Crash Recovery

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Integrity or correctness of data

- Would like data to be “accurate” or “correct” at all times

EMP

Name	Age
White	52
Green	3421
Gray	1

Integrity or consistency constraints

- Examples of predicates data must satisfy:
  - x is key of relation R
  - $x \rightarrow y$ holds in R
  - Domain(x) = {Red, Blue, Green}
  - α is valid index for attribute x of R
  - no employee should make more than twice the average salary

Definition:

- Consistent state: satisfies all constraints
- Consistent DB: DB in consistent state

Constraints (as we use here) may not capture "full correctness"

Example 1 Transaction constraints

- When salary is updated,

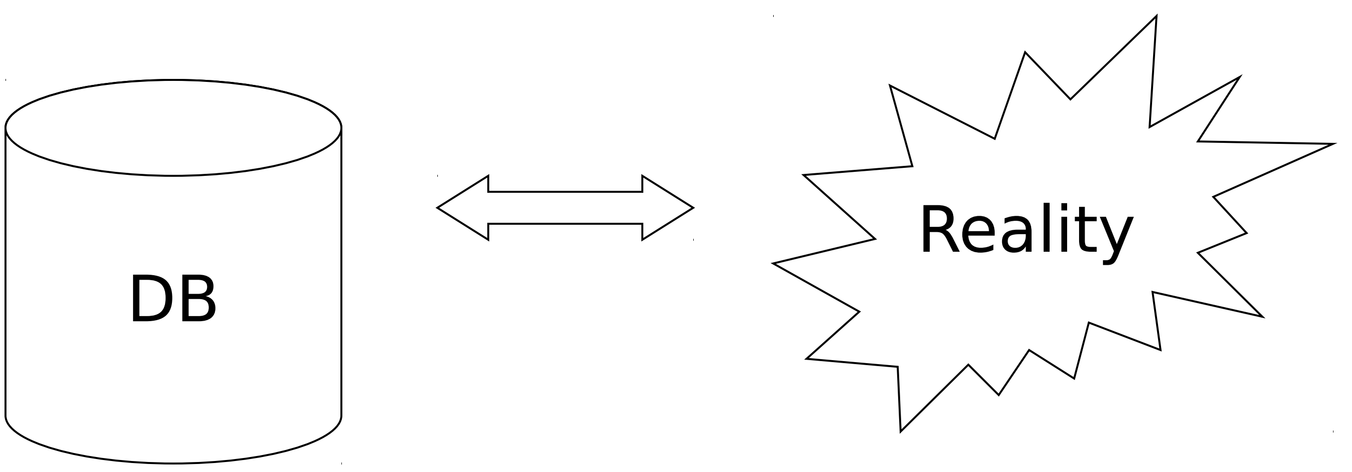
  new salary > old salary

- When account record is deleted,

  balance = 0

Constraints (as we use here) may not capture "full correctness"

Example 2   Database should reflect real world



☞ in any case, continue with constraints...

<u>Observation:</u> DB <u>cannot</u> always be consistent!

<u>Example:</u> $a_1 + a_2 + \ldots.\ a_n = TOT$ (constraint)

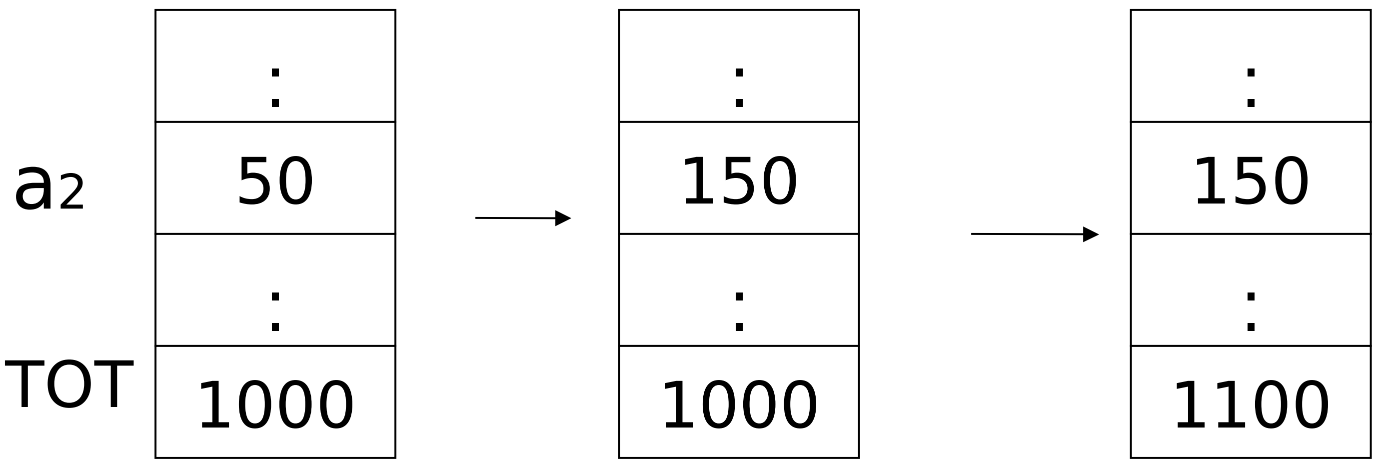
Deposit \$100 in a_2:

$$\left\{\begin{array}{l} a_2 \leftarrow a_2 + 100 \\ TOT \leftarrow TOT + 100 \end{array}\right.$$

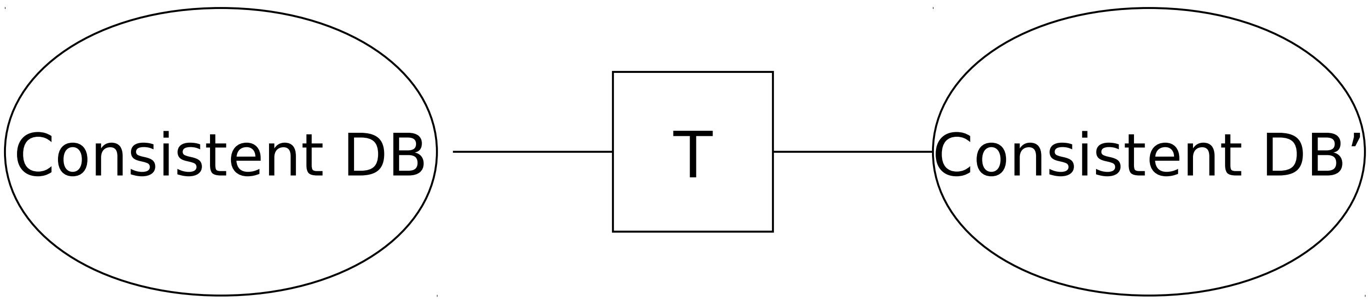
Example: $a_1 + a_2 + \ldots.\ a_n = TOT$ (constraint)

Deposit \$100 in a_2: $a_2 \leftarrow a_2 + 100$

$TOT \leftarrow TOT + 100$



<u>Transaction:</u> collection of actions
that preserve consistency



Big assumption:

If transaction T starts with consistent state + T executes in isolation

$\Rightarrow$ T leaves consistent state

Correctness (informally)

- If we stop running transactions,
  - DB left consistent
- Each transaction sees a consistent DB

How can constraints be violated?

- Transaction bug
- DBMS bug
- Hardware failure

    e.g., disk crash alters balance of account

- Data sharing

  e.g.: T1: give 10% raise to programmers

  T2: change programmers $\Rightarrow$ systems analysts

How can we prevent/fix violations?

- Chapter 17: due to failures only
- Chapter 18: due to data sharing only
- Chapter 19: due to failures and sharing

We will not consider:

- How to write correct transactions
- How to write correct DBMS
- Constraint checking & repair

  That is, solutions studied here do not need to know constraints

Crash Recovery

- First order of business:

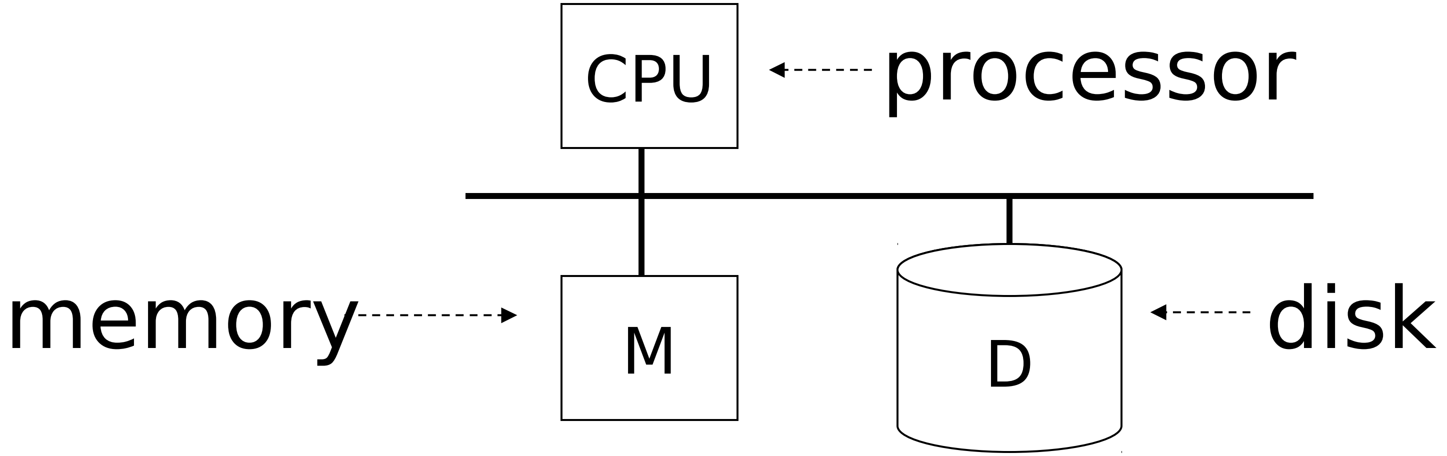
Failure Model

Events — Desired

Events — Undesired — Expected

Undesired — Unexpected

Our failure model



Desired events: see product manuals….

