Transactions and Failure Recovery

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Outline

Recap from last time

Redo logging

Undo/redo logging

External actions

Media failures

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Recap from last time

Redo logging

Undo/redo logging

External actions

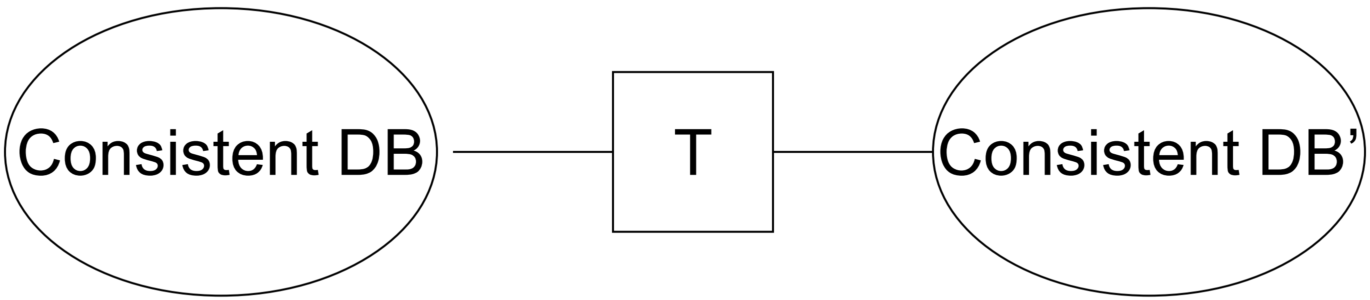
Media failures

Defining Correctness

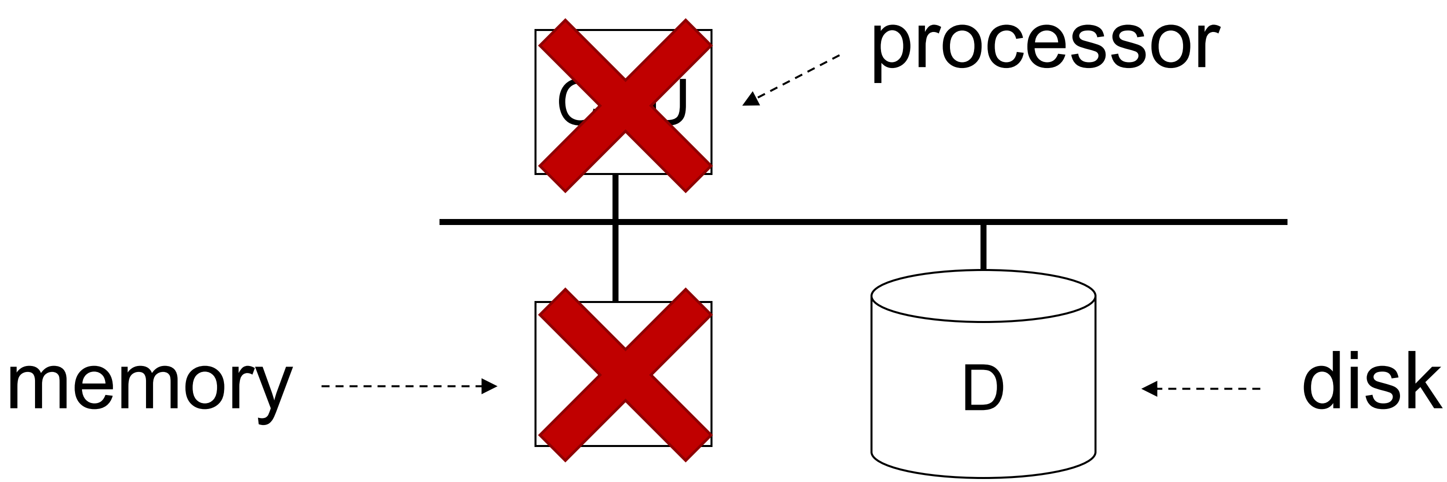
Constraint: Boolean predicate about our DB (both logical and physical data structures)

Consistent DB: satisfies all constraints

Transaction: Collection of Actions that Preserve Consistency



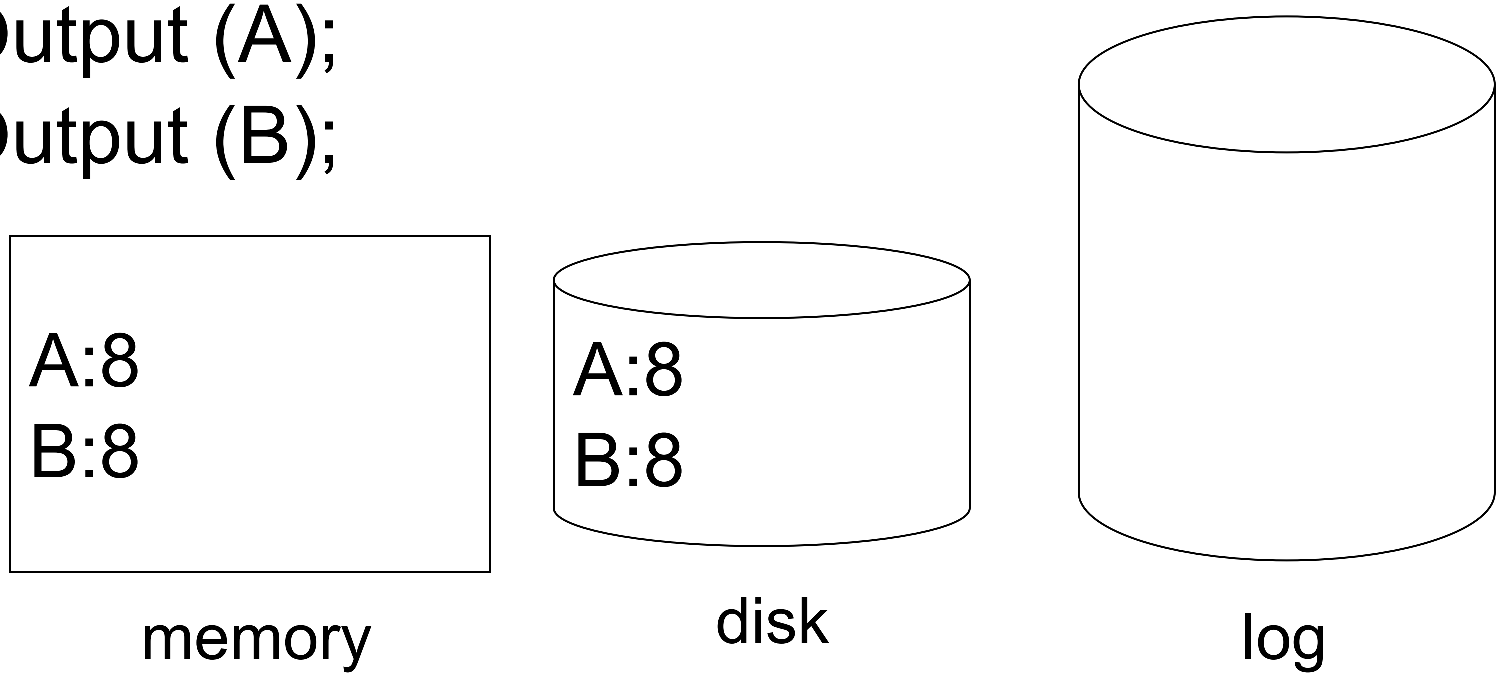
Our Failure Model



Fail-stop failures of CPU & memory, but disk survives

Undo Logging (Immediate modification)

T_1: Read (A,t); $t \leftarrow t \times 2$ A=B
Write (A,t);
Read (B,t); $t \leftarrow t \times 2$
Write (B,t);
Output (A);
Output (B);



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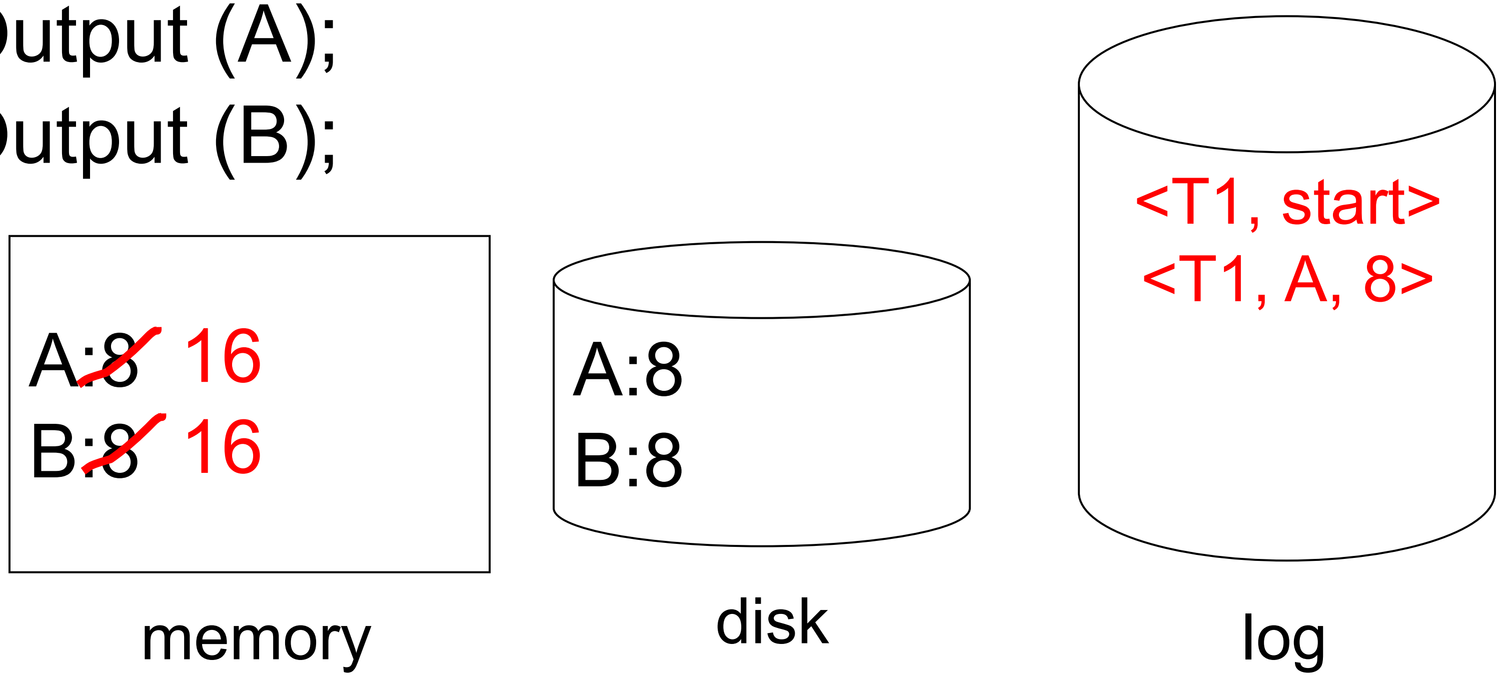

