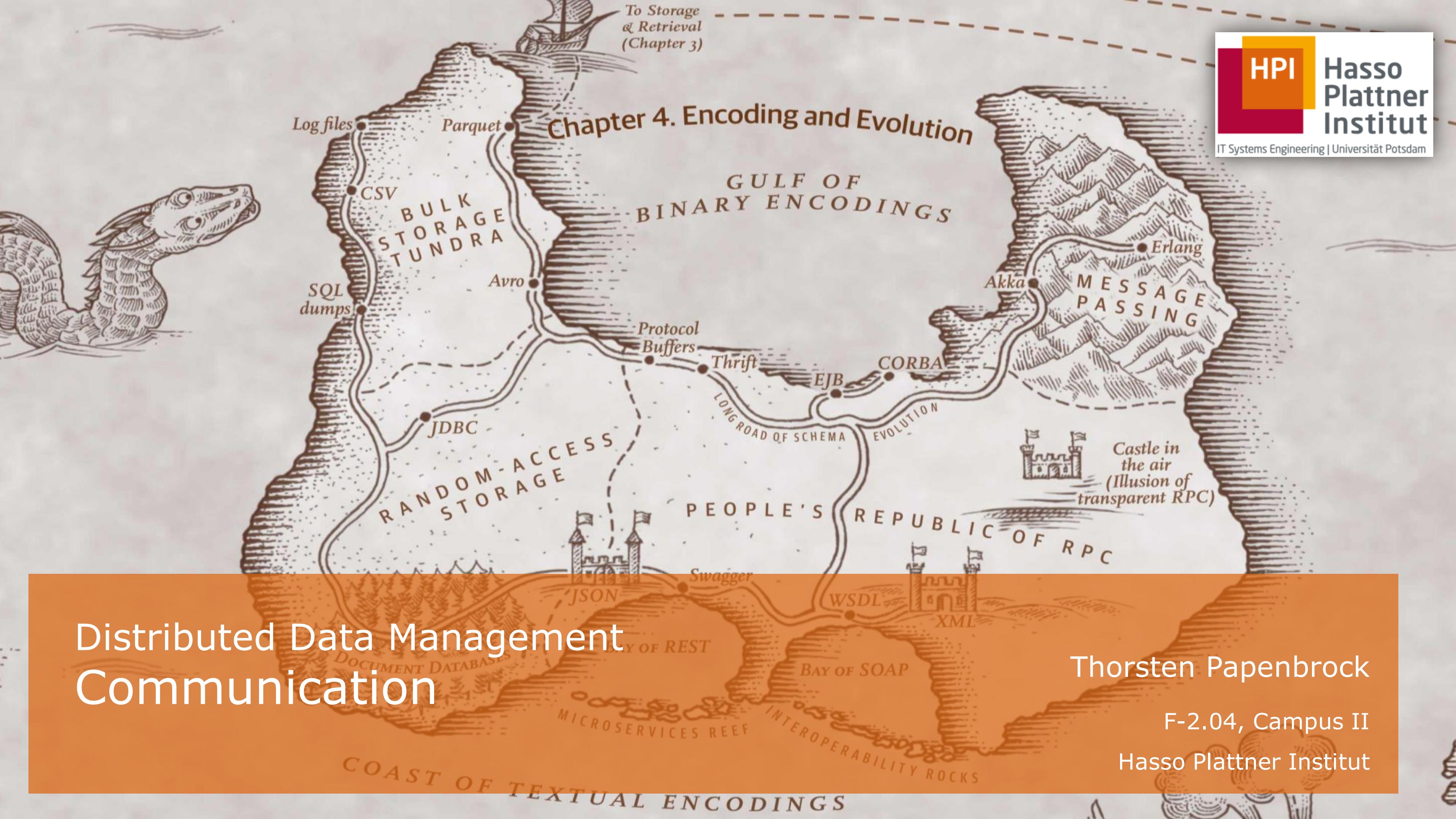
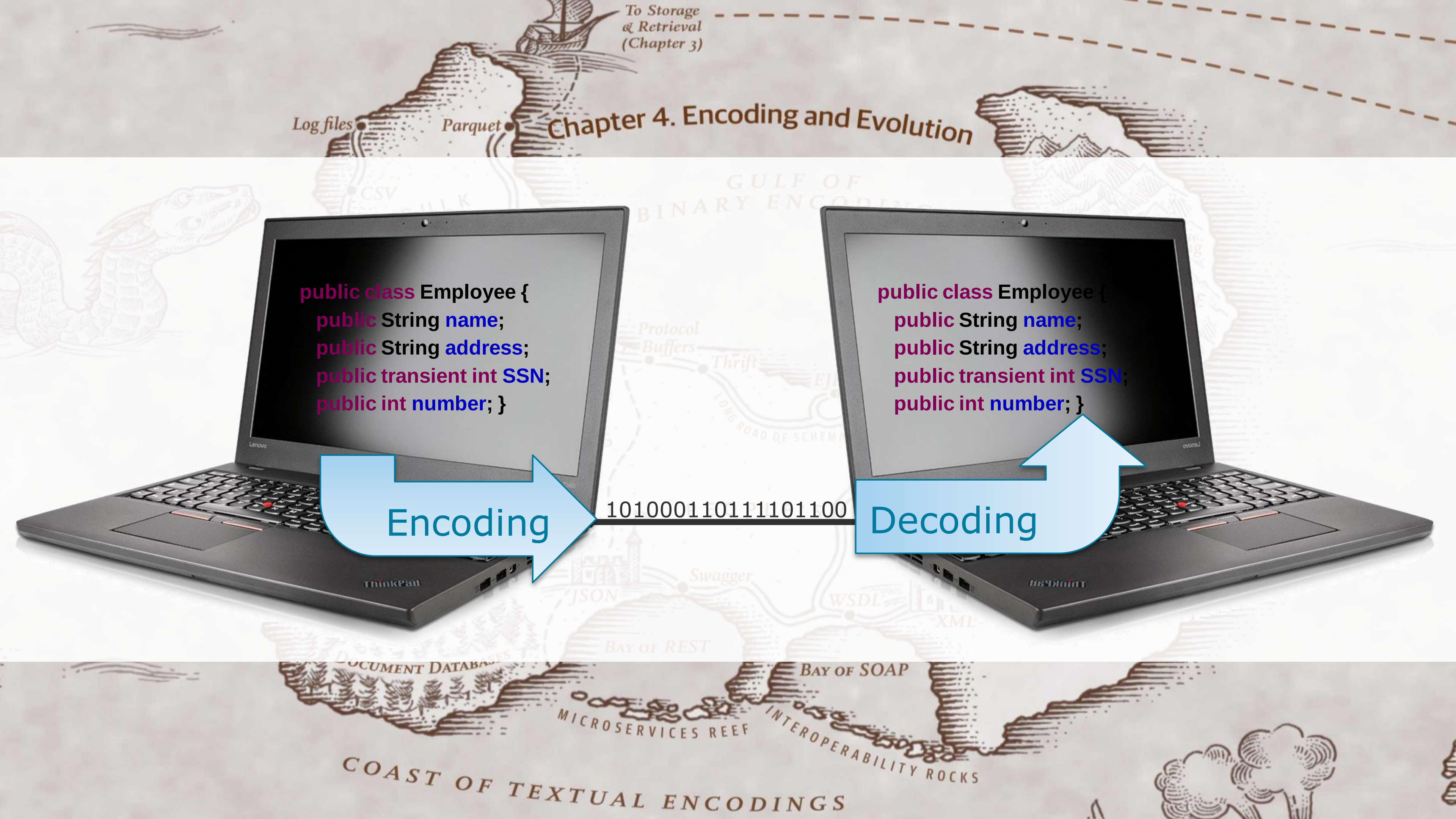


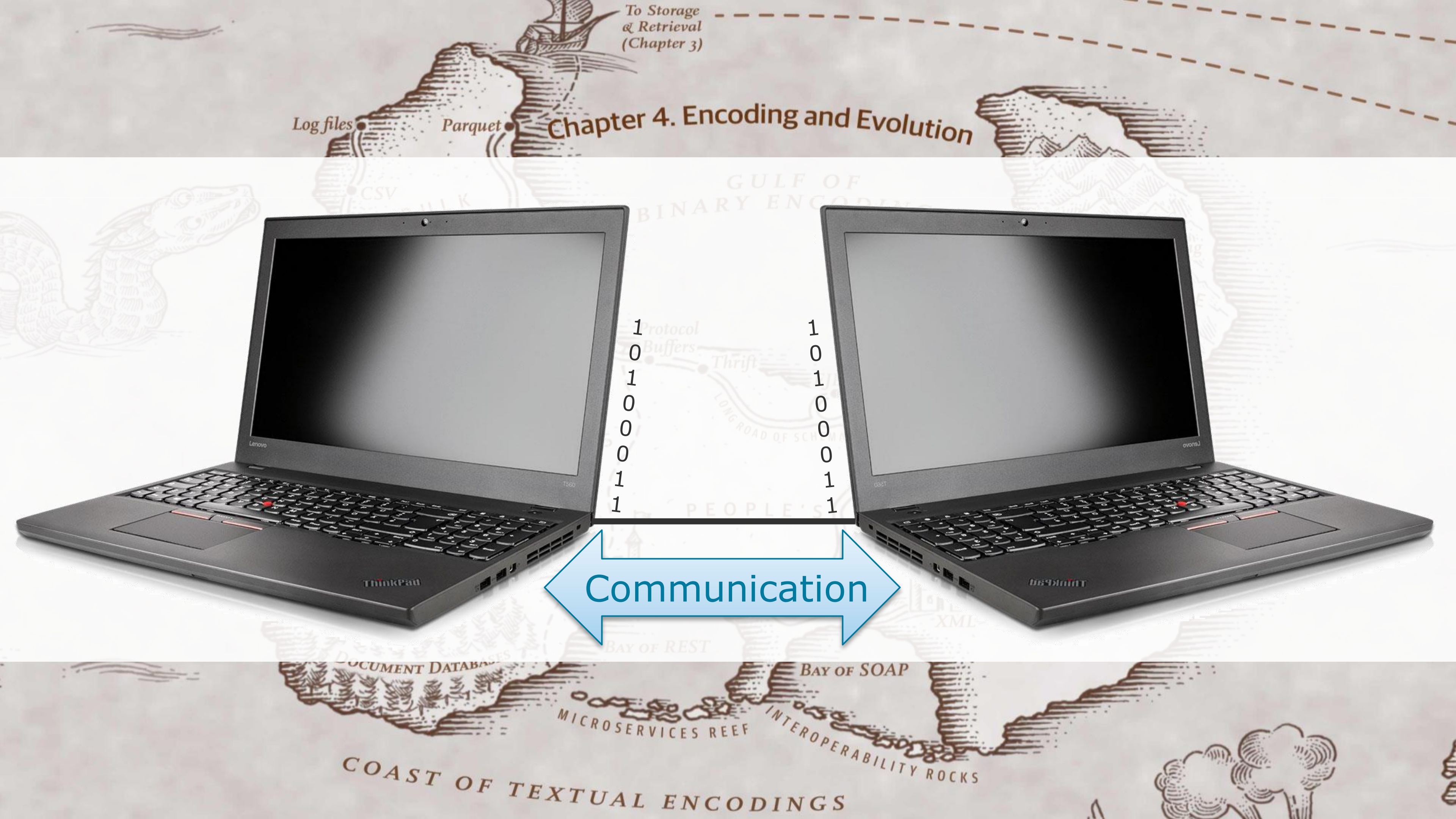
Distributed Data Management
Communication

Thorsten Papenbrock

F-2.04, Campus II

Hasso Plattner Institut


To Storage
& Retrieval
(Chapter 3)
Log files
Parquet
Chapter 4. Encoding and Evolution
public class Employee {
public String name;
public String address;
public transient int SSN;
public int number; }
Encoding
10100011011111101100
Decoding
public class Employee {
public String name;
public String address;
public transient int SSN;
public int number; }
GULF OF
CSV
Protocol
Buffers
Thrift
JSON
Swagger
WSDL
XML
BAY OF REST
BAY OF SOAP
MICROSERVICES REEF
INTEROPERABILITY ROCKS
COAST OF TEXTUAL ENCODINGS


Chapter 4. Encoding and Evolution
To Storage
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(Chapter 3)
Log files
Parquet
CSV
Protocol
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Thrift
1
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1
0
0
0
1
1
Communication
XML
Bay of REST
Bay of SOAP
Microservices Reef
Interoperability Rocks
Coast of Textual Encodings

Overview

Communication

- **Message Passing**
- OSI Model
- Socket-based Communication
- Message-oriented Middleware
- Service-oriented Middleware
- Database-oriented Middleware

Motivation

Processes communicate

- With themselves
- With other processes on the same machine
- With processes on remote machines over the network
  - ➢ Data often needs to pass process boundaries!

Processes are heterogeneous

- Different languages, address spaces, access rights, hardware resources, complexities, interfaces, …
  - ➢ Communication models/protocols needed!

Process communication is expensive

- Communication channels (buses, network, memory, …) have limited speed, bandwidth and throughput
  - ➢ Number and size of messages matters!

Terminology

Message Passing

- A communication model that restricts the exchange of information between independent entities to the actions of sending and receiving of messages.
- Entity: Thread, process, subroutine, function, object, actor, …
- Message (in some contexts "mail"):
  - Container for data that implies information or commands
  - Often carries metadata, e.g., size, receiver and sender information
  - Can have any format understood by sender and receiver
- Buffer (in some contexts "message queue" or "mailbox"):
  - Memory reserved by the communicating entities to store messages
  - (Usually) order messages by time of arrival and process them in order
  - A communication may involve multiple buffers
    (send buffers, system buffers, message queues, …)

Messages can have any format understood by sender and receiver

to enable replies

Message Passing

Thread Messaging

Arbitrary synchronization primitive (mutex, semaphore, barrier, monitor, …)

Sender (Thread)

Receiver (Thread)

```
ReentrantLock messageMutex = new ReentrantLock();
Queue<Work> messageQueue = new ArrayDeque<Work>();
```

= Shared Memory

Sender:

```
…
try {
   messageMutex.lock();
   messageQueue.offer(message);
} finally {
   messageMutex.unlock();
}
…
```

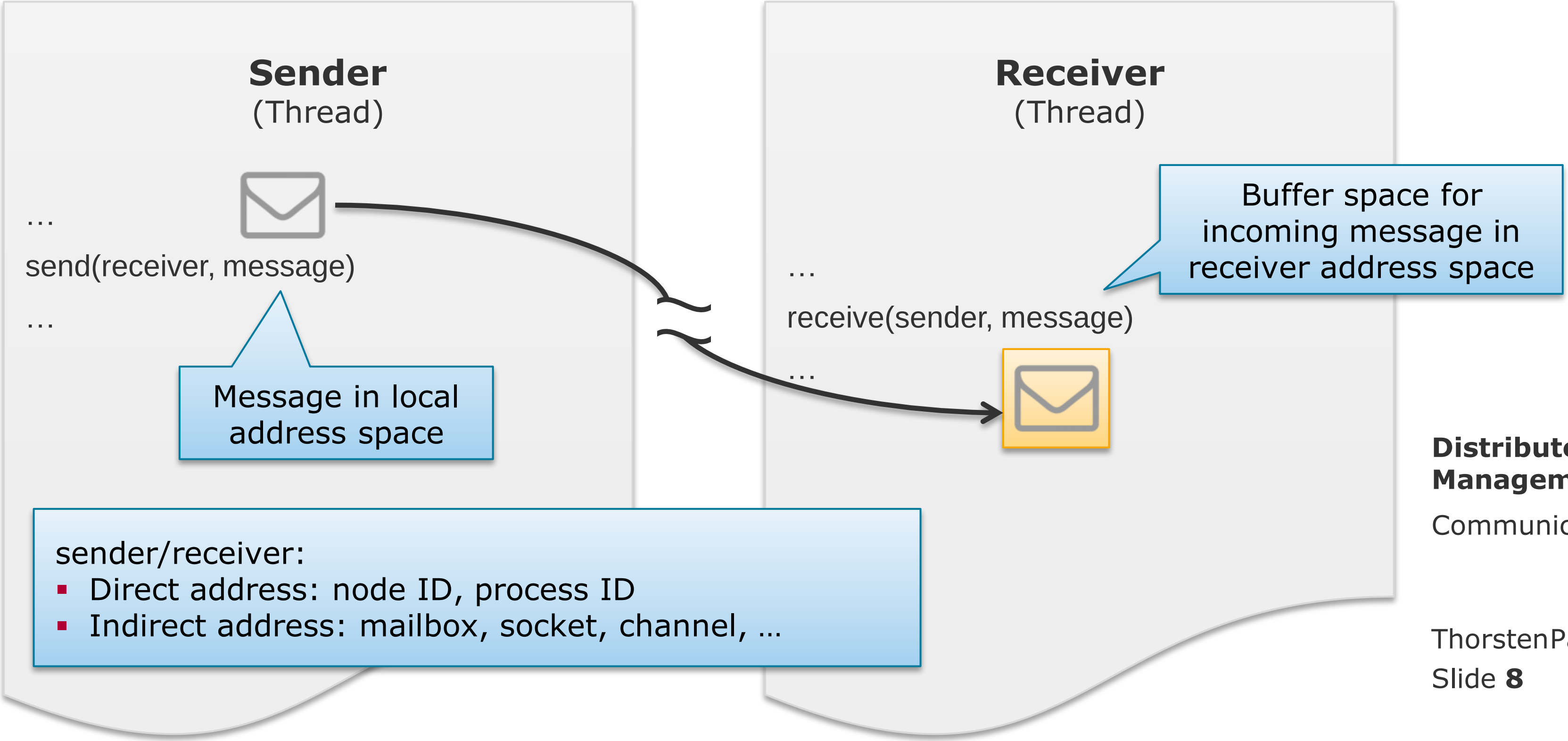
Receiver:

```
…
try {
   messageMutex.lock();
   message = messageQueue.poll();
} finally {
   messageMutex.unlock();
}
```

= Critical Section

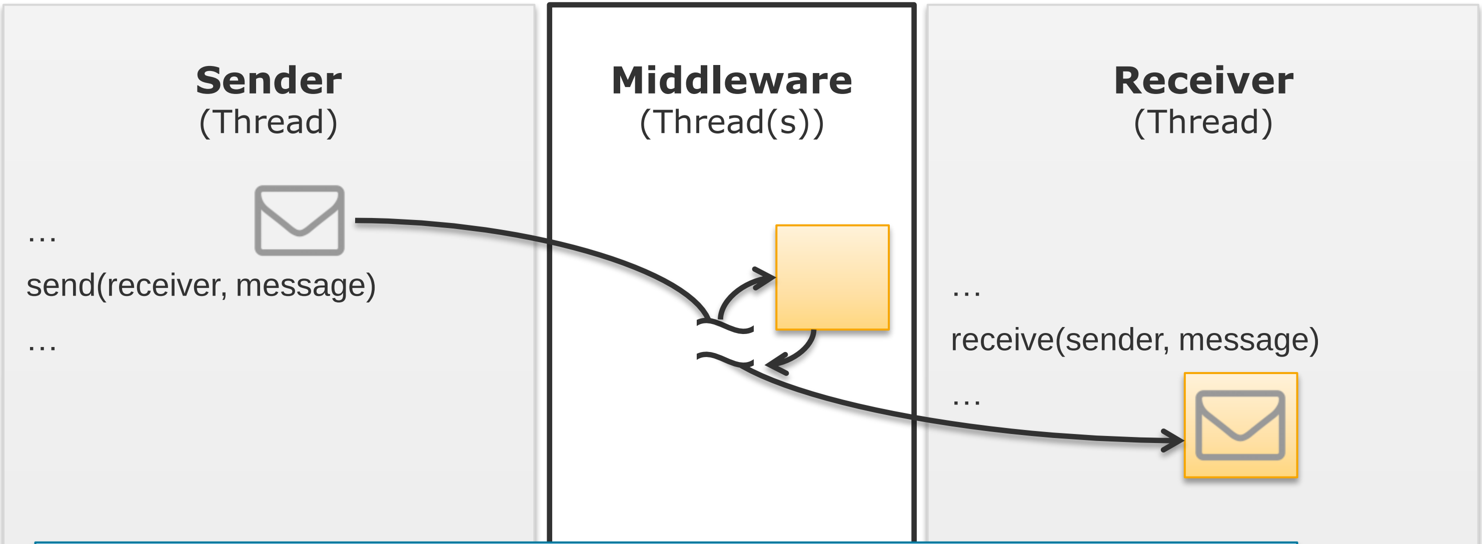
Does not work if sender and receiver live in different address spaces (i.e. processes)

Thread Messaging – Distributed Principle



sender/receiver:
- Direct address: node ID, process ID
- Indirect address: mailbox, socket, channel, …

Message Passing
Middleware

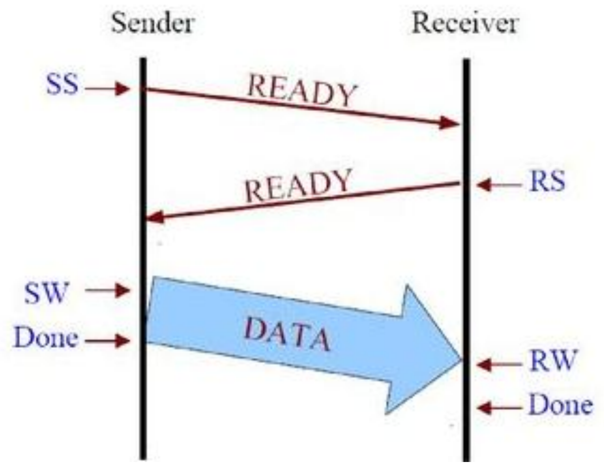


Middleware
- A distributed software layer that supports the message transfer
- Can provide additional buffers
- Usually lives partially in both the sender and the receiver address space

No Buffering vs. Buffering

No Buffering Communication

- The receiver allocates the memory for messages on demand.
- Requires rendezvou protocol on each message:
  1. Sender signals send attempt with the size of the message and waits.
  2. Receiver allocates memory when ready and signals readiness.
  3. Sender sends the message.



