CS 186 Spring 2021 Introduction to Database Systems

Final Exam

INSTRUCTIONS

This is your exam. Complete it either at exam.cs61a.org or, if that doesn't work, by emailing course staff with your solutions before the exam deadline.

This exam is intended for the student with email address `<EMAILADDRESS>`. If this is not your email address, notify course staff immediately, as each exam is different. Do not distribute this exam PDF even after the exam ends, as some students may be taking the exam in a different time zone.

For questions with **circular bubbles**, you should select exactly *one* choice.

- ◯ You must choose either this option
- ◯ Or this one, but not both!

For questions with **square checkboxes**, you may select *multiple* choices.

- ☐ You could select this choice.
- ☐ You could select this one too!

You may start your exam now. Your exam is due at <DEADLINE> Pacific Time. Go to the next page to begin.

Preliminaries

1 CS W186 Spring 2021 Final

`Do not share this exam until solutions are released.`

1.0.1 Contents:

- The final has 10 questions, each with multiple parts, and worth a total of 164 points.

1.0.2 Taking the exam:

- You have 170 minutes to complete the midterm.
- You may print this exam to work on it.
- For each question, submit only your final answer on Examtool.
- For numerical answers, do not input any suffixes (i.e. if your answer is 5 I/Os, only input 5 and not 5 I/Os or 5 IOs).
- Make sure to save your answers in Examtool at the end of the exam, although the website should autosave your answers as well.

1.0.3 Aids:

- You may use three pages (double sided) of handwritten notes as well as a calculator.
- You must work individually on this exam.

1.0.4 Grading Notes:

- All I/Os must be written as integers. There is no such thing as 1.02 I/Os – that is actually 2 I/Os.
- 1 KB = 1024 bytes. We will be using powers of 2, not powers of 10
- Unsimplified answers, like those left in log format, will receive a point penalty.

(a) What is your full name?

(b) What is your student ID number?

1. (16 points) Boba Trees

(a) (3 points) True or False

Mark all statements that are true.

i. (3 pt)

- [x] All paths from the root of a B+ tree to a leaf node will always pass through the same number of inner nodes.
- [x] Clustered Alternate 3 B+ trees are always at least as efficient as clustered Alternate 2 B+ trees in terms of I/O cost.
- [ ] A B+ tree with height h and fanout d will always have more than $(2d)(2d+1)^{(h-1)}$ keys.
- [ ] Having an index on a table makes inserts more efficient than inserts into a standard heap file.
- [ ] Alternate 2 B+ trees are useful for frequent full scans of a relation.
- [ ] Deleting a value from a B+ tree deletes it from any inner nodes it may be in as well.
- [ ] None of the above

A: True, B+ trees are self-balancing. B: True, Alternate 3 B+ trees are the same as Alternate 2 trees if there are no duplicates, and are more efficient if there are duplicates. C: False, B+ trees do not have to be completely full before splitting the root. D: False, Indices are more useful for reads, but are more costly for writes. E: False, Alternate 2 indices have more overhead for full scans. F: False, Inner nodes are never deleted.

(b) (9 points)

Up-and-coming boba store Boba Trees has a lot of information about their sales this year, and they want to use indices to speed up their queries.

Boba Trees has the following table `orders` containing information about their recent sales.

```
CREATE TABLE orders (
    sid INTEGER PRIMARY KEY,  // the sales id
    cid INTEGER,              // the customer id
    order TEXT,
    store_id INTEGER          // which of the store locations the order was at
);
```

We have 3 different indices on this table:

Index A:

- Alternative 2, clustered B+ Tree on `sid` with h = 2, d = 4
- There are 80 leaf nodes, all of which are full.
- The first record with `sid > 600` appears on the 70th leaf node (starting from the leftmost leaf node which is the 1st leaf node).

Index B:

- Alternative 3, unclustered B+ Tree on `store_id` with h = 2, d = 2
- There are 10 leaf nodes in total, and the first key with `store_id > 2` is on the second leaf node.

Index C:

- Alternative 3, unclustered B+ Tree on `cid` with h = 3, d = 3

Additional assumptions:

- The orders table has 100 data pages.
- There is exactly 1 record with cid = 50.
- There are 80 records with cid = 100.
- Assume that store_id has 20 unique values in the range [1,20], uniformly distributed.
- Each data page stores 20 records.

i. (1 pt) What is the maximum number of keys that Index A can hold?

648

D = 4, so the maximum number of values is $(8)(9)^2$

ii. (2 pt) Calculate the minimum possible I/O cost for the following query: `SELECT * FROM orders WHERE order = 'Jasmine Milk Tea';`

100

We don't have an index on order so it's most efficient to do a full scan, 100 pages so 100 I/Os.

iii. (2 pt) Calculate the minimum possible I/O cost for the following query: `SELECT * FROM orders WHERE cid = 50;`

5

Using Index C, it takes 4 IOs to get to the relevant leaf node (3 inner nodes + 1 leaf node), and 1 IO for the relevant data page.

iv. (2 pt) Calculate the minimum possible I/O cost for the following query: `SELECT * FROM orders WHERE cid = 100 AND sid > 600;`

18

Using Index A, it would take 18 IOs (2 inner nodes + 11 leaf nodes + 5 data pages). Since we have 11 leaf nodes * 8 keys per node = 88 keys to check and the index is clustered, we need to check ceil(88/20) = 5 data pages. Using Index C it would take 84 data pages(3 inner nodes, 1 leaf nodes, 80 data pages).

v. (2 pt) If we wanted to do a range scan on `store_id` to find out how many orders we had at locations with `store_id` > 2, which index should we use, if any? Explain your answer.

No index. Index B is not clustered, so you would incur far more I/Os doing an index scan rather than a full scan.

(c) (4 points) Bulkloading

Uh oh! Boba Trees had an electrical fire in their store and lost Index A. They want to use bulkloading to quickly reconstruct index A; that is, a B+ tree on `sid` with d = 4. Assuming for this problem only that `orders` now contains 900 records and they use a fill factor of 0.75, answer the following questions.

i. (2 pt) How many leaf nodes would the reconstructed tree have?

150

900 / (fill factor * number of values per leaf node) = 900 / (0.75 * 8) = 150.

ii. (2 pt) What is the minimum height of the reconstructed tree?

3

A tree of height 2 and d = 4 would only be able to have at most 81 leaf nodes; therefore the tree must be of at least height 3.

2. (10 points) Microtransactions and In-Game Concurrency

(a) (2 points) True or False

Mark all statements that are true.

i. (2 pt)

- ☐ In comparison to conflict serializability, view serializability is more efficient to check for complexity-wise.
- ☐ Locks help enforce the atomicity part of the ACID properties.
- ☐ The same graph can always be used for the conflict dependency graph and the waits-for graph.
- ■ An advantage of Strict 2PL over regular 2PL is the prevention of cascading aborts.
- ☐ None of the above

(b) (3 points) Two-Phase Locking

Analyze the following schedules, and identify whether they follow two-phase locking. You may assume that all actions taken by the transactions are valid, and that the last action in the schedule for a transaction is the last action that transaction will take before it commits.

i. (1 pt)

Transaction 1	Transaction 2
Obtain IX(database)	
	Obtain IX(database)
Obtain S(table 1)	
Release S(table 1)	
	Obtain X(table 1)
Obtain X(table 2)	
	Release X(table 1)
	Release IX(database)
Release X(table 2)	
Release IX(database)	

○ Follows 2PL

● Does not follow 2PL

Transaction 1 violates two-phase locking by obtaining an X lock on table 2 after releasing its lock on table 1.

ii. (1 pt)

Transaction 1	Transaction 2
Obtain IX(database)	
Obtain X(table 1)	
	Obtain IX(database)
Release X(table 1)	
	Obtain X(table 2)
Release IX(database)	
	Release X(table 2)
	Release IX(database)

● Follows 2PL

○ Does not follow 2PL

iii. (1 pt)

Transaction 1	Transaction 2
Obtain IS(database)	
Obtain S(table 1)	
Release S(table 1)	
Release IS(database)	
	Obtain IX(database)
	Obtain X(table 1)
	Release X(table 1)
	Release IX(database)

- [x] Follows 2PL
- [ ] Does not follow 2PL

Each individual transaction does not obtain any lock after it first releases a lock, thus being compliant with 2PL.

(c) (5 points) Deadlocks

Use the schedule of lock requests below to answer the following questions. Assume transactions hold onto any locks they obtain for the entire length of the schedule. If a transaction aborts, assume that it remains inactive for the remainder of the schedule. Also assume that priority is assigned by the time of first operation (earlier operation = higher priority).