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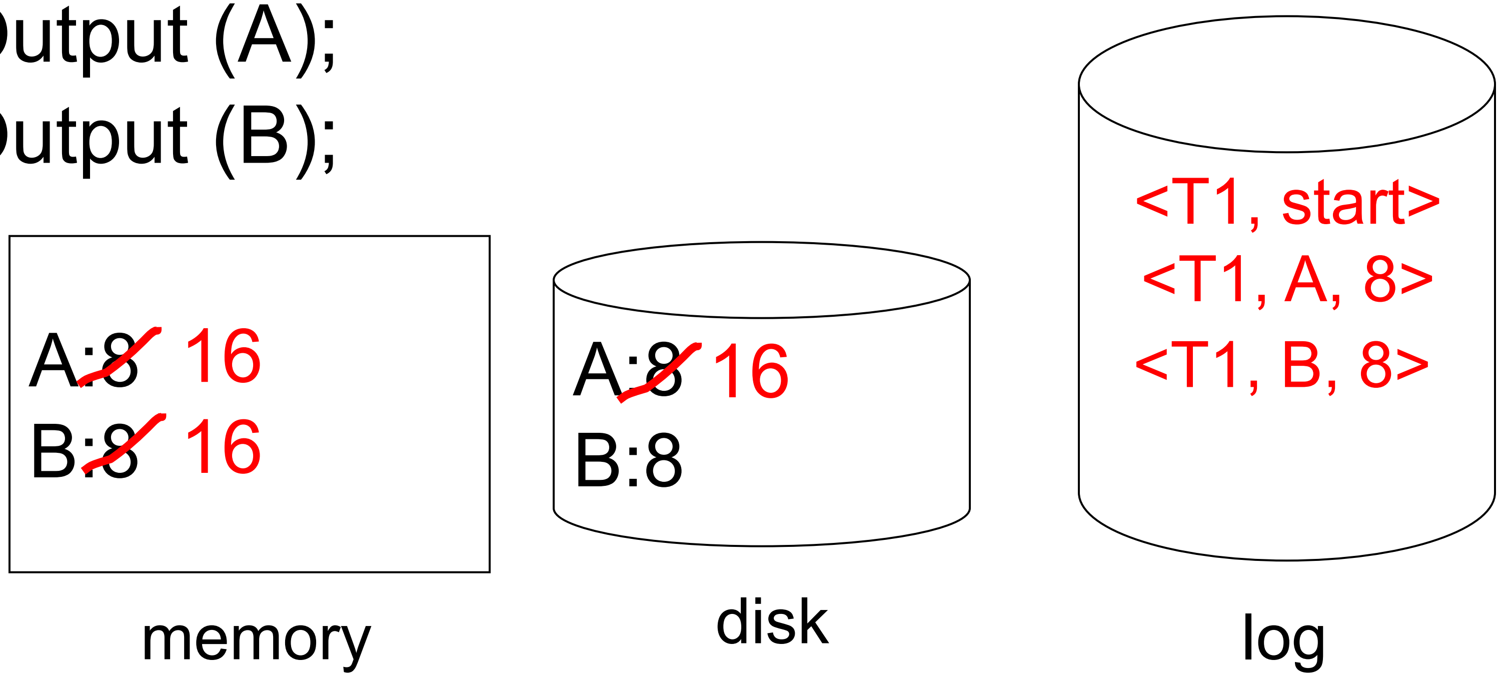

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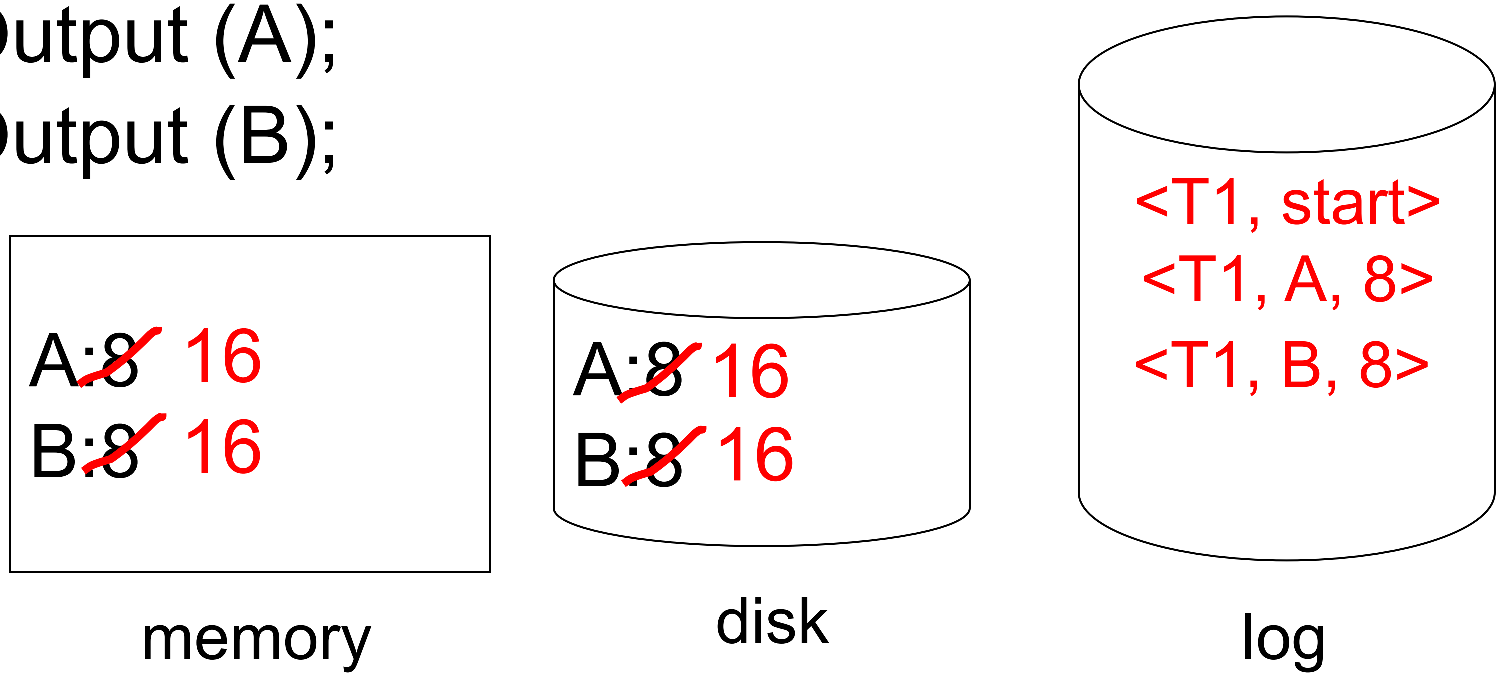
Write (A,t);

Read (B,t); $t \leftarrow t \times 2$

Write (B,t);

Output (A);

Output (B);



