Project 5: Due April 29. Last Project!

Project 4a, 4b grading update
Regrades status

Peer mentors for next semester! [https://forms.gle/h7zXQidTP4QxiwVD8](https://forms.gle/h7zXQidTP4QxiwVD8)
COURSE FEEDBACK

https://aefis.wisc.edu
AGENDA / LEARNING OUTCOMES

How to design a filesystem that performs better for small writes?

What are the design principles for systems that operate across machines?
FS STRUCTS

File System - API

Inode Blocks

Data Blocks

Take num nodes

Bitmaps

0 7 8 15 16 23 24 31 32 39 40 47 48 55 56 63
Crash consistency: Important problem in filesystem design!

Two main approaches

**FSCK:**
- Fix file system image after crash happens
- Too slow and only ensures consistency

**Journaling**
- Write a transaction before in-place updates
- Checksum, batching
- Ordered journal avoids data writes
LOG STRUCTURED FILE SYSTEM (LFS)
LFS PERFORMANCE GOAL

Motivation:
- Growing gap between sequential and random I/O performance
- RAID-5 especially bad with small random writes

Idea: use disk purely sequentially

Design for writes to use disk sequentially – how?
WRITES

log
append operations
update

Create write

Inode[j] A5

Inode[k]

log

Inode writes are also sequential
IMAP EXPLAINED

1. How to build this map.

In-memory updates wherever inside more.

Inode number: disk addr

1: 2
2: 10
3: 15

D

blk[0]: A0

I

D[1]

I[1]

A2

A3

map[k]: A1

imap

1: A2

A0

A1

Imap large?

Restart machine?
How do we find the imap, given pieces of it are also spread across the disk?

Checkpoint Region (CR):
- fixed region at say start of the disk
- pointers to the latest pieces of the inode map
  Updated every 30s or so, performance is not affected
1. Read the Checkpoint region
2. Read all imap parts, cache in mem
3. To read a file:
   1. Lookup inode location in imap
   2. Read inode
   3. Read the file block
You are given the traffic stream of writes to disk performed by LFS. Before these writes, you can assume the file system only had a root directory. You can also assume that a single inode takes up an entire block.

(a) Segment written starting at disk address 100, in a segment of size 4:

```
block 100: [ (" ", 0), (" ", 0), ("foo", 1) ]  // a data block
block 101: [ size=1, ptr=100, type=d ]  // an inode
block 102: [ size=0, ptr=-, type=r ]  // an inode
block 103: [ imap: 0->101[1]->102 ]  // a piece of the imap
```

What file system operation(s) led to this segment write?

Create /foo
(b) Segment written to disk address 104, in a segment of size 4:

block 104: [SOME DATA]  // a data block
block 105: [SOME DATA]  // a data block
block 106: [size=2, ptr=104, ptr=105, type=r]  // an inode
block 107: [imap: 0->101, 1->106]  // a piece of the imap

What file system operation(s) led to this segment write?

write("/foo", 2 blocks, 1024 bytes)
if BS~512
GARBAGE COLLECTION

No garbage

512 bytes

_close

512 bytes

blk[0]:A0

D0

Ilk]

(garbage)

A0

A1

map

1 : A5

blk[0]:A0

blk[1]:A4

D1

Ilk]

A4

A5

ifoo had 1 block

ifoo had 2 blocks

upper ifoo has 2 blocks

\rightarrow v1

\rightarrow n2

of the file
WHAT TO DO WITH OLD DATA?

Old versions of files → garbage

Approach 1: garbage is a feature!
- Keep old versions in case user wants to revert files later
- Versioning file systems
- Example: Dropbox

Approach 2: garbage collection
GARBAGE COLLECTION

Need to reclaim space:
1. When no more references (any file system)
2. After newer copy is created (COW file system)

LFS reclaims **segments** (not individual inodes and data blocks)
- Want future overwrites to be to sequential areas
- Tricky, since segments are usually partly valid
Garbage Collection

Disk segments:

- Used: 60%
- Used: 10%
- Used: 95%
- Used: 25%
- Free: 0%
- Free: 95%

Compact 2 segments to one

When moving data blocks, copy new inode to point to it
When move inode, update imap to point to it
Garbage Collection

General operation:
Pick M segments, compact into N (where N < M).

Mechanism:
How does LFS know whether data in segments is valid?

Policy:
Which segments to compact?
Garbage Collection Mechanism

Is an inode the latest version?
- Check imap to see if this inode is pointed to
- Fast!

Is a data block the latest version?
- Scan ALL inodes to see if any point to this data
- Very slow!

How to track information more efficiently?
- **Segment summary:** For every data block in segment, store its inode number (which file) and offset (which block of file)
(N, T) = SegmentSummary[A];

inode = Read(imap[N]);

if (inode[T] == A)
  // block D is alive
else
  // block D is garbage
GARBAGE COLLECTION POLICY

General operation:
Pick M segments, compact into N (where N < M).

