THE UNIVERSITY of EDINBURGH

Advanced Database Systems

Spring 2024

Lecture #29:

Revision I

1

Administrivia

New quiz deadline: **Thursday, 11 April at noon**

Last tutorial is this week

Final exam

- Topics covered in the lectures and tutorials, excluding guest lecture from week 10
- 6-8 questions, all mandatory
- Can use a calculator

2

Plan for Today

Files, Pages, Records

Buffer Management

Sorting

Joins

3

Files, Pages, Records

Tables stored as **logical files** consisting of **pages,** each containing a collection of **records**

File (corresponds to a table)

- Page (many per file)
  - Record (many per page)

The unit of access to physical disk is the page

- 1 I/O = read or write 1 page

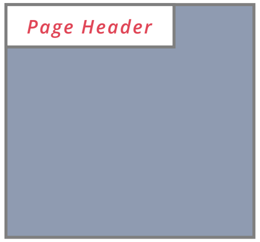
4

Page Basics

The **page header** keeps track of the records in the page

The page header may contain fields such as:

- Number of records in the page
- Pointer to segment of free space in the page
- Bitmap indicating which parts of the page are in use

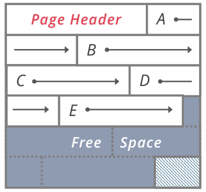


Page

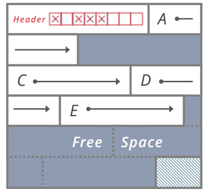
Fixed-Length Records

Fixed-length records = record lengths are fixed and field lengths are consistent

Packed Records: no gaps between records, record ID is location in page



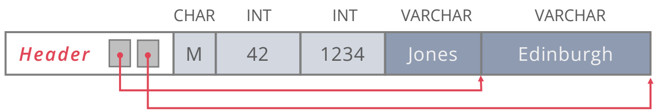
Unpacked Records: allow gaps between records, use a bitmap to keep track of where the gaps are



Variable-Length Records

Variable-length records may not have fixed & consistent field lengths

We can store variable-length records with an array of field offsets:



- Each record contains a **record header**
- Variable length fields are placed *after* fixed length fields
- Record header stores **field offset** (where variable length field ends)

Question 1

Consider the following relation:

- Assume record header stores only pointers (4B) to variable-length fields

```
CREATE TABLE Customer (
  customer_id INTEGER PRIMARY KEY,
  age INTEGER NOT NULL,
  name VARCHAR(10) NOT NULL,
  address VARCHAR(20) NOT NULL
)
```

Record header size = ???

Min record size = ???

Max record size = ???

Question 1, Part 2

Consider the following relation:

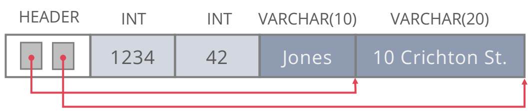
Assume record header stores only pointers (4B) to variable-length fields

```
CREATE TABLE Customer (
  customer_id INTEGER PRIMARY KEY,
  age INTEGER NOT NULL,
  name VARCHAR(10) NOT NULL,
  address VARCHAR(20) NOT NULL
)
```

Record header size = 8

Min record size = 16

Max record size = 46



Slotted Pages

Most common layout scheme is called **slotted pages**

Slot directory maps "slots" to the records' starting position offsets

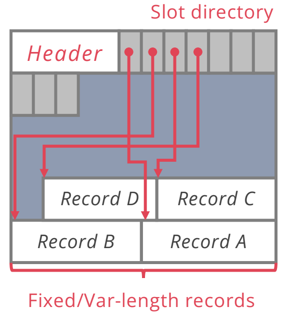
Record ID = (page ID, slot ID)

Header keeps track of:

The number of used slots

The offset of the last slot used

Records stored at the end of page



Question 2

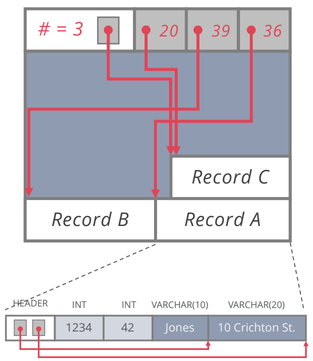
Suppose the Customer relation is stored using a slotted page layout

Page header stores the number of records and a pointer to free space

Directory slot stores a pointer and length

Page size is 8KB

Max number of records = ???



