CSE 452
Distributed Systems

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Distributed Systems

- How to make a set of computers work together
  - Reliably
  - Efficiently
  - At (huge) scale
  - With high availability
- Despite messages being lost and/or taking a variable amount of time
- Despite nodes crashing or behaving badly, or being offline

A Thought Experiment

Suppose there is a group of people, standing in a circle, two have green dots on their foreheads.

Without using a mirror or directly asking, can anyone tell if they themselves have a green dot?

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What if I say: someone has a green dot

– Something everyone already knows!

There’s a difference between what you know and what you know others know.

And what others know you know.

What is a Distributed System?

A group of computers that work together to accomplish some task

- Independent failure modes
- Connected by a network with its own failure modes

Distributed Systems, 1990

Leslie Lamport:

“A distributed system is one where you can’t get your work done because some machine you’ve never heard of is broken.”

We’ve Made Some Progress

Today a distributed system is one where you can get your work done (almost always):

- wherever you are
- whenever you want
- even if parts of the system aren’t working
- no matter how many other people are using it
- as if it was a single dedicated system just for you
- that (almost) never fails

Concurrency is Fundamental

- CSE 451: Operating Systems
  – How to make a single computer work reliably
  – With many users and processes
- CSE 461: Computer Networks
  – How to connect computers together
  – Networks are a type of distributed system
- CSE 444: Database System Internals
  – How to manage (big) data reliably and efficiently
  – Primary focus is single node databases

Course Project

Build a sharded, linearizable, available key-value store, with dynamic load balancing and atomic multi-key transactions

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Build a sharded, linearizable, available key-value store, with dynamic load balancing and atomic multi-key transactions

- Key-value store: distributed hash table
- Linearizable: equivalent to a single node
- Available: continues to work despite failures
- Sharded: keys on multiple nodes
- Dynamic load balancing: keys move between nodes
- Multi-key atomicity: linearizable for multi-key ops

Project Mechanics

- Lab 0: introduction to framework and tools
  - Do Lab 0 **before** section this week (ungraded)
- Lab 1: exactly once RPC, key-value store
  - **Next** Thursday, **individually**
  - Lab 2-4: **pairs or individually**
- Lab 2: primary backup (tolerate failures)
- Lab 3: paxos (tolerate even more failures)
- Lab 4: sharding, load balancing, transactions

Project Tools

- Automated testing
  - Run tests: all the tests we can think of
  - Model checking: try all possible message deliveries and node failures
- Visual debugger
  - Control and replay over message delivery, failures
- Java, with restrictions
  - Model checker needs to collapse equivalent states

