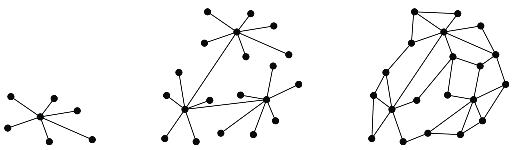
Distributed Systems

(4th edition, version 01)

Chapter 01: Introduction

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....?

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Alternative approach

Two views on realizing distributed systems

- Integrative view: connecting existing networked computer systems into a larger a system.
- Expansive view: an existing networked computer systems is extended with additional computers

Two definitions

- A decentralized system is a networked computer system in which processes and resources are necessarily spread across multiple computers.
- A distributed system is a networked computer system in which processes and resources are sufficiently spread across multiple computers.

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Some common misconceptions

Centralized solutions do not scale

Make distinction between logically and physically centralized. The root of the Domain Name System:

- logically centralized
- physically (massively) distributed
- decentralized across several organizations

Centralized solutions have a single point of failure

Generally not true (e.g., the root of DNS). A single point of failure is often:

- easier to manage
- easier to make more robust

Important

There are many, poorly founded, misconceptions regarding scalability, fault tolerance, security, etc. We need to develop skills by which distributed systems can be readily understood so as to judge such misconceptions.

Perspectives on distributed systems

Distributed systems are complex: take persepctives

- Architecture: common organizations
- Process: what kind of processes, and their relationships
- Communication: facilities for exchanging data
- Coordination: application-independent algorithms
- Naming: how do you identify resources?
- Consistency and replication: performance requires of data, which need to be the same
- Fault tolerance: keep running in the presence of partial failures
- Security: ensure authorized access to resources

What do we want to achieve?

Overall design goals

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

Sharing resources

Canonical examples

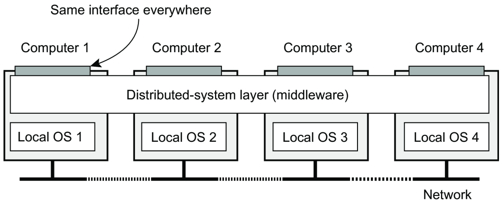
- Cloud-based shared storage and files
- Peer-to-peer assisted multimedia streaming
- Shared mail services (think of outsourced mail systems)
- Shared Web hosting (think of content distribution networks)

Observation

"The network is the computer"

(quote from John Gage, then at 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
Relocation	Hide that an object may be moved to another location while in use
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

Degree of transparency

Aiming at full distribution transparency may be too much

- There are communication latencies that cannot be hidden
- Completely hiding failures of networks and nodes is (theoretically and practically) impossible
  - You cannot distinguish a slow computer from a failing one
  - You can never be sure that a server actually performed an operation before a crash
- Full transparency will cost performance, exposing distribution of the system
  - Keeping replicas exactly up-to-date with the master takes time
  - Immediately flushing write operations to disk for fault tolerance

Degree of transparency

Exposing distribution may be good

- Making use of location-based services (finding your nearby friends)
- When dealing with users in different time zones
- When it makes it easier for a user to understand what's going on (when e.g., a server does not respond for a long time, report it as failing).

Conclusion

Distribution transparency is a nice goal, but achieving it is a different story, and it should often not even be aimed at.

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
- Systems should support portability of applications
- Systems should be easily extensible

Policies versus mechanisms

Implementing openness: policies

- What level of consistency do we require for client-cached data?
- Which operations do we allow downloaded code to perform?
- Which QoS requirements do we adjust in the face of varying bandwidth?
- What level of secrecy do we require for communication?

Implementing openness: mechanisms

- Allow (dynamic) setting of caching policies
- Support different levels of trust for mobile code
- Provide adjustable QoS parameters per data stream
- Offer different encryption algorithms

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On strict separation

Observation

The stricter the separation between policy and mechanism, the more we need to ensure proper mechanisms, potentially leading to many configuration parameters and complex management.

Finding a balance

Hard-coding policies often simplifies management, and reduces complexity at the price of less flexibility. There is no obvious solution.

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Dependability

Basics

A component provides services to clients. To provide services, the component may require the services from other components $\Rightarrow$ 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.)

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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

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Reliability versus availability

Reliability $R(t)$ of component C

Conditional probability that C has been functioning correctly during $[0,t)$ given C was functioning correctly at the time $T=0$.

