Distributed Systems

01. Introduction

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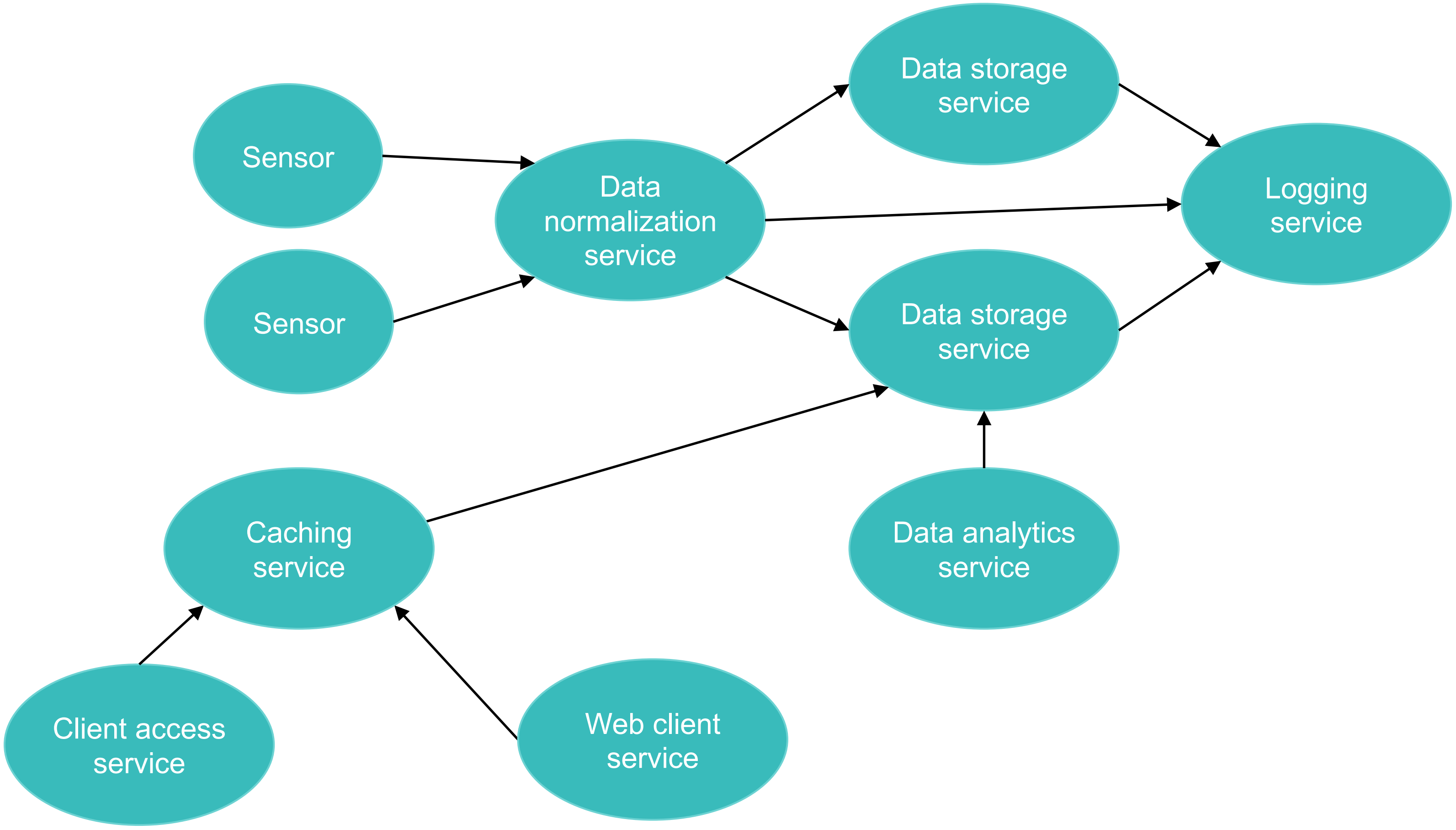
What is a Distributed System?

A collection of independent, autonomous hosts connected through a communication network.

– No shared memory (must use the network)
– No shared clock
– No shared operating system (almost always)

What is a Distributed System?

A distributed system is a collection of services accessed via network-based interfaces



Single System Image

Collection of independent computers that appears as a single system to the user(s)

- Independent = autonomous
- Single system: user not aware of distribution

Classifying parallel and distributed systems

Flynn's Taxonomy (1966)

Number of instruction streams and number of data streams

SISD
- Traditional uniprocessor system

SIMD
- Array (vector) processor
- Examples:
  - GPUs – Graphical Processing Units for video
  - AVX: Intel's Advanced Vector Extensions
  - GPGPU (General Purpose GPU): AMD/ATI, NVIDIA

MISD
- Generally not used and doesn't make sense
- Sometimes (rarely!) applied to classifying fault-tolerant redundant systems

MIMD
- Multiple computers, each with:
  - program counter, program (instructions), data
- **Parallel and distributed systems**

Subclassifying MIMD

memory

- shared memory systems: <u>multiprocessors</u>
- no shared memory: networks of computers, <u>multicomputers</u>

interconnect

- bus
- switch

delay/bandwidth

- tightly coupled systems
- loosely coupled systems

Multiprocessors & Multicomputers

Multiprocessors

– Shared memory

– Shared clock

– All-or-nothing failure

Multicomputers (networks of computers)

– No shared memory

– No shared clock

– Partial failures

– Inter-computer communication mechanism needed: the network

- Traffic much lower than memory access

Why do we want distributed systems?