Undesired expected events:

System crash

- memory lost
- cpu halts, resets

Desired events: see product manuals....

Undesired expected events:

System crash

- memory lost
- cpu halts, resets

that's it!!

Undesired Unexpected: Everything else!

Undesired Unexpected: Everything else!

Examples:

- Disk data is lost
- Memory lost without CPU halt
- CPU implodes wiping out universe….

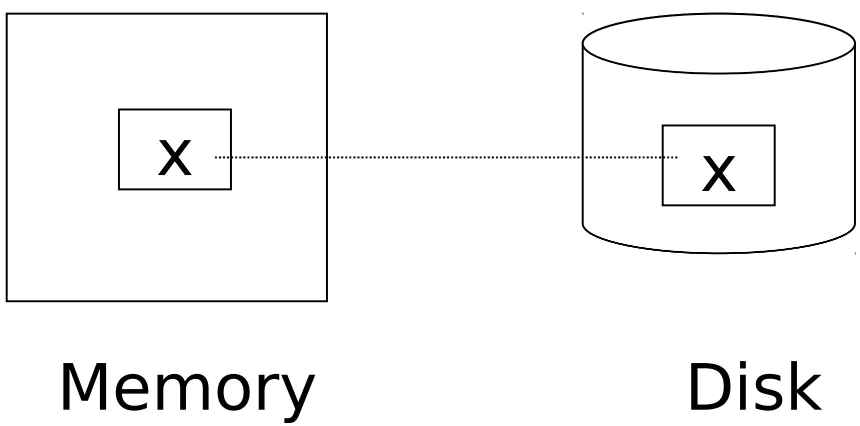
Is this model reasonable?

Approach: Add low level checks +
redundancy to increase
probability that model holds

E.g.,
- Replicate disk storage (stable store)
- Memory parity
- CPU checks

Second order of business:

Storage hierarchy



Operations:

- Input (x): block containing x $\rightarrow$ memory
- Output (x): block containing x $\rightarrow$ disk

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- Input (x): block containing x $\rightarrow$ memory
- Output (x): block containing x $\rightarrow$ disk

- Read (x,t): do input(x) if necessary
  t $\leftarrow$ value of x in block
- Write (x,t): do input(x) if necessary
  value of x in block $\leftarrow$ t

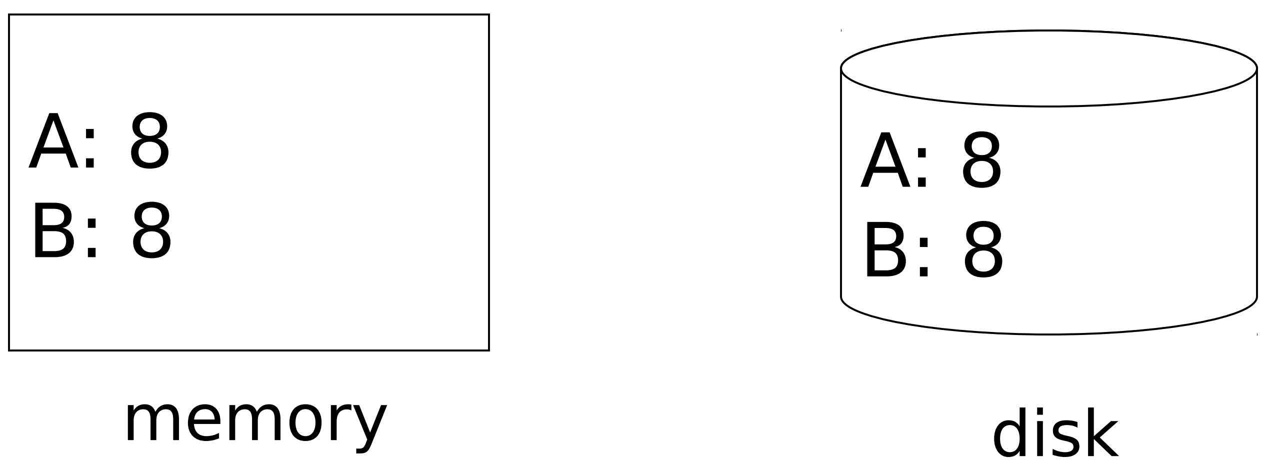
<u>Key problem</u> Unfinished transaction

Example Constraint: A=B

T_1: $A \leftarrow A \times 2$

$B \leftarrow B \times 2$

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



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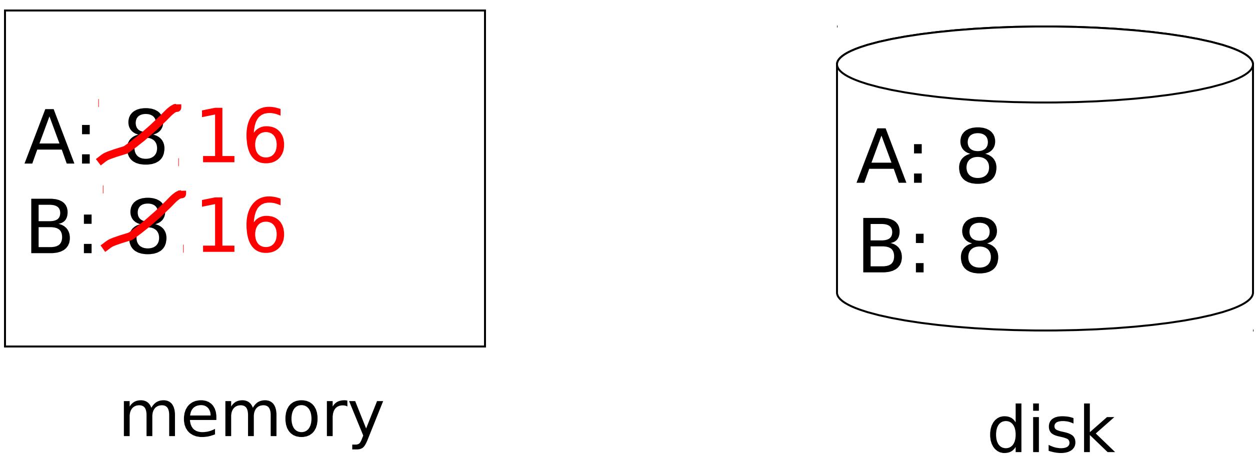


T_1: Read (A,t); $t \leftarrow t \times 2$
Write (A,t);
Read (B,t); $t \leftarrow t \times 2$
Write (B,t);
Output (A);
Output (B);

failure!

memory

disk

- Need atomicity:
  - execute all actions of a transaction or none at all

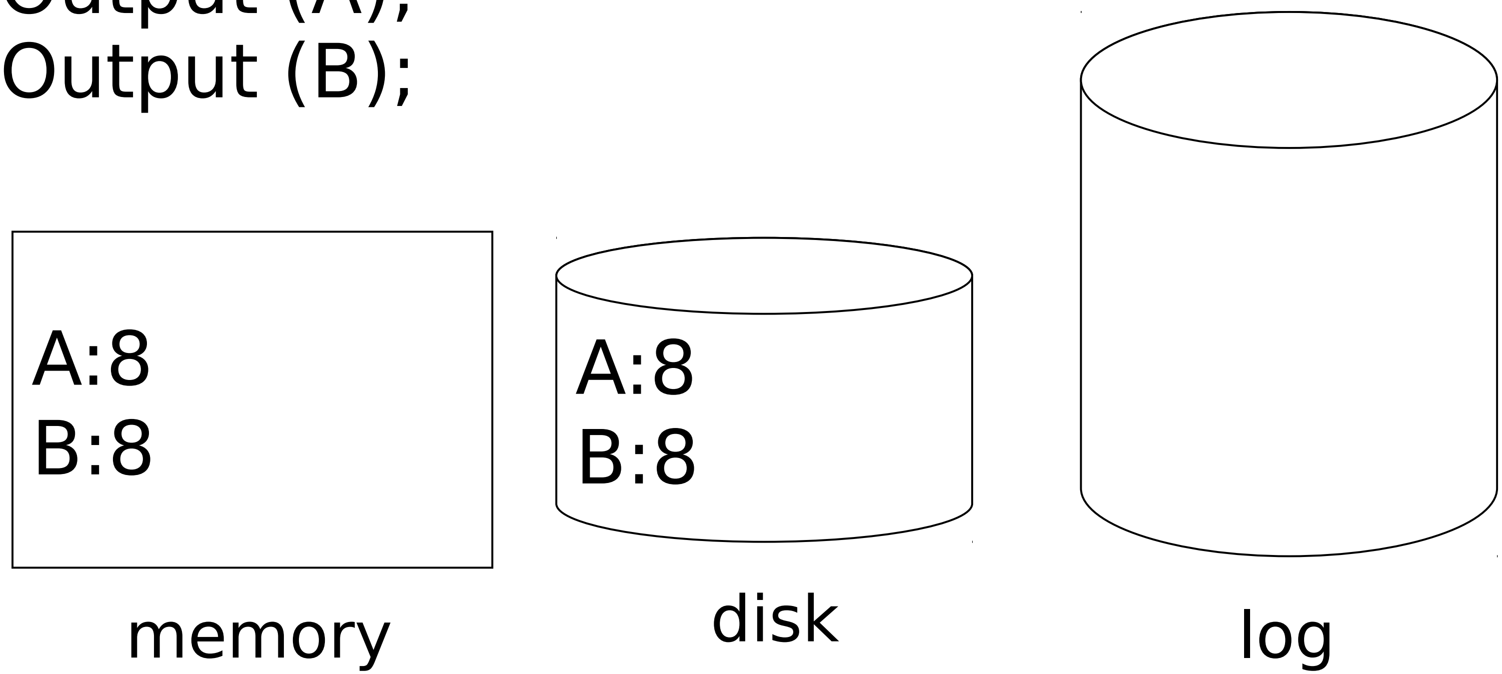
<u>One solution:</u> undo logging (immediate modification)

essentially due to:

- Hansel and Gretel, 782 AD

Undo logging (Immediate modification)

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);



Undo logging (Immediate modification)

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Write (A,t);
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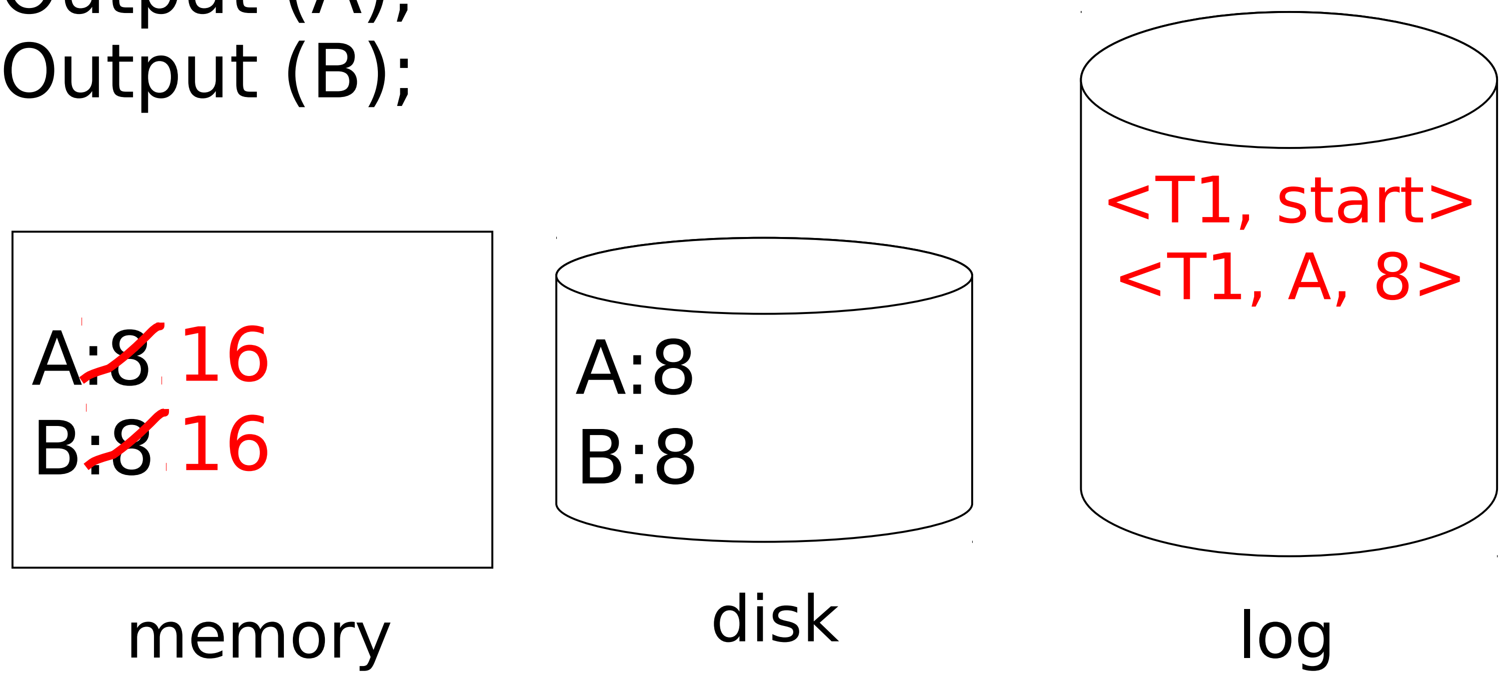

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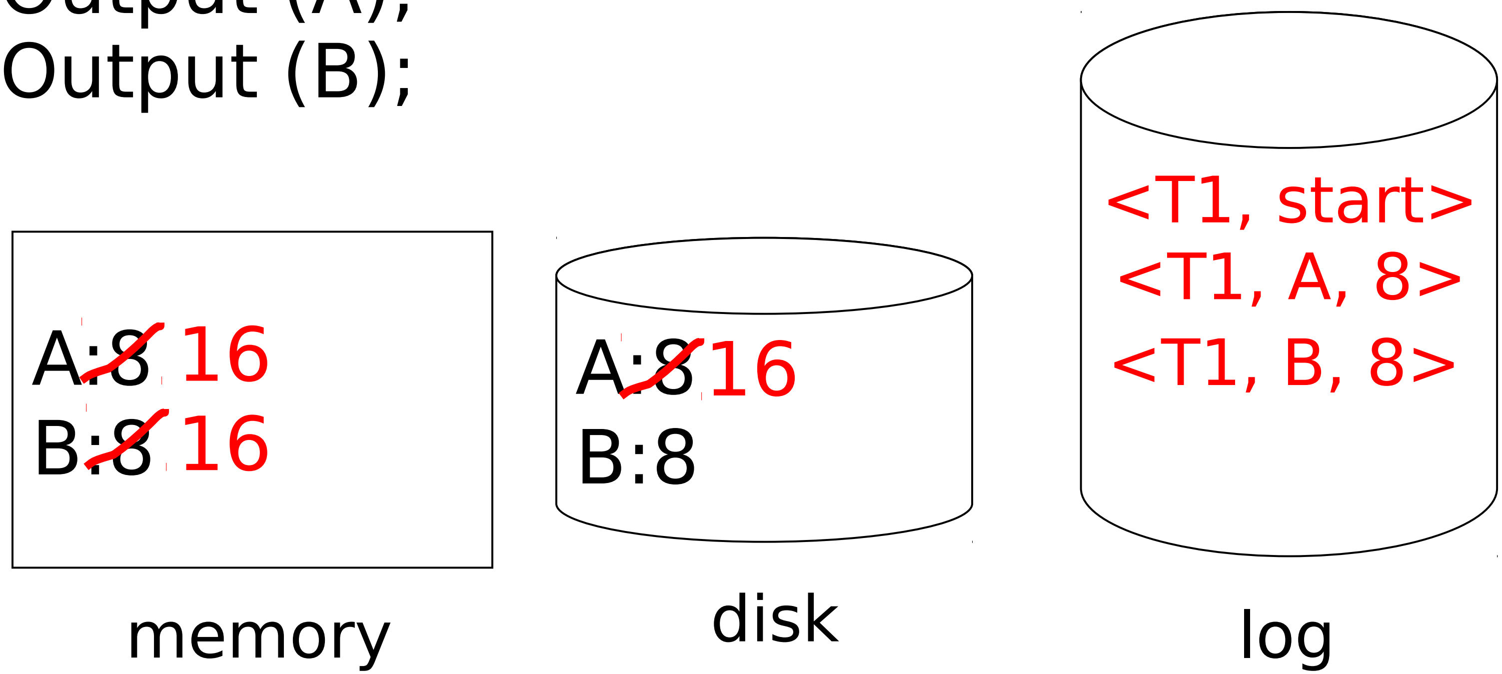

Undo logging (Immediate modification)