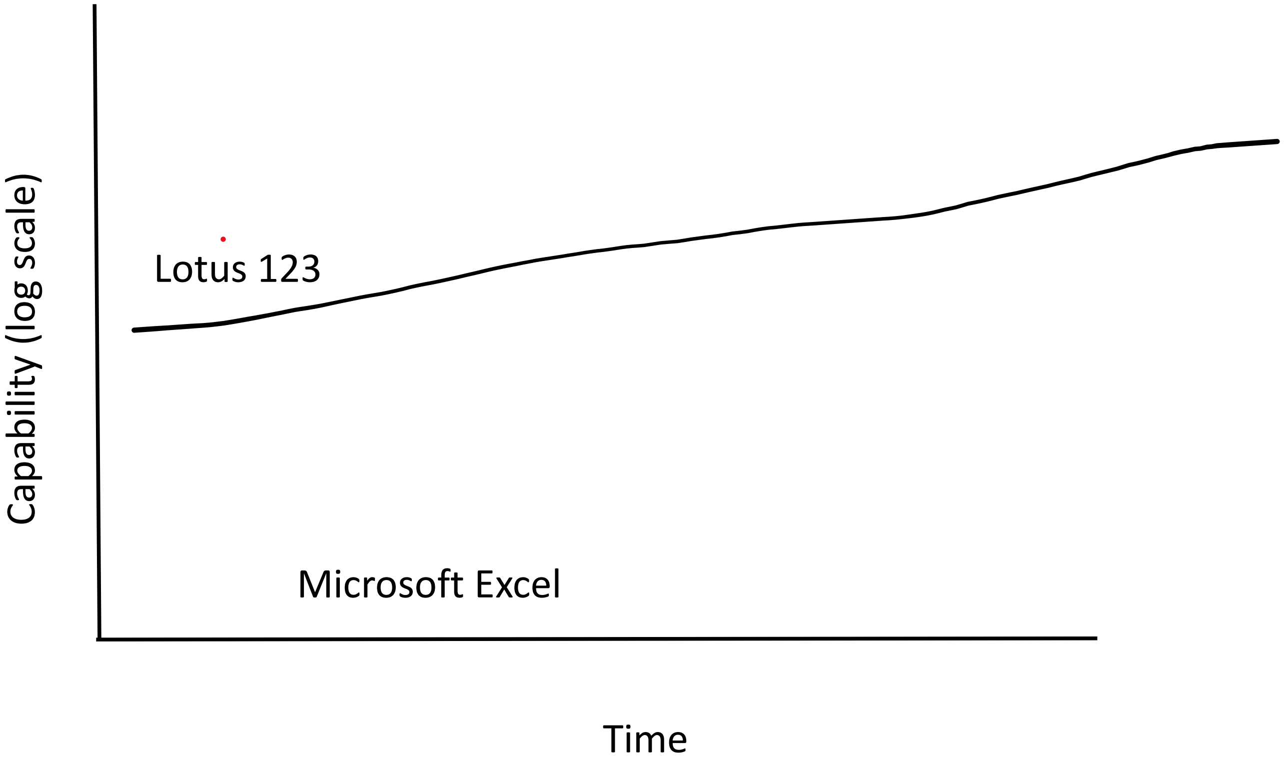
Project Rules

- OK
  - Consult with us or other students in the class
- Not OK
  - Look at other people's code (in class or out)
  - Cut and paste code

