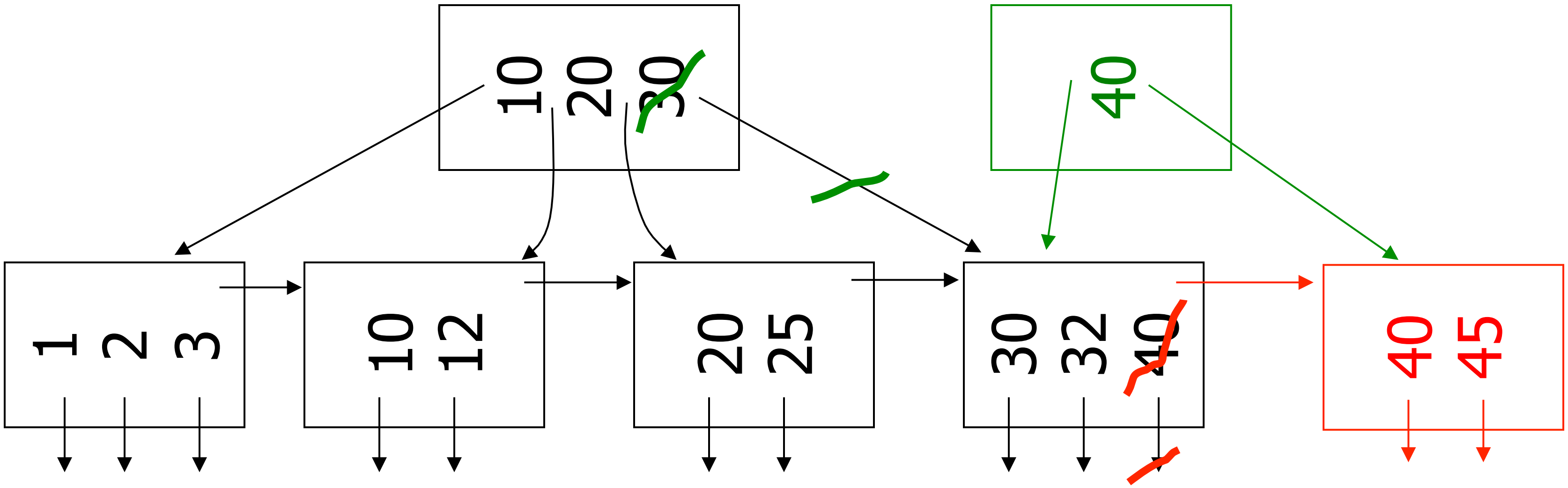
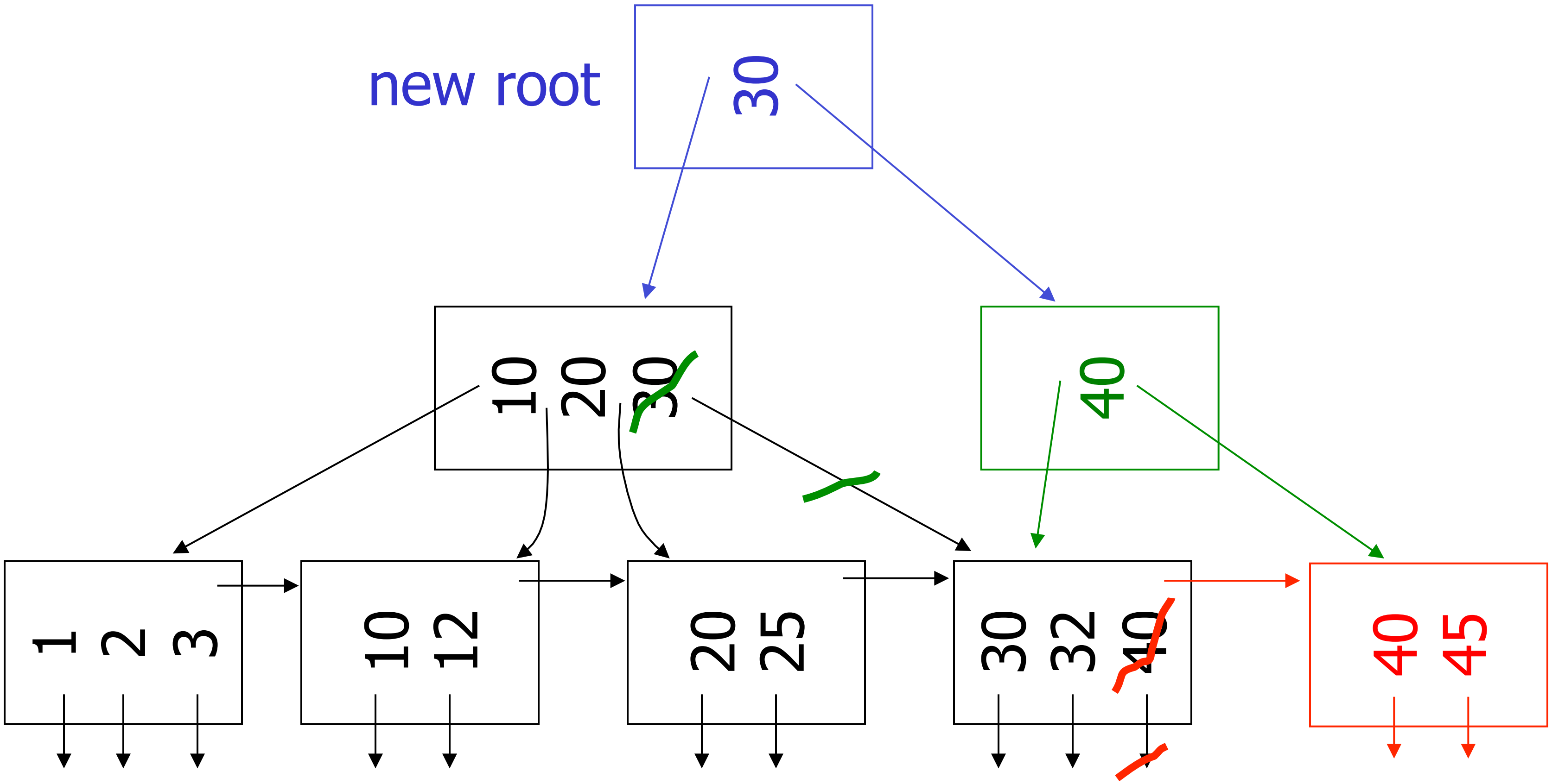


(d) New root, insert 45

n=3



Insertion Algorithm

- Insert Record with key **k**
- Search leaf node for **k**
  - Leaf node has at least one space
    - Insert into leaf
  - Leaf is full
    - Split leaf into two nodes (new leaf)
    - Insert new leaf's smallest key into parent

Insertion Algorithm cont.

- Non-leaf node is full
  - Split parent
  - Insert median key into parent
- Root is full
  - Split root
  - Create new root with two pointers and single key
- -> B-trees grow at the root

Deletion from B+tree

(a) Simple case - no example

(b) Coalesce with neighbor (sibling)

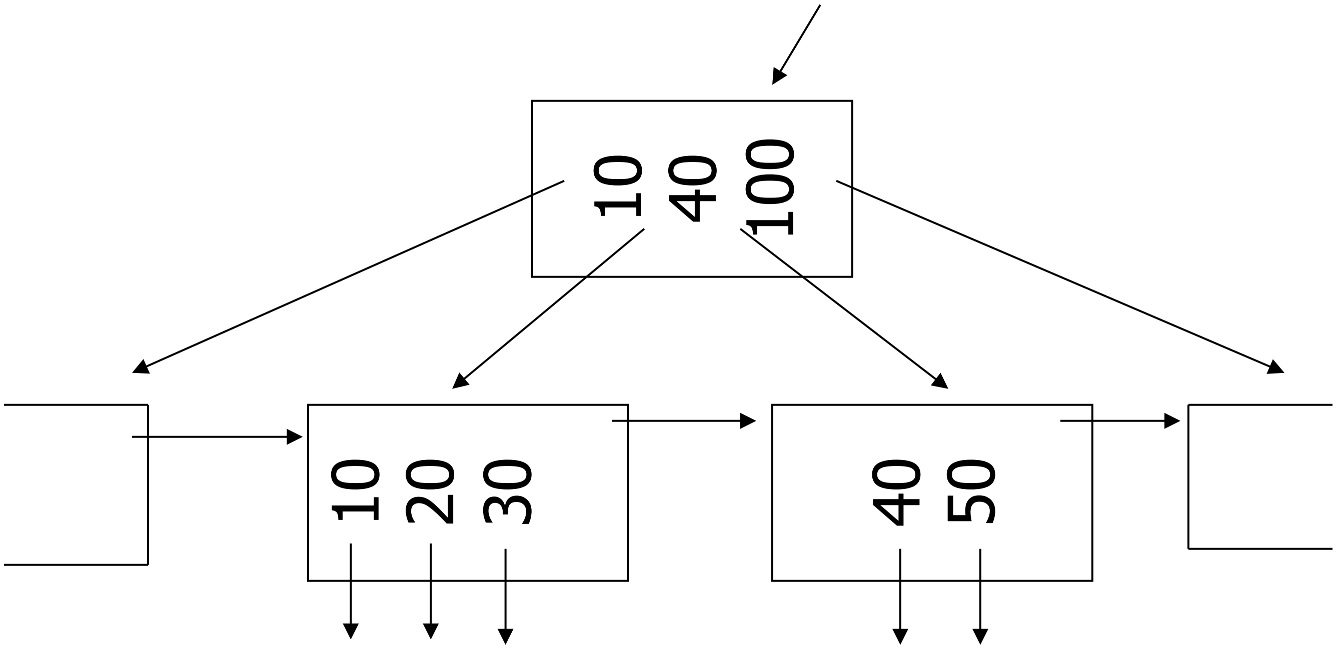
(c) Re-distribute keys

(d) Cases (b) or (c) at non-leaf

(b) Coalesce with sibling

- Delete 50

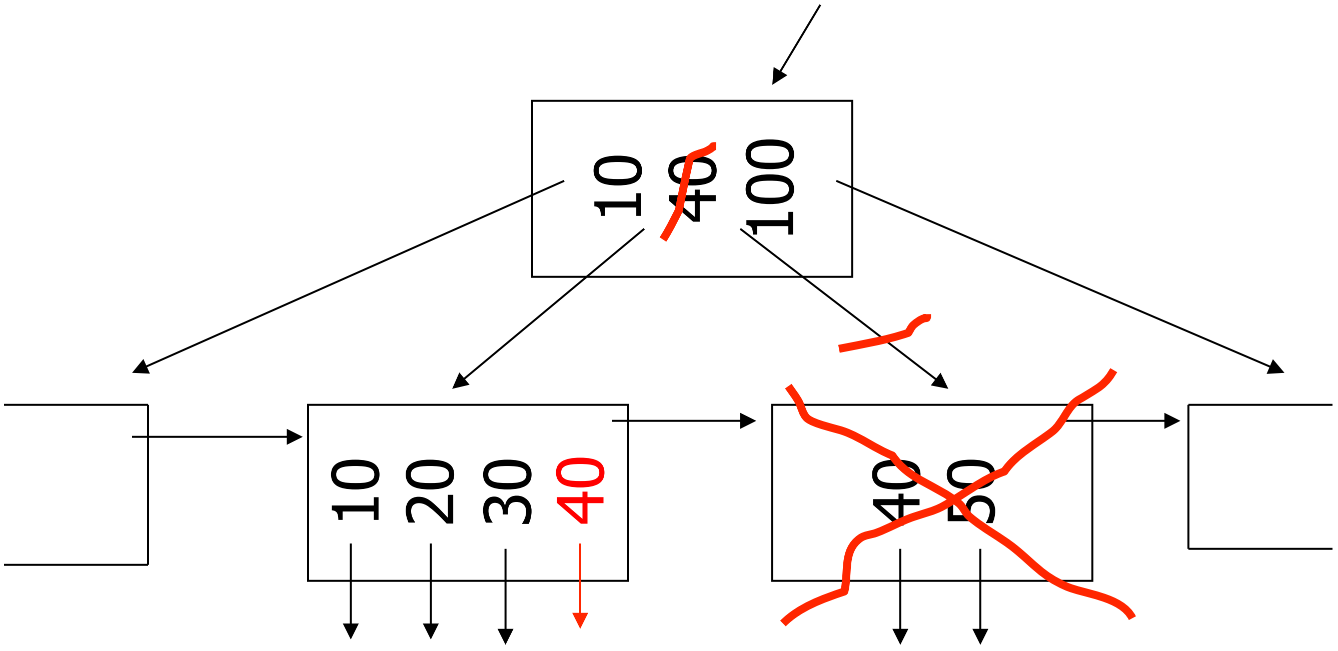
n=4



(b) Coalesce with sibling

- Delete 50

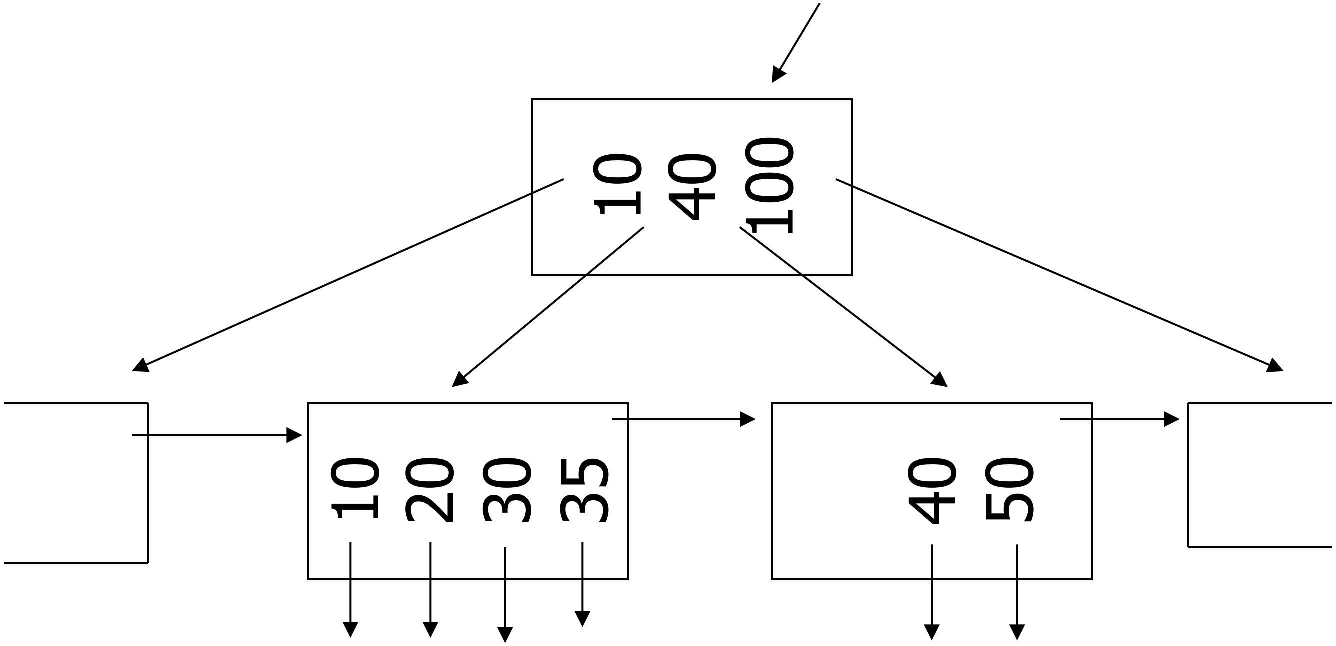
n=4



(c) Redistribute keys

- Delete 50

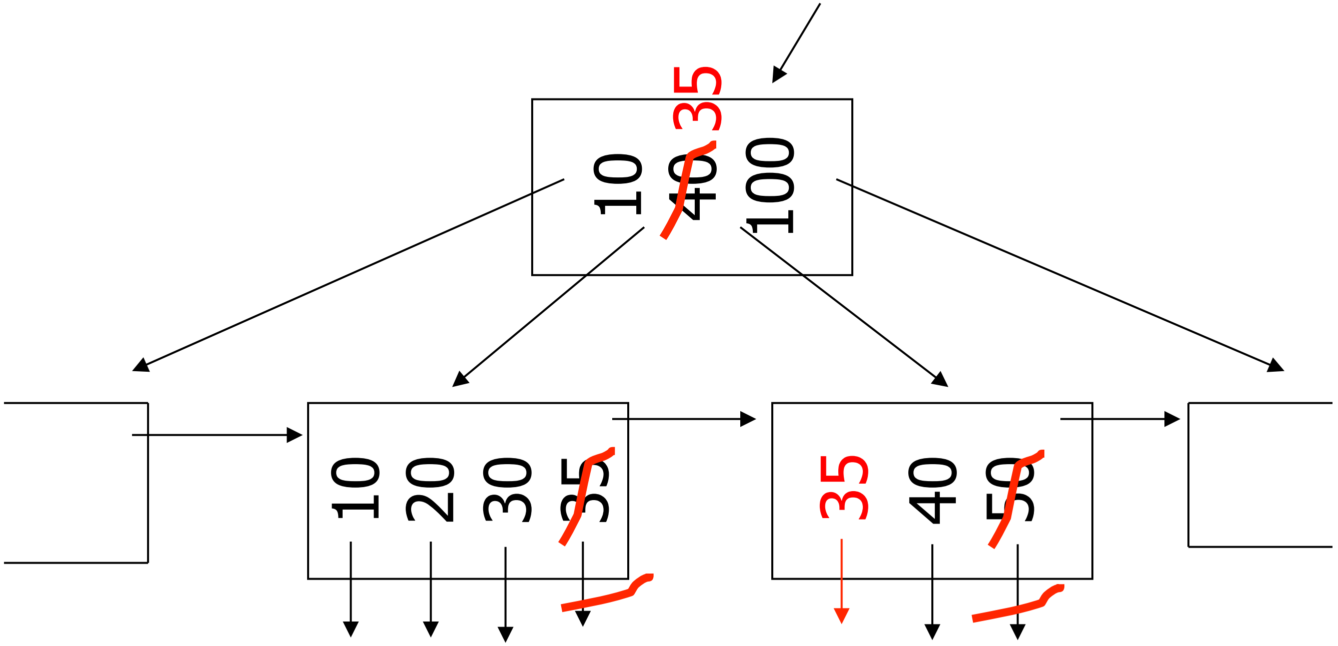
n=4



(c) Redistribute keys

- Delete 50

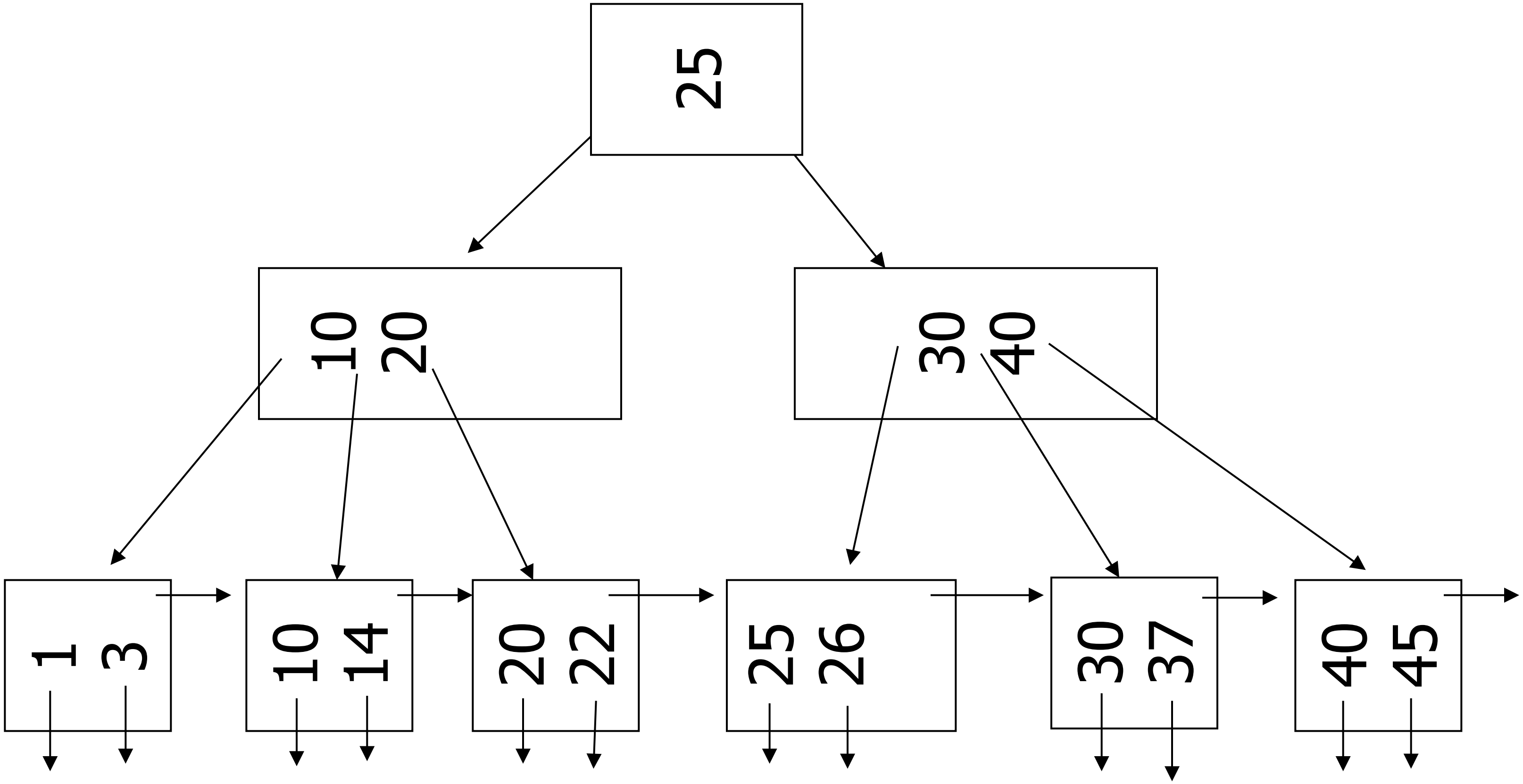
n=4



(d) Non-leaf coalese

- Delete 37

n=4



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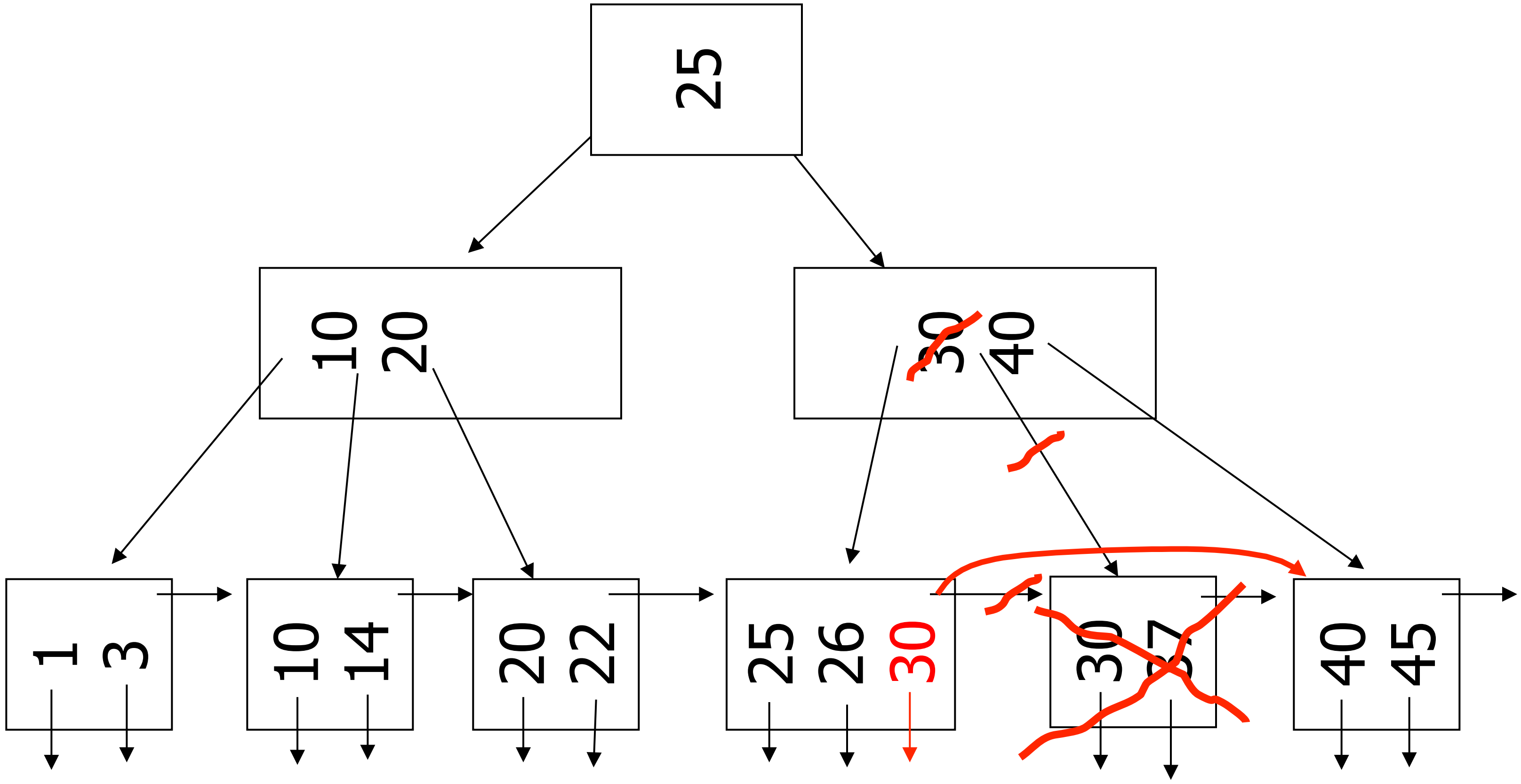
- Delete 37

n=4



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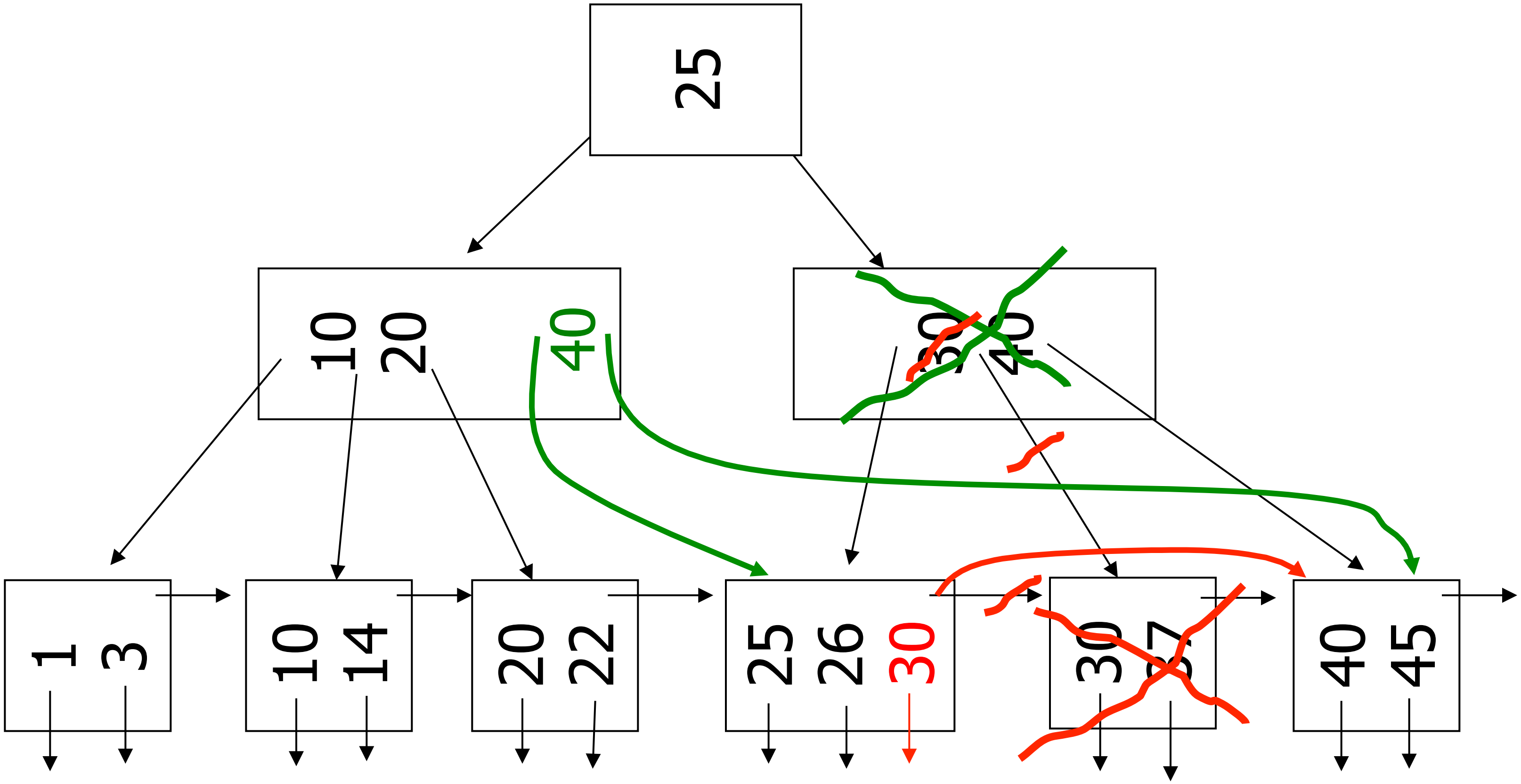
- Delete 37

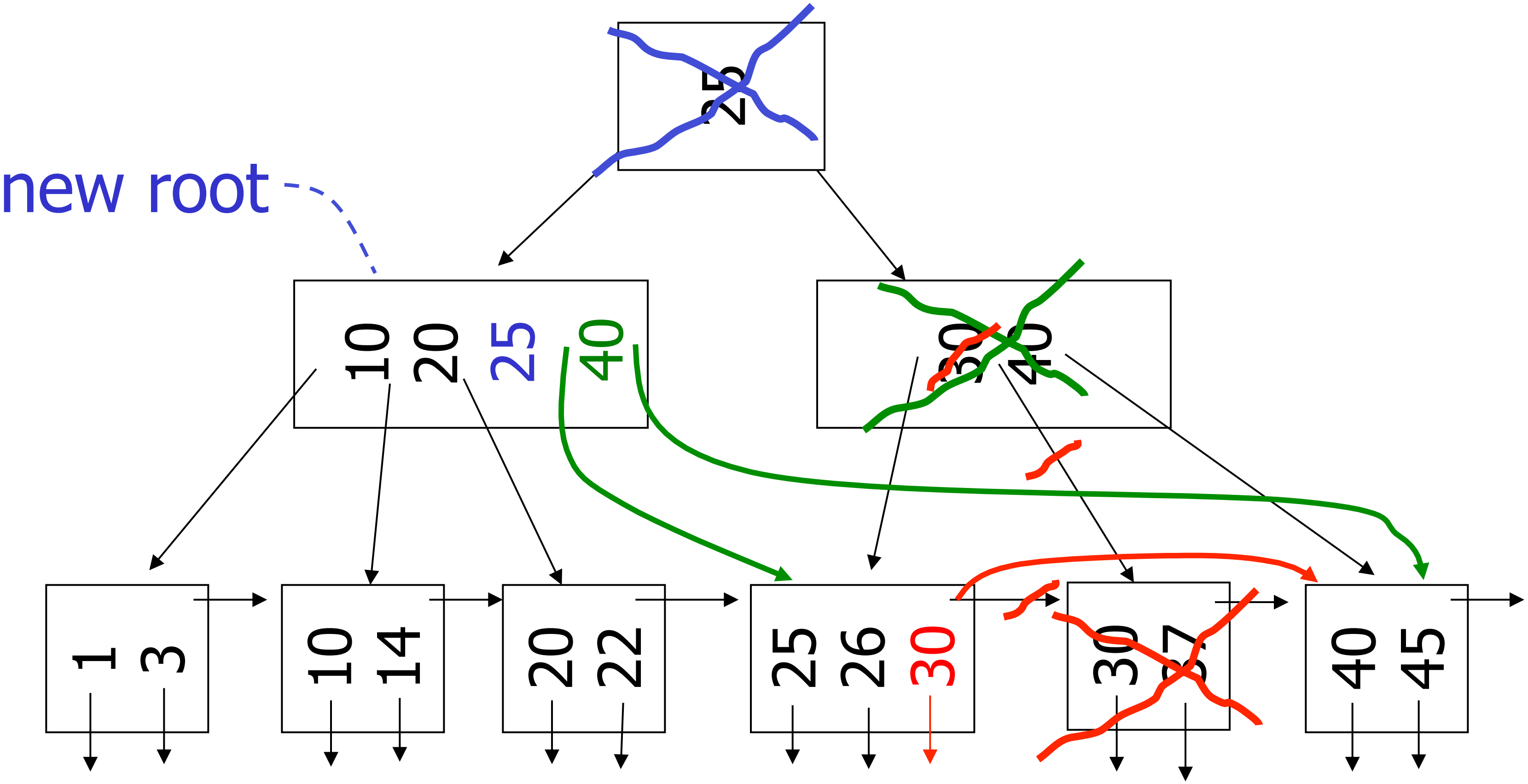
n=4



(d) Non-leaf coalese

- Delete 37

n=4



Deletion Algorithm

- Delete record with key **k**
- Search leaf node for **k**
  - Leaf has more than min entries
    - Remove from leaf
  - Leaf has min entries
    - Try to borrow from sibling
  - One direct sibling has more min entries
    - Move entry from sibling and adapt key in parent

Deletion Algorithm cont.

- Both direct siblings have min entries
  - Merge with one sibling
  - Remove node or sibling from parent
  - ->recursive deletion
- Root has two children that get merged
  - Merged node becomes new root

B+tree deletions in practice

- Often, coalescing is not implemented
  - Too hard and not worth it!
  - Assumption: nodes will fill up in time again

Comparison: B-trees vs. static indexed sequential file

<u>Ref #1:</u> Held & Stonebraker

“B-Trees Re-examined”

CACM, Feb. 1978

Ref # 1 claims:

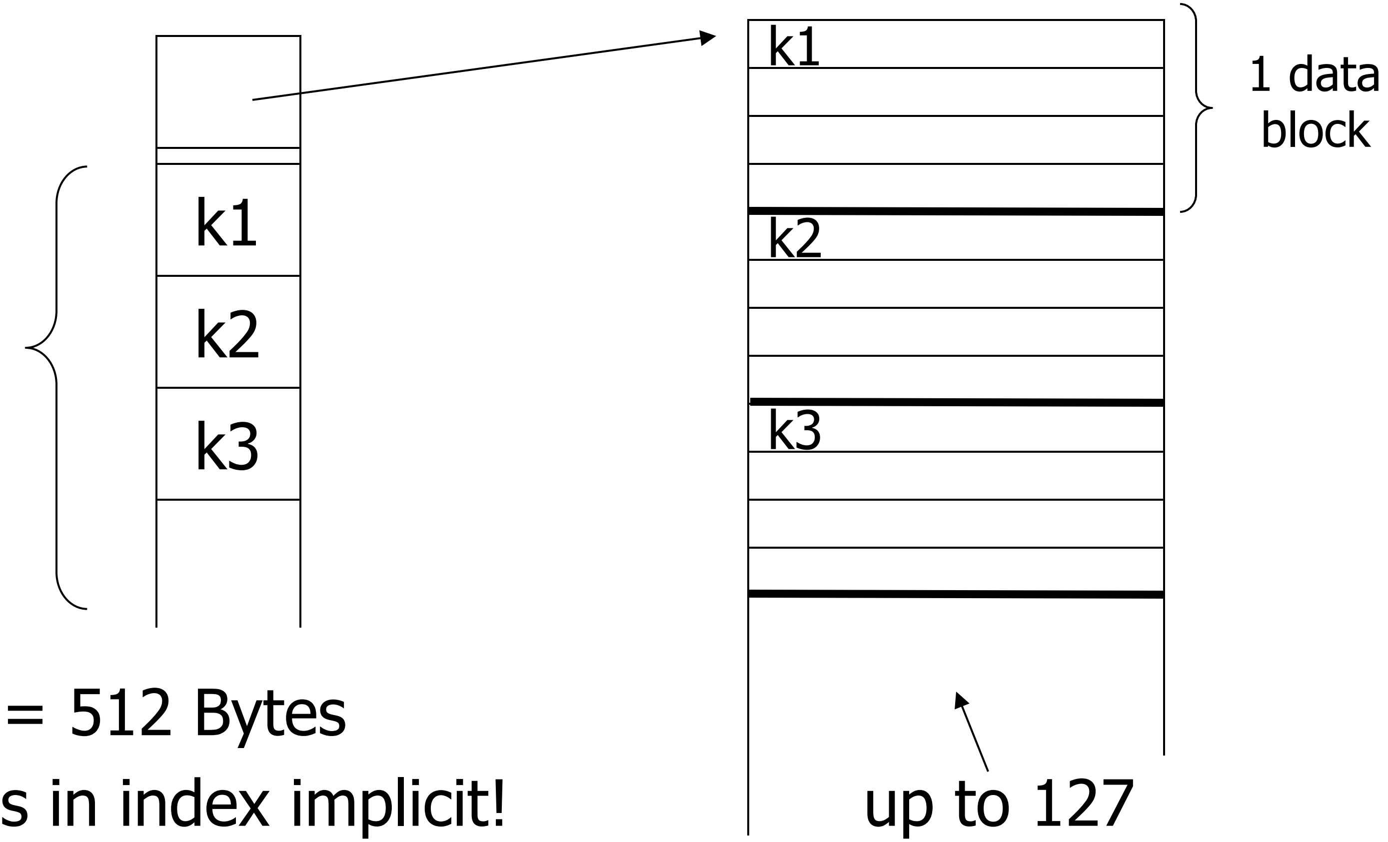
__- Concurrency control harder in B-Trees

- B-tree consumes more space

For their comparison:

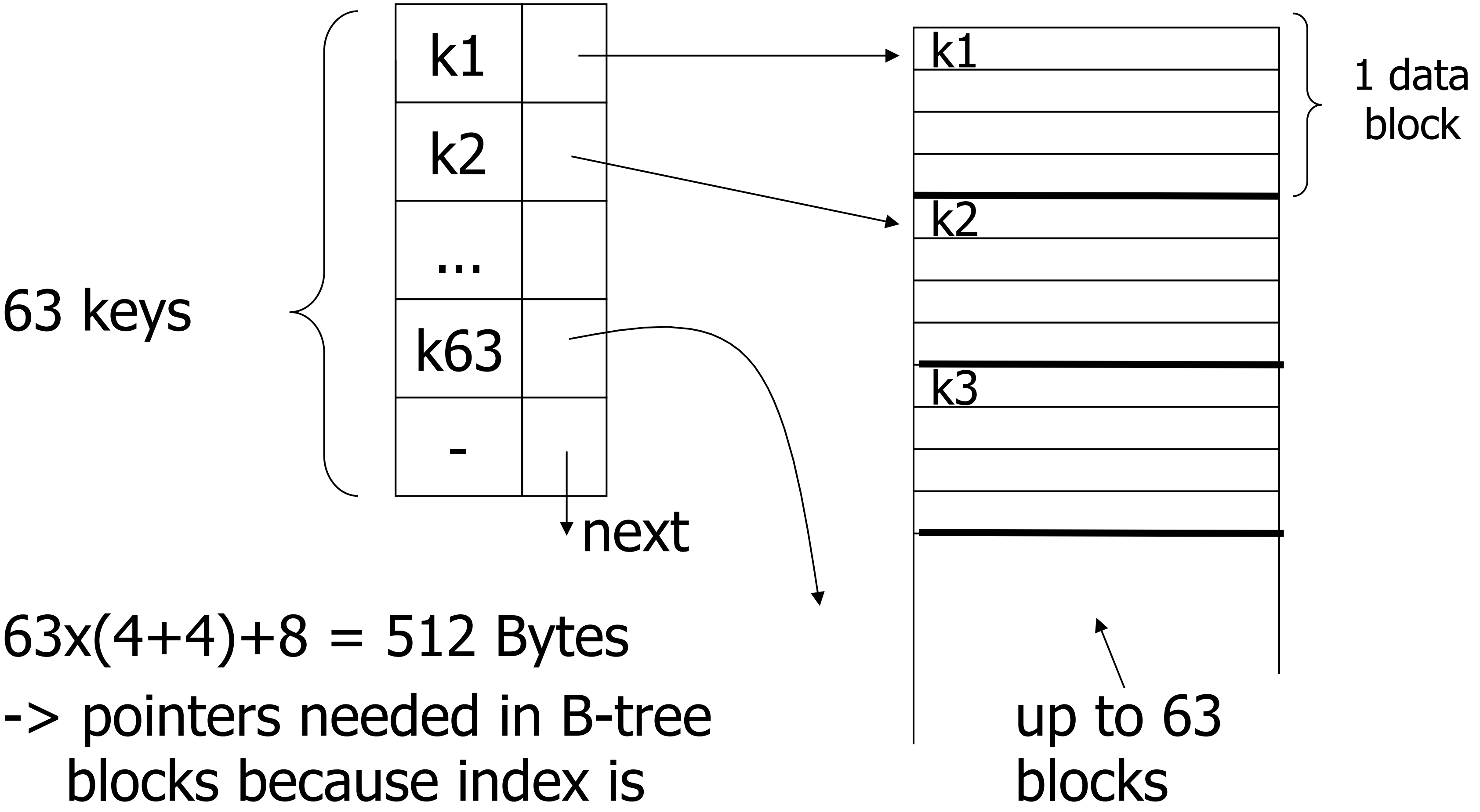
block = 512 bytes
key = pointer = 4 bytes
4 data records per block

Example: 1 block static index



(127+1)4 = 512 Bytes
-> pointers in index implicit!

Example: 1 block B-tree



63x(4+4)+8 = 512 Bytes

-> pointers needed in B-tree blocks because index is not contiguous

Size comparison Ref. #1

Static Index # data blocks	height	B-tree # data blocks	height
2 -> 127	2	2 -> 63	2
128 -> 16,129	3	64 -> 3968	3
16,130 -> 2,048,383	4	3969 -> 250,047	4
		250,048 -> 15,752,961	5

Ref. #1 analysis claims

- For an 8,000 block file,

  $\left\{\begin{array}{l}\text{after 32,000 inserts}\\ \text{after 16,000 lookups}\end{array}\right.$

  ⇒ Static index saves enough accesses to allow for reorganization

Ref. #1 analysis claims

- For an 8,000 block file,
  - after 32,000 inserts
  - after 16,000 lookups

⇒ Static index saves enough accesses to allow for reorganization

Ref. #1 conclusion ⇒ Static index better!!

<u>Ref #2:</u> M. Stonebraker,
"Retrospective on a database system," TODS, June 1980

Ref. #2 conclusion → B-trees better!!

Ref. #2 conclusion → B-trees better!!

- DBA does not know when to reorganize
- DBA does not know how full to load pages of new index

Ref. #2 conclusion B-trees better!!

- Buffering
  - B-tree: has fixed buffer requirements
  - Static index: must read several overflow blocks to be efficient (large & variable size buffers needed for this)

- Speaking of buffering…

  Is LRU a good policy for B+tree buffers?

- Speaking of buffering…

  Is LRU a good policy for B+tree buffers?

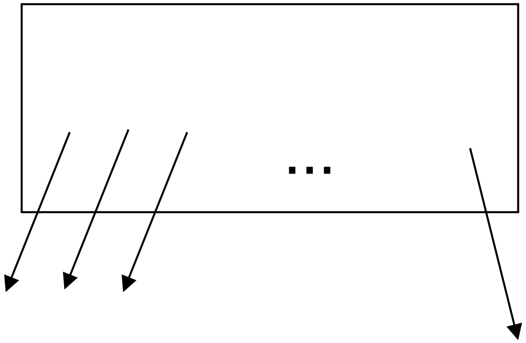
→ Of course not!

→ Should try to keep root in memory at all times

(and perhaps some nodes from second level)

Interesting problem:

For B+tree, how large should *n* be?



n is number of keys / node

Sample assumptions:

(1) Time to read node from disk is $(S+Tn)$ msec.

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(1) Time to read node from disk is
($S+Tn$) msec.

(2) Once block in memory, use binary
search to locate key:
($a + b \, \mathrm{LOG}_2 \, n$) msec.

For some constants *a,b;* Assume $a << S$

Sample assumptions:

(1) Time to read node from disk is
$(S+Tn)$ msec.

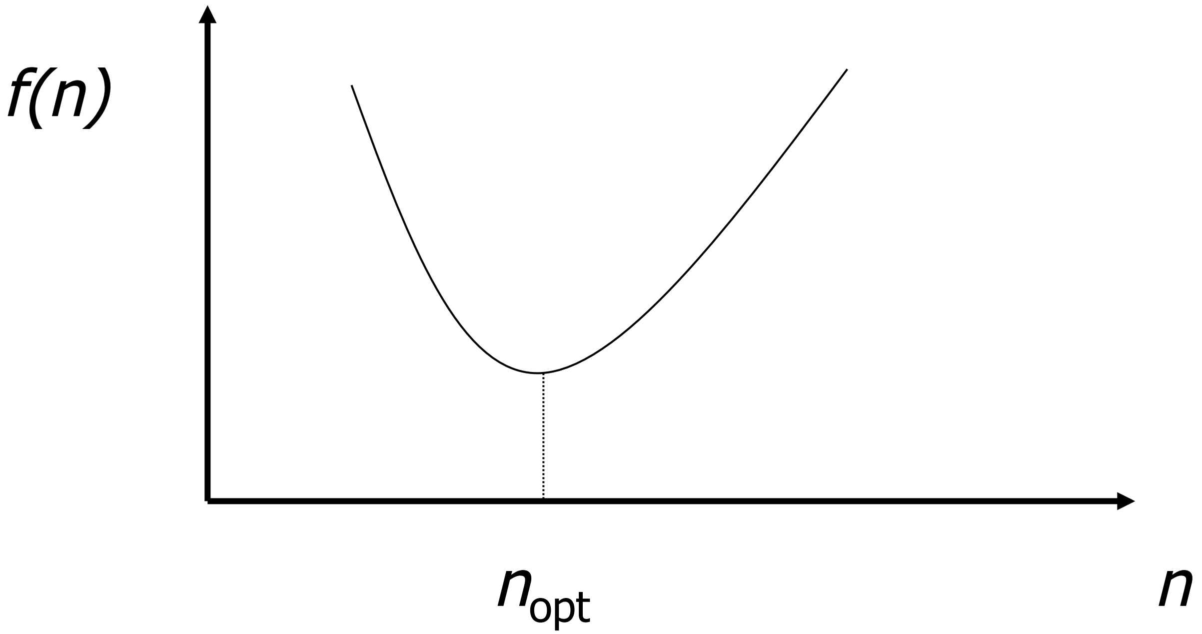
(2) Once block in memory, use binary
search to locate key:
$(a + b \text{ LOG}_2\ n)$ msec.

For some constants *a,b;* Assume a << S

(3) Assume B+tree is full, i.e.,
nodes to examine is $\text{LOG}_n N$
where N = # records

- Can get:

f(n) = time to find a record



- FIND n_{opt} by $f'(n) = 0$

Answer is n_{opt} = “few hundred”

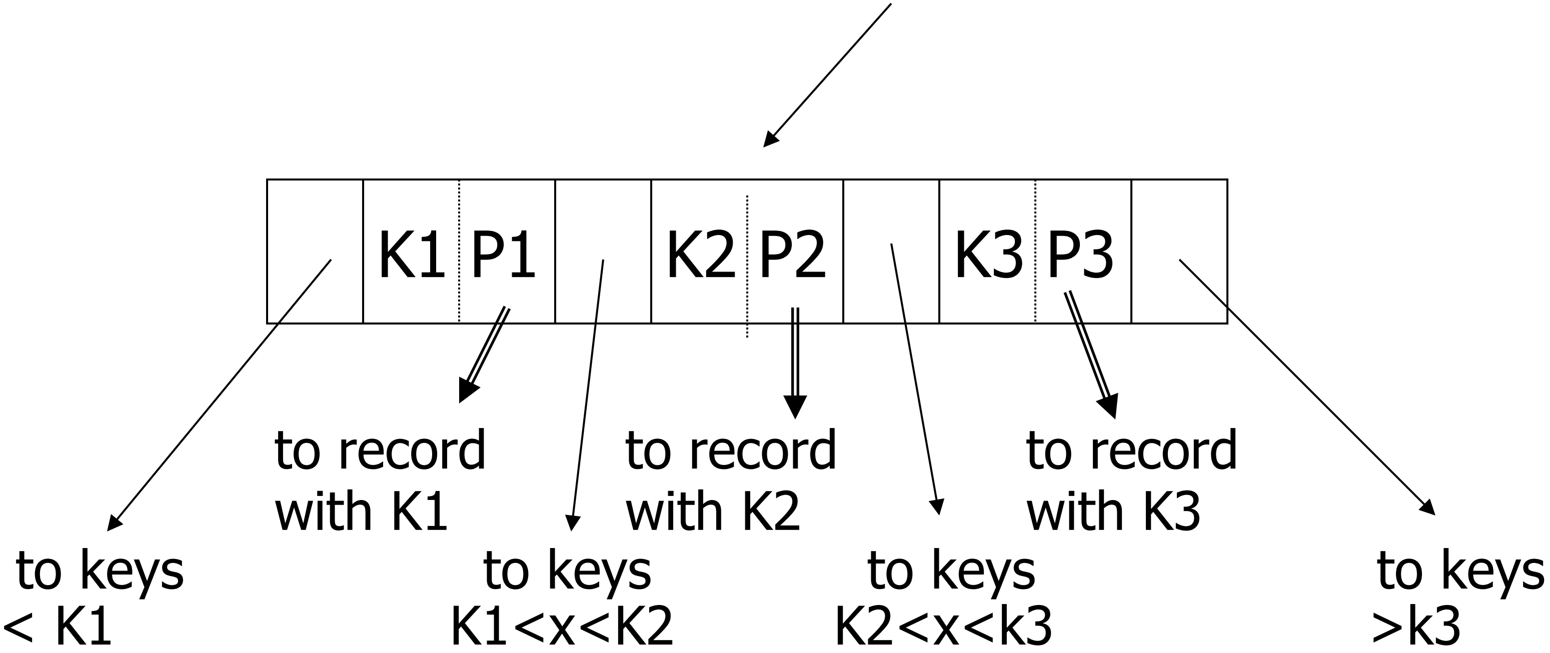
- FIND n_{opt} by $f'(n) = 0$

  Answer is n_{opt} = “few hundred”

- What happens to n_{opt} as
  - Disk gets faster?
  - CPU get faster?
  - Memory hierarchy?

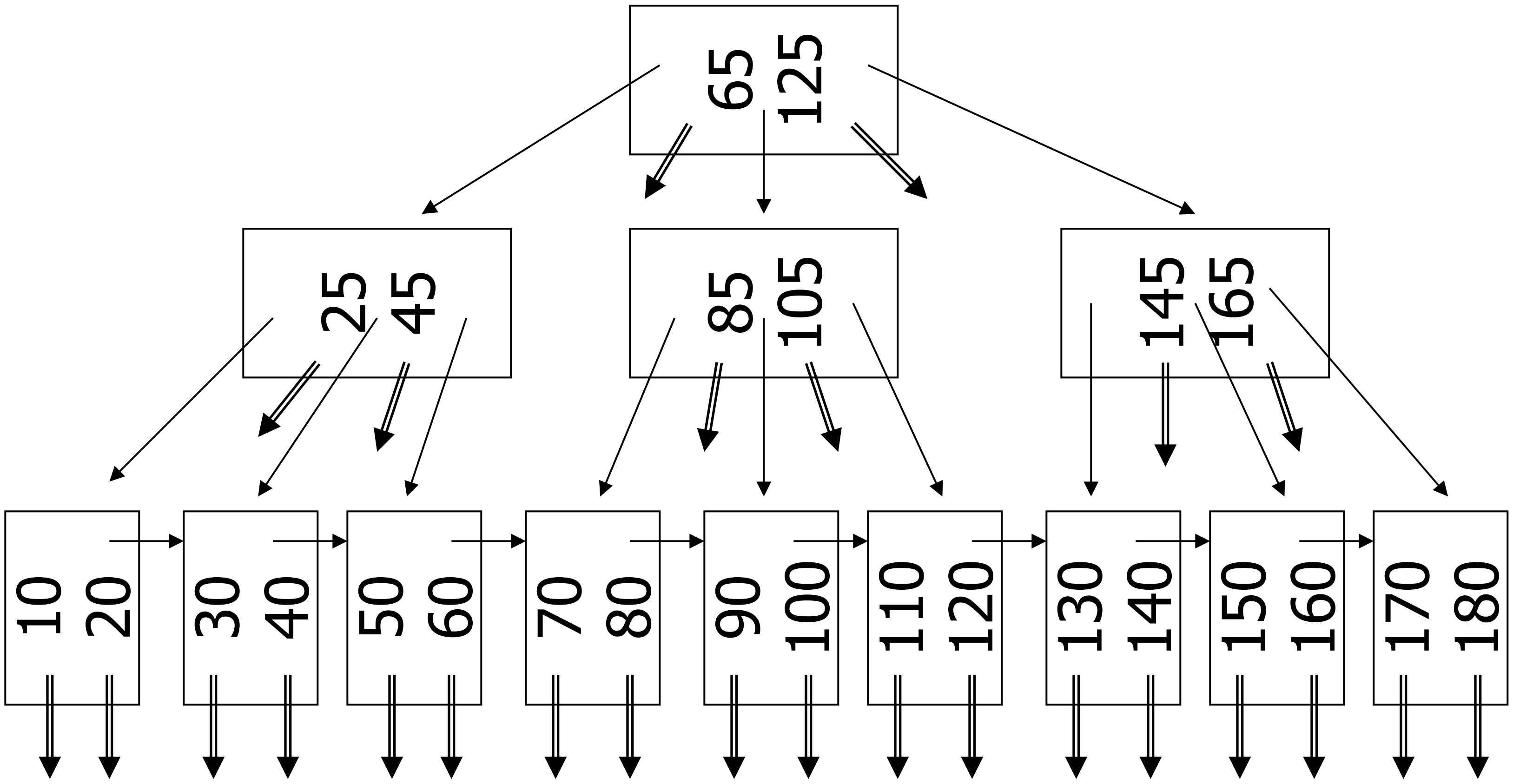
Variation on B+tree: B-tree (no +)

- Idea:
  - Avoid duplicate keys
  - Have record pointers in non-leaf nodes


K1 P1
K2 P2
K3 P3
to record with K1
to record with K2
to record with K3
to keys < K1
to keys K1<x<K2
to keys K2<x<k3
to keys >k3

B-tree example

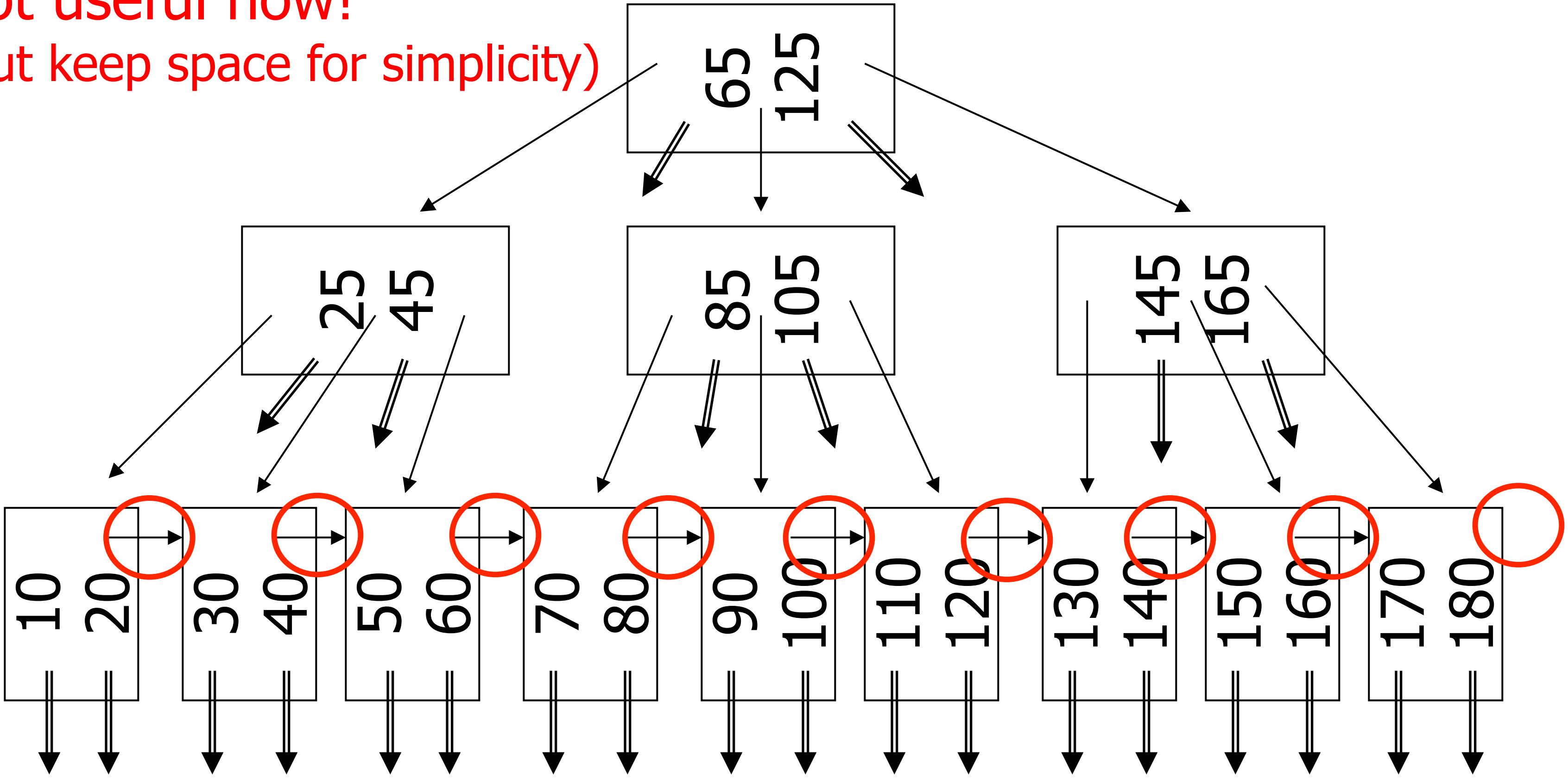
n=2



B-tree example

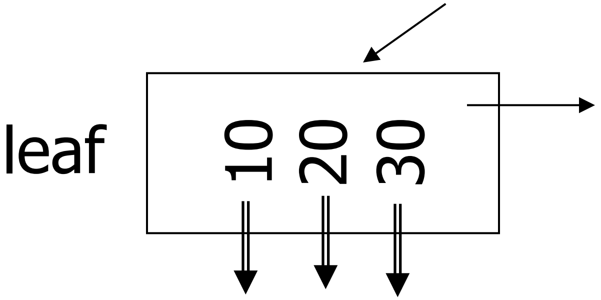
n=2

- sequence pointers not useful now!
  (but keep space for simplicity)



Note on inserts

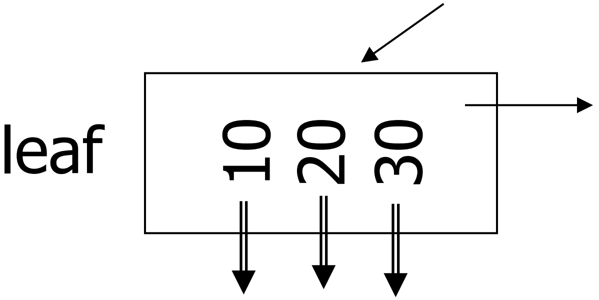
- Say we insert record with key = 25



n=3

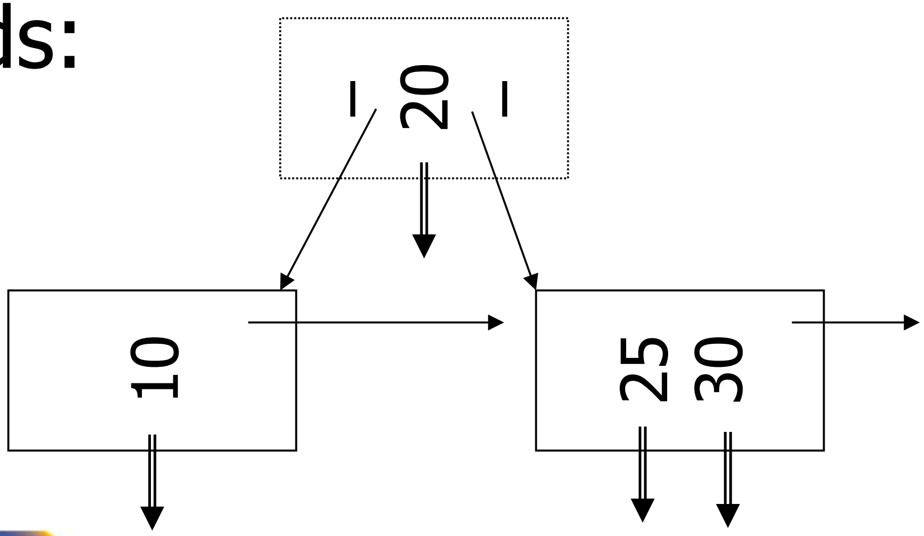
Note on inserts

- Say we insert record with key = 25



n=3

- Afterwards:



So, for B-trees:

	MAX			MIN		
	Tree Ptrs	Rec Ptrs	Keys	Tree Ptrs	Rec Ptrs	Keys
Non-leaf non-root	n+1	n	n	$\lceil(n+1)/2\rceil$	$\lceil(n+1)/2\rceil-1$	$\lceil(n+1)/2\rceil-1$
Leaf non-root	1	n	n	1	$\lfloor n/2\rfloor$	$\lfloor n/2\rfloor$
Root non-leaf	n+1	n	n	2	1	1
Root Leaf	1	n	n	1	1	1

Tradeoffs:

☺ B-trees have faster lookup than B+trees

☹ in B-tree, non-leaf & leaf different sizes
☹ in B-tree, deletion more complicated

Tradeoffs:

☺ B-trees have faster lookup than B+trees

☹ in B-tree, non-leaf & leaf different sizes

☹ in B-tree, deletion more complicated

➨ B+trees preferred!

But note:

- If blocks are fixed size

  (due to disk and buffering restrictions)

  Then lookup for B+tree is
  actually better!!

Example:

__- Pointers 4 bytes

- Keys 4 bytes
- Blocks 100 bytes (just example)
- Look at full 2 level tree

B-tree:

Root has 8 keys + 8 record pointers
+ 9 son pointers
= 8x4 + 8x4 + 9x4 = 100 bytes

B-tree:

Root has 8 keys + 8 record pointers
+ 9 son pointers
= 8x4 + 8x4 + 9x4 = 100 bytes

Each of 9 sons: 12 rec. pointers (+12 keys)
= 12x(4+4) + 4 = 100 bytes

B-tree:

Root has 8 keys + 8 record pointers
+ 9 son pointers
= 8x4 + 8x4 + 9x4 = 100 bytes

Each of 9 sons: 12 rec. pointers (+12 keys)
= 12x(4+4) + 4 = 100 bytes

2-level B-tree, Max # records =
12x9 + 8 = 116

B+tree:

Root has 12 keys + 13 son pointers

= 12x4 + 13x4 = 100 bytes

B+tree:

<u>Root</u> has 12 keys + 13 son pointers

= 12x4 + 13x4 = 100 bytes

<u>Each of 13 sons:</u> 12 rec. ptrs (+12 keys)

= 12x(4 +4) + 4 = 100 bytes

B+tree:

Root has 12 keys + 13 son pointers

= 12x4 + 13x4 = 100 bytes

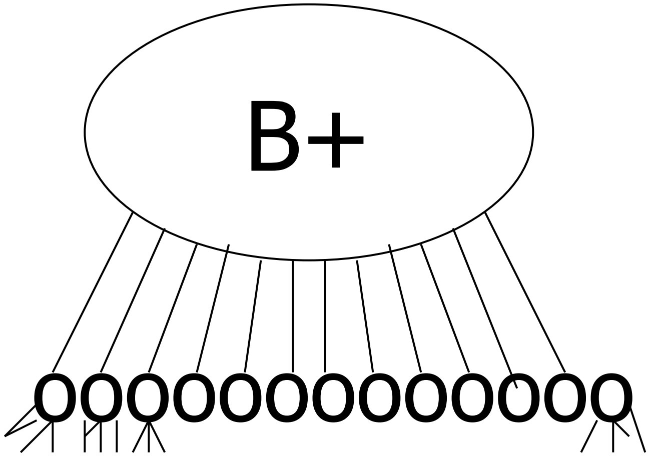
Each of 13 sons: 12 rec. ptrs (+12 keys)

= 12x(4 +4) + 4 = 100 bytes

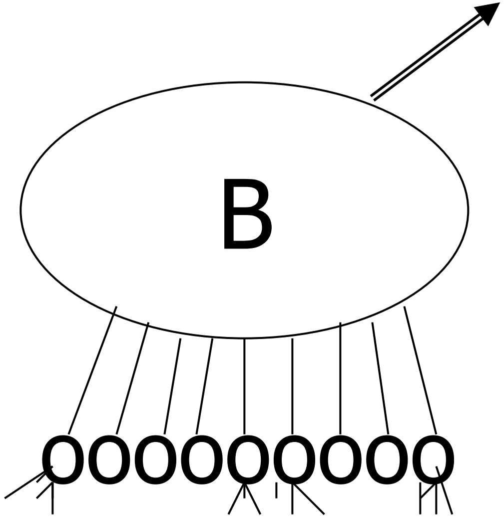
2-level B+tree, Max # records

= 13x12 = 156

So...



156 records

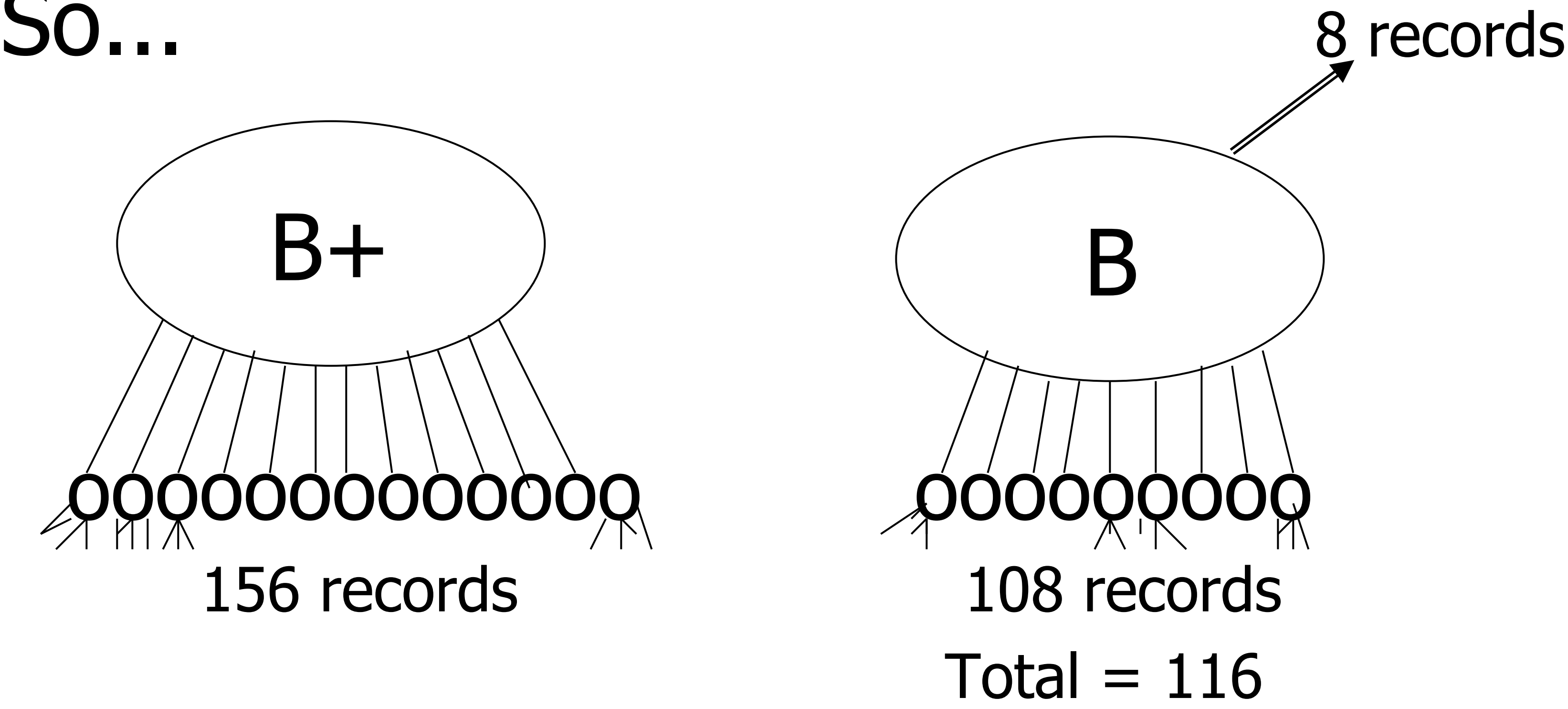


8 records

108 records

Total = 116

So...



- Conclusion:
  - For fixed block size,
  - B+ tree is better because it is bushier

Additional B-tree Variants

- B*-tree
  - Internal notes have to be 2/3 full

An Interesting Problem…

- What is a good index structure when:
  - – records tend to be inserted with keys that are larger than existing values? (e.g., banking records with growing data/time)
  - – we want to remove older data

One Solution: Multiple Indexes

- Example: I1, I2

day	days indexed I1	days indexed I2
10	1,2,3,4,5	6,7,8,9,10
11	11,2,3,4,5	6,7,8,9,10
12	11,12,3,4,5	6,7,8,9,10
13	11,12,13,4,5	6,7,8,9,10

- advantage: deletions/insertions from smaller index
- disadvantage: query multiple indexes

Another Solution (Wave Indexes)

day	I1	I2	I3	I4
10	1,2,3	4,5,6	7,8,9	10
11	1,2,3	4,5,6	7,8,9	10,11
12	1,2,3	4,5,6	7,8,9	10,11, 12
13	13	4,5,6	7,8,9	10,11, 12
14	13,14	4,5,6	7,8,9	10,11, 12
15	13,14,15	4,5,6	7,8,9	10,11, 12
16	13,14,15	16	7,8,9	10,11, 12

- advantage: no deletions
- disadvantage: approximate windows

Concurrent Access To B-trees

- Multiple processes/threads accessing the B-tree
  - Can lead to corruption
- Serialize access to complete tree for updates
  - Simple
  - Unnecessary restrictive
  - Not feasible for high concurrency

Lock Nodes

	Read	Write
Read	X	-
Write	-	-

- One solution
  - **Read** and **exclusive** locks
  - Safe and unsafe updates of nodes
    - **Safe:** No ancestor of node will be effected by update
    - **Unsafe:** Ancestor may be affected
    - Can be determined locally
      - E.g., deletion is safe is node has more than n/2

Lock Nodes

- Reading
  - Use standard search algorithm
  - Hold lock on current node
  - Release when navigating to child
- Writing
  - Lock each node on search for key
  - Release all locks on parents of node if the node is safe

Improvements?

- Try locking only the leaf for update
  - Let update use read locks and only lock leaf node with write lock
  - If leaf node is unsafe then use previous protocol
- Many more locking approaches have been proposed

Outline/summary

- Conventional Indexes
    - Sparse vs. dense
    - Primary vs. secondary
- B trees
    - B+trees vs. B-trees
    - B+trees vs. indexed sequential
- Hashing schemes --> Next
- Advanced Index Techniques

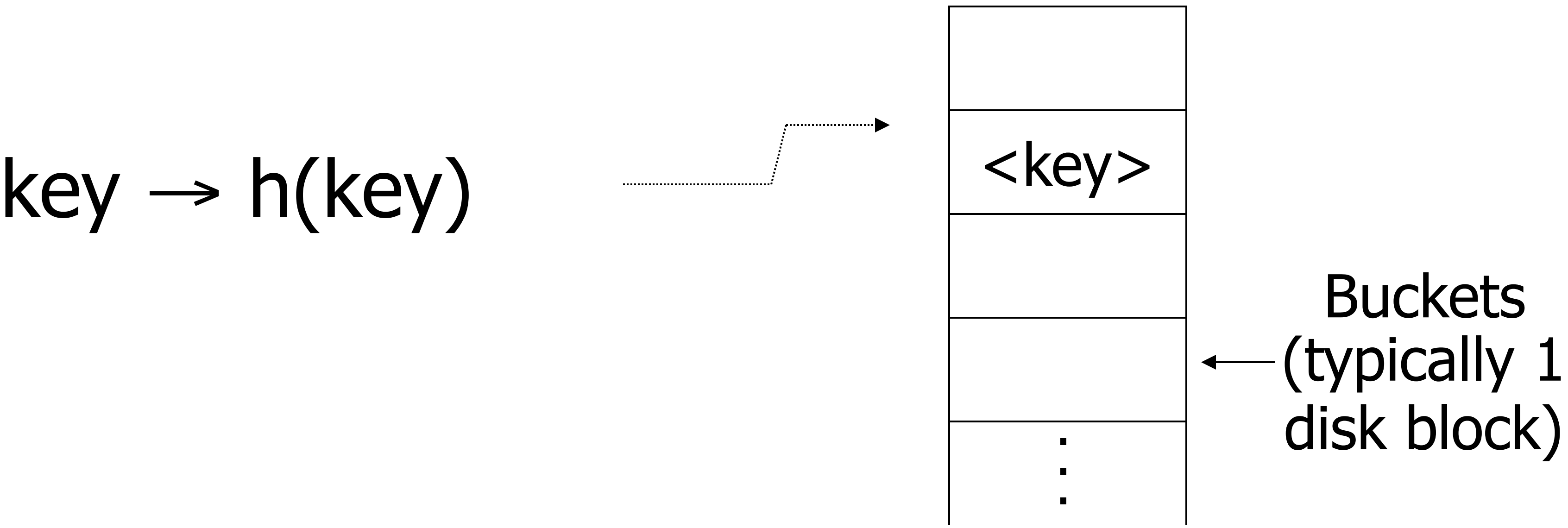
CS 525: Advanced Database Organization

05: Hashing and More

Boris Glavic

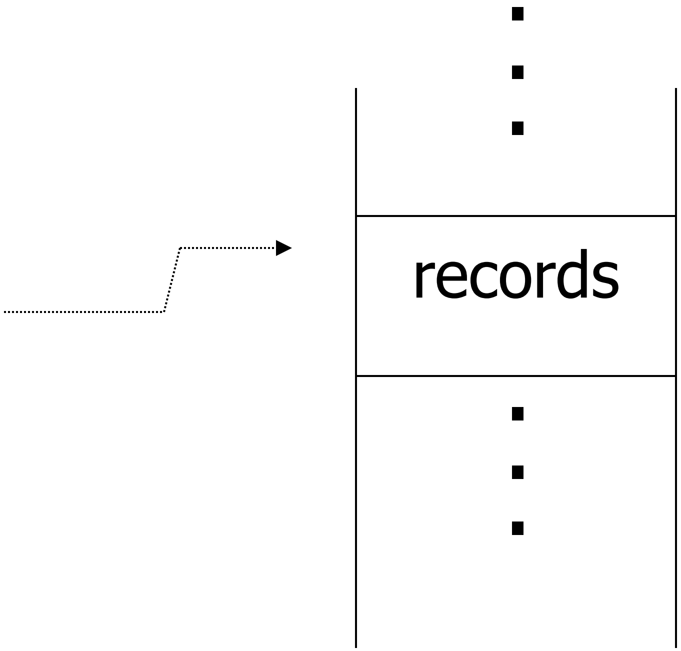
Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab

Hashing



Two alternatives

(1) key → h(key)



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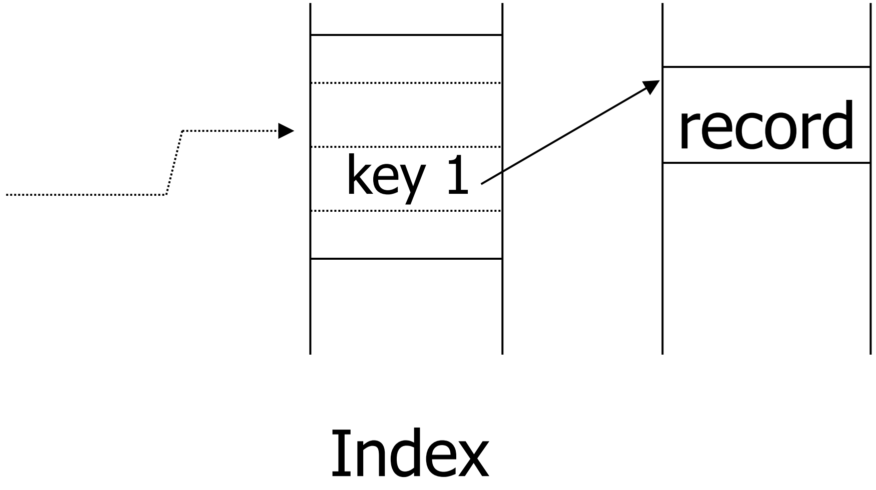

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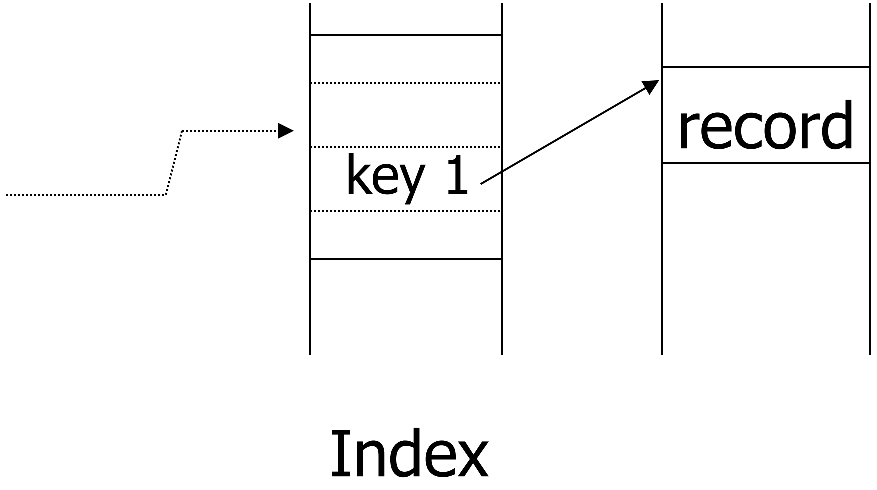

- Alt (2) for “secondary” search key

Example hash function

- Key = ‘x_1 x_2 … x_n’ *n* byte character string
- Have *b* buckets
- h: add $x_1 + x_2 + \ldots\ldots x_n$
  - compute sum modulo *b*

- This may not be best function …
- Read Knuth Vol. 3 if you really need to select a good function.

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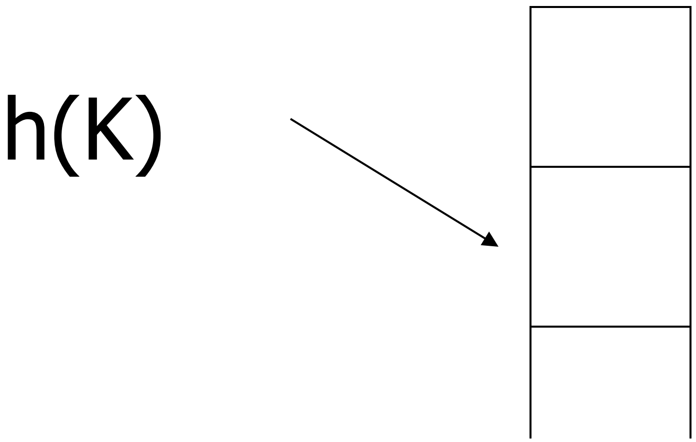
Good hash function:

☞ Expected number of keys/bucket is the same for all buckets

Within a bucket:

- Do we keep keys sorted?
- Yes, if CPU time critical
  & Inserts/Deletes not too frequent

Next: example to illustrate inserts, overflows, deletes



EXAMPLE 2 records/bucket

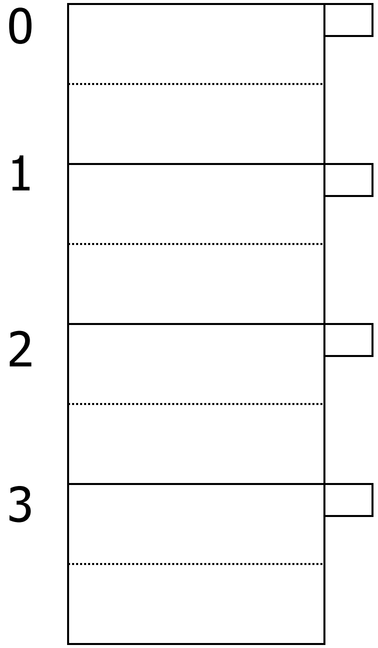
INSERT:

h(a) = 1

h(b) = 2

h(c) = 1

h(d) = 0



EXAMPLE 2 records/bucket

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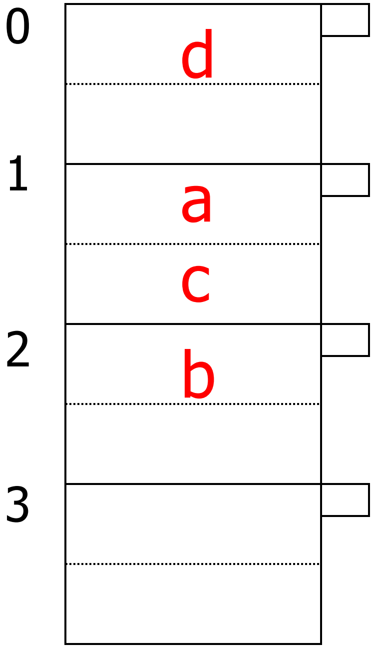

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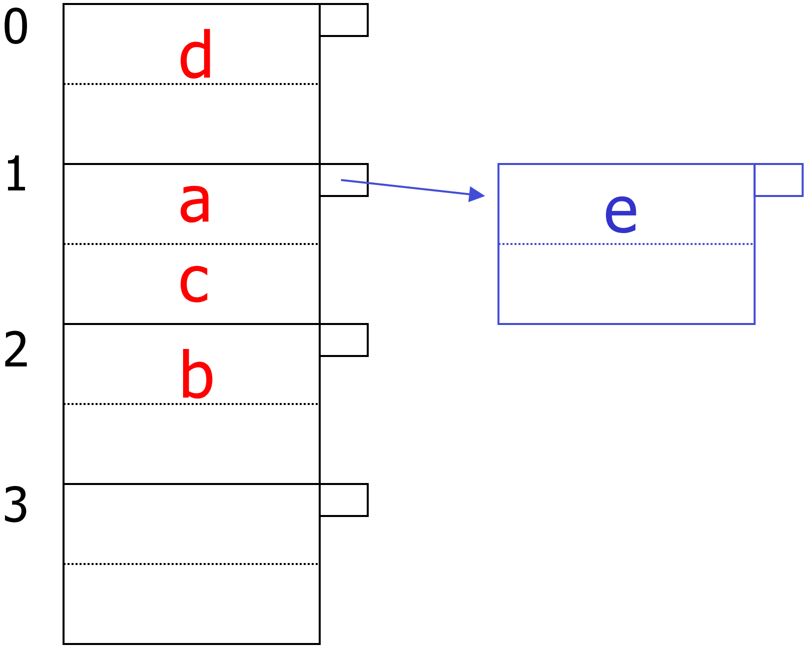
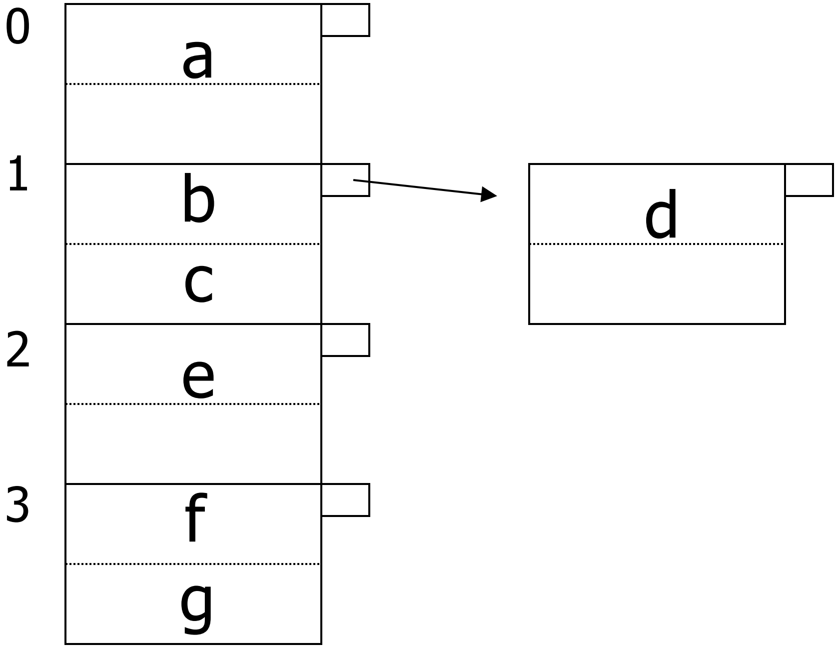


EXAMPLE: deletion

Delete:
- e
- f



EXAMPLE: deletion

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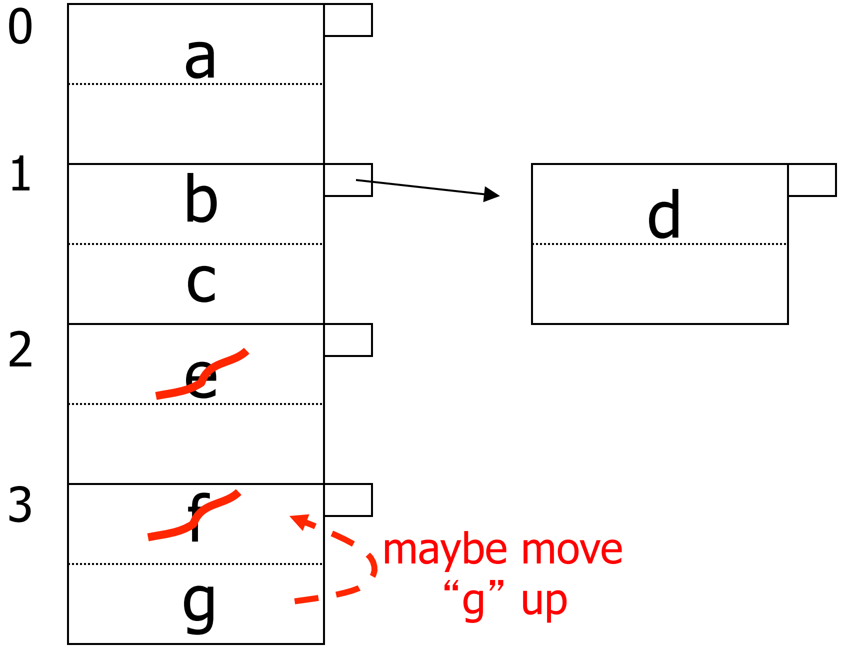
f

c



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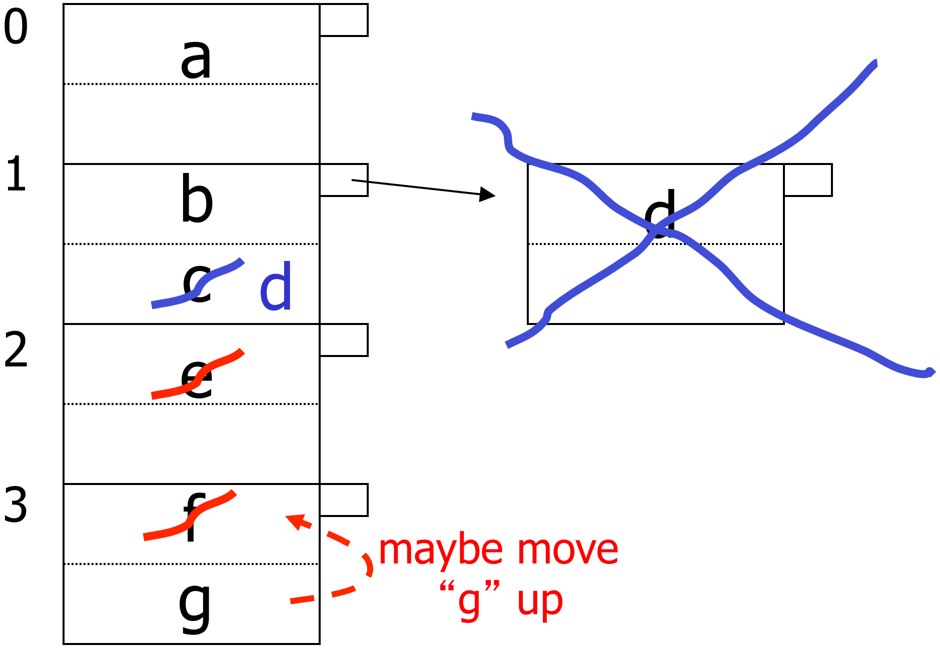

Rule of thumb:

- Try to keep space utilization between 50% and 80%

$$\text{Utilization} = \frac{\#\ \text{keys used}}{\text{total}\ \#\ \text{keys that fit}}$$

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- If < 50%, wasting space
- If > 80%, overflows significant

↖ depends on how good hash function is & on # keys/bucket

How do we cope with growth?

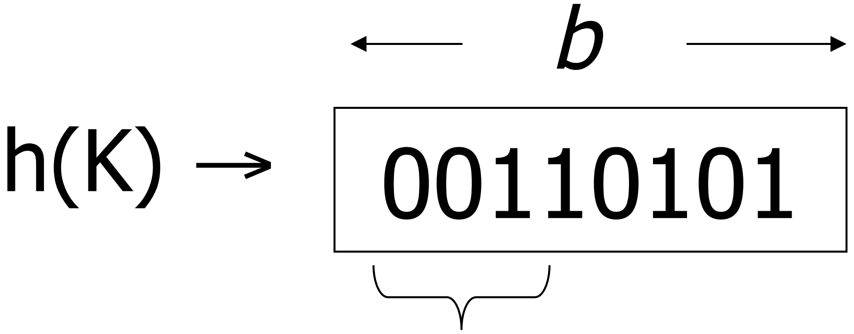
- Overflows and reorganizations
- Dynamic hashing

How do we cope with growth?

- Overflows and reorganizations
- Dynamic hashing
  - Extensible
  - Linear

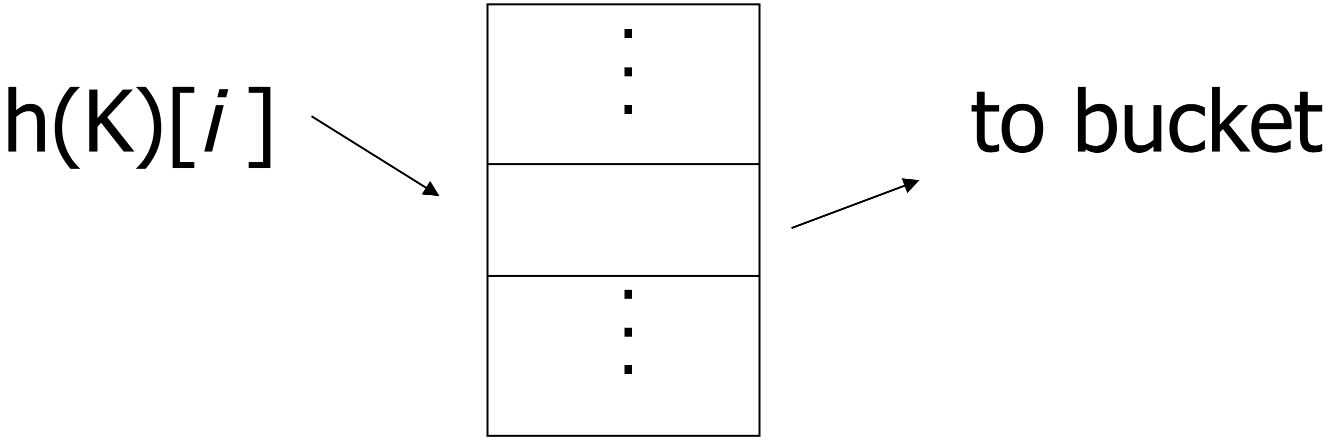
Extensible hashing: two ideas

(a) Use *i* of *b* bits output by hash function



use *i* → grows over time....

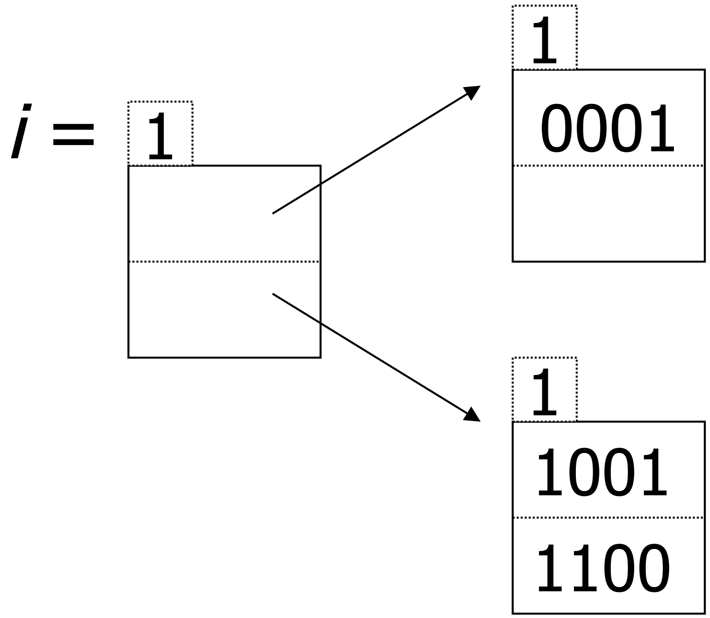
(b) Use directory



h(K)[*i*]

to bucket

Example: h(k) is 4 bits; 2 keys/bucket



Insert 1010

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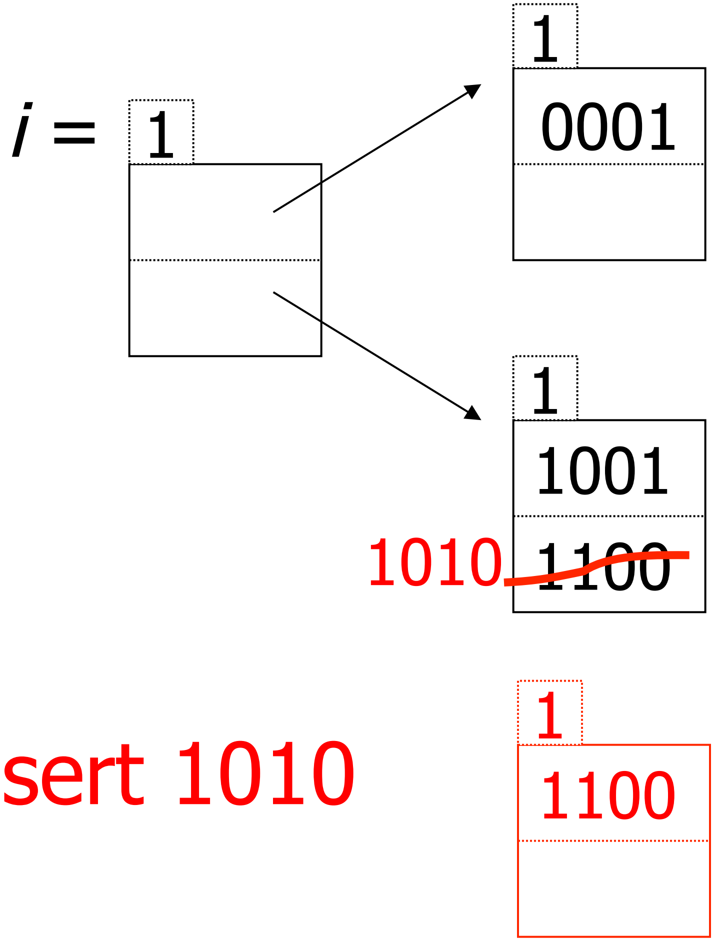

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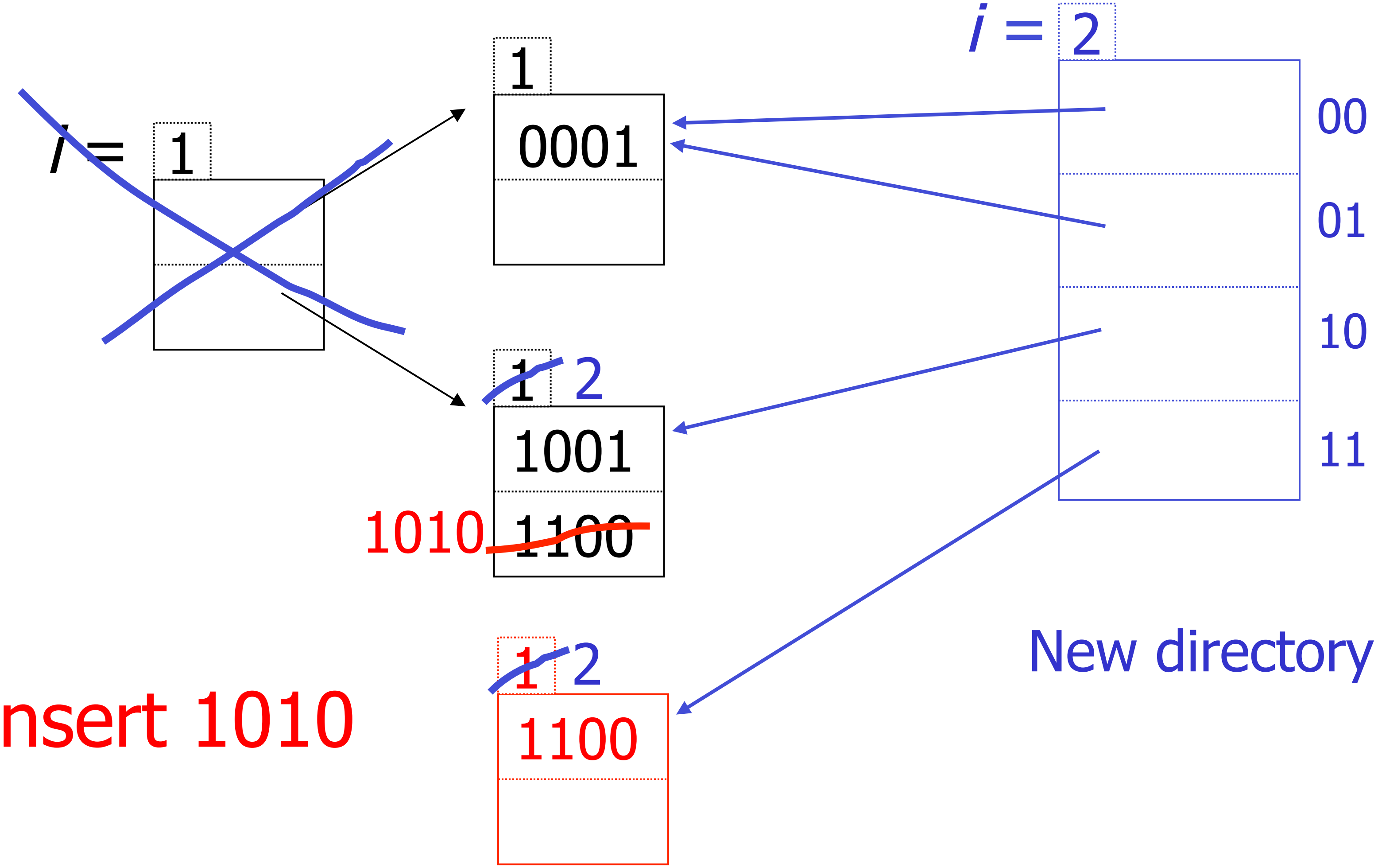
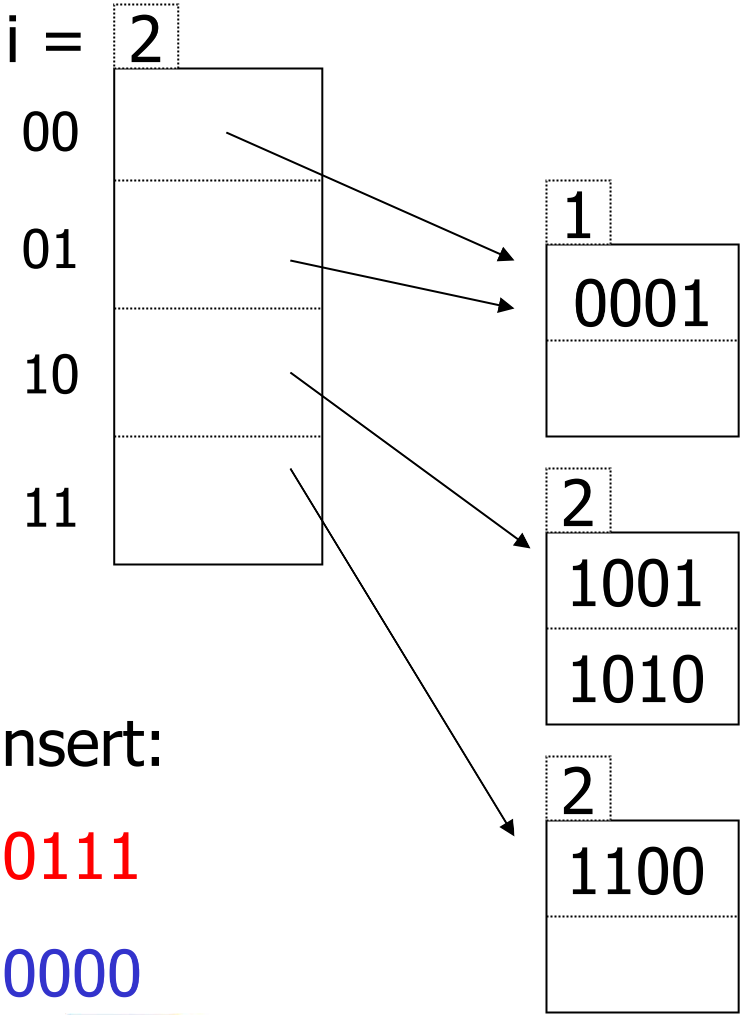
Example: h(k) is 4 bits; 2 keys/bucket



Insert 1010

Example continued

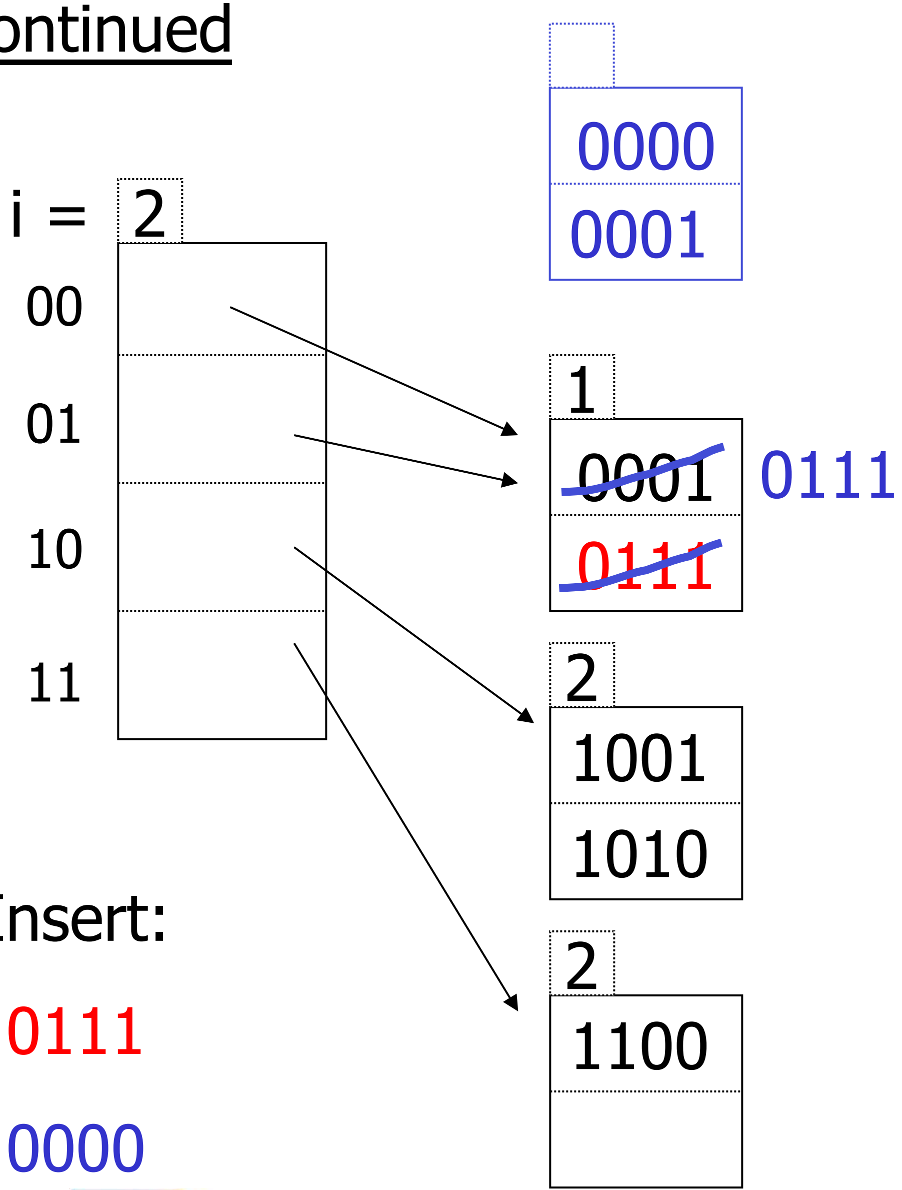


Insert:

0111

0000

Example continued

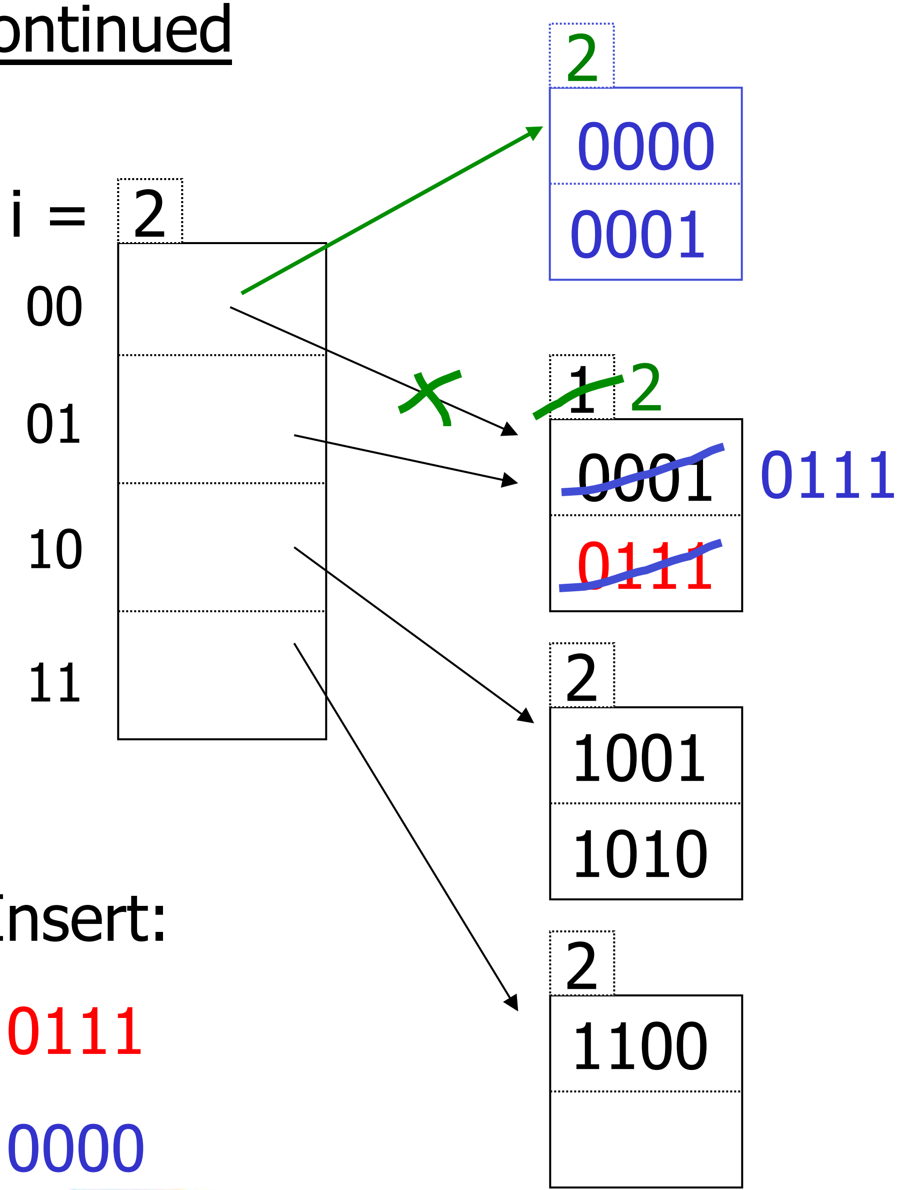


Insert:

0111

0000

Example continued

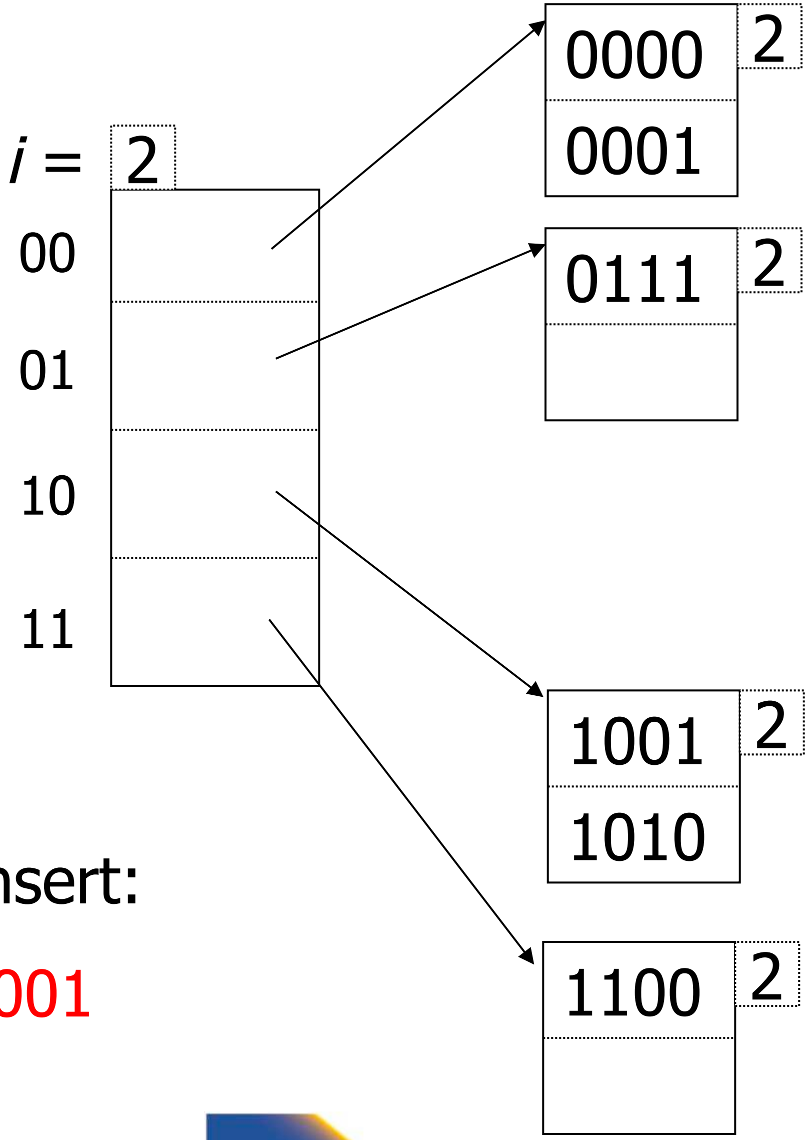


Insert:

0111

0000

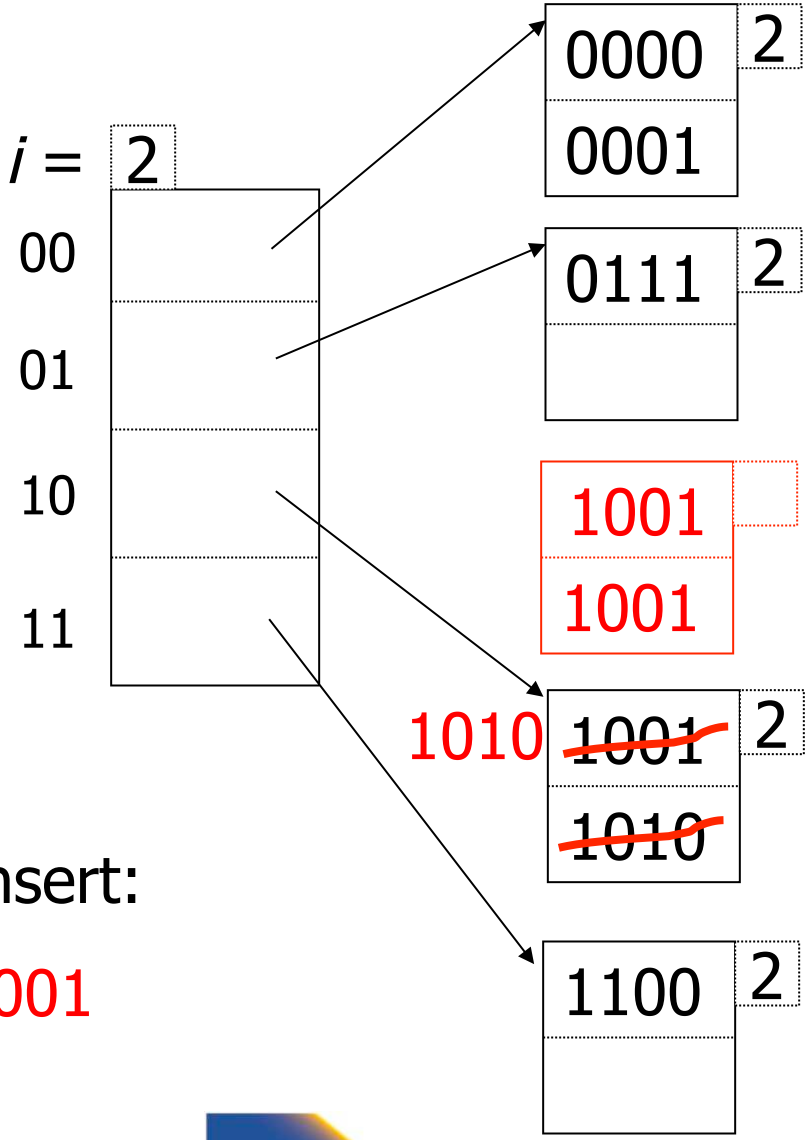
Example continued



Insert:

1001

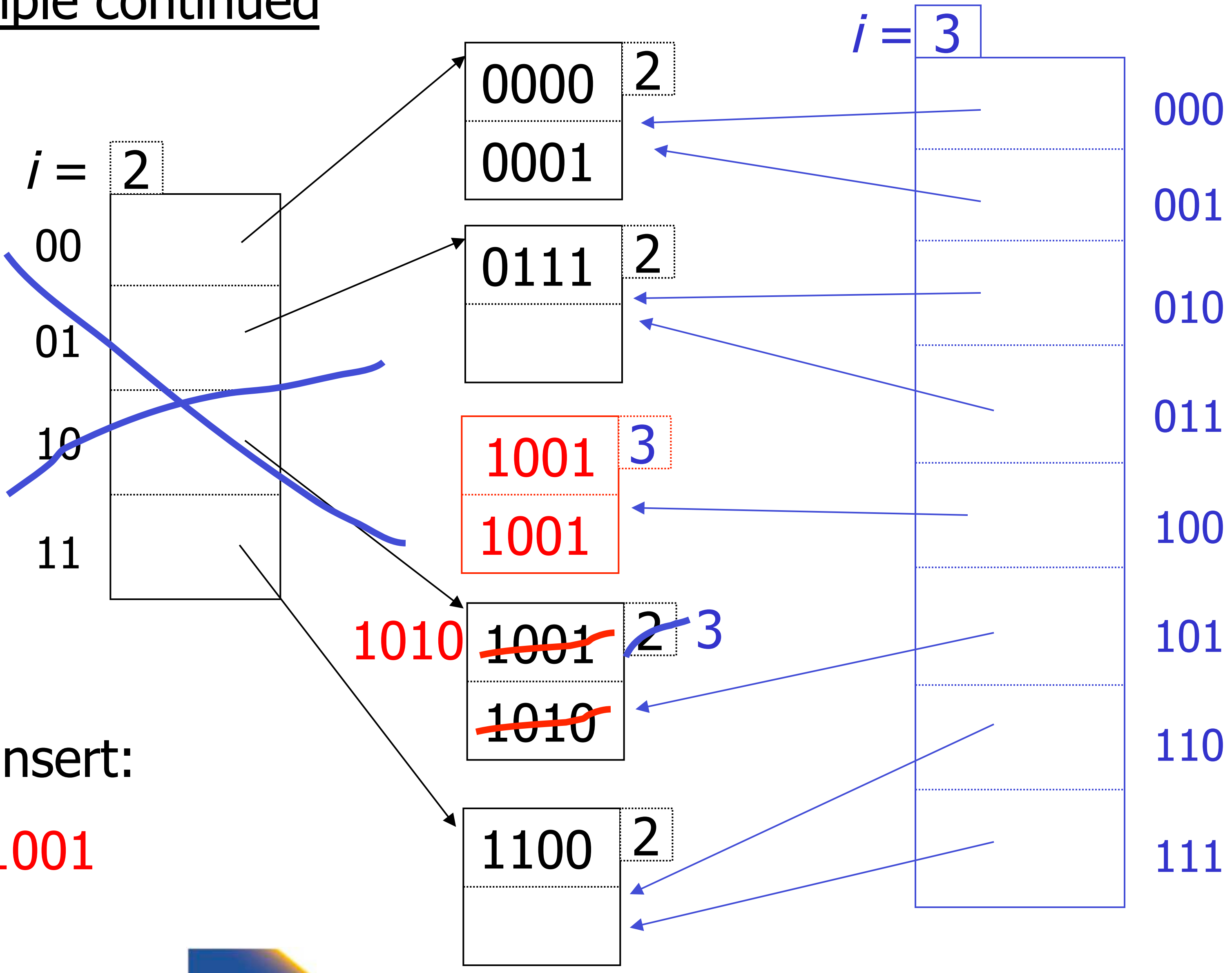
Example continued



Insert:

1001

Example continued



Insert:

1001

Extensible hashing: deletion

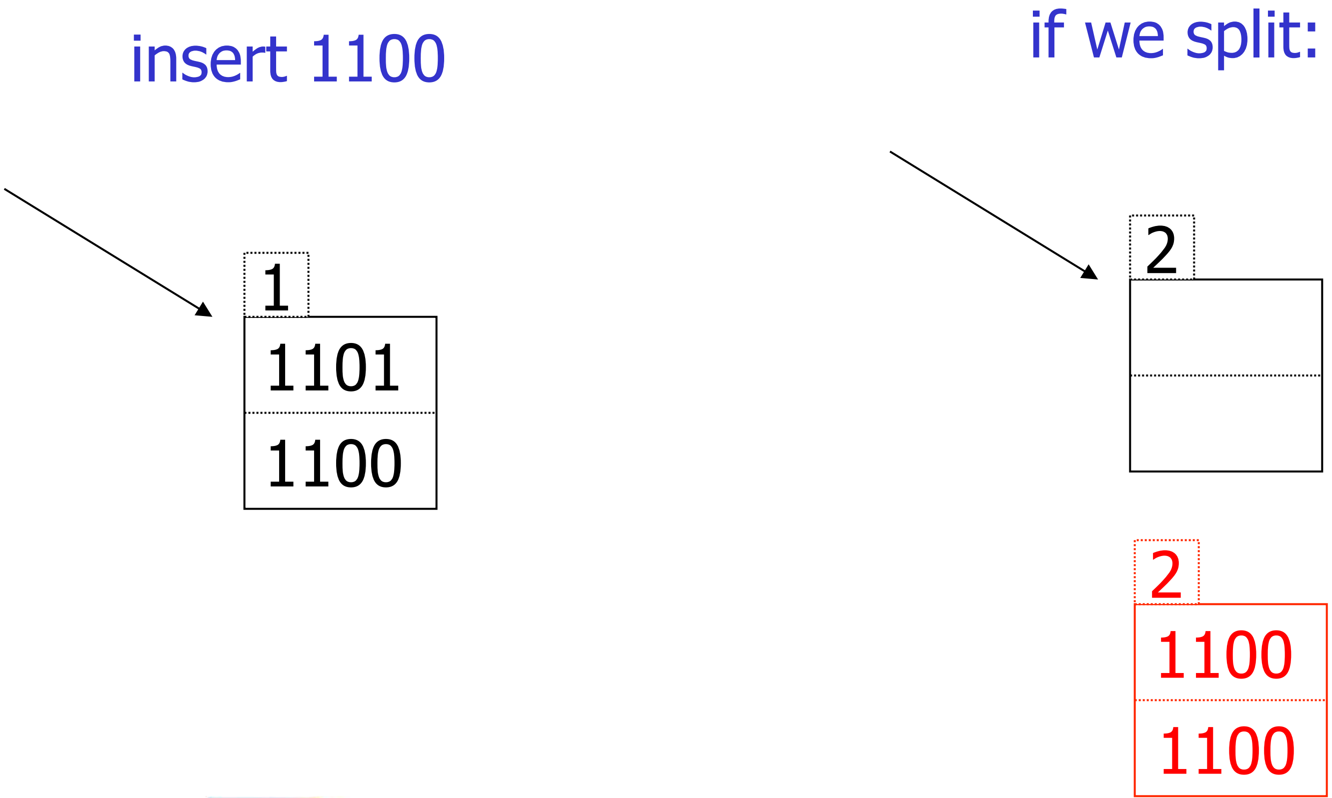
- No merging of blocks
- Merge blocks
  and cut directory if possible
  (Reverse insert procedure)

Deletion example:

- Run thru insert example in reverse!

