# Principles of Distributed Systems

inft-3507

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Autumn 2025

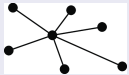
## Section 1: Introduction

*This content is based on the following public resources: https://www.distributed-systems.net/index.php/books/ds4/*

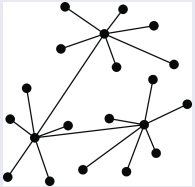
# From networked systems to distributed systems

# Distributed versus Decentralized

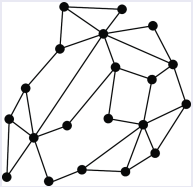
## What many people state



Centralized



Decentralized



Distributed

## When does a decentralized system become distributed?

- Adding 1 link between two nodes in a decentralized system?
- Adding 2 links between two other nodes?
- In general: adding $k > 0$ links....?

# Alternative approach

## Distributed system

- A distributed system consists of multiple computers (nodes) that work together to appear as a single system to the user.
- **Focus**: performance, scalability, fault tolerance
- **Control** typically/commonly centralized

## Decentralized system

- A decentralized system distributes control and decision-making authority across multiple independent nodes rather than relying on a central authority.
- **Focus**: autonomy, resilience to control, trust minimization
- **Control**: No single node has ultimate authority

# Control & Authority (The Main Difference)

## Distributed

Multiple nodes *compute together*, but control can still be centralized:

- Leader / coordinator often exists
- Decisions may flow from one organization or service

## Decentralized

Multiple nodes *share control*:

- No single node (or org) has ultimate authority
- Governance/decision-making spread across participants

## Key takeaway

A system can be **distributed yet centralized**; a **decentralized** system must distribute *control*.

# Architecture & Coordination

## Typical distributed coordination

- Client–server, master–worker, leader-based replication
- Specialized roles (leader, replicas, workers)

## Typical decentralized coordination

- Peer-to-peer style participation
- Collective coordination (e.g., voting/consensus-like mechanisms)

## Intuition

Distributed $\rightarrow$ “many machines, one system”
Decentralized $\rightarrow$ “many owners, shared authority”

# Fault Tolerance & Failure Modes

## Distributed systems

- Handle **node failures** (crashes, partitions)
- But may have **single point of control**

## Decentralized systems

- Handle node failures *and* control failures
- Aim to avoid **single authority failure**

## Practical distinction

Distributed: resilience to **hardware/service failure**
Decentralized: resilience to **control/censorship/authority failure**

# Trust & Security Model

## Distributed (often)

- Assumes trusted administrators / central policy
- Security enforced via access control and ops processes

## Decentralized (often)

- Assumes some participants may be malicious
- Uses mechanisms to reduce reliance on trust in any one node

## Rule of thumb

More decentralization usually means a **stronger adversarial model** (and more design complexity).

# Performance & Efficiency Trade-offs

**Distributed systems tend to optimize**

- Latency, throughput, operational efficiency
- Coordination cost kept low via leaders / centralized control

**Decentralized systems tend to trade performance for**

- Independence, robustness, shared governance
- Higher coordination overhead (more parties must agree)

**Trade-off**

Decentralization often increases cost of coordination $\Rightarrow$ lower peak performance.

# Summary Comparison

## Quick comparison

- **Goal:** Distributed → scalability/performance vs Decentralized → autonomy/resilience
- **Control:** Distributed → may be centralized vs Decentralized → shared control
- **Trust:** Distributed → trusted operators vs Decentralized → trust-minimized
- **Complexity:** Distributed → moderate vs Decentralized → higher

# Design goals

# What do we want to achieve?

## Overall design goals

- Support sharing of resources
- Distribution transparency
- Openness
- Scalability

# Sharing resources

## Canonical examples

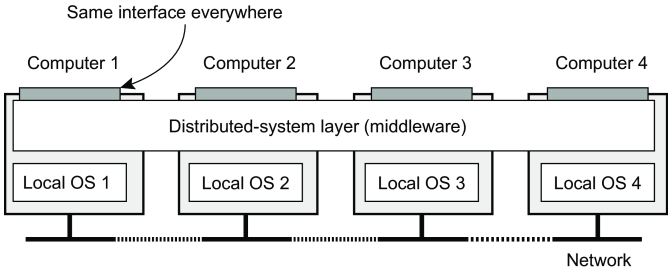
- Cloud-based shared storage and files
- Peer-to-peer assisted multimedia streaming
- Shared mail services (think of outsourced mail systems)
- Shared Web hosting (think of content distribution networks)