Transaction	1	2	3	4	5	6	7	8	9	10
T1		S(A)				S(B)			X(D)	
T2	X(B)						S(C)			
T3			X(C)	X(A)				X(D)		
T4					S(D)					S(C)

i. (1 pt) What transactions are deadlocked in this schedule? If there are multiple deadlocks, mark the transactions in the deadlock that will happen first.

- [x] T1
- [x] T2
- [x] T3
- [ ] T4
- [ ] None of the above

T1 waits for T2 on resource B. T3 waits for T1 on resource A. T2 waits for T3 on resource C.

ii. (1 pt) Assuming no use of deadlock avoidance algorithms, do any of the transactions in this schedule complete?

- ○ Yes
- ● No

T4 is the only transaction not involved in the deadlock, but it needs to wait on resource C to become free before it can finish its work.

iii. (1 pt) Now assume that we use deadlock detection throughout the execution of the schedule. Which transaction should we abort to prevent further deadlocks for the rest of the schedule?

- ○ T1
- ○ T2
- ● T3
- ○ T4
- ○ None of the above

If T3 is allowed to continue, it will eventually get into a deadlock with T4. Aborting T3 prevents this deadlock from happening.

iv. (1 pt) Now assume that we use wait-die deadlock avoidance. Which transactions are aborted?

- [x] T1
- [ ] T2
- [x] T3
- [ ] T4
- [ ] None of the above

T3 will abort when it tries to wait for T1 on resource A. T1 will abort when it tries to wait for T2 on resource B.

v. (1 pt) Now assume that we use wound-wait deadlock avoidance. Which transactions are aborted?

- [ ] T1
- [ ] T2
- [x] T3
- [x] T4
- [ ] None

T2 will force T3 to abort when T2 attempts to lock resource C. T1 will force T4 to abort when T1 attempts to lock resource D.

3. (15 points) EECS 16A anyone?

Alvin wants to use relations to store matrices. For instance, we will store the 3x2 matrix

$$M = \begin{bmatrix} 0 & 10 \\ 0 & 20 \\ 30 & 0 \end{bmatrix}$$

as the relation `M(INT row, INT col, INT val)`:

row	col	val
0	0	0
0	1	10
1	0	0
1	1	20
2	0	30
2	1	0

And the 3x1 vector

$$\vec{v} = \begin{bmatrix} 42 \\ 1 \\ 3 \end{bmatrix}$$

as the relation `v(INT row, INT val)`:

row	val
0	42
1	1
2	3

Recall a vector is a matrix with many rows but only one column. Also note the following matrix transformations:

- Transpose of a matrix: M^T is the row and col indices of M switched. For example,

$$M = \begin{bmatrix} 0 & 10 \\ 0 & 20 \\ 30 & 0 \end{bmatrix} \qquad M^T = \begin{bmatrix} 0 & 0 & 30 \\ 10 & 20 & 0 \end{bmatrix}$$

- Transpose of a vector: $\vec{v}^T$ is $\vec{v}$ but with columns instead of rows. For example,

$$\vec{v} = \begin{bmatrix} 42 \\ 1 \\ 3 \end{bmatrix} \qquad \vec{v}^T = \begin{bmatrix} 42 & 1 & 3 \end{bmatrix}$$

The following are the linear algebra operations that Alvin wants to run. Note that the first subscript letter represents the row number and the second subscript letter represents the column number (A_{ij} represents the value at ith row and jth column of A).

- Scalar-matrix sum: $C = s + A$, where $C_{ij} = s + A_{ij}$. s is an integer, and $+$ is just addition of two integers.
- Scalar-vector sum: $\vec{c} = s + \vec{a}$, where $\vec{c}_i = s + \vec{a}_i$. s is an integer, and $+$ is just addition of two integers.
- Matrix-vector product: $\vec{y} = A\vec{x}$, where $\vec{y}_i = \Sigma_j A_{ij}\vec{x}_j$. Notice that the output is a vector here.
- Vector-vector product: $\vec{x}^T\vec{y} = \Sigma_i \vec{x}_i \vec{y}_i$. Notice that the output is a scalar here.
- Matrix-matrix product: $C = AB$, where $C_{ik} = \Sigma_j A_{ij} B_{jk}$. Notice that the output is a matrix here.

- Trace of a matrix: $\text{tr}(A) = \Sigma_i A_{ii}$. Notice that the output is a scalar here.

In this problem relation `x` is the vector $\vec{x}$ and relations `A`, `B`, `C` are matrices A, B, and C, respectively. Assume all matrix multiplications are compatible.

(a) (9 points)

For each of the SQL expressions below, write the corresponding linear algebra operations for it only using the definitions above. For instance, if the query computes the trace of a matrix-matrix product between matrices A and B, write `tr(AB)` as the answer.

i. (2 pt)

```
SELECT SUM(A.val)
FROM A
WHERE A.col = A.row
```

Equivalent linear algebra operation:

- ○ AA
- ● $\text{tr}(A)$
- ○ $\text{tr}(AA)$
- ○ None of the above

ii. (2 pt)

```
SELECT A.row, A.col, A.val + SUM(B.val * C.val)
FROM A, B, C
WHERE A.row = B.row AND B.col = C.row AND C.col = A.col
GROUP BY A.row, A.col, A.val
```

Equivalent linear algebra expression:

- ○ $C + AB$
- ● $BC + A$
- ○ ABC
- ○ None of the above

iii. (2 pt)

```
SELECT SUM(A.val * x.val)
FROM A, x
WHERE A.col = x.row
GROUP BY A.row
```

Equivalent linear algebra expression:

- ○ $\text{tr}(A) + \vec{x}$
- ○ $\vec{x}^T A$
- ● $A\vec{x}$
- ○ None of the above

iv. (3 pt)

```
SELECT SUM(A.val * x1.val * x2.val)
FROM A, x AS x1, x AS x2
WHERE x1.row = A.col AND A.row = x2.row
```

Equivalent linear algebra expression:

- (●) $\vec{x}^T A\vec{x}$
- ( ) $A^T A\vec{x}$
- ( ) $\vec{x}^T \vec{x} A$
- ( ) None of the above

(b) (6 points)

Here is the matrix-relation schema again for your convenience.

$$M = \begin{bmatrix} 0 & 10 \\ 0 & 20 \\ 30 & 0 \end{bmatrix}$$

is the relation `M(INT row, INT col, INT val)`:

row	col	val
0	0	0
0	1	10
1	0	0
1	1	20
2	0	30
2	1	0

And the 3x1 vector

$$\vec{v} = \begin{bmatrix} 42 \\ 1 \\ 3 \end{bmatrix}$$

is the relation `v(INT row, INT val)`:

row	val
0	42
1	1
2	3

Alvin now wants to store the matrices and vectors to the disk. Assume the following:

- Integers and pointers are 4 bytes.
- Each page is 1024 bytes.
- Data pages follow the unpacked bitmap layout with fixed record size as presented in lecture.

i. (3 pt) What is the minimum number of pages it takes to store a 100x100 matrix? Write down the number of pages below. No need to show any calculation or explanation.

120

Each record is 12 bytes (3 int fields). Each page (1024 bytes) can store up to 84 records ($84 * 12 = 1008$ bytes for records + $\lceil 84/8 \rceil = 11$ bytes for the bitmap = 1019).

There are 10,000 records in a 100x100 matrix, so it will take $\lceil 10,000/84 \rceil = 120$ pages to store the entire matrix.

ii. (3 pt) Now suppose we change the table schema for a matrix A to be `A(BYTE row, BYTE col, INT val)` instead, where each `BYTE` integer is exactly 1 byte. What is the minimum number of pages it takes to store a 100x100 matrix? Write down the number of pages below. No need to show any calculation or explanation.

60

Each record is now $1 * 2 + 4 = 6$ bytes long. Each page (1024 bytes) can store up to 167 records ($167 * 6 = 1002$ bytes for records + $\lceil 167/8 \rceil = 21$ bytes for the bitmap = 1023). And it will take $\lceil 10,000/167 \rceil = 60$ pages to store the entire matrix.

4. (21 points) Dogejoin and Parallel Equereum

(a) (12 points)

i. (1 pt) Suppose we have table D and table E with [D] = 50, [E] = 40, and number of buffer pages B = 12. What is the minimum number of I/Os it would take to perform a Block Nested Loop Join of D and E?

