CARNEGIE MELLON UNIVERSITY
COMPUTER SCIENCE DEPARTMENT
15-445/645 – DATABASE SYSTEMS (FALL 2022)
PROF. ANDY PAVLO

Homework #5 (by Chi Zhang, Tim Lee)

Due: **Thursday Dec 4, 2022 @ 11:59pm**

IMPORTANT:

- **Upload this PDF** with your answers to **Gradescope by 11:59pm on Thursday Dec 4, 2022**.
- **Plagiarism**: Homework may be discussed with other students, but all homework is to be completed **individually**.
- **You have to use this PDF for all of your answers.**

For your information:

- Graded out of **100** points; **4** questions total

Revision : 2022/11/26 05:36

Question	Points	Score
Write-Ahead Logging	25	
Replication	20	
Two-Phase Commit	25	
Distributed Query Plan	30	
Total:	100	

Question 1: Write-Ahead Logging .... [25 points]

Consider a DBMS using write-ahead logging with physical log records with the STEAL and NO-FORCE buffer pool management policy. Assume the DBMS executes a non-fuzzy checkpoint where all dirty pages are written to disk.

Its transaction recovery log contains log records of the following form:

`<txnId, objectId, beforeValue, afterValue>`

The log also contains checkpoint, transaction begin, and transaction commit records.

The database contains three objects (i.e., A, B, and C).

The DBMS sees records as in Figure 1 in the WAL on disk after a crash.

Assume the DBMS uses ARIES as described in class to recover from failures.

LSN	WAL Record
1	`<T1 BEGIN>`
2	`<T1, B, 6, 7>`
3	`<T1, C, 42, 43>`
4	`<T2 BEGIN>`
5	`<T2, A, 33, 71>`
6	`<T1 COMMIT>`
7	`<T2, C, 43, 100>`
8	`<T3 BEGIN>`
9	`<T3, B, 7, 20>`
10	`<T2, C, 100, 67>`
11	`<`**`CHECKPOINT`**`>`
12	`<T3, B, 20, 42>`
13	`<T2, A, 71, 13>`
14	`<T2 COMMIT>`
15	`<T3, B, 42, 66>`

Figure 1: WAL

(a) **[6 points]** What are the values of A, B, and C in the database stored on disk before the DBMS recovers the state of the database?

- ☐ A=71, B=6, C=100
- ☐ A=13, B=66, C=67
- ☐ A=43, B:7, C=Not possible to determine
- ☐ A=71, B=42, C=42
- ☐ A=Not possible to determine, B:20, C=43
- ☐ A=43, B:20, C=Not possible to determine
- ☐ A:Not possible to determine, B=Not possible to determine, C:67
- ☐ A=Not possible to determine, B=20, C:Not possible to determine
- ☐ A:71, B=Not possible to determine C=42

☐ A,B,C:Not possible to determine

(b) **[3 points]** What should be the correct action on T1 when recovering the database from WAL?

☐ redo all of T1's changes
☐ undo all of T1's changes
☐ do nothing to T1

(c) **[3 points]** What should be the correct action on T2 when recovering the database from WAL?

☐ redo all of T2's changes
☐ undo all of T2's changes
☐ do nothing to T2

(d) **[3 points]** What should be the correct action on T3 when recovering the database from WAL?

☐ redo all of T3's changes
☐ undo all of T3's changes
☐ do nothing to T3

(e) **[10 points]** Assume that the DBMS flushes all dirty pages when the recovery process finishes. What are the values of A, B, and C after the DBMS recovers the state of the database from the WAL in Figure 1?

☐ A=33, B=6, C=42
☐ A=13, B=66, C=67
☐ A=13, B=6, C=100
☐ A=13, B=7, C=67
☐ A=71, B=20, C=42
☐ A=33, B=42, C=100
☐ A=71, B=7, C=100
☐ A=13, B=42, C=67
☐ A=33, B=20, C=43
☐ A=71, B=66, C=43
☐ A=13, B=42, C=42
☐ Not possible to determine

Question 2: Replication .... [20 points]

Consider a DBMS using active-passive, master-replica replication with multi-versioned concurrency control. All read-write transactions go to the master node (NODE A), while read-only transactions are routed to the replica (NODE B). You can assume that the DBMS has "instant" fail-over and master elections. That is, there is no time gap between when the master goes down and when the replica gets promoted as the new master. For example, if NODE A goes down at timestamp ① then NODE B will be elected the new master at ②.

