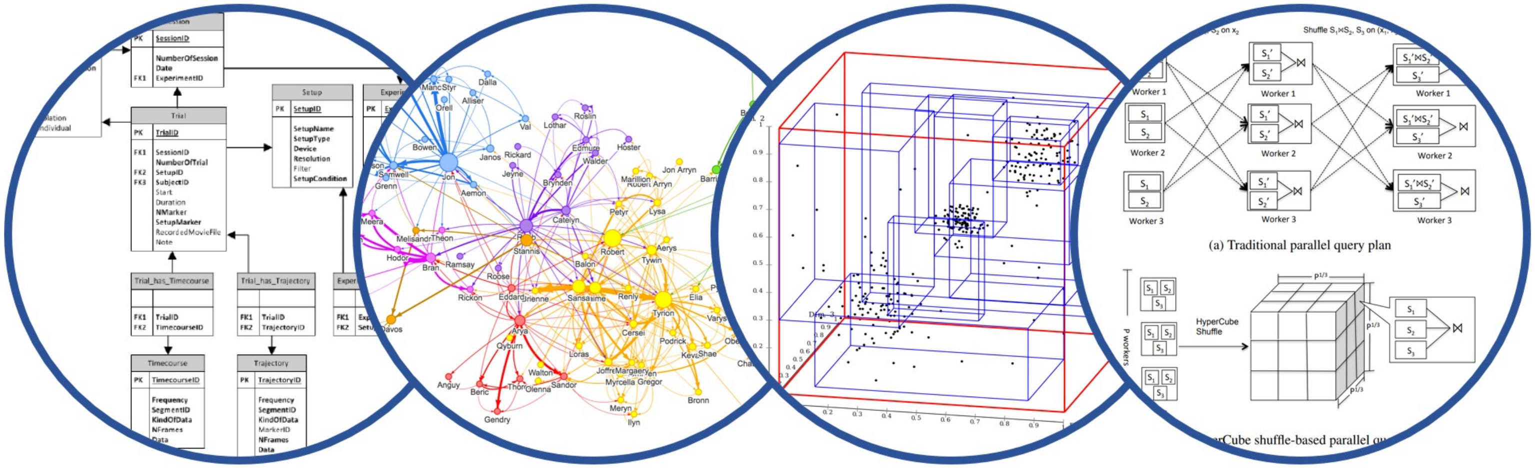


Database System Internals

Transactions: Recovery (part 2)

Paul G. Allen School of Computer Science and Engineering
University of Washington, Seattle

Force/No-steal (most strict)

- **FORCE**: Pages of committed transactions must be forced to disk before commit
- **NO-STEAL**: Pages of uncommitted transactions cannot be written to disk

Easy to implement (how?) and ensures atomicity

No-Force/Steal (least strict)

- **NO-FORCE**: Pages of committed transactions need not be written to disk

- **STEAL**: Pages of uncommitted transactions may be written to disk

In both cases, need a Write Ahead Log (WAL) to provide atomicity in face of failures

Write-Ahead Log (WAL)

The Log: append-only file containing log records

- Records every single action of every TXN
- Forces log entries to disk as needed
- After a system crash, use log to recover

Three types: UNDO, REDO, UNDO-REDO

Aries: is an UNDO-REDO log

Policies and Logs

	NO-STEAL	STEAL
FORCE	Lab 3	Undo Log
NO-FORCE	Redo Log	Undo-Redo Log

“UNDO” Log

FORCE and STEAL

Undo Logging

Log records

- <START T>
  - transaction T has begun
- <COMMIT T>
  - T has committed
- <ABORT T>
  - T has aborted
- <T,X,v>
  - T has updated element X, and its *old* value was v
  - *Idempotent, physical* log records

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

Crash !

WHAT DO WE DO ?

Action	t	Mem A	Mem B	Disk A	Disk B	**UNDO** Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	Crash !
COMMIT						<COMMIT T>

WHAT DO WE DO ?

We UNDO by setting B=8 and A=8

After Crash

- This is all we see (for example):

Disk A	Disk B
16	8

<START T>
<T,A,8>
<T,B,8>

After Crash

- This is all we see (for example):

Disk A	Disk B
16	8

<START T>
<T,A,8>
<T,B,8>

After Crash

- This is all we see (for example):
- Need to step through the log

Disk A	Disk B
16	8

<START T>
<T,A,8>
<T,B,8>

After Crash

- This is all we see (for example):
- Need to step through the log

Disk A	Disk B
16	8

<START T>
<T,A,8>
<T,B,8>

- What direction?

