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Architecture of distributed systems

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Netzprogrammierung

(Algorithmen und Programmierung V)

Our topics today

Physical model

Architectural model

- Architectural elements
  - Communication paradigms
  - Roles and responsibilities
  - Placement
- Architectural patterns

Fundamental model

- Interaction model
- Failure model
- Security model

Descriptive models for distributed system design

Physical model

- Most explicit description of a system
- Capture hardware composition in terms of computers and their interconnecting networks

Architectural model

- Describes a systems in terms of computational and communication tasks performed by computational elements

Fundamental model

- Abstract perspective in order to study the individual aspects of a system
- Three models are introduced: interaction model, failure model, and the security model

Difficulties for and threats to distributed systems

Widely varying mode of use

- Component parts of the system are subject to wide variations in workload, e.g., some web pages are accessed several million times a day
- Some parts of the systems might be disconnected or poorly connected, e.g. mobile computers
- Some applications have special requirements such as high communication bandwidth and low latency, e.g. multimedia applications

Wide range of system environments

- Distributed systems accommodate heterogeneous hardware, operating systems, networks
- Networks may differ widely in performance (wireless network vs. LAN)

External threats

- Attack of data integrity, denial of service

Physical model

Introduction physical model

A physical model is a representation of the underlying hardware elements of a distributed system that abstracts from specific details of the computer and networking technologies employed.

Baseline physical model

- Hardware and software components located at networked computers communicate and coordinate their actions only by passing messages
- Very simple physical model of a distributed system

Three generations of distributed systems

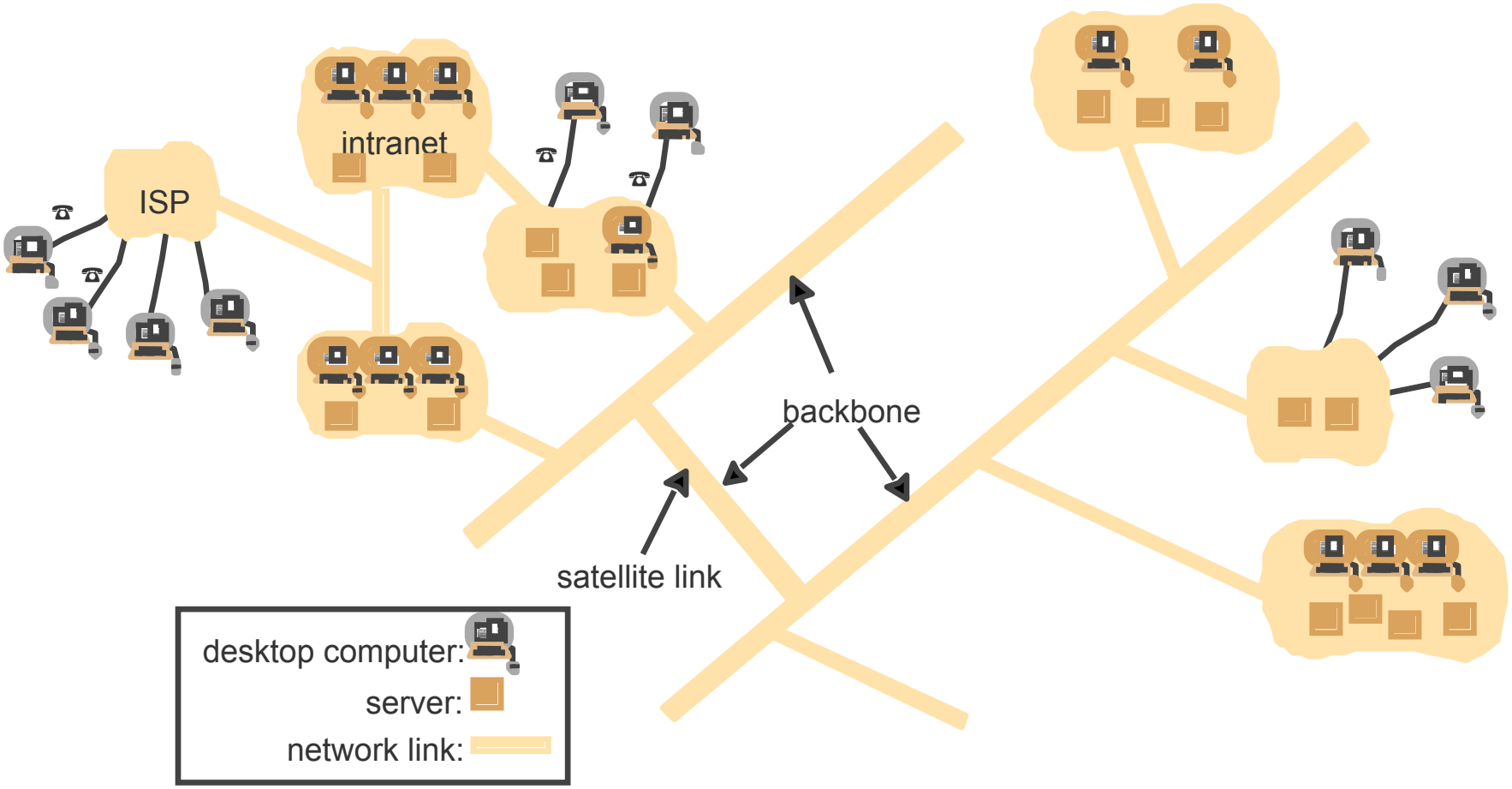
Early distributed systems

- Emerged in the late 1970s and early 1980s because of the usage of local area networking technologies
- System typically consisted of 10 to 100 nodes connected by a LAN, with limited Internet connectivity and supported services (e.g., shared local printer, file servers)

Internet-scale distributed systems

- Emerged in the 1990s because of the growth of the Internet

Physical model of the internet-scale distributed system



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Internet-scale distributed systems

- Emerged in the 1990s because of the growth of the Internet
- Infrastructure became global

Contemporary distributed systems

- Emergence of mobile computing leads to nodes that are location-independent
- Need to added capabilities such as service discovery and support for spontaneous interoperation
- Emergence of cloud computing and ubiquitous computing

Distributed system of systems

Emergence of ultra-large-scale (ULS) distributed systems

Complex systems consisting of a series of subsystems that are systems in their own right and that come together to perform particular task or tasks

Example: environmental management system for flood prediction

- Consists of sensor networks deployed to monitor the state of various environmental parameters
- Coupled with systems that predict the like hood for floods (running complex simulations)
- Additionally early warning systems to key stakeholders via mobile phones

http://www.sei.cmu.edu/library/assets/ULS_Book20062.pdf

Generations of distributed systems

Distributed systems:	*Early*	*Internet-scale*	*Contemporary*
Scale	Small	Large	Ultra-large
Heterogeneity	Limited (typically relatively homogenous configurations)	Significant in terms of platforms, languages and middleware	Added dimensions introduced including radically different styles of architecture
Openness	Not a priority	Significant priority with range of standards introduced	Major research challenge with existing standards not yet able to embrace complex systems
Quality of service	In its infancy	Significant priority with range of services introduced	Major research challenge with existing services not yet able to embrace complex systems

Architectural models

Architectural model

An architectural model of a distributed system simplifies and abstracts the functions of the individual components of a distributed system and

- Organization of components across the network of computers
- Their interrelationship, i.e., communicate with each other

Architectural elements

What are the entities that are communicating in the distributed system?

