1 Introduction

1.1 Distributed Systems Definition

A distributed system in its simplest definition is a group of computers working together as to appear as a single computer to the user.

1.2 Why Distributed Systems

- Scaling
  - Vertical: more memory, faster CPU
  - Horizontal: more machines
- Economics
  - Initially scaling vertically is cheaper until max HW
  - Current x86 max: 64 cores
- Location
  - Everything gets faster, latency stays
  - Physically bounded by the speed of light
  - New Protocols can decrease RT
  - Place services closer to user
- Fault tolerance
  - Every hardware will crash eventually

1.3 Scaling

1.3.1 Horizontal

Pros

- Lower cost with massive scale
- Easier to add fault-tolerance
- Higher availability

Cons

- Adaption of software required
- More complex system, more components involved

1.3.2 Vertical

Moore's Law: Nr. of transistors doubles every 2 years.
Nielsen's Law: High-end user's connection speed grows by 50% per year.
Kryder's Law: Disk density doubling every 13 month.
Bandwidth grows slower than computer power
Pros

- Lower cost with small scale
- No adaption of software required
- Less administrative effort

Cons

- HW limits for scaling
- Risk of HW failure causing outage
- More difficult to add fault tolerance

1.4 Distributed Systems Categorization

Tightly Coupled

- Processing Elements have access to a common memory

Loosely Coupled (this lecture)

- Processing Elements have NO access to a common memory

Homogenous System

- All processors are of the same type

Heterogeneous System (this lecture)

- Processors of different types

Small Scale

- WebApp + database

Large Scale (this lecture)

- More than 2 machines

Decentralized

- Distributed in the technical sense, but not owned by one actor

1.4.1 Controlled Distributed Systems

- 1 responsible organization
- Low churn
- Secure environment
- High availability
- Homogenous / Heterogeneous
- Examples: Amazon DynamoDB, Client/Server

Mechanisms that work well:

- Consistent hashing
- Master nodes, central coordinator

Network is under control or client/server

- no NAT issues

Consistency

- Leader election (Zookeeper, Paxos, Raft)

Replication principles

- More replicas: higher availability / reliability / performance / scalability
- Requires maintaining consistency in replicas

Transparency principles apply

1.4.2 Fully Decentralized Systems

- N responsible organizations
- High churn
- Hostile environment
- Unpredictable availability
- Heterogeneous
- Examples: BitTorrent, Blockchain

Mechanisms that work well:

- Consistent hashing (DHTs)
- Flooding/broadcasting - Bitcoin

NAT and direct connectivity huge problem
Consistency

- Weak consistency: DHTs
- Proof of work

Replication / Transparency principles apply

1.4.3 CAP theorem

A distributed data store cannot simultaneously be consistent, available and partition tolerant.

- **Consistency:** Every node has the same consistent state
- **Availability:** Every non-failing node always returns a response
- **Partition Tolerant:** The system continues to be consistent even when network partitions

Examples:

- Network partition: AP or CP
- Blockchain: CP or AP
- Cassandra (Apple): AP, can be configured CP

1.5 Transparency in DS

Distributed system should hide its distributed nature

- Location: users should not be aware of the physical location
- Access: users should access resources in a single, uniform way
- Migration, relocation: users should not be aware, that resources have moved
- Replication: Users should not be aware about replicas, it should appear as a single resource
- Concurrency: users should not be aware of other users
- Failure: Users should be aware of recovery mechanisms
- Security: Users should be minimally aware of security mechanisms

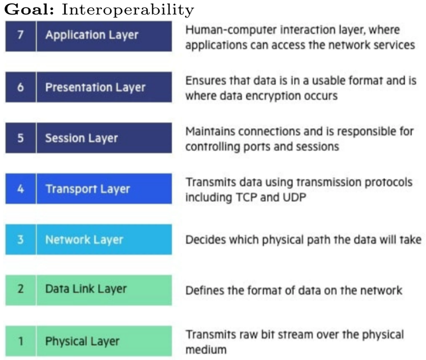
1.6 Fallacies of Distributed Computing

1. The network is reliable
2. Latency is zero
3. Bandwidth is infinite
4. The network is secure
5. Topology doesn't change
6. There is one administrator
7. Transport cost is zero
8. The network is homogenous