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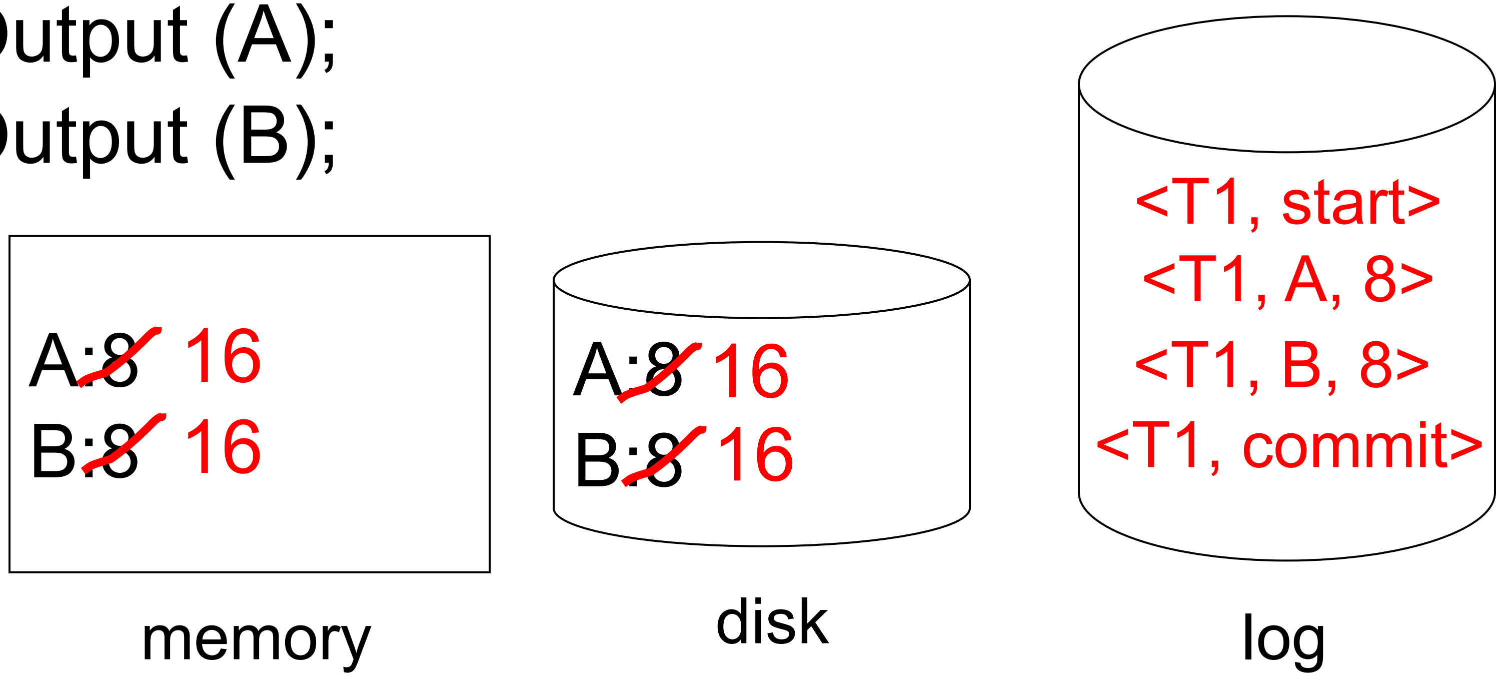
T1: Read (A,t); $t \leftarrow t \times 2$ A=B
Write (A,t);
Read (B,t); $t \leftarrow t \times 2$
Write (B,t);
Output (A);
Output (B);



Downsides of Undo Logging

Have to do a lot of I/O to commit (write all updated objects to disk first)

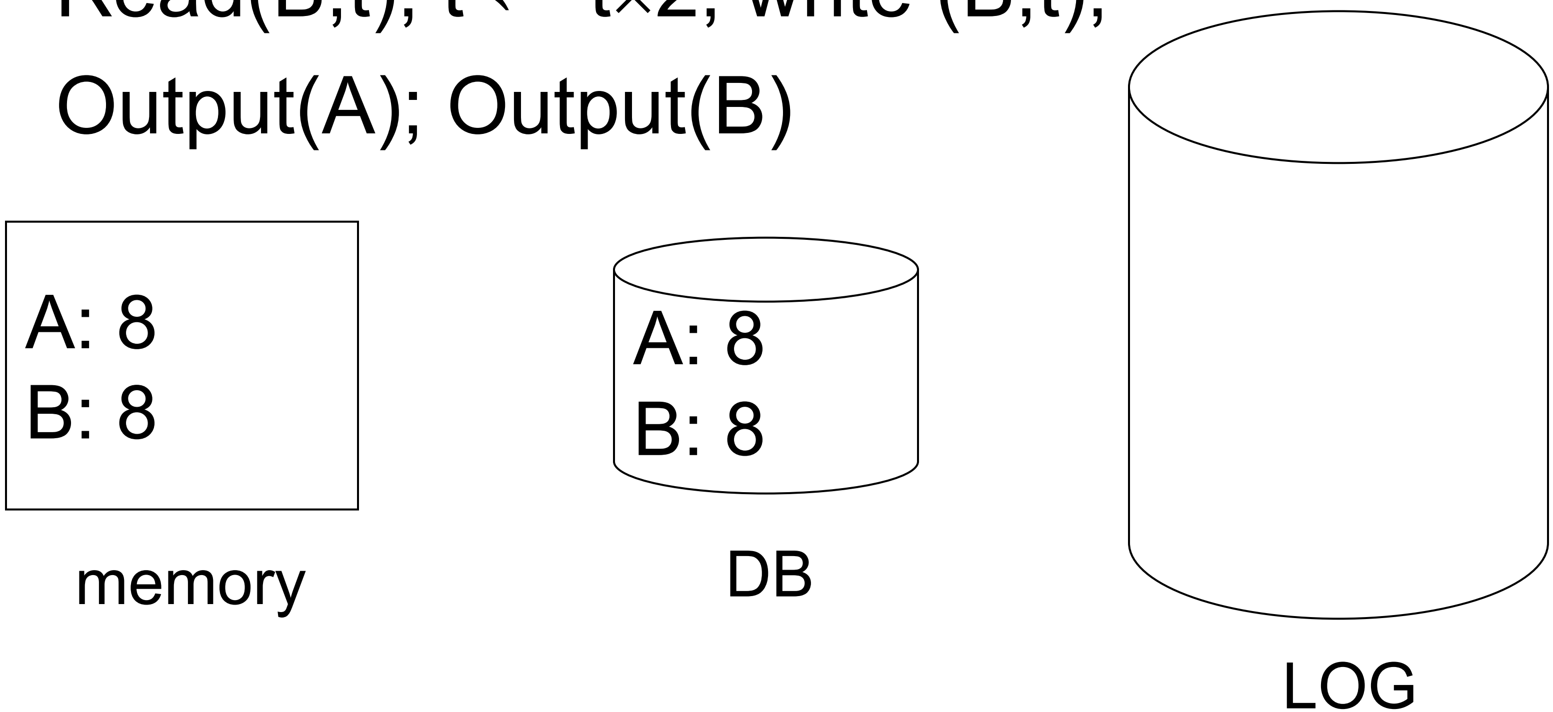
Hard to replicate database to another disk (must push **all** changes across the network)

Redo Logging

First send Gretel up with no rope,
then Hansel goes up safely with rope!

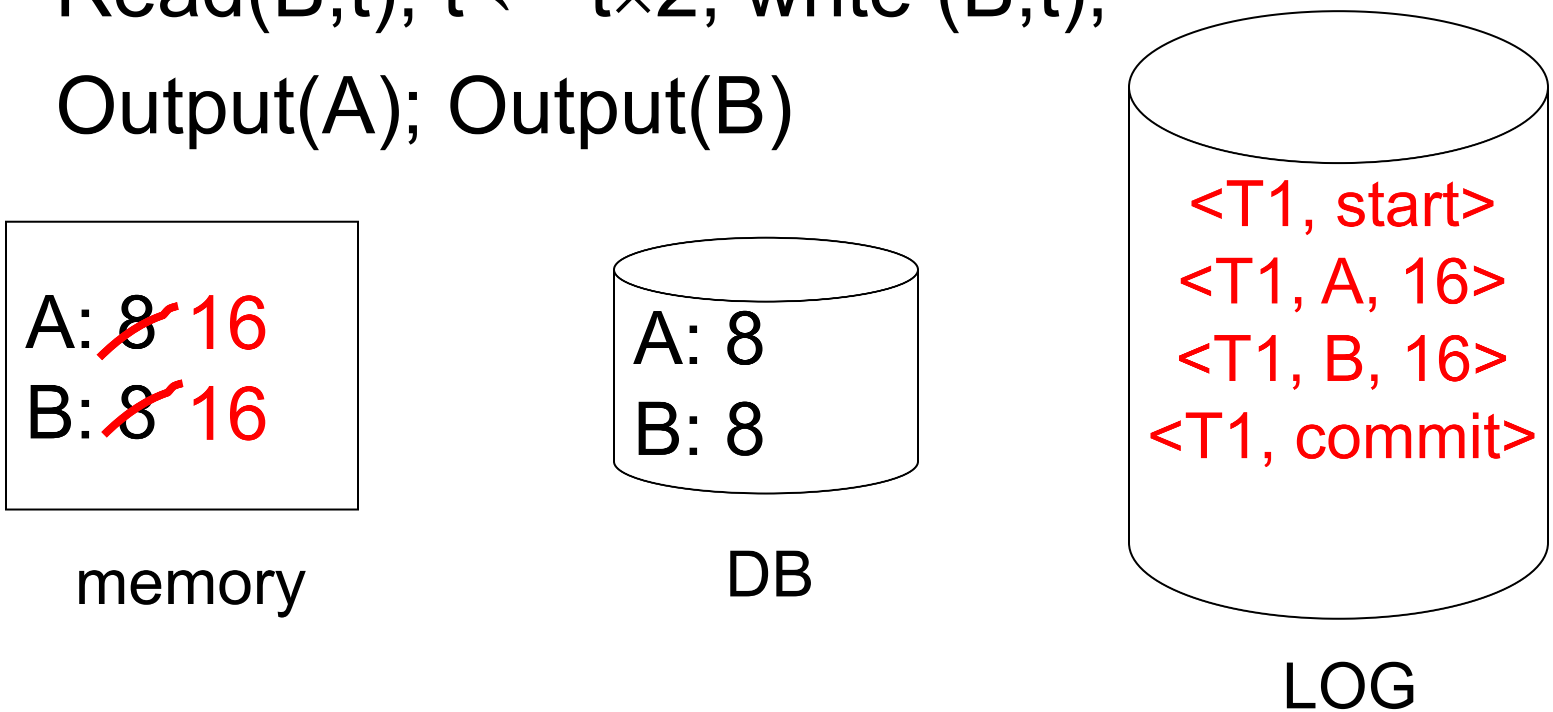
Redo Logging (deferred modification)

