# Distributed Systems

## Winter Term 2024/25

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Stand: October 24, 2024



Distributed Systems

Winter Term 2024/25

# 2 Middleware

## Content

- Communication in distributed systems
- Communication-oriented middleware
- Application-oriented middleware

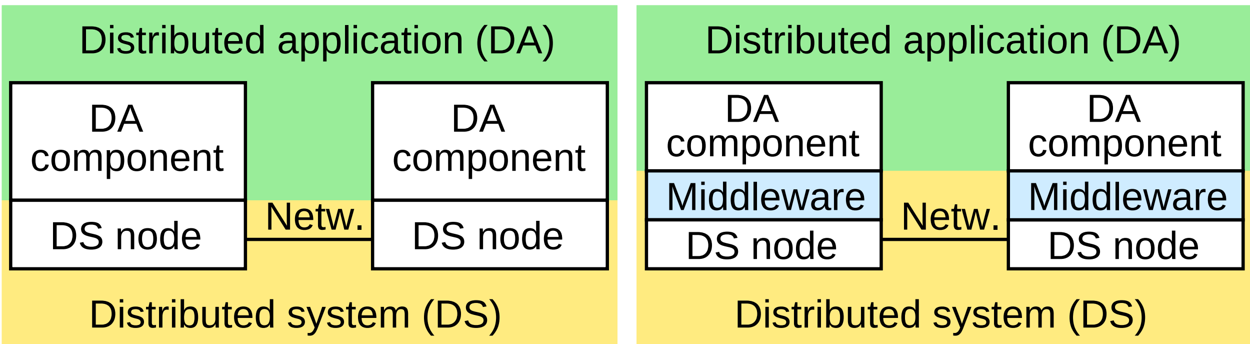
## Literature

- Hammerschall: Ch. 2, 6
- Tanenbaum, van Steen: Ch. 2
- Colouris, Dollimore, Kindberg: Ch. 4.4





(Animated slide)




- DA uses DS for communication between its components
- DSs generally only offer simple communication services
  - direct use: **network programming**
- **Middleware** offers more intelligent interfaces
  - hides details of network programming

- Middleware is the interface between distributed application and distributed system
- Goal: hide distribution aspects from application
  - transparency (☞ **1.3**)
- Middleware can also provide additional services for applications
  - huge differences in existing middleware
- Distinction:
  - **communication-oriented middleware** (☞ **2.2**)
    - (only) abstraction from network programming
  - **application-oriented middleware** (☞ **2.3**)
    - besides communication, the focus is on support of distributed applications



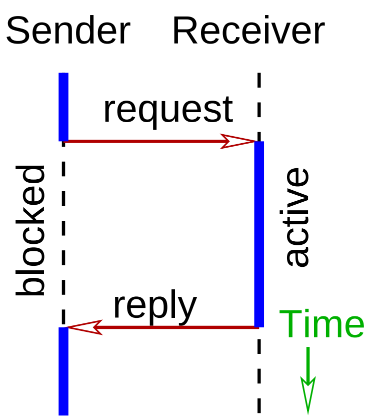


## 2.1 Communication in Distributed Systems

- Basis: **interprocess communication** (**IPC**)
  - exchange of messages between processes (☞ **BS_I: 3.2**)
    - on the same or on different nodes
    - e.g. via ports, mailboxes, streams, ...
- For distribution: network protocols (☞ **RN_I**)
  - relevant topics etc: addressing, reliability, guaranteed ordering, timeouts, acknowledgements, marshalling
- Interface for network programming: sockets (☞ **RN_II**)
  - datagrams (UDP) and streams (TCP)

## Synchronous Communication

- Sender and receiver block when calling a send or receive operation
  - receiver is waiting for a request
  - sender is waiting for the reply



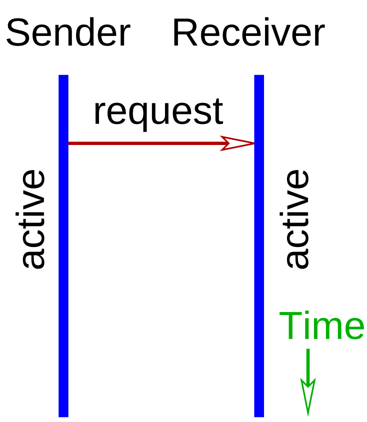

- Tight coupling between sender and receivers
  - advantage: easy to understand model
  - disadvantage: strong dependency, especially in case of error
- Prerequisites:
  - reliable and fast network connection
  - receiver process is available





