Macroarea di Ingegneria
Dipartimento di Ingegneria Civile e Ingegneria Informatica

Introduction to Distributed Systems

Sistemi Distribuiti e Cloud Computing
A.A. 2023/24

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Laurea Magistrale in Ingegneria Informatica

Technology advances

Networking

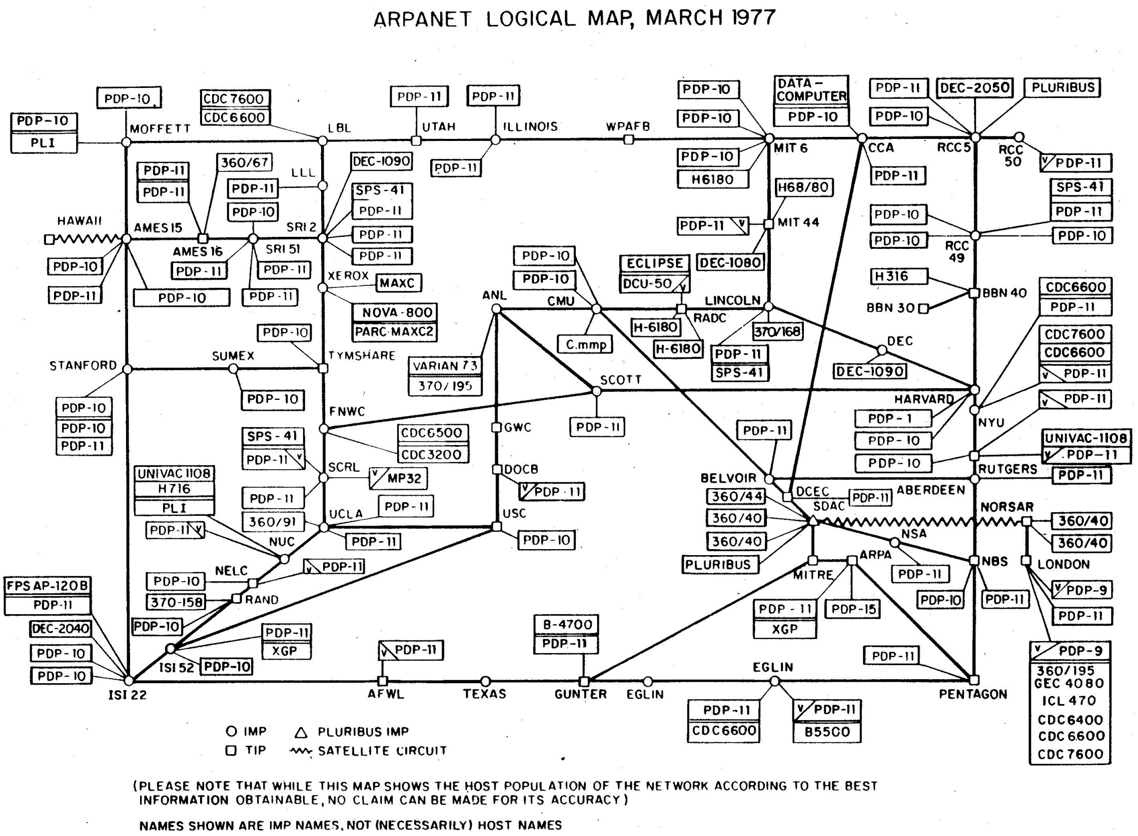
Computing power

Memory

Protocols

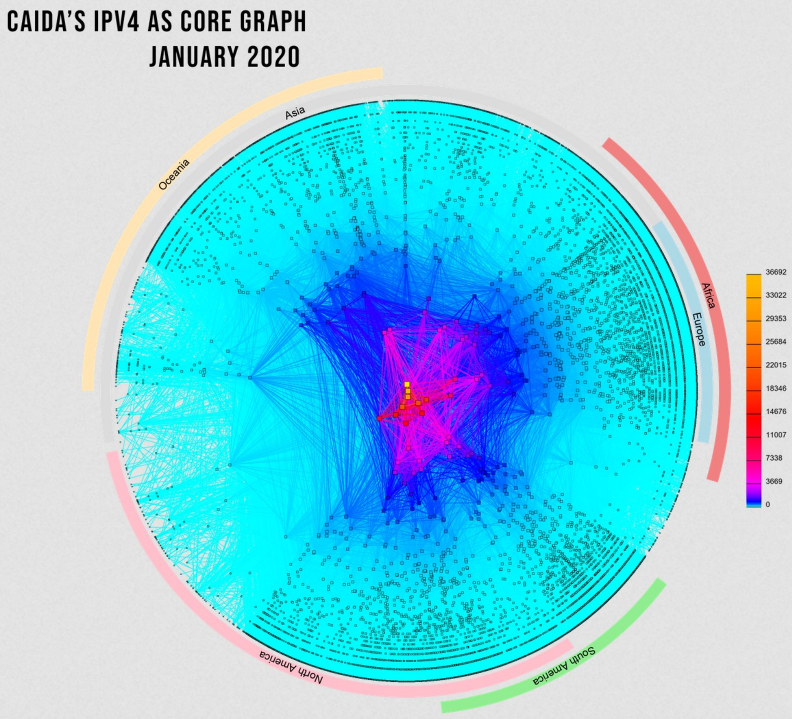
Storage

Internet evolution: 1977



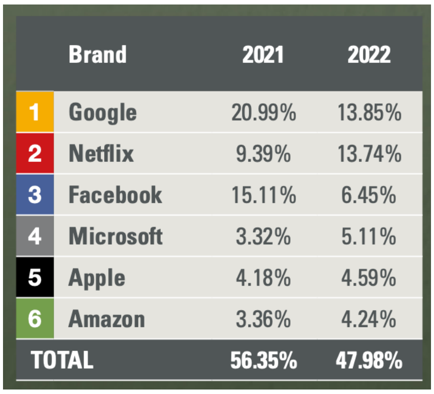
Internet evolution: after 43 years (2020)

- IPv4 AS-level Internet graph
- Interconnections of ~47000 ASs, ~150K links



Source: www.caida.org/projects/as-core/

Internet traffic in 2023



	Brand	2021	2022
1	**Google**	20.99%	13.85%
2	**Netflix**	9.39%	13.74%
3	**Facebook**	15.11%	6.45%
4	**Microsoft**	3.32%	5.11%
5	**Apple**	4.18%	4.59%
6	**Amazon**	3.36%	4.24%
	TOTAL	**56.35%**	**47.98%**

Netflix + MAMAA (Microsoft, Alphabet, Meta, Amazon, Apple) generated 48% of Internet traffic in 2022

Expanding number of app categories and greater number of apps, which are producing more data overall