T1: 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)



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)



Redo Logging (deferred modification)

T1: Read(A,t); t ← t×2; write (A,t);
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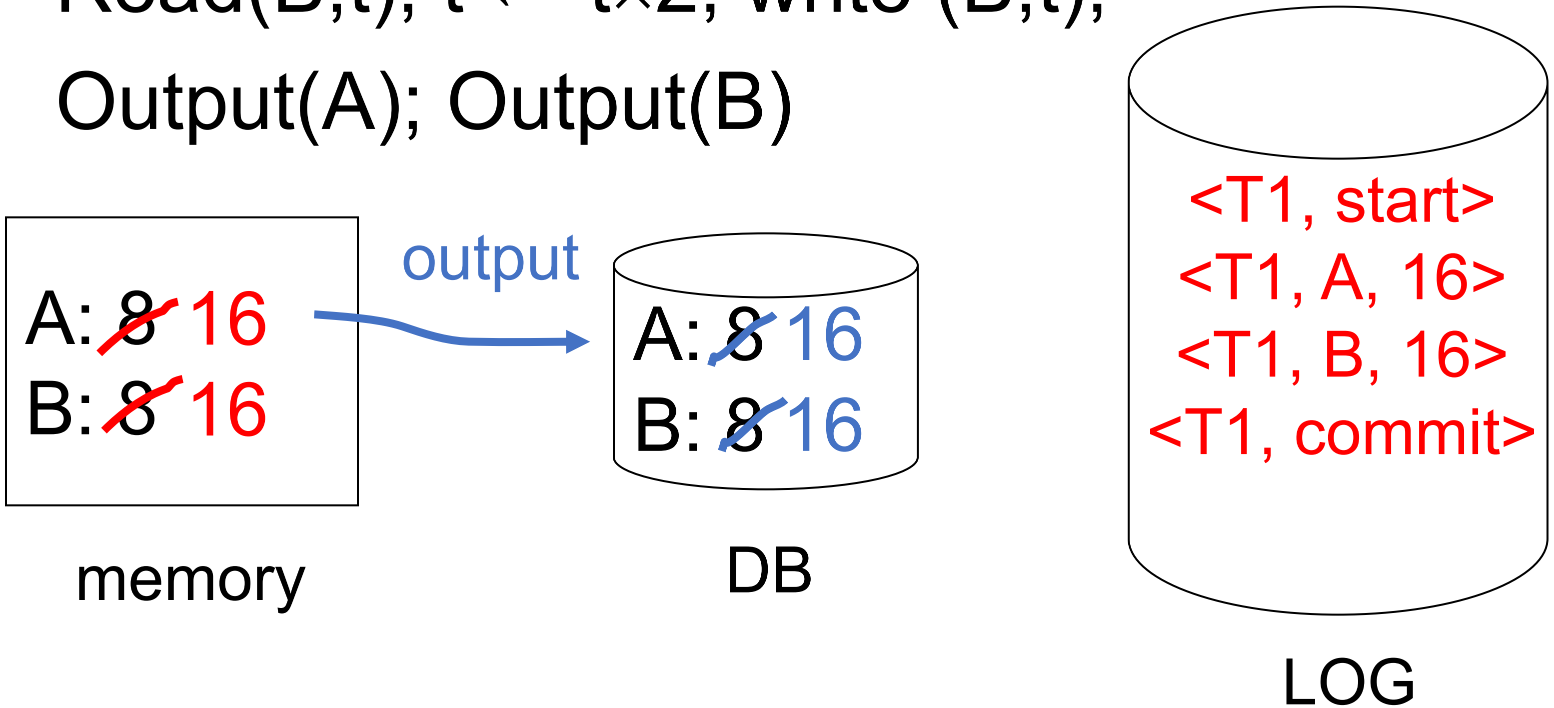
Output(A); Output(B)



Redo Logging (deferred modification)

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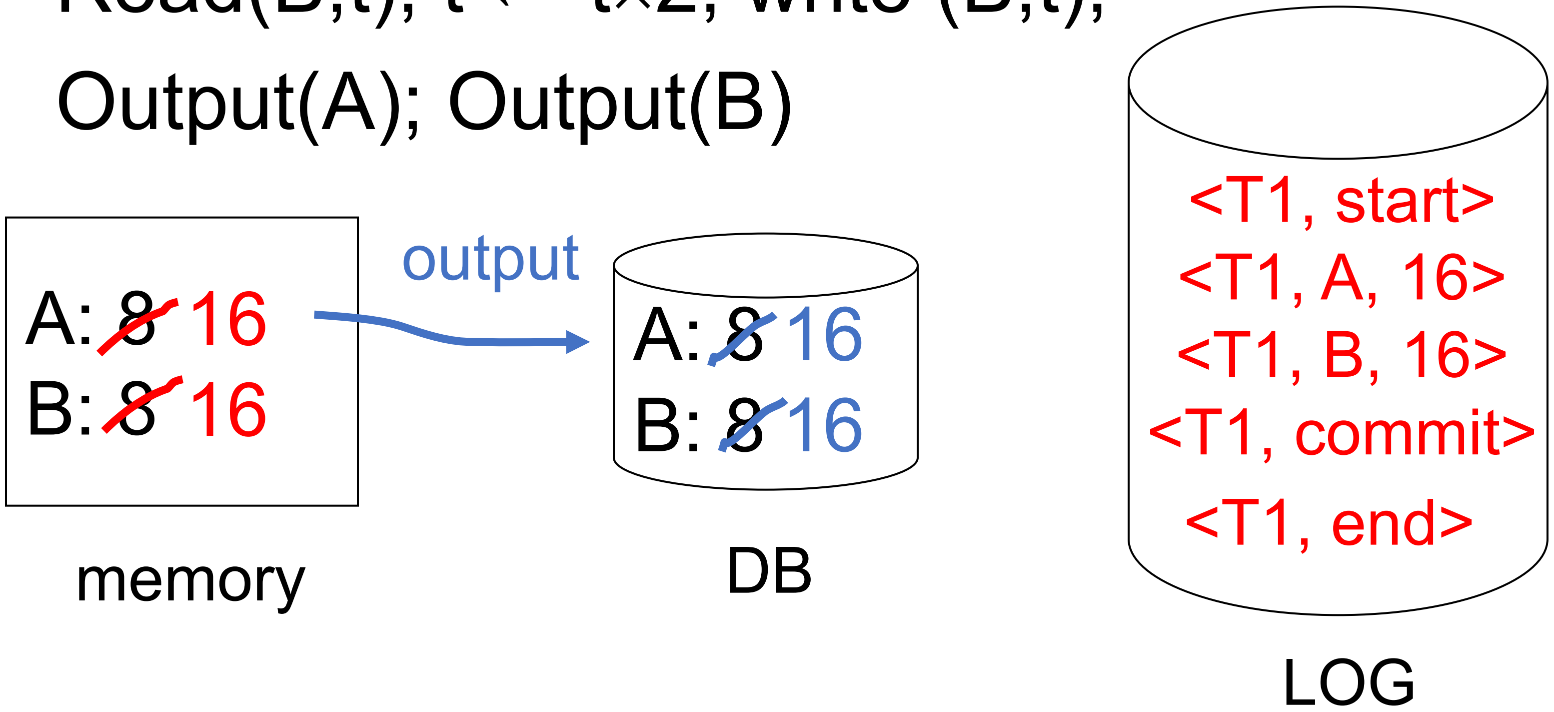

Redo Logging Rules

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

(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 { Write(X, v)
  Output(X)

(3) For each Ti ∈ S, write <Ti, end>

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...

<u>Actions:</u>
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...

<u>Actions:</u>
write X
~~output X~~
write X
~~output X~~
write X
~~output X~~
write X
output X

combined <end> record

Solution: Checkpoints

Simple, naïve checkpoint algorithm:

1. Stop accepting 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

Problems with Ideas So Far

Undo logging: need to wait for lots of I/O to commit; can't easily have backup copies of DB

Redo logging: need to keep all modified blocks in memory until commit

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Solution: Undo/Redo Logging!

Update = <Ti, X, new X val, old X val>

(X is the object updated)

Undo/Redo Logging Rules

Object X can be flushed **before or after** Ti commits

Log record (with undo/redo info) must be flushed before corresponding data (WAL)

Flush only commit record at Ti commit

Example: Undo/Redo Logging What to Do at Recovery?

Undo/redo log (disk):

...	<checkpoint>	...	<T1, A, 10, 15>	...	<T1, B, 20, 23>	...	<T1, commit>	...	<T2, C, 30, 38>	...	<T2, D, 40, 41>	Crash

Example: Undo/Redo Logging What to Do at Recovery?

