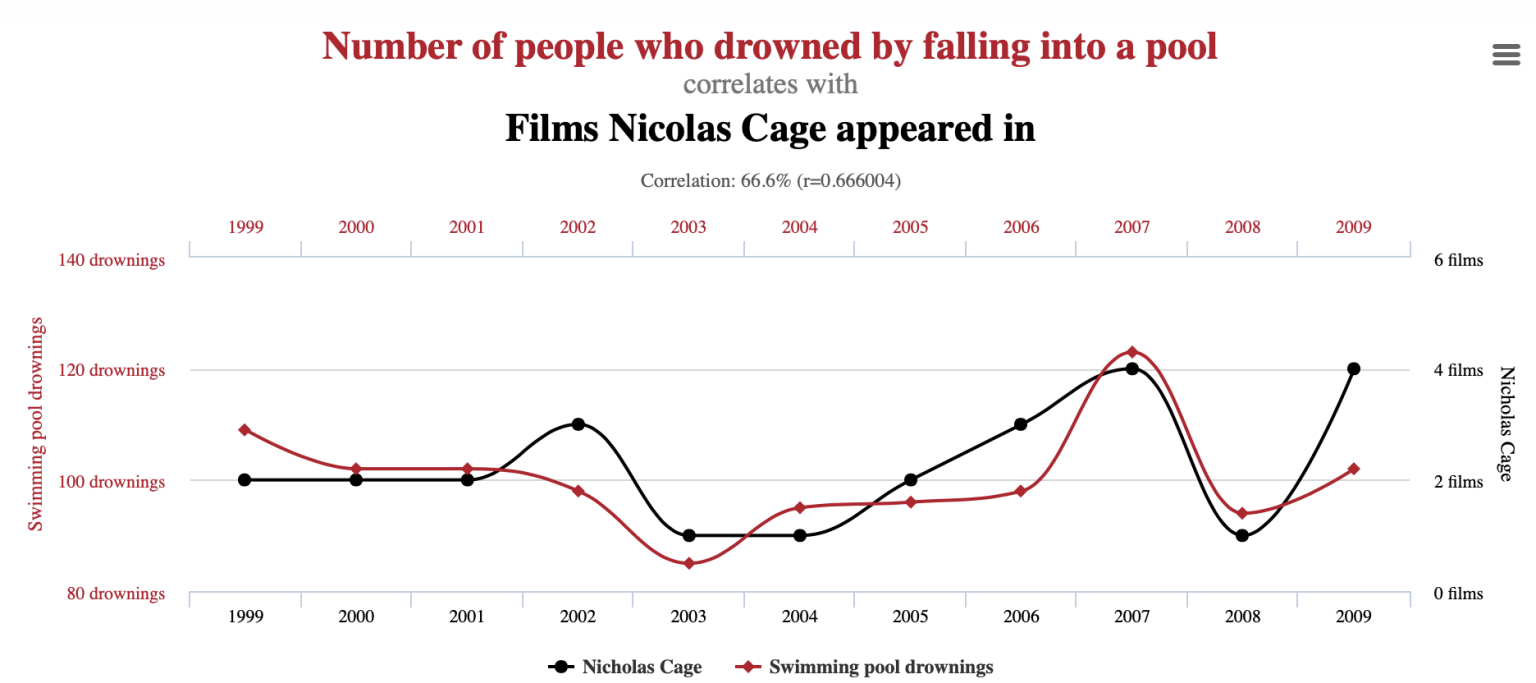
**CS 677**: Big Data

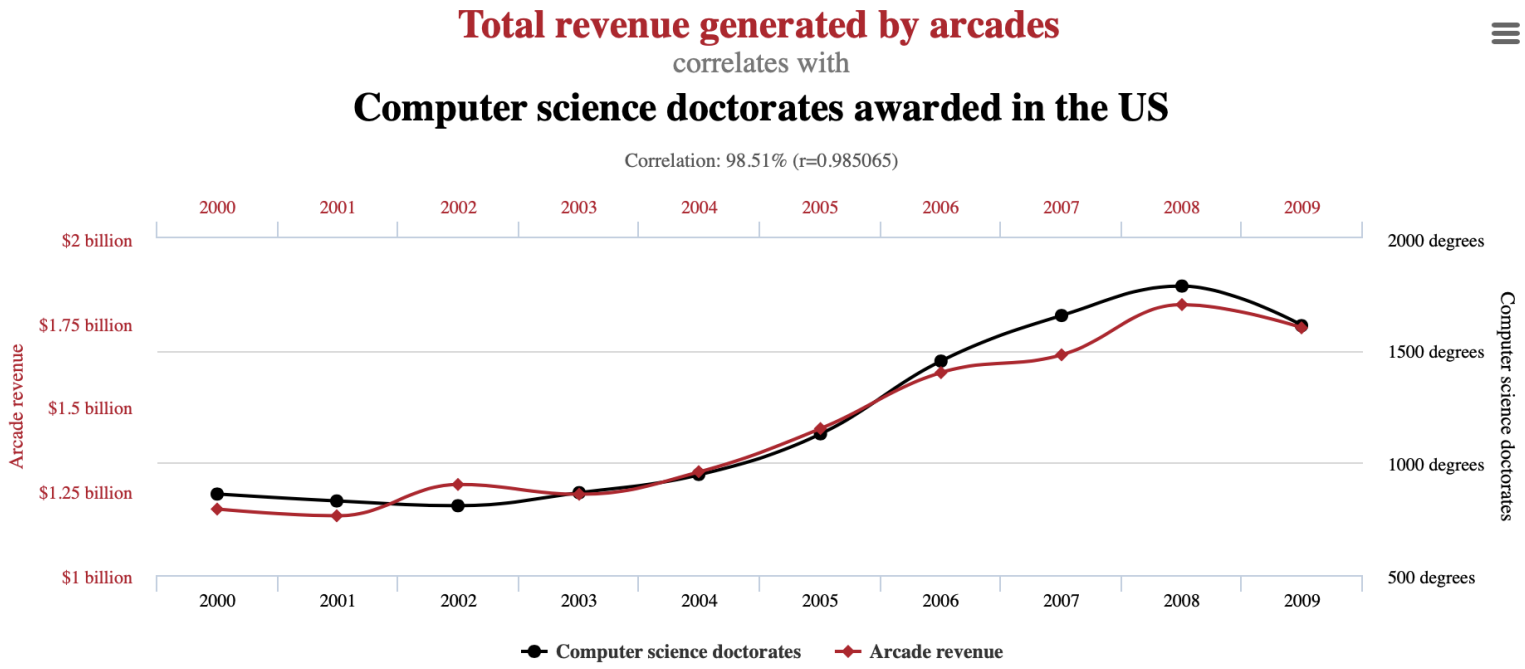
# Network Design

Lecture 5

# Spurious Correlations



# Spurious Correlations



# Today's Schedule

- Warehouse-Scale Computing
- Network Designs
- Scaling our Networking Code
- File Transfer Lab