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Write (A,t);
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Output (A);
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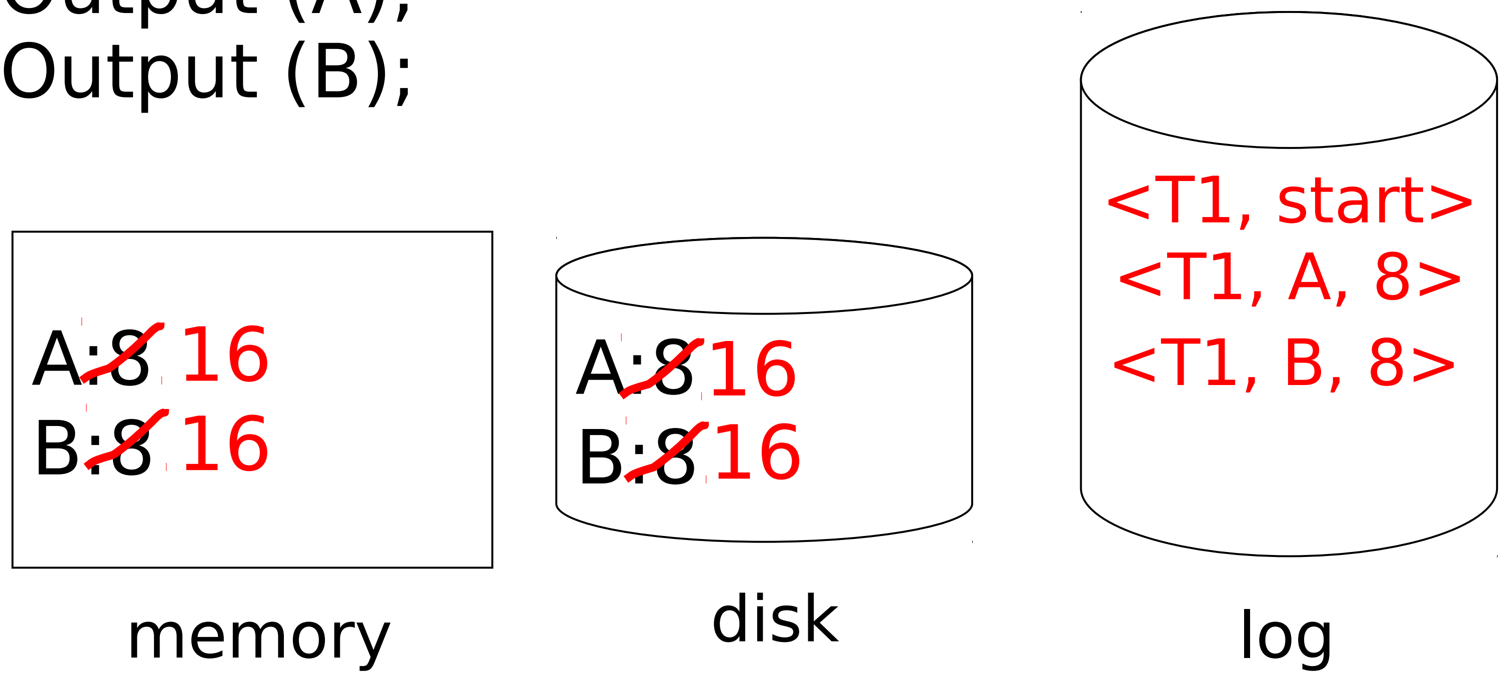

Undo logging (Immediate modification)

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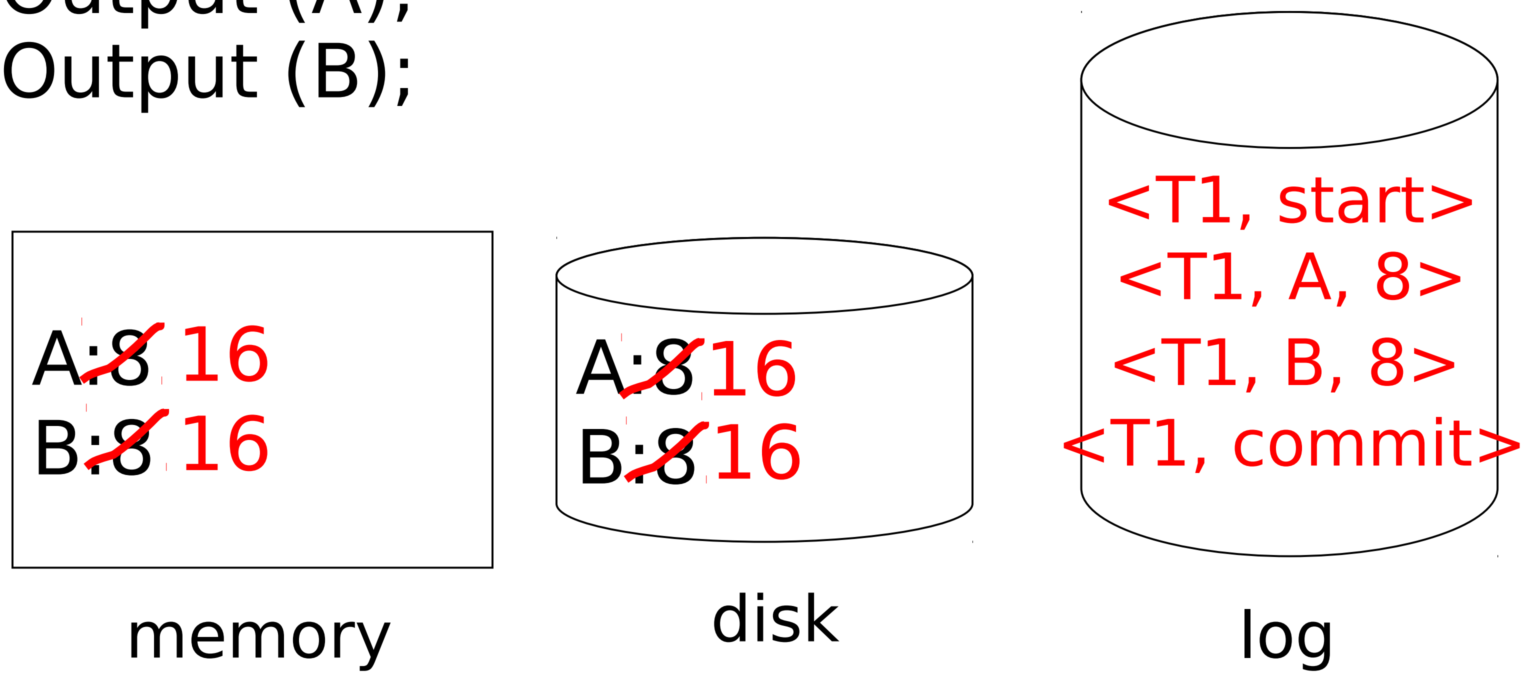
Output (A);
Output (B);

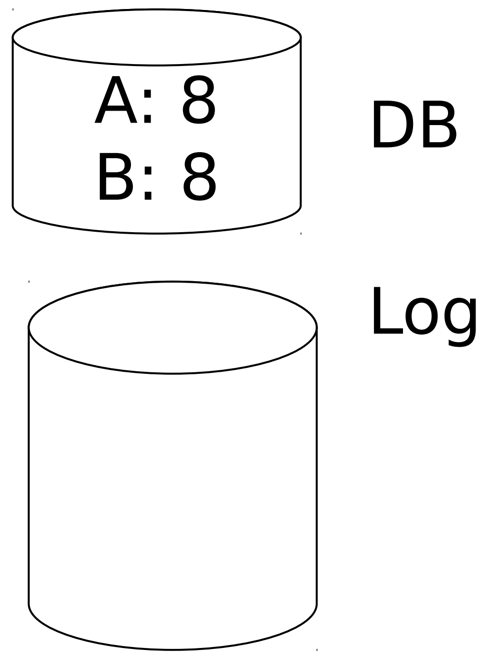


One “complication”