Undo/redo log (disk):

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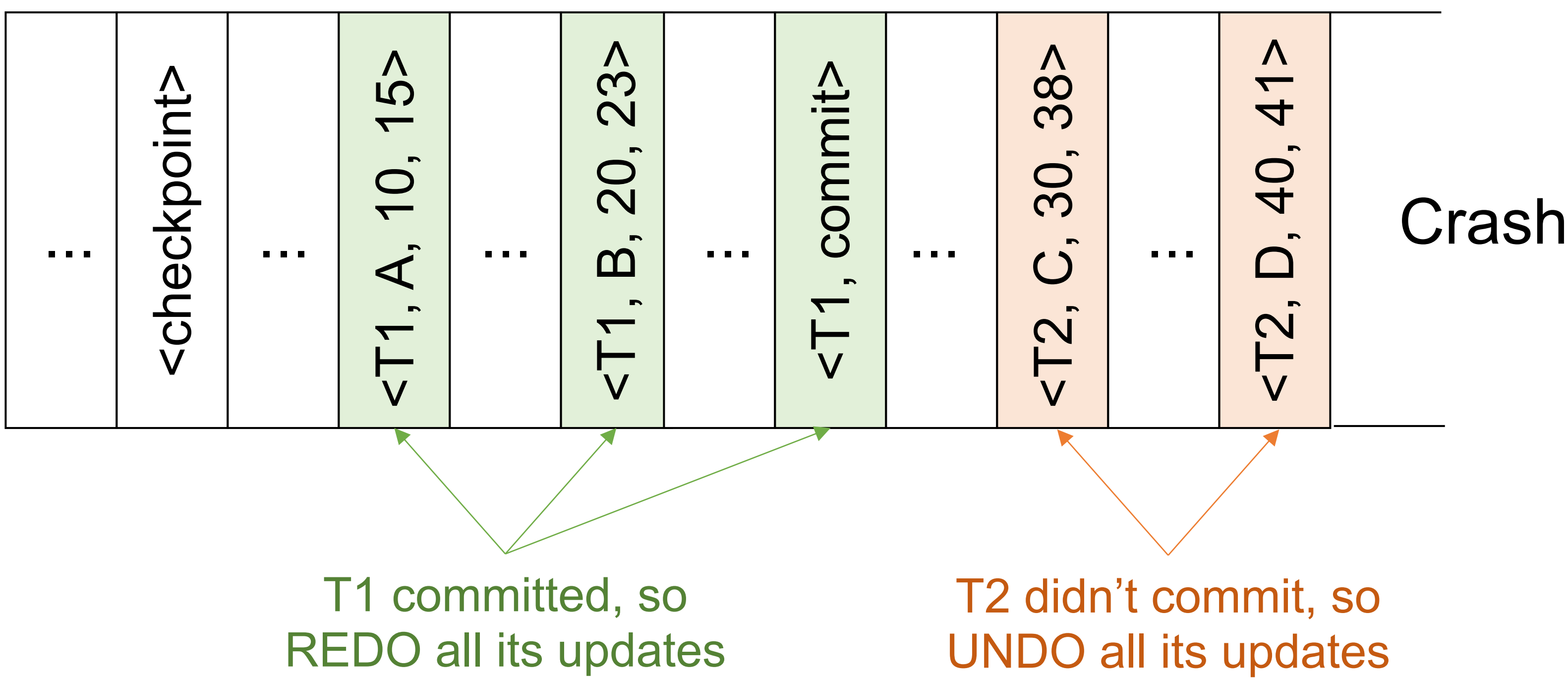
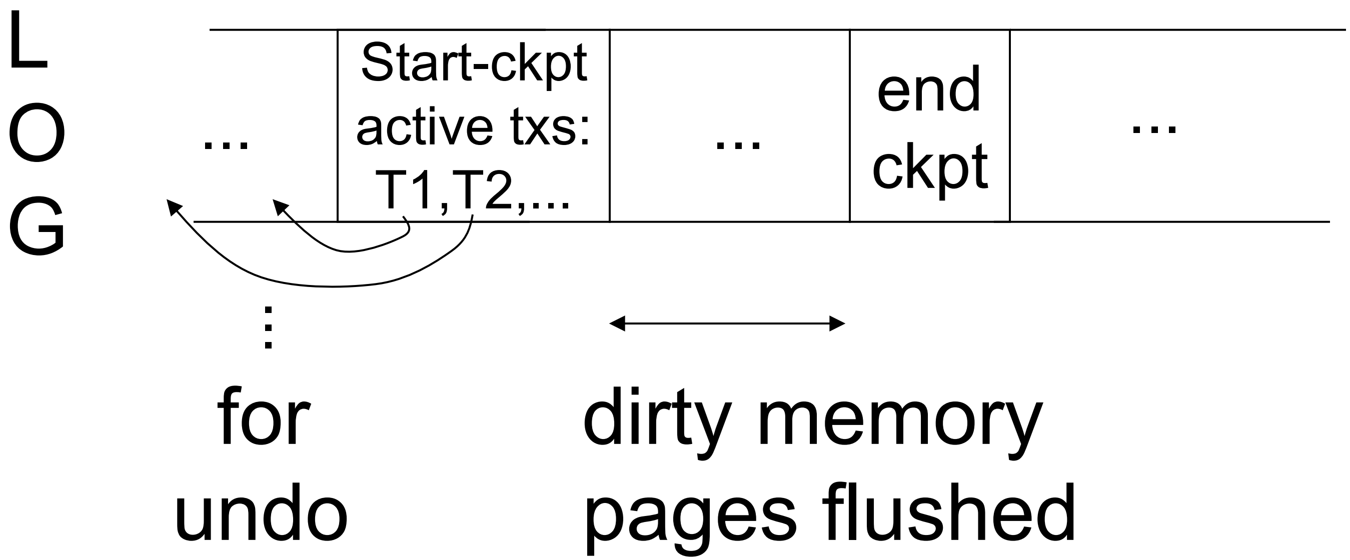
Undo/redo log (disk):



Non-Quiescent Checkpoints



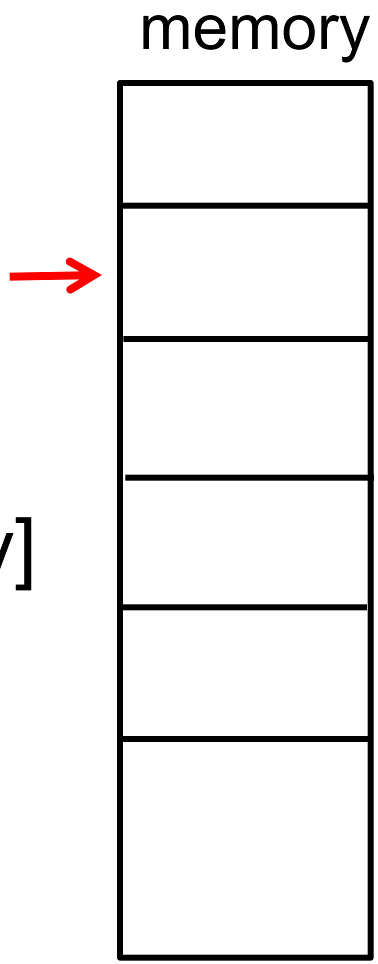
Non-Quiescent Checkpoints

checkpoint process:

for i := 1 to M do

    output(buffer i)

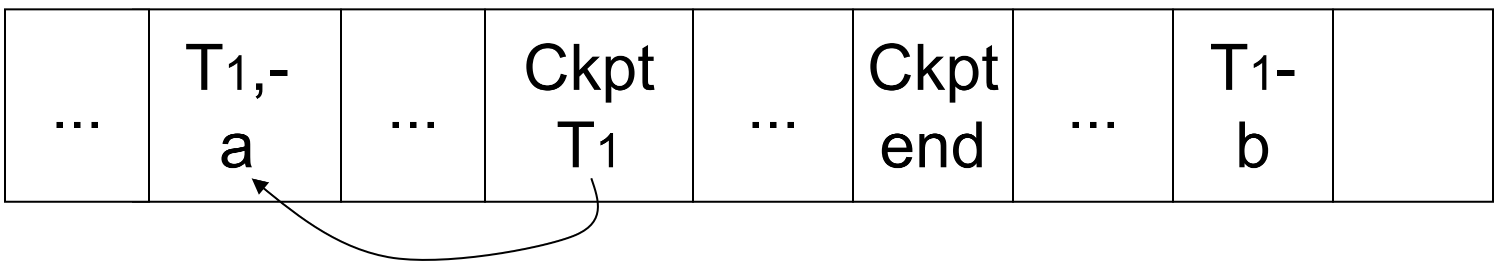
[transactions run concurrently]



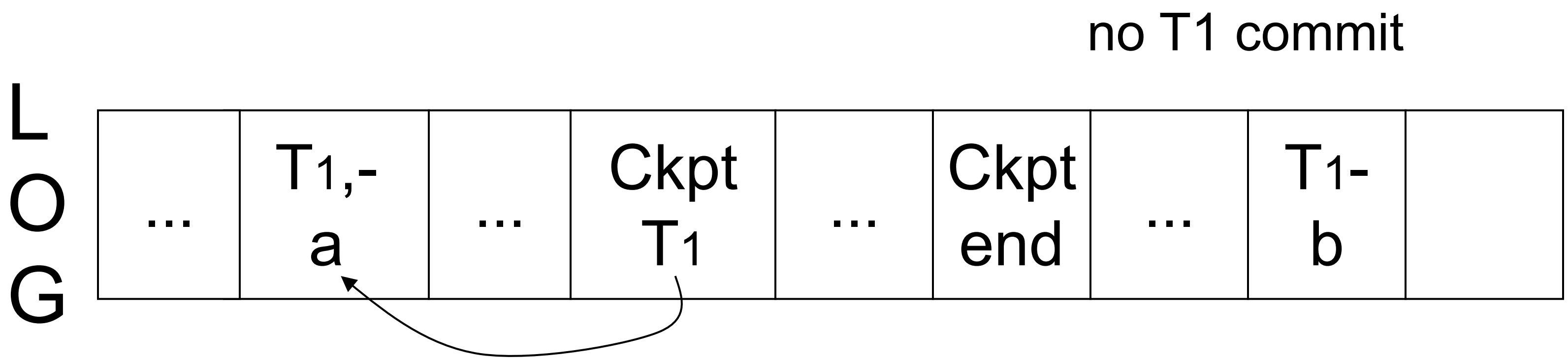
Example 1: How to Recover?