The database has a single table `foo(id,val)` with the following tuples:

id	val
1	xx
2	yy
3	zz

Table 1: **foo(id,val)**

For each questions listed below, assume that the following transactions shown in Figure 2 are executing in the DBMS: (1) Transaction #1 on NODE A and (2) Transaction #2 on NODE B. You can assume that the timestamps for each operation is the real physical time of when it was invoked at the DBMS and that the clocks on both nodes are perfectly synchronized.

time	operation
①	`BEGIN;`
②	`UPDATE foo SET val = 'x';`
③	`UPDATE foo SET val = 'yyy' WHERE id = 3;`
④	`UPDATE foo SET val = 'z' WHERE id = 1;`
⑤	`COMMIT;`

(a) Transaction #1 – NODE A

time	operation
②	`BEGIN READ ONLY;`
③	`SELECT val FROM foo WHERE id = 3;`
④	`SELECT val FROM foo WHERE id = 1;`
⑤	`SELECT val FROM foo WHERE id = 1;`
⑥	`COMMIT;`

(b) Transaction #2 – NODE B

Figure 2: Transactions executing in the DBMS.

(a) Assume that the DBMS is using *asynchronous* replication with *continuous* log streaming (i.e., the master node sends log records to the replica in the background after the transaction executes them). Suppose that NODE A crashes at timestamp ⑤ before it executes the `COMMIT` operation.

i. **[6 points]** If Transaction #2 is running under `READ COMMITTED`, what is the return result of the `val` attribute for its `SELECT` query at timestamp ⑤? Select all that are possible.

☐ zz
☐ x
☐ yy
☐ yyy
☐ z

☐ xx
☐ None of the above

ii. **[7 points]** If Transaction #2 is running under the `READ UNCOMMITTED` isolation level, what is the return result of the `val` attribute for its `SELECT` query at timestamp ⑤? Select all that are possible.

☐ zz
☐ x
☐ yy
☐ yyy
☐ z
☐ xx
☐ None of the above

(b) **[7 points]** Assume that the DBMS is using *synchronous* replication with *on commit* propagation. Suppose that both NODE A and NODE B crash at exactly the same time at timestamp ⑥ after executing Transaction #1's `COMMIT` operation. You can assume that the application was notified that the Transaction #1 was committed successfully.

After the crash, you find that NODE A had a major hardware failure and cannot boot. NODE B is able to recover and is elected the new master.

What are the values of the tuples in the database when the system comes back online? Select all that are possible.

☐ { (1,xx), (2,yy), (3,zz) }
☐ { (1,x), (2,x), (3,x) }
☐ { (1,x), (2,x), (3,yyy) }
☐ { (1,z), (2,x), (3,yyy) }
☐ { (1,xx), (2,x), (3,zz) }
☐ { (1,xx), (2,x), (3,x) }
☐ None of the above

Question 3: Two-Phase Commit ....[25 points]

Consider a distributed transaction T operating under the two-phase commit protocol with the early acknowledgement optimization. Let N_0 be the *coordinator* node, and N_1, N_2, N_3 be the *participant* nodes.

The following messages have been sent:

time	message
1	N_0 to N_2: "`Phase1:PREPARE`"
2	N_2 to N_0: "`OK`"
3	N_0 to N_1: "`Phase1:PREPARE`"
4	N_0 to N_3: "`Phase1:PREPARE`"

Figure 3: Two-Phase Commit messages for transaction T

(a) **[7 points]** Who should send a message next at time 5 in Figure 3? Select *all* the possible answers.

☐ N_0
☐ N_1
☐ N_2
☐ N_3
☐ It is not possible to determine

(b) **[6 points]** To whom? Again, select *all* the possible answers.

☐ N_0
☐ N_1
☐ N_2
☐ N_3
☐ It is not possible to determine

(c) **[6 points]** Suppose that N_0 received the "`ABORT`" response from N_1 at time 5 in Figure 3. What should happen under the two-phase commit protocol in this scenario?

☐ N_0 resends "`Phase1:PREPARE`" to N_2
☐ N_1 resends "`OK`" to N_0
☐ N_0 sends "`Phase2:COMMIT`" all of the participant nodes
☐ N_0 sends "`ABORT`" all of the participant nodes
☐ N_0 resends "`Phase1:PREPARE`" to all of the participant nodes
☐ It is not possible to determine

(d) **[6 points]** Suppose that N_0 successfully receives all of the "`OK`" messages from the participants from the first phase. It then sends the "`Phase2:COMMIT`" message to all of the participants but N_1 and N_3 crash before they receives this message. What is the status of the transaction T when N_1 comes back on-line?