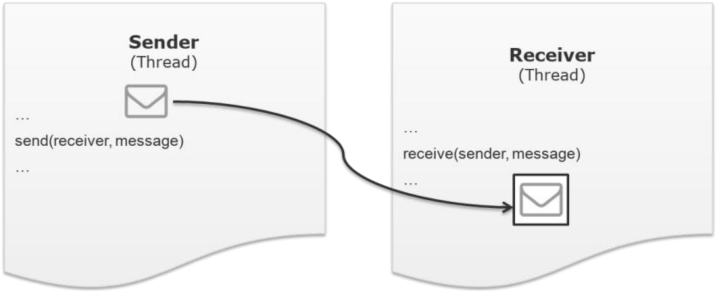
Buffering Communication

- The receiver maintains a pre-allocated buffer space for incoming messages.
- If the buffer is full, the sender blocks or drops the message.

Transient vs. Persistent

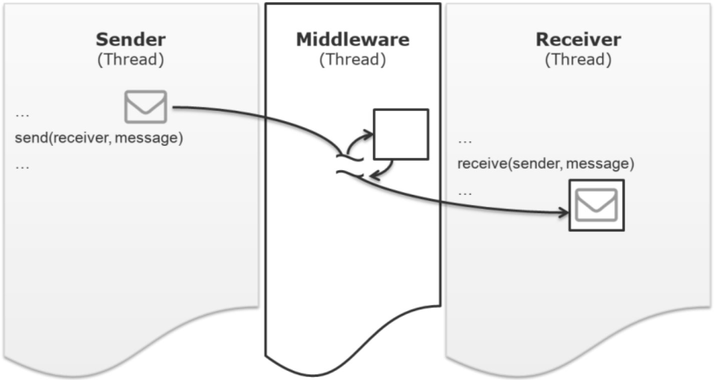
Transient Communication

- Message is copied directly from sender address space to receiver buffer.
- Both processes need to be active and memory for the message in the target buffer needs to be free.



Persistent Communication

- Message is first copied to a buffer inside the middleware and then send to the receiver.
- Middleware stores the message for as long as it takes to deliver it.



Synchronous vs. Asynchronous

Synchronous (blocking) Communication

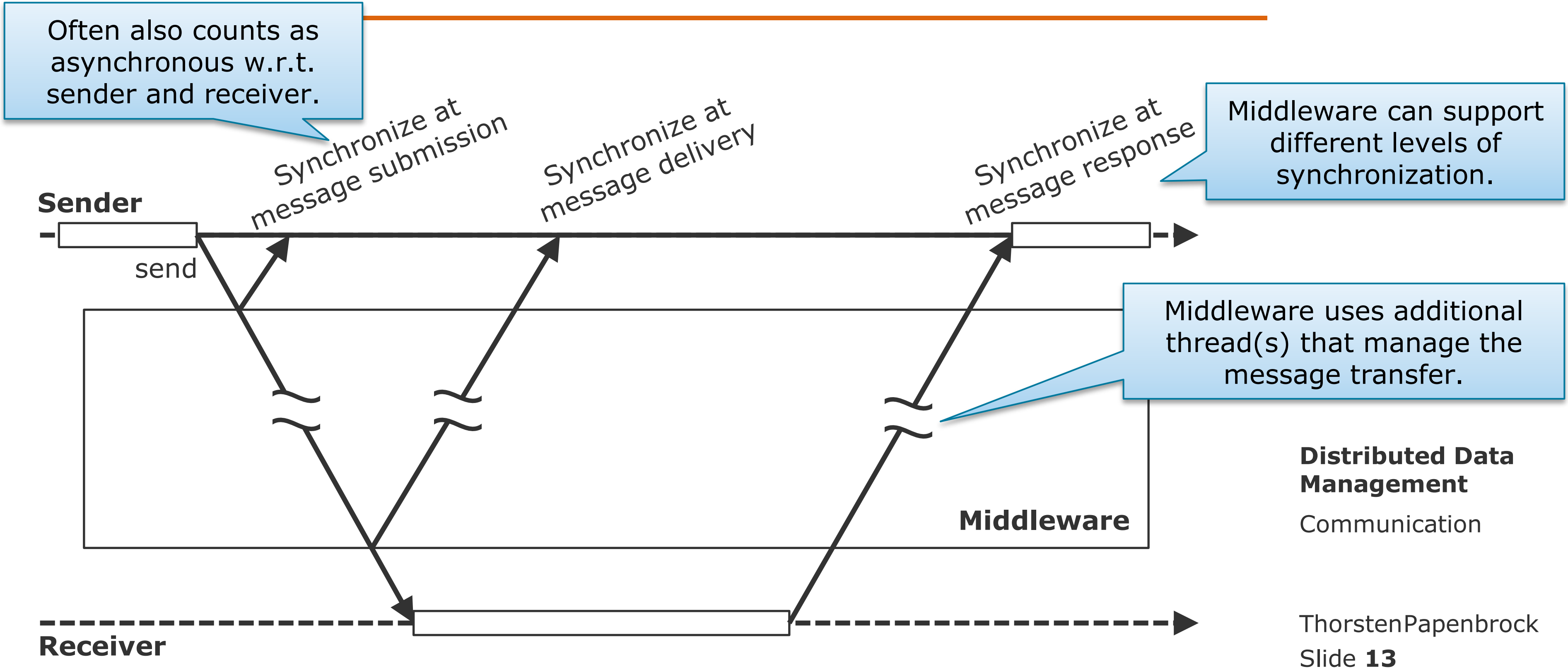
- Send() returns not until the data is copied out of its local message structure.
- Receive() returns when the message is fully received.
- After the returns:
  - The local messages/buffers can safely be modified.
  - Sender and receiver might know if the send succeeded.

Asynchronous (non-blocking) Communication

Requires middleware to transmit the data!

- Send() returns directly, which is before the data is copied out of the local message structure.
- Receive() returns directly either with message or status code.
- After the returns:
  - The local messages/buffers should not be modified.
  - Only receiver knows if the send succeeded.

Synchronization Levels with Middleware



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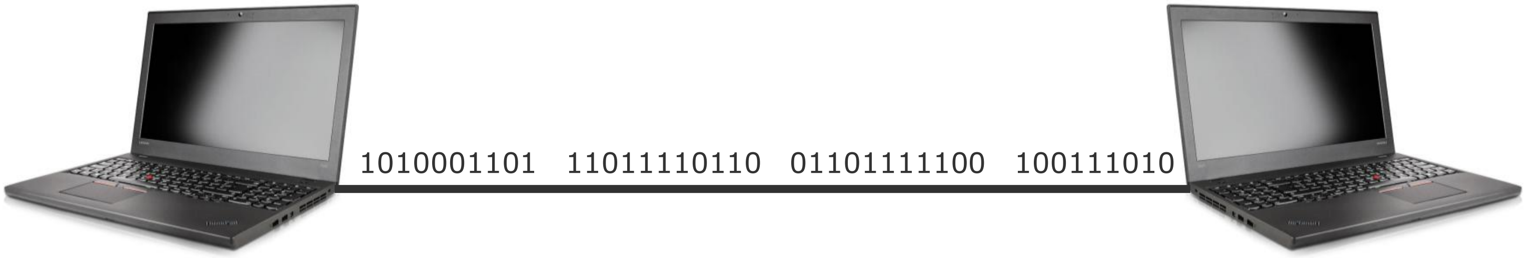
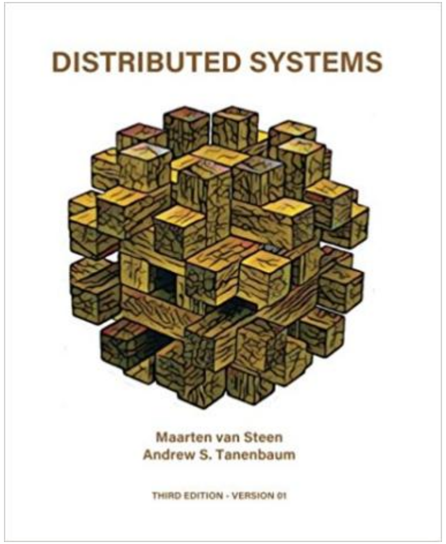
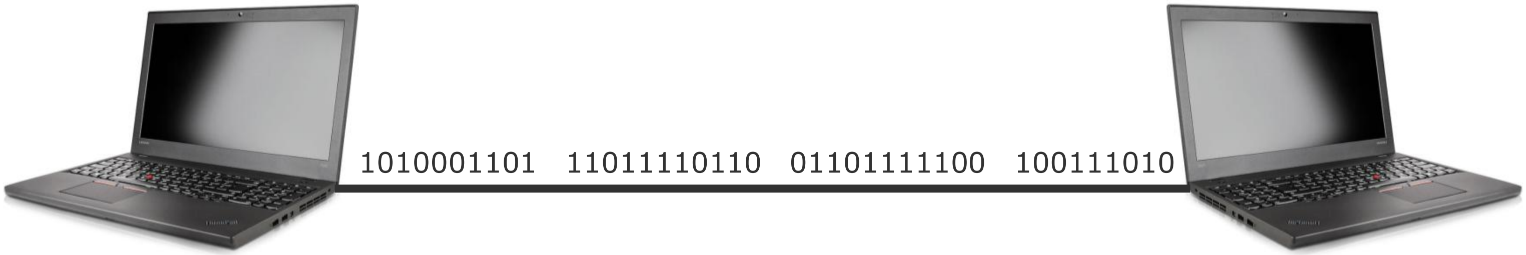
Distributed Communication



- Distributed system communication is always based on low-level message passing.
- Messages are serializes data with well defined (header) metadata.
- Higher-level communication principles based on message passing, services, or databases are implemented on top of low-level message passing subsystems.
- Message passing requires protocols for the exchange and routing of messages.



Distributed Communication



Communication Protocol

- Set of rules that govern the format, contents, and meaning of messages
- Provide standards for how to send and receive messages
- Is either connection-based (handshake before and after communication) or connectionless (no handshake, but simple message sends)

Phone call vs. dropping a letter

Open Systems Interconnection Reference Model (OSI Model)

- Layered model for network communication protocols
- Developed by the International Standards Organization (ISO) in 1983

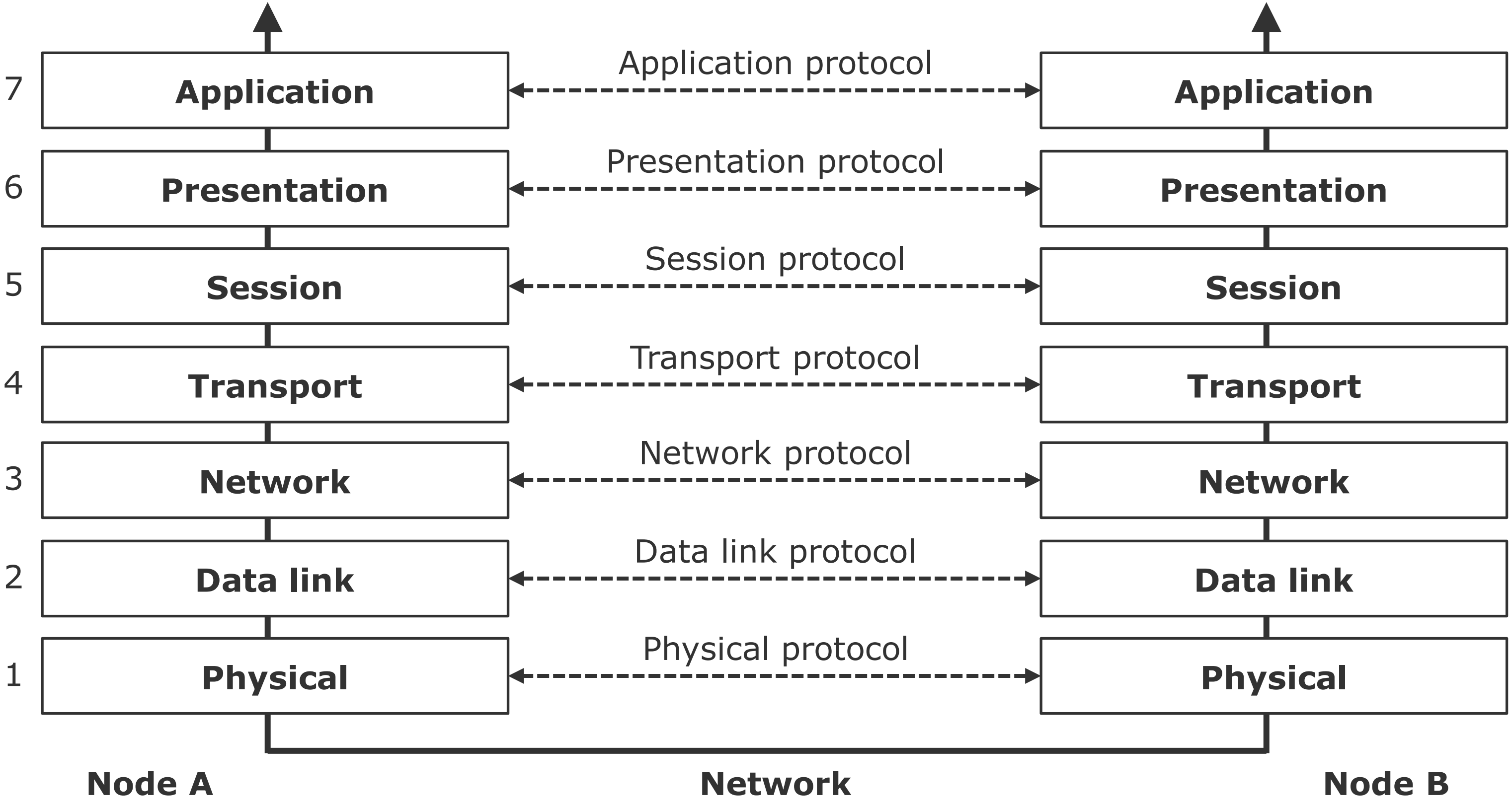
OSI Model
Communication Layers

7	**Application**	Application-specific protocols, such as e-mail, Web access or file transfer
6	**Presentation**	Description of the logical format of a message's serialized data
5	**Session**	Support for sessions between applications
4	**Transport**	Support for reliable communication or real-time streaming features
3	**Network**	Routing of messages in networks and handling message congestion via buffers
2	**Data link**	Means to detect/correct errors and keep sender/receiver in same pace
1	**Physical**	Standardization of the physical connection and representation of 0s and 1s

Network

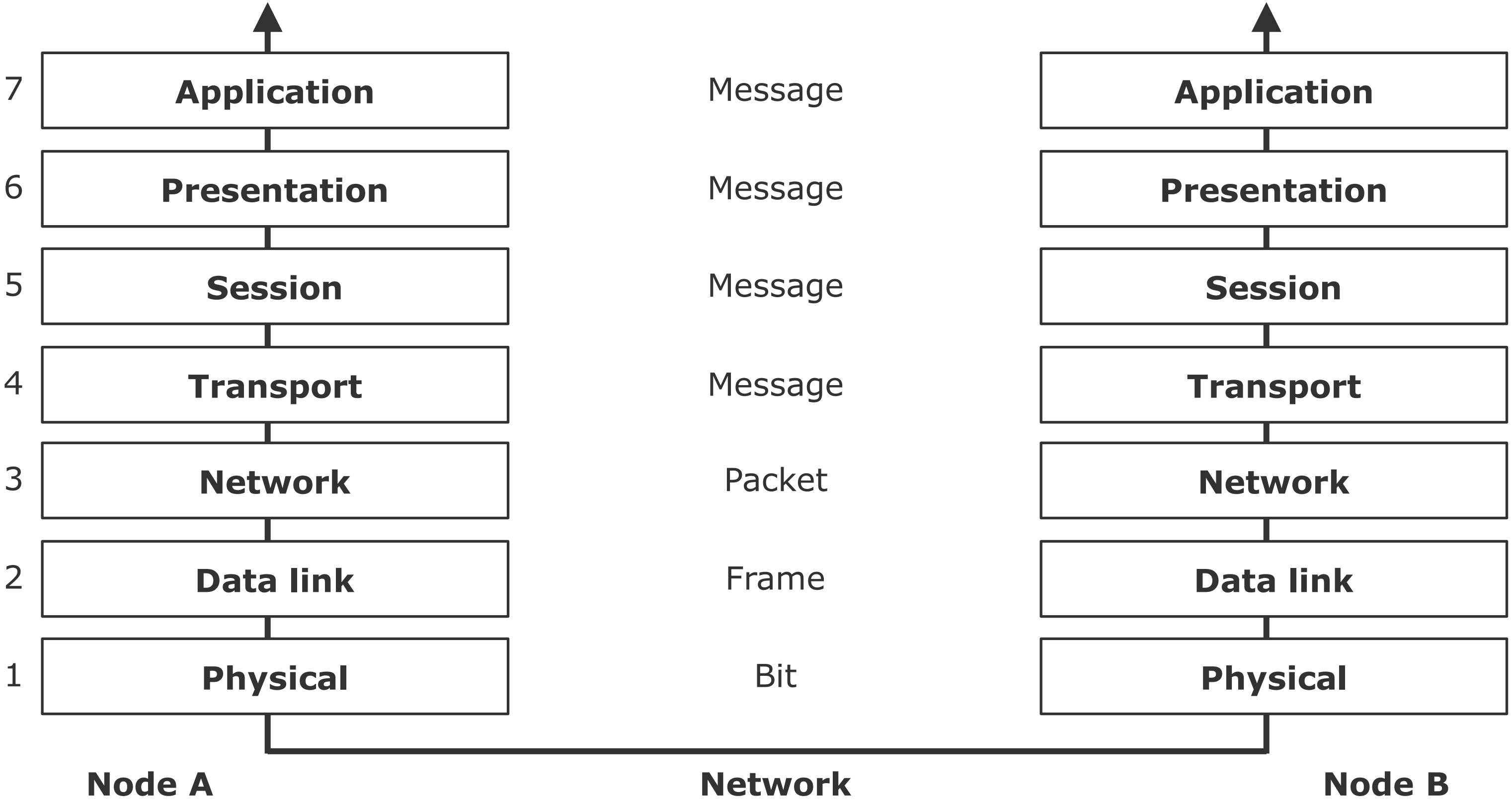
OSI Model

Communication Protocols

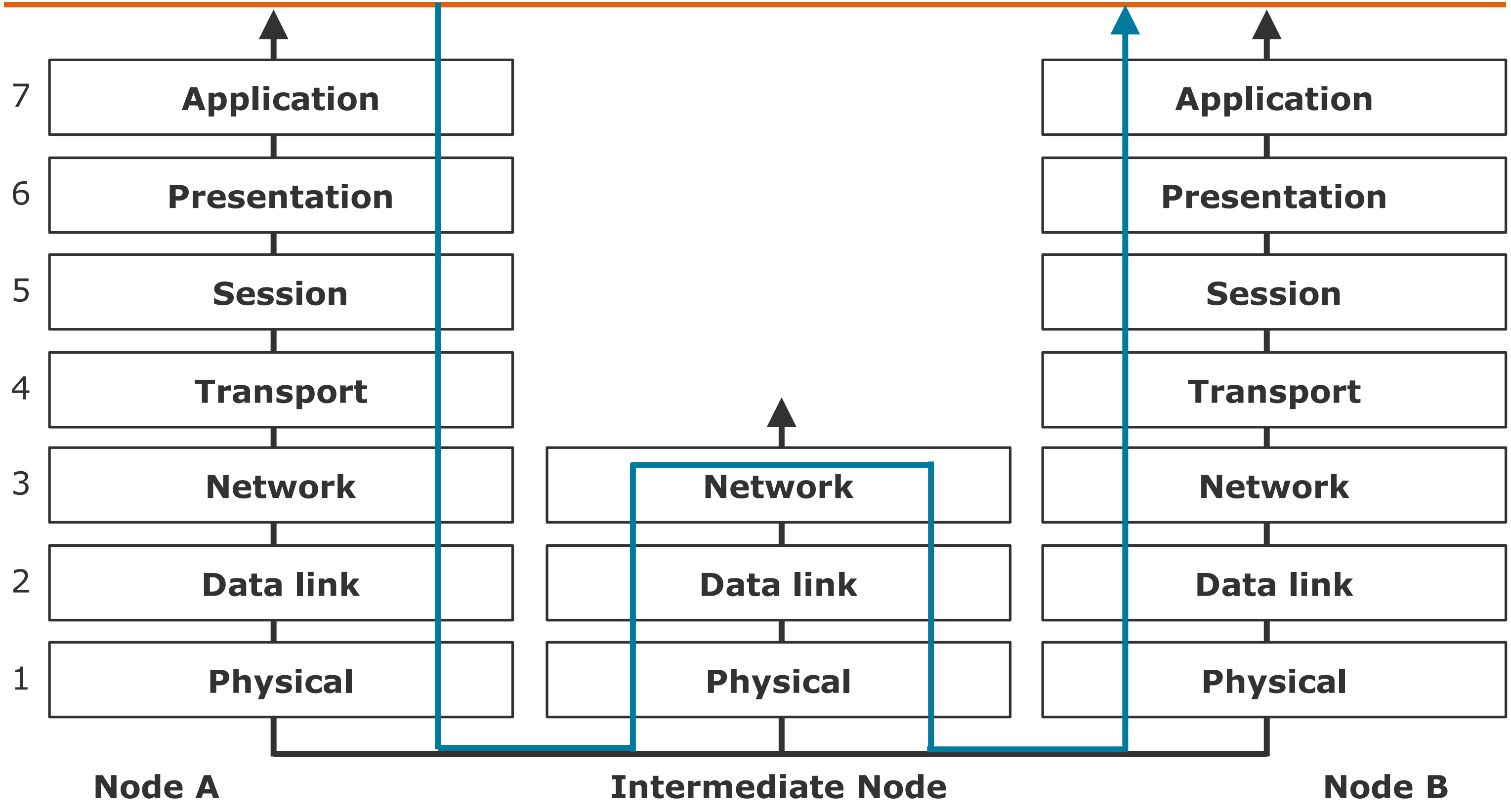


OSI Model

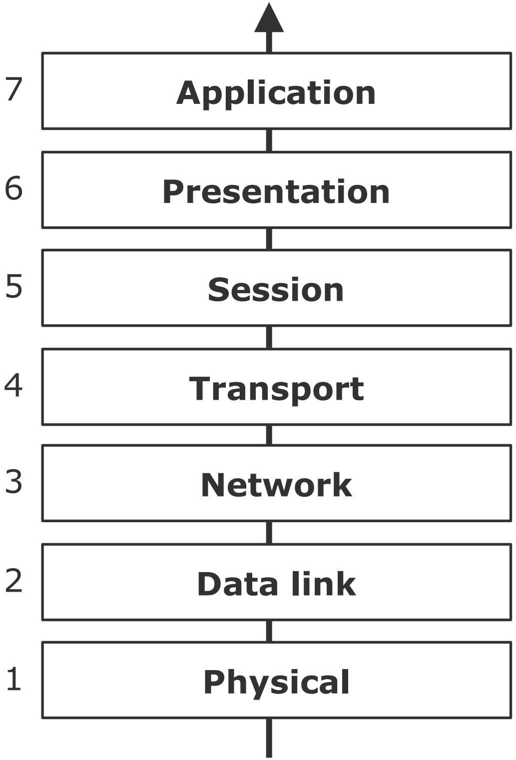
Communication Formats



OSI Model
Intermediate Nodes



Protocol Examples



7. Application layer

NNTP · SIP · SSI · DNS · FTP · Gopher · HTTP · NFS · NTP · SMPP · SMTP · SNMP · Telnet · DHCP · Netconf · *more....*