no T1 commit

L
O
G

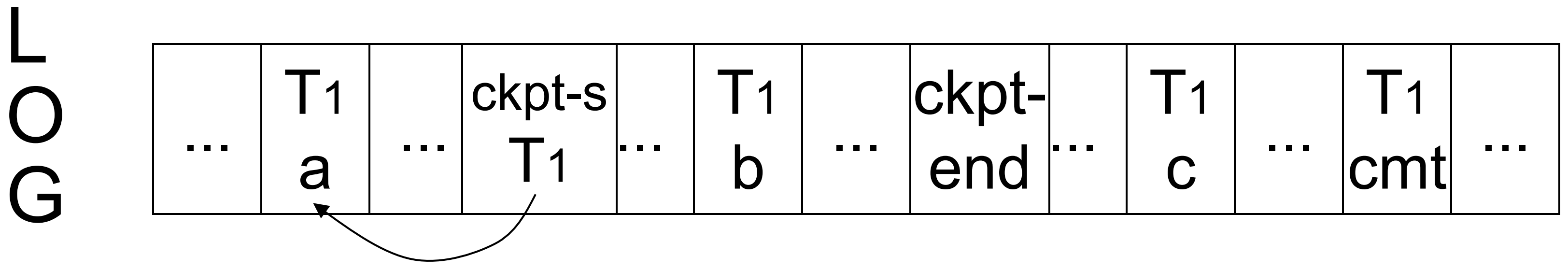


Example 1: How to Recover?

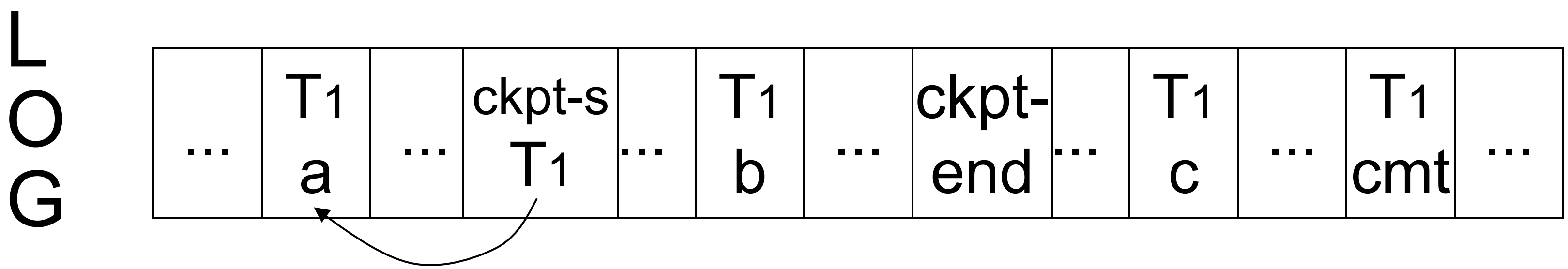


Undo T_1 (undo a,b)

Example 2: How to Recover?

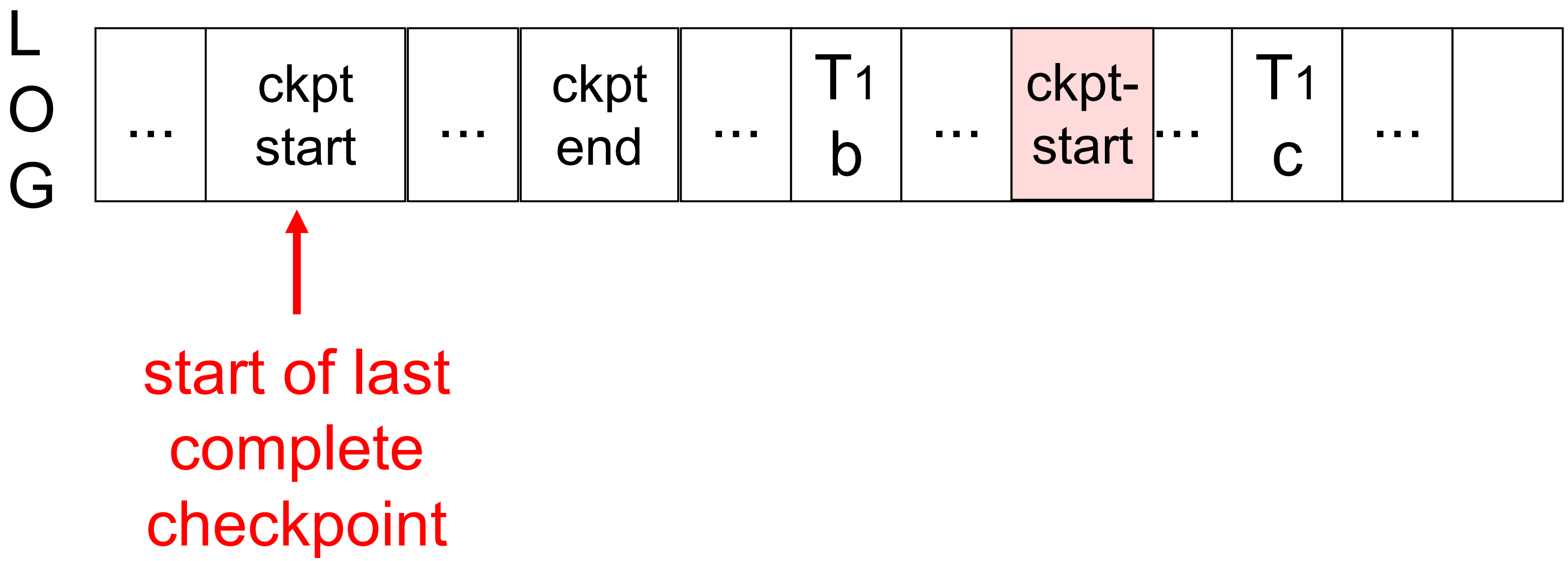


Example 2: How to Recover?



Redo T1: (redo b,c)

What if a Checkpoint Does Not Complete?



Start recovery from last **complete** checkpoint

Undo/Redo Recovery Process

Backward pass (end of log → latest valid checkpoint start)

» construct set S of committed transactions

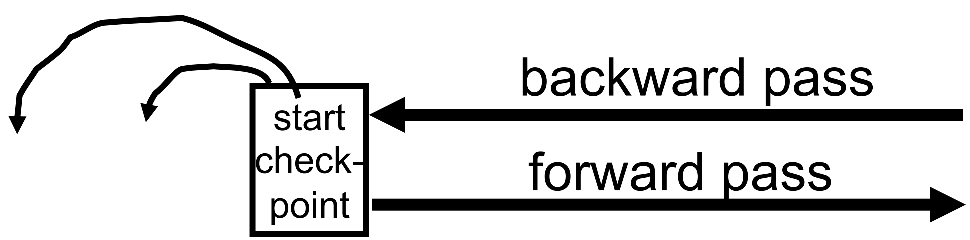
» undo actions of transactions not in S

Undo pending transactions

» follow undo chains for transactions in (checkpoint's active list) - S

Forward pass (latest checkpoint start → end of log)

» redo actions of all transactions in S



Outline

Recap from last time

Redo logging

Undo/redo logging

External actions

Media failures

External Actions

E.g., dispense cash at ATM

Ti = a1 a2 …... aj …... an

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Solution

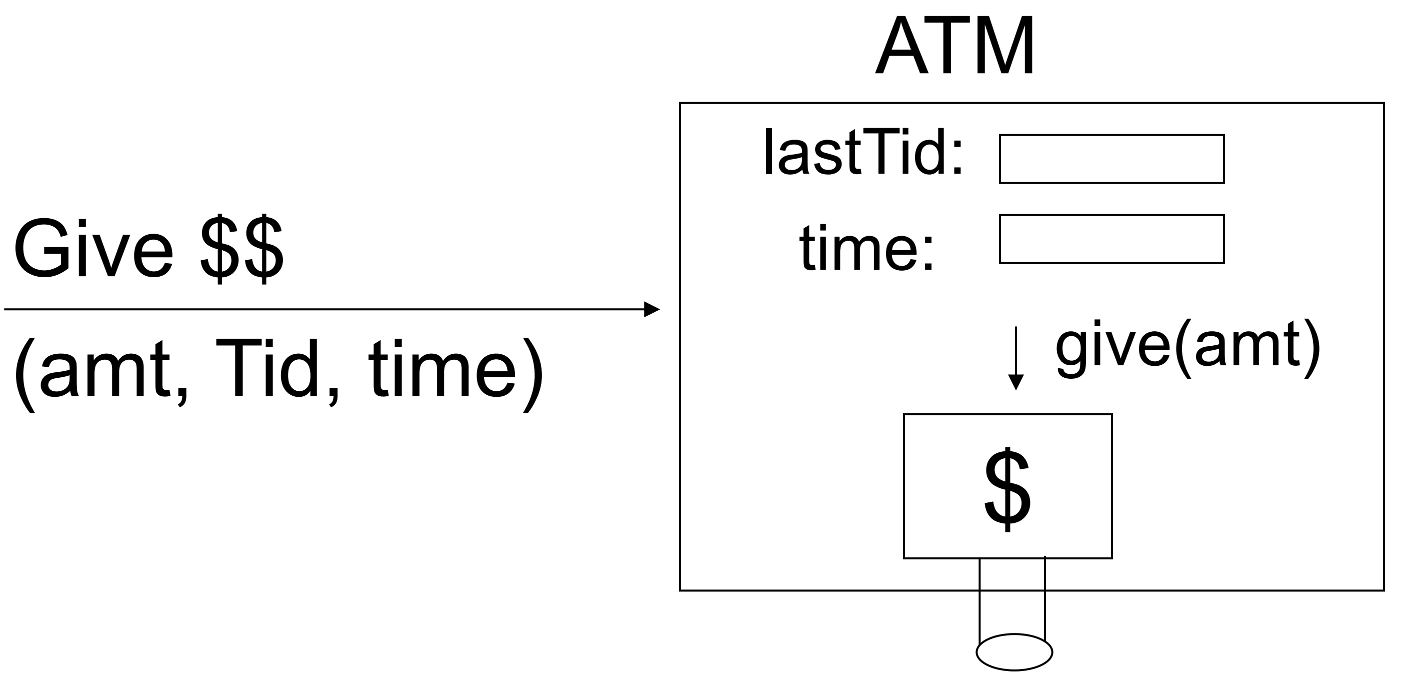
(1) Execute external actions after commit

(2) Try to make idempotent

Solution

(1) Execute real-world actions after commit

(2) Try to make idempotent



How Would You Handle These Other External Actions?