After Crash

- This is all we see (for example):
- Need to step through the log

Disk A	Disk B
16	8

<START T>
<T,A,8>
<T,B,8>

- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

- This is all we see (for example):
- Need to step through the log

Disk A	Disk B
16	8

<START T>
<T,A,8>
<T,B,8>

- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

- This is all we see (for example):
- Need to step through the log

Disk A	Disk B
16	8

<START T>
<T,A,8>
<T,B,8>

- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

- This is all we see (for example):
- Need to step through the log

Disk A	Disk B
8	8

<START T>
<T,A,8>
<T,B,8>

- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

- This is all we see (for example):
- Need to step through the log

Disk A	Disk B
8	8

<START T>
<T,A,8>
<T,B,8>

- What direction?
- In UNDO log, we start at the most recent and go backwards in time

After Crash

- If we see NO Commit statement:
  - We UNDO both changes: A=8, B=8
  - The transaction is atomic, since none of its actions have been executed

- In we see that T has a Commit statement
  - We don't undo anything
  - The transaction is atomic, since both its actions have been executed

Recovery with Undo Log

After system's crash, run recovery manager

- Decide for each transaction T whether it is completed or not
  - <START T>….<COMMIT T>….   = yes
  - <START T>….<ABORT T>…….   = yes (already cleaned up)
  - <START T>……………………….   = no

- Undo all modifications by incomplete transactions

Recovery with Undo Log

Recovery manager:

- Read log <u>from the end</u>; cases:

  <COMMIT T>: mark T as completed

  <ABORT T>: mark T as completed

  <T,X,v>: if T is not completed
  then write X=v to disk
  else ignore

  <START T>: ignore

Recovery with Undo Log

…
…
<T6,X6,v6>
…
…
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>

Crash !

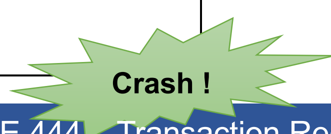
Question1: Which updates are undone ?

Question 2:
How far back do we need to read in the log ?

Question 3:
What happens if second crash during recovery?

Recovery with Undo Log

…
…
<T6,X6,v6>
…
…
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>



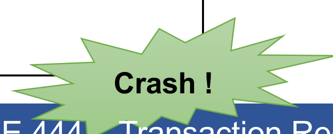
Question1: Which updates are undone ?

Question 2:
How far back do we need to read in the log ?
To the beginning.

Question 3:
What happens if second crash during recovery?

Recovery with Undo Log

…
…
<T6,X6,v6>
…
…
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>



Question1: Which updates are undone ?

Question 2:
How far back do we need to read in the log ?
To the beginning.

Question 3:
What happens if second crash during recovery?
No problem! Log records are idempotent. Can reapply.

Action	t	Mem A	Mem B	Disk A	Disk B	**UNDO** Log
						<START T>
INPUT(A)		8			8	
READ(A,t)	8				8	
t:=t*2	16	8			8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT						<COMMIT T>

When must we force pages to disk ?

Action	t	Mem A	Mem B	Disk A	Disk B	UNDO Log
						<START T>
INPUT(A)		8		8	8	
READ(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8>
INPUT(B)	16	16	8	8	8	
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	
COMMIT				FORCE		<COMMIT T>

RULES: log entry *before* OUTPUT *before* COMMIT

Undo-Logging Rules

U1: If T modifies X, then <T,X,v> must be written to disk before OUTPUT(X)

U2: If T commits, then OUTPUT(X) must be written to disk before <COMMIT T>

- Hence: OUTPUTs are done *early*, before the transaction commits

FORCE

Checkpointing

Checkpoint the database periodically

- **Stop** accepting new transactions
- Wait until all current transactions complete
- Flush log to disk
- Write a <CKPT> log record, flush
- **Resume** transactions