240

D as outer loop:
[D] + ceil([D] / (B - 2)) * [E] = 50 + (50 / 10) * 40 = 250
E as outer loop:
[E] + ceil([E] / (B - 2)) * [D] = 40 + (40 / 10) * 50 = 240

ii. (2 pt) Consider the same [D] = 50 and [E] = 40 as the previous question but suppose we can now add buffer pages. What is the minimum number of total buffer pages we can have so that a Block Nested Loop Join of D and E takes strictly fewer than 200 I/Os?

16

We have to solve two equations - one with D as outer loop and one with E as outer loop - to find the minimum number of buffer pages.
D as outer loop:
[D] + ceil([D] / (B - 2)) * [E] < 200
50 + ceil(50 / (B - 2)) * 40 < 200
Solving for B results in B >= 19
E as outer loop:
[E] + ceil([E] / (B - 2)) * [D] < 200
40 + ceil(40 / (B - 2)) * 50 < 200
Solving for B results in B >= 16

iii. (2 pt) Now assume [D] = 50, [E] = 40, and again B = 12. How many I/Os would an **unoptimized** Sort Merge Join take?

450

unoptimized_cost(SMJ) = cost(sorting D) + cost(sorting E) + [D] + [E]
= 2 * (# passes to sort D) * [D] + 2 * (# passes to sort E) * [E] + [D] + [E]
= 2 * 2 * 50 + 2 * 2 * 40 + 50 + 40
= 450

iv. (2 pt) With the same assumptions as the previous question, how many I/Os would a **fully optimized** Sort Merge Join take?

270

Let's first check if we can make the optimization. Before the last pass of each table's sort phase, in order to apply the optimization we need (# runs in D) + (# runs in E) <= B - 1 = 11. After the first pass of sorting D, we have ceil([D] / B) = ceil(50 / 12) = 5 runs. After the first pass of sorting E, we have ceil([E] / B) = ceil(40 / 12) = 4 runs. Since 5 + 4 = 9 <= 11, we can apply the optimization which subtracts 2([D] + [E]) I/Os from the unoptimized Sort Merge Join.
optimized_cost(SMJ) = unoptimized_cost(SMJ) - 2([D] + [E])
= 450 - 2(50 + 40) = 270

v. (3 pt) Now assume [D] = 50, B = 12, but we do not know [E]. We want to perform an optimized Sort Merge Join but also want to know when we can't apply the optimization. What is the minimum [E] that will prevent us from using the optimization from the previous question?

73

In order to apply the optimization we again need (# runs in D) + (# runs in E) <= B - 1 = 11. After the first pass of sorting D, we again have ceil([D] / B) = ceil(50 / 12) = 5 runs. Thus, we need (# runs in E) = 6. The maximum [E] that meets this condition is 6 * B = 72. Adding 1 to this will result in 7 runs which will prevent us from using the optimization.

vi. (2 pt) Explain your answer to the previous question.

(b) (9 points)

i. (1 pt) Suppose again we have table D and table E but now both much larger with [D] = 500 and [E] = 750. If all pages start off on one machine and we want to perform a parallel Grace Hash Join, how much network cost in KB will we incur? Assume we have 10 machines, 1 page = 4 KB, all pages start off full, and hash partitioning is uniform.

4500

The starting machine will send 9/10 of its data across to other machines. This will be 9/10 * (500 + 750) * 4 = 4500

ii. (3 pt) Building off the previous question, how many I/Os across all machines will parallel Grace Hash Join take after hash partitioning? Assume tuples are written directly to disk when coming off the network (no I/Os are incurred) and each machine has B = 11 buffer pages.

3850

Each machine receives 50 pages from D and 75 pages from E. In the first partitioning pass, we read 50 + 75 = 125 pages and write 10 * 5 + 10 * 8 = 130 pages, resulting in 10 partitions of 5 pages for D and 10 partitions of 8 pages for E. Both fit into B - 2 = 9 pages so we can start the build and probe phase which reads 130 pages. In total for 1 machine, this will be 125 + 130 + 130 = 385 I/Os. Across all 10 machines, this will be 385 * 10 = 3850 I/Os.

iii. (3 pt) Building off the previous two questions, we want to figure out how much time it will take to run the entire parallel Grace Hash Join. Assume it takes 1 ms to send 1 KB of data from one machine to another, a machine can send data to other machines in parallel, but each individual table must be transmitted serially (i.e. machine 1 can send both table D **and** E to all other machines at the same time but it can only send 1 KB of table D and 1 KB of table E to each machine every 1 ms), 1 I/O takes 5 ms, hash partitioning is uniform, all data starts on 1 machine, and the answer to the previous question is 5000 I/Os. How much time in ms will the entire parallel GHJ take?

2800

Each machine other than the starting machine needs to wait for both D and E to arrive entirely before it can begin local GHJ. This will be 300 ms since the larger table E will be the slowest to fully arrive (75 * 4 = 300). Since we assume the answer to the previous question is 5000 I/Os, the number of I/Os for each machine is 5000 / 10 = 500 I/Os. This will take 5 * 500 = 2500 ms. In total, parallel GHJ will take 300 + 2500 = 2800 ms.

iv. (2 pt) Now assume we again have 10 machines in total, table D starts off one 1 machine, [D] = 10, table E is round-robin partitioned across the 10 machines, and [E] is unknown. What is the minimum [E] such that a broadcast join with table D being sent to every machine will incur a lower network cost than a parallel Grace Hash Join with uniform partitioning?

91

The network cost of the broadcast join is 10 * 9 * 4 = 360 KB. To determine the maximum [E] such that the network cost of a parallel GHJ is less than or equal to a broadcast join, we solve the following equation:
(10 + [E]) * (9/10) * 4 <= 360
[E] <= 90
Therefore, the minimum [E] such that the broadcast join will have lower network cost is 91.

5. (16 points) Disk/Files: I'm not ready to say good-byte T_T

(a) (1 pt) Write operations are typically more time consuming, so we typically only count the number of page writes to disk when we count I/Os.

- ○ True
- ● False

We count both read costs and write costs.

(b) (1 pt) Fill in the blank. In variable length record formats where we use a record header, we store the fixed length fields _____ the variable length fields.

- ● before
- ○ after

(c) (1 pt) Fill in the blank. In variable length record formats where we use a record header, we store the pointers to the _____ of the variable length fields.

- ○ beginning
- ● end

Both design choices ensure that we are able to access whichever fields we want to access as quickly as possible.

(d) (3 pt) Suppose I have a packed, sorted page of 13 fixed length records. Each record is 10 bytes long. If I wish to delete the record with the second smallest key on the page, how many bytes will I need to change on the page? Assume all integers and pointers are 4 bytes, and that records are sorted in ascending order. Hint: consider what changes the header needs to make as well.

114

In order to maintain the packed format, all records after the second record will need to be shifted. There are 11 such records, each with a length of 10 bytes, so 110 bytes will need to be rewritten. Furthermore, the number of records on the page stored in the header will also need to change, so 114 bytes in total will be changed.

Fixed length pages do not store a pointer to free space, so answers of 118 received only partial credit. When shifting, you also do not need to clear out the old position of the 13th record, so answers of 124 received only partial credit as well.

(e) (2 pt) An unpacked page with variable length records is 4 KiB (or 4096 bytes). Assume the page has 6 bytes of metadata, saving the remainder of the page for the records and page footer. Suppose the page is initially empty and then Jerry inserts two records. The first record is 20 bytes long, and the second is 40 bytes long. How many bytes of free space are remaining? Assume all integers and pointers are 4 bytes. Hint: Remember that the page footer contains pointer/length pairs, a pointer to free space, and a slot count.

4006

The page has 4090 bytes for records and the footer. The footer contains a slot count (4 bytes), a pointer to free space (4 bytes) and two pointer / record length pairs which are 8 bytes each. In total, the footer is 24 bytes, and the records will be 60 bytes. 4090 - 60 - 24 = 4006 bytes of free space.

(f) **(2 pt)** Suppose I have an unpacked page of variable length records that currently holds 20 different records and has 1000 bytes of free space on the page. If I delete one record with a size of 50 bytes, how many bytes of free space do I have immediately after? What will my slot count be immediately after? Separate your answers to these two questions with a comma and no spaces (ex. 1000,20).

1050,20

Deleting a record will open up more free space, and the slot that corresponds to the record will be nulled out. However, the slot count does not change.