## Asynchronous Communication

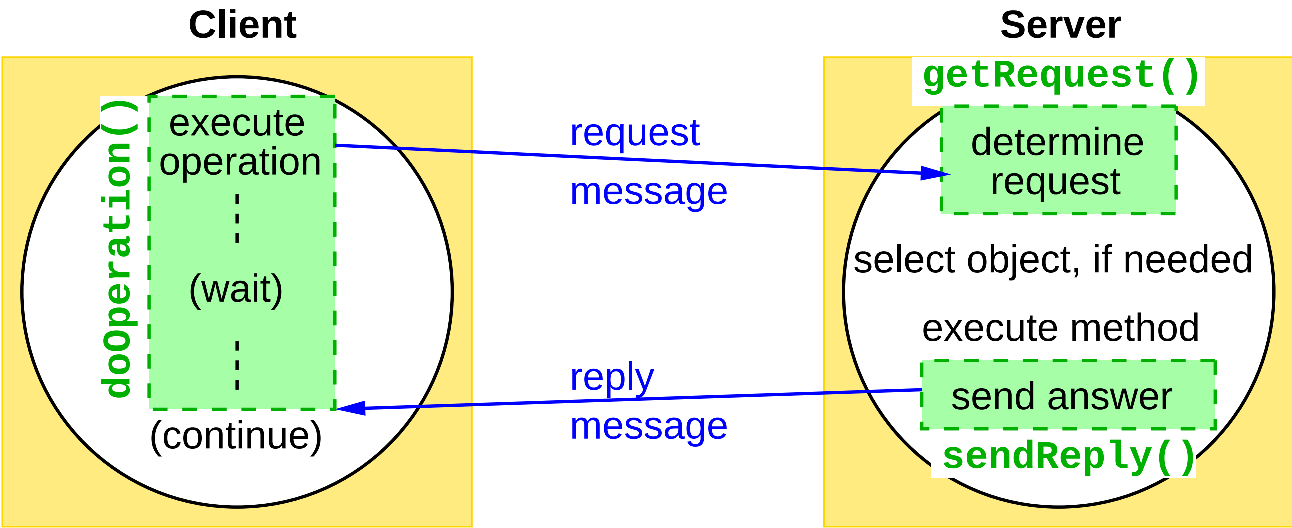
- Sender is not blocked, can continue immediately after sending the message
- Incoming messages are buffered at the receiver
- Answers are optional
  - receiver can reply asynchronously to the sender




- More complex implementation and use as with synchronous communication, but usually more efficient
- Only loose coupling between the processes
  - receiver does not have to be ready for reception
  - less dependent in case of errors

(Animated slide)

### Client/Server Communication




- Mostly synchronous: client blocked until response arrives
- Variants: asynchronous (non blocking), one way (without answer)



## 2.1 Communication in Distributed Systems ...

### Client/Server Communication: Request/Response Protocol

- Typical operations:
  - `doOperation()` – send request and wait for result
  - `getRequest()` – wait for request
  - `sendReply()` – send result
- Typical message structure:

| | |
|---|---|
| messageType | request / reply ? |
| requestID | unique ID of request (usually int) |
| objectReference | reference to remote object (if needed) |
| methodID | method to be called (int / String) |
| arguments | arguments (usually as Byte array) |

  - request ID + sender ID result in unique message ID
    - e.g. to map an answer to its query

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24.10.2024

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## 2.1 Communication in Distributed Systems ...

### Client/Server Communication: Error Handling

- Request and/or response messages may be lost
- Client sets a timeout when sending a request
  - after expiration, request is usually sent again
  - after a few repetitions: termination with exception
- Server discards duplicate requests if request has already been / is still being processed
- For lost response messages:
  - idempotent operations can be executed again
  - otherwise: save results of operations in a history
    - for repeated request: only resend the result
    - delete history entries when next request arrives; if necessary confirmations for results can also be used

**Notes for slide 58:**

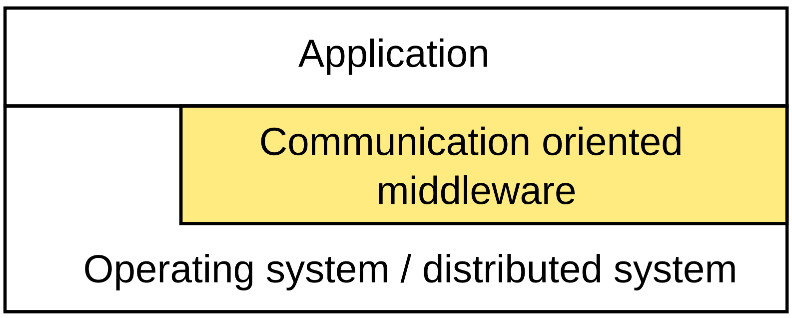
In principle, three different semantics are distinguished:

- *At most once*: The query is executed **at most once** under all circumstances. This means that lost requests or answers do not lead to a repetition of the request.
- *At least once*: The request is executed **at least once** under all circumstances. I.e., lost requests or answers lead to a repetition of the request, whereby the server does not have to recognize duplicates of a request. This semantics is useful e.g. for idempotent requests.
- *Exactly once*: The request is executed **exactly once** under all circumstances. In case of lost requests or answers, the request must be repeated. At the same time, the server must be able to recognize repeated requests as duplicates and must not execute them again.