Charge a customer's credit card

Cancel someone's hotel room

Send data into a streaming system

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Recap from last time

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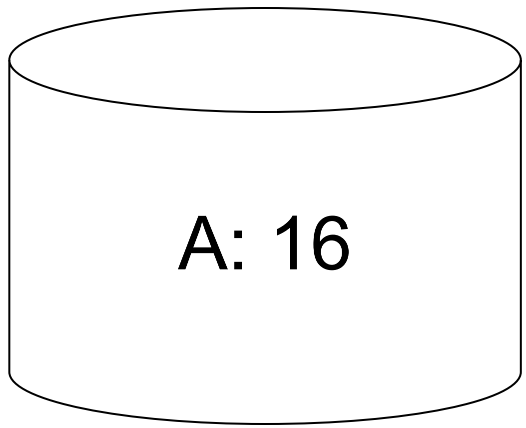
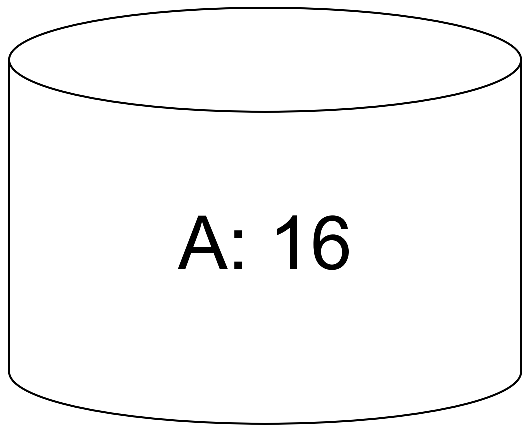
Media Failure (Loss of Nonvolatile Storage)



Media Failure (Loss of Nonvolatile Storage)



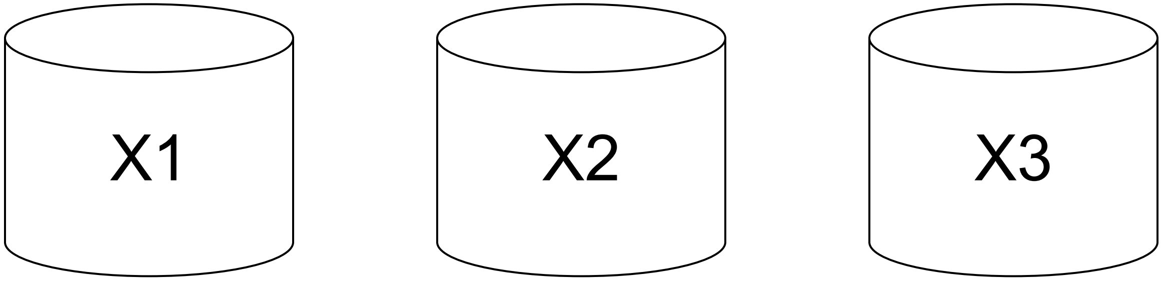
Solution: Make copies of data!

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

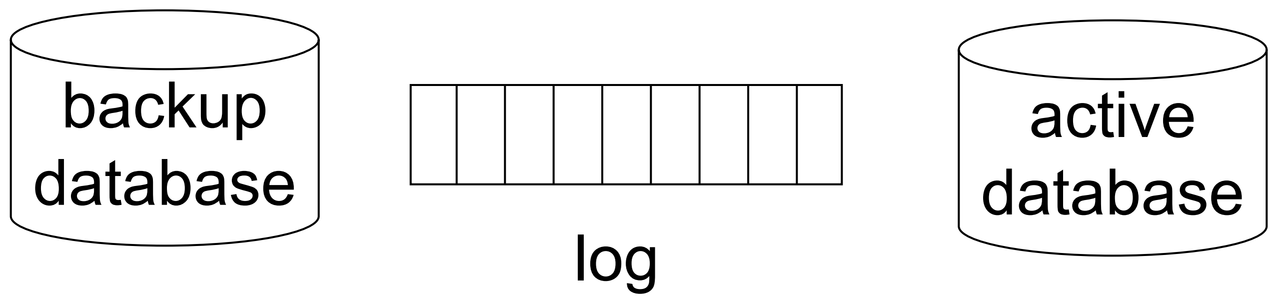
Keep N copies on separate disks

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,

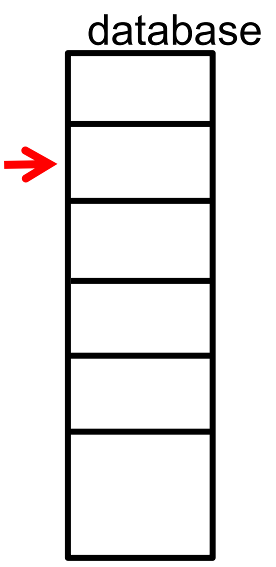
– restore active database from backup
– bring up-to-date using redo entries in log

Backup Database

Just like checkpoint, except that we write full database

create backup database:
for i := 1 to DB_Size do
   [read DB block i; write to backup]

[transactions run concurrently]



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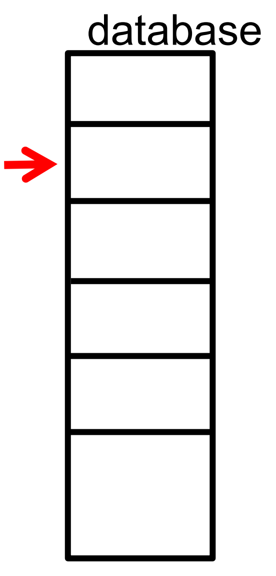
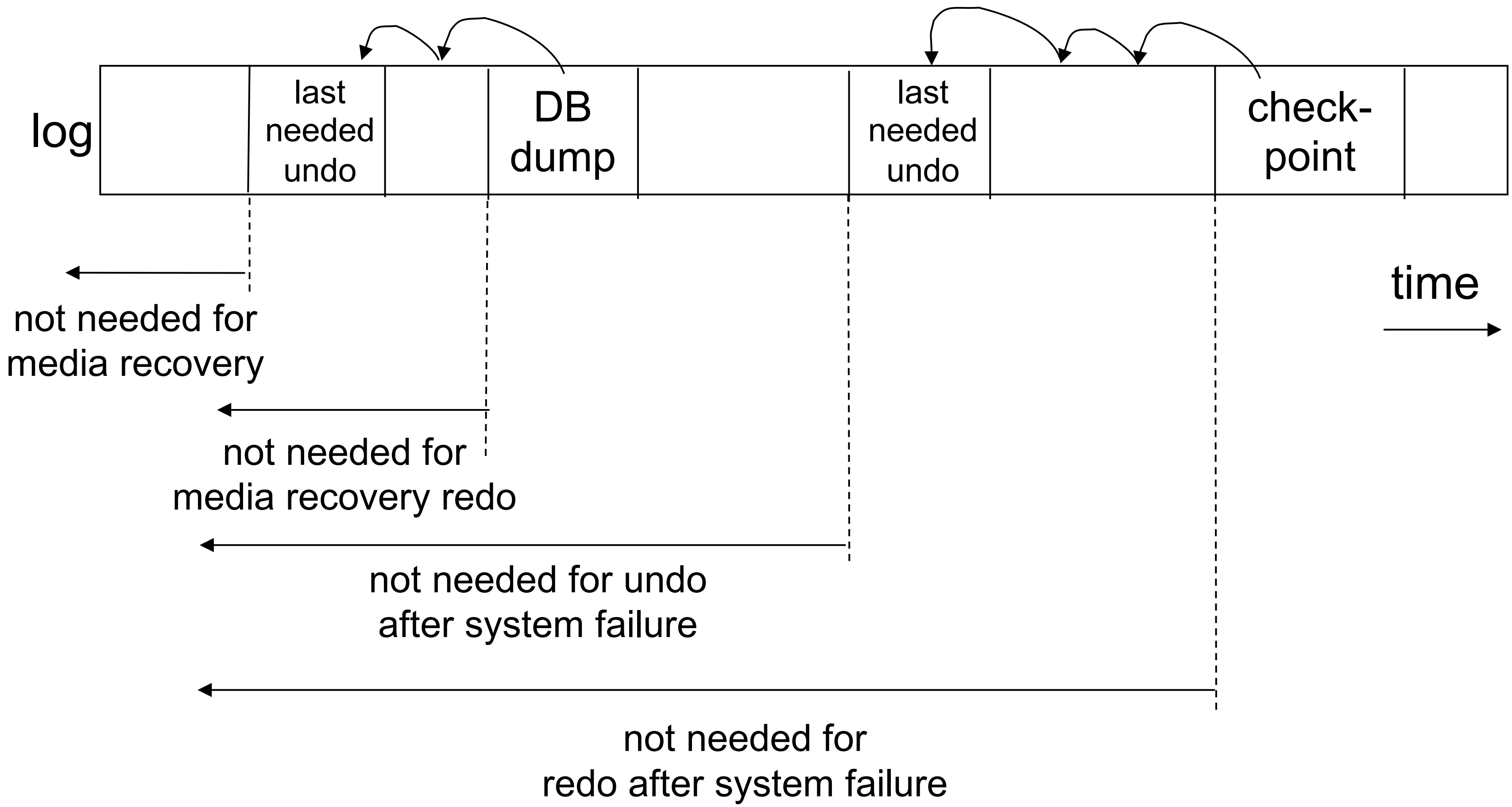


Restore from backup DB and log:
Similar to recovery from checkpoint and log

When Can Log Be Discarded?