(g) **(1 pt)** Which of the following pages may encounter fragmentation? Mark all that apply.

- ☐ Packed pages with fixed length records.
- ☐ Packed pages with variable length records.
- ☐ Unpacked pages with fixed length records.
- ■ Unpacked pages with variable length records.
- ☐ None of the above.

Fragmentation occurs when records are deleted and a page has enough free space to store a record, but the free space is not contiguous. This issue is not present in packed pages as there are no gaps between records. This issue is also not present for fixed length records because although there may be gaps, a different record is guaranteed to fit in that spot as all records are the same length.

(h) **(2 pt)** In a page directory implementation of heap files, we have 2021 data pages. Assume each header page holds information for up to 200 data pages. If we have the least number of header pages possible, what is the maximum number of I/Os it could take to insert a record assuming that at least one data page has room for said record? Assume you do not need to check for duplicate primary keys.

14

In the worst case, the very last header page out of the 11 header pages contains the pointer to the data page with free space (11 I/Os). You must then read in that page (1 I/O), insert the record, write the page back to disk (1 I/O), and update the header with the new amount of free space on the data page (1 I/O). This results in 14 I/Os in total.

(i) **(1 pt)** Jerry is writing goodbye notes. As he writes each note, he enters it into a database. The schema for the notes table includes (1) the recipient name as the primary key for each note's database entry, (2) the note's message body and (3) the address of the recipient. After writing all notes, he plans to scan through them all and send each one out to the listed address. Which page and file format combination is best for his use case?

- ● packed, heap file
- ○ unpacked, heap file
- ○ packed, sorted file
- ○ unpacked, sorted file

Jerry has no need for sorting so using a sorted file would just incur extra overhead. Furthermore, he does not delete notes, so a packed file would save the most space.

(j) **(1 pt)** Jerry realizes that he might like to update the notes after writing them but before sending them out. Thus, he would like to be able to quickly retrieve their corresponding note and make adjustments. Recall that the primary key of his database is the recipient name. Which page and file format combination is best for his use case?

- ○ packed, heap file
- ○ unpacked, heap file
- ○ packed, sorted file
- ● unpacked, sorted file

Jerry frequently makes updates to the records so a sorted file is advantageous as it helps him find the note he wishes to update. Furthermore, an unpacked format is advantageous because it allows him to make updates and deletions without having to shift other records to maintain a packed page.

(k) **(1 pt)** Jerry has received many notes as well! He decided to store the notes he received also in a database with the sender name as the primary key. In the next year, he wishes to read the note from a friend when that person's name pops into his head. Which page and file format combination is best for his use case?

- ○ packed, heap file
- ○ unpacked, heap file
- ● packed, sorted file
- ○ unpacked, sorted file

Jerry frequently makes equality searches on the records so a sorted file is advantageous as it helps him find the note he wishes to read. Furthermore, a packed format is advantageous because the notes will not be updated so a packed format saves space.

6. (21 points) Query Optimus Prime

For this question, assume that each column's values are uniformly distributed, and that all of the column distributions are independent of each other.

Schema	Pages	Table Stats
CREATE TABLE **R**(a FLOAT, b INTEGER)	50 pages with 100 records each	N/A
CREATE TABLE **S**(a FLOAT, b INTEGER)	40 pages with 100 records each	**S.a:** min = 0, max = 40; **S.b:** min = 1, max = 20, 20 unique values
CREATE TABLE **T**(a FLOAT, b INTEGER)	30 pages with 100 records each	**T.a:** min = 0, max = 40

(a) (6 points) System R Query Optimizer - Pass 1

In the remaining problems, we will optimize the following query using the System R (aka Selinger) query optimizer. Additionally, assume that the **selectivity of `T.a <= 20` is 1/2**.

```
SELECT *
FROM R INNER JOIN S ON R.a = S.a
    INNER JOIN T ON S.a = T.a
WHERE R.a <= 50 AND S.a <= 20 AND T.a <= 20
ORDER BY R.b
```

i. (1 pt) Estimate the cost in I/Os of using a full scan as our access plan for T in Pass 1.

30

We incur 30 I/Os to read in each data page. Note that it is not necessary to traverse any part of the index.

ii. (3 pt) For this problem, assume we have an unclustered, height 2, Alt. 3 B+ tree built on T.a with 20 leaf nodes. Estimate the cost in I/Os of using an index scan on T.a as our access plan for T in Pass 1.

1512

- 2 I/Os (cost to read inner nodes on path from root to leftmost leaf)
- 1/2 * 20 I/Os (cost to read in leaf nodes)
- 1/2 * 30 * 100 I/Os (cost to read in records on data pages: incur 1 I/O per matching record because index is unclustered)

iii. (2 pt) For this problem only, assume that we have the following I/O costs for single-table access plans:

Option	Access Plan	I/O Cost
a	R: Full scan	60 I/Os
b	R: Index scan on R.a	50 I/Os
c	R: Index scan on R.b	70 I/Os
d	S: Full scan	45 I/Os
e	S: Index scan on S.a	55 I/Os
f	S: Index scan on S.b	50 I/Os
g	T: Full scan	25 I/Os
h	T: Index scan on T.a	80 I/Os

Which of the following plans will be kept at the end of Pass 1?

- ☐ Option a
- ■ Option b
- ■ Option c
- ■ Option d
- ■ Option e
- ☐ Option f
- ■ Option g
- ■ Option h
- ☐ None of the above

- Option b: min cost to access R + interesting order (used in downstream join with S)
- Option c: interesting order (used in ORDER BY)
- Option d: min cost to access S
- Option e: interesting order (used in downstream join with R)
- Option g: min cost to access T
- Option h: interesting order (used in downstream join with S)

(b) (13 points) System R Query Optimizer - Pass 2/3

Let's now look at passes 2 and 3 of the System R Query Optimizer. Assume that:

- We have **B = 7** buffer pages.
- R originally has 50 pages. There are **25 pages** for which `R.a <= 50`.
- S originally has 40 pages. There are **20 pages** for which `S.a <= 20`.
- T originally has 30 pages. There are **15 pages** for which `T.a <= 20`.

For your convenience, here is a copy of the query we are optimizing:

```
SELECT *
    FROM R INNER JOIN S ON R.a = S.a
           INNER JOIN T ON S.a = T.a
    WHERE R.a <= 50 AND S.a <= 20 AND T.a <= 20
    ORDER BY R.b
```

i. (3 pt) Using the System R query optimizer, suppose we choose the full scan on R and the full scan on S as our single table access plans. What is the estimated I/O cost of R BNLJ S (with R as the outer relation and S as the inner relation) including the cost of the full scans?

250

50 + ceil(25/7-2) * 40 = 50 + 5 * 40 = 250 I/Os

ii. (1 pt) Does the previous join (R BNLJ S, using full scans as the access plans for R and S) produce an interesting order?

◯ Yes

● No

BNLJ never preserves or produces any interesting orders.

iii. (1 pt) For this problem only: suppose we use an index scan on R.b as our access plan for R, and a full scan as our access plan for S. Using these access plans, will R BNLJ S produce an interesting order?