## 2.2 Communication-oriented Middleware

- Focus: provision of a communication infrastructure for distributed applications
- Tasks:
  - communication
  - dealing with heterogeneity
  - error handling



## 2.2.1 Tasks of the Middleware

### Communication

- Provision of a middleware protocol
- Localization and identification of communication partners
- Integration with process and thread management

| |
|---|
| Application protocol |
| Middleware protocol |
| Transport protocol (e.g. TCP) |
| Lower layers of the protocol stack |



## 2.2.1 Tasks of the Middleware ...

### Heterogeneity

- Problem with data transmission:
  - heterogeneity in distributed systems
- Heterogeneous hardware and operating systems
  - different byte order
    - little endian vs. big endian
  - different character encoding
    - e.g.. ASCII / Unicode / UTF-8 / UTF-16
- Heterogeneous programming languages
  - different representation of simple and complex data types in the main memory

## Heterogeneity: Solutions (☞ RN_I)

- Use of generic, standardized data formats
  - known to all communication partners and middleware
  - platform-specific formats for middleware (e.g. CDR for CORBA) or external formats, e.g. XML
- Heterogeneity of hardware and operating system
  - is handled transparently for the applications by the middleware
- Heterogeneity of programming languages
  - applications need to convert data to higher-level format and back (**marshaling** / **unmarshaling**)
    - necessary code is usually generated automatically
      - client stub / server skeleton



2.2.1 Tasks of the Middleware ...

## Error Handling

- Possible errors due to distribution
  - incorrect transmission (incl. loss of messages)
    - handled by the protocols of the distributed system:
      - checksums, CRC
      - retransmission of packets (e.g. TCP)
  - failure of components (network, hardware, software)
    - handled by middleware or application:
      - acceptance of the error
      - retransmission of messages
      - replication of components (error avoidance)
      - controlled termination of the application

## 2.2.2 Programming Models

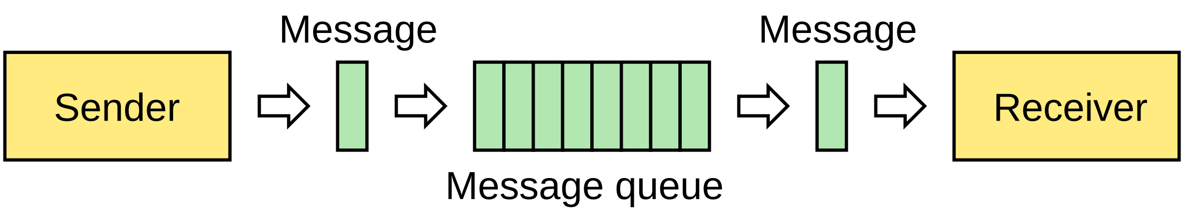
- Programming model defines two concepts:
  - communication model
    - synchronous vs. asynchronous
  - programming paradigm
    - object-oriented vs. procedural
- Three common programming models for middleware:
  - message-oriented model (asynchronous / arbitrary)
  - remote procedure call (synchronous / procedural)
  - remote method invocation (synchronous / object-oriented)





### Message-Oriented Model

- Sender puts message in receiver's queue

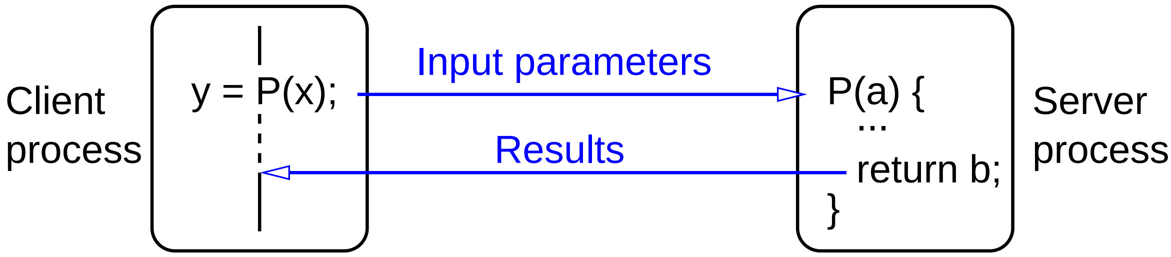



- Receiver accepts message as soon as he is ready
- Extensive decoupling of transmitter and receiver
- No method or procedure calls
  - data is packed and sent by the application
  - no automatic reply message

## 2.2.2 Programming Models ...

### Remote Procedure Call (RPC)

- Allows a client to call a procedure in a remote server process




- Communication according to request / response principle

### Remote Method Invocation (RMI)

- Allows an object to call methods of a remote object
- In principle very similar to RPC