1. Scale
2. Collaboration
3. Reduced latency
4. Mobility
5. High availability & Fault tolerance
6. Incremental cost
7. Delegated infrastructure & operations

1. Scale

Scale: Increased Performance

Computers are getting faster

Moore's Law

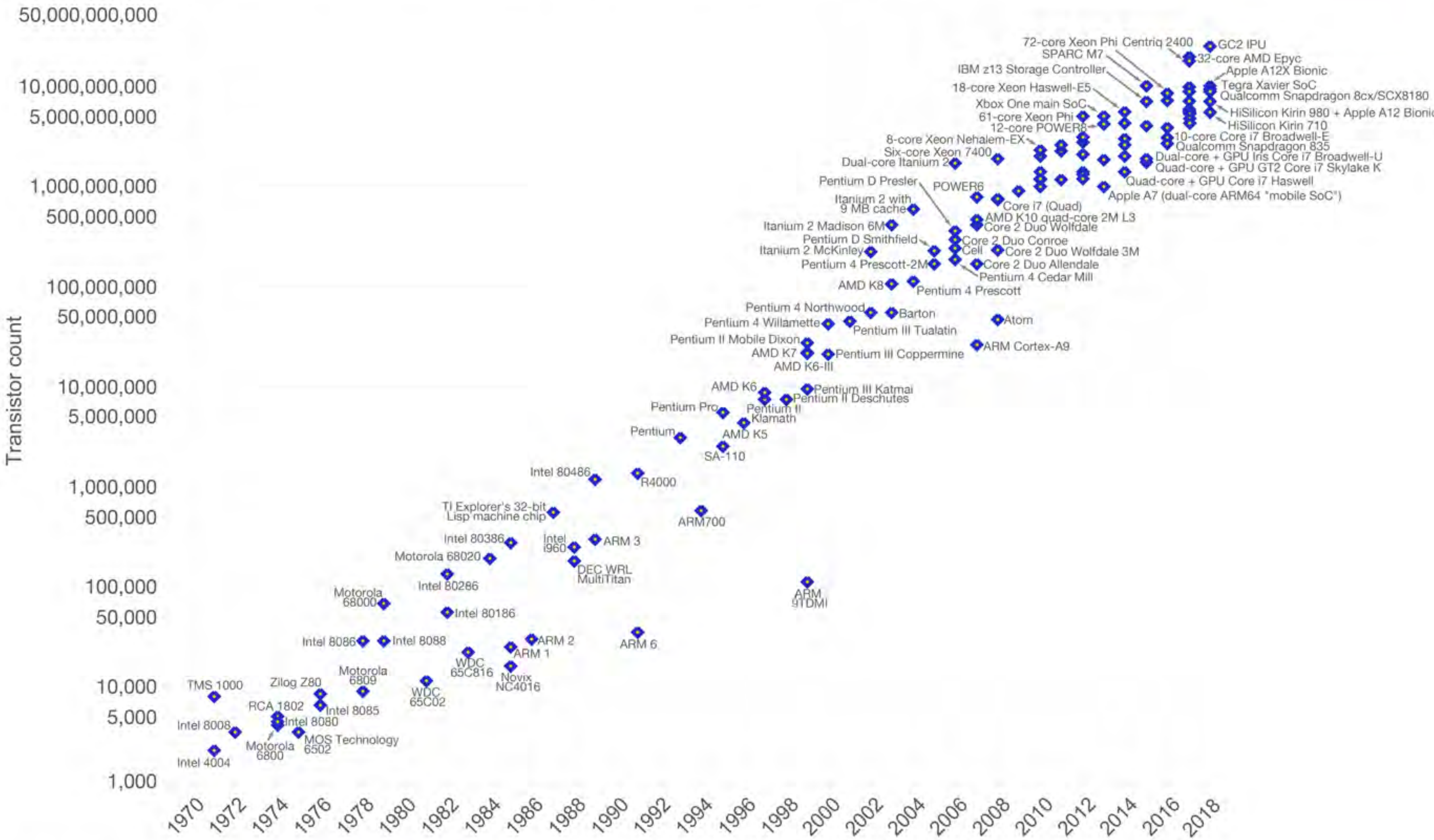
- Prediction by Gordon Moore that the number of transistors in an integrated circuit doubles approximately every two years.
- Commonly described as performance doubling every 18 months because of faster transistors and more transistors per chip

Not a real law – just an observation from the 1970s

Moore's Law – The number of transistors on integrated circuit chips (1971-2018)

Our World in Data

Moore's law describes the empirical regularity that the number of transistors on integrated circuits doubles approximately every two years. This advancement is important as other aspects of technological progress – such as processing speed or the price of electronic products – are linked to Moore's law.



