Transactions: Recovery

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CMSC424

Spring 2020 – Online Instruction Plan

- Week 1: File Organization and Indexes
- Week 2: Query Processing
- Week 3: Query Optimization; Parallel Databases 1
- Week 4: Parallel Databases; Mapreduce; Transactions 1
- Week 5: Transactions 2
- Week 6: Homework Due May 8
  - Transactions: Recovery
  - Misc 1: Distributed Transactions, and Object-oriented/Object-relational databases
  - Misc 2: OLAP and Data Cubes, and Information Retrieval

Transactions: Recovery

- Book Chapters
  - 16.1 – 16.4
- Key topics:
  - Challenges in guaranteeing Atomicity and Durability
  - STEAL and NO FORCE: Why those are desirable
  - How to use "logging" to support A and D
  - Key properties including write-ahead logging

Context

- ACID properties:
  - We have talked about Isolation and Consistency
  - How do we guarantee Atomicity and Durability ?
    - Atomicity: Two problems
      - Part of the transaction is done, but we want to cancel it
        - ABORT/ROLLBACK
      - System crashes during the transaction. Some changes made it to the disk, some didn't.
    - Durability:
      - Transaction finished. User notified. But changes not sent to disk yet (for performance reasons). System crashed.

- Essentially similar solutions

Reasons for crashes

- Transaction failures
  - **Logical errors**: transaction cannot complete due to some internal error condition
  - **System errors**: the database system must terminate an active transaction due to an error condition (e.g., deadlock)
- System crash
  - Power failures, operating system bugs etc
  - **Fail-stop assumption**: non-volatile storage contents are assumed to not be corrupted by system crash
    - Database systems have numerous integrity checks to prevent corruption of disk data
- Disk failure
  - Head crashes; ***for now we will assume***
    - ***STABLE STORAGE: Data <u>never</u> lost. Can approximate by using RAID and maintaining geographically distant copies of the data***

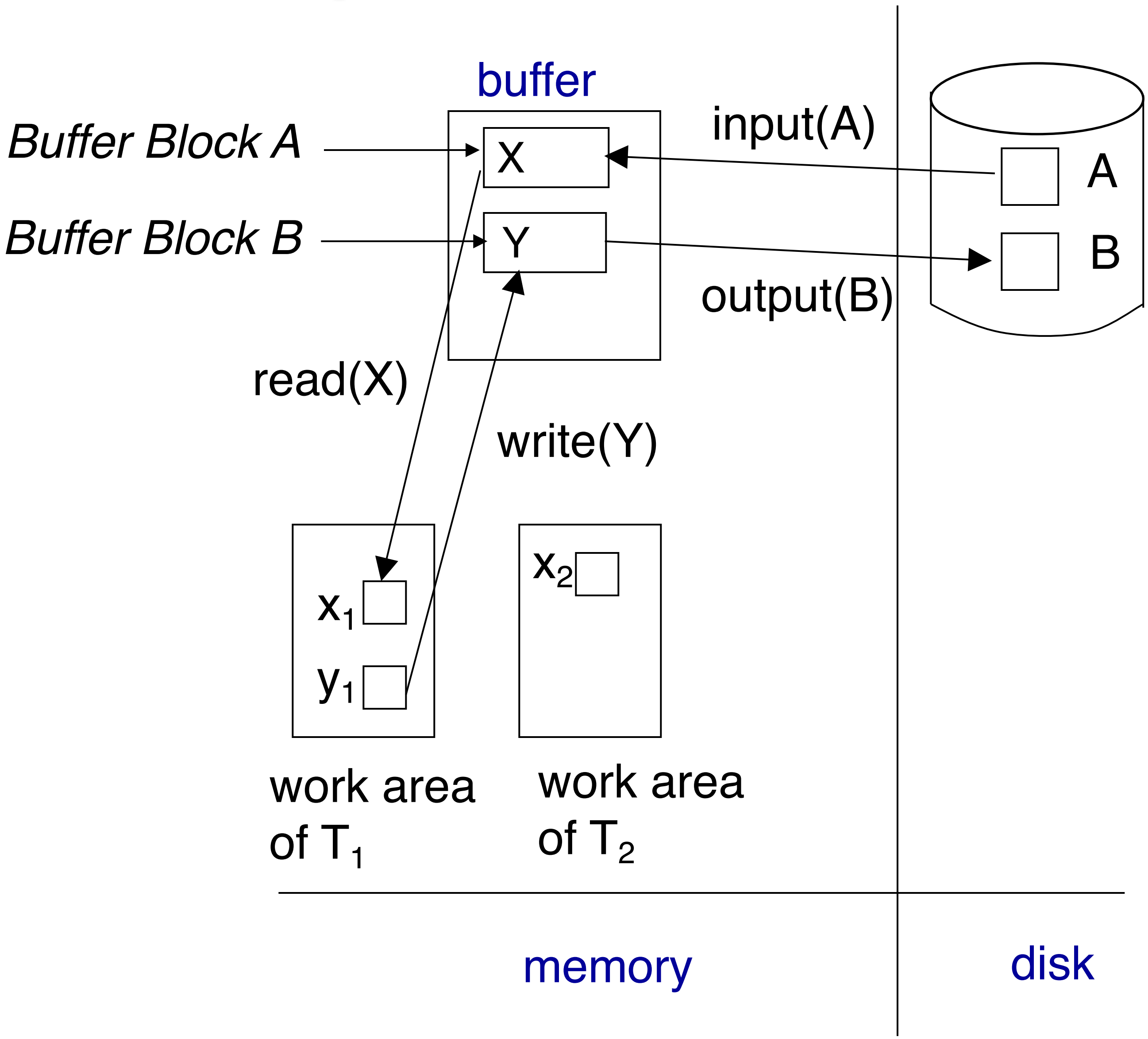
Approach, Assumptions etc..