- Log is first written in memory
- Not written to disk on every action

memory

A: ~~8~~ 16
B: ~~8~~ 16
Log:
<T_1,start>
<T_1, A, 8>
<T_1, B, 8>



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- Log is first written in memory
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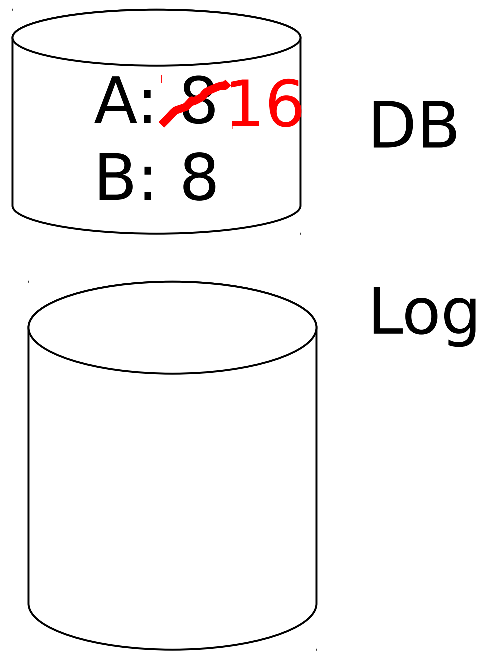
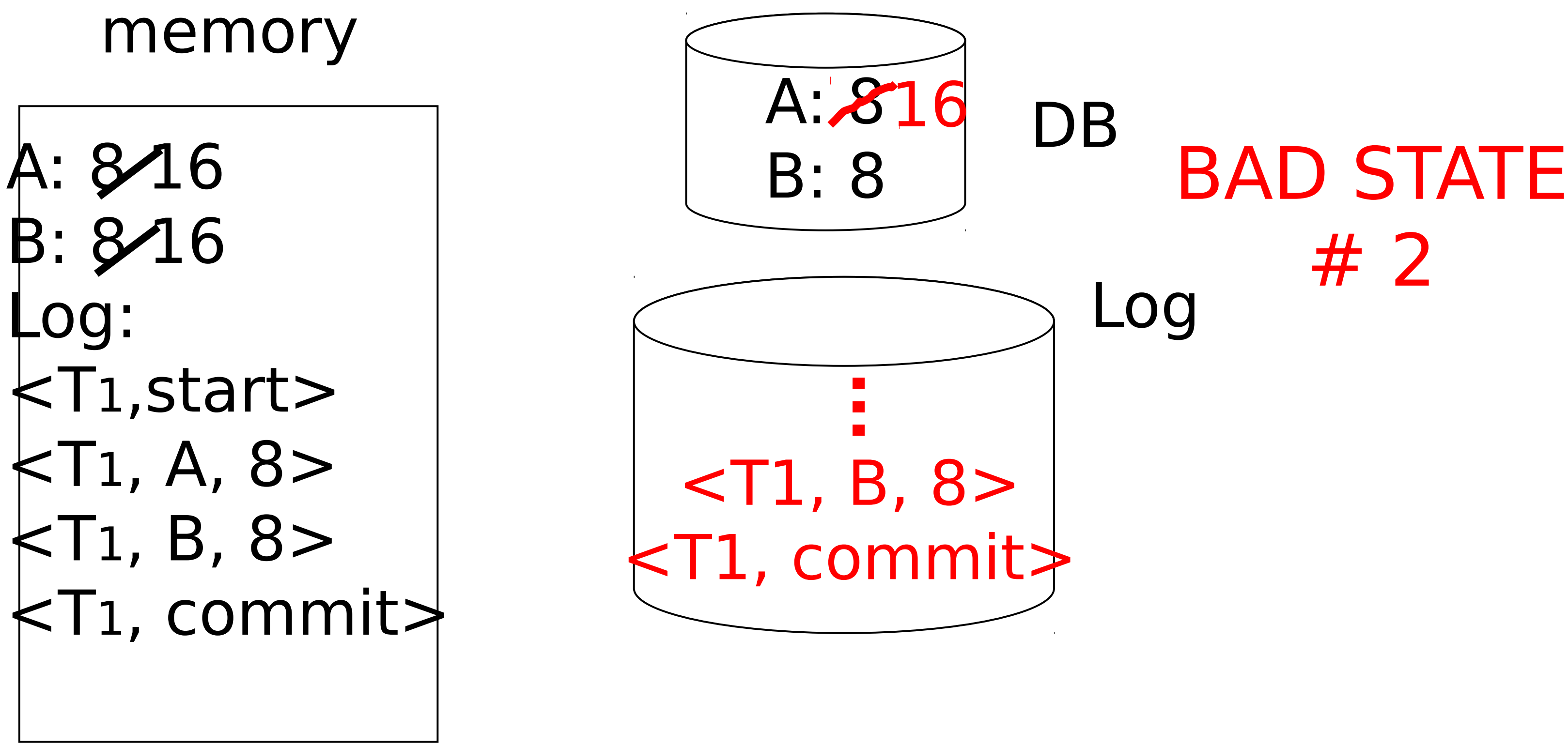


BAD STATE
1

One "complication"

- Log is first written in memory
- Not written to disk on every action



Undo logging rules

(1) For every action generate undo log record (containing old value)

(2) Before *x* is modified on disk, log records pertaining to *x* must be on disk (write ahead logging: WAL)

(3) Before commit is flushed to log, all writes of transaction must be reflected on disk

Recovery rules: Undo logging

- For every transaction Ti with <Ti, start> in log:
  - If <Ti,commit> or <Ti,abort>in log:
    do nothing

    Else

    For all <Ti, *X*, *v*> in log:

write *(X, v)*

output (*X*)

Write <Ti, abort> to log

Recovery rules: Undo logging

- For every transaction Ti with <Ti, start> in log:
  - If <Ti,commit> or <Ti,abort>in log:
    do nothing

    Else

    For all <Ti, *X*, *v*> in log:

write *(X, v)*

output (*X*)

Write <Ti, abort> to log

IS THIS CORRECT??

Recovery rules: Undo logging

(1) Let S = set of transactions with
<Ti, start> in log, but no <Ti, commit> or
<Ti, abort> record in log

(2) For each <Ti, X, v> in log,

in reverse order (latest $\rightarrow$ earliest) do:

- if Ti $\in$ S then $\left\{ \begin{array}{l} \text{- write (X, v)} \\ \text{- output (X)} \end{array} \right.$

(3) For each Ti $\in$ S do

- write <Ti, abort> to log

Question

- Can writes of <Ti, abort> records be done in any order (in Step 3)?
  - Example: T1 and T2 both write A
  - T1 executed before T2
  - T1 and T2 both rolled-back
  - <T1, abort> written but NOT <T2, abort>?
  - <T2, abort> written but NOT <T1, abort>?

What if failure during recovery?

No problem! ✏ Undo idempotent

Can we truncate the log?

- Under a heavy transaction load, the log grows quickly
- Are there parts of the log that we can discard? (i.e. are there parts we know for sure won't be needed again?)
  - E.g., everything before a <Ti, commit>?

Solution: (Simple) Checkpoint

Periodically:

(1) Do not accept new transactions

(2) Wait until all running transactions have finished and flushed their modifications to disk

(3) Flush all log records to disk (log)

(4) Write “checkpoint” record on disk (log)

(5) Resume accepting transactions

An example undo log with simple checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T2, B, 10>
<T2, C, 15>
<T1, D, 20>
<T1, commit>
<T2, commit>
<CKPT>
<T3, start>
<T3, E, 25>
<T3, F, 30>

failure!

An example undo log with simple checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T2, B, 10>
<T2, C, 15>
<T1, D, 20>
<T1, commit>
<T2, commit>

UNDO to latest checkpoint

<CKPT>
<T3, start>
<T3, E, 25>
<T3, F, 30>

failure!

An example undo log with simple checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T2, B, 10>
<T2, C, 15>
<T1, D, 20>
<T1, commit>
<T2, commit>
<CKPT>
<T3, start>
<T3, E, 25>
<T3, F, 30>

This part can be removed from the log

UNDO to latest checkpoint

failure!

Non-quiescent checkpoint

Simple checkpoints effectively shut down the system while waiting for the open transactions to commit

Therefore, a more complex technique known as *nonquiescent checkpointing* is normally used, that allows new transactions to enter the system during the checkpoint

Solution: non-quiescent checkpoint

Periodically:

(1) Write a log record <START CKPT (T1,...., TK) and flush the log. T1...Tk indentify the active transactions (not yet committed and written their changes to disk)

(2) Wait until all of T1 … Tk commit or abort, but do not prohibit other transactions form starting

(3) When all of T1 … Tk have completed, write <END CKPT> to log on disk (log)

An example undo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T2, B, 10>
<START CKPT (T1,T2)>
<T2, C, 15>
<START T3>
<T1, D, 20>
<T1, commit>
<T3, E, 25>
<T2, commit>
<END CKPT>
<T3, F, 30>

failure!

An example undo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T2, B, 10>
<START CKPT (T1,T2)>
<T2, C, 15>
<START T3>
<T1, D, 20>
<T1, commit>
<T3, E, 25>
<T2, commit>
<END CKPT>
<T3, F, 30>

failure!

UNDO to latest start checkpoint

An example undo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T2, B, 10>
<START CKPT (T1,T2)>
<T2, C, 15>
<START T3>
<T1, D, 20>
<T1, commit>
<T3, E, 25>
<T2, commit>
<END CKPT>
<T3, F, 30>

This part can be removed from the log

UNDO to latest start checkpoint

failure!

An example undo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T2, B, 10>
<START CKPT (T1,T2)>
<T2, C, 15>
<START T3>
<T1, D, 20>
<T1, commit>
<T3, E, 25>

failure!

An example undo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T2, B, 10>
<START CKPT (T1,T2)>
<T2, C, 15>
<START T3>
<T1, D, 20>
<T1, commit>
<T3, E, 25>

? UNDO to latest start checkpoint

failure!

An example undo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T2, B, 10>
<START CKPT (T1,T2)>
<T2, C, 15>
<START T3>
<T1, D, 20>
<T1, commit>
<T3, E, 25>

failure!

!

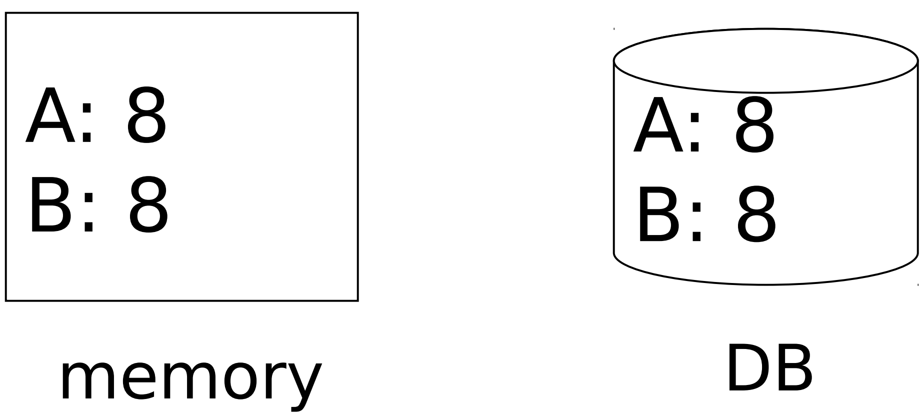
UNDO to latest **COMPLETED** start checkpoint