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# Rethinking the Network

- Handling massive datasets requires distributing the computations and storage
- To deal with this, Google pioneered the concept of *warehouse-scale computing*
- To get started, let's talk about a bit of theory…

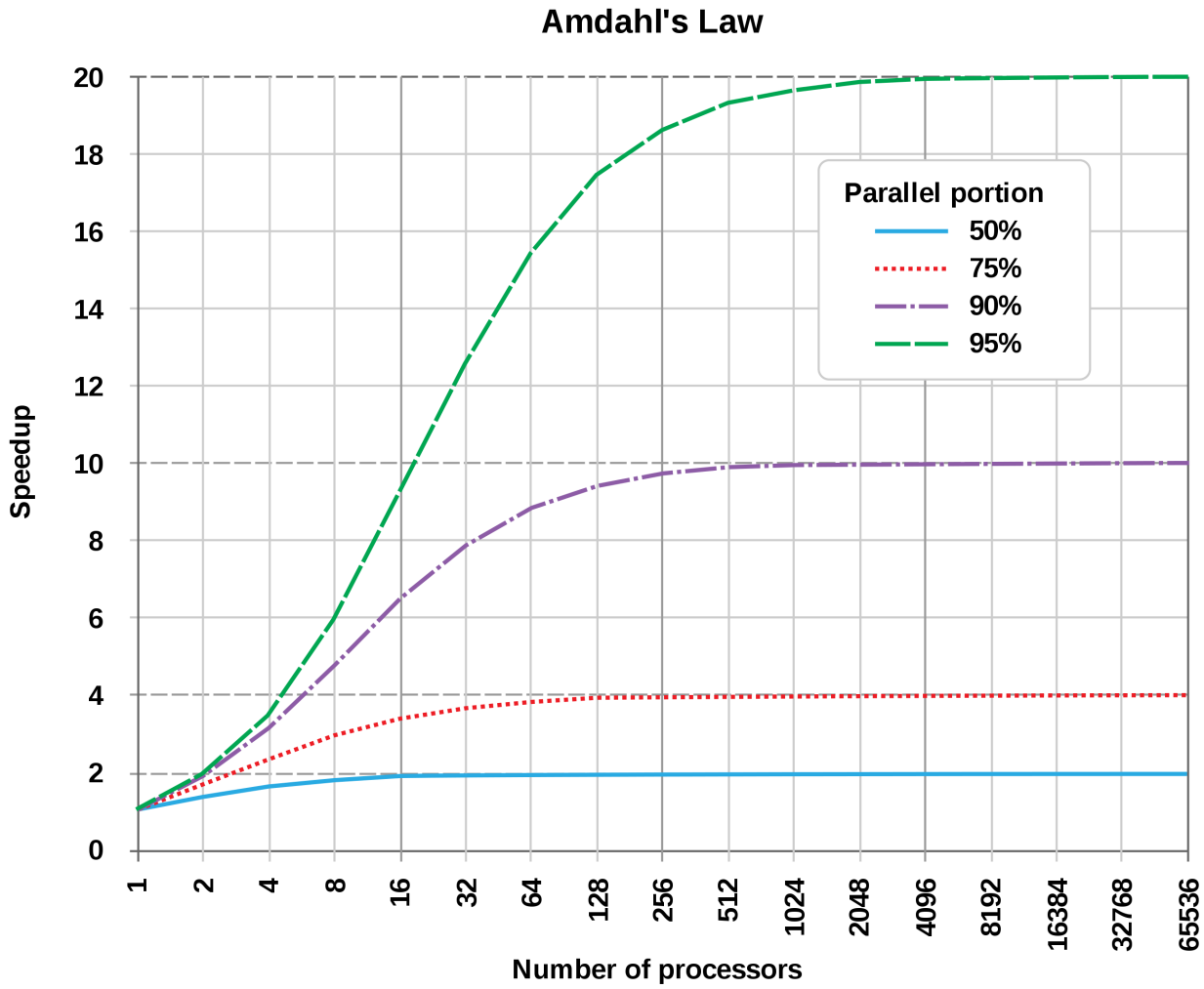
# Amdahl's Law [1/2]

- In the best case scenario, doubling the number of cores/CPUs/processing units will halve execution time
  - In practice, this is difficult
- There is overhead associated with parallelism
- Amdahl's law puts a bound on potential speedup:

$$S_N = \frac{1}{(1-P)+\frac{P}{N}}$$

  - $S$ – speedup
  - $P$ – parallelizable portion of the program
  - $N$ – number of cores/CPUs/processing units

# Amdahl's Law [2/2]



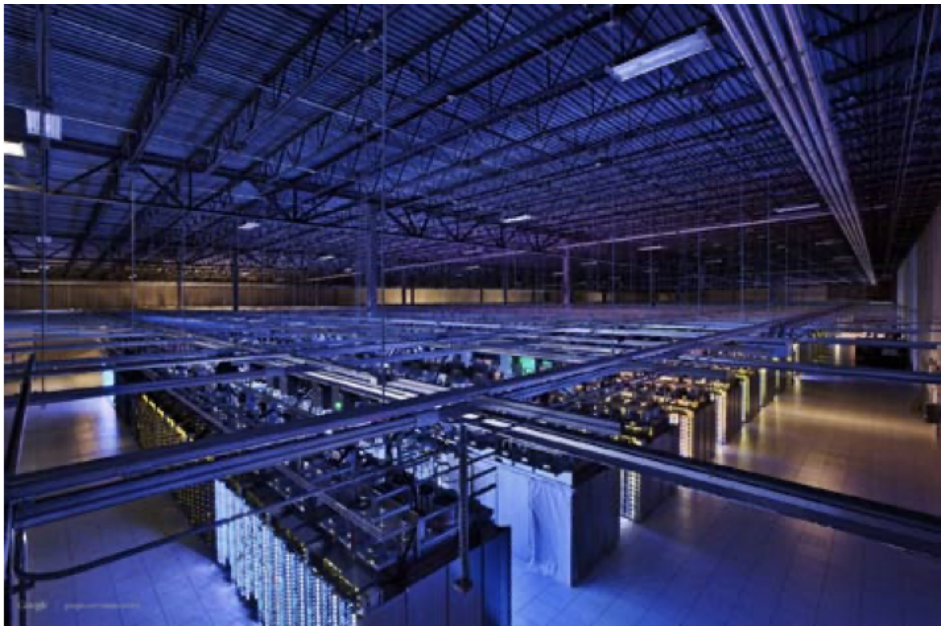
# Distributed Computation

- The whole goal of many Big Data computation frameworks is to maximize P
  - (the parallelizable portion)
- Sometimes this requires an entirely new programming model
  - **MapReduce** paradigm
  - **Restrict** what programmers can do
    - The upside: automatic parallelization (or close enough)