- Approach:
  - Guarantee A and D:
    - by controlling how the disk and memory interact,
    - by storing enough information during normal processing to recover from failures
    - by developing algorithms to recover the database state
- Assumptions:
  - System may crash, but the *disk is durable*
  - The only *atomicity* guarantee is that *a disk block write* is *atomic*
- Once again, obvious naïve solutions exist that work, but that are too expensive.
  - E.g. The shadow copy solution
    - Make a copy of the database; do the changes on the copy; do an atomic switch of the *dbpointer* at commit time
  - Goal is to do this as efficiently as possible

Data Access

- **Physical blocks** are those blocks residing on the disk.
- **Buffer blocks** are the blocks residing temporarily in main memory.
- Block movements between disk and main memory are initiated through the following two operations:
  - **input**(*B*) transfers the physical block *B* to main memory.
  - **output**(*B*) transfers the buffer block *B* to the disk, and replaces the appropriate physical block there.
- We assume, for simplicity, that each data item fits in, and is stored inside, a single block.

Example of Data Access



Data Access (Cont.)

- Each transaction T_i has its private work-area in which local copies of all data items accessed and updated by it are kept.
  - T_i's local copy of a data item X is called x_i.
- Transferring data items between system buffer blocks and its private work-area done by:
  - **read**(X) assigns the value of data item X to the local variable x_i.
  - **write**(X) assigns the value of local variable x_i to data item $\{X\}$ in the buffer block.
  - **Note: output**(B_X) need not immediately follow **write**(X). System can perform the **output** operation when it deems fit.
- Transactions
  - Must perform **read**(X) before accessing X for the first time (subsequent reads can be from local copy)
  - **write**(X) can be executed at any time before the transaction commits

STEAL vs NO STEAL, FORCE vs NO FORCE

- STEAL:
  - The buffer manager *can steal* a (memory) page from the database
    - ie., it can write an arbitrary page to the disk and use that page for something else from the disk
    - In other words, the database system doesn't control the buffer replacement policy
  - Why a problem ?
    - The page might contain *dirty writes,* ie., writes/updates by a transaction that hasn't committed
  - But, we must allow *steal* for performance reasons.