How do they communicate, or, more specifically, what communication paradigm is used?

What (potentially changing) roles and responsibilities do they have in the overall architecture?

How are they mapped on the physical distributed infrastructure (what is their placement)?

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Architectural elements

Communicating entities

System-oriented perspective

In distributed systems the entities that communicate are typically processes.

Exceptions:

- In primitive environments such as sensor networks, operating systems does not provide any abstractions, therefore nodes communicate
- In most environments processes are supplemented by threads, so threads are more the endpoints of communications

Problem-oriented perspective

Objects

- Computation consists of a number of interacting objects representing units of decomposition for the problem domain
- Objects are accessed via interfaces

Components

- Resemble objects in that they offer problem-oriented abstractions, also accessed via interfaces
- Specify not only their interfaces but also the assumptions they make in terms of other components/interfaces that must be present for a component to fulfil its function

Web services

- Software application which is identified via URI
- Supports direct interactions with other software agents

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Architectural elements

Communication paradigms

Types of communication paradigms

Interprocess communication

Remote invocation

Indirect communication

Interprocess communication

- Low-level support for communication between processes in distributed systems including message parsing-primitives

- Direct access to the API offered by Internet protocols (socket programming) and support for multicast communication

Remote invocation

Covering a range of techniques based on a two-way exchange between communicating entities

Resulting in the calling of a remote operation, procedure or method

- Request-reply protocols: more a pattern imposed on an underlying message-parsing service to support client-server computing
- Remote procedure calls: procedures in processes on remote computers can be called as if they are procedures in the local address space
- Remote method invocation: a calling object can invoke a method in a remote object

Remote invocation

Covering a range of techniques based on a two-way exchange between communicati

Resulting in t

- Reque ing message-parsing
- Remot mputers can be called
- Remot d in a remote object

- Communication represent a two-way relationship between sender and receiver
- Sender explicitly directing messages/invocations to the associated receivers
- Receivers are aware of senders
- Must exist at the same time

Remote invocation

Covering a range of techniques based on a two-way exchange between communicati

Resulting in t

- Reque ing message-parsing
- Remot mputers can be called
- Remot d in a remote object

- Sender do not need to know who they are sending to (space uncoupling)
- Senders and receivers do not need to exist in the same time (time uncoupling)

Indirect communication

Group communication

- Delivery of messages to a set of recipients
- Abstraction of a group which is represented in the system by a group identifier
- Recipients elect to receive message send to a group a joining a group

Publish-subscribe-systems

- A large number of producers (publisher) distribute information items of interest (events) to a similarly large number of consumers (subscribers)

Message queues

- Message queues offer a point-to-point service whereby producer processes can send messages to a specified queue and consumer processes can receive messages from the queue or being notified

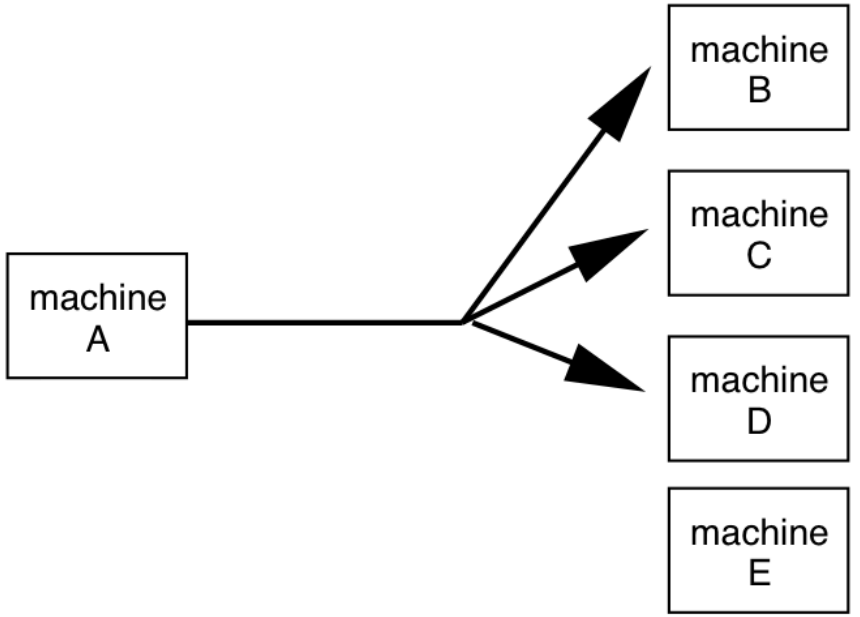
Group communication

Two kinds of group communication:

- Broadcast (message sent to everyone)
- Multicast (message sent to specific group)

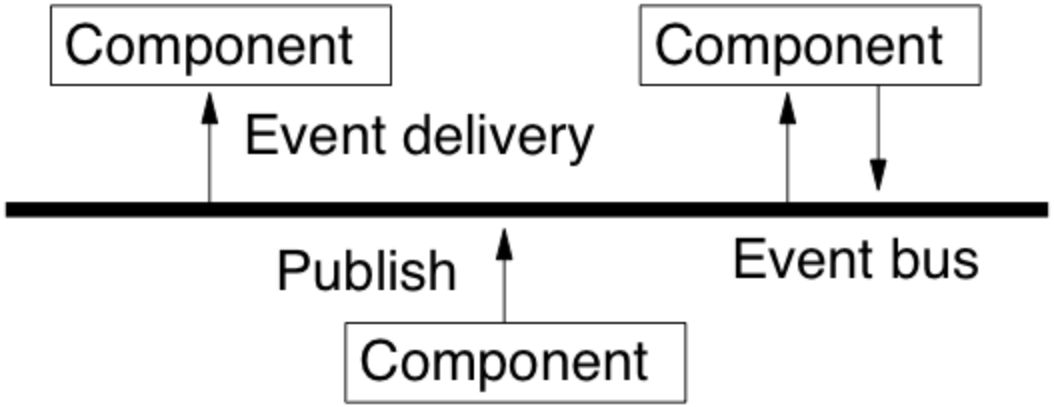
Used for:

- Replication of services
- Replication of data
- Service discovery
- Event notification



Publish-subscribe-systems (or event-based communication)

- Communication through propagation of events
- Generally associated with publish/subscribe systems
- Sender process publishes events
- Receiver process subscribes to events and receives only the ones it is interested in



Architectural elements

What are the entities that are communicating in the distributed system? ✔

How do they communicate, or, more specifically, what communication paradigm is used? ✔