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Scaling a single system has limits

Getting harder for technology to keep up with Moore's law

- More cores per chip
  → requires multithreaded programming
- There are limits to the die size and # of transistors
  - Intel Xeon W-3175X CPU: 28 cores per chip ($2,999/chip!)
    - 8 billion transistors, 255 w @ 3.1-4.3 GHz
  - NVIDIA GeForce RTX 2080 Ti: 4,352 CUDA cores per chip
    - Special purpose apps: Graphics rendering, neural networks

More performance

What if we need more performance than a single CPU?

- Combine them ⇒ multiprocessors
- But there are limits and the cost goes up quickly

Distributed systems allow us to achieve massive performance

Our computing needs exceed CPU advances

Movie rendering

- *Toy Story* (1995) – 117 computers; 45 mins - 30 hours to render a frame
  - Pixar render farm – 2,000 systems with 24,000 cores
- *Toy Story 4* (2019) – 60-160 hours to render a frame
- *Disney/Pixar's Coco* (2017) – Up to 100 hours to render one frame
- *How to Train a Dragon* (2010) – 90 million CPU hours to render
- *Big Hero 6* (2014) – average 83 hours/frame; 199 million CPU core hours
- *Monsters University* (2013) – an average of 29 hours per frame
  - 2,000 computers with 12,500 cores – total time: over 100 million CPU hours

- Google
  - Over 63,000 search queries per second on average
  - Over 130 trillion pages indexed
  - Uses hundreds of thousands of servers to do this
- Facebook
  - Approximately 100M requests per second with 4B users

Example: Google

- In 1999, it took Google one month to crawl and build an index of about 50 million pages
- In 2012, the same task was accomplished in less than one minute.
- 16% to 20% of queries that get asked every day have never been asked before
- Every query has to travel on average 1,500 miles to a data center and back to return the answer to the user
- A single Google query uses 1,000 computers in 0.2 seconds to retrieve an answer

Source: http://www.internetlivestats.com/google-search-statistics/

2. Collaboration

Collaboration & Content

- Collaborative work & play
- Social connectivity
- Commerce
- News & media

Metcalfe’s Law

The value of a telecommunications network is proportional to the square of the number of connected users of the system.

This makes networking interesting to us!

3. Reduced latency

Reduced Latency

- **Cache** data close to where it is needed
- Caching vs. replication
  - Replication: multiple copies of data for increased fault tolerance
  - Caching: temporary copies of frequently accessed data closer to where it's needed

Some caching services:

Akamai, Cloudflare, Amazon Cloudfront,
Apache Ignite, Dropbox

4. Mobility

Mobility

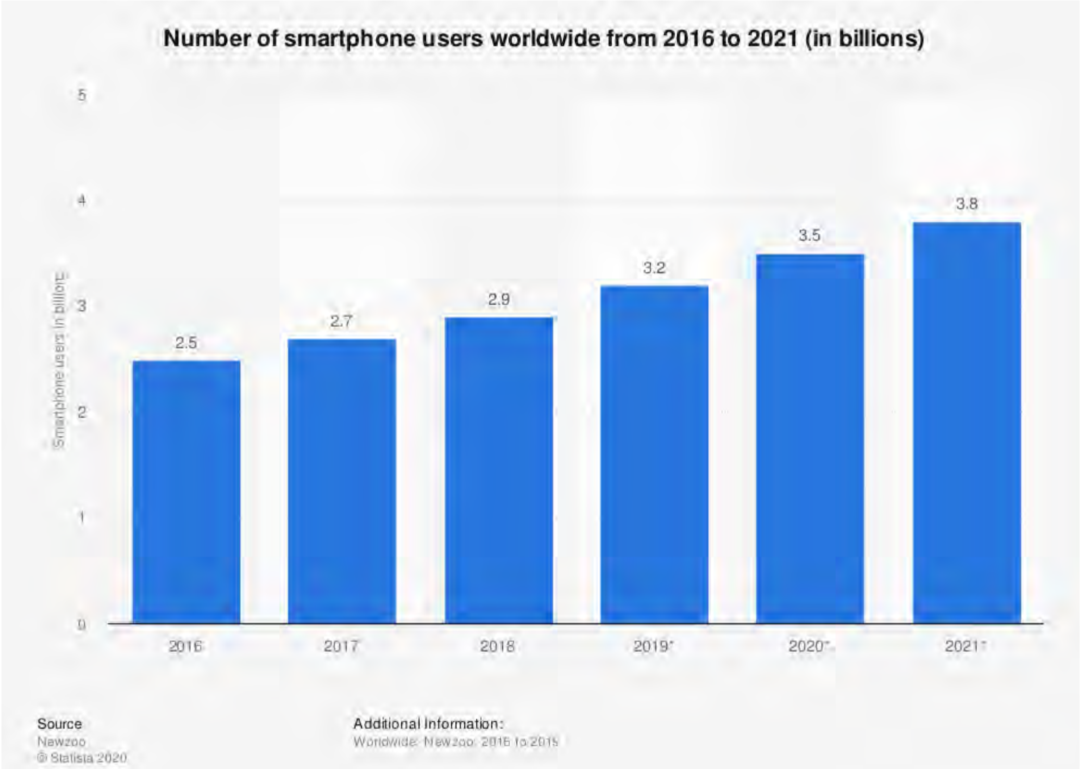
3.5 billion smartphone users

Remote sensors

- Cars
- Traffic cameras
- Toll collection
- Shipping containers
- Vending machines