- NO STEAL:
  - Not allowed. More control, but less flexibility for the buffer manager.

STEAL vs NO STEAL, FORCE vs NO FORCE

- FORCE:
  - The database system *forces* all the updates of a transaction to disk before committing
  - Why ?
    - To make its updates permanent before committing
  - Why a problem ?
    - Most probably random I/Os, so poor response time and throughput
    - Interferes with the disk controlling policies
- NO FORCE:
  - Don’t do the above. Desired.
  - Problem:
    - Guaranteeing durability becomes hard
  - We might still have to *force* some pages to disk, but minimal.

STEAL vs NO STEAL, FORCE vs NO FORCE: Recovery implications

	No Steal	Steal
No Force		Desired
Force	Trivial	

STEAL vs NO STEAL, FORCE vs NO FORCE: Recovery implications

- How to implement A and D when No Steal and Force ?
  - Only updates from committed transaction are written to disk (since no steal)
  - Updates from a transaction are forced to disk before commit (since force)
    - A minor problem: how do you guarantee that all updates from a transaction make it to the disk atomically ?
      - Remember we are only guaranteed an atomic *block write*
      - What if some updates make it to disk, and other don't ?
    - Can use something like shadow copying/shadow paging

  - No atomicity/durability problem arise.

Terminology

- Deferred Database Modification:
  - Similar to NO STEAL, NO FORCE
    - Not identical
  - Only need *redos, no undos*
  - We won't cover this today

- Immediate Database Modification:
  - Similar to STEAL, NO FORCE
  - Need both *redos, and undos*

Log-based Recovery

- Most commonly used recovery method
- Intuitively, a log is a record of everything the database system does
- For every operation done by the database, a *log record* is generated and stored <u>*typically on a different (log) disk*</u>
- *<T1, START>*
- *<T2, COMMIT>*
- *<T2, ABORT>*
- *<T1, A, 100, 200>*
  - T1 modified A; old value = 100, new value = 200

Log

- Example transactions T_0 and T_1 (T_0 executes before T_1):

  T_0: **read** (*A*)
  A: - A - 50
  write (*A*)
  read (*B*)
  B:- B + 50
  write (*B*)

  T_1 : **read** (*C*)
  C:- C- 100
  write (*C*)

- Log:

(a)	(b)	(c)
<T_0 start>	<T_0 start>	<T_0 start>
<T_0, A, 950>	<T_0, A, 950>	<T_0, A, 950>
<T_0, B, 2050>	<T_0, B, 2050>	<T_0, B, 2050>
	<T_0 commit>	<T_0 commit>
	<T_1 start>	<T_1 start>
	<T_1, C, 600>	<T_1, C, 600>
		<T_1 commit>

Log-based Recovery

- Assumptions:
  1. Log records are immediately pushed to the disk as soon as they are generated
  2. Log records are written to disk in the order generated
  3. A log record is generated *before* the actual data value is updated
  4. *Strict two-phase locking*
  - ★ The first assumption can be relaxed
  - ★ As a special case, a transaction is considered *committed* only after the *<T1, COMMIT> has been pushed to the disk*
- But, this seems like exactly what we are trying to avoid ??
  - ★ Log writes are *sequential*
  - ★ They are also typically on a different disk
- Aside: LFS == log-structured file system

Log-based Recovery

- Assumptions:
  1. Log records are immediately pushed to the disk as soon as they are generated
  2. Log records are written to disk in the order generated
  3. A log record is generated *before* the actual data value is updated
  4. *Strict two-phase locking*
  - ★ The first assumption can be relaxed
  - ★ As a special case, a transaction is considered *committed* only after the *<T1, COMMIT> has been pushed to the disk*
- NOTE: As a result of assumptions 1 and 2, if *data item A* is updated, the log record corresponding to the update is always forced to the disk before *data item A* is written to the disk
  - ★ This is actually the only property we need; assumption 1 can be relaxed to just guarantee this (called *write-ahead logging*)