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Architectural elements

Roles and responsibilities

Architectural styles

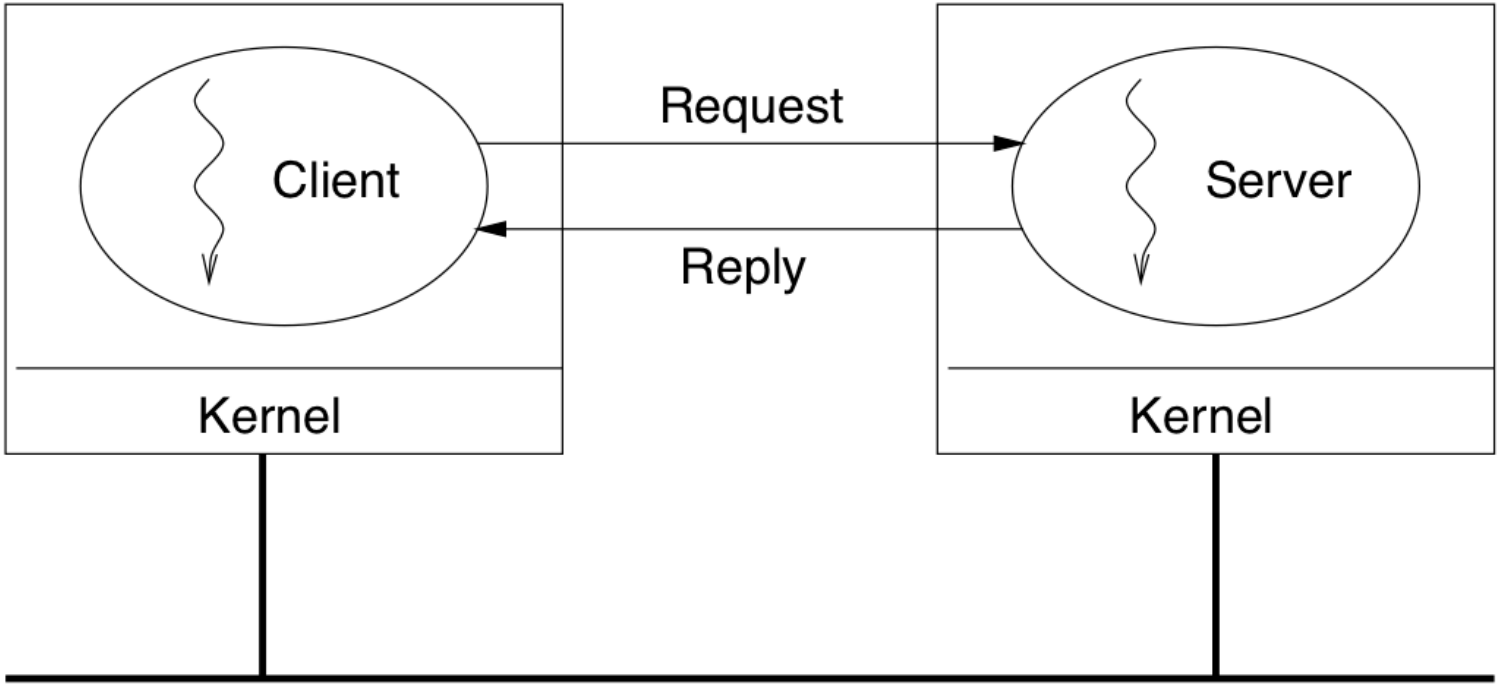
client-server

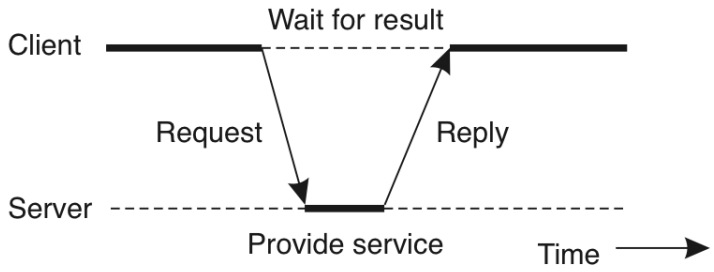
peer-to-peer

Roles and responsibilities

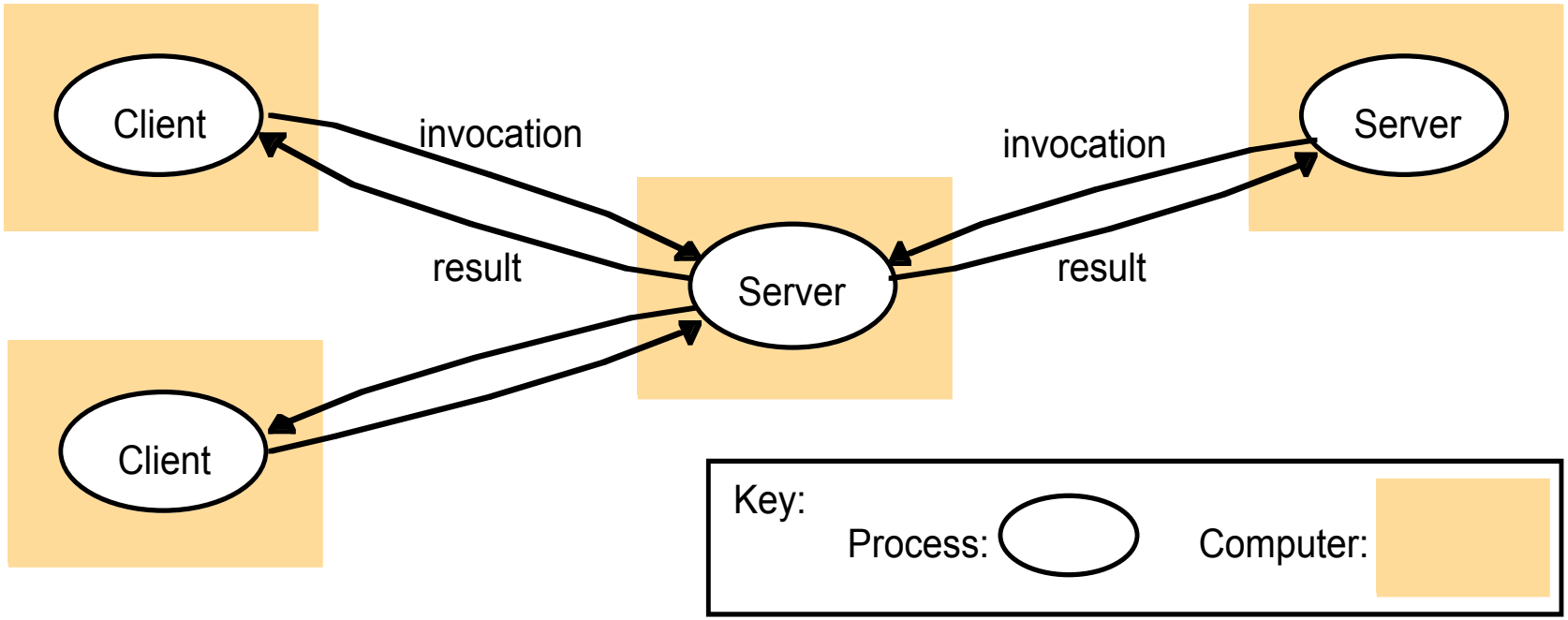
Client-server

Client-server





Clients invoke individual servers



Fundamental issue with client-server

Client server offers a direct, relatively simple approach to the sharing of data and other resources

➥ But it scales poorly

The centralization of service provision and management implied by placing a service at a single address does not scale well beyond the capacity of the computer that hosts the service and the bandwidth of its connections

Even though, there a several variations of the client-server architecture to respond to this problem but none of the really solve it