IoT = Internet of Things

- 2017: more IoT devices than humans



5. High availability & Fault tolerance

High availability

Redundancy = replicated components

– Service can run even if some systems die

Reminder:

$P(\text{A and B}) = P(\text{A}) \times P(\text{B})$

If $P(\text{any one system down}) = 5\%$

$P(\text{two systems down at the same time}) = 5\% \times 5\% = 0.25\%$

Uptime = 1 – downtime = 1 – 0.0025 = 99.75%

~~High~~ availability

No redundancy = dependence on all components

– Service cannot run if some components die

If we need *all* systems running to provide a service

P(two systems down) = 1 - P(A is up AND B is up)

= 1 - (1-5%) × (1-5%) = 1 - 0.95 × 0.95 = 9.75%

⇒ 39x greater than a single component failure!

Uptime = 1 – downtime = 1 – 0.0975 = 90.25%

With a large # of systems, P(any system down) approaches 100% !

Computing availability

Series system:

The system fails if ANY of its components fail

P(system failure) = 1 - P(system survival)

If P_i = P(component i fails) then for n components:

$$P(system\ failure) = 1 - \prod_{i}^{n}(1 - P_i)$$

Parallel system:

The system fails if ALL of its components fail

P(system failure) = P(component$_1$ fails) × P(component$_1$ fails) …

$$P(system\ failure) = \prod_{i}^{n} P_i$$

Availability requires fault tolerance

- Fault tolerance
  - Identify & recover from component failures
- Recoverability
  - Software can restart and function
  - May involve restoring state

6. Incremental growth & cost

Incremental cost

Version 1 does not have to be the full system

- Add more servers & storage over time
- Scale also implies cost – you don't need millions of $ for v1.0

- eBay
  - Perl code on one hosted FreeBSD server – flat files or Berkeley DB
- Facebook
  - Started on one rented server at $85/month
- Google
  - Original storage in 1996: 10 4GB drives = 40 GB total
  - 1998 hardware
    - Sun Ultra II, 2 Intel dual-Pentium II servers, quad-processor IBM RS/6000
    - ~ 475 GB of disks

7. Delegated infrastructure & operations

Delegated operations

- Offload responsibility
  - Let someone else manage systems
  - Use third-party services
- Speed deployment
  - Don’t buy & configure your own systems
  - Don’t build your own data center
- Modularize services on different systems
  - Dedicated systems for storage, email, etc.
- Cloud, network attached storage

Transparency as a Design Goal

Transparency

High level: hide distribution from users

Low level: hide distribution from software

- **Location transparency**
  Users don't care where resources are
- **Migration transparency**
  Resources move at will
- **Replication transparency**
  Users cannot tell whether there are copies of resources
- **Concurrency transparency**
  Users share resources transparently
- **Parallelism transparency**
  Operations take place in parallel without user's knowledge

Why are distributed systems different … and challenging?

Core issues in distributed systems design

1. Concurrency
2. Latency
3. Partial Failure

Concurrency

Concurrency

- Lots of requests may occur at the same time
- Need to deal with concurrent requests
  - Need to ensure consistency of all data
  - Understand critical sections & mutual exclusion
  - Beware: mutual exclusion (locking) can affect performance
- Replication adds complexity
  - All operations must appear to occur in the same order on all replicas

Latency

Latency

Network messages may take a long time to arrive

- **Synchronous network model**
  - There is some upper bound, *T*, between when a node sends a message and another node receives it
  - Knowing *T* enables a node to distinguish between a node that has failed and a node that is taking a long time to respond
- **Partially synchronous network model**
  - There's an upper bound for message communication but the programmer doesn't know it – it has to be discovered
  - Protocols will operate correctly only if all messages are received within some time, *T*
- **Asynchronous network model**
  - Messages can take arbitrarily long to reach a peer node
  - **This is what we get from the Internet!**