# Warehouse-Scale Computing

- Google's *warehouse scale computing* concept touches on both the software and hardware stacks
  - Barroso et al., *The Datacenter as a Computer*
- In this model, data centers are filled with commodity hardware with the best **dollar:performance** ratio
  - Don't buy a machine with a Core i9/i7… get an i5
- Connect these **nodes** with a reasonably-priced interconnect
- View the entire datacenter as a single computer and design software that matches this model

# WSCs



# Rationale

*"as computation continues to move into the cloud, the computing platform of interest no longer resembles a pizza box or a refrigerator, but a warehouse full of computers"*

-- Barroso et al., The Datacenter as a Computer

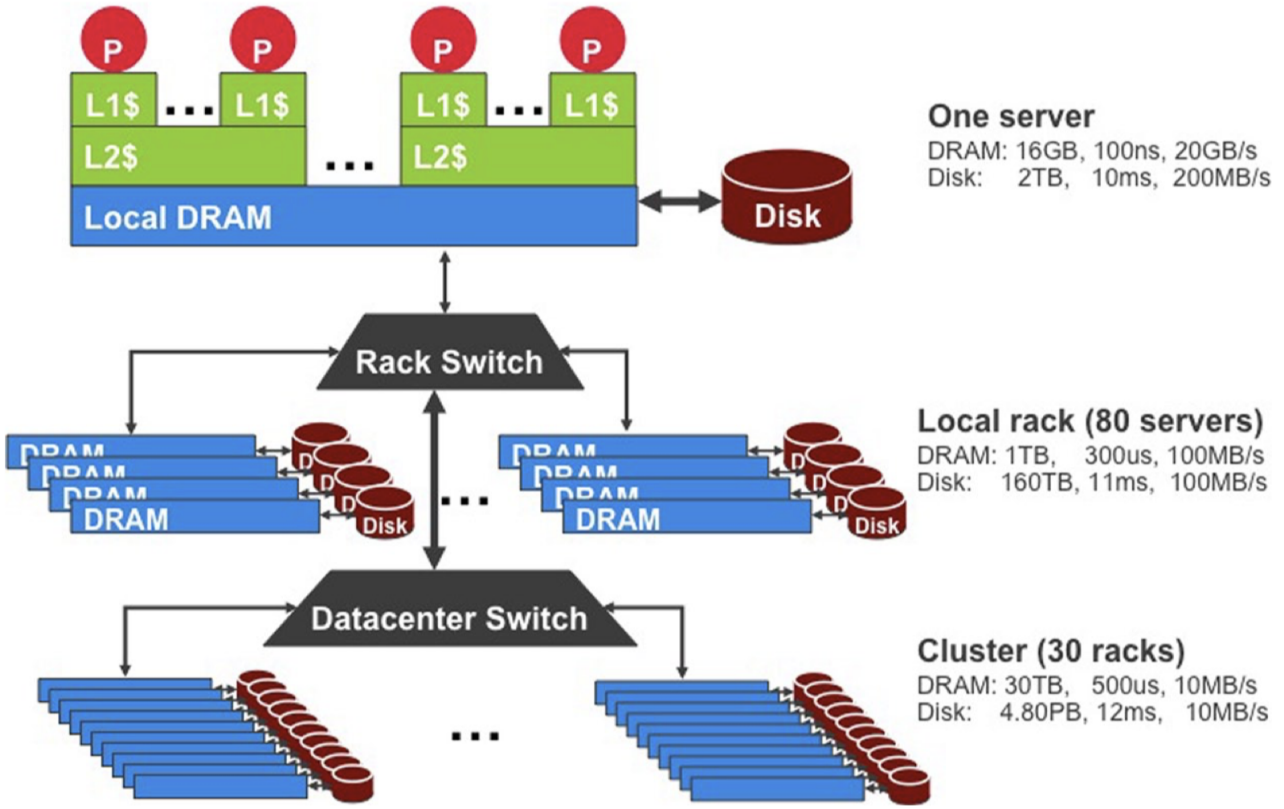
# Google Modular Data Center

- Google has a patent for data centers based on shipping containers
  - Others have employed similar technology
- Pack a shipping container with cooling, racks of servers, and a fast network
- Need more capacity? Stack a few more shipping containers on the heap!

# Warehouse-Scale Software

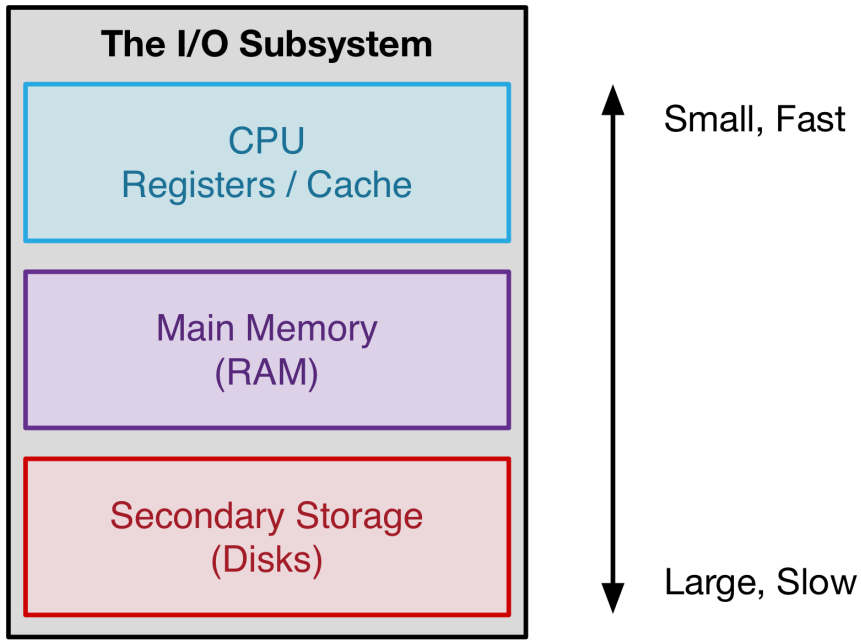
- Google's next challenge: if our datacenter is a "computer," what software does it run?
- We need a way to compute things
  - Like the process abstraction we have on operating systems
  - Led to the creation of **MapReduce**
- We need a way to store and retrieve things
  - Led to the creation of **Google File System (GFS)**
- These technologies laid the foundation for modern data-intensive computing approaches