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 $MTTF + MTTR$.

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Terminology

Failure, error, fault

Term	Description	Example
Failure	A component is not living up to its specifications	Crashed program
Error	Part of a component that can lead to a failure	Programming bug
Fault	Cause of an error	Sloppy programmer

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Terminology

Handling faults

Term	Description	Example
Fault prevention	Prevent the occurrence of a fault	Don't hire sloppy programmers
Fault tolerance	Build a component and make it mask the occurrence of a fault	Build each component by two independent programmers
Fault removal	Reduce the presence, number, or seriousness of a fault	Get rid of sloppy programmers
Fault forecasting	Estimate current presence, future incidence, and consequences of faults	Estimate how a recruiter is doing when it comes to hiring sloppy programmers

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

Keeping it simple

It's all about encrypting and decrypting data using security keys.

Notation

$K(data)$ denotes that we use key K to encrypt/decrypt *data*.

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

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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*:

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

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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.

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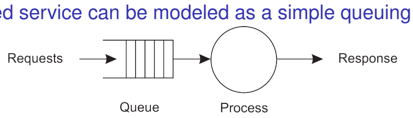
Size scalability

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

Formal analysis

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: λ
- Processing capacity service: μ requests per second

Fraction of time having k requests in the system

$$p_k = \left(1 - \frac{\lambda}{\mu}\right)\left(\frac{\lambda}{\mu}\right)^k$$

Formal analysis

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

$$U = \sum_{k>0} p_k = 1 - p_0 = \frac{\lambda}{\mu} \Rightarrow p_k = (1-U)U^k$$

Average number of requests in the system

$$\overline{N} = \sum_{k\geq 0} k \cdot p_k = \sum_{k\geq 0} k \cdot (1-U)U^k = (1-U)\sum_{k\geq 0} k \cdot U^k = \frac{(1-U)U}{(1-U)^2} = \frac{U}{1-U}$$

Average throughput

$$X = \underbrace{U \cdot \mu}_{\text{server at work}} + \underbrace{(1-U)\cdot 0}_{\text{server idle}} = \frac{\lambda}{\mu}\cdot\mu = \lambda$$

Formal analysis

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

$$R = \frac{\overline{N}}{X} = \frac{S}{1-U} \Rightarrow \frac{R}{S} = \frac{1}{1-U}$$

with $S = \frac{1}{\mu}$ being the service time.

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: decrease S.

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Problems with geographical scalability

- Cannot simply go from LAN to WAN: many distributed systems assume synchronous client-server interactions: client sends request and waits for an answer. Latency may easily prohibit this scheme.
- WAN links are often inherently unreliable: simply moving streaming video from LAN to WAN is bound to fail.
- Lack of multipoint communication, so that a simple search broadcast cannot be deployed. Solution is to develop separate naming and directory services (having their own scalability problems).

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Problems with administrative scalability

Essence

Conflicting policies concerning usage (and thus payment), management, and security

Examples

- Computational grids: share expensive resources between different domains.
- Shared equipment: how to control, manage, and use a shared radio telescope constructed as large-scale shared sensor network?

Exception: several peer-to-peer networks

- File-sharing systems (based, e.g., on BitTorrent)
- Peer-to-peer telephony (early versions of Skype)
- Peer-assisted audio streaming (Spotify)

Note: end users collaborate and not administrative entities.

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Introduction Design goals

Techniques for scaling

Hide communication latencies

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

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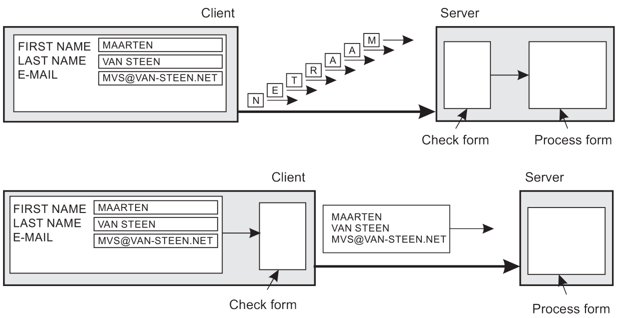
Techniques for scaling

Facilitate solution by moving computations to client



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Techniques for scaling

Partition data and computations across multiple machines

- Move computations to clients (Java applets and scripts)
- Decentralized naming services (DNS)
- Decentralized information systems (WWW)

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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)

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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.