2 Protocols

2.1 Networking Layers

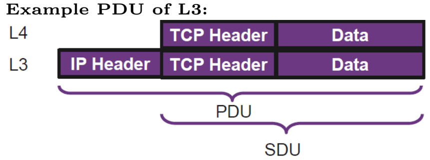
Goal: Interoperability



2.1.1 Layer Abstraction

- Protocols enable an entity to interact with an entity at the same layer in another host
- **Service definitions:** provide functionality to an (N)-layer by an (N-1) layer
- Layer N exchange protocol data units (PDUs) with layer N protocol
- Each PDU contains a header and payload, the service data unit (SDU)

Example PDU of L3:



2.2 Layer 4 - Transport

2.2.1 TCP

- Reliable
- Ordered
- Window - capacity of receiver
- Checksum - 16bit
- TCP overhead: 20 bytes
- Tries to correct errors

Connection establishment

- SYN, SYN-ACK, ACK
- Initiates TCP session: initial sequence number is random

Connection termination

- FIN, ACK + FIN, ACK
- 3-way handshake

Sequences and ACKs

- Identification each byte of data
- Order of the bytes: reconstruction
- Detecting lost data: RTO, DupACK

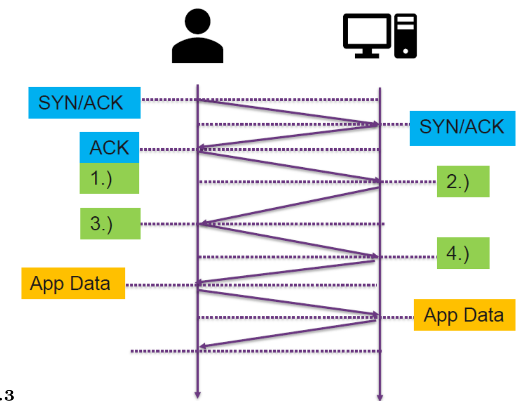
Retransmission timeout

- If no ACK is received after timeout

Flow control

- Sender is not overwhelming a receiver
- Back pressure
- Sliding window
- Congestion control
  - Slow-start
  - Congestion avoidance

2.2.2 TCP + TLS



TLS <1.3

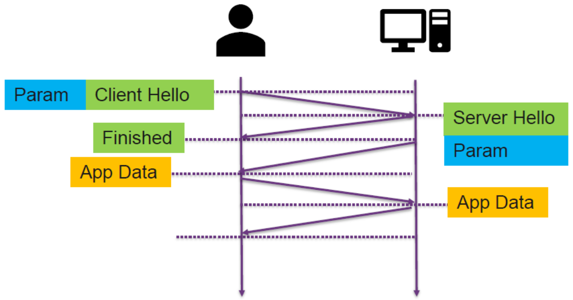
1. client hello - lists crypto information, TLS version, ciphers/keys
2. server hello - chosen cipher, session ID, random bytes, digital certificate
3. Key exchange using random bytes, now client + server can calculate secret key
4. finished - encrypted message

3RTT until first byte
TLS 1.3

- 1 RTT instead of 2
  1. Client Hello, Key share
  2. Server Hello, Key share, Verify Certificate, Finished
- 0 RTT possible for previous connections (no perfect forward secrecy)

2.2.3 QUIC

- 1 RTT (0 RTT for know connections)
- Built in security



- Multiplexing in HTTP/2
- QUIC can multiplex requests: one stream does not affect others

2.2.4 UDP

- Used for DNS, streaming
- Simple connectionless communication model
- No guarantee
  - Delivery
  - Ordering
  - Duplicate protection