# WSC Storage Hierarchy



# The I/O Subsystem

- Big Data spans the whole stack: hardware, low-level (OS) software, networking, algorithms…
- There is a *speed differential* in the hardware memory hierarchy
- Most big data is on **secondary storage**
  - The challenge? Getting it off of the disks and into cache, memory, or even the network
- Thought experiment:
  - Memory accesses are measured in ns
  - Hard disk drive accesses are measured in ms
  - If we scale up, say 1 ns = 1 s, then a single hard disk access takes at least 11.5 days!



# The General Idea

- Avoid the disk at all costs
  - If you must touch the disk, then try to limit the number of passes over the data
- Sequential read/write patterns are often faster than random
  - Even with many models of SSD!
- One of the big benefits of Spark over Hadoop MapReduce we'll see later in class is being able to cache data in memory

# Designing for WSCs

- Let's take a minute or two to think about this…
- What factors do we have to consider when designing a warehouse-scale computing platform?
  1. Low-level (systems)
  2. Network
  3. Algorithmic
  4. …Something else?
- Chat with the person next to you for a couple minutes, then let's brainstorm as a group

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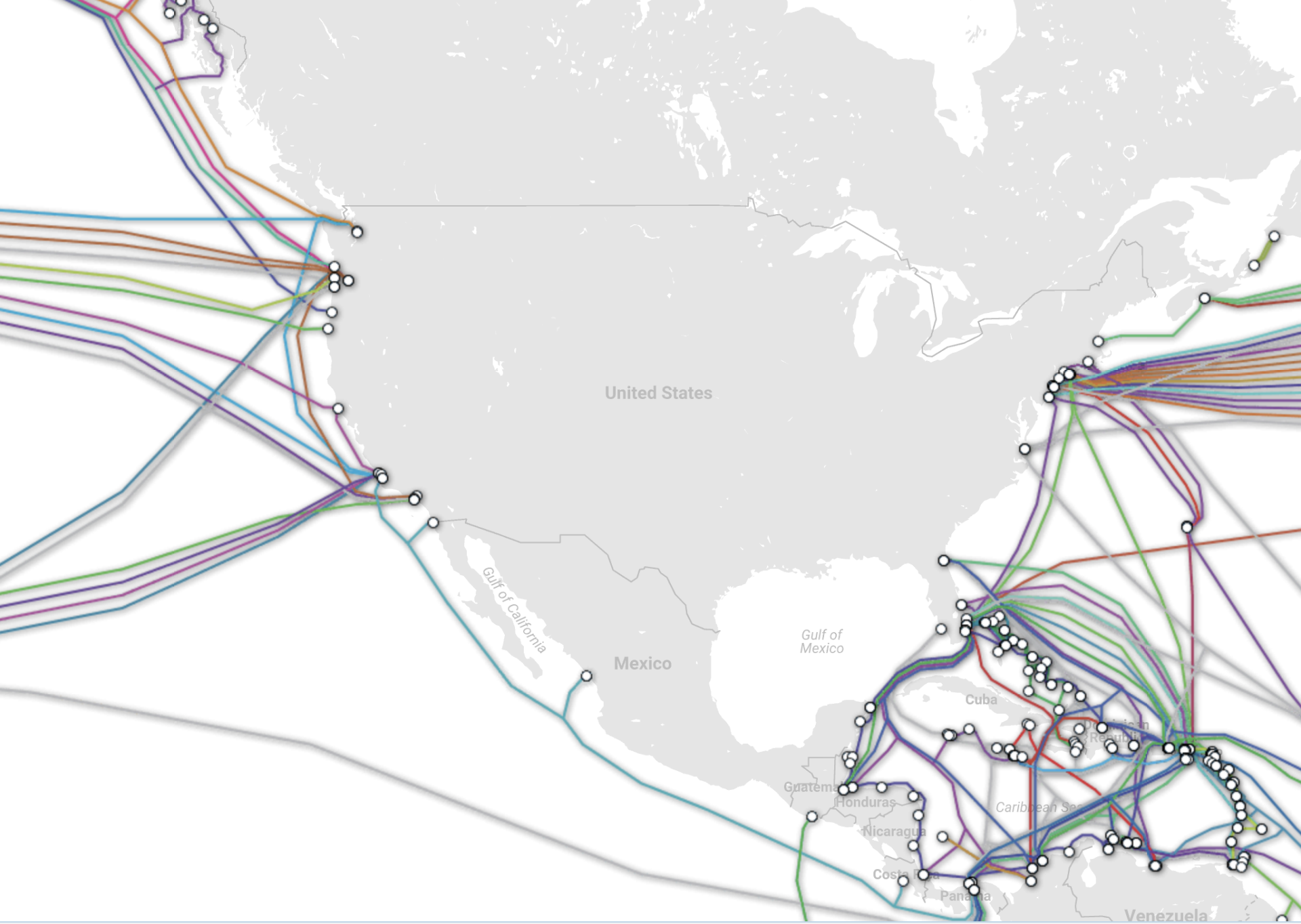
# Thinking About the Network