Note: Still need overflow chains

- Example: many records with duplicate keys



insert 1100

1

1101

1100

if we split:

2

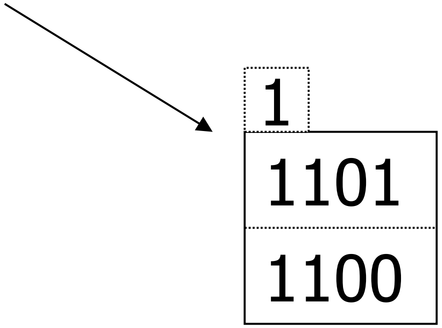
2

1100

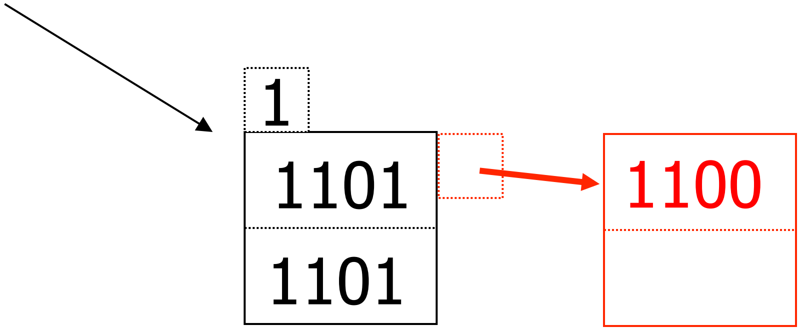
1100

Solution: overflow chains

insert 1100



add overflow block:



Summary Extensible hashing

⊕ Can handle growing files

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⊖ Indirection

(Not bad if directory in memory)

⊖ Directory doubles in size

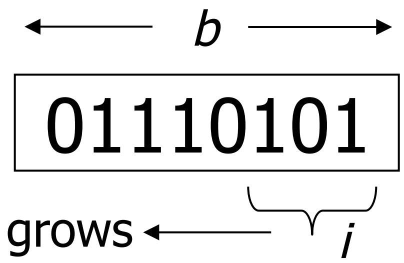
(Now it fits, now it does not)

Linear hashing

- Another dynamic hashing scheme

Two ideas:

(a) Use *i* low order bits of hash



Linear hashing

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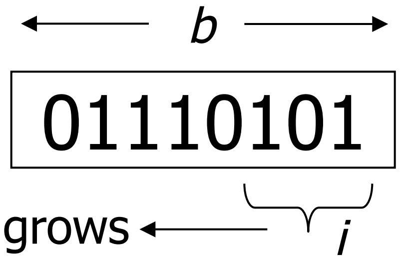
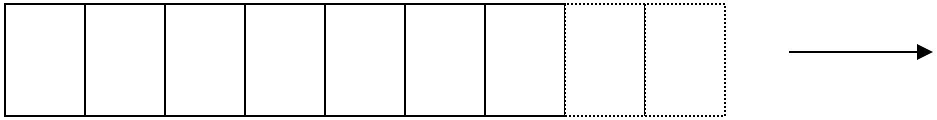
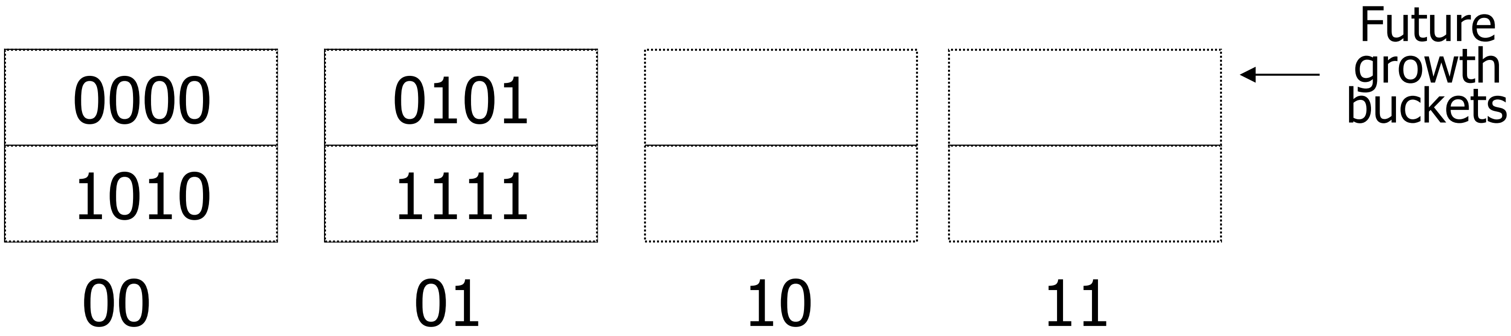


(b) File grows linearly

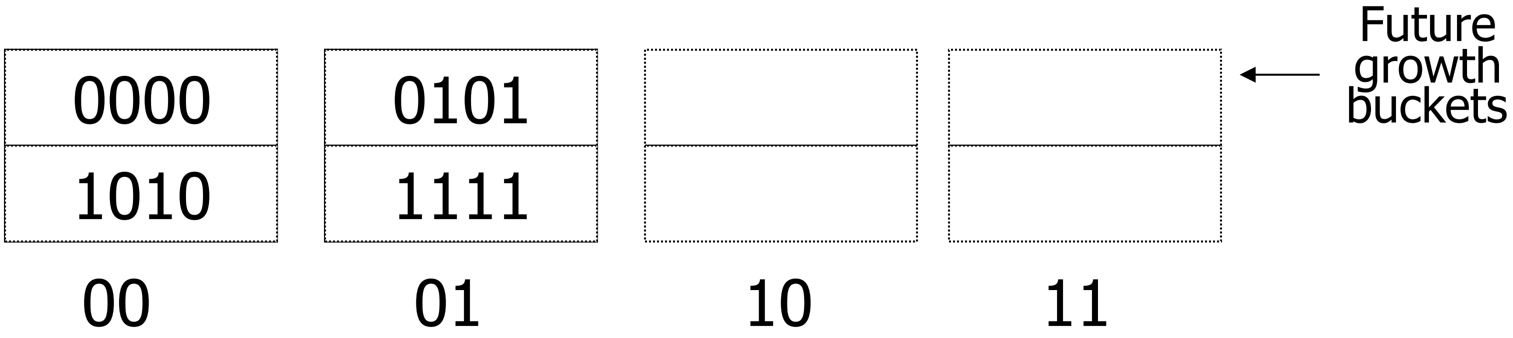


Example b=4 bits, i =2, 2 keys/bucket



m = 01 (max used block)

Example b=4 bits, i=2, 2 keys/bucket



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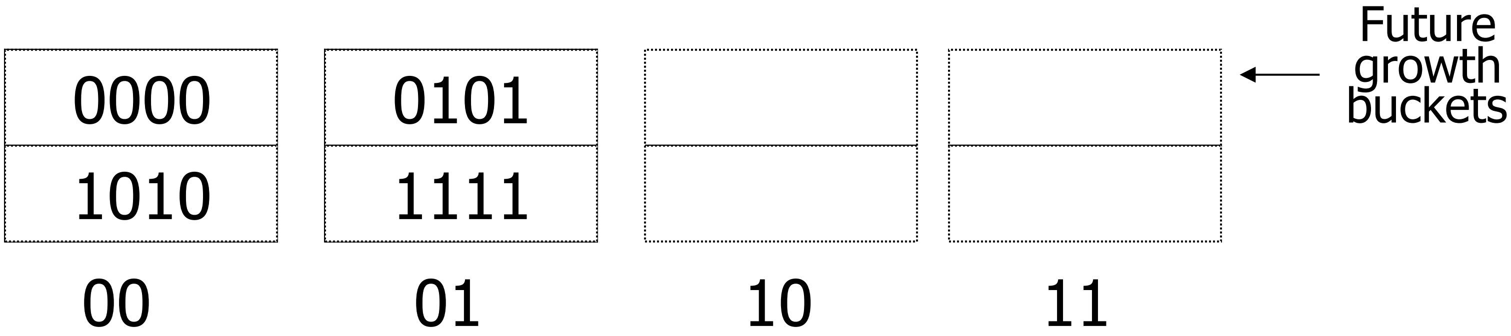
Rule If $h(k)[i] \leq m$, then

look at bucket $h(k)[i]$

else, look at bucket $h(k)[i] - 2^{i-1}$

Example b=4 bits, i =2, 2 keys/bucket

- insert 0101



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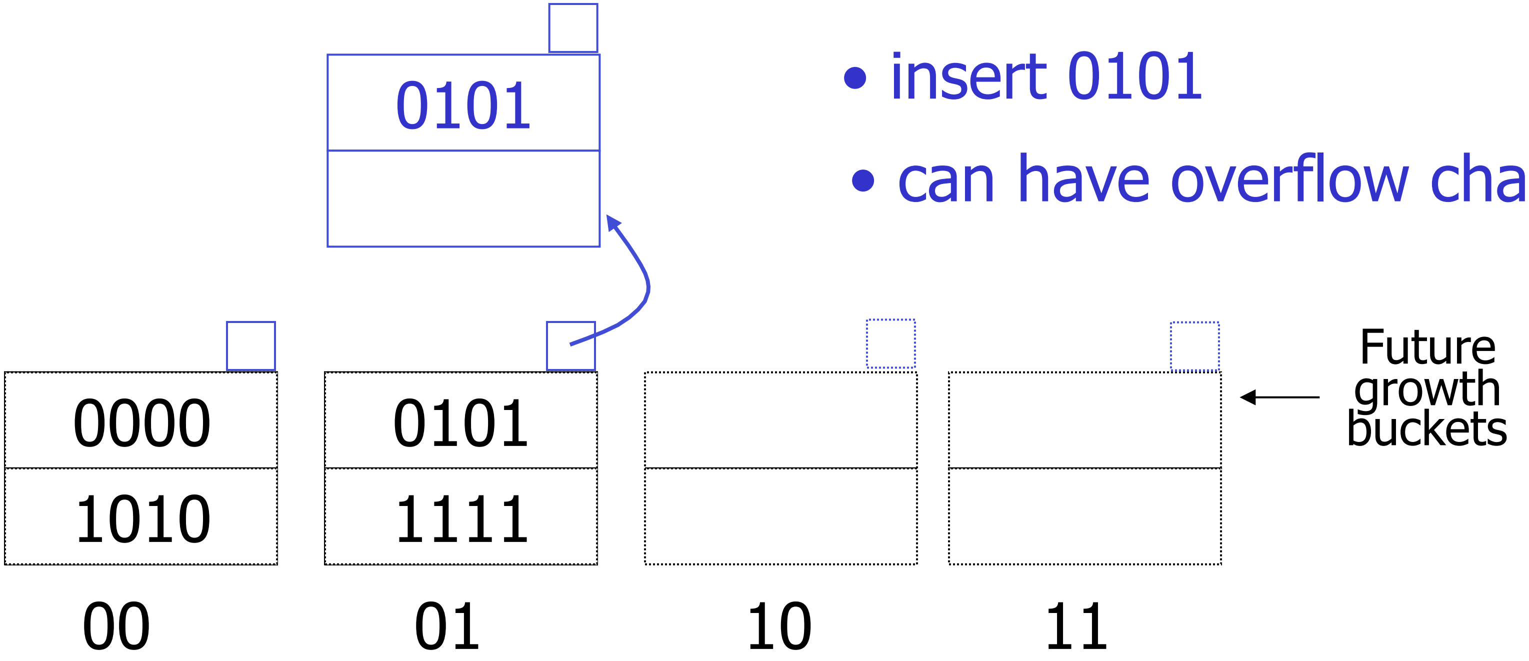


- insert 0101
- can have overflow chains!

m = 01 (max used block)

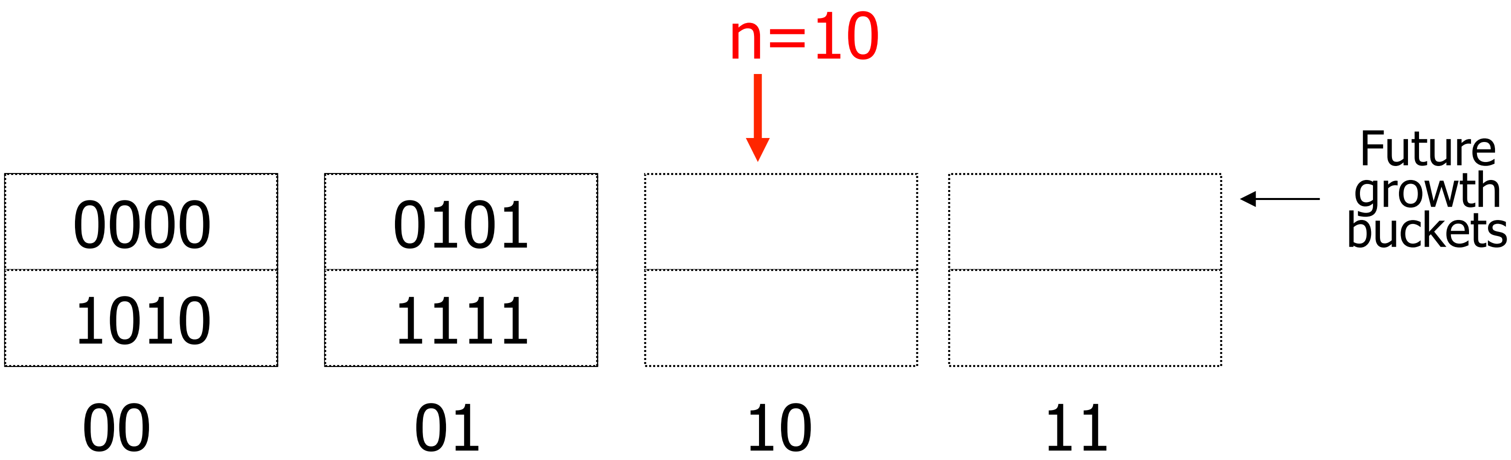
Rule If h(k)[i] ≤ m, then

look at bucket h(k)[i]

else, look at bucket h(k)[i] - 2^{i-1}

Note

- In textbook, n is used instead of m
- n=m+1


n=10

Future growth buckets

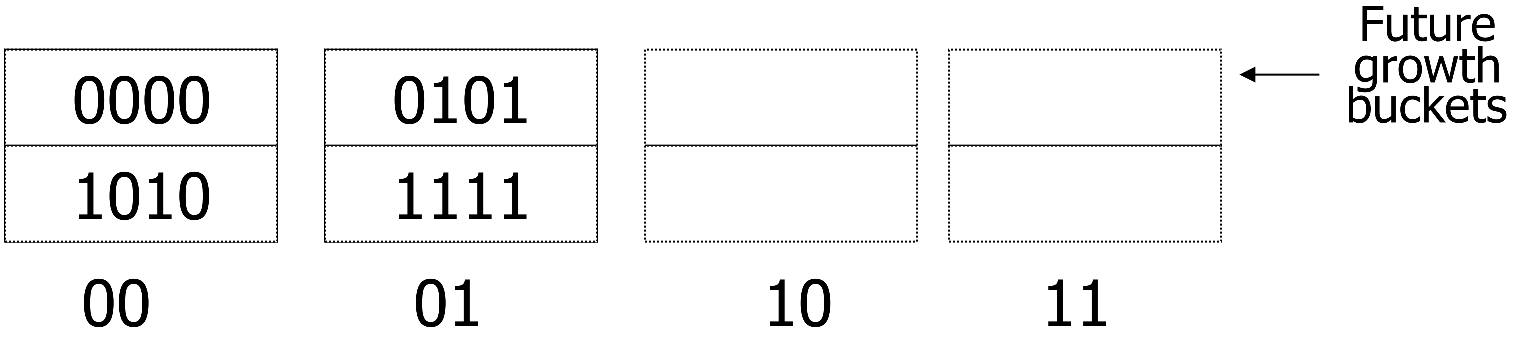
0000
1010

0101
1111

00 01 10 11

m = 01 (max used block)

Example b=4 bits, i =2, 2 keys/bucket

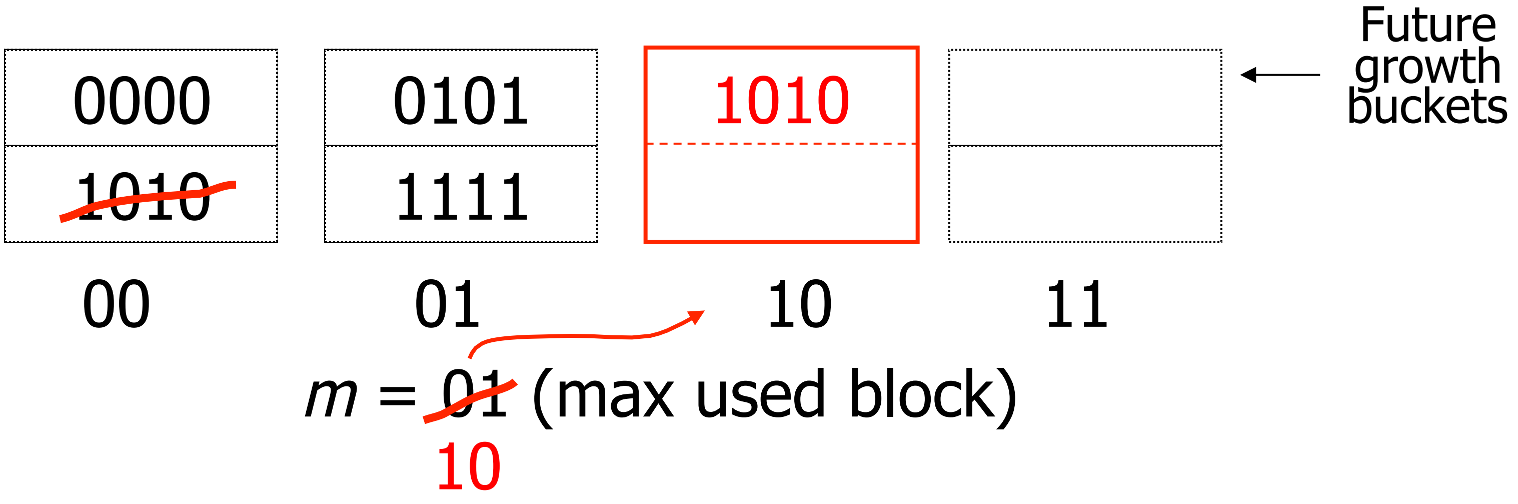


0000	0101		
1010	1111		
00	01	10	11

Future growth buckets

m = 01 (max used block)

Example b=4 bits, i =2, 2 keys/bucket



0000 | ~~1010~~

0101 | 1111

1010 |

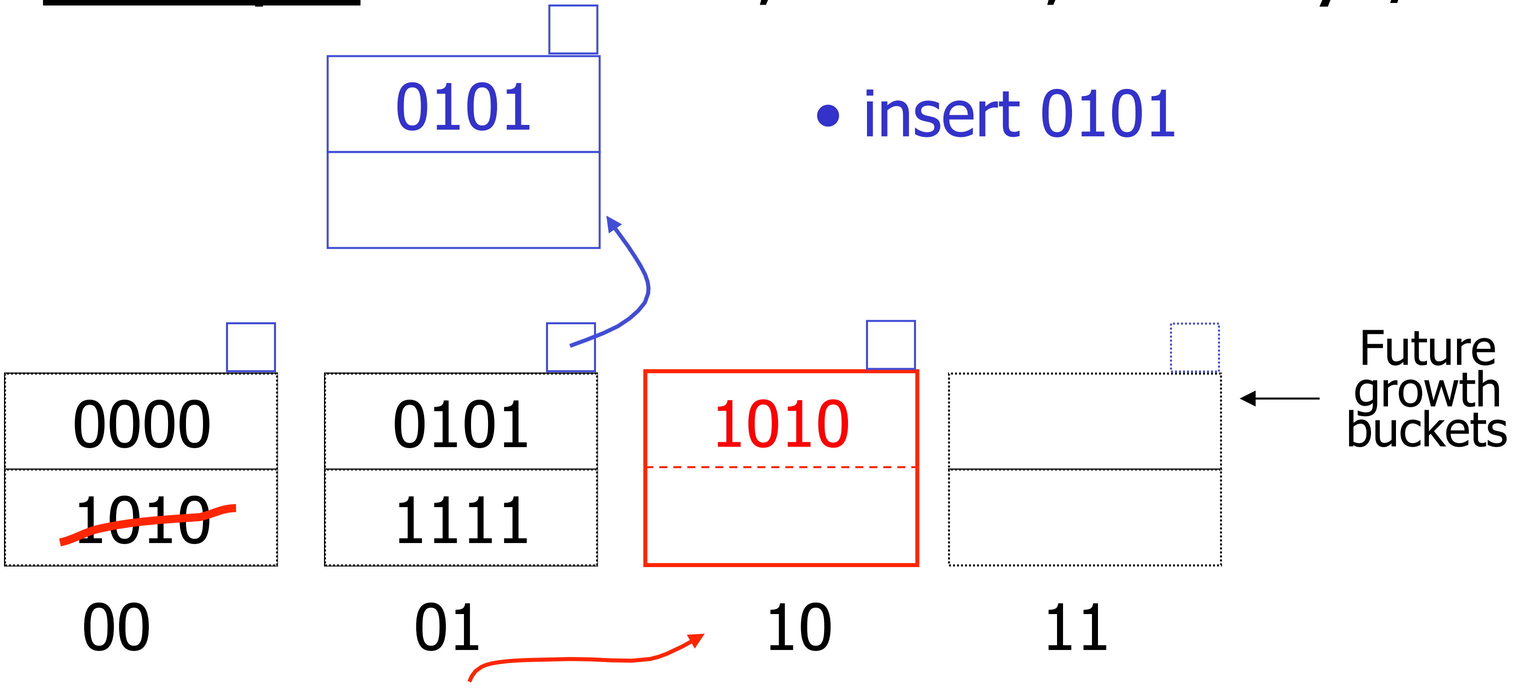
Future growth buckets

00 01 10 11

m = ~~01~~ (max used block)
10

Example *b*=4 bits, *i* =2, 2 keys/bucket

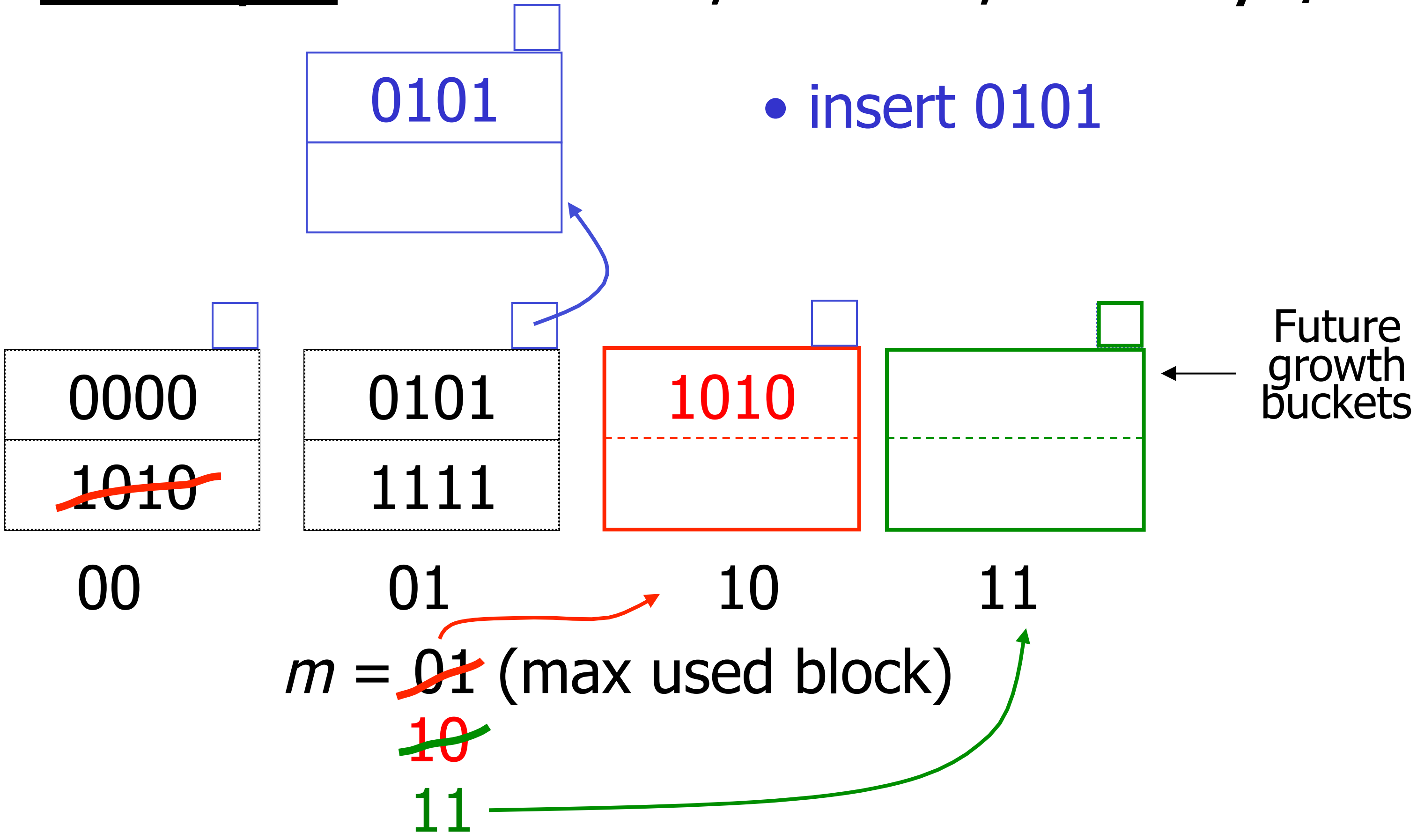
- insert 0101



m = ~~01~~ (max used block)
10

<u>Example</u> b=4 bits, i =2, 2 keys/bucket

- insert 0101



0101

0000

~~1010~~

0101

1111

1010

Future growth buckets

00 01 10 11

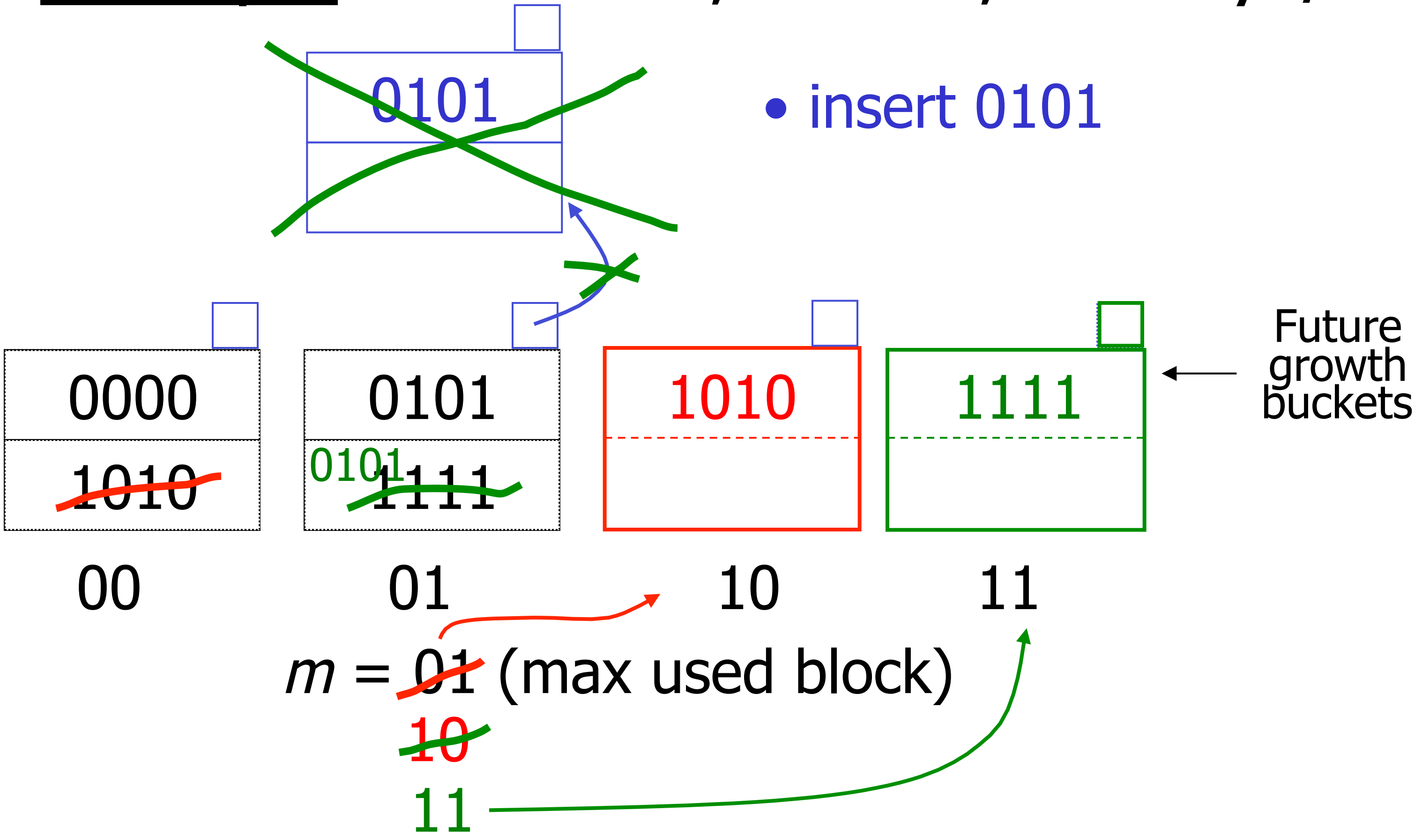
m = ~~01~~ (max used block)

~~10~~

11

<u>Example</u> b=4 bits, i=2, 2 keys/bucket

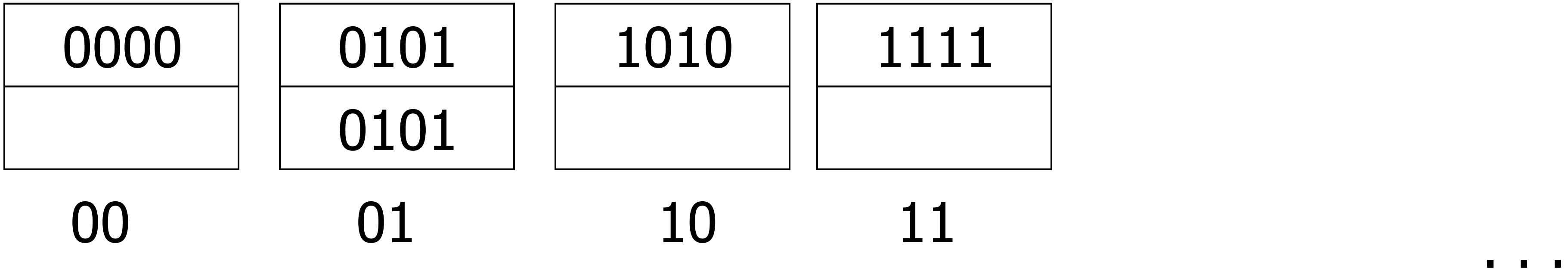
- insert 0101



m = ~~01~~ (max used block)
~~10~~
11

Example Continued: How to grow beyond this?

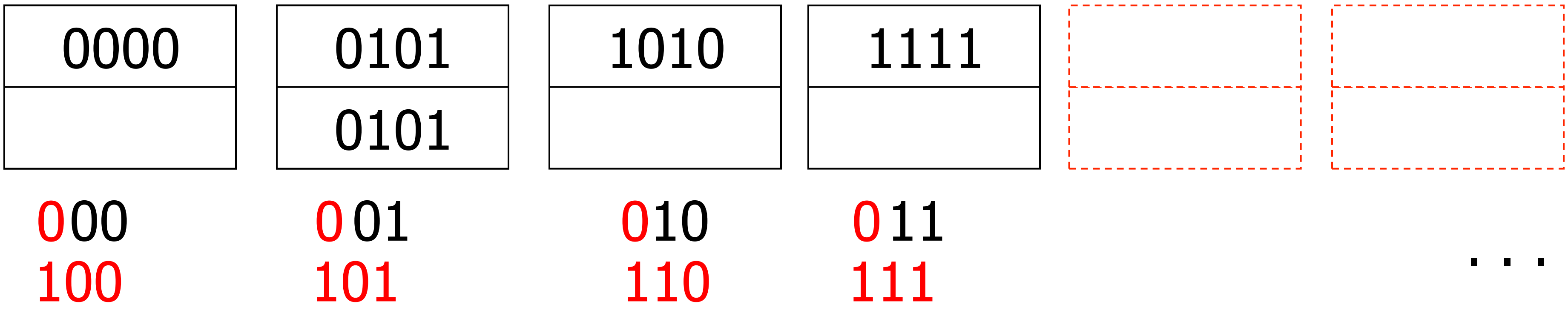
$i = 2$



$m = 11$ (max used block)

Example Continued: How to grow beyond this?

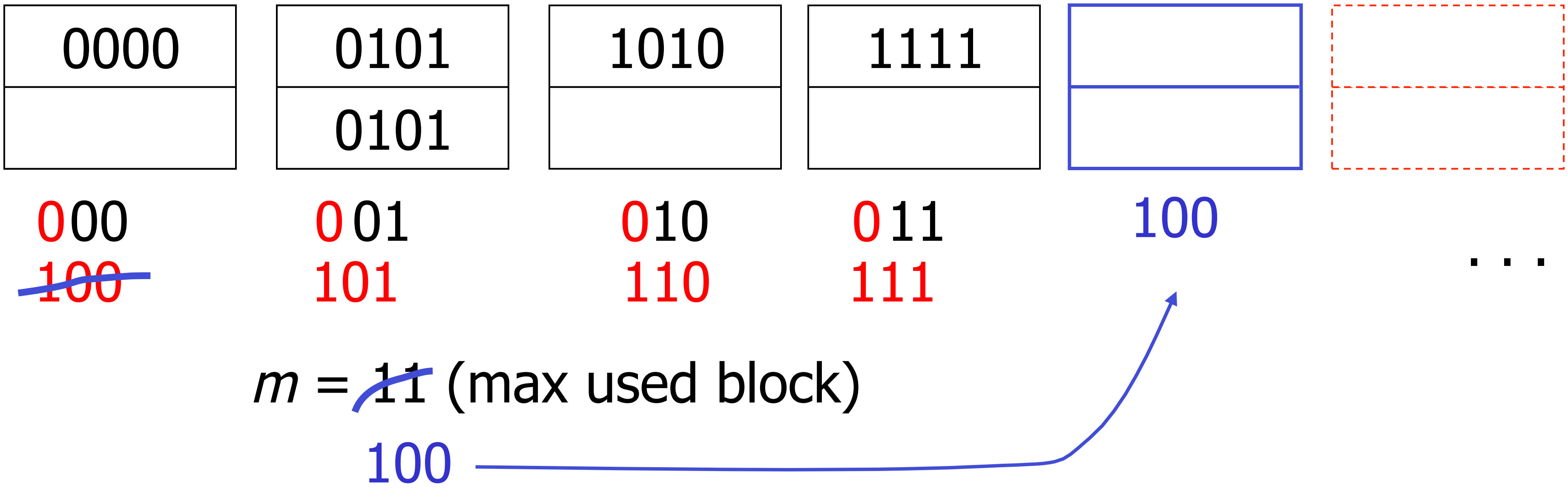
$i = \cancel{2}\ 3$



m = 11 (max used block)

Example Continued: How to grow beyond this?

i = ~~2~~ 3



0000

0101
0101

1010

1111

000
~~100~~

001
101

010
110

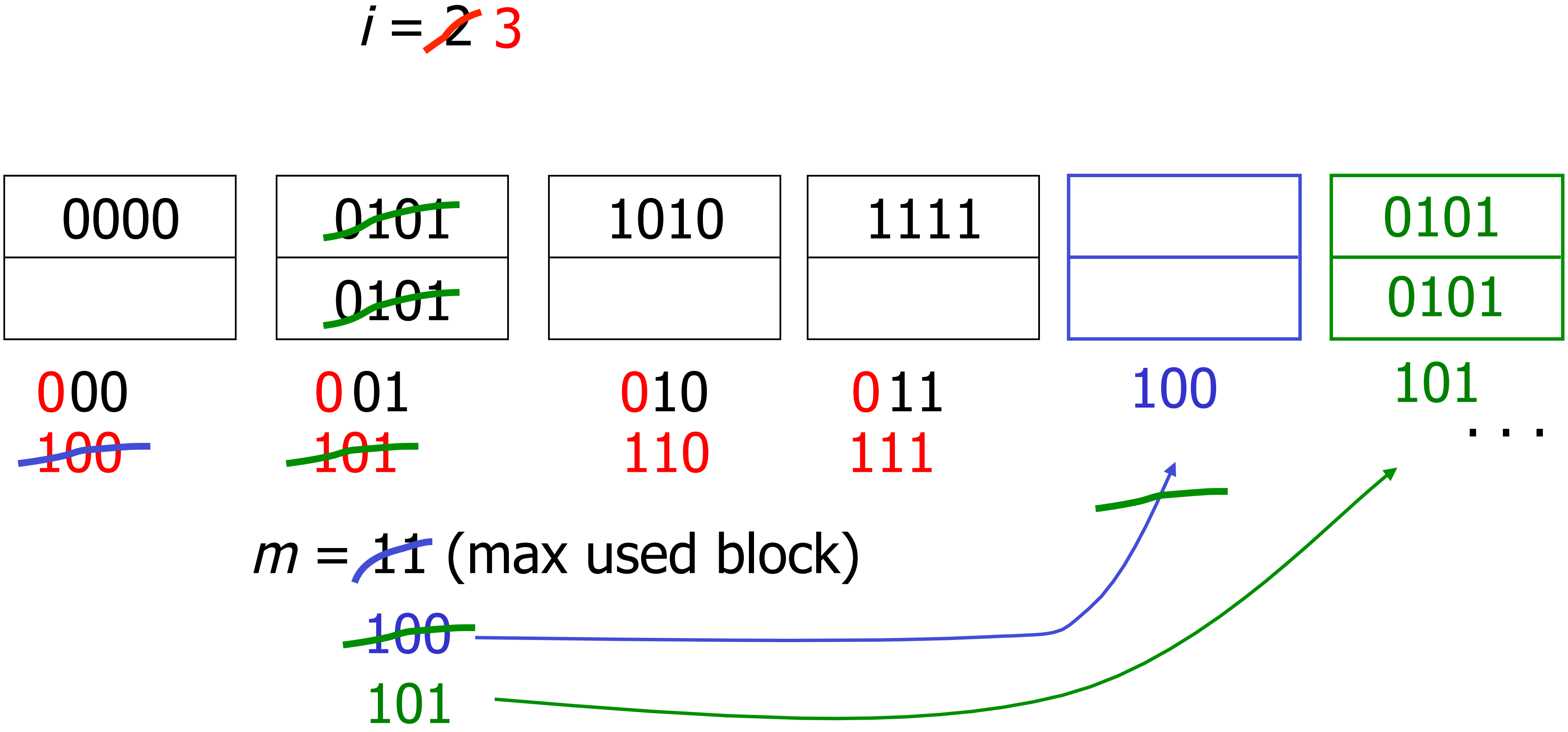
011
111

100

. . .

m = ~~11~~ (max used block)
100

Example Continued: How to grow beyond this?



i = ~~2~~ 3

0000	~~0101~~	1010	1111		0101
	~~0101~~				0101
000 ~~100~~	001 ~~101~~	010 110	011 111	100	101 . . .

m = ~~11~~ (max used block)

~~100~~

101

☛ When do we expand file?

- Keep track of: $\frac{\#\text{ used slots}}{\text{total }\#\text{ of slots}} = U$

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- Keep track of: $\dfrac{\text{\# used slots}}{\text{total \# of slots}} = U$
- If U > threshold then increase *m* (and maybe *i*)

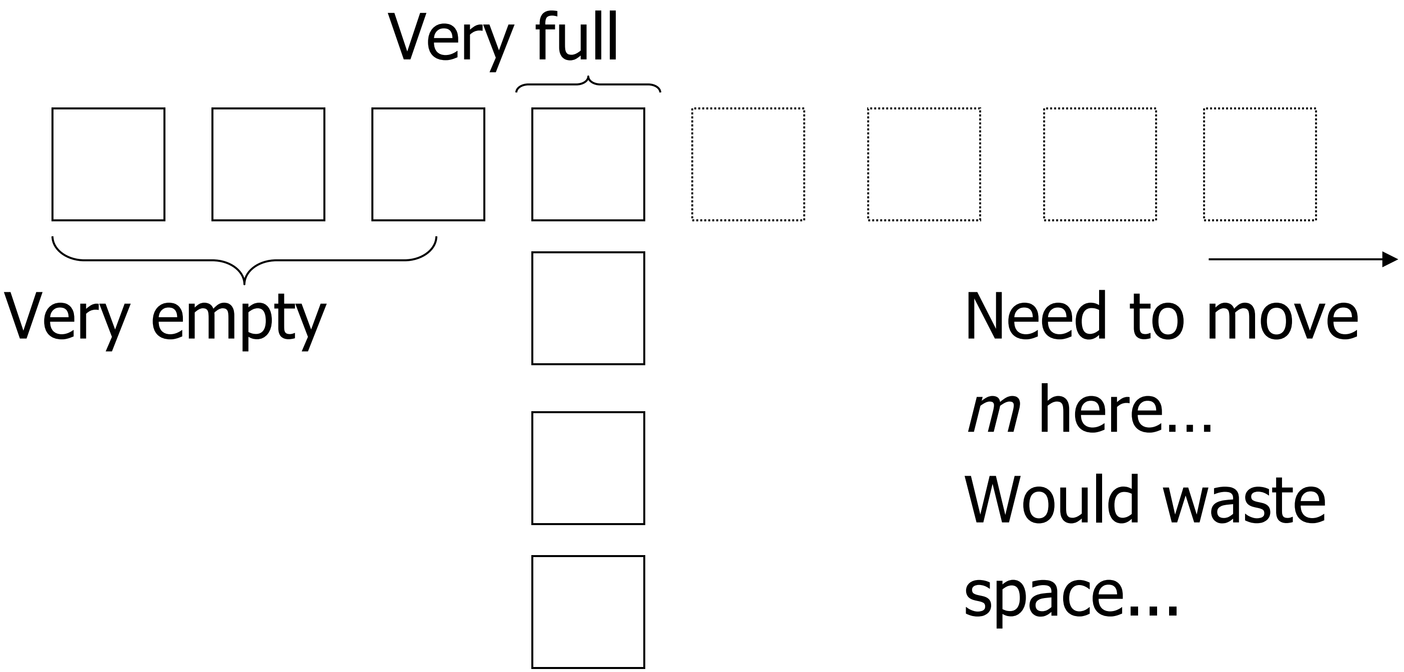
Summary Linear Hashing

⊕ Can handle growing files
- with less wasted space
- with no full reorganizations

⊕ No indirection like extensible hashing

⊖ Can still have overflow chains

Example: BAD CASE



Need to move *m* here…
Would waste space...

Summary

Hashing

- How it works
- Dynamic hashing
  - Extensible
  - Linear

Next:

- Indexing vs Hashing
- Index definition in SQL
- Multiple key access

Indexing vs Hashing

- Hashing good for probes given key

e.g., SELECT …
FROM R
WHERE R.A = 5

-> **Point Queries**

Indexing vs Hashing

- INDEXING (Including B Trees) good for

  Range Searches:

  e.g., SELECT
  FROM R
  WHERE R.A > 5

-> **Range Queries**

Index definition in SQL

- Create index name on rel (attr)
- Create unique index name on rel (attr)

defines candidate key

- Drop INDEX name

Note CANNOT SPECIFY TYPE OF INDEX

(e.g. B-tree, Hashing, …)

OR PARAMETERS

(e.g. Load Factor, Size of Hash,...)

... at least in standard SQL...

Vendor specific extensions allow that

Note ATTRIBUTE LIST ⇒ MULTIKEY INDEX (next)

e.g., CREATE INDEX foo ON R(A,B,C)

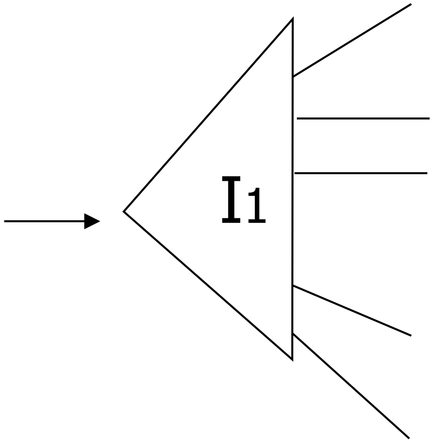
Multi-key Index

Motivation: Find records where

DEPT = “Toy” AND SAL > 50k

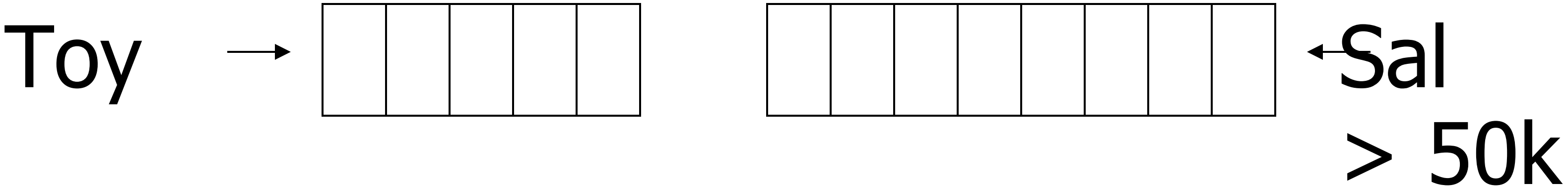
Strategy I:

- Use one index, say Dept.
- Get all Dept = "Toy" records
  and check their salary



Strategy II:

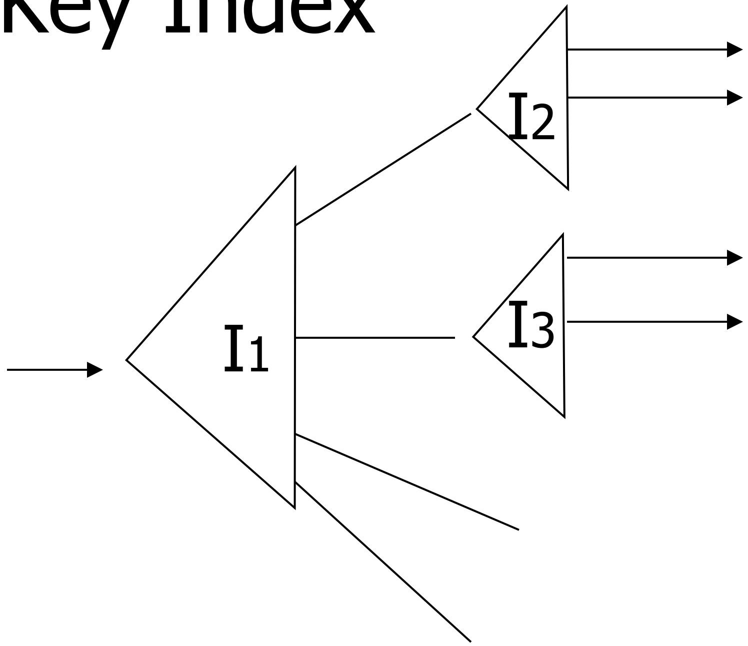
- Use 2 Indexes; Manipulate Pointers



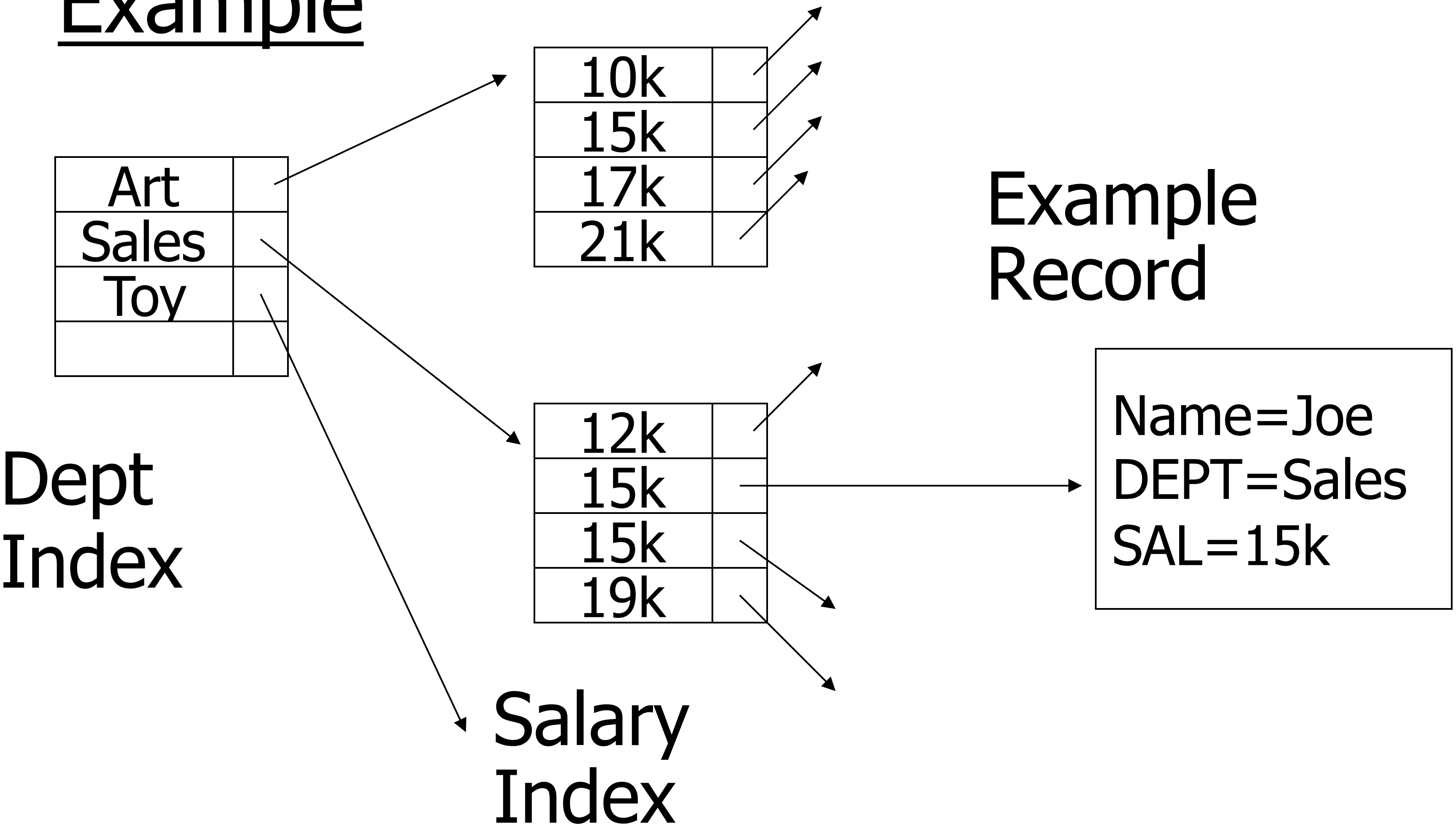
Strategy III:

- Multiple Key Index

One idea:



Example



Art
Sales
Toy

10k
15k
17k
21k

12k
15k
15k
19k

Example Record

Name=Joe
DEPT=Sales
SAL=15k

Dept Index

Salary Index

For which queries is this index good?

☐ Find RECs Dept = “Sales” $\wedge$ SAL=20k

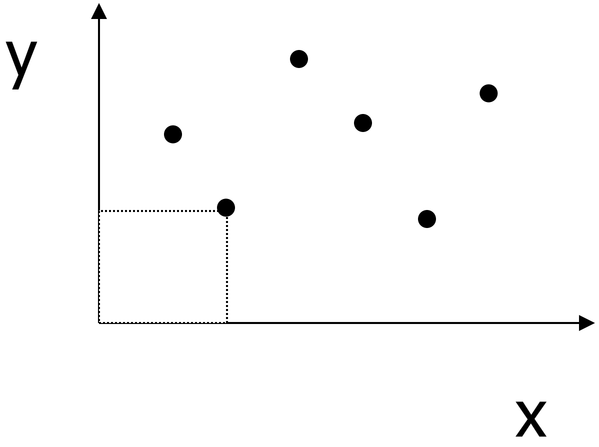
☐ Find RECs Dept = “Sales” $\wedge$ SAL $\geq$ 20k

☐ Find RECs Dept = “Sales”

☐ Find RECs SAL = 20k

Interesting application:

- Geographic Data



DATA:

<X1,Y1, Attributes>

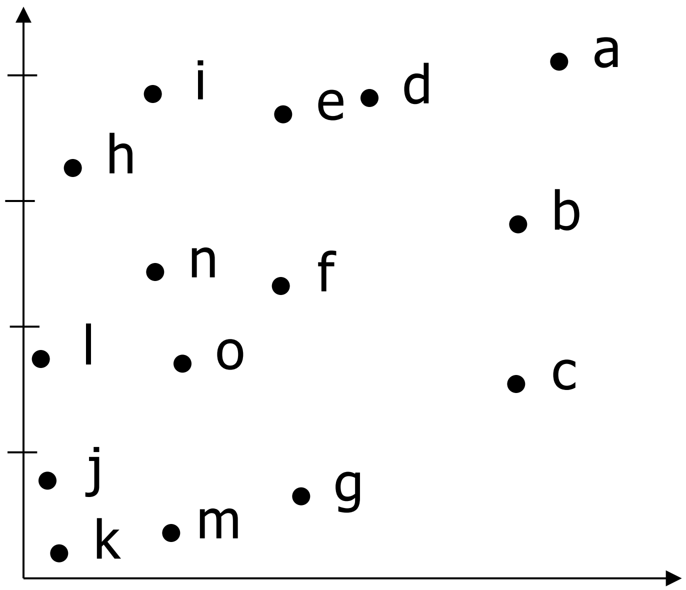
<X2,Y2, Attributes>

⋮

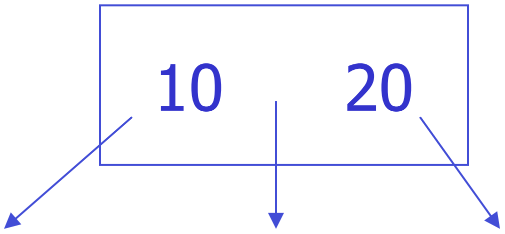
Queries:

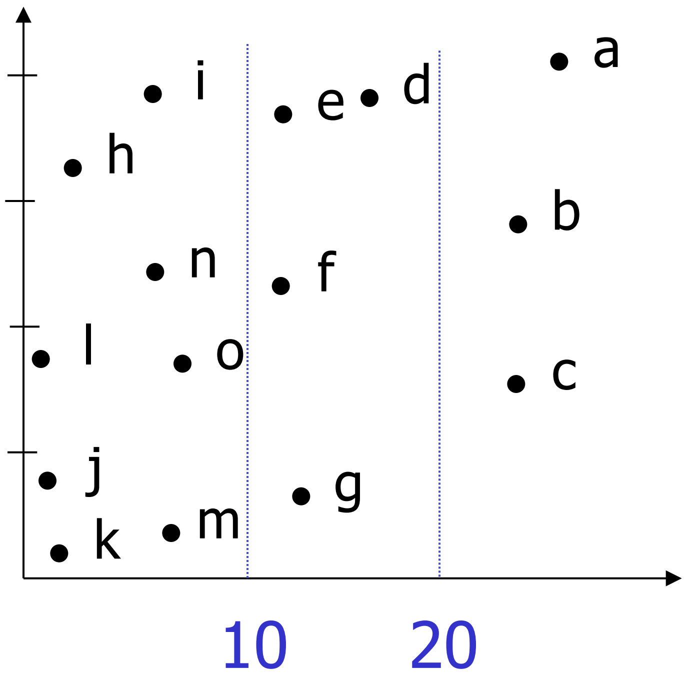
- What city is at <Xi,Yi>?
- What is within 5 miles from <Xi,Yi>?
- Which is closest point to <Xi,Yi>?

Example

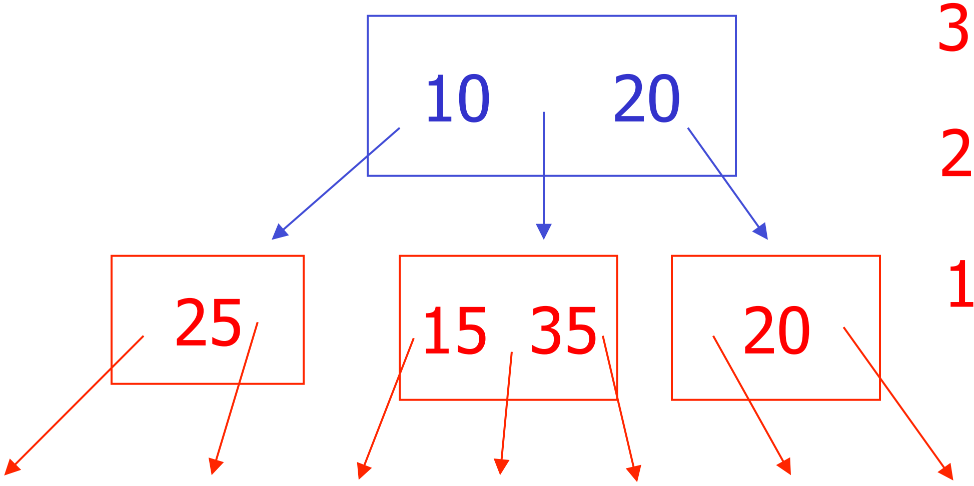


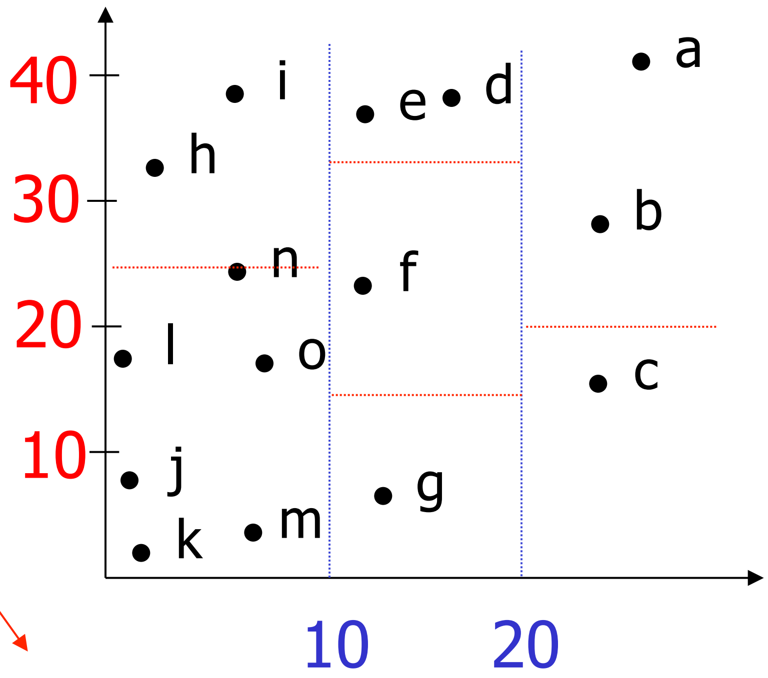
Example



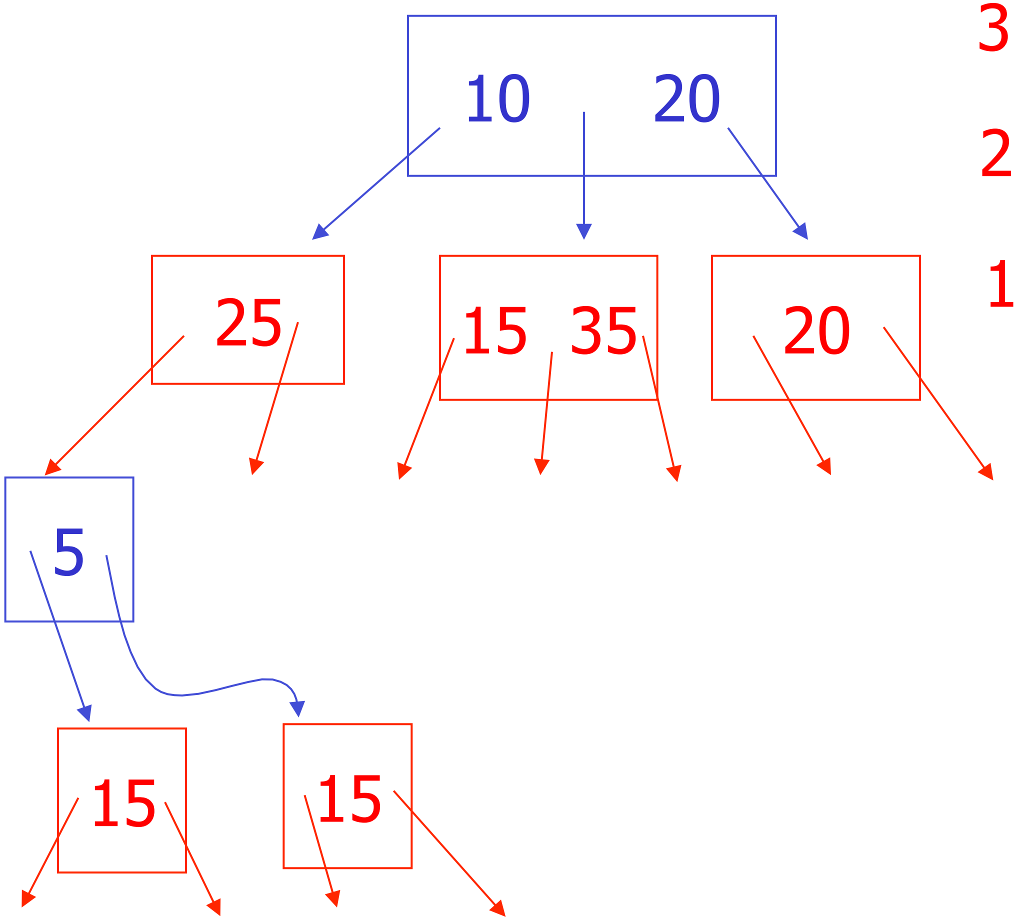


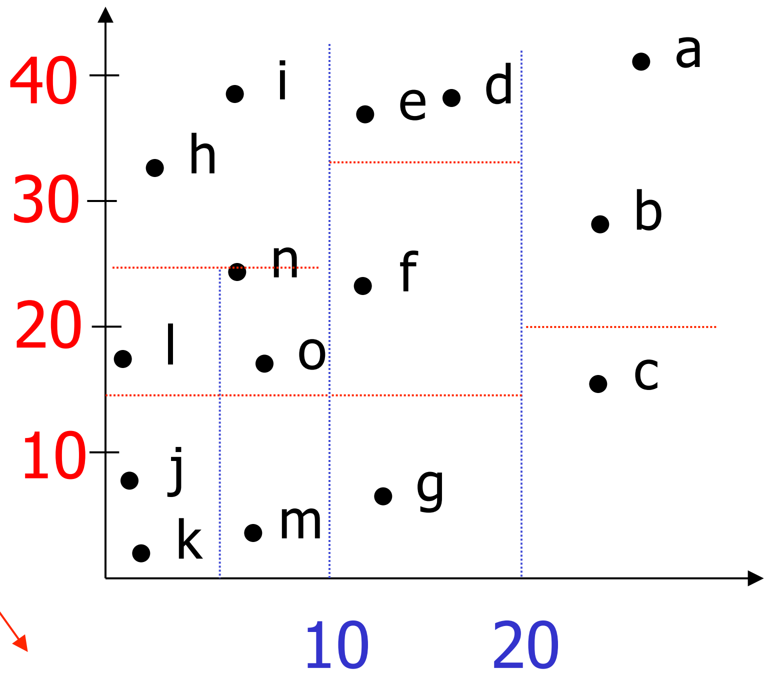
Example



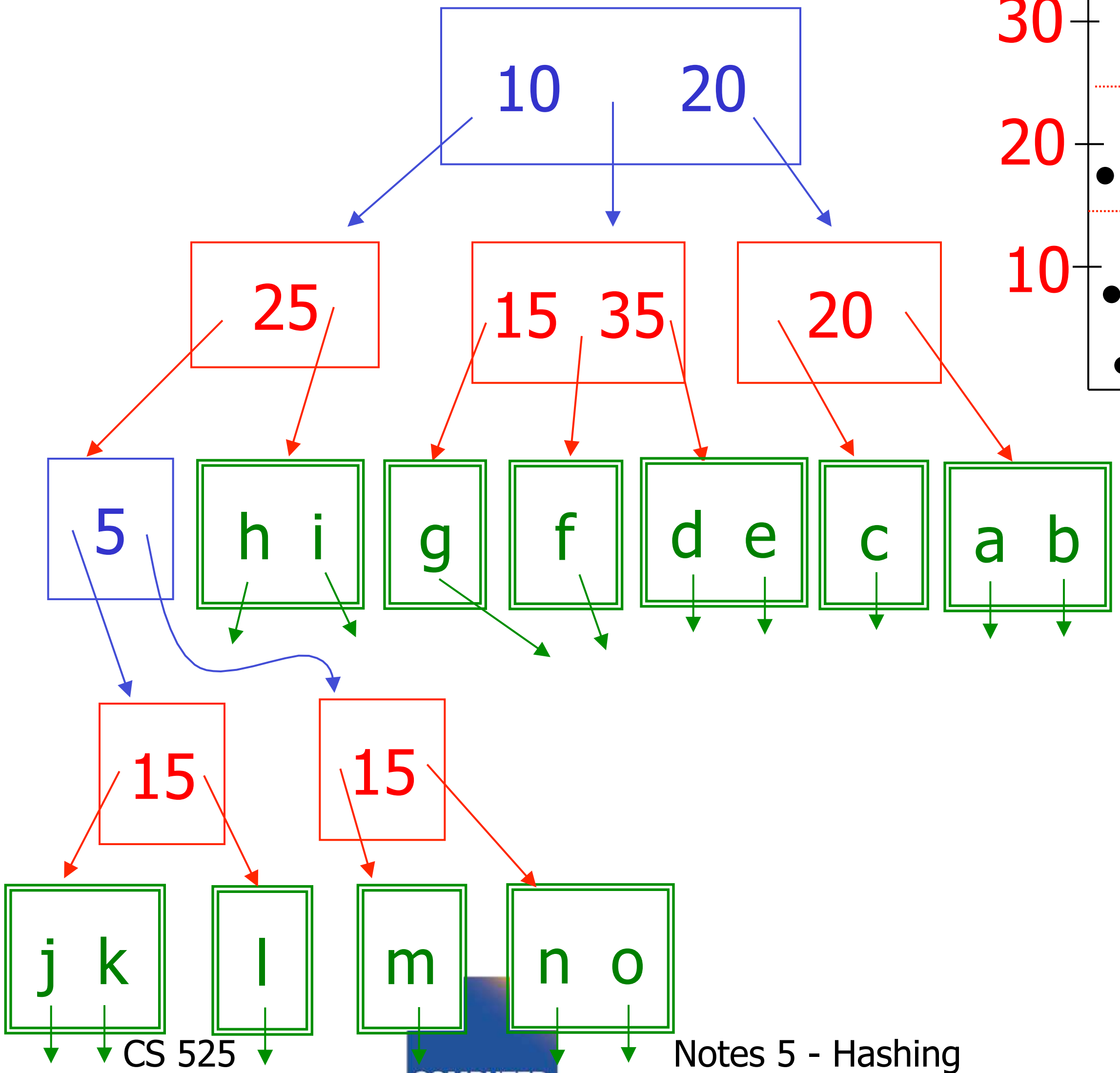


Example





Example


10 20
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15 35
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5
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d e
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a b
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15
j k
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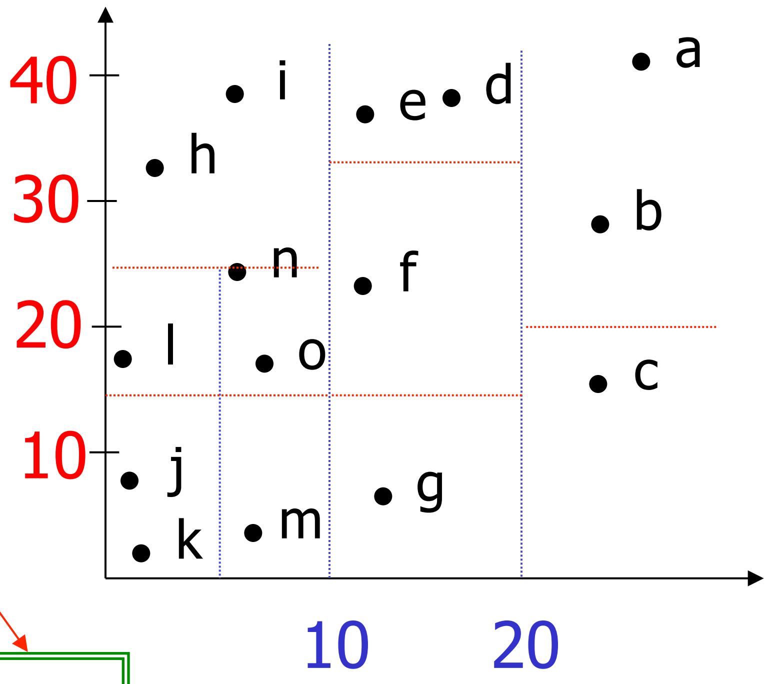
m
n o


40
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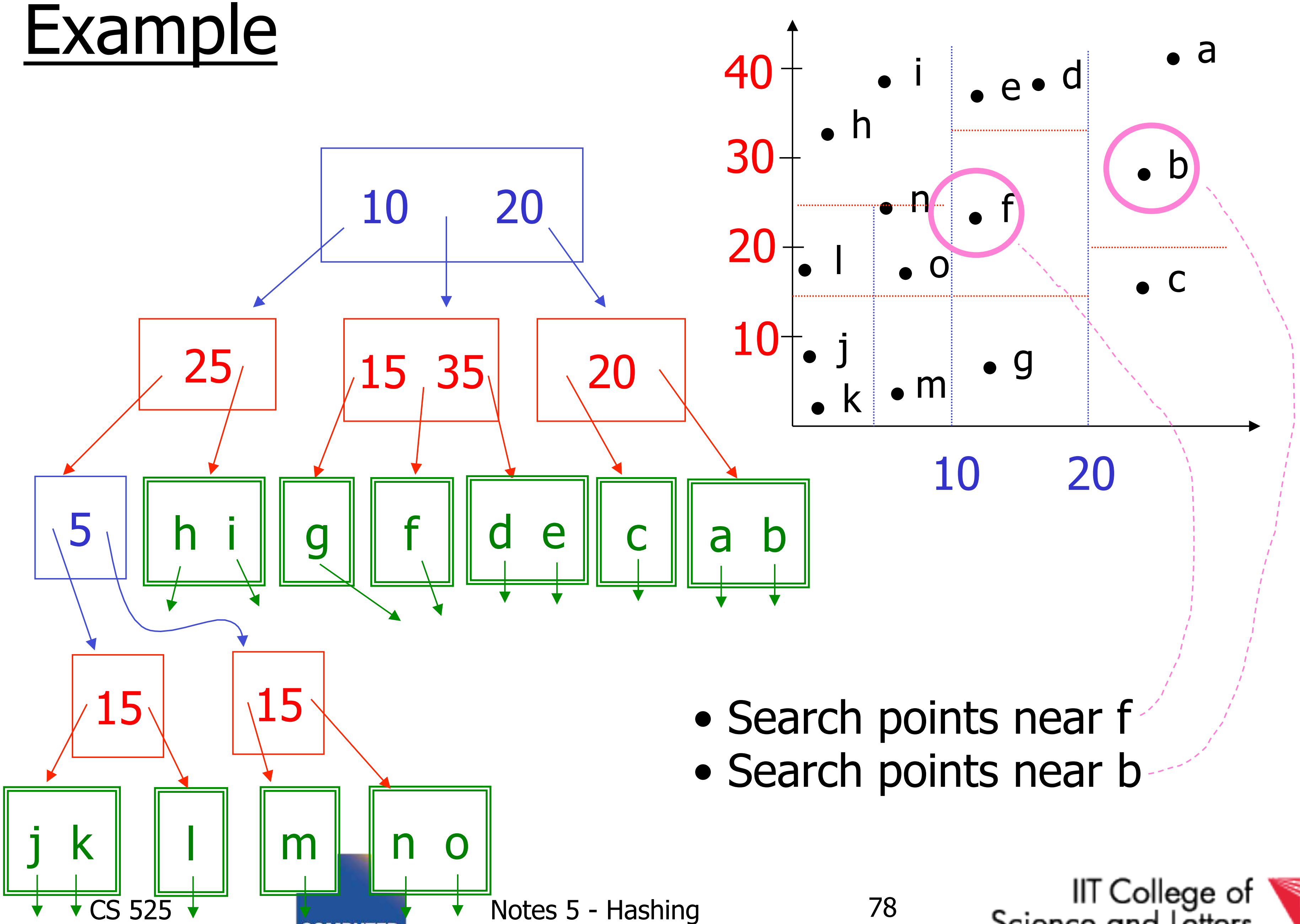
10
20

Example



- Search points near f
- Search points near b

Queries

- Find points with Yi > 20
- Find points with Xi < 5
- Find points “close” to i = <12,38>
- Find points “close” to b = <7,24>

Next

- Even more index structures ☺

CS 525: Advanced Database Organization

06: Even more index structures

Boris Glavic

Slides: adapted from a course taught by
Hector Garcia-Molina, Stanford InfoLab

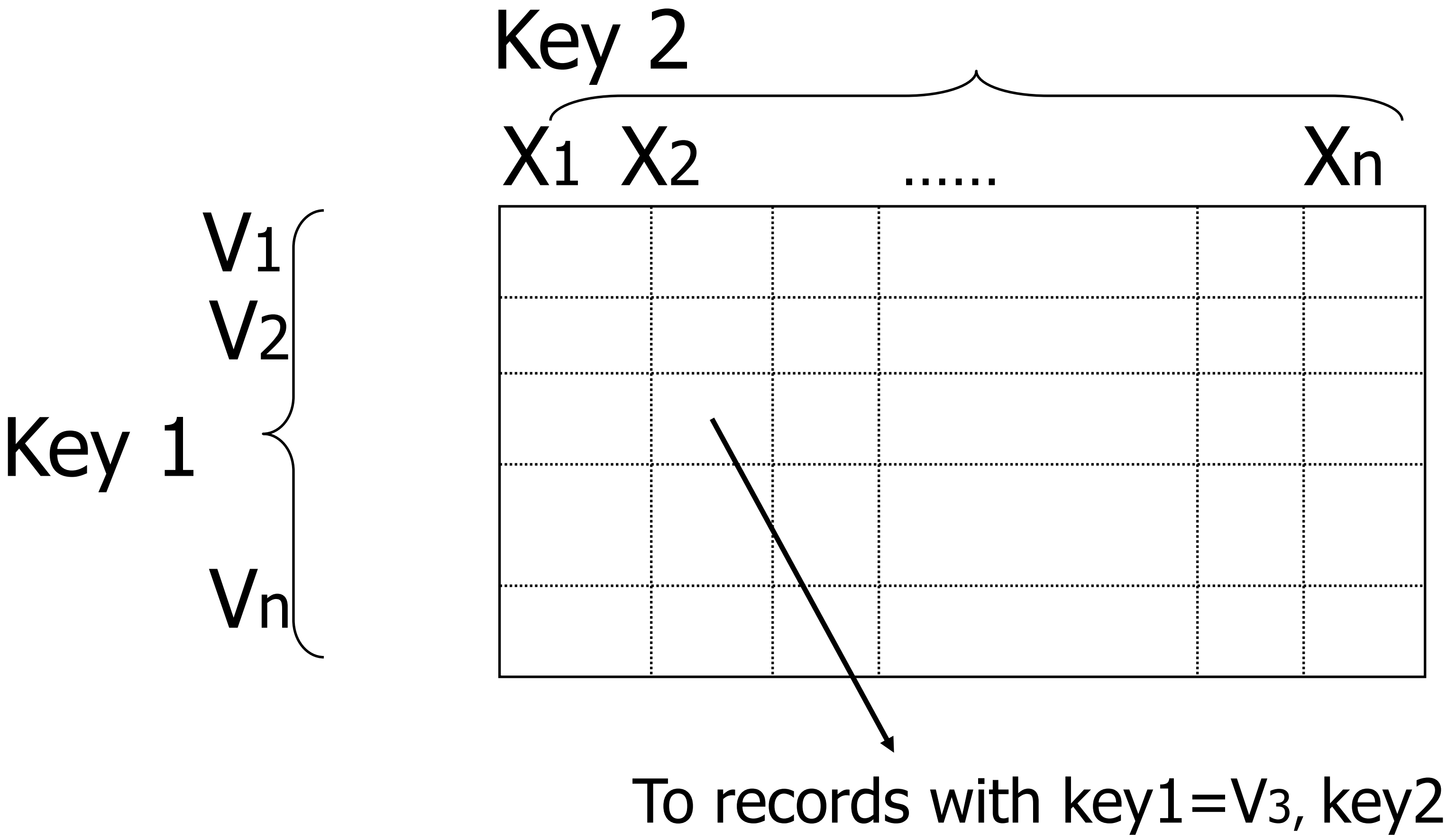
Recap

- We have discussed
  - Conventional Indices
  - B-trees
  - Hashing
  - Trade-offs
  - Multi-key indices
  - Multi-dimensional indices
    - … but no example

Today

- **Multi-dimensional index structures**
  - kd-Trees (very similar to example before)
  - **Grid File (Grid Index)**
  - Quad Trees
  - **R Trees**
  - **Partitioned Hash**
  - …
- **Bitmap-indices**
- **Tries**

Grid Index



To records with key1=V_3, key2=X_2

CLAIM

- Can quickly find records with
  - key 1 = V_i $\wedge$ Key 2 = X_j
  - key 1 = V_i
  - key 2 = X_j

CLAIM

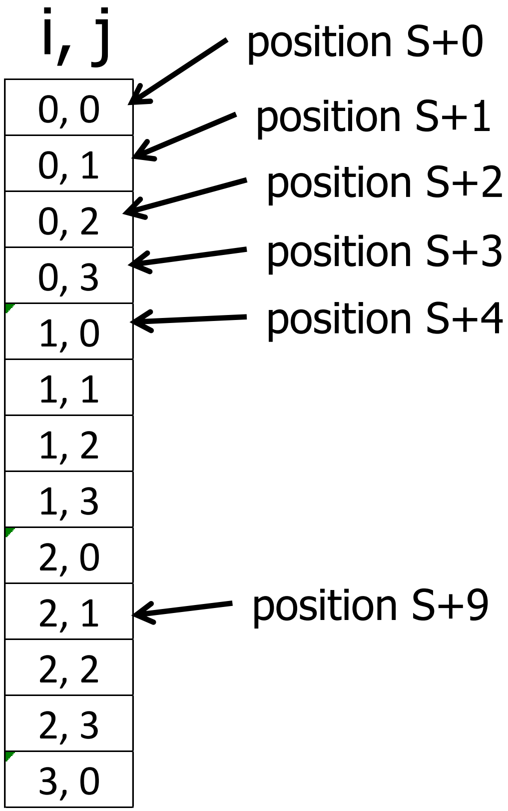
- Can quickly find records with
  - key 1 = $V_i \wedge$ Key 2 = X_j
  - key 1 = V_i
  - key 2 = X_j

- And also ranges….
  - E.g., key 1 $\geq V_i \wedge$ key 2 $< X_j$

- How do we find entry i,j in linear structure?

max number of i values N=4

pos(i, j) =



i, j	
0, 0	position S+0
0, 1	position S+1
0, 2	position S+2
0, 3	position S+3
1, 0	position S+4
1, 1	
1, 2	
1, 3	
2, 0	
2, 1	position S+9
2, 2	
2, 3	
3, 0	

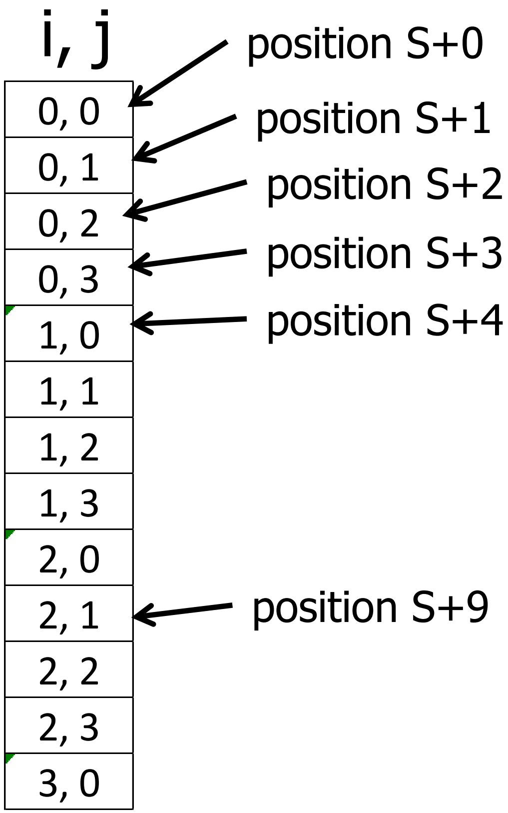
- How do we find entry i,j in linear structure?

max number of i values N=4

pos(i, j) = S + iN + j

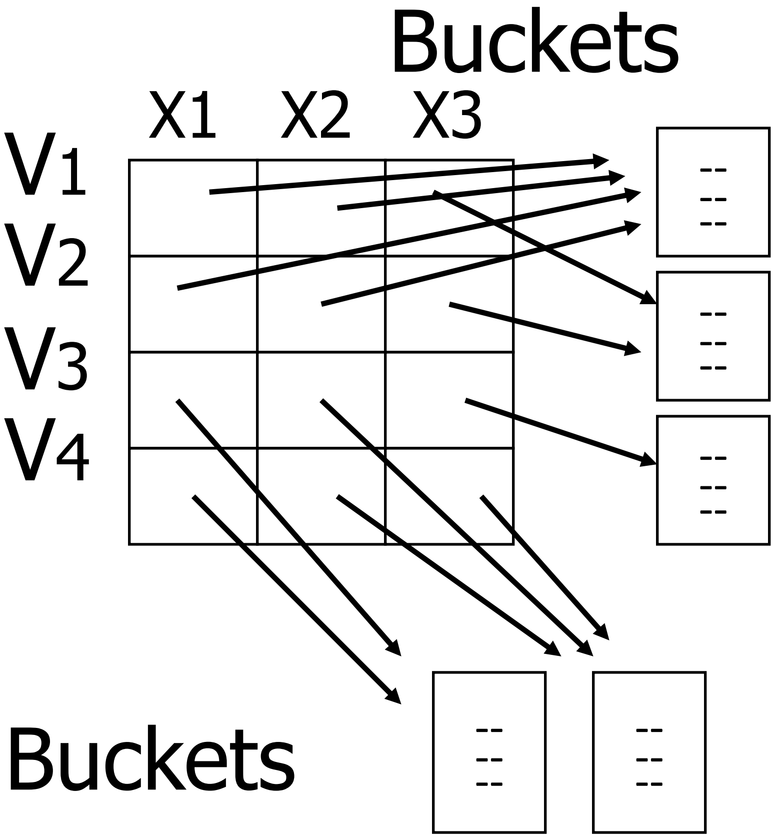
Issue: Cells must be same size, and N must be constant!

Issue: Some cells may overflow, some may be sparse...



i, j	
0, 0	position S+0
0, 1	position S+1
0, 2	position S+2
0, 3	position S+3
1, 0	position S+4
1, 1	
1, 2	
1, 3	
2, 0	
2, 1	position S+9
2, 2	
2, 3	
3, 0	

Solution: Use Indirection

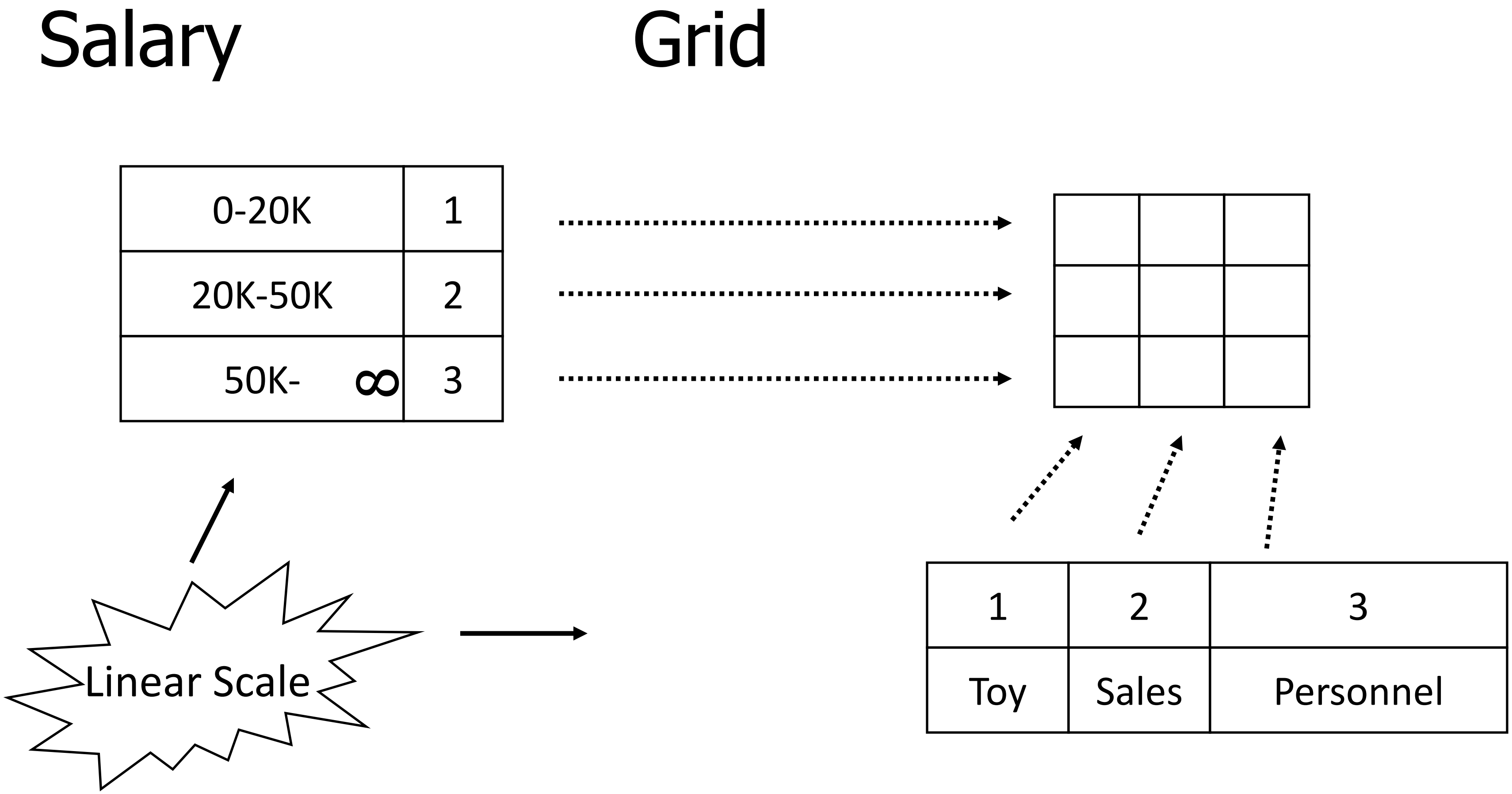


*Grid only contains pointers to buckets

With indirection:

- Grid can be regular without wasting space
- We do have price of indirection

Can also index grid on value ranges



Salary

Grid

0-20K	1
20K-50K	2
50K- ∞	3

1	2	3
Toy	Sales	Personnel

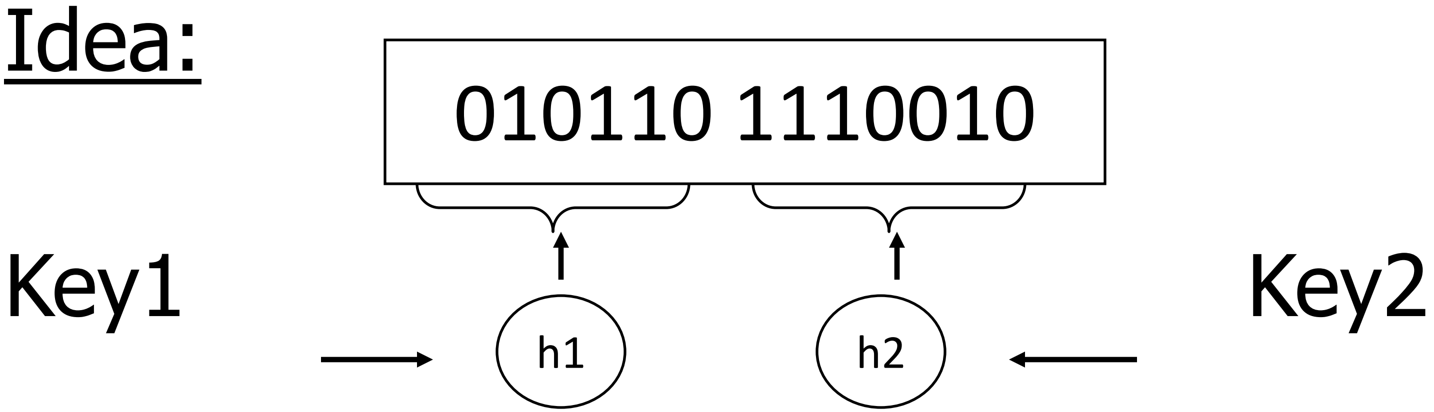
Linear Scale

Grid files

- ⊕ Good for multiple-key search
- ⊖ Space, management overhead

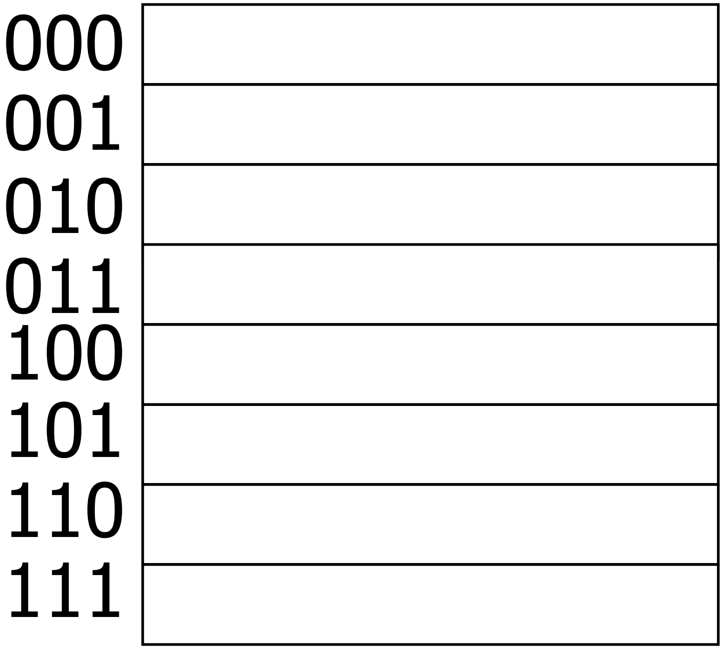
  (nothing is free)
- ⊖ Need partitioning ranges that evenly split keys

Partitioned hash function



EX:

h1(toy) =0
h1(sales) =1
h1(art) =1
.
h2(10k) =01
h2(20k) =11
h2(30k) =01
h2(40k) =00
.



Insert <Fred,toy,10k>,<Joe,sales,10k>
<Sally,art,30k>

EX:

h1(toy) =0
h1(sales) =1
h1(art) =1
.
h2(10k) =01
h2(20k) =11
h2(30k) =01
h2(40k) =00
.

000	
001	<Fred>
010	
011	
100	
101	<Joe><Sally>
110	
111	

Insert <Fred,toy,10k>,<Joe,sales,10k>
<Sally,art,30k>

EX:

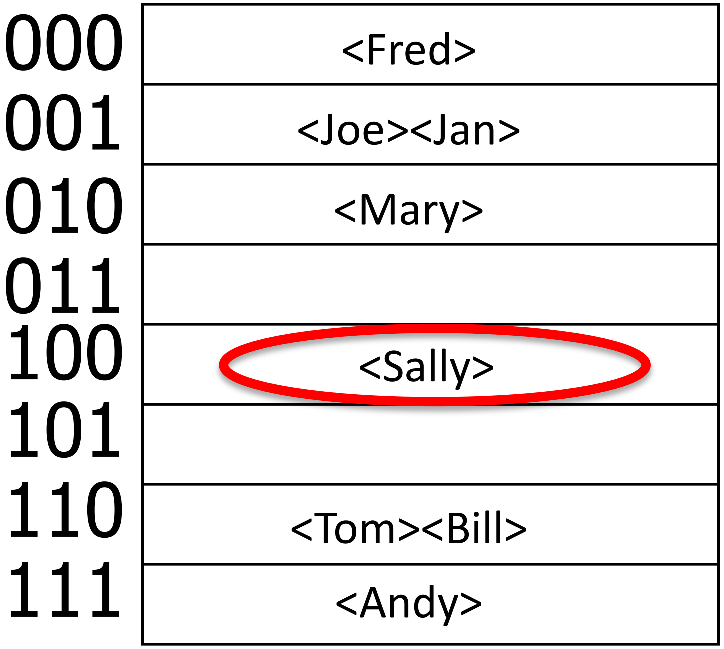
h1(toy) =0
h1(sales) =1
h1(art) =1
.
h2(10k) =01
h2(20k) =11
h2(30k) =01
h2(40k) =00
.

000	<Fred>
001	<Joe><Jan>
010	<Mary>
011	
100	<Sally>
101	
110	<Tom><Bill>
111	<Andy>

Find Emp. with Dept. = Sales $\wedge$ Sal=40k

EX:

h1(toy) =0
h1(sales) =1
h1(art) =1
.
h2(10k) =01
h2(20k) =11
h2(30k) =01
h2(40k) =00
.



000	<Fred>
001	<Joe><Jan>
010	<Mary>
011	
100	<Sally>
101	
110	<Tom><Bill>
111	<Andy>

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001	<Joe><Jan>
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011	
100	<Sally>
101	
110	<Tom><Bill>
111	<Andy>

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EX:

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.

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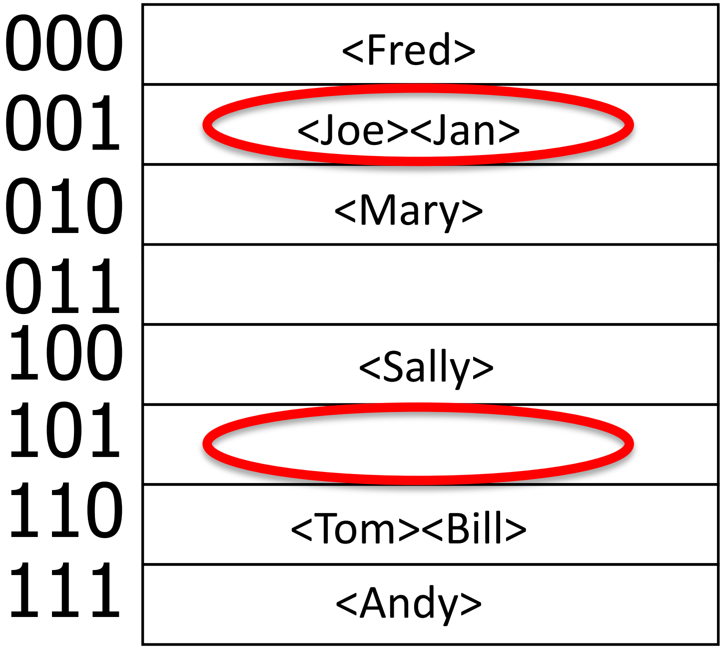
h2(30k) =01
h2(40k) =00

.



000	<Fred>
001	<Joe><Jan>
010	<Mary>
011	
100	<Sally>
101	
110	<Tom><Bill>
111	<Andy>

Find Emp. with Sal=30k

EX:

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h1(sales) =1
h1(art) =1
.
h2(10k) =01
h2(20k) =11
h2(30k) =01
h2(40k) =00
.

000	<Fred>
001	<Joe><Jan>
010	<Mary>
011	
100	<Sally>
101	
110	<Tom><Bill>
111	<Andy>

Find Emp. with Dept. = Sales

EX:

h1(toy) =0

h1(sales) =1

h1(art) =1

.

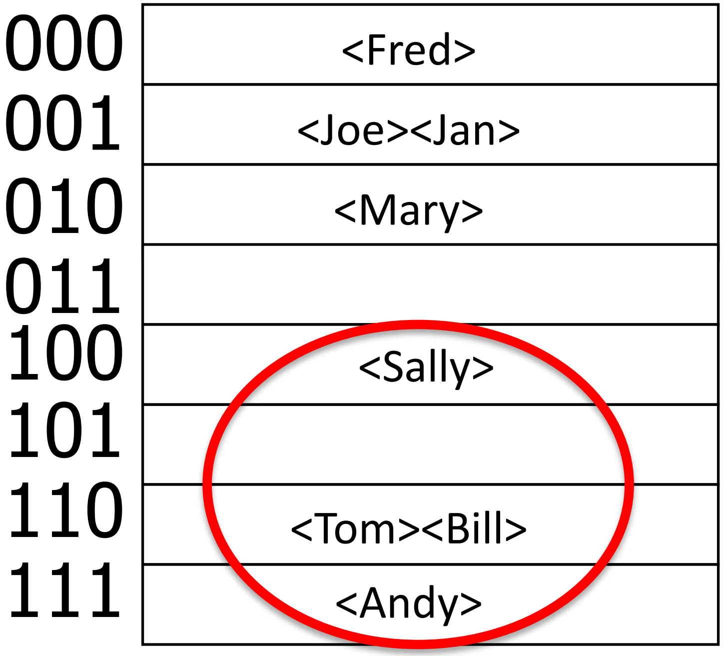
h2(10k) =01

h2(20k) =11

h2(30k) =01

h2(40k) =00

.

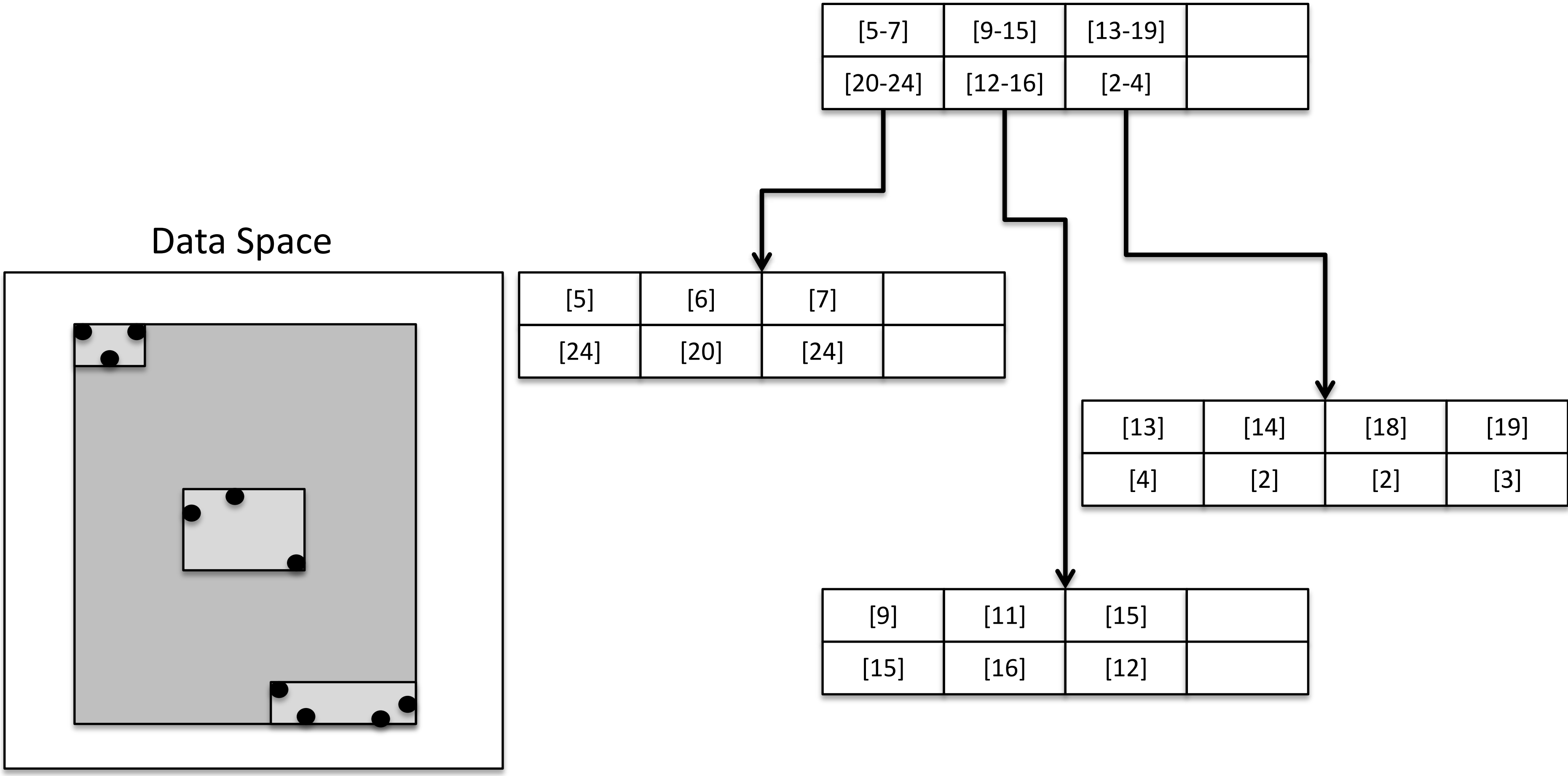


000	<Fred>
001	<Joe><Jan>
010	<Mary>
011	
100	<Sally>
101	
110	<Tom><Bill>
111	<Andy>

Find Emp. with Dept. = Sales

R-tree

- Nodes can store up to **M** entries
  - Minimum fill requirement (depends on variant)
- Each node rectangle in **n**-dimensional space
  - Minimum Bounding Rectangle (MBR) of its children
- MBRs of siblings are allowed to overlap
  - Different from B-trees
- balanced



Data Space

[5-7]	[9-15]	[13-19]	
[20-24]	[12-16]	[2-4]	

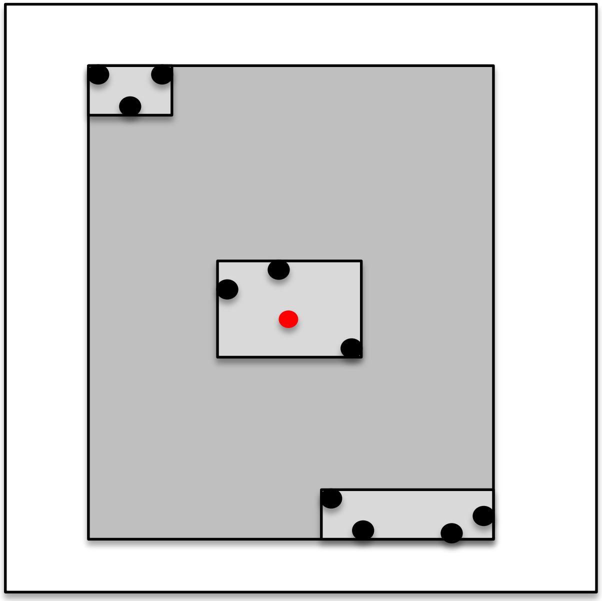
[5]	[6]	[7]	
[24]	[20]	[24]	

[13]	[14]	[18]	[19]
[4]	[2]	[2]	[3]

[9]	[11]	[15]	
[15]	[16]	[12]	

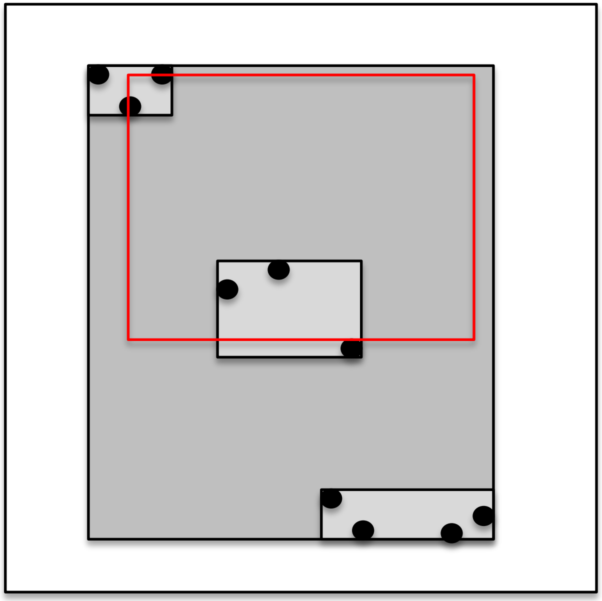
R-tree - Search

- Point Search
  - Search for p = $<x_i, y_i>$
  - Keep list of potential nodes
    - Needed because of overlap
  - Traverse to child if MBR of child contains p



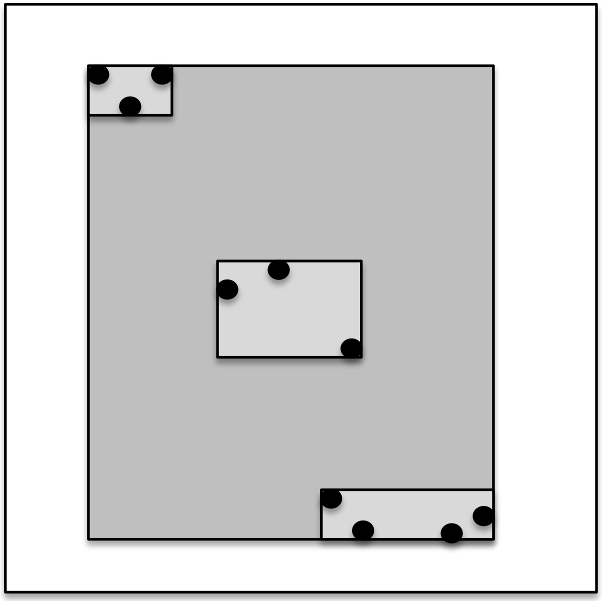
R-tree - Search

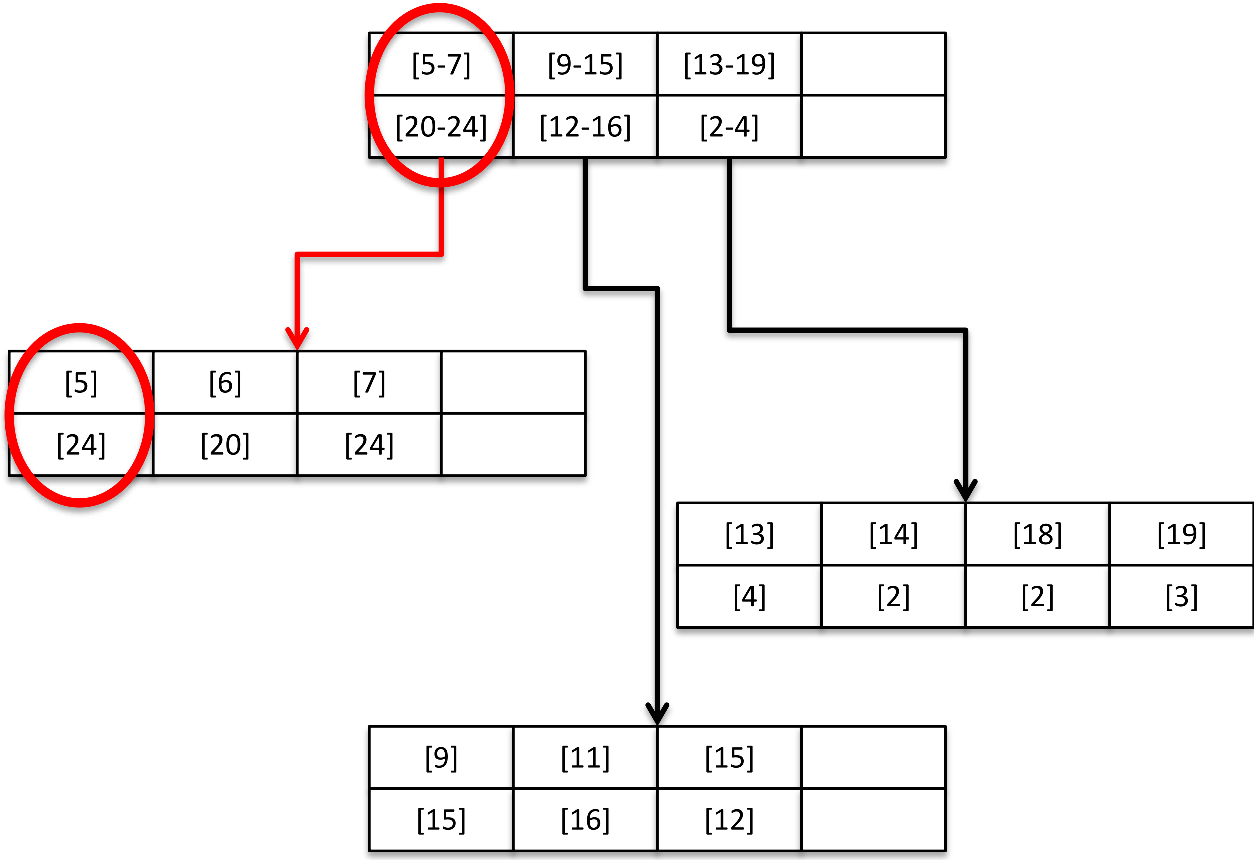
- Point Search
  - Search for points in region = <[x_{min}- x_{max}], [y_{min} -y_{max}]>
  - Keep list of potential nodes
  - Traverse to child if MBR of child overlaps with query region



Search <5,24>

Data Space





R-tree - Insert

- Similar to B-tree, but more complex
  - Overlap -> multiple choices where to add entry
  - Split harder because more choice how to split node (compare B-tree = 1 choice)
- 1) Find potential subtrees for current node
  - Choose one for insert (heuristic, e.g., the one the would grow the least)
  - Continue until leaf is found

R-tree - Insert

- 2) Insert into leaf
- 3) Leaf is full? -> split
  - Find best split (minimum overlap between new nodes) is hard ($O(2^M)$)
  - Use linear or quadratic heuristics (original paper)
- 4) Adapt parents if necessary

R-tree - Delete

- 1) Find leaf node that contains entry
- 2) Delete entry
- 3) Leaf node underflow?
  - Remove leaf node and cache entries
  - Adapt parents
  - Reinsert deleted entries

Bitmap Index

- Domain of values D = {d_1, …, d_n}
  - – Gender {male, female}
  - – Age {1, …, 120?}
- Use one vector of bits for each value
  - – One bit for each record
    - 0: record has different value in this attribute
    - 1: record has this value

Bitmap Index Example

Age

1	2	3
1	0	0
0	1	0
1	0	0
0	0	1

Todlers

Name	Age	Gender
Peter	1	male
Gertrud	2	female
Joe	1	male
Marry	3	female

Gender

male	female
1	0
0	1
1	0
0	1

Bitmap Index Example

Age

1	2	3
1	0	0
0	1	0
1	0	0
0	0	1

Todlers

Name	Age	Gender
Peter	1	male
Gertrud	2	female
Joe	1	male
Marry	3	female

Gender

male	female
1	0
0	1
1	0
0	1

Find all todlers with age **2 and** sex **female**:

Bitwise-and between vectors

0
1
0
0

Bitmap Index Example

Age

1	2	3
1	0	0
0	1	0
1	0	0
0	0	1

Todlers

Name	Age	Gender
Peter	1	male
Gertrud	2	female
Joe	1	male
Marry	3	female

Gender

male	female
1	0
0	1
1	0
0	1

Find all todlers with age **2 or** sex **female**:

Bitwise-or between vectors

0
1
0
1

Compression

- Observation:
  - Each record has one value in indexed attribute
  - For N records and domain of size |D|
    - Only 1/|D| bits are 1
  - -> waste of space
- Solution
  - Compress data
  - Need to make sure that **and** and **or** is still fast

Run length encoding (RLE)

- Instead of actual 0-1 sequence encode length of 0 or 1 runs
- One bit to indicate whether 0/1 run + several bits to encode run length
- But how many bits to use to encode a run length?
  - Gamma codes or similar to have variable number of bits

RLE Example

- 0001 0000 1110 1111 **(2 bytes)**
- 3, 1,4, 3, 1,4 **(6 bytes)**
- -> if we use one byte to encode a run we have 7 bits for length = max run length is 128(127)

Elias Gamma Codes

- $X = 2^N + (x \bmod 2^N)$
  - Write N as N zeros followed by one 1
  - Write $(x \bmod 2^N)$ as N bit number
- $18 = 2^4 + 2 = 000010010$

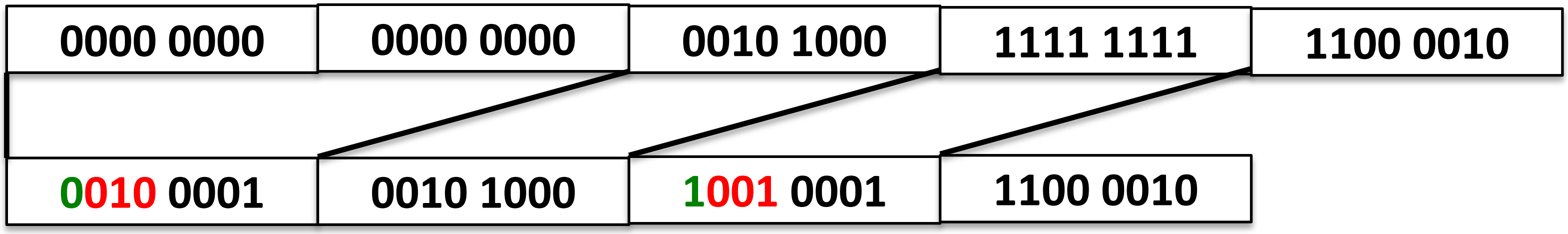
- 0001 0000 1110 1111 **(2 bytes)**
- 3, 1,4, 3, 1,4 **(6 bytes)**
- 0111 0010 0011 1001 00 **(3 bytes)**

Hybrid Encoding

- Run length encoding
  - Can waste space
  - And/or run length not aligned to byte/word boundaries
- Encode some bytes of sequence as is and only store long runs as run length
  - EWAH
  - BBC (that's what Oracle uses)

Extended Word aligned Hybrid (EWAH)

- Segment sequence in machine words (64bit)
- Use two types of words to encode
  - Literal words, taken directly from input sequence
  - Run words
    - ½ word is used to encode a run
    - ½ word is used to encode how many literals follow



0000 0000 | 0000 0000 | 0010 1000 | 1111 1111 | 1100 0010

0010 0001 | 0010 1000 | 1001 0001 | 1100 0010

Bitmap Indices

- Fast for read intensive workloads
  - Used a lot in datawarehousing
- Often build on the fly during query processing
  - As we will see later in class

Trie

- From Retrieval
- Tree index structure
- Keys are sequences of values from a domain D
  - D = {0,1}
  - D = {a,b,c,….,z}
- Key size may or may not be fixed
  - Store 4-byte integers using D = {0,1} (32 elements)
  - Strings using D={a,…,z} (arbitrary length)

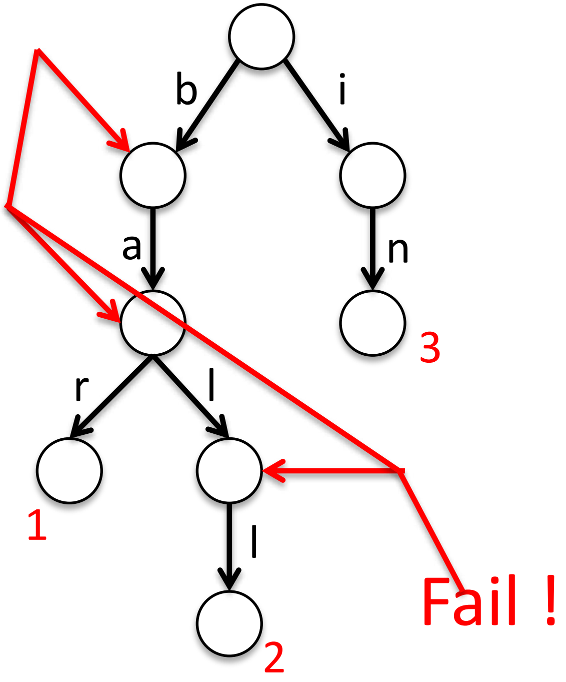
Trie

- Each node has pointers to |D| child nodes
  - One for each value of D
- Searching for a key $k = [d_1, \ldots, d_n]$
  - Start at the root
  - Follow child for value d_i

Trie Example

Words: bar, ball, in

Search for **bald**



Tries Implementation

- 1) Each node has an array of child pointers
- 2) Each node has a list or hash table of child pointers
- 3) array compression schemes derived from compressed DFA representations

Index structures in the Main Memory DBMS era

- Larger and large portions of the data fit into main memory
  - Disk I/O no longer the (only) bottleneck
  - Highly optimized and specialized operator code
    - Difference of the constant factor for full scan versus index increase
  - Increasing amounts of parallelism
    - Traditional methods for parallel access to indexes no longer effective enough
- => Do not use indexes anymore?