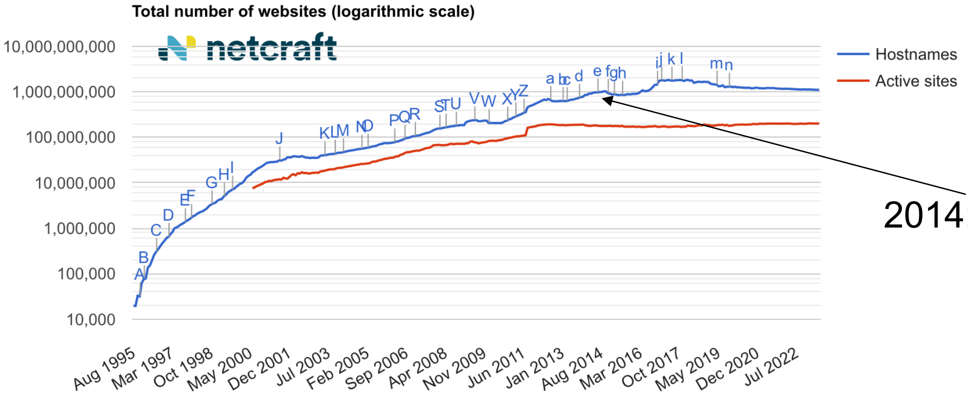
Video contributes a sizable volume of traffic ~66%

Source: Sandvine 2023 GIPR

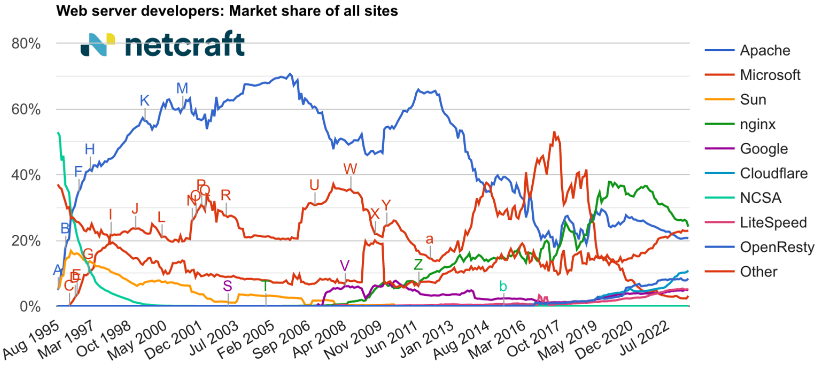
Global Top 10 Applications by Category

	Video	Games	Social	Messaging
1	Netflix	Playstation Downloads	Facebook	Generic Messaging
2	YouTube	Steam	Twitch	WhatsApp
3	Generic QUIC	ROBLOX	Instagram	Facebook
4	HTTP Media Stream	Epic Games Launcher	Snapchat	Discord Voice
5	Disney+	Nintendo Online	Reddit	Wattpad
6	Tik Tok	Xbox Live TLS	Wordpress	Telegram
7	Amazon Prime	Steam Client	Pinterest	Discord
8	Hulu	Kayo Sports	Twitter	Microsoft Teams
9	Facebook Video	Generic Gaming	VK	WeChat
10	Operator Content	League of Legends	LinkedIn	LINE

Web growth: number of Web servers



2014: 1G websites!



Metcalfe’s law

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

➡ Networking is *socially* and *economically* interesting

facebook

Google

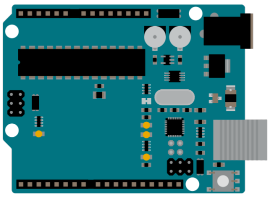
Instagram

TikTok

Computing power

- Computers got…
  - Faster
  - Cheaper
  - Power efficient
  - Smaller

- 1974: Intel 8080
  - 2 MHz, 6K transistors
- 2004: Intel P4 Prescott
  - 3.6 GHz, 125 million transistors
- 2011: Intel 10-core Xeon Westmere-EX (multicore CPUs)
  - 3.33 GHz, 2.6 billion transistors
- 2019: NVIDIA Turing GPU
  - 14.2 TFLOPS of peak single precision (FP32) performance