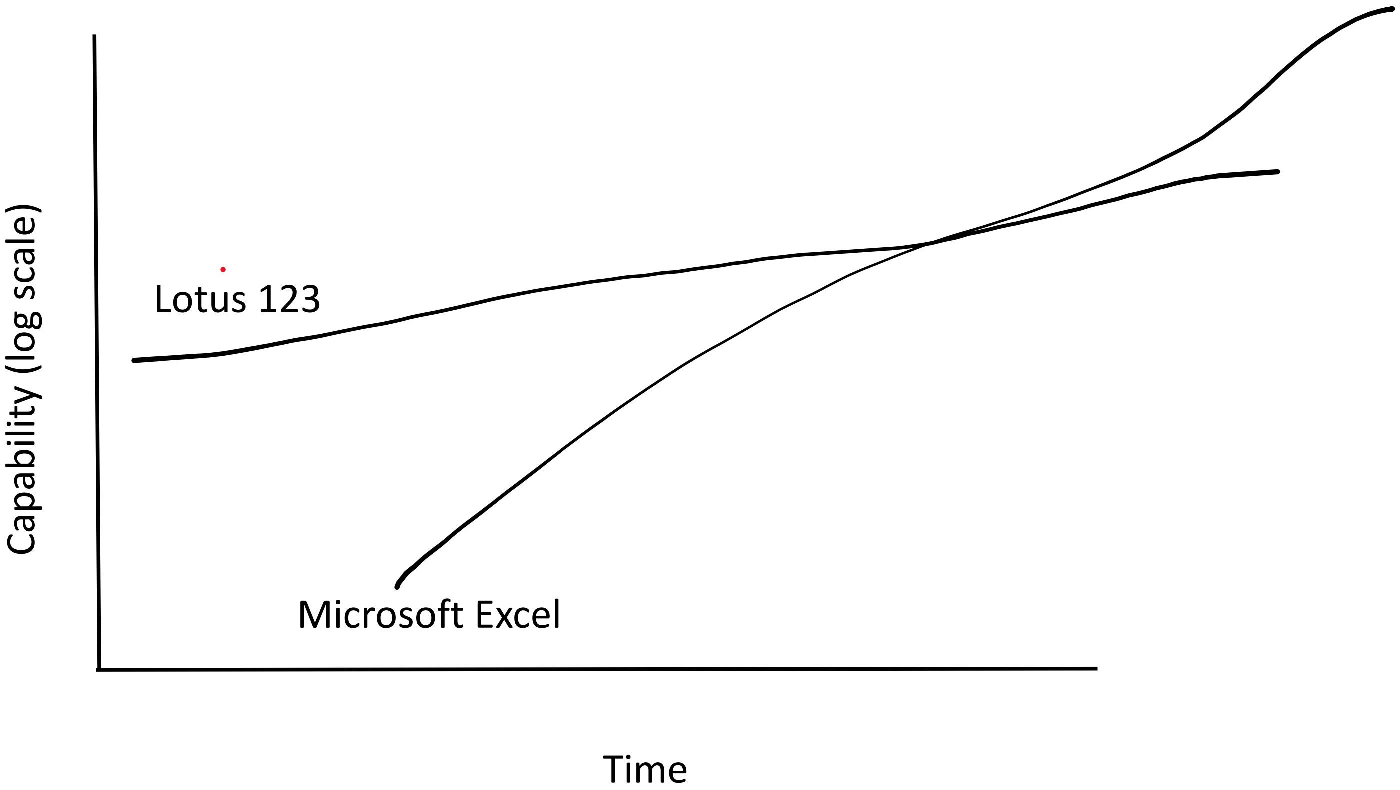
Some Career Advice

Knowledge **>>** grades

Capability vs. Time



Capability vs. Time



Readings

- There is no adequate distributed systems textbook
- Instead, we’ve assigned:
  - Some tutorials/book chapters
  - A dozen+ research papers
- Both are important
- Read **before** class
  - See course web calendar page

Blogs

- How do you read a research paper?
  - An important skill, because research ideas often make it into practice
- Practice by blogging about papers
  - Write a short thought about the paper to the Canvas discussion thread; learn from other people's blog entries
- Blog **seven** papers (one per week)

Some More Career Advice

The Technical Ladder

Knowing what should be built

Knowing what can be built

Knowing how to build it

Problem Sets

- Three problem sets
  - Done **individually**

- No midterm
- No final

- Course is not curved

Logistics

- Zoom for lectures, sections, office hours
  - Links in canvas/zoom
- Gitlab for lab assignments
  - Largely self-graded
- Ed for project Q&A
- Gradescope for problem sets and lab turn-ins
- Canvas for blog posts

Why Distributed Systems?

- Conquer geographic separation
  - 3.5B smartphone users; locality is crucial
- Availability despite unreliable components
  - System shouldn’t fail when one computer does
- Scale up capacity
  - Cycles, memory, disks, network bandwidth
- Customize computers for specific tasks
  - Ex: disaggregated storage, email, backup

End of Dennard Scaling

- Moore’s Law: transistor density improves at an exponential rate (2x/2 years)
- Dennard scaling: as transistors get smaller, power density stays constant
- Recent: power increases with transistor density
  - Scale out for performance
- All large scale computing is distributed

Example

- 2004: Facebook started on a single server
  - Web server front end to assemble each user's page
  - Database to store posts, friend lists, etc.
- 2008: 100M users
- 2010: 500M
- 2012: 1B
- 2020: 2.5B

How do we scale up beyond a single server?

Facebook Scaling

- One server running both webserver and DB
- Two servers: webserver, DB
  - System is offline 2x as often!
- Server pair for each social community
  - E.g., school or college
  - What if friends cross servers?
  - What if server fails?

Two-tier Architecture

- Scalable number of front-end web servers
  - Stateless (“RESTful”): if crash can reconnect the user to another server
  - Run application code that is rapidly changing
  - Q: how does user find a front-end?
- Scalable number of back-end database servers
  - Run carefully designed distributed systems code
  - If crash, system remains available
  - Q: how do servers coordinate updates?