- For the most part, we can rely on the network to do its job and we'll live at a higher level of abstraction
- Many networking concerns still creep up when designing our systems
  - For instance, do we use TCP or UDP?
- We still need to think about **bandwidth**, **latency**
- …especially when dealing with multiple data centers
  - https://www.submarinecablemap.com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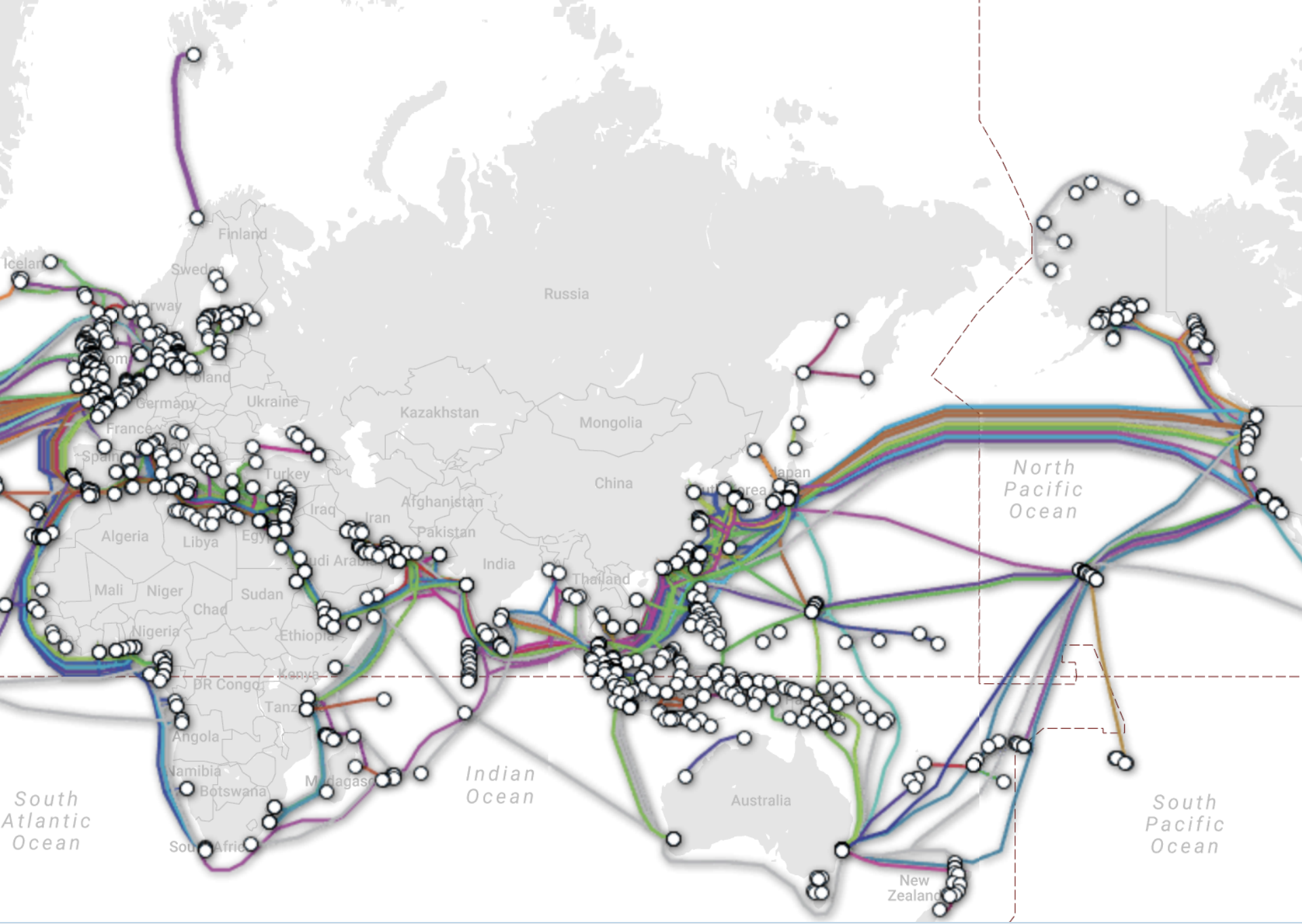
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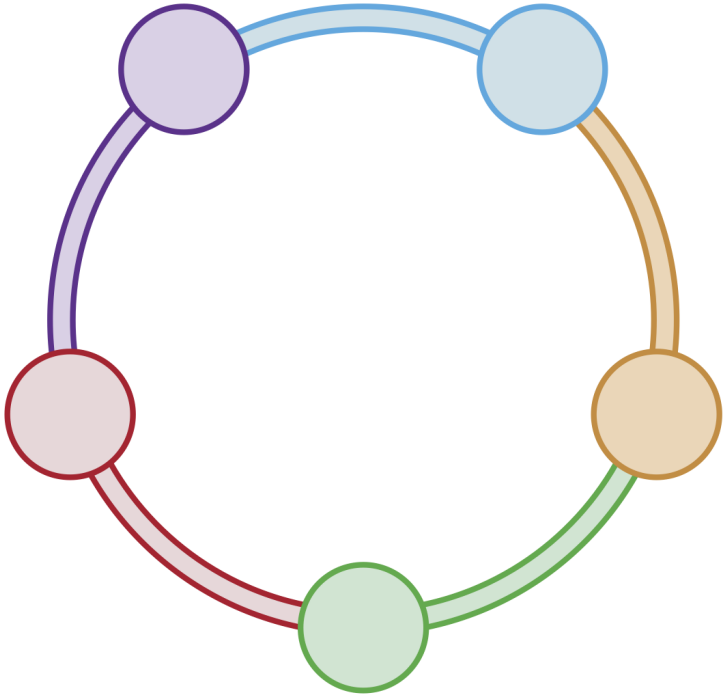
Chad
Nigeria
Ethiopia
Kenya
Angola
Namibia
Botswana
Australia
New Zealand
North Pacific Ocean
South Pacific Ocean
South Atlantic Ocean
Indian Ocean