Undo Recovery with Checkpointing

During recovery,
Can stop at first
<CKPT>

…
…
<T9,X9,v9>
…
…
(all completed)
<CKPT>
<START T2>
<START T3
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>

other transactions

transactions T2,T3,T4,T5

Nonquiescent Checkpointing

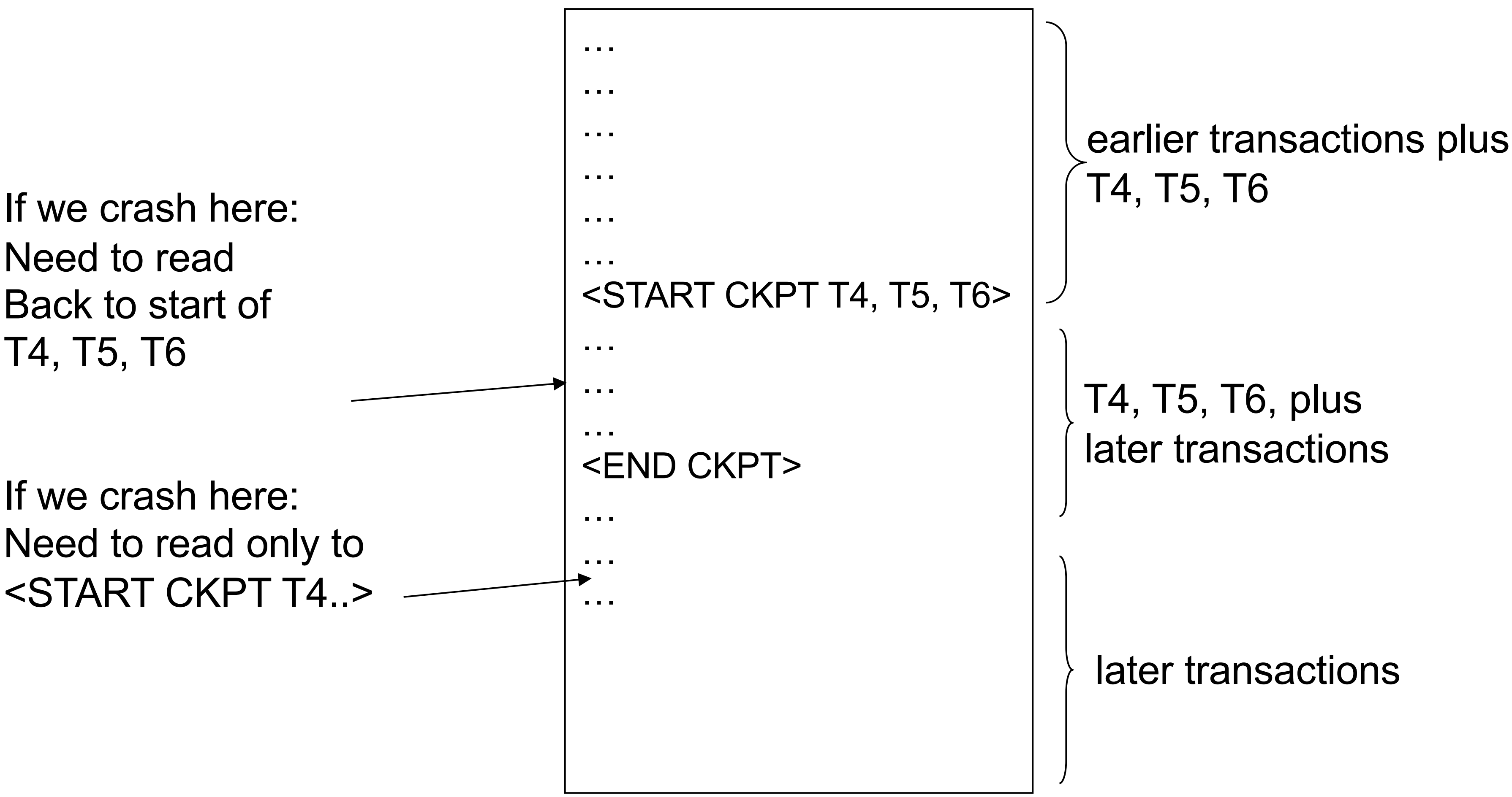
- Problem with checkpointing: database freezes during checkpoint
- Would like to checkpoint while database is operational
- Idea: nonquiescent checkpointing

Quiescent = being quiet, still, or at rest; inactive
Non-quiescent = allowing transactions to be active

