CPS216: Data-intensive Computing Systems

Failure Recovery

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Key problem  Unfinished transaction

Example  Constraint: $A=B$

$T_1:  \quad A \leftarrow A \times 2$

$B \leftarrow B \times 2$
Unexpected Events:

Examples:
- Power goes off
- Software bugs
- Disk data is lost
- Memory lost without CPU halt
- CPU misbehaves (overheating)
Storage hierarchy

- Memory
- Disk
Operations:

- Input \((x)\): block containing \(x\) → memory
- Output \((x)\): block containing \(x\) → disk
- Read \((x,t)\): do input\((x)\) if necessary
  
  \[ t \leftarrow \text{value of } x \text{ in block} \]
- Write \((x,t)\): do input\((x)\) if necessary
  
  \[ \text{value of } x \text{ in block} \leftarrow t \]
Key problem: Unfinished transaction

Example

Constraint: $A = B$

$T_1$: $A \leftarrow A \times 2$

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

failure!

A: 8
B: 8

A: 8
B: 8

memory

disk
• Need **atomicity**: execute all actions of a transaction or none at all
One solution: undo logging (immediate modification)

due to: Hansel and Gretel, 782 AD
Undo logging (Immediate modification)

$T_1$:  
Read $(A, t)$; \hspace{1em} t ← t×2 \hspace{1em} A=B
Write $(A, t)$;
Read $(B, t)$; \hspace{1em} t ← t×2
Write $(B, t)$;
Output $(A)$;
Output $(B)$;

A:8
B:8

memory

A:8
B:8

disk

A:8
B:8

log

<T1, start>
<T1, A, 8>
<T1, B, 8>
<T1, commit>
One “complication”

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

```
memory
A: 8 16
B: 8 16
Log:
<T1,start>
<T1, A, 8>
<T1, B, 8>

A: 8 16
B: 8
BAD STATE
# 1
```
One “complication”

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

Log:

\(<T_1, \text{start}>\)
\(<T_1, A, 8>\)
\(<T_1, B, 8>\)
\(<T_1, \text{commit}>\)
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 for Undo logging

• For every Ti with \(<Ti, \text{start}>\) in log:
  - Either: Ti completed ➔
    \(<Ti,\text{commit}>\) or \(<Ti,\text{abort}>\) in log
  - Or: Ti is incomplete

  Undo incomplete transactions
Recovery rules for Undo Logging (contd.)

(1) Let $S =$ set of transactions with $<T_i, \text{start}>$ in log, but no $<T_i, \text{commit}>$ or $<T_i, \text{abort}>$ record in log

(2) For each $<T_i, X, v>$ in log, in reverse order (latest $\rightarrow$ earliest) do:
   - if $T_i \in S$ then
     - write $(X, v)$
     - output $(X)$

(3) For each $T_i \in S$ do
   - write $<T_i, \text{abort}>$ to log
What if failure during recovery?

No problem: Undo is idempotent
To discuss:

- Redo logging
- Undo/redo logging, why both?
- Real world actions
- Checkpoints
- Media failures
Redo logging (deferred modification)

\[ T_1: \text{Read}(A,t); \ t \leftarrow t \times 2; \ \text{write} \ (A,t); \]
\[ \text{Read}(B,t); \ t \leftarrow t \times 2; \ \text{write} \ (B,t); \]
\[ \text{Output}(A); \ \text{Output}(B) \]
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
Recovery rules: Redo logging

• For every Ti with <Ti, commit> in log:
  – For all <Ti, X, v> in log:
    \[
    \begin{align*}
    &\text{Write}(X, v) \\
    &\text{Output}(X)
    \end{align*}
    \]

✿ IS THIS CORRECT??
Recovery rules: Redo logging

(1) Let $S =$ set of transactions with $<Ti, \text{commit}>$ in log

(2) For each $<Ti, X, v>$ in log, in forward order (earliest $\rightarrow$ latest) do:
   - if $Ti \in S$ then
     \[
     \begin{cases}
     \text{Write}(X, v) \\
     \text{Output}(X) \quad \text{optional}
     \end{cases}
     \]
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 ⇒ <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)
Recovery Rules

- Identify transactions that committed
- Undo uncommitted transactions
- Redo committed transactions
Recovery is very, very SLOW!