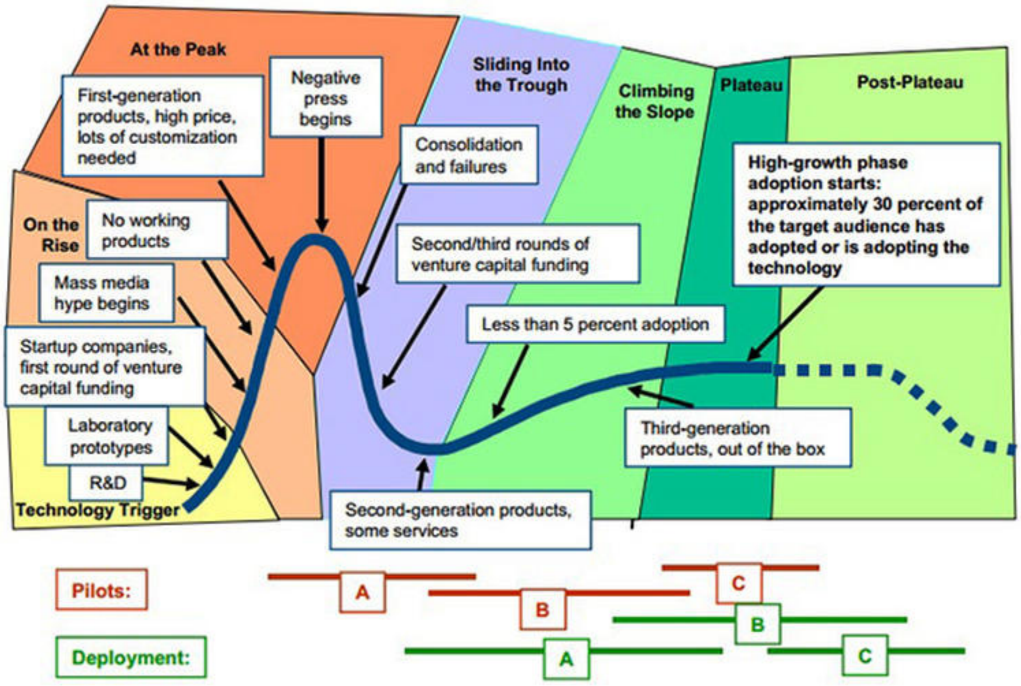


Arduino UNO: weight=25 g, width=53.4 mm, length=68.6 mm

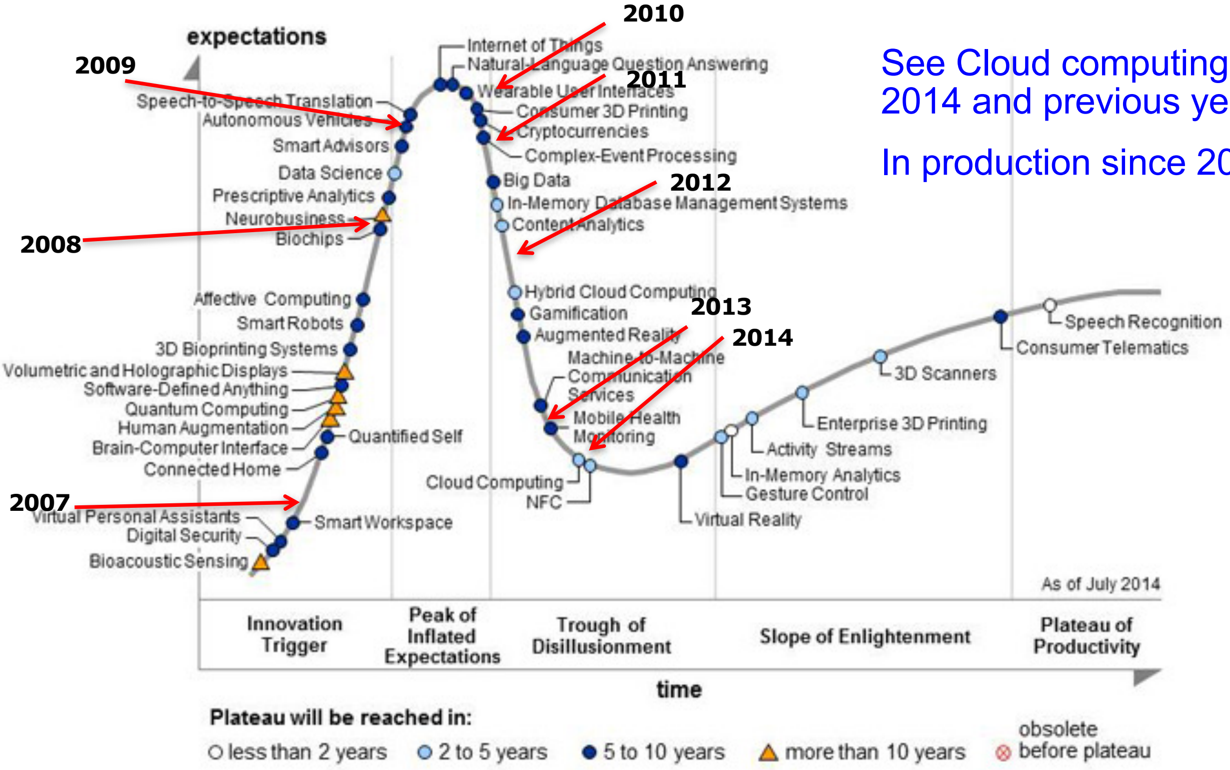
Distributed systems: not only Internet and Web

- Internet and Web: two notable examples of distributed systems
- Other examples:
  - Cloud systems, HPC systems, … sometimes accessible only through private network
  - Peer-to-peer systems
  - Home networks (home entertainment, multimedia sharing)
  - Internet of Things (IoT)

Gartner's annual IT hype cycle for emerging technologies



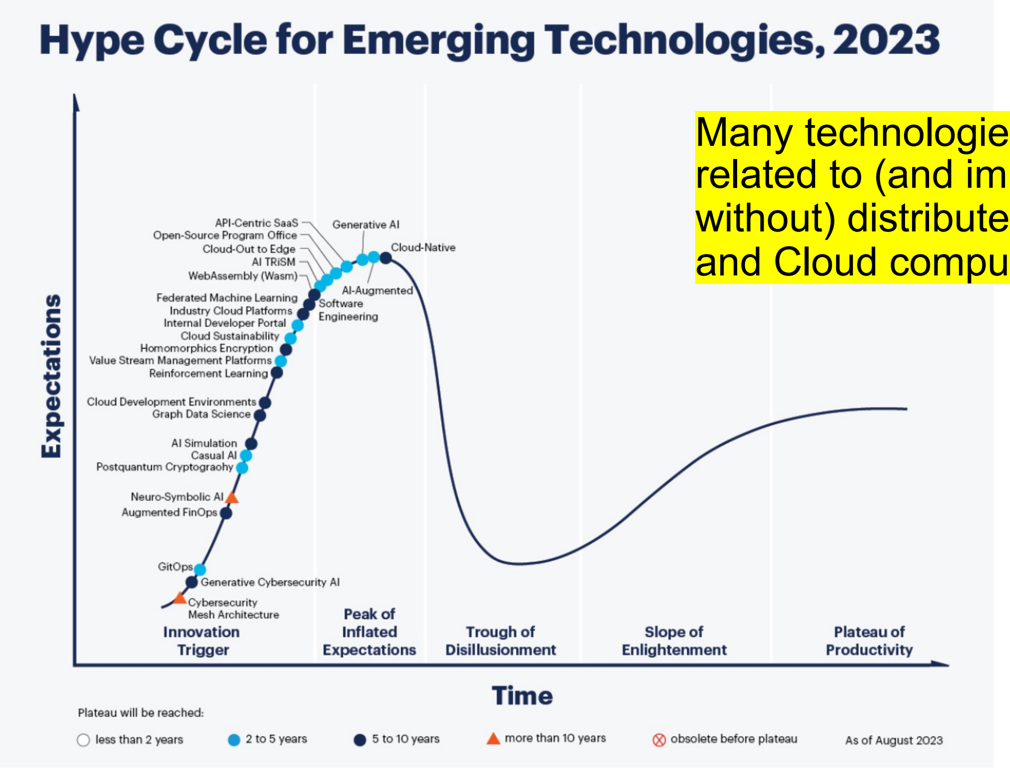
Hype cycle and cloud computing



See Cloud computing in 2014 and previous years

In production since 2015

Hype cycle in 2023



Many technologies strictly related to (and impossible without) distributed systems and Cloud computing!