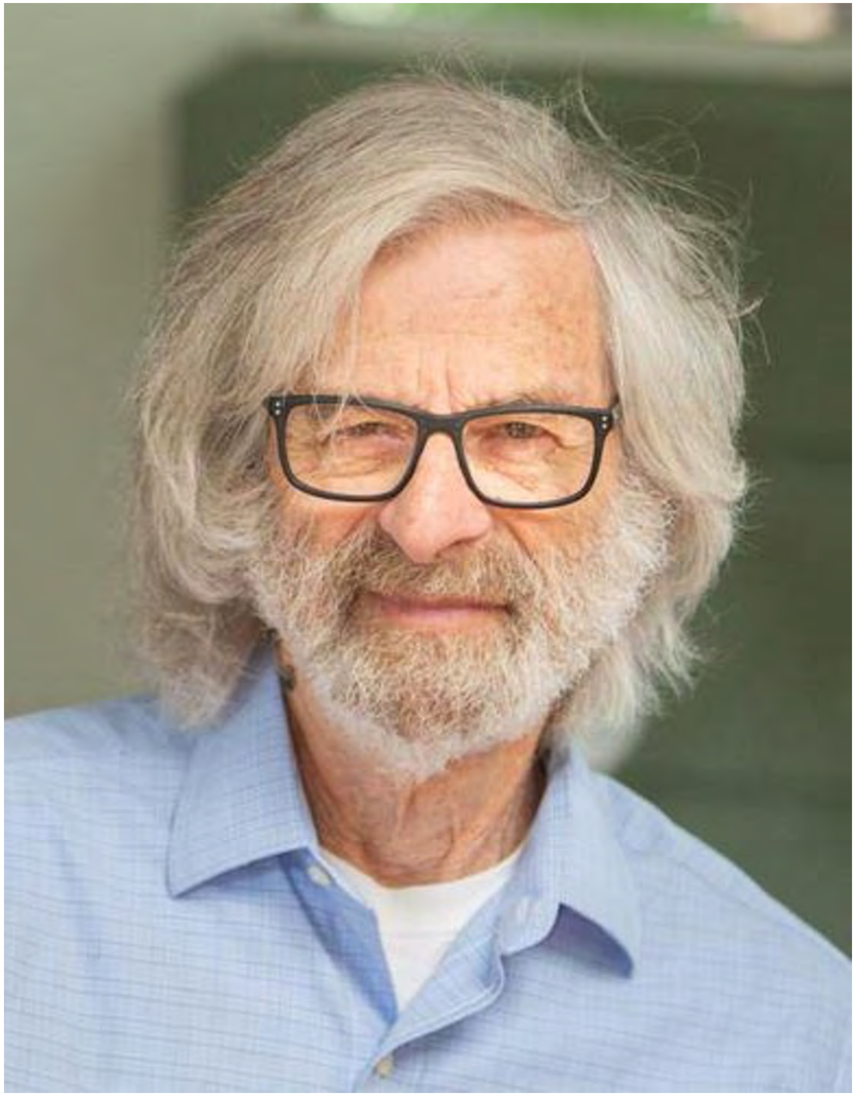
Latency

- Asynchronous networks can be a pain
- Messages may take an unpredictable amount of time
  - We may think a message is lost but it's really delayed
  - May lead to retransmissions → duplicate messages
  - May lead us to assume a service is dead when it isn't
  - May mess with our perception of time
  - May cause messages to arrive in a different order
    … or a different order on different systems

Latency

- Speed up data access via **caching** – temporary copies of data
- Keep data close to where it's processed to maximize efficiency
  - Memory vs. disk
  - Local disk vs. remote server
  - Remote memory vs. remote disk
  - **Cache coherence**: cached data can become **stale**
    - Underlying data can change → cache needs to be invalidated
    - System using the cache may change the data → propagate results
      - ***Write-through cache***
      - But updates take time → can lead to **inconsistencies** (**incoherent views**)

Partial Failure



You know you have a distributed system when the crash of a computer you've never heard of stops you from getting any work done.

– Leslie Lamport

Handling failure

Failure is a fact of life in distributed systems!

- In local systems, failure is usually **total** (all-or-nothing)
- In distributed systems, we get **partial failure**
  - A component can fail while others continue to work
  - Failure of a network link is indistinguishable from a remote server failure
  - Send a request but don't get a response
  - What happened?
- No global state
  - There is no global state that can be examined to determine errors
  - There is no agent that can determine which components failed and inform everyone else
- Need to ensure the state of the entire system is consistent after a failure

Handling failure

Need to deal with **detection**, **recovery**, and **restart**

Availability = fraction of time system is usable

- Achieve with redundancy
- But then consistency is an issue!

Reliability: data must not get lost

- Includes security

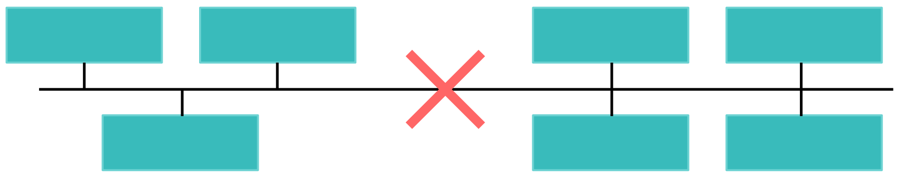
System Failure Types

- **Fail-stop**
  - Failed component stops functioning
    - Ideally, it may notify other components first
  - **Halting** = stop without notice
  - Detect failed components via **timeouts**
    - But you can't count on timeouts in asynchronous networks
      - And what if the network isn't reliable?
    - Sometimes we guess

- **Fail-restart**
  - Component stops but then restarts
  - Danger: **stale state**

Failure types

- **Omission**
  - Failure to send or receive messages
    - Queue overflow in router, corrupted data, receive buffer overflow
- **Timing**
  - Messages take longer than expected
    - We may assume a system is dead when it isn't
  - Unsynchronized clocks can alter process coordination
    - Mutual exclusion, timestamped log entries
- **Partition**
  - Network fragments into two or more sub-networks that cannot communicate with each other



Network & System Failure Types

- **Byzantine failures**
  - Instead of stopping, a component produces faulty data
  - Due to bad hardware, software, network problems, or malicious interference