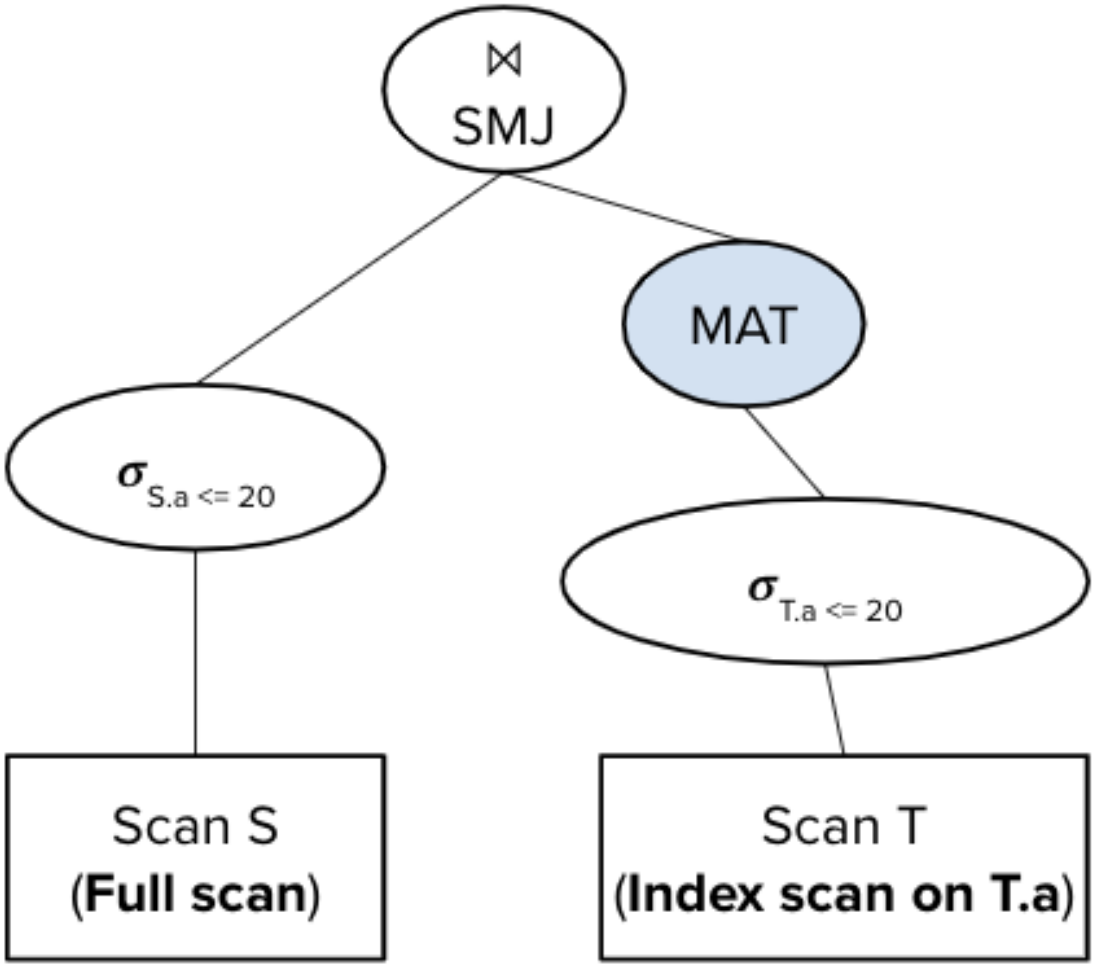
◯ Yes

● No

BNLJ never preserves or produces any interesting orders, even if the left input relation is sorted.

iv. (3 pt) For this problem only: suppose we are using a different query optimizer, which uses the following query plan. This query optimizer differs from the System R query optimizer in that it chooses to materialize the output of the single-table access plan for T.

Additionally, assume performing an index scan on T using the index on T.a (which simultaneously applies the selection on T.a) costs **80 I/Os**, and applying the selection on S.a takes place during the first pass of sorting S in the SMJ algorithm.



Using this query plan, what is the average case I/O cost of S SMJ T using **unoptimized** SMJ?

230

For S: We perform external sorting on S to sort S on S.a, which costs 100 I/Os:

- **Pass 0:** Read 40 pages; Write 20 pages (producing ceil(20/7) = 3 sorted runs)
- **Pass 1:** Read 20 pages; Write 20 pages (producing 1 sorted run)

For T: We perform an index scan on T.a to sort T's data by T.a, and then materialize the results, which costs 95 I/Os because:

- Performing the index scan takes 80 I/Os.
- After pushing down the selection, 15 pages of T remain, so the cost to materialize the data is 15 I/Os.

Merging: 20 + 15 = 35 I/Os

- We incur the cost to read in the data for S and T (after applying the selection) from disk.
- We exclude the cost of the final write, as we do for all joins.

Total: 100 + 95 + 35 = 230 I/Os

v. (1 pt) Does the previous join (S SMJ T, using a full scan as the access plan for S and an index scan on T.a as the access plan for T) produce an interesting order?

● Yes

○ No

The output will be sorted on S.a, which is used in a downstream join with R (R.a = S.a).

vi. (2 pt) Assume that we have the following I/O costs for joining 2 tables together:

Option	Access Plan	Sorted on	I/O Cost
a	R ⋈ S	N/A	300 I/Os
b	R ⋈ S	R.b	400 I/Os
c	S ⋈ R	S.a	500 I/Os
d	S ⋈ T	N/A	350 I/Os
e	T ⋈ S	T.a	400 I/Os
f	R ⋈ T	R.b	500 I/Os
g	T ⋈ R	N/A	450 I/Os

Using just this information, along with the query, which of the following plans will be kept at the end of Pass 2?

For your convenience, here is a copy of the query we are optimizing:

```
SELECT *
    FROM R INNER JOIN S ON R.a = S.a
           INNER JOIN T ON S.a = T.a
    WHERE R.a <= 50 AND S.a <= 20 AND T.a <= 20
    ORDER BY R.b
```

■ Option a

■ Option b

■ Option c

■ Option d

☐ Option e

☐ Option f

☐ Option g

☐ None of the above

- Option a: cheapest plan for {R, S}
- Option b: interesting order since R.b is used in the ORDER BY
- Option c: interesting order since S.a is used in a downstream join (S ⋈ T on S.a = T.a)
- Option d: cheapest plan for {S, T}
- Option e: not an interesting order since T.a is not used in any downstream joins, GROUP BY, or ORDER BY
- Option f: not considered because it involves a cartesian product
- Option g: not considered because it involves a cartesian product

vii. (2 pt) Assume that the access plans retained at the end of Pass 2 were R ⋈ S and S ⋈ T. Which of the following access plans will the System R query optimizer consider in Pass 3?

- [x] (R ⋈ S) ⋈ T
- [ ] (S ⋈ R) ⋈ T
- [ ] (R ⋈ T) ⋈ S
- [x] (S ⋈ T) ⋈ R
- [ ] T ⋈ (R ⋈ S)
- [ ] R ⋈ (S ⋈ T)
- [ ] S ⋈ (R ⋈ T)
- [ ] None of the above

- (S ⋈ R) ⋈ T is not considered because S ⋈ R was not retained at the end of Pass 2
- (R ⋈ T) ⋈ S is not considered because R ⋈ T is a cartesian product and was not retained at the end of pass 2
- T ⋈ (S ⋈ R), R ⋈ (S ⋈ T), and S ⋈ (R ⋈ T) are not considered because the plans are not left deep

(c) (2 points) Query Optimization in MongoDB (Brian's Guest Lecture)

i. (2 pt) Which of the following query optimization techniques are used to optimize the MongoDB aggregation pipeline?

- [x] Moving $match stages to the top of the aggregation pipeline
- [x] `$match` coalescing
- [ ] Avoiding cartesian products
- [x] Dead code elimination
- [ ] None of the above

Note: this problem was based off a guest lecture by Brian DeLeonardis in Spring 2021.

7. (15 points) A Well-Deserved Recovery

Oh no! Our database just crashed! Let's do some recovery. Assume for all parts that we're running ARIES as described and implemented in Project 5.

(a) (6 points) Analysis

Below is the **log recovered from disk when recovery starts**.

LSN	Record	PrevLSN
0	Master	-
10	T2 Updates P2	null
20	T1 Updates P1	null
30	T3 Updates P3	null
40	Commit T2	10
50	T1 Updates P1	20
60	End T2	40
70	T3 Updates P2	30
80	Abort T3	70
90	T1 Updates P4	50

The first step to performing recovery is to run the **Analysis Phase**. Answer the following questions about analysis .

i. (1 pt) Which of the following pages are in the dirty page table at the end of analysis?

- [x] P1
- [x] P2
- [x] P3
- [x] P4
- [ ] None of the above

All pages will be in the DPT at the end of analysis. During analysis, we scan through the log starting at LSN 0 and update the dirty page table every time a page is modified.

ii. (1 pt) What is T1's status at the end of analysis?

- ○ COMMITTING
- ● RECOVERY_ABORTING
- ○ RUNNING
- ○ T1 is not in the transaction table

RECOVERY_ABORTING. T1 is still running at the end of analysis. We abort running transactions.

iii. (1 pt) What is T2's status at the end of analysis?

- ○ COMMITTING
- ○ RECOVERY_ABORTING
- ○ RUNNING
- ● T2 is not in the transaction table

T2 is not in the transaction table. T2 committed and ended and so it is removed from the transaction table.

iv. (1 pt) What is T3's status at the end of analysis?