Using the log to *abort/rollback*

- STEAL is allowed, so changes of a transaction may have made it to the disk

- UNDO(T1):
  - Procedure executed to *rollback/undo* the effects of a transaction
  - E.g.
    - *<T1, START>*
    - *<T1, A, 200, 300>*
    - *<T1, B, 400, 300>*
    - *<T1, A, 300, 200>* *[[note: second update of A]]*
    - T1 decides to abort

  - Any of the changes might have made it to the disk

Using the log to *abort/rollback*

- UNDO(T1):
  - Go *backwards* in the *log* looking for log records belonging to T1
  - Restore the values to the old values
  - NOTE: Going backwards is important.
    - *A* was updated twice
  - In the example, we simply:
    - Restore A to 300
    - Restore B to 400
    - Restore A to 200
  - Write a log record $<T_i , X_j, \ V_1>$
    - such log records are called **compensation log records**
    - **<T1, A, 300>, <T1, B, 400>, <T1, A, 200>**
  - Note: No other transaction better have changed A or B in the meantime
    - *Strict two-phase locking*

Using the log to *recover*

- We don’t require FORCE, so a change made by the committed transaction may not have made it to the disk before the system crashed
  - BUT, the log record did (recall our assumptions)
- REDO(T1):
  - Procedure executed to recover a committed transaction
  - E.g.
    - *<T1, START>*
    - *<T1, A, 200, 300>*
    - *<T1, B, 400, 300>*
    - *<T1, A, 300, 200>* *[[note: second update of A]]*
    - *<T1, COMMIT>*
  - By our assumptions, all the log records made it to the disk (since the transaction committed)
  - But any or none of the changes to A or B might have made it to disk

Using the log to *recover*

- REDO(T1):
  - Go *forwards* in the *log* looking for log records belonging to T1
  - Set the values to the new values
  - NOTE: Going forwards is important.
  - In the example, we simply:
    - Set A to 300
    - Set B to 300
    - Set A to 200

Idempotency

- Both redo and undo are required to *idempotent*
  - *F is idempotent, if F(x) = F(F(x)) = F(F(F(F(…F(x)))))*
- Multiple applications shouldn't change the effect
  - This is important because we don't know exactly what made it to the disk, and we can't keep track of that
  - E.g. consider a log record of the type
    - <T1, A, *incremented by 100*>
    - Old value was 200, and so new value was 300
  - But the on disk value might be 200 or 300 (since we have no control over the buffer manager)
  - So we have no idea whether to apply this log record or not
  - Hence, *value based logging* is used (also called *physical)*, not operation based (also called *logical)*

Log-based recovery

- Log is maintained
- If during the normal processing, a transaction needs to abort
  - UNDO() is used for that purpose
- If the system crashes, then we need to do recovery using both UNDO() and REDO()
  - Some transactions that were going on at the time of crash may not have completed, and must be *aborted/undone*
  - Some transaction may have committed, but their changes didn't make it to disk, so they must be *redone*
  - Called *restart recovery*

Recovery Algorithm (Cont.)

- **Recovery from failure**: Two phases
  - **Redo phase**: replay updates of **all** transactions, whether they committed, aborted, or are incomplete
  - **Undo phase**: undo all incomplete transactions