Question 2, Part 2

Suppose the Customer relation is stored using a slotted page layout

Page header stores the number of records and a pointer to free space (4B + 4B)

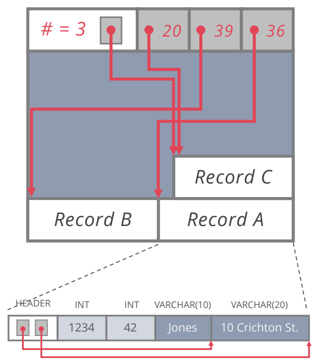
Directory slot stores a pointer and length (4B + 4B)

Page size is 8KB

Max number of records

= (page size – header size) / (min record size + slot size)

= (8192 – 8) / (16 + 8) = **341 records**



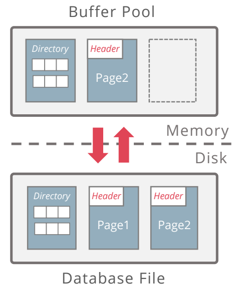
Buffer Management

Buffer Manager

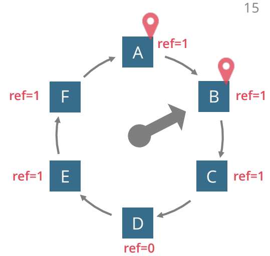
Layer that manages which pages are loaded in memory

Controls when pages are read from & written to disk

- When no space in memory, decides what page to **evict**
- Decision process is the **page replacement policy**
  - Big impact on I/Os depending on **access pattern**
- Common policies:
  - **LRU** (Least Recently Used)
  - **MRU** (Most Recently Used)
  - **Clock**



Clock



Efficient approximation of LRU

Arrange frames in a circle (like numbers on a clock)

Advance **clock hand** around the clock to find pages to evict

- Only do this if you need to evict a page

To make this approximate least recently *used* (rather than least recently *loaded*): add a **reference bit** to each frame

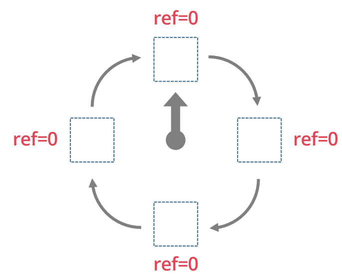
- Set to 1 on load/hit, 0 if clock hand passes the frame and the frame is unpinned
- Evict unpinned frame if clock hand reaches it and bit = 0
- (bit = 0 means less recently used than those with bit = 1)

Question 3

Page access sequence:

A B C D E B A D C A E C

Assume pages are immediately unpinned after being pinned



Buffer hits = **???**

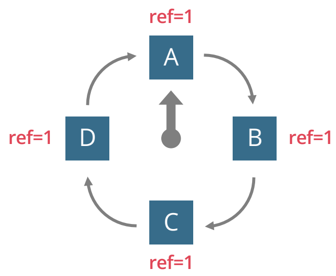
Question 3, Part 2

Page access sequence:

A B C D E B A D C A E C

Pages A, B, C, D populate the buffer pool

The clock hand stays still



Buffer hits (so far) = 0

Question 3, Part 3

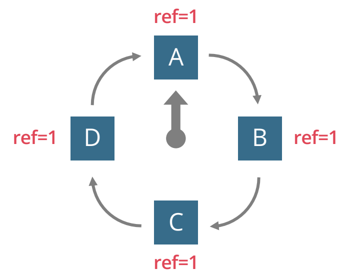
Page access sequence:

A B C D E B A D C A E C

Page E not present ⇒ buffer miss!