Index structures in the Main Memory DBMS era

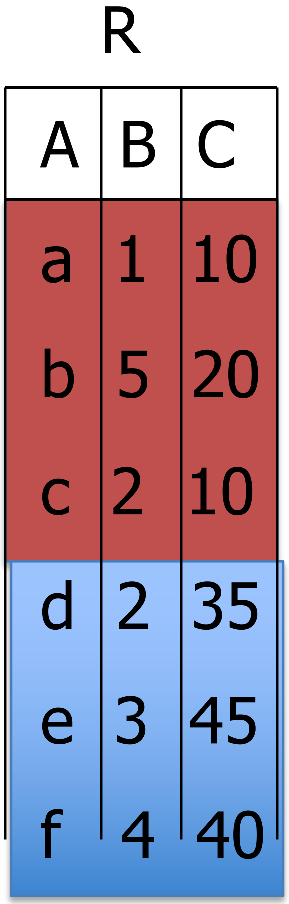
- Solutions
  - More Light-weight and coarse-grained data structures
  - Use data-structures that have less parallelization bottle-necks

Index structures in the Main Memory DBMS era

- **Solutions**
  - More Light-weight and coarse-grained data structures, e.g.:
    - Data skipping (small materialized aggregates)
    - Database cracking
  - Use data-structures that have less parallelization bottle-necks, e.g.,
    - Skip lists
    - B^w-trees

Data skipping

- Consider a relation stored in an unsorted page file
  - Regular DBMS
  - HDFS parquet file
  - …
- Main idea of data skipping
  - For each page store min/max values of each attribute
- To evaluate a selection predicate on attribute A say c1 <= A <= c2
  - if for page P: $A_{max} < c1$ or $A_{min} > c2$ then none of the tuples on that page will qualify and we can skip reading this page



R

A	B	C
a	1	10
b	5	20
c	2	10
d	2	35
e	3	45
f	4	40

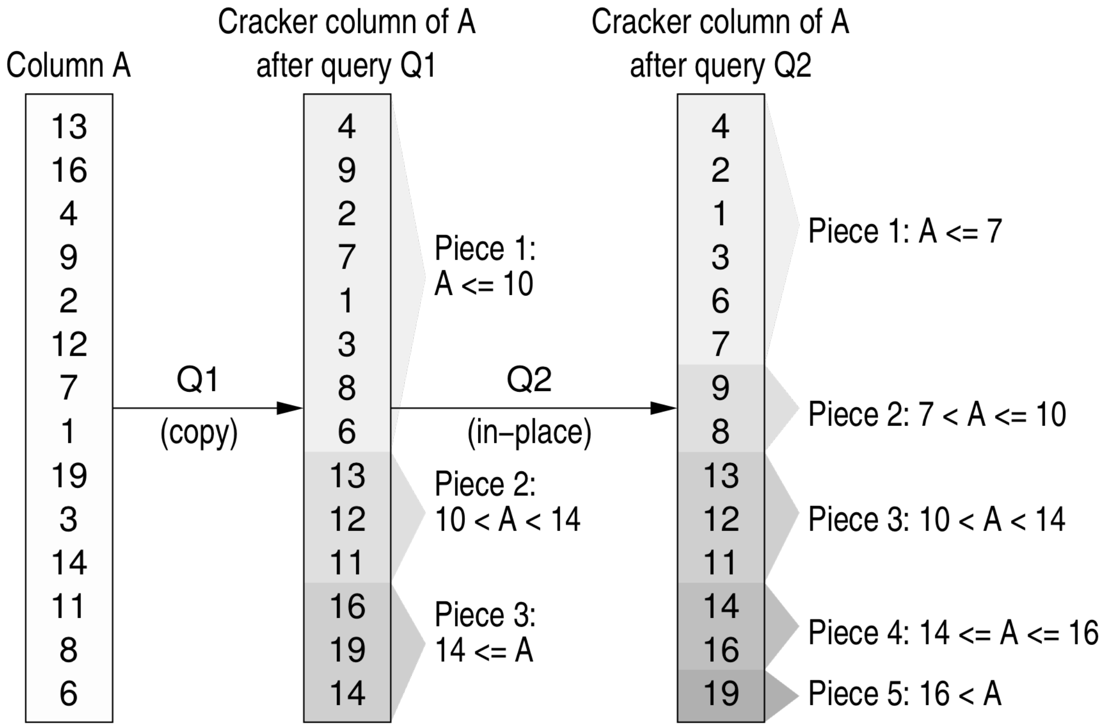
Database cracking

- Main rationale
  - Originally designed for columnar databases
  - The amount of indexing effort we spend for a part of the key space should be based on how frequently this part of the keyspace is accessed
- Basic idea
  - Start with an unsorted file
  - Whenever a query applies a selection condition on a column A, say A< 50, then split the current partition containing 50 into two fragments one with data < 50 and one with the remaining data (partial sort)
  - Keep a small in-memory tree index for these fragments

Database cracking

Q1:
select *
from R
where R.A > 10
  and R.A < 14

Q2:
select *
from R
where R.A > 7
  and R.A >= 16



Column A	Cracker column of A after query Q1	Cracker column of A after query Q2
13	4	4
16	9	2
4	2	1
9	7	3
2	1	6
12	3	7
7	8	9
1	6	8
19	13	13
3	12	12
14	11	11
11	16	14
8	19	16
6	14	19

Q1 (copy)

Piece 1: A <= 10
Piece 2: 10 < A < 14
Piece 3: 14 <= A

Q2 (in–place)

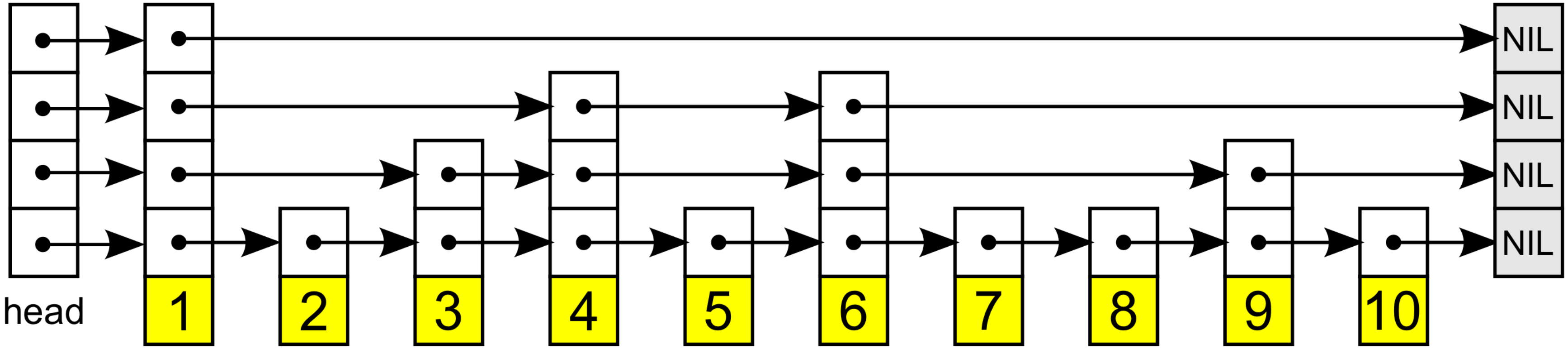
Piece 1: A <= 7
Piece 2: 7 < A <= 10
Piece 3: 10 < A < 14
Piece 4: 14 <= A <= 16
Piece 5: 16 < A

From **Database Cracking – CIDR 2007**

Skip lists

- Probabilistic datastructure
  - Behavior depends on randomization
  - Gives only probabilistic guarantees
    - => with high probability will guarantee good performance
  - Approximates a search tree using the much simpler (and easier to parallelize linked list datastructure)

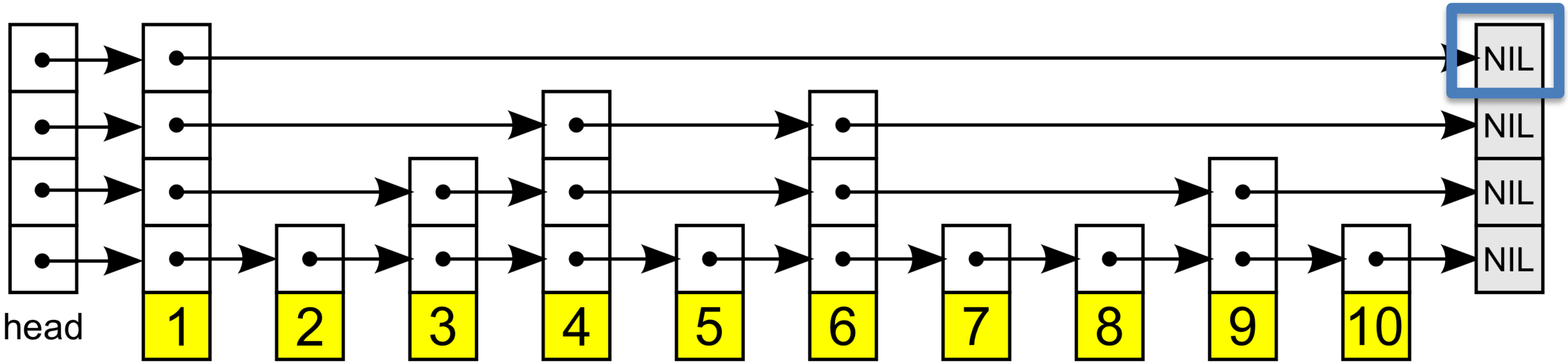
Skip lists



- **Search**:
  - Start from the top list
  - 1) Move through list until element is found or we are at a larger element/end of the list
  - 2) move to previous element (smaller than search key) and follow a down pointer to the next deeper level
  - 3) Goto 1)

Search 5

Skip lists



- **Search**:
  - Start from the top list
  - 1) Move through list until element is found or we are at a larger element/end of the list
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  - 3) Goto 1)

Search 5

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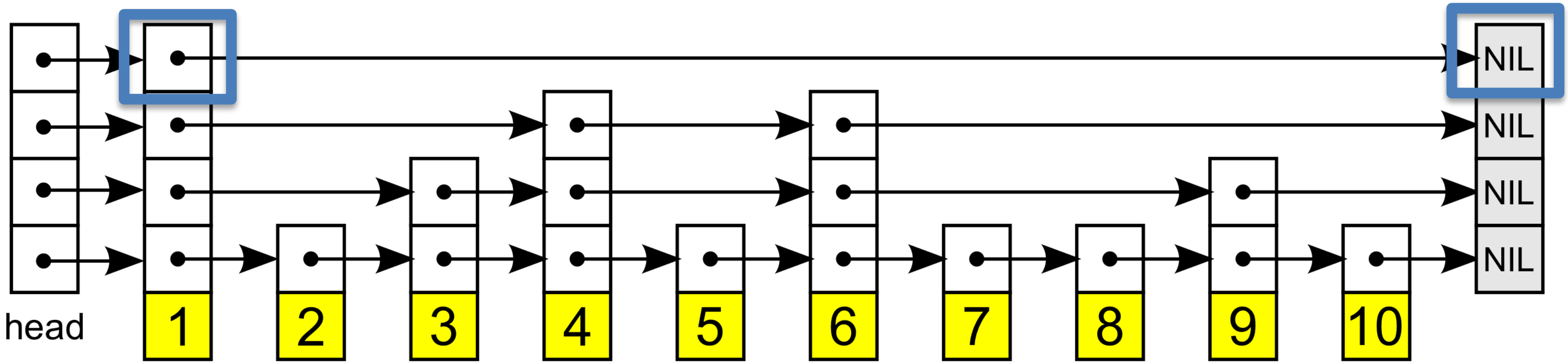

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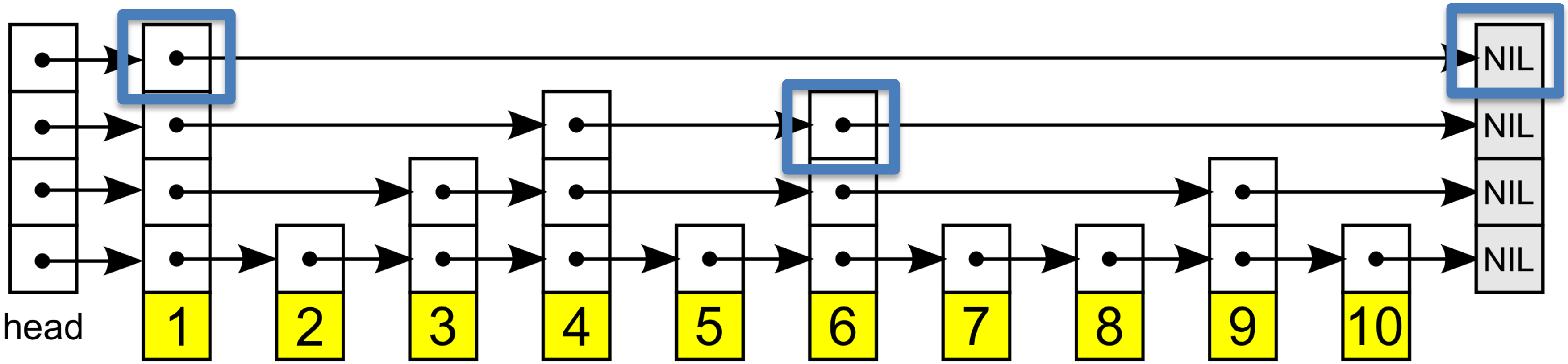

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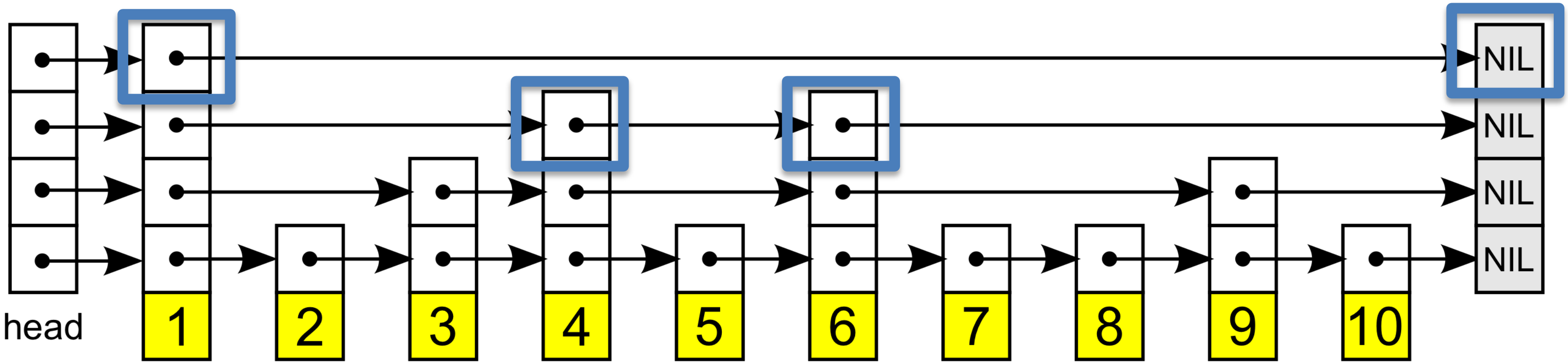

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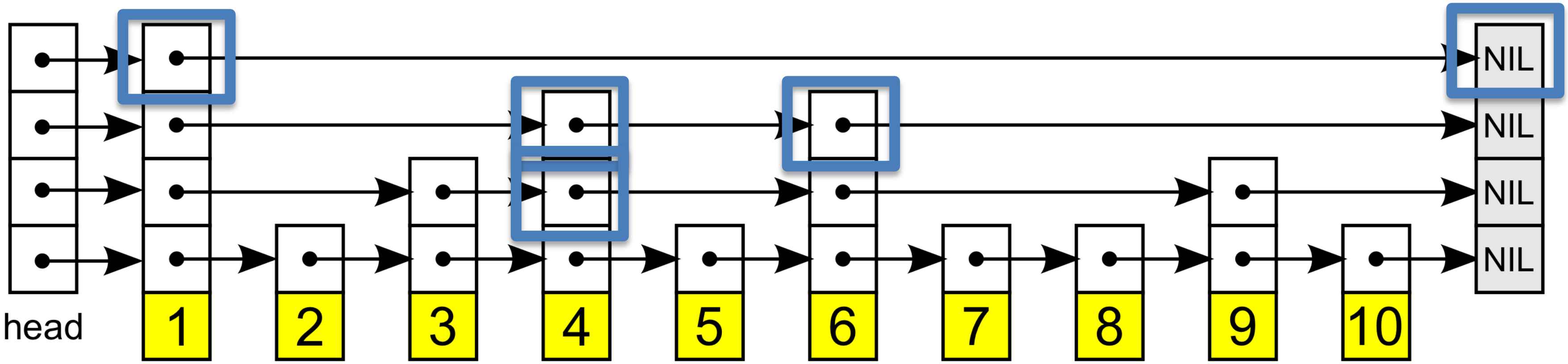

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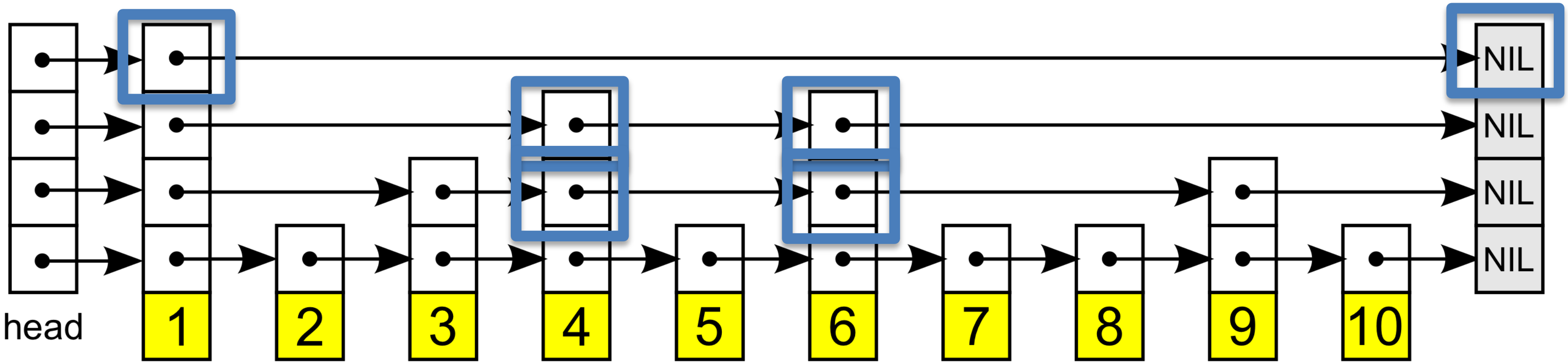

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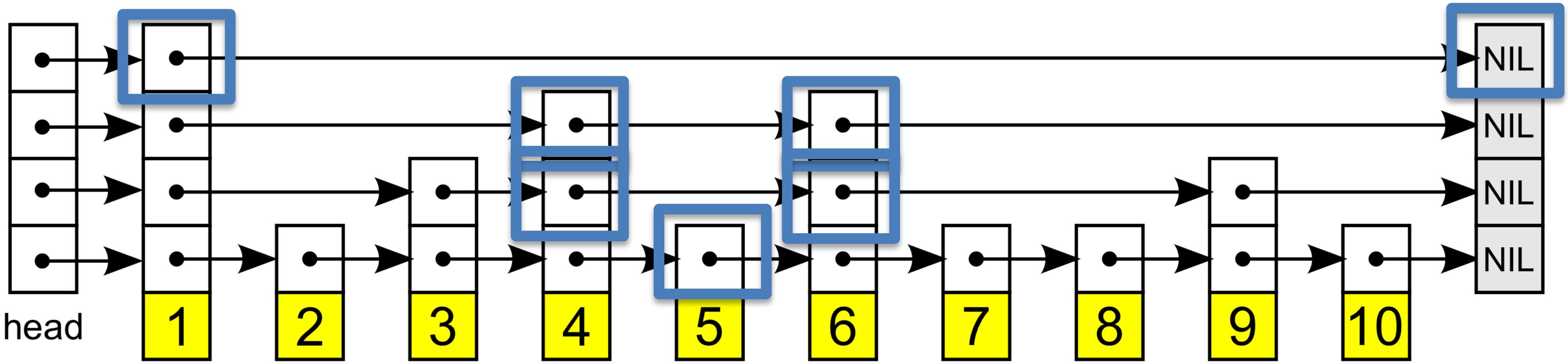
Search 5

Skip lists



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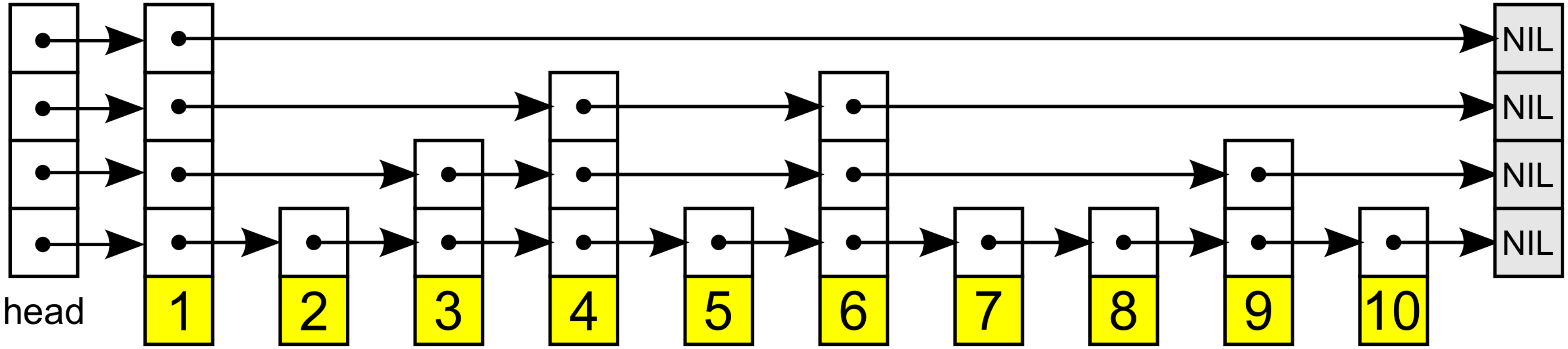
Skip lists



- **Insert**:
  - Use search to find insertion position at the lowest level (keep pointers at the higher levels)
  - Insert element in the lowest list
  - Then for every level throw a dice and insert key with probability p (typically ½)

Observation: in expectation each level has p as many nodes as the next lower level

Skip lists

- **Characteristics**
  - O(log(n)) expected performance (insert, delete, search)
  - Easy to parallelize (linked lists)
  - Simpler to implement (also less CPU ops) than B-trees
- **Example implementations**
  - MemSQL (main memory database system)
  - Lucene
  - leveldb

Improving insert/update performance

- B-tree
  - O(log(n)) I/O
- Hash-index
  - O(1) I/O, but potential reorg cost
- Consider Key-value store (e.g., Cassandra) application
  - Need fast write-throughput
  - Need fast point-lookup

One Solution: LSM-trees

- **Log-structured merge** (**LSM**) trees
  - Have small index that is memory resident (**memtable**)
  - When memtable exceeds a size threshold write it as one sorted run to disk (will explain algorithm when talking about query execution)
    - Sequential I/O!
    - Runs are immutable after being written (exception compaction)
    - Runs may contain outdated values for keys that exist in newer runs of the memtable
    - Over time me we have multiple sorted runs
  - **Inserts/Updates**
    - Always applied to memtable
  - **Lookup**
    - If we find a key in the memtable then return it
    - Otherwise lookup keys in the sorted runs in reverse chronological order

LSM-trees

- **Performance**
  - **Inserts/Updates**
    - O(1)!
  - **Lookup**
    - O(#runs)
    - => want to make sure the number of runs does not grow indefinitely
- **Compaction**
  - Merge sorted runs on disks to reduce #runs => improve lookup performance

Basic Compaction

- Have levels
  - Once there are more then x runs on a level these are merged into one larger run
  - Run sizes increase exponentially per level
- E.g., threshold is 4 runs
  - first level: runs are of same size as memtable
  - 2nd level: 4 * size of memtable
  - 3rd level: 4 * 4 * size of memtable
  - …

LSM-trees

- **Other lookup improvements**
  - – Block index in memory (similar to sparse index)
  - – Bloomfilters
    - A bloom filter is a small over-approximation of set
      - – Can be used to test if a key K is contained in a set S
        - » Returns yes, then the key **may** be in the set
        - » Returns no, then the key is guaranteed to not be in the set
    - => fast way to avoid looking a runs that are guaranteed to not contain a key

Bw-trees

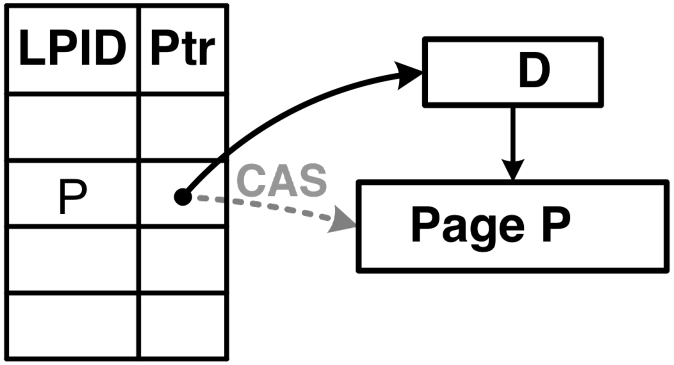
- **Motivation**
  - Improve concurrency properties of B-trees
  - Improve cache effectiveness of B-trees
  - Designed for flash-storage
    - Fast random/sequential reads
    - Fast sequential writes
    - Comparably slower random writes (albeit smaller factor

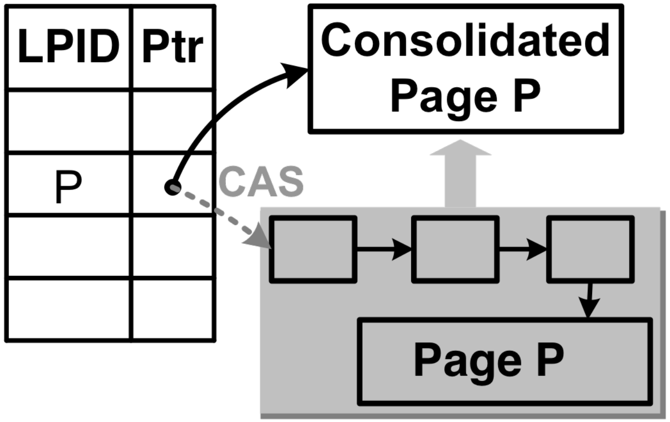
Bw-trees

- **Overview**
  - Updateable B-tree without latches
    - Threads almost never block
      - => Improved instruction cache performance
  - Backed up by log-structured storage
  - Updates never modify pages but append deltas to a page
    - Deltas are “installed” using CAS (atomic compare and swap)

Bw-trees

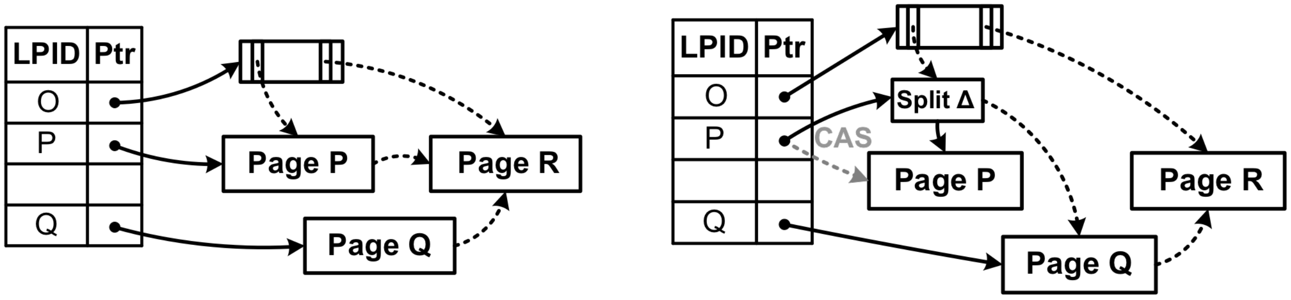
- **Mapping table**
  - Pages are logical identified by a LPID which is stable
  - Locations and size of pages can change over time
  - Updates create a delta record that points to the previous address of the page
  - The delta record's address is swapped for the current address in the mapping table using CAS



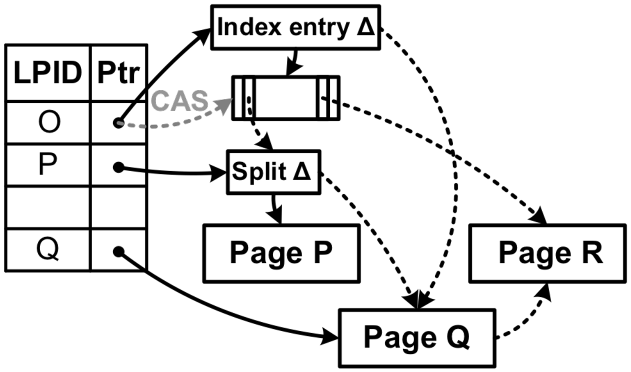


Bw-trees

- **Making page splits atomic**



(a) Creating sibling page Q (b) Installing split delta



(c) Installing index entry delta

Summary

Discussion:

- Conventional Indices
- B-trees
- Hashing (extensible, linear)
- SQL Index Definition
- Index vs. Hash
- Multiple Key Access
- Multi Dimensional Indices
  - Variations: Grid, R-tree,
- Partitioned Hash
- Bitmap indices and compression
- Tries
- Database cracking
- Data skipping (small materialized aggregates/zone maps)
- Skip-lists
- Log-structured merge trees (LSM)

CS 525: Advanced Database Organisation

07: Query Processing Overview

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab

Query Processing

Q → Query Plan

Query Processing

Q → Query Plan

Focus: Relational Systems

- Others?

Example

Select B,D

From R,S

Where R.A = “c” ∧ S.E = 2 ∧ R.C=S.C

R

A	B	C
a	1	10
b	1	20
c	2	10
d	2	35
e	3	45

S

C	D	E
10	x	2
20	y	2
30	z	2
40	x	1
50	y	3

R	A	B	C
	a	1	10
	b	1	20
	c	2	10
	d	2	35
	e	3	45

S	C	D	E
	10	x	2
	20	y	2
	30	z	2
	40	x	1
	50	y	3

Answer

B	D
2	x

- How do we execute query?

One idea

- Do Cartesian product
- Select tuples
- Do projection

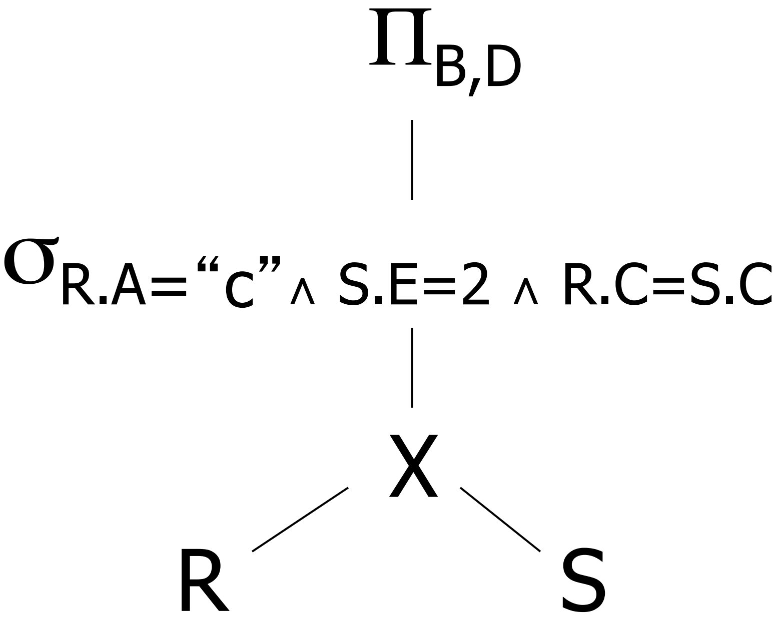
RXS

R.A	R.B	R.C	S.C	S.D	S.E
a	1	10	10	x	2
a	1	10	20	y	2
.					
.					
C	2	10	10	x	2
.					
.					

RXS	R.A	R.B	R.C	S.C	S.D	S.E
	a	1	10	10	x	2
	a	1	10	20	y	2
	.					
	.					
Bingo! →	C	2	10	10	x	2
Got one...	.					
	.					

Relational Algebra - can be used to describe plans...

Ex: Plan I



$\Pi_{B,D}$

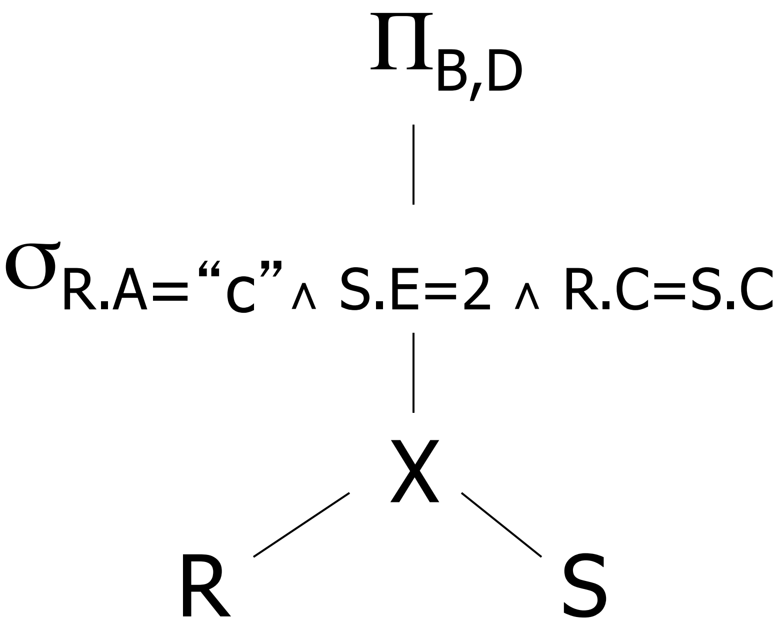
$\sigma_{R.A=\text{“c”} \wedge S.E=2 \wedge R.C=S.C}$

X

R S

Relational Algebra - can be used to describe plans...

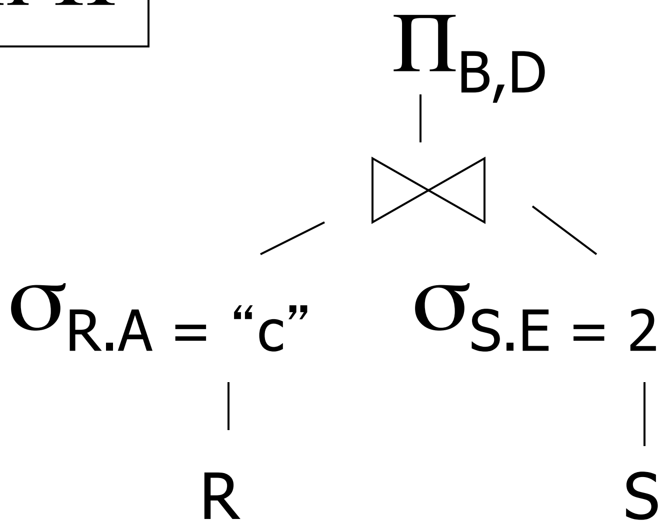
Ex: Plan I



OR: $\Pi_{B,D}[\sigma_{R.A=\text{“c”} \wedge S.E=2 \wedge R.C = S.C}(RXS)]$

Another idea:

Plan II



$\Pi_{B,D}$

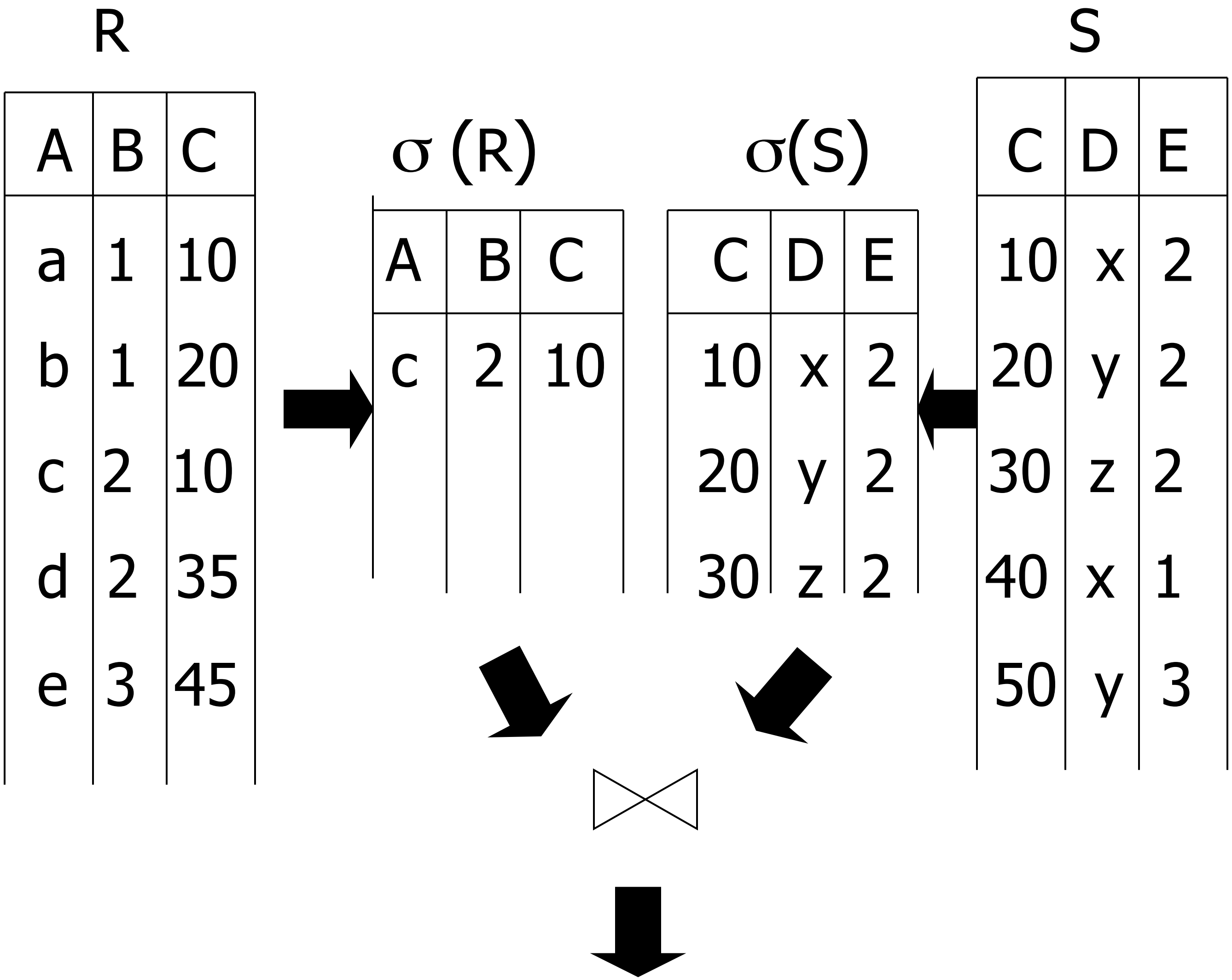
$\bowtie$

$\sigma_{R.A = \text{“c”}}$ $\sigma_{S.E = 2}$

R S

$\bowtie$

natural join



R

A	B	C
a	1	10
b	1	20
c	2	10
d	2	35
e	3	45

σ (R)

A	B	C
c	2	10

σ(S)

C	D	E
10	x	2
20	y	2
30	z	2

S

C	D	E
10	x	2
20	y	2
30	z	2
40	x	1
50	y	3

$\bowtie$

Plan III

Use R.A and S.C Indexes

(1) Use R.A index to select R tuples with R.A = “c”

(2) For each R.C value found, use S.C index to find matching tuples

Plan III

Use R.A and S.C Indexes

(1) Use R.A index to select R tuples with R.A = “c”

(2) For each R.C value found, use S.C index to find matching tuples

(3) Eliminate S tuples S.E ≠ 2

(4) Join matching R,S tuples, project B,D attributes and place in result

R

A	B	C
a	1	10
b	1	20
c	2	10
d	2	35
e	3	45

S

C	D	E
10	x	2
20	y	2
30	z	2
40	x	1
50	y	3

R

A	B	C
a	1	10
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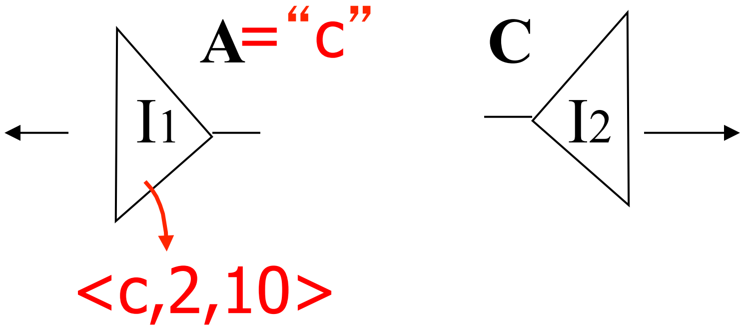

S

C	D	E
10	x	2
20	y	2
30	z	2
40	x	1
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R

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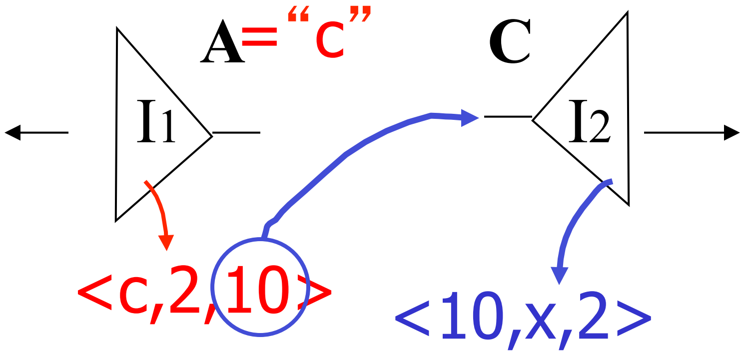

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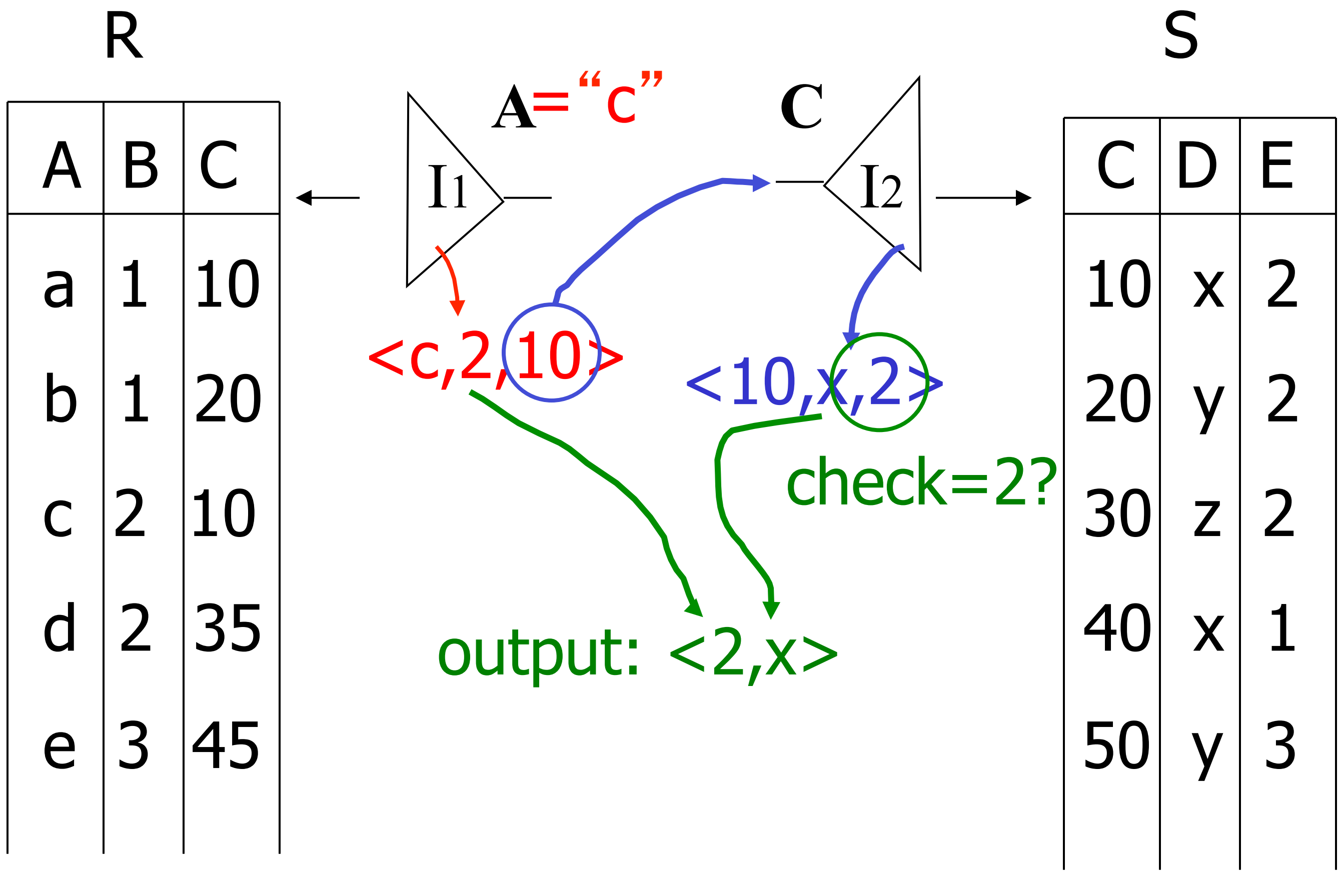

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e	3	45

S

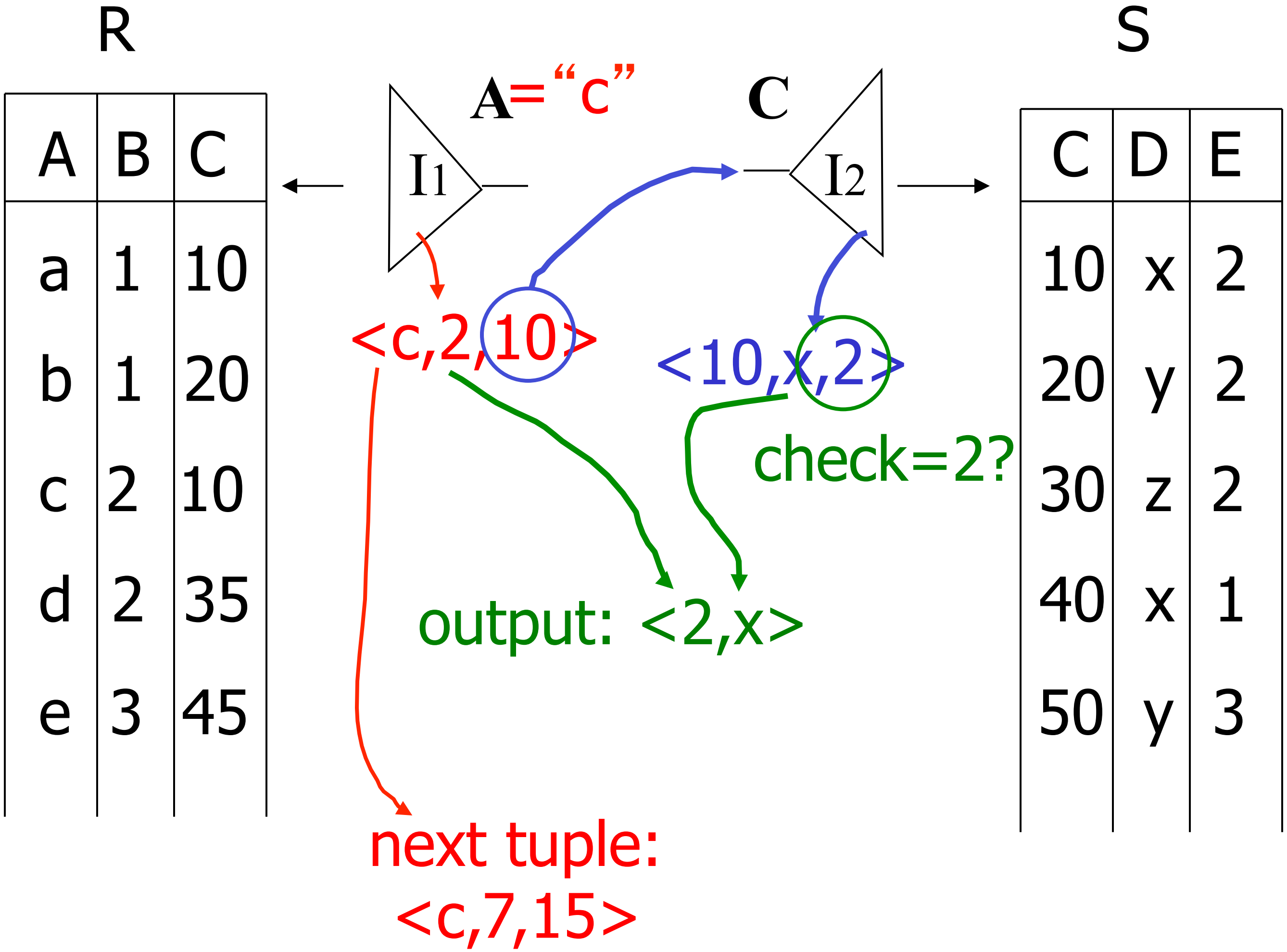
C	D	E
10	x	2
20	y	2
30	z	2
40	x	1
50	y	3

<c,2,10>

<10,x,2>

check=2?

output: <2,x>



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C	D	E
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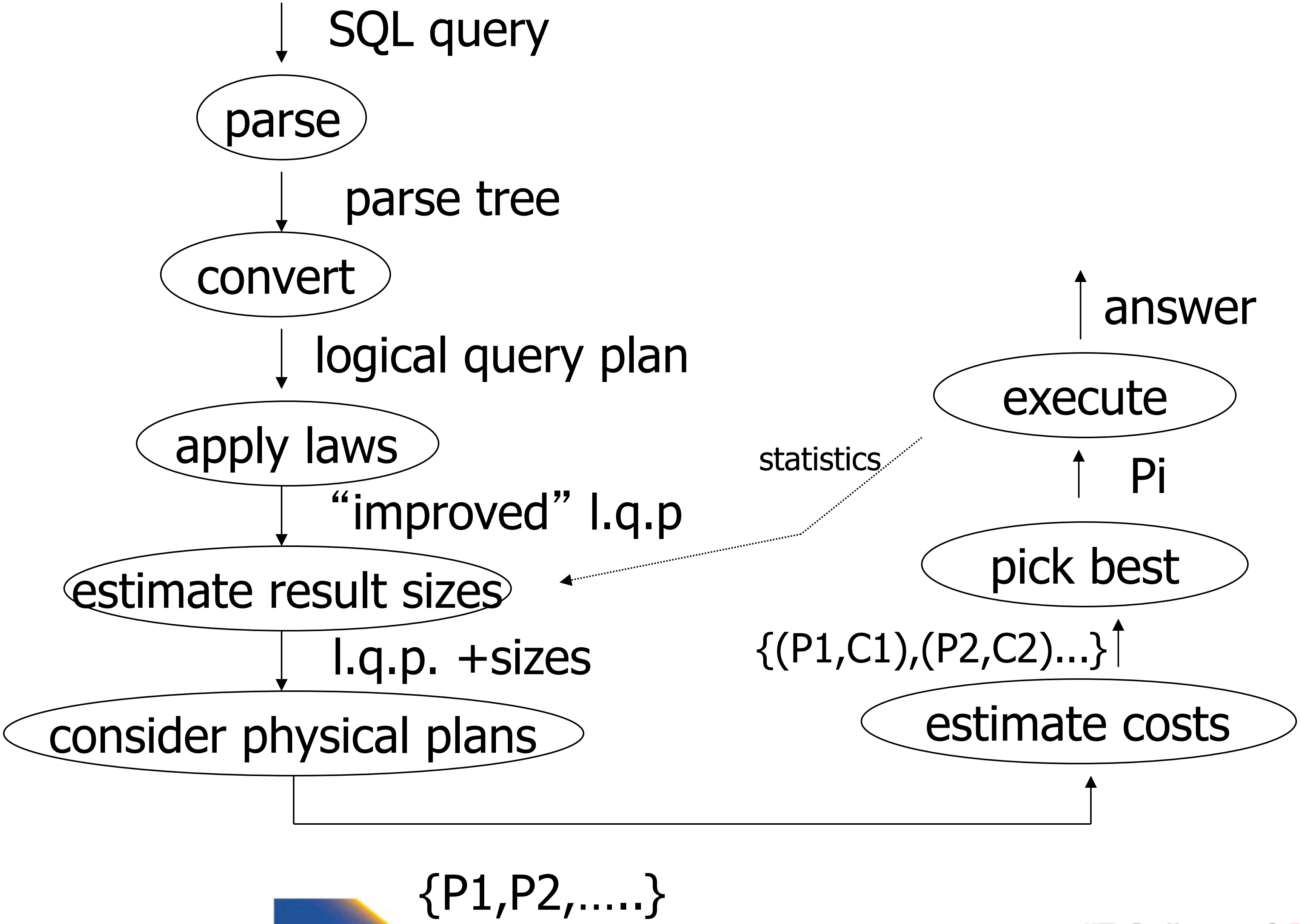
Overview of Query Optimization



SQL query

parse

parse tree

convert

logical query plan

apply laws

“improved” l.q.p

estimate result sizes

statistics

l.q.p. +sizes

consider physical plans

{P1,P2,…..}

estimate costs

{(P1,C1),(P2,C2)...}

pick best

Pi

execute

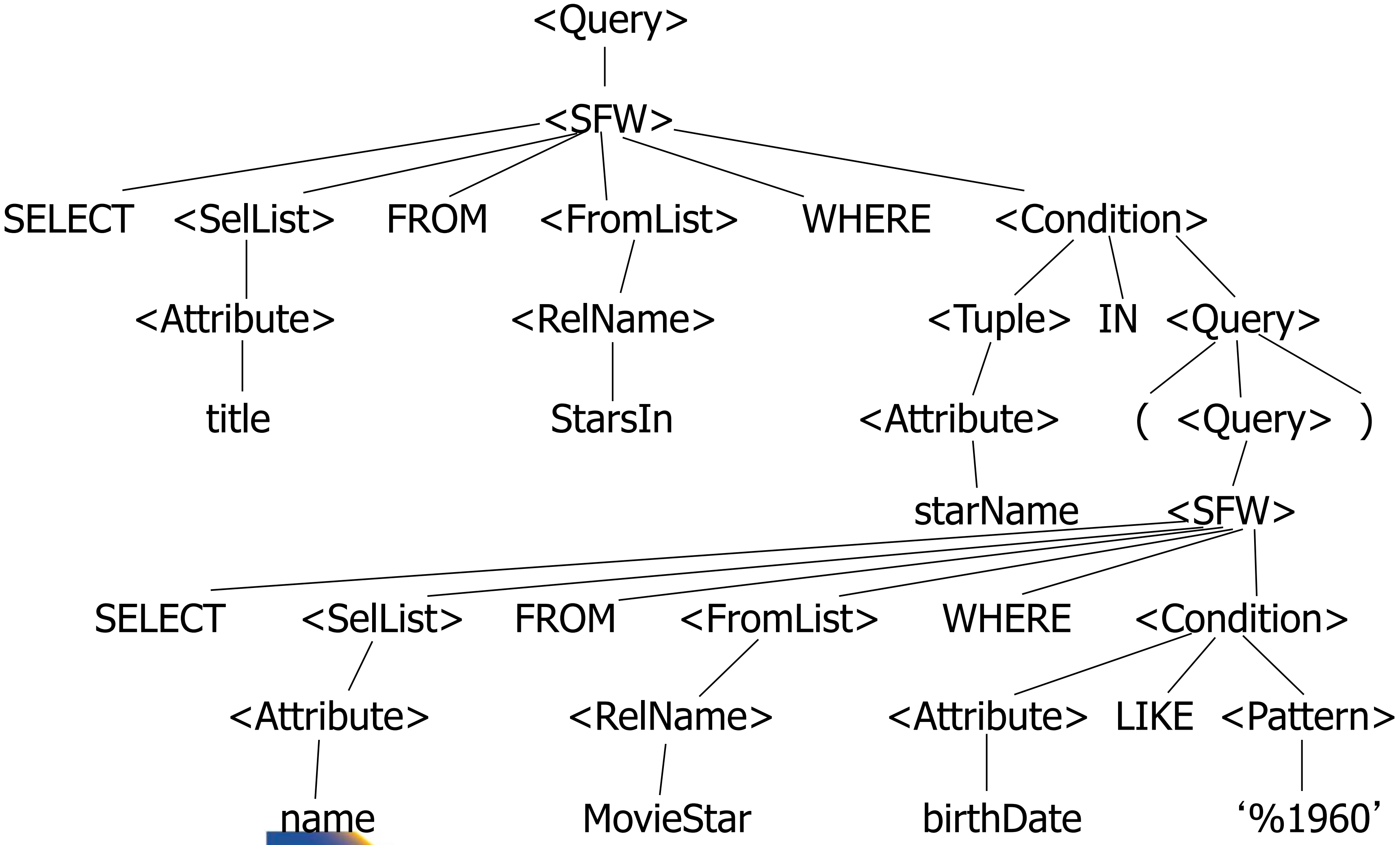
answer

Example: SQL query

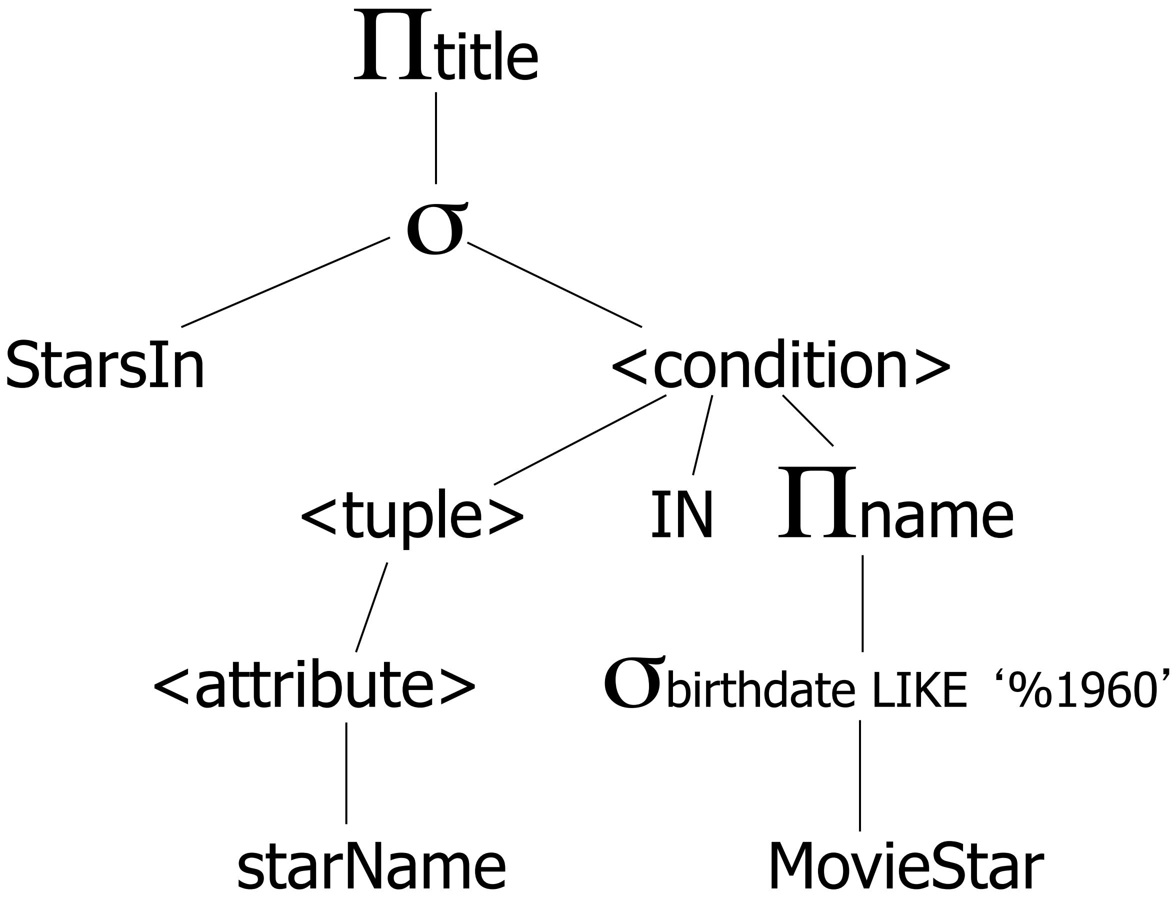
```
SELECT title
FROM StarsIn
WHERE starName IN (
        SELECT name
        FROM MovieStar
        WHERE birthdate LIKE ‘%1960’
);
```

(Find the movies with stars born in 1960)

Example: Parse Tree



Example: Generating Relational Algebra



Π_{title}

σ

StarsIn

<condition>

<tuple>

IN

Π_{name}

<attribute>

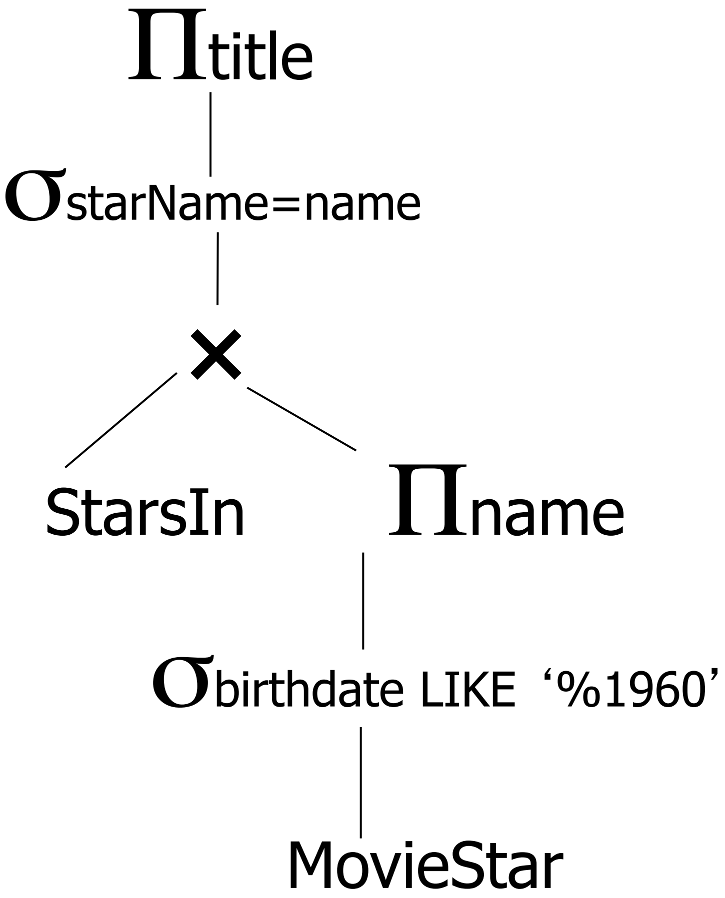
$\sigma_{\text{birthdate LIKE '\%1960'}}$

starName

MovieStar

Fig. 7.15: An expression using a two-argument σ, midway between a parse tree and relational algebra

Example: Logical Query Plan



Π_{title}

$\sigma_{\text{starName=name}}$

×

StarsIn

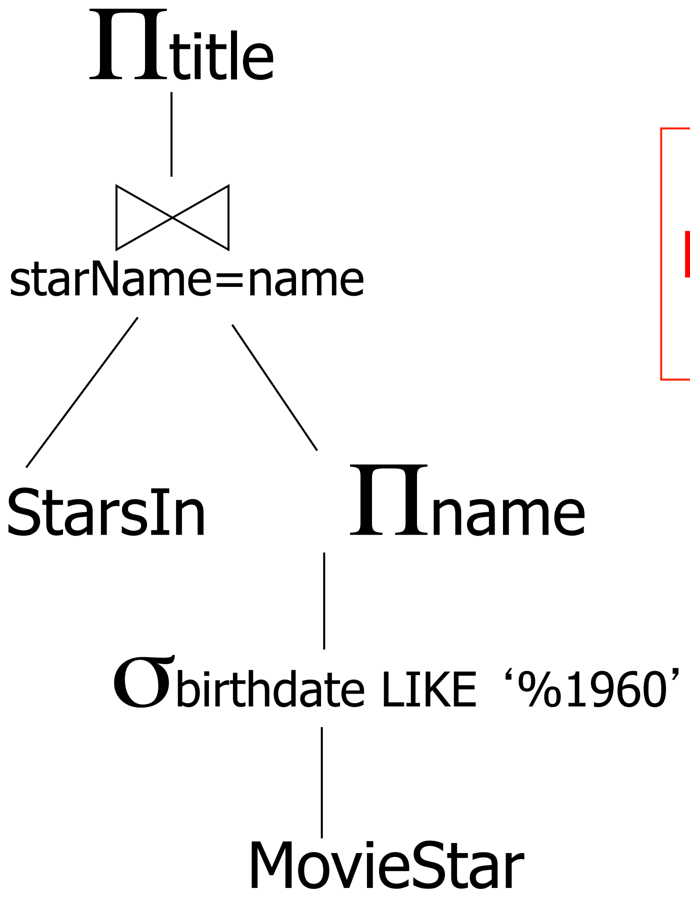
Π_{name}

$\sigma_{\text{birthdate LIKE '\%1960'}}$

MovieStar

Fig. 7.18: Applying the rule for IN conditions

Example: Improved Logical Query Plan



Π_{title}

$\bowtie_{starName=name}$

StarsIn

Π_{name}

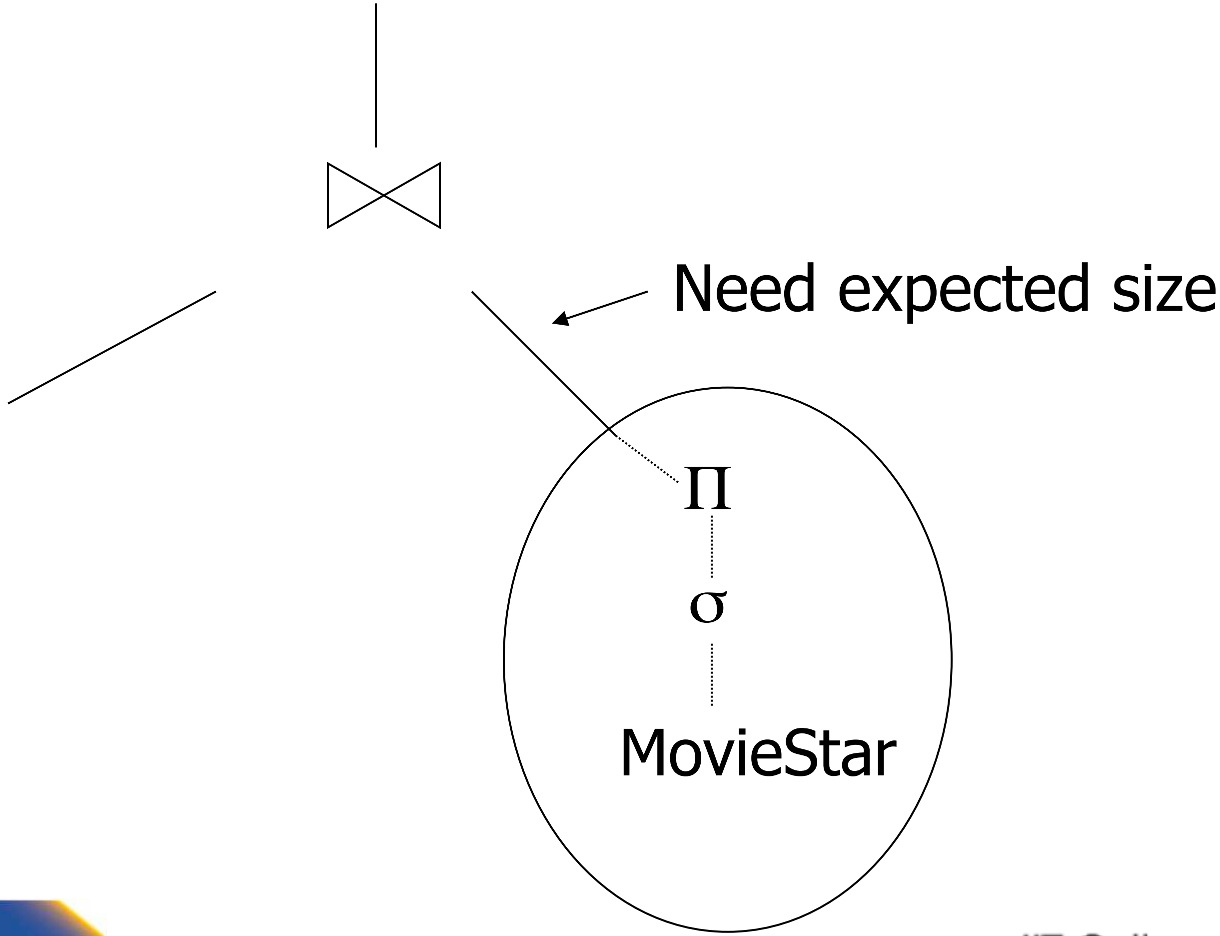
$\sigma_{birthdate\ LIKE\ '\%1960'}$

MovieStar

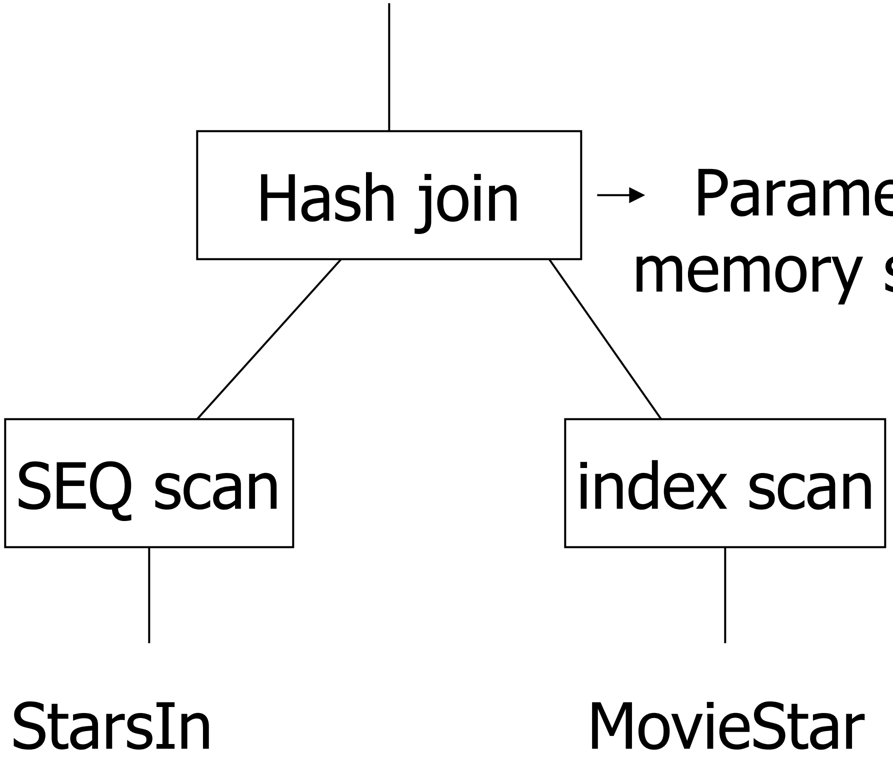
Fig. 7.20: An improvement on fig. 7.18.

Question:
Push project to
StarsIn?

Example: Estimate Result Sizes



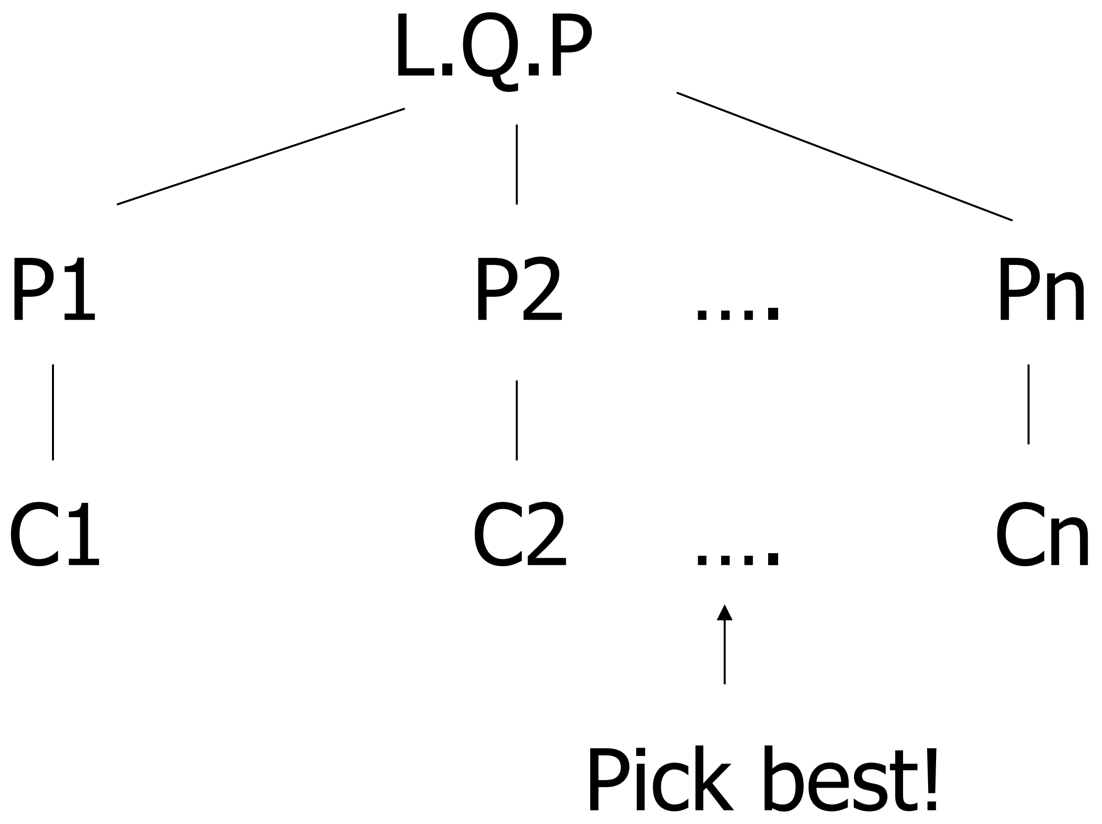
Example: One Physical Plan



→ Parameters: join order, memory size, project attributes,...

→ Parameters: Select Condition,...

Example: Estimate costs



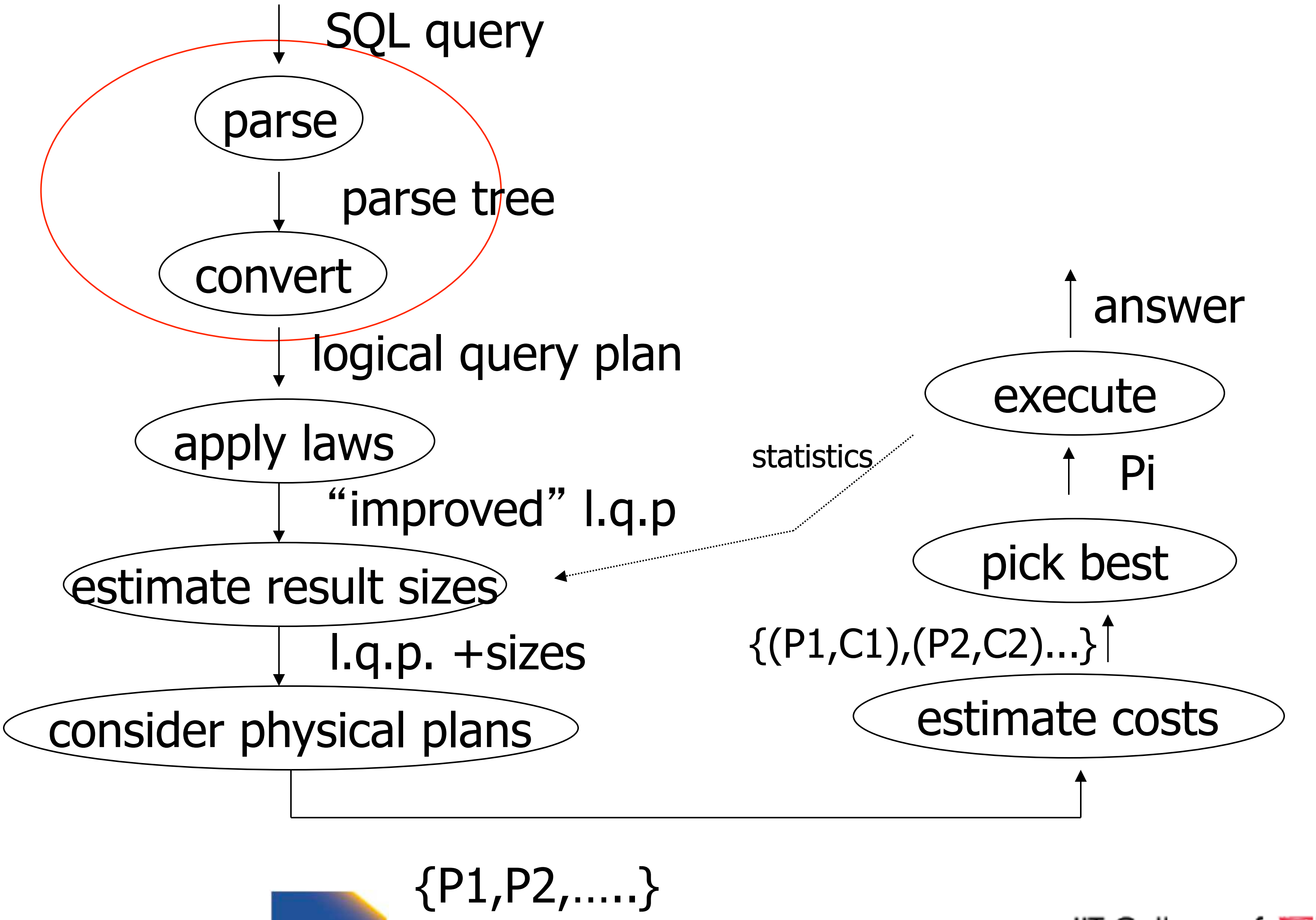
Pick best!

CS 525: Advanced Database Organisation

08: Query Processing Parsing and Analysis

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab



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estimate costs

{(P1,C1),(P2,C2)...}

pick best

Pi

execute

answer

Parsing, Analysis, Conversion

1. Parsing
   - Transform SQL text into syntax tree
2. Analysis
   - Check for semantic correctness
   - Use database catalog
   - E.g., unfold views, lookup functions and attributes, check scopes
3. Conversion
   - Transform into internal representation
   - Relational algebra or QBM

Analysis and Conversion

- Usually intertwined
- The internal representation is used to store analysis information
- Create an initial representation and complete during analysis

Parsing, Analysis, Conversion

1. Parsing
2. Analysis
3. Conversion

Parsing

- SQL -> Parse Tree
- Covered in compiler courses and books
- Here only short overview

SQL Standard

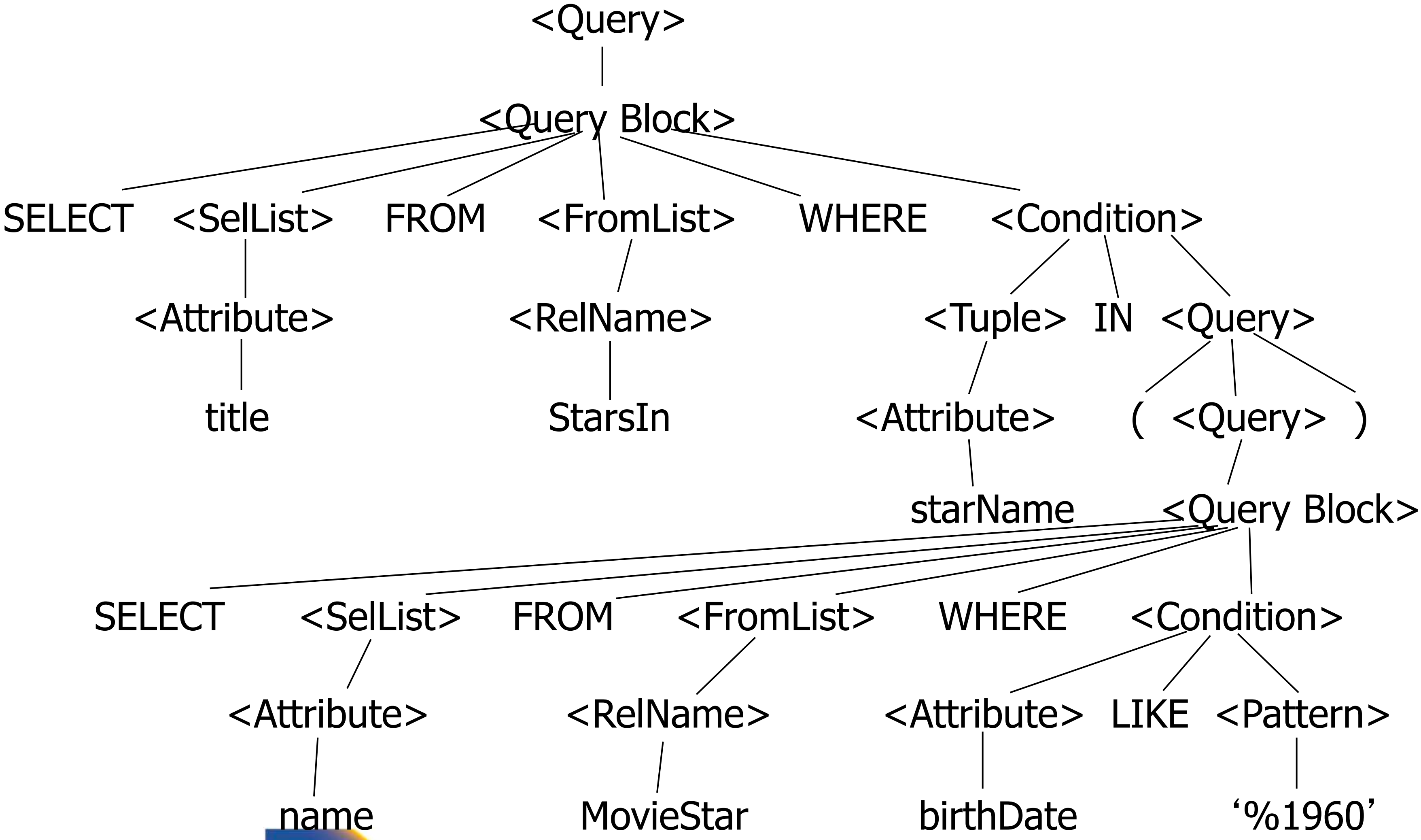
- Standardized language
  - 86, 89, 92, 99, 03, 06, 08, 11
- DBMS vendors developed their own dialects

Example: SQL query

```
SELECT title
FROM StarsIn
WHERE starName IN (
     SELECT name
     FROM MovieStar
     WHERE birthdate LIKE ‘%1960’
);
```

(Find the movies with stars born in 1960)

Example: Parse Tree



<Query>

<Query Block>

SELECT <SelList> FROM <FromList> WHERE <Condition>

<Attribute> <RelName> <Tuple> IN <Query>

title StarsIn <Attribute> (<Query>)

starName <Query Block>

SELECT <SelList> FROM <FromList> WHERE <Condition>

<Attribute> <RelName> <Attribute> LIKE <Pattern>

name MovieStar birthDate ‘%1960’

SQL Query Structure

- Organized in Query blocks

```
SELECT <select_list>
FROM <from_list>
WHERE <where_condition>
GROUP BY <group_by_expressions>
HAVING <having_condition>
ORDER BY <order_by_expressions>
```

Query Blocks

- Only **SELECT** clause is mandatory
  - Some DBMS require **FROM**

SELECT (1 + 2) AS result

result
3

SELECT clause

- List of expressions and optional name assignment + optional **DISTINCT**
  - Attribute references: R.a, b
  - Constants: 1, ‘hello’, ‘2008-01-20’
  - Operators: (R.a + 3) * 2
  - Functions (maybe UDF): substr(R.a, 1,3)
    - Single result or **set functions**
  - Renaming: (R.a + 2) AS x

SELECT clause - example

```
SELECT substring(p.name,1,1) AS initial
       p.name
FROM person p
```

person

name	gender
Joe	male
Jim	male

result

initial	name
J	Joe
J	Jim

SELECT clause – set functions

- Function `extrChar(string)`

```
SELECT extrChar(p.name) AS n
FROM person p
```

person

name	gender
Joe	male
Jim	male

result

n
J
o
e
J
i
m

SELECT clause – DISTINCT

```
SELECT DISTINCT gender
FROM person p
```

person

name	gender
Joe	male
Jim	male

result

gender
male

FROM clause

- List of table expressions
  - Access to relations
  - Subqueries (need alias)
  - Join expressions
  - Table functions
  - Renaming of relations and columns

FROM clause examples

`FROM R`

-access table R

`FROM R, S`

-access tables R and S

`FROM R JOIN S ON (R.a = S.b)`

-join tables R and S on condition (R.a = S.b)

`FROM R x`

`FROM R AS x`

-Access table R and assign alias ‘x’

FROM clause examples

```
FROM R x(c,d)
FROM R AS x(c,d)
```

-using aliases x for R and c,d for its attribues

```
FROM (R JOIN S t ON (R.a = t.b)), T
```

-join R and S, and access T

```
FROM (R JOIN S ON (R.a = S.b)) JOIN T
```

-join tables R and S and result with T

```
FROM create_sequence(1,100) AS seq(a)
```

-call table function

FROM clause examples

```
FROM
     (SELECT count(*) FROM employee)
     AS empcnt(cnt)
```

-count number of employee in subquery

FROM clause examples

```
SELECT *
FROM create_sequence(1,3) AS seq(a)
```

result

a
1
2
3

FROM clause examples

```
SELECT dep, headcnt
FROM (SELECT count(*) AS headcnt, dep
     FROM employee
     GROUP BY dep)
WHERE headcnt > 100
```

employee

name	dep
Joe	IT
Jim	Marketing
…	…

result

dep	headcnt
IT	103
Support	2506
…	…

FROM clause - correlation

- Correlation
  - Reference attributes from other FROM clause item
  - Attributes of i^{th} entry only available in j > i
  - Semantics:
    - For each row in result of i^{th} entry:
    - Substitute correlated attributes with value from current row and evaluate query

Correlation - Example

```
SELECT name, chr
FROM employee AS e,
     extrChar(e.name) AS c(chr)
```

result

name	chr
Joe	J
Joe	o
Joe	e
Jim	J
Jim	i
…	…

employee

name	dep
Joe	IT
Jim	Marketing
…	…

Correlation - Example

```
SELECT name
FROM (SELECT max(salary) maxsal
      FROM employee) AS m,
      (SELECT name
      FROM employee x
      WHERE x.salary = m.maxsal) AS e
```

employee

name	salary
Joe	20,000
Jim	30,000
…	…

result

name
Jim

WHERE clause

- A condition
  - Attribute references
  - Constants
  - Operators (boolean)
  - Functions
  - Nested subquery expressions
- Result has to be boolean

WHERE clause examples

`WHERE R.a = 3`

-comparison between attribute and constant

`WHERE (R.a > 5) AND (R.a < 10)`

-range query using boolean AND

`WHERE R.a = S.b`

-comparison between two attributes

`WHERE (R.a * 2) > (S.b – 3)`

-using operators

Nested Subqueries

- Nesting a query within an expression
- Correlation allowed
  - Access FROM clause attributes
- Different types of nesting
  - Scalar subquery
  - Existential quantification
  - Universal quantification

Nested Subqueries Semantics

- For each tuple produced by the FROM clause execute the subquery
  - If correlated attributes replace them with tuple values

Scalar subquery

- Subquery that returns one result tuple
  - How to check?
  - -> Runtime error

```
SELECT *
FROM R
WHERE R.a = (SELECT count(*) FROM S)
```

Existential Quantification

- `<expr> IN <subquery>`
  - Evaluates to true if <expr> equal to at least one of the results of the subquery

```
SELECT *
FROM users
WHERE name IN (SELECT name FROM
                        blacklist)
```

Existential Quantification

- `EXISTS <subquery>`
  - Evaluates to true if <subquery> returns at least one tuple

```
SELECT *
FROM users u
WHERE EXISTS (SELECT * FROM
               blacklist b
              WHERE b.name = u.name)
```

Existential Quantification

- `<expr> <op> ANY <subquery>`
  - Evaluates to true if <expr> <op> <tuple> evaluates to true for **at least one** result tuple
  - Op is any comparison operator: =, <, >, …

```
SELECT *
FROM users
WHERE name = ANY (SELECT name FROM
                     blacklist)
```

Universal Quantification

- `<expr> <op> ALL <subquery>`
  - Evaluates to true if <expr> <op> <tuple> evaluates to true for **all** result tuples
  - Op is any comparison operator: =, <, >, …

```
SELECT *
FROM nation
WHERE nname = ALL (SELECT nation FROM
                                blacklist)
```

Nested Subqueries Example

```
SELECT dep,name
FROM employee e
WHERE salary >= ALL (SELECT salary
                     FROM employee d
                     WHERE e.dep = d.dep)
```

employee

name	dep	salary
Joe	IT	2000
Jim	IT	300
Bob	HR	100
Alice	HR	10000
Patrice	HR	10000

result

dep	Name
IT	Joe
HR	Alice
HR	Patrice

GROUP BY clause

- A list of expressions
  - Same as WHERE
  - No restriction to boolean
  - DBMS has to know how to compare = for data type
- Results are grouped by values of the expressions
- -> usually used for aggregation

GROUP BY restrictions

- If group-by is used then
  - SELECT clause can only use group by expressions or aggregation functions

GROUP BY clause examples

`GROUP BY R.a`

-group on single attribute

`GROUP BY (1+2)`

-allowed but useless (single group)

`GROUP BY salary / 1000`

-groups of salary values in buckets of 1000

`GROUP BY R.a, R.b`

-group on two attributes

```
SELECT count(*) AS numP,
     (SELECT count(*)
     FROM friends o
     WHERE o.with = f.name) AS numF
FROM (SELECT DISTINCT name FROM friends) f
GROUP BY (SELECT count(*)
         FROM friends o
         WHERE o.with = f.name)
```

friends

name	with
Joe	Jim
Joe	Peter
Jim	Joe
Jim	Peter
Peter	Joe

result

numP	numF
1	1
2	2

HAVING clause

- A boolean expression
- Applied after grouping and aggregation
  - Only references aggregation expressions and group by expressions

HAVING clause examples

…

```
HAVING sum(R.a) > 100
```

-only return tuples with sum bigger than 100

…

```
GROUP BY dep
```

HAVING dep = ‘IT’ AND sum(salary) > 1000000

-only return group ‘IT’ and sum threshold

ORDER BY clause

- A list of expressions
- Semantics: Order the result on these expressions

ORDER BY clause examples

```
ORDER BY R.a ASC
ORDER BY R.a
```

-order ascending on R.a

```
ORDER BY R.a DESC
```

-order descending on R.a

```
ORDER BY salary + bonus
```

-order by sum of salary and bonus

New and Non-standard SQL features (excerpt)

- LIMIT / OFFSET
  - Only return a fix maximum number of rows
  - FETCH FIRST n ROWS ONLY (DB2)
  - row_number() (Oracle)
- Window functions
  - More flexible grouping
  - Return both aggregated results and input values

Parsing, Analysis, Conversion

1. Parsing
2. Analysis
3. Conversion

Analysis Goals

- Semantic checks
  - Table column exists
  - Operator, function exists
  - Determine type casts
  - Scope checks
- Rewriting
  - Unfolding views

Semantic checks

```
SELECT *
FROM R
WHERE R.a + 3 > 5
```

- Table R exists?
- Expand ∗: which attributes in R?
- R.a is a column?
- Type of constants 3, 5?
- Operator + for types of R.a and 3 exists?
- Operator > for types of result of + and 5 exists?

Database Catalog

- Stores information about database objects
- Aliases:
  - Information Schema
  - System tables
  - Data Dictionary

Typical Catalog Information

- Tables
  - Name, attributes + data types, constraints
- Schema, DB
  - Hierarchical structuring of data
- Data types
  - Comparison operators
  - physical representation
  - Functions to (de)serialize to string

Typical Catalog Information

- Functions (including aggregate/set)
  - Build-in
  - User defined (UDF)
- Triggers
- Stored Procedures
- …

Type Casts

- Similar to automatic type conversion in programming languages
- Expression: R.a + 3.0
  - Say R.a is of type integer
    - Search for a function +(int,float)
  - Does not exist?
    - Try to find a way to cast R.a, 3.0 or both to new data type
    - So that a function + exists for new types

Scope checks

- Check that references are in correct scope
- E.g., if GROUP BY is present then SELECT clause expression can only reference group by expressions or aggregated values

View Unfolding

- SQL allows for stored queries using CREATE VIEW
- Afterwards a view can be used in queries
- If view is not materialized, then need to replace view with its definition

View Unfolding Example

```
CREATE VIEW totalSalary AS
SELECT name, salary + bonus AS total
FROM employee

SELECT *
FROM totalSalary
WHERE total > 10000
```

View Unfolding Example

```
CREATE VIEW totalSalary AS
SELECT name, salary + bonus AS total
FROM employee

SELECT *
FROM (SELECT name,
             salary + bonus AS total
     FROM employee) AS totalSalary
WHERE total > 10000
```

Analysis Summary

- Perform semantic checks
  - Catalog lookups (tables, functions, types)
  - Scope checks
- View unfolding
- Generate internal representation during analysis

Parsing, Analysis, Conversion

1. Parsing
2. Analysis
3. Conversion

Conversion

- Create an internal representation
  - Should be useful for analysis
  - Should be useful optimization
- Internal representation
  - Relational algebra
  - Query tree/graph models
    - E.g., QGM (Query Graph Model) in Starburst

Relational Alegbra

- Formal language
- Good for studying logical optimization and query equivalence (containment)
- Not informative enough for analysis
  - No datatype representation in algebra expressions
  - No meta-data

Other Internal Representations

- Practical implementations
  - Mostly following structure of SQL query blocks
  - Store data type and meta-data (where necessary)

Canonical Translation to Relational Algebra

- TEXTBOOK version of conversion
- Given an SQL query
- Return an equivalent relational algebra expression

Relational Algebra Recap

- Formal query language
- Consists of operators
  - Input(s): relation
  - Output: relation
  - -> Composable
- Set and Bag semantics version

- Relation Schema
  - A set of attribute name-datatype pairs
- Relation (instance)
  - A (multi-)set of tuples with the same schema
- Tuple
  - List of attribute value pairs (or function from attribute name to value)

Set- vs. Bag semantics

- Set semantics:
  - Relations are Sets
  - Used in most theoretical work
- Bag semantics
  - Relations are Multi-Sets
    - Each element (tuple) can appear more than once
  - SQL uses bag semantics

Bag semantics notation

- We use **t^m** to denote tuple t appears with multiplicity **m**

Set- vs. Bag semantics

Set

Name	**Purchase**
Peter	Guitar
Joe	Drum
Alice	Bass

Bag

Name	**Purchase**
Peter	Guitar
Peter	Guitar
Joe	Drum
Alice	Bass
Alice	Bass

Operators

- Selection
- Renaming
- Projection
- Joins
  - Theta, natural, cross-product, outer, anti
- Aggregation
- Duplicate removal
- Set operations

Selection

- Syntax: σ_c (R)
  - R is input
  - C is a condition
- Semantics:
  - Return all tuples that match condition C
  - Set: $\{ t \mid t \, \varepsilon R$ AND t fulfills C $\}$
  - Bag: $\{ t^n \mid t^n \varepsilon R$ AND t fulfills C $\}$

Selection Example

- $\sigma_{a>5}$ (R)

R

a	b
1	13
3	12
6	14

Result

a	b
6	14

Renaming

- Syntax: ρ_A (R)
  - R is input
  - A is list of attribute renamings b ← a
- Semantics:
  - Applies renaming from A to inputs
  - Set: $\{ t.A \mid t \varepsilon R \}$
  - Bag: $\{ (t.A)^n \mid t^n \varepsilon R \}$

Renaming Example

- $\rho_{c \leftarrow a}$ (R)

R

a	b
1	13
3	12
6	14

Result

c	b
1	13
3	12
6	14

Projection

- Syntax: $\Pi_A(R)$
  - R is input
  - A is list of projection expressions
  - Standard: only attributes in A
- Semantics:
  - Project all inputs on projection expressions
  - Set: $\{ t.A \mid t \varepsilon R \}$
  - Bag: $\{ (t.A)^n \mid t^n \varepsilon R \}$

Projection Example

- Π_b (R)

R

a	b
1	13
3	12
6	14

Result

b
13
12
14

Cross Product

- Syntax: R X S
  - R and S are inputs
- Semantics:
  - All combinations of tuples from R and S
  - = mathematical definition of cross product
  - Set: { (t,s) | t εR AND sεS }
  - Bag: { $(t,s)^{n*m}$ | t^{n}εR AND s^{m}εS }

Cross Product Example

- R X S

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
1	13	a	5
1	13	b	3
1	13	c	4
3	12	a	5
3	12	b	3
3	12	c	4

Join

- Syntax: $R \bowtie_C S$
  - R and S are inputs
  - C is a condition
- Semantics:
  - All combinations of tuples from R and S that match C
  - Set: { (t,s) | t εR AND sεS AND (t,s) matches C}
  - Bag: { $(t,s)^{n*m}$ | t^nεR AND s^mεS AND (t,s)
    matches C}

Join Example

- $R \bowtie_{a=d} S$

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
3	12	b	3

Natural Join

- Syntax: R $\bowtie$ S
  - R and S are inputs
- Semantics:
  - All combinations of tuples from R and S that match on common attributes
  - A = common attributes of R and S
  - C = exclusive attributes of S
  - Set: { (t,s.C) | t εR AND sεS AND t.A=s.A}
  - Bag: { $(t,s.C)^{n*m}$ | t^nεR AND s^mεS AND t.A=s.A}

Natural Join Example

- $R \bowtie S$

R

a	b
1	13
3	12

S

c	a
a	5
b	3
c	4

Result

a	b	c
3	12	b

Left-outer Join

- Syntax: $R ⟕_{C} S$
  - R and S are inputs
  - C is condition
- Semantics:
  - R join S
  - t εR without match, fill S attributes with NULL

{ (t,s) | t εR AND sεS AND (t,s) matches C}

union

{ (t, NULL(S)) | t εR AND NOT exists sεS: (t,s) matches C }

Left-outer Join Example

- $R ⟕_{a=d} S$

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
1	13	NULL	NULL
3	12	b	3

Right-outer Join

- Syntax: $R ⟖_{C} S$
  - R and S are inputs
  - C is condition
- Semantics:
  - R join S
  - s εS without match, fill R attributes with NULL

{ (t,s) | t εR AND sεS AND (t,s) matches C}

union

{ (NULL(R),s) | s εS AND NOT exists tεR: (t,s) matches C }

Right-outer Join Example

- $R \rtimes\!\!\!\lhd_{a=d} S$

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
NULL	NULL	a	5
3	12	b	3
NULL	NULL	c	4

Full-outer Join

- Syntax: R $⟗_C$ S
  - R and S are inputs and C is condition
- Semantics:

  { (t,s) | t εR AND sεS AND (t,s) matches C}

  union

  { (NULL(R),s) | s εS AND NOT exists tεR: (t,s) matches C }

  union

  { (t, NULL(S)) | t εR AND NOT exists sεS: (t,s) matches C }

Full-outer Join Example

- $R ⟗_{a=d} S$

R

a	b
1	13
3	12

S

c	d
a	5
b	3
c	4

Result

a	b	c	d
1	13	NULL	NULL
NULL	NULL	a	5
3	12	b	3
NULL	NULL	c	4

Semijoin

- Syntax: $R \ltimes S$ and $R \rtimes S$
  - R and S are inputs
- Semantics:
  - All tuples from R that have a matching tuple from relation S on the common attributes A

{ t | t εR AND exists sεS: t.A = s.A}

Semijoin Example

- R ⋉ S

R

a	b
1	13
3	12

S

c	a
a	5
b	3
c	4

Result

a	b
3	12

Antijoin

- Syntax: $R \triangleright S$
  - R and S are inputs
- Semantics:
  - All tuples from R that have no matching tuple from relation S on the common attributes A

{ t | t εR AND NOT exists sεS: t.A = s.A}

Antijoin Example

- R ▷ S

R

a	b
1	13
3	12

S

c	a
a	5
b	3
c	4

Result

a	b
1	13

Aggregation

- Syntax: $_{G}\alpha_{A}$ (R)
  - A is list of aggregation functions
  - G is list of group by attributes
- Semantics:
  - Build groups of tuples according G and compute the aggregation functions from each group
  - $\{ (t.G, agg(G(t)) \mid t \varepsilon R \}$
  - $G(t) = \{ t' \mid t' \varepsilon R \text{ AND } t'.G = t.G \}$

Aggregation Example

- ${}_{b}\alpha_{sum(a)}\ (R)$

R

a	b
1	1
3	1
6	2
3	2

Result

sum(a)	b
4	1
9	2

Duplicate Removal

- Syntax: $\delta(R)$
  - R is input
- Semantics:
  - Remove duplicates from input
  - Set: N/A
  - Bag: $\{ t^1 \mid t^n \varepsilon R \}$

Duplicate Removal Example

- $\delta(R)$

R

a	b
1	13
1	13
6	14

Result

a	b
1	13
6	14

Set operations

- Input: R and S
  - Have to have the same schema
    - Union compatible
  - Modulo attribute names
- Types
  - Union
  - Intersection
  - Set difference

Union

- Syntax: R ∪ S
  - R and S are union-compatible inputs
- Semantics:
  - Set: { (t) | t εR OR tεS}
  - Bag: { $(t,s)^{n+m}$ | t^nεR AND s^mεS }
    - Assumption t^n with n < 1 for tuple not in relation

Union Example

- R ∪ S

R

a
1
3

S

b
1
2
3

Result

a
1
2
3
1
3

Intersection

- Syntax: $R \cap S$
  - R and S are union-compatible inputs
- Semantics:
  - Set: $\{ (t) \mid t \varepsilon R \text{ AND } t \varepsilon S \}$
  - Bag: $\{ (t,s)^{min(n,m)} \mid t^n \varepsilon R \text{ AND } s^m \varepsilon S \}$

Intersection Example

- R ∩ S

R

a
1
3

S

b
1
2
3

Result

a
1
3

Set Difference

- Syntax: R - S
  - R and S are union-compatible inputs
- Semantics:
  - Set: { (t) | t εR AND NOT tεS}
  - Bag: { $(t,s)^{n - m}$ | t^nεR AND s^mεS }

Set Difference Example

- R - S

R

a
1
5

S

b
1
2
3

Result

a
5

Canonical Translation to Relational Algebra

- TEXTBOOK version of conversion
- Given an SQL query
- Return an equivalent relational algebra expression

Canonical Translation

- **FROM** clause into joins and cross-products
  - Cross-product between list items
  - Joins into their algebra counter-part
- **WHERE** clause into selection
- **SELECT** clause into projection and renaming
  - If it has aggregation functions use aggreation
  - **DISTINCT** into duplicate removal

Canonical Translation

- **GROUP BY** clause into aggregation
- **HAVING** clause into selection
- **ORDER BY** – no counter-part

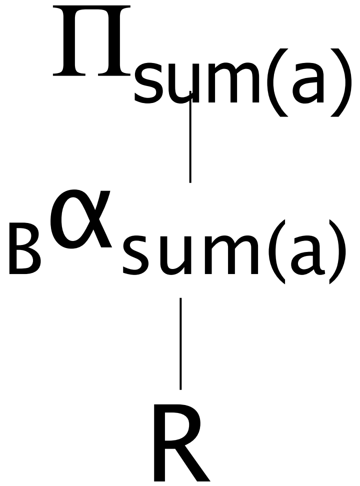
- Then turn joins into crossproducts and selections

Set Operations

- **UNION ALL** into union
- **UNION** duplicate removal over union
- **INTERSECT ALL** into intersection
- **INTERSECT** add duplicate removal
- **EXCEPT ALL** into set difference
- **EXCEPT** apply duplicate removal to inputs and then apply set difference

Example: Relational Algebra Translation

```
SELECT sum(R.a)
FROM R
GROUP BY b
```



$\Pi_{sum(a)}$

${}_{B}\alpha_{sum(a)}$

R

Example: Relational Algebra Translation

```
SELECT dep, headcnt
FROM (SELECT count(*) AS headcnt, dep
      FROM employee
      GROUP BY dep)
WHERE headcnt > 100
```

$$\Pi_{dep,\ headcnt}$$

$$\sigma_{headcnt > 100}$$

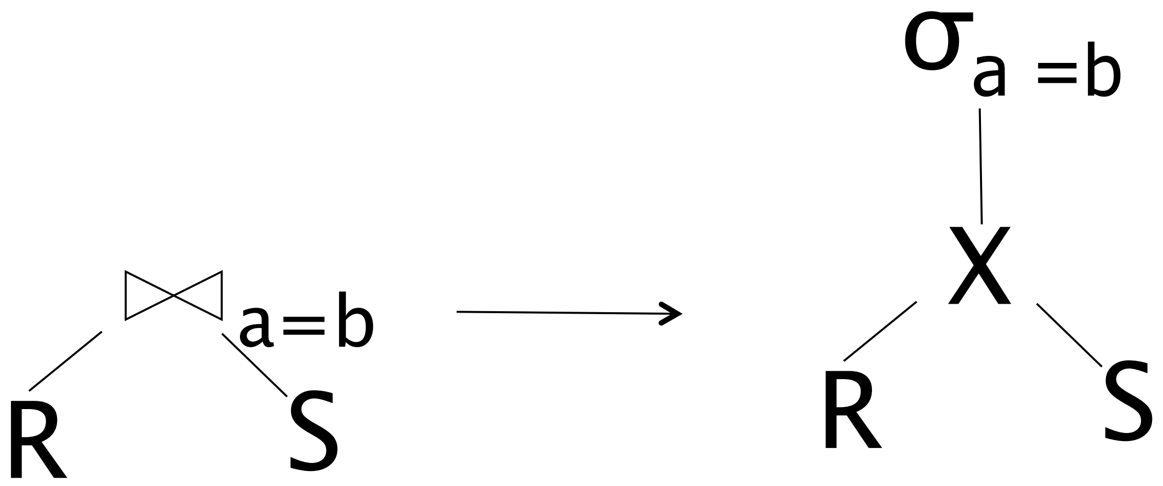
$$\rho_{headcnt \leftarrow count(*)}$$

$${}_{dep}\alpha_{count(*)}$$

$$Employee$$

Example: Relational Algebra Translation

```
SELECT *
FROM R JOIN S ON (R.a = S.b)
```



Parsing and Analysis Summary

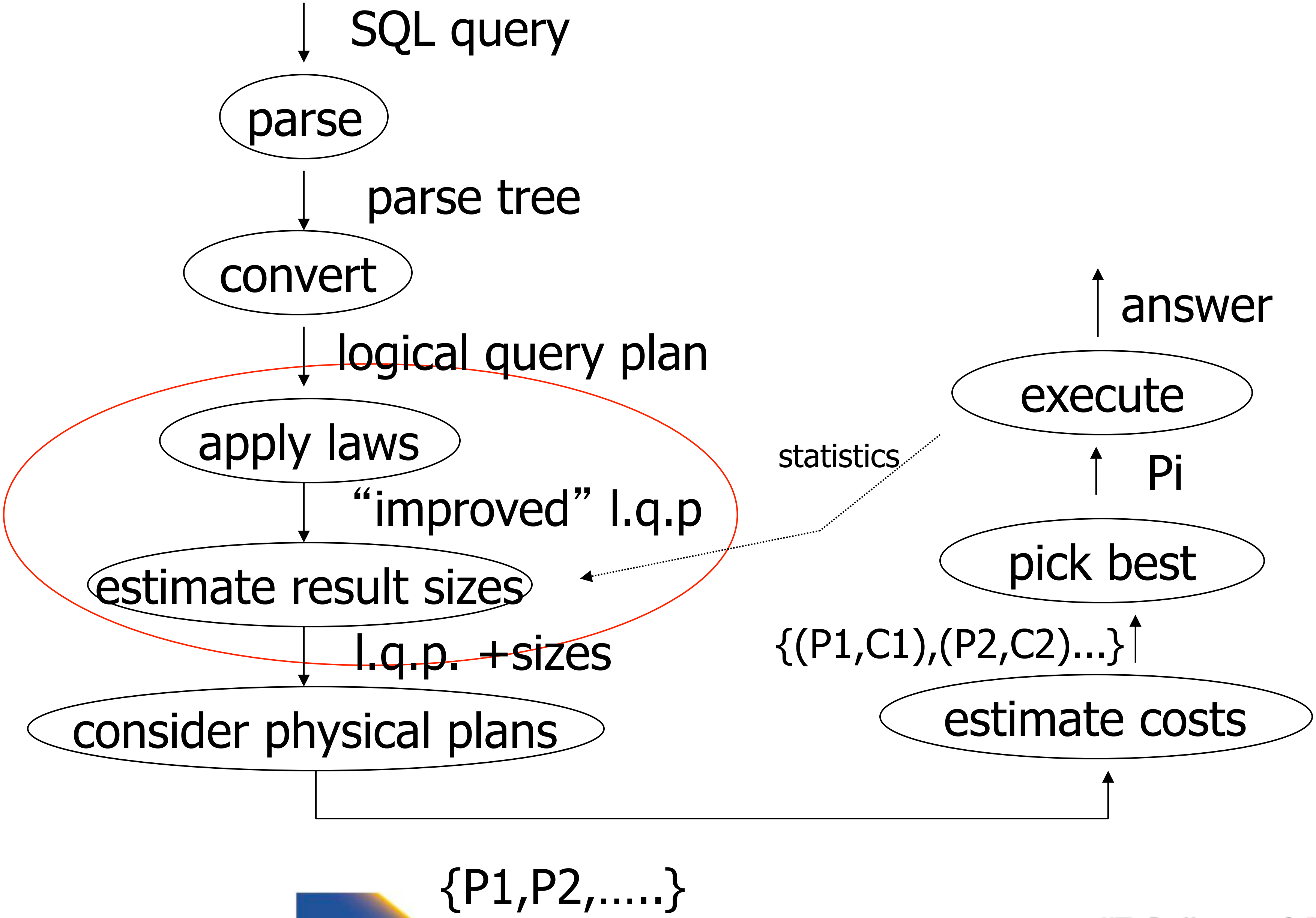
- SQL text -> Internal representation
- Semantic checks
- Database catalog
- View unfolding

CS 525: Advanced Database Organisation

09: Query Optimization - Logical

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab



SQL query

parse

parse tree

convert

logical query plan

apply laws

“improved” l.q.p

estimate result sizes

l.q.p. +sizes

consider physical plans

{P1,P2,…..}

estimate costs

{(P1,C1),(P2,C2)...}

pick best

Pi

execute

answer

statistics

Query Optimization

- Relational algebra level
- Detailed query plan level

Query Optimization

- Relational algebra level
- Detailed query plan level
    - Estimate Costs
        - without indexes
        - with indexes
    - Generate and compare plans

Relational algebra optimization

- Transformation rules
  (preserve equivalence)
- What are good transformations?
  - Heuristic application of transformations

Query Equivalence

- Two queries q and q' are equivalent:
  - If for every database instance I
    - Contents of all the tables
  - Both queries have the same result

$q \equiv q'$ iff $\forall I: q(I) = q'(I)$

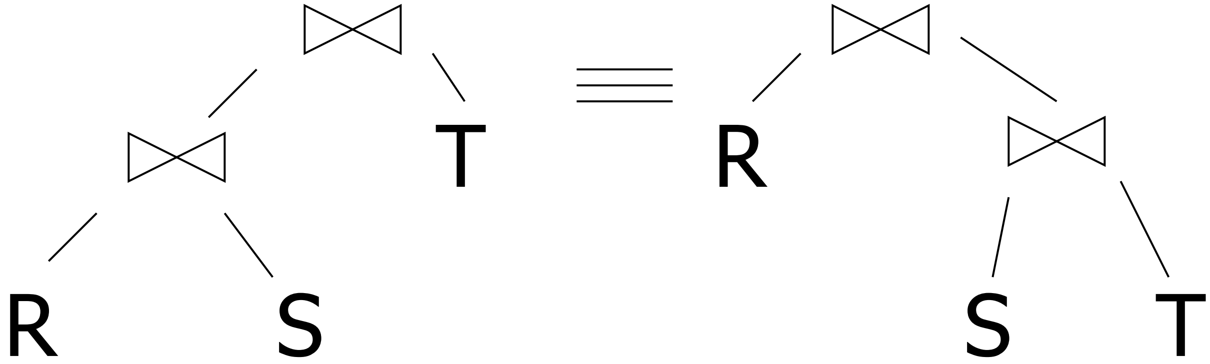
Rules: Natural joins & cross products & union

$R \bowtie S = S \bowtie R$

$(R \bowtie S) \bowtie T = R \bowtie (S \bowtie T)$

Note:

- Carry attribute names in results, so order is not important
- Can also write as trees, e.g.:



Rules: Natural joins & cross products & union

$R \bowtie S = S \bowtie R$

$(R \bowtie S) \bowtie T = R \bowtie (S \bowtie T)$

$R \times S = S \times R$

$(R \times S) \times T = R \times (S \times T)$

$R \cup S = S \cup R$

$R \cup (S \cup T) = (R \cup S) \cup T$

Rules: Selects

$\sigma_{p1 \wedge p2}(R) =$

$\sigma_{p1 \vee p2}(R) =$

Rules: Selects

$\sigma_{p1 \wedge p2}(R) = \quad \sigma_{p1} [\sigma_{p2} (R)]$

$\sigma_{p1 \vee p2}(R) = \quad [\sigma_{p1} (R)] \cup [\sigma_{p2} (R)]$

Bags vs. Sets

R = {a,a,b,b,b,c}

S = {b,b,c,c,d}

RUS = ?

Bags vs. Sets

R = {a,a,b,b,b,c}

S = {b,b,c,c,d}

RUS = ?

- Option 1 SUM

  RUS = {a,a,b,b,b,b,b,c,c,c,d}

- Option 2 MAX

  RUS = {a,a,b,b,b,c,c,d}

Option 2 (MAX) makes this rule work:

$$\sigma_{p1 \vee p2}(R) = \sigma_{p1}(R) \cup \sigma_{p2}(R)$$

Example: R={a,a,b,b,b,c}

P1 satisfied by a,b; P2 satisfied by b,c

Option 2 (MAX) makes this rule work:

$\sigma_{p1 \lor p2}(R) = \sigma_{p1}(R) \cup \sigma_{p2}(R)$

Example: R={a,a,b,b,b,c}

P1 satisfied by a,b; P2 satisfied by b,c

$\sigma_{p1 \lor p2}(R) = \{a,a,b,b,b,c\}$

$\sigma_{p1}(R) = \{a,a,b,b,b\}$

$\sigma_{p2}(R) = \{b,b,b,c\}$

$\sigma_{p1}(R) \cup \sigma_{p2}(R) = \{a,a,b,b,b,c\}$

“Sum” option makes more sense:

Senators (……) Rep (……)

T1 = $\pi_{yr,state}$ Senators; T2 = $\pi_{yr,state}$ Reps

T1

Yr	State
97	CA
99	CA
98	AZ

T2

Yr	State
99	CA
99	CA
98	CA

Union?

Executive Decision

-> Use “SUM” option for bag unions

-> Some rules cannot be used for bags

Rules: Project

Let: X = set of attributes

Y = set of attributes

XY = X U Y

$\pi_{xy}(R) =$

Rules: Project

Let: X = set of attributes

Y = set of attributes

XY = X U Y

$$\pi_{xy}(R) = \pi_{x}[\pi_{y}(R)]$$

Rules: Project

Let: X = set of attributes

Y = set of attributes

$XY = X \cup Y$

$$\pi_{xy}(R) = \xcancel{\pi_x[\pi_y(R)]}$$

Rules: $\sigma + \bowtie$ combined

Let p = predicate with only R attribs

q = predicate with only S attribs

m = predicate with only R,S attribs

$\sigma_p (R \bowtie S) =$

$\sigma_q (R \bowtie S) =$

Rules: $\sigma + \bowtie$ combined

Let p = predicate with only R attribs

q = predicate with only S attribs

m = predicate with only R,S attribs

$$\sigma_p (R \bowtie S) = [\sigma_p (R)] \bowtie S$$

$$\sigma_q (R \bowtie S) = R \bowtie [\sigma_q (S)]$$

Rules: σ + $\bowtie$ combined (continued)

Some Rules can be Derived:

$\sigma_{p \wedge q}$ (R $\bowtie$ S) =

$\sigma_{p \wedge q \wedge m}$ (R $\bowtie$ S) =

$\sigma_{p \vee q}$ (R $\bowtie$ S) =

Do one:

$$\sigma_{p\wedge q}\,(R \bowtie S) = [\sigma_p\,(R)] \bowtie [\sigma_q\,(S)]$$

$$\sigma_{p\wedge q\wedge m}\,(R \bowtie S) =$$

$$\sigma_m \left[(\sigma_p\, R) \bowtie (\sigma_q\, S)\right]$$

$$\sigma_{p\vee q}\,(R \bowtie S) =$$

$$\left[(\sigma_p\, R) \bowtie S\right] \cup \left[R \bowtie (\sigma_q\, S)\right]$$

--> Derivation for first one:

$$\sigma_{p \wedge q} (R \bowtie S) =$$

$$\sigma_p \left[\sigma_q (R \bowtie S) \right] =$$

$$\sigma_p \left[R \bowtie \sigma_q (S) \right] =$$

$$[\sigma_p (R)] \bowtie [\sigma_q (S)]$$

Rules: π, σ combined

Let x = subset of R attributes

z = attributes in predicate P

(subset of R attributes)

$$\pi_x[\sigma_p(R)] =$$

Rules: π,σ combined

Let x = subset of R attributes

z = attributes in predicate P

(subset of R attributes)

$$\pi_x[\sigma_p(R)] = \{\sigma_p[\pi_x(R)]\}$$

Rules: π,σ combined

Let x = subset of R attributes

z = attributes in predicate P (subset of R attributes)

$$\pi_x[\sigma_p(R)] = \pi_x\{\sigma_p[\overset{\pi_{xz}}{\cancel{\pi_x}}(R)]\}$$

Rules: $\pi, \bowtie$ combined

Let x = subset of R attributes

y = subset of S attributes

z = intersection of R,S attributes

$\pi_{xy}(R \bowtie S) =$

Rules: π, $\bowtie$ combined

Let x = subset of R attributes

y = subset of S attributes

z = intersection of R,S attributes

$$\pi_{xy}(R \bowtie S) =$$

$$\pi_{xy}\{[\pi_{xz}(R)] \bowtie [\pi_{yz}(S)]\}$$

$$\pi_{xy}\left\{\sigma_p\ (R \bowtie S)\right\} \quad =$$

$$\pi_{xy}\left\{\sigma_p\ (R \bowtie S)\right\} =$$

$$\pi_{xy}\left\{\sigma_p\ [\pi_{xz'}\ (R) \bowtie \pi_{yz'}\ (S)]\right\}$$

$$z' = z \cup \{\text{attributes used in } P\}$$

Rules for σ, π combined with X

similar...

e.g., $\sigma_p (R \times S) = ?$

Rules σ, U combined:

$\sigma_p(R \cup S) = \sigma_p(R) \cup \sigma_p(S)$

$\sigma_p(R - S) = \sigma_p(R) - S = \sigma_p(R) - \sigma_p(S)$

Which are "good" transformations?

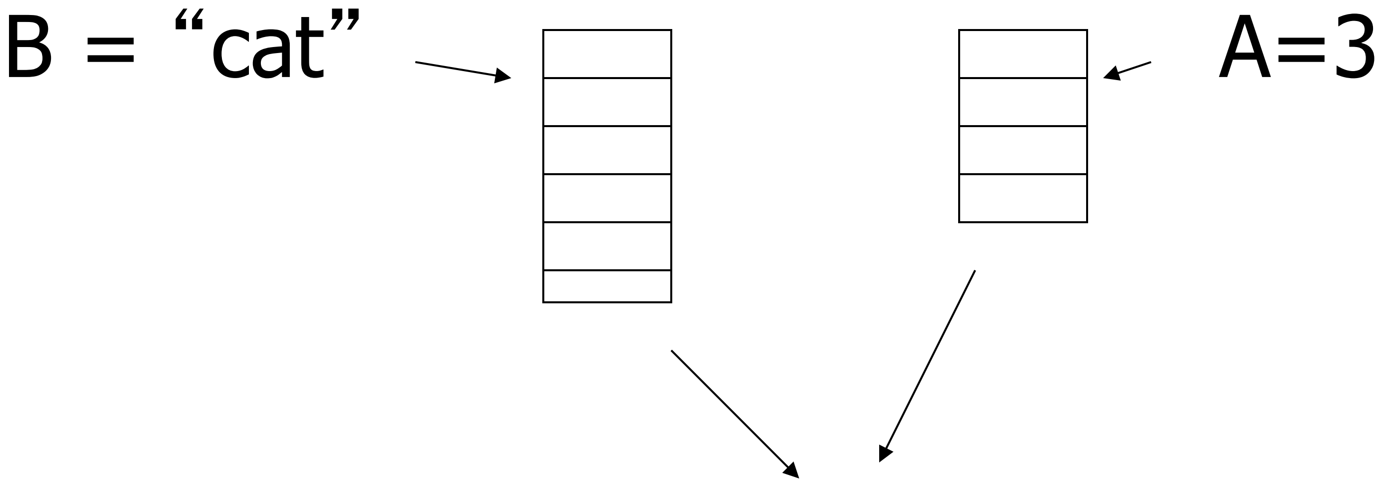
- ☐ $\sigma_{p1 \wedge p2} (R) \rightarrow \sigma_{p1} [\sigma_{p2} (R)]$
- ☐ $\sigma_{p} (R \bowtie S) \rightarrow [\sigma_{p} (R)] \bowtie S$
- ☐ $R \bowtie S \rightarrow S \bowtie R$
- ☐ $\pi_{x} [\sigma_{p} (R)] \rightarrow \pi_{x} \{\sigma_{p} [\pi_{xz} (R)]\}$

Conventional wisdom:
do projects early

Example: R(A,B,C,D,E) x={E}
P: (A=3) ∧ (B="cat")

$\pi_x \{\sigma_p\ (R)\}$ vs. $\pi_E \left\{\sigma_p\{\pi_{ABE}(R)\}\right\}$

$\boxed{\text{But}}$ What if we have A, B indexes?



Intersect pointers to get
pointers to matching tuples
e.g., using bitmaps

Bottom line:

- No transformation is always good
- Usually good: early selections
  - Exception: expensive selection conditions
  - E.g., UDFs

More transformations

- Eliminate common sub-expressions
- Detect constant expressions
- Other operations: duplicate elimination

Pushing Selections

- Idea:
  - Join conditions equate attributes
  - For parts of algebra tree (scope) store which attributes have to be the same
    - Called Equivalence classes
- Example: R(a,b), S(c,d)

$$\sigma_{b=3}(R \bowtie_{b=c} S) = \sigma_{b=3}(R) \bowtie_{b=c} \sigma_{c=3}(S)$$

Outer-Joins

- Not commutative
  - $R ⟕ S \neq S ⟕ R$
- p – condition over attributes in A
- A list of attributes from R

$\sigma_p (R ⟕_{A=B} S) \equiv \sigma_p (R) ⟕_{A=B} S$

Not $\sigma_p (R ⟕_{A=B} S) \equiv R ⟕_{A=B} \sigma_p (S)$

Summary Equivalences

- Associativity: $(R \odot S) \odot T \equiv R \odot (S \odot T)$
- Commutativity: $R \odot S \equiv S \odot R$
- Distributivity: $(R \odot S) \otimes T \equiv (R \otimes T) \odot (S \otimes T)$
- Difference between Set and Bag Equivalences
- Only some equivalence are useful

Outline - Query Processing

- Relational algebra level
  - – transformations
  - – good transformations
- Detailed query plan level
  - – estimate costs
  - – generate and compare plans

- Estimating cost of query plan

(1) Estimating <u>size</u> of results

(2) Estimating # of IOs

Estimating result size

- Keep statistics for relation R
  - T(R) : # tuples in R
  - S(R) : # of bytes in each R tuple
  - B(R): # of blocks to hold all R tuples
  - V(R, A) : # distinct values in R for attribute A

Example

R

A	B	C	D
cat	1	10	a
cat	1	20	b
dog	1	30	a
dog	1	40	c
bat	1	50	d

A: 20 byte string

B: 4 byte integer

C: 8 byte date

D: 5 byte string

Example

R

A	B	C	D
cat	1	10	a
cat	1	20	b
dog	1	30	a
dog	1	40	c
bat	1	50	d

A: 20 byte string

B: 4 byte integer

C: 8 byte date

D: 5 byte string

T(R) = 5 S(R) = 37

V(R,A) = 3 V(R,C) = 5

V(R,B) = 1 V(R,D) = 4

Size estimates for W = R1 x R2

T(W) =

S(W) =

Size estimates for W = R1 x R2

$T(W) = T(R1) \times T(R2)$

$S(W) = S(R1) + S(R2)$

Size estimate for W = $\sigma_{A=a}$ (R)

S(W) = S(R)

T(W) = ?

Example

R

A	B	C	D
cat	1	10	a
cat	1	20	b
dog	1	30	a
dog	1	40	c
bat	1	50	d

$V(R,A)=3$

$V(R,B)=1$

$V(R,C)=5$

$V(R,D)=4$

$W = \sigma_{z=val}(R)$ $T(W) =$

Example

R

A	B	C	D
cat	1	10	a
cat	1	20	b
dog	1	30	a
dog	1	40	c
bat	1	50	d

$V(R,A)=3$

$V(R,B)=1$

$V(R,C)=5$

$V(R,D)=4$

$$W = \sigma_{z=val}(R) \qquad T(W) = \frac{T(R)}{V(R,Z)}$$

Assumption:

Values in select expression Z = val
are uniformly distributed
over possible V(R,Z) values.

Alternate Assumption:

Values in select expression Z = val
are uniformly distributed
over domain with DOM(R,Z) values.

Example

R

A	B	C	D
cat	1	10	a
cat	1	20	b
dog	1	30	a
dog	1	40	c
bat	1	50	d

Alternate assumption

V(R,A)=3 DOM(R,A)=10

V(R,B)=1 DOM(R,B)=10

V(R,C)=5 DOM(R,C)=10

V(R,D)=4 DOM(R,D)=10

$W = \sigma_{z=val}(R) \quad T(W) = ?$

C=val ⇒ T(W) = (1/10)1 + (1/10)1 + ...
= (5/10) = 0.5

B=val ⇒ T(W)= (1/10)5 + 0 + 0 = 0.5

A=val ⇒ T(W)= (1/10)2 + (1/10)2 + (1/10)1
= 0.5

Example

R

A	B	C	D
cat	1	10	a
cat	1	20	b
dog	1	30	a
dog	1	40	c
bat	1	50	d

Alternate assumption

V(R,A)=3 DOM(R,A)=10

V(R,B)=1 DOM(R,B)=10

V(R,C)=5 DOM(R,C)=10

V(R,D)=4 DOM(R,D)=10

$$W = \sigma_{z=val}(R) \qquad T(W) = \frac{T(R)}{DOM(R,Z)}$$

Selection cardinality

SC(R,A) = average # records that satisfy equality condition on R.A

$$SC(R,A) = \begin{cases} \dfrac{T(R)}{V(R,A)} \\ \\ \dfrac{T(R)}{DOM(R,A)} \end{cases}$$

What about $W = \sigma_{z \geq val}(R)$?

$T(W) = ?$

What about $W = \sigma_{Z \geq val}(R)$?

$T(W) = ?$

- Solution # 1:

  $T(W) = T(R)/2$

What about $W = \sigma_{Z \geq val}(R)$?

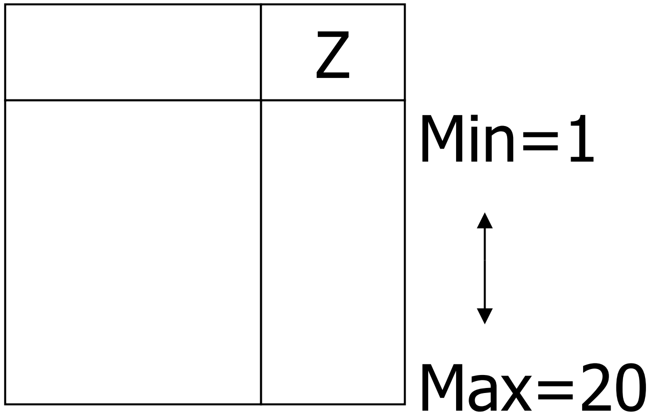
$T(W) = ?$

- Solution # 1:
  $T(W) = T(R)/2$

- Solution # 2:
  $T(W) = T(R)/3$

- Solution # 3: Estimate values in range

<u>Example</u> R

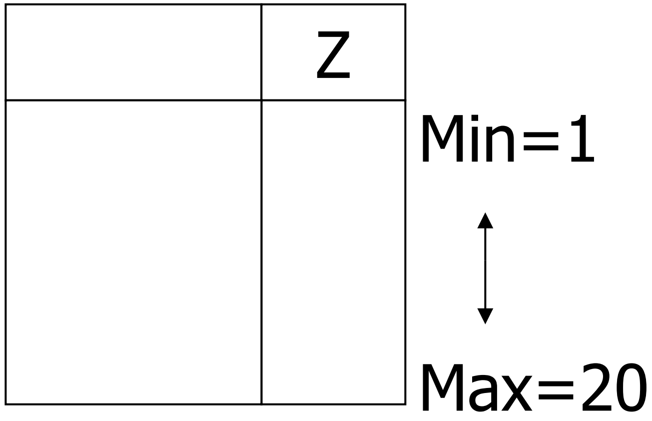


V(R,Z)=10

W= $\sigma_{Z \geq 15}(R)$

- Solution # 3: Estimate values in range

Example R


Z

Min=1

Max=20

$V(R,Z)=10$

$W = \sigma_{Z \geq 15}(R)$

$$f = \frac{20-15+1}{20-1+1} = \frac{6}{20}$$ (fraction of range)

$T(W) = f \times T(R)$

Equivalently:

$f \times V(R,Z)$ = fraction of distinct values

$$T(W) = [f \times V(Z,R)] \times \frac{T(R)}{V(Z,R)} = f \times T(R)$$

Size estimate for W = R1 $\bowtie$ R2

Let x = attributes of R1

y = attributes of R2

Size estimate for W = R1 $\bowtie$ R2

Let x = attributes of R1

y = attributes of R2

Case 1

$$X \cap Y = \emptyset$$

Same as R1 x R2

Case 2

$W = R1 \bowtie R2 \qquad X \cap Y = A$

R1

A	B	C

R2

A	D

Case 2 $W = R1 \bowtie R2$ $X \cap Y = A$

R1

A	B	C

R2

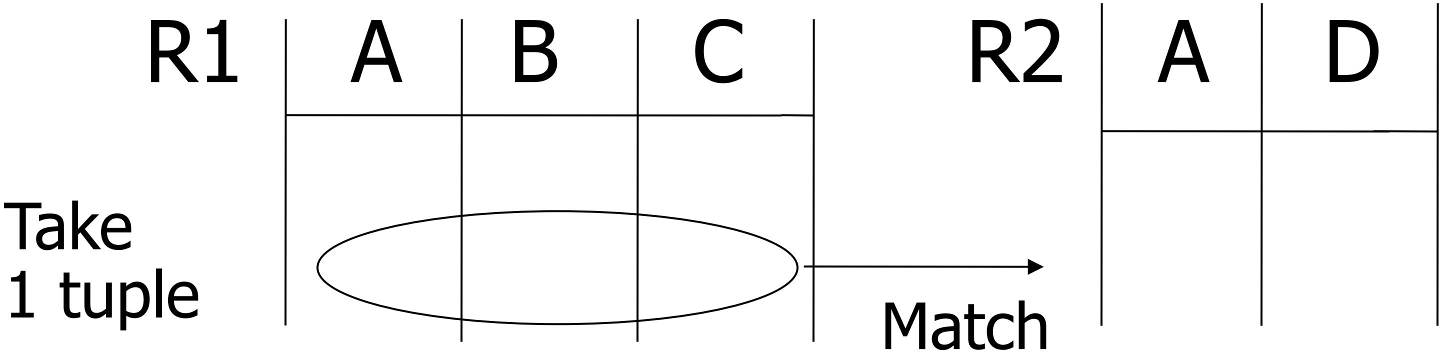
A	D

Assumption:

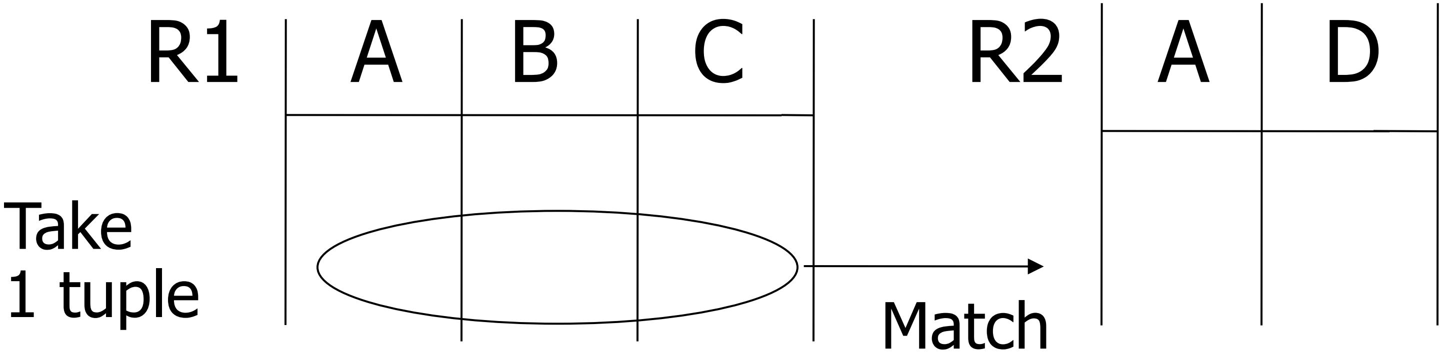
$V(R1,A) \leq V(R2,A) \Rightarrow$ Every A value in R1 is in R2

$V(R2,A) \leq V(R1,A) \Rightarrow$ Every A value in R2 is in R1

Computing T(W) when V(R1,A) ≤ V(R2,A)



Computing T(W) when V(R1,A) ≤ V(R2,A)



1 tuple matches with $\frac{T(R2)}{V(R2,A)}$ tuples...

so $T(W) = \frac{T(R2)}{V(R2, A)} \times T(R1)$

- $V(R1,A) \leq V(R2,A)$ $\quad T(W) = \dfrac{T(R2)\,T(R1)}{V(R2,A)}$

- $V(R2,A) \leq V(R1,A)$ $\quad T(W) = \dfrac{T(R2)\,T(R1)}{V(R1,A)}$

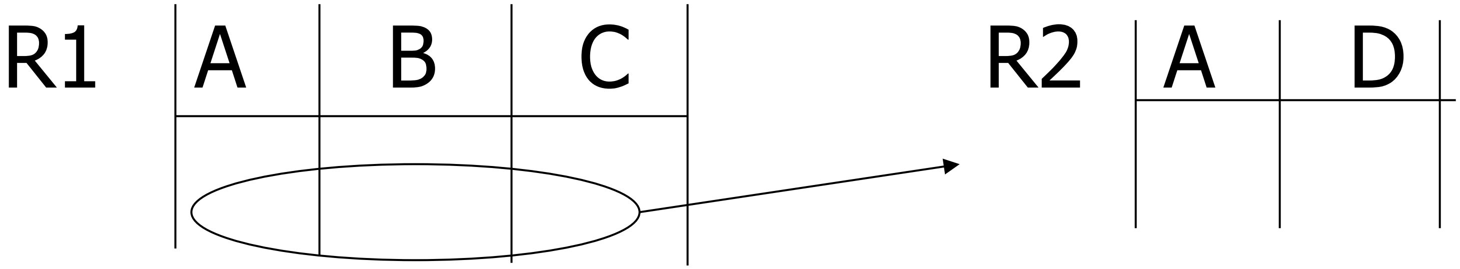
[A is common attribute]

In general $W = R1 \bowtie R2$

$$T(W) = \frac{T(R2)\,T(R1)}{\max\{\,V(R1,A),\ V(R2,A)\,\}}$$

Case 2 with alternate assumption

Values uniformly distributed over domain



This tuple matches T(R2)/DOM(R2,A) so

$$T(W) = \frac{T(R2)\ T(R1)}{DOM(R2, A)} = \frac{T(R2)\ T(R1)}{DOM(R1, A)}$$

Assume the same

In all cases:

$$S(W) = S(R1) + S(R2) - S(A)$$

size of attribute A

Using similar ideas, we can estimate sizes of:

$\Pi_{AB}(R)$

$\sigma_{A=a \wedge B=b}(R)$

$R \bowtie S$ with common attribs. A,B,C

Union, intersection, diff,

<u>Note:</u> for complex expressions, need intermediate T,S,V results.