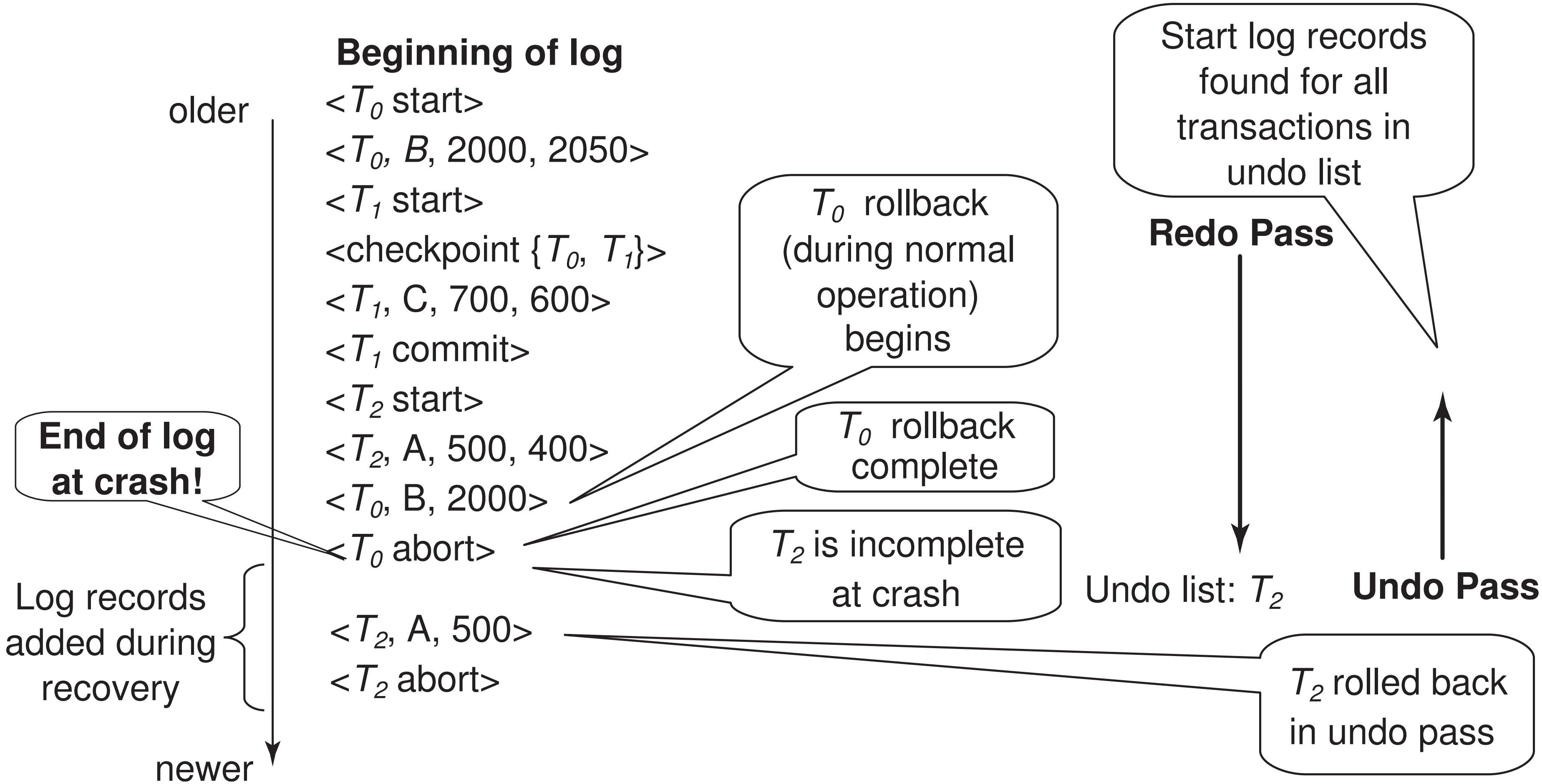
- **Redo phase**:
  1. Find last <**checkpoint** *L*> record, and set undo-list to *L*.

     - If no checkpoint record, start at the beginning
  2. Scan forward from above <**checkpoint** *L*> record
     1. Whenever a record $<T_i, X_j, V_1, V_2>$ is found, redo it by writing V_2 to X_j
     2. Whenever a log record <T_i **start**> is found, add T_i to undo-list
     3. Whenever a log record <T_i **commit**> *or* <T_i **abort**> is found, remove T_i from undo-list

Recovery Algorithm (Cont.)