- ○ COMMITTING
- ● RECOVERY_ABORTING
- ○ RUNNING
- ○ T3 is not in the transaction table

RECOVERY_ABORTING. T3 was in the process of aborting before the database crashed

v. (2 pt) The log that we recover from the disk contains records that have been flushed prior to the crash; however, there may have been other records that were not flushed. Which of the following are a possible set of log records for T1 before the crash? (Select all that apply)

LSN	Record	PrevLSN
20	T1 Updates P1	null
50	T1 Updates P1	20
90	T1 Updates P4	50
100	T1 Updates P1	90
110	T1 Updates P4	100

■

LSN	Record	PrevLSN
20	T1 Updates P1	null
50	T1 Updates P1	20
90	T1 Updates P4	50
100	T1 Updates P1	90
110	Commit T1	100
120	End T1	110

□

LSN	Record	PrevLSN
20	T1 Updates P1	null
50	T1 Updates P1	20
90	T1 Updates P4	50
100	T1 Updates P1	90
110	Abort T1	100

■

LSN	Record	PrevLSN
20	T1 Updates P1	null
50	T1 Updates P1	20
90	T1 Updates P4	50
100	T1 Updates P1	90
110	Abort T1	100
120	End T1	110

■

☐ None of the above

T1 may have aborted, ended, or made additional modifications producing log records that were not flushed to disk. If T1 committed and ended, it must have flushed it's commit record to disk so this is not possible.

(b) (6 points) Redo

This next section is independent from the previous part. Suppose we have a **different** log shown below.

LSN	Record	PrevLSN
0	Master	-
10	T1 Updates P4	null
20	T3 Updates P2	null
30	T3 Updates P3	20
40	Begin Checkpoint	-
50	T1 Updates P4	10
60	T3 Updates P2	30
70	T2 Updates P1	null
80	End Checkpoint	-
90	Commit T1	50
100	Abort T3	60
110	T2 Updates P1	70
120	CLR T3 LSN 60, undoNextLSN=30	100

Assume after running analysis on this log, we get the following transaction table and dirty page table.

Transaction Table

Transaction	Status	LastLSN
T2	RECOVERY_ABORTING	110
T3	RECOVERY_ABORTING	120

Dirty Page Table

Page Number	RecLSN
P1	70
P2	60
P4	50

The next step is the **Redo Phase**. For the following parts, assume pageLSN(disk) $<$ LSN always.

i. (1 pt) What LSN does Redo begin at?

50

Redo begins at the lowest recLSN which is 50

ii. (2 pt) Select the LSNs of all of the operations that are redone during the Redo phase.

- ☐ 10
- ☐ 20
- ☐ 30
- ☐ 40
- ■ 50
- ■ 60
- ■ 70
- ☐ 80
- ☐ 90
- ☐ 100
- ■ 110
- ■ 120
- ☐ None of the above

50, 60, 70, 110, 120. We redo all the update records and CLR records.

iii. (2 pt) At LSNs 40-80, we perform a fuzzy checkpoint. Which of the following are possible transaction tables stored in the checkpoint record? (Select all that apply)

Transaction	Status	LastLSN
T1	RUNNING	10
T3	RUNNING	20

☐

Transaction	Status	LastLSN
T1	RUNNING	50
T3	RUNNING	60

■

Transaction	Status	LastLSN
T1	RUNNING	50
T2	RUNNING	70
T3	RUNNING	60

■

Transaction	Status	LastLSN
T1	RUNNING	90
T2	RUNNING	70
T3	RUNNING	60

☐

☐ None of the above

ii, iii. i is not possible because T3's lastLSN should be at least 30 since Begin Checkpoint begins at LSN 40. iv is not possible because the checkpoint ended at LSN 80.

iv. (1 pt) What is a possible reason why P3 is not in the dirty page table when we begin analysis even though it was modified at LSN 30? Briefly explain in 1 sentence. (Hint: When do we remove pages from the dirty page table?)

P3 may have been flushed to disk prior to the checkpoint (which would cause P3 to be removed from the DPT).

(c) (3 points) Undo

The log, transaction table, and dirty page table from the previous part are copied below for convenience.

LSN	Record	PrevLSN
0	Master	-
10	T1 Updates P4	null
20	T3 Updates P2	null
30	T3 Updates P3	20
40	Begin Checkpoint	-
50	T1 Updates P4	10
60	T3 Updates P2	30
70	T2 Updates P1	null
80	End Checkpoint	-
90	Commit T1	50
100	Abort T3	60
110	T2 Updates P1	70
120	CLR T3 LSN 60, undoNextLSN=30	100

Transaction Table

Transaction	Status	LastLSN
T2	RECOVERY_ABORTING	110
T3	RECOVERY_ABORTING	120

Dirty Page Table

Page Number	RecLSN
P1	70
P2	60
P4	50

The final step is the **Undo Phase**.

i. (1 pt) Which of the following LSNs are in the initial priority queue?

- ☐ 10
- ☐ 20
- ☐ 30
- ☐ 40
- ☐ 50
- ☐ 60
- ☐ 70
- ☐ 80
- ☐ 90
- ☐ 100
- ■ 110
- ■ 120
- ☐ None of the above

110, 120. The lastLSNs of aborting transactions. 30 (undoNextLSN), 110 was also accepted.

ii. (2 pt) Which of the following records are undone?

- ☐ 10
- ■ 20
- ■ 30
- ☐ 40
- ☐ 50
- ■ 60
- ■ 70
- ☐ 80
- ☐ 90
- ☐ 100
- ■ 110
- ☐ 120
- ☐ None of the above

20, 30, 70, 110. All non-CLR records belonging to T2 or T3 are undone except for LSN 60 since that was already undone by the CLR at LSN 120.

8. (16 points) No Shirt, No Shoes, NoSQL

(a) (7 points) True/False

For the following 7 questions, indicate whether the statement is true or false.

i. (1 pt) Retrieval queries in MQL can be used to perform operations similar to INNER JOINs and GROUP BYs in SQL.

○ True

● False

False. Retrieval queries can be used to perform operations similar to SELECT, LIMIT, and SORT, but not joins or aggregations.

ii. (1 pt) In MapReduce, all mappers must complete their work before the reduce phase can start.

● True

○ False

This is true.

iii. (1 pt) In MapReduce, small intermediate results do not have to be written to disk.

○ True

● False

False. One of the shortcomings of MapReduce is that it writes all intermediate results to disk for fault tolerance, regardless of size.

iv. (1 pt) In Spark, transformations are executed immediately while actions are executed lazily.

○ True

● False

False. Transformations are executed lazily, since transformations can be composed with downstream operations so that data doesn't have to be read multiple times (similar to the query operators in a traditional RDBMS). Meanwhile, actions such as `count()` are executed immediately.

v. (1 pt) The principle of atomicity is part of both ACID and BASE.

○ True

● False

False. Atomicity isn't one of the BASE principles.

vi. (1 pt) In addition to primitives, JSON also allows for collection types like ordered lists, unordered sets, and maps.

○ True

● False

False. JSON doesn't have a set type. Objects can serve as maps from names to values, but there's no way to map values to values (for example you cannot map an integer to a boolean)

vii. (1 pt) Unlike Spark DataFrames, Spark Datasets are unordered and don't allow duplicate objects.

○ True

● False

False. The main difference between Datasets and DataFrames is that Datasets require all objects to be of the same type, not ordering/duplicates.

(b) (7 points) Multiple Guess

i. (1 pt) MapReduce utilizes which of the following types of parallelism?

- ◯ Inter-Query Parallelism
- ◯ Inter-Operator Parallelism
- ● Intra-Operator Parallelism

Intra-Operator Parallelism. In MapReduce, both the operations (map and reduce) are parallelized, with intermediate results written to disk.

ii. (2 pt) For the following question, consider the map and reduce functions and select which SQL query would be equivalent. Assume map is applied to tuples from relation R with the integer valued columns A, B, and C.

```
map(Tuple t):
    EmitIntermediate(t.B, t.A)
```

```
reduce(Integer B, Iterator values):
    r = Integer.MIN_VALUE
    for each v in values:
        if r < v:
            r = v
    Emit(B, r)
```

- ● `SELECT MAX(A) FROM R GROUP BY B;`
- ◯ `SELECT * FROM R WHERE B=186;`
- ◯ `SELECT B FROM R;`
- ◯ `SELECT COUNT(*) FROM R;`
- ◯ None of the above

iii. (2 pt) For the following question, consider the map and reduce functions and select which SQL query would be equivalent. Assume map is applied to tuples from relation R with the integer valued columns A, B, and C.

```
map(Tuple t):
    EmitIntermediate(186, t.B)
```

```
reduce(Integer N, Iterator values):
    for each v in values:
        Emit(v)
```