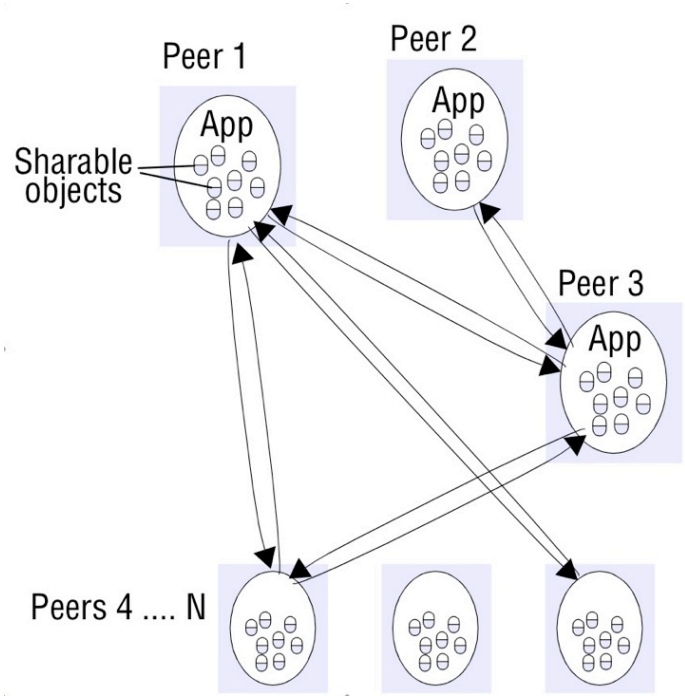
There is a need to distribute shared resources much more widely in order to share the computing and communication loads amongst a much larger number of computers and network links

Roles and responsibilities

Peer-to-peer

Peer-to-peer application

- Is composed of a large number of peer processes running on separate computers
- All processes have client and server roles: servent
- Patterns of communication between them depends entirely on application requirements
- Storage, processing and communication loads for accessing objects are distributed across computers and network links
- Each object is replicated in several computers to further distribute the load and to provide resilience in the event of disconnection of individual computers
- Need to place and retrieve individual computers is more complex then in client-server architecture



Architectural elements

What are the entities that are communicating in the distributed system? ✔

How do they communicate, or, more specifically, what communication paradigm is used? ✔

What (potentially changing) roles and responsibilities do they have in the overall architecture? ✔

How are they mapped on the physical distributed infrastructure (what is their placement)?

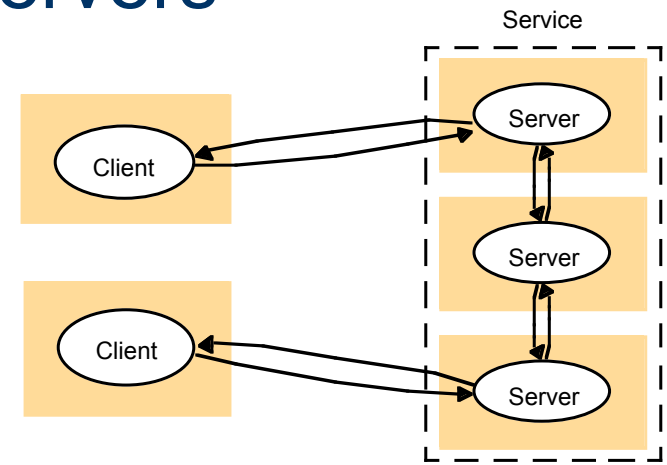
Architectural elements

Placement

Services provided by multiple servers

Option 1

- Servers partition a set of objects in which the service is based and distribute them between themselves
- Example
  - In the Web in which each web server manages it own set of resources
  - User can employ a browser to access a resource at any one of the servers



A service provided by multiple servers

Option 2

- Server maintain replicated copies of them on several hosts
- Example:
  - NIS (Network Information Service) used by computers on a LAN

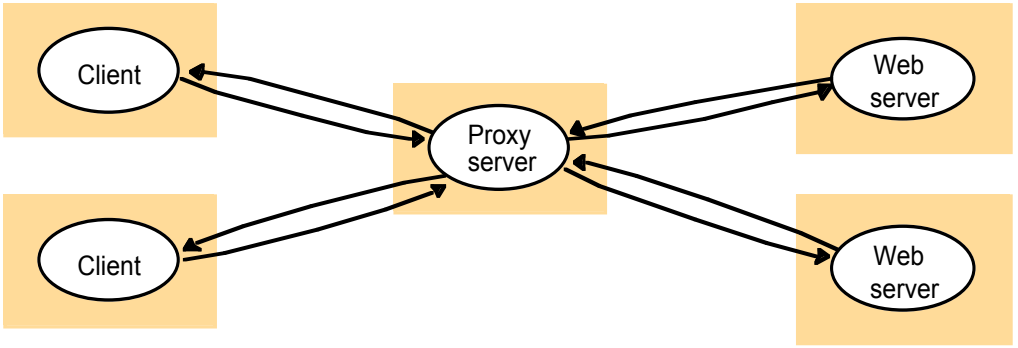
Proxy server and caches

A cache is a store of recently used data objects that is closer to the objects themselves. Caches might be co-located with each client or may be located in a proxy server that can be shared by several clients.

Process

- A new object is received at a computer > it is added to the cache store, replacing some existing objects if necessary
- Object is needed by the client process > caching service checks the checks the cache for an up-to-date copy
- If copy is not available this copy is fetched

Example?

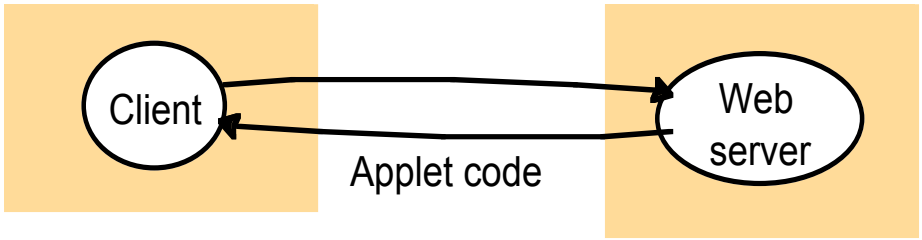


Web proxy server

Mobile code

A typical well-known and widely-used example for mobile code are applets.

a) client request results in the downloading of applet code



b) client interacts with the applet

Mobile agents

A mobile agent is a running program (both code and data) that travels from one computer to another in a network carrying out a task on someone's behalf, e.g. collecting information.

Benefits agents provide for creating distributed systems (Lange & Oshima, 1999)

- They reduce the network load.
- They overcome network latency.
- They encapsulate protocols.
- They execute asynchronously and autonomously.
- They adapt dynamically.
- They are naturally heterogeneous.
- They are robust and fault-tolerant.

Examples?