6. Presentation layer

MIME · XDR · ASN.1 · ASCII · PGP

5. Session layer

Named pipe · NetBIOS · SAP · PPTP · RTP · SOCKS · SPDY

4. Transport layer

TCP · UDP · SCTP · DCCP · SPX

3. Network layer

IP (IPv4 · IPv6) · ICMP · IPsec · IGMP · IPX · AppleTalk · X.25 PLP

2. Data link layer

ATM · ARP · IS-IS · SDLC · HDLC · CSLIP · SLIP · GFP · PLIP · IEEE 802.2 · LLC · MAC · L2TP · IEEE 802.3 · Frame Relay · ITU-T G.hn DLL · PPP · X.25 LAPB · Q.922 LAPF

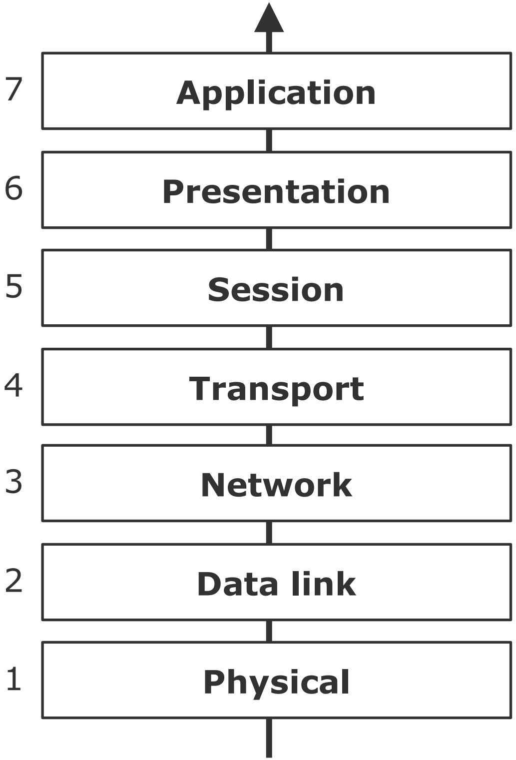
1. Physical layer

EIA/TIA-232 · EIA/TIA-449 · ITU-T V-Series · I.430 · I.431 · PDH · SONET/SDH · PON · OTN · DSL · IEEE 802.3 · IEEE 802.11 · IEEE 802.15 · IEEE 802.16 · IEEE 1394 · ITU-T G.hn PHY · USB · Bluetooth · RS-232 · RS-449

- Physical standards for network devices and interconnects
- E.g. volt specifications for 1 and 0, transmission rates, size and shape of connectors, …

OSI Model

Protocol Examples



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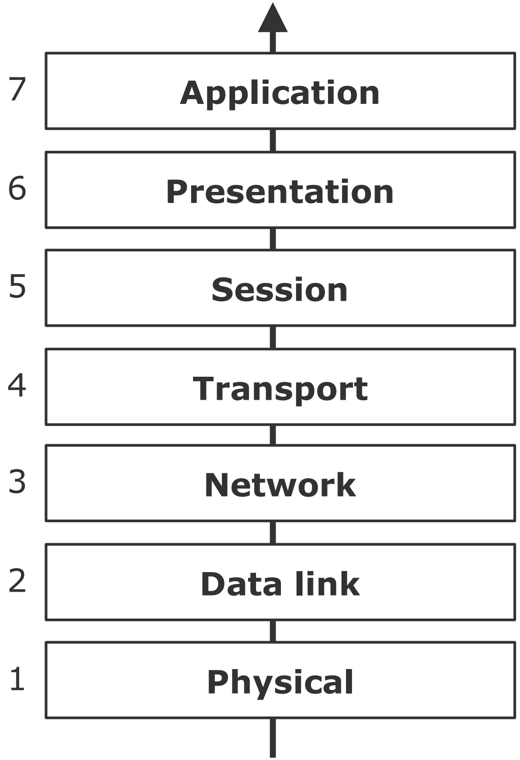
- Sending of datagrams in local network
- Direct host-to-host messaging; no routing
- Addressing e.g. via MAC address
  - e.g. 34:f3:9a:fa:fb:59
- Hardware dependent
  - ➢ drivers needed
- Abstracting hardware details to above layers

➢ Packetizing, (local) addressing, transmission and receiving of data

Protocol Examples



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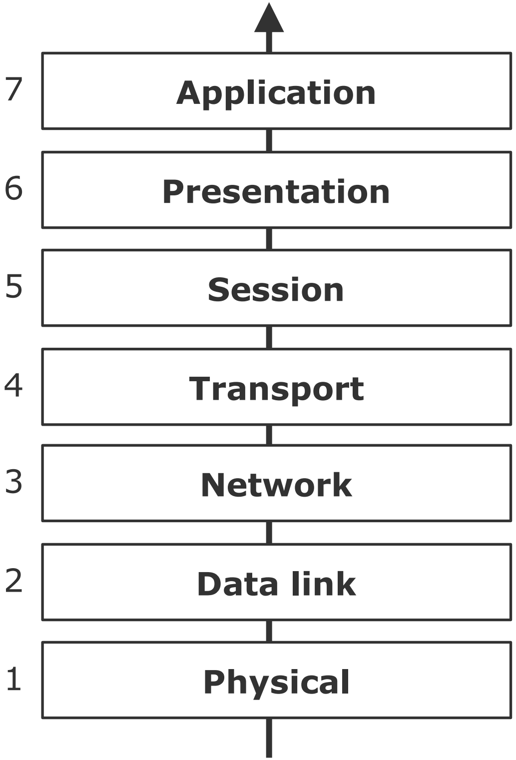
- Routing of datagrams across networks
- Addressing e.g. via IP addresses
  - for addressing and routing
  - map to MAC addresses
  - e.g. 172.17.5.57
- Abstracting the actual network topology to above layers

➢ Packetizing, (global) addressing and routing of data

OSI Model
Protocol Examples



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- Managing the datagram exchange
  - host-to-host (via arbitrary hops)
  - communication protocol
  - communication channel
- Port numbers for application addressing
  - e.g. 8080
- Abstracting communication details to above layers

➢ Packetizing of data

OSI Model

Protocol Examples

TCP

- reliable (flow control)
- connection-based
- slow
- ➢ lost-message resents
- ➢ message ordering
- ➢ error correction
- ➢ duplicate removal
- ➢ congestion control

UDP

- unreliable
- connectionless
- fast

7. Application layer

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$\boxed{\text{TCP}}$ · $\boxed{\text{UDP}}$ · SCTP · DCCP · SPX

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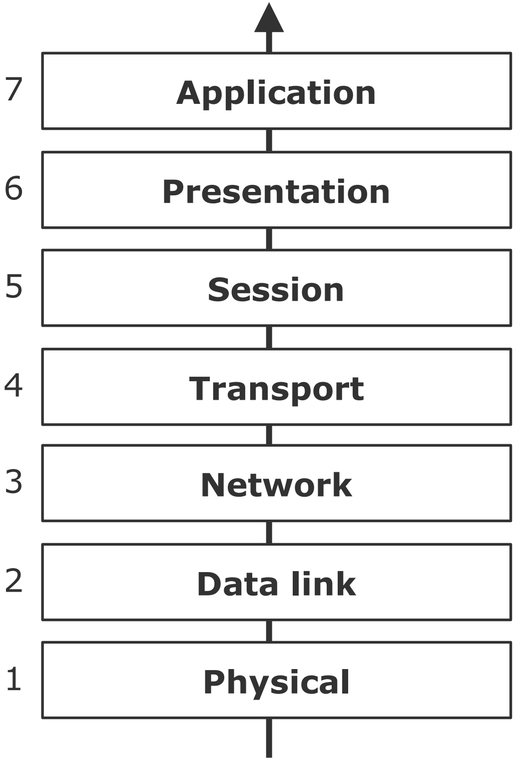
OSI Model
Protocol Examples



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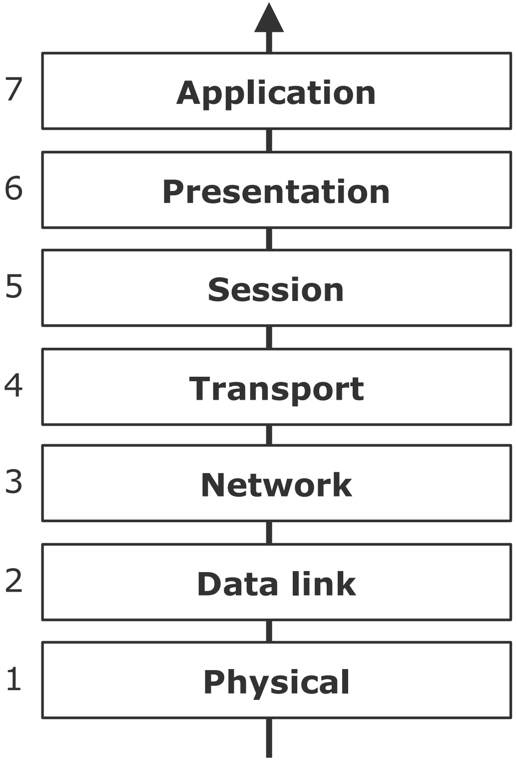
- Software layers
- Creation and interpretation of data
- Also: "Your application"
- Not all communication requires protocols from these layers

- Use the (reliable or unreliable) channels (identified by IP + Port) to send/receive data
- Higher level communication protocols
  - client-server
  - peer-to-peer
- "IP + Port + Application" is a service

OSI Model

Protocol Examples



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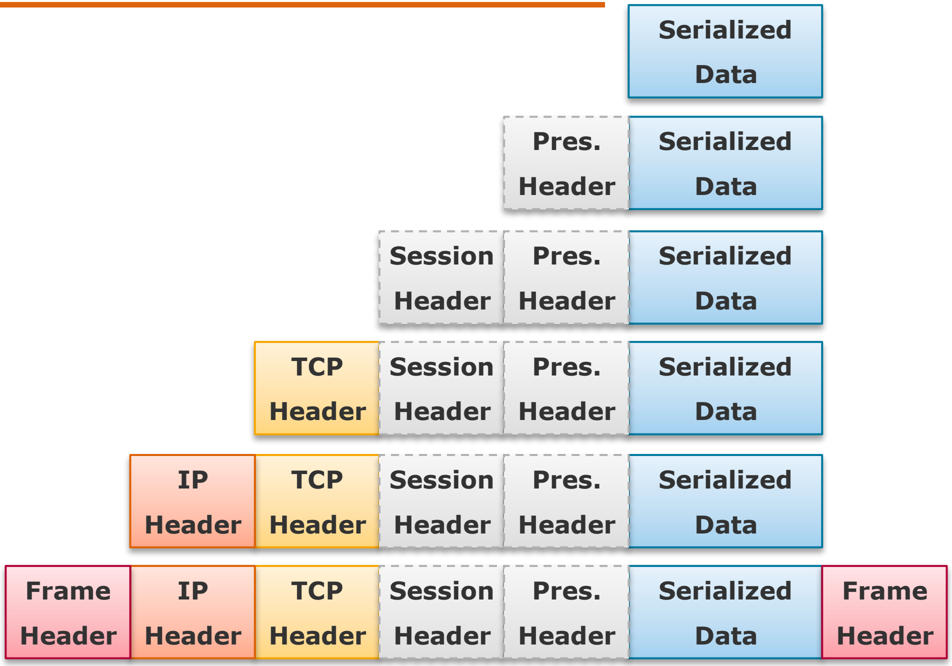

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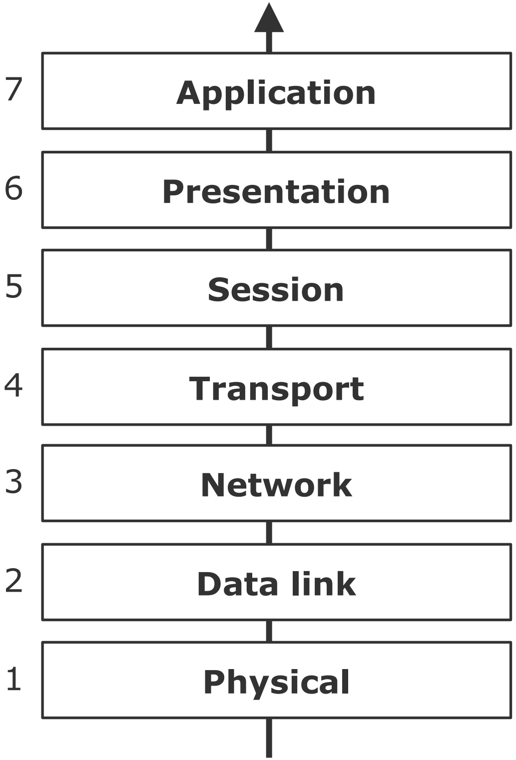

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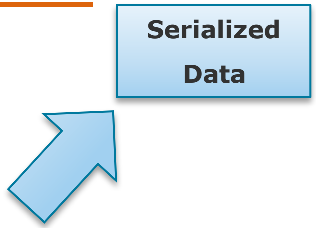
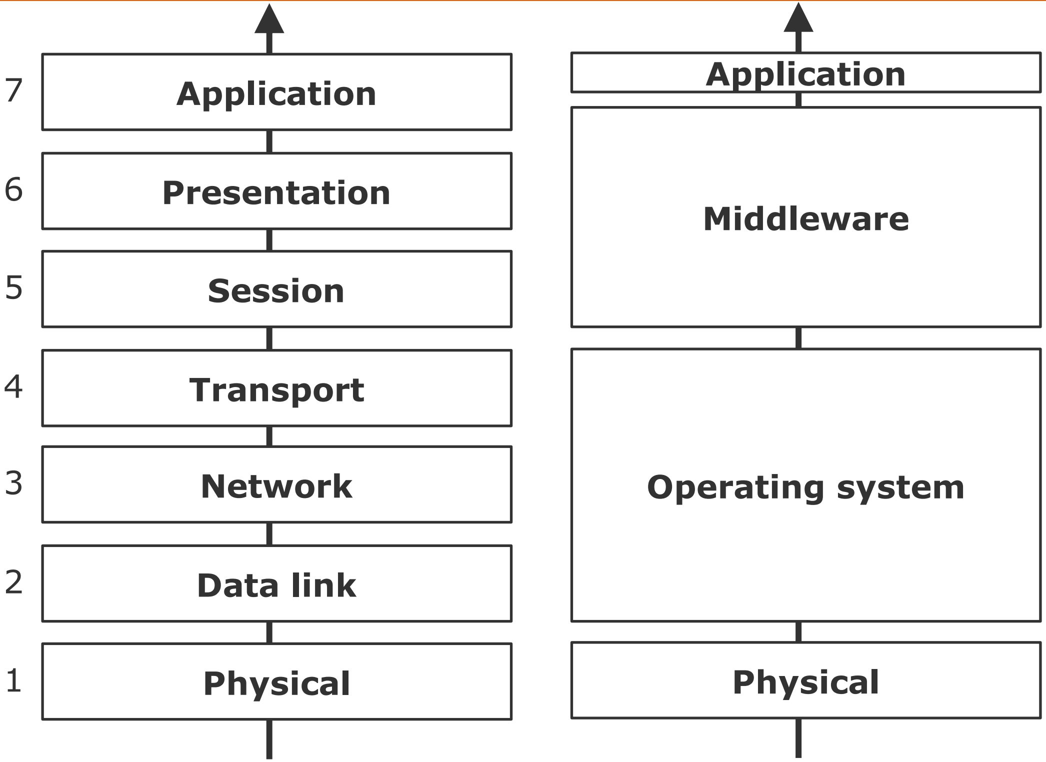


Von Neumann architecture:

- Messages may contain data and/or instructions.
- The application needs to interpret the messages.

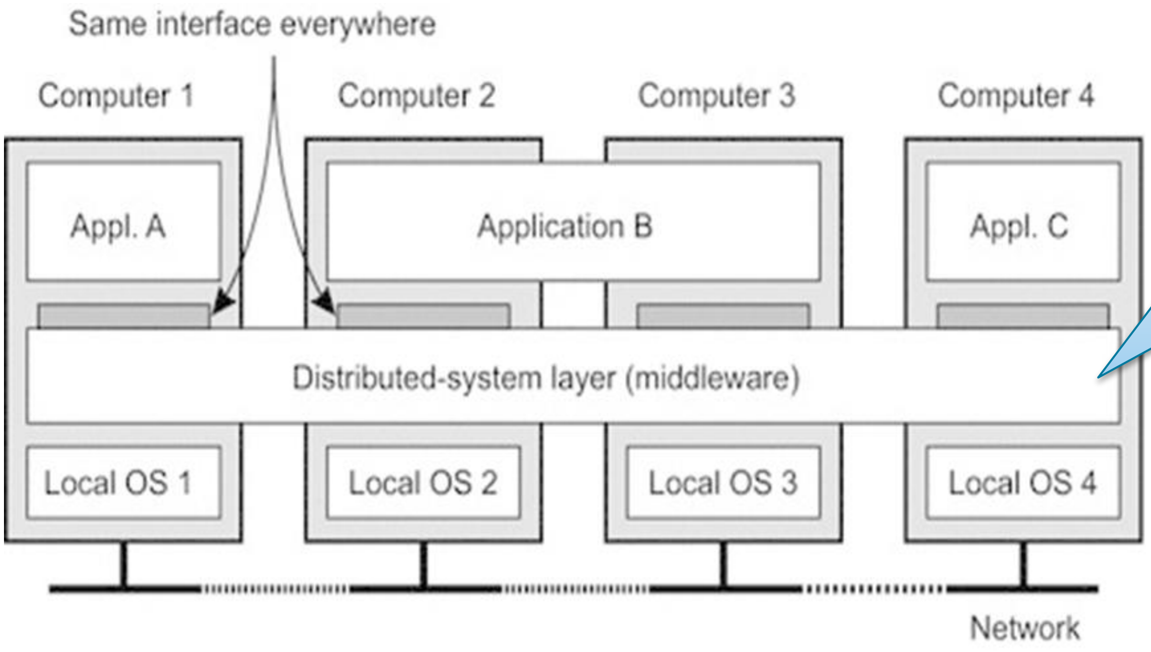
Middleware



Middleware

- A special layer for distributed systems that covers application, presentation and session layer protocols.
- Offers same APIs to applications
- Hides OS and hardware differences
- Can introduce communication principles other than basic message passing
- Eases the development of distributed software
- Examples:
  - RPC frameworks
  - Distributed databases
  - Actor models
  - Message broker
  - SOAP

OSI Model
Middleware



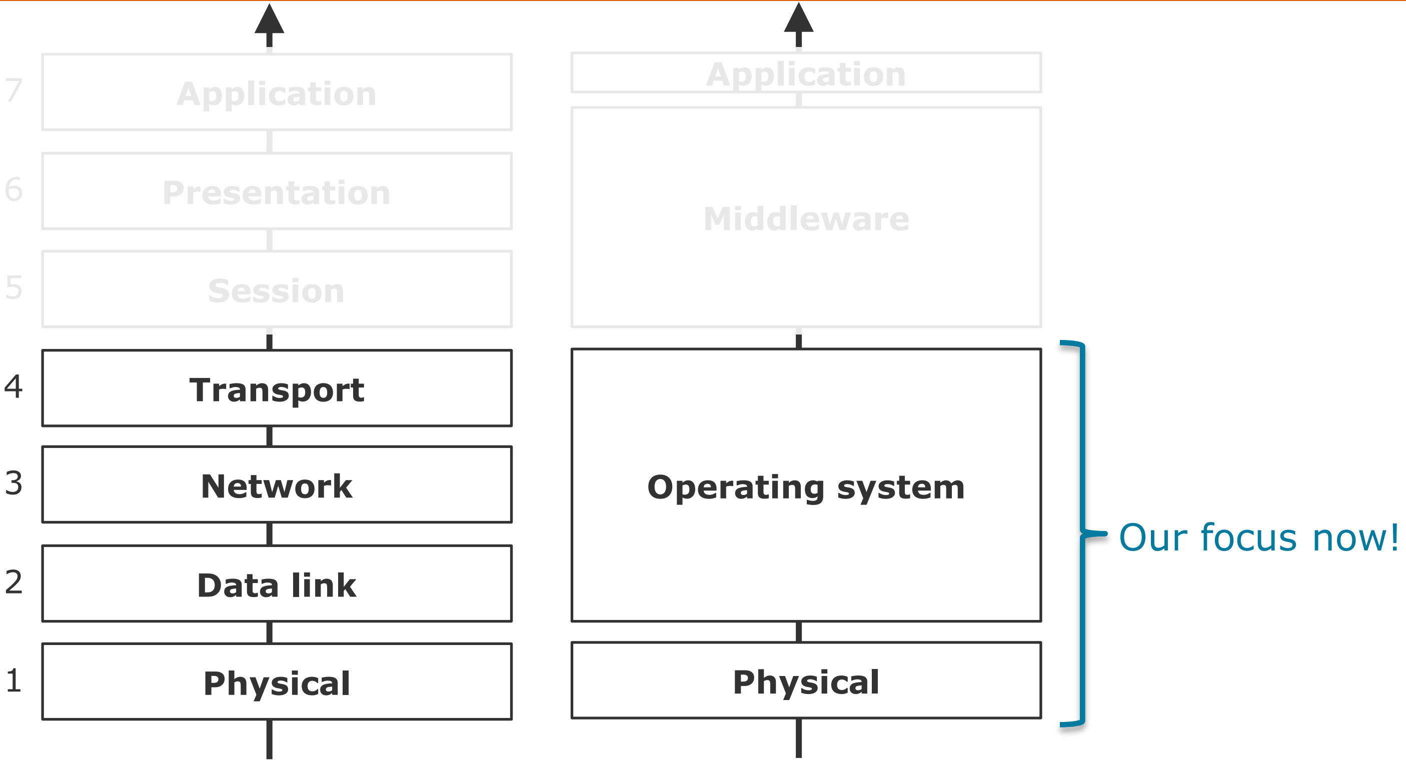
Middleware can be seen as one system that stretches multiple computers providing the same services on every computer.