Goal: avoid single points of failure

Redundancy

- We deal with failures by adding redundancy
  - Replicated components
- But this means we need to keep the **state** of those components replicated

State, replicas, and caches

- State
  - Information about some component that cannot be reconstructed
  - Network connection info, process memory, list of clients with open files, lists of which clients finished their tasks
- Replicas
  - Redundant copies of data → *address fault tolerance*
- Cache
  - Local storage of frequently-accessed data to reduce latency → *address latency*

No global knowledge

- Nobody has the true **global state** of a system
  - There is no global state that can be examined to determine errors
  - There is no agent that can determine which components failed and inform everyone else
  - No shared memory
- A process knows its current state
  - It may know the *last reported state* of other processes
  - It may periodically report its state to others

No foolproof way to detect failure in all cases

Other design considerations

Handling Scale

- Need to be able to add and remove components
- Impacts failure handling
  - If failed components are removed, the system should still work
  - If replacements are brought in, the system should integrate them

Security

- The environment
  - Public networks, remotely-managed services, 3rd party services
- Some issues
  - Malicious interference, bad user input, impersonation of users & services
  - Protocol attacks, input validation attacks, time-based attacks, replay attacks
- Rely on authentication, cryptography (hashes, encryption)
  … and good programming!
- Users also want convenience
  - Single sign-on
  - Controlled access to services

Other design considerations

- Algorithms & environment
  - Distributable vs. centralized algorithms
  - Programming languages
  - APIs and frameworks

Main themes in distributed systems

- Availability & fault tolerance
  - Fraction of time that the system is functioning
  - Dead systems, dead processes, dead communication links, lost messages
- Scalability
  - Things are easy on a small scale
  - But on a large scale
    - Geographic latency (multiple data centers), administration, dealing with many thousands of systems
- Latency & asynchronous processes
  - Processes run asynchronously: concurrency
  - Some messages may take longer to arrive than others
- Security
  - Authentication, authorization, encryption

Key approaches in distributed systems

- Divide & conquer
  - Break up data sets (sharding) and have each system work on a small part
  - Merging results is usually the easy & efficient part

- Replication
  - For high availability, caching, and sharing data
  - Challenge: keep replicas consistent even if systems go down and come up

- Quorum/consensus
  - Enable a group to reach agreement

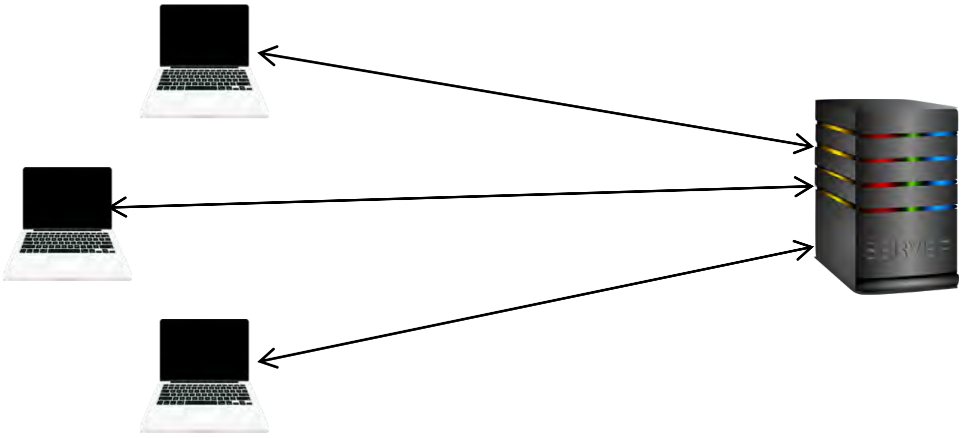
Service Models (Application Architectures)

Centralized model

- No networking
- Traditional time-sharing system
- Single workstation/PC or direct connection of multiple terminals to a computer
- One or several CPUs
- Not easily scalable
- Limiting factor: number of CPUs in system
  - Contention for same resources (memory, network, devices)

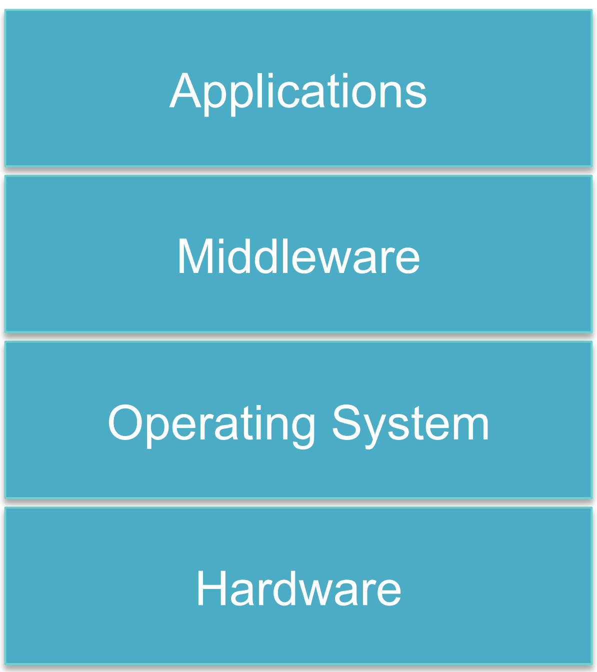
Client-Server model

- Clients send requests to servers
- A server is a system that runs a service
- The server is always on and processes requests from clients
- Clients do not communicate with other clients
- Examples
  – FTP, web, email



