Lecture S5: Transactions and reliability

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Review -- 1 min
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Naming – which blocks belong to which files?
which files belong to which names?

Directories – regular files containing name→fileID mappings

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Outline - 1 min
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Transactions
ACID: atomicity, consistency, isolation, durability
logging
LFS,

Reliability
disk reliablity
RAIDs

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Preview - 1 min
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Lecture - 20 min
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1. Motivation

File systems have lots of data structures

- bitmap of free blocks
- directory
- file header

- indirect blocks
- data blocks

For performance, all must be cached!
Ok for reads, but what about writes?

1.1 Modified data in memory ("cached writes") can be lost

Options for writing data

write through – write changes immediately to disk
problem: slow! Have to wait for each write to complete before going on.
Write back – delay writing modified data back to disk (for example, until replaced). Problem: can lose data on a crash

1.2 multiple updates

if multiple updates needed to perform some operation, crash can occur between them!

For example, to move a file between directories:
1) delete file from old directory
2) add file to new directory

to transfer $100 from your bank account to mine
(1) Debit your account
(2) Credit my account

to update an existing file (e.g., text editor checkpoint)
(1) overwrite block 1 of file with new data
(2) overwrite block 2 of file with new data
(3) …

or
(1) write new file with new data
(2) remove old file from directory
(3) add new file to directory

to create new file

1) allocate space on disk for header, data
2) write new header to disk
3) add new file to directory

What if there is a crash in the middle, even with write-through have a problem

2. Approach 1 (ad-hoc)

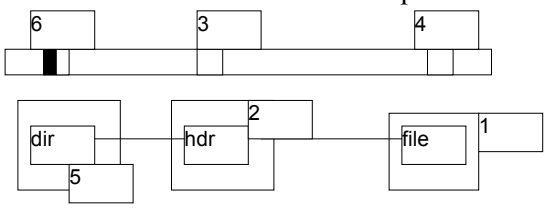
Common in older systems

metadata: needed to keep file system logically consistent (directories, bitmaps, file headers, indirect blocks, etc.)
data: user bytes

2.1 Metadata consistency

For metadata, UNIX uses synchronous write through
If multiple updates needed, does them in specific order so that if a crash occurs, run special program "fsck" that scans entire disk for internal consistency to check for "in progress" operations and then fix up anything in progress

example: for file create, first write data to file, then update file header, then mark file header "allocated" in bitmap, then mark file blocks "allocated" in bitmap, then update directory, then (if directory grew) mark new file block "allocated" in bitmap



fsck:

file header not in bitmap → only writes were to unallocated, unreachable blocks; write "disappears"

block or file header allocated, but not in bitmap → update bitmap

file created, but not yet in any directory → delete file

Challenge:
(1) need to get ad-hoc reasoning exactly right
(2) poor performance (synchronous writes)
(3) slow recovery – must scan entire disk

2.2 User data consistency

what about user data?
→ write back, forced to disk every 30 seconds (or user can call "sync" to force to disk immediately)

No guarantee blocks written to disk in any order
can lose up to 30 seconds of work

Still, sometimes metadata consistency is enough
e.g. how should vi or emacs write changes to a file to disk?

option 1:
delete old file
write new file
(how vi used to work!)

now vi does the following:
write new version to temp file
move old version to other temp file
move new version to real file
unlink old version
If a crash, look in temp area, if any files there, send e-mail to user that there might be a problem

But what if user wants to have multiple file operations occur as a unit?
Example: bank transfer
    ATM gives you $100
    debits your account
must be atomic

2.3 Implementation tricks

2.3.1 Dependencies

Instead of blocking until a write makes it to disk, then sending the next write, send series of writes separated by BARRIER

OS builds a dependency graph and ensures that a write does not go to disk until all writes on which it depends goes to disk

Example of a general problem: output commit

3. Transaction

transaction – group actions together so they are:
Atomic – all or nothing. either happens or it doesn't – no partial operations
Consistent – maintains system invariants
    e.g., "total deposits less total withdrawals = total accounts"
Isolated – serializable; transactions appear to happen one after another
Durable – persistent -- once it happens, stays happened

QUESTION: How does this compare to critical section?
Critical sections are atomic, serializable, consistent, but not durable