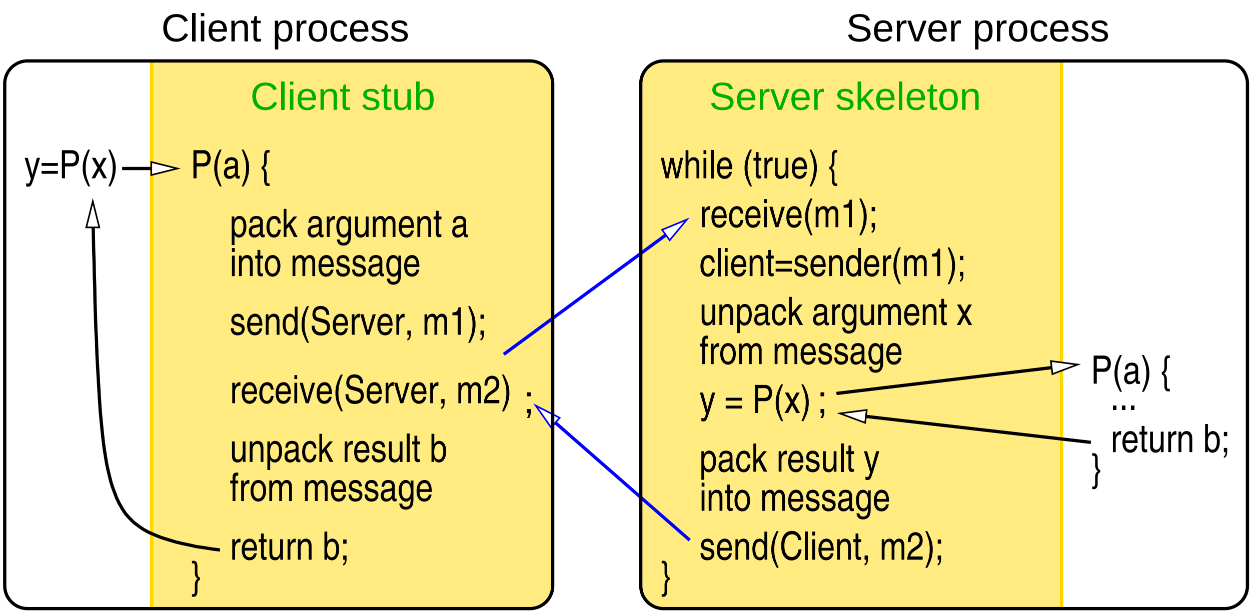
## 2.2.2 Programming Models ...

### Common Basic Concepts of Remote Calls

- Client and server are decoupled by interface definition
  - defines names of calls, parameters and return values
- Introduction of **client stubs** and **server skeletons** as an access interface
  - are automatically generated from interface definition
    - IDL compiler (IDL = interface definition language)
  - are responsible for marshaling / unmarshaling as well as for the actual communication
  - realize access and location transparency

## 2.2.2 Programming Models ...

### How Client Stub and Server Skeleton Work (RPC)



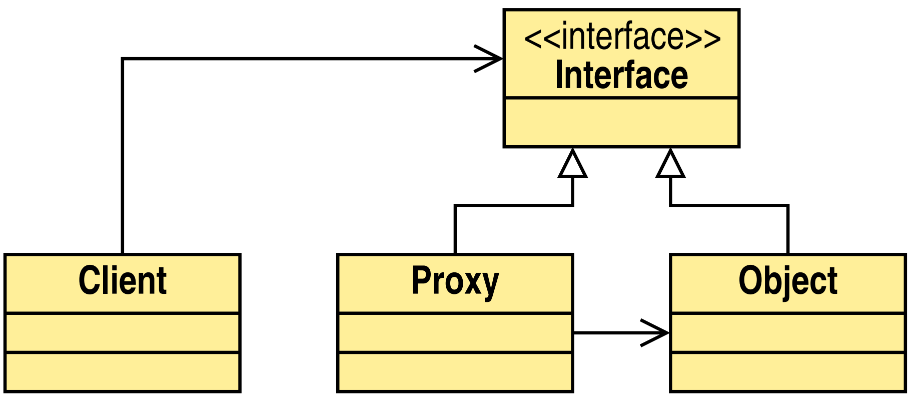




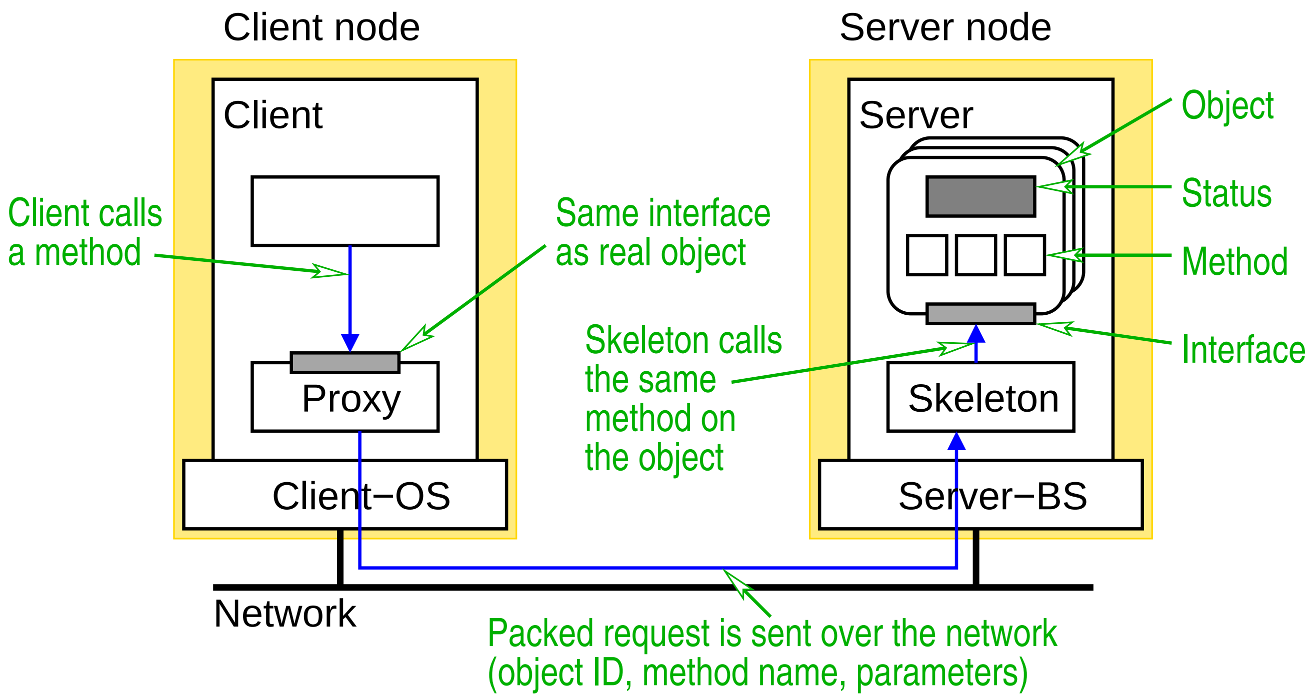
## 2.2.2 Programming Models ...