Distributed systems and AI

- Artificial Intelligence (AI) has recently become practical as the result of:
  - Distributed computing
  - Affordable cloud computing and storage costs
  - Examples: federated learning, distributed training of foundation models (huge computational and data needs)
- Distribute = to divide and dispense in portions
- A foremost strategy used in distributed computing you already know
  - Divide et impera: break larger (computational) problems down into numbers of smaller, interrelated, “manageable” pieces

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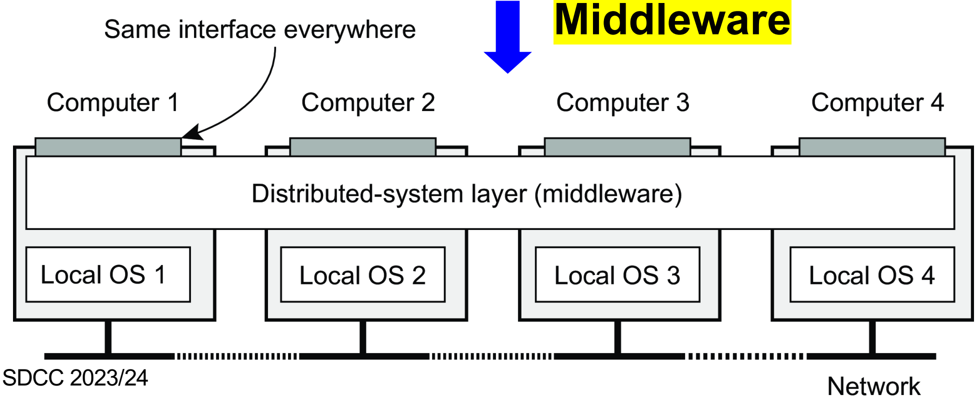
Distributed system

- Multiple definitions of **distributed system (DS)**

[van Steen & Tanenbaum] A distributed system is a collection of autonomous computing elements that appears to its users as a single coherent system

- Consists of autonomous computing elements (i.e., **nodes**), can be hardware devices (computer, phone, car, robot, …) or software processes
- Users or applications perceive it as a **single system** (how?): nodes need to collaborate



Distributed system

[Lamport] A distributed system is one in which the failure of a computer you didn't even know existed can render your own computer unusable

  - Emphasis on fault tolerance

- Who is Leslie Lamport?
  - Recipient of 2013 Turing award [video]
  - His research contributions have laid the foundations of theory and practice of DS
    - Fundamental concepts such as causality, logical clocks and Byzantine failures
    - Algorithms to solve many fundamental problems in DS

Why make a system distributed?

- Share resources
  - Resource = computing node, data, storage, service, …
- Lower costs
- Improve performance
  - e.g., get data from a nearby node rather than one halfway round the world
- Improve availability and reliability
  - even if one node fails, the system as a whole keeps functioning
- Improve security
- Solve bigger problems
  - e.g., huge amounts of data, can't fit on one machine
- Support Quality of Service (QoS)

Why study distributed systems?

- Distributed systems are more complex than centralized ones
  - e.g., no global clock, group membership, …
- Building them is harder… and building them correct is even much harder
  - “Distributed systems need radically different software than centralized systems do” (Tanenbaum)
- Managing, and, above all, testing them is difficult

Some distinguishing features of DS

- Concurrency
  - Many things happen “at the same time”
  - Centralized system: design choice
  - Distributed system: fact of life to be dealt with
- No global clock
  - Centralized system: use computer’s physical clock for synchronization
  - Distributed system: many physical clocks and not necessarily synchronized among them
- Independent and partial failures
  - Centralized system: fails completely
  - Distributed system: fails partially (i.e., only a part), often due to communication; hard (and in general impossible) to hide partial failures and their recovery

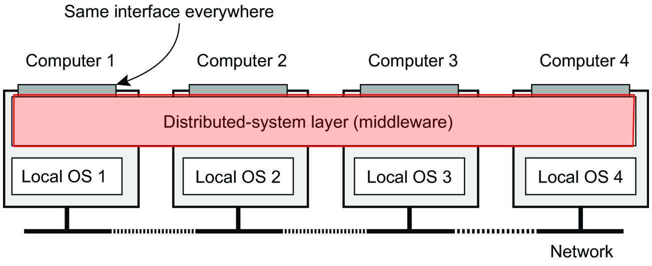
Challenges and design goals

- Challenges and goals associated with designing distributed systems
  1. **Heterogeneity**
  2. **Distribution transparency**
  3. **Openness**
  4. **Scalability**
  5. **Dependability**
  6. **Security**

while improving performance and energy efficiency, reducing monetary cost, etc.

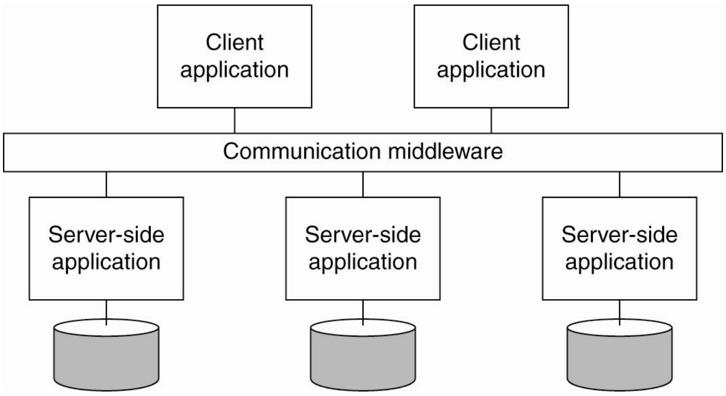
Challenge 1: Heterogeneity

- Many sources of heterogeneity: network, hardware, operating system (OS), programming language, implementations by different developers
- How to address? **Middleware**: the "OS of a DS"
  - Sw layer placed on top of OS that provides a programming abstraction as well as masks heterogeneity
  - Contains commonly used components and functionalities (e.g., communication) thus avoiding developers to implement them again and from scratch



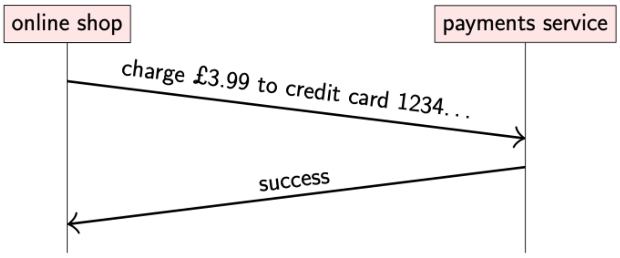
Communication middleware

- Facilitates communication among (heterogeneous) DS components/apps
- We will study
  - Remote Procedure Call (RPC)
  - Message Oriented Middleware (MOM)



Remote Procedure Call (RPC) example

- Online payment



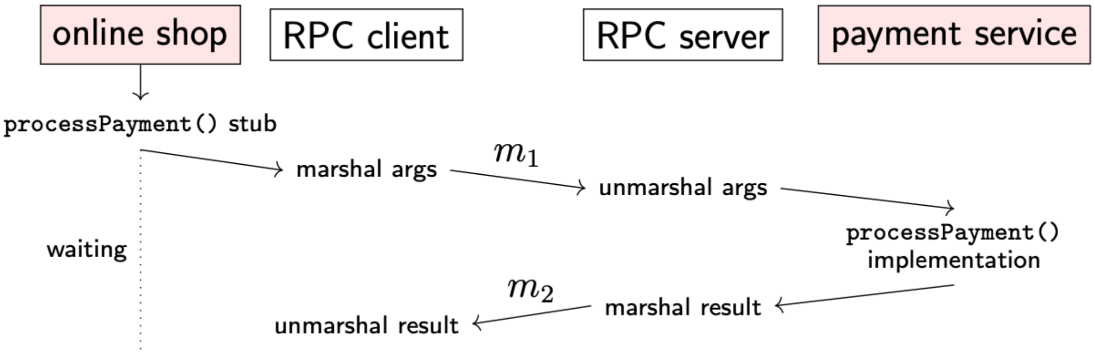
```
// Online shop handling customer's card details
Card card = new Card();
card.setCardNumber("1234 5678 8765 4321");
card.setExpiryDate("10/2024");
card.setCVC("123");

Result result = paymentsService.processPayment(card,
    3.99, Currency.GBP);

if (result.isSuccess()) {
    fulfilOrder();
}
```

Implementation of this function is on another node!