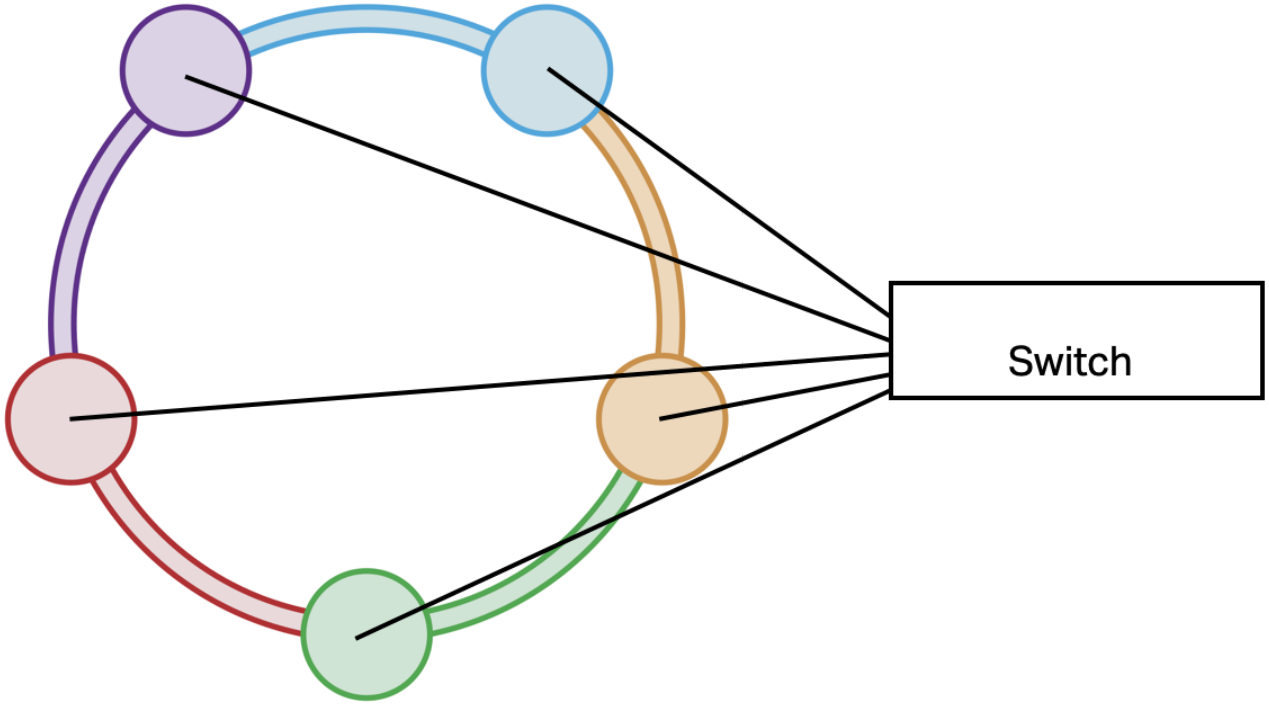
# Designing the Network

- The messages exchanged between nodes are influenced by the underlying network design
  - A P2P network operates differently than set of **NFS** servers
  - Join notifications, file locking, periodic heartbeats
- Note that this generally doesn't mean the *physical* network
- Instead, we often design distributed systems around **overlay** networks

# Overlay Network: Ring Topology



# Ring Topology: Physical Network



# Ring Messages

- In a ring topology, we can get by with one message:
  - Send to next node
- …Or, if you want to get fancy:
  - Send to next node
  - Send to previous node
- This setup only makes sense in certain situations
- It certainly isn't optimal for searching for a specific file/user/etc!
  - What might a good use case be?

# Shared Nothing Architecture

- A popular design for distributed systems is the **shared nothing** (SN) architecture
- Each node in the system is self-sufficient
  - No specialization
  - **No centralized components**
- SN helps ensure scalability
- When all the nodes are the same, failure cases are easier to handle

# Microservice Architecture

- Shared nothing design inspired loosely-coupled distributed architectures based on **microservices**
  - A server process that does one thing and does it well
- Advanced data workflows can be built by creating pipelines of microservices
- This approach was championed heavily at Amazon and likely led to their runaway success with AWS

# Bezos' Mandate [1/3]

- There was an internal post by a former Amazon employee (now at Google) that accidentally went public
- In 6 years, Amazon went from an online bookstore to a $1bn IaaS provider
  - Google should've owned the cloud market! How did this happen? Why is Google unable to build quickly?
- Bezos ***reportedly*** issued a mandate to his company in the early years that built a foundation for services success
  - (when he wasn't wearing cowboy hats and blasting off into space…)

# Bezos' Mandate [2/3]

- All teams will henceforth expose their data and functionality through service interfaces.
- Teams must communicate with each other through these interfaces.
- There will be no other form of inter-process communication allowed: no direct linking, no direct reads of another team's data store, no shared-memory model, no back-doors whatsoever. The only communication allowed is via service interface calls over the network.

# Bezos' Mandate [3/3]

- It doesn't matter what technology you use.
- All service interfaces, without exception, must be designed from the ground up to be externalizable. That is to say, the team must plan and design to be able to expose the interface to developers in the outside world. No exceptions.
- Anyone who doesn't do this will be fired.  Thank you; have a nice day!
  - (This part is ***probably*** made up… 😄)

# Business Advantage

- This approach makes it obvious why Amazon can build new services so quickly
- Things get built internally and already have a “public”-ready interface
  - Get tested internally
- Want to sell it as a service? Make a UI, spin up instances to support the service, and sell it

# The Downsides of Shared Nothing

- Complicated development: assuming all nodes are the same means dealing with many corner cases
  - What if the underlying hardware is different?
  - Sometimes it's just easier to put some information in a central repository
- If excessive state information must be transferred, the system will be more susceptible to latency
  - Same goes for algorithms that require more coordination
- There is a very recent trend back towards 'monoliths'…