E.g. $W = \underbrace{[\sigma_{A=a}(R1)]}_{\text{Treat as relation U}} \bowtie R2$

$T(U) = T(R1)/V(R1,A) \qquad S(U) = S(R1)$

Also need V (U, *) !!

To estimate Vs

E.g., $U = \sigma_{A=a}(R1)$

Say R1 has attribs A,B,C,D

$V(U, A) =$

$V(U, B) =$

$V(U, C) =$

$V(U, D) =$

Example

R1

A	B	C	D
cat	1	10	10
cat	1	20	20
dog	1	30	10
dog	1	40	30
bat	1	50	10

V(R1,A)=3

V(R1,B)=1

V(R1,C)=5

V(R1,D)=3

$U = \sigma_{A=a}(R1)$

Example

R1

A	B	C	D
cat	1	10	10
cat	1	20	20
dog	1	30	10
dog	1	40	30
bat	1	50	10

$V(R1,A)=3$

$V(R1,B)=1$

$V(R1,C)=5$

$V(R1,D)=3$

$U = \sigma_{A=a}(R1)$

$V(U,A)=1$ $V(U,B)=1$ $V(U,C) = \frac{T(R1)}{V(R1,A)}$

V(D,U) ... somewhere in between

Possible Guess $U = \sigma_{A=a}(R)$

$V(U,A) = 1$

$V(U,B) = V(R,B)$

For Joins $U = R1(A,B) \bowtie R2(A,C)$

$V(U,A) = \min \{ V(R1, A), V(R2, A) \}$

$V(U,B) = V(R1, B)$

$V(U,C) = V(R2, C)$

Example:

$$Z = R1(A,B) \bowtie R2(B,C) \bowtie R3(C,D)$$

R1	T(R1) = 1000	V(R1,A)=50	V(R1,B)=100
R2	T(R2) = 2000	V(R2,B)=200	V(R2,C)=300
R3	T(R3) = 3000	V(R3,C)=90	V(R3,D)=500

Partial Result: $U = R1 \bowtie R2$

$$T(U) = \frac{1000 \times 2000}{200}$$

$V(U,A) = 50$

$V(U,B) = 100$

$V(U,C) = 300$

$$Z = U \bowtie R3$$

$$T(Z) = \frac{1000 \times 2000 \times 3000}{200 \times 300}$$

$V(Z,A) = 50$

$V(Z,B) = 100$

$V(Z,C) = 90$

$V(Z,D) = 500$

Approximating Distributions

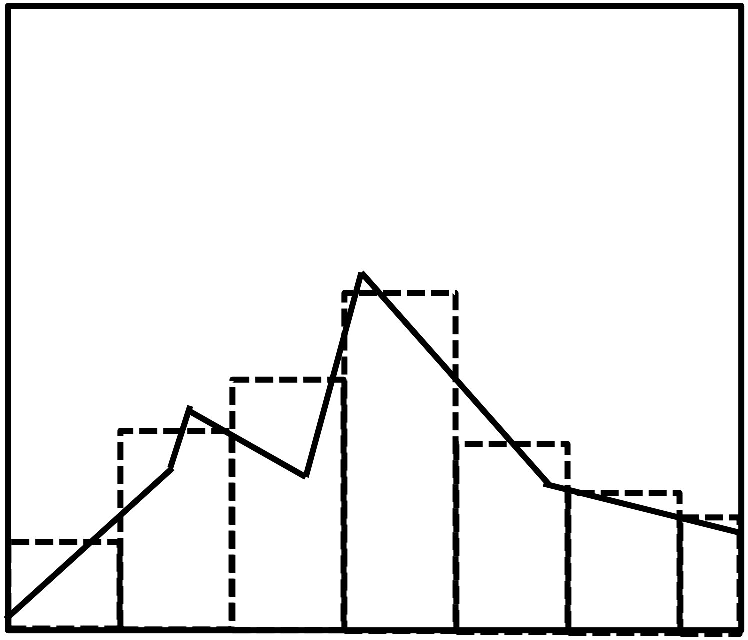
- Summarize the distribution
  - Used to better estimate result sizes
  - Without the need to look at all the data
- Concerns
  - Error metric: How to measure preciseness
  - Memory consumption
  - Computational Complexity

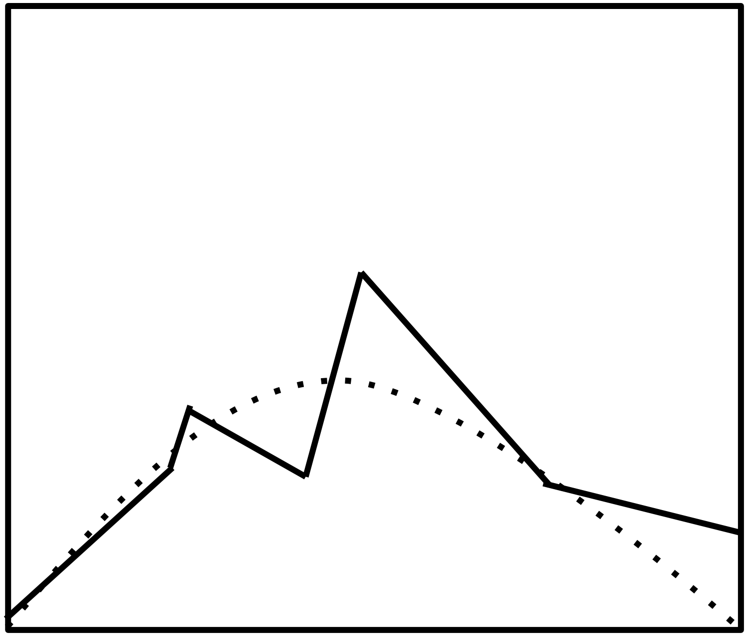
Approximating Distributions

- Parameterized distribution
  - E.g., gauss distribution
  - Adapt parameters to fit data
- Histograms
  - Divide domain into ranges (buckets)
  - Store the number of tuples per bucket
- Both need to be maintained

Histograms

Parameterized Distribution

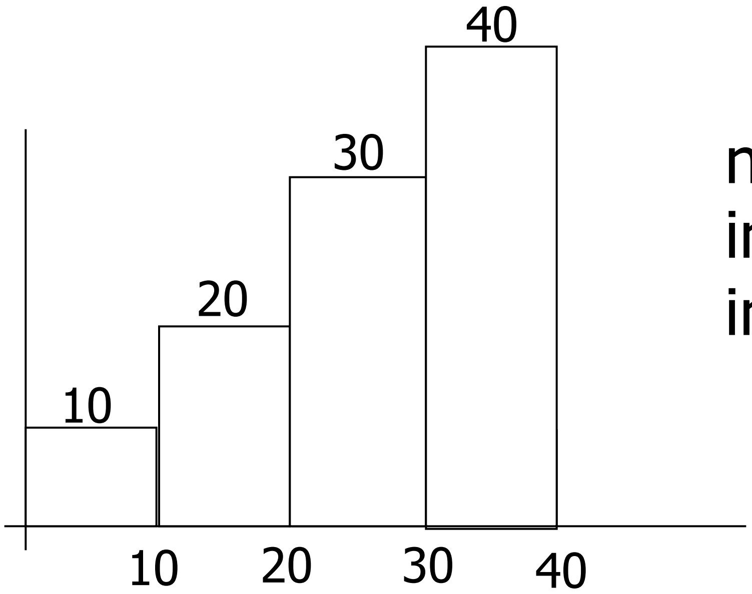




Maintaining Statistics

- Use separate command that triggers statistics collection
  - Postgres: `ANALYZE`
- During query processing
  - Overhead for queries
- Use Sampling?

Estimating Result Size using Histograms



number of tuples in R with A value in given range

$\sigma_{A=val}(R) = ?$

Estimating Result Size using Histograms

- $\sigma_{A=val}(R) = ?$
- |B| - number of values per bucket
- #B – number of records in bucket

$$\frac{\#B}{|B|}$$

Join Size using Histograms

- R ⋈ S
- Use

$$T(W) = \frac{T(R2)\,T(R1)}{\max\{\,V(R1,A),\,V(R2,A)\,\}}$$

- Apply for each bucket

Join Size using Histograms

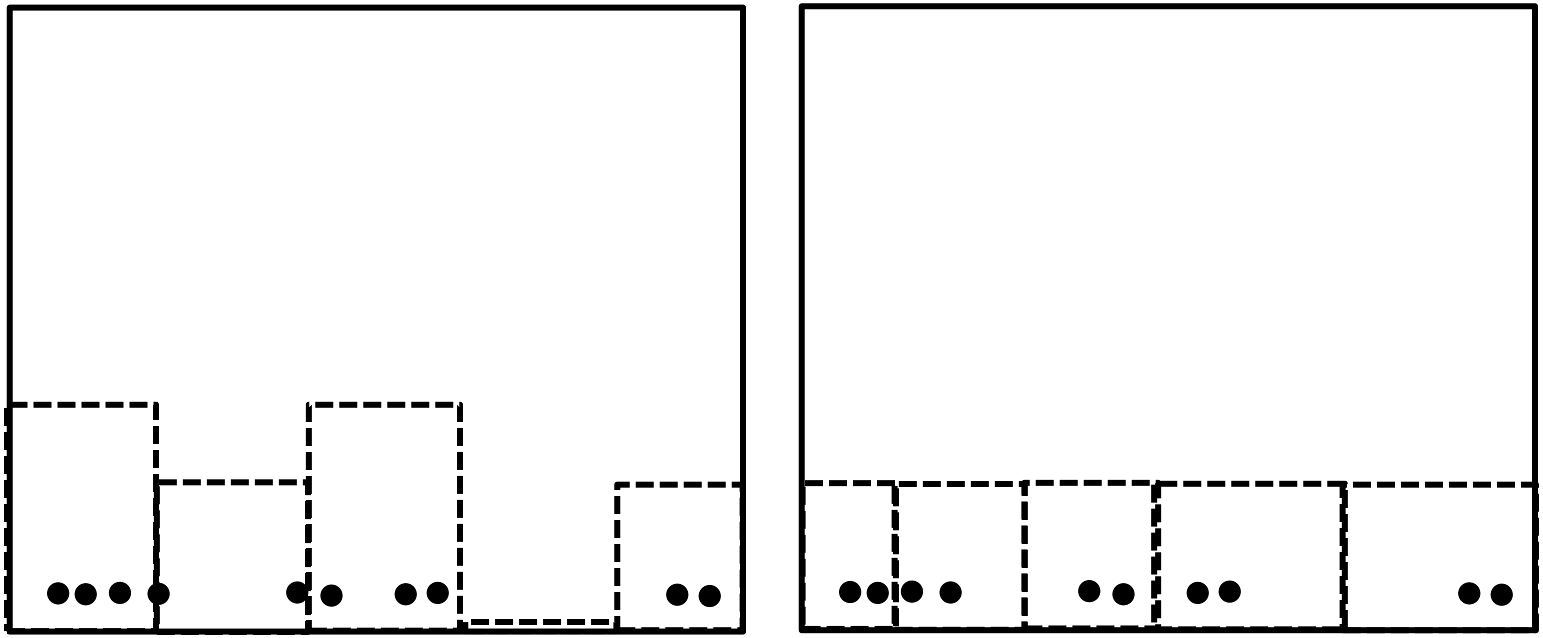
- V(R1,A) = V(R2,A) = bucket size |B|

$$T(W) = \sum_{\text{buckets}} \frac{\#B(R2)\ \#B(R1)}{|B|}$$

Equi-width vs. Equi-depth

- Equi-width
  - All buckets contain the same number of values
  - Easy, but inaccurate
- Equi-depth (used by most DBMS)
  - All buckets contain the same number of tuples
  - Better accuracy, need to sort data to compute

Equi-width vs. Equi-depth



Construct Equi-depth Histograms

- Sort input
- Determine size of buckets
  - #bucket / #tuples
- Example 3 buckets

1, 5,44, 6,10,12, 3, 6, 7

1, 3, 5, 6, 6, 7,10,12,44

[1–5] [6–8] [9–44]

Advanced Techniques

- Wavelets
- Approximate Histograms
- Sampling Techniques
- Compressed Histograms

Summary

- Estimating size of results is an "art"

- Don't forget:

  Statistics must be kept up to date…

  (cost?)

Outline

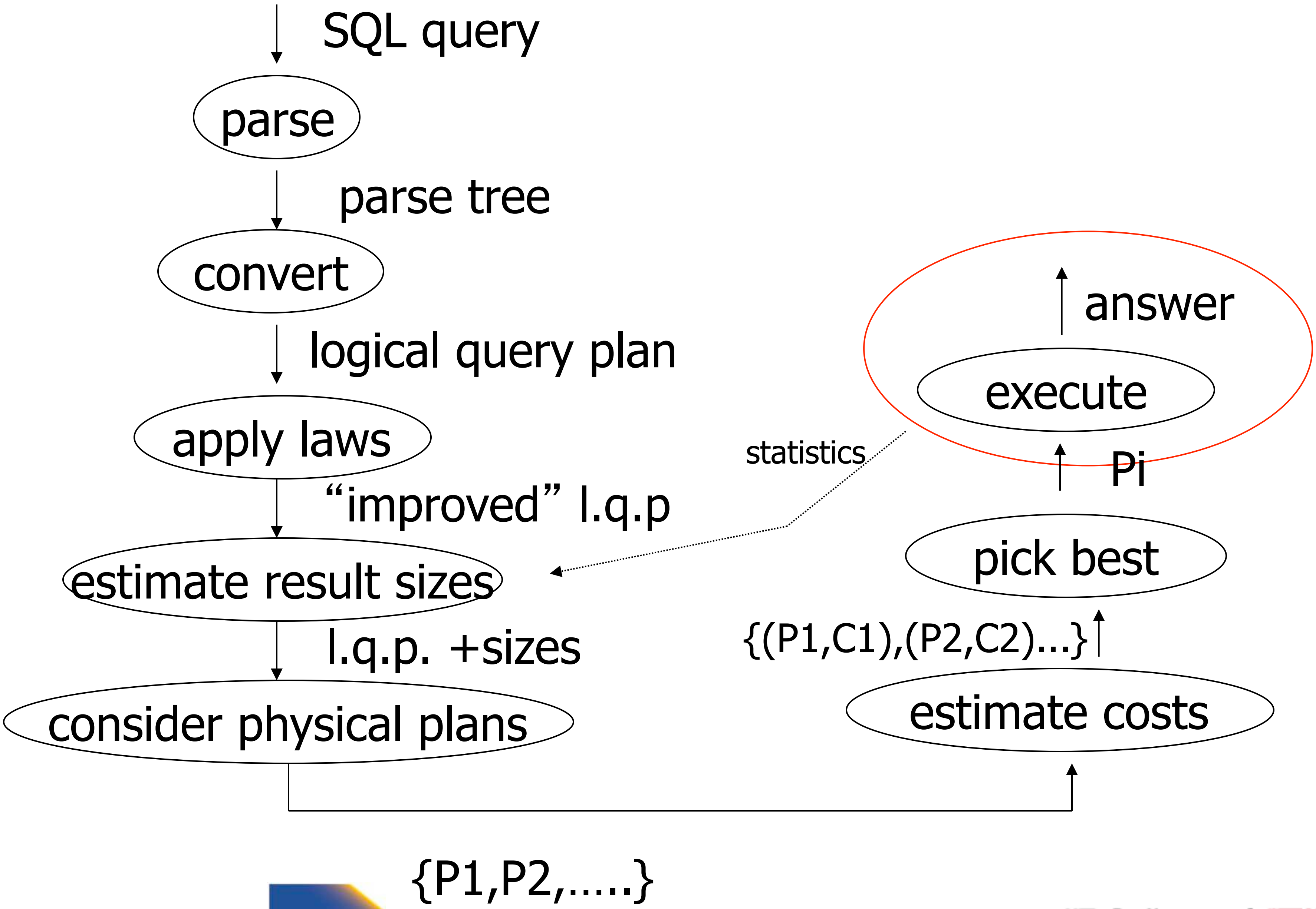
- Estimating cost of query plan
  - Estimating size of results ← done!
  - Estimating # of IOs ← next…
  - Operator Implementations
- Generate and compare plans

CS 525: Advanced Database Organization

10: Query Execution

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab


SQL query
parse
parse tree
convert
logical query plan
apply laws
"improved" l.q.p
estimate result sizes
l.q.p. +sizes
consider physical plans
{P1,P2,…..}
estimate costs
{(P1,C1),(P2,C2)...}
pick best
Pi
execute
answer
statistics

Query Execution

- Here only:
  - how to implement operators
  - what are the costs of implementations
  - how to implement queries
    - Data flow between operators
- Next part:
  - How to choose good plan

Execution Plan

- A tree (DAG) of physical operators that implement a query
- May use indices
- May create temporary relations
- May create indices on the fly
- May use auxiliary operations such as sorting

How to estimate costs

- If everything fits into memory
  - Standard computational complexity
- If not
  - Assume fixed memory available for buffering pages
  - Count I/O operations
  - Real systems combine this with CPU estimations

Estimating IOs:

- Count # of disk blocks that must be read (or written) to execute query plan

To estimate costs, we may have additional parameters:

B(R) = # of blocks containing R tuples

f(R) = max # of tuples of R per block

M = # memory blocks available

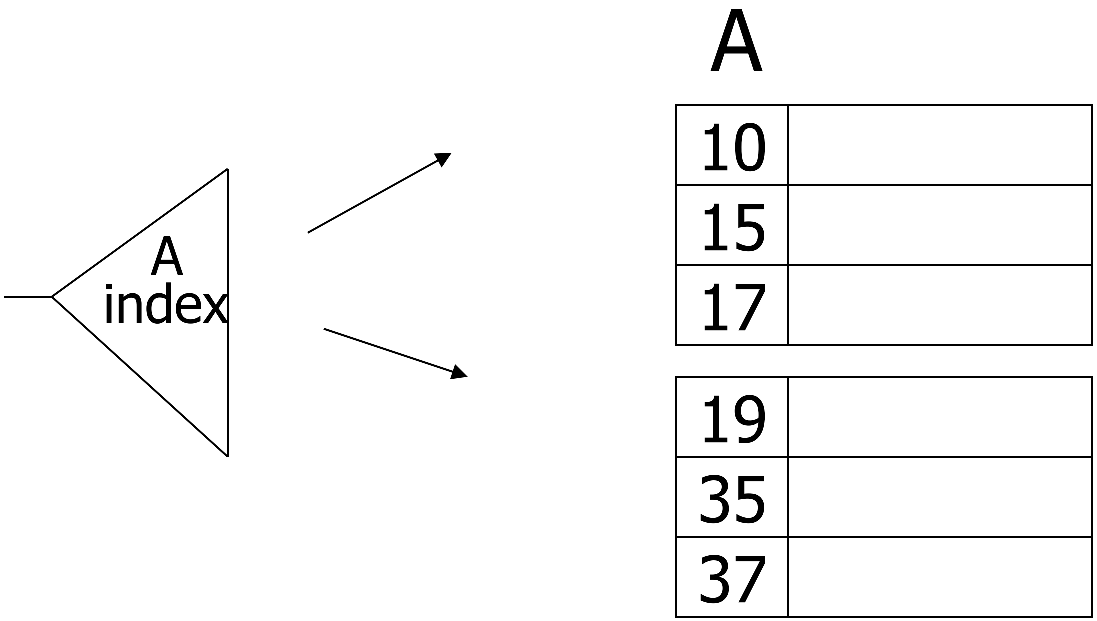
To estimate costs, we may have additional parameters:

B(R) = # of blocks containing R tuples
f(R) = max # of tuples of R per block
M = # memory blocks available

HT(i) = # levels in index i
LB(i) = # of leaf blocks in index i

Clustered index

Index that allows tuples to be read in an order that corresponds to physical order



Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, …)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

Operator Profiles

- Algorithm
- In-memory complexity: e.g., $O(n^2)$
- Memory requirements
  - Runtime based on available memory
- #I/O if operation needs to go to disk
- Disk space needed
- Prerequisites
  - Conditions under which the operator can be applied

Execution Strategies

- Compiled
  - Translate into C/C++/Assembler code
  - Compile, link, and execute code
- Interpreted
  - Generic operator implementations
  - Generic executor
    - Interprets query plan

Virtual Machine Approach

- Implement virtual machine of low-level DBMS operations
- Compile query into machine-code for that machine

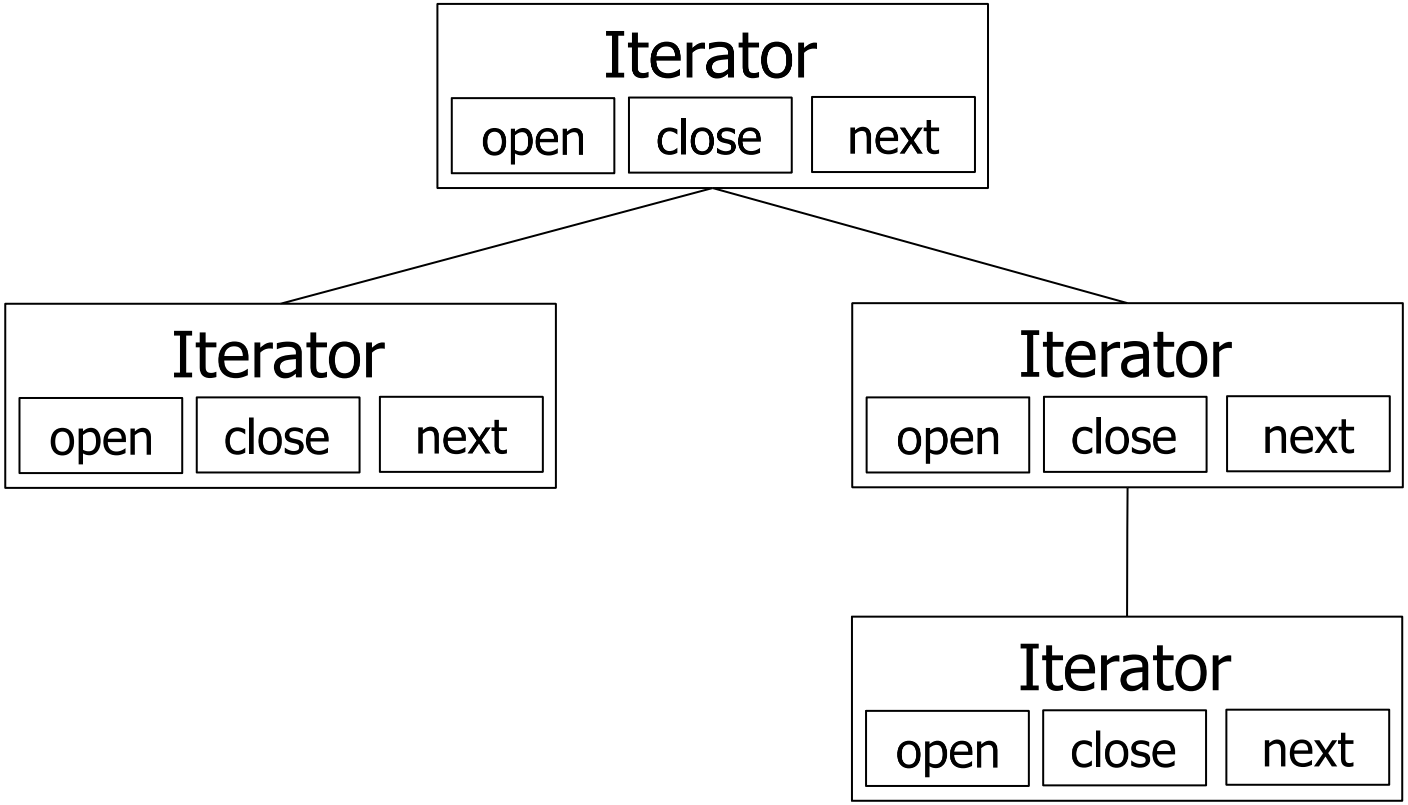
Iterator Model

- Need to be able to combine operators in different ways
  - E.g., join inputs may be scans, or outputs of other joins, …
  - -> define generic interface for operators
  - be able to arbitrarily compose complex plans from a small set of operators

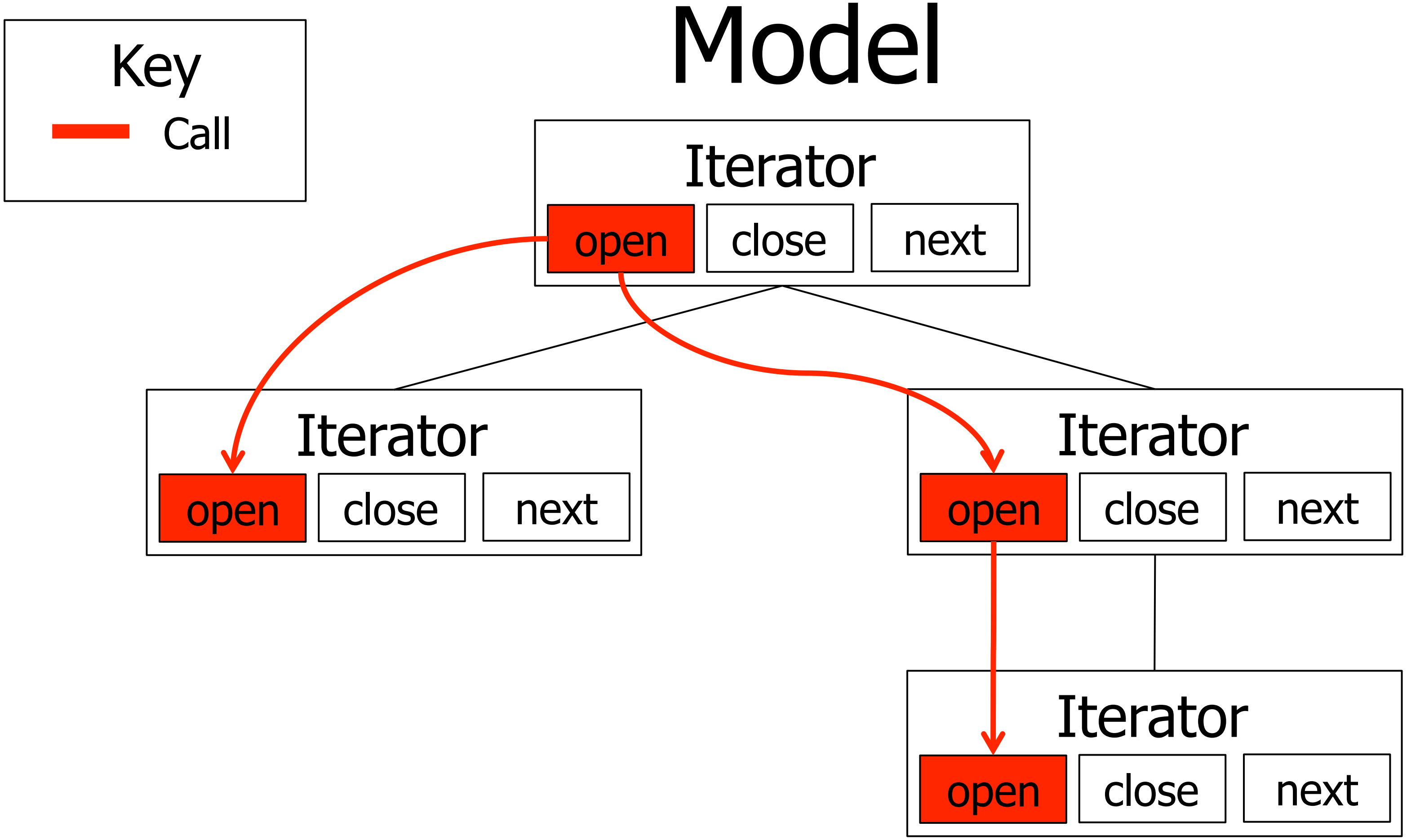
Iterator Model - Interface

- **Open**
  - Prepare operator to read inputs
- **Close**
  - Close operator and clean up
- **Next**
  - Return next result tuple

Query Execution – Iterator Model



Query Execution – Iterator Model



Key

🟥 Call

Iterator

open close next

Iterator

open close next

Iterator

open close next

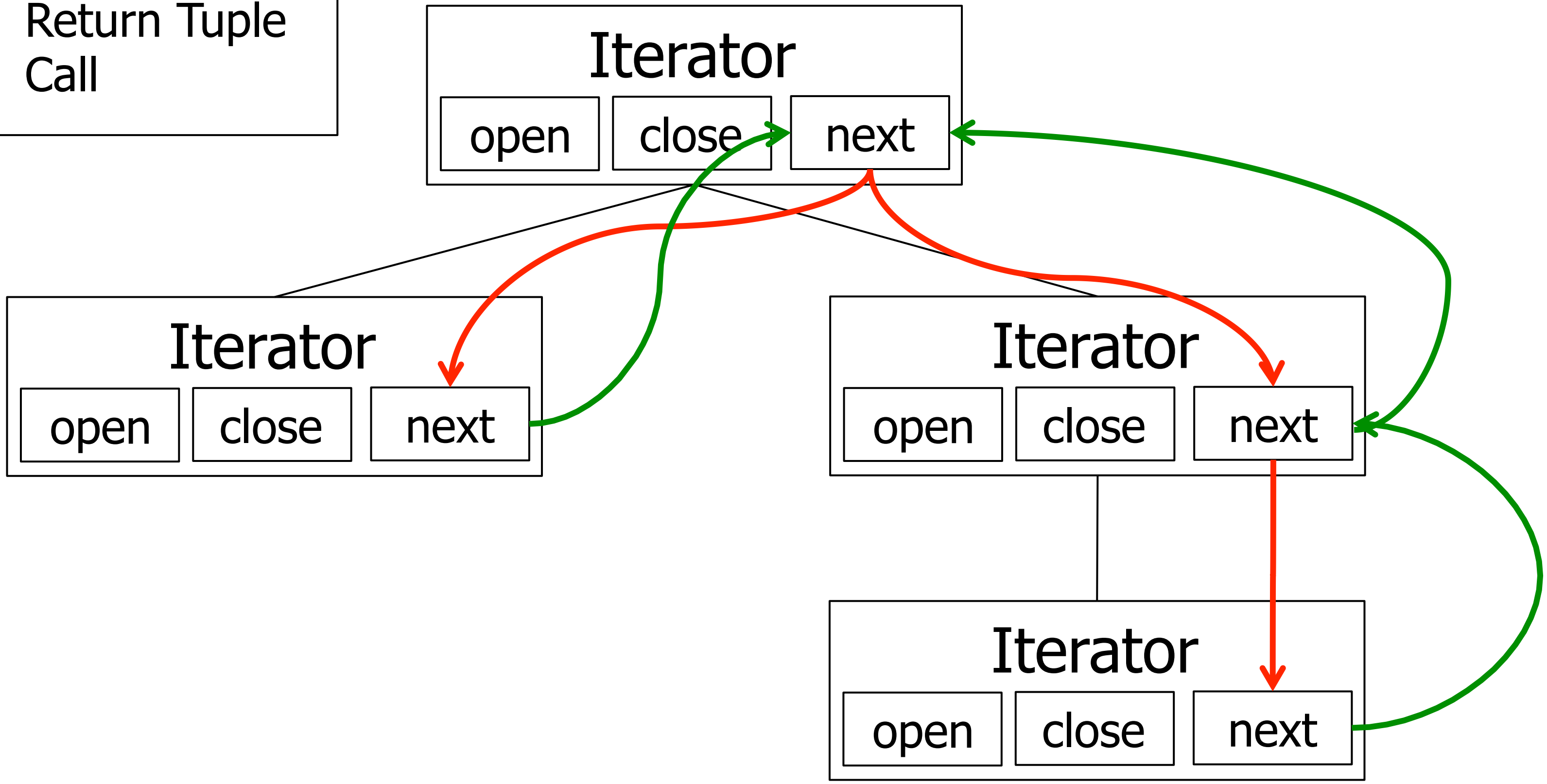
Iterator

open close next

Query Execution – Iterator Model

Key

🟩 Return Tuple
🟥 Call



Iterator
open close next

Iterator
open close next

Iterator
open close next

Iterator
open close next

Parallelism

- Iterator Model
  - **Pull-based** query execution
- Potential types of parallelism
  - Inter-query (every multiuser system)
  - Intra-operator
  - Inter-operator

Intra-Operator Parallelism

- Execute portions of an operator in parallel
  - Merge-Sort
    - Assign a processor to each merge phase
  - Scan
    - Partition tables
    - Each process scans one partition

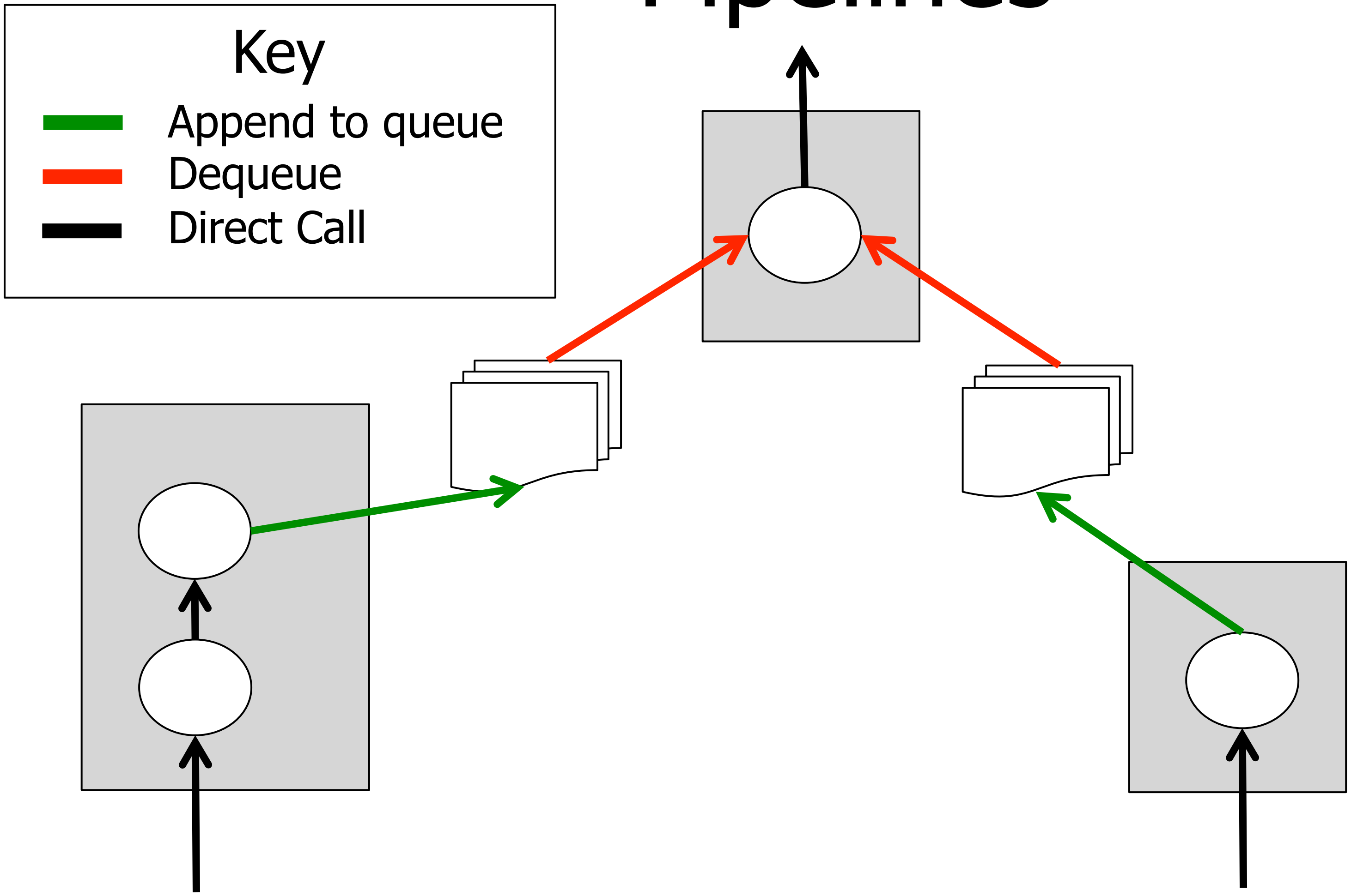
Inter-Operator Parallelism

- Each process executes one or more operators
- **Pipelining**
  - **Push-based** query execution
  - Chain operators to directly produce results
  - Pipeline-breakers
    - Operators that need to consume the whole input (or large parts) before producing outputs

Pipelining Communication

- Queues
  - Operators push their results to queues
  - Operators read their inputs from queues
- Direct call
  - Operator calls its parent in the tree with results
  - Within one process

Pipelines



Key

🟩 Append to queue

🟥 Dequeue

⬛ Direct Call

Pipeline-breakers

- Sorting
  - All operators that apply sorting
- Aggregation
- Set Difference
- Some implementations of
  - Join
  - Union

Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, …)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

Sorting

- Why do we want/need to sort
  - Query requires sorting (ORDER BY)
  - Operators require sorted input
    - Merge-join
    - Aggregation by sorting
    - Duplicate removal using sorting

In-memory sorting

- Algorithms from data structures 101
    - Quick sort
    - Merge sort
    - Heap sort
    - Intro sort
    - …

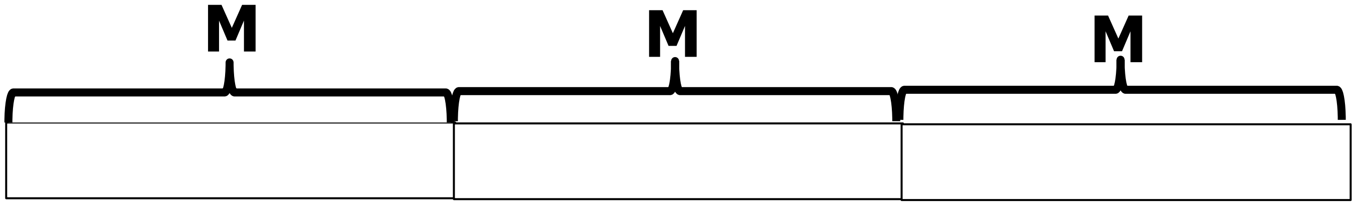
External sorting

- Problem:
  - Sort **N** pages of data with **M** pages of memory

- Solutions?

First Idea

- Split data into runs of size **M**
- Sort each run in memory and write back to disk
  - $\lceil \mathbf{N/M} \rceil$ sorted runs of size **M**
- Now what?



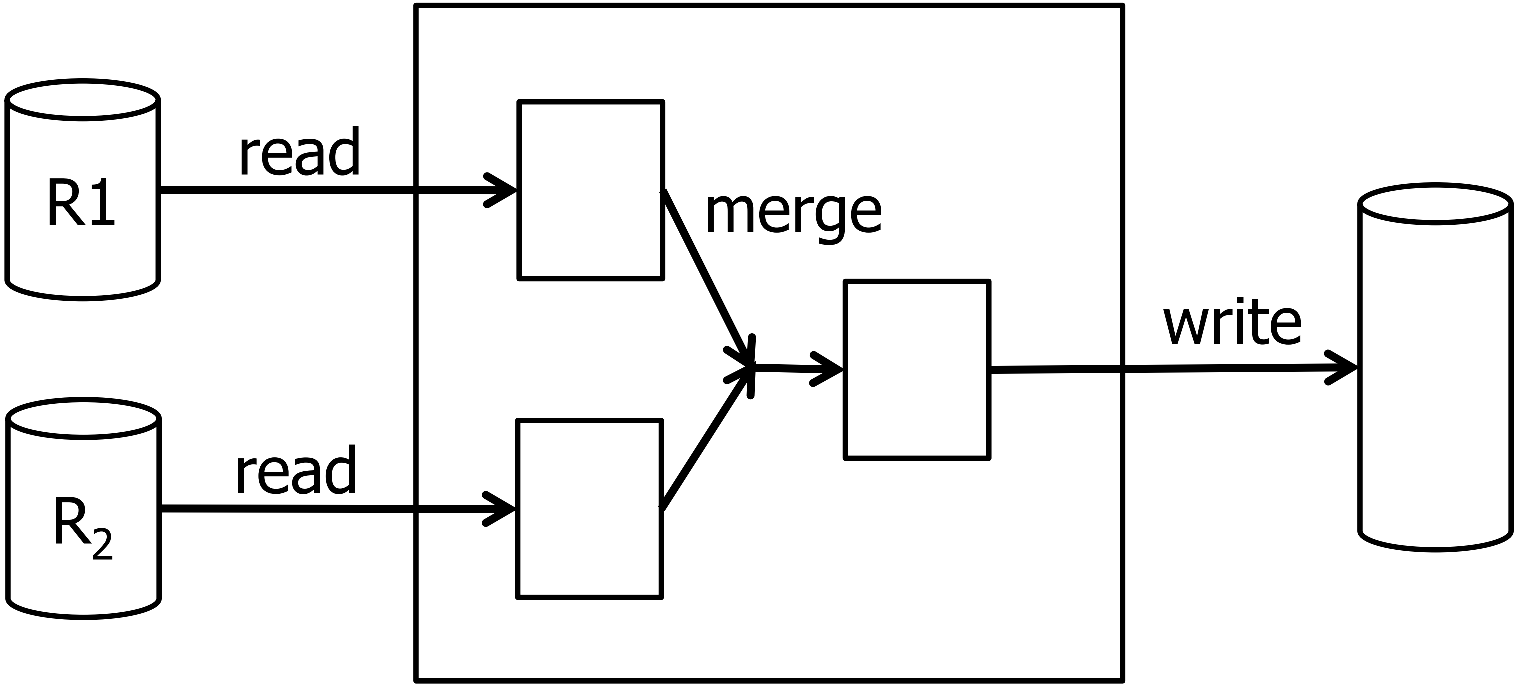
Merging Runs

- Need to create bigger sorted runs out of sorted smaller runs
  - Divide and Conquer
  - Merge Sort?
- How to merge two runs that are bigger than **M?**

Merging Runs using 3 pages

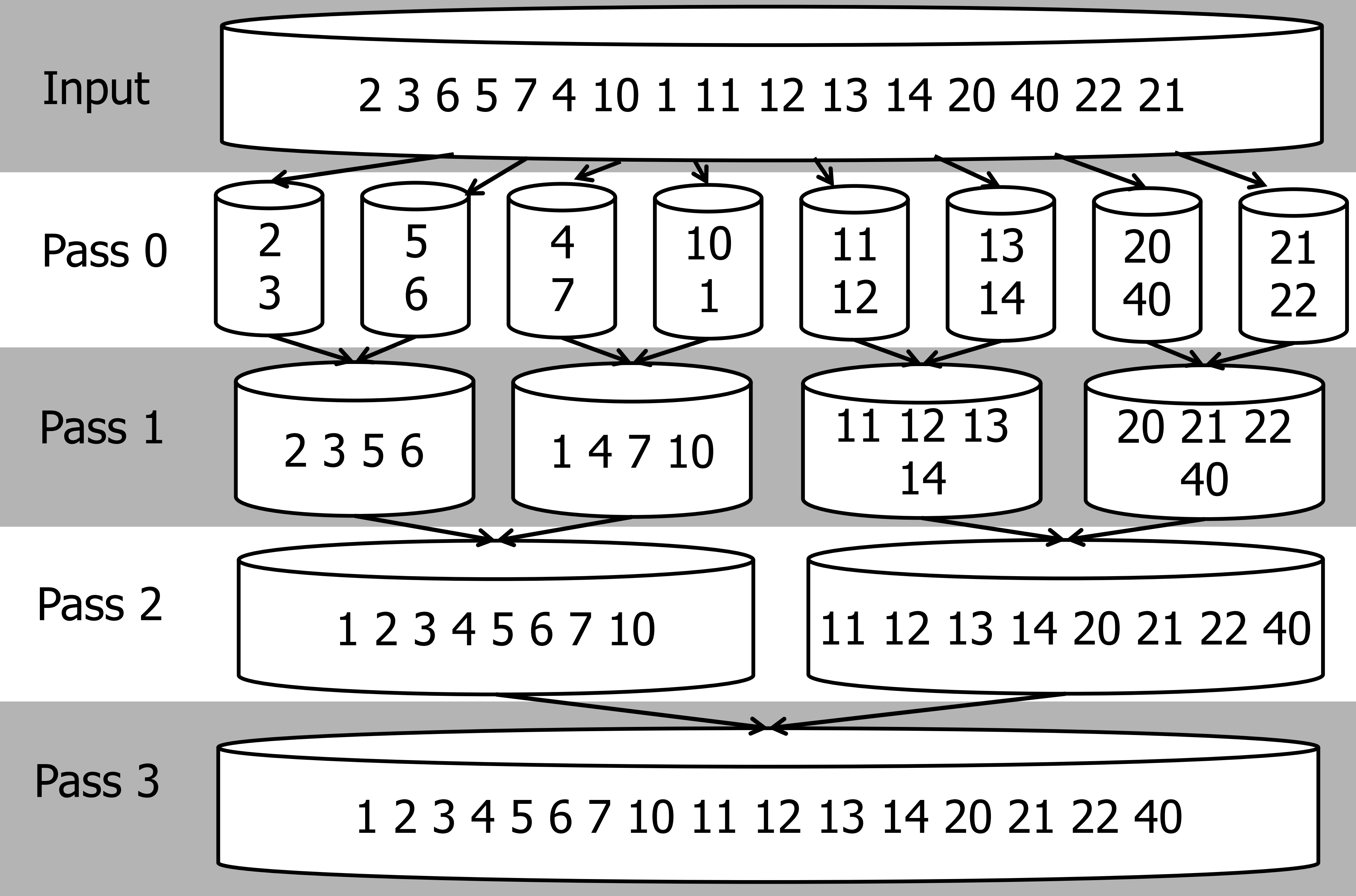
- Merging sorted runs R_1 and R_2
- Need 3 pages
  - One page to buffer pages from R_1
  - One page to buffer pages from R_2
  - One page to buffer the result
    - Whenever this buffer is full, write it to disk

Merging Runs



2-Way External Mergesort

- Repeat process until we have one sorted run
- Each iteration (pass) reads and writes the whole table once: **2 B(R)** I/Os
- Each pass doubles the run size
  - $\mathbf{1 + \lceil \log_2 (B(R) / M) \rceil}$ runs
  - $\mathbf{2\, B(R) * (1 + \lceil \log_2 (B(R) / M) \rceil)}$ I/Os



Input
2 3 6 5 7 4 10 1 11 12 13 14 20 40 22 21

Pass 0
2 3
5 6
4 7
10 1
11 12
13 14
20 40
21 22

Pass 1
2 3 5 6
1 4 7 10
11 12 13 14
20 21 22 40

Pass 2
1 2 3 4 5 6 7 10
11 12 13 14 20 21 22 40

Pass 3
1 2 3 4 5 6 7 10 11 12 13 14 20 21 22 40

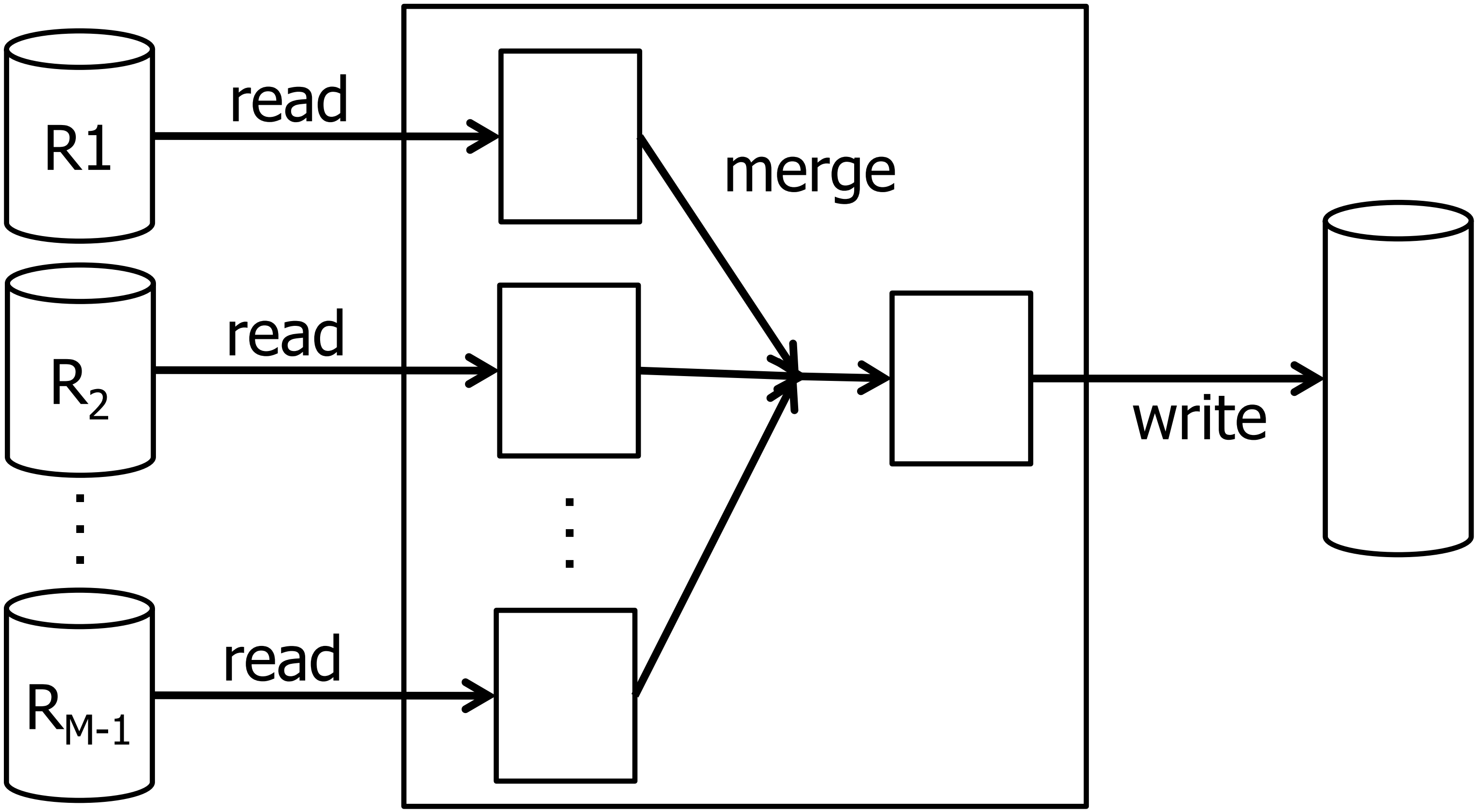
N-Way External Mergesort

- How to utilize **M** buffer during merging?
- Each pass merges **M-1** runs at once
  - One memory page as buffer for each run
- #I/Os

$$\mathbf{1 + \lceil log_{M-1} (B(R) / M) \rceil} \text{ runs}$$

$$\mathbf{2\, B(R) \ast (1 + \lceil log_{M-1} (B(R) / M) \rceil)} \text{ I/Os}$$

Merging Runs



How many passes do we need?

N	M=17	M=129	M=257	M=513	M=1025
100	2	1	1	1	1
1,000	3	2	2	2	1
10,000	4	2	2	2	2
100,000	5	3	3	2	2
1,000,000	5	3	3	3	2
10,000,000	6	4	3	3	3
100,000,000	7	4	4	3	3
1,000,000,000	8	5	4	4	3

To put into perspective

- Scenario
  - Page size 4KB
  - 1TB of data (250,000,000)
  - 10MB of buffer for sorting (250)
- Passes
  - 4 passes

Merge

- In practice would want larger I/O buffer for each run
- Trade-off between number of runs and efficiency of I/O

Improving in-memory merging

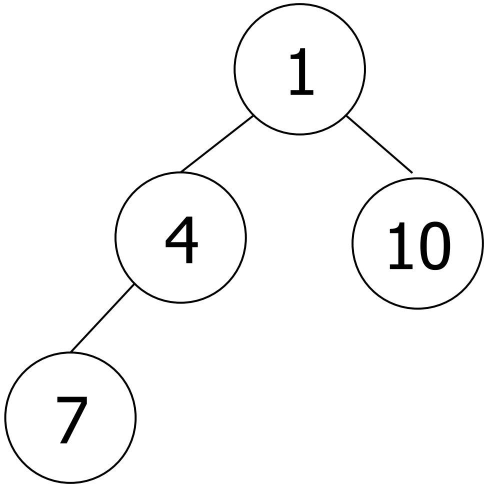
- Merging **M** runs
  - To choose next element to output
  - Have to compare **M** elements
  - -> complexity linear in **M**: **O(M)**
- How to improve that?
  - Use priority queue to store current element from each run
  - -> $\mathbf{O(log_2(M))}$

Priority Queue

- Queue for accessing elements in some given order
  - **`pop-smallest`** = return and remove smallest element in set
  - **`Insert(e)`** = insert element into queue

Min-Heap

- Implementation of priority queue
  - Store elements in a binary tree
  - All levels are full (except leaf level)
  - Heap property
    - Parent is smaller than child
- Example: { 1, 4, 7, 10 }



Min-Heap Insertion

- **`insert(e)`**
  1. Add element at next free leaf node
     - This may invalidate heap property
  2. If node smaller than parent then
     - Switch node with parent
  3. Repeat until 2) cannot be applied anymore

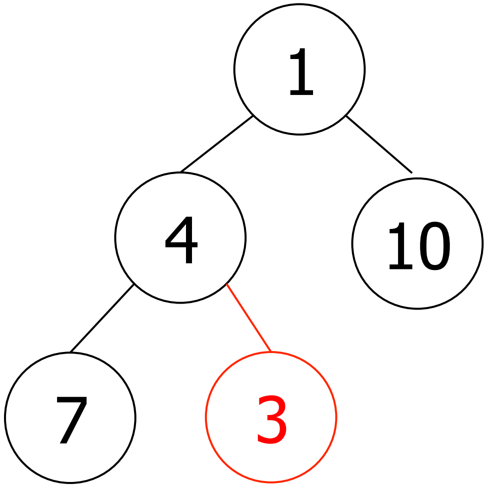
Min-Heap Dequeue

- **`pop–smallest`**
  1. Return Root and use right-most leaf as new root
     - This may invalidate heap property
  2. If node smaller than child then
     - Switch node with smaller child
  3. Repeat until 2) cannot be applied anymore

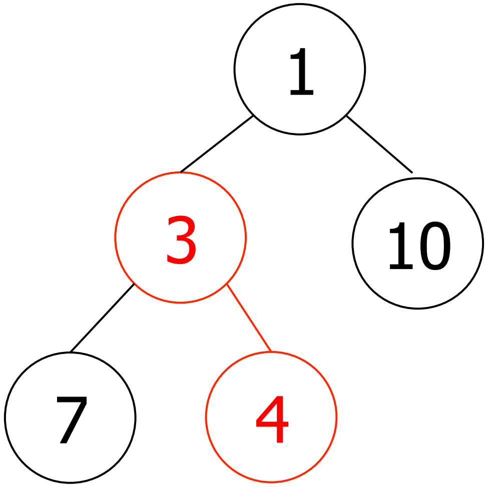
Insertion

- Insert 3

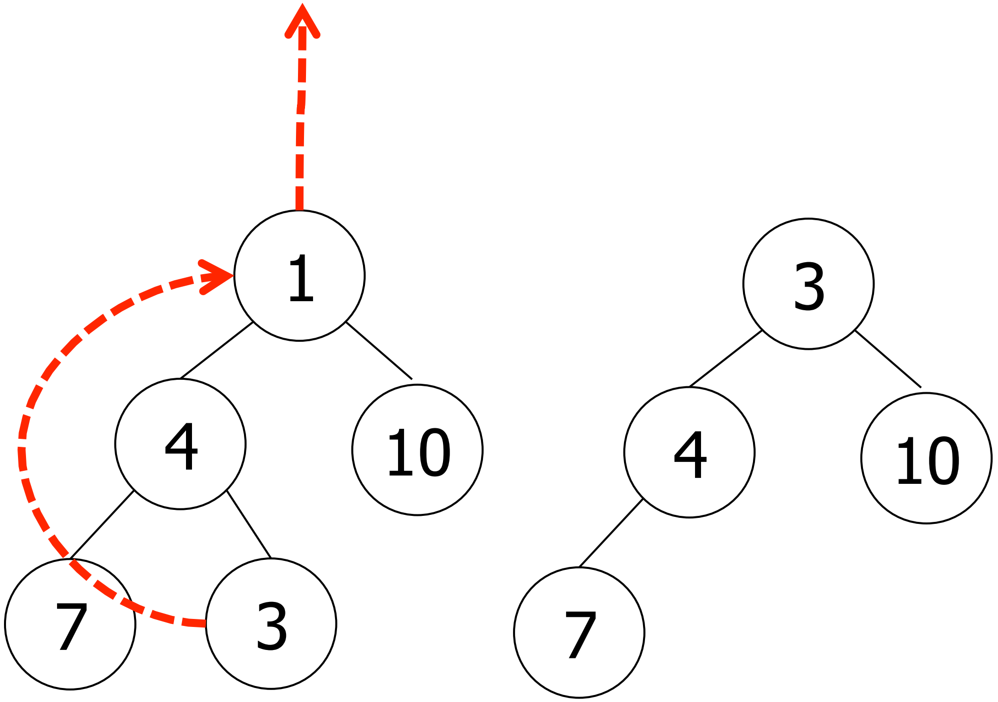
Insert at first free position



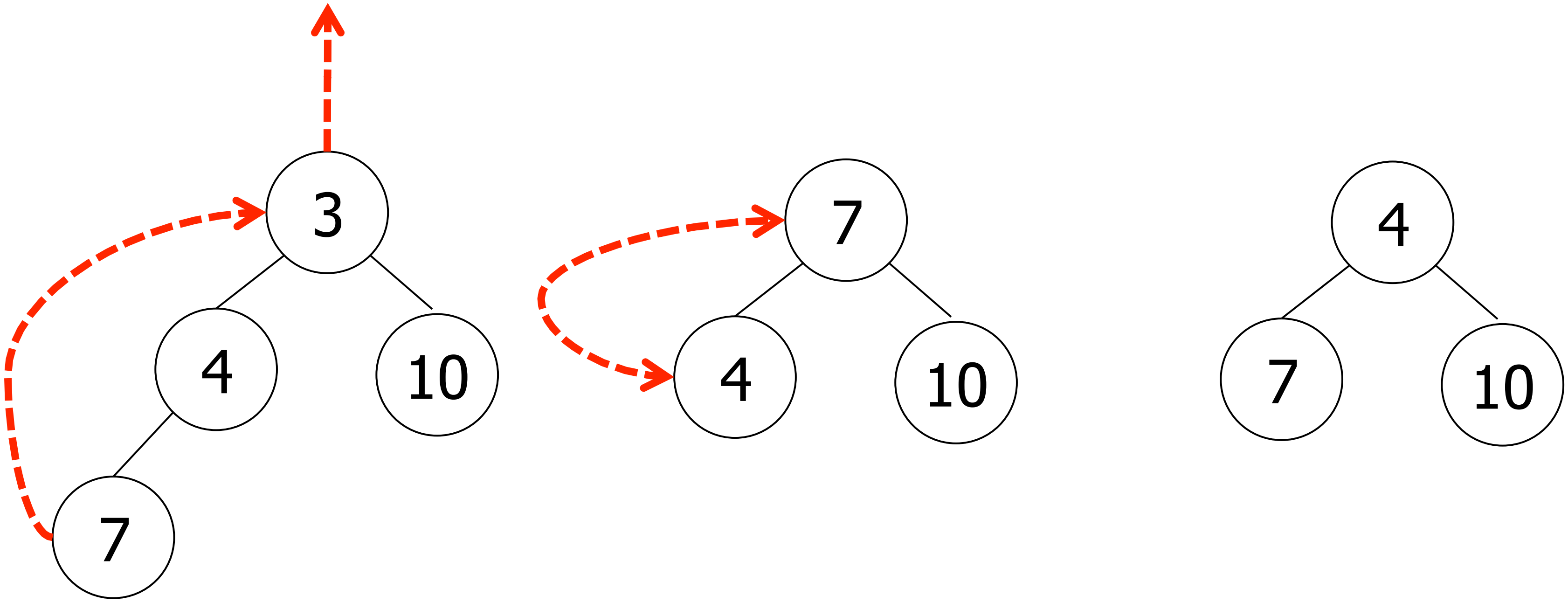
Restore heap property



Dequeue



Dequeue

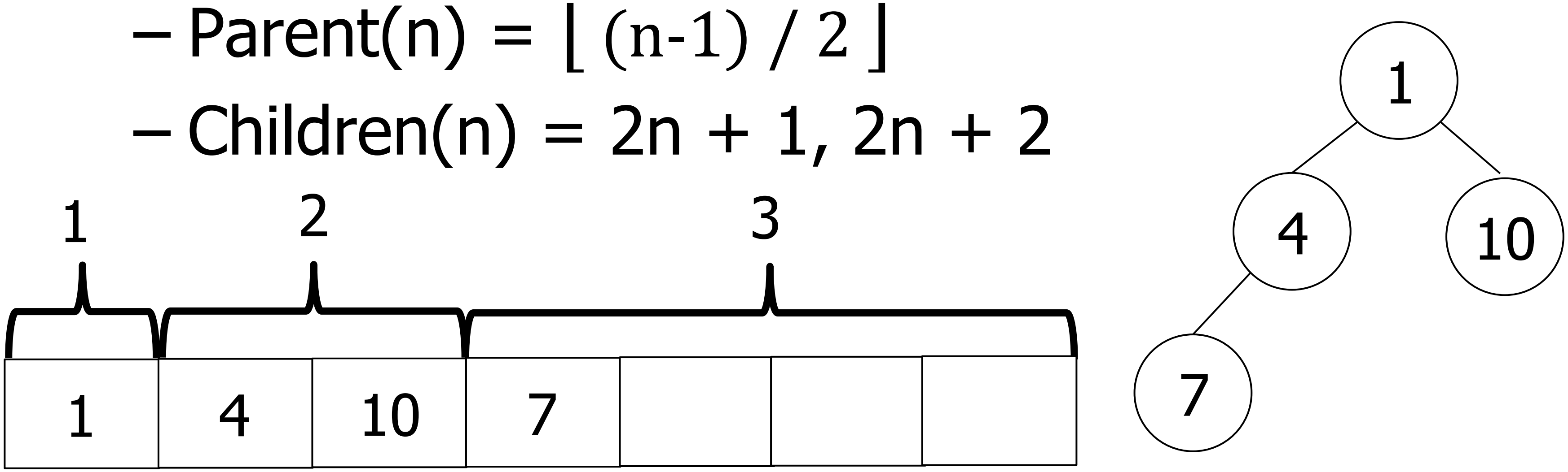


Min/Max-Heap Complexity

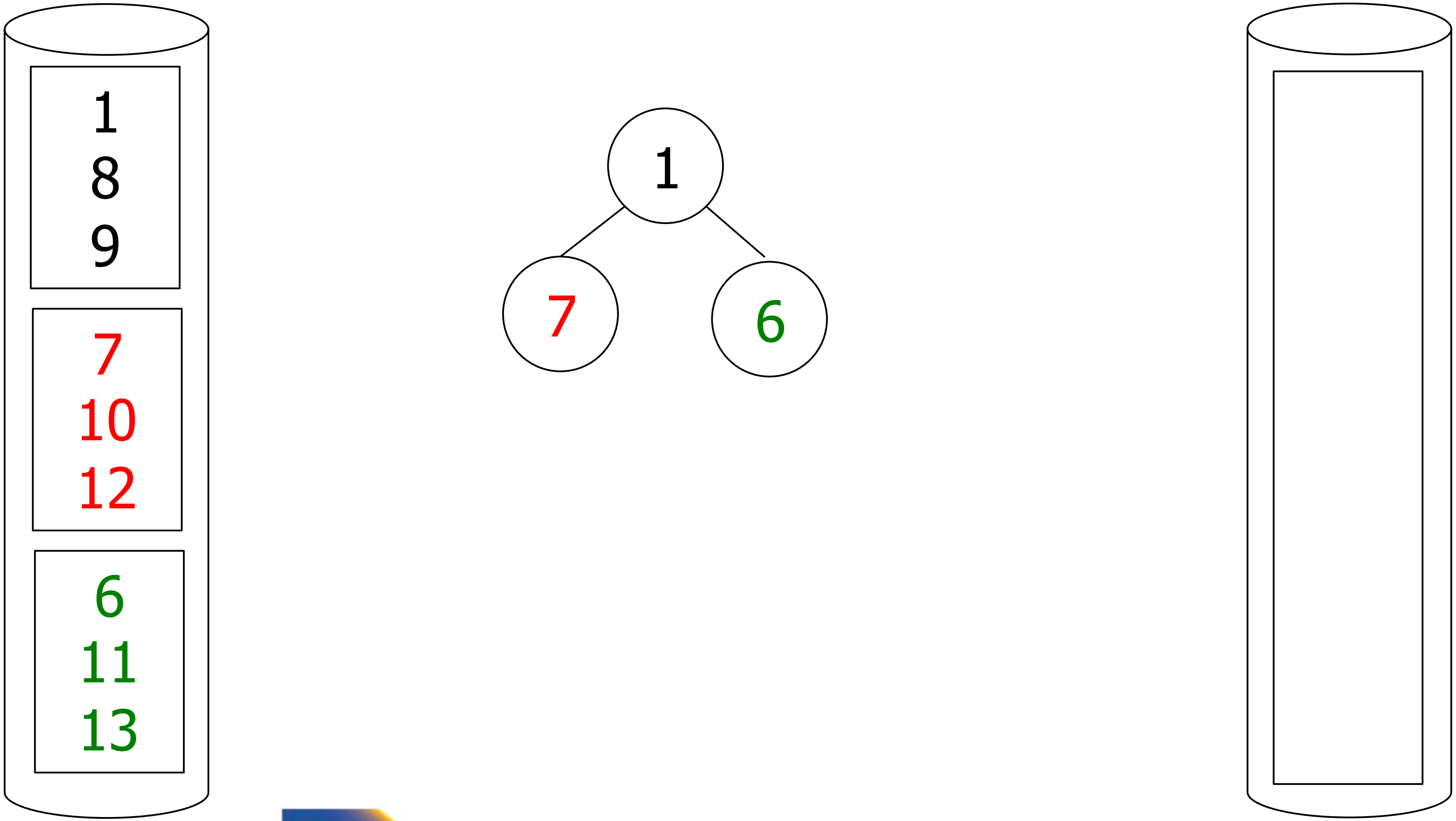
- Heap is a complete tree
  - Height is O($\log_2(n)$)
- Insertion
  - Maximal height of the tree switches
  - -> O($\log_2(n)$)
- Dequeue
  - Maximal height of the tree switches
  - -> O($\log_2(n)$)

Min-Heap Implementation

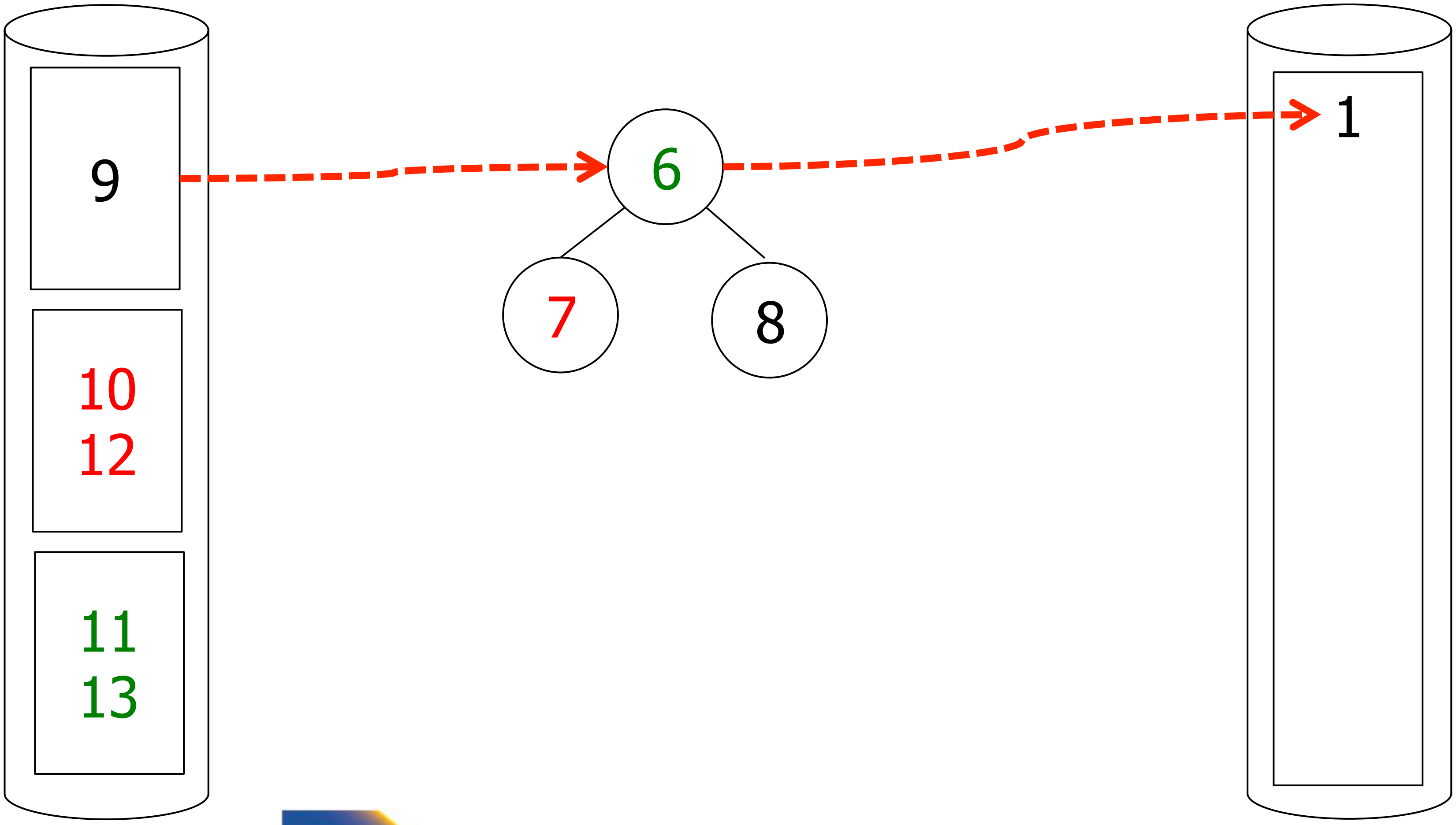
- Full tree
  - Use array to implement tree
- Compute positions
  - Parent(n) = $\lfloor (n-1) / 2 \rfloor$
  - Children(n) = 2n + 1, 2n + 2



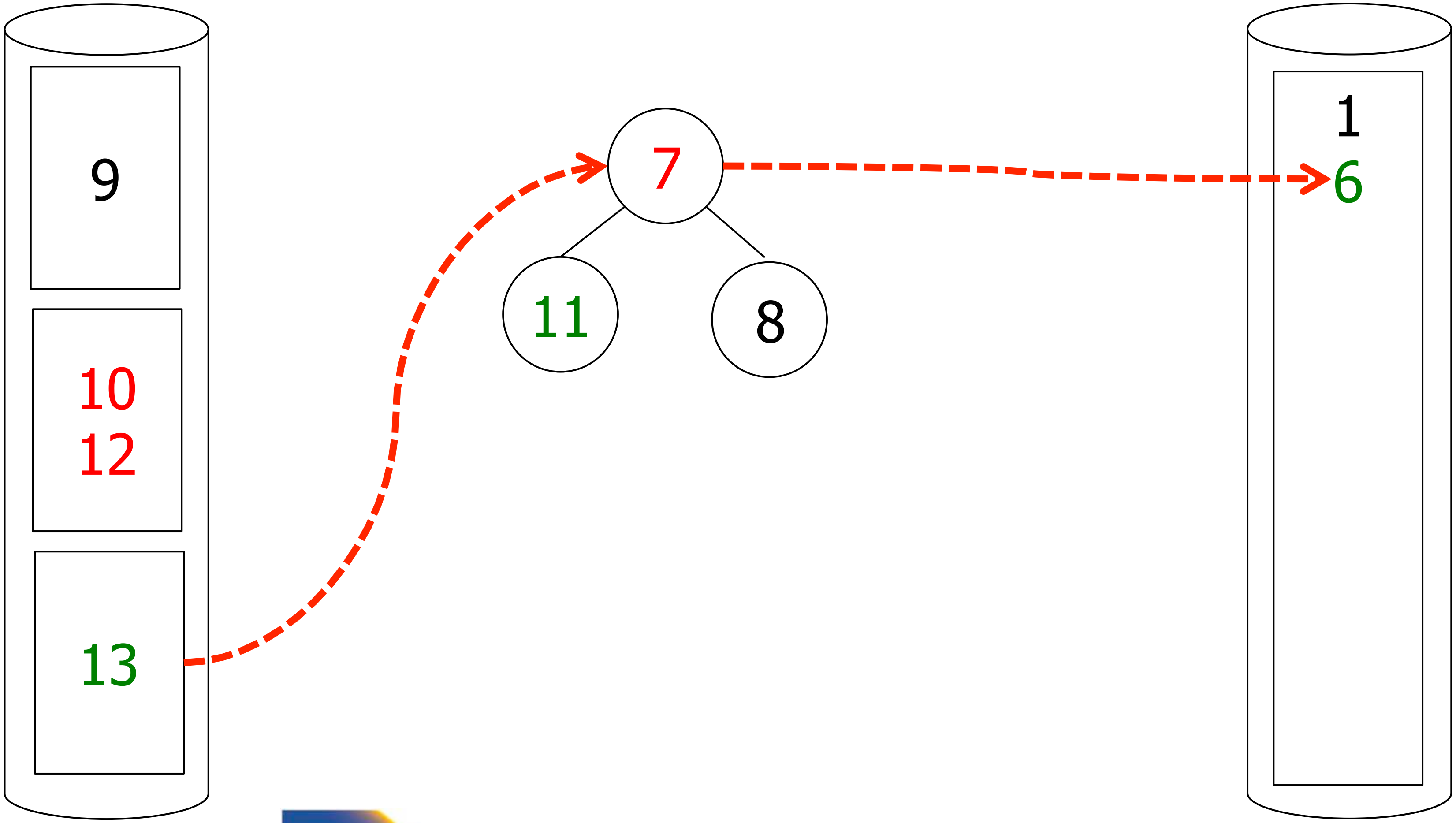
Merging with Priority Queue



Merging with Priority Queue



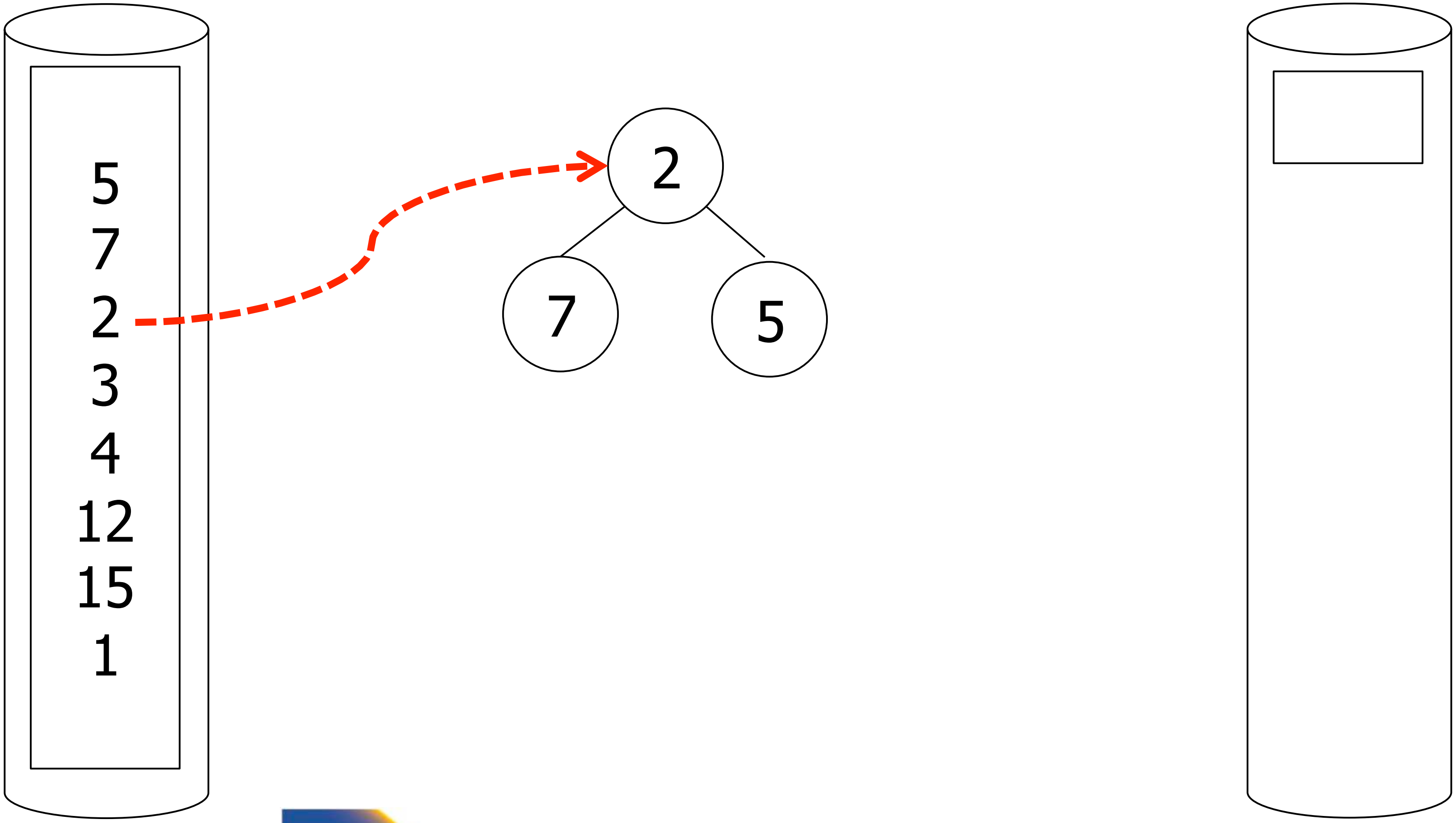
Merging with Priority Queue



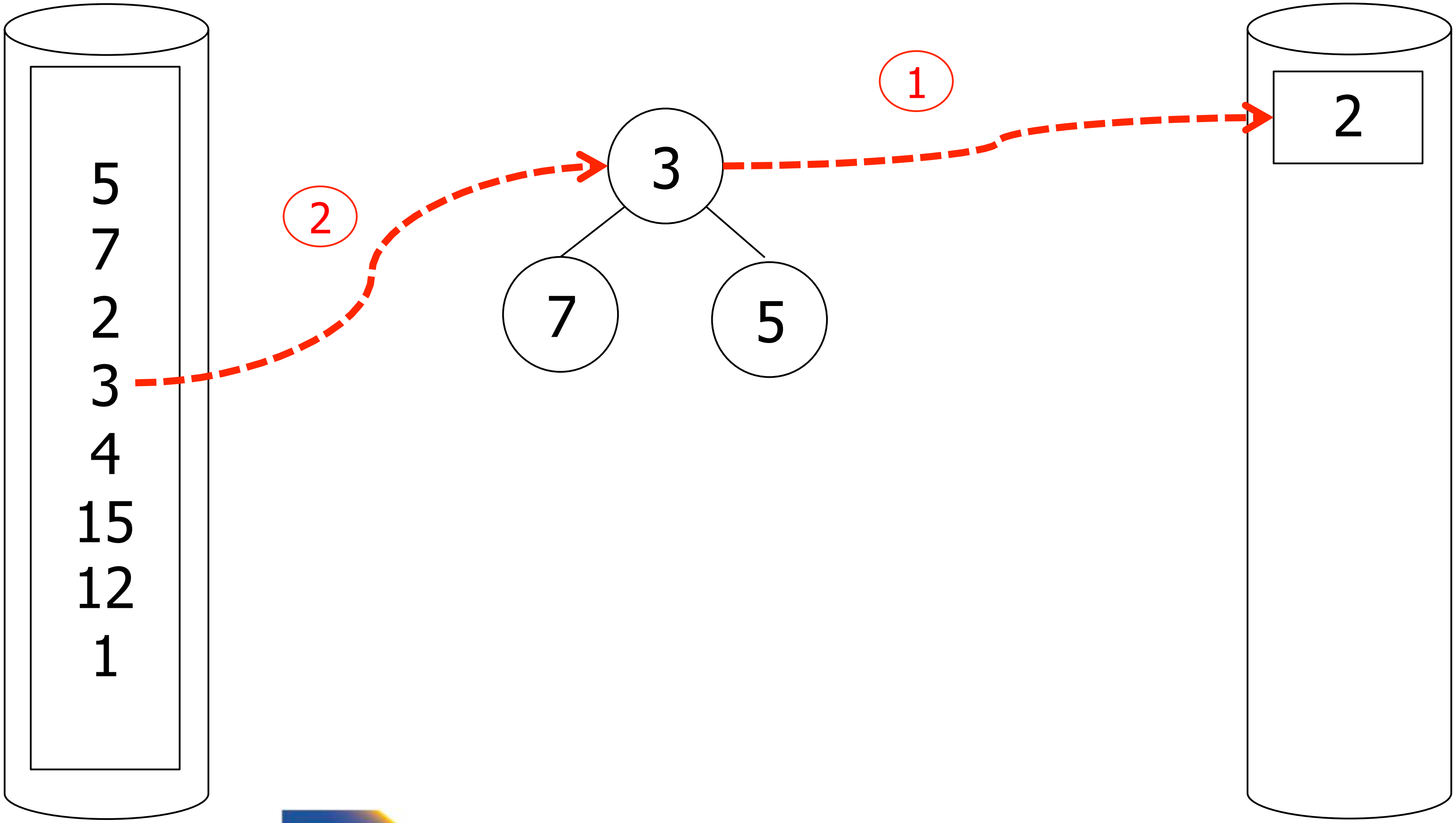
Using a heap to generate runs

- Read inputs into heap
  - Until available memory is full
- Replace elements
  - Remove smallest element from heap
    - If larger then last element written of current run then write to current run
    - Else create a new run
  - Add new element from input to heap

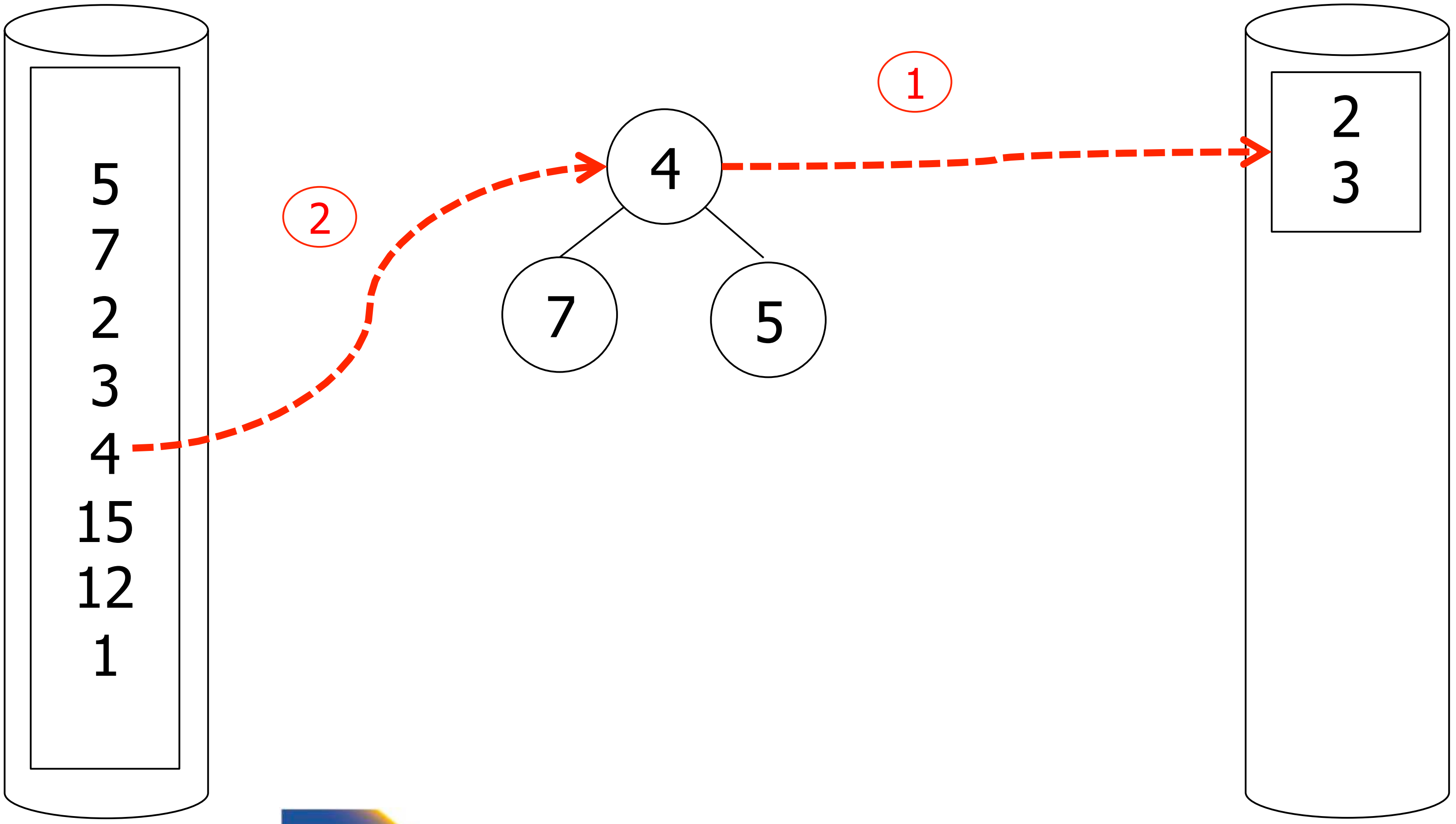
Using a heap to generate runs



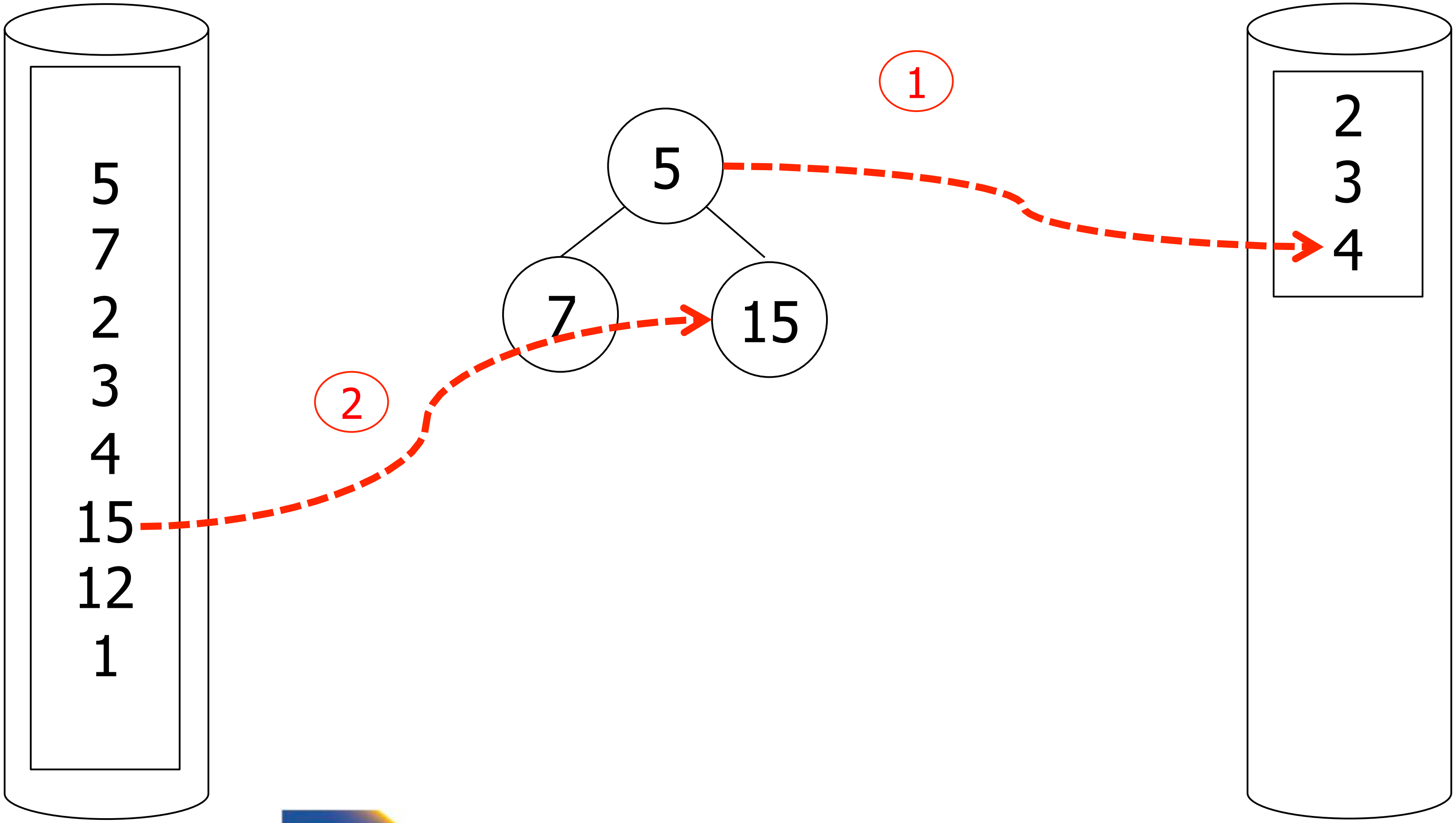
Using a heap to generate runs



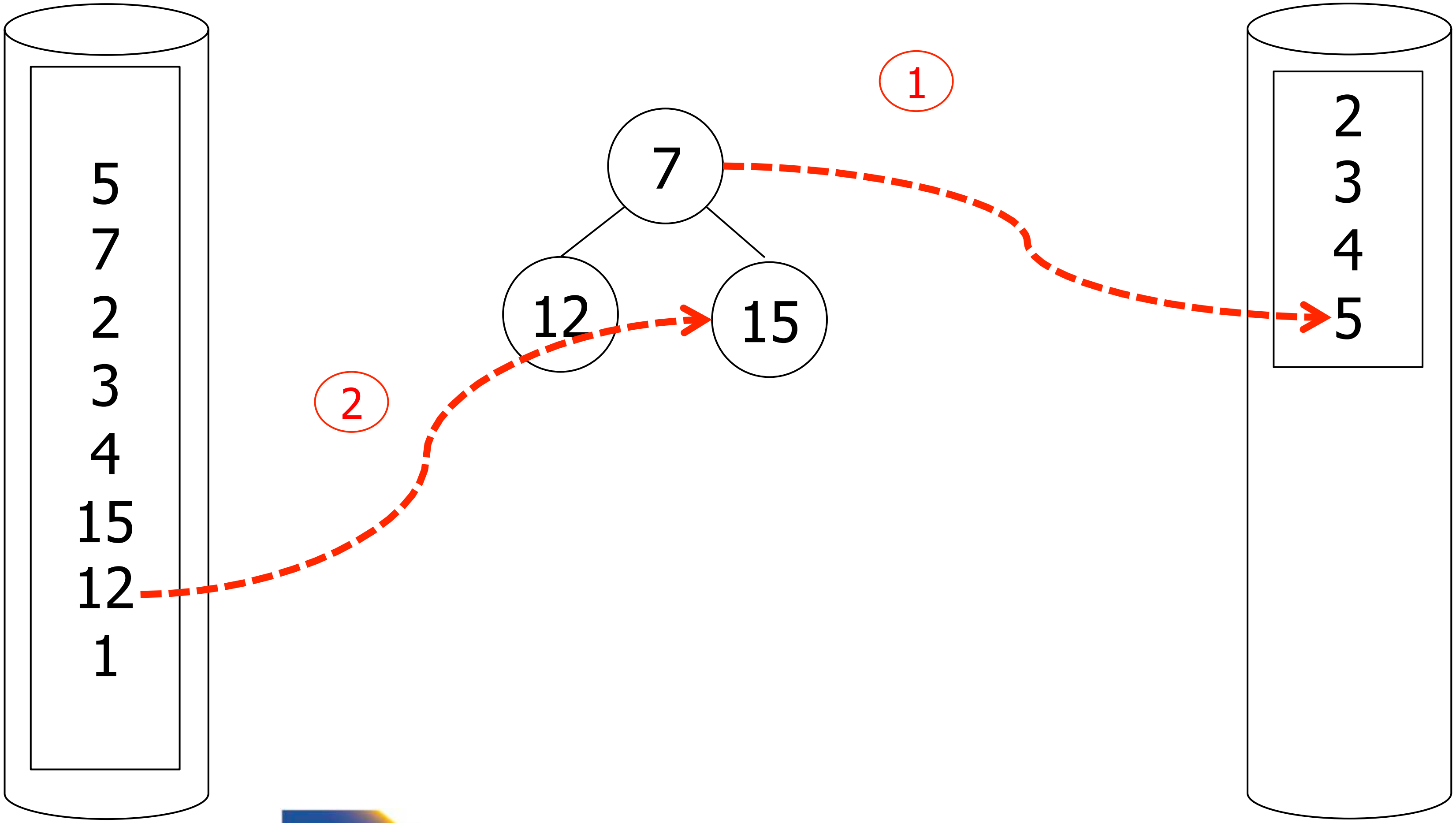
Using a heap to generate runs



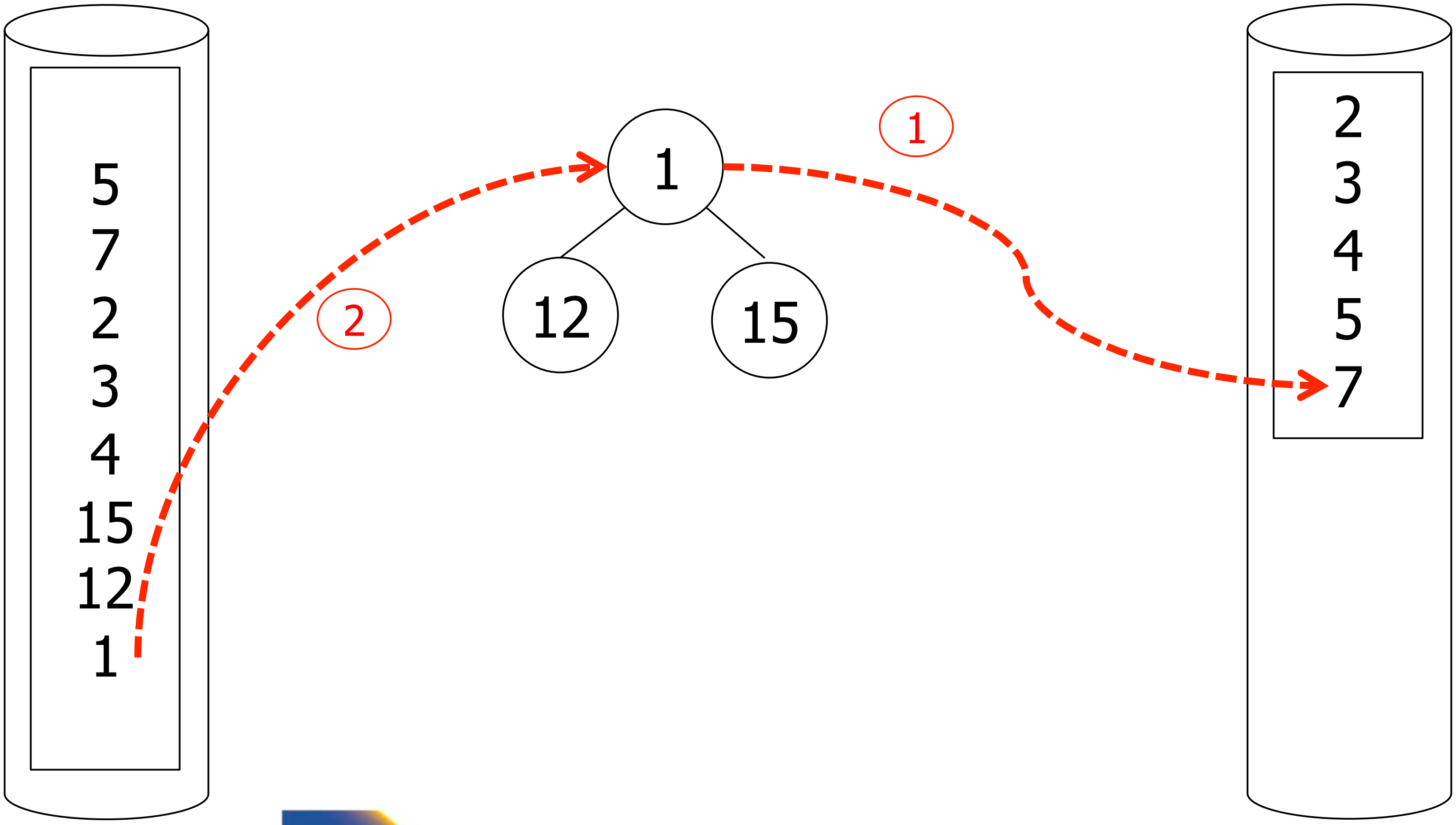
Using a heap to generate runs



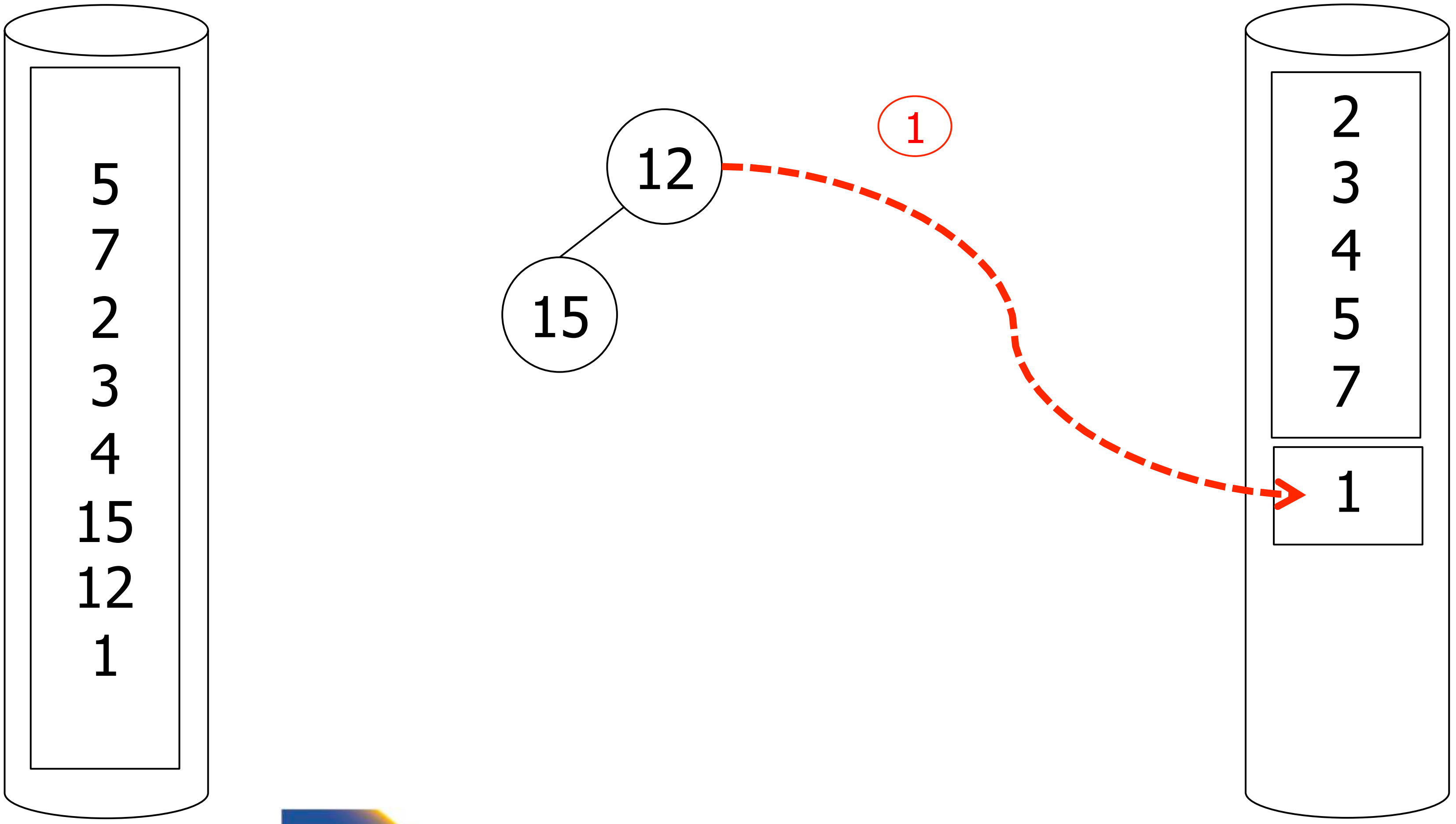
Using a heap to generate runs



Using a heap to generate runs



Using a heap to generate runs



Using a heap to generate runs

- Increases the run-length
  - On average by a factor of 2 (see Knuth)

Use clustered B+-tree

- Keys in the B+-tree **I** are in sort order
  - If B+-tree is clustered traversing the leaf nodes is sequential I/O!
  - **K** = #keys/leaf node
- Approach
  - Traverse from root to first leaf: **HT(I)**
  - Follow sibling pointers: **|R| / K**
  - Read data blocks**: B(R)**

I/O Operations

- **HT(I) + |R| / K + B(R)** I/Os
- Less than **2 B(R)** = 1 pass external mergesort
- ->Better than external merge-sort!

Unclustered B+-tree?

- Each entry in a leaf node may point to different page of relation R
  - For each leaf page we may read up to **K** pages from relation R
  - Random I/O
- In worst-case we have
  - **K $*$ B(R)**
  - **K = 500**
    - **500 $*$ B(R)** = 250 merge passes

Sorting Comparison

B(R) = number of block of R
M = number of available memory blocks
#RB = records per page
HT = height of B+-tree (logarithmic)
K = number of keys per leaf node

Property	**Ext. Mergesort**	**B+ (clustered)**	**B+ (unclustered)**
Runtime	$O(N \log_{M-1}(N))$	O(N)	O(N)
#I/O (random)	$2 B(R) * (1 + \lceil \log_{M-1}(B(R) / M) \rceil)$	HT + |R| / K + B(R)	HT + |R| / K + K ∗ #RB
Memory	M	1 (better HT + X)	1 (better HT + X)
Disk Space	2 B(R)	0	0
Variants	1) Merge with heap 2) Run generation with heap 3) Larger Buffer		

Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, …)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

Scan

- Implements access to a table
  - Combined with selection
  - Probably projection too
- Variants
  - **Sequential**
    - Scan through all tuples of relation
  - **Index**
    - Use index to find tuples that match selection

Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, ...)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

Options

- Transformations: $R_1 \bowtie_c R_2$, $R_2 \bowtie_c R_1$
- Joint algorithms:
  - Nested loop
  - Merge join
  - Join with index
  - Hash join
- Outer join algorithms

Nested Loop Join (conceptually)

```
    for each $r \in R_1$ do
        for each $s \in R_2$ do
            if $(r,s) \vDash C$ then output $(r,s)$
```

Applicable to:

- Any join condition C
- Cross-product

- Merge Join (conceptually)

```
(1) if $R_1$ and $R_2$ not sorted, sort them
(2) $i \leftarrow 1$; $j \leftarrow 1$;
    While $(i \leq T(R_1)) \wedge (j \leq T(R_2))$ do
        if $R_1\{ i \}.C = R_2\{ j \}.C$ then outputTuples
        else if $R_1\{ i \}.C > R_2\{ j \}.C$ then $j \leftarrow j+1$
        else if $R_1\{ i \}.C < R_2\{ j \}.C$ then $i \leftarrow i+1$
```

Applicable to:

- C is conjunction of equalities or </>:

$A_1 = B_1$ AND … AND $A_n = B_n$

Procedure Output-Tuples

```
While $(R_1\{ i \}.C = R_2\{ j \}.C) \wedge (i \leq T(R_1))$ do
    [jj ← j;
    while $(R_1\{ i \}.C = R_2\{ jj \}.C) \wedge (jj \leq T(R_2))$ do
            [output pair $R_1\{ i \}, R_2\{ jj \}$;
             jj ← jj+1  ]
    i ← i+1  ]
```

Example

i	$R_1\{i\}.C$	$R_2\{j\}.C$	j
1	10	5	1
2	20	20	2
3	20	20	3
4	30	30	4
5	40	30	5
		50	6
		52	7

Index nested loop (Conceptually)

Assume R_2.C index

```
For each $r \in R_1$ do
    [ $X \leftarrow$ index ($R_2$, C, r.C)
        for each $s \in X$ do
            output (r,s) pair]
```

Note: $X \leftarrow$ index(rel, attr, value)

then X = set of rel tuples with attr = value

Hash join (conceptual)

Hash function h, range 0 → k

Buckets for R_1: G_0, G_1, ... G_k

Buckets for R_2: H_0, H_1, ... H_k

Applicable to:

- C is conjunction of equalities

$$A_1 = B_1 \text{ AND } \ldots \text{ AND } A_n = B_n$$

Hash join (conceptual)

Hash function h, range 0 → k

Buckets for R_1: G_0, G_1, ... G_k

Buckets for R_2: H_0, H_1, ... H_k

Algorithm

```
(1) Hash $R_1$ tuples into G buckets
(2) Hash $R_2$ tuples into H buckets
(3) For i = 0 to k do
        match tuples in $G_i$, $H_i$ buckets
```

Simple example hash: even/odd

R_1	R_2
2	5
4	4
3	12
5	3
8	13
9	8
	11
	14

Buckets

	R_1	R_2
Even:	2 4 8	4 12 8 14
Odd:	3 5 9	5 3 13 11

Factors that affect performance

(1) Tuples of relation stored physically together?

(2) Relations sorted by join attribute?

(3) Indexes exist?

Example 1(a) NL Join $R_1 \bowtie R_2$

- Relations not contiguous
- Recall

$$\left\{\begin{array}{l} T(R_1) = 10{,}000 \quad T(R_2) = 5{,}000 \\ S(R_1) = S(R_2) = 1/10 \text{ block} \\ MEM = 101 \text{ blocks} \end{array}\right.$$

Example 1(a)

Nested Loop Join $R_1 \bowtie R_2$

- Relations not contiguous
- Recall $\begin{cases} T(R_1) = 10{,}000 \quad T(R_2) = 5{,}000 \\ S(R_1) = S(R_2) = 1/10 \text{ block} \\ MEM = 101 \text{ blocks} \end{cases}$

Cost: for each R_1 tuple:

$$[\text{Read tuple} + \text{Read } R_2]$$

Total $= 10{,}000\ [1 + 500] = 5{,}010{,}000$ IOs

- Can we do better?

- Can we do better?

Use our memory

(1) Read 100 blocks of R_1

(2) Read all of R_2 (using 1 block) + join

(3) Repeat until done

Cost: for each R_1 chunk:

Read chunk: 100 IOs

Read R_2: 500 IOs

$$\begin{array}{r} 100 \\ \underline{500} \\ 600 \end{array}$$

Cost: for each R_1 chunk:

Read chunk: 100 IOs

Read R_2: $\underline{500}$ IOs

600

Total = $\frac{1,000}{100}$ x 600 = 6,000 IOs

- Can we do better?

- Can we do better?