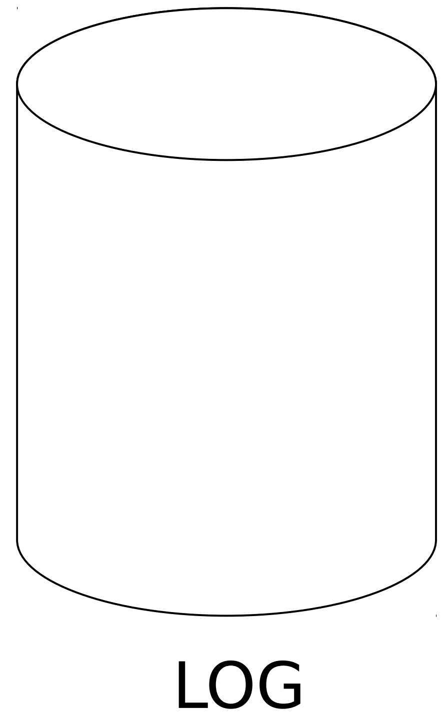
To discuss:

- Redo logging
- Undo/redo logging, why both?
- Real world actions
- Media failures

Redo logging (deferred modification)

T_1: Read(A,t); t ← t×2; write (A,t);
Read(B,t); t ← t×2; write (B,t);
Output(A); Output(B)





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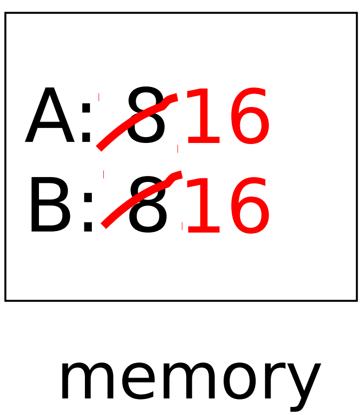

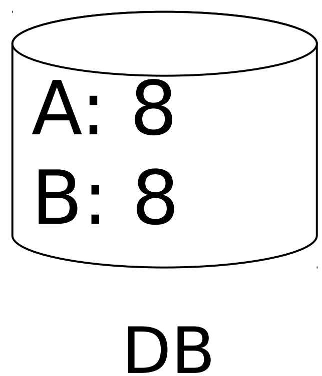

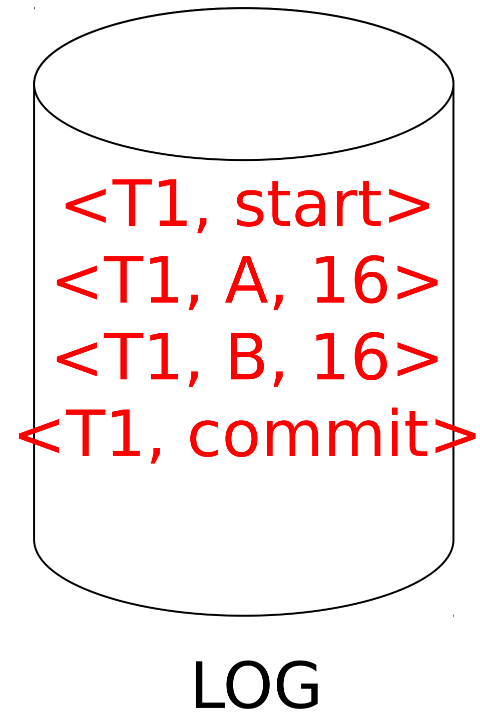

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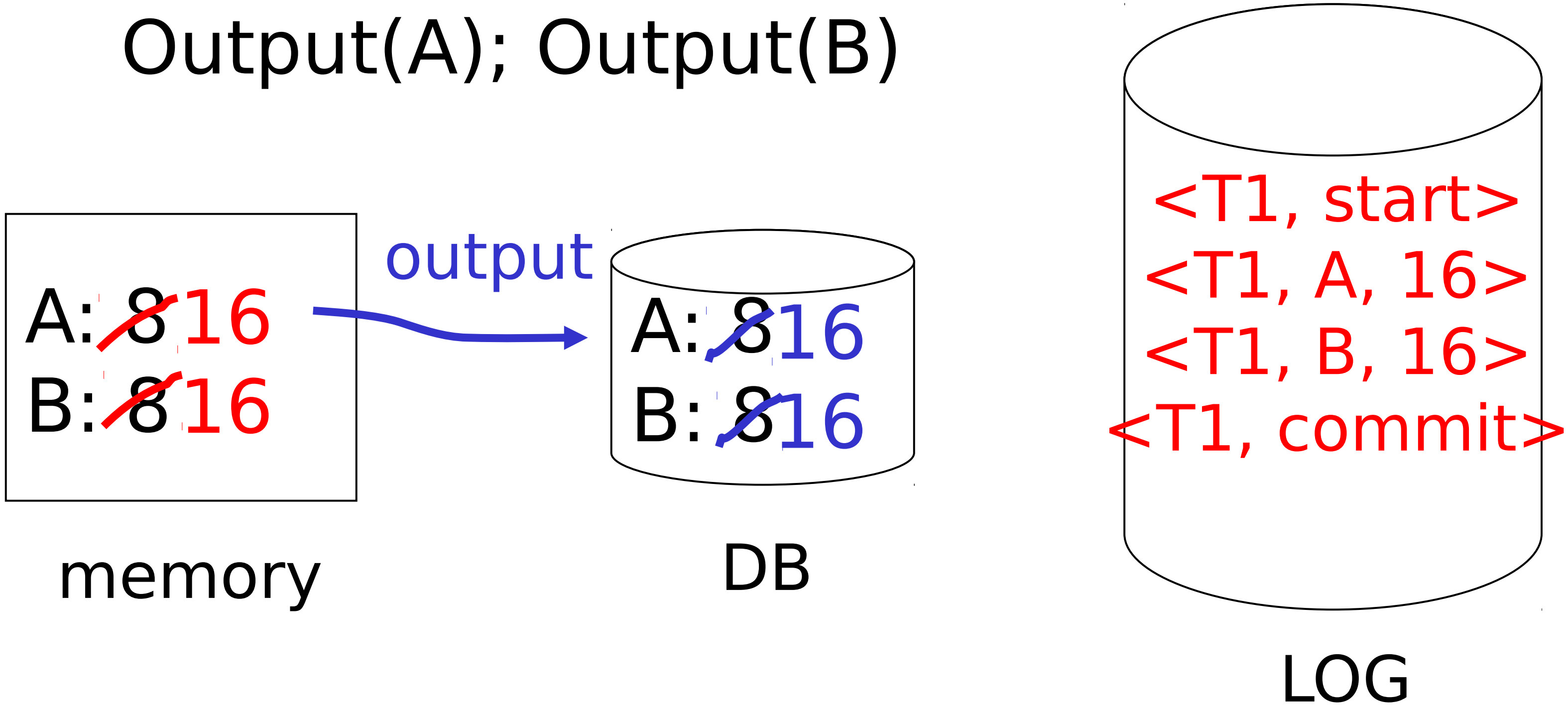
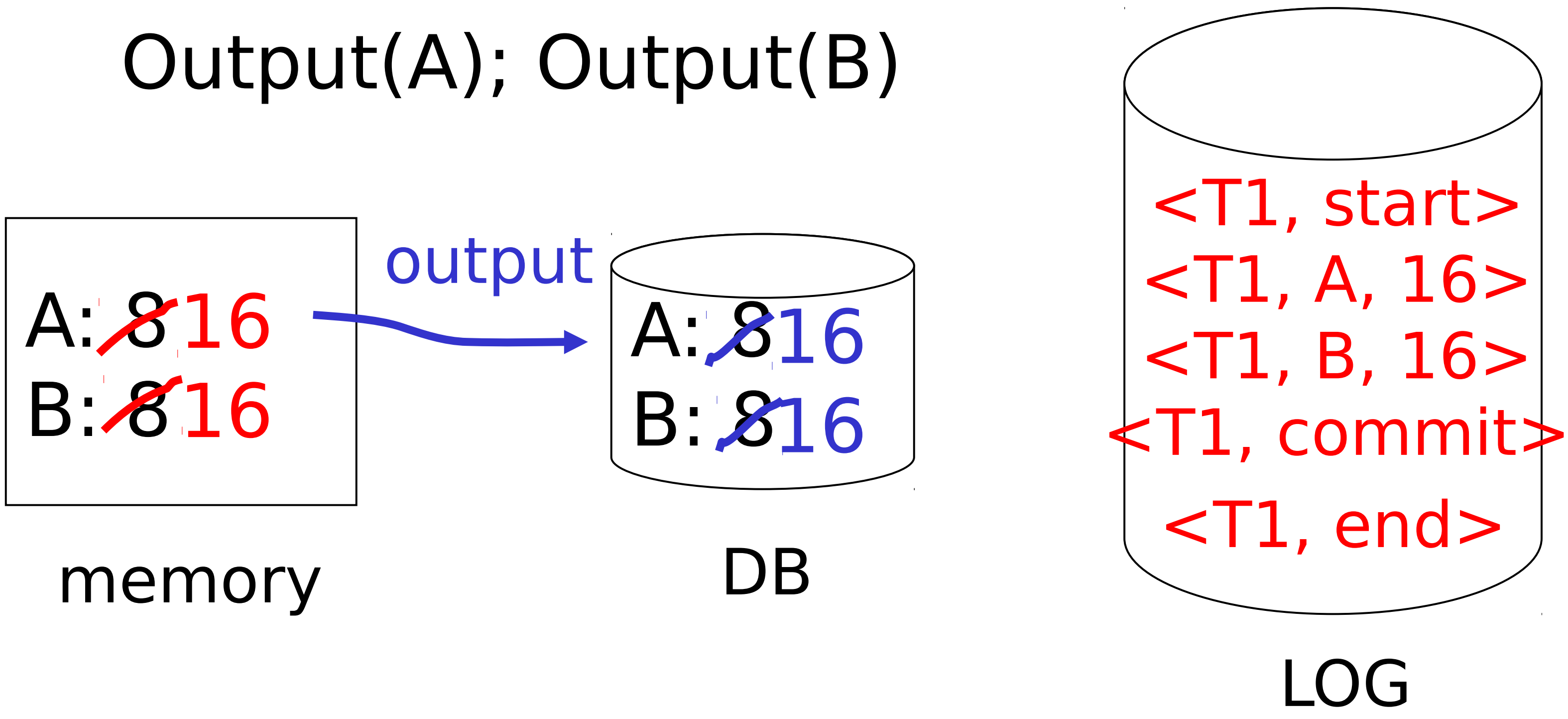