### Basis of RMI: The Proxy Pattern

- Client works with a deputy object (**proxy**) of the actual server object
  - proxy and server object implement the same interface
  - client only knows / uses this interface



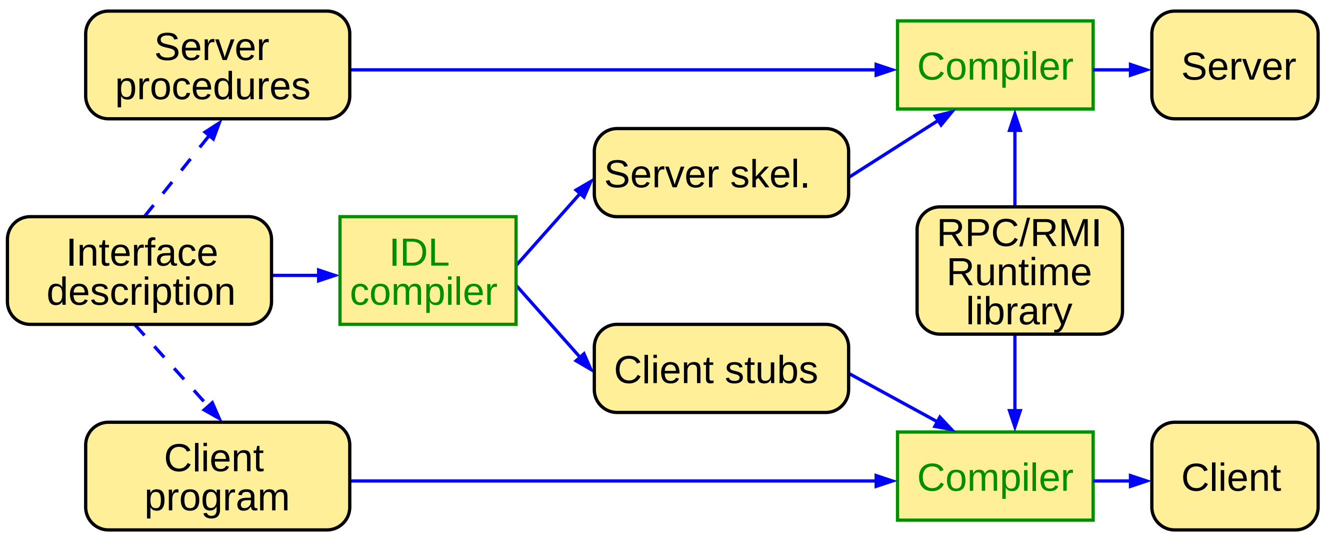
### Flow of a Remote Method Call








### Creation of a Client/Server Program




➥ Applies in principle to all realizations of remote calls

### 2.2.3 Middleware Technologies

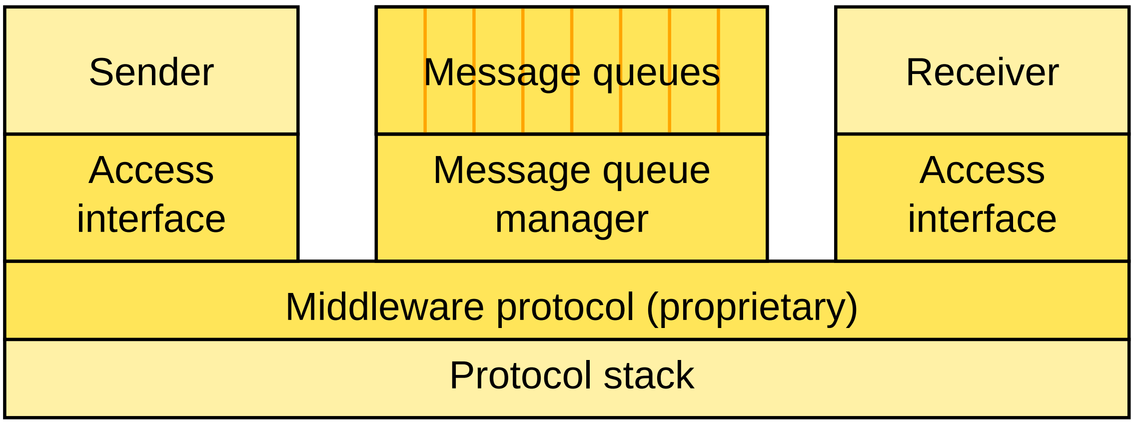
- Realize (at least) one of the programming models
  - rely on open standards / standardized interfaces
- Remote procedure call
  - SUN RPC, DCE RPC, Web Services, ...
- Remote method invocation
  - Java RMI (☞ 3), CORBA, ...
- Message-oriented middleware technologies
  - MOM: message oriented middleware, messaging systems
  - mainly for EAI
  - Java Message Service, WebSphereMQ (MQSeries), ...



2.2 Communication-oriented Middleware ...

### 2.2.4 Message Oriented Middleware (MOM)

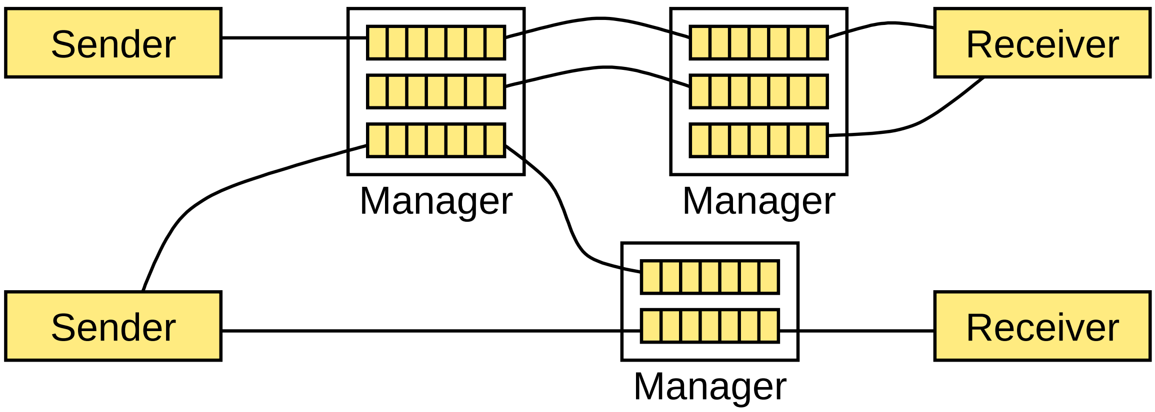
- Middleware technology for the message-oriented model
- In addition to message exchange also other services, especially queue management



## 2.2.4 Message Oriented Middleware (MOM) ...

### Message Queue Infrastructure

- Access to queues is only possible locally