Three-tier Architecture

- Scalable number of front-end web servers
  - Stateless (“RESTful”): if crash can reconnect the user to another server
- Scalable number of cache servers
  - Lower latency (better for front end)
  - Reduce load (better for database)
  - Q: how do we keep the cache layer consistent?
- Scalable number of back-end database servers
  - Run carefully designed distributed systems code

And Beyond

- Worldwide distribution of users
  - Cross continent Internet delay ~ half a second
  - Amazon: reduction in sales if latency > 100ms
- Many data centers
  - One near every user
  - Smaller data centers just have web and cache layer
  - Larger data centers include storage layer as well
  - Q: how do we coordinate updates across DCs?

Properties We Want (Google Paper)

- Fault-Tolerant: It can recover from component failures without performing incorrect actions. (Lab 2)
- Highly Available: It can restore operations, permitting it to resume providing services even when some components have failed. (Lab 3)
- Scalable: It can operate correctly even as some aspect of the system is scaled to a larger size. (Lab 4)

Typical Year in a Data Center

- ~0.5 data centers fail per year due to overheating
- ~1 power distribution failure (~500-1000 machines offline)
- ~1 rack-move (~500-1000 machines powered down)
- ~1 network rewiring (rolling outage of ~5% of machines down)
- ~20 rack failures (40-80 machines instantly disappear)
- ~5 racks go wonky (40-80 machines see 50% packet loss)
- ~8 network maintenances (random connectivity losses)
- ~12 router reloads
- ~3 router failures
- ~dozens of 30-second DNS outages
- ~1000 individual machine failures
- ~1000+ hard drive failures
- slow disks, bad memory, misconfigured machines, flaky machines, …

Other Properties We Want (Google Paper)

- Consistent: The system can coordinate actions by multiple components often in the presence of concurrency and failure. (Labs 2-4)
- Predictable Performance: The ability to provide desired responsiveness in a timely manner. (Week 8)
- Secure: The system authenticates access to data and services (CSE 484)

Next Time: Remote Procedure Call

- Remote procedure call (RPC)
  - Abstraction of a procedure call, with arguments and return values
  - Executed on a remote node
- Challenges
  - Remote node might have failed
  - Network may have failed
  - Request may be dropped
  - Reply may be dropped

Thought Experiment

- Client sends a request to Amazon
- Network is flaky
  - Don’t hear back for a second
- Can you tell?
  - Request was lost
  - Server was down
  - Request got through, reply was lost
- Should the client resend?

Thought Experiment

- The client resends
- But the original packet got through
- What should the server do?
  - Crash?
  - Do the operation twice?
  - Something else?

Why Is DS So Hard?

- System design
  - Partitioning of responsibilities: what should client do, the caching layer, the storage layer?
- Failures are endemic, partial and ambiguous
  - If a server doesn’t reply, how do you tell if it is (a) the network, (b) the server, or c) neither: they are both just being slow?
- Concurrency and consistency
  - Distributed state, replicated state, caching
  - How do we keep this state consistent?

Why Is DS So Hard?

- Performance
  - Generating a single FB page involves calls to hundreds of different machines
  - Performance can be variable and unpredictable
  - Tail latency: limited by slowest machine
- Implementation and testing
  - Nearly impossible to test/reproduce all failure cases
- Security
  - Adversary can silently compromise machines and manipulate messages

Why Are Distributed Systems Hard?

- Asynchrony
  - Different nodes run at different speeds
  - Messages can be unpredictably, arbitrarily delayed
- Failures (partial and ambiguous)
  - Parts of the system can crash
  - Can’t tell crash from slowness
- Concurrency and consistency
  - Replicated state, cached on multiple nodes
  - How to keep many copies of data consistent?

Why Are Distributed Systems Hard?

- Performance
  - Have to efficiently coordinate many machines
  - Performance is variable and unpredictable
  - Tail latency: only as fast as slowest machine
- Testing and verification
  - Almost impossible to test all failure cases
  - Proofs (emerging field) are really hard
- Security
  - Need to assume adversarial nodes

Another Thought Experiment: Local vs. Remote Operations

- How long does it take to do a simple procedure call on a modern server?

- How long does it take to do the same operation on a different server in the same data center?

- On a server in a remote data center?
  - Speed of light is ~ 5us/mile