☐ T's status is *aborted*

☐ T's status is *committed*

☐ It is not possible to determine

Question 4: Distributed Query Plan . . . . [30 points]

The CMUDB group is working on a brand new shared-nothing distributed database system called BusTub*. They are developing the distributed query engine.

Given the following schema:

```
CREATE TABLE t1(PARTITION KEY v1 int, v2 int);
CREATE TABLE t2(PARTITION KEY v3 int, v4 int);
CREATE TABLE t3(PARTITION KEY v5 int, v6 int);
CREATE TABLE t4(PARTITION KEY v7 int, v8 int);
```

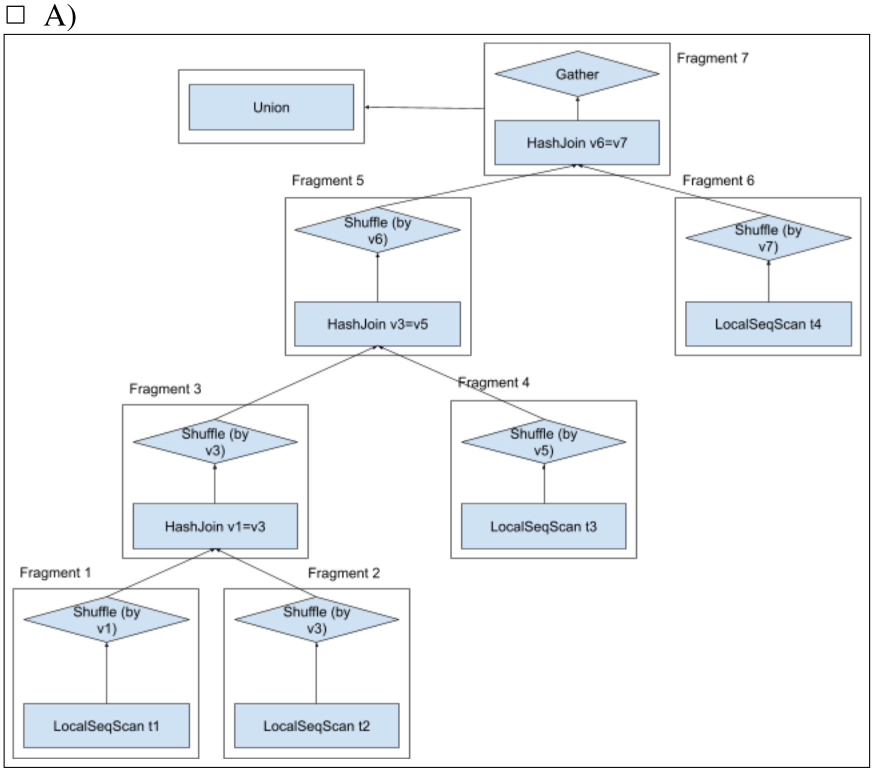
The database system partitions the tables by key range. That is to say, each node in the system manages rows of the table within a non-overlapping range of keys.

Given the following query:

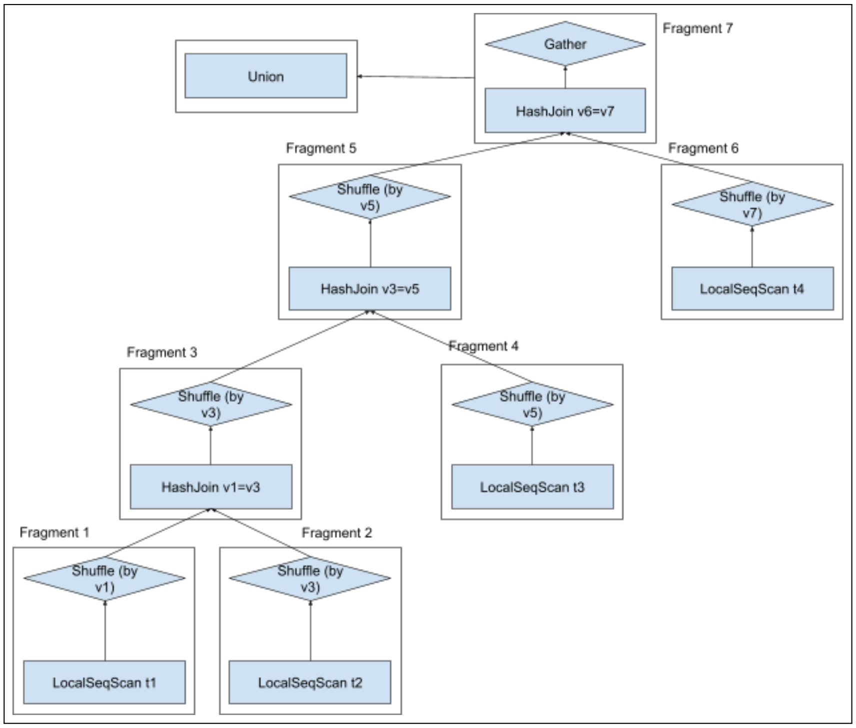
```sql
SELECT * FROM ((t1 INNER JOIN t2 ON v1 = v3)
    INNER JOIN t3 ON v3 = v5)
    INNER JOIN t4 ON v6 = v7;
```