  - local: same computer or same subnet
- Transport of messages across subnet boundaries by queue administrators (routers)







## 2.2.4 Message Oriented Middleware (MOM) ...


### Variants of message exchange

- Point-to-point communication
  - communication between two defined processes
  - simplest model: asynchronous communication
  - enhancement: request/reply model
    - enables synchronous communication via asynchronous middleware
- Broadcast communication
  - Message is sent to all reachable receivers
  - one implementation: publish/subscribe model
    - publishers publish messages/news on a topic
    - subscribers subscriber to certain topics
    - mediation via a broker

## 2.2.4 Message Oriented Middleware (MOM) ...

### Example: Java Message Service

- Part of the Java Enterprise Edition (Java EE)
- Unified Java interface for MOM services
- Distinguishes two roles:
  - JMS provider: the respective MOM server
  - JMS client: sender or receiver of messages
- JMS supports:
  - asynchronous point-to-point communication
  - request/reply model
  - publish/subscribe model
- JMS defines corresponding access objects and methods



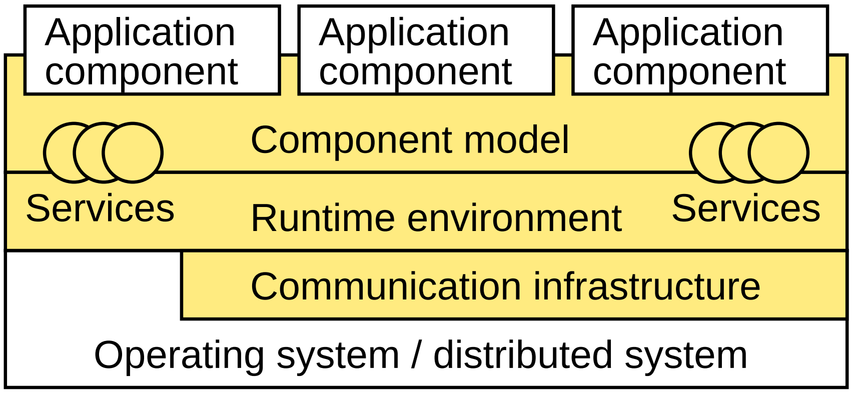
## 2.2 Communication-oriented Middleware ...