Layered architectures

- Break functionality into multiple layers
- Each layer handles a specific abstraction
  - Hides implementation details and specifics of hardware, OS, network abstractions, data encoding, …



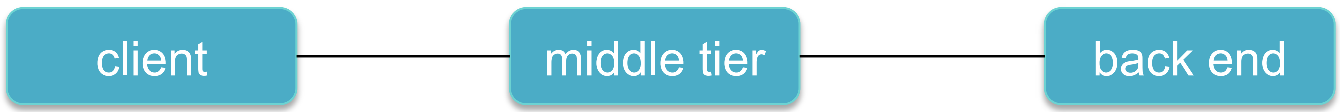
Includes naming, security, persistence, notifications, agreement, remote procedures, data encoding, …

Includes layering for file systems, networking, devices, memory

Tiered architectures

- Tiered (multi-tier) architectures
  - Distributed systems analogy to a layered architecture
- Each tier (layer)
  - Runs as a network service
  - Is accessed by surrounding layers
- The basic client-server architecture is a two-tier model
  - Clients: typically responsible for user interaction
  - Servers: responsible for back-end services (data access, printing, …)

Multi-tier example

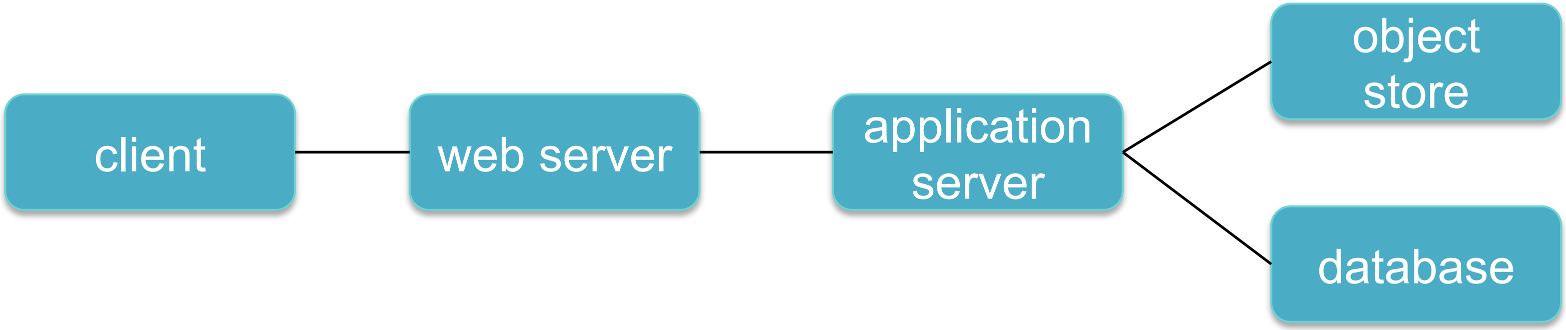


User interface
Data presentation
& validation

- Queuing requests
- Coordinating a transaction among multiple servers
- Managing connections
- Formatting/converting data