RPC: Behind the curtains



online shop

RPC client

RPC server

payment service

`processPayment()` stub

waiting

marshal args

m_1

unmarshal args

`processPayment()` implementation

marshal result

m_2

unmarshal result

$m_1 =$

```
{
  "request": "processPayment",
  "card": {
    "number": "1234567887654321",
    "expiryDate": "10/2024",
    "CVC": "123"
  },
  "amount": 3.99,
  "currency": "GBP"
}
```

$m_2 =$

```
{
  "result": "success",
  "id": "XP61hHw2Rvo"
}
```

Challenge 2: Distribution transparency

- **Distribution transparency**: single coherent system where the distribution of its *objects* (processes and resources) is *transparent* (i.e., invisible) to users and apps
- **Types** of distribution transparency (*ISO 10746*, Reference Model of Open Distributed Processing)

Access transparency

- Hide differences in data representation and how objects are accessed
  - e.g., use same mechanism for local or remote call

Location transparency

- Hide where objects are located
  - e.g., URL hides IP address

Relocation transparency

- Hide that objects may be moved to another location while in use

Challenge 2: Distribution transparency

Migration transparency

- Hide that objects may move to another location
  - e.g., communication between mobile phones

Replication transparency

- Hide that multiple replicas of an object exist
  - How? Same name for all replicas, e.g., type in terminal `$ dig www.youtube.com`
  - Require also location transparency

Concurrency transparency

- Hide that objects may be shared by several independent users
  - E.g.: concurrent access to same DB table by multiple users
  - Issue: leave shared object in a consistent state, e.g., by *locking* mechanisms

Failure transparency

- Hide failure and recovery of objects (see Lamport's definition)

Degree of distribution transparency

- Aiming at *full* distribution transparency may be too much
  - We cannot always hide communication latency: sending a message from Rome to New York requires ~23 ms
  - We cannot completely hide failures in a large-scale DS
    - Cannot distinguish a slow computer from a failing one
    - Cannot be sure that a server actually performed an operation before crashing
  - Price for achieving full transparency may be too high in term of performance
    - e.g., keeping data replicas *exactly* up-to-date takes time
    - e.g., immediately flushing write operations to disk for fault tolerance
    - **Trade-off** between consistency and performance

Challenge 3: Openness

- Open DS: offers components that can easily be used by or integrated into other systems; consists of components that originate from elsewhere
- Systems should conform to well-defined interfaces
  - Defined through IDL (**Interface Definition Language**)
    - Nearly always capture only syntax, not semantics
    - Complete and neutral
    - IDL examples: XDR, Thrift, WSDL, OMG IDL
- Systems should easily interoperate
- Systems should support portability of applications
- Systems should be easily extensible
- Examples: Java EE, .Net, Web Services

"Practice shows that many distributed systems are not as open as we'd like" (van Steen & Tanenbaum)

Separating policies from mechanisms

- To implement open and flexible DS, we need to organize the DS as a collection of relatively small and easily replaceable or adaptable component rather than as a monolithic system
- How? Separate policies from mechanisms
- E.g., caching in web browsers:
  - Mechanism: store data and allow (dynamic) setting of caching policies
  - Caching policies:
    - Where to cache data?
    - How to free space when cache fills up?
    - When to refresh cached data?
    - Private or shared cache?

Separating policies from mechanisms

- The other side of the coin
  - Strict separation can be counterproductive: 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
- Need to find a balance
- Possible solution: *self-configurable systems*

"Finding the right balance in separating policies from mechanisms is one of the reasons why designing a distributed system is sometimes more an art than a science" (van Steen & Tanenbaum)

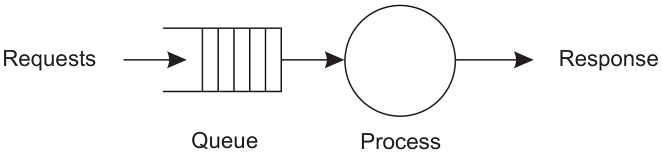
Challenge 4: Scalability

- **Scalability** is the property of a (distributed) *system* to keep an adequate level of performance notwithstanding a growing amount of:
  - Number of users and resources (**size** scalability)
  - Maximum distance between nodes (**geographical** scalability)
  - Number of administrative domains (**administrative** scalability)
- Most systems account only, to a certain extent, for size scalability

"Many developers of modern distributed systems easily use the adjective scalable without making clear why their system actually scales." (van Steen)

Size scalability

- Root causes for scalability problems in centralized system
  - Computational capacity, limited by CPUs
  - Storage capacity, including transfer rate between CPUs and disks
  - Network between user and centralized service
- Formal analysis (see PMCS course)