(a) **[5 points]** Assume that the query optimizer doesn't know the ranges of data stored on each node and only knows the tables are sharded by some keys, what are the correct distributed query plans for this query?

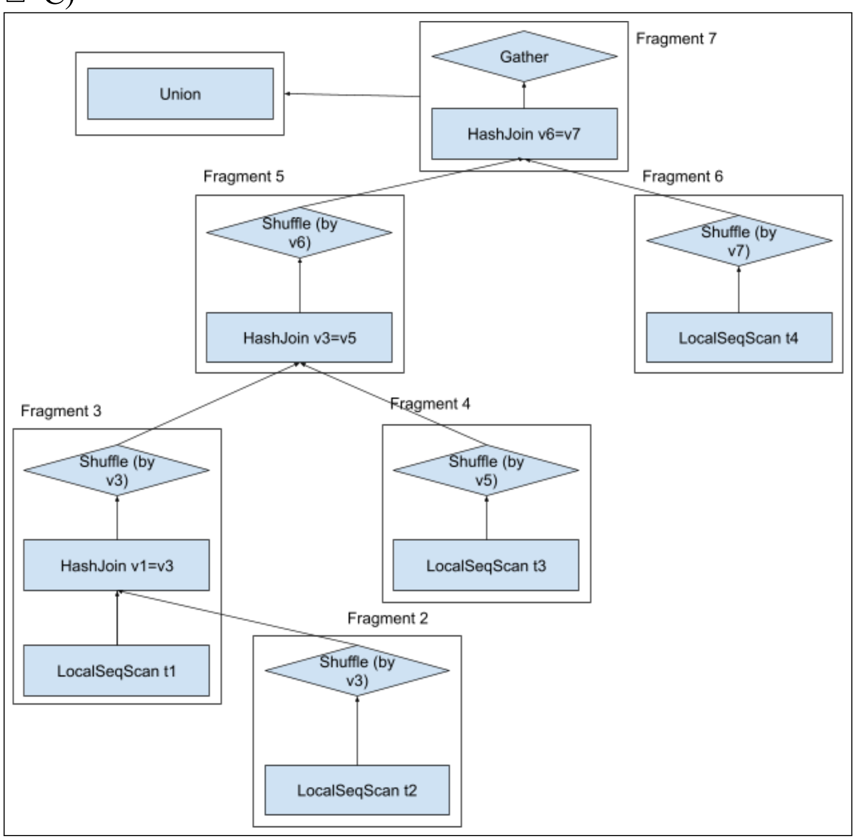
☐ A)



☐ B)


Fragment 7
Gather
HashJoin v6=v7
Union
Fragment 5
Shuffle (by v5)
HashJoin v3=v5
Fragment 6
Shuffle (by v7)
LocalSeqScan t4
Fragment 3
Shuffle (by v3)
HashJoin v1=v3
Fragment 4
Shuffle (by v5)
LocalSeqScan t3
Fragment 1
Shuffle (by v1)
LocalSeqScan t1
Fragment 2
Shuffle (by v3)
LocalSeqScan t2