Overview

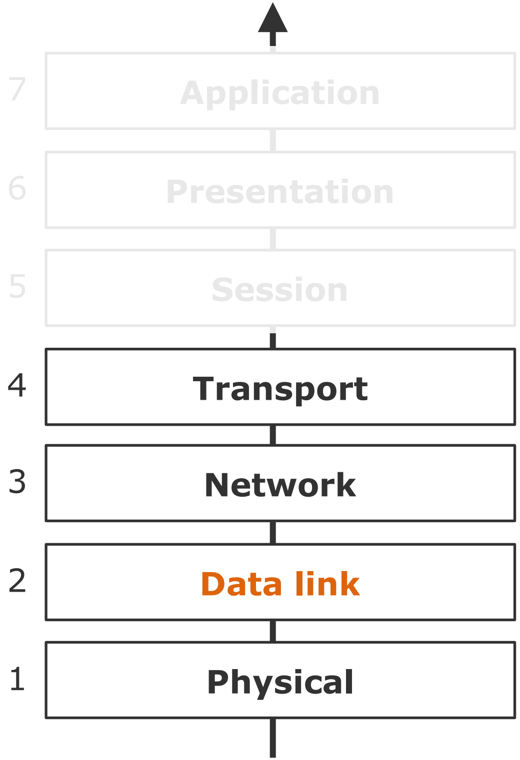
Communication

- Message Passing
- OSI Model
- **Socket-based Communication**
- Message-oriented Middleware
- Service-oriented Middleware
- Database-oriented Middleware

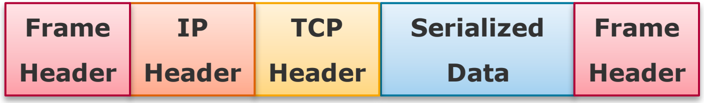
Low-level Message Passing



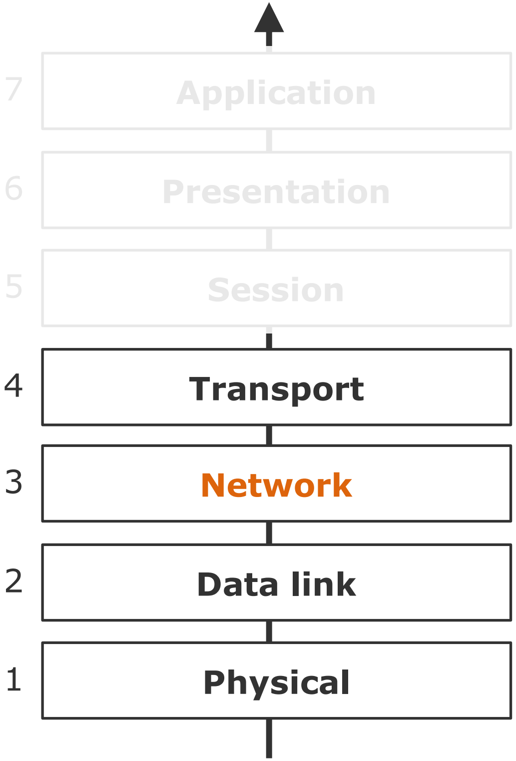
Low-level Message Passing



- Listens on the network.
- Checks every incoming message on whether it is addressed to this node's MAC.
- If yes, it serves the message to the network layer protocol.



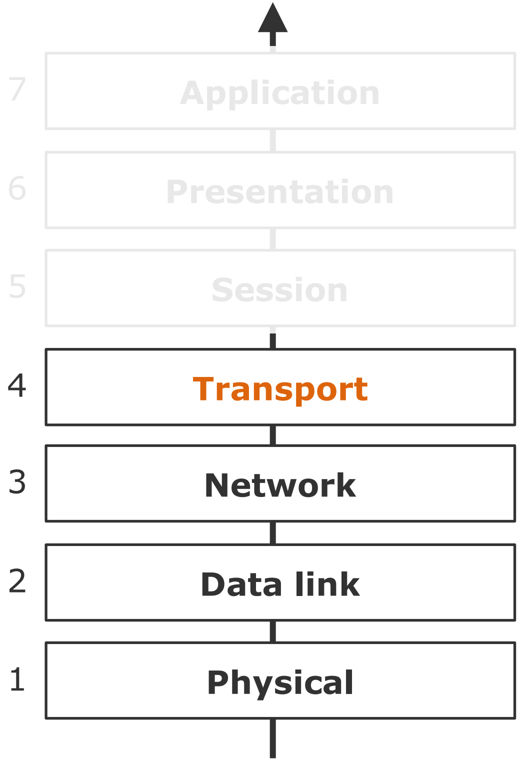
Low-level Message Passing



- Provides system buffer space for messages.
- Checks every incoming message on whether it is addressed to this node's IP.
- If yes, serves the message to the transport layer protocol.
- If no, finds the IP for the next best hop and serves the message back to the data link protocol.

IP Header	TCP Header	Serialized Data

Low-level Message Passing

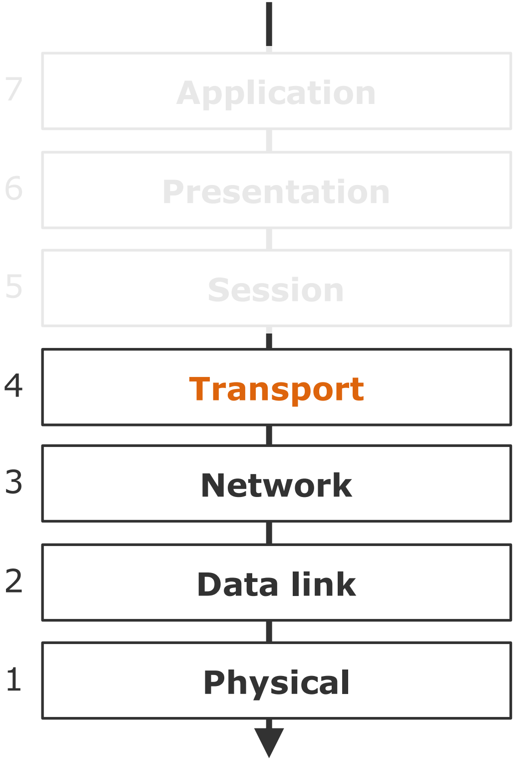


- Re-assembles data into logical messages.
- Serves the message to a communication end point provided by the operating system.

- Lots of other services:
  - Connections
  - Reliable message sends
    (e.g. via re-sending/re-questing lost messages)
  - Streaming
  - …

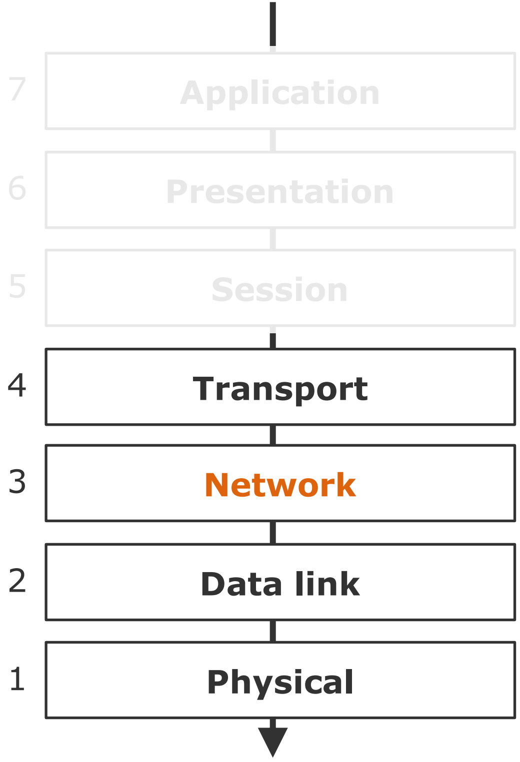
Socket-based Communication

Low-level Message Passing

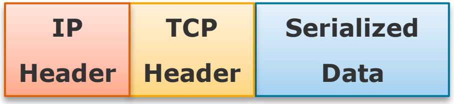


- Is triggered when a new message has been copied into a communication end point.
- Splits the message into smaller, equally-sized parts, which better fit low-level buffer sizes (in e.g. the data link layer).
- Serves the message to the network layer.

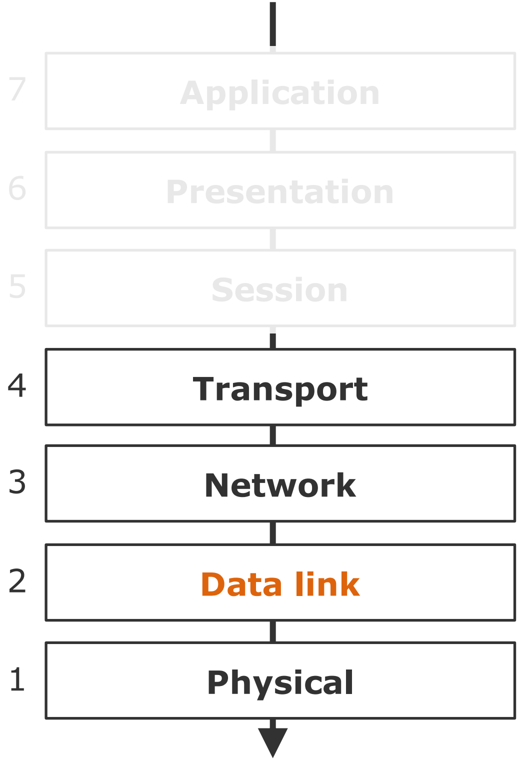
Low-level Message Passing



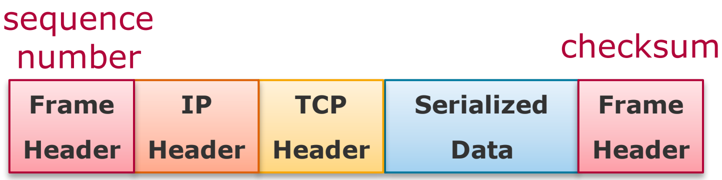
- Provides system buffer space for outgoing messages.
- Finds the IP for the next best hop and serves the message to the data link protocol.
- Serves the message to the data link layer.



Low-level Message Passing



- Frames the data with the target's MAC, a sequence number and a checksum.
- Sends the frame to the physical layer and, hence, the network.
- If messages collide or bits get damaged, the message is resend (sequence numbers and checksums help to detect this).

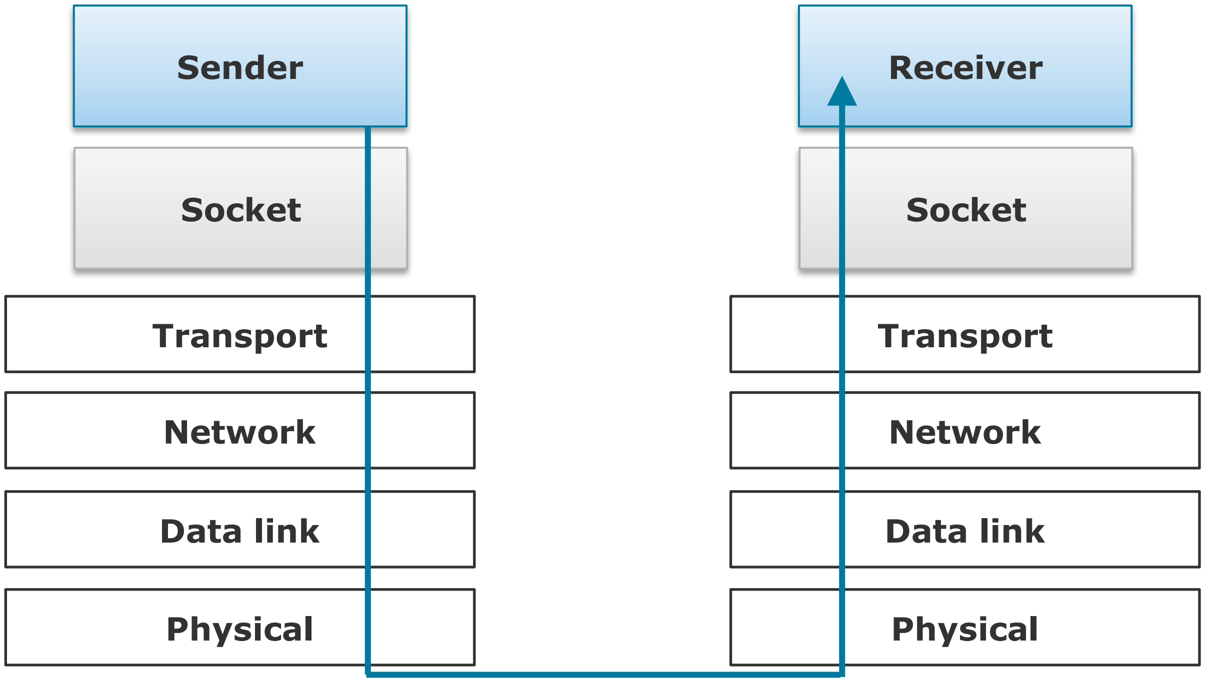


Sockets

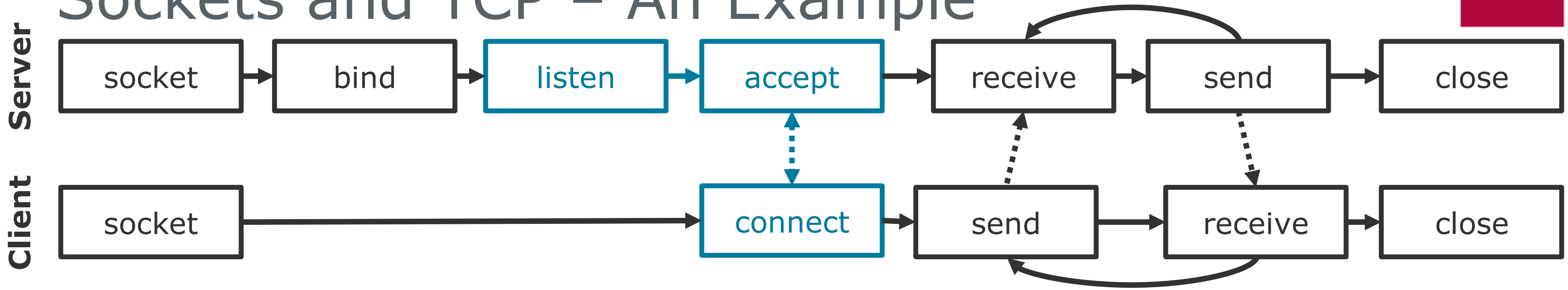
Socket

- A socket is a communication end point to which an application can write data that are to be send out over the underlying network, and from which incoming data can be read.
  - Sockets are buffers to exchange messages with the transport layer.
  - Sockets are described by protocol (usually TCP or UDP), IP address and port number.
  - Sockets are symmetric, i.e., both sender and receiver must speak the same protocol.
  - Think of a file to which the application can hold a handle (sometimes sockets actually have file semantics, as in Java).
  - Both application and transport layer have access to the socket.
    - Read/Write operations to sockets need to be synchronized.
  - Different socket implementations exist, but the interface is standardized.
  - Sockets are by far the most popular form of cross-platform inter-process communication primitives and used within most distributed systems.
  - Date back to RFC 147 (ARPANET, 1971) and Berkeley's BSD Unix (1983)

Sockets


Sender
Socket
Transport
Network
Data link
Physical
Receiver
Socket
Transport
Network
Data link
Physical

Sockets and TCP – An Example



Operation	Description
socket	Create a new connection end point; allocate system resources.
bind	Associate a specific local address (IP and port) with a socket; if not called, OS will dynamically allocate a port und use the local IP (see client).
listen	Specify maximum number of pending connections; OS will buffer these requests.
accept	(blocking) Create a new socket for an arriving request to represent the connection: original socket for further connection requests; new socket for this specific connection (e.g., to fork a dedicated thread).
connect	(blocking) Attempt to establish a connection with a remote end point; uses a three-way handshake to exchange request, final port number and acknowledgement.
send	Send some data over the connection.
receive	Receive some data over the connection.
close	Release the connection, i.e., socket resources and bindings.

Steps that move a communication to a dedicated socket and, in this way, make it **connection-based**.

Sockets and TCP – An Example in Python

Server

```
from socket import *
s = socket(AF_INET, SOCK_STREAM)   # Specifies socket type; STREAM is for TCP
s.bind(“192.168.0.1”, 80)          # Binds to IP and port
s.listen(1)                        # Allows 1 pending wait spot
(sc, addr) = s.accept()            # Returns new socket and client addr
while True:
   data = sc.recv(1024)            # Receives 1024 bytes
   if not data: break              # Stops if client stopped
   sc.send(str(data)+”*”)          # Sends received data plus an “*”
sc.close()                         # Closes the connection
```

These two codes design an application protocol!

Client

```
from socket import *
s = socket(AF_INET, SOCK_STREAM)   # Specifies socket type
s.connect (“192.168.0.1”, 80)      # Connects to server
s.send(”hello”)                    # Sends a string message
data = conn.recv(1024)             # Receives 1024 bytes
print data
s.close()                          # Closes the connection
```

Sockets and TCP – An Example in Python


```
from socket import *
s = socket(AF_INET, SOCK_STREAM)
s.bind("192.168.0.1", 80)
s.listen(1)
(sc, addr) = s.accept()
while True:
   data = sc.recv(1024)
   if not data: break
   sc.send(str(data)+"*")
sc.close()
```

In reality a bit more complex:

- send() and recv() calls return when the associated network buffers have been filled (send) or emptied (recv).
  - They do not necessarily handle all the bytes, but tell how many bytes they handled.
  - The application needs to call them again until the entire message has been sent.
- When a recv returns 0 bytes, it means the other side has closed (or is in the process of closing) the connection.

➢ One reason to appreciate middleware systems ;-)

```
from socket import *
s = socket(AF_INET, SOCK_STREAM)   # Specifies socket type
s.connect ("192.168.0.1", 80)      # Connects to server
s.send("hello")                    # Sends a string message
data = conn.recv(1024)             # Receives 1024 bytes
print data
s.close()                          # Closes the connection
```

To find the end, messages must either

- **be fixed length**;
- be delimited;
- **indicate how long they are**; or
- end by shutting down the connection.

Sockets and TCP – An Example in Python

```
from socket import *
s = socket(AF_INET, SOCK
s.bind("192.168.0.1", 80)
s.listen(1)
(sc, addr) = s.accept()
while True:
    data = sc.recv(1024)
    if not data: break
    sc.send(str(data)+"*")
sc.close()
```

```
from socket import *
s = socket(AF_INET, SOCK
s.connect ("192.168.0.1", 8(
s.send("hello")
data = conn.recv(1024)
print data
s.close()                        # Closes the connection
```

```
# Send
length = len(msg)                       # Measures byte length assuming string
s.send(toBytes(length, 8))              # Sends message length as 8 byte message
bytessent = 0
while bytessent < length:               # Sends chunks until message is fully send
    sent = s.send(msg[bytessent:])
    bytessent = bytessent + sent

# Receive
length = fromBytes(s.recv(8))           # Receives message length
chunks = []                                 # which is send as a fixed-length message of size 8
bytesrecv = 0
while bytesrecv < length:               # Receives chunks until message is fully received
    chunk = s.recv(min(length - bytesrecv, 1048))
    chunks.append(chunk)
    bytesrecv = bytesrecv + len(chunk)
return b''.join(chunks)                 # Joins chunks as new byte array
```

https://docs.python.org/3/howto/sockets.html

Sockets

Buffering or No-Buffering?

- Buffering, because a socket pre-allocates buffer space.

Synchronous or Asynchronous?

- Both socket variant exist, but usually synchronous:
  - send() blocks until all data has been written to the socket.
  - receive() blocks until data is available to be read.

Transient or Persistent?

- Transient, because both processes need to be active for messaging.
  - ➢ But sockets have a buffer and manage the transmission!
    - ➢ Yes, but the message as a whole is not stored and maintained, i.e., if the message is larger than the sockets' buffers, the transport layer will never see the entire message.