☛ Reverse join order: $R_2 \bowtie R_1$

$$\text{Total} = \frac{500}{100} \times (100 + 1{,}000) =$$

$$5 \times 1{,}100 = 5{,}500 \text{ IOs}$$

Cost of Block Nested Loop

- ☛ Reverse join order: $R_1 \bowtie R_2$

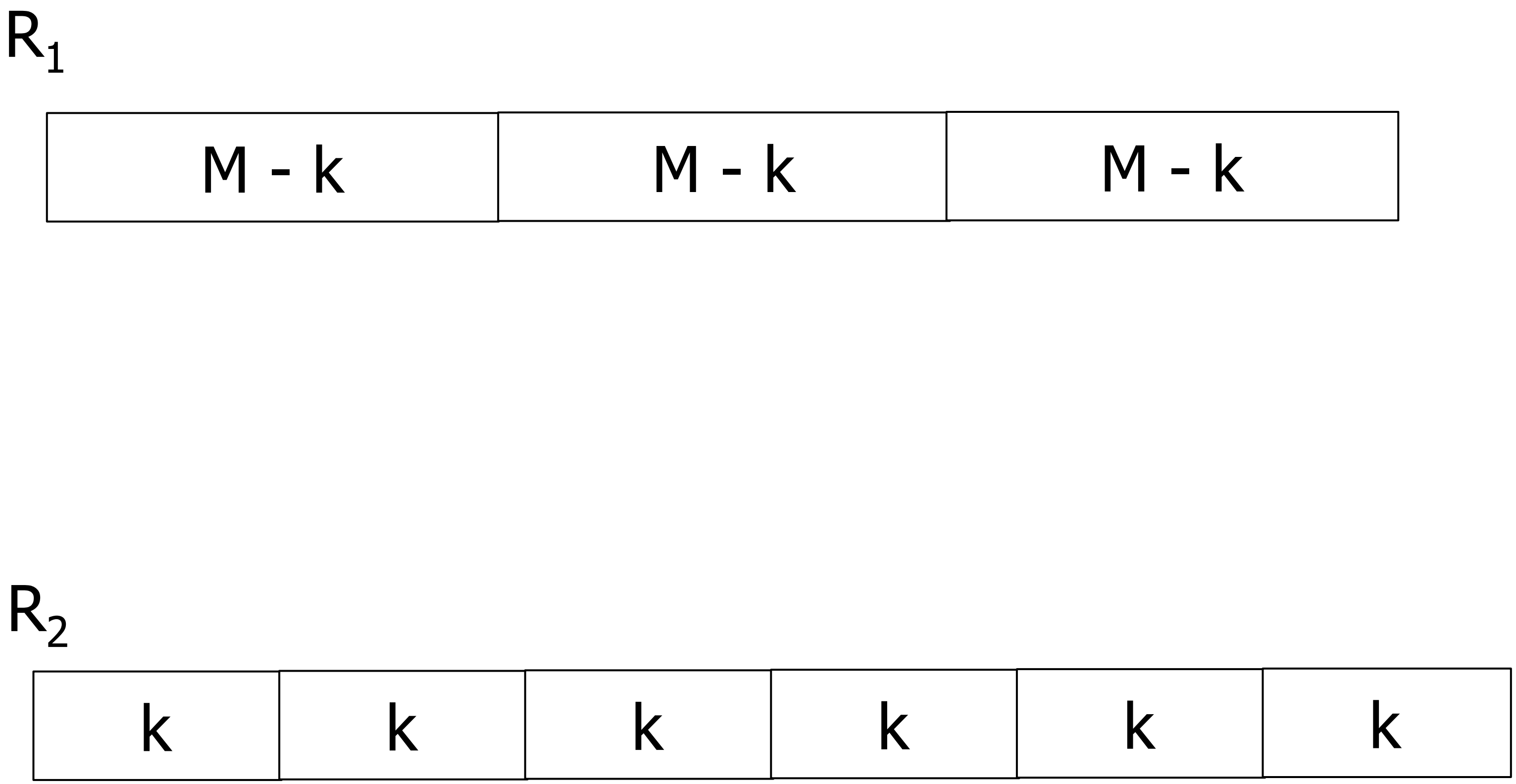
$$\text{Total} = \left\lceil \frac{B(R1)}{M-1} \right\rceil \text{x} \ (\min(B(R1), M-1) + B(R2))$$

Block-Nested Loop Join (conceptual)

```
for each M-1 blocks of $R_1$ do
    read M-1 blocks of $R_1$ into buffer
    for each block of $R_2$ do
        read next block of $R_2$
        for each tuple r in $R_1$ block
            for each tuple s in $R_2$ block
            if $(r,s) \models C$ then output (r,s)
```

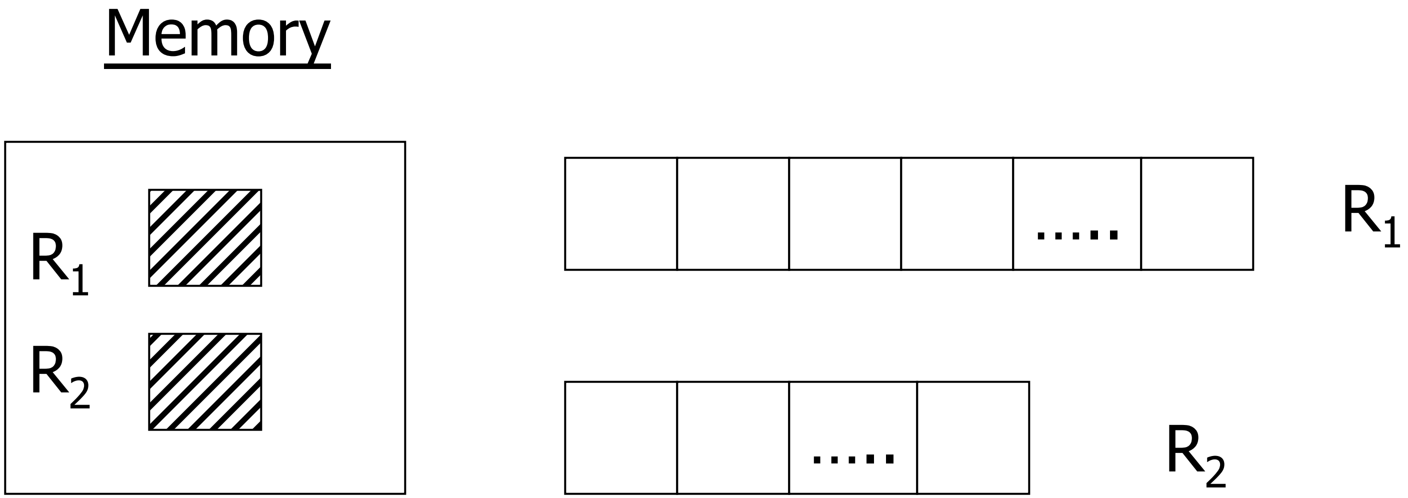
Note

- How much memory for buffering inner and for outer chunks?
  - 1 for inner would minimize I/O
  - But, larger buffer better for I/O


R_1
M - k
M - k
M - k
R_2
k
k
k
k
k
k

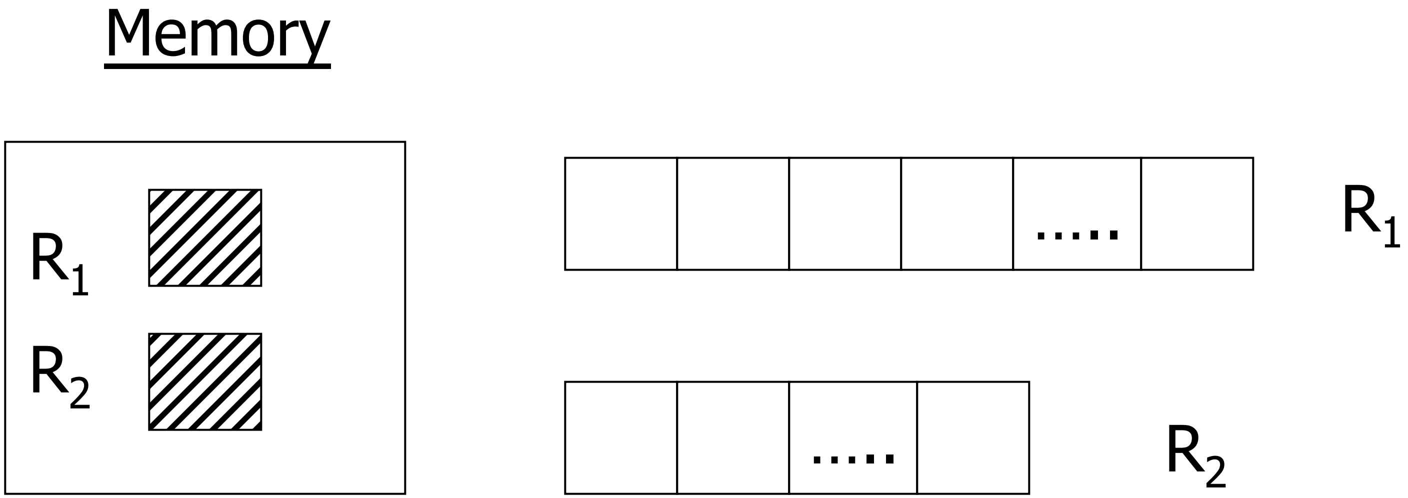
Example 1(b) Merge Join

- Both R_1, R_2 ordered by C; relations contiguous



Example 1(b)   Merge Join

- Both R_1, R_2 ordered by C; relations contiguous



Total cost: Read R_1 cost + read R_2 cost

= 1000 + 500 = 1,500 IOs

Merge Join Example

$R \bowtie_{B=C} S$

Output: (a,1,1,X)

R

A	B
a	1
b	1
a	2
c	3
d	4
e	5

$\leftarrow Z_R$

$Z_S \rightarrow$

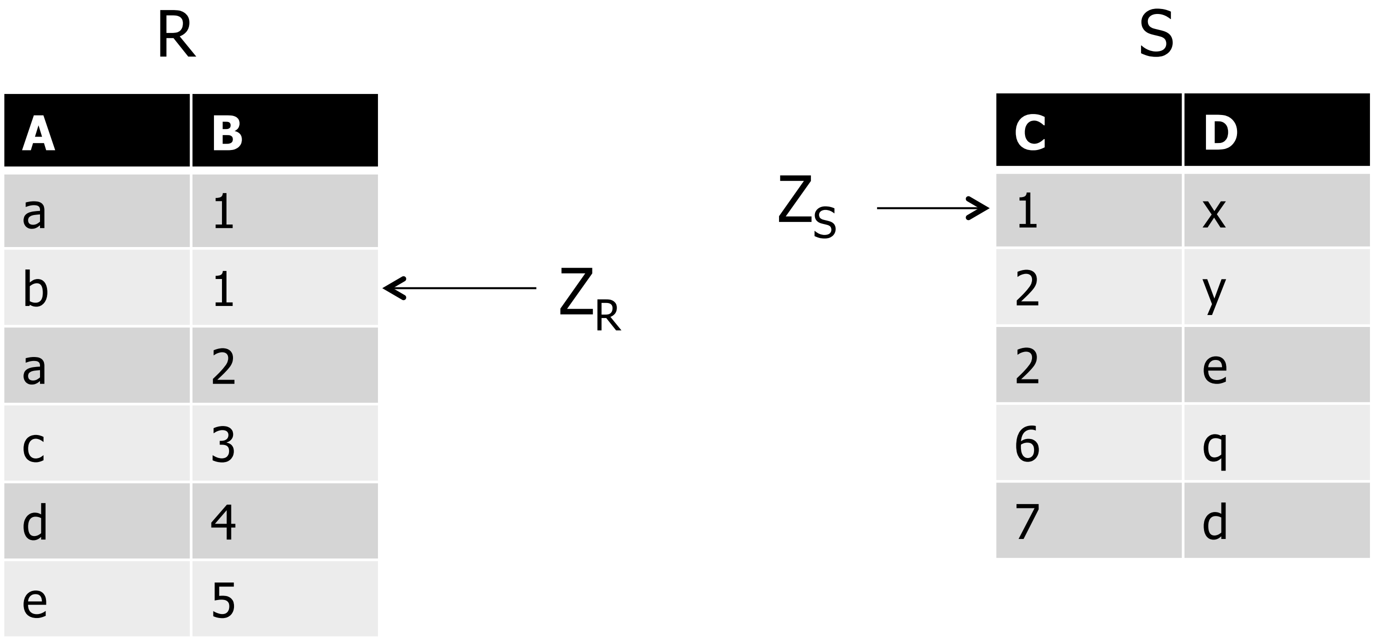
S

C	D
1	x
2	y
2	e
6	q
7	d

Merge Join Example

$R \bowtie_{B=C} S$

Output: (b,1,1,X)



R

A	B
a	1
b	1
a	2
c	3
d	4
e	5

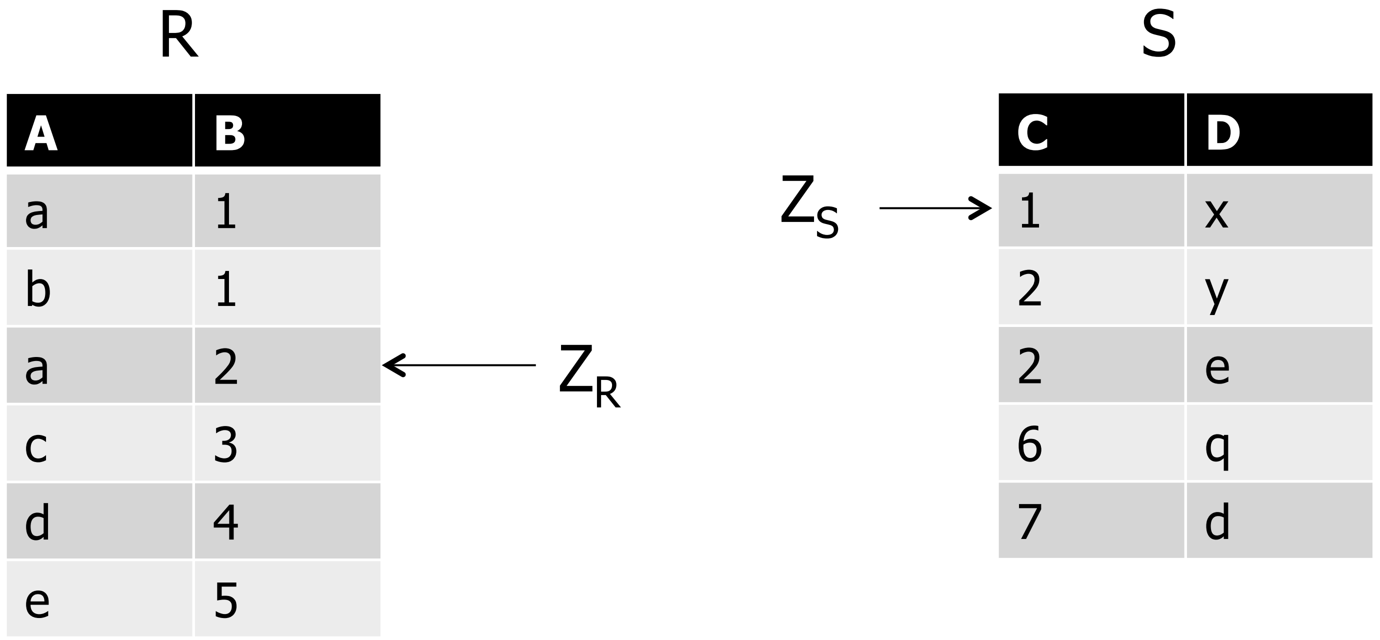
S

C	D
1	x
2	y
2	e
6	q
7	d

Merge Join Example

$R \bowtie_{B=C} S$

R.B > S.C: advance Z_S



R

A	B
a	1
b	1
a	2
c	3
d	4
e	5

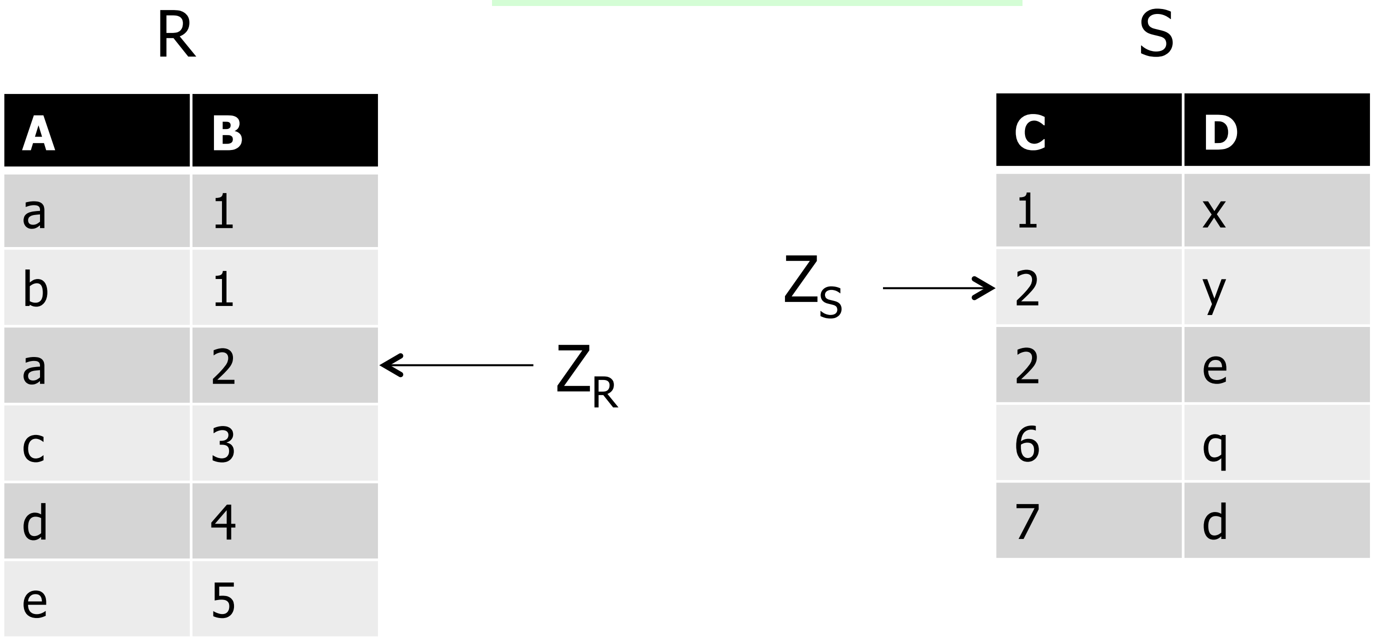
S

C	D
1	x
2	y
2	e
6	q
7	d

Merge Join Example

$R \bowtie_{B=C} S$

Output: (a,2,2,y)



R

A	B
a	1
b	1
a	2
c	3
d	4
e	5

Z_R → row (a, 2)

S

C	D
1	x
2	y
2	e
6	q
7	d

Z_S → row (2, y)

Merge Join Example

$R \bowtie_{B=C} S$

Output: (a,2,2,e)

R

A	B
a	1
b	1
a	2
c	3
d	4
e	5

← Z_R

Z_S →

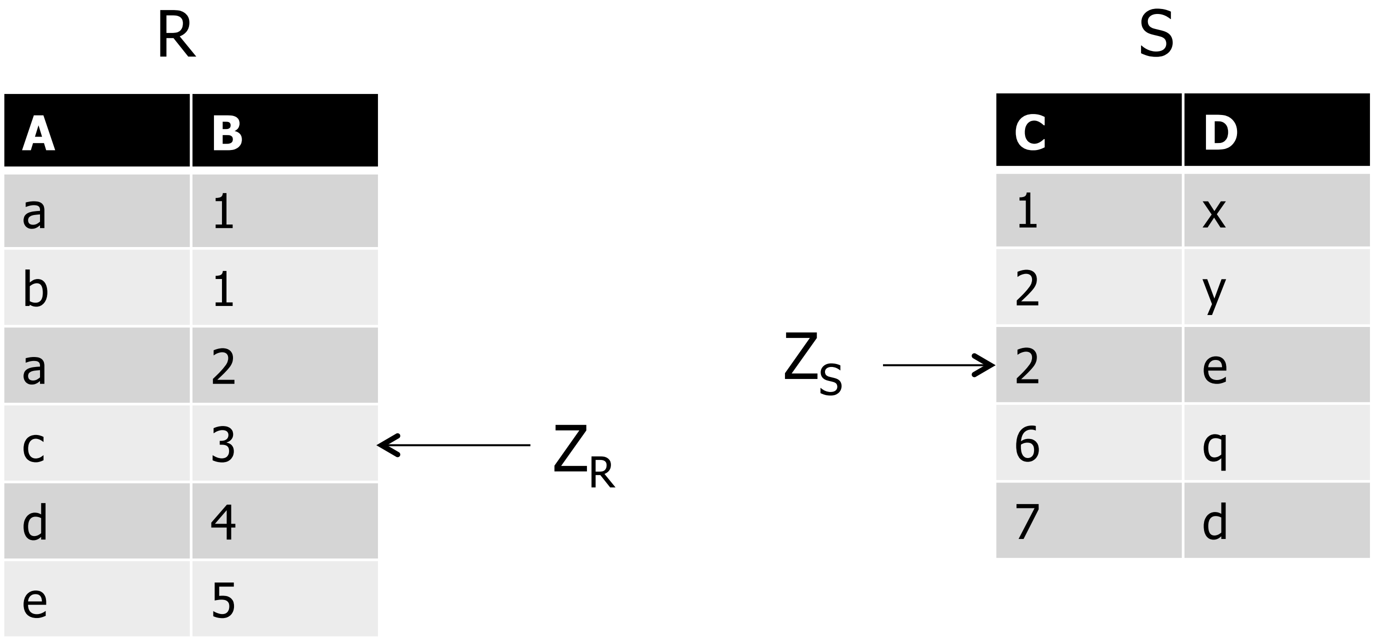
S

C	D
1	x
2	y
2	e
6	q
7	d

Merge Join Example

$R \bowtie_{B=C} S$

R.B > S.C: advance Z_S



R

A	B
a	1
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a	2
c	3
d	4
e	5

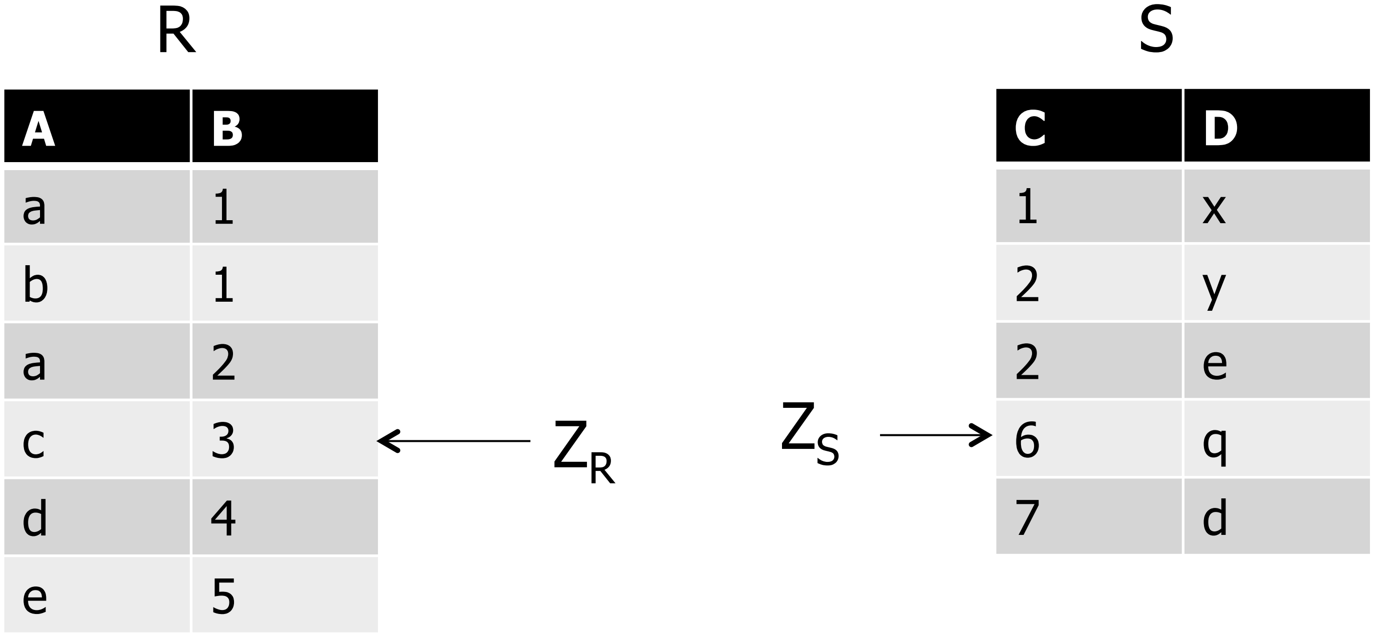
S

C	D
1	x
2	y
2	e
6	q
7	d

Merge Join Example

$R \bowtie_{B=C} S$

R.B < S.C: advance Z_R



R

A	B
a	1
b	1
a	2
c	3
d	4
e	5

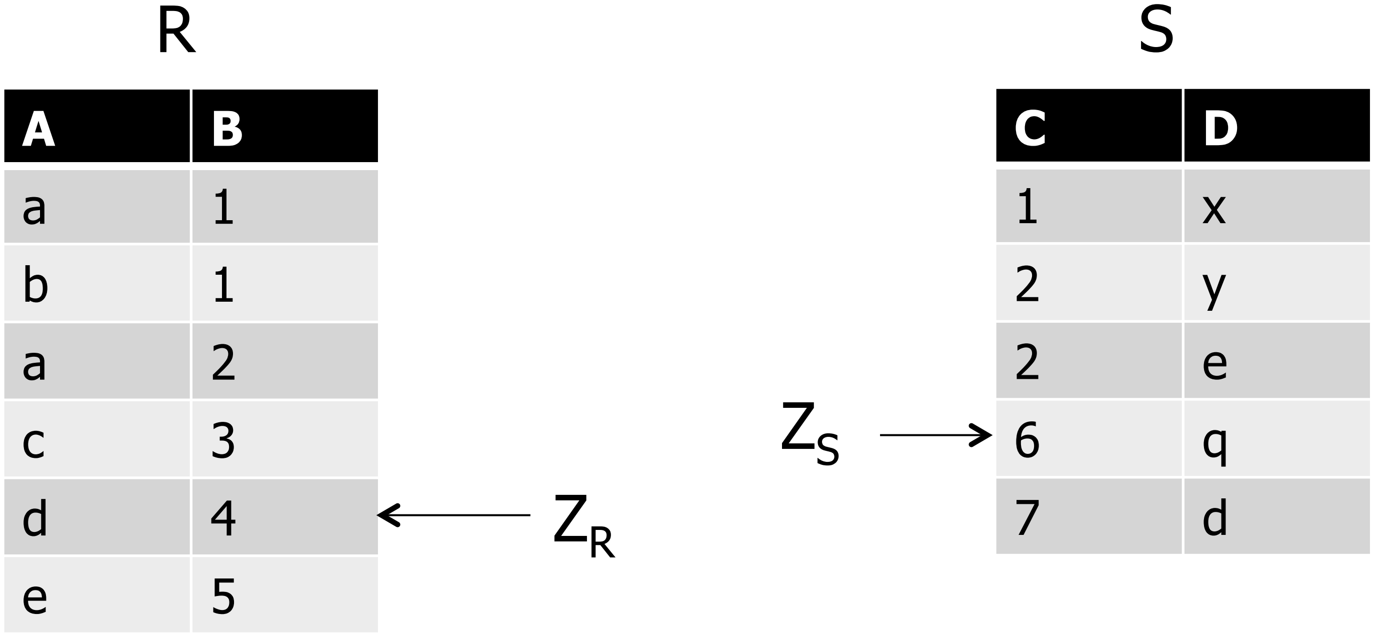
S

C	D
1	x
2	y
2	e
6	q
7	d

Merge Join Example

$R \bowtie_{B=C} S$

R.B < S.C: advance Z_R



R

A	B
a	1
b	1
a	2
c	3
d	4
e	5

S

C	D
1	x
2	y
2	e
6	q
7	d

Merge Join Example

$R \bowtie_{B=C} S$

R.B < S.C: **DONE**

R

A	B	
a	1	
b	1	
a	2	
c	3	
d	4	
e	5	$\leftarrow Z_R$

S

	C	D
	1	x
	2	y
	2	e
$Z_S \rightarrow$	6	q
	7	d

Example 1(c)   Merge Join

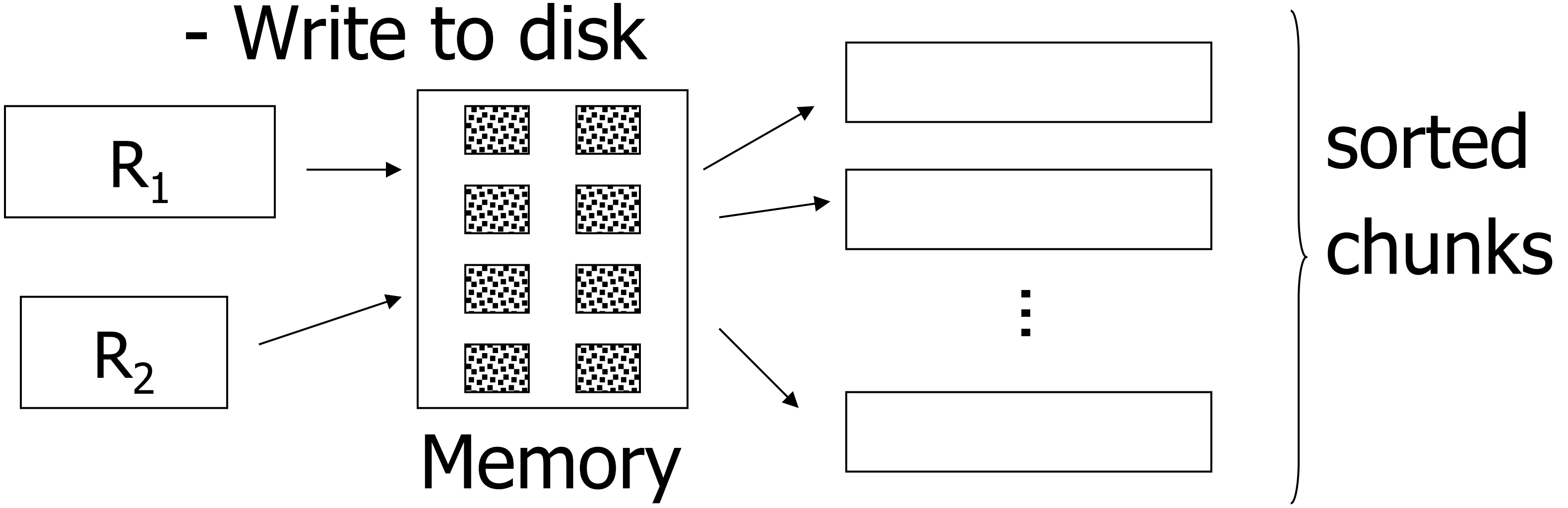
- R_1, R_2 not ordered, but contiguous

--> Need to sort R_1, R_2 first

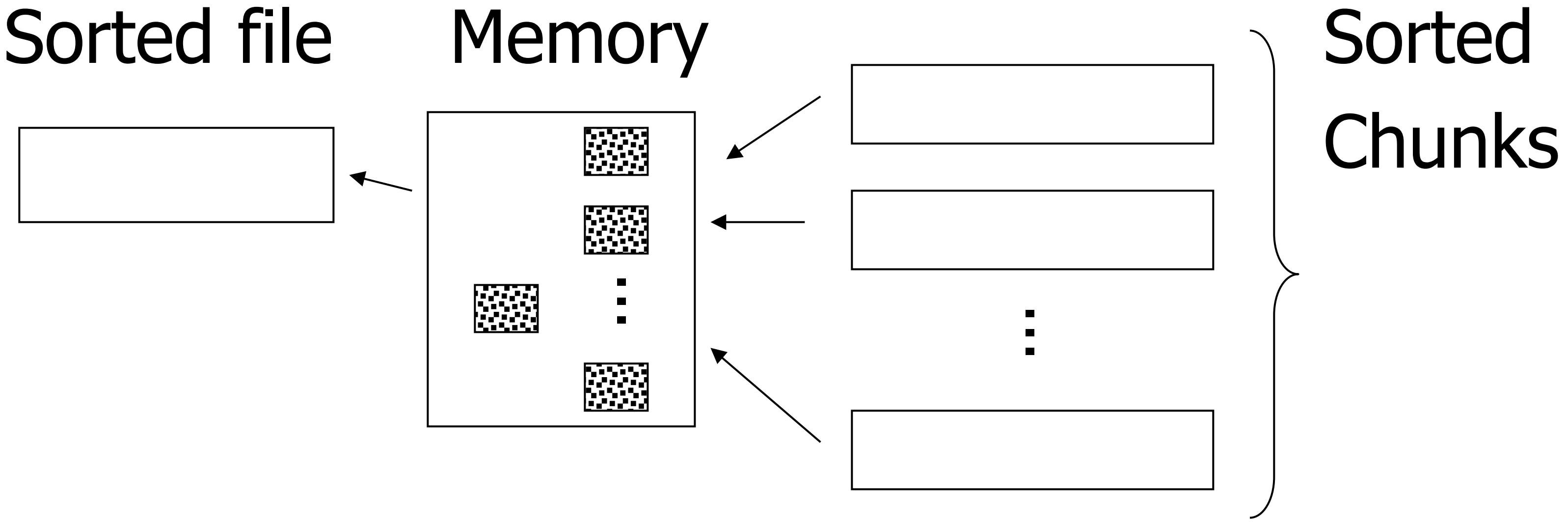
<u>One way to sort:</u> Merge Sort

(i) For each 100 blk chunk of R:

- Read chunk
- Sort in memory
- Write to disk



(ii) Read all chunks + merge + write out



Cost: Sort

Each tuple is read,written,
read, written

so...

Sort cost R_1: 4 x 1,000 = 4,000

Sort cost R_2: 4 x 500 = 2,000

Example 1(d) Merge Join (continued)

R_1,R_2 contiguous, but unordered

Total cost = sort cost + join cost

= 6,000 + 1,500 = 7,500 IOs

Example 1(c) Merge Join (continued)

R_1,R_2 contiguous, but unordered

Total cost = sort cost + join cost

= 6,000 + 1,500 = 7,500 IOs

But: Iteration cost = 5,500

so merge joint does not pay off!

But say R_1 = 10,000 blocks contiguous
R_2 = 5,000 blocks not ordered

<u>Iterate:</u> $\frac{5000}{100} \times (100+10{,}000) = 50 \times 10{,}100$

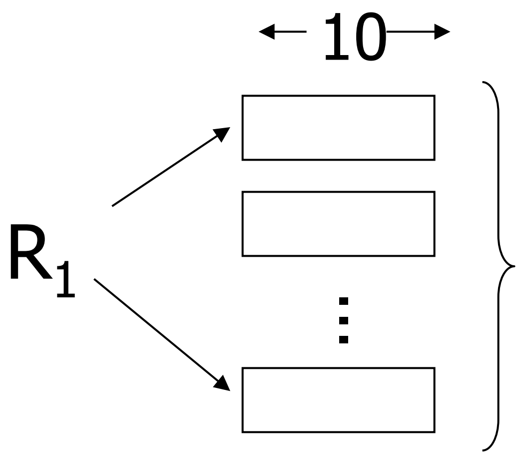
$= 505{,}000$ IOs

<u>Merge join:</u> 5(10,000+5,000) = 75,000 IOs

Merge Join (with sort) WINS!

How much memory do we need for merge sort?

E.g: Say I have 10 memory blocks



100 chunks ⇒ to merge, need 100 blocks!

In general:

Say k blocks in memory

x blocks for relation sort

chunks = (x/k)   size of chunk = k

In general:

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x blocks for relation sort

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chunks < buffers available for merge

In general:

Say k blocks in memory

x blocks for relation sort

chunks = (x/k)   size of chunk = k

chunks < buffers available for merge

so... $(x/k) \le k$

or $k^2 \ge x$ or $k \ge \sqrt{x}$

In our example

R_1 is 1000 blocks, $k \geq 31.62$

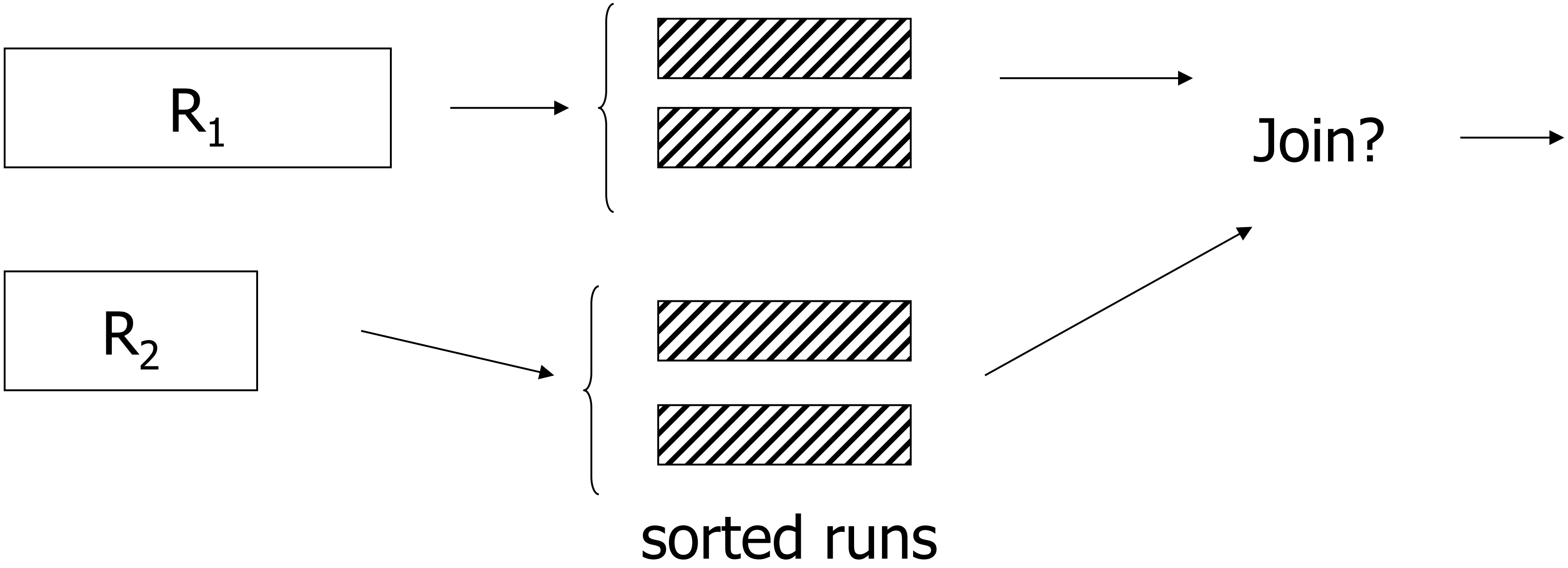
R_2 is 500 blocks, $k \geq 22.36$

Need at least 32 buffers

Again: in practice we would not want to use only one buffer per run!

Can we improve on merge join?

Hint: do we really need the fully sorted files?



R_1

R_2

Join?

sorted runs

Cost of improved merge join:

C = Read R_1 + write R_1 into runs

+ read R_2 + write R_2 into runs

+ join

= 2,000 + 1,000 + 1,500 = 4,500

--> Memory requirement?

Example 1(d) Index Join

- Assume R_1.C index exists; 2 levels
- Assume R_2 contiguous, unordered

- Assume R_1.C index fits in memory

Cost: Reads: 500 IOs

for each R_2 tuple:

- probe index - free
- if match, read R_1 tuple: 1 IO

What is expected # of matching tuples?

(a) say R_1.C is key, R_2.C is foreign key

then expect = 1

(b) say $V(R_1,C) = 5000$, $T(R_1) = 10,000$

with uniform assumption

expect = 10,000/5,000 = 2

What is expected # of matching tuples?

(c) Say $DOM(R_1, C)=1{,}000{,}000$

$T(R_1) = 10{,}000$

with alternate assumption

$$\text{Expect} = \frac{10{,}000}{1{,}000{,}000} = \frac{1}{100}$$

Total cost with index join

(a) Total cost = 500+5000(1)1 = 5,500

(b) Total cost = 500+5000(2)1 = 10,500

(c) Total cost = 500+5000(1/100)1=550

What if index does not fit in memory?

Example: say R_1.C index is 201 blocks

- Keep root + 99 leaf nodes in memory
- Expected cost of each probe is

$$E = (0)\frac{99}{200} + (1)\frac{101}{200} \approx 0.5$$

Total cost (including probes)

= 500+5000 [Probe + get records]

= 500+5000 [0.5+2] uniform assumption

= 500+12,500 = 13,000 (case b)

Total cost (including probes)

= 500+5000 [Probe + get records]

= 500+5000 [0.5+2]   uniform assumption

= 500+12,500 = 13,000   (case b)

For case (c):

= 500+5000[0.5 × 1 + (1/100) × 1]

= 500+2500+50 = 3050 IOs

So far

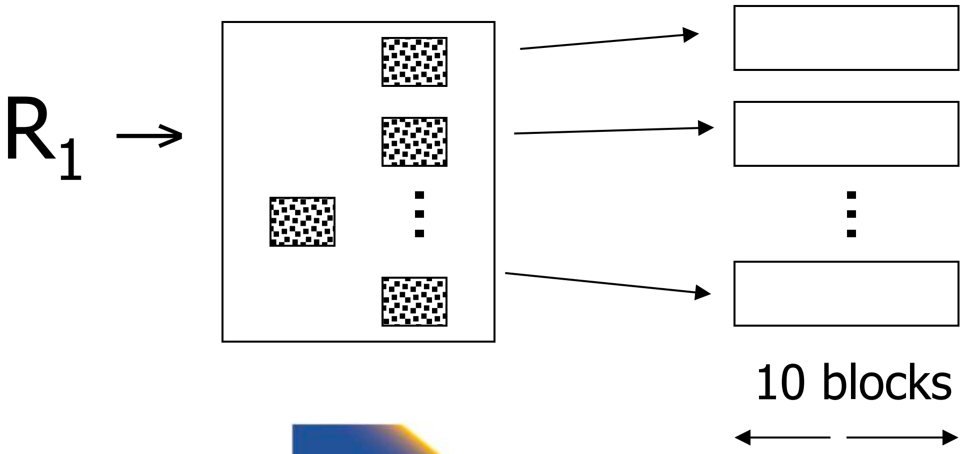
Nested Loop	5500
Merge join	1500
Sort+Merge Join	7500 → 4500
R_1.C Index	5500 → 3050 → 550
R_2.C Index	________

Example 1(e) Partition Hash Join

- R_1, R_2 contiguous (un-ordered)

→ Use 100 buckets

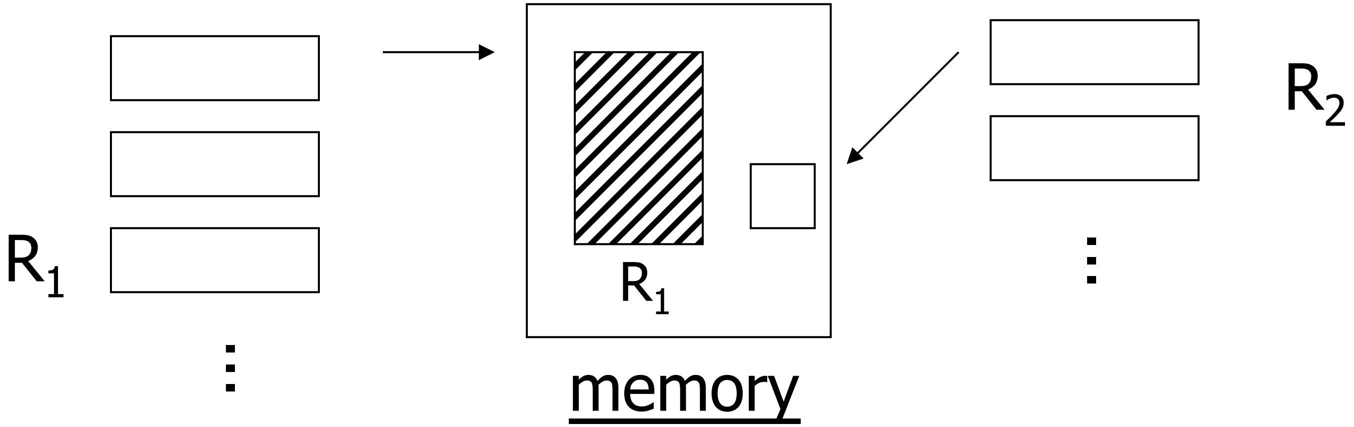
→ Read R_1, hash, + write buckets



-> Same for R_2

-> Read one R_1 bucket; build memory hash table
  -using different hash function h'

-> Read corresponding R_2 bucket + hash probe



✏ Then repeat for all buckets

Cost:

“Bucketize:” Read R_1 + write

Read R_2 + write

Join: Read R_1, R_2

Total cost = 3 x [1000+500] = 4500

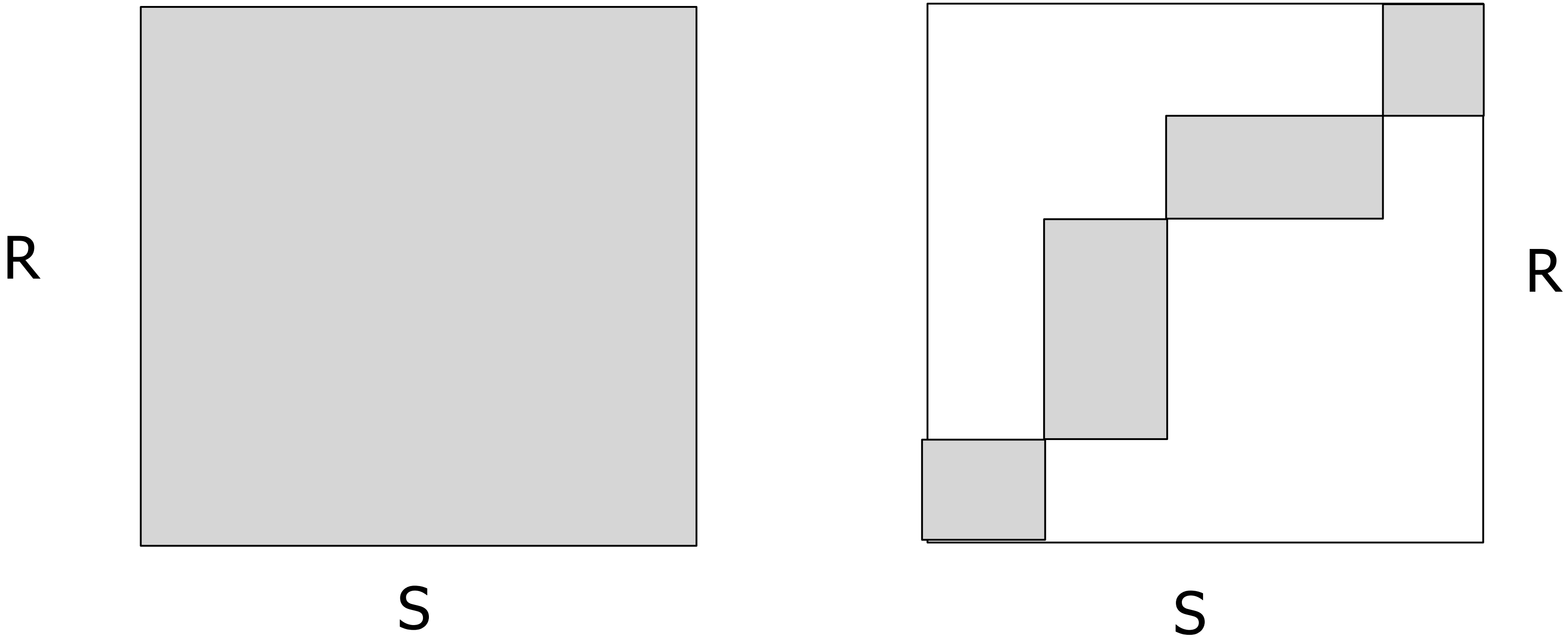
Cost:

"Bucketize:"	Read R_1 + write
	Read R_2 + write
Join:	Read R_1, R_2

Total cost = 3 x [1000+500] = 4500

Note: this is an approximation since buckets will vary in size and we have to round up to blocks

Why is Hash Join good?



Minimum memory requirements:

Size of R_1 bucket = (x/k)

k = number of memory buffers

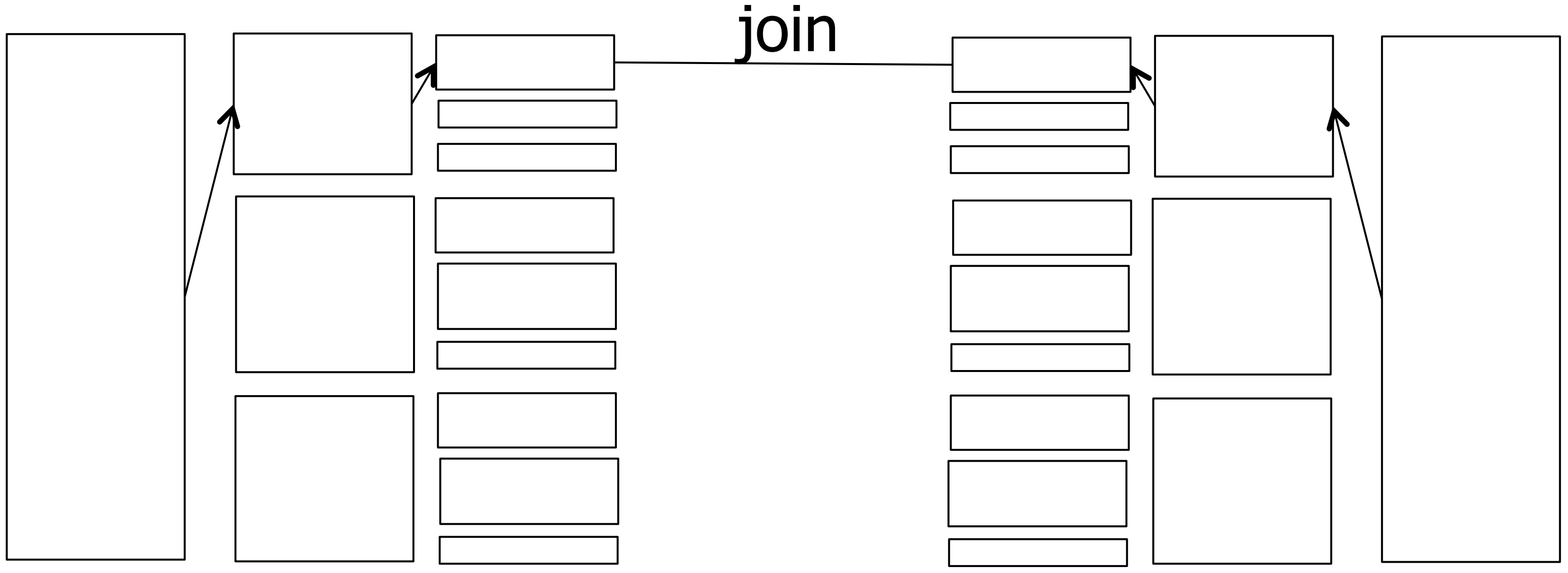
x = number of R_1 blocks

So... $(x/k) < k$

$k > \sqrt{x}$ need: k+1 total memory buffers

Can we use Hash-join when buckets do not fit into memory?:

- Treat buckets as relations and apply Hash-join recursively

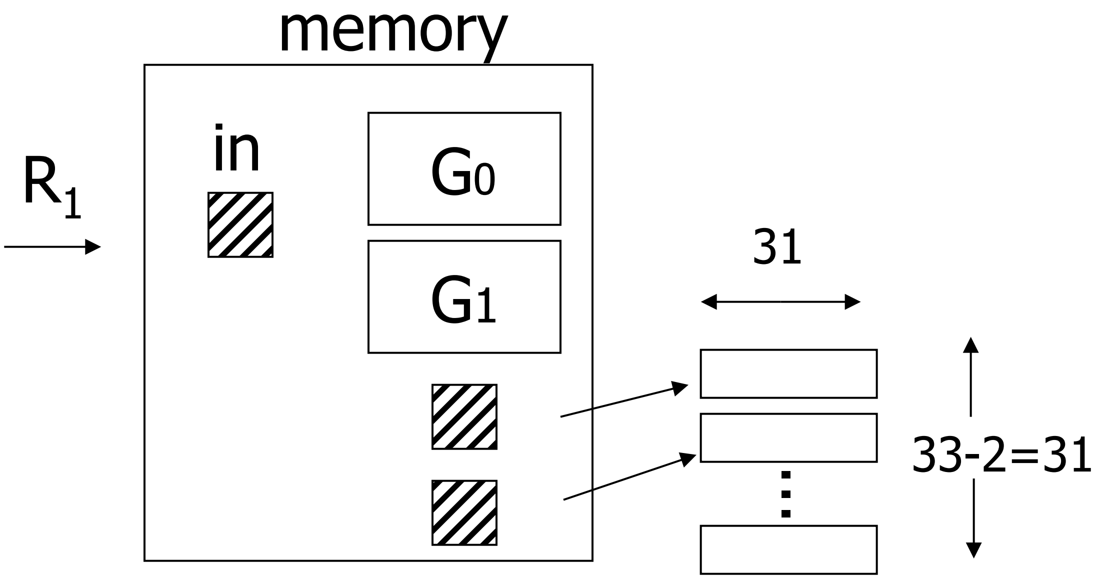


Duality Hashing-Sorting

- Both partition inputs
- Until input fits into memory
- Logarithmic number of phases in memory size

Trick: keep some buckets in memory

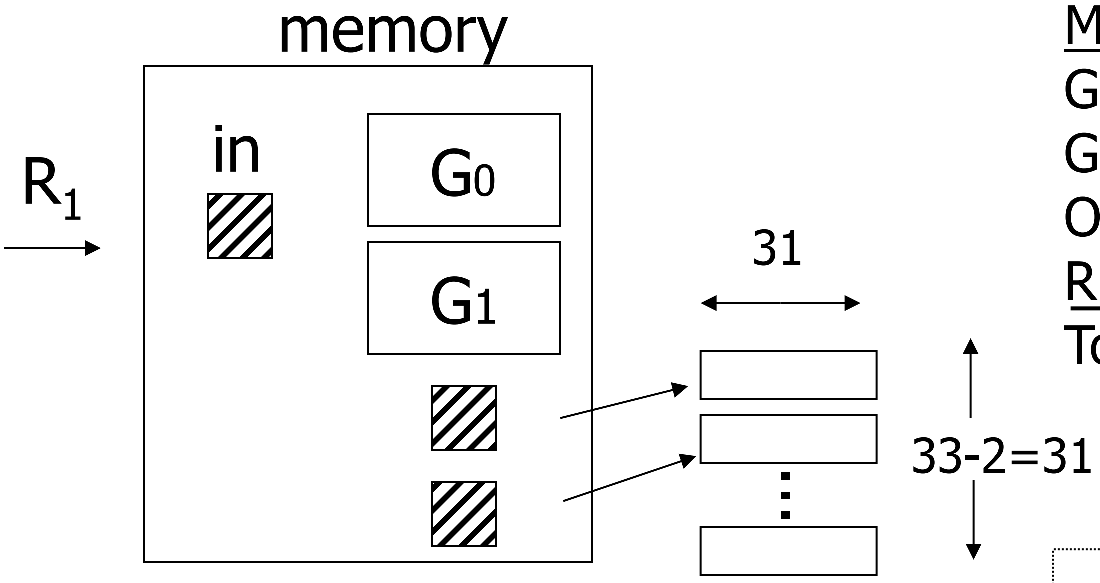
E.g., k' =33 R_1 buckets = 31 blocks
keep 2 in memory



called hybrid hash-join

Trick: keep some buckets in memory

E.g., k' =33 R_1 buckets = 31 blocks
keep 2 in memory



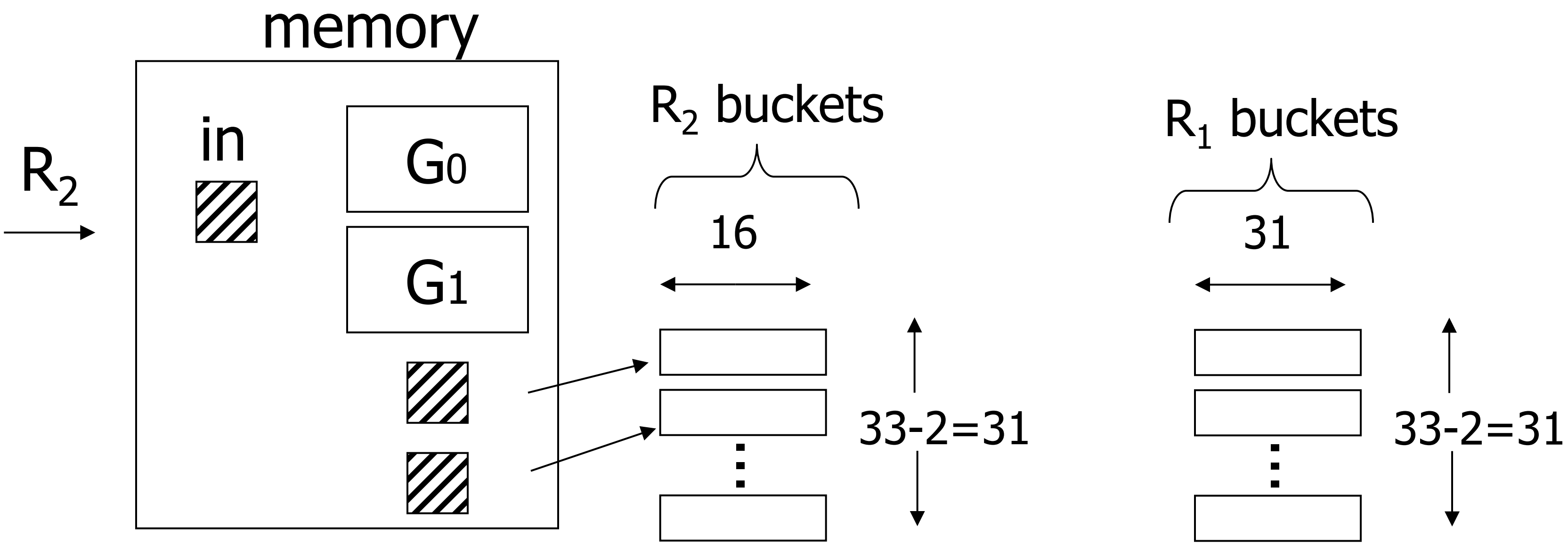
Memory use:	
G_0	31 buffers
G_1	31 buffers
Output	33-2 buffers
R_1 input	1
Total	94 buffers

6 buffers to spare!!

called hybrid hash-join

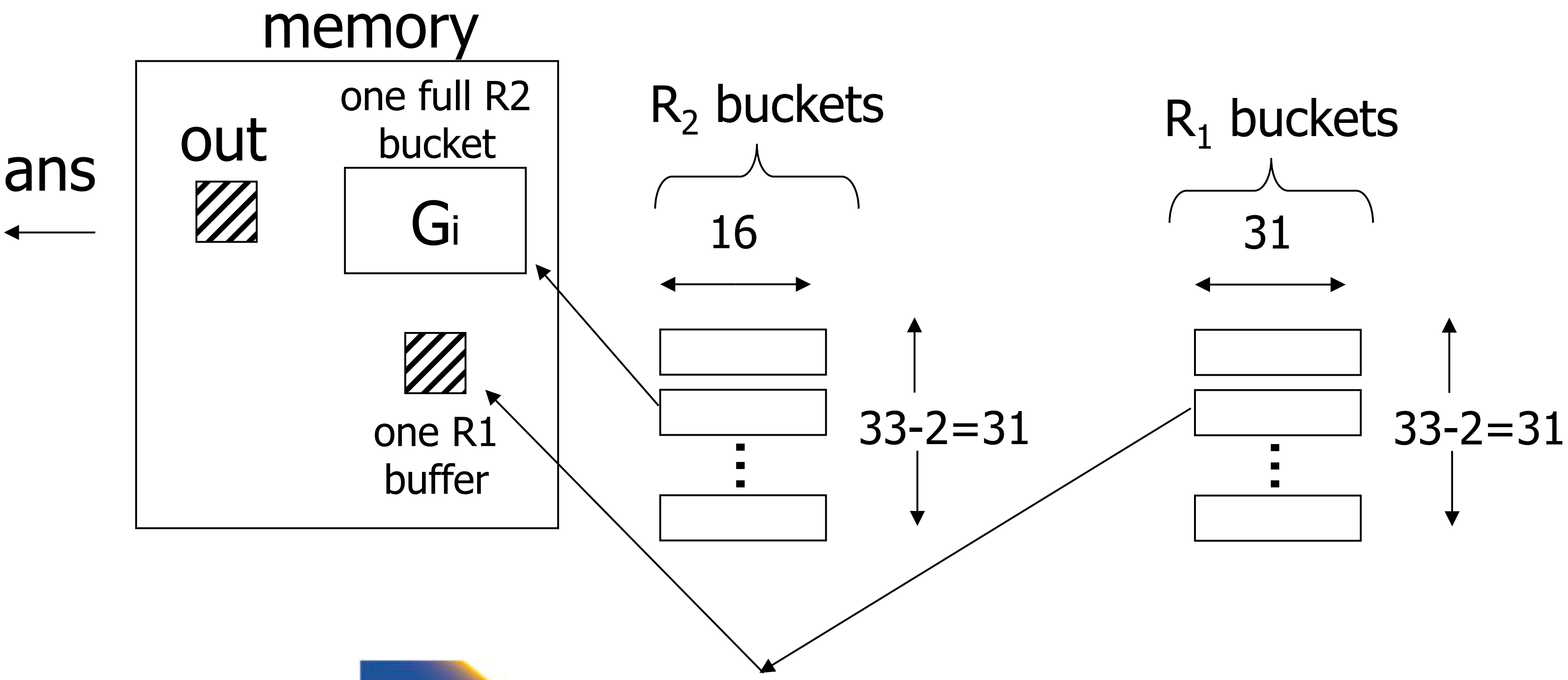
Next: Bucketize R_2

- R_2 buckets =500/33= 16 blocks
- Two of the R_2 buckets joined immediately with G_0,G_1



Finally: Join remaining buckets

- for each bucket pair:
  - read one of the buckets into memory
  - join with second bucket

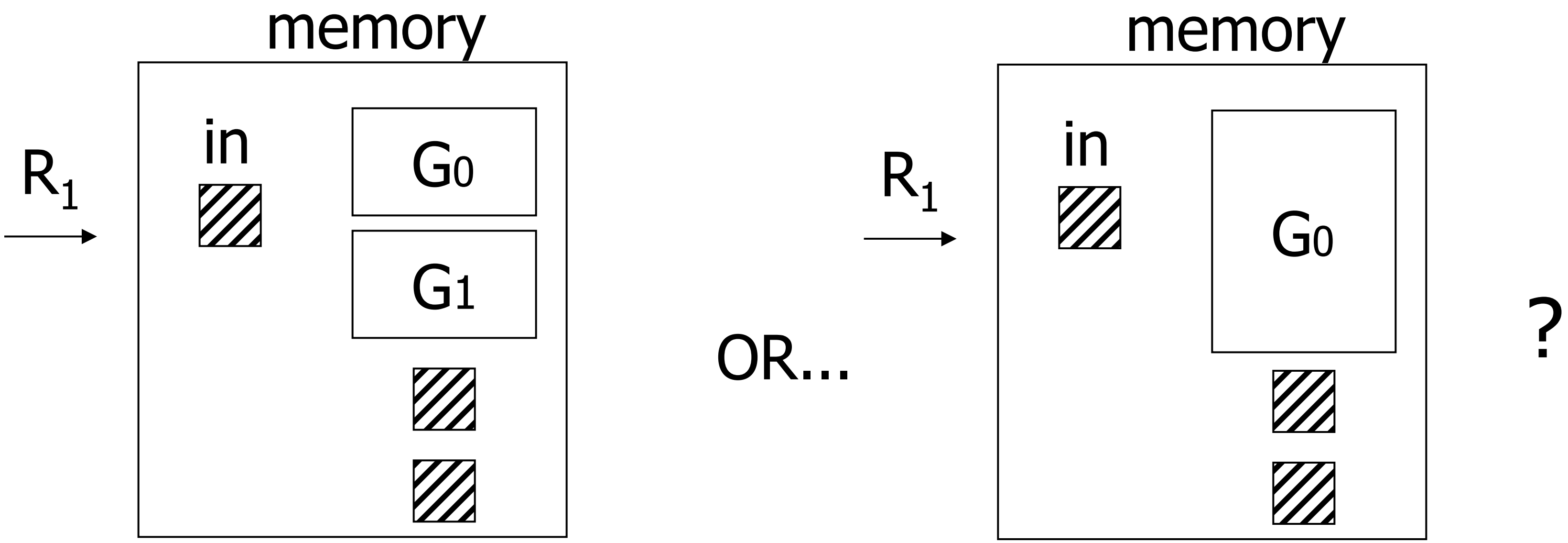


Cost

- Bucketize R_1 = 1000+31×31=1961
- To bucketize R_2, only write 31 buckets:
  so, cost = 500+31×16=996
- To compare join (2 buckets already done)
  read 31×31+31×16=1457

Total cost = 1961+996+1457 = 4414

How many buckets in memory?



☛ See textbook for answer...

Another hash join trick:

- Only write into buckets
  <val,ptr> pairs
- When we get a match in join phase,
  must fetch tuples

- To illustrate cost computation, assume:
  - 100 <val,ptr> pairs/block
  - expected number of result tuples is 100

- To illustrate cost computation, assume:
  - 100 <val,ptr> pairs/block
  - expected number of result tuples is 100
- Build hash table for R_2 in memory
  5000 tuples → 5000/100 = 50 blocks
- Read R_1 and match
- Read ~ 100 R_2 tuples

- To illustrate cost computation, assume:
  - 100 <val,ptr> pairs/block
  - expected number of result tuples is 100
- Build hash table for R_2 in memory
  5000 tuples → 5000/100 = 50 blocks
- Read R_1 and match
- Read ~ 100 R_2 tuples

Total cost =	Read R_2:	500
	Read R_1:	1000
	Get tuples:	100
		1600

So far:

Iterate	5500
Merge join	1500
Sort+merge joint	7500
R_1.C index	5500 → 550
R_2.C index	______
Build R_1.C index	______
Build R_2.C index	______
Hash join	4500+
with trick,R_1 first	4414
with trick,R_2 first	______
Hash join, pointers	1600

Yet another hash join trick:

- Combine the ideas of
  - block nested-loop with hash join
- Use memory to build hash-table for one chunk of relation
- Find join partners in O(1) instead of O(M)
- Trade-off
  - Space-overhead of hash-table
  - Time savings from look-up

Summary

- Nested Loop ok for “small” relations (relative to memory size)
  - Need for complex join condition
- For equi-join, where relations not sorted and no indexes exist, hash join usually best

- Sort + merge join good for non-equi-join (e.g., $R_1.C > R_2.C$)
- If relations already sorted, use merge join
- If index exists, it <u>could</u> be useful

(depends on expected result size)

Join Comparison

N_i= number of tuples in R_i
$B(R_i)$ = number of blocks of R_i
#P = number of partition steps for hash join
P_{ij} = average number of join partners

Algorithm	#I/O	Memory	Disk Space
Nested Loop (block)	$B(R_1) / (M-1) * [\min(B(R), M-1) + B(R_2)]$	3	0
Index Nested Loop	$B(R_1) + N_1 * P_{12}$	B(Index) + 2	0
Merge (sorted)	$B(R_1) + B(R_2)$	Max tuples =	0
Merge (unsorted)	$B(R_1) + B(R_2) +$ (sort – 1 pass)	sort	$B(R_1) + B(R_2)$
Hash	$(2\#P + 1) (B(R_1) + B(R_2))$	root(max($B(R_1)$, $B(R_2)$), #P + 1)	~$B(R_1) + B(R_2)$

Why do we need nested loop?

- Remember not all join implementations work for all types of join conditions

Algorithm	Type of Condition	Example
Nested Loop	any	a LIKE '%hello%'
Index Nested Loop	Supported by index: Equi-join (hash) Equi or range (B-tree)	a = b a < b
Merge	Equalities and ranges	a < b, a = b AND c = d
Hash	Equi-join	a = b

Outer Joins

- How to implement (left) outer joins?
- Nested Loop and Merge
  - Use a flag that is set to true if we find a match for an outer tuple
  - If flag is false fill with NULL
- Hash
  - If no matching tuple fill with NULL

Merge Left Outer Join

$R ⟕_{B=C} S$

Output: (a,1,1,X)

R

A	B
a	1
d	4
e	5

Z_R

Z_S

S

C	D
1	x
2	y
2	e
6	q
7	d

Merge Left Outer Join

$R ⟕_{B=C} S$

No match for (d,4)
Output: (d,4,NULL,NULL)

R

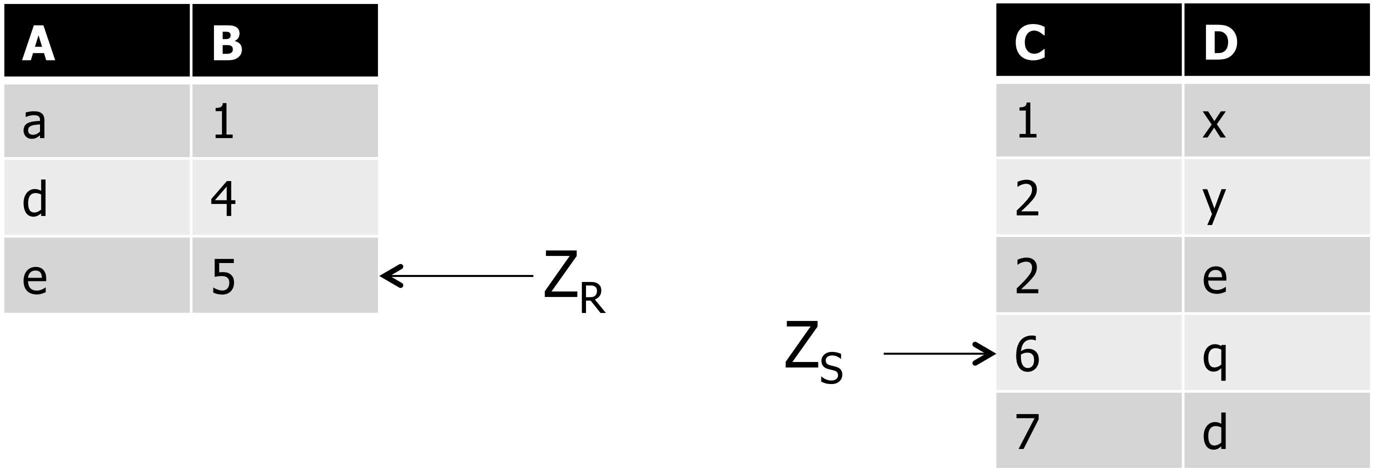
A	B	
a	1	
d	4	← Z_R
e	5	

	C	D
	1	x
	2	y
	2	e
Z_S →	6	q
	7	d

Merge Left Outer Join

$R ⟕_{B=C} S$

No match for (e,5)
Output: (e,5,NULL,NULL)



R

A	B
a	1
d	4
e	5

C	D
1	x
2	y
2	e
6	q
7	d

Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, …)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

Aggregation

- Have to compute aggregation functions
  - for each group of tuples from input
- Groups
  - Determined by equality of group-by attributes

Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```

a	b
3	1
4	2
3	1
1	2
1	2

sum(a)	b
6	1
6	2

Aggregation Function Interface

- `init()`
  - Initialize state
- `update(tuple)`
  - Update state with information from tuple
- `close()`
  - Return result and clean-up

Implementation SUM(A)

- `init()`
  - `sum := 0`
- `update(tuple)`
  - `sum += tuple.A`
- `close()`
  - `**return** sum`

Aggregation Implementations

- Sorting
  - Sort input on group-by attributes
  - On group boundaries output tuple
- Hashing
  - Store current aggregated values for each group in hash table
  - Update with newly arriving tuples
  - Output result after processing all inputs

Grouping by sorting

- Similar to Merge join
- Sort R on group-by attribute
- Scan through sorted input
  - If group-by values change
    - Output using close() and call init()
  - Otherwise
    - Call update()

Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```

sort

a	b
3	1
4	2
3	1
1	2
1	2

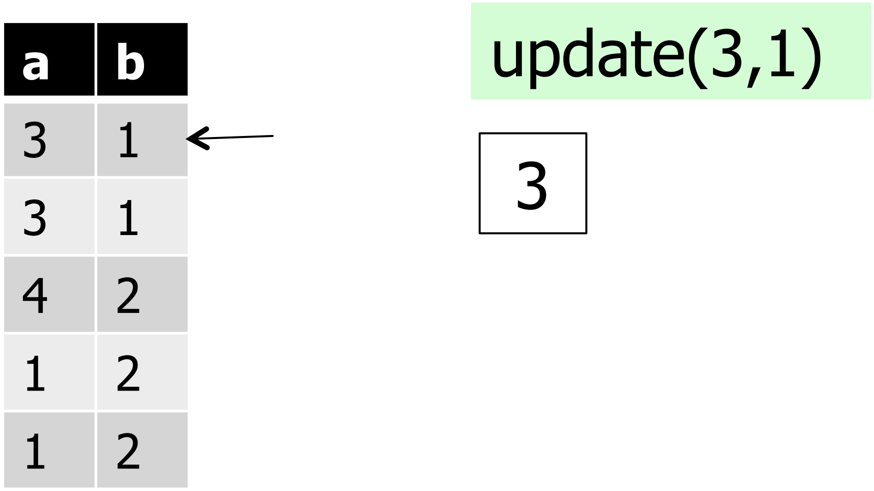
a	b
3	1
3	1
4	2
1	2
1	2

init()

0

Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```



a	b
3	1
3	1
4	2
1	2
1	2

update(3,1)

3

Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```

a	b
3	1
3	1
4	2
1	2
1	2

update(3,1)

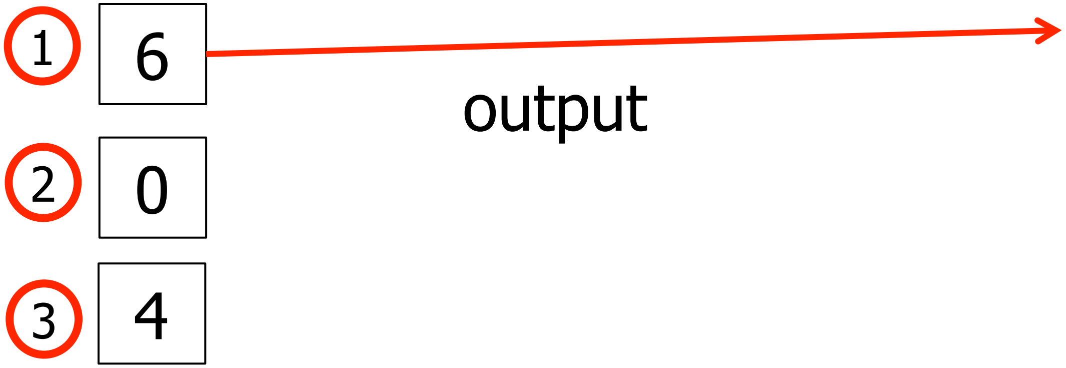
6

Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```

a	b
3	1
3	1
4	2
1	2
1	2

Group by changed!
close(), init(), update(4,2)



① 6

② 0

③ 4

output

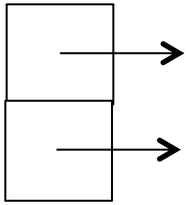
Grouping by Hashing

- Create in-memory hash-table
- For each input tuple probe hash table with group by values
  - If no entry exists then call init(), update(), and add entry
  - Otherwise call update() for entry
- Loop through all entries in hash-table and ouput calling close()

Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```

a	b
3	1
4	2
3	1
1	2
1	2

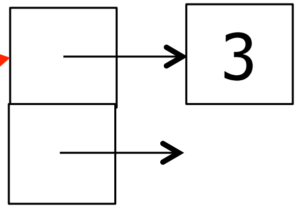


Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```

Init() and update(3,1)

a	b
3	1
4	2
3	1
1	2
1	2

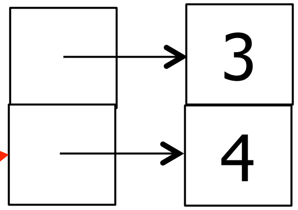


Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```

Init() and update(4,2)

a	b
3	1
4	2
3	1
1	2
1	2

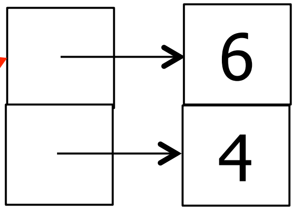


Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```

update(3,1)

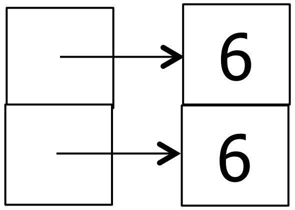
a	b
3	1
4	2
3	1
1	2
1	2



Aggregation Example

```
SELECT sum(a),b
FROM R
GROUP BY b
```

- Loop through hash table entries
- Output tuples



a	b
3	1
4	2
3	1
1	2
1	2

Aggregation Summary

- Hashing
  - No sorting -> no extra I/O
  - Hash table has to fit into memory
  - No outputs before all inputs have been processed
- Sorting
  - No memory required
  - Output one group at a time

Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, …)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

Duplicate Elimination

- Equivalent to group-by on all attributes
- -> Can use aggregation implementations
- Optimization
  - Hash
    - Directly output tuple and use hash table only to avoid outputting duplicates

Operators Overview

- (External) Sorting
- Joins (Nested Loop, Merge, Hash, …)
- Aggregation (Sorting, Hash)
- Selection, Projection (Index, Scan)
- Union, Set Difference
- Intersection
- Duplicate Elimination

Set Operations

- Can be modeled as join
  - – with different output requirements
- As aggregation/group by on all columns
  - – with different output requirements

Union

- Bag union
  - Append the two inputs
  - E.g., using three buffers
- Set union
  - Apply duplicate removal to result

Intersection

- Set version
  - Equivalent to join + project + duplicate removal
  - 3-state aggregate function (found left, found right, found both)
- Bag version
  - Join + project + min(i,j)
  - Aggegate min(count(i),count(j))

Set Difference

- Using join methods
  - Find matching tuples
  - If no match found, then output
- Using aggregation
  - count(i) – count(j) **(bag)**
  - true(i) AND false(j) **(set)**

Summary

- Operator implementations
  - Joins!
  - Other operators
- Cost estimations
  - I/O
  - memory
- Query processing architectures

Next

- Query Optimization Physical
- -> How to **efficiently** choose an **efficient** plan

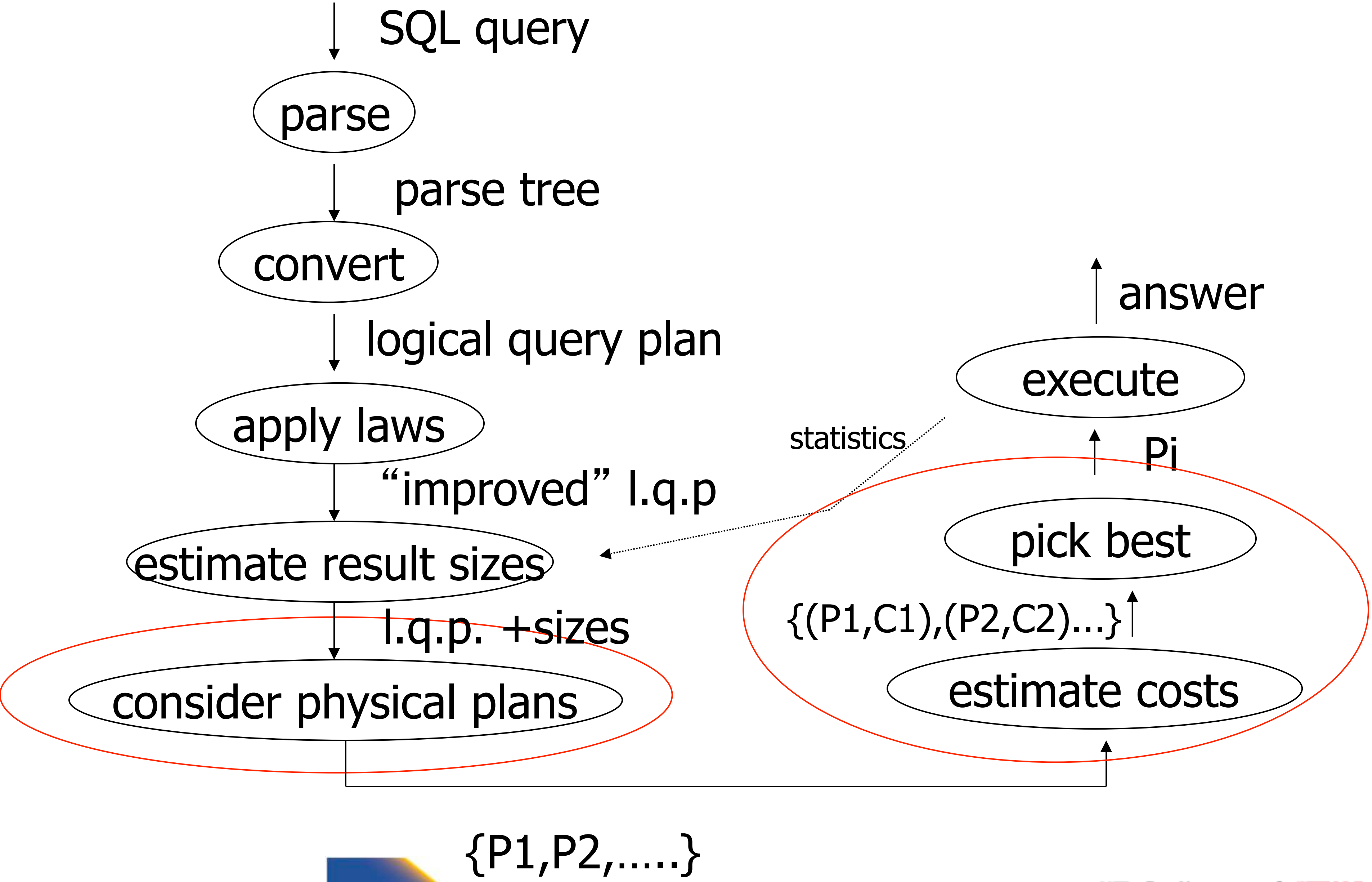
CS 525: Advanced Database Organization

11: Query Optimization

Physical

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab



SQL query

parse

parse tree

convert

logical query plan

apply laws

“improved” l.q.p

estimate result sizes

l.q.p. +sizes

consider physical plans

{P1,P2,.....}

estimate costs

{(P1,C1),(P2,C2)...}

pick best

Pi

execute

answer

statistics

Cost of Query

- Parse + Analyze
- Optimization – Find plan
- Execution
- Return results to client

Cost of Query

- Parse + Analyze
  - Can parse MB of SQL code in milisecs
- **Optimization – Find plan**
  - **Generating plans, costing plans**
- **Execution**
  - **Execute plan**
- Return results to client
  - Can be expensive but not discussed here

Physical Optimization

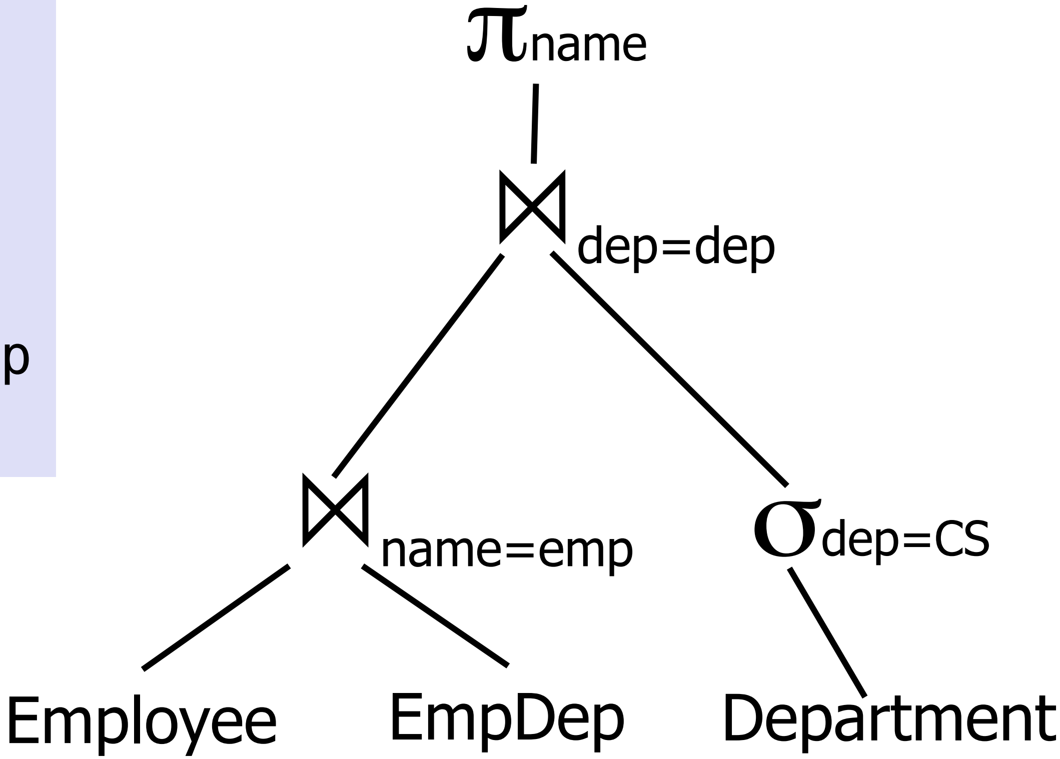
- Apply after applying heuristics in logical optimization
- 1) Enumerate potential execution plans
  - All?
  - Subset
- 2) Cost plans
  - What cost function?

Physical Optimization

- To apply pruning in the search for the best plan
  - Steps 1 and 2 have to be interleaved
  - Prune parts of the search space
    - if we know that it cannot contain any plan that is better than what we found so far

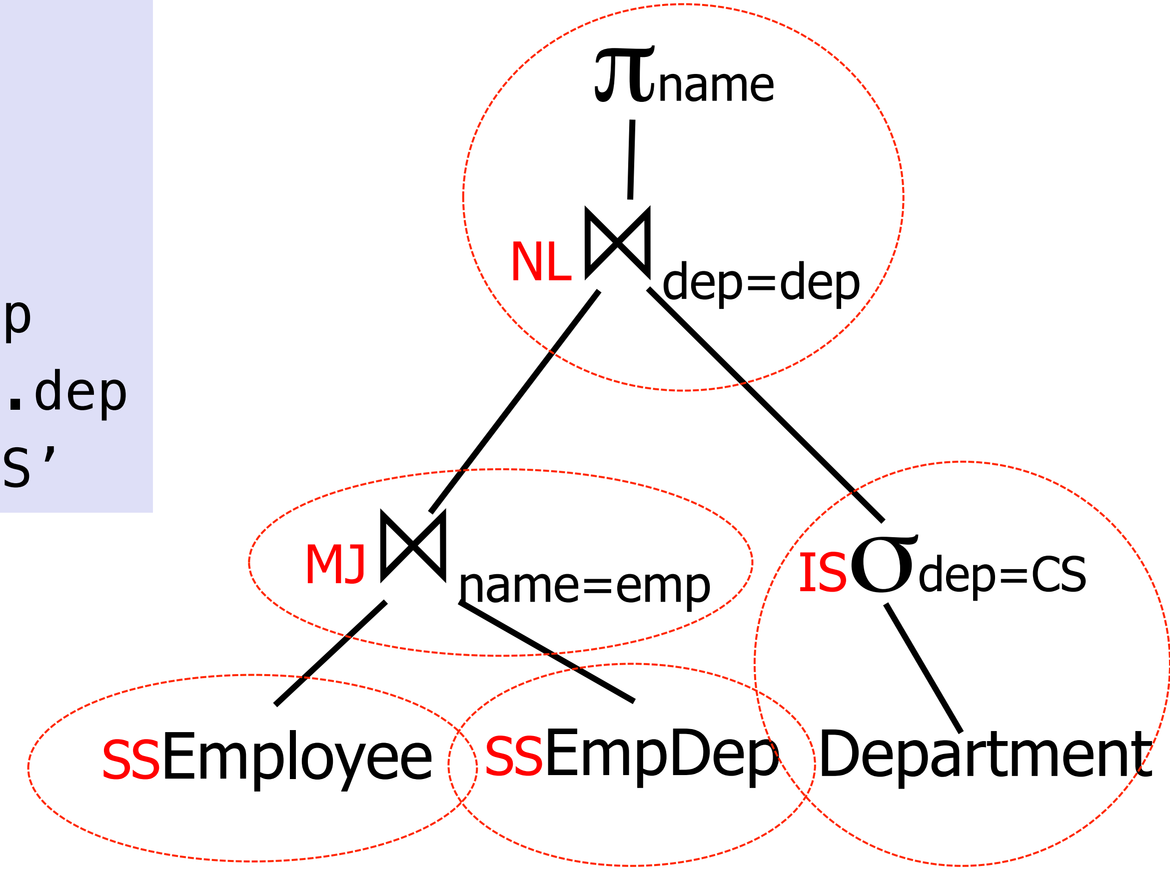
Example Query

```
SELECT e.name
FROM Employee e,
     EmpDep ed,
     Department d
WHERE e.name = ed.emp
      AND ed.dep = d.dep
      AND d.dep = ‘CS’
```



Example Query – Possible Plan

```
SELECT e.name
FROM Employee e,
     EmpDep ed,
     Department d
WHERE e.name = ed.emp
      AND ed.dep = d.dep
      AND d.dep = ‘CS’
```



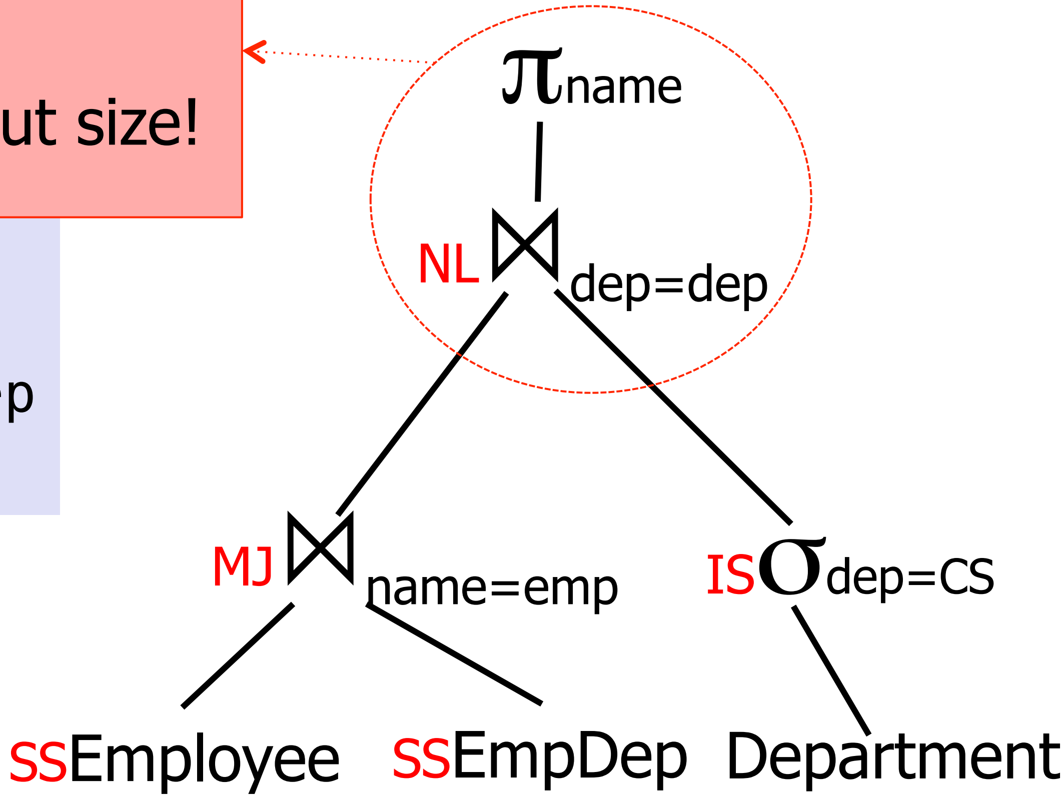
Cost Model

- Cost factors
  - **#disk I/O**
  - **CPU cost**
  - Response time
  - Total **execution time**
- Cost of operators
  - I/O as discussed in query execution (part 10)
  - Need to know **size of intermediate results** (part 09)

Example Query – Possible Plan

```
SELECT e.name
FROM Employee e
     EmpDep ed,
     Department d
WHERE e.name = ed.emp
      AND ed.dep = d.dep
      AND d.dep = 'CS'
```

Cost?
Need input size!



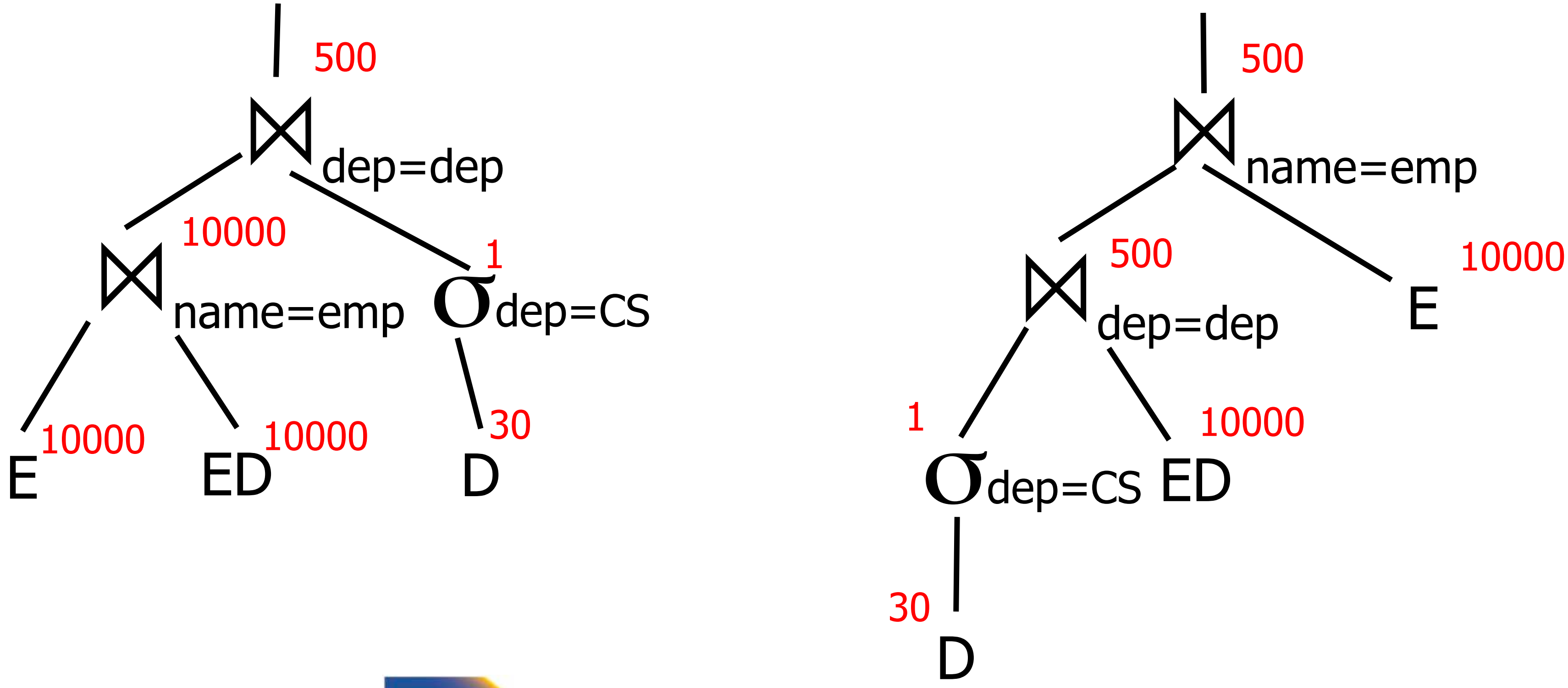
Cost Model Trade-off

- **Precision**
  - – Incorrect cost-estimation -> choose suboptimal plan
- **Cost of computing cost**
  - – Cost of costing a plan
    - We may have to cost millions or billions of plans
  - – Cost of maintaining statistics
    - Occupies resources needed for query processing

Plan Enumeration

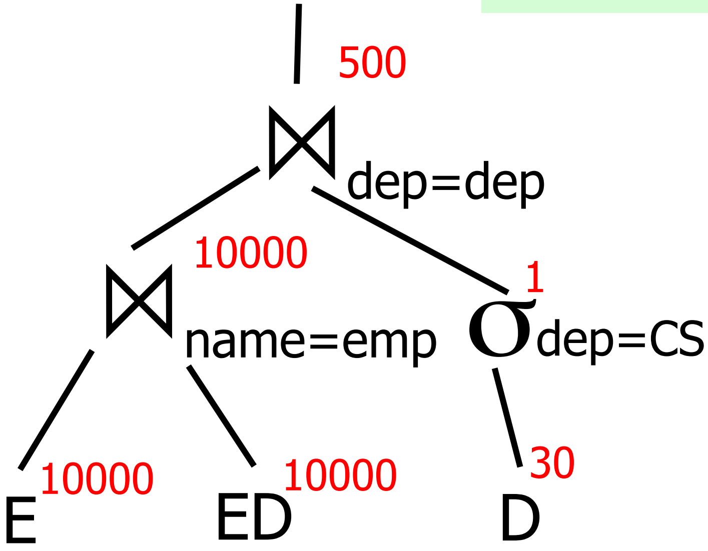
- For each operator in the query
  - Several implementation options
- Binary operators (joins)
  - Changing the order may improve performance a lot!
- -> consider both **different implementations** and **order of operators** in plan enumeration

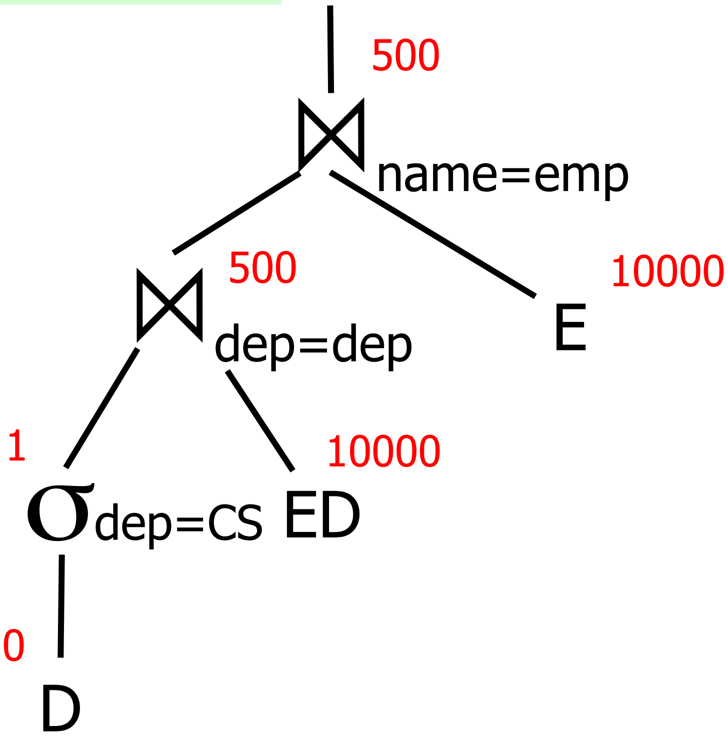
Example Join Ordering Result Sizes



Example Join Ordering Cost (only NL)

S(E) = S(ED) = S(D) = 1/10 block
M = 101

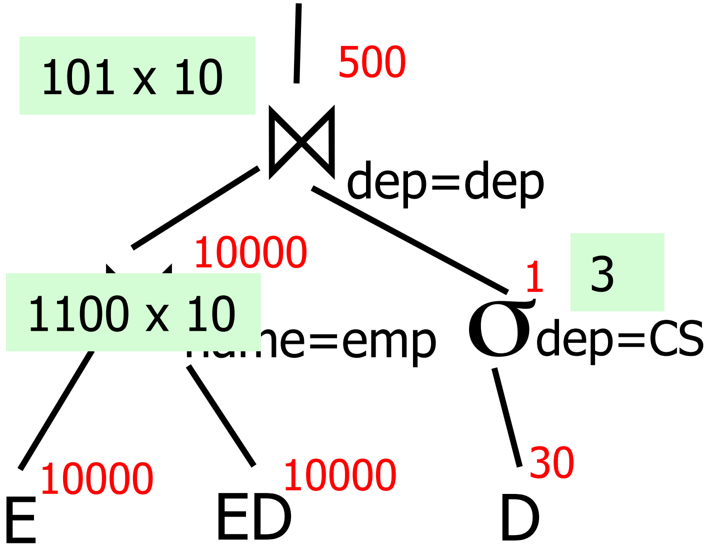


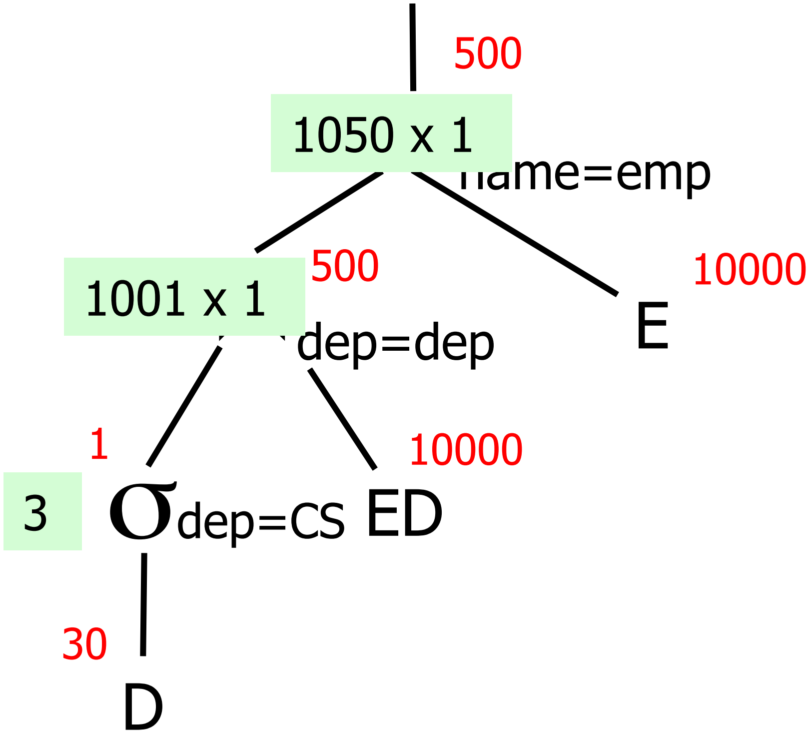


S(E) = S(ED) = S(D) = 1/10 block
M = 101
I/O costs only
No pipelining, write all results to disk

1100 x 10 + 101 x 10 + 3 (operator costs)
+ 1000 + 1 + 50 (write results)
= 13064 I/Os

1001 + 1050 + 3 (operator costs)
+ 1 + 50 + 50
= 2155 I/Os





Plan Enumeration

- All
  - Consider all potential plans of a certain type (discussed later)
  - Prune only if sure
- Heuristics
  - Apply heuristics to prune search space
- Randomized Algorithms

Plan Enumeration Algorithms

- All
  - Dynamic Programming (System R)
  - A* search
- Heuristics
  - Minimum Selectivity, Intermediate result size, …
  - KBZ-Algorithm, AB-Algorithm
- Randomized
  - Genetic Algorithms
  - Simulated Annealing

Reordering Joins Revisited

- Equivalences (Natural Join)
  1. $R \bowtie S \equiv S \bowtie R$
  2. $(R \bowtie S) \bowtie T \equiv R \bowtie (S \bowtie T)$
- Equivalences Equi-Join
  1. $R \bowtie_{a=b} S \equiv S \bowtie_{a=b} R$
  2. $(R \bowtie_{a=b} S) \bowtie_{c=d} T \equiv R \bowtie_{a=b} (S \bowtie_{c=d} T)$?
  3. $\sigma_{a=b} (R \times S) \equiv R \bowtie_{a=b} S$?

Equi-Join Equivalences

- $(R \bowtie_{a=b} S) \bowtie_{c=d} T \equiv R \bowtie_{a=b} (S \bowtie_{c=d} T)$
- What if c is attribute of R?

$(R \bowtie_{a=b} S) \bowtie_{c=d} T \equiv R \bowtie_{a=b \wedge c=d} (S \text{ X } T)$

- $\sigma_{a=b} (R \text{ X } S) \equiv R \bowtie_{a=b} S$?
- Only useful if a is from R and S from b (vice-versa)

Why Cross-Products are bad

- We discussed efficient join algorithms
  - Merge-join O(n) resp. O(n log(n))
  - Vs. Nested-loop $O(n^2)$
- R X S
  - Result size is $O(n^2)$
    - Cannot be better than $O(n^2)$
  - Surprise, surprise: merge-join doesn't work

    no need to sort, but degrades to nested loop

Agenda

- Given some query
  - How to enumerate all plans?
- Try to avoid cross-products
- Need way to figure out if equivalences can be applied
  - Data structure: **Join Graph**

Join Graph

- Assumptions
  - Only equi-joins (a = b)
    - a and b are either constants or attributes
  - Only conjunctive join conditions (AND)

Join Graph

- Nodes: Relations R_1, … , R_n of query
- Edges: Join conditions
  - Add edge between R_i and R_j labeled with C
    - if there is a join condition C
    - That equates an attribute from R_i with an attribute from R_j
  - Add a self-edge to R_i for each simple predicate

Join Graph Example

```
SELECT e.name
FROM Employee e,
     EmpDep ed,
     Department d
WHERE e.name = ed.emp
      AND ed.dep = d.dep
      AND d.dep = ‘CS’
```

Department

EmpDep

Employee

Join Graph Example

```
SELECT e.name
FROM Employee e,
     EmpDep ed,
     Department d
WHERE e.name = ed.emp
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      AND d.dep = 'CS'
```
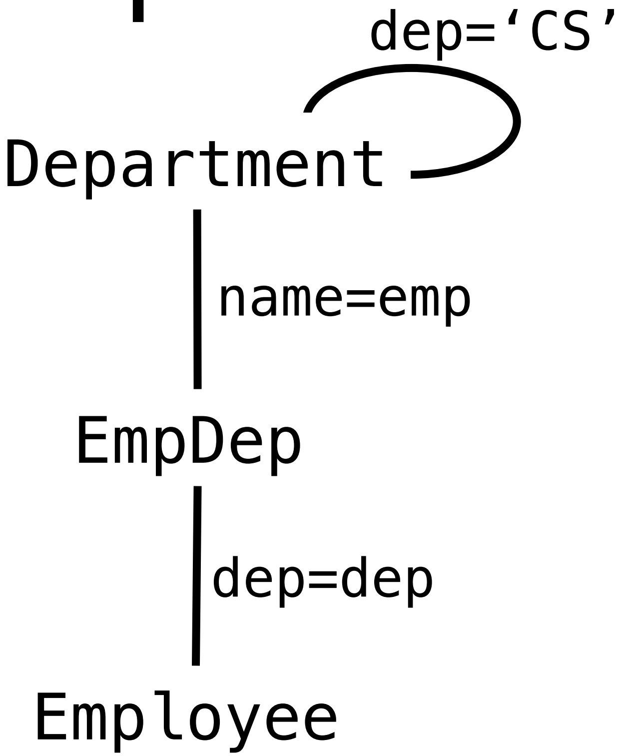



dep='CS'

Department

name=emp

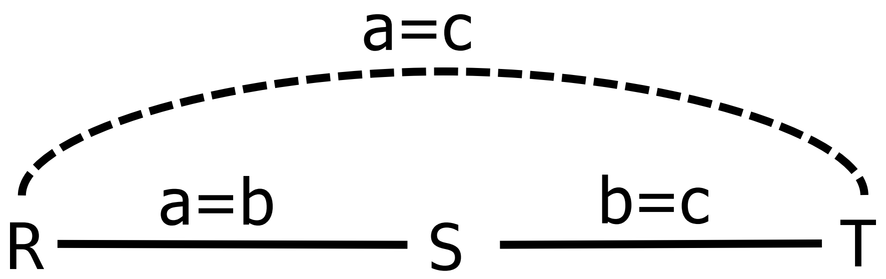
EmpDep

dep=dep

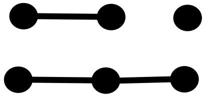
Employee

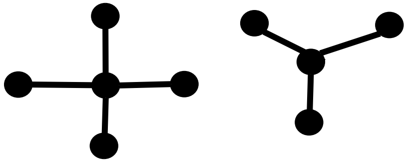
Notes on Join Graph

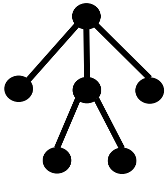
- Join Graph tells us in which ways we can join without using cross products
- However, …
  - Only if transitivity is considered

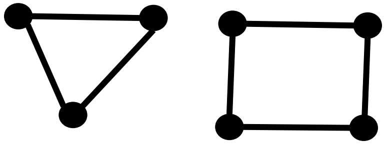


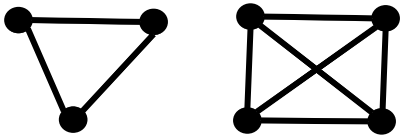
Join Graph Shapes


Chain queries

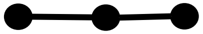

Star queries


Tree queries


Cycle queries


Clique queries

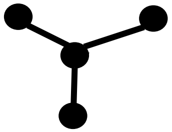
Join Graph Shapes



Chain queries

```
SELECT *
FROM R,S,T
WHERE R.a = S.b
      AND S.c = T.d
```

Join Graph Shapes

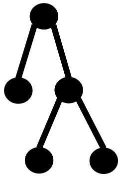


Star queries

```
SELECT *
FROM R,S,T,U
WHERE R.a = S.a
      AND R.b = T.b
      AND R.c = U.c
```

Join Graph Shapes

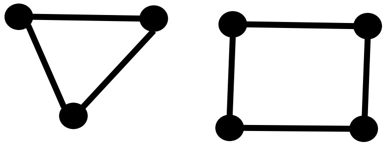
```
SELECT *
FROM R,S,T,U,V
WHERE R.a = S.a
      AND R.b = T.b
      AND T.c = U.c
      AND T.d = V.d
```



Tree queries

Join Graph Shapes

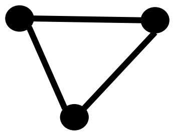
```
SELECT *
FROM R,S,T
WHERE R.a = S.a
      AND S.b = T.b
      AND T.c = R.c
```



Cycle queries

Join Graph Shapes

```
SELECT *
FROM R,S,T
WHERE R.a = S.a
      AND S.b = T.b
      AND T.c = R.c
```



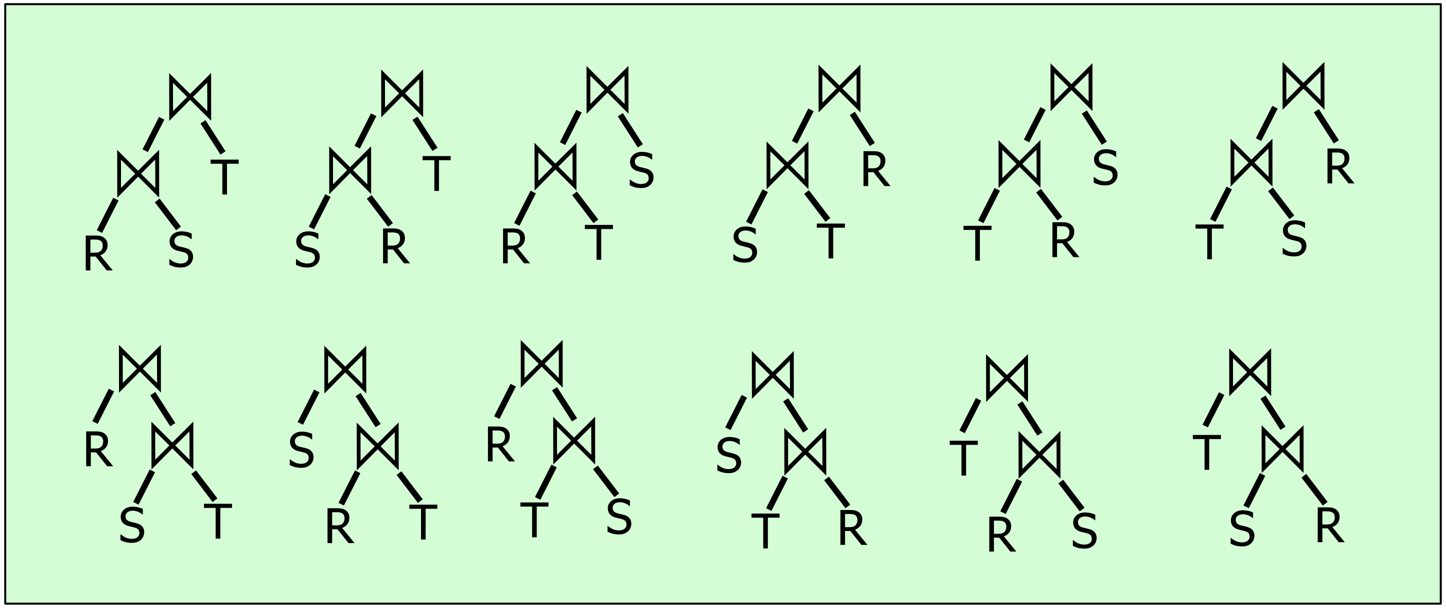
Clique queries

How many join orders?

- Assumption
  - Use cross products (can freely reorder)
  - Joins are binary operations
    - Two inputs
    - Each input either join result or relation access

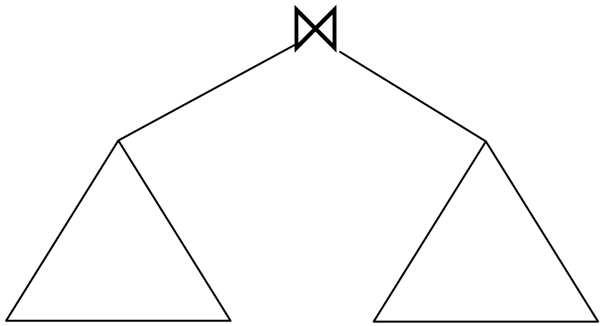
How many join orders?

- Example 3 relations R,S,T
  - 12 orders



How many join orders?

- A join over **n+1** relations requires **n** binary joins
- The root of the join tree joins **k** with **n – k – 1** join operators (0 <= k <= n-1)



k joins

n – k - 1 joins

How many join orders?

- This are the **Catalan numbers**

$$C_n = \sum_{k=0}^{n-1} C_k \times C_{n-k-1} = (2n)! / (n+1)!n!$$

$$C_0 = 1$$

How many join orders?

- This are the **Catalan numbers**
- For each such tree we can permute the input relations **(n+1)!** Permutations

(2n)! / (n+1)!n! * (n+1)! = (2n)!/n!

How many join orders?

#relations	#join trees
2	2
3	12
4	120
5	1,680
6	30,240
7	665,280
8	17,297,280
9	17,643,225,600
10	670,442,572,800
11	28,158,588,057,600

How many join orders?

- If for each join we consider **k** join algorithms then for **n** relations we have
  - Multiply with a factor $\mathbf{k}^{\mathbf{n-1}}$
- Example consider
  - Nested loop
  - Merge
  - Hash

How many join orders?

#relations	#join trees
2	6
3	108
4	3240
5	136,080
6	7,348,320
7	484,989,120
8	37,829,151,360
9	115,757,203,161,600
10	13,196,321,160,422,400
11	1,662,736,466,213,222,400

Too many join orders?

- Even if costing is cheap
  - Unrealistic assumption 1 CPU cycle
  - Realistic are thousands or millions of instructions
- Cost all join options for 11 relations
  - 3GHz CPU, 8 cores
  - 69,280,686 sec > 2 years

How to deal with excessive number of combinations?

- Prune parts based on optimality
  - Dynamic programming
  - A*-search
- Only consider certain types of join trees
  - Left-deep, Right-deep, zig-zag, bushy
- Heuristic and random algorithms

Dynamic Programming

- Assumption: **Principle of Optimality**
  - To compute the **global** optimal plan it is only necessary to consider the optimal solutions for its **sub-queries**
- Does this assumption hold?
  - Depends on cost-function

What is dynamic programming?

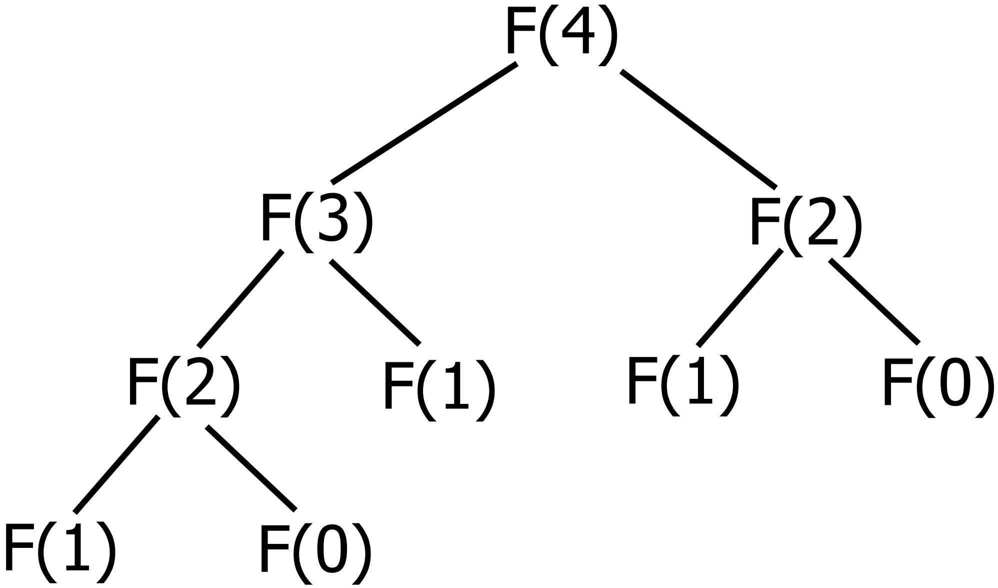
- Recall data structures and algorithms 101!
- Consider a **Divide-and-Conquer** problem
  - Solutions for a problem of size **n** can be build from solutions for sub-problems of smaller size (e.g., **n/2** or **n-1**)
- **Memoize**
  - Store solutions for sub-problems
  - -> Each solution has to be only computed once
  - -> Needs extra memory

Example Fibonacci Numbers

- F(n) = F(n-1) + F(n-2)
- F(0) = F(1) = 1

```
Fib(n)
{
      if (n = 0) return 0
      else if (n = 1) return 1
      else return Fib(n–1) + Fib(n–2)
}
```

Example Fibonacci Numbers



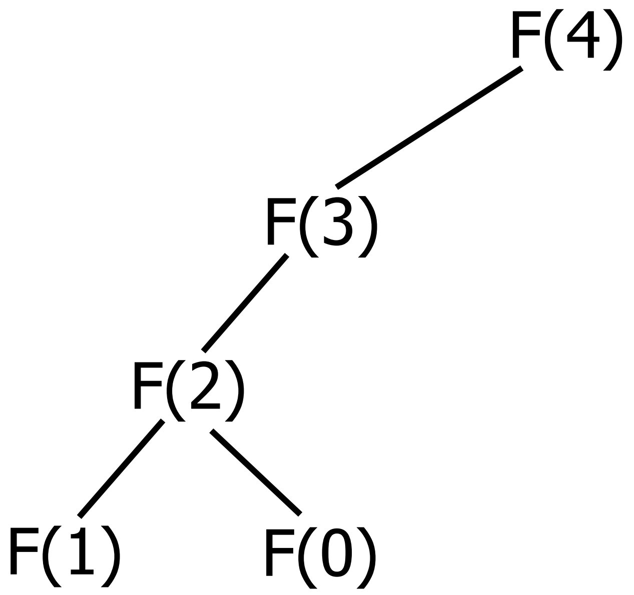
Complexity

- Number of calls
  - $C(n) = C(n-1) + C(n-2) + 1 = Fib(n+2)$
  - $O(2^n)$

Using dynamic programming

```
Fib(n)
{
     int[] fib;
     fib[0] = 1;
     fib[1] = 1;

     for(i = 2; i < n; i++)
          fib[i] = fib[i-1] + fib[i-2]

     return fib[n];
}
```

Example Fibonacci Numbers



What do we gain?

- $O(n)$ instead of $O(2^n)$

Dynamic Programming for Join Enumeration

- Find cheapest plan for n-relation join in n passes
- For each **i** in **1** … **n**
  - Construct solutions of size **i** from best solutions of size **< i**

DP Join Enumeration

```
optPlan ← Map({R},{plan})

find_join_dp(q($R_1$,…,$R_n$))
{
  for i=1 to n
    optPlan[{$R_i$}] ← access_paths($R_i$)
  for i=2 to n
    foreach S ⊆ {$R_1$,…,$R_n$} with |S|=i
      optPlan[S] ← ∅
      foreach O ⊂ S with O ≠ ∅
        optPlan[S] ← optPlan[S] ∪
              possible_joins(optPlan(O), optPlan(S\O))
      prune_plans(optPlan[S])
  return optPlan[{$R_1$,…,$R_n$}]
}
```

Dynamic Programming for Join Enumeration

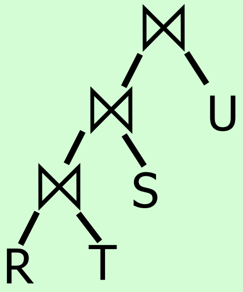
- `access_paths (R)`
  - Find cheapest access path for relation R
- `possible_joins(plan, plan)`
  - Enumerate all joins (merge, NL, …) variants between the input plans
- `prune_plans({plan})`
  - Only keep cheapest plan from input set

DP-JE Complexity

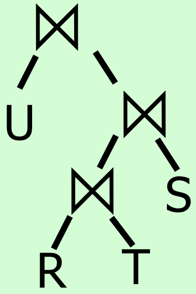
- Time: $O(3^n)$
- Space: $O(2^n)$
- Still to much for large number of joins (10-20)

Types of join trees

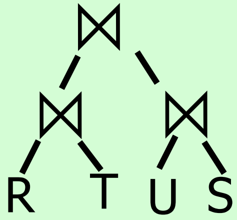
Left-deep



zig-zag



bushy

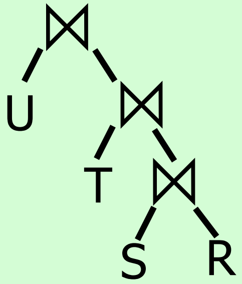


+left

+ zig-zag

+right

Right-deep



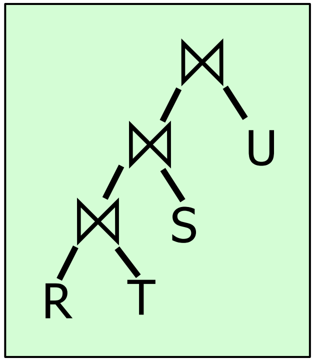
Number of Join-Trees

- Number of join trees for **n** relations
- Left-deep: **n!**
- Right-deep: **n!**
- Zig-zag: $\mathbf{2^{n-2}n!}$

How many join orders?

#relations	#bushy join trees	#left-deep join trees
2	2	2
3	12	6
4	120	24
5	1,680	120
6	30,240	720
7	665,280	5040
8	17,297,280	40,230
9	17,643,225,600	362,880
10	670,442,572,800	3,628,800
11	28,158,588,057,600	39,916,800

DP with Left-deep trees only



- Reduced search-space
- Each join is with input relation
  - ->can use index joins
  - ->easy to pipe-line
- DP with left-deep plans was introduced by system R, the first relational database developed by IBM Research

Revisiting the assumption

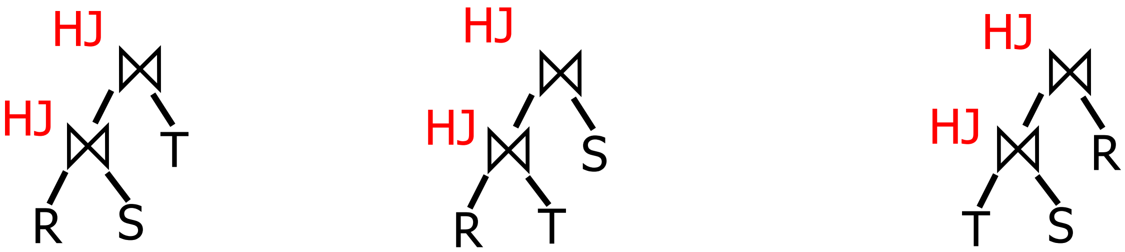
- Is it really sufficient to only look at the best plan for every sub-query?
- Cost of merge join depends whether the input is already sorted
  - -> A sub-optimal plan may produce results ordered in a way that reduces cost of joining above
  - Keep track of **interesting orders**

Interesting Orders

- Number of interesting orders is usually small
- ->Extend DP join enumeration to keep track of interesting orders
  - Determine interesting orders
  - For each sub-query store best-plan for each interesting order

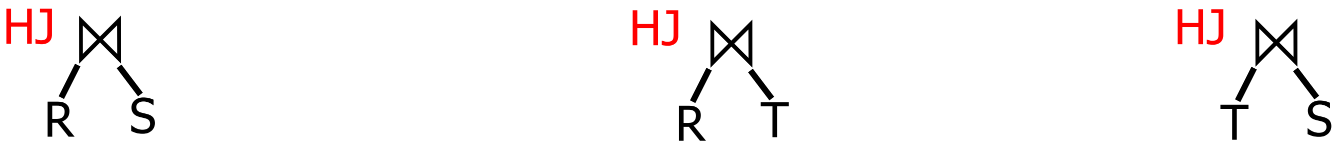
Example Interesting Orders

Left-deep best plans: 3-way {R,S,T}



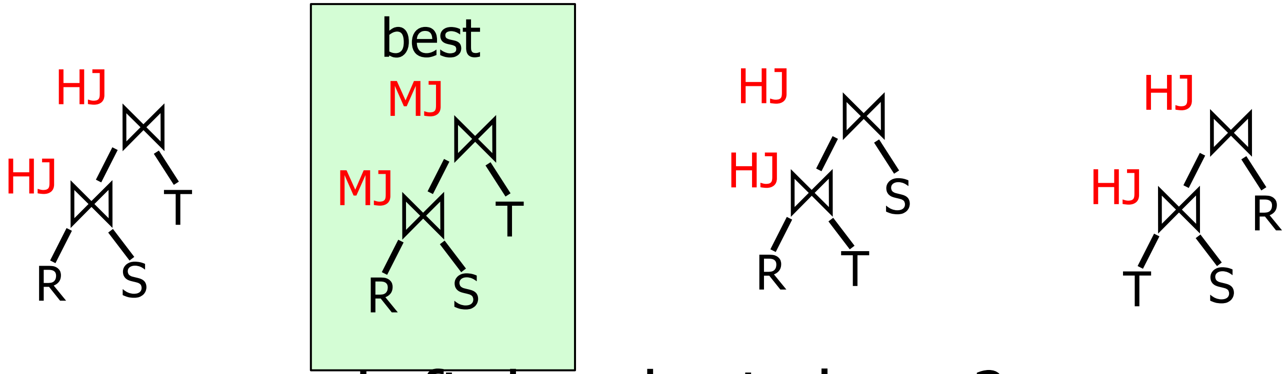
Left-deep best plans: 2-way

{R,S} {R,T} {S,T}

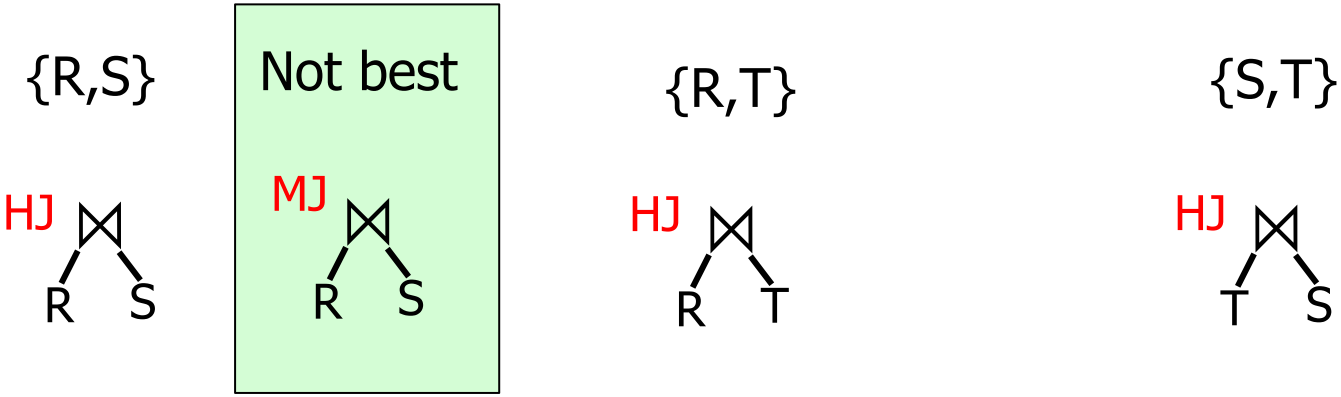


Example Interesting Orders

Left-deep best plans: 3-way {R,S,T}



Left-deep best plans: 2-way



Greedy Join Enumeration

- Heuristic method
  - Not guaranteed that best plan is found
- Start from single relation plans
- In each iteration greedily join to plans with the minimal cost
- Until a plan for the whole query has been generated

Greedy Join Enumeration

```
plans ← list({plan})

find_join_dp(q($R_1$,…,$R_n$))
{
  for i=1 to n
    plans ← plans ∪ access_paths($R_i$)
  for i=n to 2
    cheapest = $\text{argmin}_{j,k \in \{1,\dots,n\}}$ (cost($P_j \bowtie P_k$))
    plans ← plans \ {$P_j$,$P_k$} ∪ {$P_j \bowtie P_k$}
  return plans // single plan left
}
```

Greedy Join Enumeration

- Time: $O(n^3)$
  - Loop iterations: $O(n)$
  - In each iterations looking of pairs of plans in of max size n: $O(n^2)$
- Space: $O(n^2)$
  - Needed to store the current list of plans

Randomized Join-Algorithms

- Iterative improvement
- Simulated annealing
- Tabu-search
- Genetic algorithms

Transformative Approach

- Start from (random) complete solutions
- Apply transformations to generate new solutions
  - Direct application of equivalences
    - Commutativity
    - Associativity
  - Combined equivalences
    - E.g., $(R \bowtie S) \bowtie T \equiv T \bowtie (S \bowtie R)$

Concern about Transformative Approach

- Need to be able to generate random plans fast
- Need to be able to apply transformations fast
  - Trade-off: space covered by transformations vs. number and complexity of transformation rules

Iterative Improvement

```
improve(q($R_1$,…,$R_n$))
{
  best ← random_plan(q)
  while (not reached time limit)
    curplan ← random_plan(q)
    do
      prevplan ← curplan
      curplan ← apply_random_trans (prevplan)
    while (cost(curplan) < cost(prevplan))
    if (cost(prevplan) < cost(best)
      best ← prevplan
  return best
}
```

Iterative Improvement

- Easy to get stuck in local minimum
- **Idea:** Allow transformations that result in more expensive plans with the hope to move out of local minima
  - ->Simulated Annealing

Simulated Annealing

```
SA($q(R_1,…,R_n)$)
{
  best ← random_plan(q)
  curplan ← best
  t ← $t_{init}$ // “temperature”
  while (t > 0)
    newplan ← apply_random_trans(curplan)
    if cost(newplan) < cost(curplan)
      curplan ← newplan
    else if random() < $e^{-(cost(newplan)-cost(curplan))/t}$
      curplan ← newplan
    if (cost(curplan) < cost(best)
      best ← curplan
   reduce(t)
  return best
}
```

Simulated Annealing

```
SA(q($R_1$,…,$R_n$))
{
  best ← random_plan(q)
  curplan ← best
  t ← $t_{init}$ // “temperature”
  while (t > 0)
    newplan ← apply_random_trans(curplan)
    if cost(newplan) < cost(curplan)
      curplan ← newplan
    else if random() < $e^{-(cost(newplan)-cost(curplan))/t}$
      curplan ← newplan
    if (cost(curplan) < cost(best)
      best ← curplan
    reduce(t)
  return best
}
```

Until “cooled down”

Reduce
Chance
To “jump”

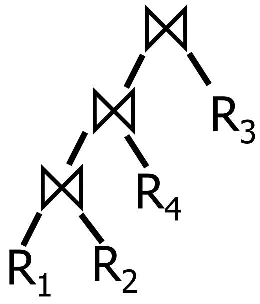
Probability to
Take “bad” plan
Based on temp.

Genetic Algorithms

- Represent solutions as sequences (strings) = genome
- Start with random population of solutions
- Iterations = Generations
  - Mutation = random changes to genomes
  - Cross-over = Mixing two genomes

Genetic Join Enumeration for Left-deep Plans

- A left-deep plan can be represented as a permutation of the relations
  - Represent each relation by a number
  - E.g., encode this tree as "1243"



Mutation

- Switch random two random positions
- Is applied with a certain fixed probability
- E.g., “1342” -> “4312”

Cross-over

- Sub-set exchange
  - For two solutions find subsequence
    - equals length with the same set of relations
  - Exchange these subsequences
- Example
  - J_1 = "5632478" and J_2 = "5674328"
  - Generate J' = "5643278"

Survival of the fittest

- Probability of survival determined by rank within the current population
- Compute ranks based on costs of solutions
- Assign Probabilities based on rank
  - Higher rank -> higher probability to survive
- Roll a dice for each solution

Genetic Join Enumeration

- Create an initial population **P** random plans
- Apply crossover and mutation with a fixed rate
  - E.g., crossover 65%, mutation 5%
- Apply selection until size is again **P**
- Stop once no improvement for at least **X** iterations

Comparison Randomized Join Enumeration

- Iterative Improvement
  - Towards local minima (easy to get stuck)
- Simulated Annealing
  - Probability to “jump” out of local minima
- Genetic Algorithms
  - Random transformation
  - Mixing solutions (crossover)
  - Probabilistic chance to keep solution based on cost

Join Enumeration Recap

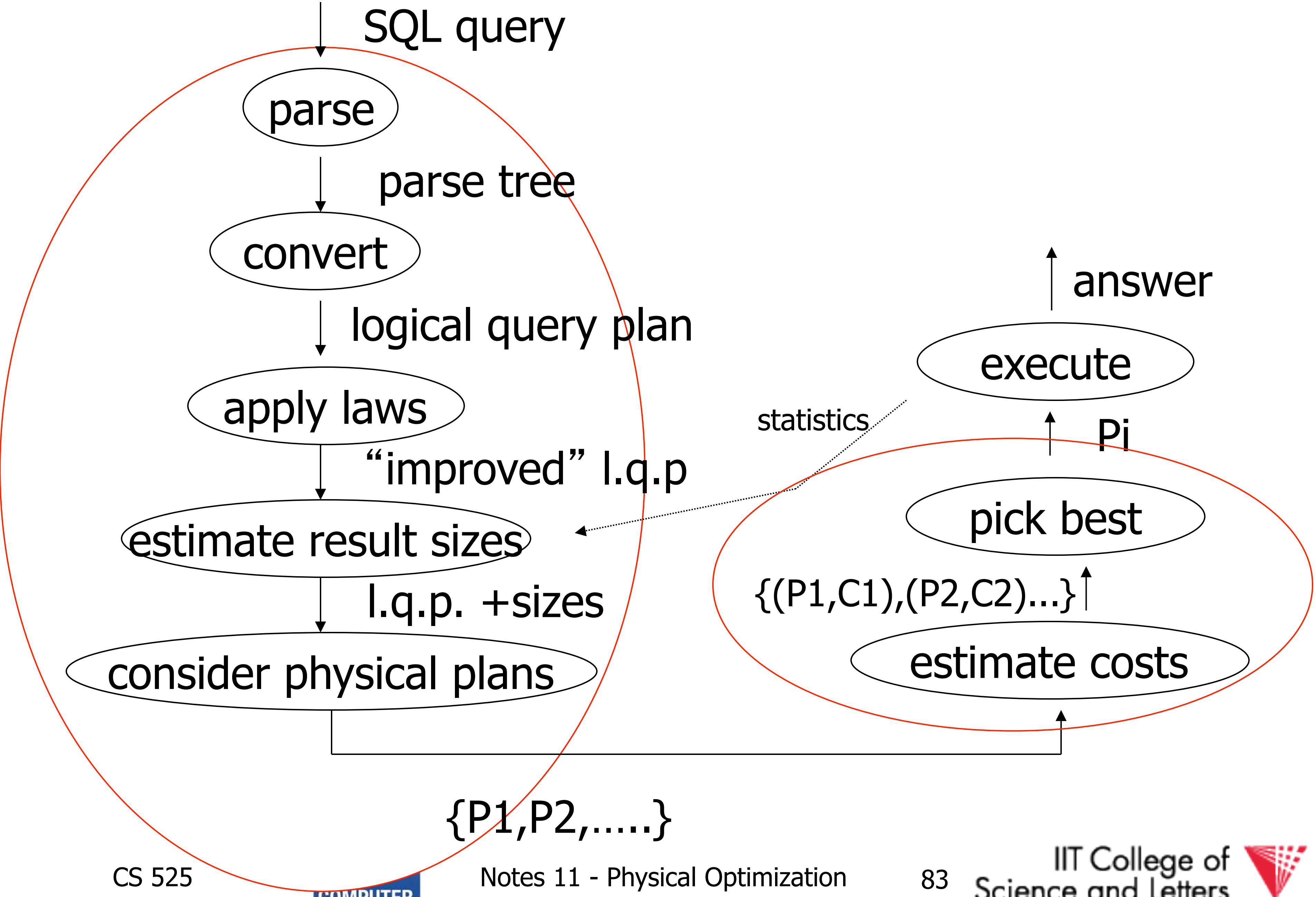
- Hard problem
  - Large problem size
    - Want to reduce search space
  - Large cost differences between solutions
    - Want to consider many solution to increase chance to find a good one.

Join Enumeration Recap

- Tip of the iceberg
  - More algorithms
  - Combinations of algorithms
  - Different representation subspaces of the problem
  - Cross-products / no cross-products
  - …

From Join-Enumeration to Plan Enumeration

- So far we only know how to reorder joins
- What about other operations?
- What if the query does consist of several SQL blocks?
- What if we have nested subqueries?