☐ C)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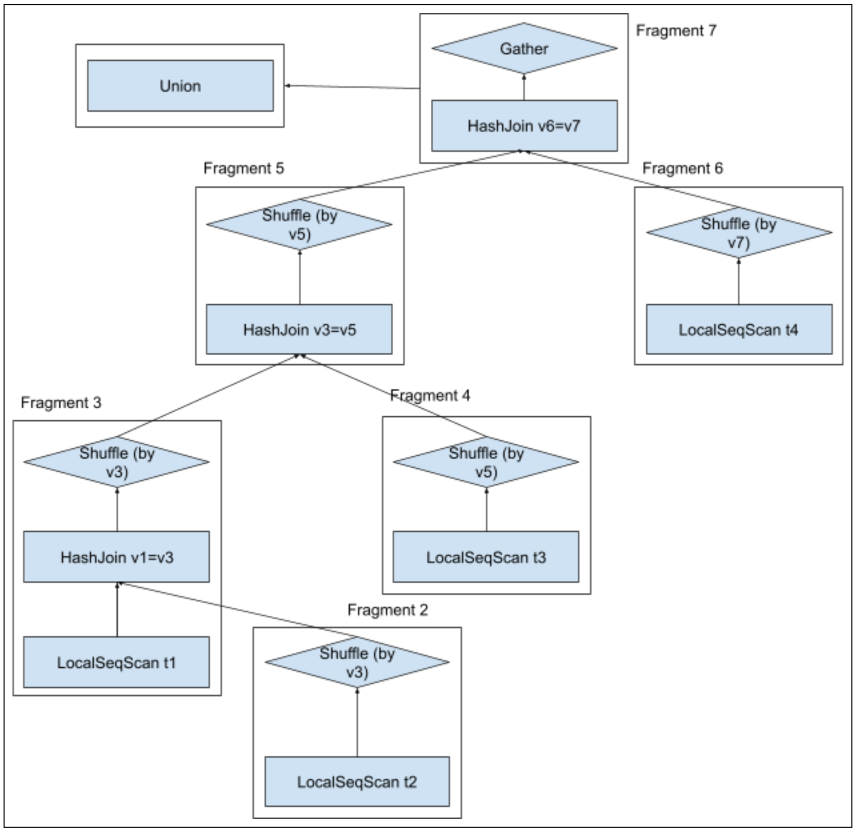
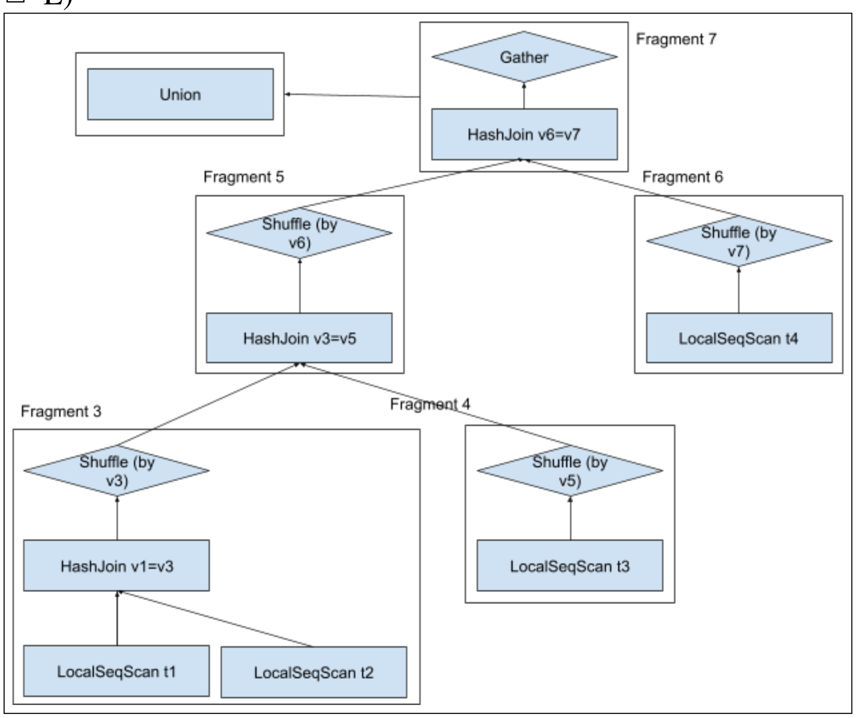
LocalSeqScan t3
Fragment 2
Shuffle (by v3)
LocalSeqScan t2

☐ D)



☐ E)



(b) **[5 points]** Assume there are 3 nodes in the system and the data ranges in each node are as follows:

	$t1.v1$	$t2.v3$	$t3.v5$	$t4.v7$
$Node\ 1$	0 - 999	0 - 999	1000 - 1999	0 - 999
$Node\ 2$	1000 - 1999	1000 - 1999	0 - 999	1000 - 1999
$Node\ 3$	2000 - 2999	2000 - 2999	2000 - 2999	2000 - 2999

Table 2: Data distribution for table $t1$ to $t4$

Assume the data are shuffled by range. Which is the best and correct schedule for the query?