Find first frame with ref = 0

If ref = 1, unset it and move the hand



Buffer hits (so far) = 0

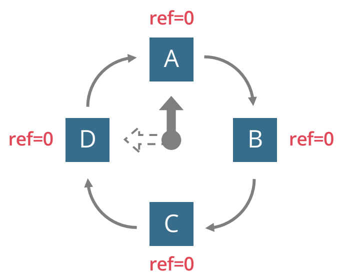
Question 3, Part 4

Page access sequence:

A B C D E B A D C A E C

Resets bits of A, B, C, D while moving the hand

First frame with ref = 0 holds A



Buffer hits (so far) = 0

Question 3, Part 5

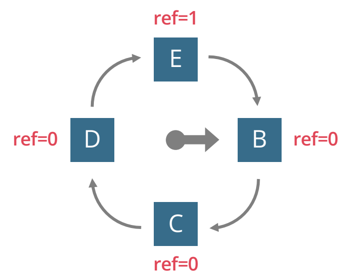
Page access sequence:

A B C D E B A D C A E C

Resets bits of A, B, C, D while moving the hand

First frame with ref = 0 holds A

Replace A with E, set reference bit, move the hand



Buffer hits (so far) = 0

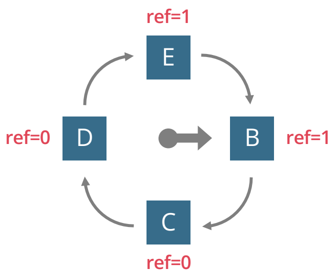
Question 3, Part 6

Page access sequence:

A B C D E B A D C A E C

Page B is present ⇒ buffer hit!

Set refence bit



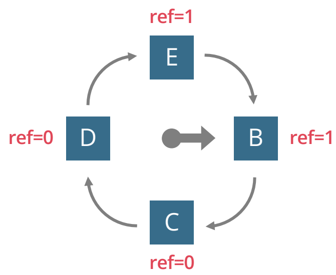
Buffer hits (so far) = 1

Question 3, Part 7

Page access sequence:

A B C D E B A D C A E C

Page A not present ⇒ buffer miss!



Buffer hits (so far) = 1

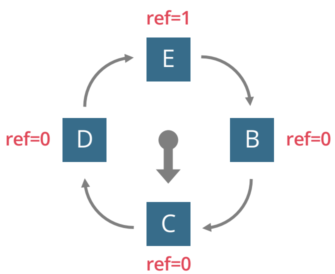
Question 3, Part 8

Page access sequence:

A B C D E B A D C A E C

Page A not present ⇒ buffer miss!

Unset refence bit for B, move the hand



Buffer hits (so far) = 1

Question 3, Part 9

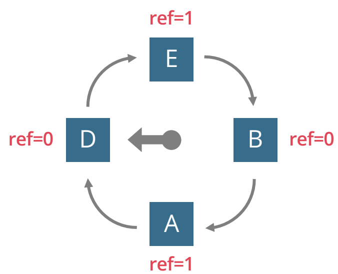
Page access sequence:

A B C D E B A D C A E C

Page A not present ⇒ buffer miss!

Unset refence bit for B, move the hand

Replace C with A, set refence bit, move the hand



Buffer hits (so far) = 1

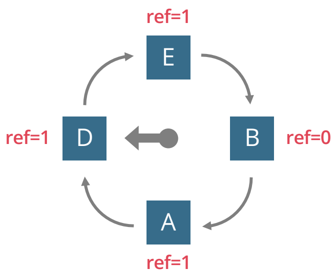
Question 3, Part 10

Page access sequence:

A B C D E B A D C A E C

Page D is present ⇒ buffer hit!

Set refence bit



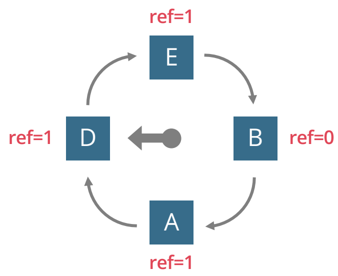
Buffer hits (so far) = 2

Question 3, Part 11

Page access sequence:

A B C D E B A D C A E C

Page C is not present ⇒ buffer miss!