## Observation

*"The network is the computer"*

(John Gage, Sun Microsystems)

# Distribution transparency




## What is transparency?

*The phenomenon by which a distributed system attempts to hide the fact that its processes and resources are physically distributed across multiple computers, possibly separated by large distances.*

## Observation

Distribution transparancy is handled through many different techniques in a layer between applications and operating systems: a middleware layer

# Distribution transparency

## Types

| Transparency | Description |
|---|---|
| **Access** | Hide differences in data representation and how an object is accessed |
| **Location** | Hide where an object is located |
| **Migration** | Hide that an object may move to another location |
| **Replication** | Hide that an object is replicated |
| **Concurrency** | Hide that an object may be shared by several independent users |
| **Failure** | Hide the failure and recovery of an object |

# Openness of distributed systems

## Open distributed system

*A system that offers components that can easily be used by, or integrated into other systems. An open distributed system itself will often consist of components that originate from elsewhere.*

## What are we talking about?

Be able to interact with services from other open systems, irrespective of the underlying environment:

- Systems should conform to well-defined interfaces
- Systems should easily interoperate
- Theis means publicly documented protocols and APIs
- Vendor-neutral standards
- Interoperability and extensibility

# Dependability

## Basics

A component provides services to clients. To provide services, the component may require the services from other components ⇒ a component may depend on some other component.

## Specifically

A component $C$ depends on $C^*$ if the correctness of $C$'s behavior depends on the correctness of $C^*$'s behavior. (Components are processes or channels.)

# Dependability

## Requirements related to dependability

| Requirement | Description |
|---|---|
| **Availability** | Readiness for usage |
| **Reliability** | Continuity of service delivery |
| **Safety** | Very low probability of catastrophes |
| **Maintainability** | How easy can a failed system be repaired |

# Traditional reliability - MTTF/MTTR

The following *traditional* metrics were derived from shop-floor machine reliability modelling over many years.

## Traditional metrics

- **Mean Time To Failure** (*MTTF*): The average time until a component fails.
- **Mean Time To Repair** (*MTTR*): The average time needed to repair a component.
- **Mean Time Between Failures** (*MTBF*): Simply $MTTF + MTTR$.

You will often see *MTTF*, *MTTR*, *MTBF* used for modelling system reliability over time.

# Reliability v Availability

- *Availability* is about how much of the time the system is usable, allowing multiple failures and repairs.
- *Availability* is measured in *Uptime percentage* or *SLA "nines"* (eg, 5 9s)

$$A = \lim_{T \to \infty} \frac{\text{time system is up in } [0, T]}{T}$$

- *Reliability*: time to first failure
- *Reliability* is about whether failure occurs at all during an interval.

$$R(t) = \Pr\{\text{system survives without failure for time } t\}$$

- *Reliability* is measured Failure rate $\lambda$ or MTTF

# Availability v Reliability: Numerical Example

## System 1

- Fails every 10 minutes
- Repair time $=$ 1 second
- *Availability* $\approx$ 99.83%
- *Reliability over 1 hour* $\approx$ almost zero

## System 2

- Fails every 6 months
- Repair time $=$ 6 hours
- *Availability* $\approx$ 99.83%
- *Reliability over 1 hour* $\approx$ almost 1

**Conclusion**: Two systems, with the same *availability*, but completely different *reliability*.

# A Note on Security

**Observation**

A distributed system that is not secure, is not dependable

**What we need**

- Confidentiality: information is disclosed only to authorized parties
- Integrity: Ensure that alterations to assets of a system can be made only in an authorized way

**Authorization, Authentication, Trust**

- Authentication: verifying the correctness of a claimed identity
- Authorization: does an identified entity has proper access rights?
- Trust: one entity can be assured that another will perform particular actions according to a specific expectation

# Security mechanisms

## Symmetric cryptosystem

With encryption key $E_K(data)$ and decryption key $D_K(data)$:
*if* $data = D_K(E_K(data))$ *then* $D_K = E_K$. Note: encryption and descryption key are the same and should be kept secret.