Nonquiescent Checkpointing

- Write a <START CKPT(T1,…,Tk)> where T1,…,Tk are all active transactions. Flush log to disk
- Continue normal operation
- When all of T1,…,Tk have **completed**, write <END CKPT>, flush log to disk

Undo with Nonquiescent Checkpointing



Implementing ROLLBACK

- Recall: a transaction can end in COMMIT or ROLLBACK
- Idea: use the undo-log to implement ROLLBACK
- How ?
  - LSN = Log Sequence Number
  - Log entries for the same transaction are linked, using the LSN’s
  - Read log in reverse, using LSN pointers

Implementing ROLLBACK

- Rec… RO…
- Ide… …CK
- Ho…
  - L…
  - L… t… …sing
  - F…

…
…
<T9,X9,v9>
…
…
(all completed)
<CKPT>
<START T2>
<START T3
<START T5>
<START T4>
<T1,X1,v1>
<T5,X5,v5>
<T2,X1,v2>
<T4,X4,v4>
<COMMIT T5>
<T3,X3,v3>
<T2,X2,v2>

REDO

NO-FORCE and NO-STEAL

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
t:=t*2	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
t:=t*2	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
t:=t*2	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
t:=t*2	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Is this bad ?

Yes, it's bad: A=16, B=8

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
t:=t*2	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
t:=t*2	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
t:=t*2	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
t:=t*2	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Is this bad ?

Yes, it's bad: lost update

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
t:=t*2	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
t:=t*2	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Is this bad ?

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
t:=t*2	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
t:=t*2	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Is this bad ?

No: that’s OK.

Action	t	Mem A	Mem B	Disk A	Disk B
READ(A,t)	8	8		8	8
t:=t*2	16	8		8	8
WRITE(A,t)	16	16		8	8
READ(B,t)	8	16	8	8	8
t:=t*2	16	16	8	8	8
WRITE(B,t)	16	16	16	8	8
COMMIT					
OUTPUT(A)	16	16	16	16	8
OUTPUT(B)	16	16	16	16	16

Crash !

Redo Logging

One minor change to the undo log:

- <T,X,v>= T has updated element X, and its *new* value is v

Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	

Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	

Crash !

How do we recover ?

Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	

Crash !

How do we recover ?

We REDO by setting A=16 and B=16

Recovery with Redo Log

After system's crash, run recovery manager

- Step 1. Decide for each transaction T whether it is committed or not
  - <START T>….<COMMIT T>…. = yes
  - <START T>….<ABORT T>……. = no
  - <START T>……………………… = no
- Step 2. Read log from the beginning, redo all updates of *committed* transactions

Recovery with Redo Log

<START T1>
<T1,X1,v1>
<START T2>
<T2, X2, v2>
<START T3>
<T1,X3,v3>
<COMMIT T2>
<T3,X4,v4>
<T1,X5,v5>

Crash !

Show actions during recovery

Nonquiescent Checkpointing

- Write a <START CKPT(T1,…,Tk)>
  where T1,…,Tk are all active txn's
- Begin flush to disk all blocks of committed transactions before the START CKPT (e.g. dirty block from T0 that committed already)
- Meantime, continue normal operation
- When all blocks have been written, write
  <END CKPT>

END CKPT has different meaning here than in Undo log! It does not mean that T1,…,Tk are complete. It means that commited transactions like T0 are written to disk

Nonquiescent Checkpointing

Step 1: look for
The last
<END CKPT> and it's
<START CKPT>

All OUTPUTs
of T1 are
known to be on disk

Cannot
use

…
<START T1>
…
<COMMIT T1>
…
<START T4>
…
<START CKPT T4, T5, T6>
…
…
…
…
<END CKPT>
…
…
…
<START CKPT T9, T10>
…

Step 2: redo
from the
earliest
start of
T4, T5, T6
ignoring
transactions
committed
earlier

Action	t	Mem A	Mem B	Disk A	Disk B	**REDO** Log
			[illegible]	[illegible]		<START T>
READ(A,t)	8	8	[illegible]	[illegible]	8	
t:=t*2	16	8	[illegible]	[illegible]	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	

When must we force pages to disk ?