Buffer hits (so far) = 2

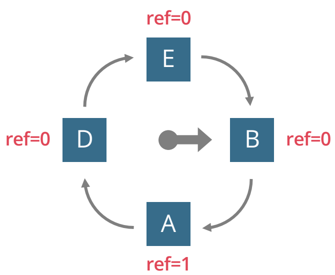
Question 3, Part 12

Page access sequence:

A B C D E B A D C A E C

Page C is not present ⇒ buffer miss!

Unset ref bits for D & E, move the hand to B



Buffer hits (so far) = 2

Question 3, Part 13

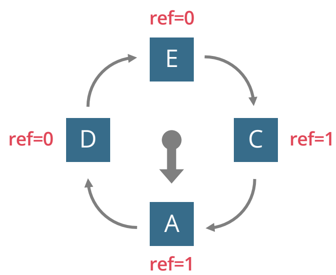
Page access sequence:

A B C D E B A D C A E C

Page C is not present ⇒ buffer miss!

Unset ref bits for D & E, move the hand to B

Replace B with C, set refence bit, move the hand



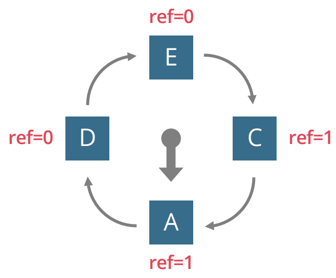
Buffer hits (so far) = 2

Question 3, Part 14

Page access sequence:

A B C D E B A D C **A** E C

Pages A, E, C are present ⇒ buffer hits!



Buffer hits (so far) = 2

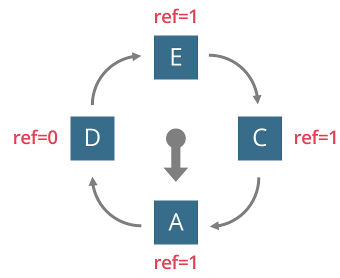
Question 3, Part 15

Page access sequence:

A B C D E B A D C A E C

Pages A, E, C are present ⇒ buffer hits!

Set their reference bits



Buffer hits = 5

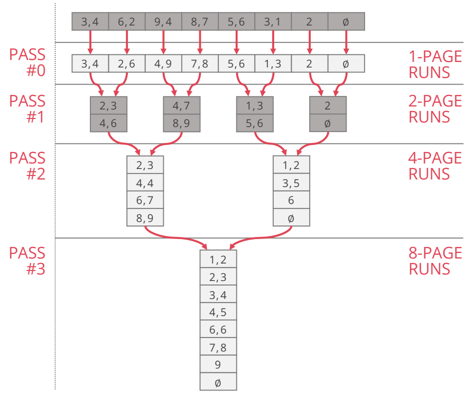
Sorting

Sorting

We first sort small amounts of data into **runs** of sorted tuples

Given runs of sorted tuples, we can **merge** them into 1 larger run of sorted tuples

- Same as in-memory merge sort
- Stream in the two runs and stream out the new run



General External Merge Sort

How many passes do we need?

- We sort B pages at once, so we have $\lceil N/B \rceil$ runs after Pass 0
- We merge B-1 pages at once, so we have to do $\lceil \log_{B-1}(\# \text{ runs}) \rceil$ merge passes
- So we have $1 + \lceil \log_{B-1} \lceil N/B \rceil \rceil$ passes over the data

I/O cost:

- Read and write each page per pass
- Total I/O cost = $2N \cdot (1 + \lceil \log_{B-1} \lceil N/B \rceil \rceil)$

General External Merge Sort

Number of passes = $1 + \lceil \log_{B-1} \lceil N/B \rceil \rceil$

How many pages can be sorted in P passes?

- Two passes can sort $B \cdot (B-1)$ pages
- Three passes can sort $B \cdot (B-1)^2$ pages
- P passes can sort $B \cdot (B-1)^{P-1}$ pages

Question 4

Suppose the page size is 4 KB and the buffer pool size is 1 MB

How many I/Os are required to sort a relation of size 800 KB?