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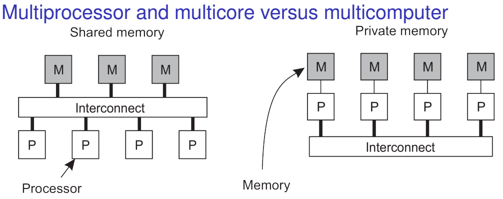
Parallel computing

Observation

High-performance distributed computing started with parallel computing

Multiprocessor and multicore versus multicomputer



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Distributed shared memory systems

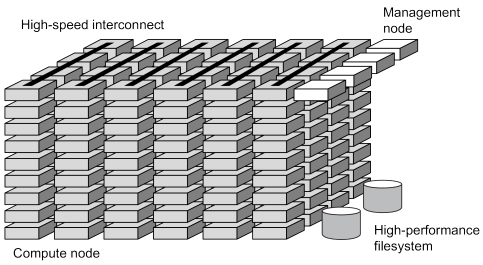
Observation
Multiprocessors are relatively easy to program in comparison to multicomputers, yet have problems when increasing the number of processors (or cores). Solution: Try to implement a shared-memory model on top of a multicomputer.

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)



Grid computing

The next step: plenty of nodes from everywhere
- Heterogeneous
- Dispersed across several organizations
- Can easily span a wide-area network

Note
To allow for collaborations, grids generally use virtual organizations. In essence, this is a grouping of users (or better: their IDs) that allows for authorization on resource allocation.

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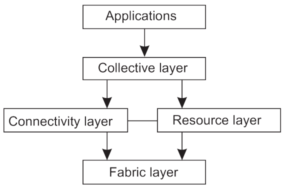
Architecture for grid computing



The layers

- Fabric: Provides interfaces to local resources (for querying state and capabilities, locking, etc.)
- Connectivity: Communication/transaction protocols, e.g., for moving data between resources. Also various authentication protocols.
- Resource: Manages a single resource, such as creating processes or reading data.
- Collective: Handles access to multiple resources: discovery, scheduling, replication.
- Application: Contains actual grid applications in a single organization.

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Integrating applications

Situation

Organizations confronted with many networked applications, but achieving interoperability was painful.

Basic approach

A networked application is one that runs on a server making its services available to remote clients. Simple integration: clients combine requests for (different) applications; send that off; collect responses, and present a coherent result to the user.

Next step

Allow direct application-to-application communication, leading to Enterprise Application Integration.

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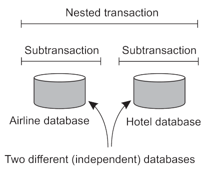
Example EAI: (nested) transactions

Transaction

Primitive	Description
BEGIN_TRANSACTION	Mark the start of a transaction
END_TRANSACTION	Terminate the transaction and try to commit
ABORT_TRANSACTION	Kill the transaction and restore the old values
READ	Read data from a file, a table, or otherwise
WRITE	Write data to a file, a table, or otherwise

Issue: all-or-nothing



- Atomic: happens indivisibly (seemingly)
- Consistent: does not violate system invariants
- Isolated: not mutual interference
- Durable: commit means changes are permanent

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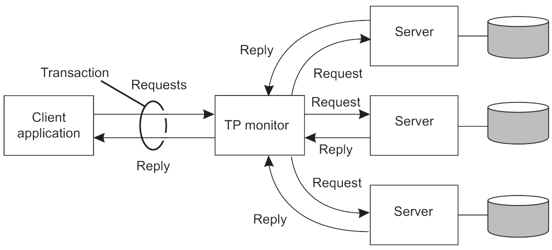
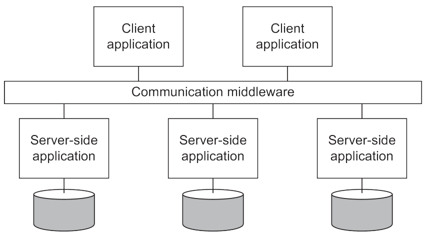
TPM: Transaction Processing Monitor



Observation

Often, the data involved in a transaction is distributed across several servers. A TP Monitor is responsible for coordinating the execution of a transaction.

Middleware and EAI



Middleware offers communication facilities for integration

Remote Procedure Call (RPC): Requests are sent through local procedure call, packaged as message, processed, responded through message, and result returned as return from call.