Action	t	Mem A	Mem B	Disk A	Disk B	REDO Log
						<START T>
READ(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,16>
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,16>
COMMIT						<COMMIT T>
OUTPUT(A)	16	16	16	16	8	
OUTPUT(B)	16	16	16	16	16	

RULE: OUTPUT *after* COMMIT

NO-STEAL

Redo-Logging Rules

R1: If T modifies X, then both <T,X,v> and <COMMIT T> must be written to disk before OUTPUT(X)

- Hence: OUTPUTs are done *late*

NO-STEAL

Comparison Undo/Redo

- Undo logging:

  Steal/Force

  - OUTPUT must be done early
  - If <COMMIT T> is seen, T definitely has written all its data to disk (hence, don't need to redo) – inefficient
- Redo logging

  No-Steal/No-Force

  - OUTPUT must be done late
  - If <COMMIT T> is not seen, T definitely has not written any of its data to disk (hence there is not dirty data on disk, no need to undo) – inflexible
- Would like more flexibility on when to OUTPUT: undo/redo logging (next)

  Steal/No-Force

Undo/Redo Logging

Log records, only one change

- <T,X,u,v>= T has updated element X, its *old* value was u, and its *new* value is v

Undo/Redo-Logging Rule

UR1: If T modifies X, then <T,X,u,v> must be written to disk before OUTPUT(X)

Note: we are free to OUTPUT early or late relative to <COMMIT T>

Action	T	Mem A	Mem B	Disk A	Disk B	Log
						<START T>
REAT(A,t)	8	8		8	8	
t:=t*2	16	8		8	8	
WRITE(A,t)	16	16		8	8	<T,A,8,16>
READ(B,t)	8	16	8	8	8	
t:=t*2	16	16	8	8	8	
WRITE(B,t)	16	16	16	8	8	<T,B,8,16>
OUTPUT(A)	16	16	16	16	8	
						<COMMIT T>
OUTPUT(B)	16	16	16	16	16	

Can OUTPUT whenever we want: before/after COMMIT

Recovery with Undo/Redo Log

After system's crash, run recovery manager

- Redo all committed transaction, top-down
- Undo all uncommitted transactions, bottom-up

Recovery with Undo/Redo Log

<START T1>
<T1,X1,v1>
<START T2>
<T2, X2, v2>
<START T3>
<T1,X3,v3>
<COMMIT T2>
<T3,X4,v4>
<T1,X5,v5>
…
…

ARIES

Aries

- ARIES pieces together several techniques into a comprehensive algorithm
- Developed at IBM Almaden, by Mohan
- IBM botched the patent, so everyone uses it now
- Several variations, e.g. for distributed transactions

ARIES Recovery Manager

Log entries:

- <START T> -- when T begins
- Update: <T,X,u,v>
  - T updates X, <u>*old*</u> value=u, <u>*new*</u> value=v
  - Logical description of the change
- <COMMIT T> or <ABORT T> then <END>
- <CLR> – we'll talk about them later.

ARIES Recovery Manager

Rule:

- If T modifies X, then <T,X,u,v> must be written to disk before OUTPUT(X)

We are free to OUTPUT early or late w.r.t commits

LSN = Log Sequence Number

- **LSN** = identifier of a log entry
  - Log entries belonging to the same TXN are linked with extra entry for previous LSN
- Each page contains a **pageLSN**:
  - LSN of log record for latest update to that page

ARIES Data Structures

- **Active Transactions Table**
  - Lists all active TXN's
  - For each TXN: lastLSN = its most recent update LSN
- **Dirty Page Table**
  - Lists all dirty pages
  - For each dirty page: recoveryLSN (recLSN)= first LSN that caused page to become dirty
- **Write Ahead Log**
  - LSN, prevLSN = previous LSN for same txn

Data Structures

$W_{T100}(P7)$
$W_{T200}(P5)$
$W_{T200}(P6)$
$W_{T100}(P5)$

Dirty pages

pageID	recLSN
P5	102
P6	103
P7	101

Log (WAL)

LSN	prevLSN	transID	pageID	Log entry
101	-	T100	P7	
102	-	T200	P5	
103	102	T200	P6	
104	101	T100	P5	

Active transactions

transID	lastLSN
T100	104
T200	103

Buffer Pool

P8	**P2**	. . .
	. . .	
P5 PageLSN=104	**P6** PageLSN=103	**P7** PageLSN=101

ARIES Normal Operation

T writes page P

- What do we do ?

ARIES Normal Operation

T writes page P

- What do we do ?