Redo logging (deferred modification)

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 rules

(1) For every action, generate redo log record (containing new value)

(2) Before X is modified on disk (DB), all log records for transaction that modified X (including commit) must be on disk

(3) Flush log at commit

(4) Write END record after DB updates flushed to disk

Recovery rules: Redo logging

- For every Ti with <Ti, commit> in log:
  - For all <Ti, X, v> in log:

    Write(X, v)

    Output(X)

Recovery rules: Redo logging

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  - For all <Ti, X, v> in log:

    Write(X, v)

    Output(X)

IS THIS CORRECT??

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 $\rightarrow$ latest) do:

- if Ti $\in$ S then $\left\{\begin{array}{l}\text{Write(X, v)}\\ \text{Output(X)}\end{array}\right.$

(3) For each Ti $\in$ S, write <Ti, end>

Non-quiescent checkpointing a redo log

Periodically:

(1) Write a log record <START CKPT (T1,…,Tk) where T1,…,Tk are all the active (uncommitted) transactions, and flush the log.

(2) Write to disk all database elements written to buffers but not yet to disk by transactions that had already committed when the start ckpt record was written to the log

(3) Write the <END CKPT> record and flush the log

An example redo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T1, commit>
<T2, B, 10>
<START CKPT (T2)>
<T2, C, 15>
<START T3>
<T3, D, 20>
<T1, end>
<END CKPT>
<COMMIT T2>
<COMMIT T3>

failure!

An example redo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T1, commit>
<T2, B, 10>
<START CKPT (T2)>
<T2, C, 15>
<START T3>
<T3, D, 20>
<T1, end>
<END CKPT>
<COMMIT T2>
<COMMIT T3>

REDO all committed transactions that were active (uncommitted) when the checkpoint began, or started later: T2 and T3

failure!

An example redo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T1, commit>
<T2, B, 10>
<START CKPT (T2)>
<T2, C, 15>
<START T3>
<T3, D, 20>
<T1, end>
<END CKPT>
<COMMIT T2>
<COMMIT T3>

failure!

An example redo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T1, commit>
<T2, B, 10>
<START CKPT (T2)>
<T2, C, 15>
<START T3>
<T3, D, 20>
<T1, end>
<END CKPT>
<COMMIT T2>
<COMMIT T3>

REDO all committed transactions that were active (uncommitted) when the checkpoint began, or started later:
Only T2

failure!

An example redo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T1, commit>
<T2, B, 10>
<START CKPT (T2)>
<T2, C, 15>
<START T3>
<T3, D, 20>
<T1, end>
<END CKPT>
<COMMIT T2>
<COMMIT T3>

failure!

An example redo log with nonquiescent checkpoint (disk)

<T1, start>
<T1, A, 5>
<T2, start>
<T1, commit>
<T2, B, 10>
<START CKPT (T2)>
<T2, C, 15>
<START T3>
<T3, D, 20>
<T1, end>
<END CKPT>
<COMMIT T2>
<COMMIT T3>

REDO until the previous **complete** <START CKPT> (or to the beginning of the log)

failure!

Note:

- In the presence of non-quiescent checklogging, the <Ti, end> log records are redundant (the checkpoint gives the same information). The book hence does **not** use such log records.
- The exercises do **not** use such records

Key drawbacks:

- *Undo logging:* cannot bring backup DB copies up to date

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

Solution: undo/redo logging!

Update $\Rightarrow$ <Ti, Xid, New X val, Old X val>

page X

Rules

- Page X can be flushed before or after Ti commit
- Log record flushed before corresponding updated page (WAL)
- Flush at commit (log only)

Non-quiescent checkpointing an undo/redo log

Periodically:

(1) Write a log record <START CKPT (T1,...,Tk) where T1,...,Tk are all the active (uncommitted) transactions, and flush the log.

(2) Write to disk all buffers that are dirty,i.e., they contain one or more changed database elements.

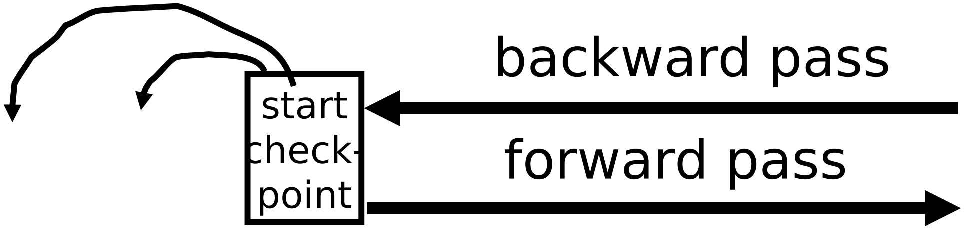
(3) Write the <END CKPT> record and flush the log

Recovery process:

- Backwards pass (end of log -> latest valid checkpoint start)
  - construct set S of committed transactions
  - undo actions of transactions not in S
- Undo pending transactions
  - follow undo chains for transactions in (checkpoint active list) - S

Forward pass (latest valid checkpoint start -> end of log)