- **Undo phase:**
  1. Scan log backwards from end
     1. Whenever a log record <T_i, X_j, V_1, V_2> is found where T_i is in undo-list perform same actions as for transaction rollback:
        1. perform undo by writing V_1 to X_j.
        2. write a log record <T_i , X_j, V_1>
     2. Whenever a log record <T_i **start**> is found where T_i is in undo-list,
        1. Write a log record <T_i **abort**>
        2. Remove T_i from undo-list
     3. Stop when undo-list is empty
        - i.e. <T_i **start**> has been found for every transaction in undo-list
- After undo phase completes, normal transaction processing can commence

Example of Recovery



Checkpointing

- How far should we go back in the log while constructing redo and undo lists ??
  - It is possible that a transaction made an update at the very beginning of the system, and that update never made it to disk
    - very very unlikely, but possible (because we don't do force)
  - For correctness, we have to go back all the way to the beginning of the log
  - Bad idea !!

- Checkpointing is a mechanism to reduce this

Checkpointing

- Periodically, the database system writes out everything in the memory to disk
  - Goal is to get the database in a state that we know (not necessarily consistent state)
- Steps:
  - Stop all other activity in the database system
  - Write out the entire contents of the memory to the disk
    - Only need to write updated pages, so not so bad
    - Entire === all updates, whether committed or not
  - Write out all the log records to the disk
  - Write out a special log record to disk
    - *<CHECKPOINT LIST_OF_ACTIVE_TRANSACTIONS>*
    - The second component is the list of all active transactions in the system right now
  - Continue with the transactions again

Restart Recovery w/ checkpoints

- Key difference: Only need to go back till the last checkpoint
- Steps:
  - undo_list:
    - Go back till the checkpoint as before.
    - Add all the transactions that were active at that time, and that didn't commit
      - e.g. possible that a transactions started before the checkpoint, but didn't finish till the crash
  - redo_list:
    - Similarly, go back till the checkpoint constructing the redo_list
    - Add all the transactions that were active at that time, and that did commit
  - Do UNDOs and REDOs as before

Recap so far …

- Log-based recovery
  - Uses a *log* to aid during recovery
- UNDO()
  - Used for normal transaction abort/rollback, as well as during restart recovery
- REDO()
  - Used during restart recovery
- Checkpoints
  - Used to reduce the restart recovery time

Write-ahead logging

- We assumed that log records are written to disk as soon as generated
  - Too restrictive
- Write-ahead logging:
  - Before an update on a data item (say A) makes it to disk, the log records referring to the update must be forced to disk
  - How ?
    - Each log record has a log sequence number (LSN)
      - Monotonically increasing
    - For each page in the memory, we maintain the LSN of the *last log record* that updated a record on this page
      - *pageLSN*
    - If a page *P* is to be written to disk, all the log records till *pageLSN(P)* are forced to disk

Write-ahead logging

- Write-ahead logging (WAL) is sufficient for all our purposes
  - All the algorithms discussed before work

- Note the special case:
  - A transaction is not considered committed, unless the <T, commit> record is on disk

Other issues

- The system halts during checkpointing
  - Not acceptable
  - Advanced recovery techniques allow the system to continue processing while checkpointing is going on
- System may crash during recovery
  - Our simple protocol is actually fine
  - In general, this can be painful to handle
- B+-Tree and other indexing techniques
  - Strict 2PL is typically not followed (we didn't cover this)
  - So physical logging is not sufficient; must have logical logging

Other issues

- ARIES: Considered *the canonical description of log-based recovery*
  - Used in most systems
  - Has many other types of log records that simplify recovery significantly
- Loss of disk:
  - Can use a scheme similar to checkpoining to periodically dump the database onto *tapes* or *optical storage*
  - Techniques exist for doing this while the transactions are executing (called *fuzzy dumps)*
- Shadow paging:
  - Read up

Recap

- STEAL vs NO STEAL, FORCE vs NO FORCE
  - We studied how to do STEAL and NO FORCE through log-based recovery scheme

	No Steal	Steal
No Force		Desired
Force	Trivial	

	No Steal	Steal
No Force	REDO NO UNDO	REDO UNDO
Force	NO REDO NO UNDO	NO REDO UNDO

Recap

- ACID Properties
  - Atomicity and Durability :
    - Logs, undo(), redo(), WAL etc
  - Consistency and Isolation:
    - Concurrency schemes
  - Strong interactions:
    - We had to assume Strict 2PL for proving correctness of recovery