Two more terms
commit – when transaction is done (visible, durable)

rollback – "forget" uncomitted transaction (e.g. if failure occurs in middle of transaction, it didn't happen at all)

4. Implementation (one thread)

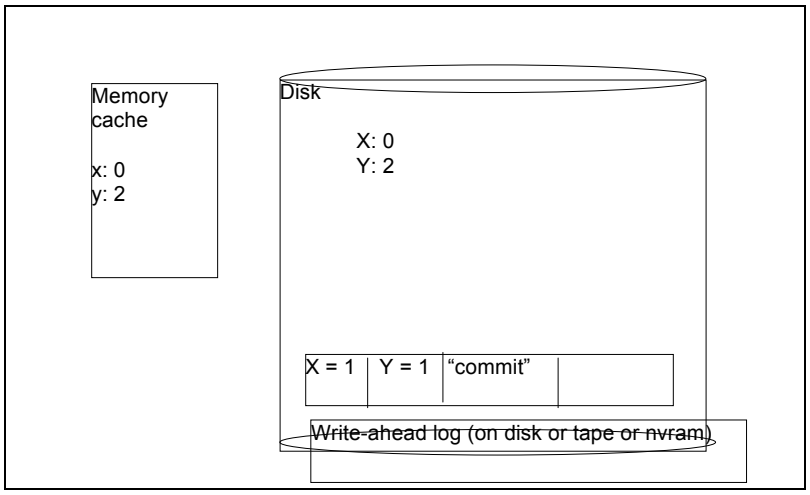
Key idea – fix problem of how you make multiple updates to disk atomically, by turning multiple updates into a single disk write!

Illustrate with simple money transfer from acct x to acct y

```
Begin transaction
    x = x + 1
    y = y - 1
Commit transaction
```

Keep "write-ahead" log ("redo log") on disk of all changes in transaction

A log is like a journal – never erased, record of everything you've done
Once both changes are in log, write is committed
Then can "write behind" changes to disk/checkpoint/final location – if crash after commit, replay log to make sure updates get to disk/checkpoint/final location



Sequence of steps to execute transaction
1) write new value of x to log (and cache)
2) write new value of y to log (and cache)
3) write "commit" to log
4) write x to disk
5) write y to disk
6) reclaim space on log

QUESTION: what if we crash after 1?
→ no commit, nothing on disk, so ignore changes
what if after 2?
→ ditto
what if after 3, before 4 or 5?
→ commit written to log, so replay those changes back to disk.

What if we crash while writing commit?
As with concurrency, need some primitive atomic operation, or else can't build anything else.
Writing a single sector on disk (with a CRC) is atomic!

4.1.1 Barriers and write order

The above 6 steps make sense (I hope) if done in that order.

As with memory writes, system (typically) may reorder pending requests.

Option 1: wait for each operation to complete (get to disk) before starting the next

What's wrong? SLOW
-- E.g., wait an entire revolution between two writes to log (1 v. 2)

Solution: Barrier -- tell OS "Finish all before here before starting any after here"

QUESTION: Where do we need BARRIER in above steps?

variations
-- block until completion
-- BARRIER in stream of requests (OS disk scheduler must handle)
-- DAG -- directed acyclic graph defines required partial order among requests
...

Note that **commit** must block until data on disk (so BARRIER not enough) (but, see "Rethink the sync" below)

4.1.2 Alternative: can we write x back to disk before commit?

Yes: keep an "undo log" – save old values along with new value

If transaction doesn't commit, "undo" change!

QUESTION: can we do transaction with just undo log?
Just redo log?

4.1.3 Details -- API and log record format:

What needs to be in a log record?

Name of transaction:
[Previous log record of this transaction:]
[Next log record of this transaction:]
[Time:]
Type of operation:
Object of operation:
Old value:
New value:

What needs to be in commit record?

What does API look like to programmer?

In above example,
-- API includes TID in read/write calls
e.g.,
tid = beginTransaction();
x = read(tid, "x")
write(tid, "x", x+1)
y = read(tid, "y");
write(tid, "y", y+1);
commitTransaction(tid);

QUESTION: What does to log?