☐ A)

```
1. HashJoin v1=v3: 0-999 on node 1, 1000-1999 on node 3,
   2000-2999 on node 2
2. HashJoin v3=v5: 0-999 on node 1, 1000-1999 on node 2,
   2000-2999 on node 3
3. HashJoin v6=v7: 0-999 on node 1, 1000-1999 on node 2,
   2000-2999 on node 3
4. Union: on node 1
```

☐ B)

```
1. HashJoin v1=v3: 0-999 on node 1, 1000-1999 on node 2,
   2000-2999 on node 3
2. HashJoin v3=v5: 0-999 on node 3, 1000-1999 on node 2,
   2000-2999 on node 1
3. HashJoin v6=v7: 0-999 on node 1, 1000-1999 on node 2,
   2000-2999 on node 3
4. Union: on node 1, 2, 3
```

☐ C)

```
1. HashJoin v1=v3: 0-999 on node 1, 1000-1999 on node 2,
   2000-2999 on node 3
2. HashJoin v3=v5: 0-999 on node 1, 1000-1999 on node 2,
   2000-2999 on node 3
3. HashJoin v6=v7: 0-999 on node 1, 1000-1999 on node 2,
   2000-2999 on node 3
4. Union: on node 1
```

(c) **[5 points]** Given the following assumptions:

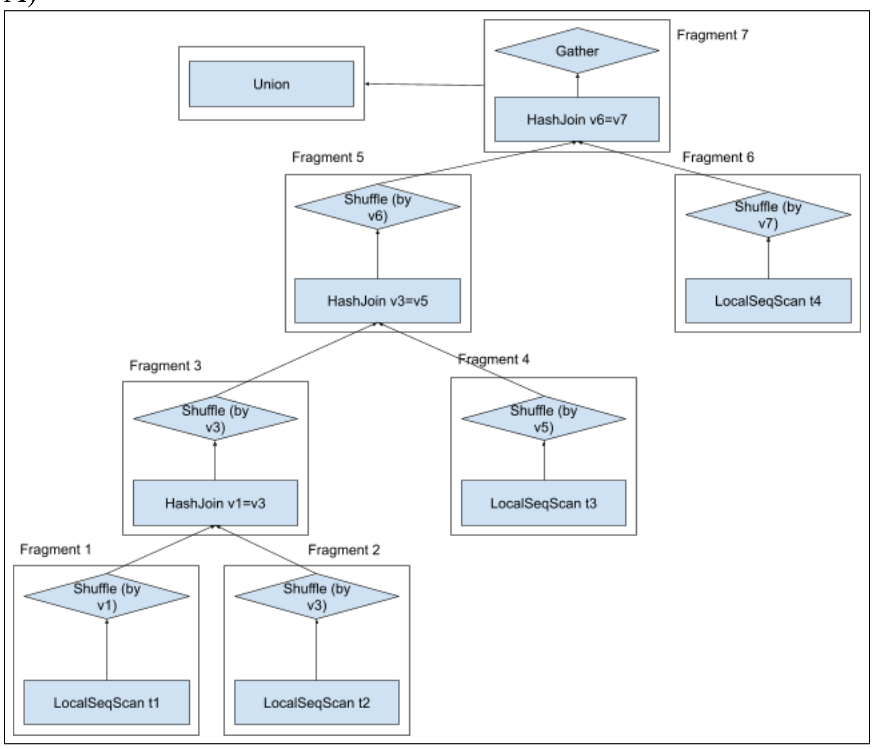
1. t1 contains 3000 rows and v1 has all values across (0-2999)
2. t2 contains 3000 rows and v3 has all values across (0-2999)
3. t3 contains 3000 rows, v5 has all values across (0-2999) and so as v6
4. t4 contains 300 rows and v7 values are uniformly distributed across 0-2999
5. All joins produce a number of rows equal to *min*{*cardinality of left child, cardinality of right child*}.

Using the data distribution of Table 2, how much data is expected to be transferred over the network when executing the plan with the best schedule in question (b)? (**Hint**: Calculate the answer by summing up all the expected (**rows** * **columns**) that would be shuffled before each `HashJoin` and `Union`.