Requests

Queue

Process

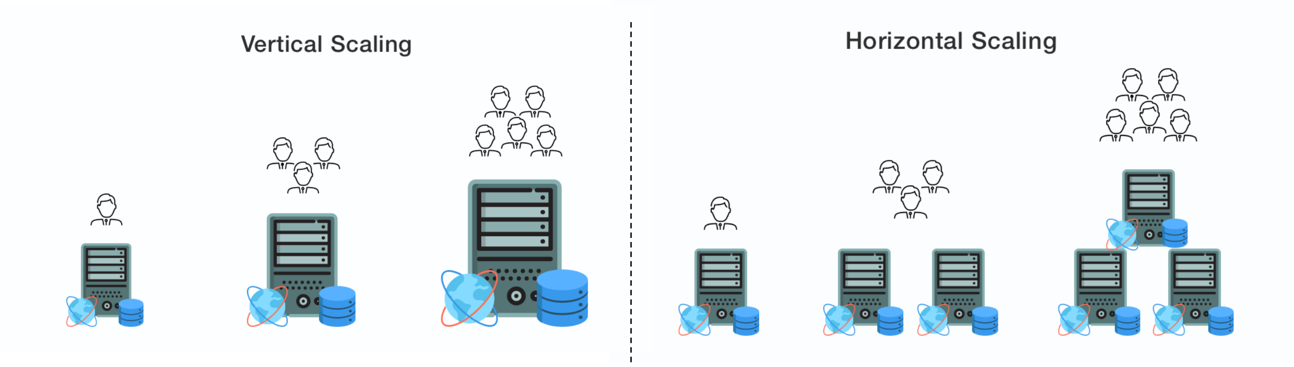
Response

$$\frac{R}{S} = \frac{1}{1-U}$$

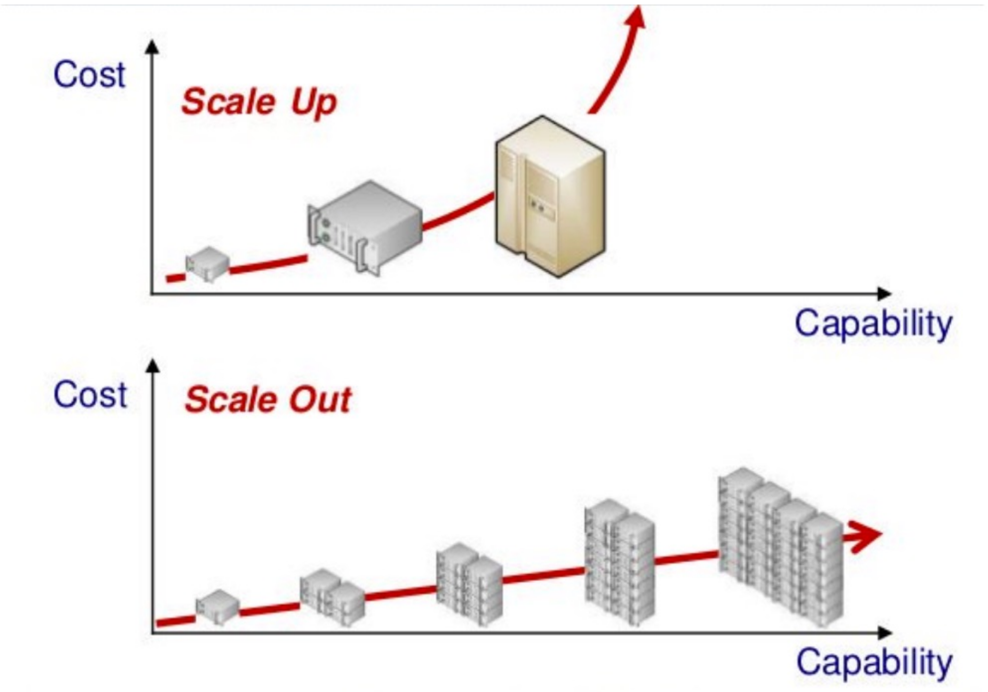
  - Service time S
  - Utilization U: fraction of time the service is busy
  - Response time R: total time take to process a request its arrival
  - If U is small, response-to-service time is close to 1: request is immediately processed
  - If U goes up to 1, system comes to a grinding halt. Solution: decrease S

Size scalability

- Two directions for size scalability
  - **Vertical (scale-up)**: more powerful resources
  - **Horizontal (scale-out)**: more resources with same capacity

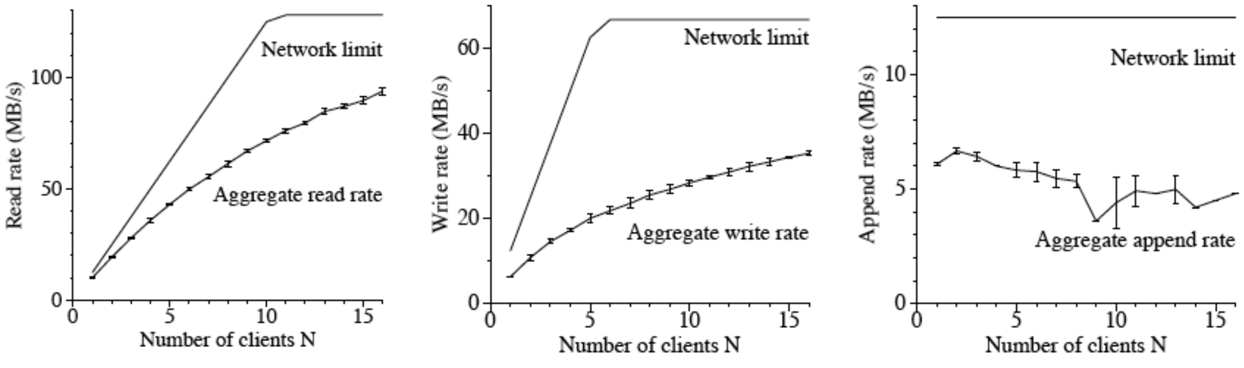


Scale-up vs. scale-out



Size scalability: example

- Google File System
  - Distributed file system realized by Google’s researchers



(a) Reads (b) Writes (c) Record appends

- Scale parameter: number of clients
- Scalability metric: aggregated read/write/append throughput (random file access)
- Scalability criterion: the closer to network limit, the better

Techniques for scaling

1. Hide communication latency
   - Make use of asynchronous communication
   - Have separate handler for incoming response
   - Problem: not every app fits this model

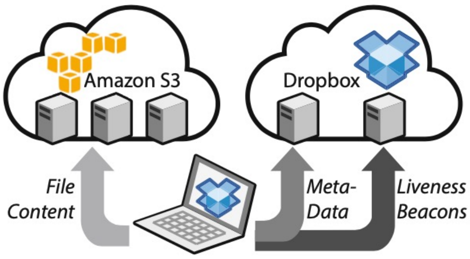
2. Facilitate solution by moving computations to clients

3. Partition data and computation across multiple resources
   - Divide et impera: partition data and computation into smaller parts and distribute them across multiple DS resources
   - E.g.: decentralized naming service (DNS), data-intensive distributed computation (Hadoop MapReduce and Spark)

Techniques for scaling

4. Replicate DS resources and data
   - Make copies of data available at different DS nodes
   - Distribute processing on multiple DS nodes
   - Examples:
     - Distributed file systems and databases
     - Replicated Web servers
     - Web caches (in browsers and proxies)

- Practical example: in a cloud storage service (e.g., Dropbox, OneDrive, GDrive) data are locally cached on your device and replicated across multiple cloud servers



The problem with replication

- Applying replication is easy, but
- Having multiple copies leads to inconsistency: modifying one copy makes that copy different from the rest
- Trade-off: depending on application type, a certain degree of inconsistency can be tolerated
  - Blog, shared file, shopping cart, on-line auction, air traffic control
- We will study different consistency models to choose from

Challenge 5: Dependability

- **Dependability** refers to the degree that a computer system can be relied upon to operate as expected
  - partial failures make it intricate for distributed systems
- Requirements related to dependability
  - **Availability**: readiness for usage
  - **Reliability**: continuity of service delivery
  - **Safety**: very low probability of catastrophic consequences
  - **Maintainability**: how easily a failed system can be repaired

Dependability: availability

Can I use the system now?