ZeroMQ

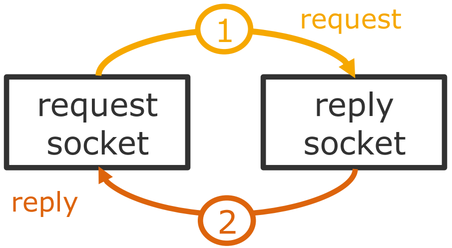
- An asynchronous, transient messaging library that supports message queues.
- Message queues are variable-length buffers:
  - Can take entire messages (unlike TCP, which uses byte streams)
    - ➢ Message-awareness
  - Enables asynchronicity (sender continues after message submit)
- Despite the asynchronicity, recv()-calls still block if no message is present.

- ZeroMQ extends traditional sockets by providing a higher level of abstraction:
  - ZeroMQ sockets support many-to-one and one-to-many communication:
    - A socket can be associated with multiple addresses.
    - A socket can connect to multiple addresses/sockets.
  - ZeroMQ sockets support pairing of sockets into popular patterns.

ZeroMQ – Communication Patterns

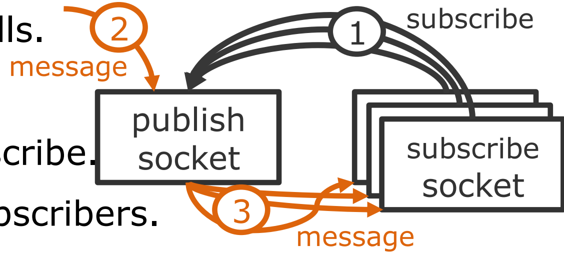
Request-Reply

- A pair of request socket (client) and reply socket (server)
- Every message to the request socket causes a reply to the reply socket.
- Connection handshake is implicit.
- Useful to implement synchronized calls, such as remote procedure calls.



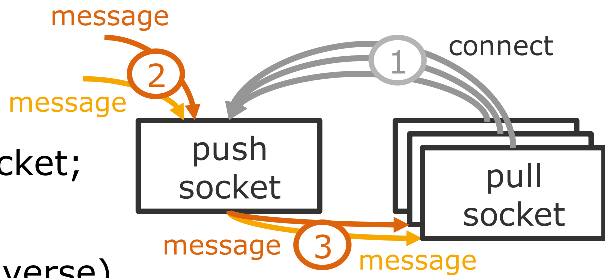
Publish-Subscribe

- A publish socket (server) to which subscribe sockets (client) can subscribe.
- Every message submitted to the publish socket is forwarded to all subscribers.
- Useful to implement multicasting.



Pipeline (or Push-Pull)

- A push socket (server) connected to many pull sockets (clients).
- Every message submitted to the push socket is send to one pull socket; the first client to pull a message receives it.
- Useful to implement task distribution (or collection when used in reverse).



ZeroMQ – Communication Patterns

Request-Reply

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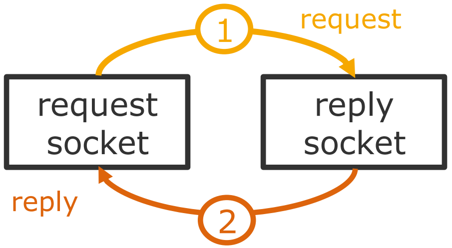


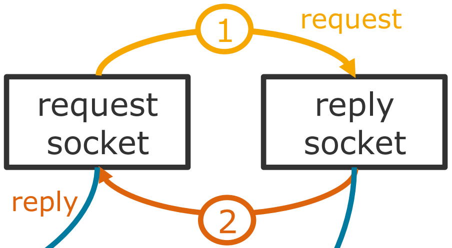
Server

```
import zmq
context = zmq.Context()
p1 = "tcp://" + HOST + ":" + PORT1        # address 1
p2 = "tcp://" + HOST + ":" + PORT2        # address 2; both can be used to send message to the same socket
s = context.socket(zmq.REP)               # create a reply socket
s.bind(p1)                                # bind socket to address 1
s.bind(p2)                                # bind socket to address 2

while True:
  message = s.recv()                      # block and wait for incoming message; message is the entire message object
  if not "STOP" in message:               # interpret message; no need to create a new socket due to message-awareness
    s.send(message + "*")                 # reply to the sender of the last message; destination is implicit due to zmq.REP
  else:
    break
```

ZeroMQ – Communication Patterns

Request-Reply

- A pair of request socket (client) and reply socket (server)
- Every message to the request socket causes a reply to the reply socket.
- Connection handshake is implicit.




```
import zmq
context = zmq.Context()
p1 = “tcp://” + HOST + “:” + PORT1
p2 = “tcp://” + HOST + “:” + PORT2
s = context.socket(zmq.REP)
s.bind(p1)
s.bind(p2)

while True:
  message = s.recv()
  if not “STOP” in message:
    s.send(message + “*”)
  else:
    break
```

Client

```
import zmq
context = zmq.Context()
p1 = “tcp://” + HOST + “:” + PORT1        # address 1
s = context.socket(zmq.REQ)               # create a request socket
s.connect(p1)                             # block until connected

s.send(“Hello World”)                     # send message
message = s.recv()                        # block until response
s.send(“STOP”)                            # send stop message
print message                             # print result
```

Overview

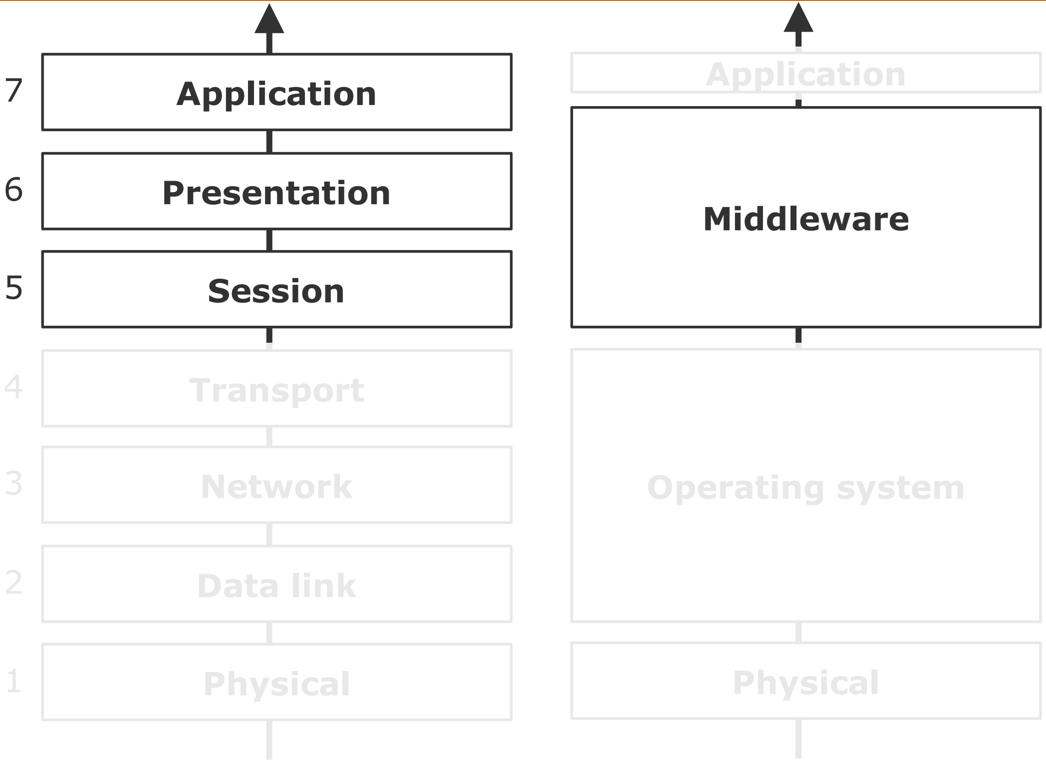
Communication

- Message Passing
- OSI Model
- Socket-based Communication
- **Message-oriented Middleware**
- Service-oriented Middleware
- Database-oriented Middleware

Motivation

- Sockets are not suitable for all transport layer protocols (especially not for proprietary protocols used in high-speed networks).
  - Transport layer protocols come with different, often complex interfaces (that require e.g. special buffering or synchronization features).
  - Transport layer protocols have numerous interfaces:
    - ATP, AppleTalk Transaction Protocol
    - CUDP, Cyclic UDP
    - DCCP, Datagram Congestion Control Protocol
    - FCP, Fibre Channel Protocol
    - IL, IL Protocol
    - MPTCP, Multipath TCP
    - RDP, Reliable Data Protocol
    - RUDP, Reliable User Datagram Protocol
    - SCTP, Stream Control Transmission Protocol
    - SPX, Sequenced Packet Exchange
    - SST, Structured Stream Transport
    - TCP, Transmission Control Protocol
    - UDP, User Datagram Protocol
    - UDP-Lite
    - µTP, Micro Transport Protocol
- Transport layer interfaces are sufficient, but not convenient (every communication involves a lot of redundant code).
- Transport layer buffering capabilities are limited (usually fixed sized buffers where flexible message queues are needed).

Middleware

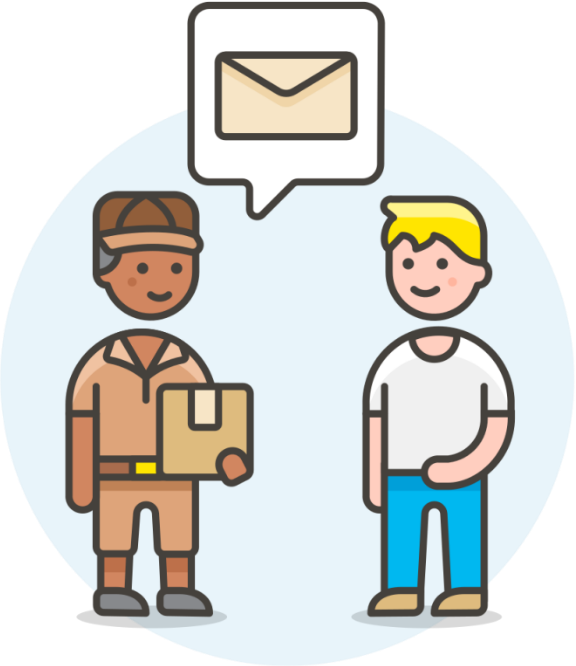


Our focus now!

A special layer for distributed systems that provides a unified API and may offer additional convenience features (w.r.t. buffering, communication protocols, failure handling, ...)

Middleware

- **Message Passing Interface (MPI)**
  - **Transient message-passing**
  - **Focus: high performance**
- Actor programming
  - Transient message passing
  - Focus: reactivity, fault-tolerance, maintainability
- Message-queuing systems
  - Persistent message passing
  - Focus: data-intensive, large-scale applications



MPI

Message Passing Interface

- A specification for a family of transient message-passing libraries:
  - Popular implementations exist for C, C++ and Fortran
  - e.g. MVAPICH, Open MPI, Intel MPI, IBM Spectrum MPI, … (most are Linux-based)
- Most popular middleware for high-performance computing.
- Highly efficient:
  - Supports various transport protocols and their features
  - Can exploit special hardware features
- Highly versatile:
  - Supports buffered/non-buffered communication
  - Supports synchronous/asynchronous communication
- Small weaknesses:
  - Still complex API with many (>440) low-level messaging functions

MPI – Core Concepts

Message awareness

- MPI manages messages (of variable length) as entities for transmission, i.e., it sends and receives messages as defined by the application.

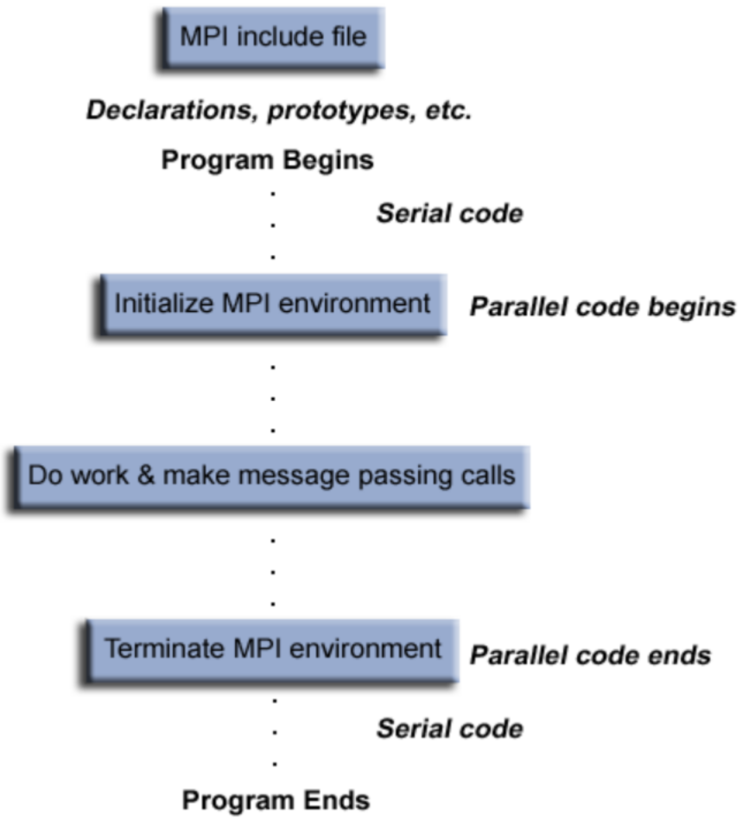
Abstract process identifier

- MPI associates a process with an identifier and translates these identifiers transparently into process addresses (i.a., IPs and ports).
- MPI organizes communicating processes in groups, which also receive abstract identifiers.
  - A pair (groupID, processID) uniquely identifies a source/destination.

Transient communication

- MPI does not persist messages and requires all processes to be reachable.

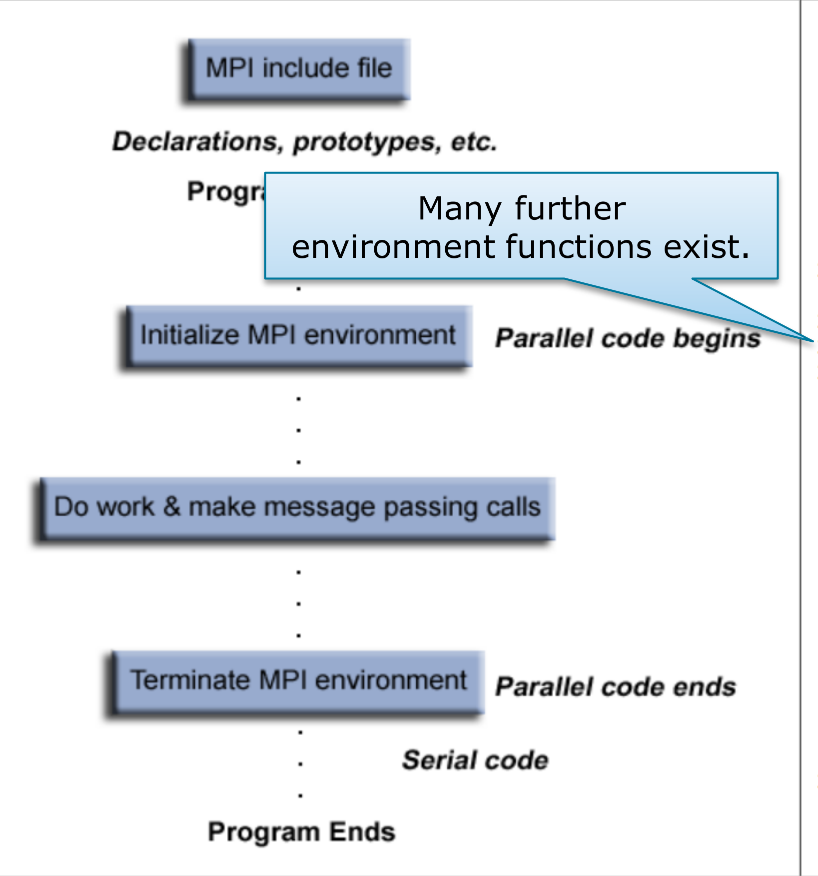
MPI – Send and Receive by Example




```c
#include "mpi.h"
#include <stdio.h>
#include <stdlib.h>

int main (int argc, char *argv[])
{
int numtasks, rank, dest, source, rc, count, tag=1;
char inmsg, outmsg='x';
MPI_Status Stat;

MPI_Init(&argc,&argv);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);

if (rank == 0) {
  dest = 1;
  source = 1;
  rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
  rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
  }

else if (rank == 1) {
  dest = 0;
  source = 0;
  rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
  rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
  }

MPI_Finalize();
}
```

https://computing.llnl.gov/tutorials/mpi/

MPI – Send and Receive by Example



Many further environment functions exist.

```
#include "mpi.h"
#include <stdio.h>
#include <stdlib.h>

int main (int argc, char *argv[])
{
int numtasks, rank, dest, so
char inmsg, outmsg='x';
MPI_Status Stat;

MPI_Init(&argc,&argv);
MPI_Comm_size(MPI_COMM_WORLD, &numtasks);
MPI_Comm_rank(MPI_COMM_WORLD, &rank);

if (rank == 0) {
  dest = 1;
  source = 1;
  rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
  rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
  }

else if (rank == 1) {
  dest = 0;
  source = 0;
  rc = MPI_Recv(&inmsg, 1, MPI_CHAR, source, tag, MPI_COMM_WORLD, &Stat);
  rc = MPI_Send(&outmsg, 1, MPI_CHAR, dest, tag, MPI_COMM_WORLD);
  }

MPI_Finalize();
}
```

= all known processes of the cluster

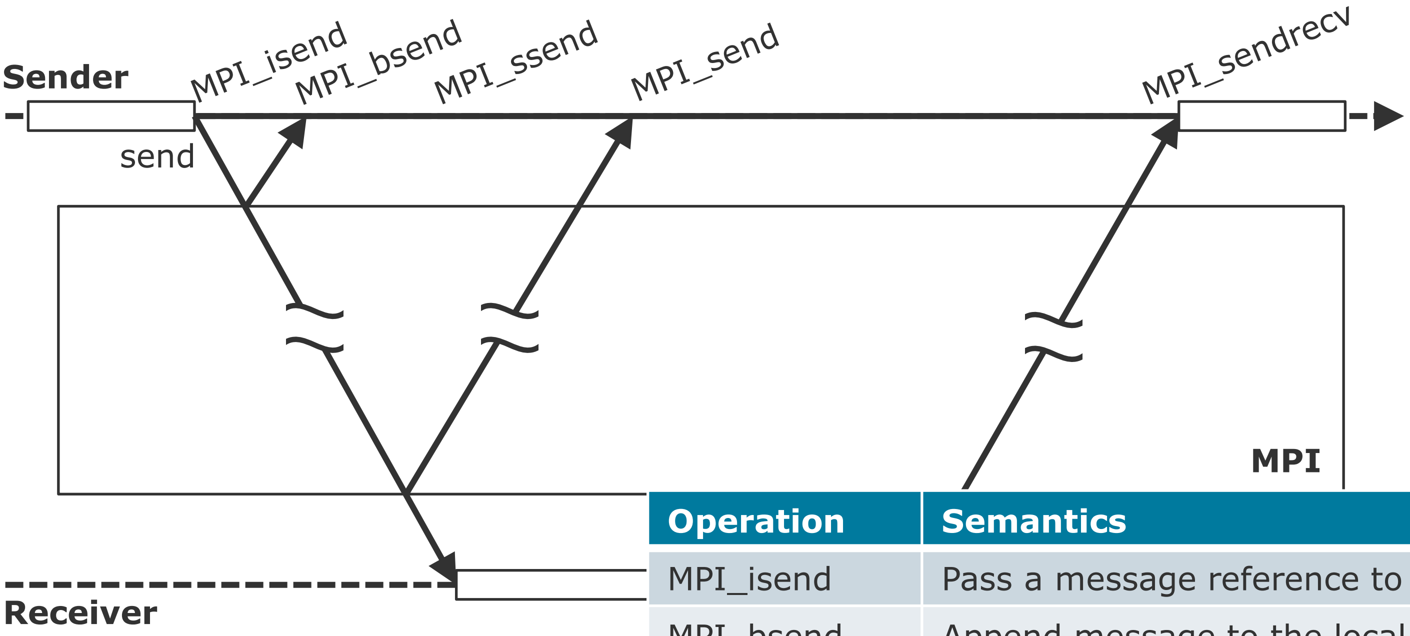
= our process ID in the cluster

If this is process 0, first send and then receive a message.

If this is process 1, first receive and then send a message.

https://computing.llnl.gov/tutorials/mpi/

MPI – Synchronization Options



Operation	Semantics
MPI_isend	Pass a message reference to MPI and continue.
MPI_bsend	Append message to the local buffer and continue.
MPI_ssend	Send message and wait until transmission starts.
MPI_send	Send message and wait until copied to remote buffer.
MPI_sendrecv	Send message and wait for a reply.