SQL query
parse
parse tree
convert
logical query plan
apply laws
"improved" l.q.p
estimate result sizes
l.q.p. +sizes
consider physical plans
{P1,P2,…..}
estimate costs
{(P1,C1),(P2,C2)...}
pick best
Pi
execute
answer
statistics

From Join-Enumeration to Plan Enumeration

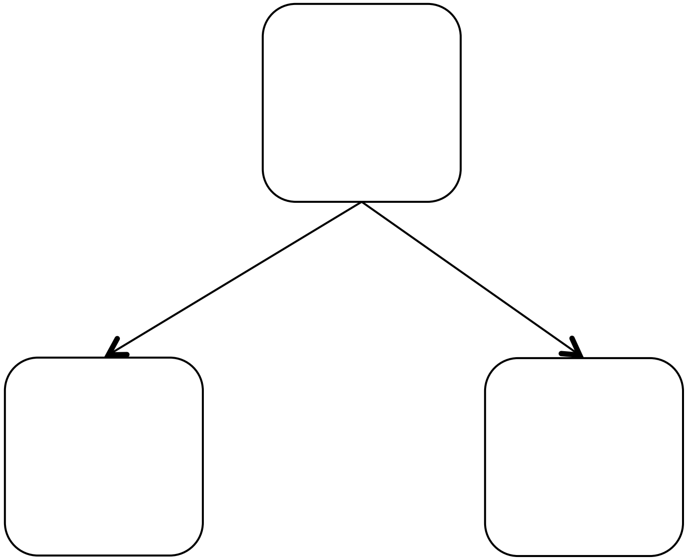
- Lets reconsider the input to plan enumeration!
  - We briefly touched on **Query graph models**
  - We discussed briefly why relational algebra is not sufficient

Query Graph Models

- Represents an SQL query as query blocks
  - A query block corresponds to the an SQL query block (SELECT FROM WHERE …)
  - Data type/operator/function information
    - Needed for execution and optimization decisions
  - Structured in a way suited for optimization

QGM example

```
SELECT name, city
FROM
     (SELECT *
     FROM person) AS p,
     (SELECT *
     FROM address) AS a
WHERE p.addrId = a.id
```



Postgres Example

```
{QUERY
          :commandType 1
          :querySource 0
          :canSetTag true
          :utilityStmt <>
          :resultRelation 0
          :intoClause <>
          :hasAggs false
          :hasSubLinks false
          :rtable (
             {RTE
             :alias
                {ALIAS
                :aliasname p
                :colnames <>
                }
             :eref
                {ALIAS
                :aliasname p
                :colnames ("name" "addrid")
                }
             :rtekind 1
             :subquery
                {QUERY
                :commandType 1
                :querySource 0
                :canSetTag true
…
```

How to enumerate plans for a QGM query

- Recall the correspondence between SQL query blocks and algebra expressions!
- If block is (A)SPJ
  - Determine join order
  - Decide which aggregation to use (if any)
- If block is set operation
  - Determine order

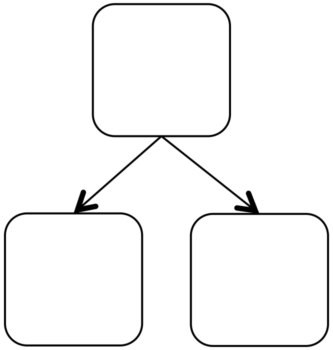
More than one query block

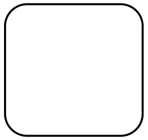
- Recursive create plans for subqueries
  - Start with leaf blocks
- Consider our example
  - Even if blocks are only SPJ we would not consider reordering of joins across blocks
  - -> try to “pull up” subqueries before optimization

Subquery Pull-up

```
SELECT name, city
FROM
     (SELECT *
     FROM person) AS p,
     (SELECT *
     FROM address) AS a
WHERE p.addrId = a.id
```

```
SELECT name, city
FROM
     person p,
     address a
WHERE p.addrId = a.id
```





Parameterized Queries

- Problem
  - Repeated executed of similar queries
- Example
  - Webshop
  - Typical operation: Retrieve product with all user comments for that product
  - Same query modulo product id

Parameterized Queries

- Naïve approach
  - Optimize each version individually
  - Execute each version individually
- Materialized View
  - Store common parts of the query
  - -> Optimizing a query with materialized views
  - -> Separate topic not covered here

Caching Query Plans

- Caching Query Plans
  - Optimize query once
  - Adapt plan for specific instances
  - **Assumption:** varying values do not effect optimization decisions
  - **Weaker Assumption**: Additional cost of "bad" plan less than cost of repeated planning

Parameterized Queries

- How to represent varying parts of a query
  - Parameters
  - Query planned with parameters assumed to be unknown
  - For execution replace parameters with concrete values

PREPARE statement

- In SQL
  - **`PREPARE`** `name (parameters)` **`AS`** `query`
  - **EXECUTE** name (parameters)

Nested Subqueries

```
SELECT name
FROM person p
WHERE EXISTS (SELECT newspaper
              FROM hasRead h
              WHERE h.name = p.name
                AND h.newspaper = ‘Tribune’)
```

How to evaluate nested subquery?

- If no correlations:
  - Execute once and cache results
- For correlations:
  - Create plan for query with parameters
- -> called nested iteration

Nested Iteration - Correlated

```
q ← outer query
q’ ← inner query
result ← execute(q)
foreach tuple t in result
  q_t ← q’(t) // parameterize q’ with values from t
  result’ ← execute (q_t)
  evaluate_nested_condition (t,result’)
```

Nested Iteration - Uncorrelated

```
q ← outer query
q' ← inner query
result ← execute(q)
result' ← execute ($q_t$)
foreach tuple t in result
  evaluate_nested_condition (t,result')
```

Nested Iteration - Example

```
SELECT name
FROM person p
WHERE EXISTS (SELECT newspaper
                FROM hasRead h
                WHERE h.name = p.name
                      AND h.newspaper = ‘Tribune’)
```

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

Nested Iteration - Example

```
q ← outer query
q’ ← inner query
result ← execute(q)
foreach tuple t in result
  $q_t$ ← q’(t)
  result’ ← execute ($q_t$)
  evaluate_nested_condition (t,result’)
```

```
SELECT newspaper
FROM hasRead h
WHERE h.name = p.name
      AND h.newspaper
         = ‘Tribune’)
```

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

Nested Iteration - Example

```
q ← outer query
q’ ← inner query
result ← execute(q)
foreach tuple t in result
→ q_t ← q’(t)
  result’ ← execute (q_t)
  evaluate_nested_condition (t,result’)
```

```
SELECT newspaper
FROM hasRead h
WHERE h.name = ‘Alice’
      AND h.newspaper
          = ‘Tribune’)
```

person

	name	gender
→	Alice	female
	Bob	male
	Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

Nested Iteration - Example

```
q ← outer query
q’ ← inner query
result ← execute(q)
foreach tuple t in result
  $q_t$ ← q’(t)
→ result’ ← execute ($q_t$)
  evaluate_nested_condition (t,result’)
```

```
SELECT newspaper
FROM hasRead h
WHERE h.name = p.name
      AND h.newspaper
          = ‘Tribune’)
```

person

name	gender
→ Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

result’

newspaper
Tribune

Nested Iteration - Example

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  q_t ← q'(t)
  result' ← execute (q_t)
→evaluate_nested_condition (t,result')
```

EXISTS evaluates to true!

Output(Alice)

person

name	gender
→ Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

result'

newspaper
Tribune

Nested Iteration - Example

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  $q_t$ ← q'(t)
  result' ← execute ($q_t$)
  evaluate_nested_condition (t,result')
```

Empty result set -> EXISTS evaluates to false

person

name	gender
Alice	female
Bob	male
Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

result'

newspaper

Nested Iteration - Example

```
q ← outer query
q' ← inner query
result ← execute(q)
foreach tuple t in result
  q_t ← q'(t)
  result' ← execute (q_t)
  evaluate_nested_condition (t,result')
```

Empty result set -> EXISTS evaluates to false

person

name	gender
Alice	female
Bob	male
→ Joe	male

hasRead

name	newspaper
Alice	Tribune
Alice	Courier
Joe	Courier

result'

newspaper

Nested Iteration - Discussion

- Repeated evaluation of nested subquery
  - If correlated
  - Improve:
    - Plan once and substitute parameters
    - EXISTS: stop processing after first result
    - IN/ANY: stop after first match
- No optimization across nesting boundaries

Unnesting and Decorrelation

- Apply equivalences to transform nested subqueries into joins
- **Unnesting:**
  - Turn a nested subquery into a join
- **Decorrelation:**
  - Turn correlations into join expressions

Equivalences

- Classify types of nesting
- Equivalence rules will have preconditions
- Can be applied heuristically before plan enumeration or using a transformative approach

N-type Nesting

- Properties
  - Expression ANY comparison (or IN)
  - No Correlations
  - Nested query does not use aggregation
- Example

```
SELECT name
FROM orders o
WHERE o.cust IN (SELECT cId
                 FROM customer
                 WHERE region = ‘USA’)
```

A-type Nesting

- Properties
  - Expression is ANY comparison (or scalar)
  - No Correlations
  - Nested query uses aggregation
  - No Group By
- Example

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i)
```

J-type Nesting

- Properties
  - Expression is ANY comparison (IN)
  - Nested query uses equality comparison with correlated attribute
  - No aggregation in nested query
- Example

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
              FROM orders i
              WHERE i.cust = o.cust
                    AND i.shop = ‘New York’)
```

JA-type Nesting

- Properties
  - Expression equality comparison
  - Nested query uses equality comparison with correlated attribute
  - Nested query uses aggregation and no GROUP BY
- Example

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

Unnesting A-type

- Move nested query to FROM clause
- Turn nested condition (op ANY, IN) into op with result attribute of nested query

Unnesting N/J-type

- Move nested query to FROM clause
- Add DISTINCT to SELECT clause of nested query
- Turn equality comparison with correlated attributes into join conditions
- Turn nested condition (op ANY, IN) into op with result attribute of nested query

Example

1. To FROM clause
2. Add DISTINCT
3. Correlation to join
4. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
                   FROM orders i
                   WHERE i.cust = o.cust
                         AND i.shop = ‘New York’)
```

```
SELECT name
FROM orders o,
     (SELECT amount
     FROM orders i
     WHERE i.cust = o.cust
           AND i.shop = ‘New York’) AS sub
```

Example

1. To FROM clause
2. Add DISTINCT
3. Correlation to join
4. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
              FROM orders i
              WHERE i.cust = o.cust
                    AND i.shop = ‘New York’)
```

```
SELECT name
FROM orders o,
     (SELECT DISTINCT amount
     FROM orders i
     WHERE i.cust = o.cust
           AND i.shop = ‘New York’) AS sub
```

Example

1. To FROM clause
2. Add DISTINCT
3. Correlation to join
4. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
              FROM orders i
              WHERE i.cust = o.cust
                   AND i.shop = ‘New York’)
```

```
SELECT name
FROM orders o,
     (SELECT DISTINCT amount, cust
     FROM orders i
     WHERE i.shop = ‘New York’) AS sub
WHERE sub.cust = o.cust
```

Example

1. To FROM clause
2. Add DISTINCT
3. Correlation to join
4. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount IN (SELECT amount
              FROM orders i
              WHERE i.cust = o.cust
                    AND i.shop = ‘New York’)
```

```
SELECT name
FROM orders o,
     (SELECT DISTINCT amount, cust
     FROM orders i
     WHERE i.shop = ‘New York’) AS sub
WHERE sub.cust = o.cust
      AND o.amount = sub.amount
```

Unnesting JA-type

- Move nested query to FROM clause
- Turn equality comparison with correlated attributes into
  - GROUP BY
  - Join conditions
- Turn nested condition (op ANY, IN) into op with result attribute of nested query

Example

1. To FROM clause
2. Introduce GROUP BY and join conditions
3. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                FROM orders i
                WHERE i.cust = o.cust)
```

```
SELECT name
FROM orders o,
    (SELECT max(amount)
    FROM orders I
    WHERE i.cust = o.cust) sub
```

Example

1. To FROM clause
2. Introduce GROUP BY and join conditions
3. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

```
SELECT name
FROM orders o,
    (SELECT max(amount) AS ma, i.cust
    FROM orders i
    GROUP BY i.cust) sub
WHERE i.cust = sub.cust
```

Example

1. To FROM clause
2. Introduce GROUP BY and join conditions
3. Nesting condition to join

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

```
SELECT name
FROM orders o,
    (SELECT max(amount) AS ma, i.cust
    FROM orders i
    GROUP BY i.cust) sub
WHERE sub.cust = o.cust
      AND o.amount = sub.ma
```

Unnesting Benefits Example

- N(orders) = 1,000,000
- V(cust,orders) = 10,000
- S(orders) = 1/10 block

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

```
SELECT name
FROM orders o,
    (SELECT max(amount) AS ma, i.cust
    FROM orders i
    GROUP BY i.cust) sub
WHERE sub.cust = o.cust
      AND o.amount = sub.ma
```

- N(orders) = 1,000,000
- V(cust,orders) = 10,000
- S(orders) = 1/10 block
- M = 10,000

```
SELECT name
FROM orders o
WHERE o.amount = (SELECT max(amount)
                  FROM orders i
                  WHERE i.cust = o.cust)
```

- Inner query:
  - One scan B(orders) = 100,000 I/Os
- Outer query:
  - One scan B(orders) = 100,000 I/Os
  - 1,000,000 tuples
- Total cost: 1,000,001 x 100,000=~ 10^{11} I/Os

- N(orders) = 1,000,000
- V(cust,orders) = 10,000
- S(orders) = 1/10 block
- M = 10,000

```
SELECT name
FROM orders o,
    (SELECT max(amount) AS ma, i.cust
    FROM orders i
    GROUP BY i.cust) sub
WHERE sub.cust = o.cust
      AND o.amount = sub.ma
```

- Inner queries:
  - One scan B(orders) = 100,000 I/Os
    - 1,000,000 result tuples
  - Aggregation: Sort (assume 1 pass) = 3 x 100,000 = 300,000 I/Os
    - 10,000 result tuples -> + 1,000 pages to write to disk
- The join: use merge – join during merge
  - 3 x (1,000 + 100,000) I/Os = 303,000 I/Os
- Total cost: 604,000 I/Os

CS 525: Advanced Database Organization

12: Transaction Management

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab

Concurrency and Recovery

- DBMS should enable multiple clients to access the database concurrently
  - This can lead to problems with correctness of data because of interleaving of operations from different clients
  - ->System should ensure correctness (concurrency control)

Concurrency and Recovery

- DBMS should enable reestablish correctness of data in the presence of failures
  - ->System should restore a correct state after failure (recovery)

Integrity or correctness of data

- Would like data to be “accurate” or “correct” at all times

EMP

Name	Age
White	52
Green	3421
Gray	1

Integrity or consistency constraints

- Predicates data must satisfy
- Examples:
  - x is key of relation R
  - x → y holds in R
  - Domain(x) = {Red, Blue, Green}
  - α is valid index for attribute x of R
  - no employee should make more than twice the average salary

Definition:

- Consistent state: satisfies all constraints
- Consistent DB: DB in consistent state

Constraints (as we use here) may not capture "full correctness"

Example 1 Transaction constraints

- When salary is updated,
  new salary > old salary
- When account record is deleted,
  balance = 0

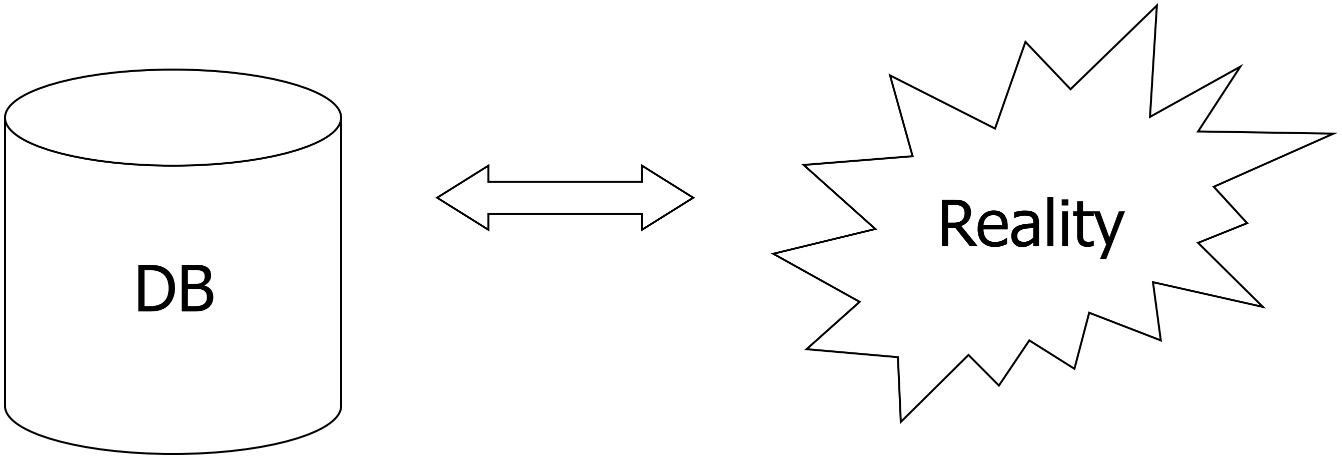
Note: could be "emulated" by simple constraints, e.g.,

account

Acct #	….	balance	deleted?

Constraints (as we use here) may not capture "full correctness"

Example 2 Database should reflect real world



☞ in any case, continue with constraints...

Observation: DB cannot be consistent always!

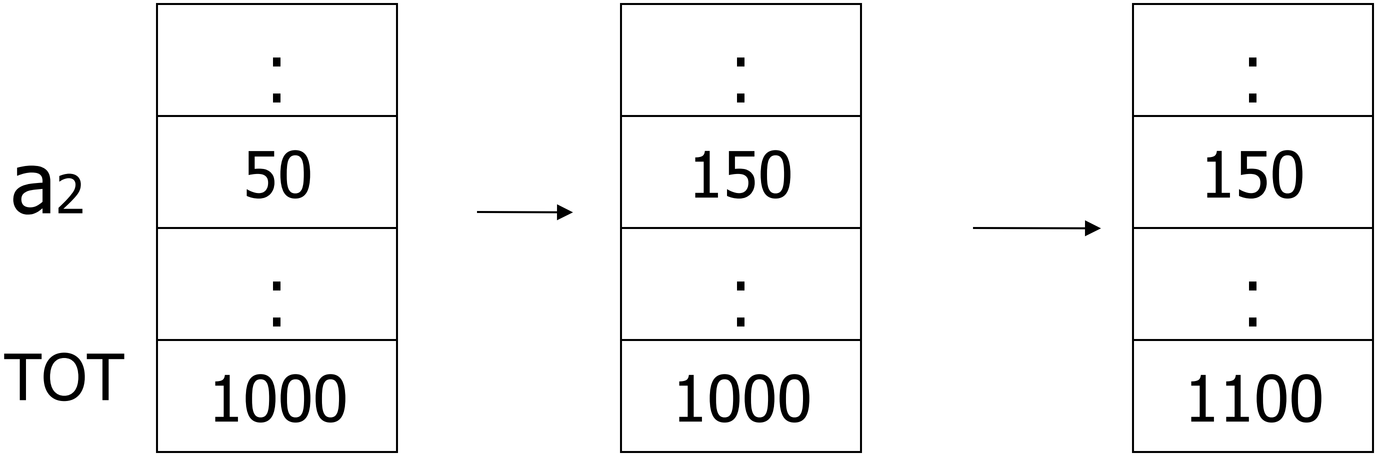
Example: $a_1 + a_2 + \ldots. a_n = TOT$ (constraint)

Deposit \$100 in a_2: $\begin{cases} a_2 \leftarrow a_2 + 100 \\ TOT \leftarrow TOT + 100 \end{cases}$

Example: $a_1 + a_2 + \ldots a_n = TOT$ (constraint)

Deposit \$100 in a_2: $a_2 \leftarrow a_2 + 100$

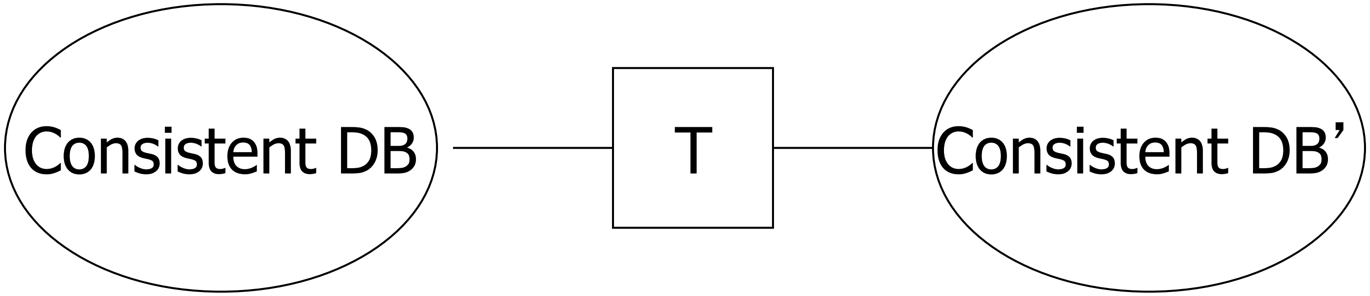
$TOT \leftarrow TOT + 100$



Transactions

- **Transaction:** Sequence of operations executed by one concurrent client that preserve consistency

Transaction: collection of actions that preserve consistency



Big assumption:

If T starts with consistent state +
T executes in isolation
⇒ T leaves consistent state

Correctness (informally)

- If we stop running transactions,
  DB left consistent
- Each transaction sees a consistent DB

Transactions - ACID

- **A**tomicity
  - Either all or no commands of transaction are executed (their changes are persisted in the DB)
- **C**onsistency
  - After transaction DB is consistent (if before consistent)
- **I**solation
  - Transactions are running isolated from each other
- **D**urability
  - Modifications of transactions are never lost

How can constraints be violated?

- Transaction bug
- DBMS bug
- Hardware failure

    e.g., disk crash alters balance of account

- Data sharing

e.g.: T1: give 10% raise to programmers

T2: change programmers ⇒ systems analysts

How can we prevent/fix violations?

- Part 13 (Recovery):
  - due to failures
- Part 14 (Concurrency Control):
  - due to data sharing

Will not consider:

- How to write correct transactions
- How to write correct DBMS
- Constraint checking & repair

That is, solutions studied here do not need to know constraints

Data Items:

- **Data Item / Database Object** / …
- Abstraction that will come in handy when talking about concurrency control and recovery
- Data Item could be
  - Table, Row, Page, Attribute value

Operations:

- Input (x): block containing x → memory
- Output (x): block containing x → disk

Operations:

- Input (x): block containing x → memory
- Output (x): block containing x → disk

- Read (x,t): do input(x) if necessary
  t ← value of x in block
- Write (x,t): do input(x) if necessary
  value of x in block ← t

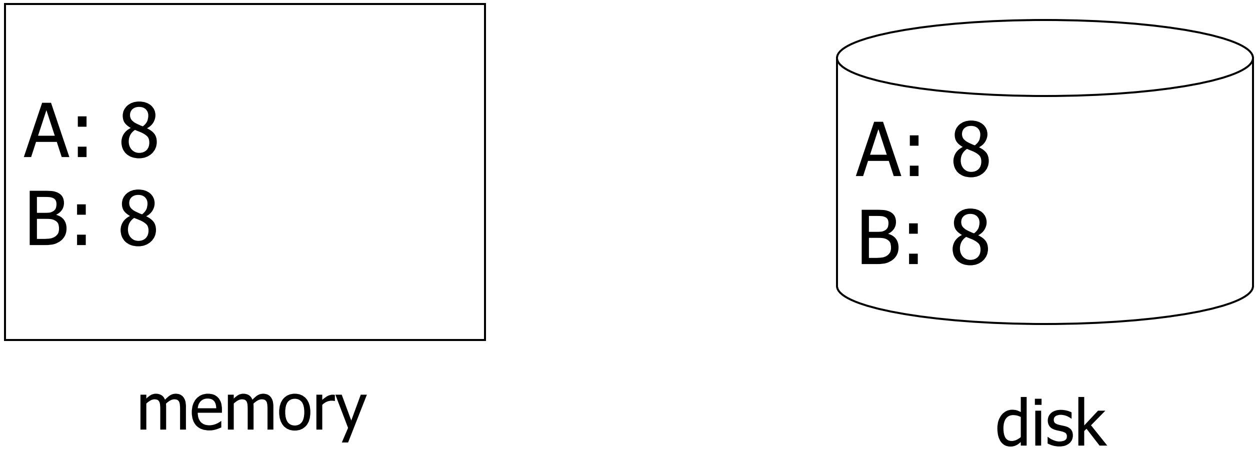
<u>Key problem</u> Unfinished transaction (**Atomicity**)

Example Constraint: A=B

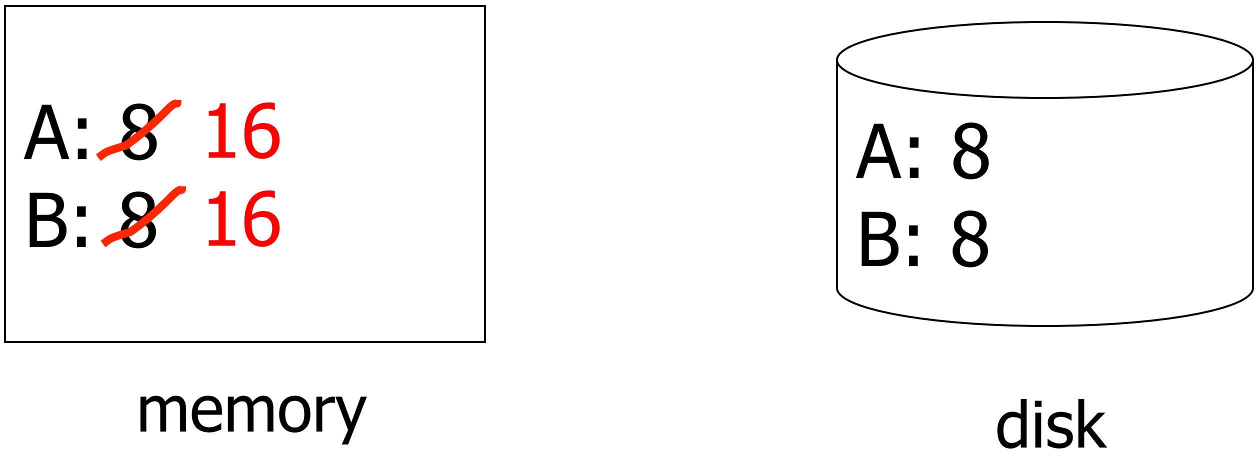
T_1: A ← A × 2

B ← B × 2

T_1:
```
Read (A,t);  t ← t×2
Write (A,t);
Read (B,t);  t ← t×2
Write (B,t);
Output (A);
Output (B);
```



```
T1:   Read (A,t);  t ← t×2
      Write (A,t);
      Read (B,t);  t ← t×2
      Write (B,t);
      Output (A);
      Output (B);
```



A: ~~8~~ 16

B: ~~8~~ 16

memory

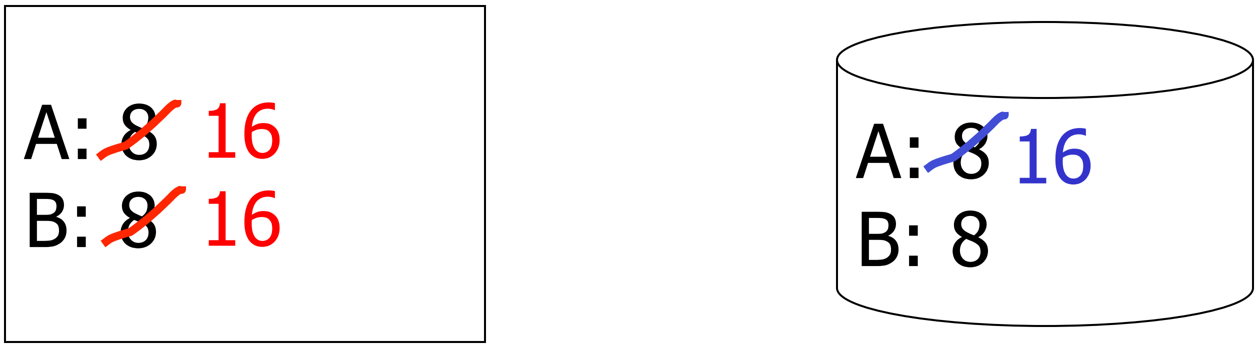
A: 8

B: 8

disk

T_1: Read (A,t); t ← t×2
Write (A,t);
Read (B,t); t ← t×2
Write (B,t);
Output (A);
Output (B);

failure!



A: ~~8~~ 16
B: ~~8~~ 16

memory

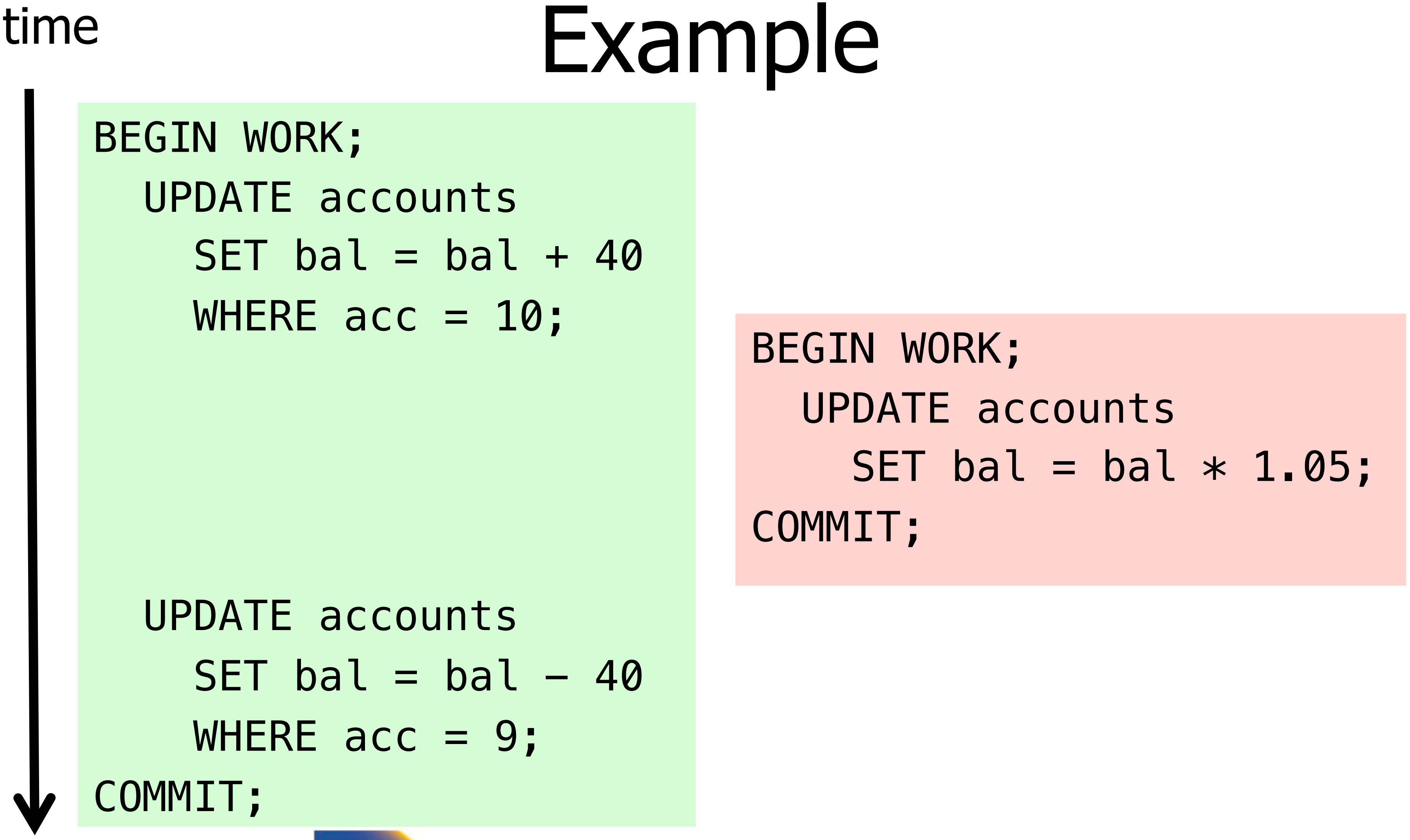
A: ~~8~~ 16
B: 8

disk

Transactions in SQL

- BEGIN WORK
  - Start new transaction
  - Often implicit
- COMMIT
  - Finish and make all modifications of transactions persistent
- ABORT/ROLLBACK
  - Finish and undo all changes of transaction

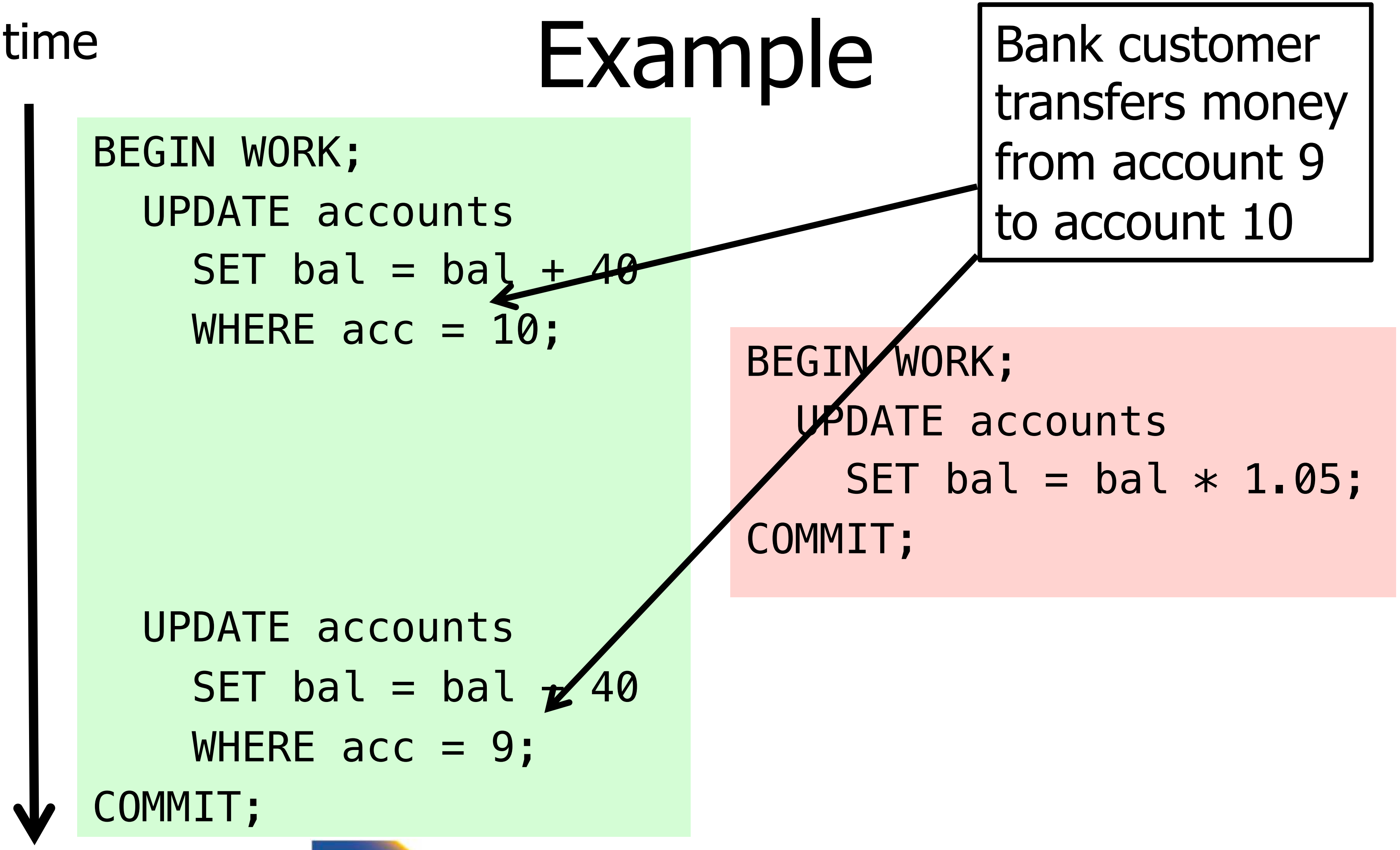
Example



```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal + 40
    WHERE acc = 10;




  UPDATE accounts
    SET bal = bal – 40
    WHERE acc = 9;
COMMIT;
```

```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal * 1.05;
COMMIT;
```

Example



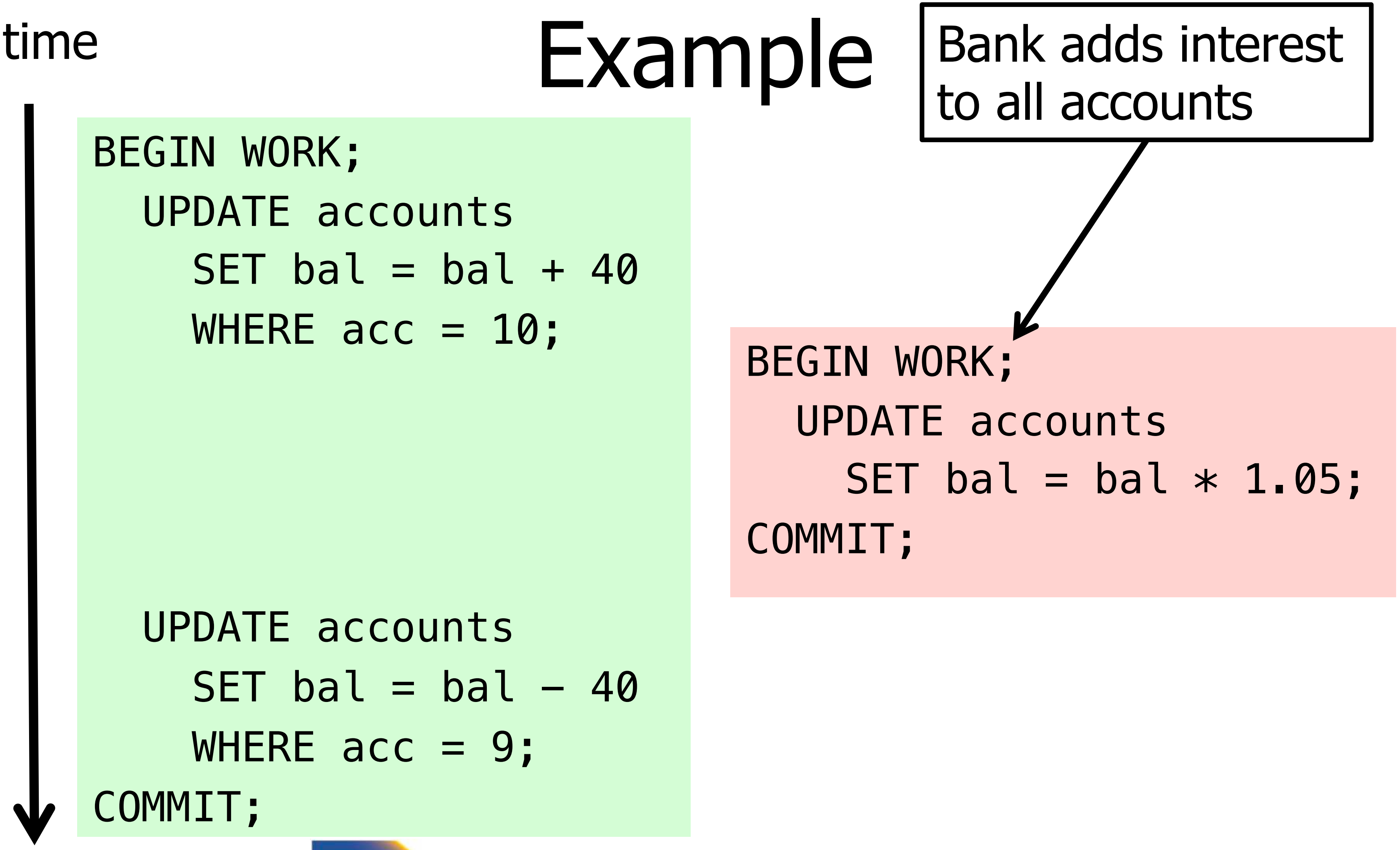
time

```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal + 40
    WHERE acc = 10;




  UPDATE accounts
    SET bal = bal - 40
    WHERE acc = 9;
COMMIT;
```

Bank customer transfers money from account 9 to account 10

```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal * 1.05;
COMMIT;
```

Example



time

```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal + 40
    WHERE acc = 10;
```

Bank adds interest to all accounts

```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal * 1.05;
COMMIT;
```

```
  UPDATE accounts
    SET bal = bal – 40
    WHERE acc = 9;
COMMIT;
```

Potential Problems:

1. Transactions are interrupted
   - No reduction in bal of acc 9
   - Only some accounts got interest
2. Interleaving of Transaction
   - Acc 9 too much interest (before 40 has been deducted)

time

```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal
    WHERE acc = 10




  UPDATE accounts
    SET bal = bal – 40
    WHERE acc = 9;
COMMIT;
```

```
    SET bal = bal * 1.05;
COMMIT;
```

Modeling Transactions and their Interleaving

- Transaction is sequence of operations
  - **read**: $\mathbf{r_i(x)}$ = transaction **i** read item **x**
  - **write**: $\mathbf{w_i(x)}$ = transaction **i** wrote item **x**
  - **commit**: $\mathbf{c_i}$ = transaction **i** committed
  - **abort:** $\mathbf{a_i}$ =transaction **i** aborted

$T_1 = r_1(a_{10}), w_1(a_{10}), r_1(a_9), w_1(a_9), c_1$

time

```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal + 40
    WHERE acc = 10;




  UPDATE accounts
    SET bal = bal – 40
    WHERE acc = 9;
COMMIT;
```

$T_1=r_1(a_{10}),w_1(a_{10}),r_1(a_9),w_1(a_9),c_1$

$T_2=r_2(a_1),w_2(a_1),r_2(a_2),w_2(a_2),r_2(a_9),w_2(a_9),r_2(a_{10}),w_2(a_{10}),c_1$

Assume we have accounts: a_1,a_2,a_9,a_{10}

```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal + 40
    WHERE acc = 10;




  UPDATE accounts
    SET bal = bal – 40
    WHERE acc = 9;
COMMIT;
```

```
BEGIN WORK;
  UPDATE accounts
    SET bal = bal * 1.05;
COMMIT;
```

Schedules

- A **schedule S** for a set of transactions $T = \{T_1, \ldots, T_n\}$ is an partial order over operations of T so that
  - **S** contains a prefix of the operations of each T_i
  - Operations of Ti appear in the same order in **S** as in Ti
  - For any two conflicting operations they are ordered

Note

- For simplicity: We often assume that the schedule is a total order

How to model execution order?

- Schedules model the order of the execution for operations of a set of transactions

Conflicting Operations

- Two operations are conflicting if
  - At least one of them is a write
  - Both are accessing the same data item
- Intuition
  - The order of execution for conflicting operations can influence result!

Conflicting Operations

- Examples
  - $w_1(X)$, $r_2(X)$ are conflicting
  - $w_1(X)$, $w_2(Y)$ are not conflicting
  - $r_1(X)$, $r_2(X)$ are not conflicting
  - $w_1(X)$, $w_1(X)$ are not conflicting

Complete Schedules = History

- A **schedule S** for T is complete if it contains all operations from each transaction in T
- We will call complete schedules **histories**

$T_1 = r_1(a_{10}), w_1(a_{10}), r_1(a_9), w_1(a_9), c_1$

$T_2 = r_2(a_1), w_2(a_1), r_2(a_2), w_2(a_2), r_2(a_9), w_2(a_9), r_2(a_{10}), w_2(a_{10}), c_1$

Complete Schedule

$S = r_2(a_1), r_1(a_{10}), w_2(a_1), r_2(a_2), w_1(a_{10}), w_2(a_2), r_2(a_9), w_2(a_9),$
$r_1(a_9), w_1(a_9), c_1\ r_2(a_{10}), w_2(a_{10}), c_1$

Incomplete Schedule

$S = r_2(a_1), r_1(a_{10}), w_2(a_1), w_1(a_{10})$

Not a Schedule

$S = r_2(a_1), r_1(a_{10}), c_1$

$T_1 = r_1(a_{10}), w_1(a_{10}), r_1(a_9), w_1(a_9), c_1$

$T_2 = r_2(a_1), w_2(a_1), r_2(a_2), w_2(a_2), r_2(a_9), w_2(a_9), r_2(a_{10}), w_2(a_{10}), c_1$

Conflicting operations

- Conflicting operations $w_1(a_{10})$ and $w_2(a_{10})$
- Order of these operations determines value of a_{10}
- `S1 and S2 do not generate the same result`

$S_1 = \ldots\ w_2(a_1)\ \ldots\ w_1(a_{10})$

$S_2 = \ldots\ w_1(a_1)\ \ldots\ w_2(a_{10})$

Why Schedules?

- Study properties of different execution orders
  - Easy/Possible to recover after failure
  - Isolation
  - -> preserve ACID properties
- Classes of schedules and protocols to guarantee that only "good" schedules are produced

CS 525: Advanced Database Organization

13: Failure and Recovery

Boris Glavic

Slides: adapted from a course taught by Hector Garcia-Molina, Stanford InfoLab

Now

- Crash recovery

Correctness (informally)

- If we stop running transactions,
  DB left consistent
- Each transaction sees a consistent DB

How can constraints be violated?

- Transaction bug
- DBMS bug
- Hardware failure

  e.g., disk crash alters balance of account

- Data sharing

  e.g.: T1: give 10% raise to programmers

  T2: change programmers ⇒ systems analysts

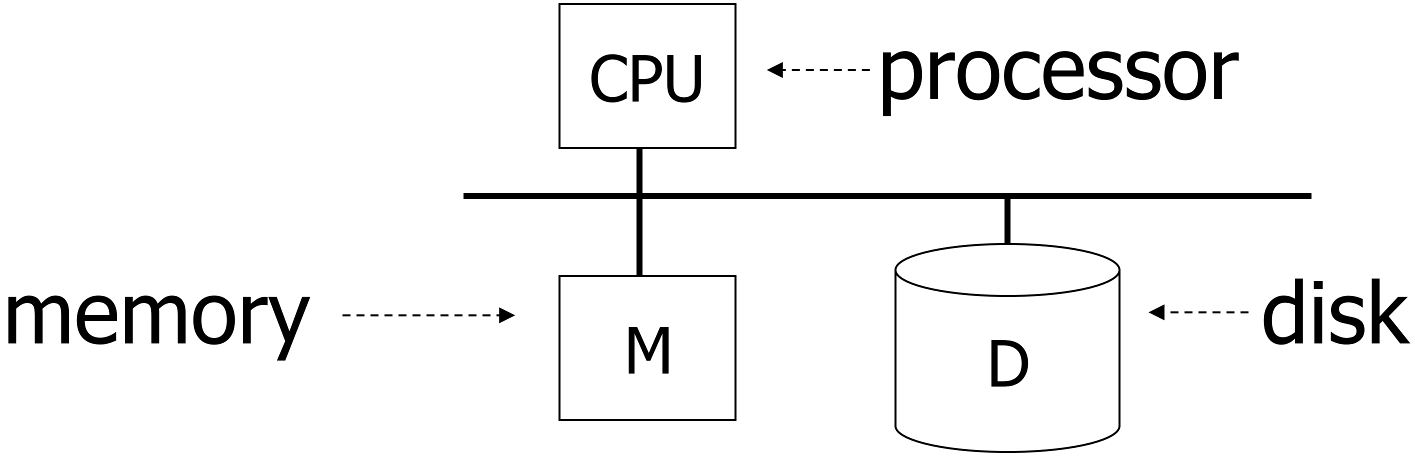
Recovery

- First order of business:

  <u>Failure Model</u>

- Events
  - Desired
  - Undesired
    - Expected
    - Unexpected

Our failure model



Desired events: see product manuals….

Undesired expected events:

System crash

- memory lost
- cpu halts, resets

<u>Desired events:</u> see product manuals….

<u>Undesired expected events:</u>

System crash

- memory lost
- cpu halts, resets

---

that's it!!

<u>Undesired Unexpected:</u> Everything else!

Undesired Unexpected: Everything else!

Examples:

- Disk data is lost
- Memory lost without CPU halt
- CPU implodes wiping out universe….

Is this model reasonable?

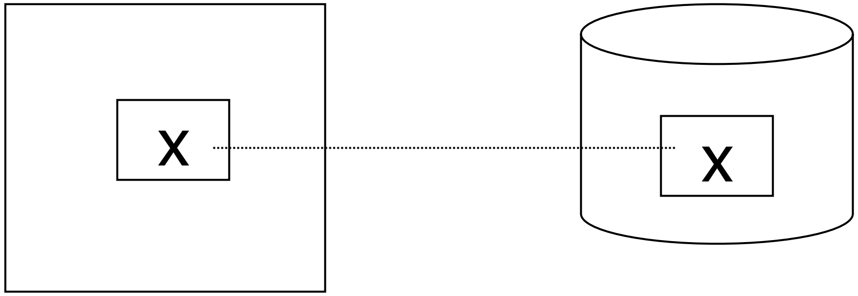
Approach: Add low level checks + redundancy to increase probability model holds

E.g.,

- Replicate disk storage (stable store)
- Memory parity
- CPU checks

Second order of business:

Storage hierarchy



Memory

DB Buffer

Disk

Operations:

- Input (x): block containing x → memory
- Output (x): block containing x → disk

Operations:

- Input (x): block containing x → memory
- Output (x): block containing x → disk

- Read (x,t): do input(x) if necessary
  t ← value of x in block
- Write (x,t): do input(x) if necessary
  value of x in block ← t

Key problem Unfinished transaction

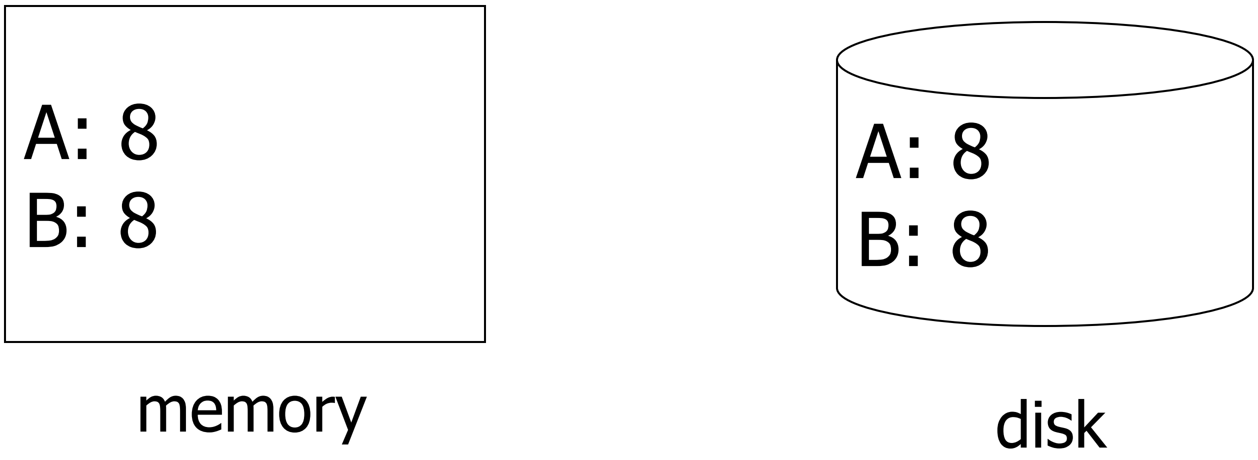
Example

Constraint: A=B

T_1: A ← A × 2

B ← B × 2

T_1: Read (A,t); $t \leftarrow t \times 2$
Write (A,t);
Read (B,t); $t \leftarrow t \times 2$
Write (B,t);
Output (A);
Output (B);

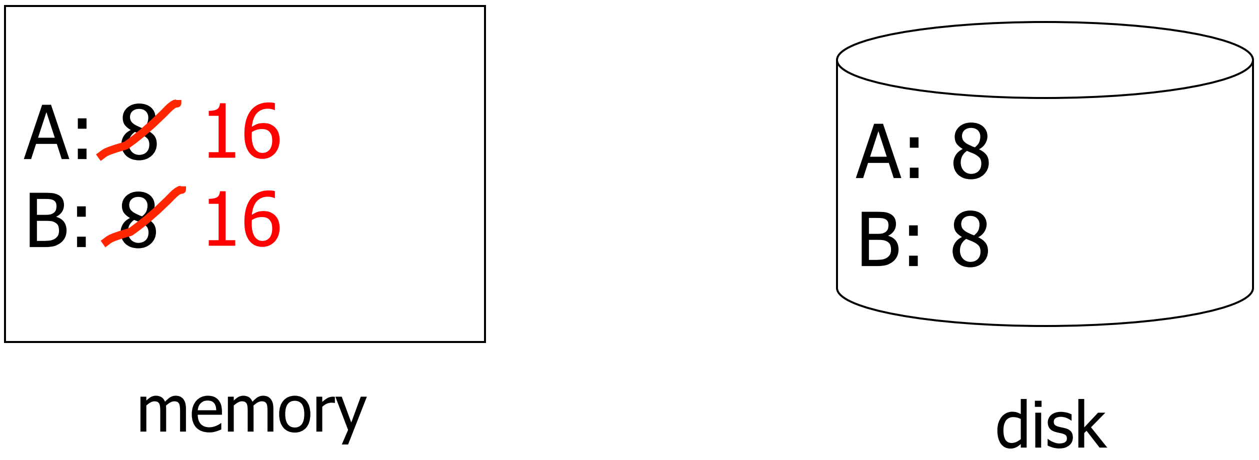

A: 8
B: 8

memory

A: 8
B: 8

disk

```
$T_1$:  Read (A,t);  t ← t×2
        Write (A,t);
        Read (B,t);  t ← t×2
        Write (B,t);
        Output (A);
        Output (B);
```



A: ~~8~~ 16

B: ~~8~~ 16

memory

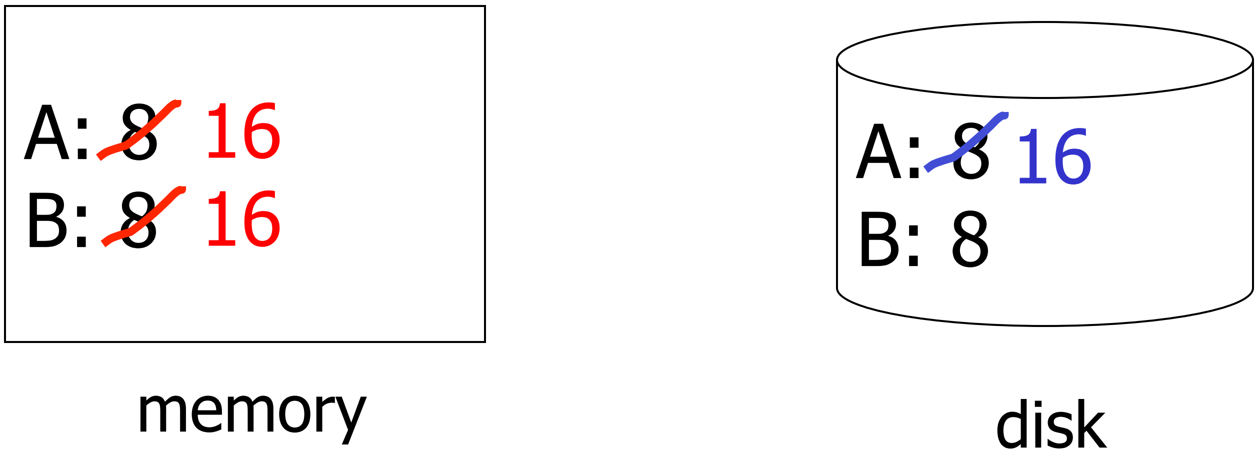
A: 8

B: 8

disk

T_1: Read (A,t); t ← t×2
Write (A,t);
Read (B,t); t ← t×2
Write (B,t);
Output (A);
Output (B);

failure!



- Need atomicity:
  - execute all actions of a transaction or none at all

How to restore consistent state after crash?

- Desired state after recovery:
  - Changes of committed transactions are reflected on disk
  - Changes of unfinished transactions are not reflected on disk
- After crash we need to
  - **Undo** changes of unfinished transactions that have been written to disk
  - **Redo** changes of finished transactions that have not been written to disk

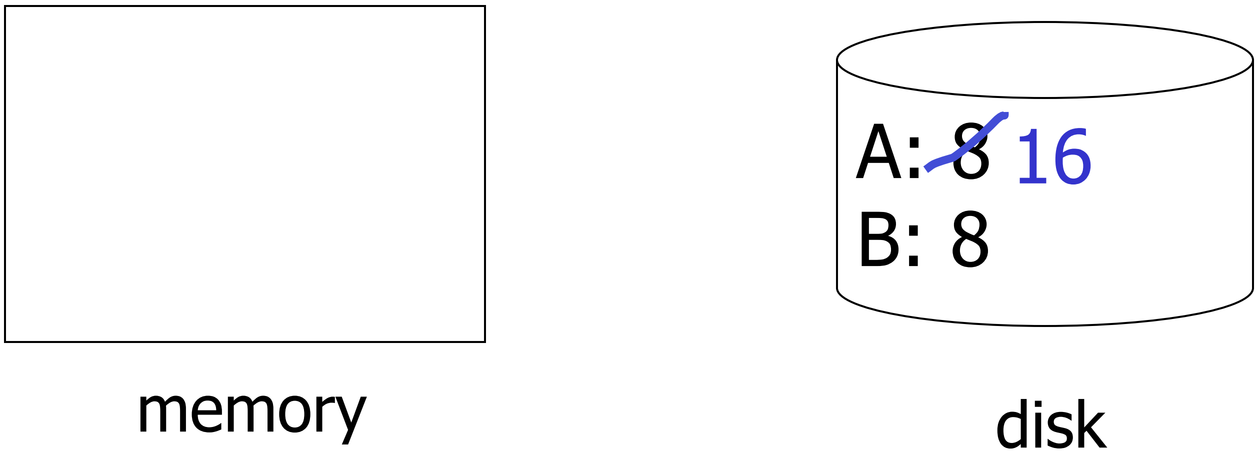
How to restore consistent state after crash?

- After crash we need to
  - **Undo** changes of unfinished transactions that have been written to disk
  - **Redo** changes of finished transactions that have not been written to disk
- We need to either
  - Store additional data to be able to Undo/Redo
  - Avoid ending up in situations where we need to Undo/Redo

T1: Read (A,t); t ← t×2
Write (A,t);
Read (B,t); t ← t×2
Write (B,t);
Output (A);
Output (B);

failure!

T_1 is unfinished
-> need to undo the write to A to recover to consistent state



Logging

- After crash need to
  - **Undo**
  - **Redo**
- We need to know
  - Which operations have been executed
  - Which operations are reflected on disk
- ->**Log** upfront what is to be done

Buffer Replacement Revisited

- Now we are interested in knowing how buffer replacement influences recovery!

Buffer Replacement Revisited

- **Steal**: all pages with fix count = 0 are replacement candidates
  - Smaller buffer requirements
- **No steal:** pages that have been modified by active transaction -> not considered for replacement
  - No need to undo operations of unfinished transactions after failure

Buffer Replacement Revisited

- **Force**: Pages modified by transaction are flushed to disk at end of transaction
  - No redo required
- **No force:** modified (dirty) pages are allowed to remain in buffer after end of transaction
  - Less repeated writes of same page

Effects of Buffer Replacement

	force	**No force**
No steal	• No Undo • No Redo	• No Undo • Redo
steal	• Undo • No Redo	• Redo • Undo

Schedules and Recovery

- Are there certain schedules that are easy/hard/impossible to recover from?

Recoverable Schedules

- We should never have to rollback an already committed transaction (D in ACID)
- **Recoverable** (**RC**) schedules require that
  - A transaction does not commit before every transaction that is has read from has committed
  - A transaction **T** reads from another transaction **T'** if it reads an item X that has last been written by T' and T' has not aborted before the read

$T_1 = w_1(X), c_1$

$T_2 = r_2(X), w_2(X), c_2$

Recoverable (RC) Schedule

$S_1 = w_1(X), r_2(X), w_2(X), c_1, c_2$

Nonrecoverable Schedule

$S_2 = w_1(X), r_2(X), w_2(X), c_2, c_1$

Cascading Abort

- Transaction **T** has written an item that is later read by **T'** and **T** aborts after that
  - we have to also abort **T'** because the value it read is no longer valid anymore
  - This is called a **cascading abort**
  - Cascading aborts are complex and should be avoided

$S = \ldots\ w_1(X)\ \ldots\ r_2(X)\ \ldots\ a_1$

Cascadeless Schedules

- **Cascadeless (CL)** schedules guarantee that there are no cascading aborts
  - Transactions only read values written by already committed transactions

$T_1 = w_1(X), c_1$

$T_2 = r_2(X), w_2(X), c_2$

Cascadeless (CL) Schedule

$S_1 = w_1(X), c_1, r_2(X), w_2(X), c_2$

Recoverable (RC) Schedule

$S_2 = w_1(X), r_2(X), w_2(X), c_1, c_2$

Nonrecoverable Schedule

$S_3 = w_1(X), r_2(X), w_2(X), c_2, c_1$

$T_1 = w_1(X), a_1$

$T_2 = r_2(X), w_2(X), c_2$

Consider what happens if T1 aborts!

Cascadeless (CL) Schedule

$S_1 = w_1(X), a_1, r_2(X), w_2(X), c_2$

Recoverable (RC) Schedule

$S_2 = w_1(X), r_2(X), w_2(X), a_1, a_2$

Nonrecoverable Schedule

$S_3 = w_1(X), r_2(X), w_2(X), c_2, a_1$

Strict Schedules

- **Strict (ST)** schedules guarantee that to Undo the effect of an transaction we simply have to undo each of its writes
  - Transactions do not read nor write items written by uncommitted transactions

$T_1 = w_1(X), c_1$

$T_2 = r_2(X), w_2(X), c_2$

Cascadeless (CL) + Strict Schedule (ST)

$S_1 = w_1(X), c_1, r_2(X), w_2(X), c_2$

Recoverable (RC) Schedule

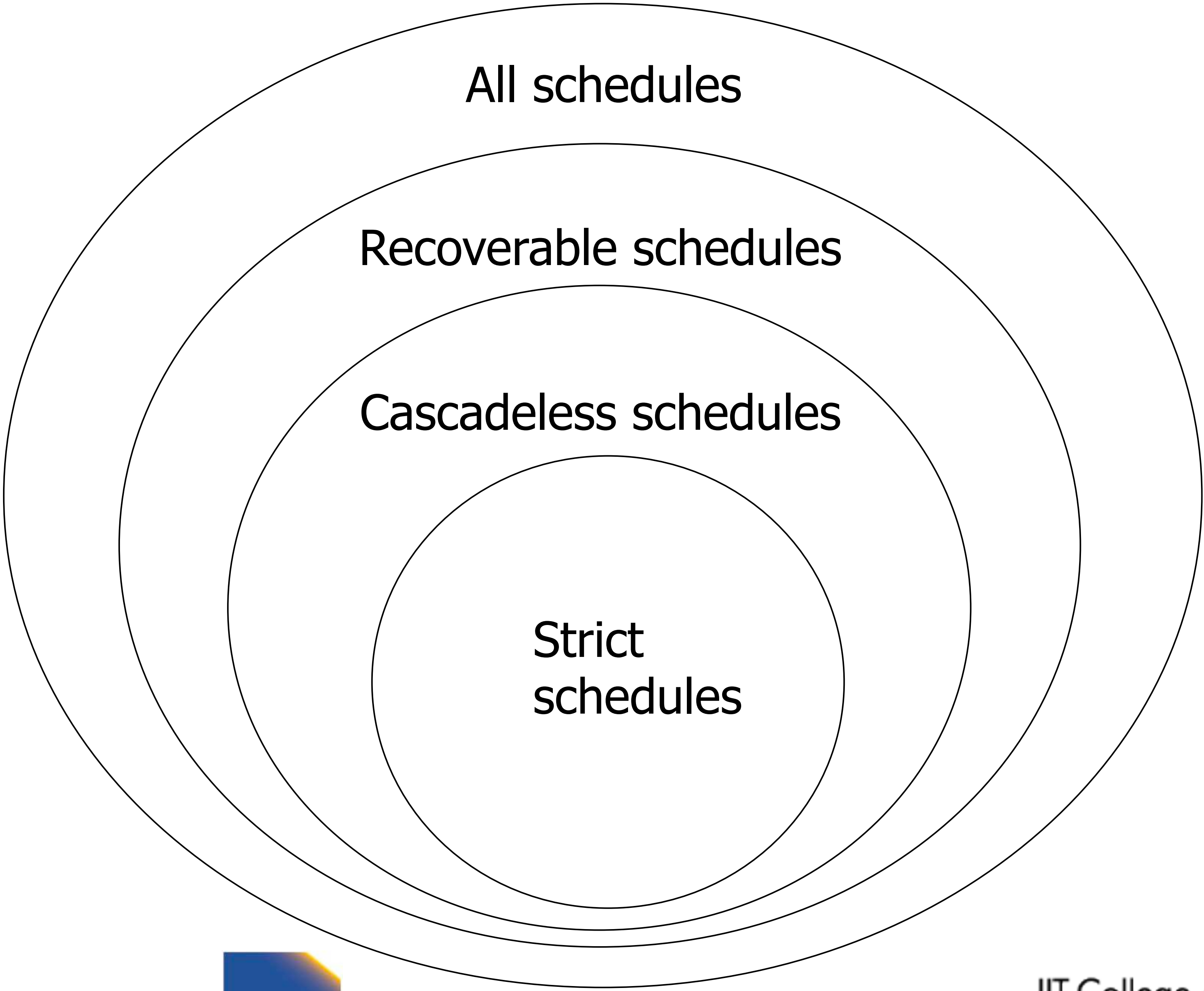
$S_2 = w_1(X), r_2(X), w_2(X), c_1, c_2$

Nonrecoverable Schedule

$S_3 = w_1(X), r_2(X), w_2(X), c_2, c_1$

Compare Classes

$$\mathbf{ST} \subset \mathbf{CL} \subset \mathbf{RC} \subset \mathbf{ALL}$$


All schedules

Recoverable schedules

Cascadeless schedules

Strict schedules

Logging and Recovery

- We now discuss approaches for logging and how to use them in recovery

<u>One solution:</u> undo logging (immediate modification)

due to: Hansel and Gretel, 782 AD

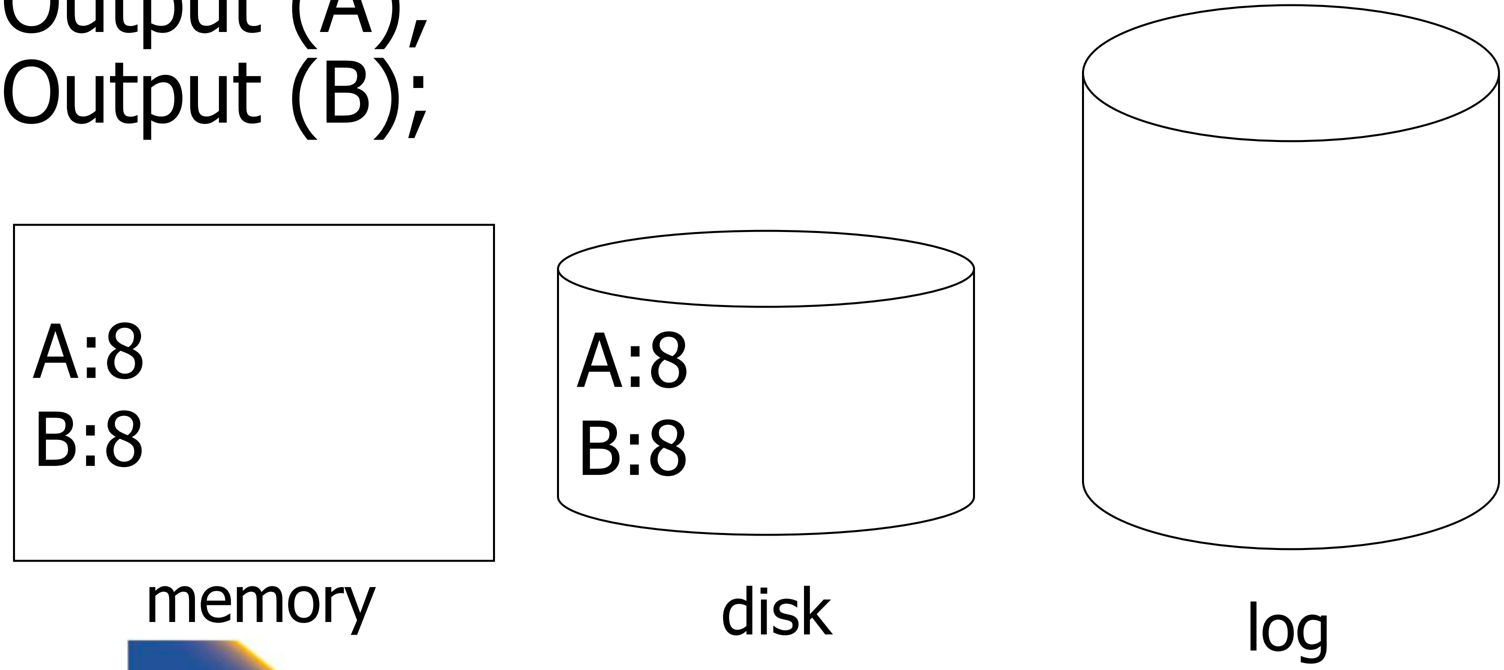
<u>One solution:</u> undo logging (immediate modification)

due to: Hansel and Gretel, 782 AD

- Improved in 784 AD to durable undo logging

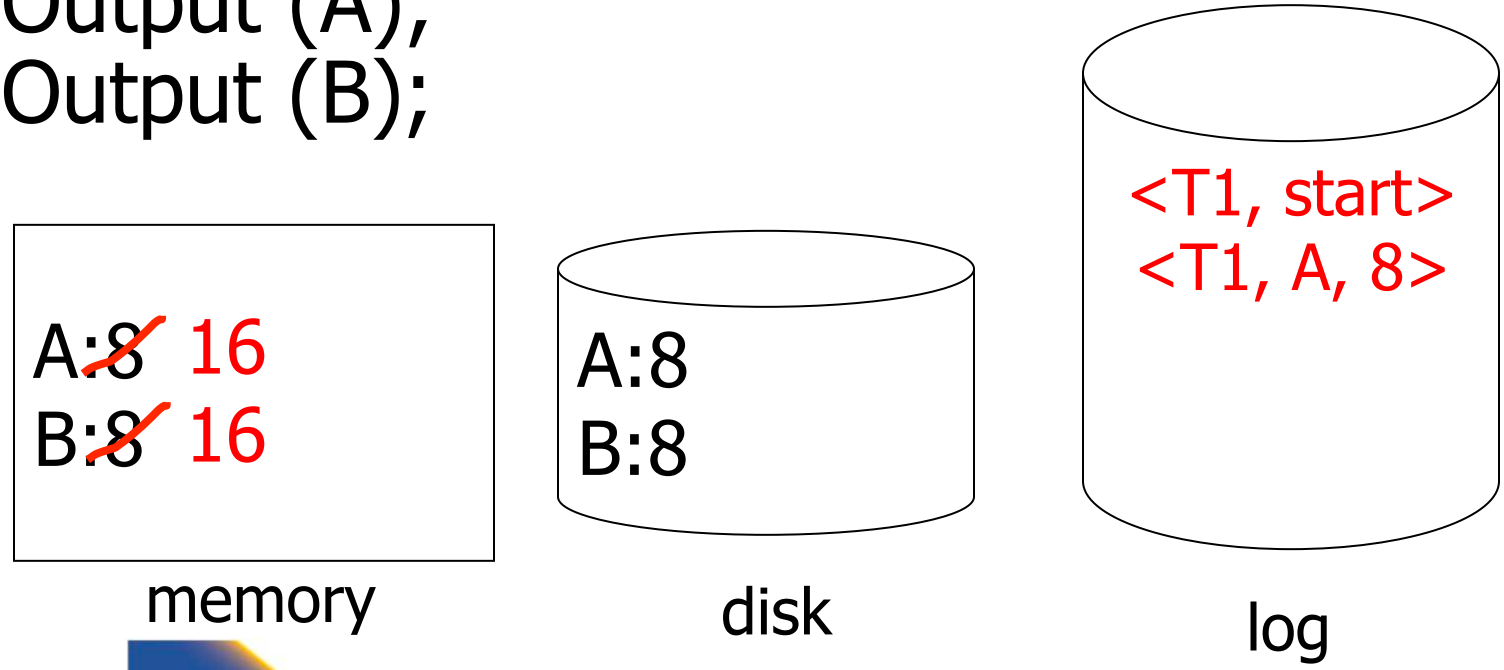
Undo logging (Immediate modification)

T_1: Read (A,t); t ← t×2 A=B
Write (A,t);
Read (B,t); t ← t×2
Write (B,t);
Output (A);
Output (B);



Undo logging (Immediate modification)

T1: Read (A,t); t ← t×2 A=B
Write (A,t);
Read (B,t); t ← t×2
Write (B,t);
Output (A);
Output (B);



A:~~8~~ 16
B:~~8~~ 16

memory

A:8
B:8

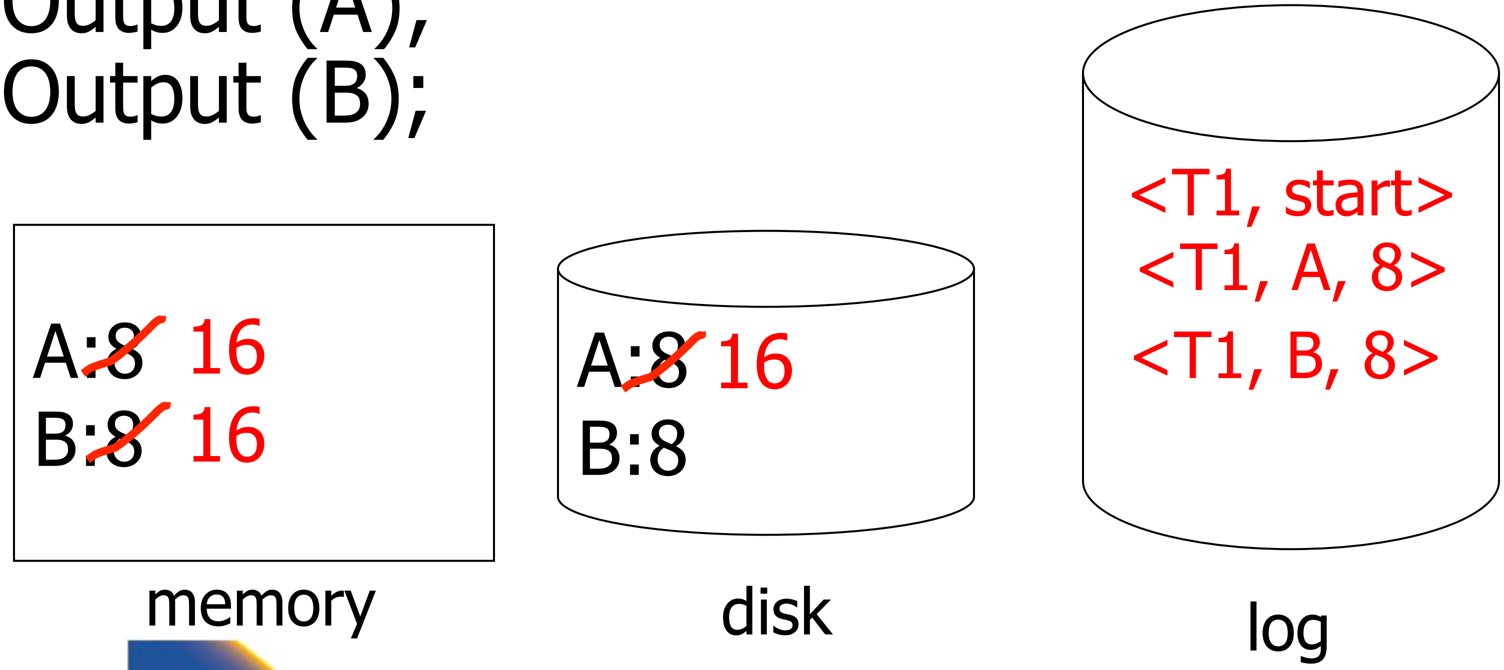
disk

<T1, start>
<T1, A, 8>

log

Undo logging (Immediate modification)

```
T1:  Read (A,t);  t ← t×2        A=B
     Write (A,t);
     Read (B,t);  t ← t×2
     Write (B,t);
     Output (A);
     Output (B);
```



A:~~8~~ 16
B:~~8~~ 16

memory

A:~~8~~ 16
B:8

disk

<T1, start>
<T1, A, 8>
<T1, B, 8>

log

Undo logging (Immediate modification)

T_1: Read (A,t); t ← t×2 A=B
Write (A,t);
Read (B,t); t ← t×2
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Output (A);
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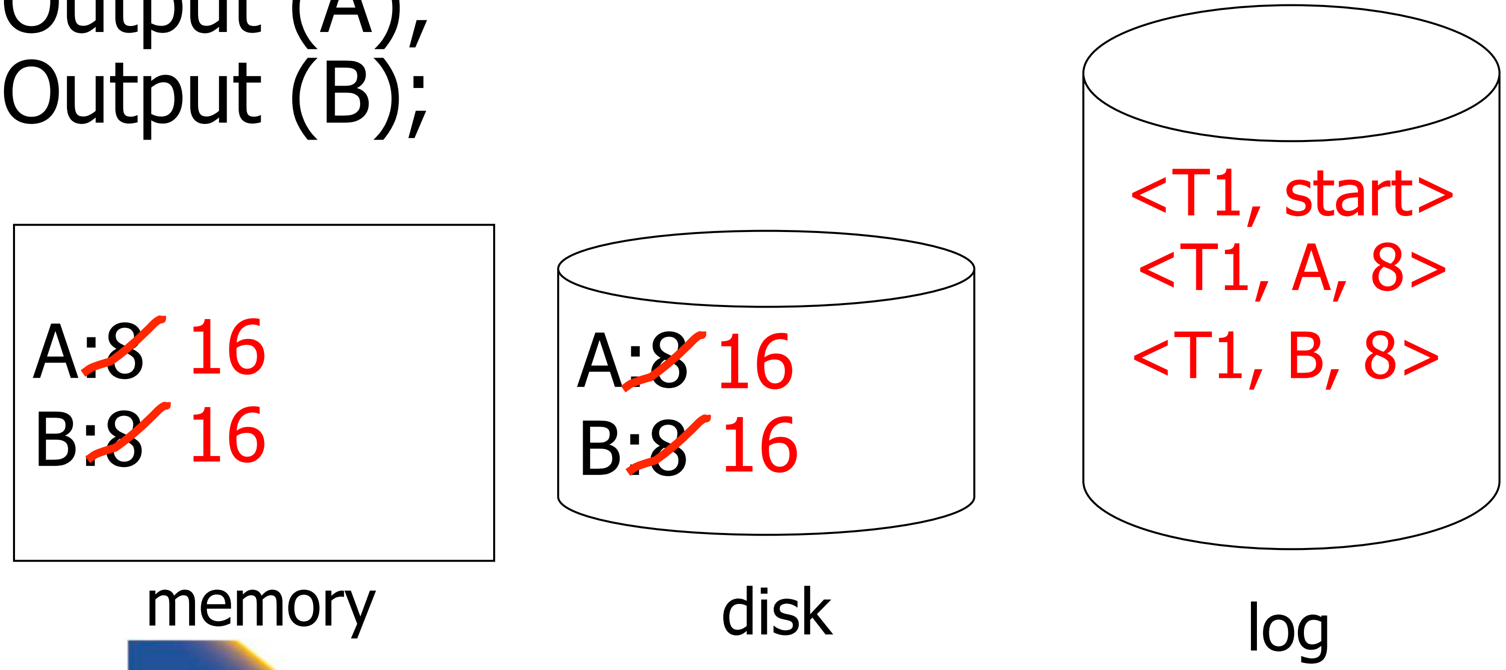
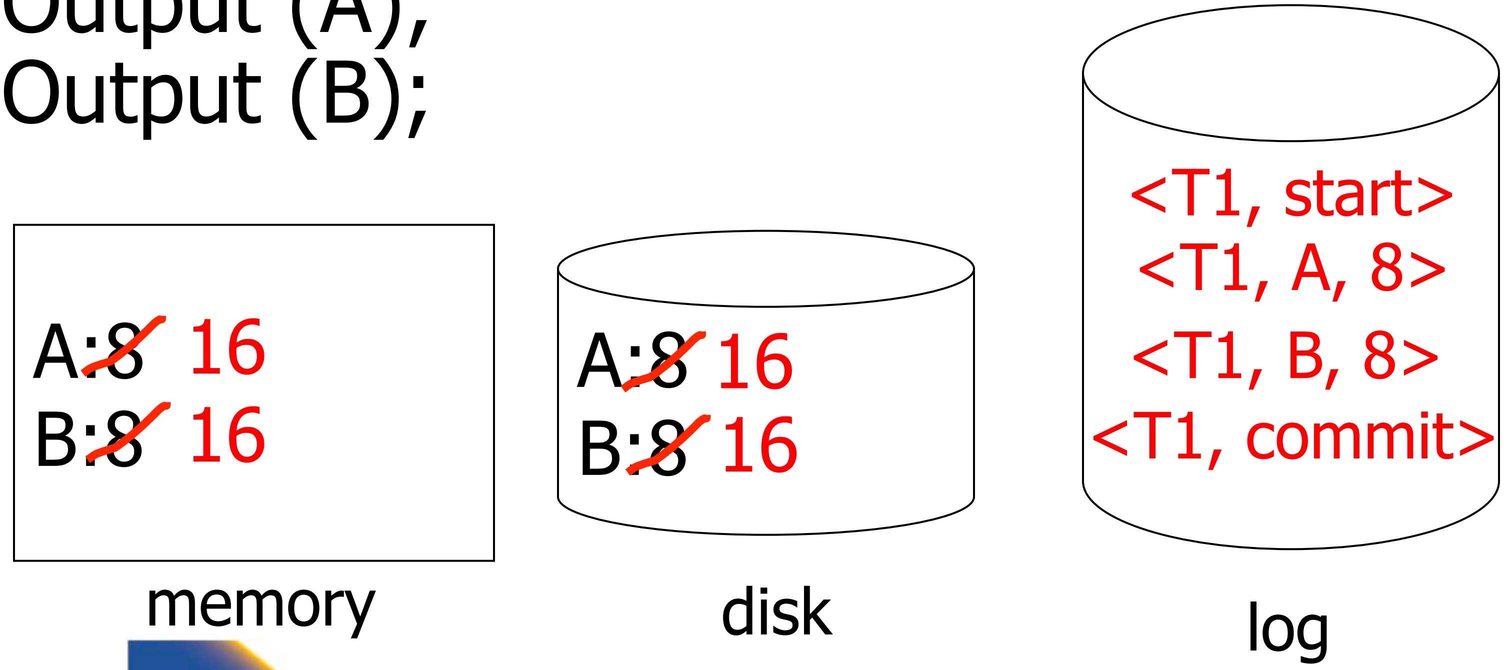


Undo logging (Immediate modification)

```
T1:  Read (A,t);  t ← t×2        A=B
     Write (A,t);
     Read (B,t);  t ← t×2
     Write (B,t);
     Output (A);
     Output (B);
```



A:~~8~~ 16

B:~~8~~ 16

memory

A:~~8~~ 16

B:~~8~~ 16

disk

<T1, start>

<T1, A, 8>

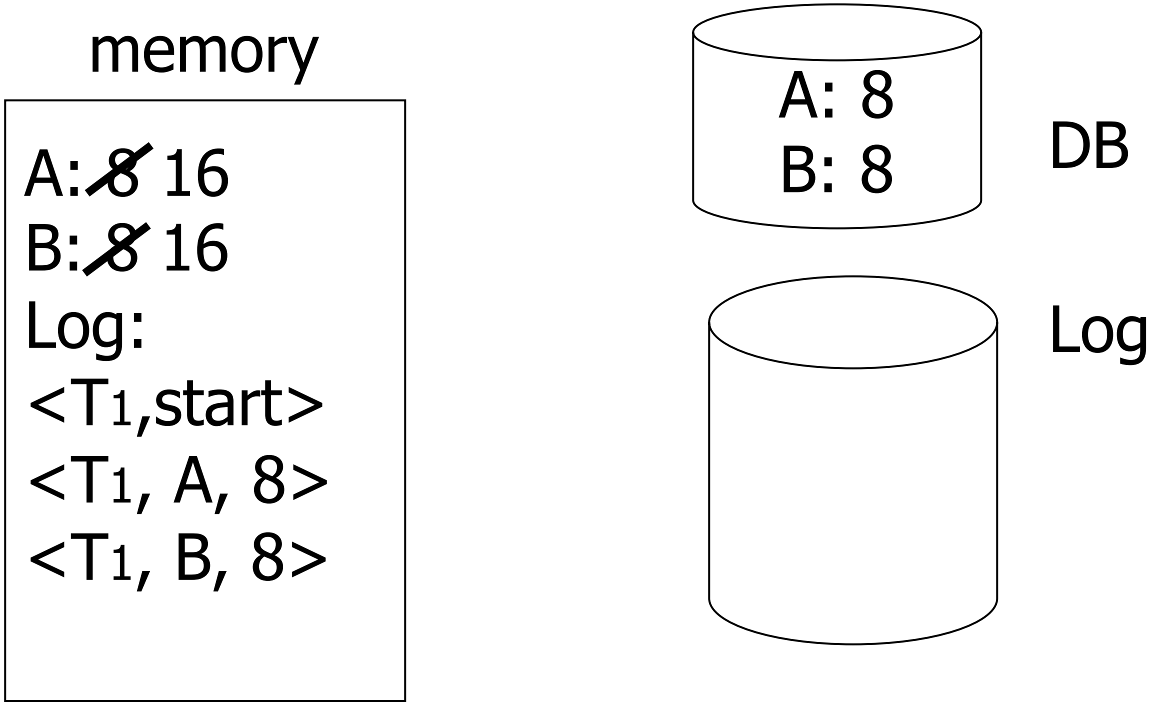
<T1, B, 8>

<T1, commit>

log

One "complication"

- Log is first written in memory
- Not written to disk on every action



memory

A: ~~8~~ 16
B: ~~8~~ 16
Log:
<T_1,start>
<T_1, A, 8>
<T_1, B, 8>

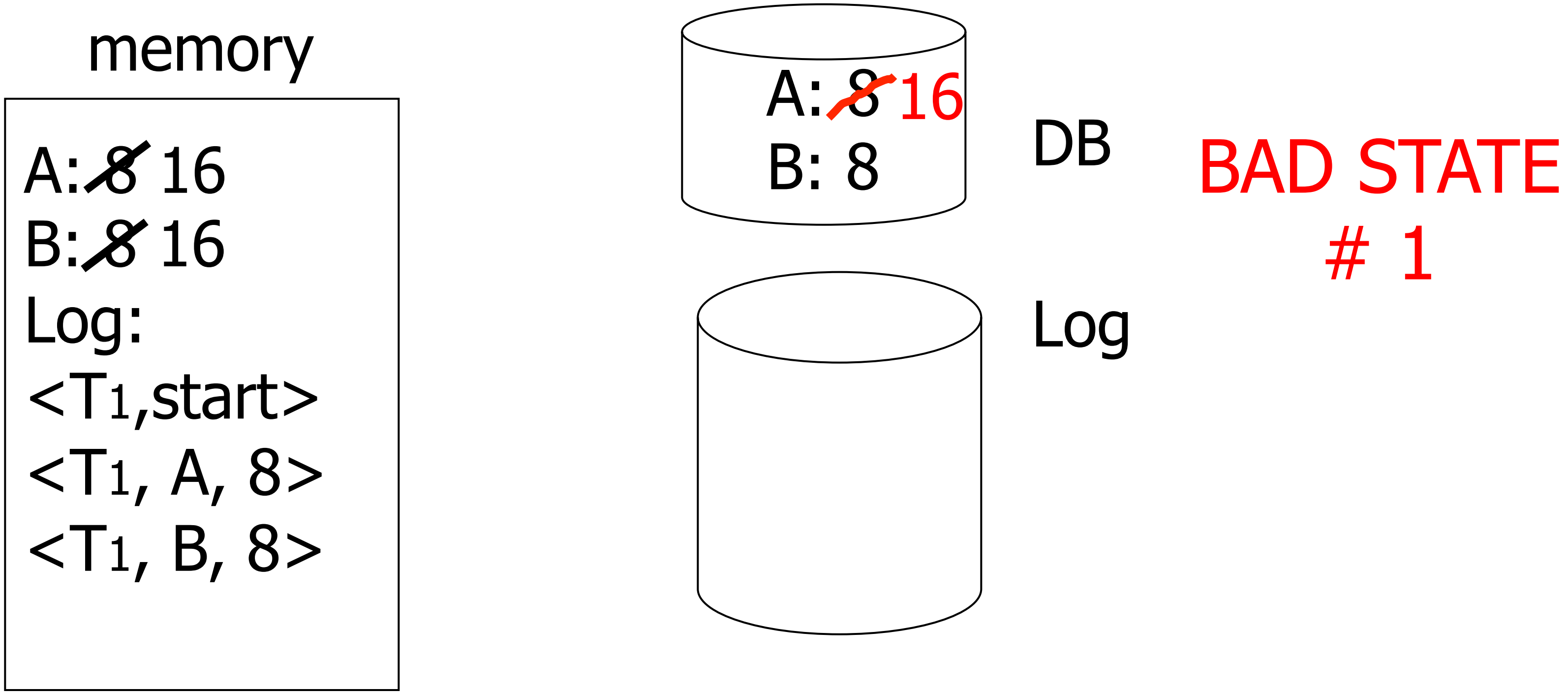
A: 8
B: 8

DB

Log

One "complication"

- Log is first written in memory
- Not written to disk on every action



memory

A: ~~8~~ 16
B: ~~8~~ 16
Log:
<T_1,start>
<T_1, A, 8>
<T_1, B, 8>

A: ~~8~~ 16
B: 8

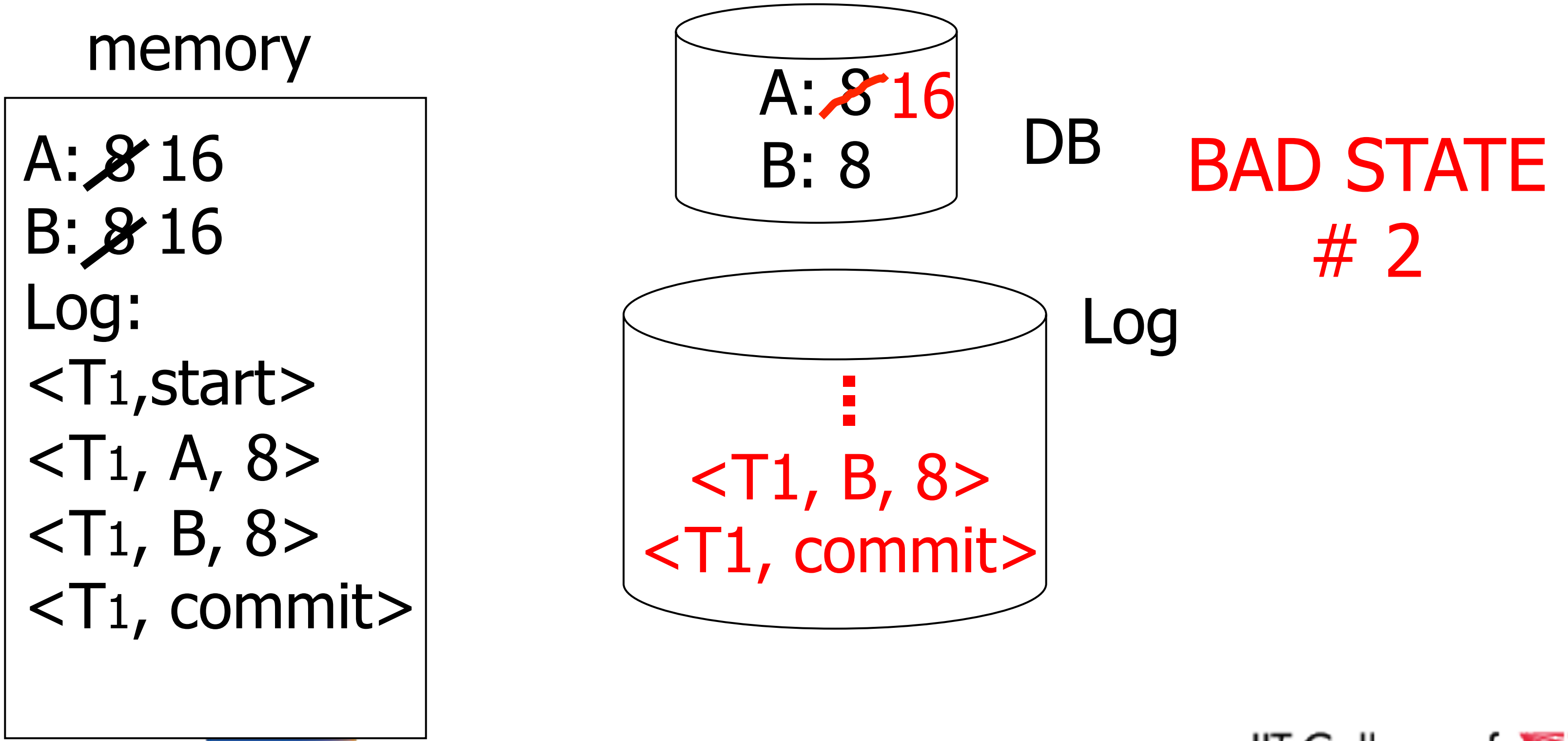
DB

Log

BAD STATE
1

One "complication"

- Log is first written in memory
- Not written to disk on every action



memory

A: ~~8~~ 16
B: ~~8~~ 16
Log:
<T1,start>
<T1, A, 8>
<T1, B, 8>
<T1, commit>

A: ~~8~~ 16
B: 8

DB

BAD STATE
2

Log

⋮
<T1, B, 8>
<T1, commit>

Undo logging rules

(1) For every action generate undo log record (containing old value)

(2) Before *x* is modified on disk, log records pertaining to *x* must be on disk (write ahead logging: **WAL**)

(3) Before commit is flushed to log, all writes of transaction must be reflected on disk

Recovery rules: Undo logging

- For every Ti with <Ti, start> in log:
  - If <Ti,commit> or <Ti,abort> in log, do nothing
  - Else
    - For all <Ti, X, v> in log:
      - write (X, v)
      - output (X)
    - Write <Ti, abort> to log

Recovery rules: Undo logging

- For every Ti with <Ti, start> in log:
  - If <Ti,commit> or <Ti,abort> in log, do nothing
  - Else
    - For all <Ti, *X*, *v*> in log:
      - write (*X*, *v*)
      - output (*X*)
    - Write <Ti, abort> to log

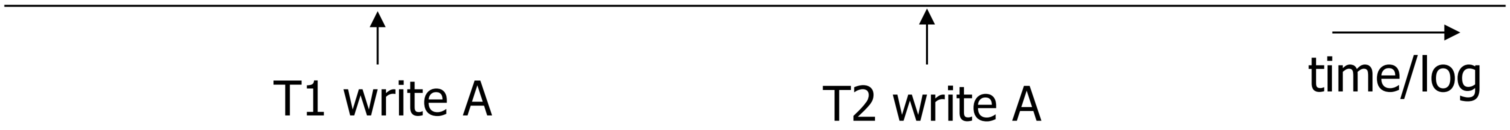
IS THIS CORRECT??

Recovery rules: Undo logging