Message Oriented Middleware (MOM): Messages are sent to logical contact point (published), and forwarded to subscribed applications.

How to integrate applications

File transfer: Technically simple, but not flexible:

- Figure out file format and layout
- Figure out file management
- Update propagation, and update notifications.

Shared database: Much more flexible, but still requires common data scheme next to risk of bottleneck.

Remote procedure call: Effective when execution of a series of actions is needed.

Messaging: RPCs require caller and callee to be up and running at the same time. Messaging allows decoupling in time and space.

Distributed pervasive systems

Observation

Emerging next-generation of distributed systems in which nodes are small, mobile, and often embedded in a larger system, characterized by the fact that the system naturally blends into the user's environment.

Three (overlapping) subtypes

- Ubiquitous computing systems: pervasive and continuously present, i.e., there is a continuous interaction between system and user.
- Mobile computing systems: pervasive, but emphasis is on the fact that devices are inherently mobile.
- Sensor (and actuator) networks: pervasive, with emphasis on the actual (collaborative) sensing and actuation of the environment.

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Ubiquitous systems

Core elements

1. (Distribution) Devices are networked, distributed, and accessible transparently
2. (Interaction) Interaction between users and devices is highly unobtrusive
3. (Context awareness) The system is aware of a user's context to optimize interaction
4. (Autonomy) Devices operate autonomously without human intervention, and are thus highly self-managed
5. (Intelligence) The system as a whole can handle a wide range of dynamic actions and interactions

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Mobile computing

Distinctive features

- A myriad of different mobile devices (smartphones, tablets, GPS devices, remote controls, active badges).
- Mobile implies that a device's location is expected to change over time $\Rightarrow$ change of local services, reachability, etc. Keyword: discovery.
- Maintaining stable communication can introduce serious problems.
- For a long time, research has focused on directly sharing resources between mobile devices. It never became popular and is by now considered to be a fruitless path for research.

Bottomline

Mobile devices set up connections to stationary servers, essentially bringing mobile computing in the position of clients of cloud-based services.

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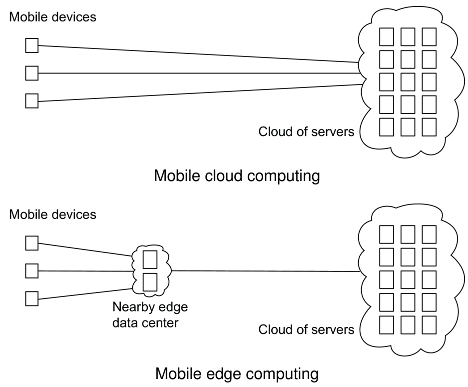
Mobile computing



Sensor networks

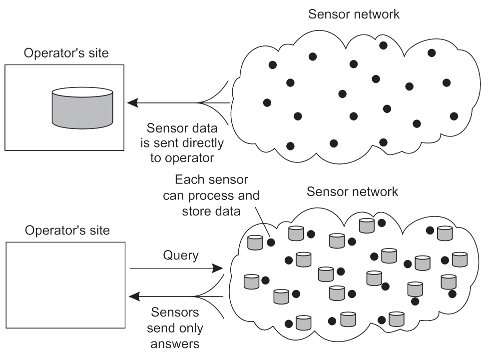
Characteristics

The nodes to which sensors are attached are:

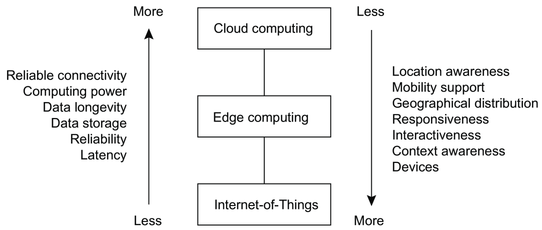
- Many (10s-1000s)
- Simple (small memory/compute/communication capacity)
- Often battery-powered (or even battery-less)

Sensor networks as distributed databases

Two extremes



The cloud-edge continuum



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Developing distributed systems: Pitfalls

Observation

Many distributed systems are needlessly complex, caused by mistakes that required patching later on. Many false assumptions are often made.

False (and often hidden) assumptions

- The network is reliable
- The network is secure
- The network is homogeneous
- The topology does not change
- Latency is zero
- Bandwidth is infinite
- Transport cost is zero
- There is one administrator

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