Different MPI libraries may interpret and implement these API semantics differently…

MPI – Synchronization Options

In this terminology,
RabbitMQ, Kafka, Akka and other
JVM-based message broker are
non-blocking + asynchronous
(messages should not be modified
and arrived in the message broker)

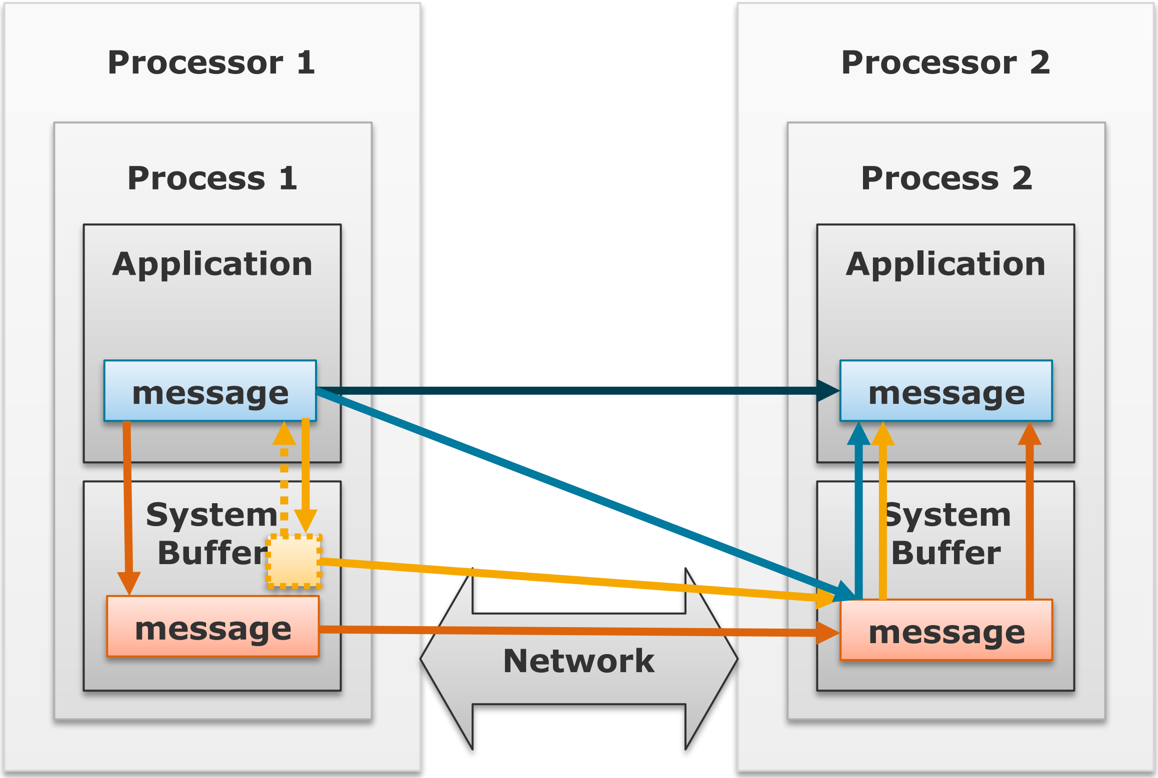
Blocking

- Send() call returns if the data was send.
- The message in the send buffer can safely be modified.
- Synchronous
  - The receiving side acknowledged having received the data.
- Asynchronous
  - The system buffer acknowledged having received the data
    (the system buffer copied the data and will make sure it gets send).

Non-Blocking

- Send() call returns immediately.
- The message in the send buffer should not be modified.

MPI – Send and Receive by Example



Blocking, synchronous, non-buffered

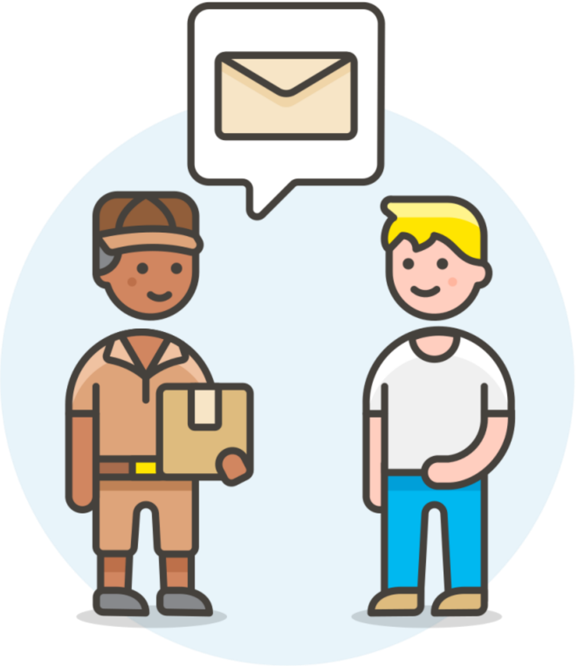
Blocking, synchronous, buffered

Blocking, asynchronous, buffered

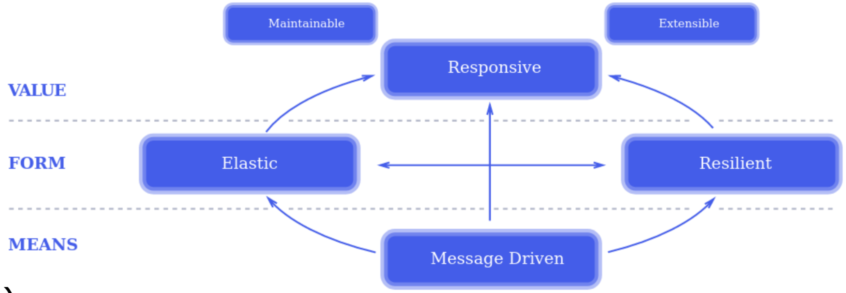
Non-Blocking, asynchronous, buffered

Middleware

- Message Passing Interface (MPI)
  - Transient message-passing
  - Focus: high performance
- **Actor programming**
  - **Transient message passing**
  - **Focus: reactivity, fault-tolerance, maintainability**
- Message-queuing systems
  - Persistent message passing
  - Focus: data-intensive, large-scale applications



Reactive Systems



https://www.reactivemanifesto.org/

Responsiveness

- The system responds in a timely manner (if possible).
- To user interaction, failures, events, state changes, data characteristics, …

Resilience

- The system stays responsive in the face of failures.
- Achieved by replication, containment, isolation and delegation.

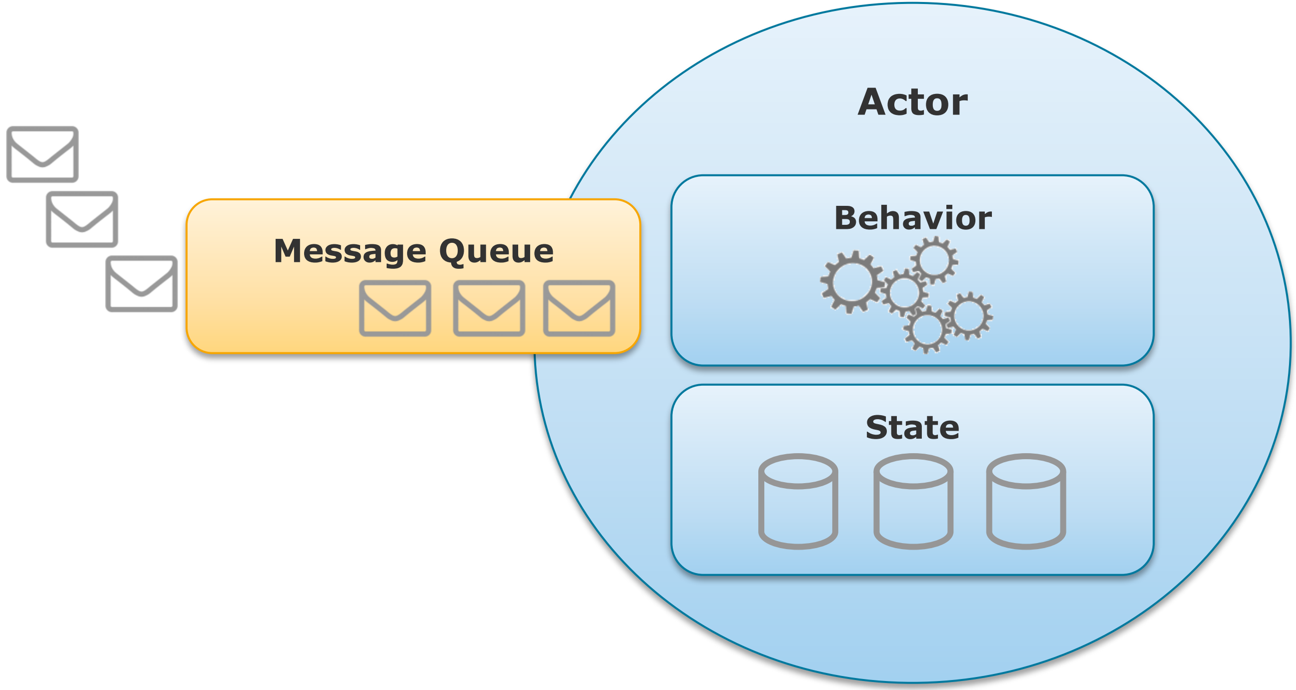
Elasticity

- The system stays responsive under varying workloads.
- Achieved by dynamic resource (de-)allocation, sharding, replication and decentralization.

Messaging

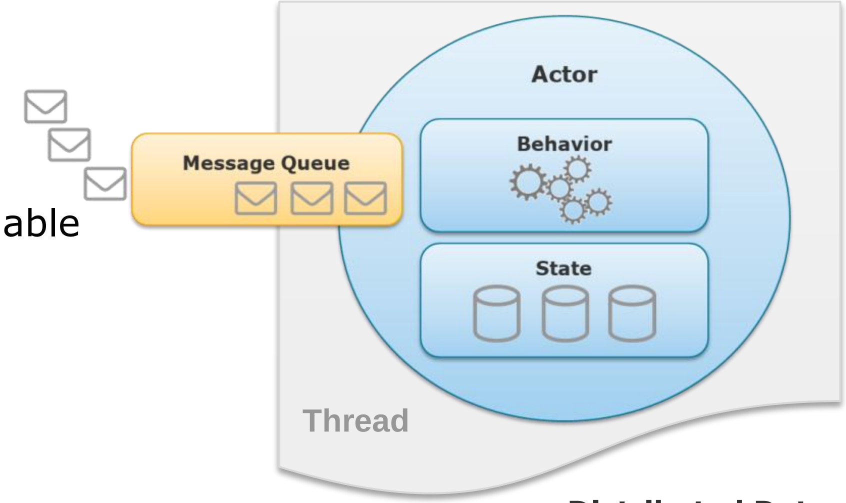
- The system relies on asynchronous message-passing between loosely coupled, isolated and location transparent components.
- Enables workload distribution, parallelization, failure delegation, load management, and flow control.

Actor

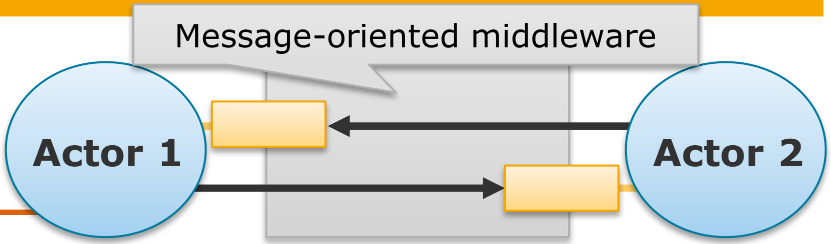


Actor

- Object with strictly private state and behavior
- Owns exactly one message queue
- Is dynamically scheduled on threads
  if messages are queued and resources are available
- Constitutes the smallest unit of parallelization;
  execution within an actor is strongly sequential
- Reacts to incoming messages;
  is passive like any object otherwise
- Reactions:
  - Send a finite number of messages to (other) actors
  - Change own state and/or behavior for next message
  - Create a finite number of new actors

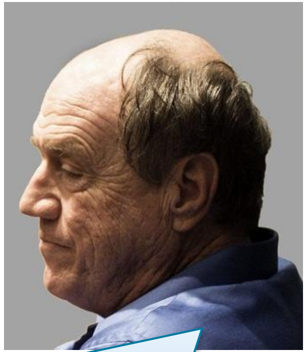


Actor Model



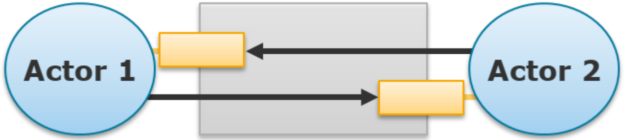
The actor model is a mathematical, object-oriented message-passing model that treats actors as the universal primitives of concurrent computation.

- Actors in the actor model …
  - are concurrent, fully encapsulated, self-contained entities.
  - address one another via abstract references that identify an actor object (pointer) inside a process (ID) on some node (IP + port).
- Message-oriented middleware required to i.a. …
  - resolve abstract addresses.
  - deliver messages from sender to receiver actors.
  - schedule actors on threads.
- Shared memory is strictly forbidden:
  - ➢ Actor model helps to prevent many parallel programming issues (concurrent memory access, race conditions, locking, deadlocks, …)



Carl Eddie Hewitt,
designer of the Actor Model in 1973.
[Carl Hewitt, Peter Bishop and Richard Steiger, "A Universal Modular Actor Formalism for Artificial Intelligence‟, 1973, IJCAI]

Actor Model Principles



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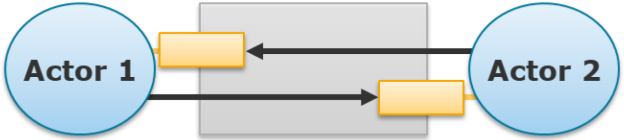
The actor model follows certain programming principles:

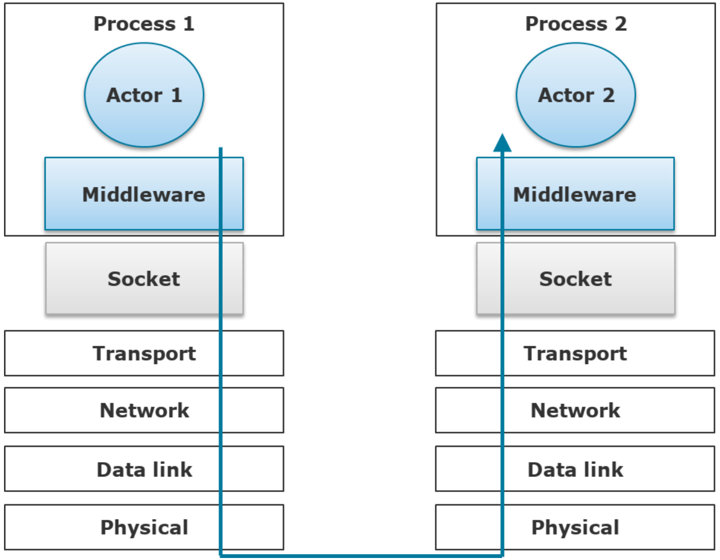
- Asynchronicity
  - Actors fire-and-forget messages
- Encapsulation
  - Actors have strictly private state and behavior
- Distribution
  - Actor locations are transparent
- Parallelization
  - Actors execute concurrently
- Synchronization
  - Actors synchronize explicitly

Actor Model Principles

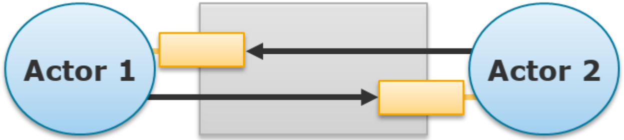


Asynchronicity

- Actor-to-Actor communication is asynchronous (fire-and-forget)
- Actor-to-Middleware communication can be synchronous or asynchronous (depending on the actor model implementation)
  - Note: Actor-to-Middleware communication is within the same process and can therefore use shared memory (middleware implementation hides this from developer)
- Middleware communication is usually based on synchronous TCP or UDP sockets



Actor Model Principles

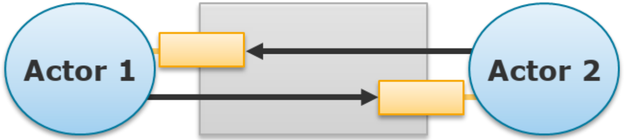


Encapsulation

- Communicating entities have private state and private behavior.
- Communication means sending messages and reacting on received messages.
- Communicate "what" is to be done not "how"!
  - The recipient decides how and if it handles a certain message.
- Communication protocols define the etiquette:
  - Commonly agreed message formats
  - Patterns for message exchanges

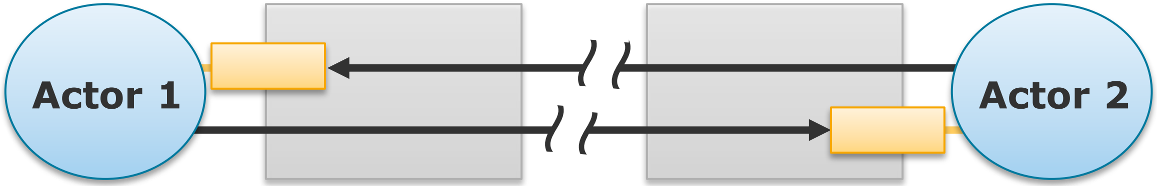
It is the developers task to define actor-based application protocols that form viable applications!

Actor Model Principles

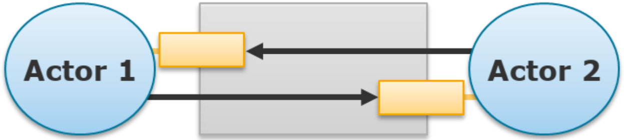


Distribution

- Messages can pass through busses, channels, networks, …
- Actors use abstract references to identify each other.
- Message-passing system i.e. the middleware resolves addresses and automatically routes messages from senders to receivers.
  - ➢ Allows actors to be transparently distributed, i.e., actors do not need to know where their communication partners actually are.



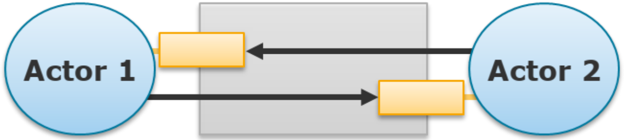
Actor Model Principles



Parallelization

- Actors process one message at a time but different actors operate independently (parallelization between actors not within an actor).
- Actors may spawn new actors if needed (dynamic parallelization).
- Task parallelism:
  - Different actors execute different tasks.
- Data parallelism:
  - Different actors execute the same task on different data elements.

Actor Model Principles



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Synchronization

Message passing ≠ no Synchronization

- Synchronization happens explicitly via messaging and state changes.
- Immutable messages and private actor states prevent concurrency conflicts (e.g. concurrent memory access).
- Deadlocks, starvation and live-locks are easier to avoid with message passing, because resource ownership and waiting behavior is more explicit; still all are possible if communication protocols are faulty implemented.
- Actor-Middleware and Middleware-Actor communication still requires synchronization primitives or lock-free data structures.
  - Message passing can be implemented via locking/atomic operations on the message queue(s) or buffer(s).
  - Vice versa: Locks can be implemented via exchange of messages (e.g. the request/response pattern introduces waiting behavior).

See also http://web.mit.edu/6.031/www/fa17/classes/22-queues
and https://stackoverflow.com/questions/7140544/message-passing-vs-locking

Message-oriented Middleware

Actor Model Principles

Arbitrary synchronization primitive (mutex, semaphore, barrier, monitor, …)

```
ReentrantLock messageMutex = new ReentrantLock();
Queue<Work> messageQueue = new ArrayDeque<Work>();
```

= Shared Memory

Actor
(Thread)

```
…
try {
  messageMutex.lock();
  messageQueue.offer(message);
} finally {
  messageMutex.unlock();
}
…
```

Middleware
(Thread)

```
…
try {
  messageMutex.lock();
  message = messageQueue.poll();
} finally {
  messageMutex.unlock();
}
…
```

= Critical Section

Actor Model Principles

Lock-based Queue

Actor
(Thread)

Middleware
(Thread)

```
BlockingQueue<Message> myQueue = new BlockingQueue<Message>;
```

```
private void send(Message message) {
  myQueue.add(message);
}
```

Blocks if middleware reads from queue.

```
private Message receive() {
  while (true) {
    message = myQueue.remove();
    if (message != null)
      return message;
}
```

Blocks if actor reads from queue.