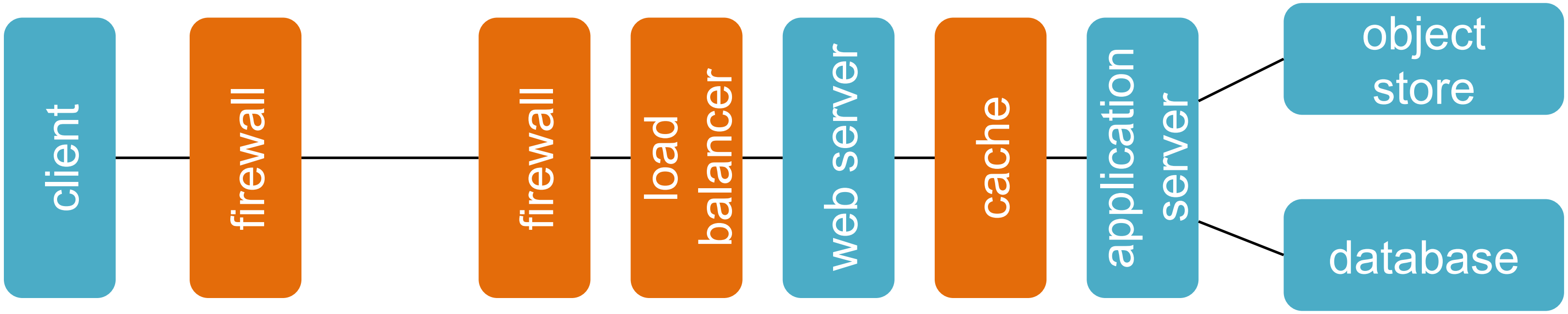
- Database system
- Legacy software

Multi-tier example



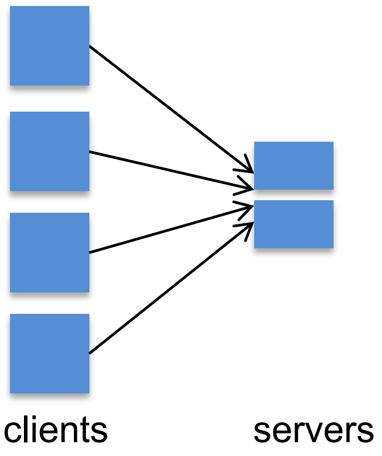
Multi-tier example

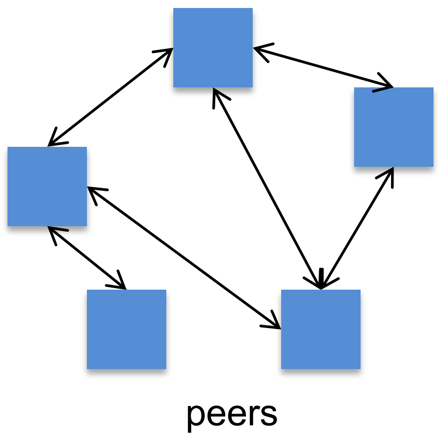
Some tiers may be transparent to the application



Peer-to-Peer (P2P) Model

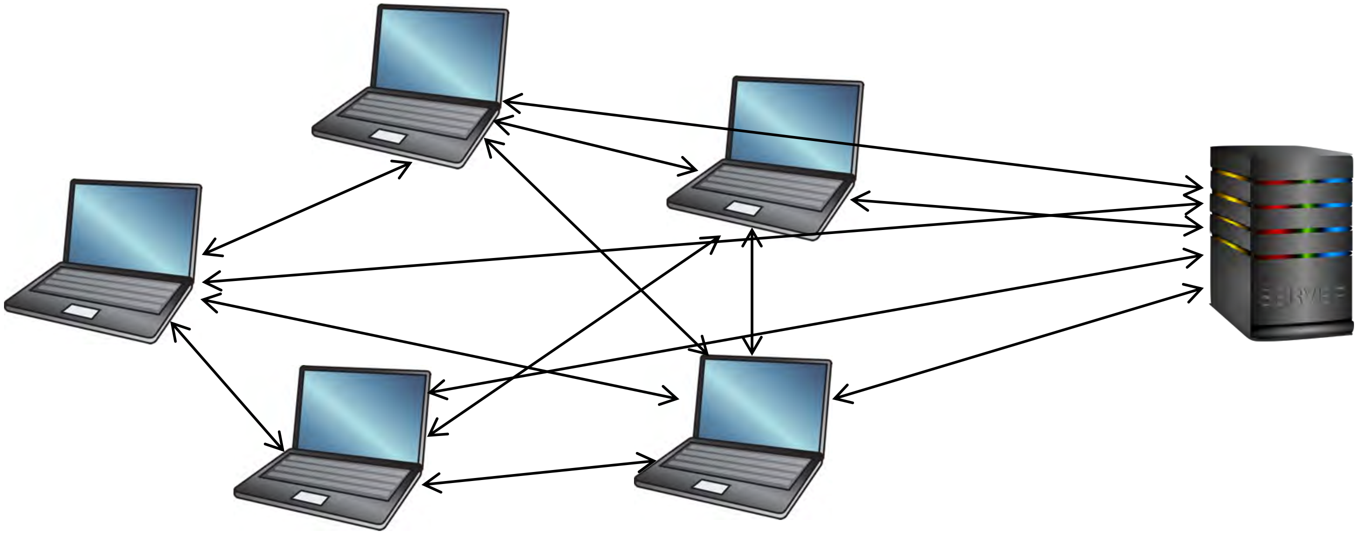
- No reliance on servers
- Machines (peers) communicate with each other
- Goals
  - Robustness
    - Expect that some systems may be down
  - Self-scalability: the system can handle greater workloads as more peers are added
- Examples
  - BitTorrent, Skype





Hybrid model

- Many peer-to-peer architectures still rely on a server
  - Look up, track users
  - Track content
  - Coordinate access
- But traffic-intensive workloads are delegated to peers



Images from: http://clipart-library.com/laptop-cliparts.html

Processor pool model

- Collection of CPUs that can be assigned processes on demand
- Similar to hybrid model
  - Coordinator dispatches work requests to available processors
- Render farms, big data processing, machine learning

Cloud Computing

Resources are provided as a network (Internet) service

- Software as a Service (SaaS)
  Remotely hosted software: email, productivity, games, …
  - *Salesforce.com, Google Apps, Microsoft Office 365*
- Platform as a Service (PaaS)
  Execution runtimes, databases, web servers, development environments, …
  - *Google App Engine, AWS Elastic Beanstalk*
- Infrastructure as a Service (IaaS)
  Compute + storage + networking: VMs, storage servers, load balancers
  - *Microsoft Azure, Google Compute Engine, Amazon Web Services*
- Storage
  Remote file storage
  - *Dropbox, Box, Google Drive, OneDrive, …*

The end