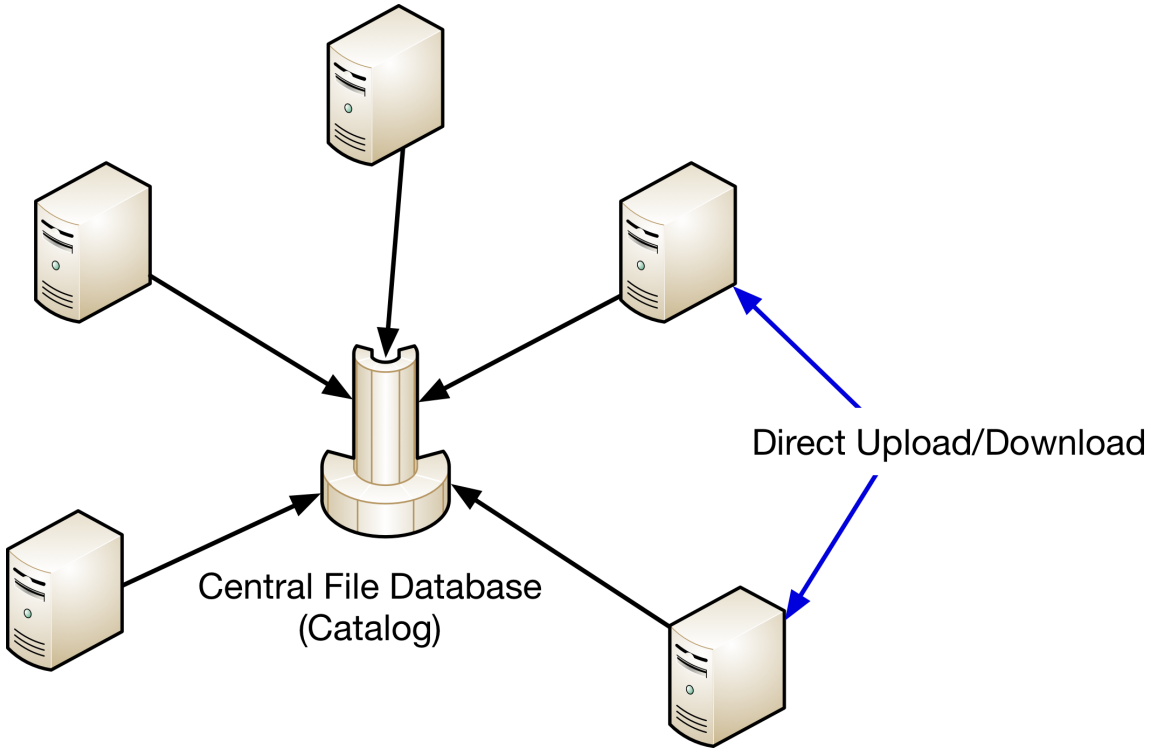
# (Semi)-Centralized Networks

- An alternative is to include centralized/specialized components
  - Far simpler
  - Represents a single point of failure
- GFS: central catalog of all files
- To help deal with failures, hierarchical designs spread out the state information
  - Example: DNS

# Napster (P2P)

- The original Napster (not the streaming service) was one of the first popular P2P file sharing tools
  - Laid the groundwork for today's distributed systems
- On startup, the Napster client transmitted its list of files to a central database
  - Napster didn't host any files, it just maintained a database
  - The paradigm was a bit revolutionary at the time

# Napster Network Layout



# Napster's Database

- The central database ended up being Napster's undoing
- As the service got popular, the server was flooded with requests and couldn't keep up
- It also was an easy target for law enforcement to shut down

# Gnutella

- Learning from Napster's mistakes, *Gnutella* was designed to be completely decentralized
- Instead of using a central database, queries **flooded** through the entire network
  - Unstructured network
- This poses some problems though:
  - Performance: querying gets slower with more users
  - How do you know when your query is over?

# KaZaA

- Gnutella didn't catch on, but *KaZaA* did
- Struck a balance between the two approaches
- **Supernodes** functioned as local databases
- Client queries were sent to the supernodes, which would also query their peers
- In other words: a hierarchical approach

# Today: BitTorrent

- Nowadays most folks download their favorite non-copyrighted songs, public domain media, and Linux distributions using BitTorrent
  - But certainly not copyrighted material
- Puts the responsibility of indexing the files on websites/users
- Recent versions support **magnet**, backed by a distributed hash table
- IPFS employs a similar paradigm for sharing data

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# Scaling Threads

- A common paradigm when designing servers is the **fork-join** model
- Split off when work can be handled by a single thread, then merge back together when shared state is necessary
- Web server: for each incoming connection, start up a new thread
  - The thread handles direct communication with the client

# Thread Overhead

- It takes time to create threads
  - Updating OS data structures, creating a new lightweight process
  - **Overhead** from thread context: each has an individual stack
- Generally in this model when a thread is performing I/O, it **blocks**
  - Has to be context switched out so others can use the CPU for useful work

# Apache / C10K Problem

- One of the most popular web servers, Apache, followed this model
  - Thread-per-connection
- The server would famously crumble when hit with huge amounts of traffic
  - Their main competitor at the time, Microsoft IIS, wasn't much better
- This led to the formulation of the C10K problem
  - "It's time for web servers to handle ten thousand clients simultaneously, don't you think? After all, the web is a big place now."

# An Update: C10M

- On modern hardware, you can achieve 10,000 connections using Visual Basic 6 and a network interconnect composed of carrier pigeons
  - See RFC 1149, *IP over Avian Carriers*
- Around ~2010 WhatsApp demonstrated 2m active connections on a single 1U server
  - 24 cores running Erlang on FreeBSD

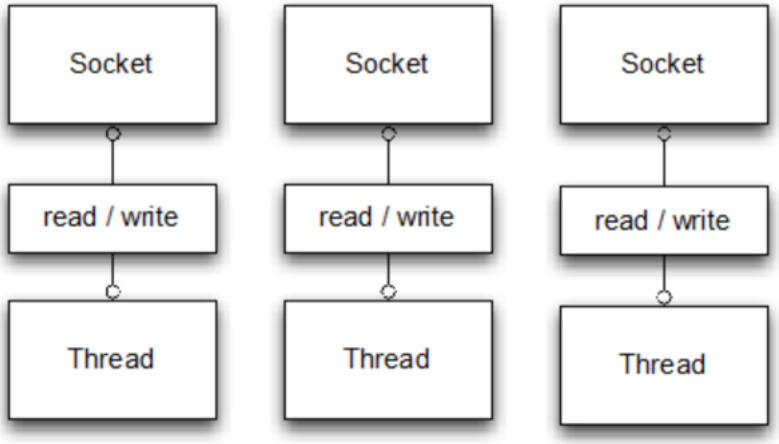
# How? Asynchronous I/O

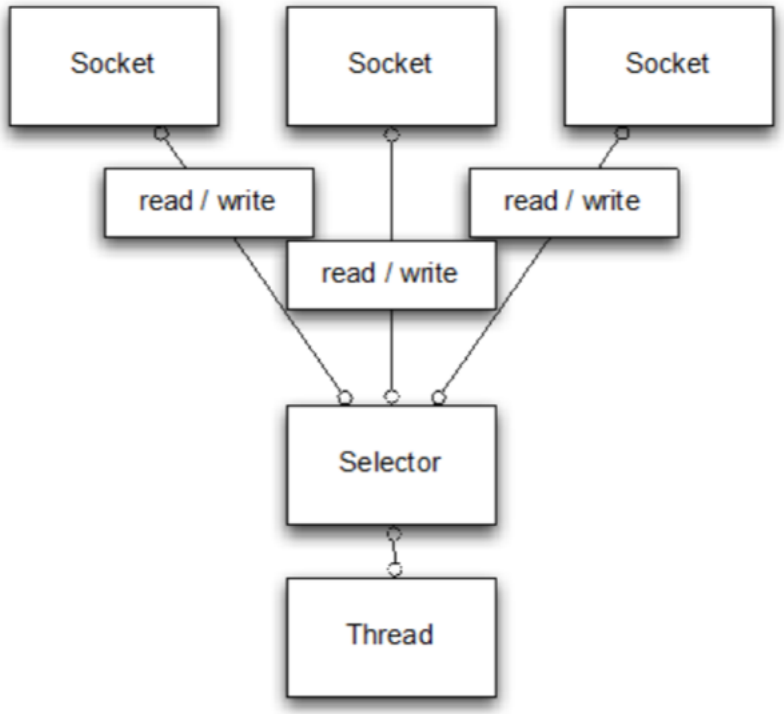
- Usual setup: we're sending a 5 MB file. Start writing it to a socket, which blocks our thread
  - OS context switches out the thread, something else runs on that CPU/core
- Rather than blocking, wouldn't it be better to tell the OS "send this message," and then go work on something else?
  - This is the idea behind asynchronous (or non-blocking) I/O