## Asymmetric cryptosystem

Distinguish a public key $PK(data)$ and a private (secret) key $SK(data)$.

- Encrypt message from *Alice* to *Bob*: $data = \underbrace{SK_{bob}(\overbrace{PK_{bob}(data)}^{\text{Sent by Alice}})}_{\text{Action by Bob}}$
- Sign message for *Bob* by *Alice*: $[data, \underbrace{data \stackrel{?}{=} PK_{alice}(SK_{alice}(data))}_{\text{Check by Bob}}] = \underbrace{[data, SK_{alice}(data)]}_{\text{Sent by Alice}}$

# Security mechanisms

## Secure hashing

In practice, we use secure hash functions: $H(data)$ returns a fixed-length string.

- Any change from $data$ to $data^*$ will lead to a completely different string $H(data^*)$.
- Given a hash value, it is computationally impossible to find a $data$ with $h = H(data)$

## Practical digital signatures

Sign message for *Bob* by *Alice*:

$$[data, \underbrace{H(data) \stackrel{?}{=} PK_{alice}(sgn)}_{\text{Check by Bob}}] = \underbrace{[data, H, sgn = SK_{alice}(H(data))]}_{\text{Sent by Alice}}$$

# Scale in distributed systems

## Observation

Many developers of modern distributed systems easily use the adjective “scalable” without making clear why their system actually scales.

## At least three components

- Number of users or processes (size scalability)
- Maximum distance between nodes (geographical scalability)
- Number of administrative domains (administrative scalability)

## Observation

Most systems account only, to a certain extent, for size scalability. Often a solution: multiple powerful servers operating independently in parallel. Today, the challenge still lies in geographical and administrative scalability.

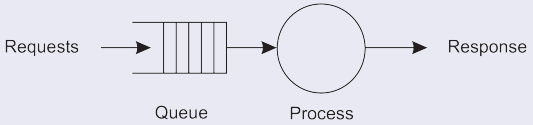
# Size scalability

**Root causes for scalability problems with centralized solutions**

- The computational capacity, limited by the CPUs
- The storage capacity, including the transfer rate between CPUs and disks
- The network between the user and the centralized service

# Performance models

## A centralized service can be modeled as a simple queuing system




## Assumptions and notations

- The queue has infinite capacity $\Rightarrow$ arrival rate of requests is not influenced by current queue length or what is being processed.
- Arrival rate requests: $\lambda$
- Processing capacity service: $\mu$ requests per second

# Performance models

**Utilization $U$ of a service is the fraction of time that it is busy**

$$U = \frac{\lambda}{\mu}$$

**Average number of requests in the system**

$$\overline{N} = \frac{U}{1-U}$$

**Average throughput**

$$X = \frac{\lambda}{\mu} \cdot \mu = \lambda$$

via the Principle of Equilibrium (or conservation)

# Performance models

## Response time: total time take to process a request after submission

From Little's Law:

$$\overline{N} = X \cdot R \Rightarrow R = \frac{\overline{N}}{X}$$

$$\Rightarrow R = \frac{1}{\mu \cdot (1 - U)}$$

## Observations

- If $U$ is small, response-to-service time is close to 1: a request is immediately processed
- If $U$ goes up to 1, the system comes to a grinding halt.
  Solution: increase $\mu$.