- Write **<T,P,u,v>** in the **Log**
- **pageLSN**=**LSN**
- **prevLSN=lastLSN**
- **lastLSN**=**LSN**
- **recLSN**=if isNull then **LSN**

ARIES Normal Operation

Buffer manager wants to OUTPUT(P)

- What do we do ?

Buffer manager wants INPUT(P)

- What do we do ?

ARIES Normal Operation

Buffer manager wants to OUTPUT(P)

- Flush log up to **pageLSN**
- Remove P from **Dirty Pages** table

Buffer manager wants INPUT(P)

- What do we do ?

ARIES Normal Operation

Buffer manager wants to OUTPUT(P)

- Flush log up to **pageLSN**
- Remove P from **Dirty Pages** table

Buffer manager wants INPUT(P)

- Create entry in **Dirty Pages** table
  recLSN = NULL

ARIES Normal Operation

Transaction T starts

- What do we do ?

Transaction T commits/aborts

- What do we do ?

ARIES Normal Operation

Transaction T starts

- Write <START T> in the log
- New entry T in Active TXN; lastLSN = null

Transaction T commits

- What do we do ?

ARIES Normal Operation

Transaction T starts

- Write **<START T>** in the log
- New entry T in Active TXN; lastLSN = null

Transaction T commits

- Write **<COMMIT T>** in the log
- Flush log up to this entry
- Write **<END>**

Checkpoints

Write into the log

- Entire active transactions table
- Entire dirty pages table

Recovery always starts by analyzing latest checkpoint

Background process periodically flushes dirty pages to disk

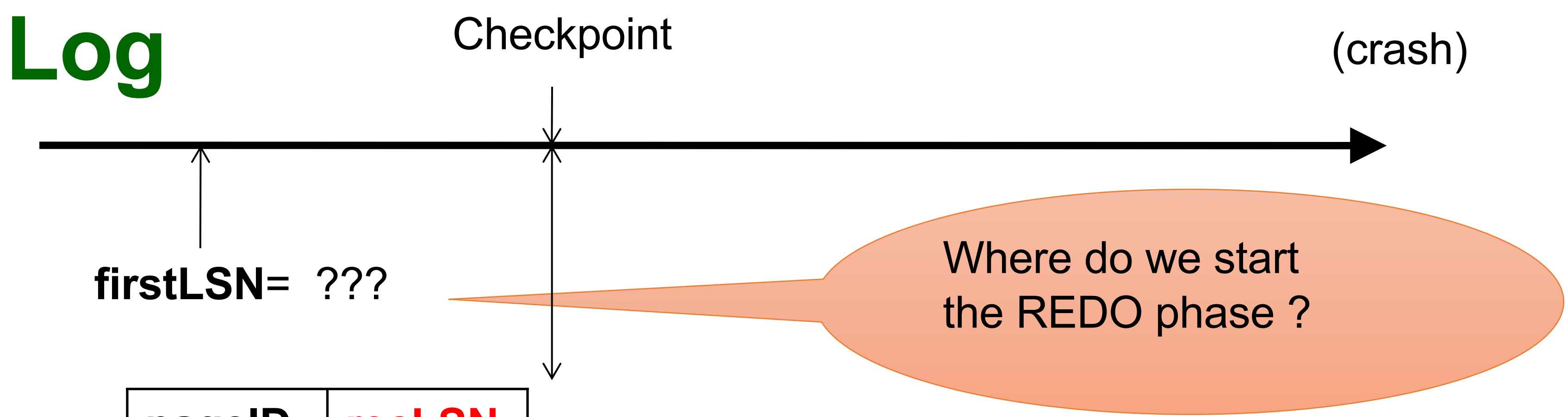
ARIES Recovery

1. **Analysis pass**
   - Figure out what was going on at time of crash
   - List of dirty pages and active transactions
2. **Redo pass (repeating history principle)**
   - Redo all operations, even for transactions that will not commit
   - Get back to state at the moment of the crash
3. **Undo pass**
   - Remove effects of all uncommitted transactions
   - Log changes during undo in case of another crash during undo

1. Analysis Phase

- Goal
  - Determine point in log where to start REDO
  - Determine set of dirty pages when crashed
    - Conservative estimate of dirty pages
  - Identify active transactions when crashed
- Approach
  - Rebuild active transactions table and dirty pages table
  - Reprocess the log from the checkpoint
    - Only update the two data structures
  - Compute: **firstLSN** = smallest of all recoveryLSN