Redo log:

First Record (1 year ago)
T1 wrote A,B Committed a year ago
... ...
... ...
Last Record
Crash

--> STILL, Need to redo after crash!!
Solution: Checkpoint  (simple version)

Periodically:
(1) Do not accept 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):

<table>
<thead>
<tr>
<th>...</th>
<th>&lt;T1,A,16&gt;</th>
<th>...</th>
<th>&lt;T1,commit&gt;</th>
<th>...</th>
<th>Checkpoint</th>
<th>...</th>
<th>&lt;T2,B,17&gt;</th>
<th>...</th>
<th>&lt;T2,commit&gt;</th>
<th>...</th>
<th>&lt;T3,C,21&gt;</th>
<th>Crash</th>
</tr>
</thead>
</table>

System stops accepting new transactions
Non-quiescent checkpoint for Undo/Redo logging

LOG

... Start-ckpt active TR: T1,T2,... ... end ckpt ...
Example: Undo/Redo + Non Quiiescent Chkpt.

\[
\begin{align*}
&\text{<start T1> } \\
&T1,A,4,5 > \\
&\text{<start T2> } \\
&T2,B,9,10 > \\
&\text{<start chkpt(T2)> } \\
&T2,C,14,15 > \\
&\text{<start T3> } \\
&T3,D,19,20 > \\
&\text{<end checkpt> } \\
&\text{<commit T2> } \\
&\text{<commit T3> }
\end{align*}
\]

1. Flush log
2. Flush all dirty buffers. May start new transactions
3. Write <end checkpt>. Flush log
Examples  what to do at recovery time?

LOG

| ... | T₁⁻ | ... | Ckpt T₁ | ... | Ckpt end | ... | T₁⁻ |

- no T₁ commit

❌ Undo T₁  (undo a,b)
Example

LOG

... T1... ckpt-s T1... T1... ckpt-end... T1... T1 cmt... T1...

❌ Redo T1: (redo b,c)
Recovery process:

- **Backwards pass** (end of log ⇑ latest 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 checkpoint start ⇑ end of log)
  - redo actions of S transactions
Example: Redo + Non Quiescent Chkpt.

\[\text{<start T1>}
\text{<T1,A,5>}
\text{<start T2>}
\text{<commit T1>}
\text{<T2,B,10>}
\text{<start chkpt(T2)>}
\text{<T2,C,15>}
\text{<start T3>}
\text{<T3,D,20>}
\text{<end chkpt>}
\text{<commit T2>}
\text{<commit T3>}\]

1. Flush log
2. Flush data elements written by transactions that committed before <start chkpt>.
   May start new transactions.
3. Write <end chkpt>. Flush log
Example: Undo + Non Quiescent Chkpt.

<start T1>
<T1,A,5>
<start T2>
<T2,B,10>
=start chkpt(T1,T2)>
<T2,C,15>
<start T3>
<T1,D,20>
<commit T1>
<T3,E,25>
<commit T2>
<end chkpt>
<T3,F,30>

1. Flush log
2. Wait for active transactions to complete. New transactions may start
3. Write <end checkpt>. Flush log
Real world actions

E.g., dispense cash at ATM

\[ Ti = a_1 a_2 \ldots \ldots a_j \ldots \ldots a_n \]

$
Solution

(1) execute real-world actions after commit
(2) try to make idempotent
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

X1  X2  X3
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
Non-quiescent Archiving

- Log may look like:
  
  `<start dump>
  <start checkpt(T1,T2)>
  <T1,A,1,3>
  <T2,C,3,6>
  <commit T2>
  <end checkpt>
  Dump completes
  <end dump>`
When can log be discarded?

- 
  - db dump
  - last needed undo
  - checkpoint

not needed for media recovery
not needed for redo after system failure
not needed for undo after system failure
Summary

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