### 2.2.5 Summary

- Tasks: Communication, dealing with heterogeneity, error handling
- Programming models:
  - message-oriented model (asynchronous)
    - basis: message queues
    - refinements:
      - request/reply model (synchronous)
      - publish/subscribe model (broadcast)
  - remote procedure or method calls
    - synchronous: request and response
    - generated stubs for (un-)marshaling

## 2.3 Application-oriented Middleware

- Based on communication-oriented middleware
- Extends it by:
  - runtime environment
  - services
  - component model






### 2.3.1 Runtime environment

- Based on node operating systems of the distributed system
  - Operating system (OS) manages processes, memory, I/O, ...
  - provides basic functionality
    - starting / stopping processes, scheduling, ...
    - interprocess communication, synchronization, ...
- Runtime environment extends functionality of the OS:
  - improved resource management
    - e.g. concurrency, connection management
  - improved availability
  - improved security mechanisms

## 2.3.1 Runtime environment ...

### Resource management

- Middleware goes beyond simple OS functionality
  - e.g. independently managed main memory areas with individual security criteria
  - pooling of processes, threads, connections
    - are created for stock and made available as required
  - possible, since middleware is specific to certain classes of applications
- Goal: improved performance, scalability and availability





### Concurrency

- Concurrency in this context:
  - isolated parallel processing of requests
- Concurrency can be implemented via processes or threads
  - threads (lightweight processes): concurrent activities within processes
    - threads in the same process share all resources
  - advantages and disadvantages:
    - processes: high resource requirements, not well scalable, good protection, with low concurrency
    - threads: well scalable, no mutual protection, with high concurrency

### Concurrency ...

- Middleware takes over automatic generation / administration of threads in the case of concurrent orders, e.g.
  - *single-threaded*
    - only one thread, sequential processing
  - *thread-per-request*
    - a new thread is created for each request
  - *thread-per-session*
    - a new thread is created for each session (client)
  - *thread pool*
    - fixed number of threads, incoming requests are distributed automatically
      - saves thread generation costs
      - limits resource consumption





### Connection management

- Connection here means: endpoints of communication channels
  - occur at tier boundaries (between process spaces)
    - e.g. client/server interface, database access
  - are assigned to a process/thread, if in the active state
  - require resources (memory, processor time)
  - opening and closing connections is costly
- To save resources: pooling of connections
  - connections are initialized to stock and placed in pool
  - each thread/process receives a connection on demand
  - after use: return connection to pool

## 2.3.1 Runtime environment ...

### Availability

- Requirement to the application, but mainly implemented by the runtime environment
- Downtimes are caused by
  - failure of a hardware or software component
  - overload of a hardware or software component
  - maintenance of a hardware or software component
- Frequent technology for ensuring availability: cluster
  - replication of hardware and software
  - cluster appears externally as one unit
  - two types: fail-over cluster / load-balancing cluster



## 2.3.1 Runtime environment ...

### Security

- Distributed applications are vulnerable due to their distribution
- Middleware supports different security models
- Security requirements:
  - **authentication**:
    - proves the identity of the user / a component
    - e.g. by password query (for users) or cryptographic techniques and certificates (for components)
  - **authorization**:
    - definition of access rights for users to specific services
      - or more fine grained: methods and attributes
    - requires secure authentication

## Security ...

- Security requirements ...:
  - **confidentiality**
    - information cannot be intercepted during transmission in the network
    - technique: encryption
  - **integrity**
    - transmitted data cannot be changed without being noticed
    - techniques: cryptographic checksum (message digest, fingerprint), digital signature
      - digital signature also ensures authenticity of the sender



2.3.1 Runtime environment ...

## Security ...

- Security mechanisms:
  - encryption
    - symmetric (e.g. AES, IDEA)
      - same key for encryption and decryption
    - asymmetric (public key algorithms, e.g. RSA)
      - public key for encryption
      - private key for decrypting
  - digital signature
    - ensures integrity of a message and authenticity of the sender as well as nonrepudiation
  - certificate
    - certifies that public key and person (or component) belong together

## 2.3.2 Services

### Name service (directory service) (☞ 4)

- Publication of available services
  - in the intranet or Internet
- Assignment of names to references (addresses)
  - name serves as a unique / unchangeable identifier
  - the client can request the address of a service via its name
    - address can change e.g. at restart
  - goal: decoupling of client and server
- Examples: JNDI, RMI registry, CORBA interoperable naming service, UDDI registry, LDAP server, Active Directory, ...



## 2.3.2 Services ...

### Session management

- In interactive systems: each instance of a client is assigned its own **session**
  - deleted when logging out or closing the client
- Session stores all relevant data (in main memory)
  - e.g. identification of the user, browser type, "‘shopping cart"’, ...
  - data stored in the server or in the client
  - transient data: deleted at the end of the session
  - persistent data: is written to a data carrier (database) at the end of the session.
- Middleware implements/supports the assignment of requests to sessions (often transparent)
  - e.g. cookies, HTTP-sessions, session beans, ...