- ◯ `SELECT B, MIN(A) FROM R GROUP BY B;`
- ◯ `SELECT * FROM R WHERE B=186;`
- ● `SELECT B FROM R;`
- ◯ `SELECT COUNT(*) FROM R;`
- ◯ None of the above

iv. (2 pt) For the following question, consider the map and reduce functions and select which SQL query would be equivalent. Assume map is applied to tuples from relation R with the integer valued columns A, B, and C.

```
map(Tuple t):
    if  t.B = 186:
        EmitIntermediate(t.B, t);
```

```
reduce(Integer A, Iterator values):
    for each v in values:
        Emit(v);
```

- ○ `SELECT MIN(A) FROM R GROUP BY B;`
- ● `SELECT * FROM R WHERE B=186;`
- ○ `SELECT B FROM R;`
- ○ `SELECT COUNT(*) FROM R;`
- ○ None of the above

(c) (2 points) Short Answer

i. (1 pt) Consider the MongoDB collection `stuff` with the following documents:

```
{a: 61,  b: [1,2]}
{a: 82,  b: [3]}
{a: 123, b: [4,5,6]}
{a: 220, b: [7,8,9,10]}
```

How many documents would the following query yield? (Your answer should be an integer)

```
db.stuff.aggregate([
    {$match: { a: {$gte: 70}}},
    {$unwind: "$b"}
]);
```

8

ii. (1 pt) Consider the MongoDB collection `stuff` with the following documents:

```
{a: 61,  b: [1,2]}
{a: 82,  b: [3]}
{a: 123, b: [4,5,6]}
{a: 220, b: [7,8,9,10]}
```

The following query yields a single document with the field `thing`. What value would the `thing` field of the resulting document be? (Your answer should be an integer)

```
db.stuff.aggregate([
    {$sort: {a: -1}},
    {$limit: 2},
    {$group: {_id: null, thing: {$sum: {$first: "$b"}}}}
]);
```

11

9. (16 points) Sorted Eggs and Hash Browns

(a) (3.5 points) I/Os and Dollars

Your company is switching compute plans, and they need your help to figure out the most cost-efficient way to process your data. Each buffer page costs $10, but the cost of each IO is variable. You're given a choice between three plans.

Plan 1: 100 buffer pages, $0.01 per IO
Plan 2: 50 buffer pages, $0.05 per I/O
Plan 3: 10 buffer pages, $0.25 per I/O

Your company decides to go with a trial plan first and gives a small table to sort to see how it goes. With a file size of N=100 pages...

i. (1 pt) In sorting the file, how many I/Os are incurred under plan 1?

200

This will take 1 pass, so it will take 1 * 2 * 100 = 200 I/Os

ii. (1 pt) How many I/Os are incurred under plan 2?

400

This will take 2 passes and will incur 2 * 2 * N = 400 I/Os

iii. (1 pt) How many I/Os are incurred under plan 3?

600

This will take 3 passes (1 + ceil(log910) = 3) and will incur 3 * 2 * N = 600 I/Os

iv. (0.5 pt) What plan is cheapest for the N=100 pages scenario?

- ○ PLAN 1
- ○ PLAN 2
- ● PLAN 3

Plan 1 costs 1002 dollars, Plan 2 costs 520 dollars, and plan 3 costs 250 dollars. So plan 3 is cheapest

(b) (3.5 points)

Your company is happy with the results and decides to now try sorting a file size of N=10,000 pages.

i. (1 pt) How many I/Os are incurred under plan 1?

60000

Number of passes: (1 + ceil(log99(10,000/100) = 3). This will take 3 * 2 * 10,000 = 60,000 I/Os

ii. (1 pt) How many I/Os are incurred under plan 2?

60000

Number of passes: (1 + ceil(log49(10,000/50) = 3). This will take 3 * 2 * 10,000 = 60,000 I/Os

iii. (1 pt) How many I/Os are incurred under plan 3?

100000

Number of passes: (1 + ceil(log9(10,000/10) = 5). This will take 2 * 5 * 10,000 = 100,000 I/Os

iv. (0.5 pt) What plan is cheapest for the N=10,000 pages scenario?

- (●) PLAN 1
- ( ) PLAN 2
- ( ) PLAN 3

Plan 1 costs $600 + $1000 = $1600. Plan 2 costs $3000 + $500 = $3500. Plan 3 costs $42,500 + $100, so the cheapest is easily Plan 1.

(c) (7 points)

Your company also inquires about hashing a smaller table of theirs, where N=100. Assume uniform hashing with a perfect hash function.

i. (2 pt) How many I/Os will this take to hash this table under Plan 1?

200

This takes 1 pass, so it will take 1 * 2 * 100 = 200 I/Os

ii. (2 pt) How many I/Os does it take under Plan 2?

541

On the first pass, we read in 100 pages and hash it into 49 buckets each, so each bucket gets 3 pages (rounding up). This gives us 100 + 49 * 3 = 247 I/Os for pass 1. Pass 2 is where in-memory hash tables are built, so you read in and write out 49 * 3 pages each, which is 147 * 2 = 294 I/Os for pass 2. Thus, this takes 247 + 294 = 541 I/Os.

iii. (2 pt) How many I/Os does it take under Plan 3?

802

On the first pass, we read in 100 pages and hash it into 9 buckets. Each bucket gets 12 pages, so 100 + 9 * 12 = 208 I/Os for pass 1. The second pass takes in each partition of 12 pages and hashes it into 9 buckets, so each sub-partition gets 2 pages (we thus write out 18 pages for every 12 we read in). Thus, this pass takes 12 * 9 + 18 * 9 = 270 I/Os. The last pass is the in-memory hash table, so we read in and write out 18 * 9 pages each, giving us 2 * 18 * 9 = 324 I/Os. Thus, the total cost is 324 + 270 + 208 = 802 I/Os.

iv. (1 pt) What is the cheapest plan?

- ○ PLAN 1
- ○ PLAN 2
- ● PLAN 3

Plan 1 costs 100 * 10 + 200 * 0.01 = $1002. Plan 2 costs 451 * 0.05 + 50 * 10 = $522.55. Plan 3 costs 802 * 0.25 + 10 * 10 = $300.50, so Plan 3 is the cheapest.

(d) (2 points) True or False

Mark all statements that are true.

i. (2 pt)

- ☐ Hashing will always result in the same number of I/Os writing to disk as the I/Os reading from disk.
- ■ Sorting will always result in the same number of I/Os writing to disk as the I/Os reading from disk.
- ☐ You can only build an in-memory hash table if you have B-1 pages as your partition file size, where B is the number of pages in the buffer.
- ■ Assuming uniform data spread and no key skew, with B pages of memory and a file size of N pages, hashing a table will always be at least as costly as sorting it.
- ☐ None of the above

10. (18 points) 2 Faze (Commit) 2 Furious

(a) (2 points) True or False

For the following 4 questions, select whether the statement is True or False.

i. (0.5 pt) Presumed abort always results in fewer messages sent across the network than regular 2PC.

○ True

● False

This is not true for commits.

ii. (0.5 pt) Presumed abort always results in fewer flushed log writes than regular 2PC.

○ True

● False

This is not true for commits.

iii. (0.5 pt) Machine M1 can be the coordinator for transaction $T1$ at the same time that machine M2 is the coordinator for transaction $T2$.

● True

○ False

There can be more than 1 coordinator, as long as each transaction is assigned to just 1 coordinator.

iv. (0.5 pt) If all participants crash at the same time, the transaction will always abort.