4.1.4 What about performance?

Write all data twice – surely that is horrible?

Compare 100 1KB random writes – direct write v. log + writeback

Direct write: 100 * T_randomWrite ~= 1 second

Pessimistic:
Log + writeback: 100*T_sequential write + 100 * T_randomWrite ~= 1000KB/50MB/s + 100 * T_randomWrite ~= 2ms + 1s

Realistic: writeback is done in background
→ better response time
→ more opportunities for disk head scheduling → 100 random writes takes less time for writeback than for direct write case

My opinion: a well designed writeback system can often have performance comparable to or better than update in place

~~5. Implementation (Advanced) – rethink the sync~~

~~5.1.1 Rethink the sync (research idea not yet widely deployed)~~

~~If a tree falls in the forest and no one hears, does it make a sound?~~

If the OS lies about what is on disk but no one catches it, did it reall lie?

When application says "sync this to disk", the OS can lie and say "OK, it's on disk."

If machine doesn't crash and data eventually makes it to disk, no one is the wiser

What if machine crashes? You can only be upset if you thought the data was already on disk (you can't be upset if machine crashes before the write, right?) → Don't let external users believe the data is on disk before it really is → block writes to screen and network until the data is **really** on disk

Program disk screen
Commit A
Print "A"
Commit B
Print "B"
Commit C
Print "C"
A, B, C done
"ABC"

→ can write A, B, C together and sequentially to log (rather than writing each on a rotation)

Example of general problem – **output commit**

some actions cannot be undone (spit money out of ATM, unlaunch the missile, move the airplane flaps) → cannot roll back state → only take these actions once transaction is certain to commit

Here the trick is move output commit from program to user/external machines

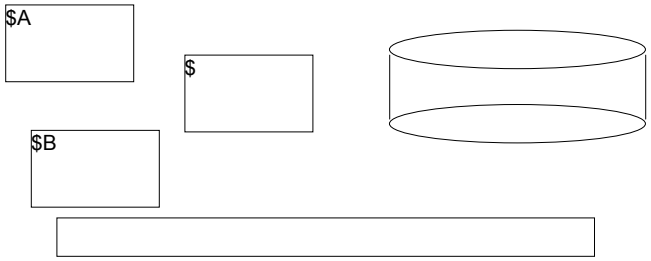
6. Concurrency

Transaction A	transaction B
W1	
	W2
	R1
	R2
W3	
Commit	

7. Concurrency: Reads

Requirement: Need to ensure *isolation* – transaction 1 cannot see the result of transaction 2 until transaction 2 commits.

~~7.1 Option 1: Per-transaction views~~



~~Store uncommitted writes with transaction~~
~~Store committed writes in shared cache (asynchronously write to disk…once they are safely on disk, mark cache entry as "clean/replacable")~~

~~Note for redo log~~

~~Uncommitted → committed, cached, dirty → committed cached, clean → committed uncached~~

7.2 ~~Option 2:~~ Two-phase locking

What if two threads run same transaction at same time?

Concurrency → use locks

```
Begin transaction
    lock x, y
        x = x+1
        y = y-1
    Unlock x, y
commit
```

What if A grabs locks, modifies x, y, writes to log, unlocks, and right before committing, then B comes in, grabs lock, writes x, y, unlocks, does commit
Then A crashes before commit
→ problem. B commits values for x, y that depend on A committing

Solution: two-phase locking
Phase 1: only allowed to acquire lock
Phase 2: All unlocks happen at commit

Thus, B can't see any of A's changes until A commits and releases locks
→ provides serializability

serializability -- result of execution is equivalent to an execution where transactions are sequenced in some *serial order* and one transaction runs at a time in that order

Also note – gives us a way to avoid deadlock
What happens if you try to grab a lock and it is already held?
(or what if you wait on a lock for > 1 second, or ….)
→ abort transaction!
→ avoids "no-revocation" condition of deadlock

Generalization: readers/writers locks

8. Concurrency: Writes

Requirement: durability -- once a transaction completes, its effects remain

Issue: ordering on recovery. Suppose two concurrent transactions T1 and T2 write to same location; T2 "wins" (is later) and is observed by T3; now we reboot, and during recovery T1 "wins". E.g., log:

W2 W1 Commit1 Commit2

Solution 1: Always make sure recovery writes happen in commit order

Solution 2: Two-phase locking; still need to make sure recovery happens in commit order; but this guaranteed to also match write order in log so may be simpler

e.g.,

W2 Commit2 W1 Commit1

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Admin - 3 min
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Lecture - 35 min
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9. Transactions in file systems

9.1 write-ahead logging

Almost all file systems built since 1985 use write-ahead logging (windows NT, solaris, OSF, Linux JFS, SGI XFS, etc)
Idea: write all changes in a transaction log (update directory, allocate blocks, etc) before sending any changes to disk
→ "create file", "delete file", "move file" etc are transactions

eliminates need to "fsck" after crash

If crash
    read log
        if log isn't committed, no change
        if log is comitted, apply all changes to disk
        if log is zero, then all updates have gotten to disk

Advantage:
    + reliability
    + asynch write-behind (seeks)
    DA: all data written twice (→ often, only log metadata)

9.2 Log-structured file system

Idea: write data only once by having log be only copy on disk
→ as you modify disk blocks, just store them out on disk in the log.
Put everything: data blocks, file headers, etc. on log

If need to get data from disk, get it from the log
- can store data blocks, indirect blocks, etc anywhere on disk, so no problem to put in log
- put inodes in log, too

→ need some way to find them
- imap is array of pointers to inodes

inodes no longer in fixed location, but imap is in fixed location (actually two fixed locations called "checkpoints")

"apply changes to disk" now means update on-disk imap
"replay log after crash" now means apply changes of comitted transactions to imap.

Advantages

- all writes are sequential!

No seeks, except for reads, but

- RAM getting bigger → caches getting bigger
  - in extreme case (infinite cache) → disk I/O only for writes (only for durability of data)

→ conclude, optimize for writes. LFS does that

Cleaning

Eventually, log wraps around – run out of room
→ have to garbage collect.

Majority of files deleted within first 5 minutes, so go back over log, and compress pieces that are no longer in use

As disk gets full, need to clean more frequently, so keep disk under-utilized

Pros & cons
+ write performance
+ read performance (if write order predicts read order)
■ cleaning cost (off-line?)
■ bad if disk full, random updates to files

SEE
http://www.cs.utexas.edu/users/dahlin/Classes/GradOS/lectures/lfs.pdf

10. Reliability

Challenges (basic model):
-- disk failure (lose one disk)
-- sector corruption (lose a few sectors on a disk)
    -- detected in HW or not

Remember: manufacturer gives MTTF estimate but, your milage may vary
-- correlated failures
-- bathtub curve
-- environmental challenges
-- Google reports seeing about 2% of disks fail per year

Key techniques
(1) Transactions (see above)
(2) End-to-end checksum a la ZFS
-- Previously: rely on disk HW checksums
-- Many recent new file systems include additional checksums (ZFS, google FS, HDFS, ...)
(3) RAID: Redundancy

11. RAIDS and reliability

Data stored to disk is supposed to be permanent. Physical reality -- disks fail
    -- Today disks advertise ~1.4million hour MTTF
    -- 1.4M hours/8760 hours/year = annualized failure rate of .6%
    -- expect to lose ~.5-1% of your disks each year
    -- some reports from large deployed systems see higher annualized failure rates (~2%)

Note MTTF 1.4M hours = 160 year MTTF does not mean disks will last 100+ years. This is failure rate during useful life (bathtub curve)

If you have 1 disk, this should make you nervous. You shouldn't ignore it.
If you have 10 or 100 disks, you can't ignore it.

Organization may have hundreds or thousands of disks
Suppose you need to store more data than fits on a single disk? How should you arrange data across disks?