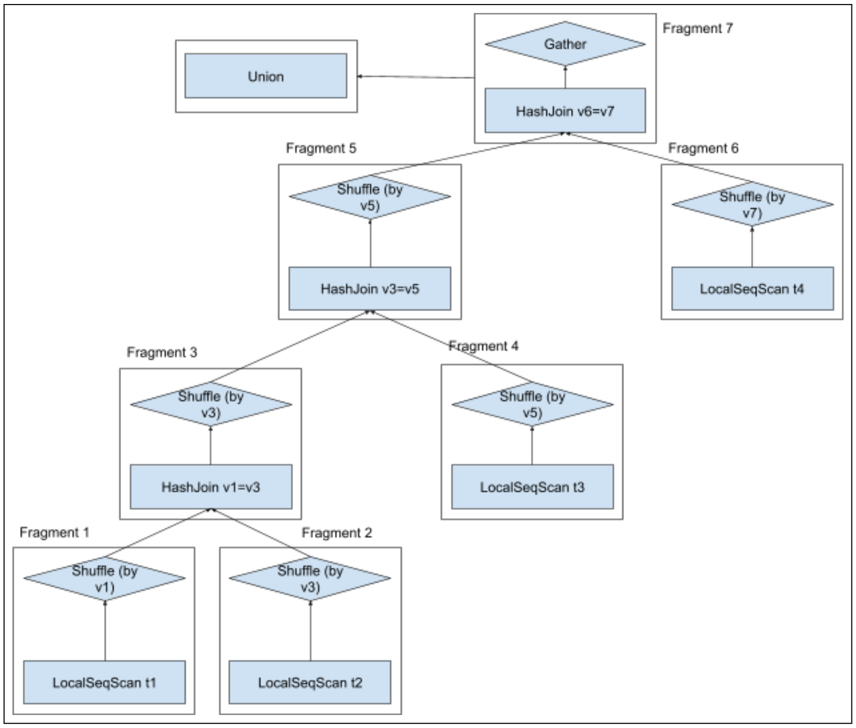
- ☐ $0 - 5000$
- ☐ $5000 - 10000$
- ☐ $15000 - 22000$
- ☐ $22000 - 40000$
- ☐ ≥ 40000

(d) **[5 points]** An engineer realized that t4 is very small so they configured the table to be stored on all nodes. Which of the following plans is correct?

- ☐ A)



- ☐ B)



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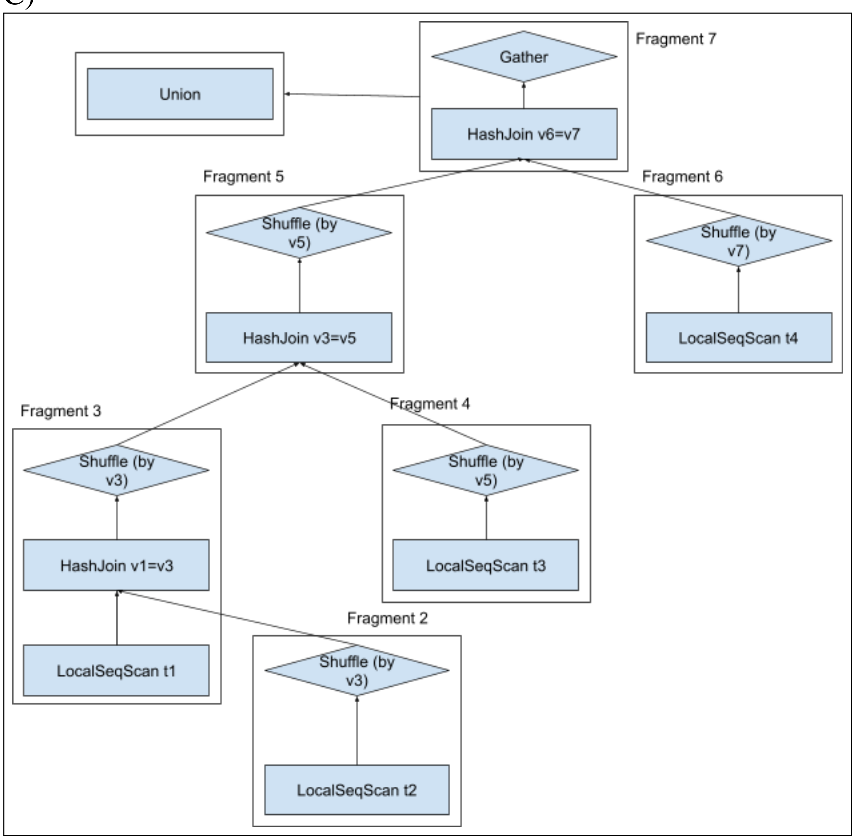
☐ C)