Architectural elements

What are the entities that are communicating in the distributed system? ✔

How do they communicate, or, more specifically, what communication paradigm is used? ✔

What (potentially changing) roles and responsibilities do they have in the overall architecture? ✔

How are they mapped on the physical distributed infrastructure (what is their placement)? ✔

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Architectural models

Architectural patterns

Concept of layering

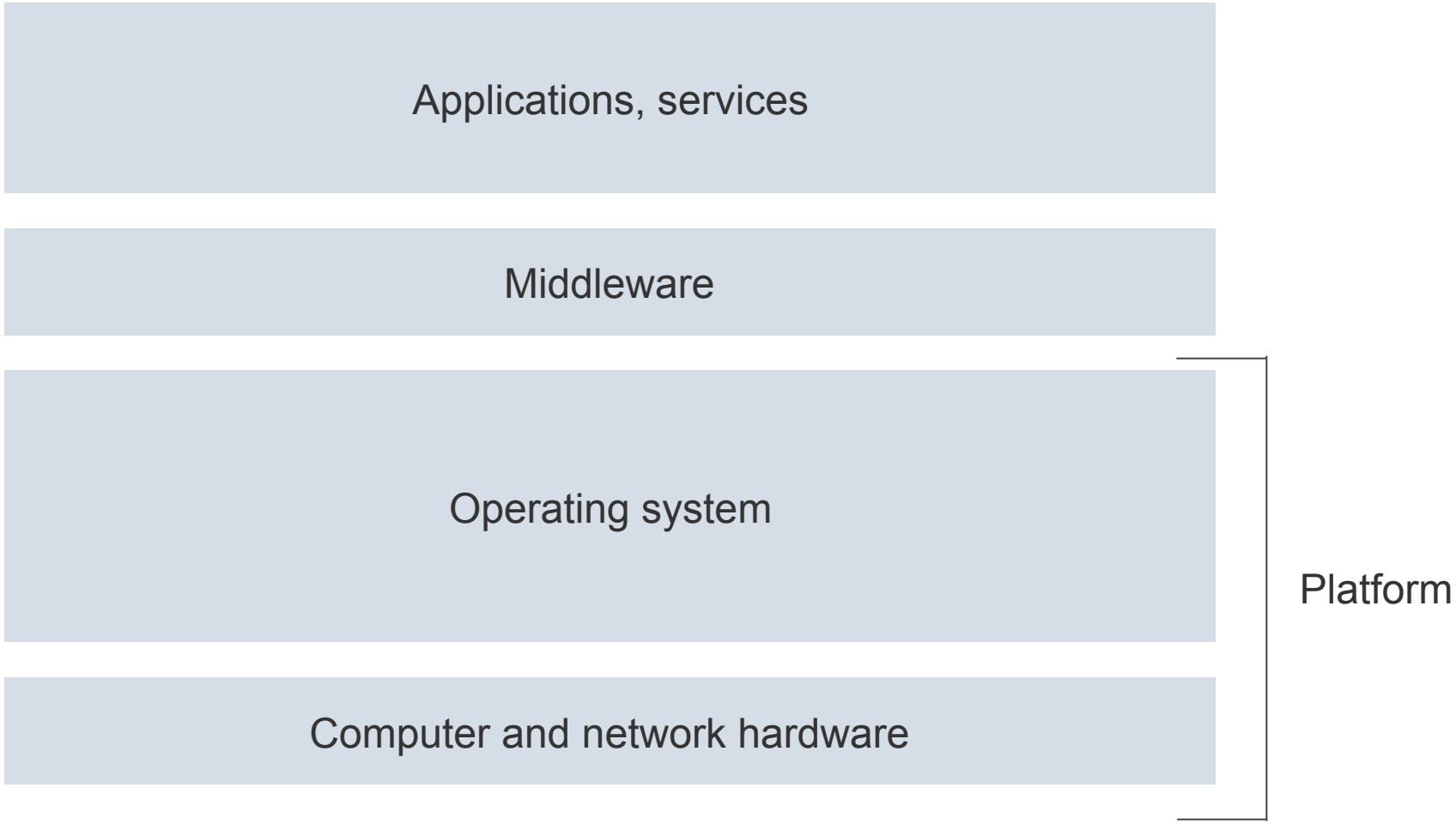
Vertical organization of services into a service layers

Distributed services can be provided by one or more server processes, interacting with each other and with client processes in order to maintain a consistent system-wide view of the service's resources

Example

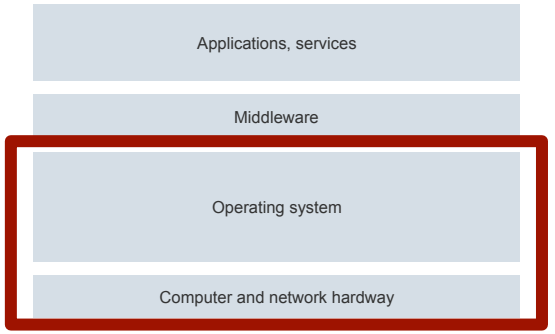
- Network time service is implemented on the Internet based on the Network Time Protocol (NTP) by server processes running on hosts throughout the Internet that supply current time to any client that request it

Software and hardware service layers



Platform

Lowest level hardware and software layers for distributed systems and applications



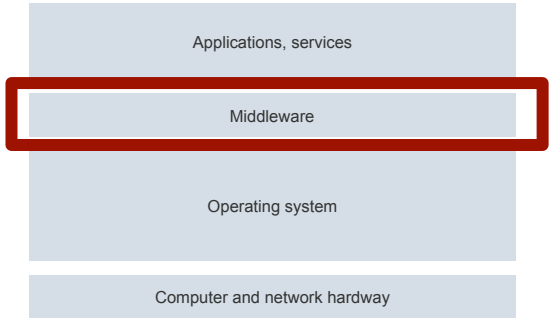
Characteristics

- provide services to the layers above them
- implemented independently in each computer
- Bringing the system's programming interface up to a level that facilitates communication and coordination between processes

Examples

x86/Windows, intel x86/Solaris, PowerPC/Mac OS X, Intel x86/Linux

Middleware



Is a layer of software whose purpose is to mask hetero-geneity and to provide a convenient programming model to application programmers

is represented by processes or objects in a set of computers that interact with each other to implement communication and resource-sharing support

Is concerned with providing useful building blocks for the construction of software components that can work with one another

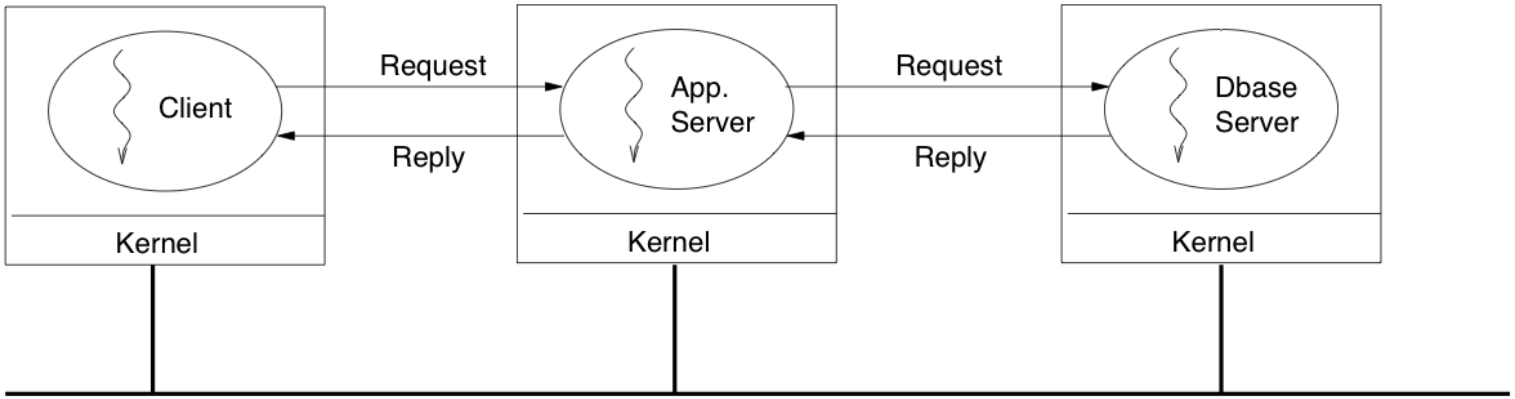
Limitations of middleware

- Many distributed applications rely entirely on services provided by middleware to support their needs for communication and data sharing
- Example, application that is suited to the client-server model such a database of names and addresses an rely on middleware that provides only remote method invocation