2.2.5 SCTP - Stream Control Transmission Protocol

- Message based
- Allows data to be divided into multiple streams
- Syn cookies: Four-way handshake with a signed cookie
- Multi-homing multiple IP addresses of endpoints

3 Virtualization

Creation of a virtual machine that acts like a real computer with an operating system.
Host: machine where the virtualization SW runs.
Guest: VM
Hypervisor: runs VM

- Type 1: bare-metal e.g. Xen
- Type 2: hosted e.g. VirtualBox

Needs to be the same architecture

- Otherwise emulation needed

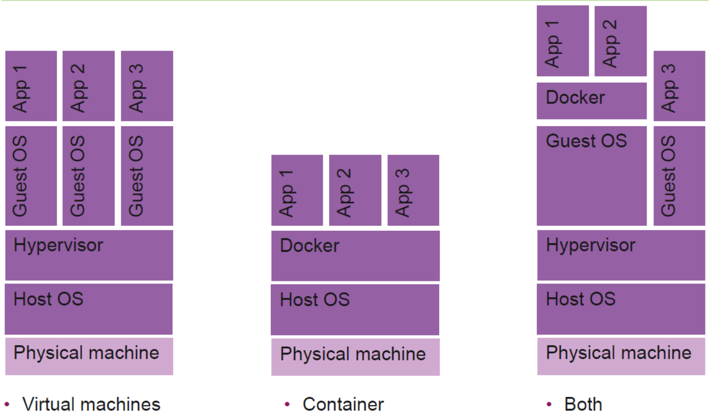
Virtual desktop infrastructure (VDI)

- Interact with a VM over a network

Containers

- Isolated user-space instances
- Share the OS

3.1 VM vs. Container



- Containers are more agile than VMs
- Containers enable hybrid and multi-cloud adoption
- Integrate Containers with your existing IT processes
- Containers safe on VM licensing

3.1.1 Container

\+ Reduced IT management resources
\+ Reduced size of snapshots
\+ Quicker spinning up apps
+/- Available memory is shared
+/- Process-based isolation (share same kernel)
Use case: complex application setup, with container less complex config

3.1.2 Virtual Machine

\+ App can access all OS resources
\+ Live migrations
+/- Pre allocates memory
+/- Full isolation
Use case: better hardware utilization / resource sharing

3.2 Docker

- Containerization platform
- Software delivery framework
- Packages software into containers
- Provides OS-level virtualization
- Containers are isolated from each other

Docker Compose

- Deploy multiple containers

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4 Loadbalancing

Distribution of workloads across multiple computing resources.
Horizontal scaling: Distributes client requests or network load efficiently across multiple servers.

4.1 Why?

- Ensures high availability and reliability
- Sending requests only to servers that are online
- Provides flexibility to add/subtract servers on demand

4.2 Types of Load Balancers

4.2.1 Hardware Load Balancer

- Use proprietary software, which often uses specialized processes
  - Less generic, more performance
  - Some use open-source SW
- Only if you control your datacenter
- E.g. loadbalancer.org, F5, Cisco

4.2.2 Software Load Balancer

- L2/L3: Seesaw
- L4: Traefik, Nginx, LoadMaster, etc.
- L7: Traefik, Envoy, Neutrino, Envoy, etc.

DNS Load Balancing

- Round-robin DNS
  - Very easy to set up
  - Static
  - Caching with no fast changes
- Split horizon DNS
  - Different DNS information
  - Depending on source of the DNS request
- Anycast
  - Difficult and time consuming
  - Return the IP with lowest latency

4.2.3 Cloud-based Load Balancer

- Pay for use
- Many offerings
  - AWS, Google Cloud, Cloudflare, DigitalOcean, Azure

4.3 Load Balancing Algorithms (L4/L7)

- Round robin: loop sequentially
- Weighted round robin: some server are more powerful
- Least connections
- Least time: fastest response time + fewest connections
- Least pending requests
- Agent-based: service reports on its load
- Hash: Distributes based on a key
- Random