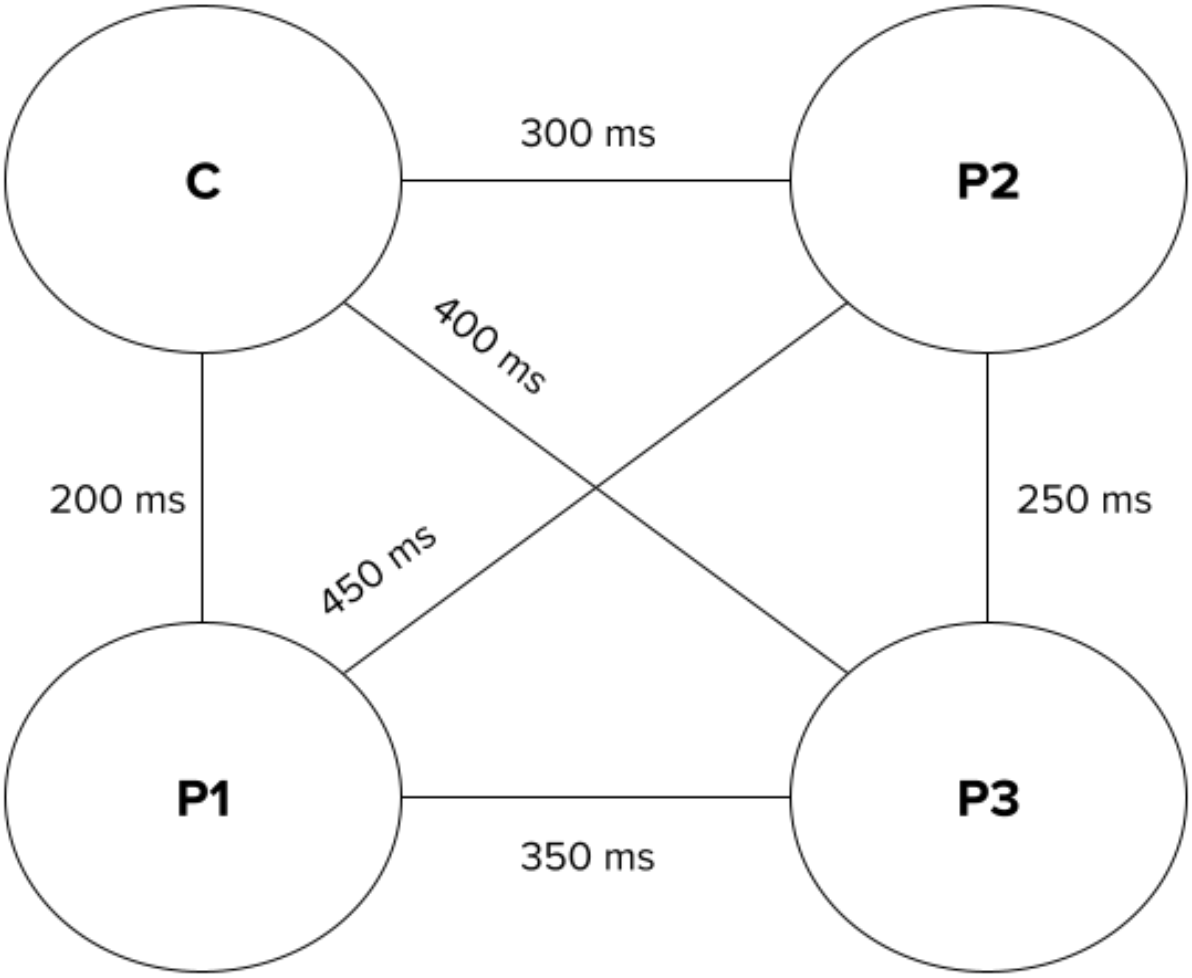
○ True

● False

If all crashed after sending an ACK, the transaction can still commit.

(b) (16 points)

Our database runs 2 Phase Commit **without any optimizations** with coordinator C and 3 participants: $P1$, $P2$, and $P3$. The communication latencies to send a message between each machine are shown in the diagram below. All latencies are in milliseconds. The latencies are symmetric (i.e. it takes 200 ms to send a message from C to $P1$ and also to send a message from $P1$ to C).



Assume the following information:

- Flushing a log record to disk takes 50 ms. All other operations (except sendings messages) occur instantaneously.
- Timeouts occur after 2500 ms.
- All participants vote YES.
- When a participant wants to ask the coordinator about the status of a transaction, it sends a STATUS INQUIRY message.

For the rest of this question, consider the following chronological sequence of events. All event times are shown in milliseconds since the 2PC round began.

- 0 ms: C begins the 2PC round.
- 500 ms: $P3$ crashes.
- 1000 ms: $P3$ recovers.
- 1500 ms: C crashes.
- 2000 ms: C recovers.

NOTE: ***A coordinator sending a message to all participants at the same time counts as sending ONE message.***

For questions that ask at what time an event occurs, provide the time in milliseconds since the 2PC round began and input ONLY the number.

i. (1 pt) What is the 1st message C receives?

- ○ PREPARE
- ○ COMMIT
- ○ ACK
- ○ STATUS INQUIRY
- ● VOTE YES
- ○ VOTE NO

ii. (1 pt) What is the latest time at which C receives VOTE YES? Put NONE if C never receives VOTE YES.

850

P3 sends VOTE YES at 450 and C receives it at 850.

TIME	C	P1 (200ms)	P2 (300ms)	P
PHASE 1 STARTS				
0	Sends PREPARE			
200		Receives PREPARE, flushes PREPARE		
250		Sends VOTE YES		
300			Receives PREPARE, flushes PREPARE	
350			Sends VOTE YES	
400				
450				Se
450	Receives VOTE YES from P1 (⅓)			
500				
650	Receives VOTE YES from P2 (⅔)			
850	Receives VOTE YES from P3 (3/3), flushes COMMIT			

Full table of events for this problem:

PHASE 2 Starts				
900	**Sends** COMMIT			
1000				Recovers, sees PREPARE, **sends** STATUS INQUIRY
1100		Receives COMMIT, **flushes** COMMIT		
1150		**Sends** ACK		
1200			Receives COMMIT, **flushes** COMMIT	
1250			**Sends** ACK	
1300				Receives COMMIT, **flushes** COMMIT
1350				**Sends** ACK
1350	Receives ACK from P1 (⅓)			
1400	Receives STATUS INQUIRY from P3, **sends** COMMIT to P3			
1500	**CRASHES** *Note: C had received 1 out of 3 ACKs before the crash, but they*			
1800				Receives COMMIT, already in log so no need to

iii. (1 pt) For this question only, assume the answer to the previous question is 750.

What is the earliest time at which C sends COMMIT? Put NONE if C never sends COMMIT.

800

C would flush a COMMIT log record, which takes 50 ms and then send COMMIT.

iv. (1 pt) Select all of the following that belong in the blank.

At time _____ , C receives ACK.

- [x] 1350
- [ ] 1550
- [ ] 2000
- [x] 2400
- [ ] None of the above

v. (1 pt) Select all of the following that belong in the blank.

At time _____ , C sends COMMIT.

- [ ] 850
- [x] 2000
- [ ] 2200
- [ ] 2400
- [ ] None of the above

vi. (1 pt) For this question only, assume C sends 4 COMMIT messages in total.

How many messages does C send in total?

5

1 PREPARE and the 4 COMMITs

vii. (1 pt) Select all of the following that belong in the blank.

At time _____ , $P1$ begins to flush a log record to disk.

- [ ] 100
- [x] 200
- [x] 1100
- [ ] 2200
- [ ] None of the above

viii. (1 pt) How many messages does $P1$ receive in total?

3

1 PREPARE, 2 COMMITS

ix. (1 pt) For this question only, assume the answer to the previous question is 6.

How many messages does $P1$ send in total?

6

P1 does not have any failure, so each message received will have a response sent.

x. (1 pt) Select all of the following that belong in the blank.

At time _____ , $P2$ begins to flush COMMIT to disk.

- ☐ 300
- ☐ 500
- ■ 1200
- ☐ 2300
- ☐ None of the above

xi. (1 pt) Select whether the following statement is True or False.

$P2$ sends more messages than $P1$.

- ○ True
- ● False

xii. (1 pt) Select all of the following that belong in the blank.

After time 500, $P3$ sends _____.

- ☐ PREPARE
- ☐ COMMIT
- ■ ACK
- ■ STATUS INQUIRY
- ☐ VOTE YES
- ☐ VOTE NO
- ☐ $P3$ sends no messages after time 500.

xiii. **(1 pt)** What machine sends the final message?

- ○ C
- ○ $P1$
- ○ $P2$
- ● $P3$

P3 sends an ACK at 2400.

xiv. **(1 pt)** What is the earliest time at which an END log record can be emitted?

2600

This is when C receives all ACKs.

xv. **(2 pt)** Consider an optimization to 2PC, where the coordinator flushes an ACK log record everytime it receives an ACK from a participant. In case the coordinator crashes, it will know upon recovery which participants have already sent an ACK.

Using this optimization, how many milliseconds earlier can an END log record be emitted in comparison to the regular case without the optimization.

For example, if this optimization allows an END log record to be emitted at 4000 and the answer to the previous the question is 4500, your answer would be 500.

0

There is no change, because P2 does not send the ACK until 2600. However, C would not have to send COMMIT to P1 when C recovers, since it had already received an ACK from P1 at the time of failure.

No more questions.