### Transaction management (☞ 7.4)

- Service for interactive, data-centric applications
  - consistency / integrity of data is important
  - this means that the entire (maybe distributed) dataset must represent a valid state in itself
- Typical sequence in applications:
  1. client requests data
  2. client changes the data
  3. client requests that the data be rewritten
  - problem: steps 1-3 could be performed by two clients at the same time
- Transaction management allows execution of a sequence of actions as an atomic unit



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## 2.3.2 Services ...

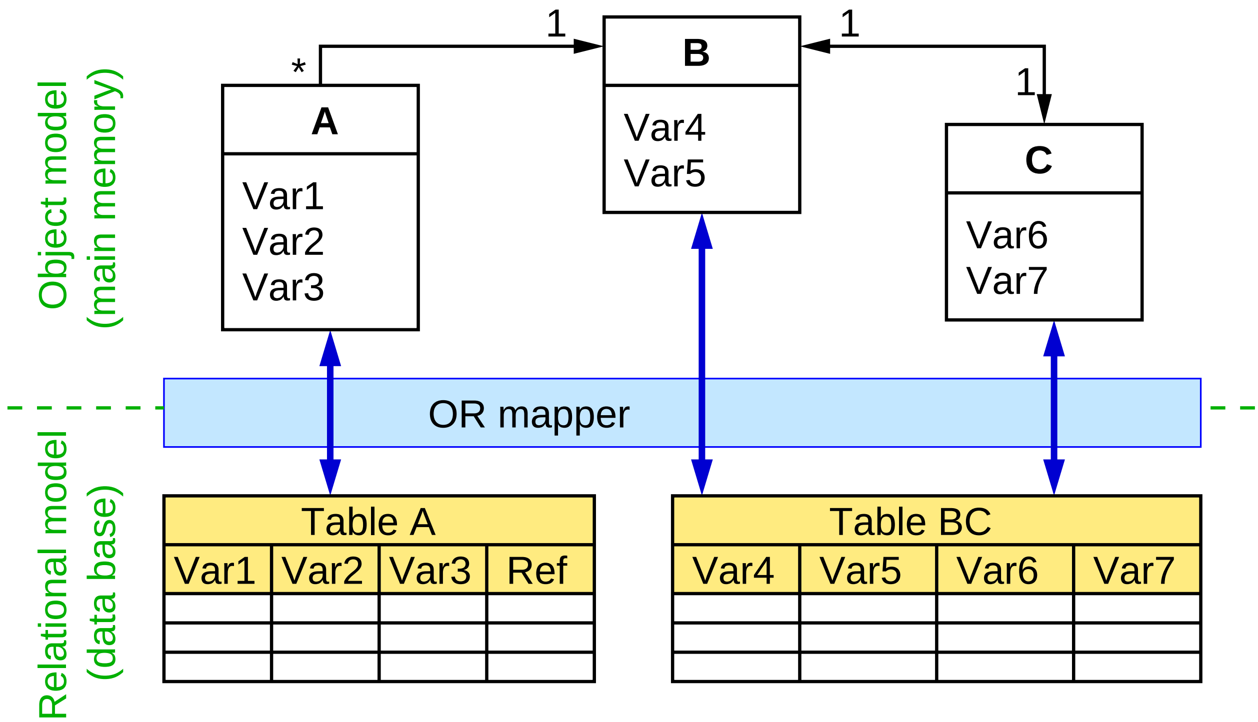
### Persistence service

- Persistence: all measures for the permanent storage of main memory data
- Persistence service: intelligent interface to the database
  - integrated in middleware or as an independent component
  - most important service for data-centered applications besides transaction management
- Most common type: object-relational mapper (OR-Mapper)
  - maps objects in memory to tables in a relational database
    - class → table
    - attribute → column
    - object → row
  - mapping rules are controlled by application developer



## 2.3.2 Services ...

### Persistence service ...



## 2.3.3 Component model

- Components: “large” objects for structuring applications
- A component model defines:
  - the term “component”
    - structure and properties of the components
    - mandatory and optional interfaces
  - interface contracts
    - how do components interact with each other and with the runtime environment?
  - component runtime environment
    - management of the life cycle of components
    - implicit provision of services: component only specifies its requirements (e.g. persistence)



## 2.3.4 Middleware Technologies

- Object request broker (ORB)
  - distributed objects, remote method calls
  - variety of services, only basic runtime environment
  - example: CORBA
- Application server
  - focus: support of application logic (middle tier)
  - services, runtime environment, and component model
  - today only as part of a middleware platform
- Middleware platforms
  - extension of application servers: support of all tiers
    - distributed applications as well as EAI
  - examples: Java EE/EJB, .NET/COM, CORBA 3.0/CCM

## Application-oriented middleware

- Runtime environment
  - resource management, availability, security
- Services
  - name service, session management, transaction management, persistence service
- Component model
  - defintion of components, interface contracts, runtime environment