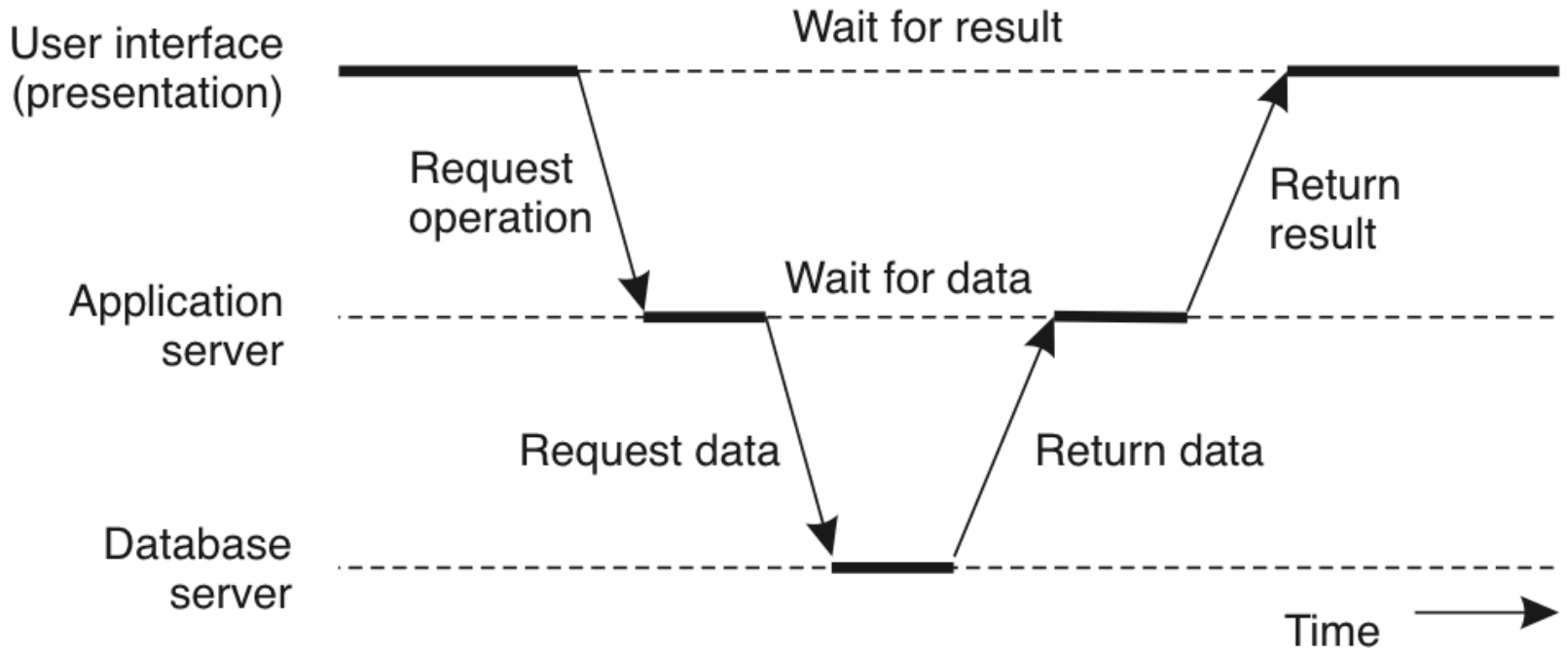
Vertical Distribution (Multi-Tier)

An extension of the client-server architecture

Distributes the traditional server functionality over multiple servers



Communication in a multi-tier system



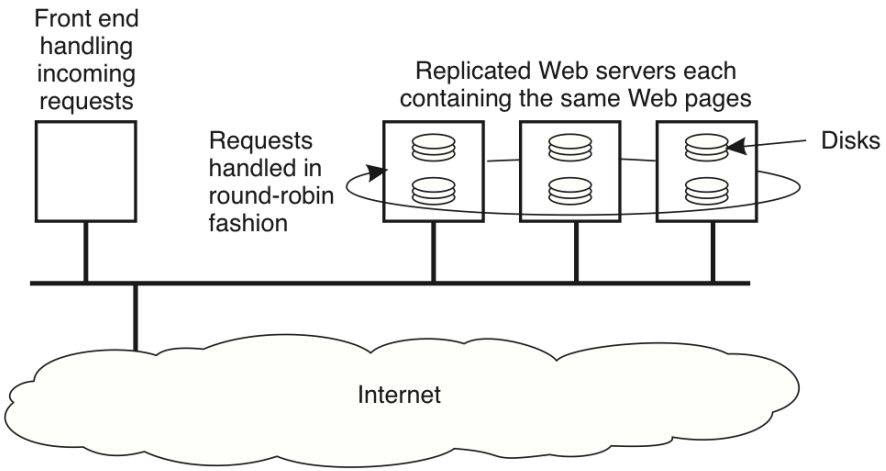
Horizontal Distribution

Involves replicating a server's functionality over multiple computers

Typical example: replicated Web server

- Each server machine contains a complete copy of all hosted Web pages
- Client requests are passed on to the servers in a round robin fashion

Is used to improve scalability (by reducing the load on individual servers) and reliability (by providing redundancy)



Thin and fat client implementations

Decomposed a typical client-server application into three logical parts

- the interface part
- the application logic part, and
- the data part

Thin client implementation

- Provides a minimal user interface layer, and leave everything else to the server

Fat client implementation

- Include all of the user interface and application logic in the client
- Rely only on the server to store and provide access to data

Implementations in between will split up the interface or application logic parts over the clients and server in different ways.

Fundamental models

Requirements on the fundamental model

Questions that should be addressed by a system model

1. What are the main entities of the system?
2. How do they interact?
3. What are the characteristics that affect their individual and collective behavior?

Aspects of distributed systems that are considered are

- Interaction
- Failure
- Security

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Fundamental models

Interaction model

Performance of communication channels

Latency

- Delay between the start of a message's transmission from one process and the beginning of its receipt by another
- It includes:
  - Time taken for the first string of bits transmitted through a network to reach its destination
  - Delay in accessing the network
  - Time taken by the operating system communication services at both the sending and the receiving processes

Bandwidth

- total amount of information that can be transmitted over a computer network in a given time.

Jitter

- Variation in the time taken to deliver a series of messages.