What is the size of the largest relation that would need two passes to sort?

Question 4, Part 2

Suppose the page size is 4 KB and the buffer pool size is 1 MB

- B = 1024KB / 4KB = 256 pages

How many I/Os are required to sort a relation of size 800 KB?

- N = 800KB / 4KB = 200 pages
- The relation can completely fit into the buffer, so we only need to read it in, sort it (no I/Os required for sorting), then write the sorted pages back to disk. Total: **400 I/Os**.

What is the size of the largest relation that would need two passes to sort?

- Max number of pages: $B \cdot (B - 1)$ = 256 · 255 = 65,280
- Max relation size = 65,280 · 4KB = 261,120KB

Joins

Nested Loops Joins

Simple / Page / Block Nested Loop Joins:

(all pages of left table) + (number of passes of right table) * (all pages of right table)

Number of passes:

Simple: one per left row

Page: one per left page

Block: one per left block

Nested Loops Joins

Simple Nested Loops Join: **pages(R) + tuples(R) · pages(S)**

Page Nested Loops Join: **pages(R) + pages(R) · pages(S)**

Block Nested Loops Join: **pages(R) + ⌈pages(R) / (B – 2)⌉ · pages(S)**

where **B** is the number of available buffer pages

Index Nested Loops Join

Index Nested Loop Join: **pages(R) + tuples(R) · cost to find matching S tuples**

(all pages of left table) + (number of right index lookups) · (cost of right index lookup)

Cost to find matching S tuples:

Variant A: just cost to traverse root to leaf + read all the leaves with matching tuples

Variant B/C: cost of retrieving RIDs (similar to Variant A) + cost to fetch actual tuples

1 I/O per **page** if clustered, 1 I/O per **tuple** if not

Sort Merge Join

Sort Merge Join:

- Cost to sort R using external sorting +
  - Cost to sort S using external sorting +
    - pages(R) + pages(S)

Note that, if a relation is already sorted, we can exclude that cost

Sort Merge Join

Sort Merge Join optimisation: combine last sort pass with merging

Normally:

- Last sort pass:
  - Load runs R1, R2, R3 into buffers, merge into run R, stream (write) R to disk
  - Load runs S1,S2, S3 into buffers, merge into run S, stream (write) S to disk
- Merging:
  - Load run R and run S into buffers, merge into R ⋈ S

Sort Merge Join

Sort Merge Join optimisation: combine last sort pass with merging

Sort-merge join optimisation:

- Last sort pass:
  - Load runs R1, R2, R3 into buffers, ~~merge into run R, stream (write) R to disk~~
  - Load runs S1,S2, S3 into buffers, ~~merge into run S, stream (write) S to disk~~
- Merging:
  - ~~Load run R and run S into buffers~~, merge into R ⋈ S
- Note that in this example, previously we needed only 3 input buffers, but the optimized version needed 6 input buffers!

Sort Merge Join

Sort Merge Join optimisation: combine last sort pass with merging

Sort-merge join optimisation:

- In general, this optimization is only possible if you happen to have enough buffers to stream **BOTH** last runs in memory
- You can also do a partial version where you finish sorting one table normally, then do the join with the runs of the unmerged table and the one run of the merged table
- You save 2 · (pages(R) + pages(S)) by doing this optimization
- The partial version saves either 2 · pages(R) or 2 · pages(S), depending on which table you wait to merge

Grace Hash Join

- Grace Hash Join: similar to external hash, but…
  - **Partitioning phase:** Partition ***R*** into ***B-1*** buckets and also ***S*** into ***B-1*** buckets
    - Recursively partition pairs of ***R*** and ***S*** partitions until one partition in a pair fits in ***B-2*** pages
  - **Joining phase:** for each pair of partitions where at least one is at most ***B-2*** pages,
    - Load smaller side (e.g., R) into memory, and make a hash table
    - Stream in pages of S ⟶ match against hash table ⟶ stream out matches
- Cost: Depends on the construction of the tables. It's similar to external hashing, but your parameters for stopping are different