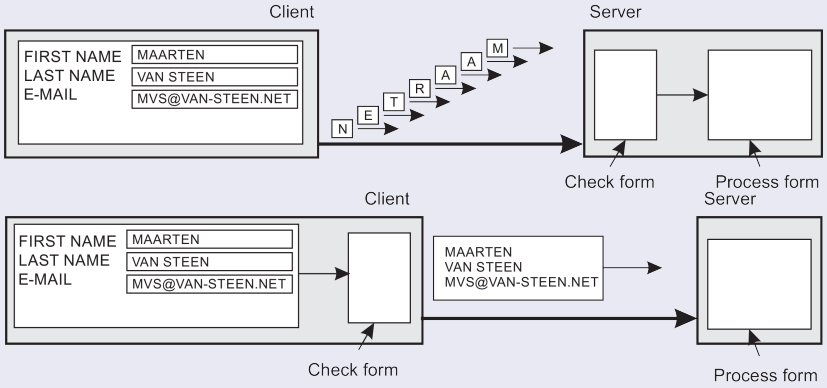
# Techniques for scaling

## Hide communication latencies

- Make use of asynchronous communication
- Have separate handler for incoming response
- Problem: not every application fits this model

# Techniques for scaling

## Facilitate solution by moving computations to client



# Techniques for scaling

**Partition data and computations across multiple machines**

- Move computations to clients (Java/ECMA script)
- Decentralized naming services (DNS)
- Decentralized information systems (WWW)

# Techniques for scaling

**Replication and caching: Make copies of data available at different machines**

- Replicated file servers and databases
- Mirrored Websites
- Web caches (in browsers and proxies)
- File caching (at server and client)

# Scaling: The problem with replication

## Applying replication is easy, except for one thing

- Having multiple copies (cached or replicated), leads to inconsistencies: modifying one copy makes that copy different from the rest.
- Always keeping copies consistent and in a general way requires global synchronization on each modification.
- Global synchronization precludes large-scale solutions.

## Observation

If we can tolerate inconsistencies, we may reduce the need for global synchronization, but tolerating inconsistencies is application dependent.

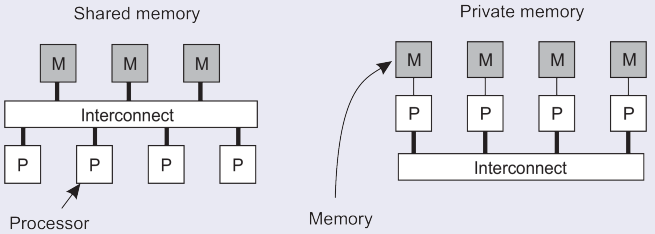
# A simple classification of distributed systems

# Parallel computing

## Observation

High-performance distributed computing started with parallel computing

## Multiprocessor and multicore versus multicomputer



# Distributed shared memory systems

## Observation

Multiprocessors are relatively easy to program in comparison to multicomputers, yet have problems when increasing the number of processors (or cores). Solution: Try to implement a shared-memory model on top of a multicomputer.

## Example through virtual-memory techniques

Map all main-memory pages (from different processors) into one single virtual address space. If a process at processor $A$ addresses a page $P$ located at processor $B$, the OS at $A$ traps and fetches $P$ from $B$, just as it would if $P$ had been located on local disk.

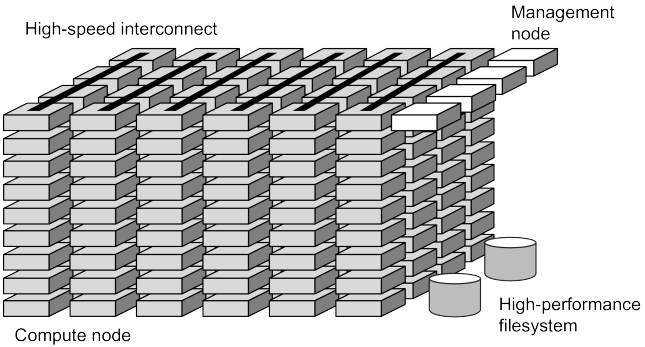
## Problem

Performance of distributed shared memory could never compete with that of multiprocessors, and failed to meet the expectations of programmers. It has been widely abandoned by now.

# Cluster computing

## Essentially a group of high-end systems connected through a LAN

- Homogeneous: same OS, near-identical hardware
- Single, or tightly coupled managing node(s)



# Summary

# Summary and Conclusions

We have discussed some important principles in Distributed Systems, namely:

- Centralized, Decentralized and Distributed Types
- Support sharing of resources
- Distribution transparency
- Openness and Security
- Performance and Scalability