# Async I/O in Java

- Java is the most widely-used language for building scalable distributed systems
  - **(FOR NOW! 😉)**
- There an `nio` package that provides non-blocking I/O functionality
  - Wrapper over OS mechanism (Unix select, Linux epoll, FreeBSD kqueue)
  - Notoriously hard to use
- Many folks use the **netty** library (built on top of nio) or something similar

# Sync vs. Async



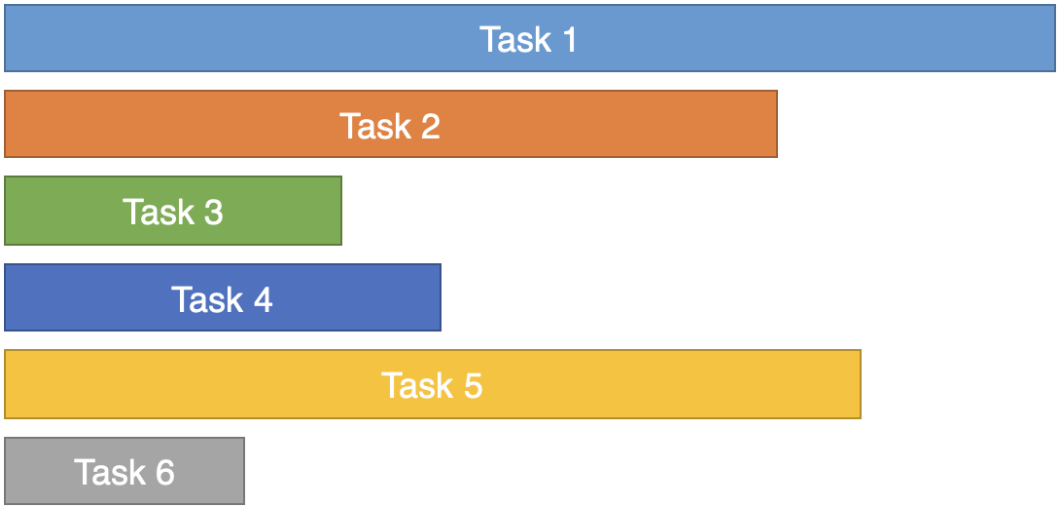




Maurer & Wolfthal. ***Netty in Action***

# How it Works: Server Side

- Connections are registered with the OS `select()` mechanism
- The server blocks on the selector rather than an individual socket connection
- When data is available, the selector gives the server a list of channels that are ready to read
  - Includes other states as well
- The server reads from the channels, buffering data if necessary
- Once a complete message has arrived, it gets passed to a thread pool for handling
- Fun fact: this is more or less the way node.js operates

# Blocking vs. Non-Blocking




- Assume tasks arrive in numeric order all within 1 ns of each other.
- The width of the bar indicates how much data is being received
- Computational costs are proportional to task size
- Which task finishes first for blocking and non-blocking I/O?

# Asynchronous Send

- Blocking: send(data):
  - wait until 'data' is sent
- Non-blocking: send(data):
  - returns immediately even though the send hasn't finished yet
  - (or maybe it hasn't even started)
- How do we know when the operation actually finished though?

# Futures

- If we have to eventually know the result of an asynchronous task, we can use **futures**
- Say we send a message, start doing some other work, and then want to make sure the recipient got the message
  - Future.getResult()
    - This operation will block if the send hasn't finished yet

      We have more control over where we actually block, and if the send is already done it doesn't slow us down!

# Operating System Mechanism

- At a 1000 ft view, this functionality requires the OS kernel to send an **event** to indicate a socket (or file descriptor) is ready
- Naturally leads to event-based systems
  - Each **action** is an event
  - Each runtime-level thread maps to an OS-level thread that blocks
- Note: this programming model can be cumbersome
  - Alternatives: green threads, fibers, actors

# Actors and Green Threads

- The **actor** pattern can be used to encapsulate events and represent how they are processed between entities
- **Green threads** are runtime-level threads; they are not backed by an OS thread
- Oracle et al. are incorporating green threads into the JVM
  - Allows more control over scheduling, requires less heavyweight OS resources to run
- Many other languages are adding support for this (if they don't have it already)
  - Async/Await style programming? Avoid!
- You might be wondering what the concurrency story is in Go…

# goroutines

- Rather than mapping each Go thread to an OS thread, the runtime:
  1. Allocates a flexible number of worker threads
  2. Schedules green threads (called *goroutines*) itself
     - goroutines **yield** when they are about to block, letting a different goroutine to take over the OS-level thread
- Effectively allows the programmer to write *blocking* code that operates in a *non-blocking* way behind the scenes!
  - It is fairly well-established that blocking code is much easier for programmers to understand and reason about

# Launching a goroutine

- `go functionName()` will run `functionName()` as a goroutine, which essentially acts like a separate thread
  - Whatever comes after the `go` statement will run immediately as well, i.e., there is no blocking
- Like other languages, you *might* need to think about thread safety
  - But the recommended approach is to avoid situations that need thread safety
    - 🤔

# Communicating Sequential Processes (CSP)

- Go's concurrency model is based on *Communicating Sequential Processes*
- The basic idea: goroutines share data by **communicating**, not via shared memory
  - Shared memory can be very fast, but is also the source of many concurrency problems
- To share data between goroutines, use a **channel**

# Channels

Here's an example from Go by Example:

```
package main
import "fmt"

func main() {
    messages := make(chan string)
    go func() { messages <- "ping" }()
    msg := <-messages
    fmt.Println(msg)
}
```

What will this program output?

# Idiomatic Go vs. Getting Done

- It's great to write perfect, idiomatic Go code that uses channels for communication between goroutines
  - I would encourage you to research and follow best practices for Go – not just general best practices
- However, sometimes you'll need things like mutexes to get your work done
  - That's okay
- Don't forget to balance learning the new language with GSD (getting stuff done!)

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# File Transfer Lab

- With the time remaining, let's discuss and work on the file transfer lab
- If you haven't already, find a partner to share your `.proto` with
  - Your projects should be separate implementations, but compatible at the wire format level