- System is ready to use (i.e., operational) immediately
- Availability *A*(*t*) of component *C*: probability that *C* is functioning correctly at time *t*

- Availability = uptime / (uptime + downtime)

- Normally expressed as number of 9's
  - A = 99%: two nines

    1-A=1% average days per year

    downtime per year = 0.01*365.2425 d = 3d 15h 39m 29.5s
  - A = 99.99%: four nines

    downtime per year = 0.01*365.2425 d = 52 m 35.7 s
  - See uptime.is

Dependability: availability

- Metrics

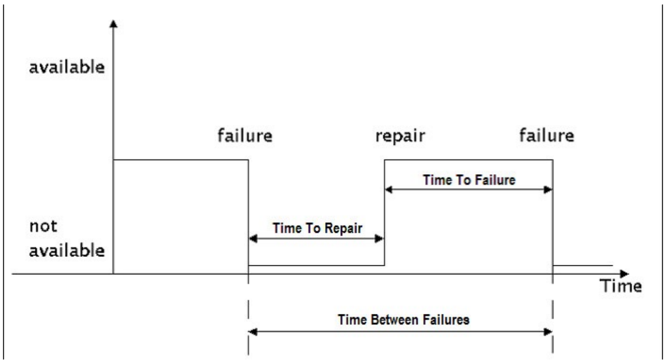
  A = MTTF/(MTTF + MTTR)

  Mean Time To Failure (MTTF): average time until a component fails

  Mean Time To Repair (MTTR): average time needed to repair a component

  Mean Time Between Failures (MTBF): MTTF + MTTR

  MTBF = total operating time / number of failures

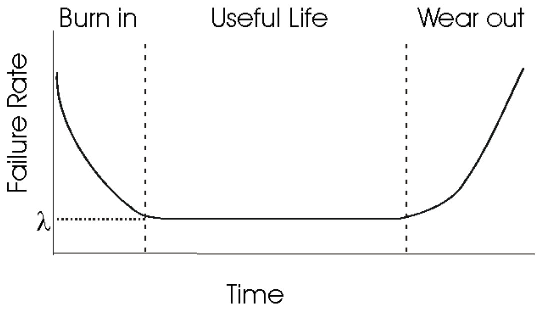


Dependability: reliability

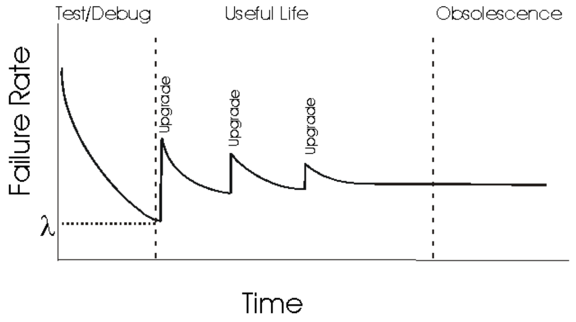
Will the system be up as long as I need it?

  - System will run continuously without failure
  - 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
- Metrics: MTTF (and failure rate)

Bathtub curve for hardware



Revised bathtub curve for software



Availability vs reliability

- Availability ≠ reliability (when the system is repairable)
- Example 1: system that goes down for 1 ms every hour
  - Highly available: > 99,9999% (= 1 - 1/(3600*1000))
  - Unreliable, because MTBF = 1 hour and there are 24*365=8780 failures per year
- Example 2: system that never crashes but is shutdown for 2 weeks every year
  - Highly reliable, because MTBF = 1 year and there is only 1 failure per year
  - But only 96% available (= 1 - 14/365)

Failure, error and fault

- **Failure**: a component is not living up to its specifications
  - Example: crashed program
- **Error**: part of a component that can lead to a failure
  - Example: programming bug
- **Fault:** cause of an error
  - Can be: transient, intermittent, permanent
  - Example: sloppy programmer

Chain **fault → error → failure**

Dependability: tools

- **Fault prevention**
  - Prevent the occurrence of a fault
- **Fault tolerance**
  - Build a component and make it mask the occurrence of a fault
- **Fault removal**
  - Reduce the presence, number, or seriousness of a fault
- **Fault forecasting**
  - Estimate current presence, future incidence, and consequences of faults

Challenge 6: Security

- 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

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Security mechanisms

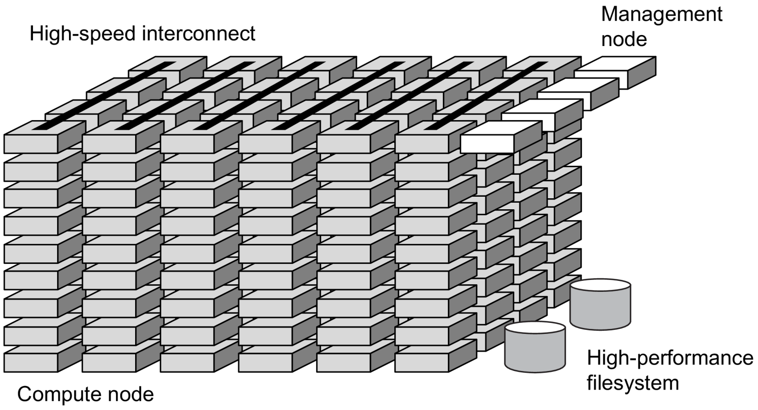
- Keeping it simple: it is all about encrypting and decrypting data using security keys
- Symmetric vs asymmetric cryptosystem
  - Symmetric: same encryption and decryption key
  - Asymmetric: public key and private key
- Secure hashing
  - In practice, we use secure hash functions: $H(data)$ returns a fixed-length string

Categories of distributed systems

- High-performance distributed computing systems
  - Cluster computing
  - Cloud computing
  - Edge computing
- Distributed information systems
- Distributed pervasive systems

Cluster computing

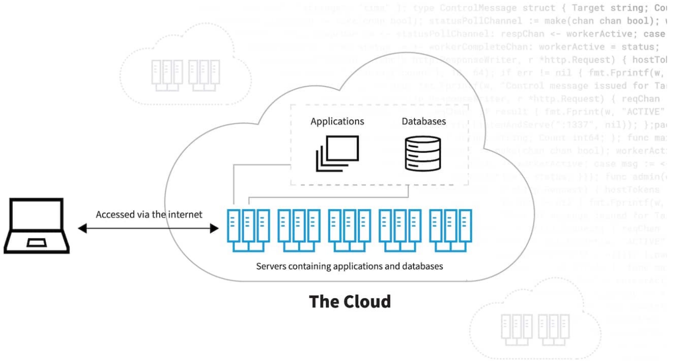
- Cluster: group of high-end systems connected through a LAN
  - Typically homogeneous: same OS, near-identical hardware
  - Single, or tightly coupled managing node(s)