Conclusion

- Easiest: Round-robin
- Stateless: don't store anything in the service
- Health checks: Tell LB if you are low on resources
- L7 LB is more resource intensive than L4 LB

4.4 Traefik

- Open Source, SW based
- L4/L7
- Golang, single binary
- Authentication
- Experimental HTTP/3 support

4.5 Caddy

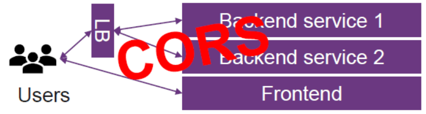
- Open Source, SW based
- L7
- Reverse proxy
- Static file server
- Experimental HTTP/3 support

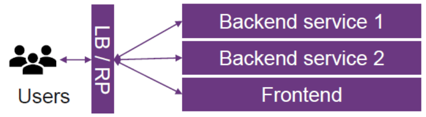
4.6 NGINX

- Free + commercial version
- HTTP / Mail / reverse proxy
- No active health checks (commercial)
- No sticky sessions (commercial)

4.7 CORS

For security reasons, browsers restrict cross-origin HTTP requests initiated from scripts.
Solution:
Use reverse proxy with builtin webserver e.g. nginx, or use reverse proxy with external webserver.
The client only sees the same origin for the API and the frontend assets.





Access-Control-Allow-Origin
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5 Authentication

Confidentiality: Protects transmitted data against eavesdropper.
Integrity: Provides protection against modification.
Availability: Data needs to be available when needed.
Non-repudiation: No one can deny an action.
Identification: Username connects to a person.
Authentication: Verifying a claim of identity with:

- Something you know
- Something you have
- Something you are

Authorization: Determines what resources a user can access.

5.1 Software Token

TOTP: Time-based One-time Password

- Often used as 2nd factor
- Based on keyed-hash message authentication code

5.2 Basic Auth

- Load balancer
- Services (keep state!)
- Only with HTTPS
- Can be encoded in URL: *user:pw@domain*
- Server will reply with header: *WWW-Authenticate*

5.3 Digest Auth

- Based on Basic Auth
- Also available in traefik
- Hash + nonce, against replay attacks

Advantages

- PW not in clear text (MD5), can be SHA-256
- Nonce for replay protection for client/server

Disadvantages

- Browser L&F
- Cannot use scrypt or bcrypt to store PWs

5.4 Create SSL CA certificates for server

- Create CA
- Create certificate
- Add nginx security in your local network

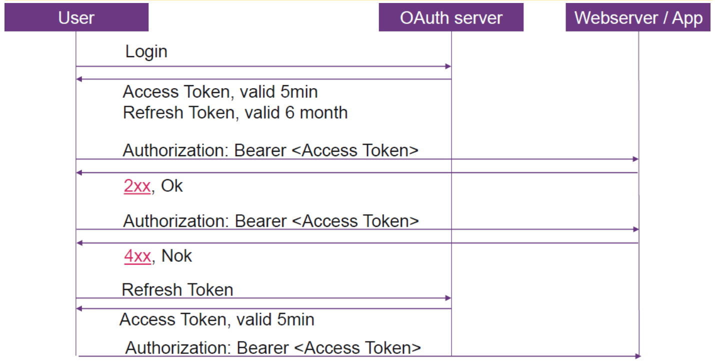
5.5 Session-based authentication

- Sticky session required
- Authenticate in Service Instance

5.6 JWT

- Stateless
- All server instances know a secret token / public key
- When user logs in, server send back token
- Client sends: Authorization: Bearer ¡token¿
- Client can store token in local storage

5.6.1 Access Token / Refresh Token



Access Token
- Short lifetime (10min)

Refresh Token
- Used to get a new access token
- IAM / Auth server creates access tokens

6 Application Protocols