- redo actions of S transactions



Real world actions

E.g., dispense cash at ATM

$$Ti = a_1\, a_2 \ldots\ldots\, a_j \ldots\ldots\, a_n$$

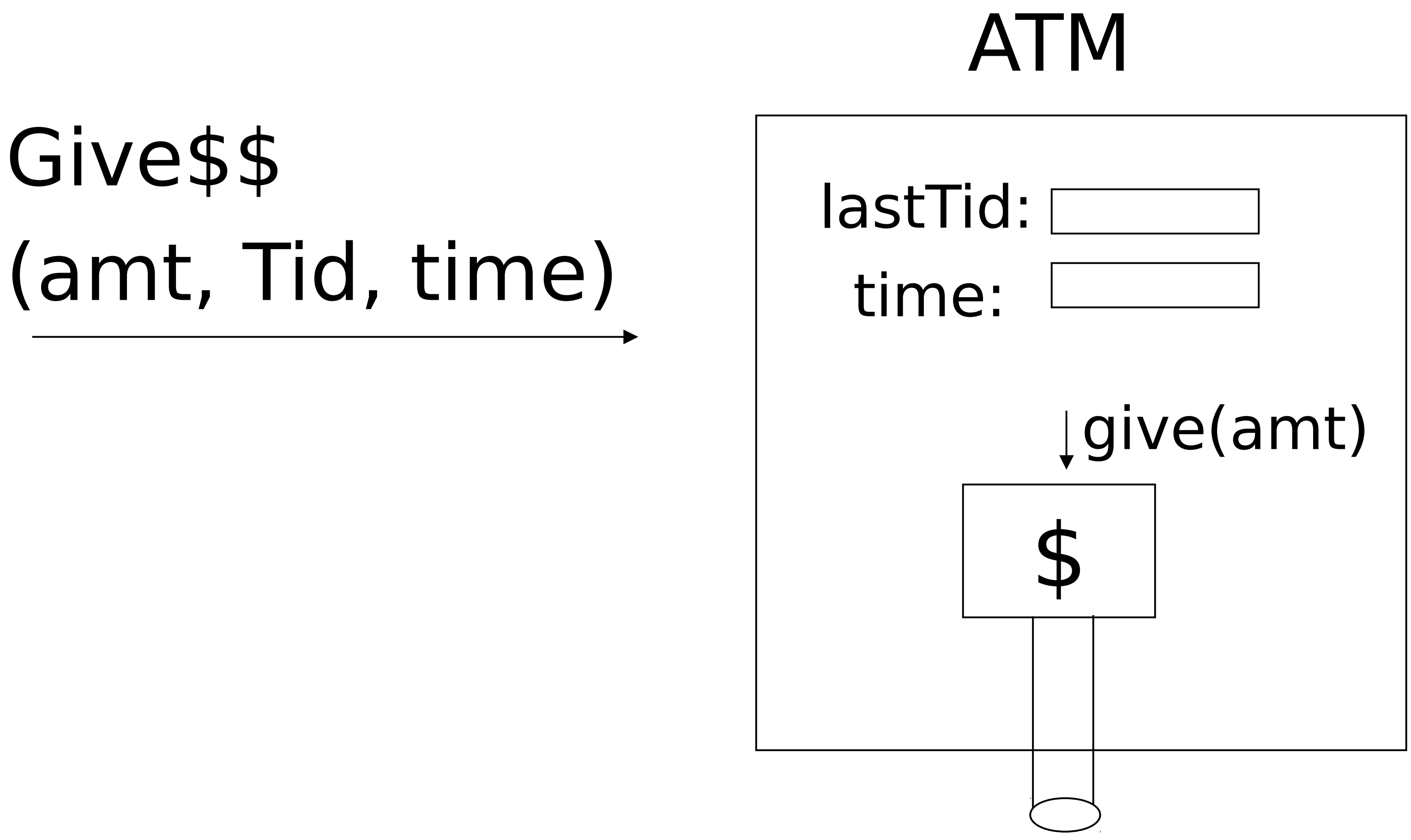
$$\downarrow$$

$

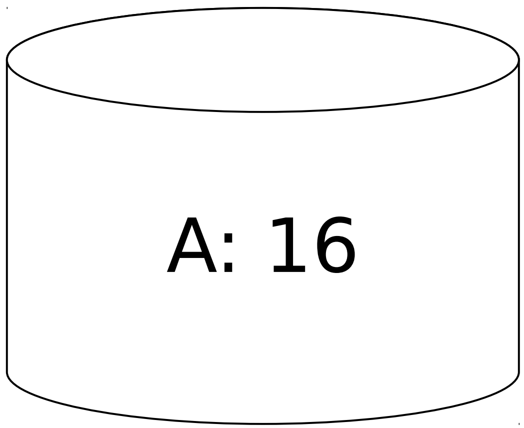
Solution

(1) execute real-world actions after commit

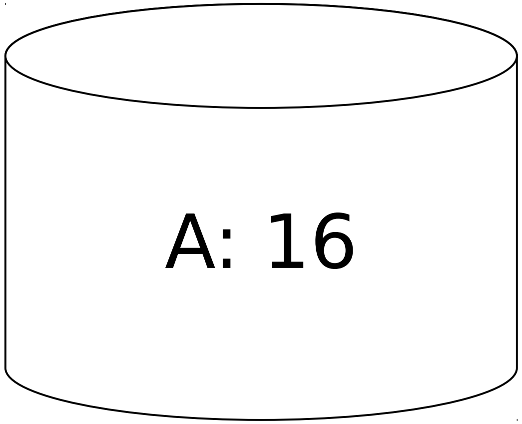
(2) try to make idempotent


Give$$
(amt, Tid, time)
ATM
lastTid:
time:
give(amt)
$

Media failure (loss of non-volatile storage)



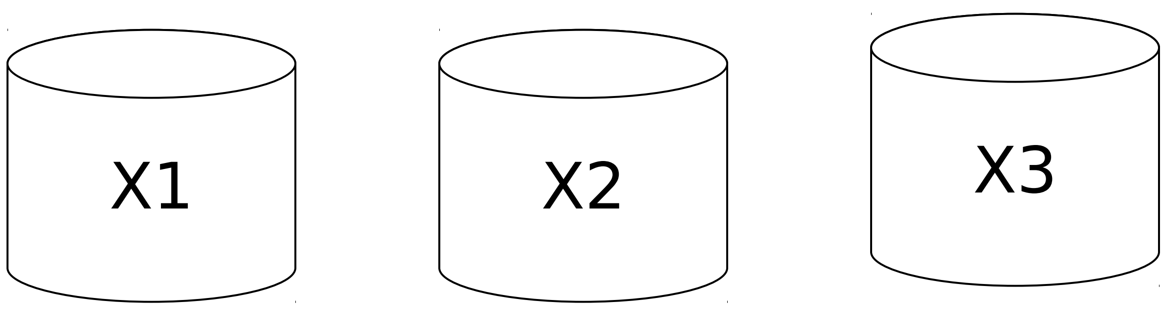
Media failure (loss of non-volatile storage)



Solution: Make copies of data!

Example 1 Triple modular redundancy

- Keep 3 copies on separate disks
- Output(X) --> three outputs
- Input(X) --> three inputs + vote



Example #2 Redundant writes, Single reads

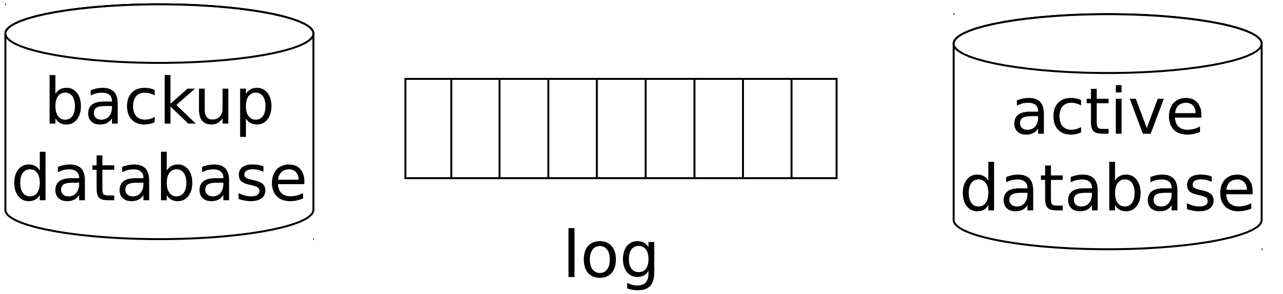
- Keep N copies on separate disks
- Output(X) --> N outputs
- Input(X) --> Input one copy

  - if ok, done

  - else try another one

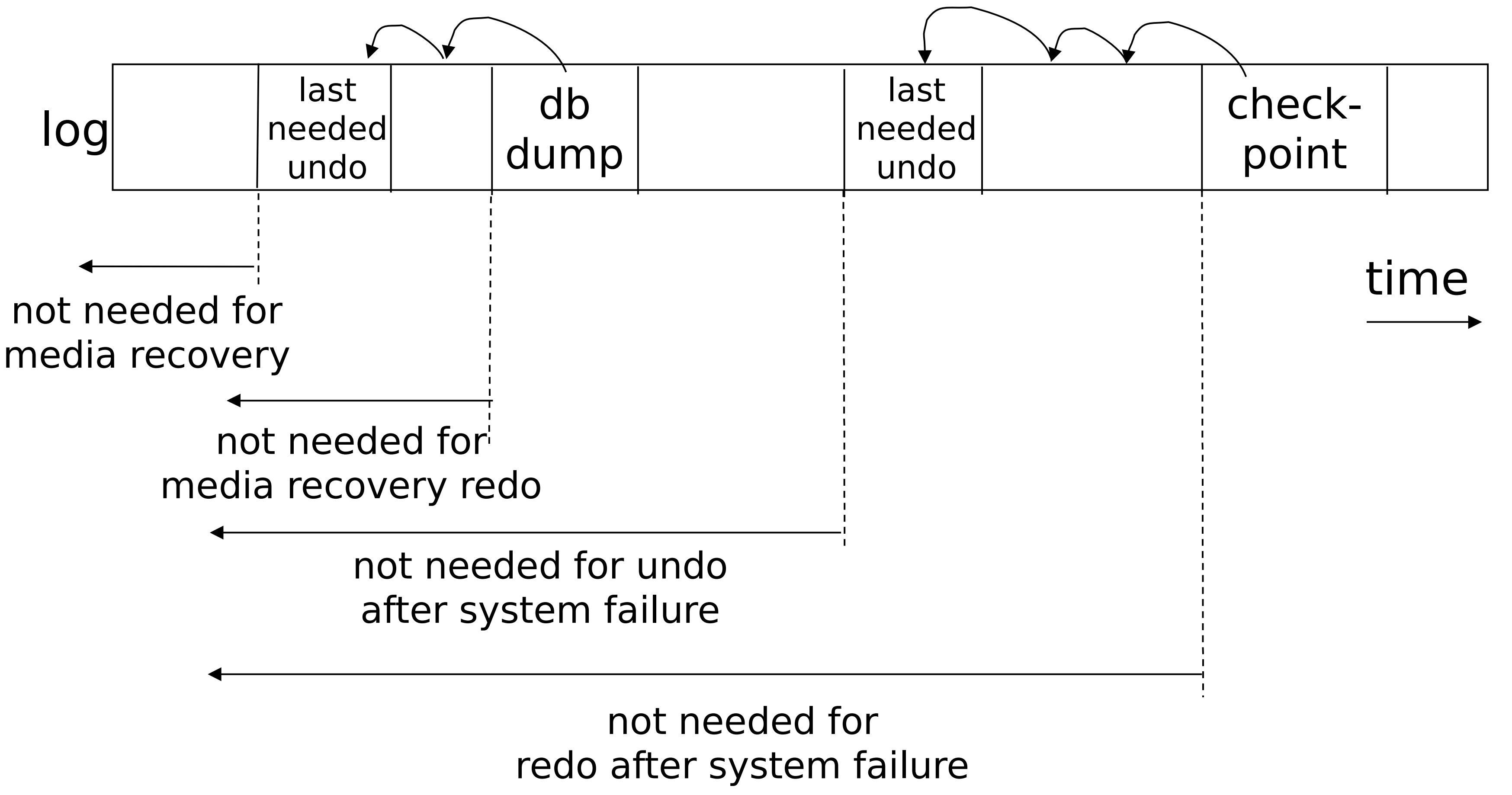
Assumes bad data can be detected

Example #3: DB Dump + Log



- If active database is lost,
  - restore active database from backup
  - bring up-to-date using redo entries in log

When can log be discarded?



Summary

- Consistency of data
- One source of problems: failures
  - Logging
  - Redundancy
- Another source of problems:
  Data Sharing..... next