1. Analysis Phase



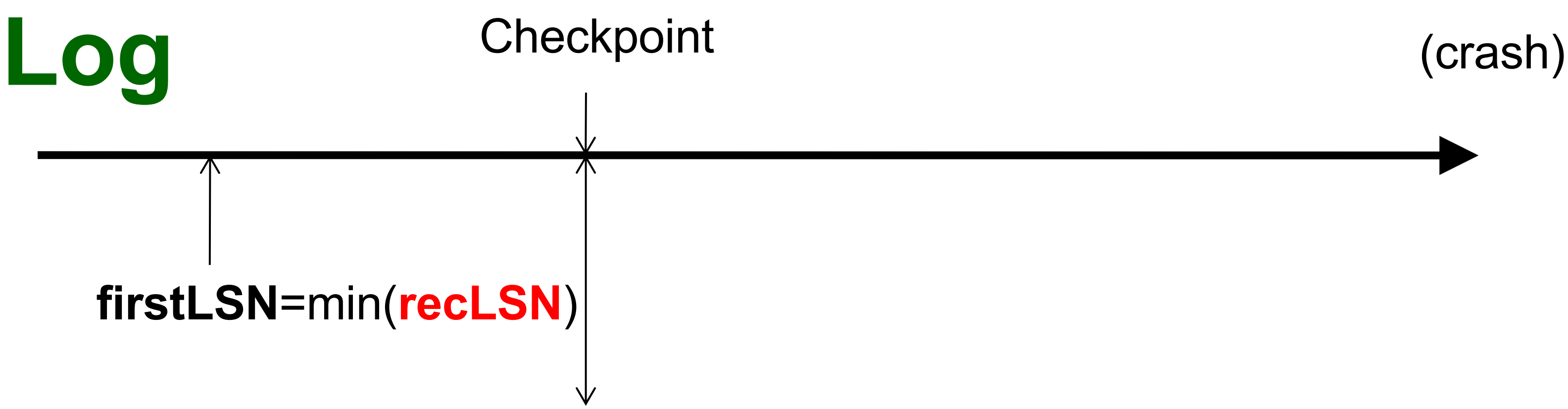
Dirty pages

pageID	recLSN

Active txn

transID	lastLSN

1. Analysis Phase



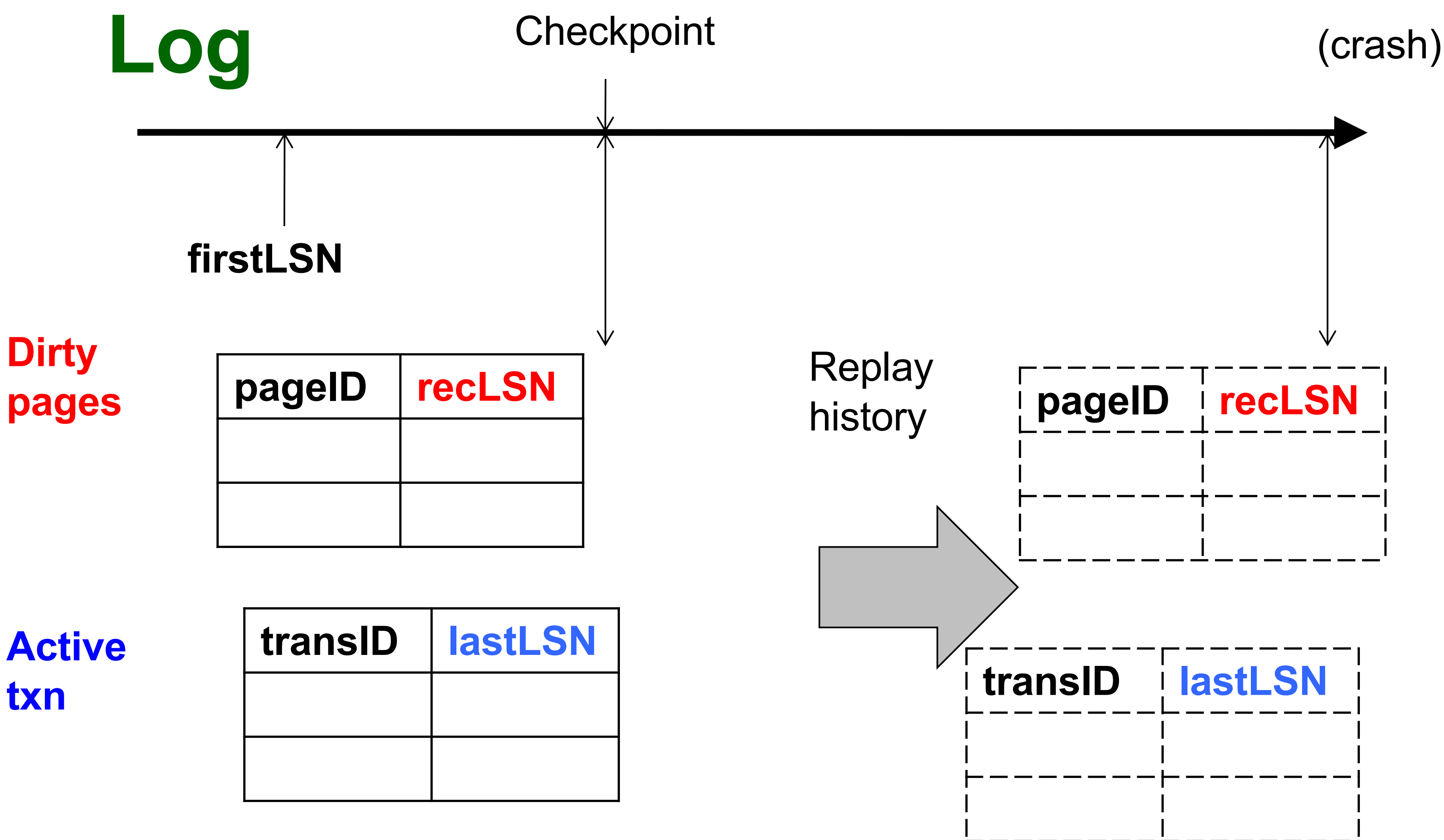
Dirty pages

pageID	recLSN

Active txn

transID	lastLSN

1. Analysis Phase



2. Redo Phase

Main principle: replay history

- Process Log forward, starting from **firstLSN**
- Read every log record, sequentially
- Redo actions are not recorded in the log
- Needs the Dirty Page Table

2. Redo Phase: Details

For each Log entry record LSN: **<T,P,u,v>**

- Redo the action P=u and WRITE(P)
- Only redo actions that need to be redone

2. Redo Phase: Details

For each Log entry record LSN: **<T,P,u,v>**

- If P is not in Dirty Page then **no update**
- If recLSN > LSN, then **no update**
- Read page from disk:
  If **pageLSN** >= LSN, then **no update**
- Otherwise perform update

2. Redo Phase: Details

What happens if system crashes during REDO ?

2. Redo Phase: Details

What happens if system crashes during REDO ?

We REDO again ! The pageLSN will ensure that we do not reapply a change twice

3. Undo Phase

- Cannot "unplay" history, in the same way as we "replay" history
- WHY NOT ?

3. Undo Phase

- Cannot "unplay" history, in the same way as we "replay" history
- WHY NOT ?
  - Undo only the loser transactions
  - Need to support ROLLBACK: selective undo, for one transaction
- Hence, *logical* undo v.s. *physical* redo

3. Undo Phase

Main principle: “logical” undo

- Start from end of Log, move backwards
- Read only affected log entries
- Undo actions *are* written in the Log as special entries: CLR (Compensating Log Records)
- CLRs are redone, but never undone

3. Undo Phase: Details

- "Loser transactions" = uncommitted transactions in Active Transactions Table

- **ToUndo** = set of lastLSN of loser transactions

3. Undo Phase: Details

While **ToUndo** not empty:

- Choose most recent (largest) LSN in **ToUndo**
- If LSN = regular record **<T,P,u,v>**:
  - Write a CLR where CLR.undoNextLSN = LSN.prevLSN
  - Undo v
- If LSN = CLR record:
  - Don't undo !
- if CLR.**undoNextLSN** not null, insert in **ToUndo**
  otherwise, write **<END>** in log

3. Undo Phase: Details

What happens if system crashes during UNDO ?

3. Undo Phase: Details

What happens if system crashes during UNDO ?

We do not UNDO again ! Instead, each CLR is a REDO record: we simply redo the undo