Mechanism:
Use segment summary, imap to determine liveness

Policy:
Which segments to compact?
• clean most empty first
• clean coldest (ones undergoing least change)
• more complex heuristics…
What data needs to be recovered after a crash? Need imap (lost in volatile memory)
CHECKPOINT SUMMARY

Checkpoint occasionally (e.g., every 30s)

Upon recovery:
- read checkpoint to find most imap pointers and segment tail
- find rest of imap pointers by reading past tail

What if crash during checkpoint?
Have two checkpoint regions
Only overwrite one checkpoint at a time
Use checksum/timestamps to identify newest checkpoint
Managing I/O devices is a significant part of OS!

Disk drives: storage media with specific geometry

Filesystems: OS provided API to access disk

Simple FS: FS layout with SB, Bitmaps, Inodes, Datablocks

FFS: Split simple FS into groups. Key idea: put inode, data close to each other

LFS: Puts data where it's fastest to write, hope future reads cached in memory

https://www.eecs.harvard.edu/~margo/papers/usenix95-lfs/supplement/

FSCK, Journaling

Crash consistency
DISTRIBUTED SYSTEMS
HOW DOES GOOGLE SEARCH WORK?
WHAT IS A DISTRIBUTED SYSTEM?

A distributed system is one where a machine I’ve never heard of can cause my program to fail.
— Leslie Lamport

Definition:
More than 1 machine working together to solve a problem

Examples:
– client/server: web server and web client
– cluster: page rank computation
WHY GO DISTRIBUTED?

More computing power

More storage capacity

Fault tolerance

Data sharing
NEW CHALLENGES

System failure: need to worry about partial failure

Communication failure: links unreliable
  - bit errors
  - packet loss
  - node/link failure

Why are network sockets less reliable than pipes?
COMMUNICATION OVERVIEW

Raw messages: UDP
Reliable messages: TCP
Remote procedure call: RPC
RAW MESSAGES: UDP

UDP: User Datagram Protocol

API:
- reads and writes over socket file descriptors
- messages sent from/to ports to target a process on machine

Provide minimal reliability features:
- messages may be lost
- messages may be reordered
- messages may be duplicated
- only protection: checksums to ensure data not corrupted
RAW MESSAGES: UDP

Advantages

– Lightweight
– Some applications make better reliability decisions themselves (e.g., video conferencing programs)

Disadvantages

– More difficult to write applications correctly
RELIABLE MESSAGES: LAYERING STRATEGY

TCP: Transmission Control Protocol

Using software to build
reliable logical connections over unreliable physical connections
TECHNIQUE #1: ACK

<table>
<thead>
<tr>
<th>Sender</th>
<th>Receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>[send message]</td>
<td>[recv message]</td>
</tr>
<tr>
<td>[recv ack]</td>
<td>[send ack]</td>
</tr>
</tbody>
</table>

Ack: Sender knows message was received
What to do about message loss?
TECHNIQUE #2: TIMEOUT

Sender
[send message]
[start timer]

… waiting for ack …

[timer goes off]
[send message]

[recv ack]

Receiver
[recv message]
[send ack]
How long to wait?

Too long?
  – System feels unresponsive

Too short?
  – Messages needlessly re-sent
  – Messages may have been dropped due to overloaded server. Resending makes overload worse!
LOST ACK PROBLEM

Sender
[send message]
[timeout]
[send message]
[recv ack]

Receiver
[recv message]
[send ack]
[ignore message]
[send ack]
Sequence numbers
- senders gives each message an increasing unique seq number
- receiver knows it has seen all messages before N

Suppose message K is received.
- if $K \leq N$, Msg K is already delivered, ignore it
- if $K = N + 1$, first time seeing this message
- if $K > N + 1$?
TCP: Transmission Control Protocol

Most popular protocol based on seq nums
Buffers messages so arrive in order
Timeouts are adaptive
COMMUNICATIONS OVERVIEW

Raw messages: UDP

Reliable messages: TCP

Remote procedure call: RPC
Remote Procedure Call

What could be easier than calling a function?

**Approach:** create wrappers so calling a function on another machine feels just like calling a local function!
int main(...) {
    int x = foo("hello");
}

int foo(char *msg) {
    send msg to B
    recv msg from B
}

void foo_listener() {
    while(1) {
        recv, call foo
    }
}
int main(…) {
    int x = foo("hello");
}

int foo(char *msg) {
    send msg to B
    recv msg from B
}

void foo_listener() {
    while(1) {
        recv, call foo
    }
}
RPC TOOLS

RPC packages help with two components

(1) Runtime library
   - Thread pool
   - Socket listeners call functions on server

(2) Stub generation
   - Create wrappers automatically
   - Many tools available (rpcgen, thrift, protobufs)
Wrappers must do conversions:
- client arguments to message
- message to server arguments
- convert server return value to message
- convert message to client return value

Need uniform endianness (wrappers do this)
Conversion is called marshaling/unmarshaling, or serializing/deserializing
WRAPPER GENERATION: POINTERS

Why are pointers problematic?

Address passed from client not valid on server

Solutions? Smart RPC package: follow pointers and copy data
RPC OVER TCP?

Sender
[call]
[tcp send]

Receiver
[recv]
[ack]
[exec call]
...
[return]
[tcp send]
RPC OVER UDP

Strategy: use function return as implicit ACK

Piggybacking technique

What if function takes a long time?
then send a separate ACK
NEXT STEPS

Next class: Distributed NFS

Discussion this week: Worksheet and review, Q&A for P5