Two variants of the interaction model

Synchronous distributed systems

The following bounds are defined:

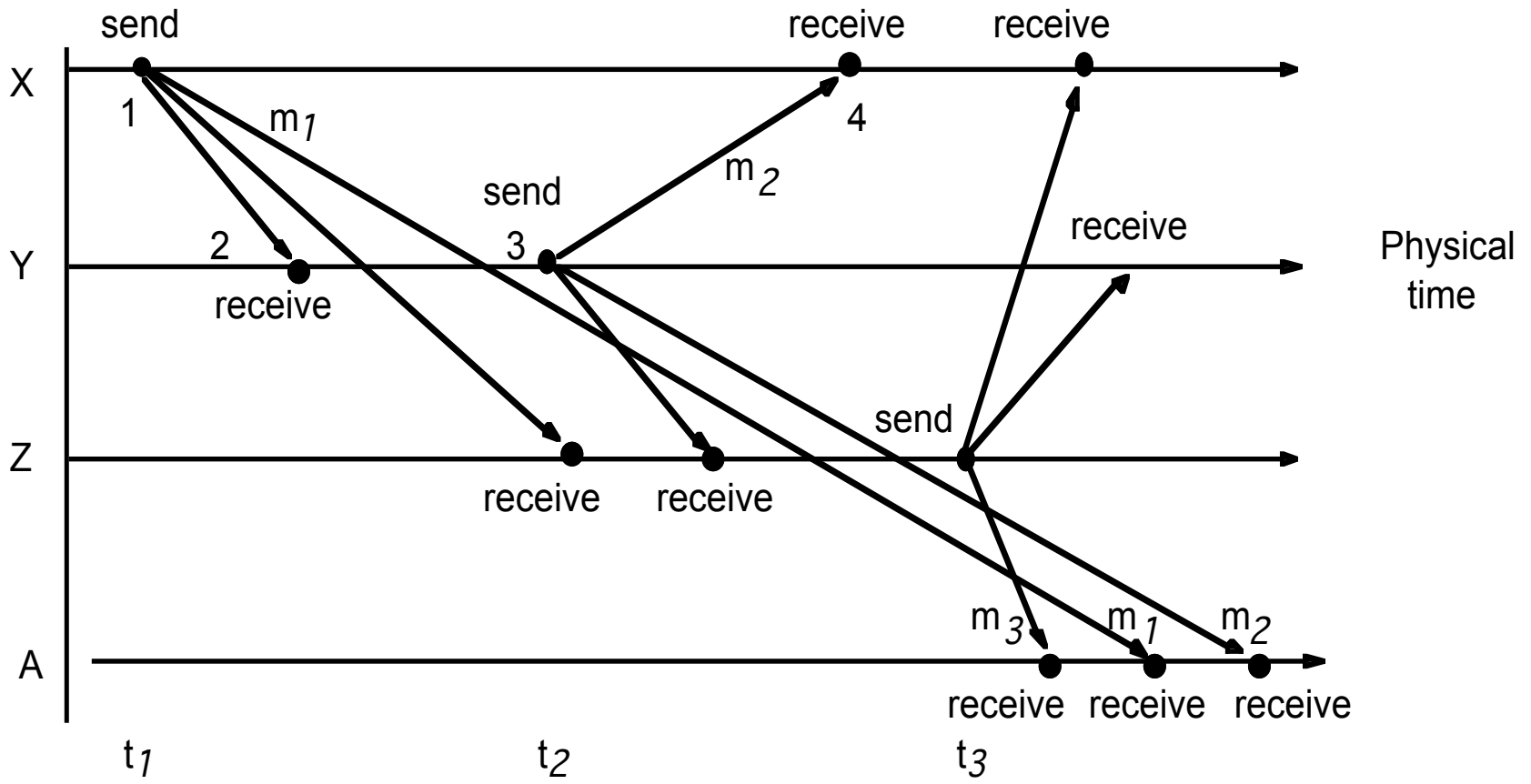
- The time to execute each step of a process has known lower and upper bounds
- Each message transmitted over a channel is received within a known bounded time.
- Each process has a local clock whose drift rate from real time has known bound.

Asynchronous distributed system

There are no bounds on:

- Process execution speed
- Message transmission delays
- Clock drift rate

Event ordering



Fundamental models

Failure model

Introducing the failure model

The failure model defines ways in which failure may occur in order to provide an understanding of the effects of failure.

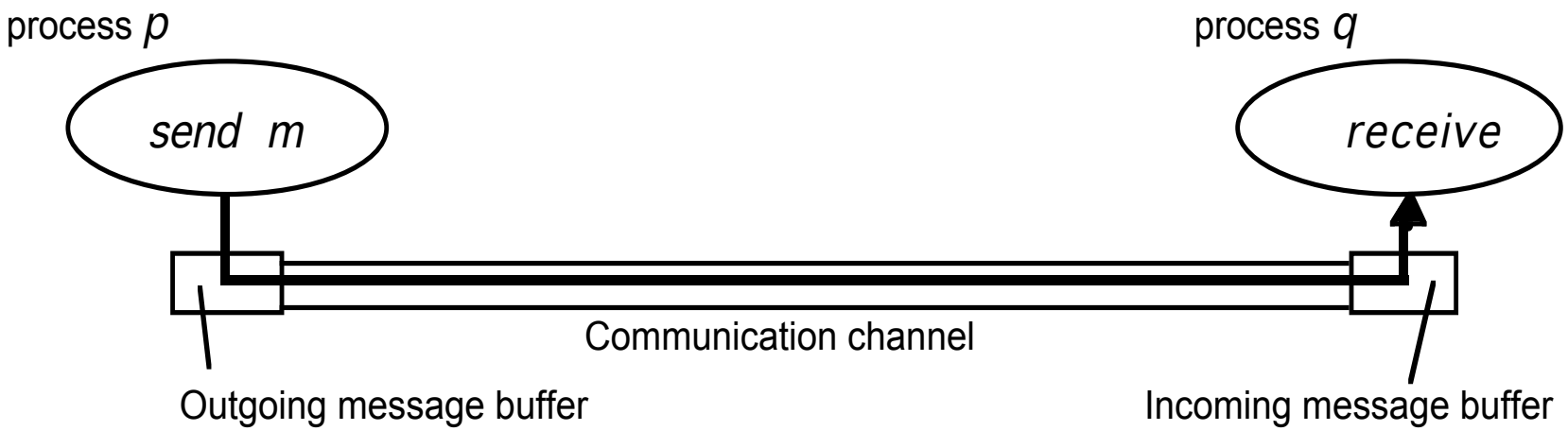
Taxonomy of failures of processes and communication channels (Hadzilacos & Toueg, 1994)

- Omission failures
- Arbitrary failures
- Timing failure

Omission failures

Class of failure	Affects	Description
Fail-stop	Process	Process halts and remains halted. Other processes may detect the state.
Crash	Process	Process halts and remains halted. Other processes may not be able detect this state.
Omission	Channel	A message inserted in an outgoing message buffer never arrives at the other end's incoming message buffer.
Send-omission	Process	A process completes a send operation but the message is not put in its outgoing message buffer.
Receive-omission	Process	A message is put in a process's incoming message buffer but that process does not receive it.

Processes and channels



Arbitrary failures

Often called Byzantine failure.