Summary

Consistency of data: maintain constraints

One source of problems: failures

- » Logging
- » Redundancy

Another source of problems: data sharing

- » We'll cover this next!

Concurrency Control

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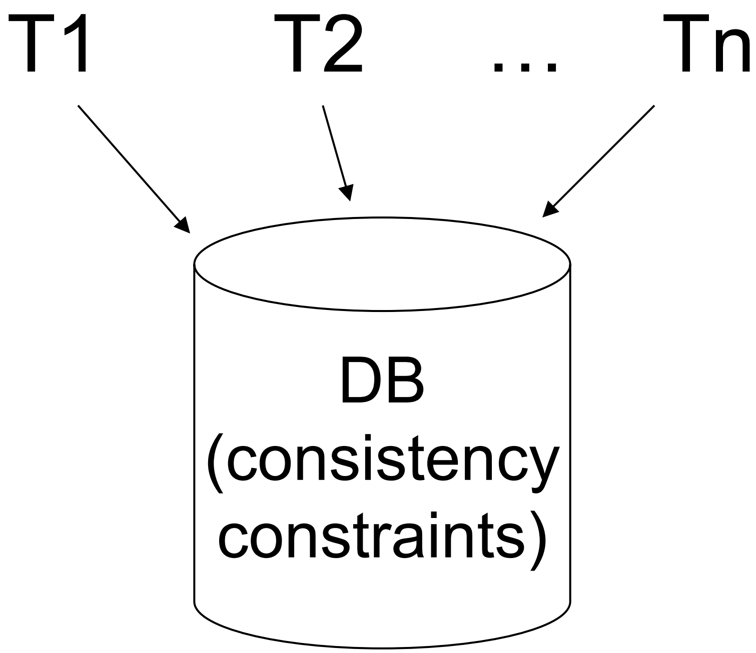
The Problem



Different transactions may need to access data items at the same time, violating constraints

Example

Constraint: all interns have equal salaries

T1: add $1000 to each intern's salary

T2: double each intern's salary

Salaries:					
	~~2000~~	~~2000~~	~~2000~~	~~2000~~	~~2000~~
	~~3000~~	~~3000~~	~~3000~~	~~4000~~	~~4000~~
	6000	6000	6000	5000	5000

😱

The Problem

Even if each transaction maintains constraints by itself, interleaving their actions does not

Could try to run just one transaction at a time (**serial schedule**), but this has problems

» **Too slow!** Especially with external clients & IO

High-Level Approach

Define **isolation levels**: sets of guarantees about what transactions may experience

Strongest level: **serializability** (result is same as some serial schedule)

Many others possible: **snapshot isolation**, **read committed**, **read uncommitted**, …

Fundamental Tradeoff

Stronger isolation level

Weaker isolation level

Easier to reason about
(can’t see others’ changes)

See others’ changes,
but more concurrency

Interesting Fact

SQL standard defines serializability as "same as a serial schedule", but then also lists 3 types of "anomalies" to define levels:

Isolation Level	Dirty Reads	Unrepeatable Reads	Phantom Reads
Read uncommitted	Y	Y	Y
Read committed	N	Y	Y
Repeatable read	N	N	Y
Serializable	N	N	N

Interesting Fact

There are isolation levels other than serializability that meet the 2nd definition!

» I.e. don't exhibit those 3 anomalies

Virtually no commercial DBs do serializability by default, and some can't do it at all

Time to call the lawyers?

In This Course

We'll first discuss how to offer serializability

» Many ideas apply to other isolation levels

We'll see other isolation levels after

Outline

What makes a schedule serializable?

Conflict serializability

Precedence graphs

Enforcing serializability via 2-phase locking

» Shared and exclusive locks

» Lock tables and multi-level locking

Optimistic concurrency with validation

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Example

T1: Read(A)	T2: 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); $A \leftarrow A+100$	
Write(A);	
Read(B); $B \leftarrow B+100$;	
Write(B);	
	Read(A); $A \leftarrow A\times2$;
	Write(A);
	Read(B); $B \leftarrow B\times2$;
	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 $\leftarrow$ A$\times$2;
	Write(A);
	Read(B); B $\leftarrow$ B$\times$2;
	Write(B);
Read(A); A $\leftarrow$ A+100	
Write(A);	
Read(B); B $\leftarrow$ B+100;	
Write(B);	

Schedule B

T1	T2	A	B
		25	25
	Read(A); $A \leftarrow A \times 2$;		
	Write(A);	50	
	Read(B); $B \leftarrow B \times 2$;		
	Write(B);		50
Read(A); $A \leftarrow A+100$			
Write(A);		150	
Read(B); $B \leftarrow B+100$;			
Write(B);			150
		150	150

Schedule C

T1	T2
Read(A); A $\leftarrow$ A+100	
Write(A);	
	Read(A); A $\leftarrow$ A$\times$2;
	Write(A);
Read(B); B $\leftarrow$ B+100;	
Write(B);	
	Read(B); B $\leftarrow$ B$\times$2;
	Write(B);

Schedule C

T1	T2	A	B
		25	25
Read(A); A $\leftarrow$ A+100			
Write(A);		125	
	Read(A); A $\leftarrow$ A$\times$2;		
	Write(A);	250	
Read(B); B $\leftarrow$ B+100;			
Write(B);			125
	Read(B); B $\leftarrow$ B$\times$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); $A \leftarrow A+100$			
Write(A);		125	
	Read(A); $A \leftarrow A \times 2$;		
	Write(A);	250	
	Read(B); $B \leftarrow B \times 2$;		
	Write(B);		50
Read(B); $B \leftarrow B+100$;			
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+50;
	Write(A);
	Read(B); B ← B+50;
	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+50;		
	Write(A);	175	
	Read(B); B ← B+50;		
	Write(B);		75
Read(B); B ← B+100;			
Write(B);			175
		175	175

Our Goal

Want schedules that are “good”, regardless of

» initial state and

» transaction semantics ← We don’t know the logic in external client apps!

Only look at **order of read & write operations**

Example:

$$Sc = r_1(A)w_1(A)r_2(A)w_2(A)r_1(B)w_1(B)r_2(B)w_2(B)$$

Example:

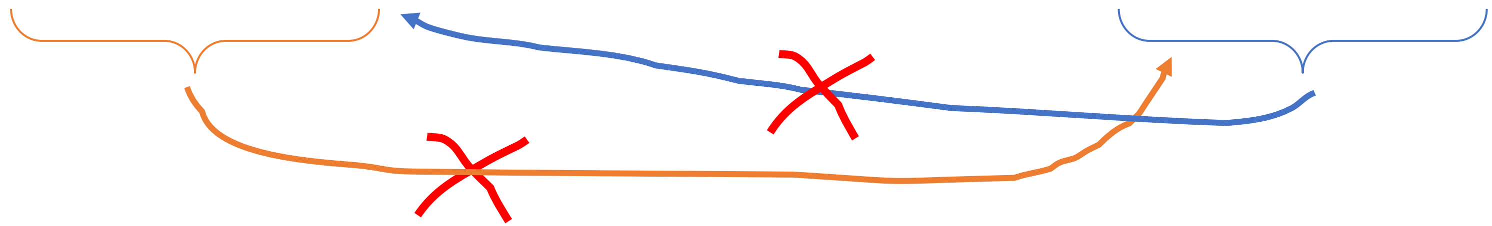
$$S_C = r1(A)w_1(A)r_2(A)w_2(A)r_1(B)w_1(B)r_2(B)w_2(B)$$

$$S_C' = r_1(A)w_1(A)r_1(B)w_1(B)r_2(A)w_2(A)r_2(B)w_2(B)$$

T_1 T_2

However, for S_D:

$$S_D = r_1(A)w_1(A)r_2(A)w_2(A)\ r_2(B)w_2(B)r_1(B)w_1(B)$$



Another way to view this:

- » $r_1(B)$ after $w_2(B)$ means T_1 should be after T_2 in an equivalent serial schedule ($T_2 \rightarrow T_1$)
- » $r_2(A)$ after $w_1(A)$ means T_2 should be after T_1 in an equivalent serial schedule ($T_1 \rightarrow T_2$)
- » Can’t have both of these!

Returning to S_C

$S_C = r_1(A) w_1(A) r_2(A) w_2(A) r_1(B) w_1(B) r_2(B) w_2(B)$

$T_1 \rightarrow T_2$ $\qquad$ $T_1 \rightarrow T_2$

No cycles $\Rightarrow$ Sc is equivalent to a serial schedule (in this case T_1, T_2)

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Precedence graphs

Enforcing serializability via 2-phase locking
- » Shared and exclusive locks
- » Lock tables and multi-level locking

Optimistic concurrency with validation