```
(1) Let S = set of transactions with
        <Ti, start> in log, but no
        <Ti, commit> (or <Ti, abort>) record in log
(2) For each <Ti, X, v> in log,
    in reverse order (latest → earliest) do:
        - if $Ti \in S$ then { - write (X, v)
                             { - output (X)
(3) For each $Ti \in S$ do
        - write <Ti, abort> to log
```

Question

- Can writes of <Ti, abort> records be done in any order (in Step 3)?
  - Example: T1 and T2 both write A
  - T1 executed before T2
  - T1 and T2 both rolled-back
  - <T1, abort> written but NOT <T2, abort>?
  - <T2, abort> written but NOT <T1, abort>?



T1 write A

T2 write A

time/log

What if failure during recovery?

No problem! ✏ Undo idempotent

- An operation is called **idempotent** if the number of times it is applied do not effect the result
- For Undo:
  - Undo(log) = Undo(Undo(… (Undo(log)) …))

Undo is idempotent

- We store the values of data items before the operation
- Undo can be executed repeatedly without changing effects
  - idempotent

Physical vs. Logical Logging

- How to represent values in log entries?
- Physical logging
  - Content of pages before and after
- Logical operations
  - Operation to execute for undo/redo
    - E.g., delete record x
- Hybrid (Physiological)
  - Delete record x from page y

To discuss:

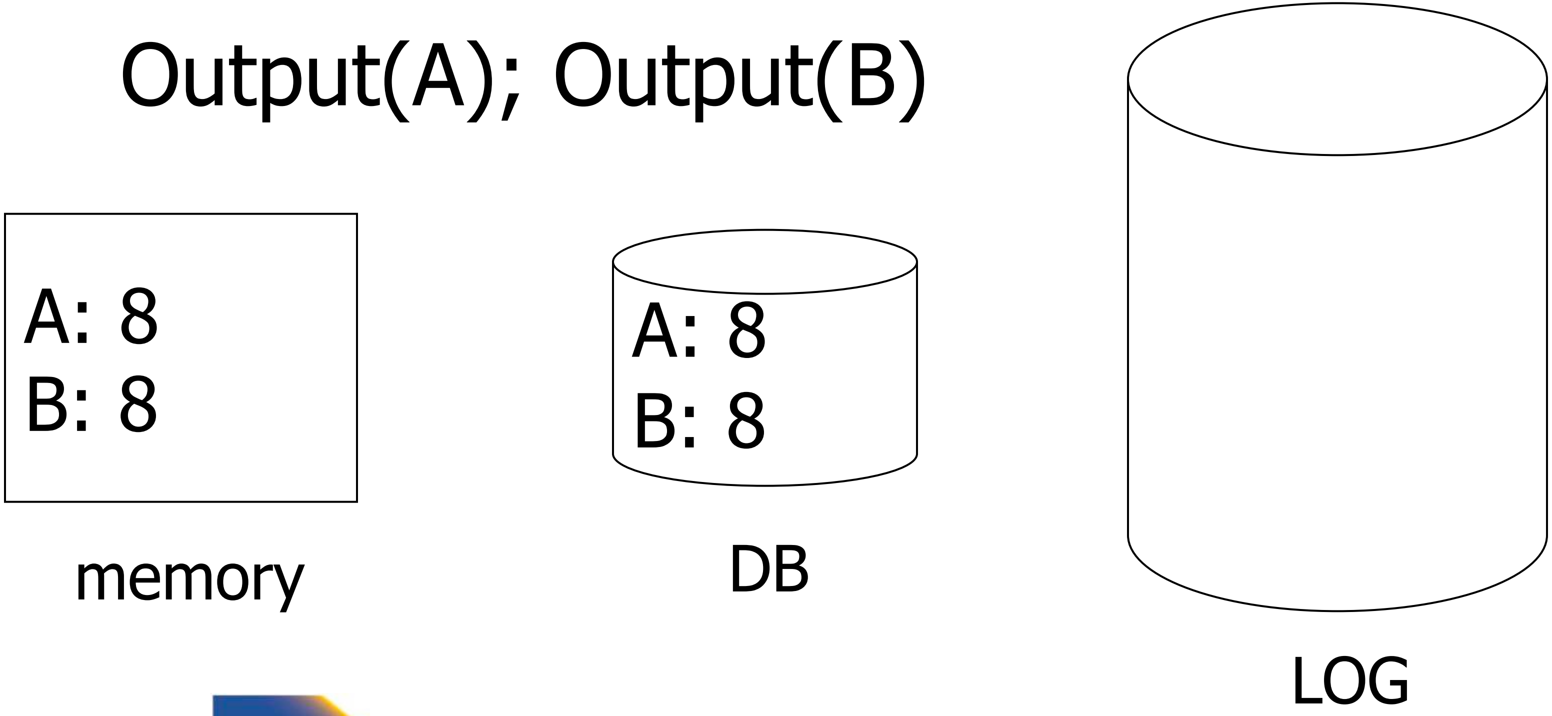
- Redo logging
- Undo/redo logging, why both?
- Real world actions
- Checkpoints
- Media failures

Redo logging (deferred modification)

T_1: Read(A,t); t← t×2; write (A,t);

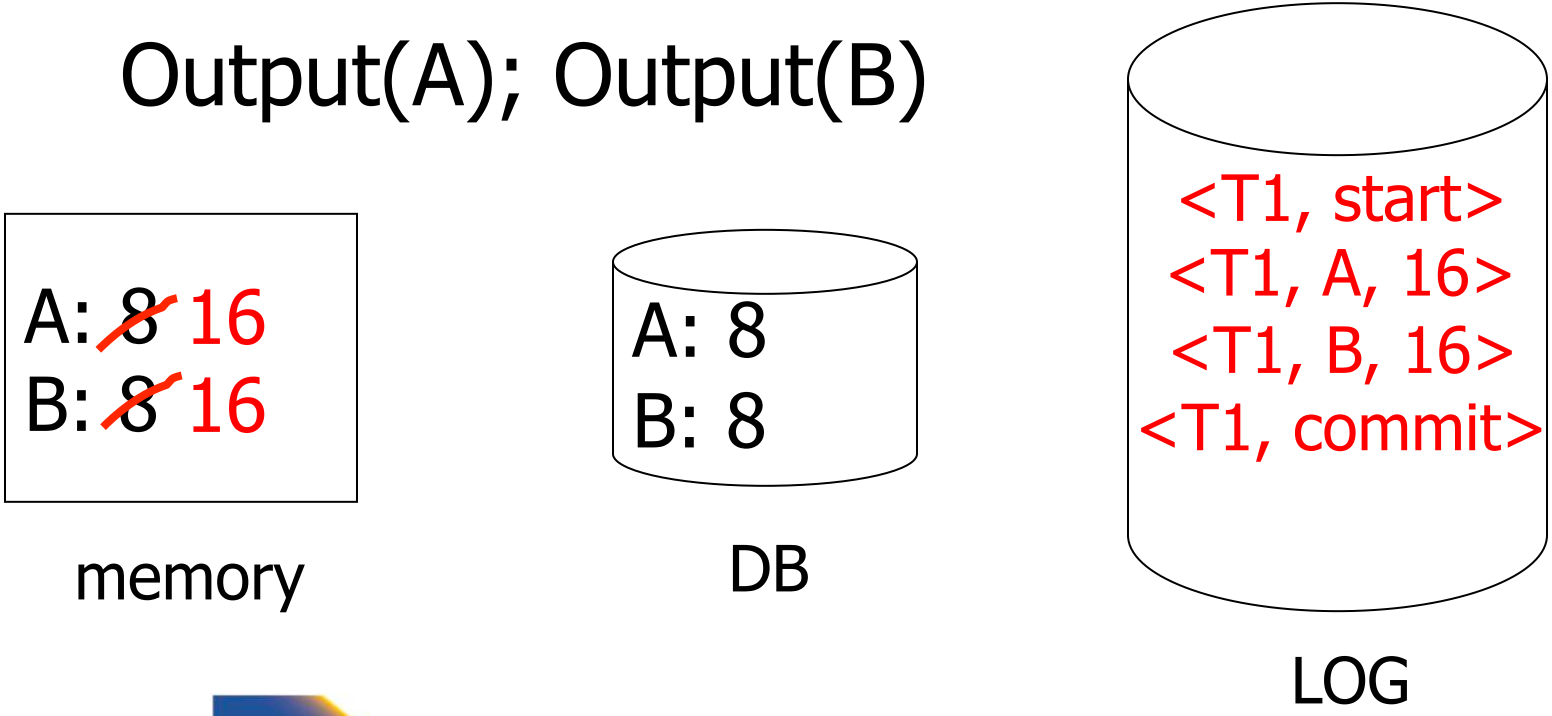
Read(B,t); t←t×2; write (B,t);

Output(A); Output(B)



Redo logging (deferred modification)

T_1: Read(A,t); t← t×2; write (A,t);
Read(B,t); t←t×2; write (B,t);
Output(A); Output(B)



A: ~~8~~ 16
B: ~~8~~ 16

memory

A: 8
B: 8

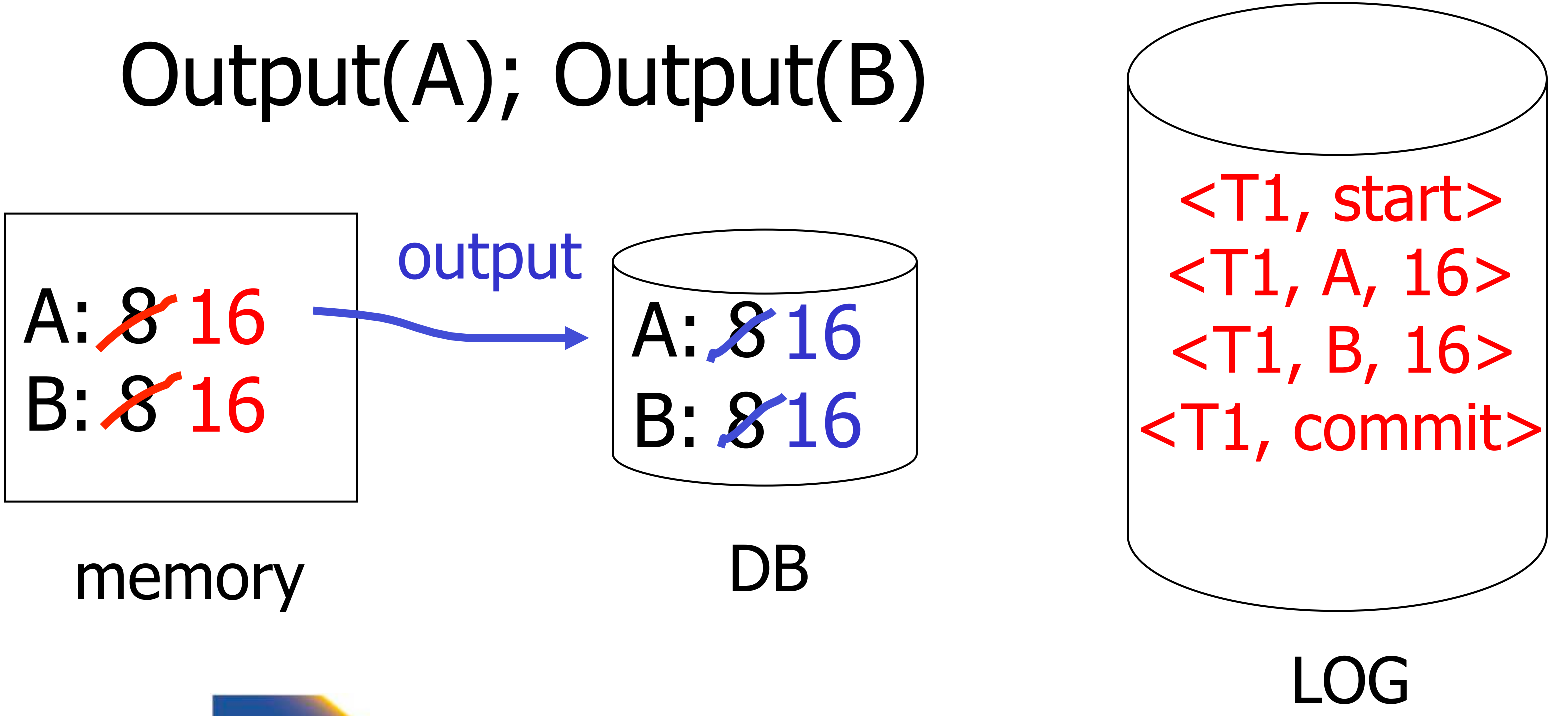
DB

<T1, start>
<T1, A, 16>
<T1, B, 16>
<T1, commit>

LOG

Redo logging (deferred modification)

T1: Read(A,t); t← t×2; write (A,t);
Read(B,t); t← t×2; write (B,t);
Output(A); Output(B)



A: ~~8~~ 16
B: ~~8~~ 16

memory

output

A: ~~8~~ 16
B: ~~8~~ 16

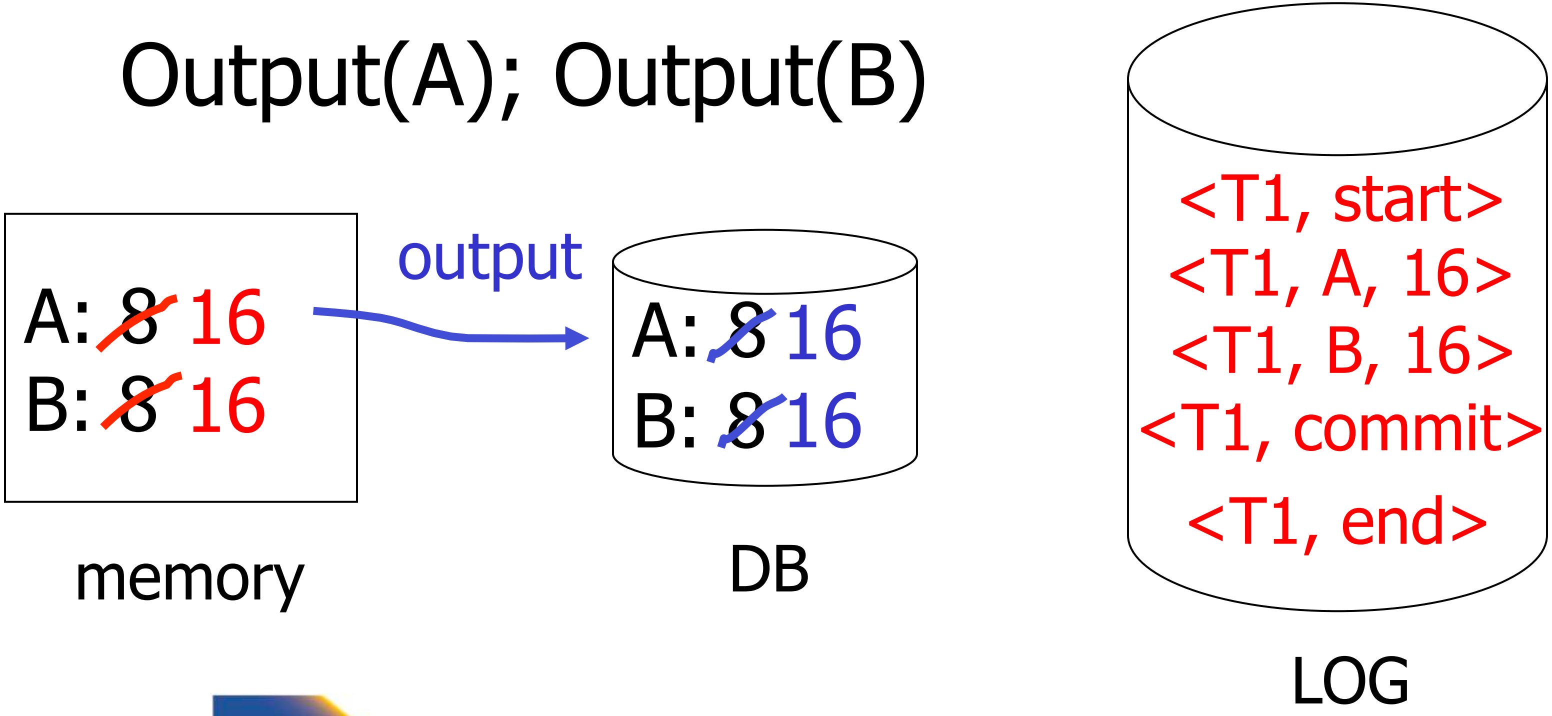
DB

<T1, start>
<T1, A, 16>
<T1, B, 16>
<T1, commit>

LOG

Redo logging (deferred modification)

T_1: Read(A,t); t ← t×2; write (A,t);
Read(B,t); t ← t×2; write (B,t);
Output(A); Output(B)



Redo logging rules

(1) For every action, generate redo log record (containing new value)

(2) Before X is modified on disk (DB), all log records for transaction that modified X (including commit) must be on disk

(3) Flush log at commit

(4) Write END record after DB updates flushed to disk

Recovery rules: Redo logging

- For every Ti with <Ti, commit> in log:
  - For all <Ti, X, v> in log:

$$\left\{\begin{array}{l}\text{Write}(X, v)\\ \text{Output}(X)\end{array}\right.$$

Recovery rules: Redo logging

- For every Ti with <Ti, commit> in log:
  - For all <Ti, X, v> in log:

$$\begin{cases} \text{Write(X, v)} \\ \text{Output(X)} \end{cases}$$

➽IS THIS CORRECT??

<u>Recovery rules:</u> Redo logging

(1) Let S = set of transactions with <Ti, commit> (and no <Ti, end>) in log

(2) For each <Ti, X, v> in log, in forward order (earliest → latest) do:

- if Ti ∈ S then $\begin{cases} \text{Write}(X, v) \\ \text{Output}(X) \end{cases}$

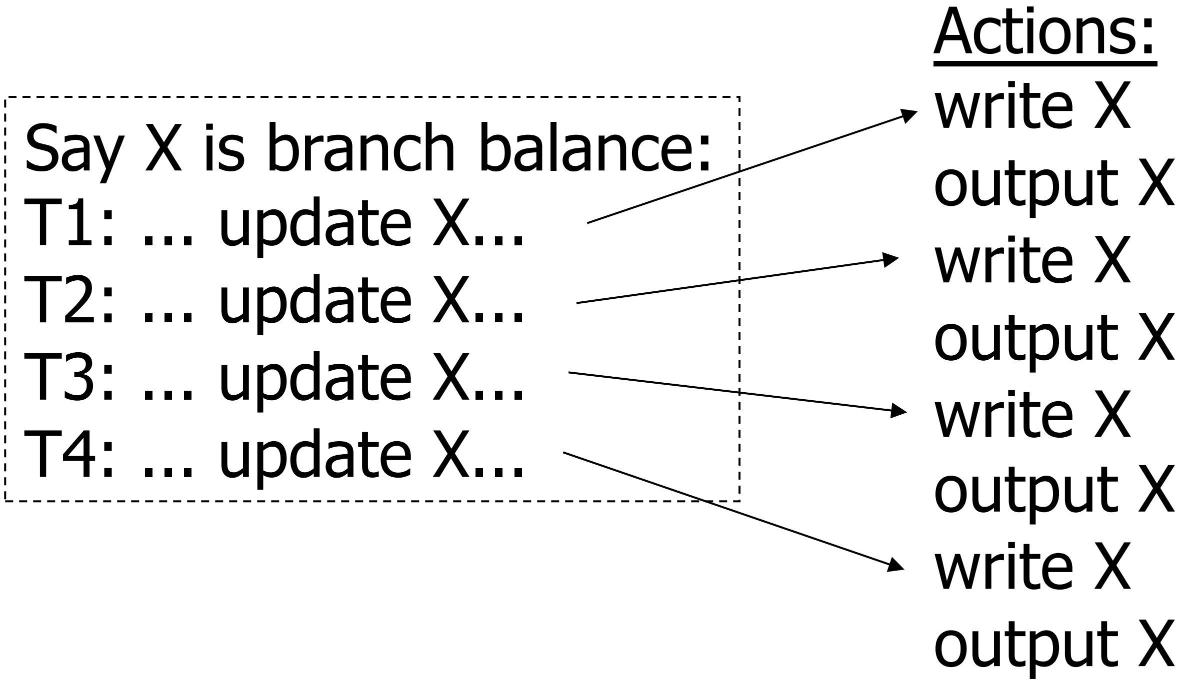
(3) For each Ti ∈ S, write <Ti, end>

Crash During Redo

- Since Redo log contains values after writes, repeated application of a log entry does not change result
  - ->idempotent

Combining <Ti, end> Records

- Want to delay DB flushes for hot objects

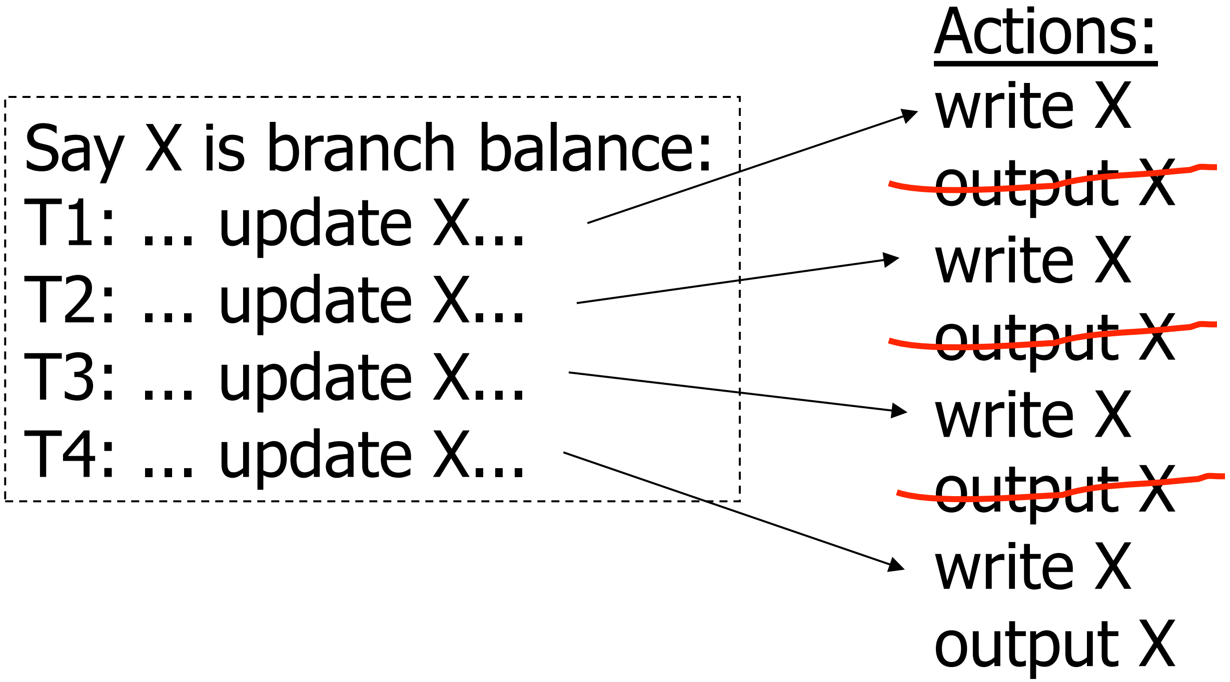


Say X is branch balance:
T1: ... update X...
T2: ... update X...
T3: ... update X...
T4: ... update X...

Actions:
write X
output X
write X
output X
write X
output X
write X
output X

Combining <Ti, end> Records

- Want to delay DB flushes for hot objects



Say X is branch balance:
T1: ... update X...
T2: ... update X...
T3: ... update X...
T4: ... update X...

Actions:
write X
~~output X~~
write X
~~output X~~
write X
~~output X~~
write X
output X

combined <end> (checkpoint)

Solution: Checkpoint

- no <ti, end> actions>
- simple checkpoint

Periodically:

(1) Do not accept new transactions

(2) Wait until all transactions finish

(3) Flush all log records to disk (log)

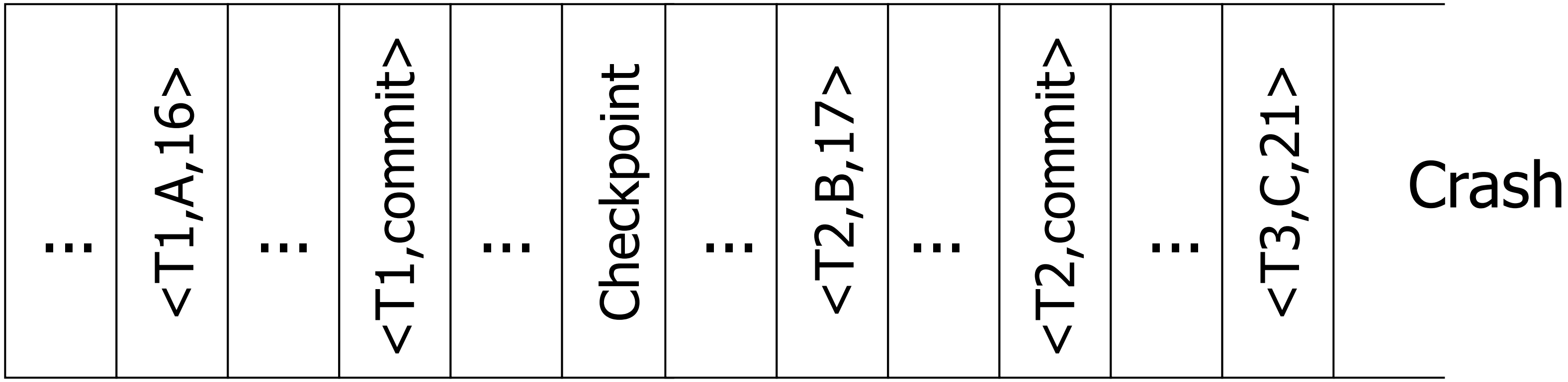
(4) Flush all buffers to disk (DB) (do not discard buffers)

(5) Write "checkpoint" record on disk (log)

(6) Resume transaction processing

Example: what to do at recovery?

Redo log (disk):



...	<T1,A,16>	...	<T1,commit>	...	Checkpoint	...	<T2,B,17>	...	<T2,commit>	...	<T3,C,21>	

Crash

Advantage of Checkpoints

- Limits recovery to parts of the log after the checkpoint
  - Think about system that has been online for months
    - ->Analyzing the whole log is too expensive!
- Source of backups
  - If we backup checkpoints we can use them for media recovery!

Checkpoints Justification

- Checkpoint should be consistent DB state
  - No active transactions
    - Do not accept new transactions
    - Wait until all transactions finish
  - DB state reflected on disk
    - Flush log
    - Flush buffers

Key drawbacks:

- *Undo logging:*
  - – cannot bring backup DB copies up to date
- *Redo logging:*
  - – need to keep all modified blocks in memory until commit

Solution: undo/redo logging!

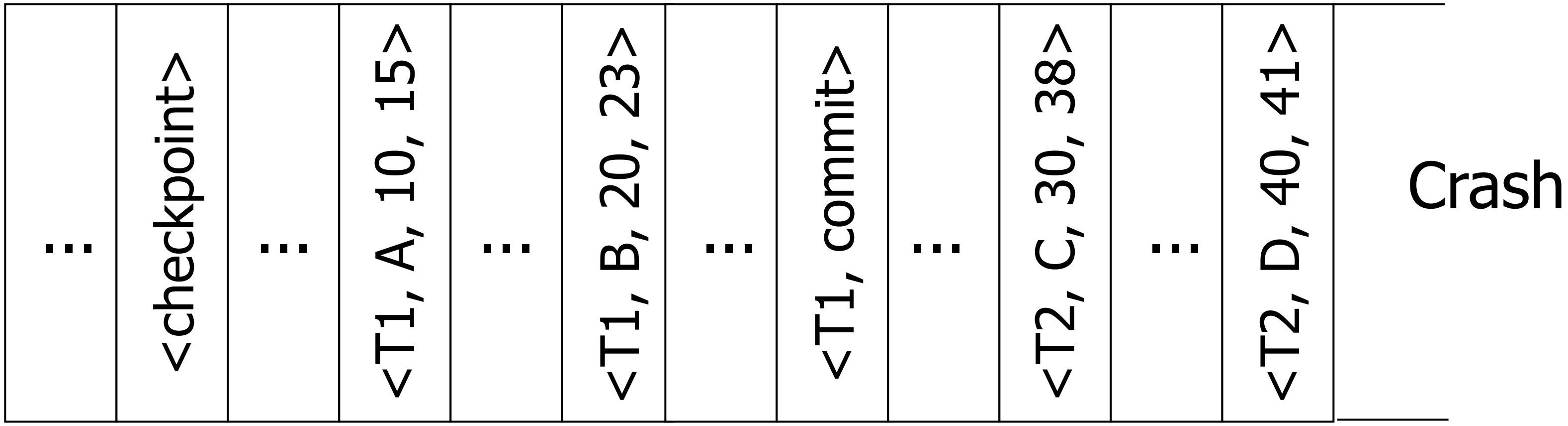
Update ⇒ <Ti, Xid, New X val, Old X val>
page X

Rules

- Page X can be flushed before or after Ti commit
- Log record flushed before corresponding updated page (WAL)
- Flush at commit (log only)

Example: Undo/Redo logging
what to do at recovery?

log (disk):



...

<checkpoint>

...

<T1, A, 10, 15>

...

<T1, B, 20, 23>

...

<T1, commit>

...

<T2, C, 30, 38>

...

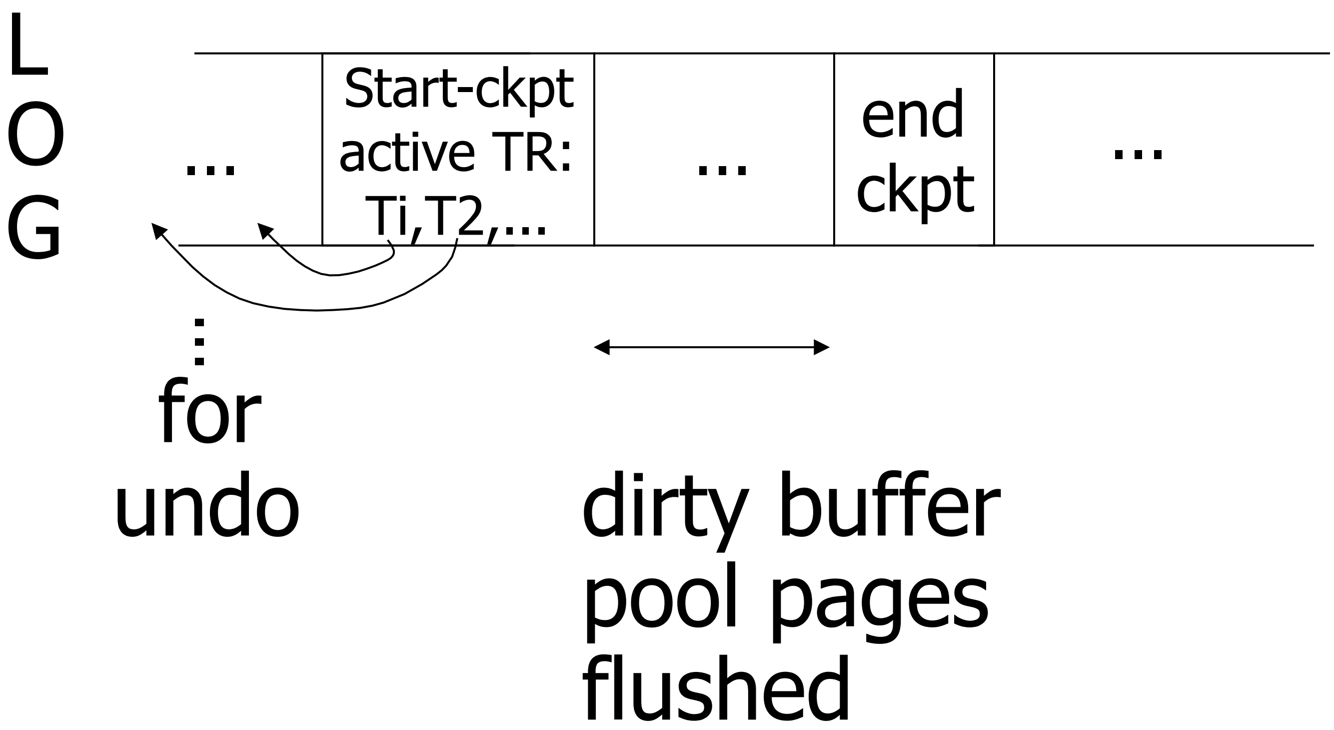
<T2, D, 40, 41>

Crash

Checkpoint Cost

- Checkpoints are expensive
  - No new transactions can start
  - A lot of I/O
    - Flushing the log
    - Flushing dirty buffer pages

Non-quiesce checkpoint



L
O
G

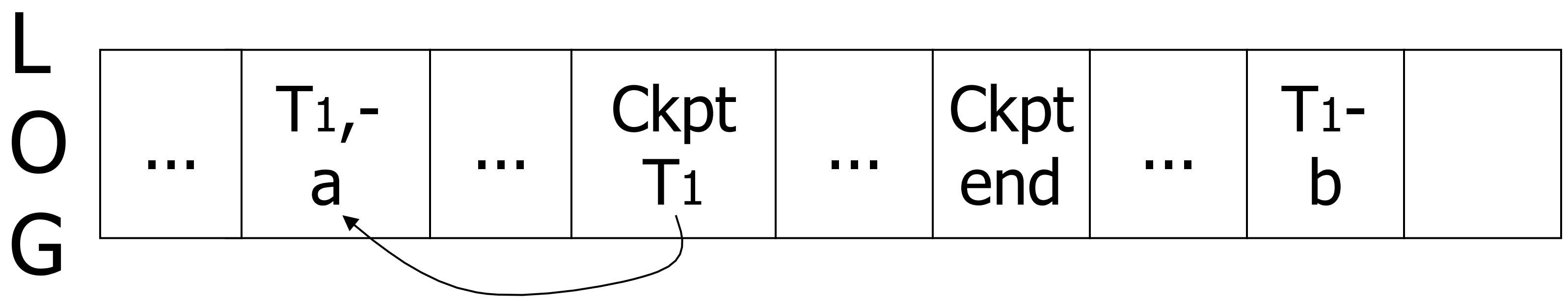
...	Start-ckpt active TR: Ti,T2,...	...	end ckpt	...

⋮
for
undo

dirty buffer
pool pages
flushed

Examples what to do at recovery time?

no T1 commit



LOG

…

T_1,-a

…

Ckpt T_1

…

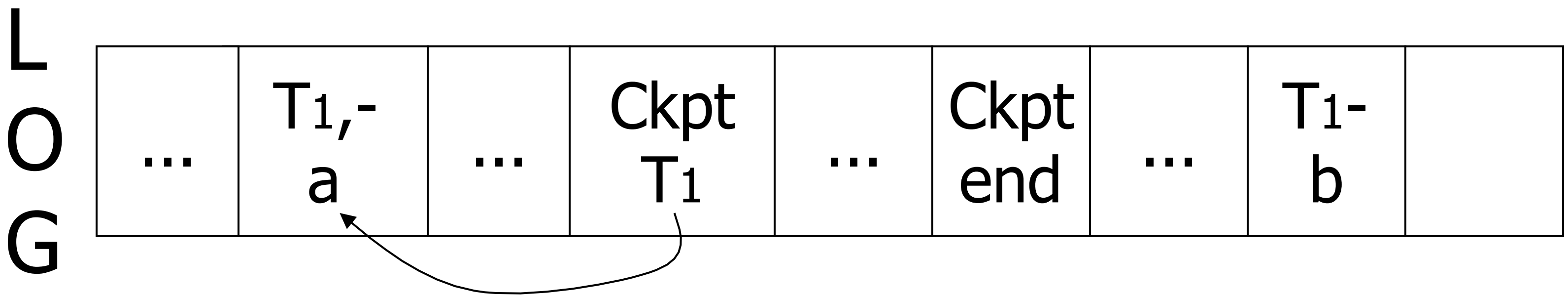
Ckpt end

…

T_1-b

Examples what to do at recovery time?

no T1 commit

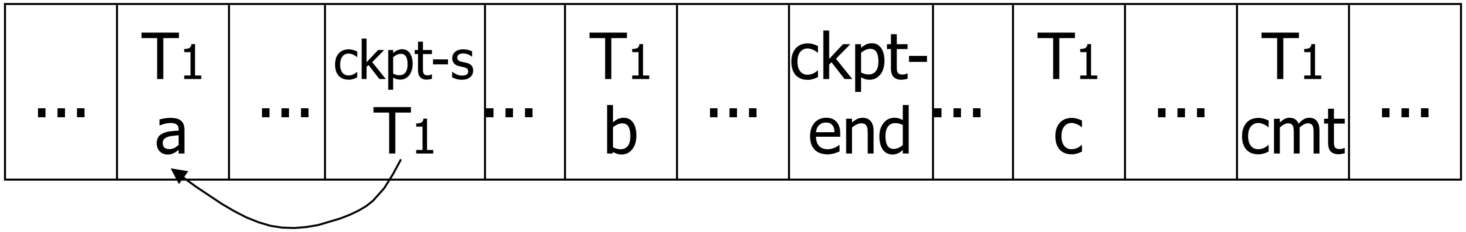


L O G	…	T1,-a	…	Ckpt T1	…	Ckpt end	…	T1-b	

- ➽ Undo T1 (undo a,b)

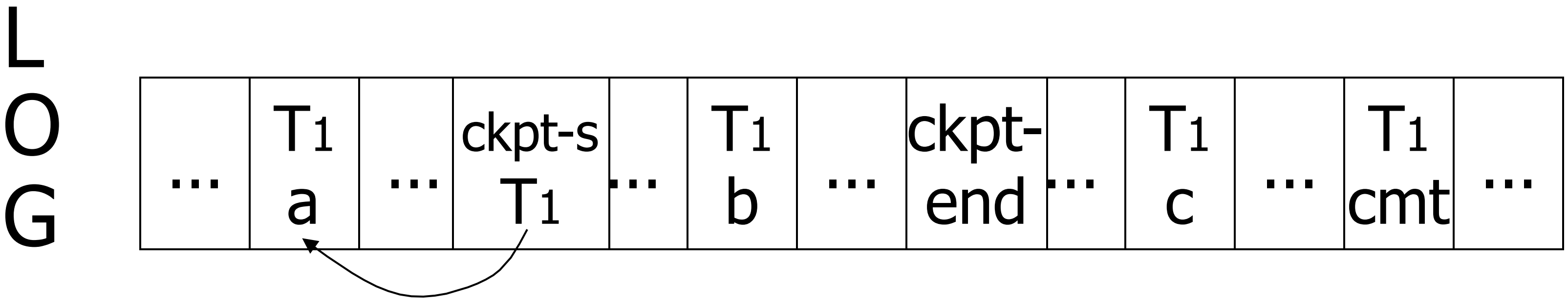
Example

L
O
G



…	T_1 a	…	ckpt-s T_1	…	T_1 b	…	ckpt- end	…	T_1 c	…	T_1 cmt	…

Example

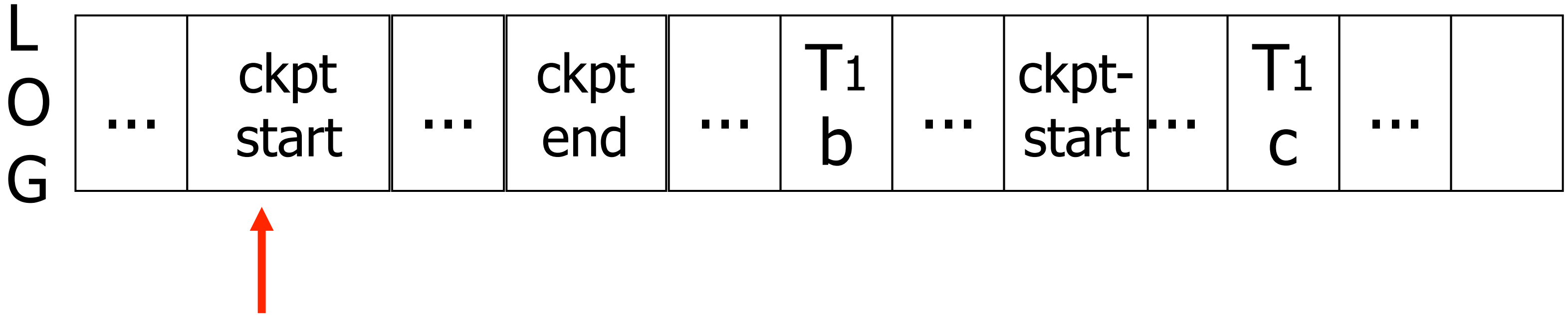


LOG

…	T1 a	…	ckpt-s T1	…	T1 b	…	ckpt- end	…	T1 c	…	T1 cmt	…

- Redo T1: (redo b,c)

Recover From Valid Checkpoint:

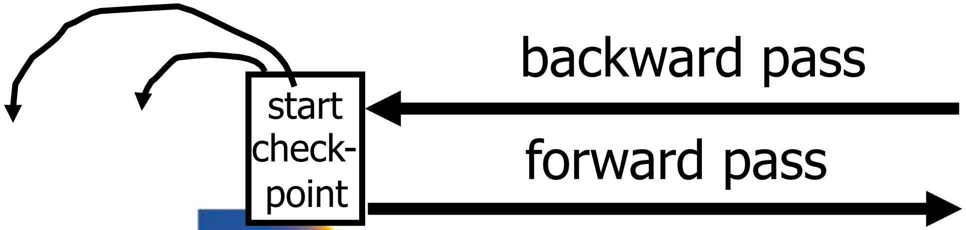


LOG	…	ckpt start	…	ckpt end	…	T_1 b	…	ckpt- start	…	T_1 c	…	

start
of latest
valid
checkpoint

Recovery process:

- Backwards pass (end of log ➜ latest valid checkpoint start)
  - construct set S of committed transactions
  - undo actions of transactions not in S
- Undo pending transactions
  - follow undo chains for transactions in (checkpoint active list) - S
- Forward pass (latest checkpoint start ➜ end of log)
  - redo actions of S transactions



Real world actions

E.g., dispense cash at ATM

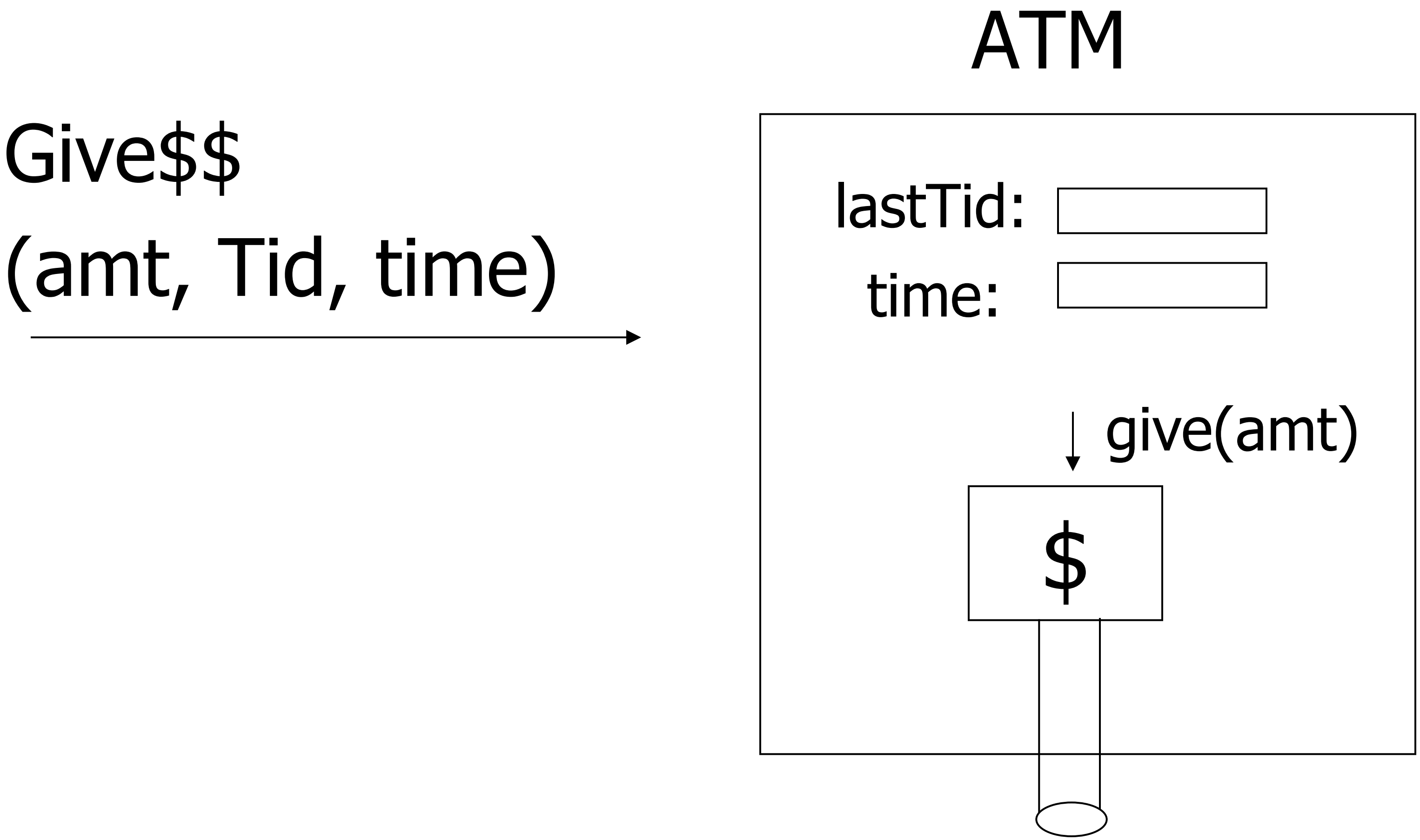
$Ti = a_1 \, a_2 \ldots\ldots \, a_j \ldots\ldots \, a_n$

$\downarrow$

$\$$

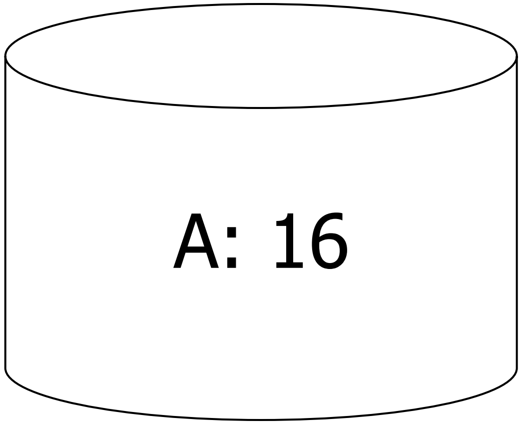
Solution

(1) execute real-world actions after commit
(2) try to make idempotent

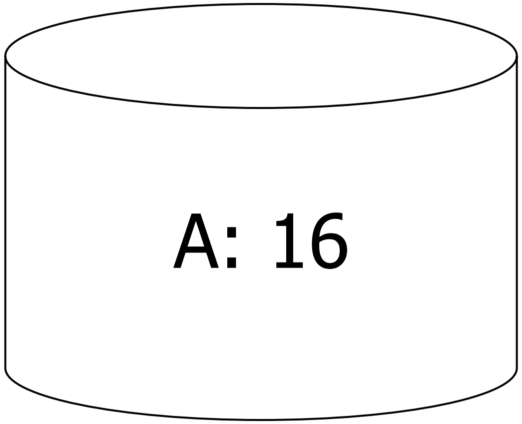


Give$$
(amt, Tid, time)

Media failure (loss of non-volatile storage)



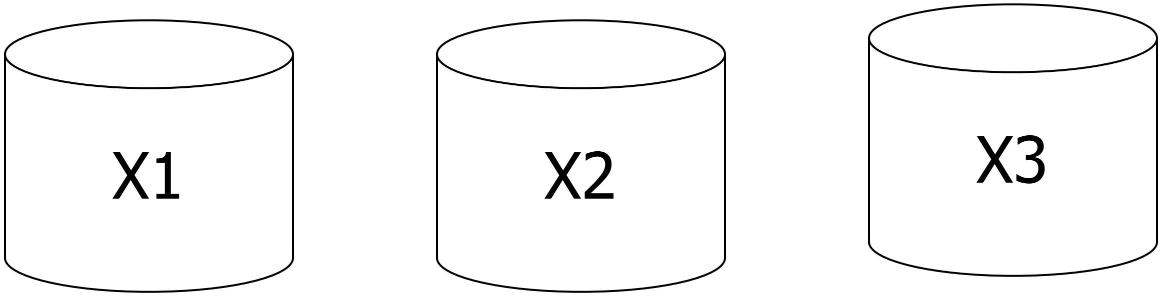
Media failure (loss of non-volatile storage)



Solution: Make copies of data!

Example 1 Triple modular redundancy

- Keep 3 copies on separate disks
- Output(X) --> three outputs
- Input(X) --> three inputs + vote

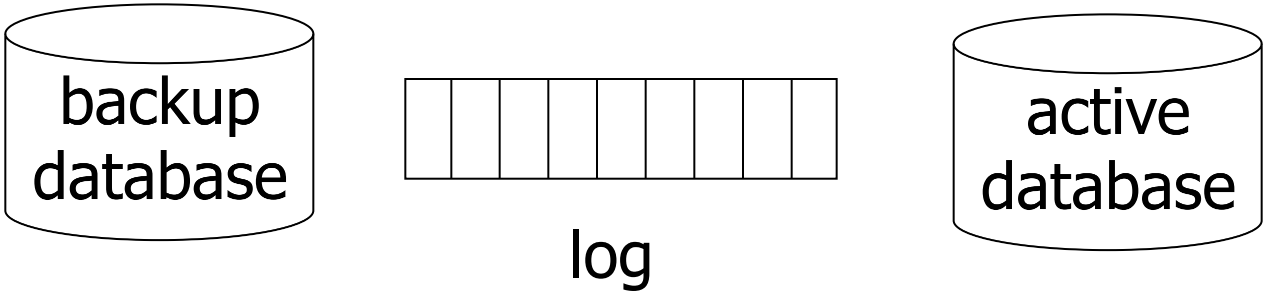


Example #2 Redundant writes, Single reads

- Keep N copies on separate disks
- Output(X) --> N outputs
- Input(X) --> Input one copy
  - if ok, done
  - else try another one

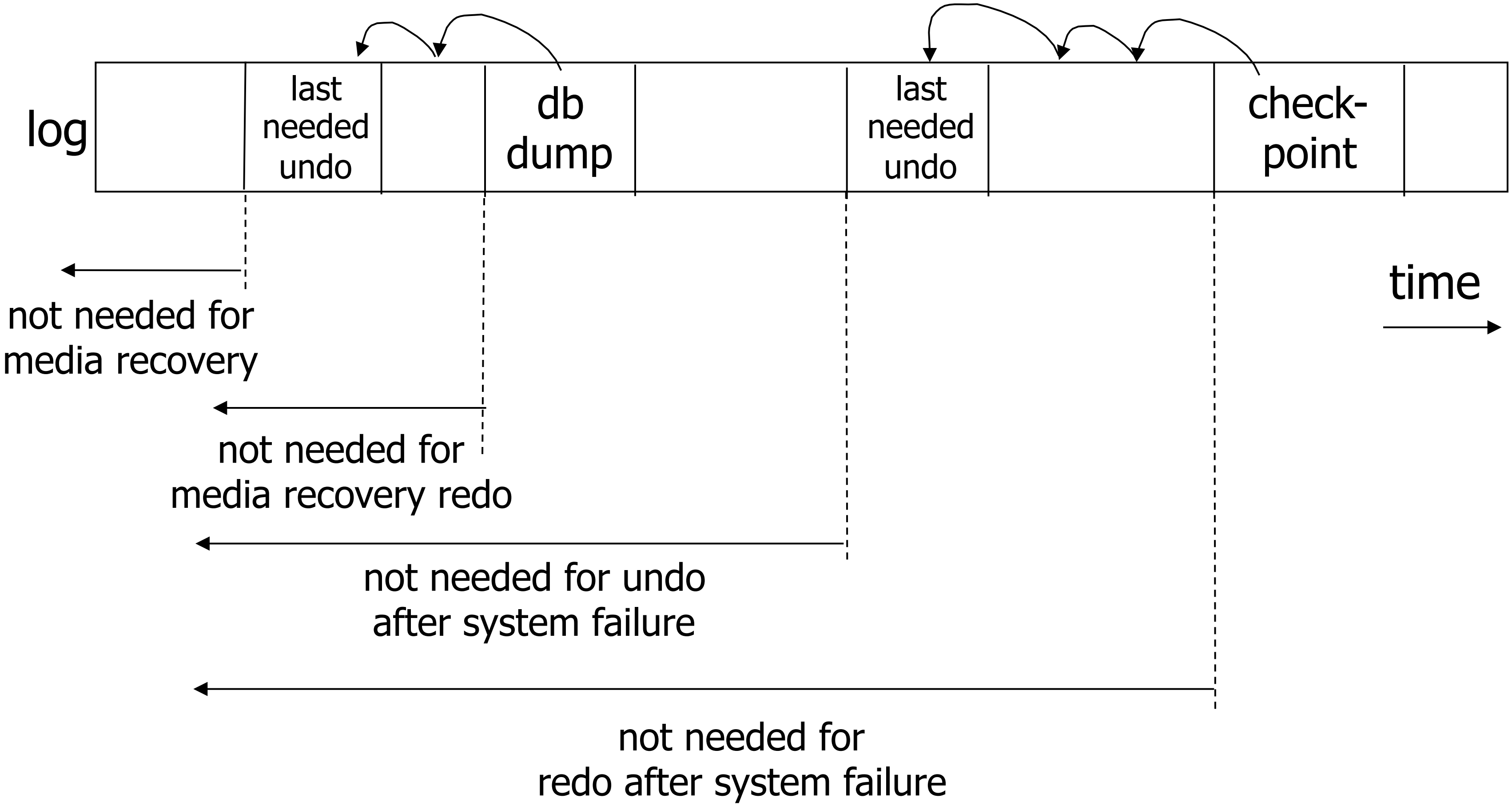
➳ Assumes bad data can be detected

Example #3: DB Dump + Log



- If active database is lost,
  - restore active database from backup
  - bring up-to-date using redo entries in log

When can log be discarded?



log

last needed undo

db dump

last needed undo

check-point

time

not needed for media recovery

not needed for media recovery redo

not needed for undo after system failure

not needed for redo after system failure

Practical Recovery with ARIES

- **ARIES**
  - **A**lgorithms for **R**ecovery and **I**solation **E**xploiting **S**emantics
- Implemented in, e.g.,
  - DB2
  - MSSQL

Underlying Ideas

- Keep track of state of pages by relating them to entries in the log
- **WAL**
- Recovery in **three phases**
  - Analysis, Redo, Undo
- Log entries to track state of Undo for repeated failures
- **Redo**: page-oriented -> efficient
- **Undo**: logical -> permits higher level of concurrency

Log Entry Structure

- **LSN**
  - **L**og **s**equence **n**umber
  - Order of entries in the log
  - Usually **log file id** and **offset** for direct access

- **LSN**
- **Entry type**
  - Update, compensation, commit, …
- **TID**
  - Transaction identifier
- **PrevLSN**
  - LSN of previous log record for same transaction
- **UndoNxtLSN**
  - Next undo operation for CLR (later!)
- **Undo/Redo data**
  - Data needed to undo/redo the update

Page Header Additions

- **PageLSN**
  - **LSN** of the last update that modified the page
  - Used to know which changes have been applied to a page

Forward Processing

- Normal operations when no ROLLBACK is required
  - WAL: write redo/undo log record for each action of a transaction
- Buffer manager has to ensure that
  - changes to pages are not persisted before the corresponding log record has been persisted
  - Transactions are not considered committed before all their log records have been flushed

Dirty Page Table

- **PageLSN**
  - Entries **<PageID,RecLSN>**
  - Whenever a page is first fixed in the buffer pool with indention to modify
    - Insert **<PageId,RecLSN>** with **RecLSN** being the current end of the log
  - Flushing a page removes it from the Dirty page table

Dirty Page Table

- Used for checkpointing
- Used for recovery to figure out what to redo

Transaction Table

- TransID
  - Identifier of the transaction
- State
  - Commit state
- LastLSN
  - LSN of the last update of the transaction
- UndoNxtLSN
  - If last log entry is a CLR then UndoNxtLSN from that record
  - Otherwise = LastLSN

Transaction Table:

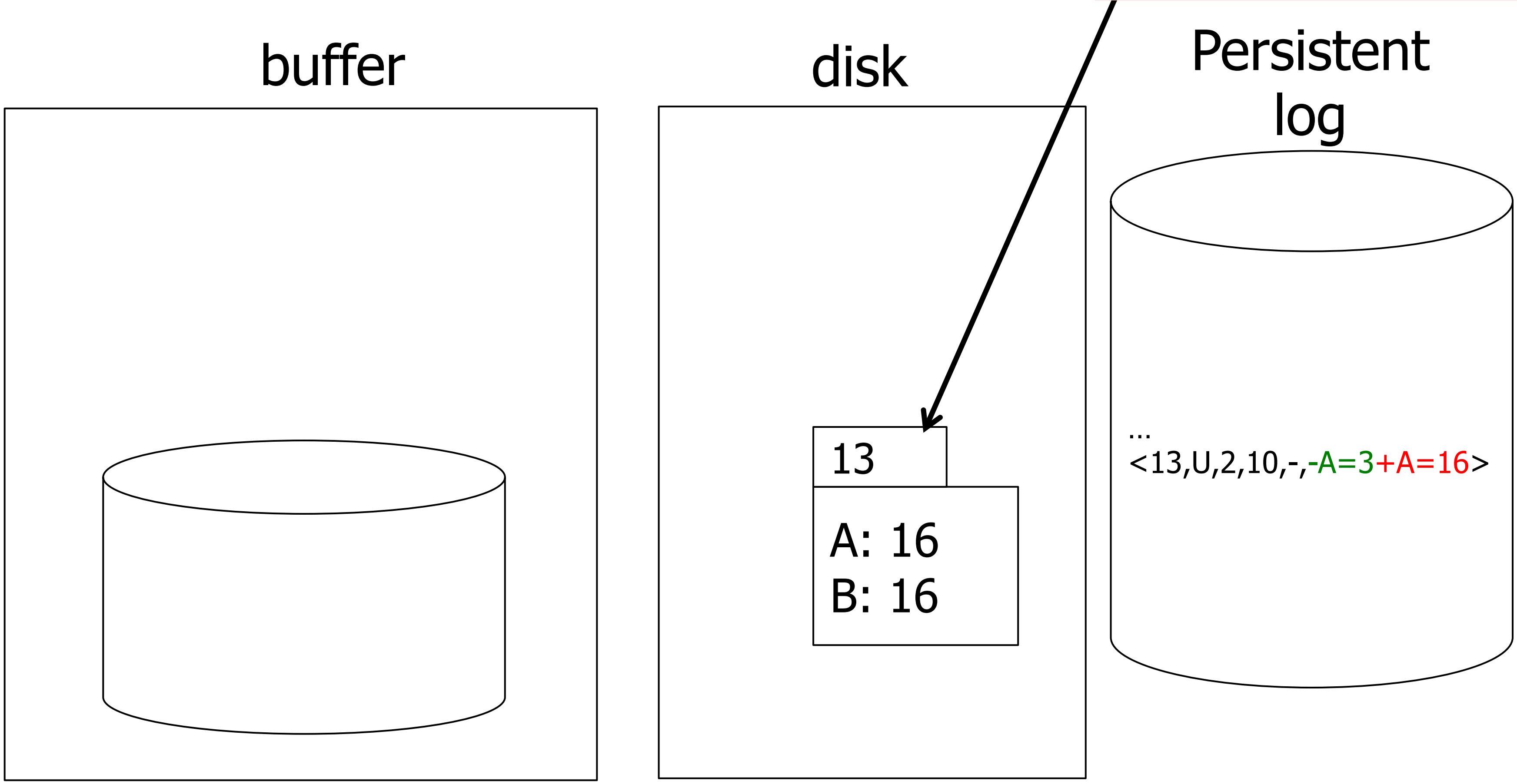
<1, U, -, ->

Dirty Page Table:

Page_LSN:

LSN of last modification to page

$T_1=r_1(A),A=A*2,w_1(A)$



…

<13,U,2,10,-,-A=3+A=16>

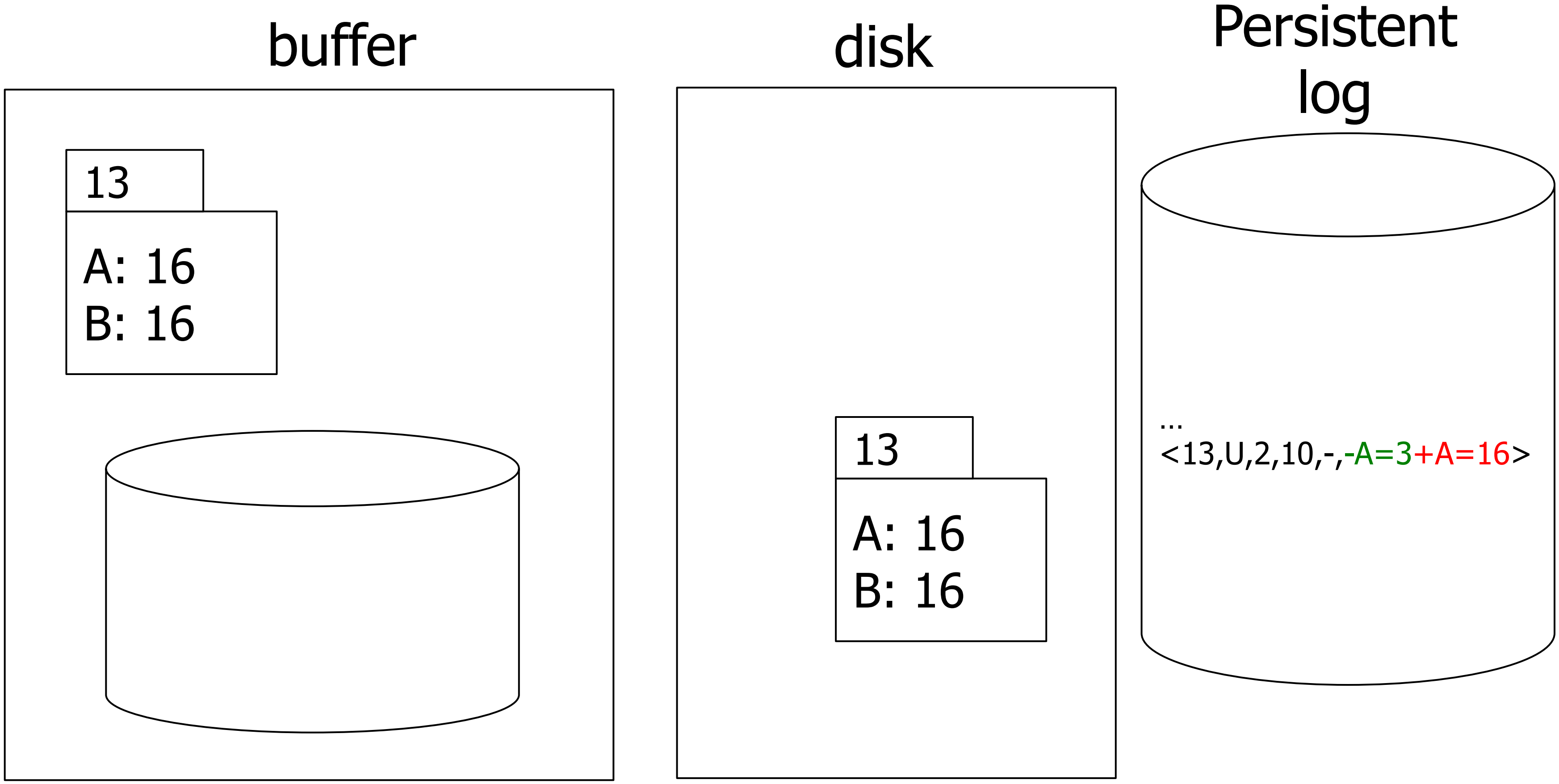
Transaction Table:

<1, U, -, ->

Dirty Page Table:

<100, 14>

$T_1=r_1(A),A=A*2,w_1(A)$



buffer

13

A: 16
B: 16

disk

13

A: 16
B: 16

Persistent log

…
<13,U,2,10,-,-A=3+A=16>

Transaction Table:

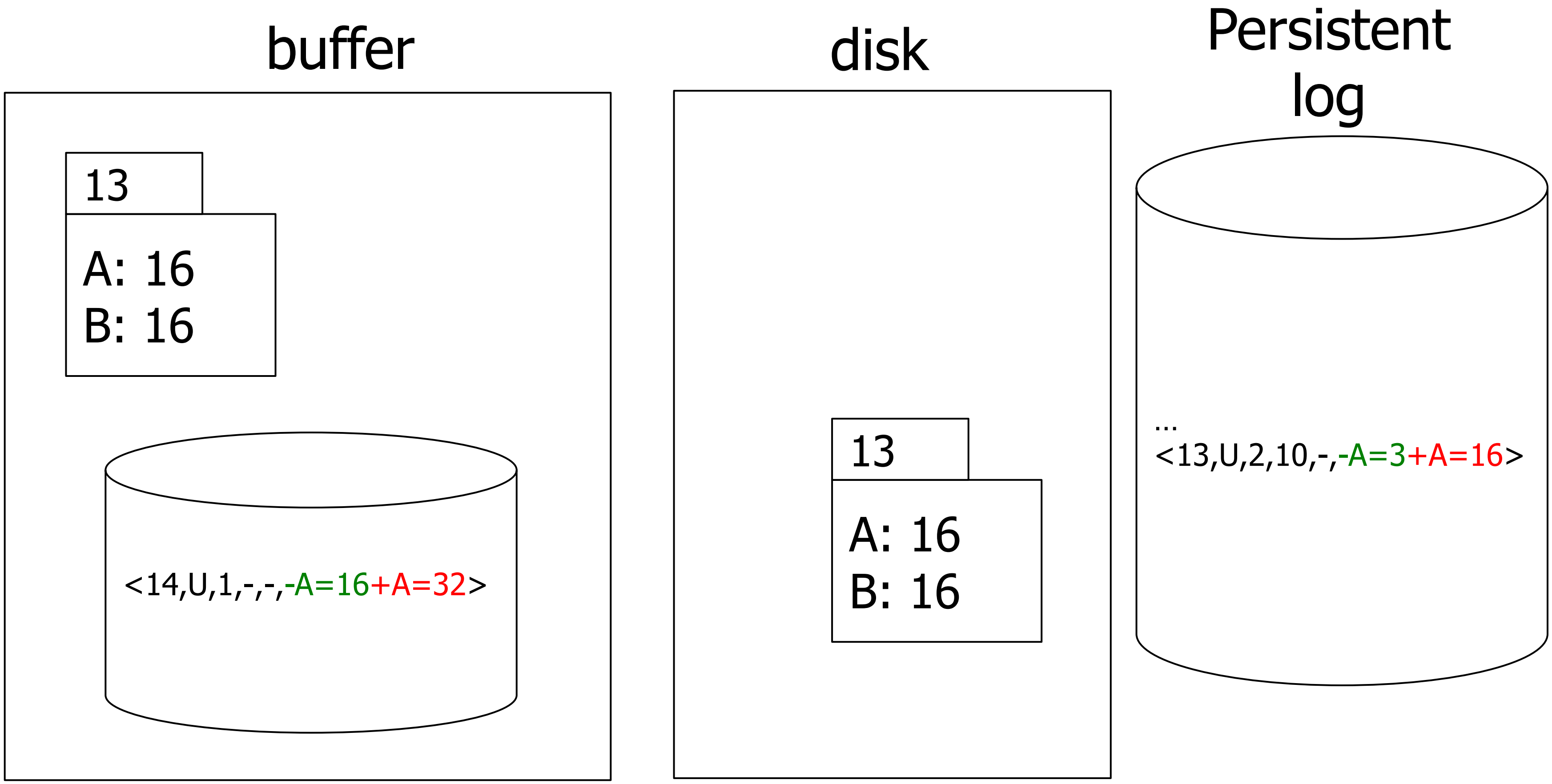
<1, U, -, ->

Dirty Page Table:

<100, 14>

Write log entry

$T_1 = r_1(A), A = A*2, w_1(A)$



buffer

13

A: 16
B: 16

<14,U,1,-,-,-A=16+A=32>

disk

13

A: 16
B: 16

Persistent log

…
<13,U,2,10,-,-A=3+A=16>

Transaction Table:

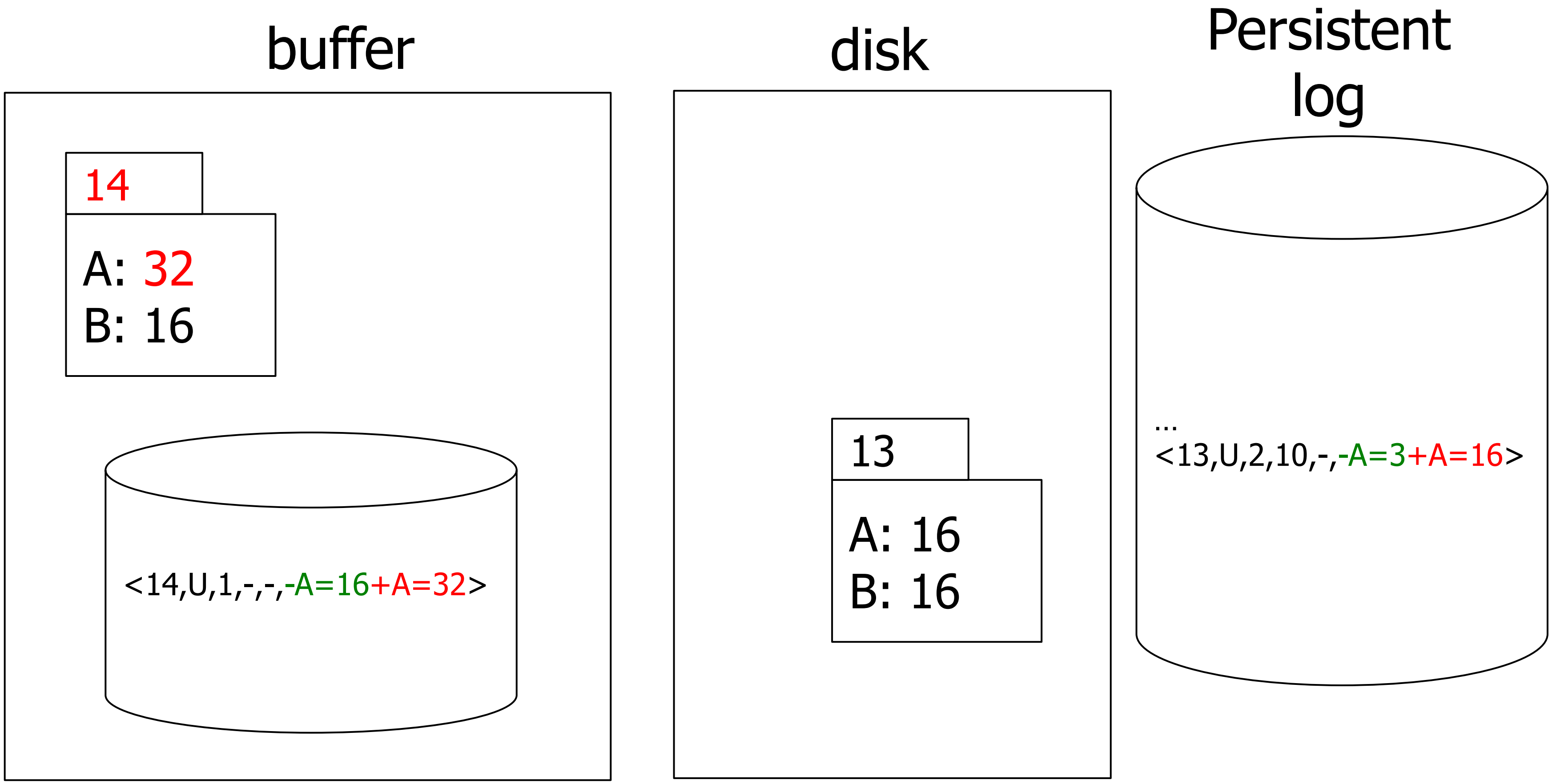
<1, U, 14, 14>

Dirty Page Table:

<100, 14>

Update page

$T_1=r_1(A),A=A*2,w_1(A)$



buffer

14

A: 32
B: 16

<14,U,1,-,-,-A=16+A=32>

disk

13

A: 16
B: 16

Persistent log

…
<13,U,2,10,-,-A=3+A=16>

Transaction Table:

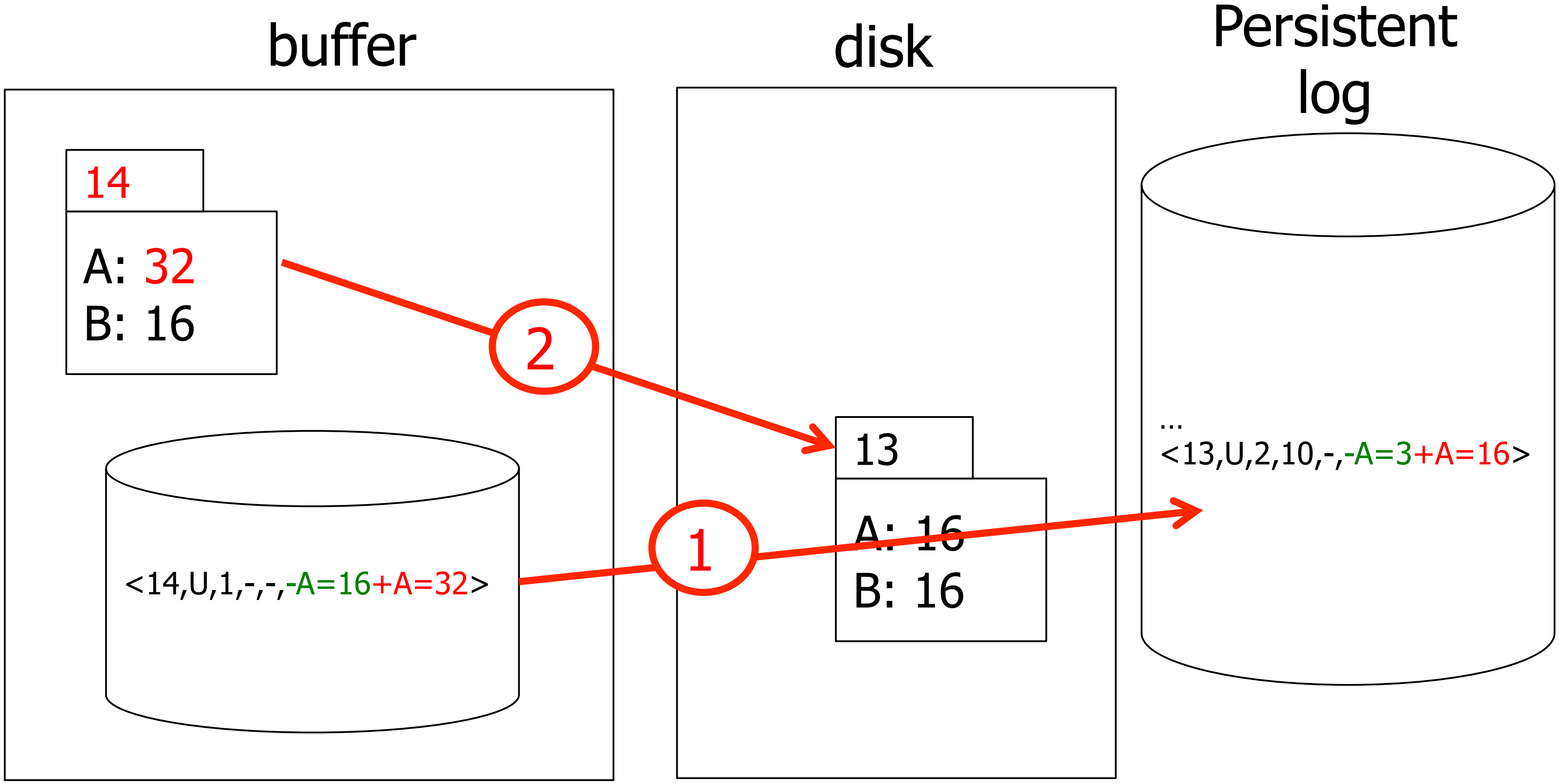
<1, U, 14, 14>

Dirty Page Table:

<100, 14>

Can wait with flushing page, but log has to be flushed first!

$T_1=r_1(A),A=A*2,w_1(A)$



buffer

14

A: 32
B: 16

<14,U,1,-,-,-A=16+A=32>

2

1

disk

13

A: 16
B: 16

Persistent log

…
<13,U,2,10,-,-A=3+A=16>

Undo during forward processing

- Transaction was rolled back
  - User aborted, aborted because of error, …
- Need to undo operations of transaction
- During Undo
  - Write log entries for every undo
  - **Compensation Log Records (CLR)**
  - Used to avoid repeated undo when failures occur

Undo during forward processing

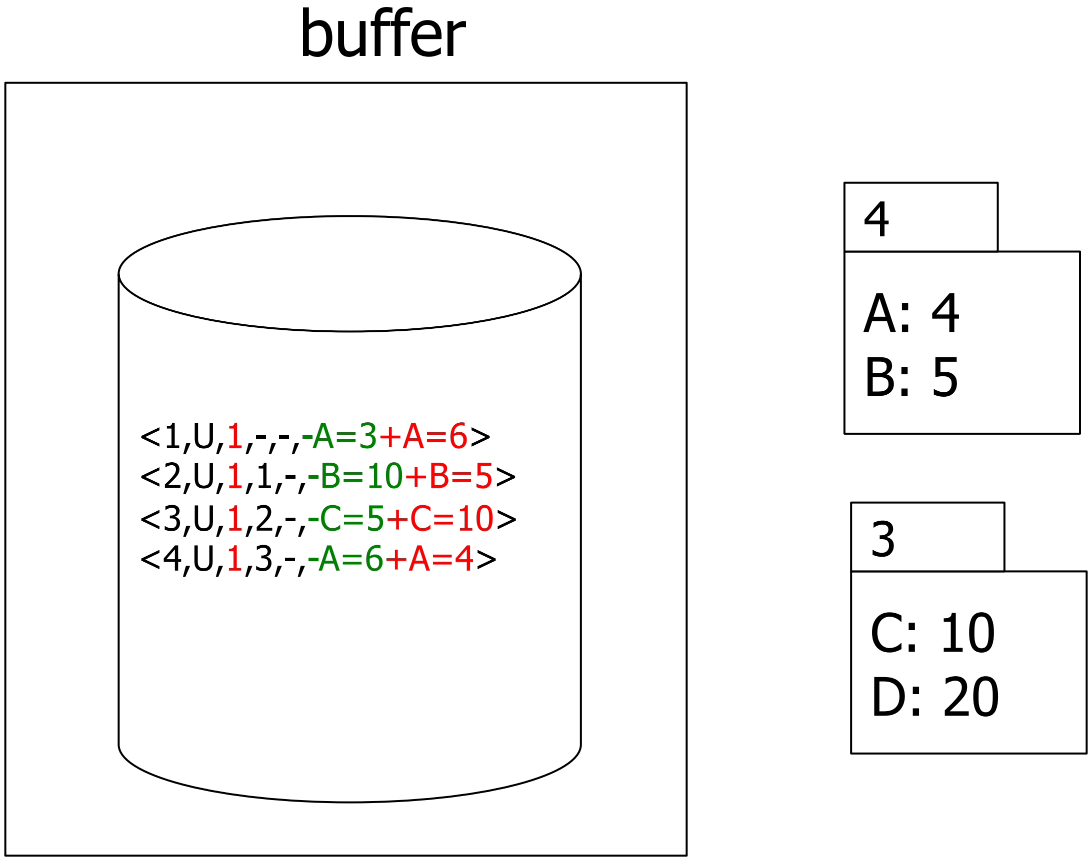
- Starting with the LastLSN of transaction from transaction table
  - Traverse log entries of transaction last to first using PrevLSN pointers
  - For each log entry use undo information to undo action
    - **<LSN, Type, TID, PrevLSN, -, Undo/Redo data>**
  - Before modifying data write an CLR that stores redo-information for the undo operation
    - **UndoNxtLSN** = **PrevLSN** of log entry we are undoing
    - **Redo data** = How to redo the undo

Transaction Table:

<1, U, 4, 4>

Undo T_1

$T_1 = w_1(A),\ w_1(B),\ w_1(C),\ w_1(A),\ a_1$



buffer

<1,U,1,-,-,-A=3+A=6>
<2,U,1,1,-,-B=10+B=5>
<3,U,1,2,-,-C=5+C=10>
<4,U,1,3,-,-A=6+A=4>

4

A: 4
B: 5

3

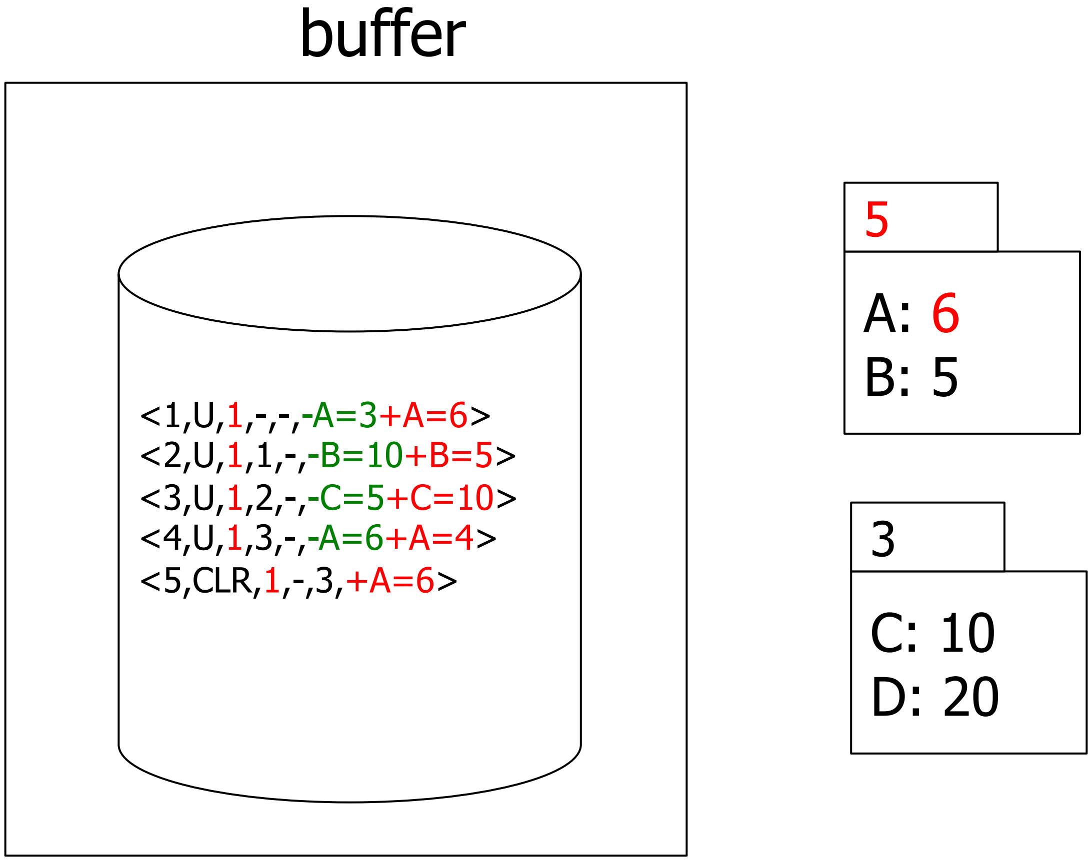
C: 10
D: 20

Transaction Table:

<1, U, 5, 3>

Undo T_1

T_1= w_1(A), w_1(B), w_1(C), w_1(A), a_1



buffer

<1,U,1,-,-,-A=3+A=6>
<2,U,1,1,-,-B=10+B=5>
<3,U,1,2,-,-C=5+C=10>
<4,U,1,3,-,-A=6+A=4>
<5,CLR,1,-,3,+A=6>

5

A: 6
B: 5

3

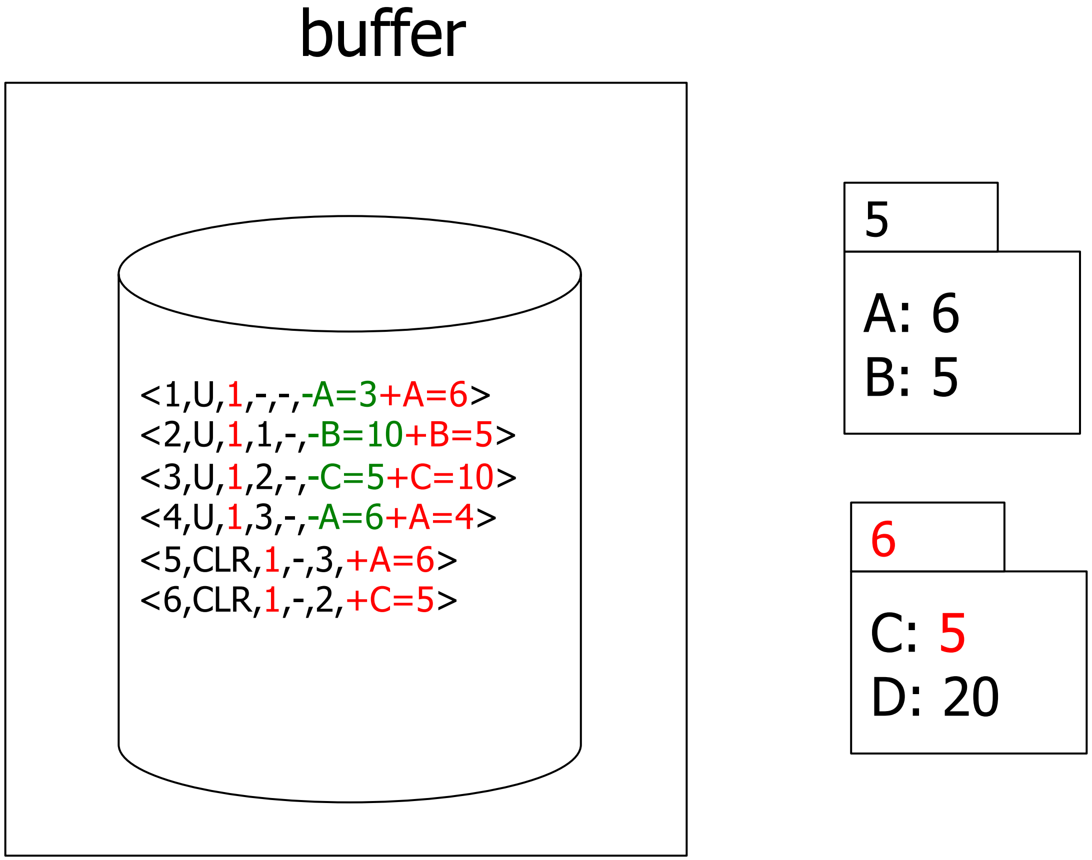
C: 10
D: 20

Transaction Table:

<1, U, 6, 2>

Undo T_1

$T_1 = w_1(A), w_1(B), w_1(C), w_1(A), a_1$



buffer

<1,U,1,-,-,-A=3+A=6>
<2,U,1,1,-,-B=10+B=5>
<3,U,1,2,-,-C=5+C=10>
<4,U,1,3,-,-A=6+A=4>
<5,CLR,1,-,3,+A=6>
<6,CLR,1,-,2,+C=5>

5

A: 6
B: 5

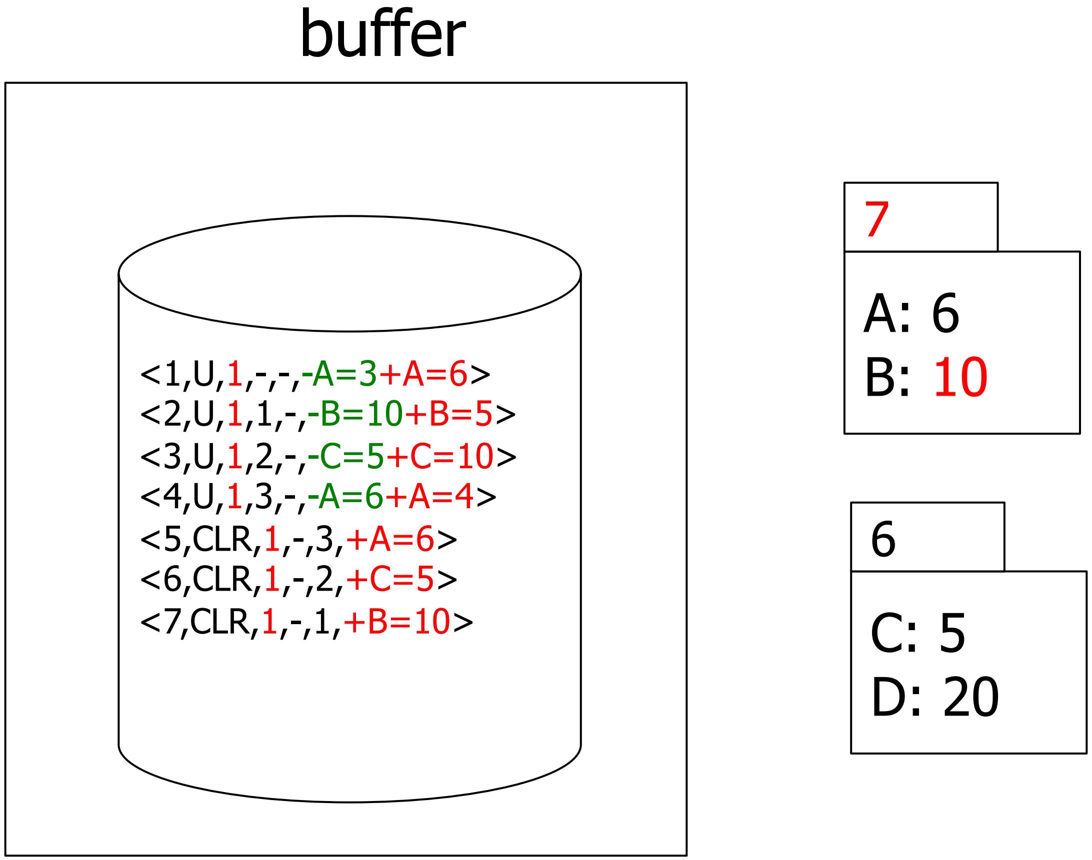
6

C: 5
D: 20

Transaction Table:
<1, U, 7, 1>

Undo T_1

T_1= w_1(A), w_1(B), w_1(C), w_1(A), a_1



<1,U,1,-,-,-A=3+A=6>
<2,U,1,1,-,-B=10+B=5>
<3,U,1,2,-,-C=5+C=10>
<4,U,1,3,-,-A=6+A=4>
<5,CLR,1,-,3,+A=6>
<6,CLR,1,-,2,+C=5>
<7,CLR,1,-,1,+B=10>

7
A: 6
B: 10

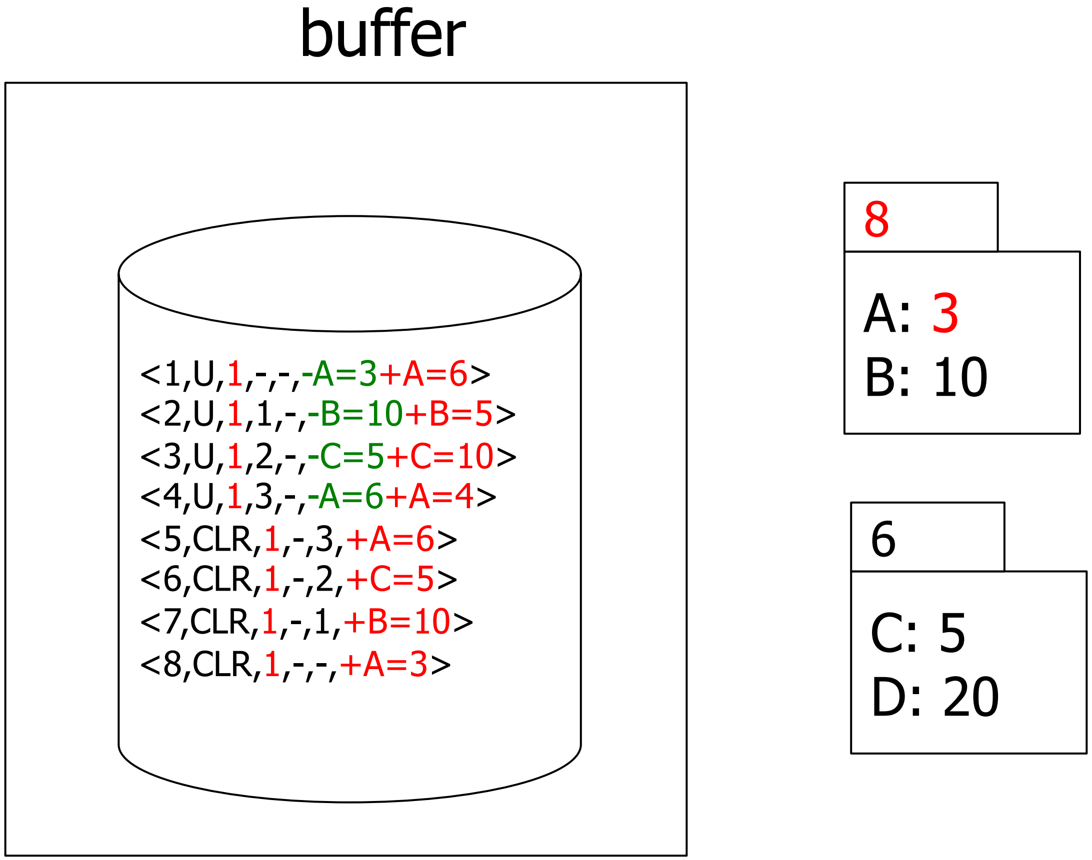
6
C: 5
D: 20

Transaction Table:

<1, U, 8, ->

Undo T_1

$T_1 = w_1(A), w_1(B), w_1(C), w_1(A), a_1$



buffer

<1,U,1,-,-,-A=3+A=6>
<2,U,1,1,-,-B=10+B=5>
<3,U,1,2,-,-C=5+C=10>
<4,U,1,3,-,-A=6+A=4>
<5,CLR,1,-,3,+A=6>
<6,CLR,1,-,2,+C=5>
<7,CLR,1,-,1,+B=10>
<8,CLR,1,-,-,+A=3>

8
A: 3
B: 10

6
C: 5
D: 20

Fuzzy Checkpointing in ARIES

- Begin of checkpoint
  - Write **begin_cp** log entry
  - Write **end_cp** log entry with
    - Dirty page table
    - Transaction table
- **Master Record**
  - LSN of begin_cp log entry of last complete checkpoint

Restart Recovery

1. Analysis Phase
2. Redo Phase
3. Undo Phase

Analysis Phase

1) Determine LSN of last checkpoint using Master Record

2) Get Dirty Page Table and Transaction Table from checkpoint end record

3) RedoLSN = min(RecLSN) from Dirty Page Table or checkpoint LSN if no dirty page

Analysis Phase

4) Scan log forward starting from RedoLSN

- Update log entry from transaction
  - If necessary: Add Page to Dirty Page Table
  - Add Transaction to Transaction Table or update LastLSN
- Transaction end entry
  - Remove transaction from Transaction Table

Analysis Phase

- Result
  - Transaction Table
    - Transactions to be later undone
  - RedoLSN
    - Log entry to start Redo Phase
  - Dirty Page Table
    - Pages that may not have been written back to disk

Redo Phase

- Start at RedoLSN scan log forward
- Unconditional Redo
  - Even redo actions of transactions that will be undone later
- Only redo once
  - Only redo operations that have not been reflected on disk (PageLSN)

Redo Phase

- For each update log entry
  - If affected page is not in Dirty Page Table or RecLSN > LSN
    - skip log entry
  - Fix page in buffer
    - If PageLSN >= LSN then operation already reflected on disk
      - Skip log entry
    - Otherwise apply update

Redo Phase

- Result
  - State of DB before Failure

Undo Phase

- Scan log backwards from end using Transaction Table
  - Repeatedly take log entry with max LSN from all the current actions to be undone for each transaction
    - Write CLR
    - Update Transaction Table

Undo Phase

- All unfinished transactions have been rolled back

Idempotence?

- Redo
  - We are not logging during Redo so repeated Redo will result in the same state
- Undo
  - If we see CLRs we do not undo this action again

Avoiding Repeated Work

- Redo
  - If operation has been reflected on disk (PageLSN) we do not need to redo it again
- Undo
  - If we see CLRs we do not undo this action again

T_1 = w_1(A), w_1(B), w_1(C), w_1(A), c_1

T_2 = w_1(X), r(A), w(A)

Log

<1,begin(T_1), ->
<2,begin(T_2), ->
<3,write(A,T_1),1>
<4,write(X,T_2),2>
<5,write(B,T_1),3>
<6,write(C,T_1),5>
<7,write(A,T_1),6>
<8,commit(T_1),7>
<9,write(A,T_2),4>

$T_1 = w_1(A), \qquad w_1(B), w_1(C), w_1(A), c_1$

$T_2 = \qquad w_1(X), \qquad r(A), w(A)$

Analysis Phase:

- start at log entry 1
- add T_1 to transaction table (rec. 1)
- add T_2 to transaction table (rec. 2)
- add A to dirty page table (RecLSN 3)
- add X to dirty page table (RecLSN 4)
- add B to dirty page table (RecLSN 5)
- add C to dirtypage table (RecLSN 6)
- remove T1 from Transaction Table (rec. 8)

Log

<1,begin(T_1), ->
<2,begin(T_2), ->
<3,write(A,T_1),1>
<4,write(X,T_2),2>
<5,write(B,T_1),3>
<6,write(C,T_1),5>
<7,write(A,T_1),6>
<8,commit(T_1),7>
<9,write(A,T_2),4>

$T_1 = w_1(A), \quad w_1(B), w_1(C), w_1(A), c_1$

$T_2 = \quad w_1(X), \quad r(A), w(A)$

Analysis Phase Result:

- Transaction Table:
  - $<T_2, 9>$
- Dirty Page Table:
  - <A, 3>, <B, 5>, <C, 6>, <X, 4>
- RedoLSN = min(3,5,6,4) = 3

Log

$<1, begin(T_1), ->$
$<2, begin(T_2), ->$
$<3, write(A,T_1), 1>$
$<4, write(X,T_2), 2>$
$<5, write(B,T_1), 3>$
$<6, write(C,T_1), 5>$
$<7, write(A,T_1), 6>$
$<8, commit(T_1), 7>$
$<9, write(A,T_2), 4>$

$T_1 = w_1(A), \quad w_1(B), w_1(C), w_1(A), c_1$

$T_2 = \quad w_1(X), \quad r(A), w(A)$

Redo Phase (RedoLSN 3):

- Read A if PageLSN < 3 apply write
- Read X if PageLSN < 4 apply write
- Read B if PageLSN < 5 apply write
- Read C if PageLSN < 6 apply write
- Read A if PageLSN < 7 apply write
- Read A if PageLSN < 9 apply write

Log

<1,begin(T_1), ->
<2,begin(T_2), ->
<3,write(A,T_1),1>
<4,write(X,T_2),2>
<5,write(B,T_1),3>
<6,write(C,T_1),5>
<7,write(A,T_1),6>
<8,commit(T_1),7>
<9,write(A,T_2),4>

$T_1 = w_1(A), \quad w_1(B), w_1(C), w_1(A), c_1$

$T_2 = \quad w_1(X), \quad r(A), w(A)$

Undo Phase (T_2):

- Undo entry 9
  - -write CLR with UndoNxtLSN = 4
  - -modify page A
- Undo entry 4
  - -write CLR with UndoNxtLSN = 2
  - -modify page X
- Done

Log

<1,begin(T_1), ->
<2,begin(T_2), ->
<3,write(A,T_1),1>
<4,write(X,T_2),2>
<5,write(B,T_1),3>
<6,write(C,T_1),5>
<7,write(A,T_1),6>
<8,commit(T_1),7>
<9,write(A,T_2),4>
<10,CLR(A,T_2),4>
<11,CLR(X,T_2),->

ARIES take away messages

- Provide good performance by
  - Not requiring complete checkpoints
  - Linking of log records
  - Not restricting buffer operations (no-force/steal is ok)
- Logical Undo and Physical (Physiological) Redo
- Idempotent Redo and Undo
  - Avoid undoing the same operation twice

Media Recovery

- What if disks where log or DB is stored failes
  - ->keep backups of log + DB state

Log Backup

- Split log into several files
- Is append only, backup of old files cannot interfere with current log operations

Backup DB state

- Copy current DB state directly from disk
- May be inconsistent
- ->Use log to know which pages are up-to-date and redo operations not yet reflected

Summary

- Consistency of data
- One source of problems: failures
    - Logging
    - Redundancy
- Another source of problems:
  Data Sharing..... next

CS 525: Advanced Database Organization

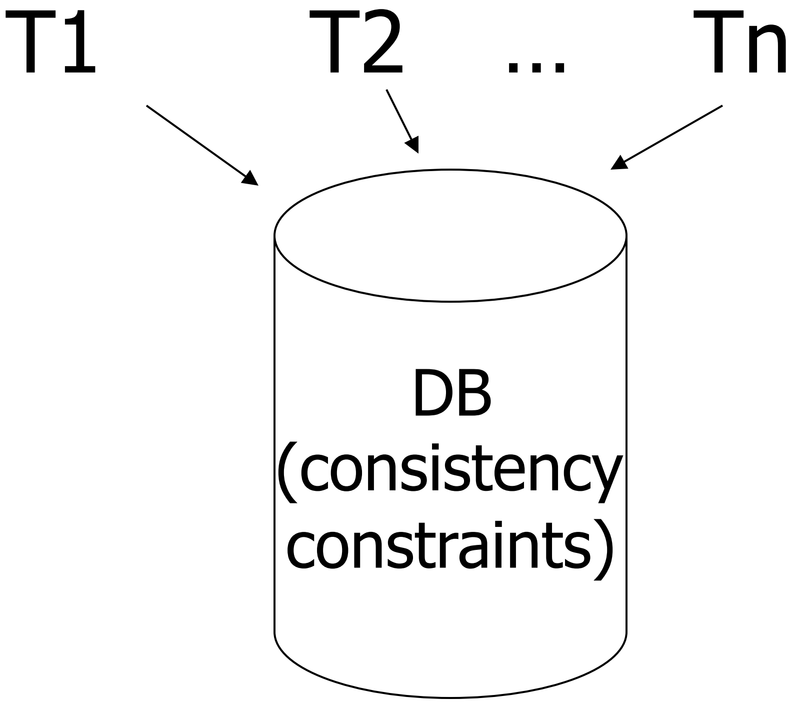
14: Concurrency Control

Boris Glavic

Slides: adapted from a course taught by

Hector Garcia-Molina, Stanford InfoLab

Chapter 18 [18] Concurrency Control



T1 T2 … Tn

DB
(consistency
constraints)

Example:

T1:	T2:
Read(A)	Read(A)
$A \leftarrow A+100$	$A \leftarrow A \times 2$
Write(A)	Write(A)
Read(B)	Read(B)
$B \leftarrow B+100$	$B \leftarrow B \times 2$
Write(B)	Write(B)

Constraint: $A=B$

Schedule A

T1	T2
Read(A); A ← A+100	
Write(A);	
Read(B); B ← B+100;	
Write(B);	
	Read(A);A ← A×2;
	Write(A);
	Read(B);B ← B×2;
	Write(B);

Schedule A

T1	T2	A	B
		25	25
Read(A); A ← A+100			
Write(A);		125	
Read(B); B ← B+100;			
Write(B);			125
	Read(A);A ← A×2;		
	Write(A);	250	
	Read(B);B ← B×2;		
	Write(B);		250
		250	250

Schedule B

T1	T2
	Read(A);A ← A×2;
	Write(A);
	Read(B);B ← B×2;
	Write(B);
Read(A); A ← A+100	
Write(A);	
Read(B); B ← B+100;	
Write(B);	

Schedule B

T1	T2	A	B
		25	25
	Read(A);A ← A×2;		
	Write(A);	50	
	Read(B);B ← B×2;		
	Write(B);		50
Read(A); A ← A+100			
Write(A);		150	
Read(B); B ← B+100;			
Write(B);			150
		150	150

Schedule C

T1	T2
Read(A); A ← A+100	
Write(A);	
	Read(A);A ← A×2;
	Write(A);
Read(B); B ← B+100;	
Write(B);	
	Read(B);B ← B×2;
	Write(B);

Schedule C

T1	T2	A	B
		25	25
Read(A); A ← A+100			
Write(A);		125	
	Read(A);A ← A×2;		
	Write(A);	250	
Read(B); B ← B+100;			
Write(B);			125
	Read(B);B ← B×2;		
	Write(B);		250
		250	250

Schedule D

T1	T2
Read(A); A ← A+100	
Write(A);	
	Read(A);A ← A×2;
	Write(A);
	Read(B);B ← B×2;
	Write(B);
Read(B); B ← B+100;	
Write(B);	

Schedule D

T1	T2	A	B
		25	25
Read(A); A ← A+100			
Write(A);		125	
	Read(A);A ← A×2;		
	Write(A);	250	
	Read(B);B ← B×2;		
	Write(B);		50
Read(B); B ← B+100;			
Write(B);			150
		250	150

Schedule E

Same as Schedule D but with new T2’

T1	T2’
Read(A); A ← A+100	
Write(A);	
	Read(A);A ← A×1;
	Write(A);
	Read(B);B ← B×1;
	Write(B);
Read(B); B ← B+100;	
Write(B);	

Schedule E

Same as Schedule D
but with new T2’

T1	T2’	A	B
		25	25
Read(A); A ← A+100			
Write(A);		125	
	Read(A);A ← A×1;		
	Write(A);	125	
	Read(B);B ← B×1;		
	Write(B);		25
Read(B); B ← B+100;			
Write(B);			125
		125	125

Serial Schedules

- As long as we do not execute transactions in parallel and each transaction does not violate the constraints we are good
  - All schedules with no interleaving of transaction operations are called **serial** schedules

Definition: Serial Schedule

- No transactions are interleaved
  - There exists no two operations from transactions Ti and Tj so that both operations are executed before either transaction commits

$T_1 = r_1(A), w_1(A), r_1(B), w_1(B), c_1$

$T_2 = r_2(A), w_2(A), r_2(B), w_2(B), c_2$

Serial Schedule

$S_1 = r_2(A), w_2(A), r_2(B), w_2(B), c_2, r_1(A), w_1(A), r_1(B), w_1(B), c_1$

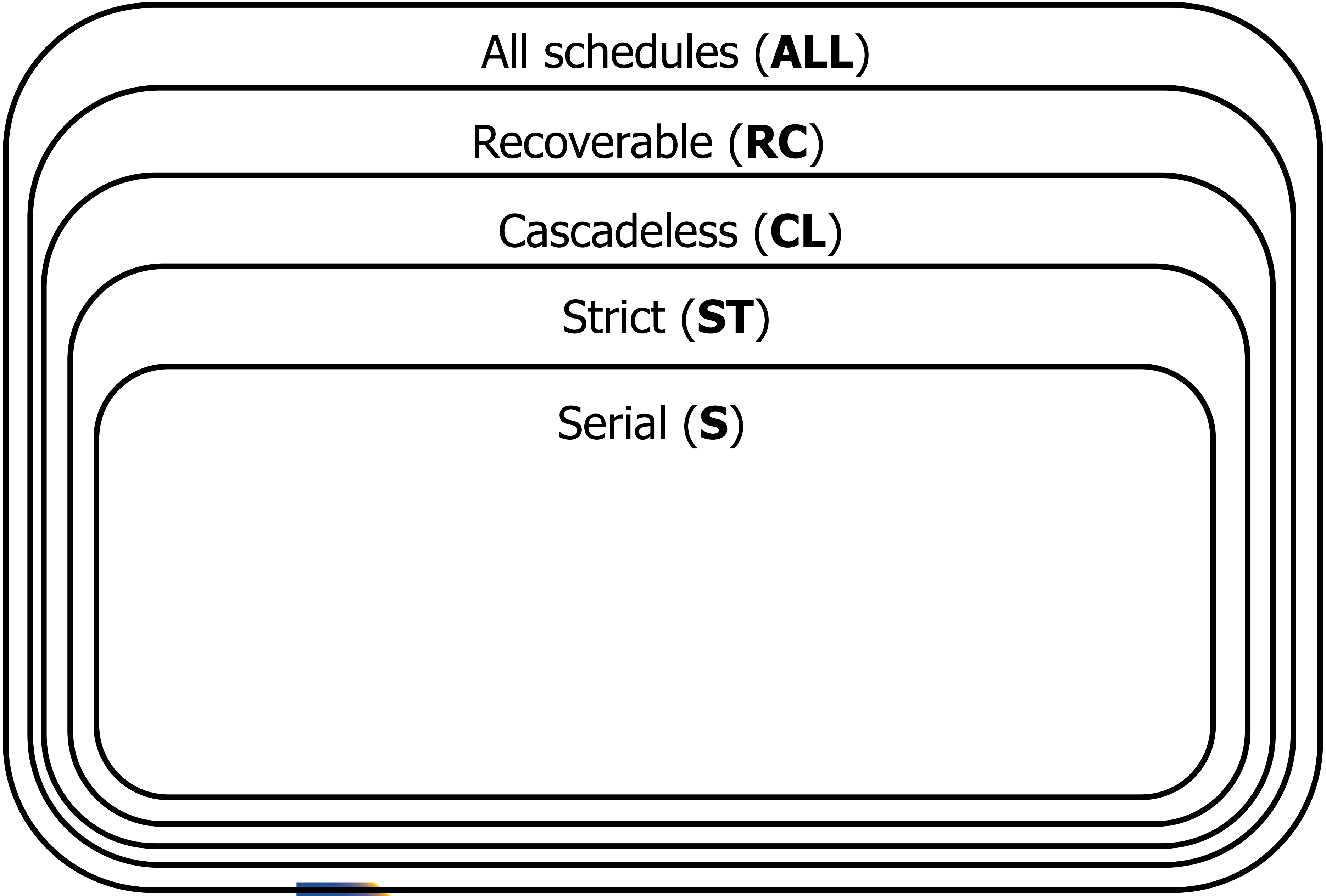
Nonserial Schedule

$S_2 = r_2(A), w_2(A), r_1(A), w_1(A), r_2(B), w_2(B), c_2, r_1(B), w_1(B), c_1$

Compare Classes

S ⊂ ST ⊂ CL ⊂ RC ⊂ ALL

- Abbreviations
  - S = Serial
  - ST = Strict
  - CL = Cascadeless
  - RC = Recoverable
  - ALL = all possible schedules



All schedules (**ALL**)

Recoverable (**RC**)

Cascadeless (**CL**)

Strict (**ST**)

Serial (**S**)

Why not serial schedules?

- No concurrency! ☹

- Want schedules that are “good”, regardless of
  - initial state and
  - transaction semantics
- Only look at order of read and writes

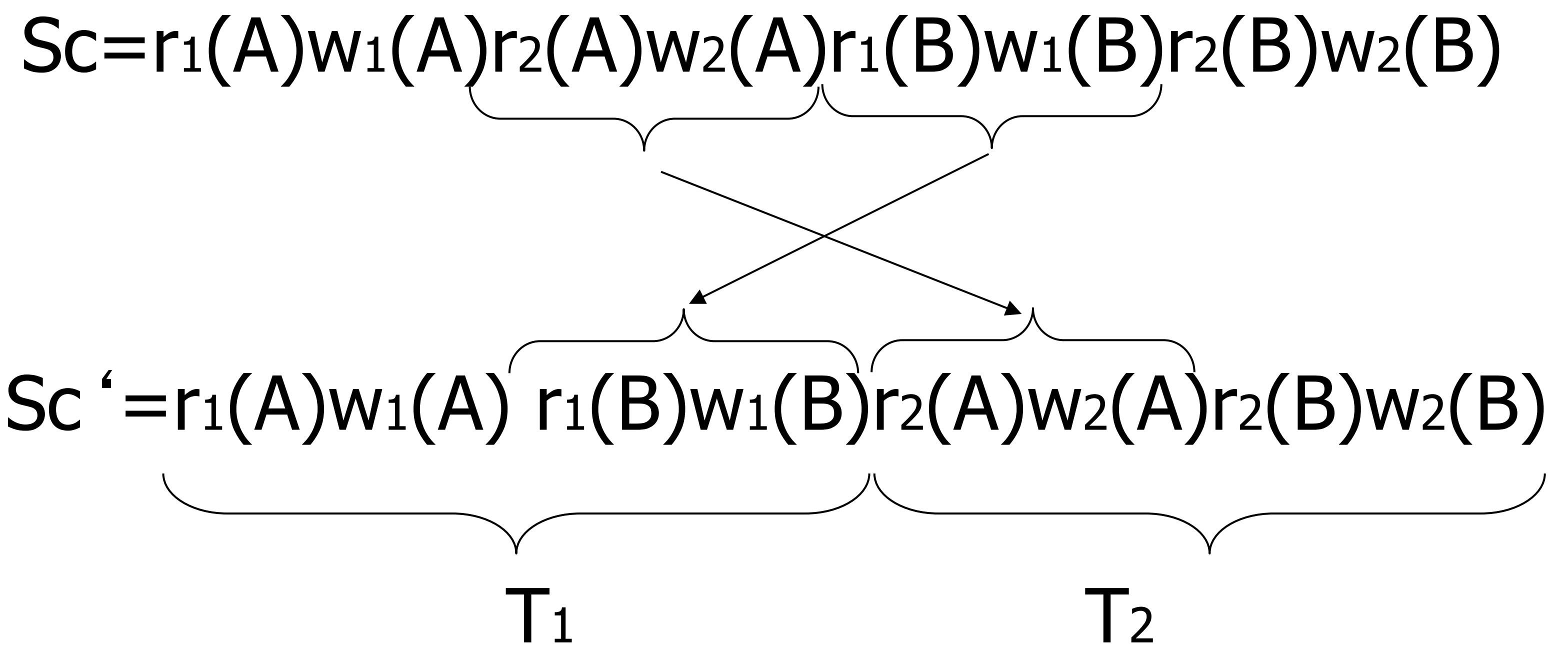
Example:

$Sc=r_1(A)w_1(A)r_2(A)w_2(A)r_1(B)w_1(B)r_2(B)w_2(B)$

Outline

- Since serial schedules have good properties we would like our schedules to behave like (be **equivalent** to) serial schedules
  1. Need to define equivalence based solely on order of operations
  2. Need to define class of schedules which is equivalent to serial schedule
  3. Need to design scheduler that guarantees that we only get these good schedules

Example:

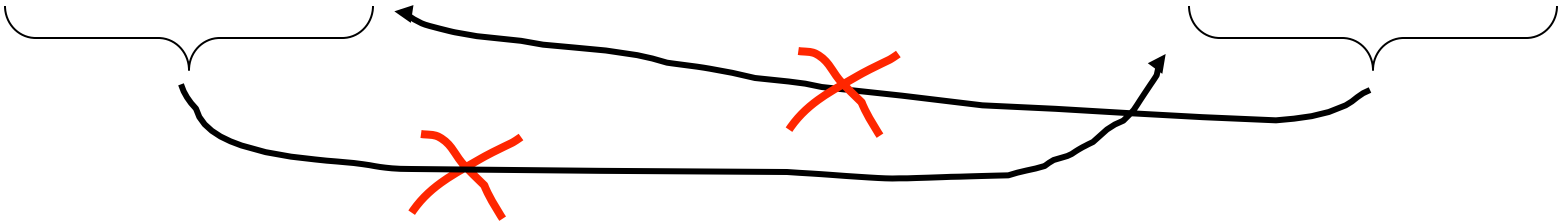


$Sc=r_1(A)w_1(A)r_2(A)w_2(A)r_1(B)w_1(B)r_2(B)w_2(B)$

$Sc'=\underbrace{r_1(A)w_1(A)\ r_1(B)w_1(B)}_{T_1}\underbrace{r_2(A)w_2(A)r_2(B)w_2(B)}_{T_2}$

However, for Sd:

$$Sd=\underbrace{r_1(A)w_1(A)}r_2(A)w_2(A)\ r_2(B)w_2(B)\underbrace{r_1(B)w_1(B)}$$



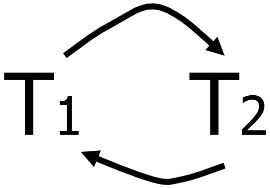
- as a matter of fact,

  T_2 must precede T_1

  in any equivalent schedule,

  i.e., $T_2 \rightarrow T_1$

- $T_2 \rightarrow T_1$
- Also, $T_1 \rightarrow T_2$

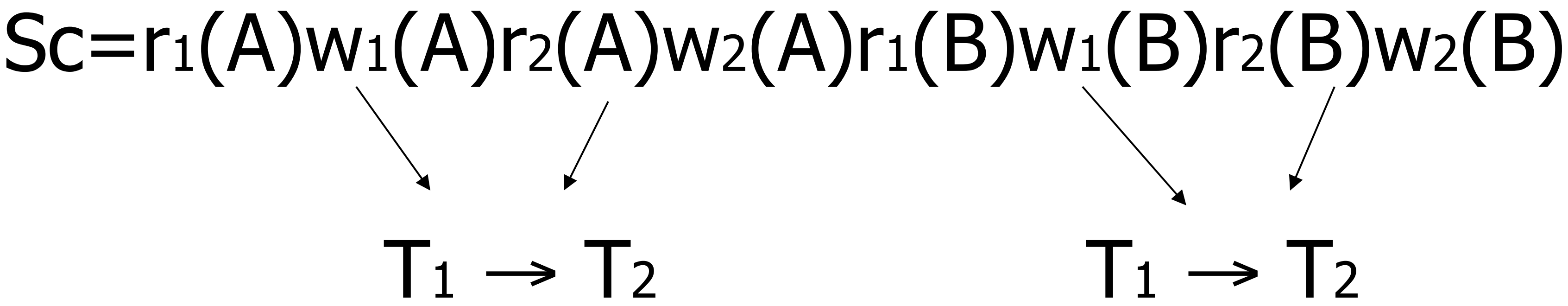


⇨ Sd cannot be rearranged into a serial schedule

⇨ Sd is not "equivalent" to any serial schedule

⇨ Sd is "bad"

Returning to Sc

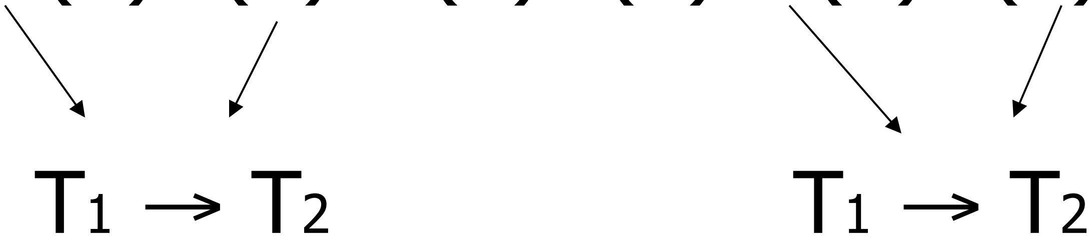


$Sc = r_1(A) w_1(A) r_2(A) w_2(A) r_1(B) w_1(B) r_2(B) w_2(B)$

$T_1 \rightarrow T_2$ $\qquad$ $T_1 \rightarrow T_2$

Returning to Sc

$$Sc=r_1(A)w_1(A)r_2(A)w_2(A)r_1(B)w_1(B)r_2(B)w_2(B)$$



$T_1 \rightarrow T_2$ $T_1 \rightarrow T_2$

- ☛ no cycles ⇒ Sc is “equivalent” to a serial schedule (in this case T_1,T_2)

Concepts

Transaction: sequence of $r_i(x)$, $w_i(x)$ actions

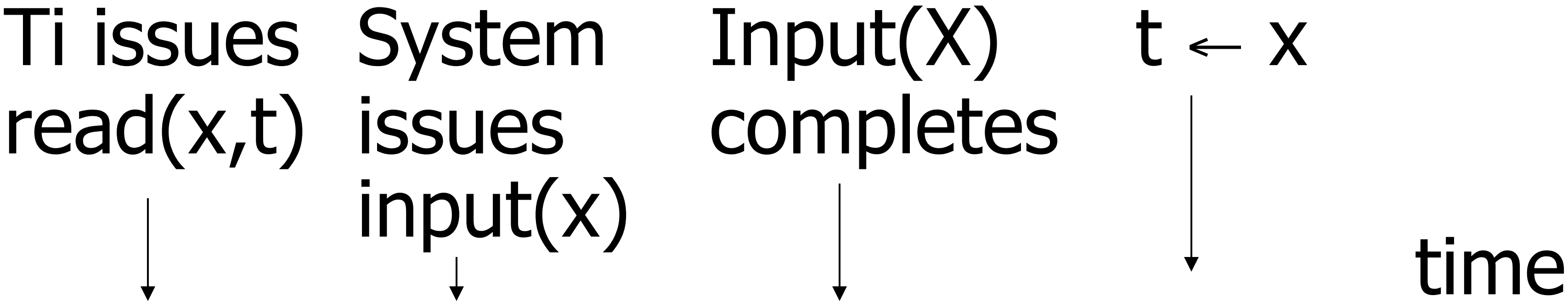
Conflicting actions: $r_1(A)$ $w_2(A)$ $w_1(A)$

$w_2(A)$ $r_1(A)$ $w_2(A)$

Schedule: represents chronological order
in which actions are executed

Serial schedule: no interleaving of actions
or transactions

What about concurrent actions?



Ti issues read(x,t)

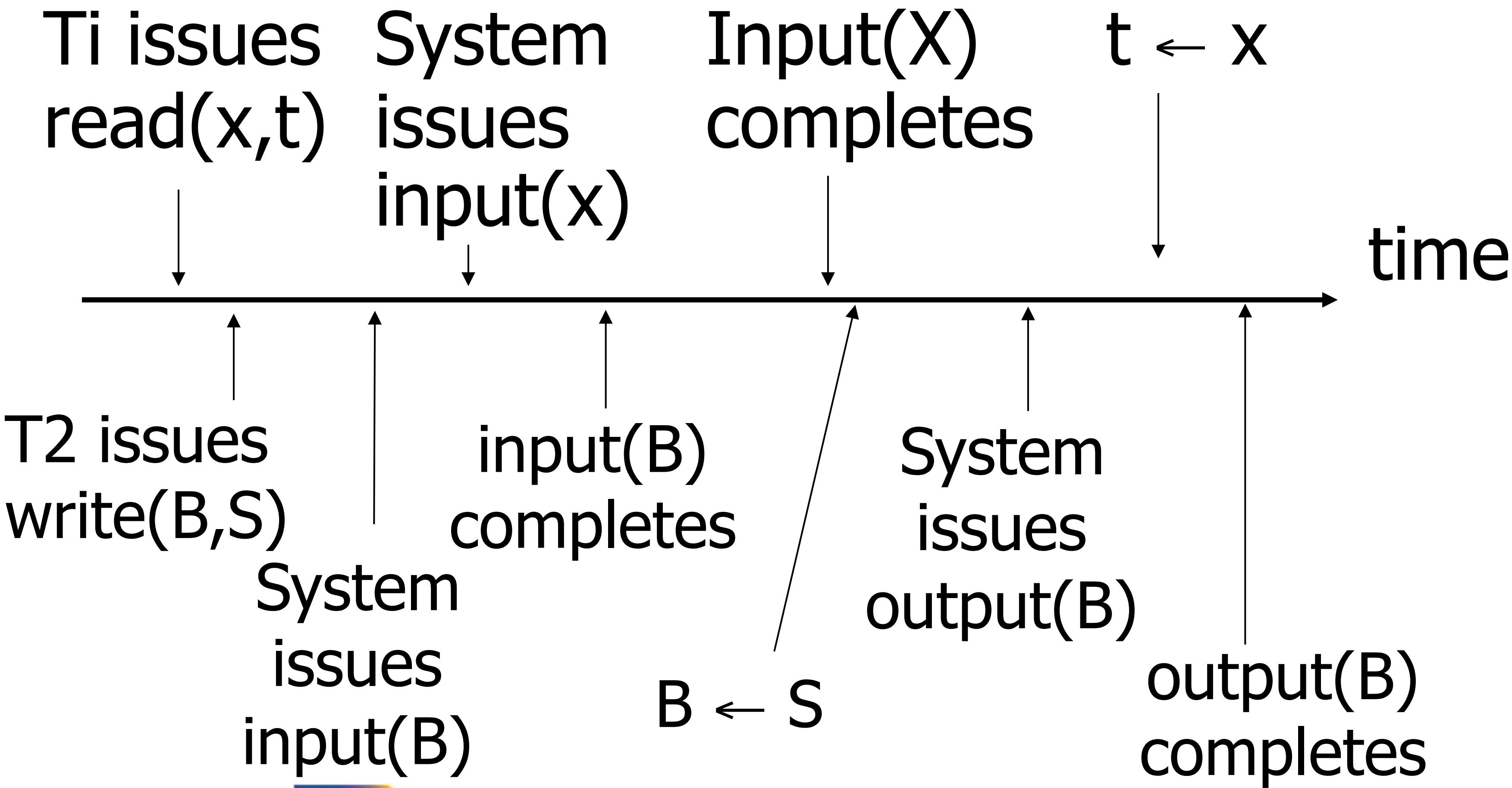
System issues input(x)

Input(X) completes

t ← x

time

What about concurrent actions?



Ti issues read(x,t)

System issues input(x)

Input(X) completes

t ← x

time

T2 issues write(B,S)

System issues input(B)

input(B) completes

B ← S

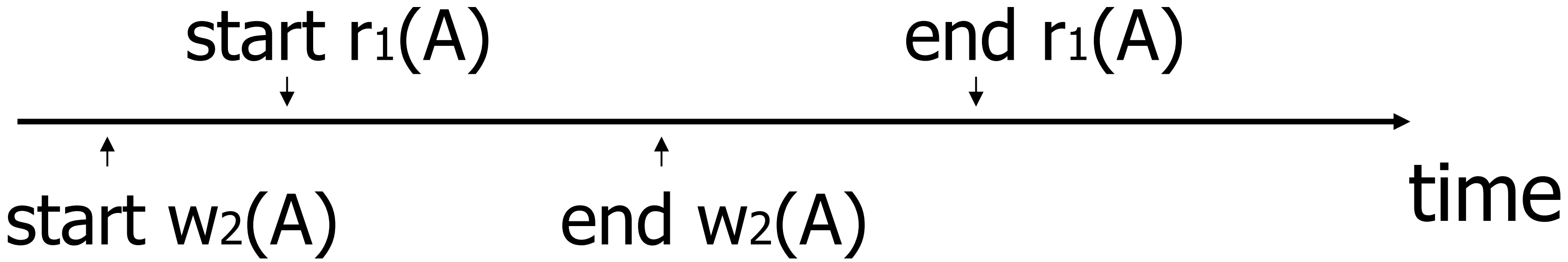
System issues output(B)

output(B) completes

So net effect is either

- $S=\ldots r_1(x)\ldots w_2(b)\ldots$ or
- $S=\ldots w_2(B)\ldots r_1(x)\ldots$

What about conflicting, concurrent actions on same object?



start $r_1(A)$

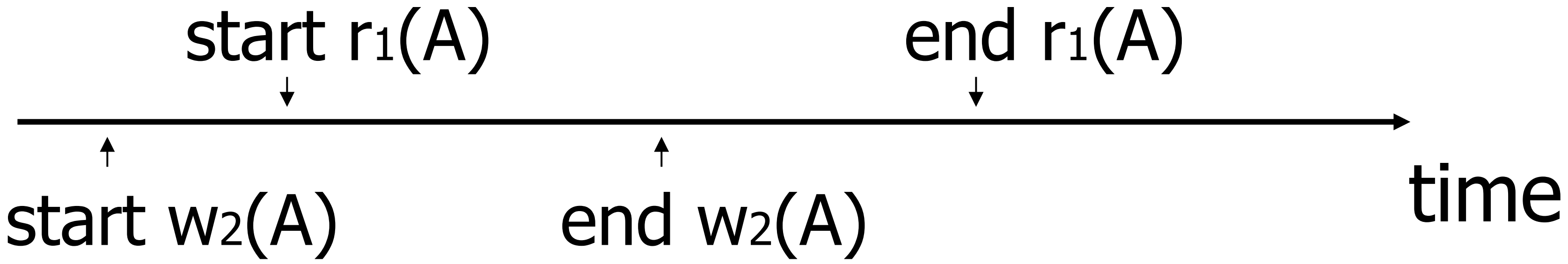
end $r_1(A)$

start $w_2(A)$

end $w_2(A)$

time

What about conflicting, concurrent actions on same object?



start $r_1(A)$ end $r_1(A)$

start $w_2(A)$ end $w_2(A)$

time

- Assume equivalent to either $r_1(A)$ $w_2(A)$
  or $w_2(A)$ $r_1(A)$
- ⇒ low level synchronization mechanism
- Assumption called “atomic actions”

Outline

- Since serial schedules have good properties we would like our schedules to behave like (be **equivalent** to) serial schedules
  1. Need to define equivalence based solely on order of operations
  2. Need to define class of schedules which is equivalent to serial schedule
  3. Need to design scheduler that guarantees that we only get these good schedules

Conflict Equivalence

- Define equivalence based on the order of conflicting actions

Definition

S_1, S_2 are conflict equivalent schedules if S_1 can be transformed into S_2 by a series of swaps on non-conflicting actions.

Alternatively:

If the order of conflicting actions in S_1 and S_2 is the same

Outline

- Since serial schedules have good properties we would like our schedules to behave like (be **equivalent** to) serial schedules
  1. Need to define equivalence based solely on order of operations
  2. Need to define class of schedules which is equivalent to serial schedule
  3. Need to design scheduler that guarantees that we only get these good schedules

Definition

A schedule is conflict serializable (**CSR**) if it is conflict equivalent to some serial schedule.

How to check?

- Compare orders of all conflicting operations
- Can be simplified because there is some redundant information here, e.g.,

$S_1 = w_2(A), w_2(B), r_1(A), w_1(B)$

  - W2(A) conflicts with R1(A)
  - W2(B) conflicts with W1(B)
  - Both imply that T2 has to be executed before T1 in any equivalent serial schedule

Conflict graph P(S) (S is schedule)

Nodes: transactions in S

Arcs: Ti → Tj whenever

- $p_i(A)$, $q_j(A)$ are actions in S
- $p_i(A) <_S q_j(A)$
- at least one of p_i, q_j is a write

Exercise:

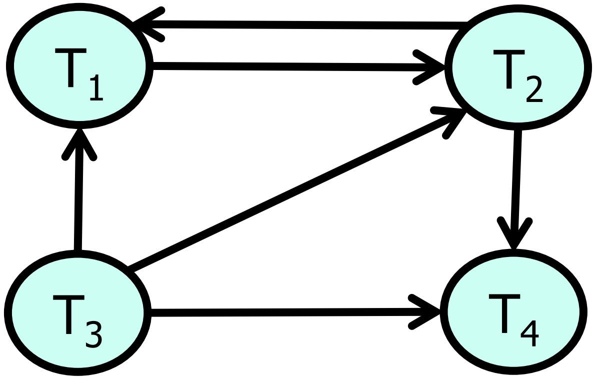
- What is P(S) for

  S = $w_3(A)\ w_2(C)\ r_1(A)\ w_1(B)\ r_1(C)\ w_2(A)\ r_4(A)\ w_4(D)$

- Is S serializable?

Exercise:

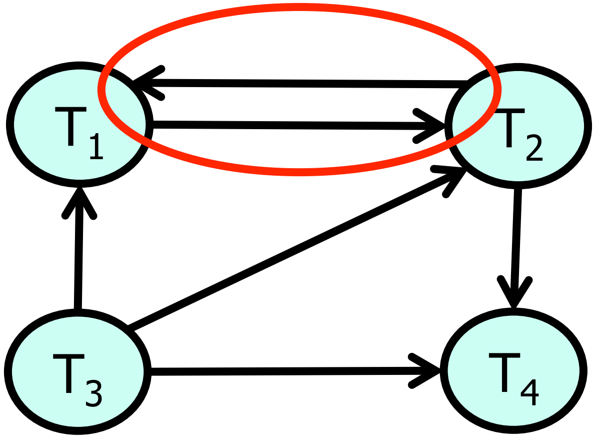
- What is P(S) for
  $S = w_3(A)\ w_2(C)\ r_1(A)\ w_1(B)\ r_1(C)\ w_2(A)\ r_4(A)\ w_4(D)$



- Is S serializable?

Exercise:

- What is P(S) for
  S = $w_3(A)$ $w_2(C)$ $r_1(A)$ $w_1(B)$ $r_1(C)$ $w_2(A)$ $r_4(A)$ $w_4(D)$



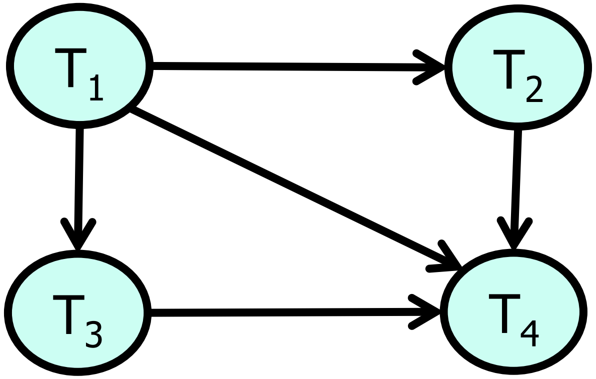
- Is S serializable?

Another Exercise:

- What is P(S) for
  $S = w_1(A)\ r_2(A)\ r_3(A)\ w_4(A)$?

Another Exercise:

- What is P(S) for
  S = $w_1(A)\ r_2(A)\ r_3(A)\ w_4(A)$?



Lemma

S_1, S_2 conflict equivalent $\Rightarrow P(S_1)=P(S_2)$

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S_1, S_2 conflict equivalent $\Rightarrow P(S_1)=P(S_2)$

Proof: $(a \rightarrow b$ same as $\neg b \rightarrow \neg a)$

Assume $P(S_1) \neq P(S_2)$

$\Rightarrow \exists T_i: T_i \rightarrow T_j$ in S_1 and not in S_2

$$\left.\begin{array}{l} \Rightarrow S_1 = \ldots p_i(A) \ldots q_j(A) \ldots \\ \quad\; S_2 = \ldots q_j(A) \ldots p_i(A) \ldots \end{array}\right\} \begin{array}{l} p_i, q_j \\ \text{conflict} \end{array}$$

$\Rightarrow S_1, S_2$ not conflict equivalent

Note: $P(S_1)=P(S_2) \not\Rightarrow S_1, S_2$ conflict equivalent

Note: $P(S_1)=P(S_2) \not\Rightarrow S_1, S_2$ conflict equivalent

Counter example:

$S_1=w_1(A)\ r_2(A) \quad w_2(B)\ r_1(B)$

$S_2=r_2(A)\ w_1(A) \quad r_1(B)\ w_2(B)$

Theorem

$P(S_1)$ acyclic $\Longleftrightarrow$ S_1 conflict serializable

($\Leftarrow$) Assume S_1 is conflict serializable

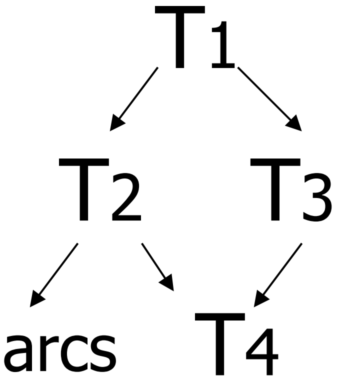
$\Rightarrow \exists\, S_s$: S_s, S_1 conflict equivalent

$\Rightarrow P(S_s) = P(S_1)$

$\Rightarrow P(S_1)$ acyclic since $P(S_s)$ is acyclic

Theorem

$P(S_1)$ acyclic $\Longleftrightarrow$ S_1 conflict serializable



($\Rightarrow$) Assume $P(S_1)$ is acyclic

Transform S_1 as follows:

(1) Take T_1 to be transaction with no incident arcs

(2) Move all T_1 actions to the front

$S_1 = \ldots\ldots.\ q_j(A)\ldots\ldots.p_1(A)\ldots..$

(3) we now have S_1 = < T_1 actions ><... rest ...>

(4) repeat above steps to serialize rest!

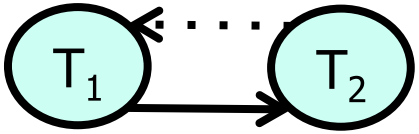
What’s the damage?

- Classification of “bad” things that can happen in “bad” schedules
  - Dirty reads
  - Non-repeatable reads
  - Phantom reads (later)

Dirty Read

- A transaction T_1 read a value that has been updated by an uncommitted transaction T_2
- If T_2 aborts then the value read by T_1 is invalid

Dirty Read



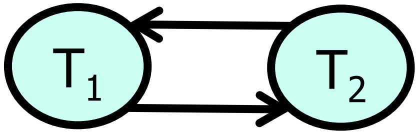
T_1	T_2	A=50
Read(A), A += 100		T_1: A = 150
Write(A);		A = 150
	Read(A), A +=200	T_2: A = 350
Abort		
	Write(A);	

$S_1 = r_1(A), w_1(A), r_2(A), a_1, w_2(A)$

Non-repeatable Read

- A transaction T_1 reads items; some before and some after an update of these item by a transaction T_2
- Problem
  - Repeated reads of the same item see different values
  - Some values are modified and some are not

Inconsistent Read



T_1	T_2	A = 100
Read(A)		
	Read(A), A /= 2	A = 50
	Write(A)	
	Commit	
Read(A)		A = 50
Commit		

$S_1 = r_1(A), r_2(A), w_2(A), c_2, r_1(A), c_1$

How to enforce serializable schedules?

Option 1: run system, recording P(S);
at end of day, check for P(S)
cycles and declare if execution
was good

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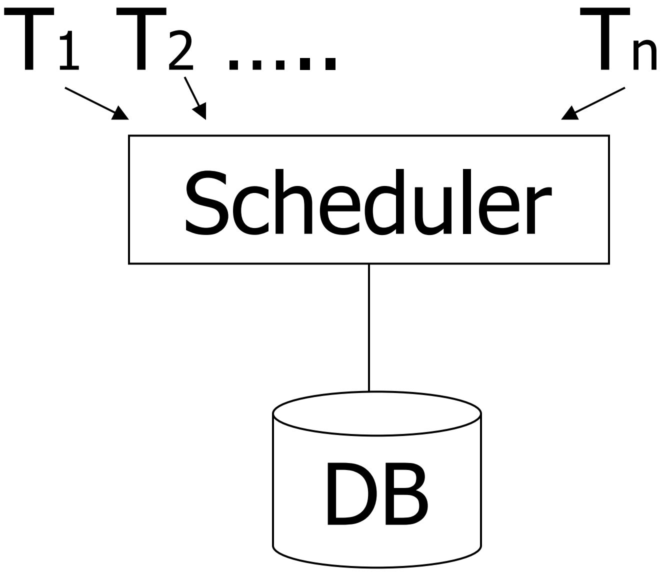
This is called **optimistic concurrency control**

How to enforce serializable schedules?

Option 2: prevent P(S) cycles from occurring



How to enforce serializable schedules?

Option 2: prevent P(S) cycles from occurring

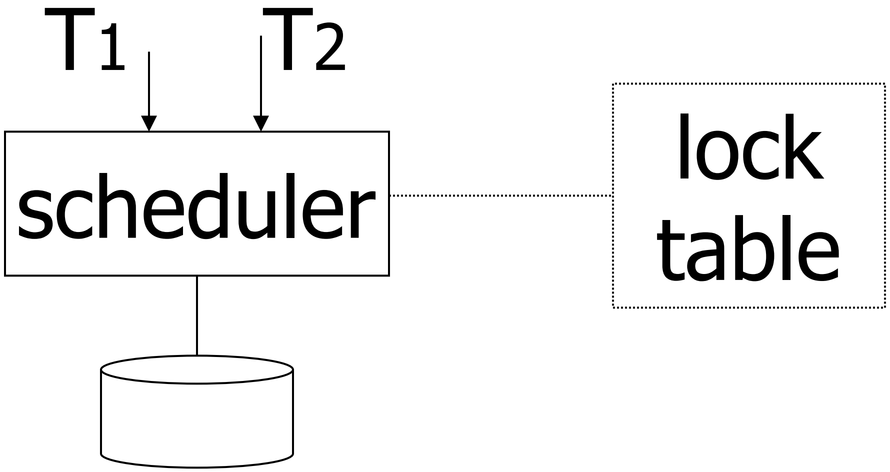
This is called **pessimistic concurrency control**

A locking protocol

Two new actions:

lock (exclusive): l_i (A)

unlock: u_i (A)



Rule #1: Well-formed transactions

T_i: … $l_i(A)$ … $p_i(A)$ … $u_i(A)$ …

1) Transaction has to lock A before it can access A
2) Transaction has to unlock A eventually
3) Transaction cannot access A after unlock

Rule #2 Legal scheduler

$S = \ldots\ldots\ldots\; l_i(A) \underbrace{\ldots\ldots\ldots\ldots}_{\text{no } l_j(A)} u_i(A) \ldots\ldots\ldots$

4) Only one transaction can hold a lock on A at the same time

Exercise:

- What schedules are legal?
  What transactions are well-formed?

$S_1 = l_1(A)l_1(B)r_1(A)w_1(B)l_2(B)u_1(A)u_1(B)$
$r_2(B)w_2(B)u_2(B)l_3(B)r_3(B)u_3(B)$

$S_2 = l_1(A)r_1(A)w_1(B)u_1(A)u_1(B)$
$l_2(B)r_2(B)w_2(B)l_3(B)r_3(B)u_3(B)$

$S_3 = l_1(A)r_1(A)u_1(A)l_1(B)w_1(B)u_1(B)$
$l_2(B)r_2(B)w_2(B)u_2(B)l_3(B)r_3(B)u_3(B)$

Exercise:

- What schedules are legal?
  What transactions are well-formed?

$S1 = l_1(A)l_1(B)r_1(A)w_1(B)l_2(B)u_1(A)u_1(B)$
$r_2(B)w_2(B)u_2(B)l_3(B)r_3(B)u_3(B)$

$S2 = l_1(A)r_1(A)w_1(B)u_1(A)u_1(B)$
$l_2(B)r_2(B)w_2(B)l_3(B)r_3(B)u_3(B)$

$S3 = l_1(A)r_1(A)u_1(A)l_1(B)w_1(B)u_1(B)$
$l_2(B)r_2(B)w_2(B)u_2(B)l_3(B)r_3(B)u_3(B)$

Schedule F

T1	T2
l_1(A);Read(A)	
A ← A+100;Write(A);u_1(A)	
	l_2(A);Read(A)
	A ← Ax2;Write(A);u_2(A)
	l_2(B);Read(B)
	B ← Bx2;Write(B);u_2(B)
l_1(B);Read(B)	
B ← B+100;Write(B);u_1(B)	

Schedule F

T1	T2	A	B
		25	25
l_1(A);Read(A)			
A←A+100;Write(A);u_1(A)		125	
	l_2(A);Read(A)		
	A←Ax2;Write(A);u_2(A)	250	
	l_2(B);Read(B)		
	B←Bx2;Write(B);u_2(B)		50
l_1(B);Read(B)			
B←B+100;Write(B);u_1(B)			150
		250	150

<u>Rule #3</u> Two phase locking (**2PL**)

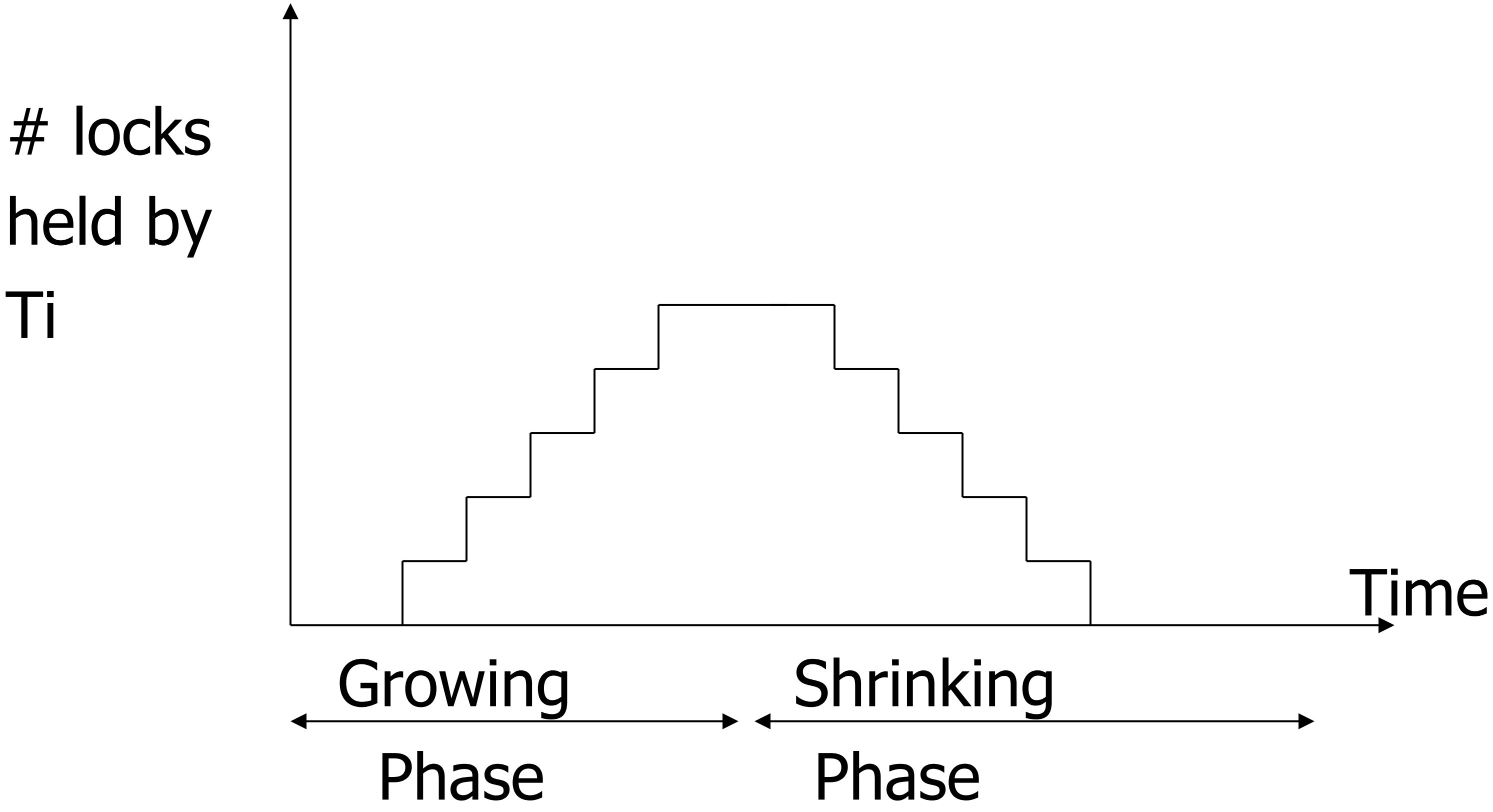
for transactions

T_i = ……. $l_i(A)$ ……….. $u_i(A)$ ………

no unlocks

no locks

5) A transaction does not require new locks after its first unlock operation


locks
held by
Ti
Time
Growing
Phase
Shrinking
Phase

Schedule G

T1	T2
l_1(A);Read(A)	
A←A+100;Write(A)	
l_1(B); u_1(A)	
	l_2(A);Read(A)
	A←Ax2;Write(A);l_2(B)

delayed

Schedule G

T1	T2
$l_1(A)$;Read(A)	
A ← A+100;Write(A)	
$l_1(B)$; $u_1(A)$	
	$l_2(A)$;Read(A)
	A ← Ax2;Write(A); $l_2(B)$ delayed
Read(B);B ← B+100	
Write(B); $u_1(B)$	

Schedule G

T1	T2
$l_1(A)$;Read(A)	
$A \leftarrow A+100$;Write(A)	
$l_1(B)$; $u_1(A)$	
	$l_2(A)$;Read(A)
	$A \leftarrow Ax2$;Write(A); $l_2(B)$ delayed
Read(B);$B \leftarrow B+100$	
Write(B); $u_1(B)$	
	$l_2(B)$; $u_2(A)$;Read(B)
	$B \leftarrow Bx2$;Write(B);$u_2(B)$;

Schedule H (T$_2$ reversed)

T1	T2
$l_1(A)$; Read(A)	$l_2(B)$;Read(B)
A ← A+100;Write(A)	B ← Bx2;Write(B)
$l_1(B)$ delayed	$l_2(A)$ delayed

Deadlock

- Two or more transactions are waiting for each other to release a lock
- In the example
  - T_1 is waiting for T_2 and is making no progress
  - T_2 is waiting for T_1 and is making no progress
  - -> if we do not do anything they would wait forever

- Assume deadlocked transactions are rolled back
  - They have no effect
  - They do not appear in schedule
  - **Come back to that later**

E.g., Schedule H = $\underbrace{\qquad\qquad\qquad\qquad\qquad\qquad}_{\text{This space intentionally left blank!}}$

Next step:

Show that rules #1,2,3 ⇒ conflict-serializable schedules

Conflict rules for $l_i(A)$, $u_i(A)$:

- $l_i(A)$, $l_j(A)$ conflict
- $l_i(A)$, $u_j(A)$ conflict

Note: no conflict $< u_i(A), u_j(A)>$, $< l_i(A), r_j(A)>$,...

<u>Theorem</u> Rules #1,2,3 ⇒ conflict
(2PL) serializable
schedule

Theorem Rules #1,2,3 ⇒ conflict
(2PL) serializable
schedule

To help in proof:

Definition Shrink(Ti) = SH(Ti) =
first unlock
action of Ti

Lemma

$Ti \rightarrow Tj$ in $S \Rightarrow SH(Ti) <_S SH(Tj)$

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$Ti \rightarrow Tj$ in $S \Rightarrow SH(Ti) <_S SH(Tj)$

Proof of lemma:

$Ti \rightarrow Tj$ means that

$S = \ldots p_i(A) \ldots q_j(A) \ldots;$ p,q conflict

By rules 1,2:

$S = \ldots p_i(A) \ldots u_i(A) \ldots l_j(A) \ldots q_j(A) \ldots$

Lemma

$Ti \rightarrow Tj$ in $S \Rightarrow SH(Ti) <_S SH(Tj)$

Proof of lemma:

$Ti \rightarrow Tj$ means that

$S = \ldots\ p_i(A)\ \ldots\ \ q_j(A)\ \ldots;$ p,q conflict

By rules 1,2:

$S = \ldots\ p_i(A)\ \ldots\ u_i(A)\ \ldots\ l_j(A)\ \ldots\ q_j(A)\ \ldots$

$\longleftarrow\!\!\!\!\dashv \qquad \vdash\!\!\!\!\longrightarrow$

By rule 3: $SH(Ti)$ $\qquad$ $SH(Tj)$

So, $SH(Ti) <_S SH(Tj)$

Theorem Rules #1,2,3 $\Rightarrow$ conflict
(2PL) serializable
schedule

Proof:

(1) Assume P(S) has cycle

$$T_1 \rightarrow T_2 \rightarrow \ldots T_n \rightarrow T_1$$

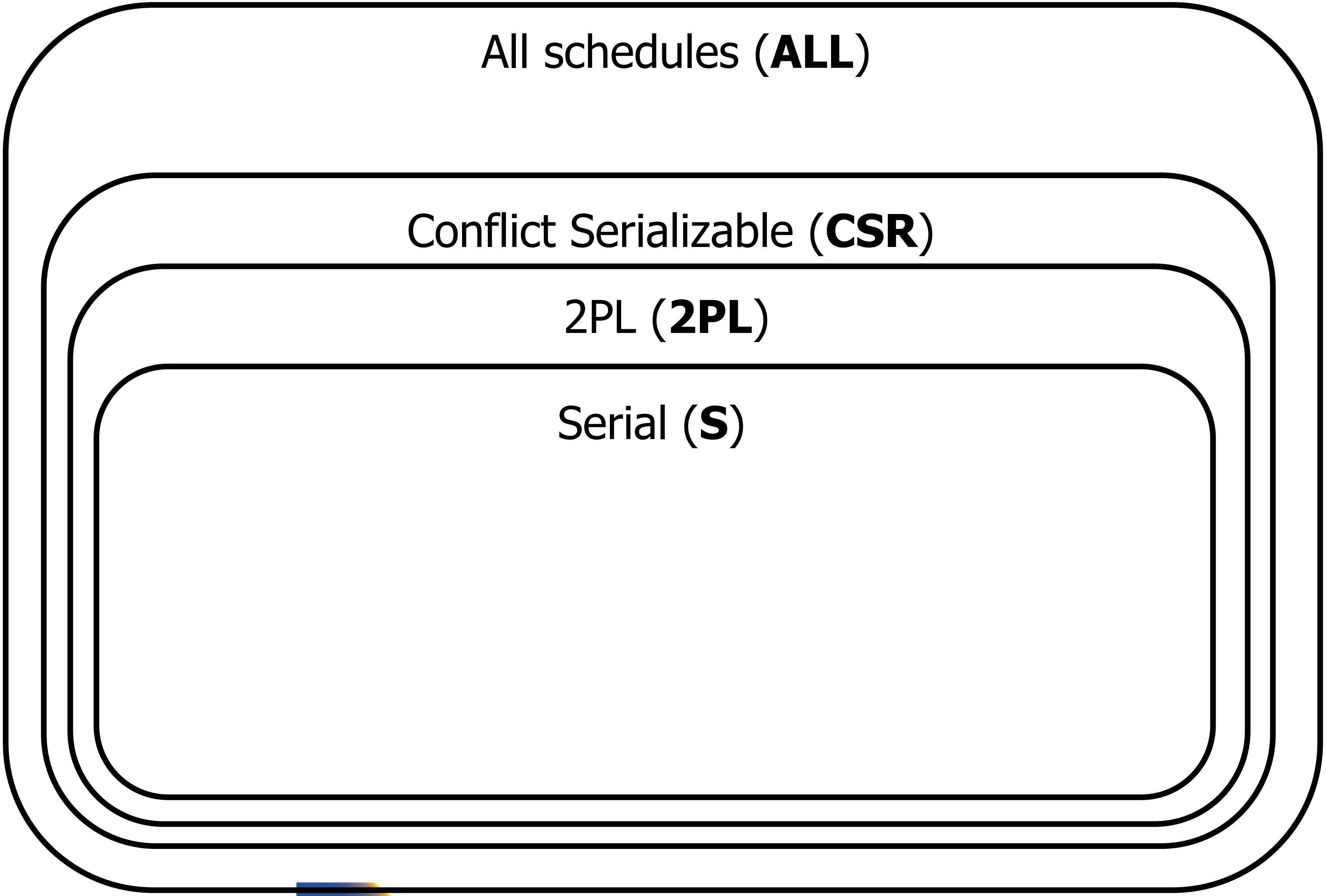
(2) By lemma: $SH(T_1) < SH(T_2) < \ldots < SH(T_1)$

(3) Impossible, so P(S) acyclic

(4) $\Rightarrow$ S is conflict serializable

2PL subset of Serializable

$$\mathbf{S} \subset \mathbf{2PL} \subset \mathbf{CSR} \subset \mathbf{ALL}$$



All schedules (**ALL**)

Conflict Serializable (**CSR**)

2PL (**2PL**)

Serial (**S**)

S1: w1(x) w3(x) w2(y) w1(y)

- S1 cannot be achieved via 2PL:
  The lock by T1 for y must occur after w2(y), so the unlock by T1 for x must occur after this point (and before w1(x)). Thus, w3(x) cannot occur under 2PL where shown in S1 because T1 holds the x lock at that point.
- However, S1 is serializable
  (equivalent to T2, T1, T3).

If you need a bit more practice:

Are our schedules S_C and S_D 2PL schedules?

S_C: w1(A) w2(A) w1(B) w2(B)

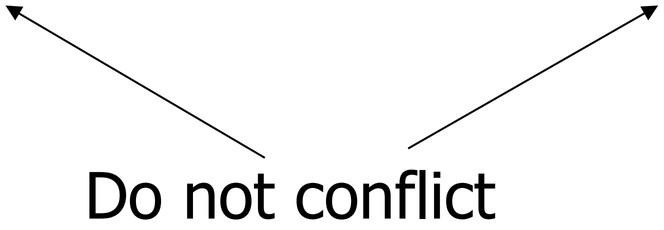
S_D: w1(A) w2(A) w2(B) w1(B)

- Beyond this simple **2PL** protocol, it is all a matter of improving performance and allowing more concurrency….
  - Shared locks
  - Multiple granularity
  - Avoid Deadlocks
  - Inserts, deletes and phantoms
  - Other types of C.C. mechanisms
    - Multiversioning concurrency control

Shared locks

So far:

$S = \ldots l_1(A)\ r_1(A)\ u_1(A)\ \ldots\ l_2(A)\ r_2(A)\ u_2(A)\ \ldots$



Do not conflict

Shared locks

So far:

$S = \ldots l_1(A)\ r_1(A)\ u_1(A)\ \ldots\ l_2(A)\ r_2(A)\ u_2(A)\ \ldots$

Do not conflict

Instead:

$S = \ldots\ ls_1(A)\ r_1(A)\ ls_2(A)\ r_2(A)\ \ldots.\ us_1(A)\ us_2(A)$

Lock actions

l-t_i(A): lock A in t mode (t is S or X)

u-t_i(A): unlock t mode (t is S or X)

Shorthand:

u_i(A): unlock whatever modes
T_i has locked A

Rule #1 Well formed transactions

$T_i = \ldots\ l\text{-}S_1(A)\ \ldots\ r_1(A)\ \ldots\ u_1(A)\ \ldots$

$T_i = \ldots\ l\text{-}X_1(A)\ \ldots\ w_1(A)\ \ldots\ u_1(A)\ \ldots$

- What about transactions that read and write same object?

Option 1: Request exclusive lock

T_i = ...l-X_1(A) … r_1(A) ... w_1(A) ... u(A) …

- What about transactions that read and write same object?

Option 2: Upgrade

(E.g., need to read, but don't know if will write…)

T_i=... l-S_1(A) … r_1(A) ... l-X_1(A) ...w_1(A) ...u(A)...

Think of
- Get 2nd lock on A, or
- Drop S, get X lock

Rule #2 Legal scheduler

$S = \ldots.l\text{-}S_i(A) \ldots \quad \ldots u_i(A) \ldots$

$\longleftrightarrow$

no $l\text{-}X_j(A)$

$S = \ldots l\text{-}X_i(A) \ldots \quad \ldots u_i(A) \ldots$

$\longleftrightarrow$

no $l\text{-}X_j(A)$

no $l\text{-}S_j(A)$

A way to summarize Rule #2

Compatibility matrix

Comp

	S	X
S	true	false
X	false	false

Rule # 3 2PL transactions

No change except for upgrades:

(I) If upgrade gets more locks
(e.g., S → {S, X}) then no change!

(II) If upgrade releases read (shared) lock (e.g., S → X)
- can be allowed in growing phase

Theorem Rules 1,2,3 $\Rightarrow$ Conf.serializable
for S/X locks schedules

Proof: similar to X locks case

Detail:

l-t_i(A), l-r_j(A) do not conflict if comp(t,r)

l-t_i(A), u-r_j(A) do not conflict if comp(t,r)

Lock types beyond S/X

Examples:

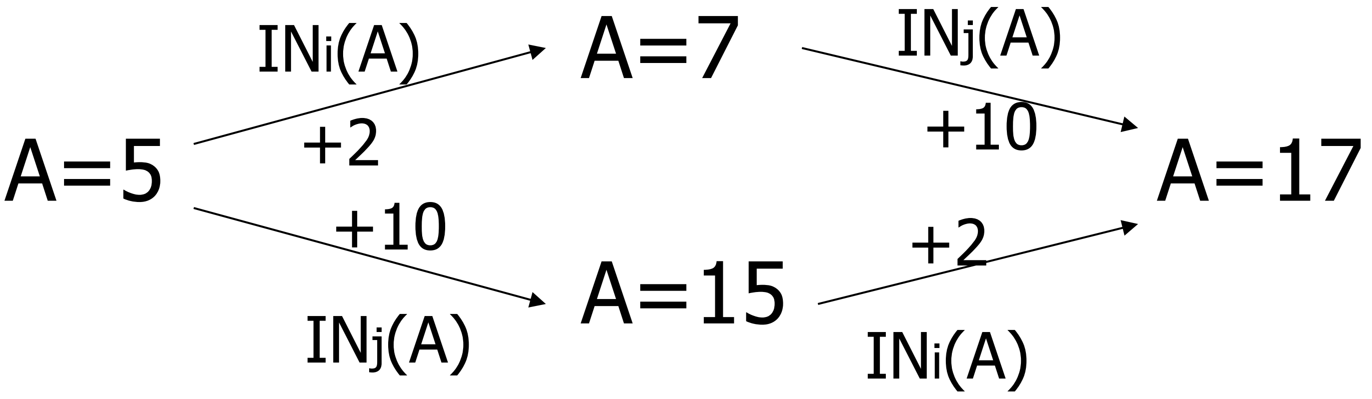
(1) increment lock

(2) update lock

Example (1): increment lock

- Atomic increment action: $IN_i(A)$

  $\{Read(A);\ A \leftarrow A+k;\ Write(A)\}$
- $IN_i(A)$, $IN_j(A)$ do not conflict!



Comp

	S	X	I
S			
X			
I			

Comp

	S	X	I
S	T	F	F
X	F	F	F
I	F	F	T

Update locks

A common deadlock problem with upgrades:

T1	T2
l-S_1(A)	
	l-S_2(A)
l-X_1(A)	
	l-X_2(A)

--- Deadlock ---

Solution

If T_i wants to read A and knows it may later want to write A, it requests <u>update</u> lock (not shared)

Comp

New request

Lock already held in

	S	X	U
S			
X			
U			

Comp

New request

Lock already held in

	S	X	U
S	T	F	T
X	F	F	F
U	TorF	F	F

-> symmetric table?

Note: object A may be locked in different modes at the same time...

$$S_1 = \ldots l\text{-}S_1(A) \ldots l\text{-}S_2(A) \ldots l\text{-}U_3(A) \ldots \begin{cases} l\text{-}S_4(A) \ldots ? \\ l\text{-}U_4(A) \ldots ? \end{cases}$$

Note: object A may be locked in different modes at the same time...

$S_1 = \ldots l\text{-}S_1(A) \ldots l\text{-}S_2(A) \ldots l\text{-}U_3(A) \ldots \left\{ \begin{array}{l} l\text{-}S_4(A) \ldots ? \\ l\text{-}U_4(A) \ldots ? \end{array} \right.$

- To grant a lock in mode t, mode t must be compatible with all currently held locks on object

How does locking work in practice?

- Every system is different

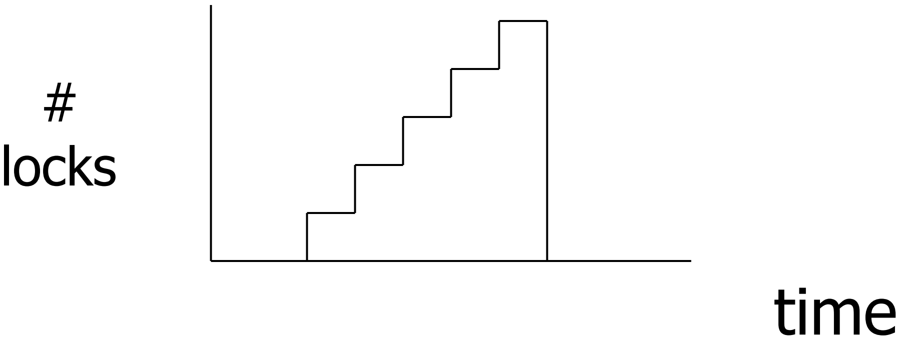
  (E.g., may not even provide
  CONFLICT-SERIALIZABLE schedules)

- But here is one (simplified) way ...

Sample Locking System:

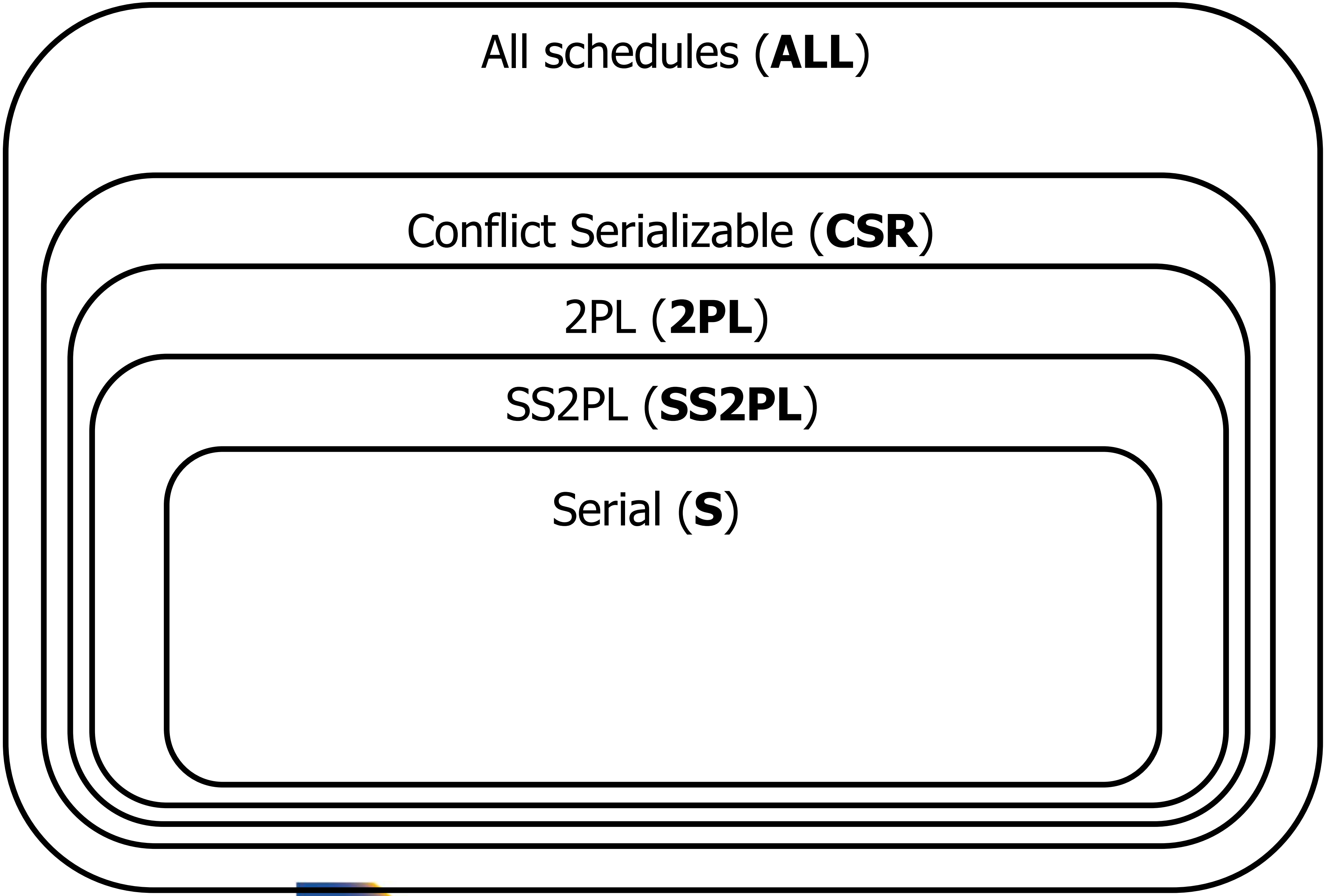
(1) Don't trust transactions to request/release locks

(2) Hold all locks until transaction commits



Strict Strong 2PL (**SS2PL**)

- 2PL + (2) from the last slide
- All locks are held until transaction end
- Compare with schedule class **strict** (**ST**) we defined for recovery
  - A transaction never reads or writes items written by an uncommitted transactions
- **SS2PL** = (**ST** ∩ **2PL**)



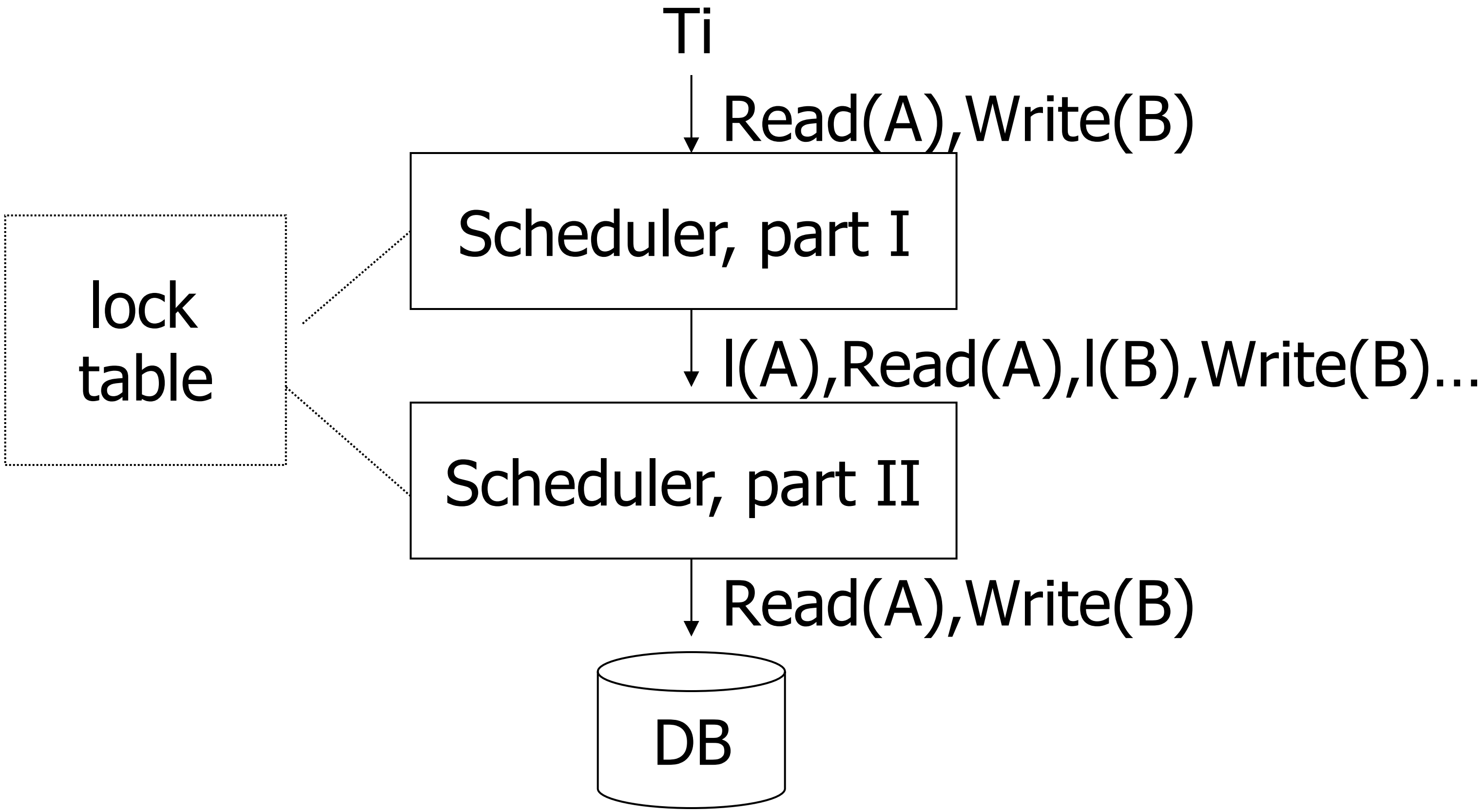
All schedules (**ALL**)

Conflict Serializable (**CSR**)

2PL (**2PL**)

SS2PL (**SS2PL**)

Serial (**S**)



Ti

Read(A),Write(B)

Scheduler, part I

lock table

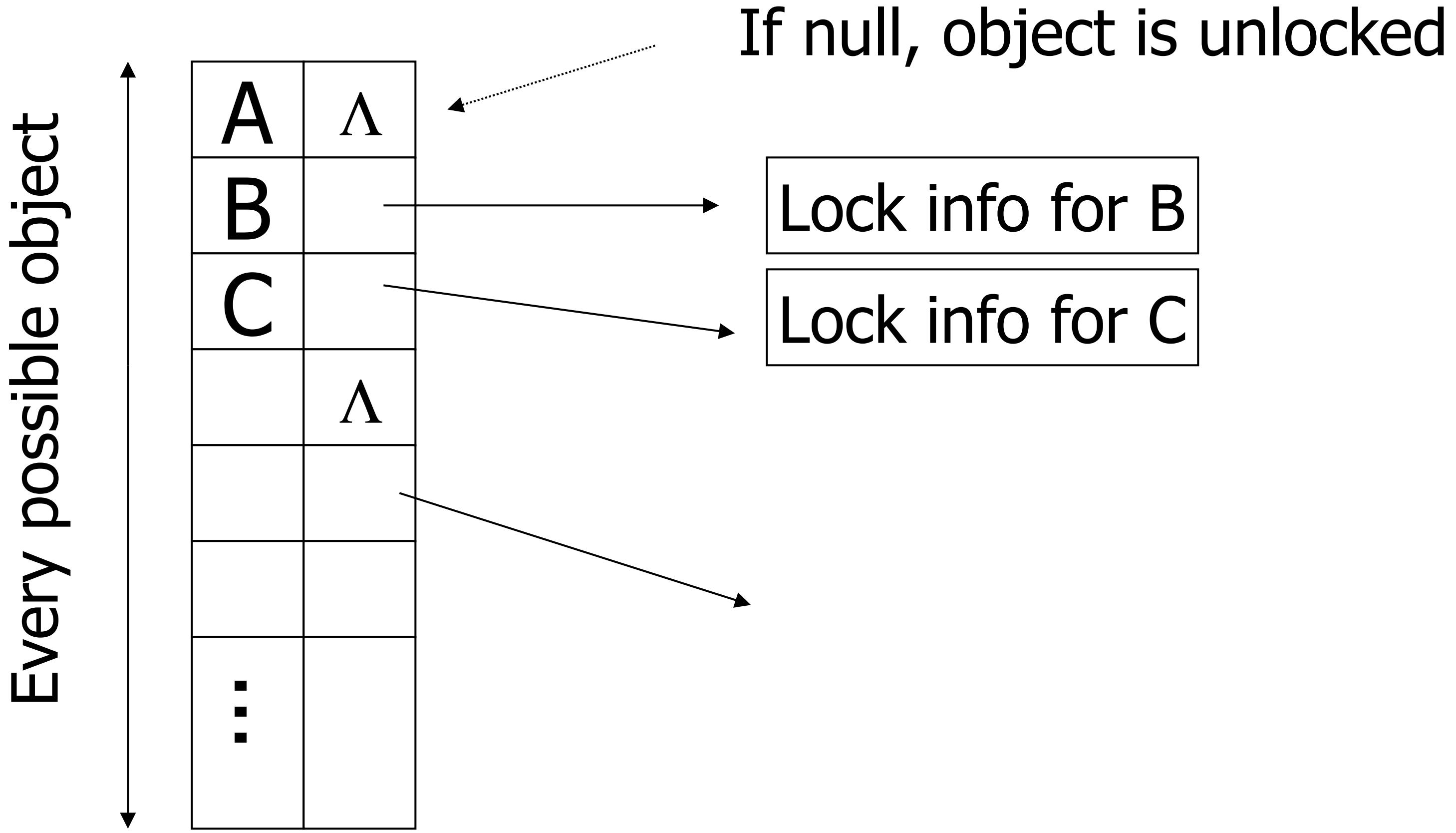
l(A),Read(A),l(B),Write(B)…

Scheduler, part II

Read(A),Write(B)

DB

Lock table Conceptually



Every possible object

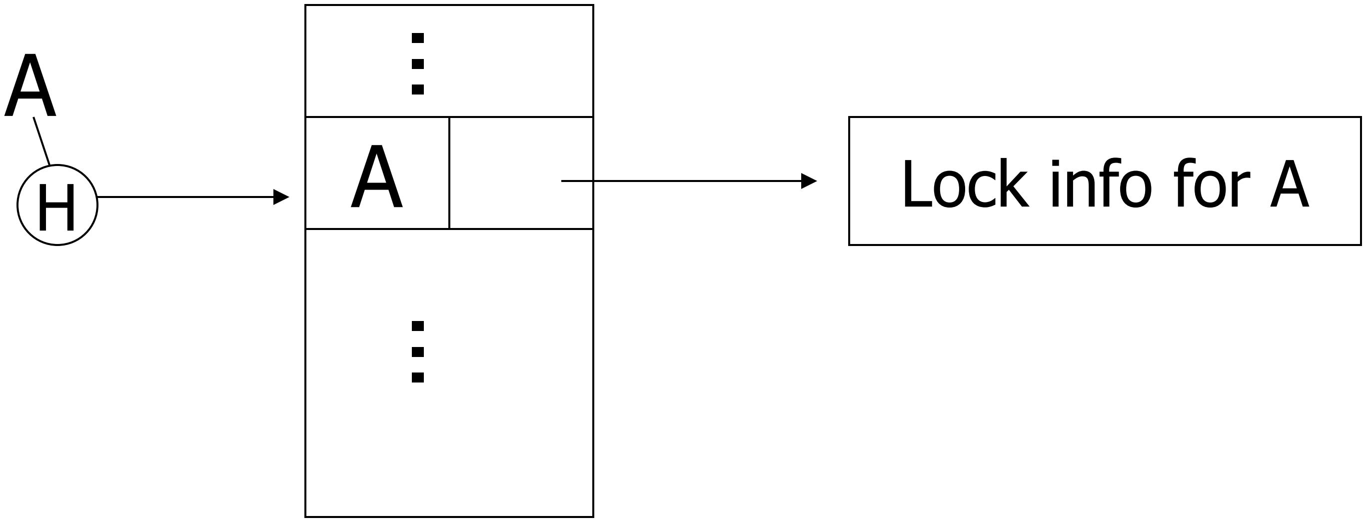
A	Λ
B	
C	
	Λ
⋮	

If null, object is unlocked

Lock info for B

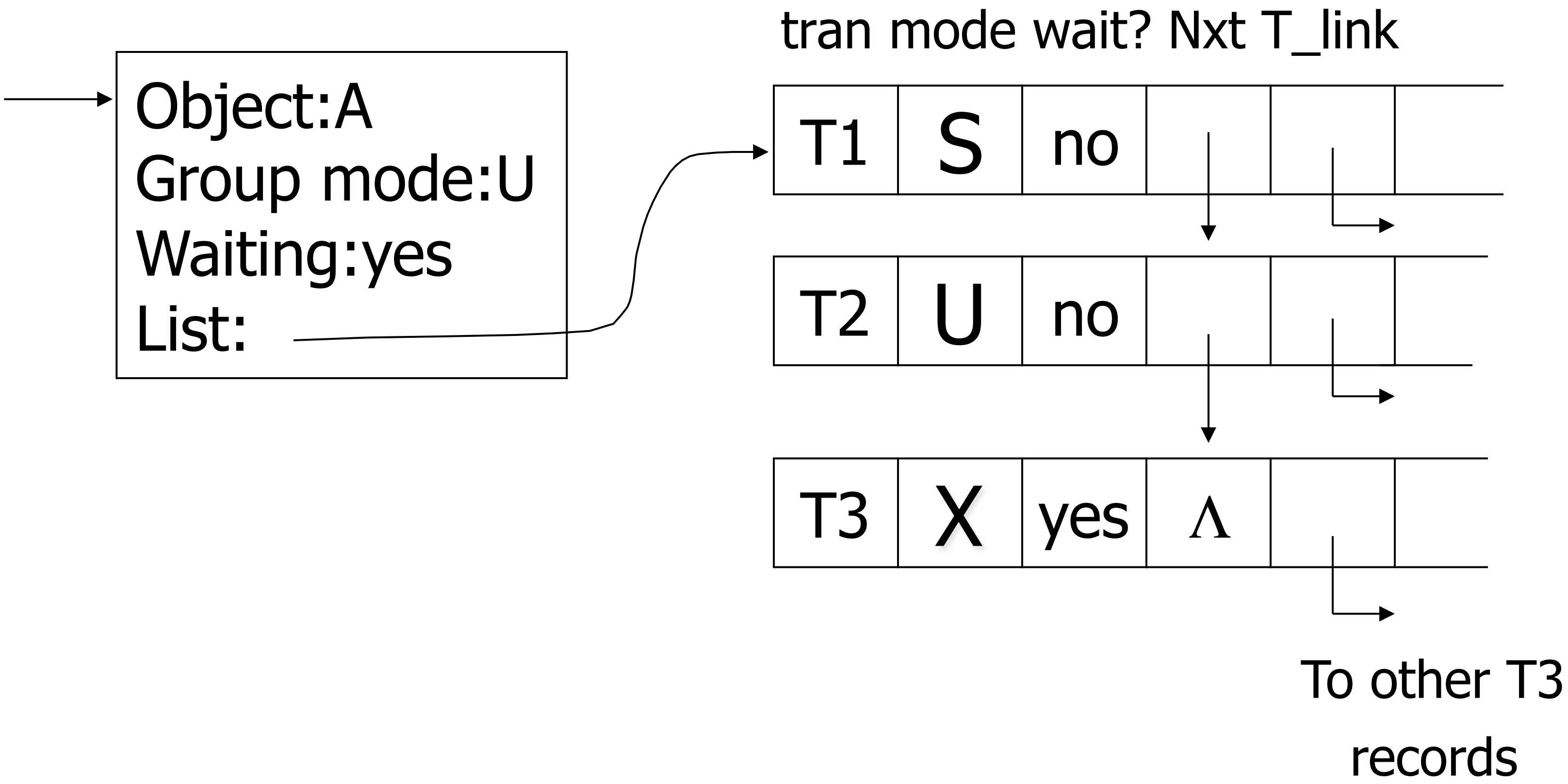
Lock info for C

But use hash table:



If object not found in hash table, it is unlocked

Lock info for A - example

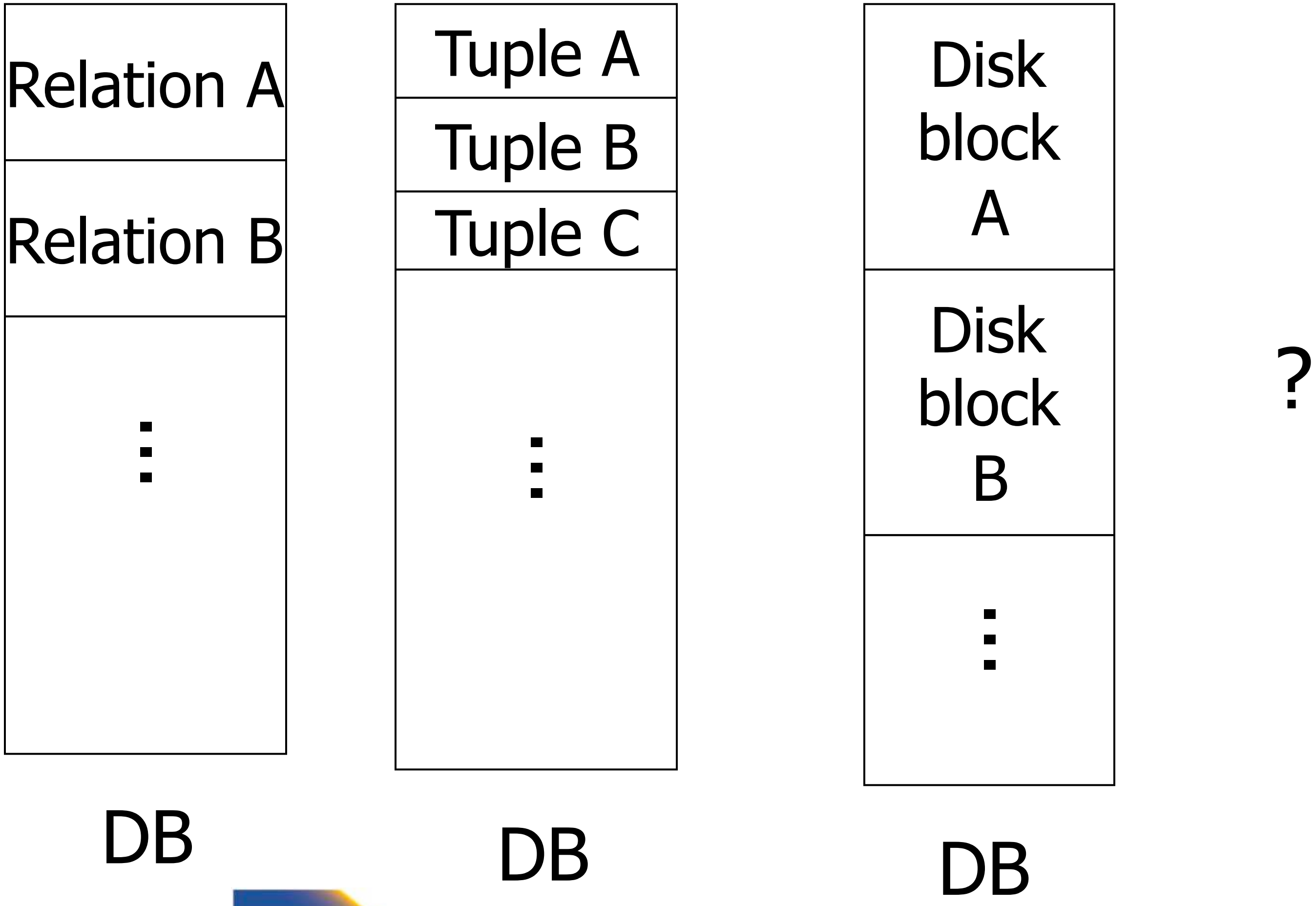


Object:A
Group mode:U
Waiting:yes
List:

tran	mode	wait?	Nxt	T_link
T1	S	no		
T2	U	no		
T3	X	yes	Λ	

To other T3 records

What are the objects we lock?



Relation A
Relation B
⋮
DB

Tuple A
Tuple B
Tuple C
⋮
DB

Disk block A
Disk block B
⋮
DB

?

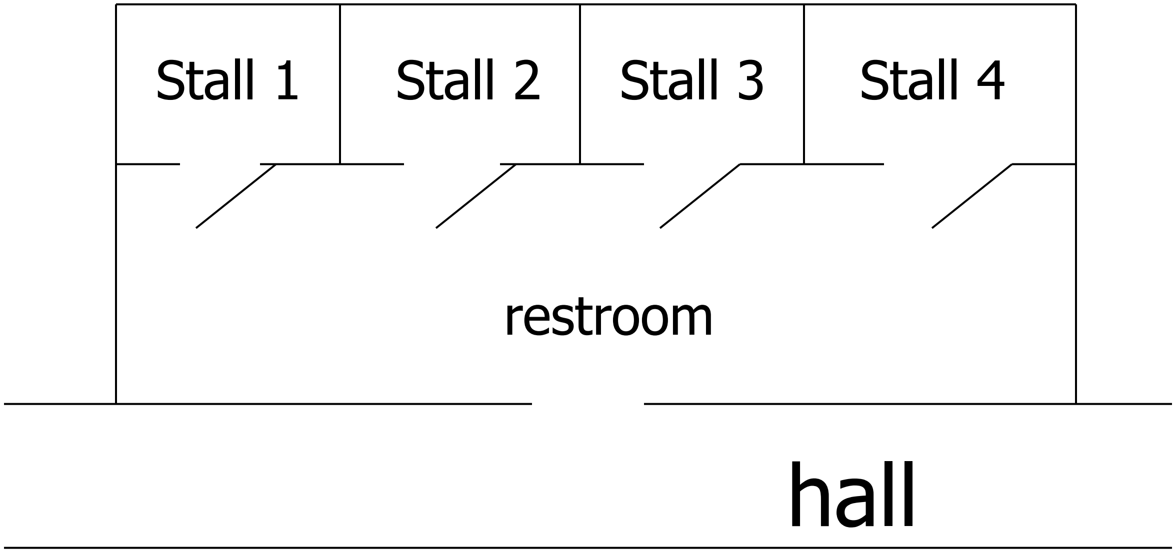
- Locking works in any case, but should we choose small or large objects?

- Locking works in any case, but should we choose small or large objects?

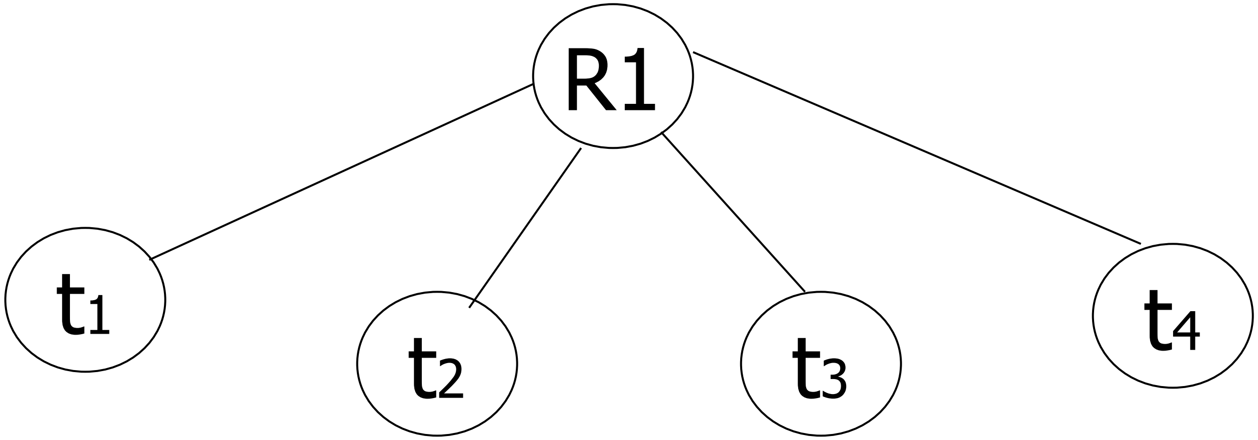
- If we lock large objects (e.g., Relations)
  - Need few locks
  - Low concurrency
- If we lock small objects (e.g., tuples,fields)
  - Need more locks
  - More concurrency

We can have it both ways!!

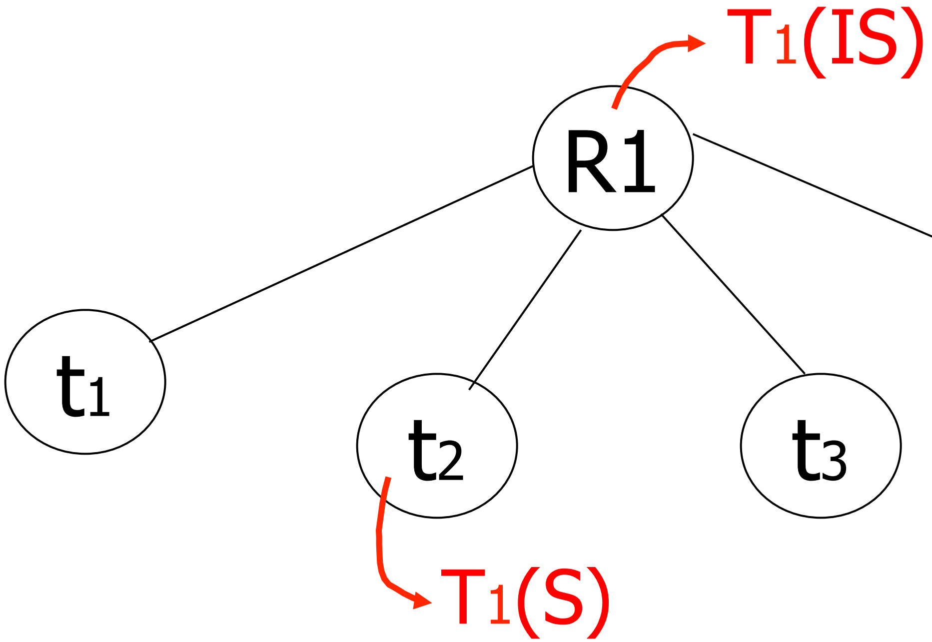
Ask any janitor to give you the solution...



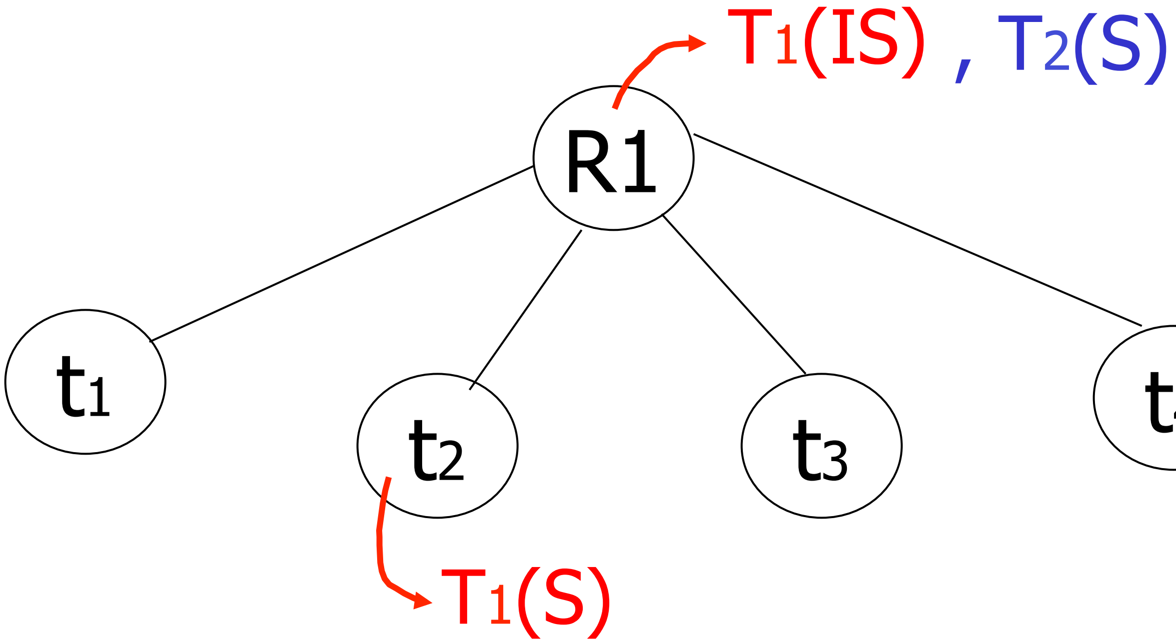
Example



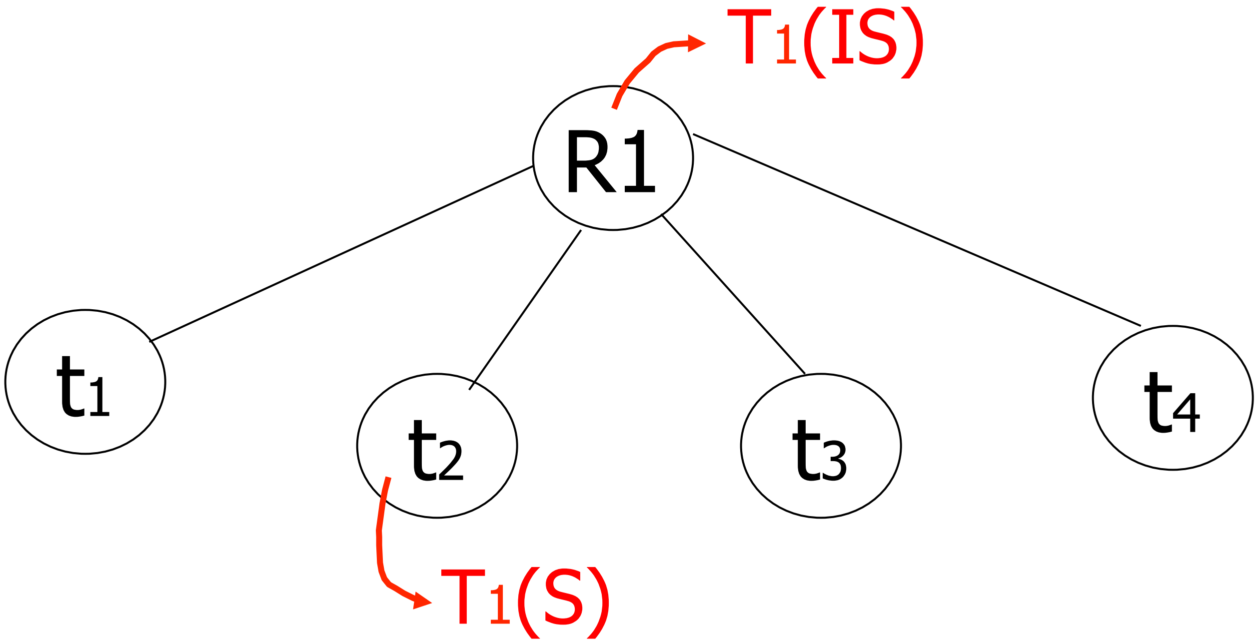
Example



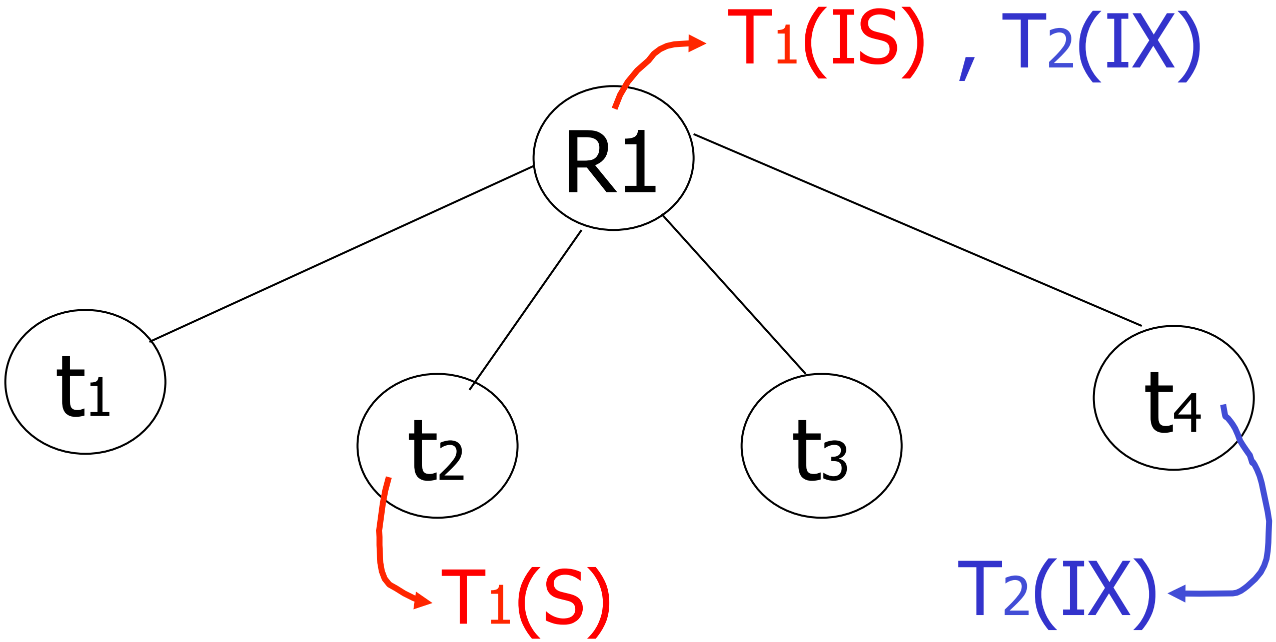
Example



Example (b)



Example



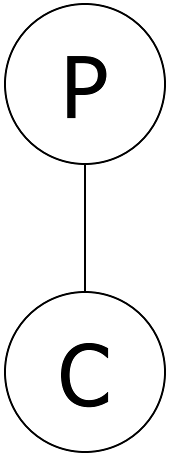
Multiple granularity

Comp		Requestor				
		IS	IX	S	SIX	X
	IS					
Holder	IX					
	S					
	SIX					
	X					

Multiple granularity

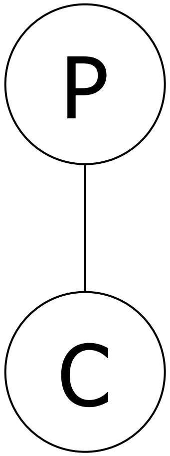
Comp		Requestor				
		IS	IX	S	SIX	X
	IS	T	T	T	T	F
Holder	IX	T	T	F	F	F
	S	T	F	T	F	F
	SIX	T	F	F	F	F
	X	F	F	F	F	F

Parent locked in	Child can be locked in
IS	
IX	
S	
SIX	
X	



Parent locked in	Child can be locked by same transaction in
IS	IS, S
IX	IS, S, IX, X, SIX
S	none
SIX	X, IX, [SIX]
X	none

not necessary



Rules

(1) Follow multiple granularity comp function

(2) Lock root of tree first, any mode

(3) Node Q can be locked by Ti in S or IS only if parent(Q) locked by Ti in IX or IS

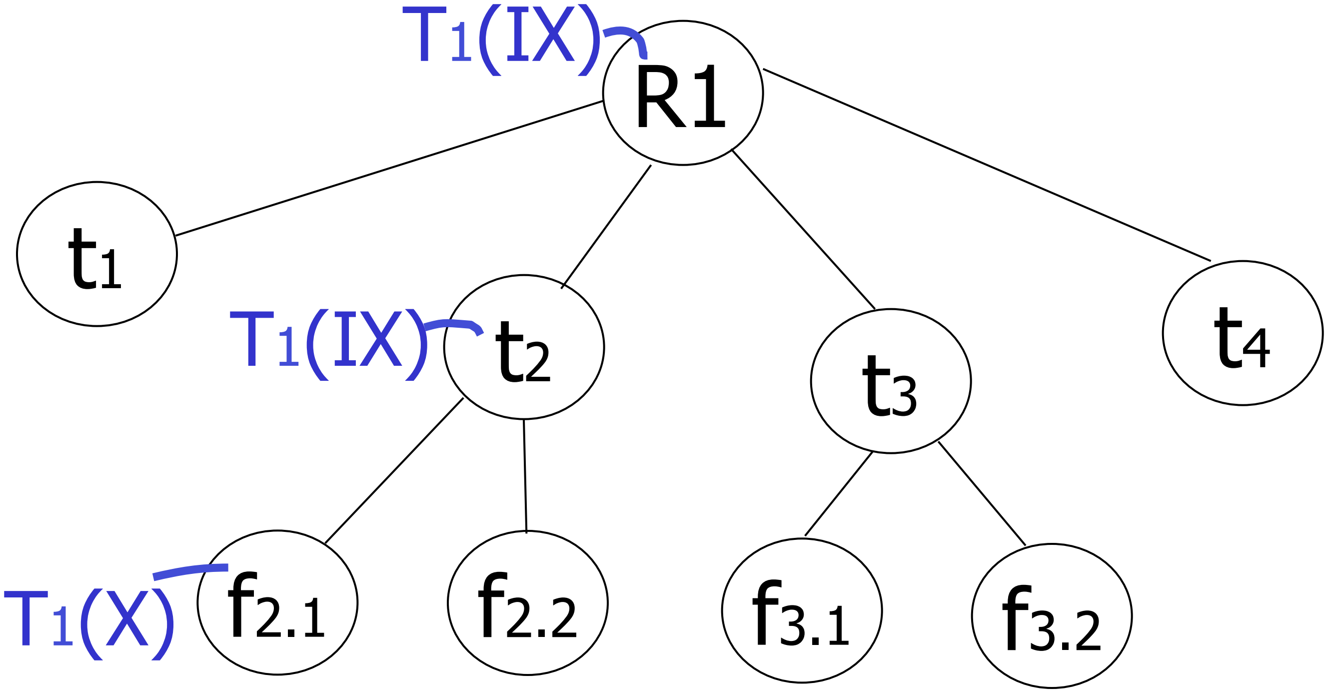
(4) Node Q can be locked by Ti in X,SIX,IX only if parent(Q) locked by Ti in IX,SIX

(5) Ti is two-phase

(6) Ti can unlock node Q only if none of Q's children are locked by Ti

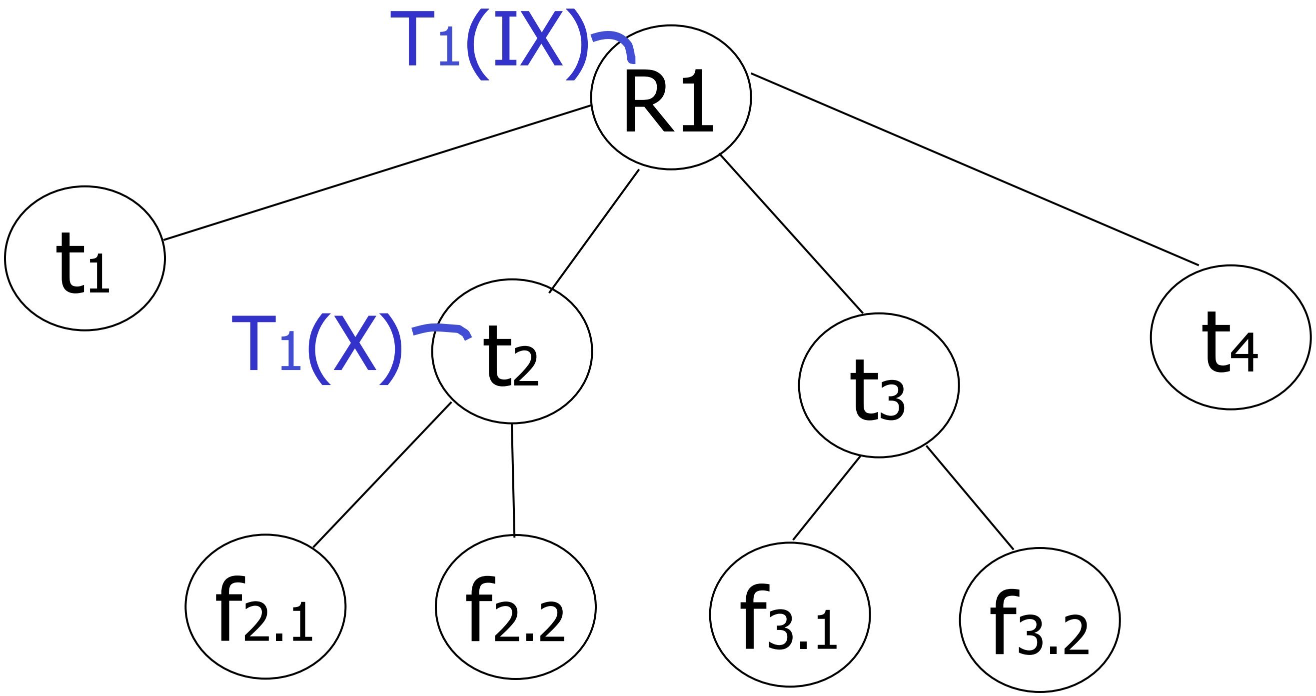
Exercise:

- Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



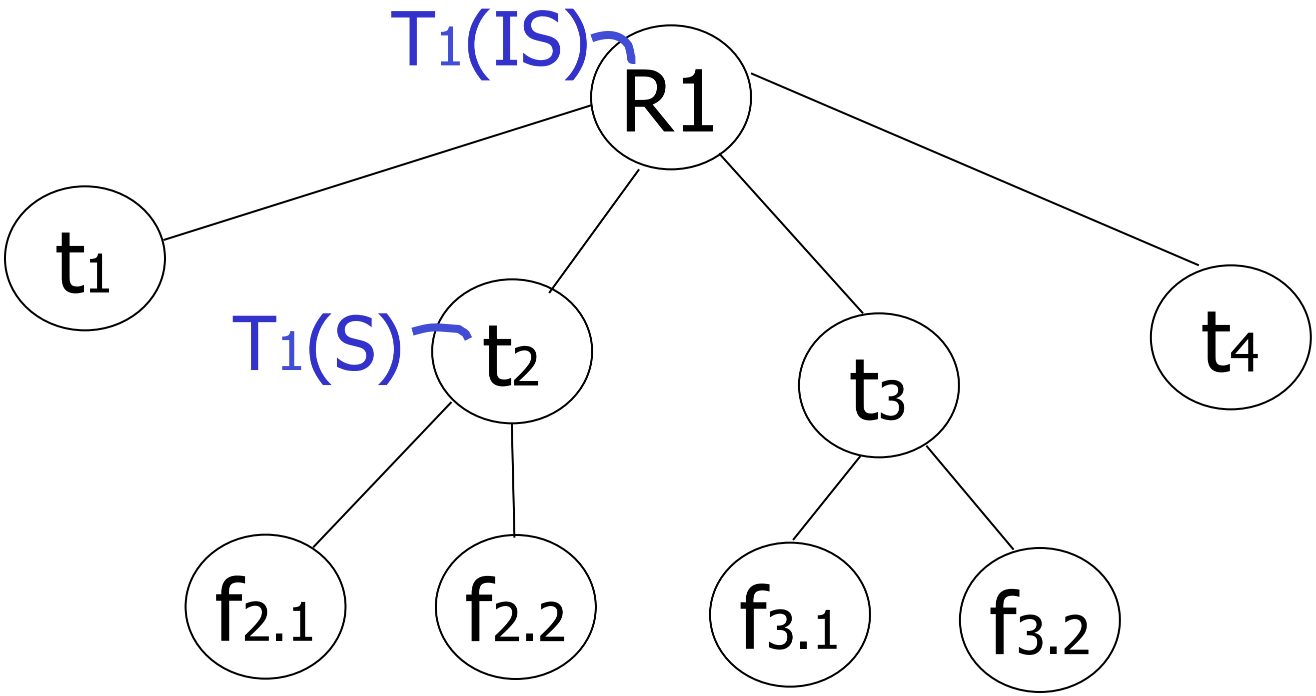
Exercise:

- Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



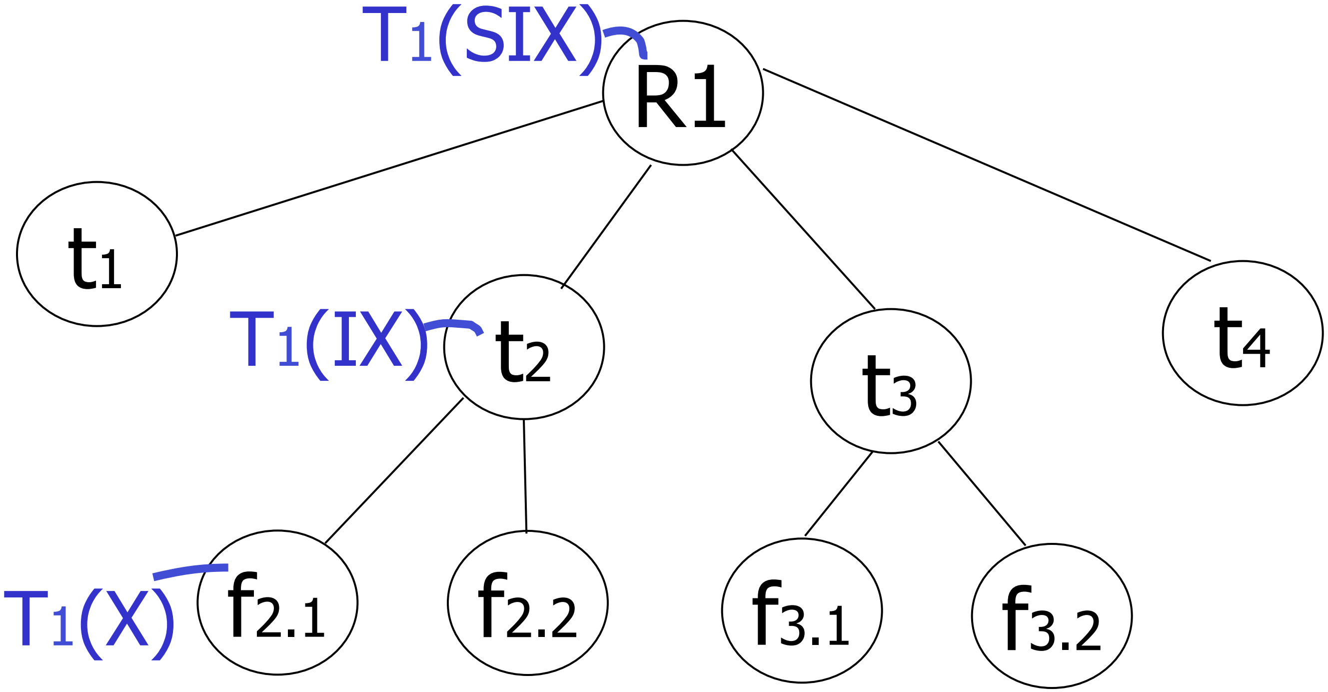
Exercise:

- Can T_2 access object $f_{3.1}$ in X mode? What locks will T_2 get?



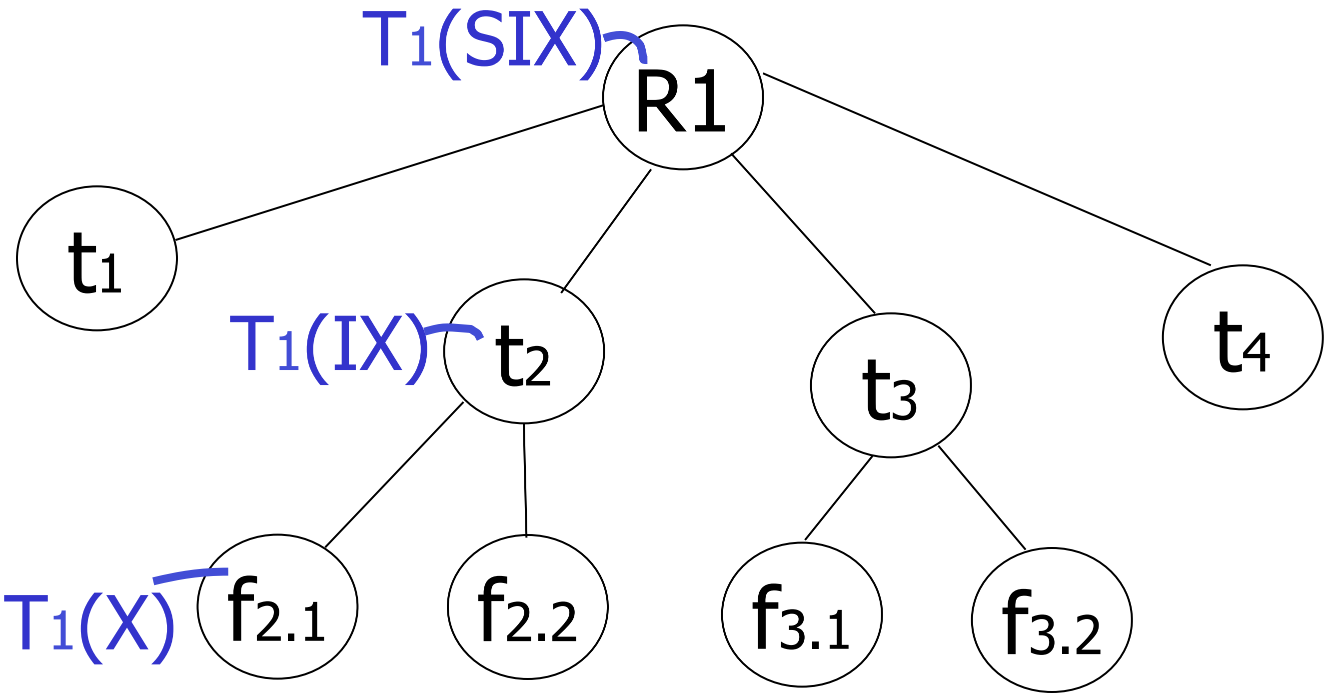
Exercise:

- Can T_2 access object $f_{2.2}$ in S mode? What locks will T_2 get?

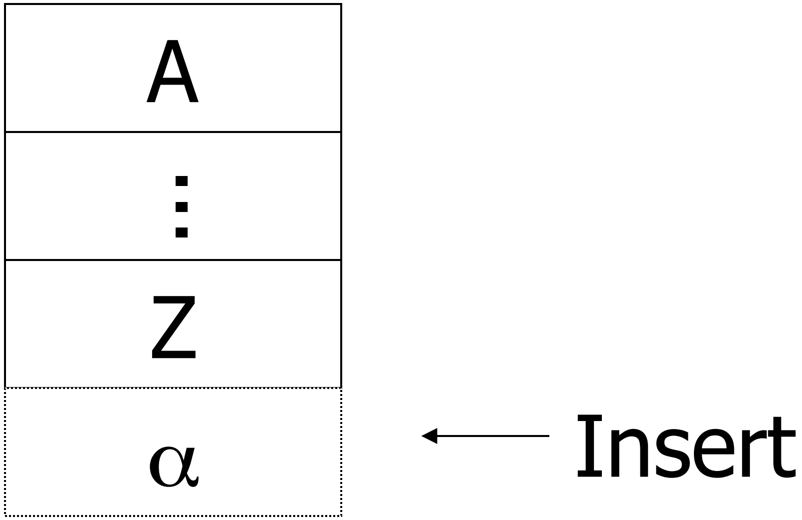


Exercise:

- Can T_2 access object $f_{2.2}$ in X mode? What locks will T_2 get?



Insert + delete operations



Modifications to locking rules:

(1) Get exclusive lock on A before deleting A

(2) At insert A operation by Ti,
Ti is given exclusive lock on A

Still have a problem: **Phantoms**

Example: relation R (E#,name,…)

constraint: E# is key

use tuple locking

R

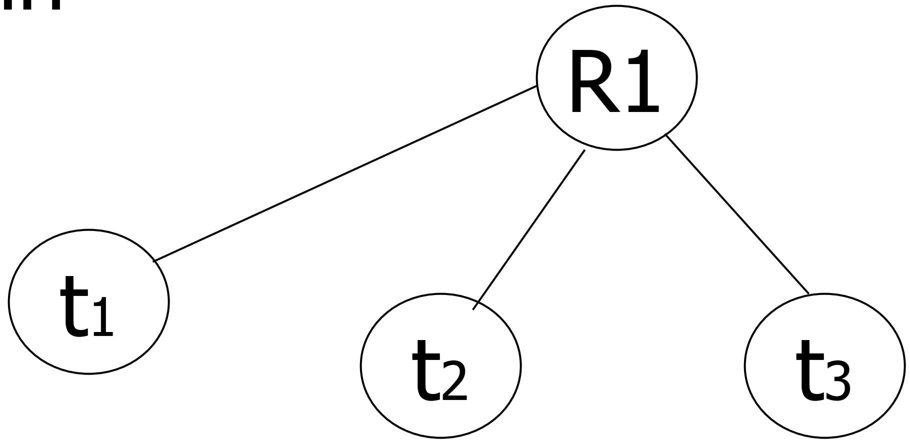
	E#	Name	….
o1	55	Smith	
o2	75	Jones	

T_1: Insert <08,Obama,…> into R
T_2: Insert <08,McCain,…> into R

T_1	T_2
$S_1(o_1)$	$S_2(o_1)$
$S_1(o_2)$	$S_2(o_2)$
Check Constraint	Check Constraint
⋮	⋮
Insert o_3[08,Obama,..]	
	Insert o_4[08,McCain,..]

Solution

- Use multiple granularity tree
- Before insert of node Q,
  lock parent(Q) in
  X mode

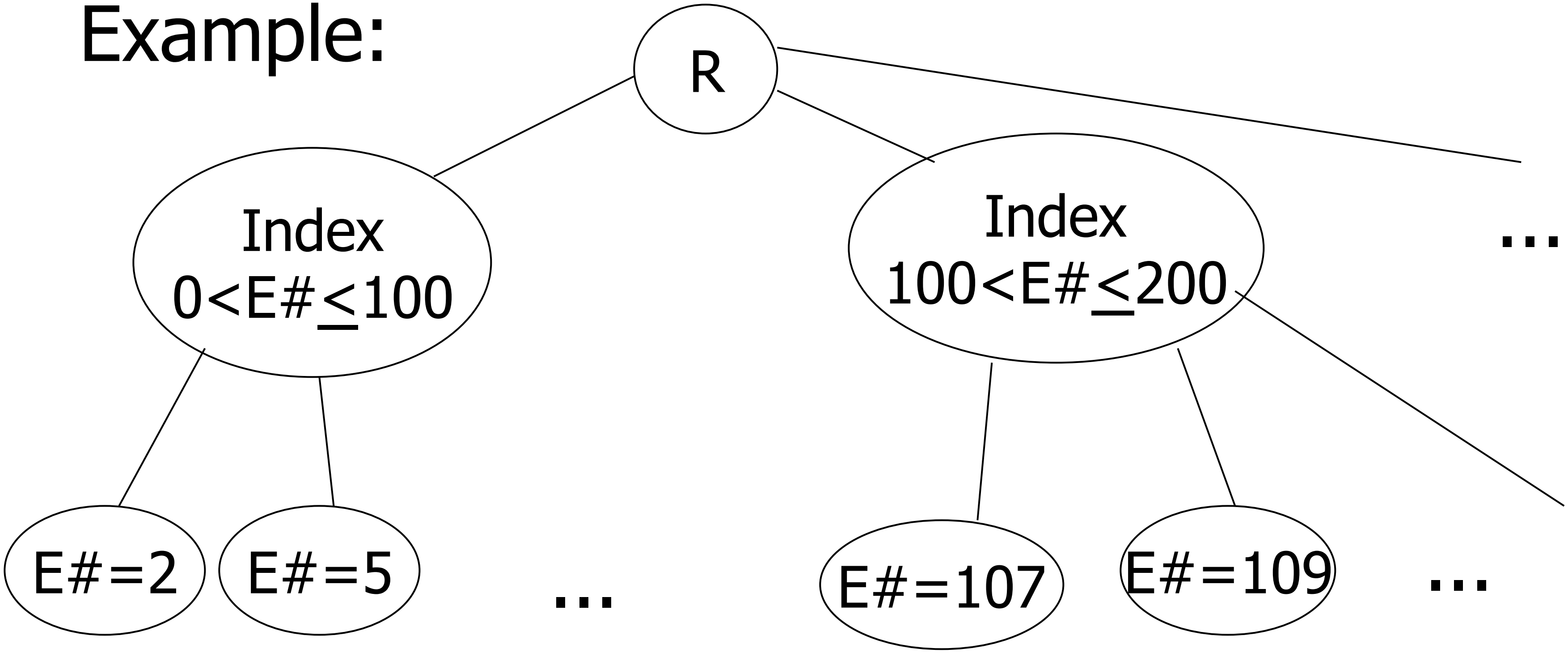


Back to example

T_1: Insert<04,Kerry>	T_2: Insert<04,Bush>
T_1	T_2
$X_1(R)$	
	$X_2(R)$ *delayed*
Check constraint	
Insert<04,Kerry>	
$U(R)$	
	$X_2(R)$
	Check constraint
	Oops! e# = 04 already in R!

Instead of using R, can use index on R:

Example:



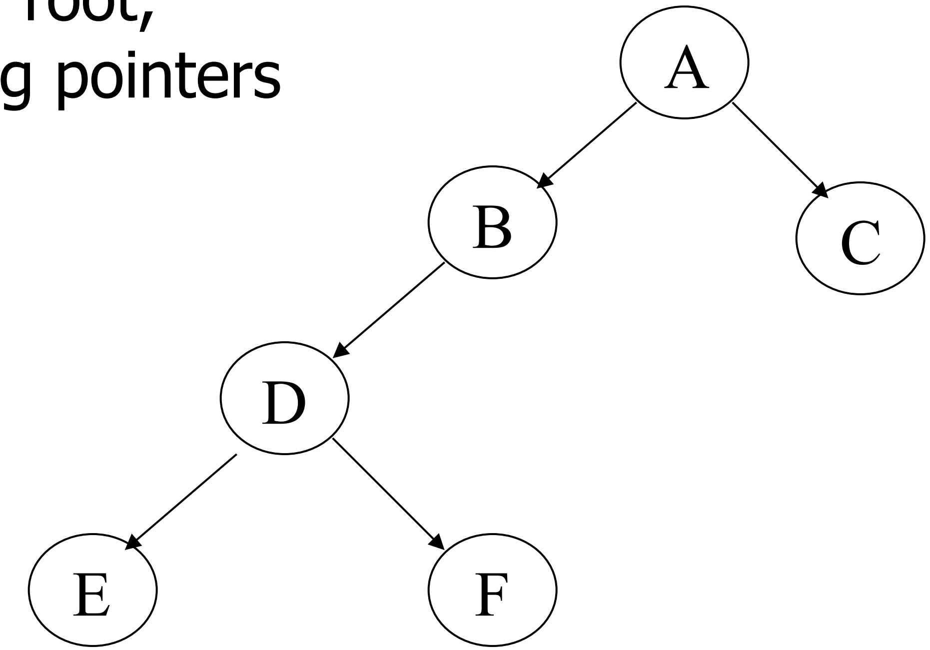
- This approach can be generalized to multiple indexes...

Next:

- Tree-based concurrency control
- Validation concurrency control

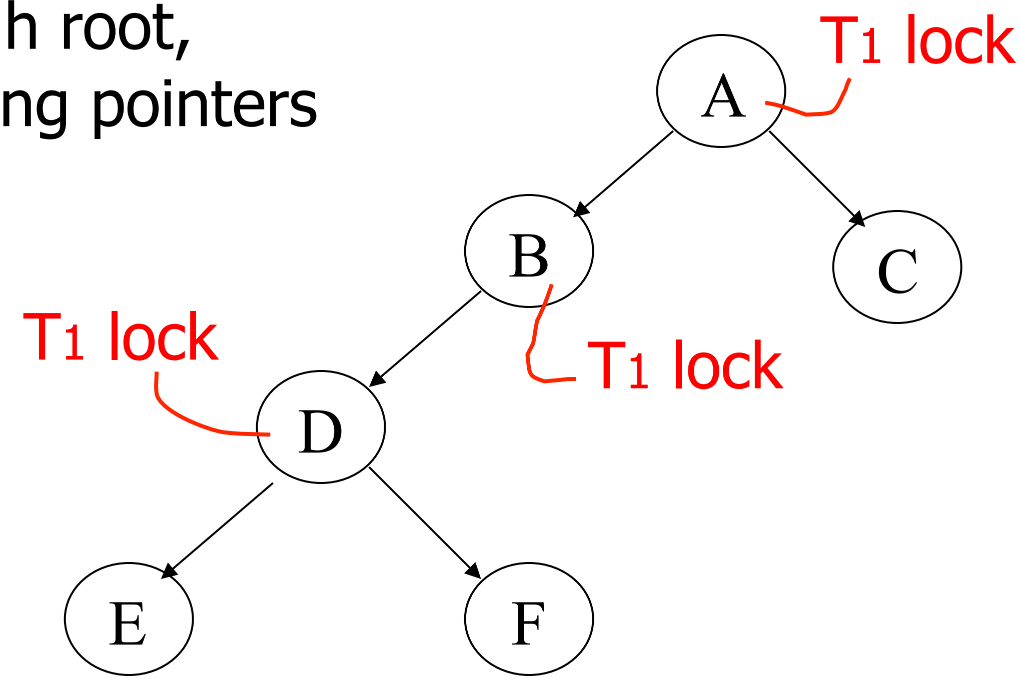
Example

- all objects accessed through root, following pointers



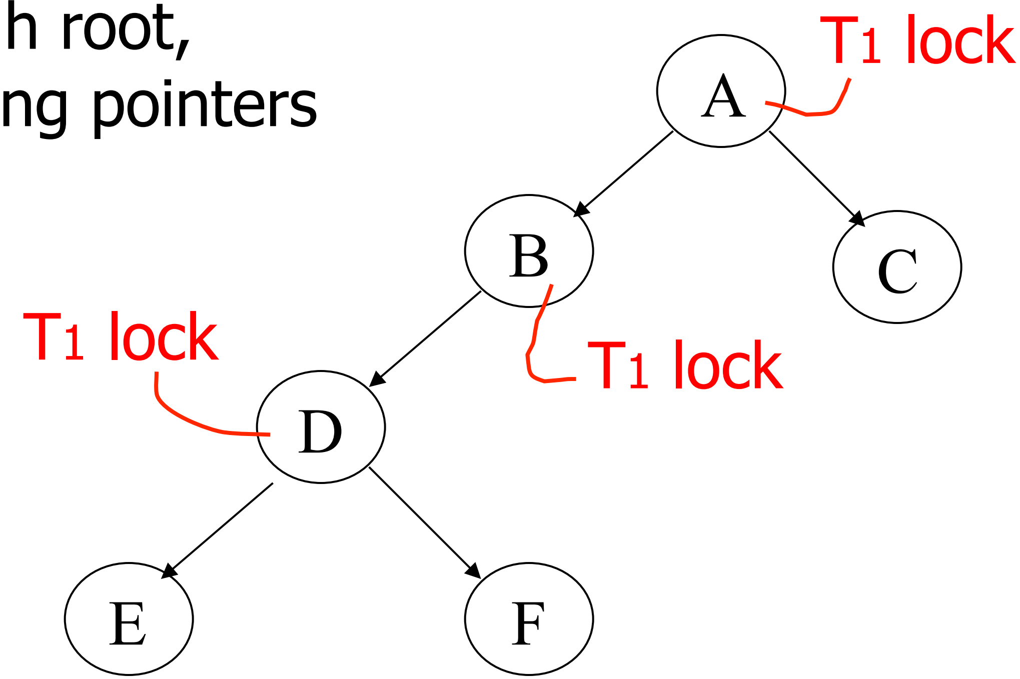
Example

- all objects accessed through root, following pointers



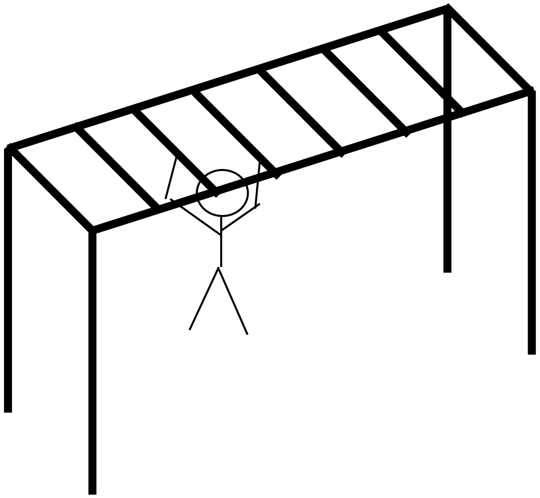
Example

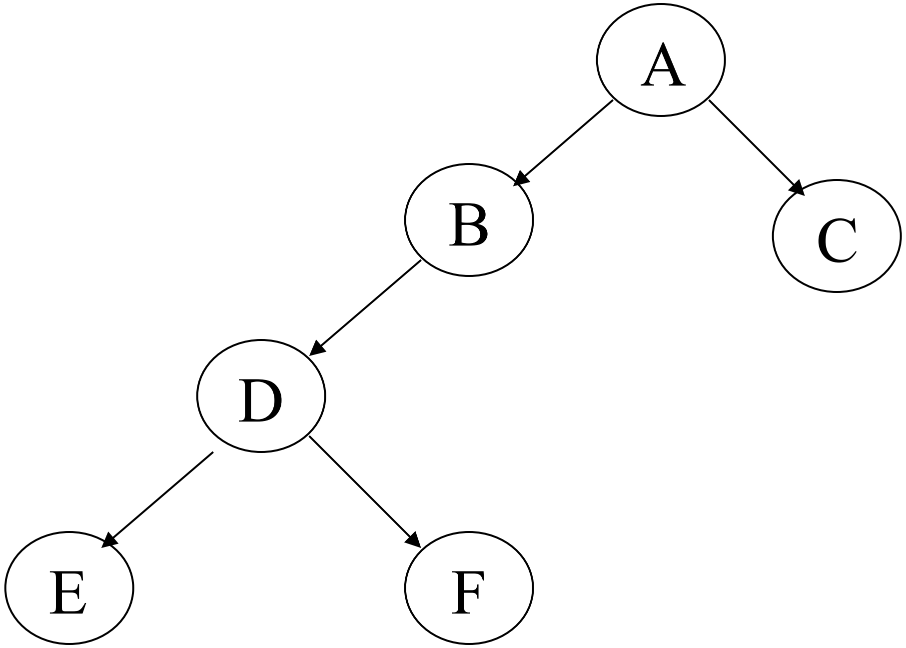
- all objects accessed through root, following pointers



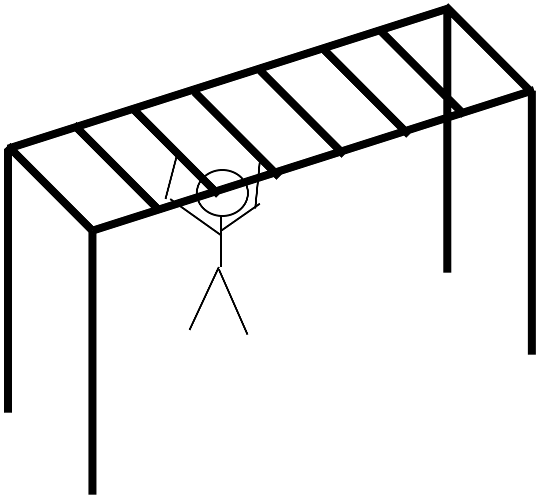
☛ can we release A lock if we no longer need A??

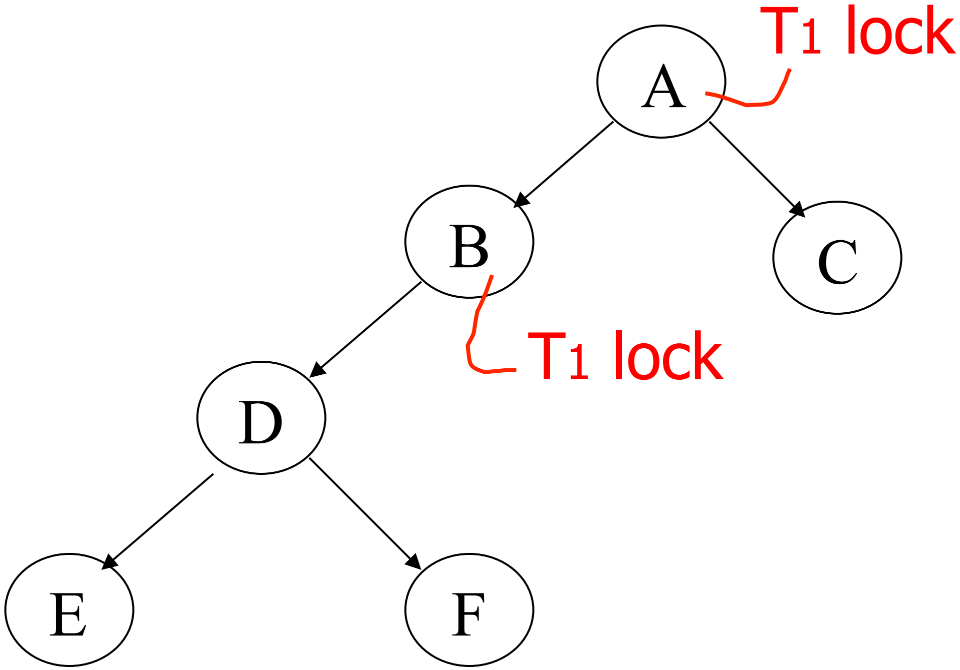
Idea: traverse like "Monkey Bars"



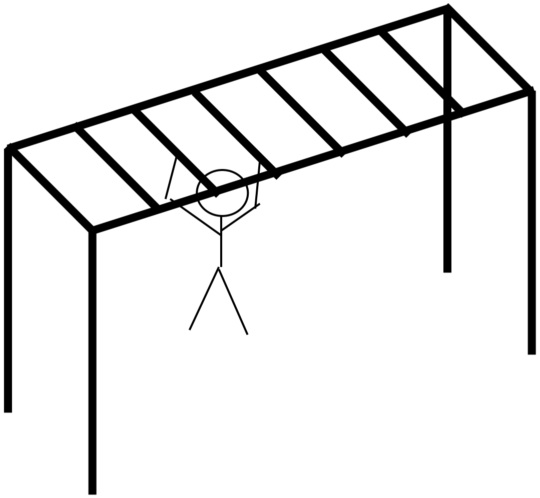


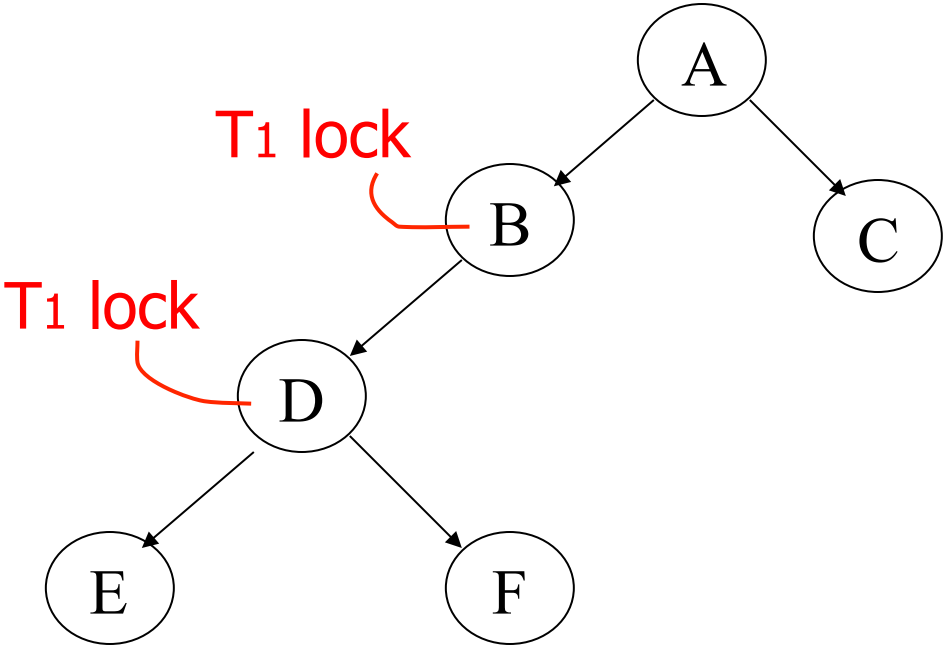
Idea: traverse like "Monkey Bars"





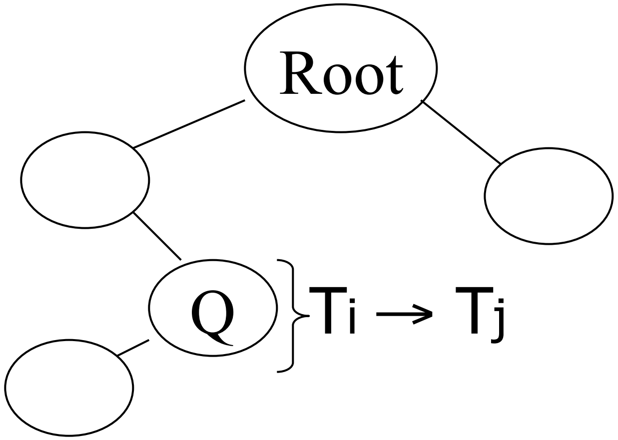
Idea: traverse like "Monkey Bars"





Why does this work?

- Assume all T_i start at root; exclusive lock
- $T_i \rightarrow T_j \Rightarrow T_i$ locks root before T_j



- Actually works if we don't always
  start at root

Rules: tree protocol (exclusive locks)

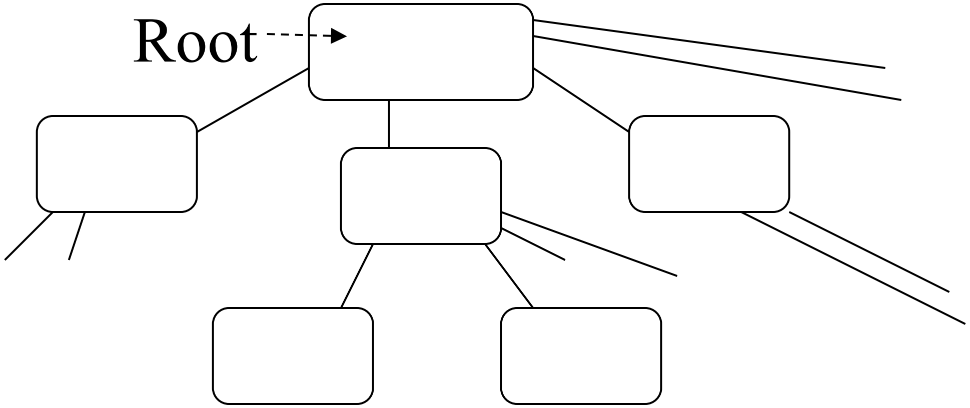
(1) First lock by T_i may be on any item

(2) After that, item Q can be locked by T_i only if parent(Q) locked by T_i

(3) Items may be unlocked at any time

(4) After T_i unlocks Q, it cannot relock Q

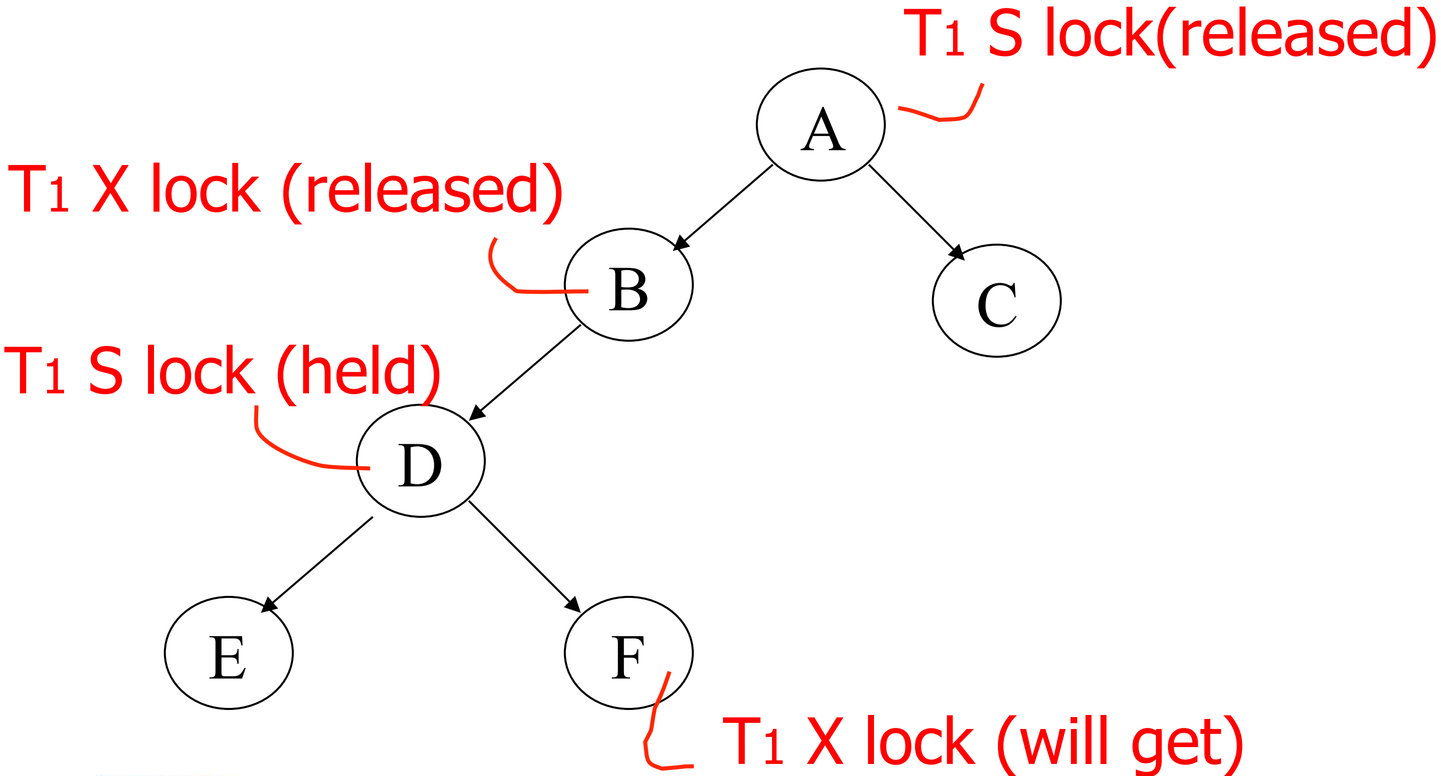
- Tree-like protocols are used typically for B-tree concurrency control



E.g., during insert, do not release parent lock, until you are certain child does not have to split

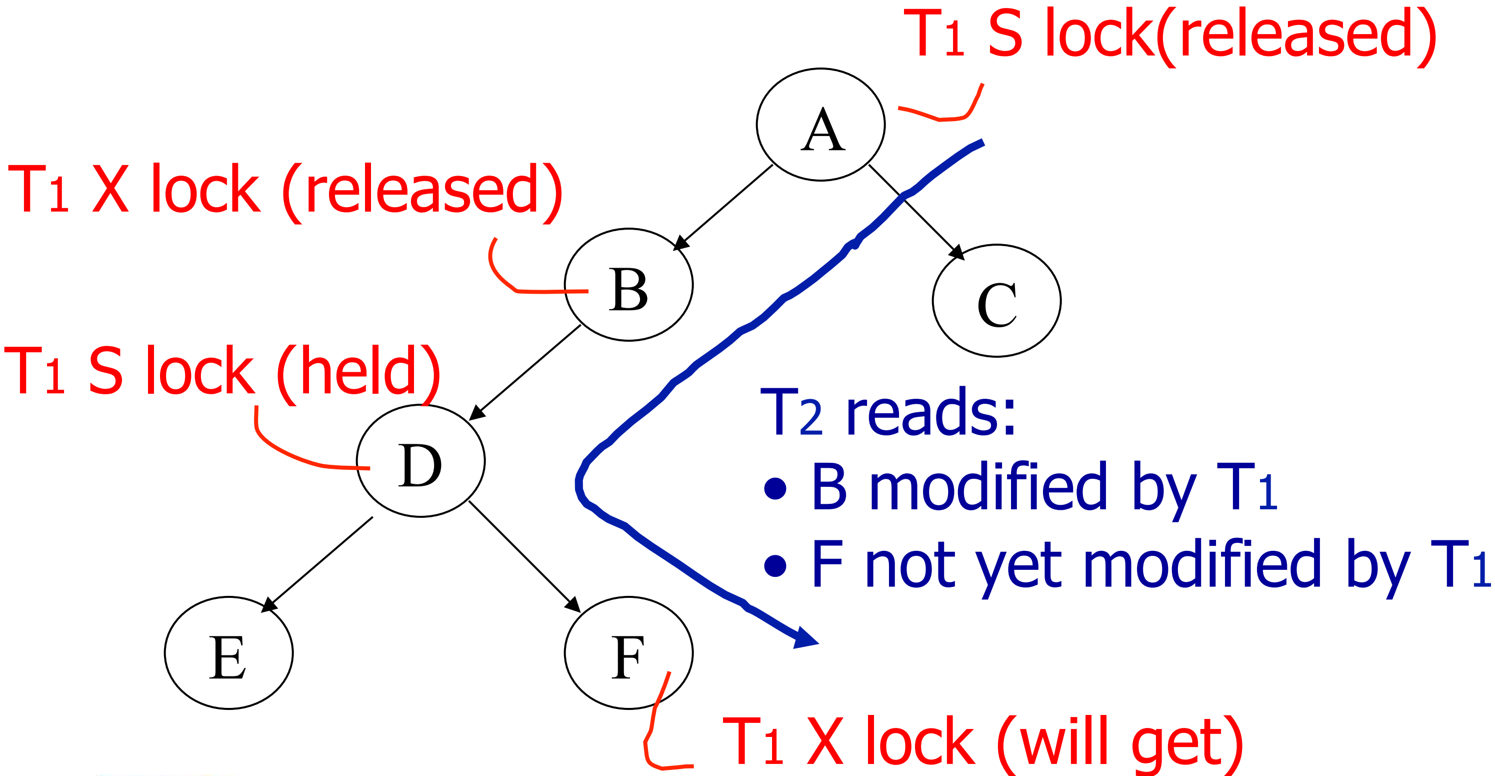
Tree Protocol with Shared Locks

- Rules for shared & exclusive locks?



Tree Protocol with Shared Locks

- Rules for shared & exclusive locks?



T2 reads:

- B modified by T1
- F not yet modified by T1

Tree Protocol with Shared Locks

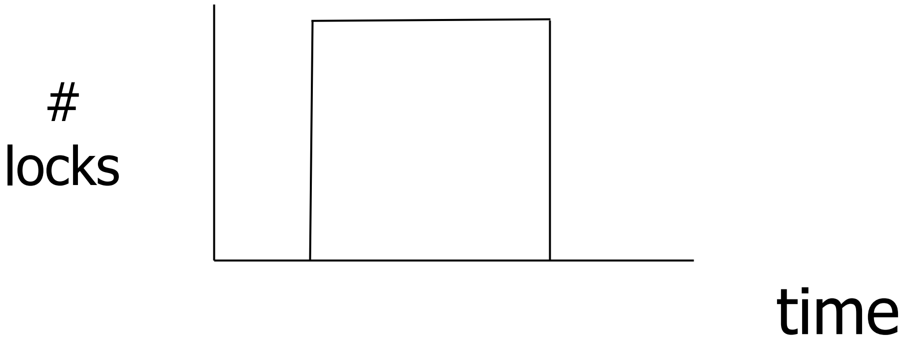
- Need more restrictive protocol
- Will this work??
  - Once T_1 locks one object in X mode, all further locks down the tree must be in X mode

Deadlocks (again)

- Before we assumed that we are able to detect deadlocks and resolve them
- Now two options
  - (1) Deadlock detection (and resolving)
  - (2) Deadlock prevention

Deadlock Prevention

- Option 1:
  - 2PL + transaction has to acquire all locks at transaction start following a global order



Deadlock Prevention

- Option 1:
  - Long lock durations ☹
  - Transaction has to know upfront what data items it will access ☹
    - E.g.,

      UPDATE R **SET** a = a + 1 **WHERE** b < 15
    - We don’t know what tuples are in R!

Deadlock Prevention

- Option 2:
  - Define some global order of data items O
  - Transactions have to acquire locks according to this order
- Example (X < Y < Z)

$l_1(X), l_1(Z)$ (OK)

$l_1(Y), l_1(X)$ (NOT OK)

Deadlock Prevention

- Option 2:
  - – Accessed data items have to be known upfront ☹
  - – or access to data has to follow the order ☹

Deadlock Prevention

- Option 3 (**Preemption**)
  - Roll-back transactions that wait for locks under certain conditions
  - 3 a) **wait-die**
    - Assign timestamp to each transaction
    - If transaction T_i waits for T_j to release a lock
      - Timestamp $T_i < T_j$ -> wait
      - Timestamp $T_i > T_j$ -> roll-back T_i

Deadlock Prevention

- Option 3 (**Preemption**)
  - Roll-back transactions that wait for locks under certain conditions
  - 3 a) **wound-wait**
    - Assign timestamp to each transaction
    - If transaction T_i waits for T_j to release a lock
      - Timestamp $T_i < T_j$ -> roll-back T_j
      - Timestamp $T_i > T_j$ -> wait

Deadlock Prevention

- Option 3:
  - Additional transaction roll-backs ☹

Timeout-based Scheme

- Option 4:
  - After waiting for a lock longer than X, a transaction is rolled back

Timeout-based Scheme

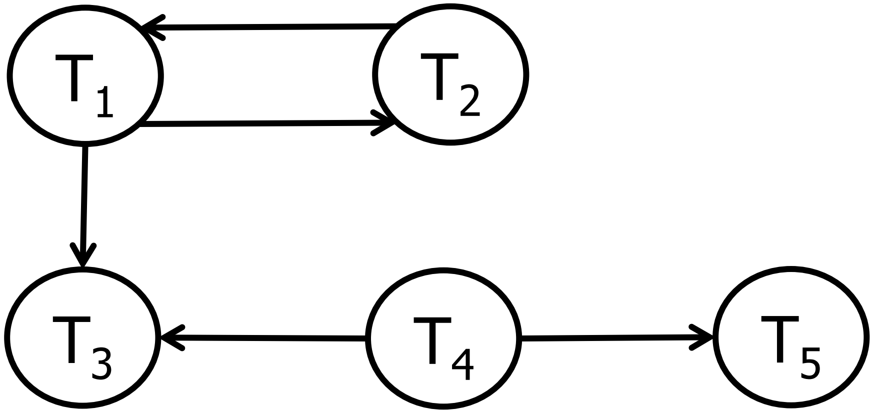
- Option 4:
  - Simple scheme ☺
  - Hard to find a good value of X
    - To high: long wait times for a transaction before it gets eventually aborted
    - To low: to many transaction that are not deadlock get aborted

Deadlock Detection and Resolution

- Data structure to detect deadlocks: **wait-for** graph
  - One node for each transaction
  - Edge T_i->T_j if T_i is waiting for T_j
  - Cycle -> Deadlock
    - Abort one of the transaction in cycle to resolve deadlock

Deadlock Detection and Resolution

- When do we run the detection?
- How to choose the victim?



Optimistic Concurrency Control: Validation

Transactions have 3 phases:

(1) Read

- all DB values read
- writes to temporary storage
- no locking

(2) Validate

- check if schedule so far is serializable

(3) Write

- if validate ok, write to DB

Key idea

- Make validation atomic
- If $T_1, T_2, T_3, \ldots$ is validation order, then resulting schedule will be conflict equivalent to $S_s = T_1\, T_2\, T_3 \ldots$

To implement validation, system keeps <u>two sets</u>:

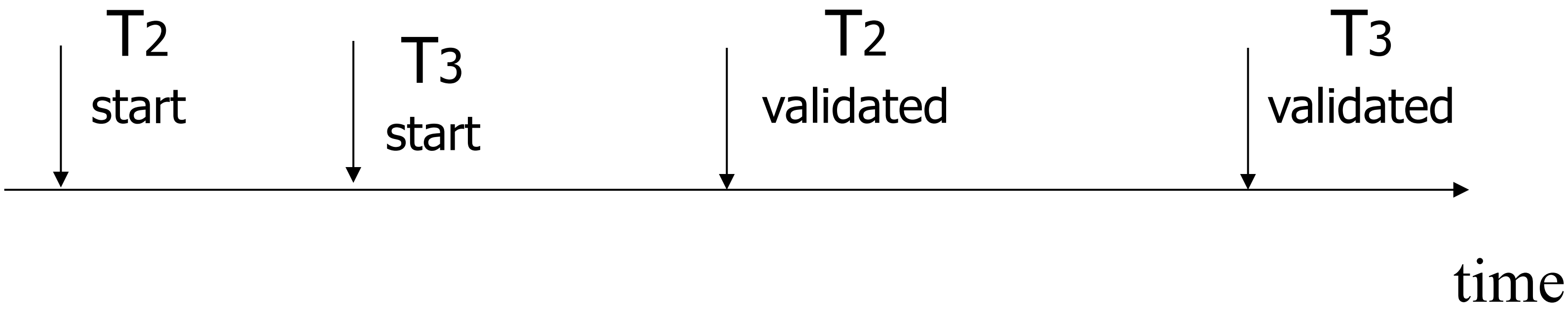
- <u>FIN</u> = transactions that have finished phase 3 (and are all done)
- <u>VAL</u> = transactions that have successfully finished phase 2 (validation)

Example of what validation must prevent:

$RS(T_2)=\{B\}$

$WS(T_2)=\{B,D\} \cap RS(T_3)=\{A,B\} \neq \phi$

$WS(T_3)=\{C\}$



T2 start

T3 start

T2 validated

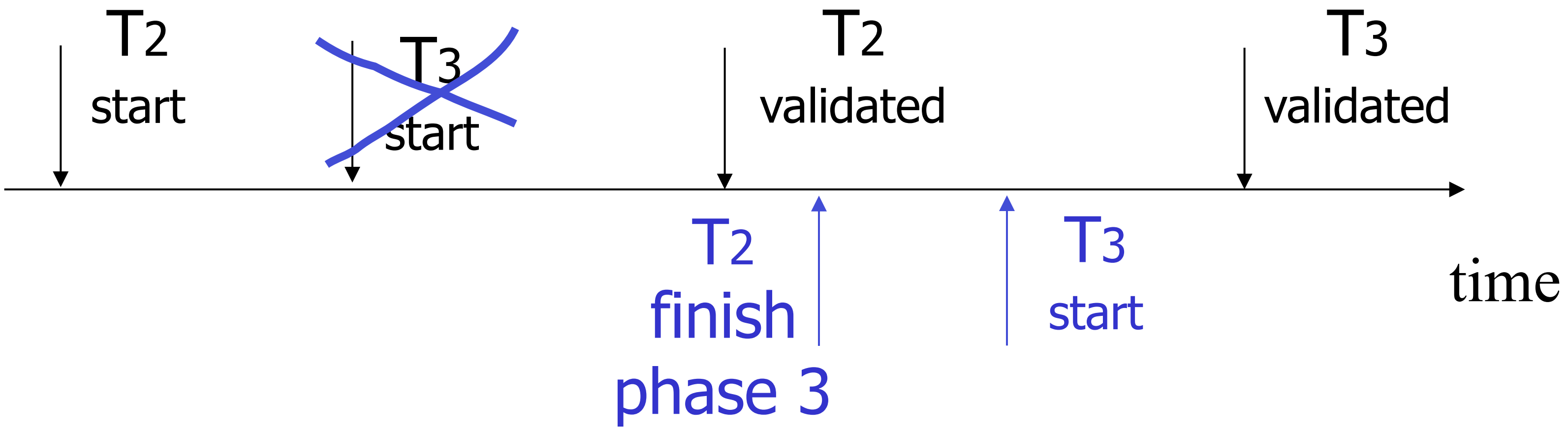
T3 validated

time

Example of what validation must allow ~~prevent~~:

$RS(T_2)=\{B\}$ $\cap$ $RS(T_3)=\{A,B\} \neq \phi$

$WS(T_2)=\{B,D\}$ $WS(T_3)=\{C\}$



T_2 start

~~T_3 start~~

T_2 validated

T_3 validated

T_2 finish phase 3

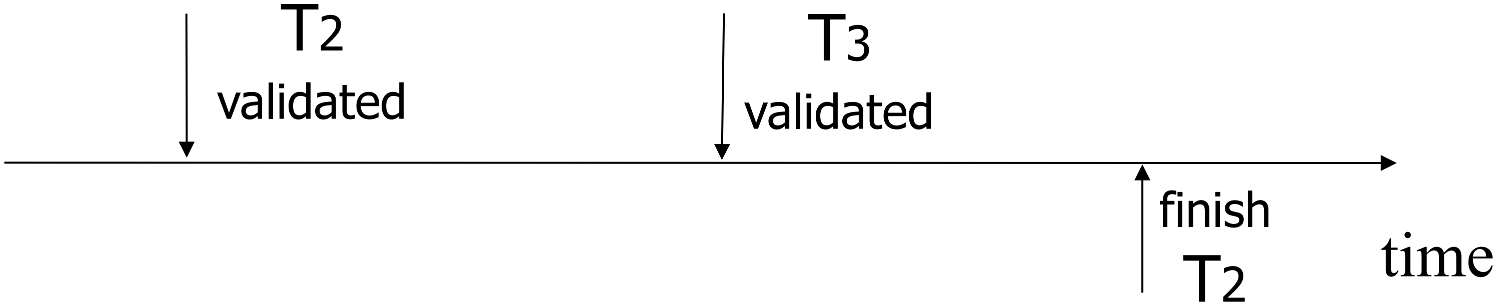
T_3 start

time

Another thing validation must prevent:

$RS(T_2)=\{A\}$ $RS(T_3)=\{A,B\}$

$WS(T_2)=\{D,E\}$ $WS(T_3)=\{C,D\}$



Another thing validation must prevent:

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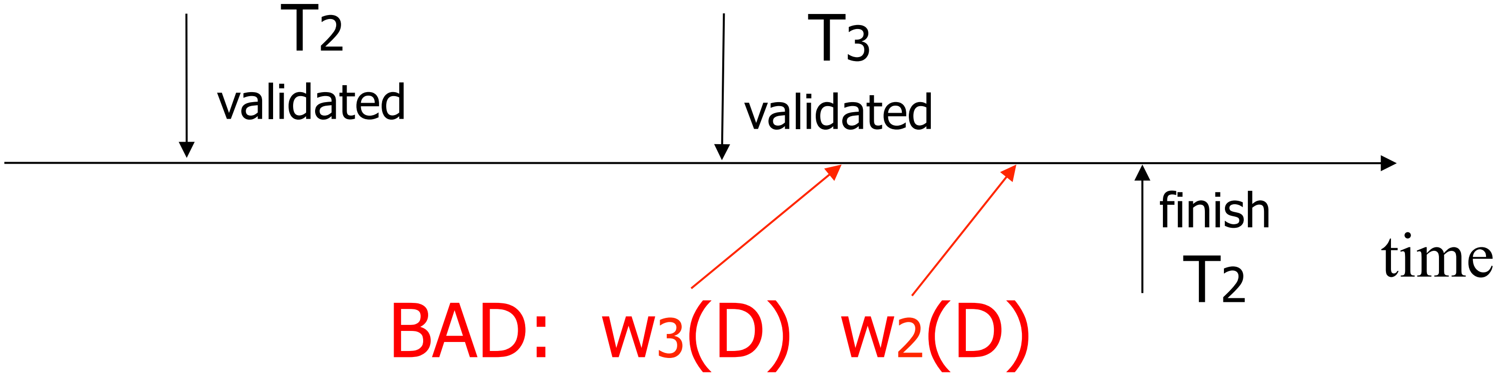


T_2 validated

T_3 validated

finish T_2

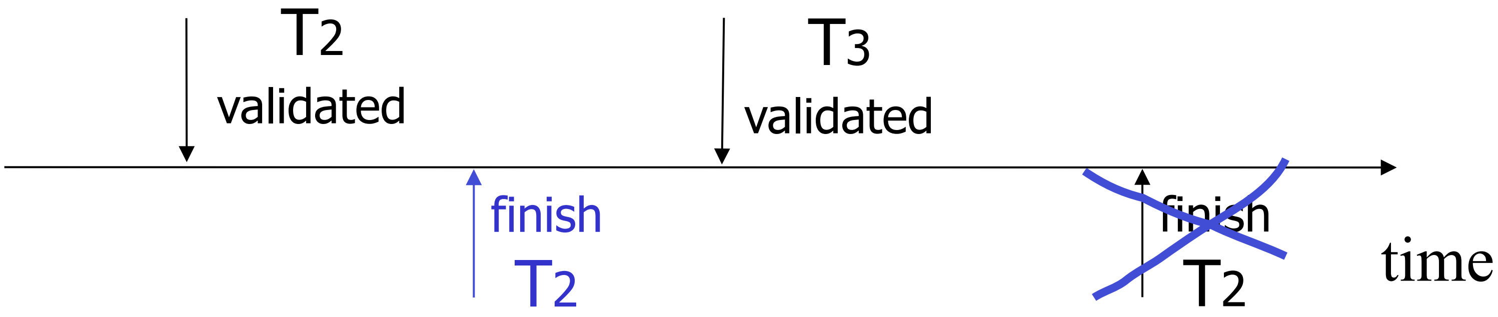
time

BAD: $w_3(D)$ $w_2(D)$

Another thing validation must ~~prevent~~ allow:

$RS(T_2)=\{A\}$ $RS(T_3)=\{A,B\}$

$WS(T_2)=\{D,E\}$ $WS(T_3)=\{C,D\}$



Validation rules for T_j:

(1) When T_j starts phase 1:

```
    ignore($T_j$) ← FIN
```

(2) at T_j Validation:

```
        if check ($T_j$) then
            [ VAL ← VAL U {$T_j$};
              do write phase;
              FIN ← FIN U {$T_j$} ]
```

```
Check ($T_j$):
    For $T_i \in$ VAL - IGNORE ($T_j$)  DO
            IF [ $WS(T_i) \cap RS(T_j) \neq \emptyset$ OR
      $T_i \notin$ FIN ] THEN RETURN false;
    RETURN true;
```

Check (T_j):

```
For $T_i \in VAL - IGNORE(T_j)$ DO
    IF [ $WS(T_i) \cap RS(T_j) \neq \emptyset$ OR
  $T_i \notin FIN$ ] THEN RETURN false;
RETURN true;
```

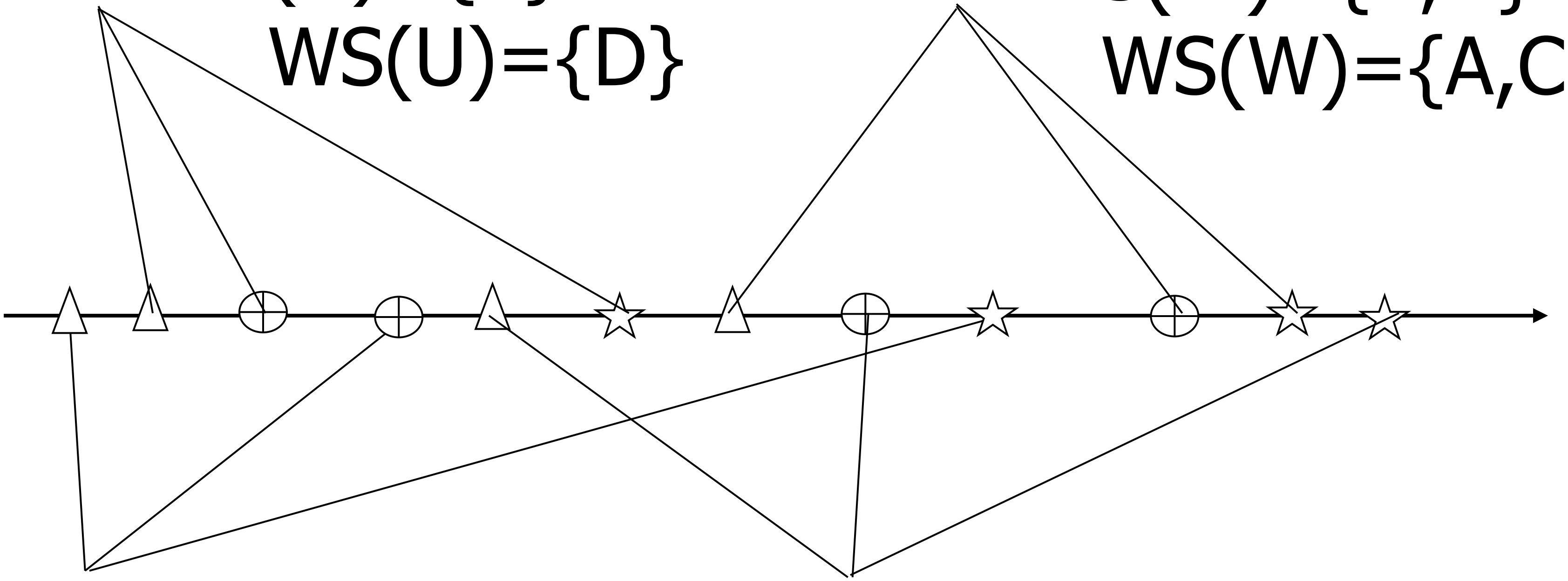
Is this check too restrictive ?

Improving Check(T_j)

```
For $T_i \in VAL - IGNORE(T_j)$ DO
    IF [ $WS(T_i) \cap RS(T_j) \neq \emptyset$ OR
        $(T_i \notin FIN$ AND $WS(T_i) \cap WS(T_j) \neq \emptyset)$]
            THEN RETURN false;
RETURN true;
```

Exercise:

△ start
⊕ validate
☆ finish



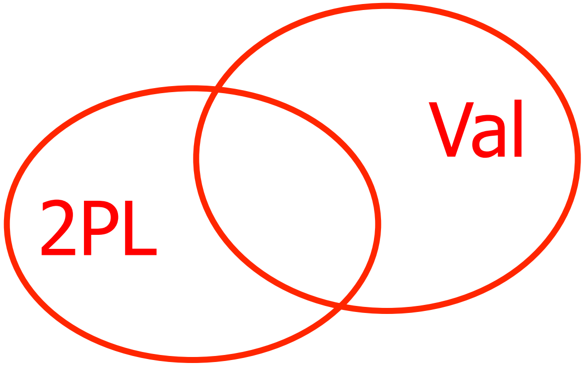
U: RS(U)={B}
WS(U)={D}

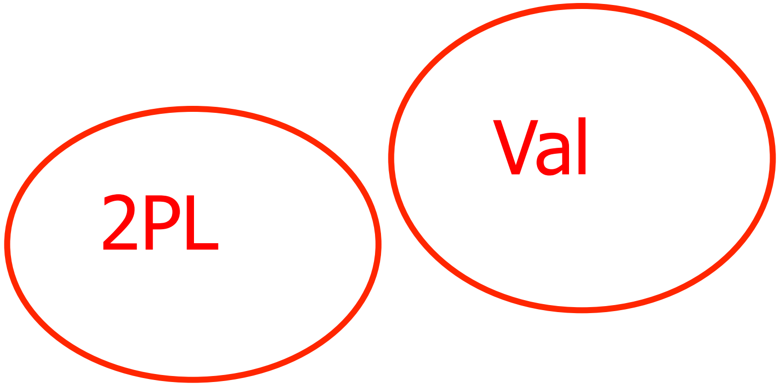
W: RS(W)={A,D}
WS(W)={A,C}

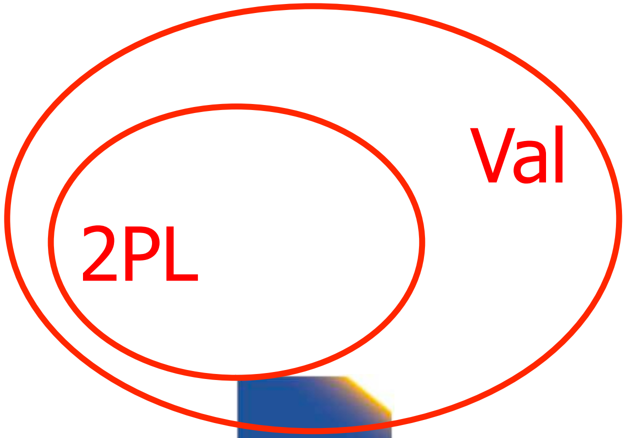
T: RS(T)={A,B}
WS(T)={A,C}

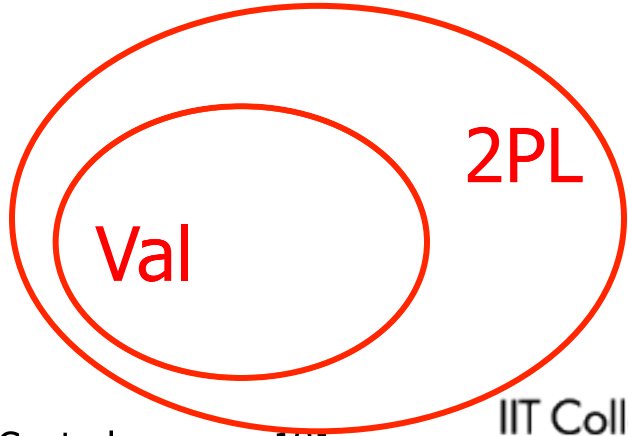
V: RS(V)={B}
WS(V)={D,E}

Is Validation = 2PL?









S2: w2(y) w1(x) w2(x)

- S2 can be achieved with 2PL:
  l2(y) w2(y) l1(x) w1(x) u1(x) l2(x) w2(x) u2(y) u2(x)
- S2 cannot be achieved by validation:
  The validation point of T2, val2 must occur before w2(y) since transactions do not write to the database until after validation. Because of the conflict on x, val1 < val2, so we must have something like
  S2: val1 val2 w2(y) w1(x) w2(x)
  With the validation protocol, the writes of T2 should not start until T1 is all done with its writes, which is not the case.

Validation subset of 2PL?

- Possible proof (Check!):
  - Let S be validation schedule
  - For each T in S insert lock/unlocks, get S’:
    - At T start: request read locks for all of RS(T)
    - At T validation: request write locks for WS(T); release read locks for read-only objects
    - At T end: release all write locks
  - Clearly transactions well-formed and 2PL
  - Must show S’ is legal (next page)

- Say S' not legal:
  S' : … l1(x) w2(x) r1(x) val1 u2(x) …
  - At val1: T2 not in Ignore(T1); T2 in VAL
  - T1 does not validate: WS(T2) ∩ RS(T1) ≠ ∅
  - contradiction!
- Say S' not legal:
  S' : … val1 l1(x) w2(x) w1(x) u2(x) …
  - Say T2 validates first (proof similar in other case)
  - At val1: T2 not in Ignore(T1); T2 in VAL
  - T1 does not validate:
    T2 ∉ FIN AND WS(T1) ∩ WS(T2) ≠ ∅)
  - contradiction!

Validation (also called **optimistic concurrency control**) is useful in some cases:

- Conflicts rare
- System resources plentiful
- Have real time constraints

Multiversioning Concurrency Control (MVCC)

- Keep old versions of data item and use this to increase concurrency
- Each write creates a new version of the written data item
- Use version numbers of timestamps to identify versions

Multiversioning Concurrency Control (MVCC)

- **Different transactions** operate over **different versions** of data items
- -> readers never have to wait for writers
- -> great for combined workloads
  - **OLTP** workload (writes, only access small number of tuples, short)
  - **OLAP** workload (reads, access large portions of database, long running)

MVCC schemes

- MVCC timestamp ordering
- MVCC 2PL
- Snapshot isolation (SI)
  - We will only cover this one

Snapshot Isolation (SI)

- Each transaction **T** is assigned a timestamp **S(T)** when it starts
- Each write creates a new data item version timestamped with the current timestamp
- When a transaction commits, then the latest versions created by the transaction get a timestamp **C(T)** as of the commit

Snapshot Isolation (SI)

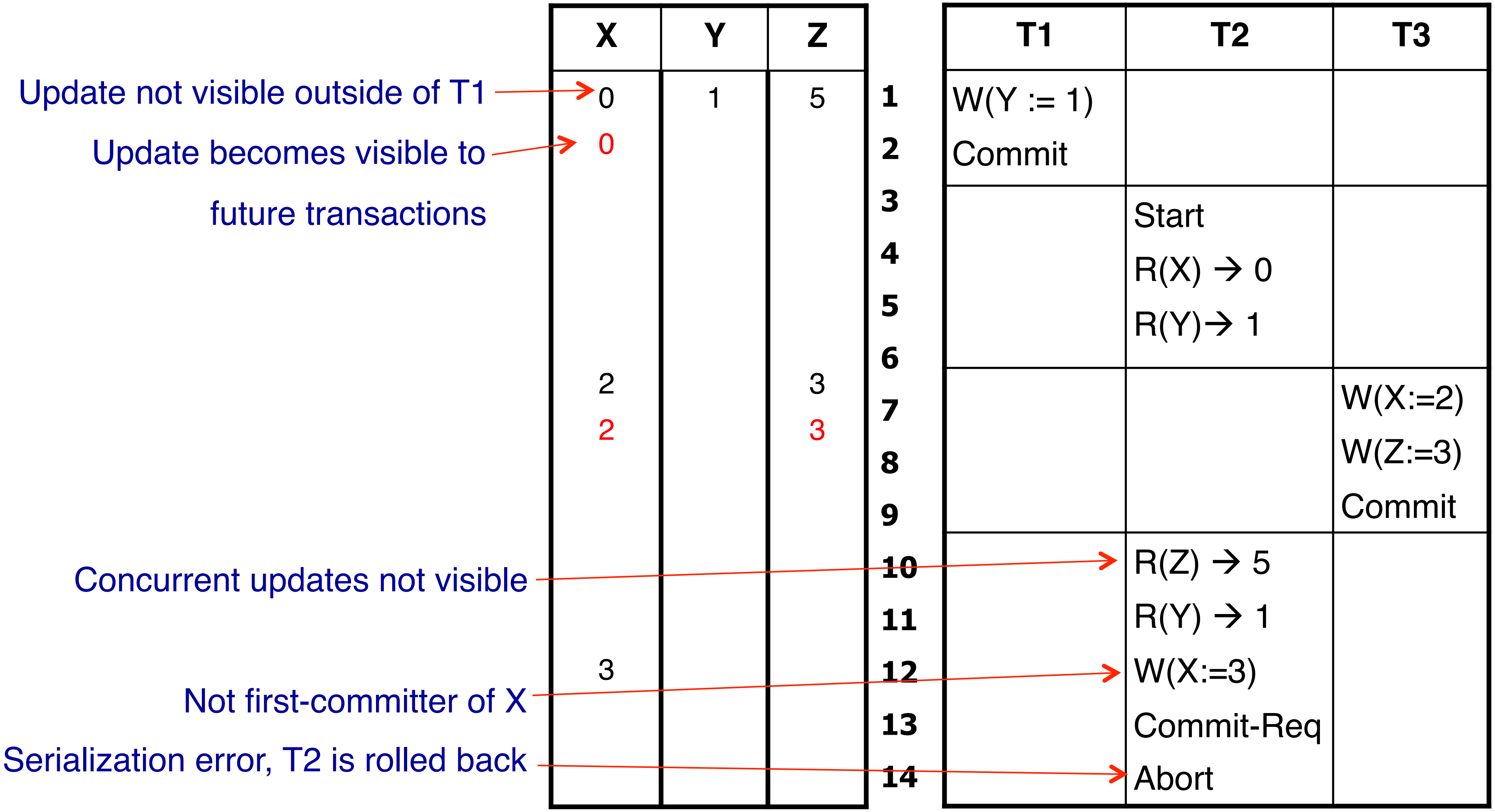
- Under snapshot isolation each transaction T sees a consistent snapshot of the database as of S(T)
  - It only sees data item versions of transactions that committed before T started
  - It also sees its own changes

First Updater Wins Rule (FUW)

- Two transactions Ti and Tj may update the same data item A
  - To avoid lost updates only one of the two can be safely committed
- **First Updater Wins Rules**
  - The transaction that updated A first is allowed to commit
  - The other transaction is aborted

First Committer Wins Rule (FCW)

- Two transactions Ti and Tj may update the same data item A
  - To avoid lost updates only one of the two can be safely committed
- **First Committer Wins Rules**
  - The transaction that attempts to commit first is allowed to commit
  - The other transaction is aborted



X	Y	Z		T1	T2	T3
0	1	5	**1**	W(Y := 1)		
0			**2**	Commit		
			3		Start	
			4		R(X) → 0	
			5		R(Y)→ 1	
			6			
2		3	**7**			W(X:=2)
2		3	**8**			W(Z:=3)
			9			Commit
			10		R(Z) → 5	
			11		R(Y) → 1	
3			**12**		W(X:=3)	
			13		Commit-Req	
			14		Abort	

Update not visible outside of T1

Update becomes visible to future transactions

Concurrent updates not visible

Not first-committer of X

Serialization error, T2 is rolled back

Why does that work?

- Since all transactions see a consistent snapshot and their changes are only made "public" once they commit
  - It looks like the transactions have been executed in the order of their commits*

* Recall the writes to the same data item are disallowed for concurrent transactions

Is that serializable?

- Almost ;-)
- There is still one type of conflict which cannot occur in serialize schedules called **write-skew**

Write Skew

- Consider two data items A and B
  - A = 5, B = 5
- Concurrent Transactions T1 and T2
  - T1: A = A + B
  - T2: B = A + B
- Final result under SI
  - A = 10, B = 10

Write Skew

- Consider serial schedules:
  - T1, T2: A=10, B=15
  - T2, T1: A=15, B=10
- What is the problem
  - Under SI both T1 and T2 do not see each others changes
  - In any serial schedule one of the two would see the others changes

Example: Oracle

- Tuples are updated in place
- Old versions in separate ROLLBACK segment
  - GC once nobody needs them anymore
- How to implement the FCW or FUW?
  - Oracle uses write locks to block concurrent writes
  - Transaction waiting for a write lock aborts if transaction holding the lock commits

SI Discussion

- Advantages
  - Readers and writers do not block each other
  - If we do not GC old row versions we can go back to previous versions of the database -> Time travel
    - E.g., show me the customer table as it was yesterday
- Disadvantages
  - Storage overhead to keep old row versions
  - GC overhead
  - Not strictly serializable

Summary

Have studied CC mechanisms used in practice

- 2 PL variants
- Multiple lock granularity
- Deadlocks
- Tree (index) protocols
- Optimistic CC (Validation)
- Multiversioning Concurrency Control (MVCC)