Actor Model Principles

Lock-free Queue

Actor
(Thread)

Middleware
(Thread)

```
NonBlockingQueue<Message> myQueue = new NonBlockingQueue<Message>;
```

```
private void send(Message message) {
   myQueue.add(message);
}
```

```
private Message receive() {
   while (true) {
      message = myQueue.remove();
      if (message != null)
         return message;
}
```

NonBlockingQueue

- A non-blocking Queue data structure
- Based on the atomic compare-and-set operation
- Extension of the TreiberStack* data structure

* R. K. Treiber, *Systems programming: Coping with parallelism*. International Business Machines Incorporated, Thomas J. Watson Research Center, 1986.

```
public class NonBlockingQueue<T> {
    private final AtomicReference<Node<T>> head;
    private final AtomicReference<Node<T>> tail;

    public NonBlockingQueue() {
        this.head = new AtomicReference<T>(null);
        this.tail = new AtomicReference<T>(null);
    }

    private class Node<T> {
        public volatile T message;
        public volatile Node<T> next;
        public volatile Node<T> previous;

        public Node(T message) {
            this. message = message;
            this.next = null;
        }
    }

    public void add(T message) { … }
    public T remove() { … }
}
```

```
public void add(T message) {
    Node<T> newNode = new Node<T>(message);
    Node<T> currentTail;
    do {
        currentTail = this.tail.get();
        node.previous = currentTail;
    } while (! this.tail.compareAndSet(currentTail, newNode));

    if (newNode.previous != null)
        newNode.previous.next = newNode;

    this.head.compareAndSet(null, newNode);
}
```

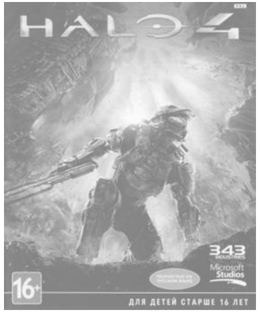
Atomic operations

```
public T remove() {
    if (this.head.get() == null)
        return null;

    Node<T> currentHead, nextNode;
    do {
        currentHead = this.head.get();
        nextNode = currentHead.next;
    } while (! this.head.compareAndSet(currentHead, nextNode));

    return currentHead.getValue();
}
```

Atomic operations

Actor Model Implementations

- Erlang:
  - Actor library natively included in the Erlang language
  - First popular actor implementation
  - Special: Native language support and strong actor isolation
- Akka:
  - Actor library for the JVM (Java und Scala)
  - Most popular actor implementation (a.t.m.)
  - Special: Actor hierarchies and typed actors
- Orleans:
  - Actor library for Microsoft .NET/C#
  - Very popular in research and industry (due to Microsoft)
  - Special: Virtual actors (persistent state and transparent location)



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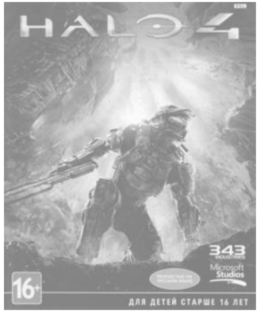


Message-oriented Middleware

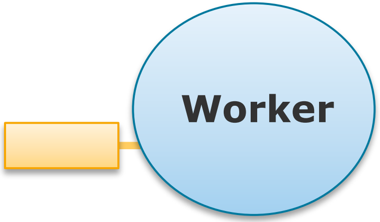
Actor Model – Akka

Akka Actors: Core actor model classes for concurrency and distribution	Akka Cluster: Classes for the resilient and elastic distribution over multiple nodes	Akka Streams: Asynchronous, non-blocking, backpressured, reactive stream classes	Akka Http: Asynchronous, streaming-first HTTP server and client classes
Cluster Sharding: Classes to decouple actors from their locations referencing them by identity	Akka Persistence: Classes to persist actor state for fault tolerance and state restore after restarts	Distributed Data: Classes for an eventually consistent, distributed, replicated key-value store	Alpakka: Stream connector classes to other technologies

- Implements the actor modell
- A free and open-source toolkit and runtime for building concurrent and distributed applications on the JVM (https://akka.io/)
- Written in Scala (https://scala-lang.org/)
- Offers APIs for Java und Scala

- Invented by Jonas Bonér
- Maintained by Lightbend (https://lightbend.com/)

Actor Model – Akka



Called in default actor constructor and set as the actor's behavior

```
public class Worker extends AbstractActor {
  @Override
  public Receive createReceive() {
    return receiveBuilder()
      .match(String.class, this::respondTo)
      .matchAny(object -> System.out.println("Could not understand received message"))
      .build();
  }
  private void respondTo(String message) {
    System.out.println(message);
    this.sender().tell("Received your message, thank you!", this.self());
  }
}
```

Inherit default actor behavior, state and mailbox implementation

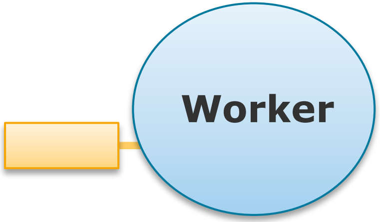
The **Receive** class performs pattern matching and de-serialization

A builder pattern for constructing a **Receive** object with otherwise many constructor arguments

Send a response to the sender of the last message (asynchronously, non-blocking)

Message-oriented Middleware

Actor Model – Akka

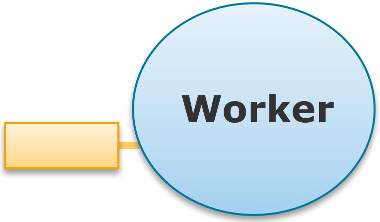



```java
public class Worker extends AbstractActor {
  @Override
  public Receive createReceive() {
    return receiveBuilder()
      .match(String.class, s -> this.sender().tell("Hello!", this.self()))
      .match(Integer.class, i -> this.sender().tell(i * i, this.self()))
      .match(Double.class, d -> this.sender().tell(d > 0 ? d : 0, this.self()))
      .match(MyMessage.class, s -> this.sender().tell(new YourMessage(), this.self()))
      .matchAny(object -> System.out.println("Could not understand received message"))
      .build();
  }
}
```

The message types (= classes) define how the actor reacts.

Message-oriented Middleware

Actor Model – Akka

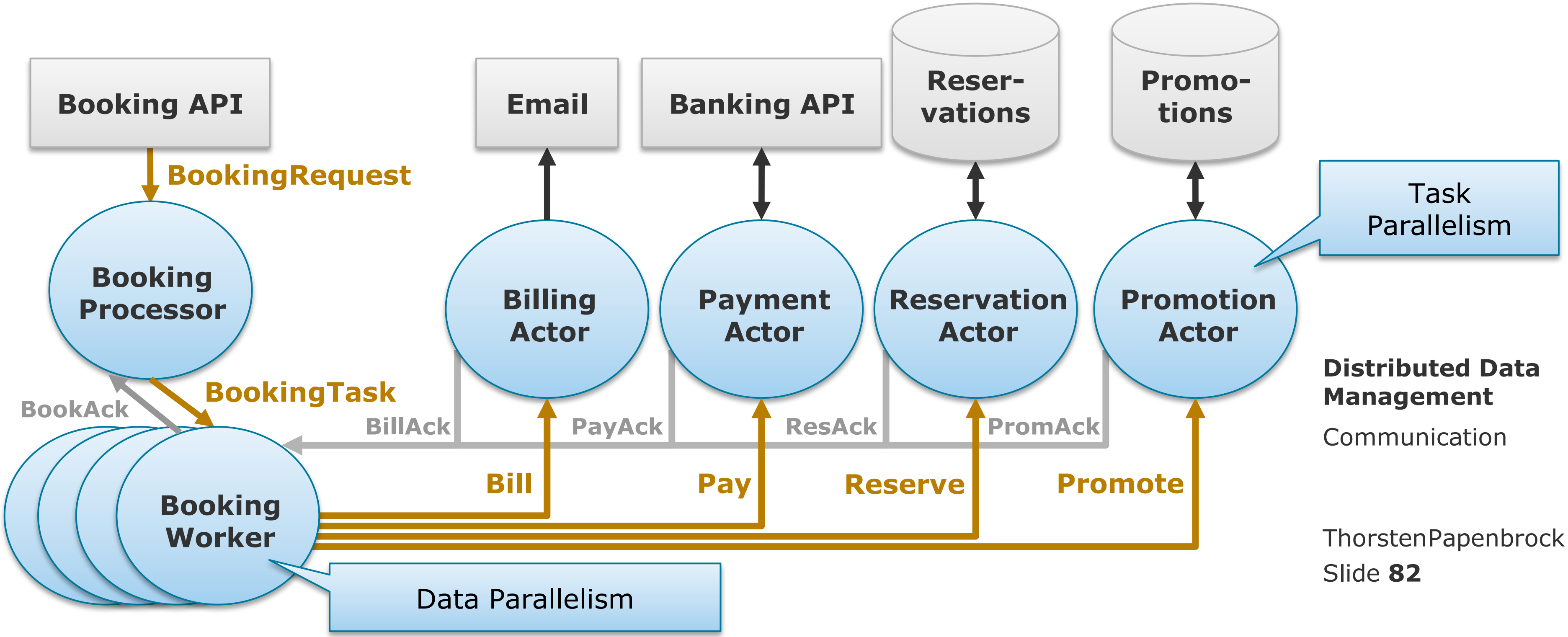



```java
public class Worker extends AbstractActor {

  public static class MyMessage implements Serializable {}

  @Override
  public Receive createReceive() {
    return receiveBuilder()
      .match(MyMessage.class, s -> this.sender().tell(new OtherActor.YourMessage(), this.self()))
      .matchAny(object -> System.out.println("Could not understand received message"))
      .build();
  }
}
```

Good practice:
Actors define their messages
(provides kind of an interface description)

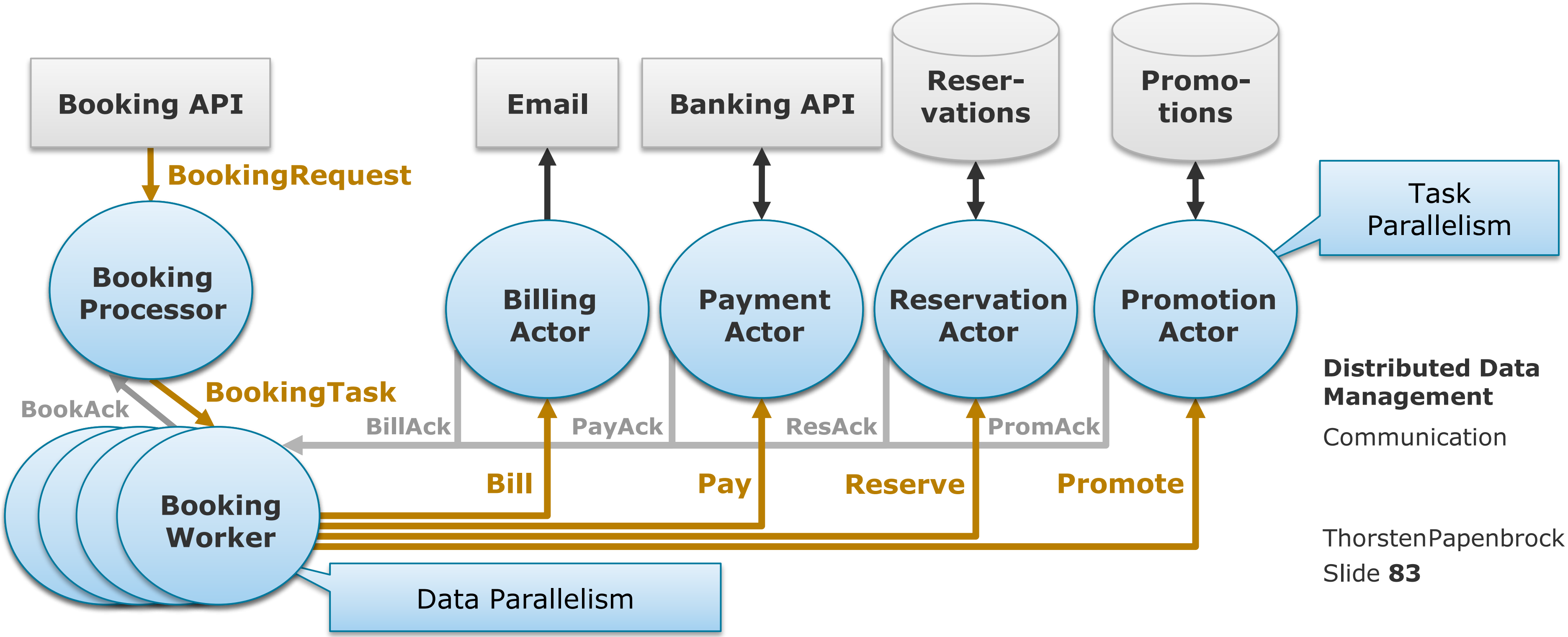
Actor Model – Akka

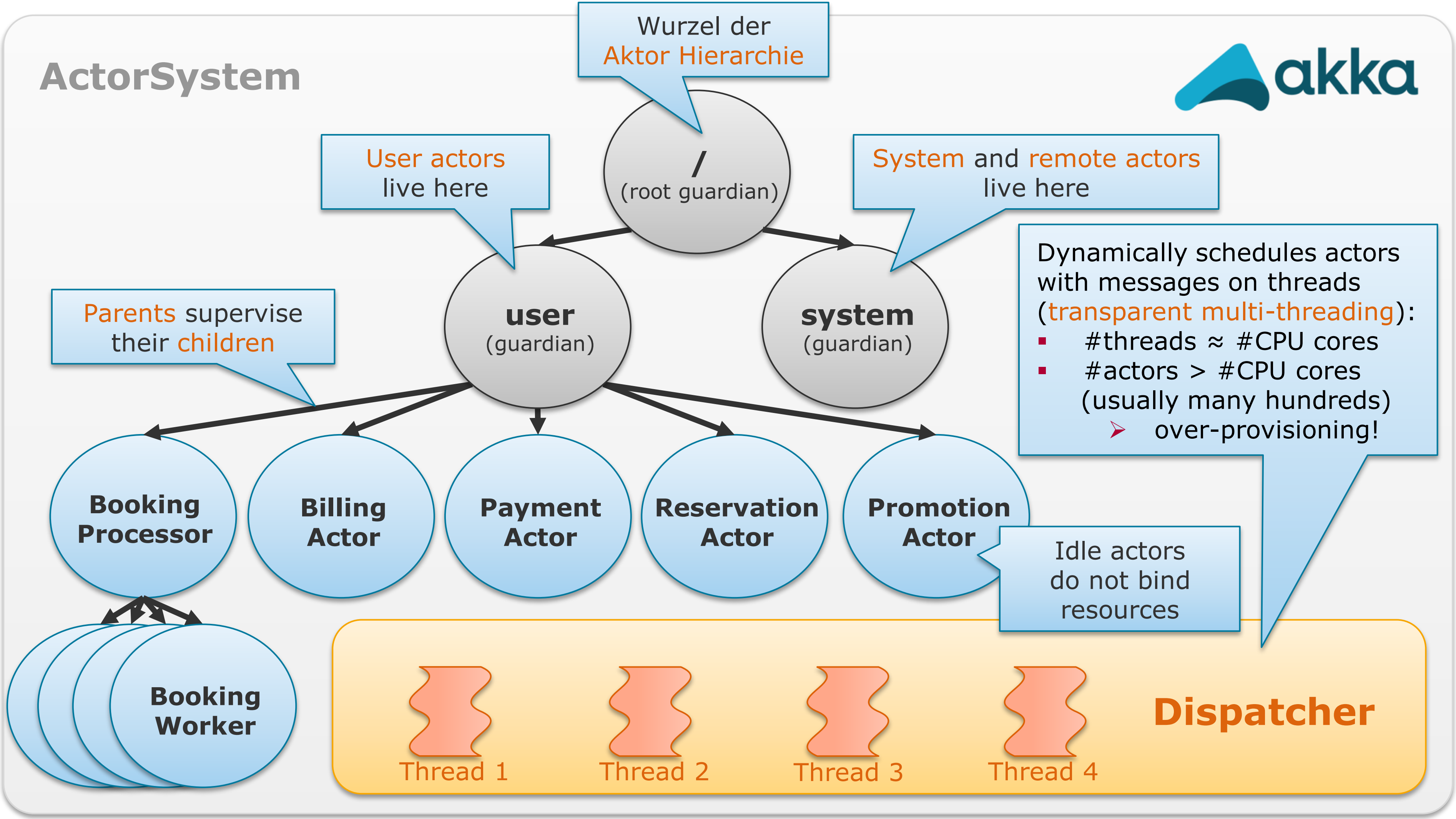
Example: A flight booking system



Actor Model – Akka

Example: A flight booking system

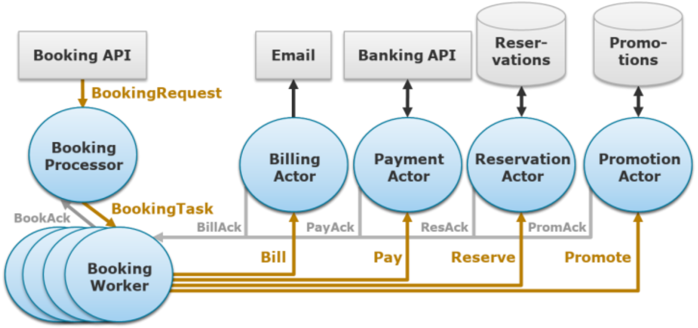



ActorSystem
akka
Wurzel der
Aktor Hierarchie
/
(root guardian)
User actors
live here
System and remote actors
live here
user
(guardian)
system
(guardian)
Parents supervise
their children
Dynamically schedules actors
with messages on threads
(transparent multi-threading):
#threads ≈ #CPU cores
#actors > #CPU cores
(usually many hundreds)
over-provisioning!
Booking
Processor
Billing
Actor
Payment
Actor
Reservation
Actor
Promotion
Actor
Idle actors
do not bind
resources
Booking
Worker
Thread 1
Thread 2
Thread 3
Thread 4
Dispatcher

Actor Model and Fault Tolerance

Reactive Programming

- A declarative programming paradigm based on event and message flows.
- Program components (= actors) declare how they react on certain messages.
- Instead of following a fixed calculation plan, components behave dynamically and independent of each other.
  - ➢ Writing a reactive algorithm is more like declaring rules for how to react on certain input changes rather than defining a step-by-step execution plan.
- Reactions are triggered by data or changes in the environment.
- Reaction:
  - changing state (= private variables)
  - changing behavior (= private code)
  - changing algorithm topology (= child actors)
  - sending further messages
- Reactivity helps to optimize resource utilization, robustness and elasticity.



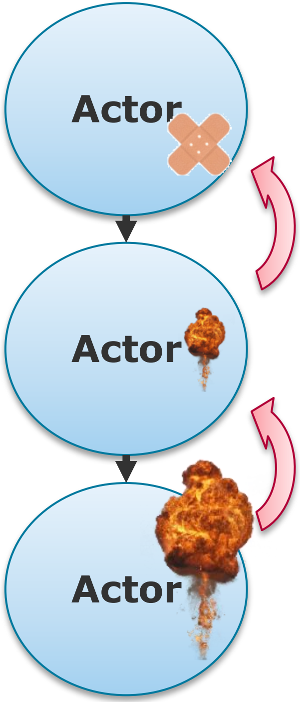
Actor Model and Fault Tolerance

"Let it crash" philosophy

- Distributed systems are inherently prone to errors (because there is simply more to go wrong/break).
  - Message loss, unreachable mailboxes, crashing actors …
- Make sure that critical code is supervised by some entity that knows how errors can be handled.
- Then, if an error occurs, do not (desperately) try to fix it: let it crash!
  - Errors are propagated to supervisors that can deal better with them.
- Example: Actor discovers a parsing error and crashes.
  - Maybe message was corrupted in message transfer.
    - Its supervisor restarts the actor and resends the message.

Fault tolerance tools

- Lifecycle management (e.g. automatic restart of failed actors)
- Supervision (let it crash)
- Dead letters (e.g. resent/re-route of failed messages)

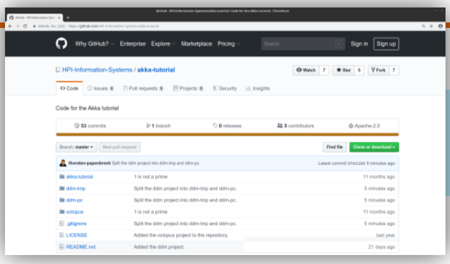


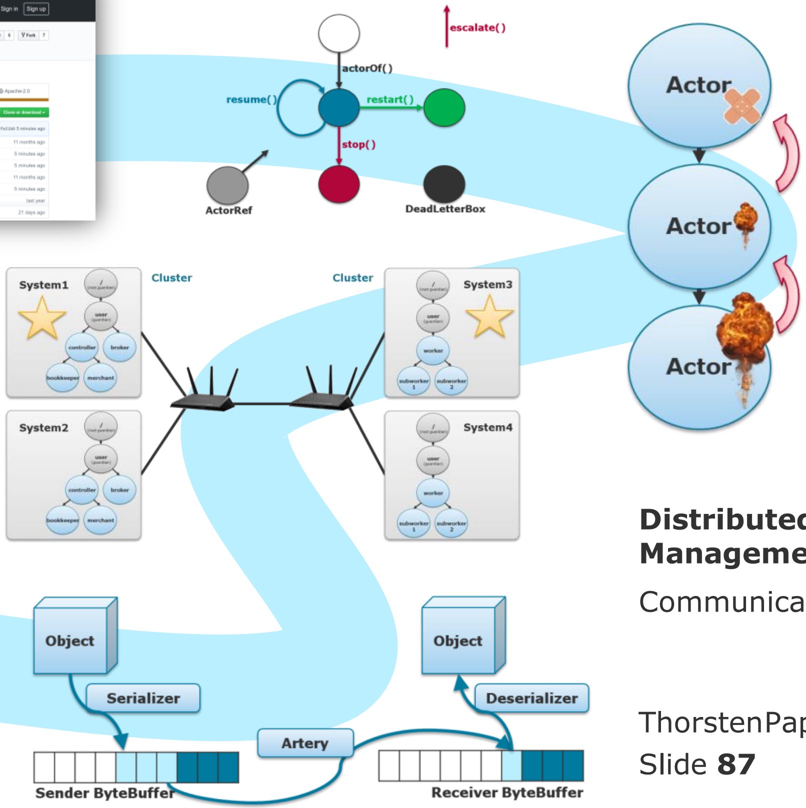
Message-oriented Middleware

Actor Model – Akka

Akka hands-on:

- Demo
- Actor lifecycle
- Messaging guarantees
- Fault tolerance
- Remoting
- Scheduling
- Patterns
  - Maszer/Worker
  - Reaper
  - Proxy
  - Singleton
  - ...



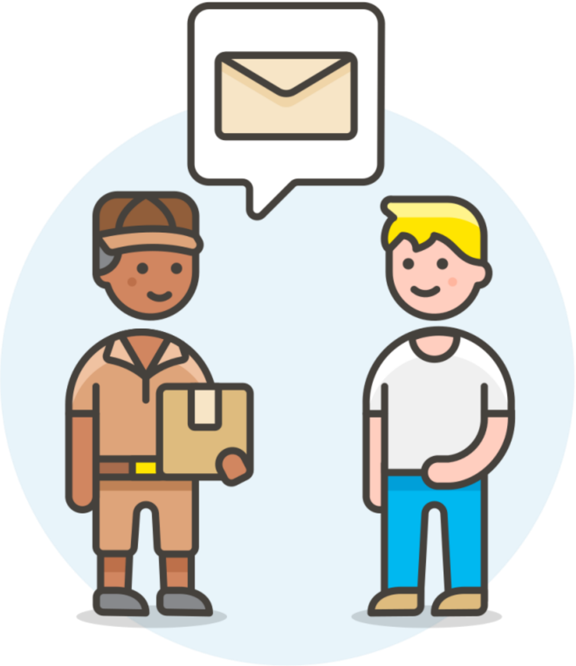


Middleware

- Message Passing Interface (MPI)
  - Transient message-passing
  - Focus: high performance

- Actor programming
  - Transient message passing
  - Focus: reactivity, fault-tolerance, maintainability

- **Message-queuing systems**
  - **Persistent message passing**
  - **Focus: data-intensive, large-scale applications**



Message-Queuing Systems

A message-queuing system is a message-oriented middleware that provides various services for (persistent) asynchronous communication.