This is the worst possible failure semantics, in which any type of error may occur.

Example of an arbitrary failure of a process

- A process arbitrarily omits intended processes steps or takes unintended processing steps

Example of an arbitrary failure of a communication channel

- Message content may be corrupted, nonexistent messages may be delivered or real messages may be delivered more than once
- Solutions: *checksum* to detect corrupted messages and *message sequence numbers* to detect nonexistent and duplicated messages

Timing failures

Class of Failure	Affects	Description
Clock	Process	Process's local clock exceeds the bounds on its rate of drift from real time.
Performance	Process	Process exceeds the bounds on the interval between two steps.
Performance	Channel	A message's transmission takes longer than the stated bound.

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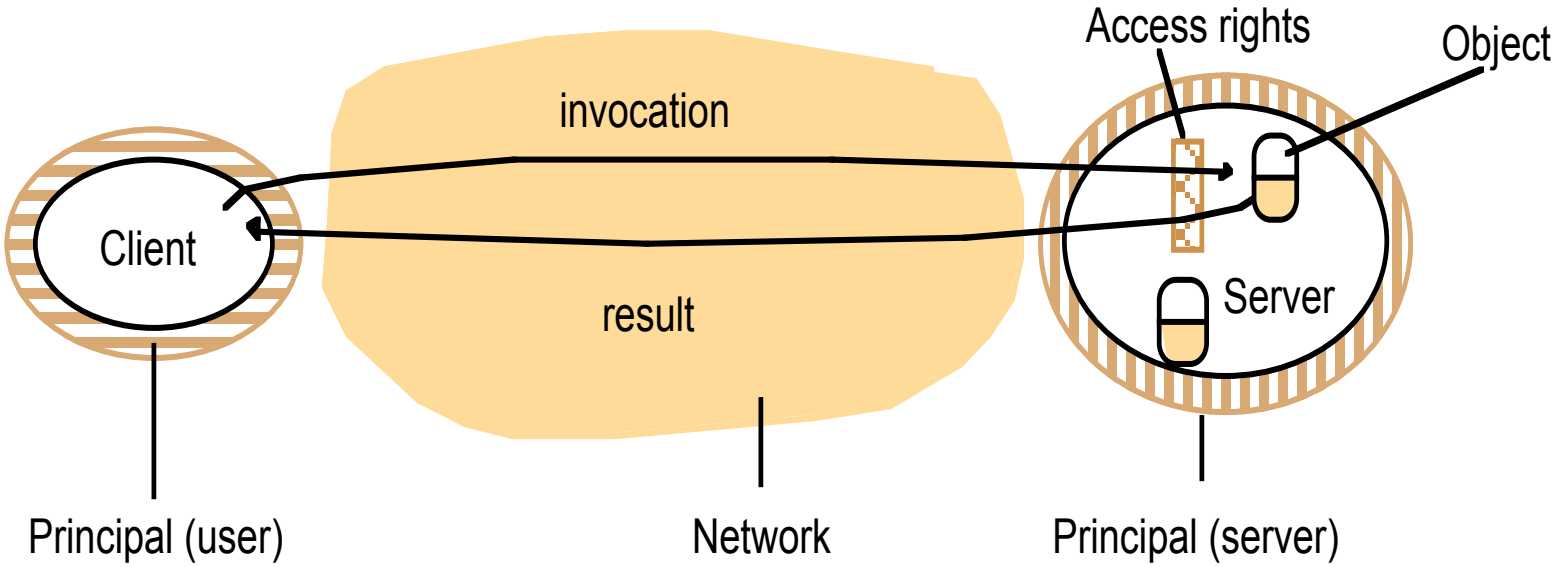
Fundamental models

Security model

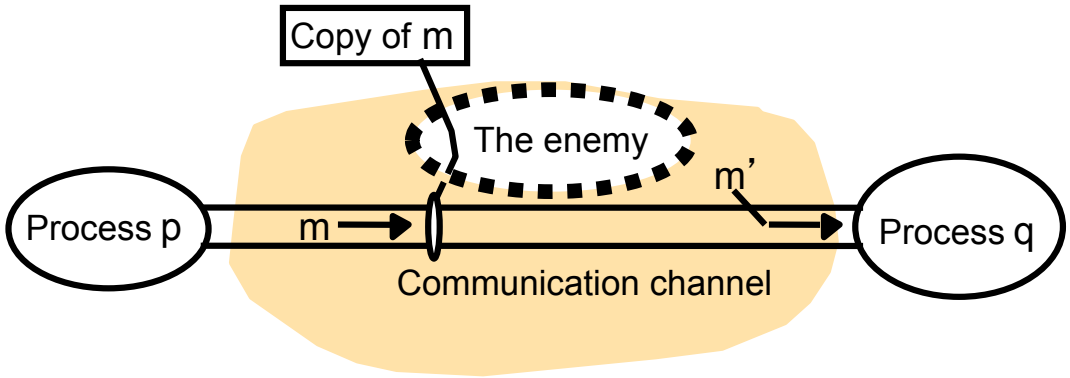
Introducing the security model

The security of a distributed system can be archived by securing the processes and the channels used for their interactions and by protecting the objects that they encapsulate against unauthorized access.

Protecting objects



Securing processes and their interactions



Threats to processes

- Without reliable knowledge a server can not tell the principal's identity behind an invocation
- The same applies to a client who receives the result from an invocation but it is not sure if this is from the intended server

Threats to communication channels

- An 'enemy' can copy, alter, or inject messages as they travel across the network -> Threat to privacy and integrity of information
- Another attack is saving copies of messages and reply them later, e.g. an invocation message requesting transferring a sum of money from one bank account to another

Defeating security threads

Cryptography and shared secrets

- Example
  - Pair of processes shares a secret and nobody other know this
  - By exchanging a message the pair of processes includes information that proves the senders knowledge of this secret
- Cryptography is based on an encryption algorithm that uses secret keys

Authentication

- Providing the identities supplied by their senders
- Basic technique: include in a message an encrypted portion that contains enough of the contents of the message to guarantee its authentication

Encryption and authentication are used to build secure channels on top of existing communication services.

Summary

- Three generations of distributed systems and the emergence of ultra-large-scale (ULS) distributed systems
- Types of communication paradigms:
  - Interprocess communication
  - Remote invocation
  - Indirect communication
- Architectural styles: client-server and peer-to-peer
- Vertical distribution (Multi-Tier) and horizontal distribution of c/s systems
- Characteristics of synchronous distributed systems and asynchronous distributed system
- Omission failures, arbitrary failures, timing failure in distributed computing
- Defeating security threads with encryption and authentication

Next class

Ad hoc network programming (communication over sockets)

References

Main resource for this lecture:

George Coulouris, Jean Dollimore, Tim Kindberg: *Distributed Systems: Concepts and Design*. 5th edition, Addison Wesley, 2011

Further readings

Danny B. Lange and Mitsuru Oshima. 1999. Seven good reasons for mobile agents. *Commun. ACM* 42, 3 (March 1999), 88-89. DOI=10.1145/295685.298136

Vassos Hadzilacos and Sam Toueg. 1994. *A Modular Approach to Fault-Tolerant Broadcasts and Related Problems*. Technical Report. Cornell University, Ithaca, NY, USA.