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HashJoin v1=v3
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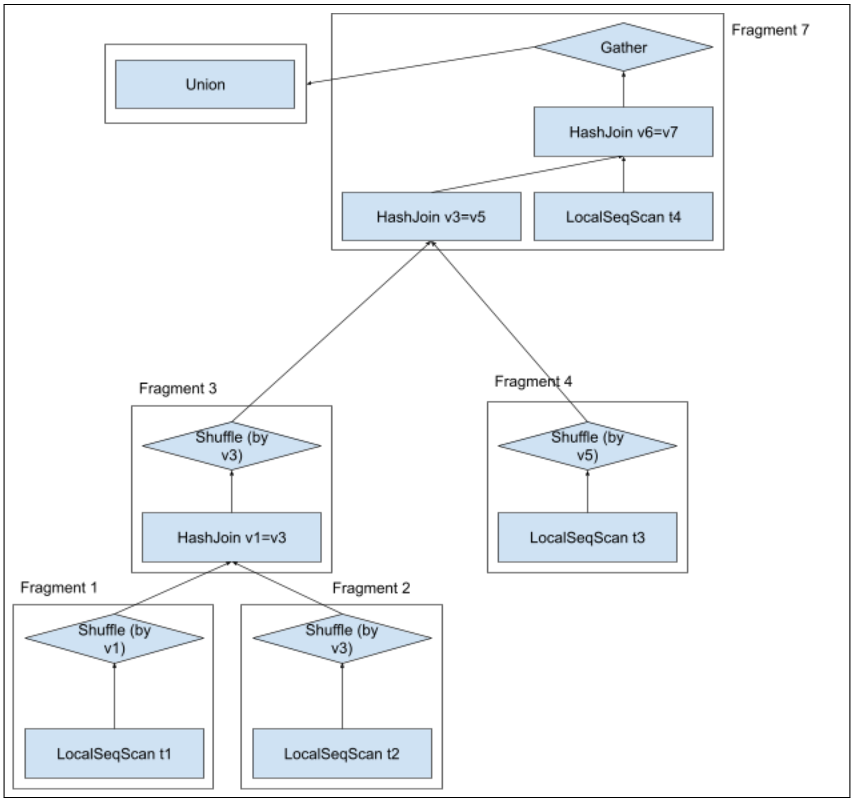
LocalSeqScan t3
Fragment 2
Shuffle (by v3)
LocalSeqScan t2

☐ D)



(e) **[4 points]** In the correct case of question (d), how much data is expected to be transferred over the network, given the same assumptions in question (c)? (**Hint**: Calculate the answer by summing up all the expected (**rows** * **columns**) that would be shuffled before each `HashJoin` and `Union`.

- ☐ 0 – 5000
- ☐ 5000 – 10000
- ☐ 15000 – 22000
- ☐ 22000 – 40000
- ☐ $\geq$ 40000

(f) **[6 points]** The BusTub* developers decide to replicate data using multiple groups of Multi-Paxos to ensure high availability. Here is the latest setup of the database (Range = the range of the partition key of a table):

Range / Table	$t1$	$t2$	$t3$	$t4$
0 - 999	Paxos Group 1	Paxos Group 2	Paxos Group 3	Paxos Group 10
1000 - 1999	Paxos Group 4	Paxos Group 5	Paxos Group 6	Paxos Group 10
2000 - 2999	Paxos Group 7	Paxos Group 8	Paxos Group 9	Paxos Group 10

Table 3: Paxos Group IDs

Assuming the following status of the database (L = Leader, A = Acceptor):

What's the maximum number of nodes that can go down before this query cannot be successfully executed? (Assume reads / writes all go through the leader).

Node / Paxos Group	1	2	3	4	5	6	7	8	9	10
Node 1	L				A	A	L			
Node 2	A	L				A	A	L		
Node 3	A	A	L				A	A	L	
Node 4		A	A	L				A	A	L
Node 5			A	A	L				A	A
Node 6				A	A	L				A

Table 4: Current Leader / Acceptor nodes of Paxos groups

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4
- ☐ 5