Naive option: treat disk as huge pool of disk blocks so that:
disk 1 has blocks 1, k+1, 2k+1, ….
Disk 2 has blocks 2, k+2, …
…

Benefits
- load gets balanced automatically across disks
- can transfer large files at aggregate BW of all disks

Problem: what if one disk fails?
Big problem: for k disks k times as likely to have a failed disk at any given time

Availability v. reliability

Availiability – never lose access to data; system should continue working even if some components are not working (liveness)
Reliability – never lose data (safety)

(Battery runs out on my laptop makes storage unavailable but hopefully not unreliable)

RAID

RAID -- redundant array of inexpensive disks
-- use redundancy to improve reliablity

In RAID, dedicate one disk to hold parity for other disks in stripe

disk 1 has blocks 1, K+1, 2K+1, …

disk 2 has blocks 2, K+2, 2K+2, …
…
parity disk has blocks parity(1…k), parity(K+1…2K)…

If lose any disk, can recover data from other disks plus parity
ex:

disk 1 has 1 0 0 1
disk 2 has 0 1 0 1
disk 3 has 1 0 0 0
parity has 0 1 0 0

What if we lose disk 2? Its contents are parity of remainder!
Thus can lose any disk, and data is still available

Details:

- disk failures are "fail-stop" – disks tell you when they fail
- update – read-modify-write data and parity *atomically*
  - solution – write-ahead logging or log-structure

Preferred Customer
Comment:

Simple (naïve) analysis

why does this work?

Suppose MTTF = 100K hours (11.5 years)
Department has 100 disks → 100K/100 until first failure = 1000 hours = lose data every 41.66 days!

Suppose MTTR = 10 hours and we arrange disks as 99 disks + 1 parity
QUESTION: 1% better? 2x better? 10x better?

Assuming independent failures(*) – need to get unlucky and have a second failure before the first disk is fixed

e.g., 41 days until the first failure happens, then race to fix disk before next one fails. Since I fix the disk in 10 hours and the next disk is expected to fail in 1000 hours, I win this race 99 out of 100 times

→ MTTDL = 100 * 1000 = 100K hours

ANSWER 100x better. 1% reduction in effective space gets 100x improvement in reliability!

Of course, I can improve this further by
(1) using more redundancy (e.g., 1 parity per 10 rather than 1 per 100)

Typical deployments – 1-2 parity per 1-10 disks; (e.g., 3 replicas of data in Google file system)

MTTDL = MTTF^2_disk / (N * (G-1) * MTTR_disk)

e.g., 100 disks in groups of 9 data + 1 parity

100K^2 / (100 * 9 * 10) = 1.1M hours (>100 years)

Intution: MTTF/N = time for first failure
MTTF/G-1 = time to second failure after first occurs
(MTTF/G-1)/MTTR_disk -- probability second failure occurs before first disk repaired

(2) improving repair time
"Hot swap" – immediate switch to new disk in seconds/minutes (possibly w/o operator intervention)

Limited by time to read/write data – if dedicate 100% of disk BW to repair, 1TB/50MB/s = 20K seconds – 6 hours; more if reads are slowed down because of non-repair traffic; technology trends – this number is rising
→
(a) Have enough redundancy to survive multi-hour MTTR
(b) Declustering – spread repair load – instead of organizing 100 disks into 10 groups of 10, send each data item to 10 random disks out of 100 ; if a disk fails, send the repair traffic to a random disk (excluding the ones already used for that data) → each remaining disk supplies 1% of the repair reads and receives 1% of the repair writes → repair in minutes not hours

Less naive models

The above equation is wildly optimistic. 100 disks in groups of 9+1 → 100 years? No way.

NOTE: independent failure assumption is way too optimistic

(1) "bathtub" lifetime – quoted MTTF only valid during intended service lifetime (e.g., first 3-5 years of services possibly not including burn-in)

(2) environmental correlation – power surges, vibration, manufacturing defect, faulty controller or server, …

Common configurations today:
Mirrored: 2 identical disks (write to both, read from either)
3-5 data + 1 parity
3-way replication
5-10 data + 2 parity

Other "advanced" sources of failure

- Operator error
- Malicious operator
- Malware: Virus, ransomware
- Fire, flood, hurricane, …
- Bankruptcy of outsourced storage provider
- FBI raid on collocation center (!)
  http://blog.wired.com/27bstroke6/2009/04/data-centers-ra.html
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One solution: SafeStore – geographic, operator, organization, software diversity; restrict interface;

http://www.cs.utexas.edu/users/dahlin/papers/SafeStore-USENIX07.pdf

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Summary - 1 min
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Key idea: log