- Clusters dominate TOP500 architectures
  www.top500.org

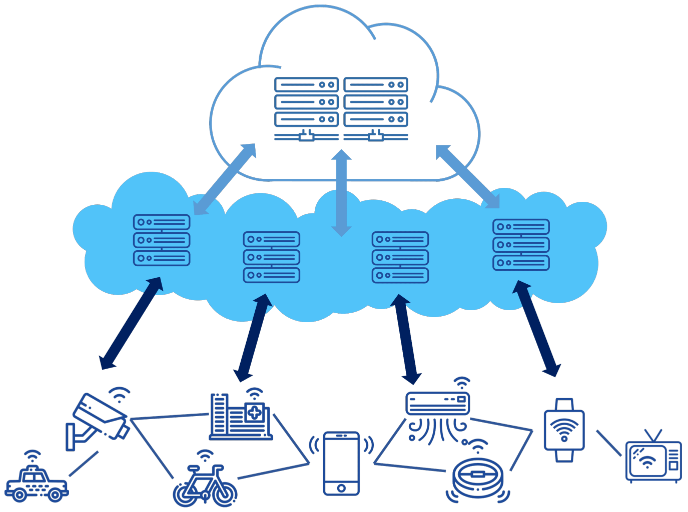
Cloud computing

- Cluster computing is a major milestone that lead to Cloud computing
- But Cloud is:
  - available to anyone
  - on a much wider scale
  - does not require users to physically own or use hardware



Edge computing

- Brings computation and storage at the network edges, in proximity of data producers (e.g., IoT devices) and consumers (e.g., users)



Cloud

Edge nodes

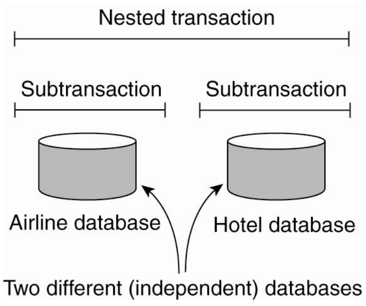
Edge devices

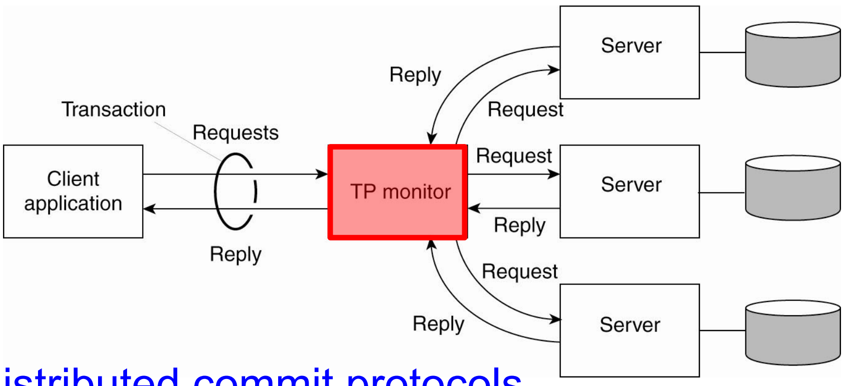
Distributed information systems

- Among distributed information systems let us consider transaction processing systems
- Database operations are carried out in the form of transactions
- **Transaction**: unit of work that you want to see as a whole and is treated in a coherent and reliable way independent of other transaction
- **ACID** properties
  - Atomic: happens indivisibly (seemingly)
  - Consistent: does not violate system invariants
  - Isolated: no mutual interference
  - Durable: commit means changes are permanent

Distributed transactions

- Distributed (or nested) transaction: composed by multiple sub-transactions which are distributed across multiple servers
  - Transaction Processing (TP) Monitor: responsible for coordinating the execution of distributed transactions
  - Example: Oracle Tuxedo





- We will study distributed commit protocols

Distributed pervasive systems

- Distributed systems whose nodes are
  - small, mobile, battery-powered and often embedded in a larger system
  - characterized by the fact that the system naturally blends into the user's environment
- Three (overlapping) subtypes of pervasive systems
  - Ubiquitous computing systems: pervasive and continuously present, i.e. continuous interaction between system and users
  - Mobile computing systems: pervasive, with emphasis on the fact that devices are inherently mobile
  - Sensor networks: pervasive, with emphasis on the actual (collaborative) sensing and actuation of the environment

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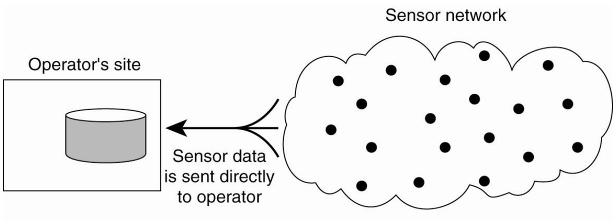
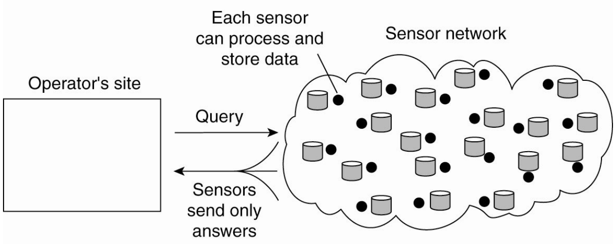
Sensor networks

- Characteristics of nodes
  - Many: 10-10^3
  - Simple: small memory, compute and communication capacity
  - Often battery-powered (or even battery-less)
- Sensor networks as distributed databases: two extremes
  - (a) Store and process data in a centralized way only on the *sink* node
  - (b) Store and process data in a distributed way on the sensors (active and autonomous)



(a)



(b)

Pitfalls in realizing distributed systems

- Many distributed systems are needlessly complex because of errors in design and implementation that were patched later
- Common wrong assumptions by architects and designers of distributed systems ("The Eight Fallacies of Distributed Computing", Peter Deutsch, 1991-92):
  1. The network is reliable
     - "You have to design distributed systems with the expectation of failure" (Ken Arnold)
  2. Latency is zero
     - Latency is more problematic than bandwidth
     - "At roughly 300,000 km/s, it will always take at least 30 ms to send a ping from Europe to the US and back, even if the processing would be done in real time." (Ingo Rammer)
  3. Bandwidth is infinite

Pitfalls in realizing distributed systems

4. The network is secure
5. The topology does not change
   - That's right, it doesn't--as long as it stays in the test lab!
6. There is one administrator
7. Transport cost is zero
   - Going from the application level to the transport level is not free
   - Costs for setting and running the network are not free
8. The network is homogeneous

Technology is not the solution to everything!

Read Fallacies of distributed computing explained

Listen to Episode 470: L. Peter Deutsch on the fallacies of distributed computing

References

- Chapter 1 of van Steen & Tanenbaum book
- A brief introduction to distributed systems
- Fallacies of distributed computing explained
- Notes on distributed systems for young bloods