- Message queue:
  - Intermediate-term storage capacity maintained by the middleware
  - Stores messages until delivered to (all) recipients
  - Sometimes tied to sender and/or receiver (see actor model); sometimes subscription-based (see RabbitMQ)
  - Holds a logical, location-independent, system-wide unique identifier
- Queue manager:
  - Part of the message-queuing system that handles queue lifecycles and all message traffic
  - A separate process and/or library that is linked into the application
  - Message-queuing system requires a queue manager on every node

Message-Queuing Systems

A message-queuing system is a me
various services for (persistent) as

- Message queue:
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  - Part of the message-queui
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  - A separate process and/or library that is linked into the application
  - Message-queuing system requires a queue manager on every node

Strictly speaking:

If all queue manager run within application processes, i.e., there is no separate queue manager process, then the message transfer requires both sender and receiver process to run simultaneously (at some point in time).

➢ Can be considered non-persistent

(although local queue manager can in principle wait with the transfer until the target system is up without blocking local application threads)

Message-Queuing Systems

A message-queuing system is a message-oriented middleware that provides various services for (persistent) asynchronous communication.

- Sender/receiver:
  - May not be active at the same time
  - May be programmed in different languages (in some MQ systems)
- Messages:
  - Need to be understood by sender/receiver
  - May not be understood by the message-queuing system (byte arrays)
  - Need to be properly addressed to a message queue (unique ID)
- Messaging:
  - Message transfers may take longer than with Sockets, MPI, RPCs, …
  - Middleware guarantees that the message will eventually be delivered to the recipient (no guarantee on when or if the message is read).

Sender/Receiver may refer to processes or threads

Message-Queuing Systems – Interface

A message-queuing system is a message-oriented middleware that provides various services for (persistent) asynchronous communication.

- (Basic) Interface:

Operation	Description
put	Append a message to a specific queue (non-blocking).
get	Remove first message from a queue (blocking)
poll	Try to remove first message from a queue (non-blocking).
notify	Install a handler that is called when a message is put into a queue.

Message pulling (active receiver)

Message pushing (active queue)

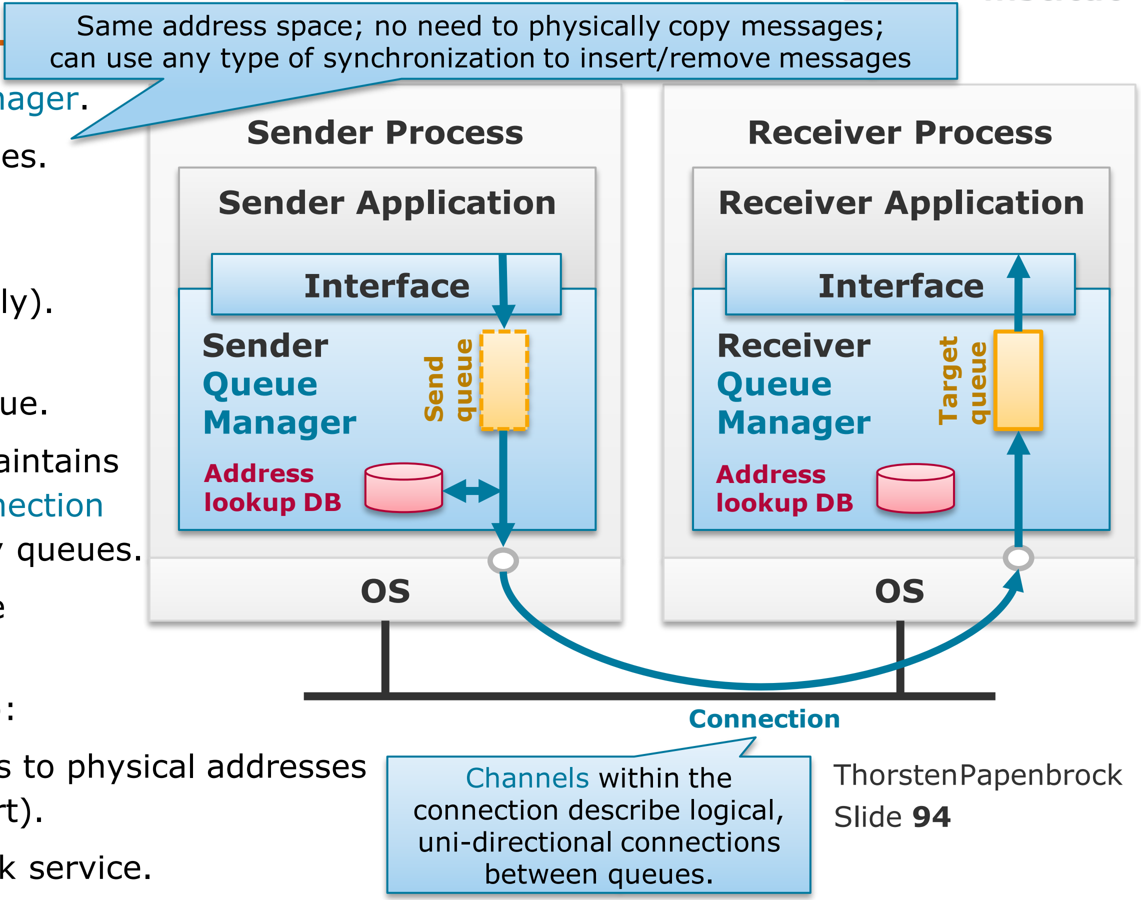
- Variations:
  - get/poll may take but not remove the element
  - get/poll may not return the first but a different element (based on priority, a search pattern, sender or index)

Message-Queuing Systems – Tasks

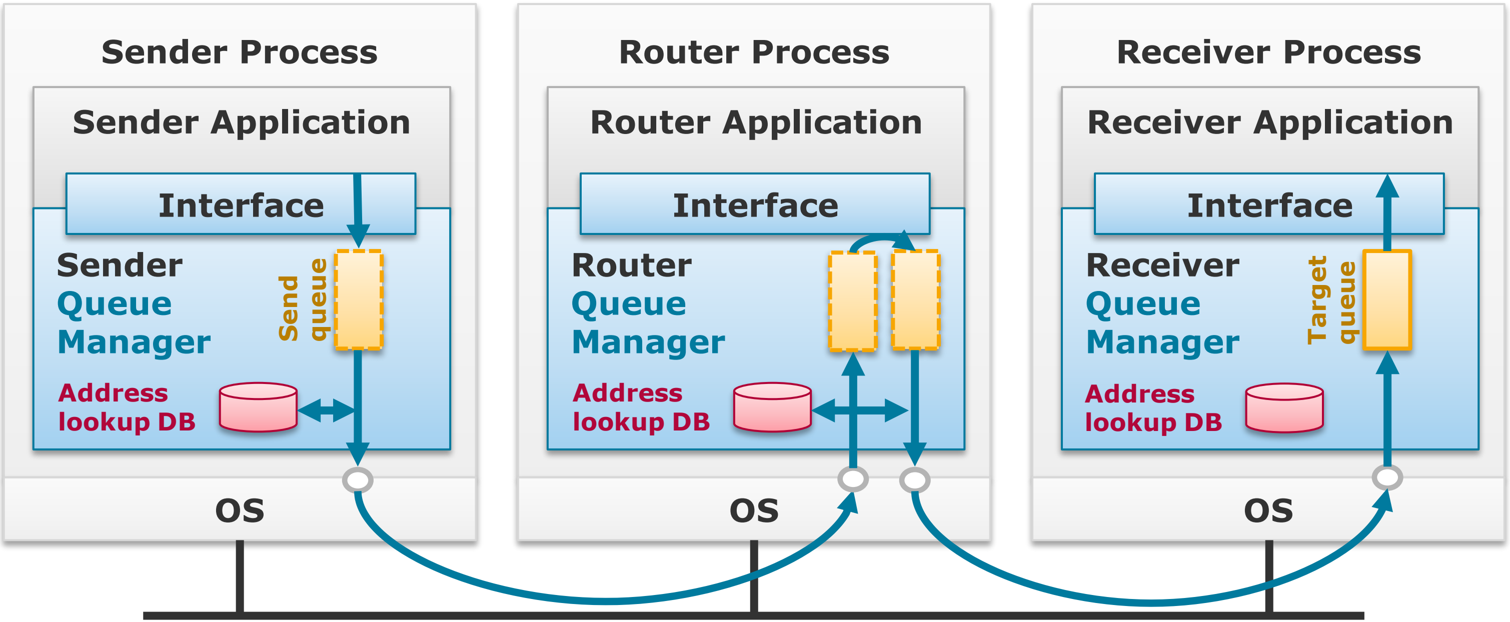
- Message Buffering:
  - Maintenance of message queues and their subscribers/owners
- Message Delivery:
  - Answering of poll-requests or notification of recipients
  - (sometimes) Ensuring reliable message sends (message loss detection and resending)
  - (sometimes) Enabling synchronous message sends
- Address Resolution:
  - Translation of symbolic addresses into physical references, ports and IP-addresses (enables location transparent communication)
- Data Transmission:
  - Routing: one-to-one messages
  - Broadcasting: one-to-many messages
- Encoding:
  - Serialization and deserialization for messages that are send across process boundaries

Message-Queuing Systems – Transmission

- A message queue lives in some queue manager.
- Applications can write/read only local queues.
    - To write/read remote queues, queue manager create local queues (usually dynamically and transparently).
    - In the example: Sender sends to a remote target queue.
- Each pair of communicating processes maintains (usually) exactly one transport-level connection (e.g. TCP) for all traffic between arbitrary queues.
- A process maintains (usually) exactly one send queue for each connection.
- Address lookup database (or routing table):
    - stores a mapping of logical queue IDs to physical addresses (e.g. transport protocol, host and port).
    - can be a replicated store or a network service.

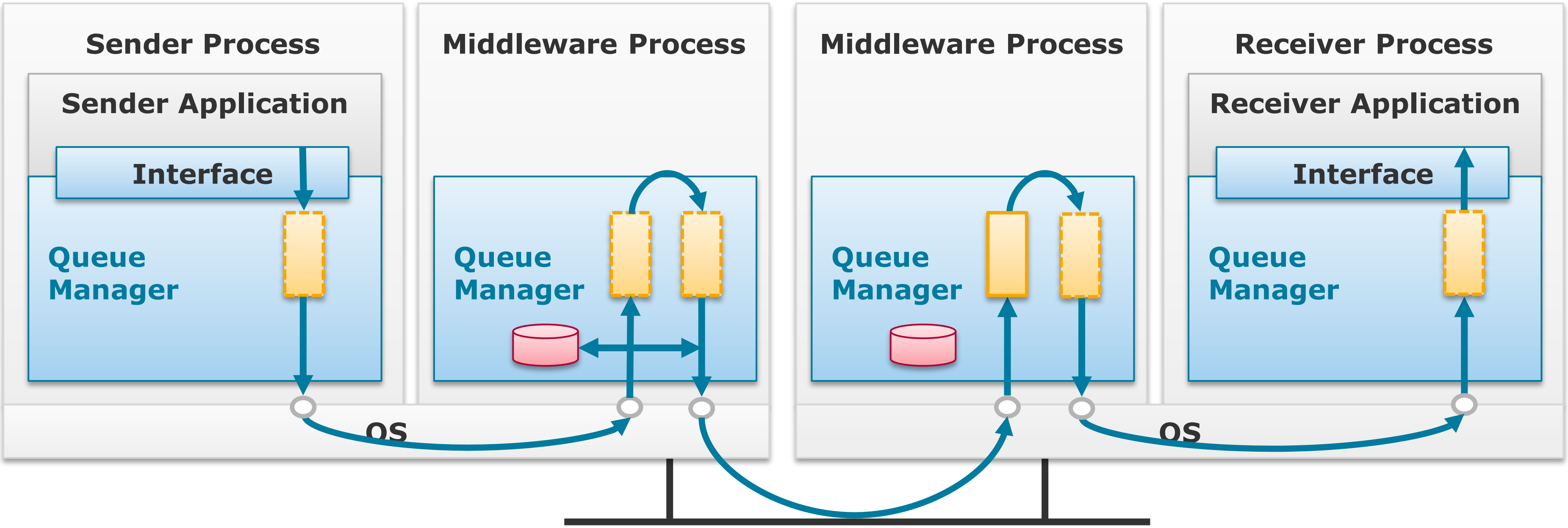


Message-Queuing Systems – Transmission



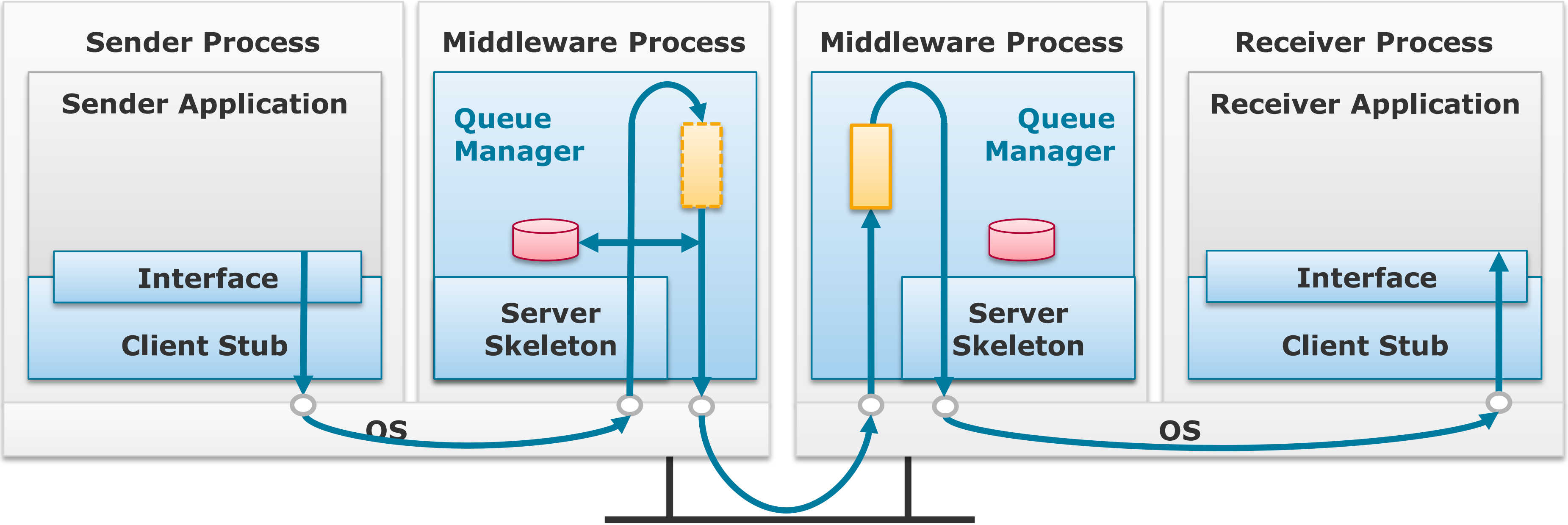
- Routers:
  - are queue manager that forward messages addressed to non-local message queues.
  - are needed if the address lookup database is incomplete or network topologies are complex so that messages cannot be send directly to the target queues.

Message-Queuing Systems – Transmission



Queue manager in different processes and
<u>message passing</u> between application and middleware

Message-Queuing Systems – Transmission

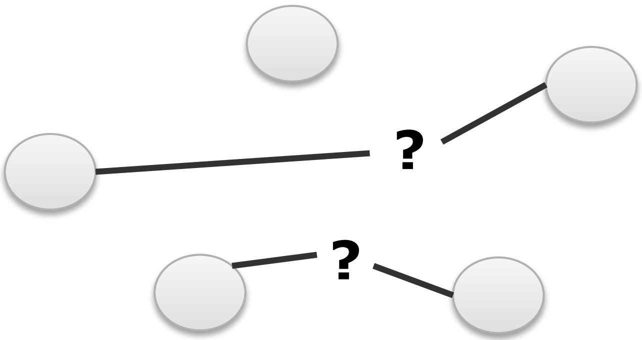


Queue manager in different processes and
RPC between application and middleware

Message-Queuing Systems – Message Broker

Distributed systems usually consist of more than two nodes!

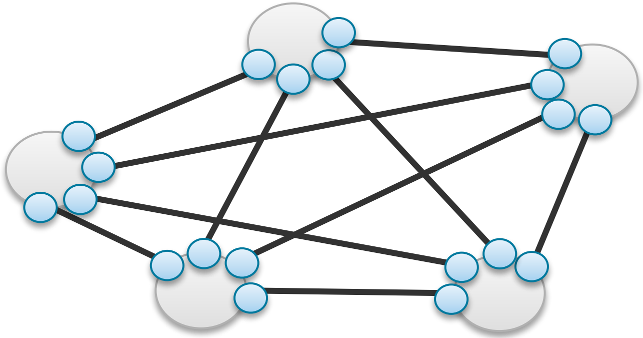
- Assume we want to integrate different, potentially heterogeneous systems into a single, coherent distributed information system.
- Each system speaks its own protocols and message formats.
- Due to the complexity and abstractions made by middleware layers, it is often not possible to let all systems agree on one communication protocol.



Message-Queuing Systems – Message Broker

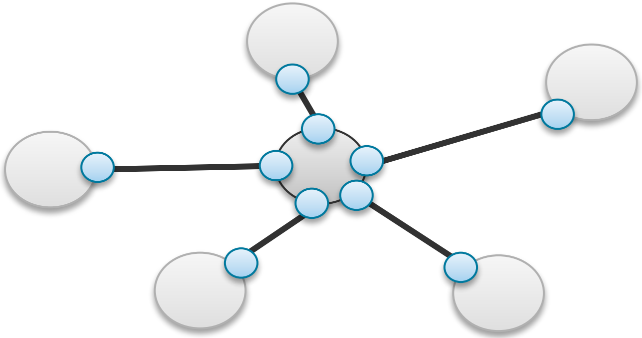
Solution 1: Wrappers

- Peer-to-peer communication channels between all systems using wrappers
- Requires $O(N^2)$ wrappers
- Works well for homogeneous systems (like MPI or actor systems) but causes scalability issues and code duplication for heterogeneous systems



Solution 2: Message Broker

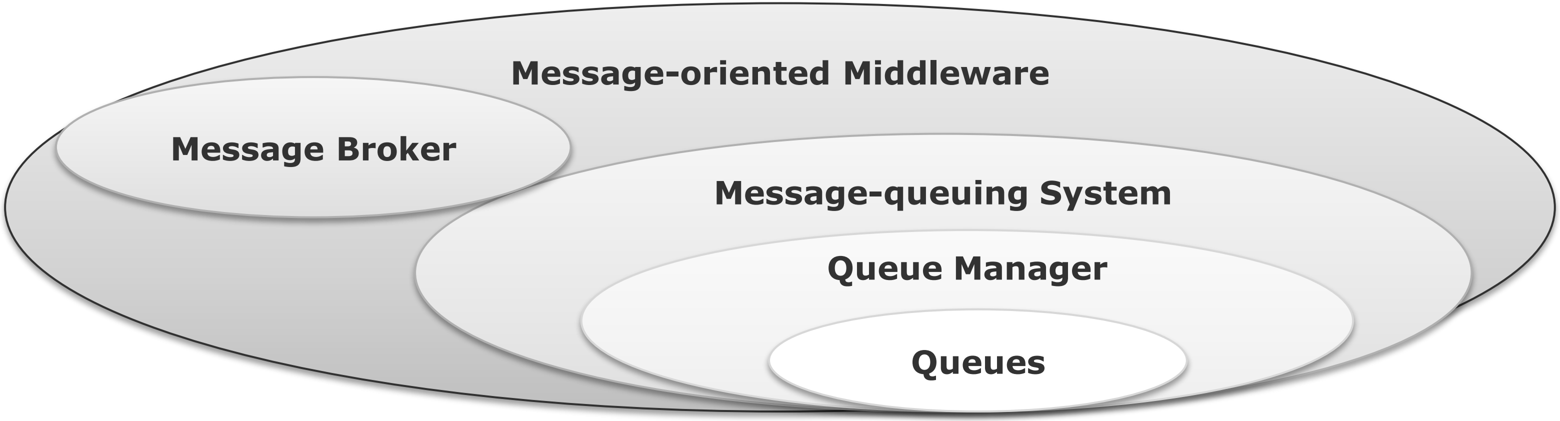
- Centralized communication hub with message translation capabilities
- Requires $O(N)$ wrappers
- Is slower than peer-to-peer communication



Message-Queuing Systems – Message Broker

Message Broker

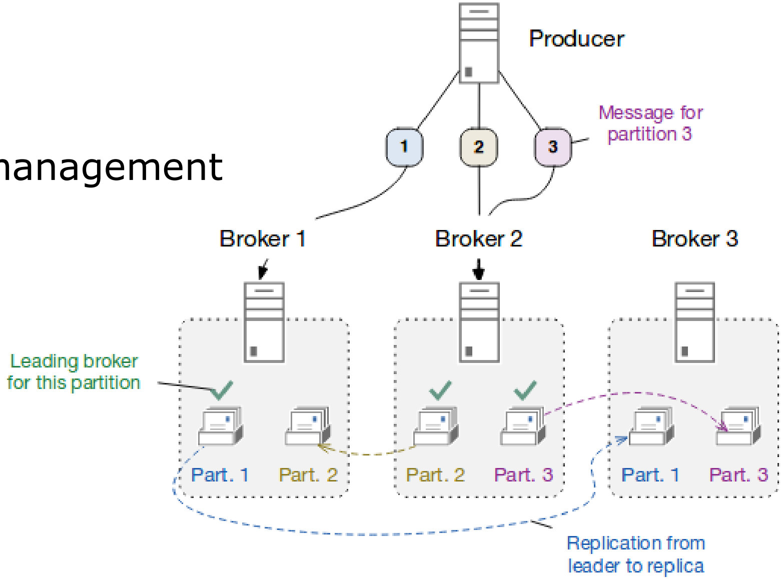
- An application-level gateway on top of a message-queuing system that routes and translates messages.
- The message-queuing system treats the broker as yet another application.
- Message-queuing system plus message broker are one form of message-oriented middleware:



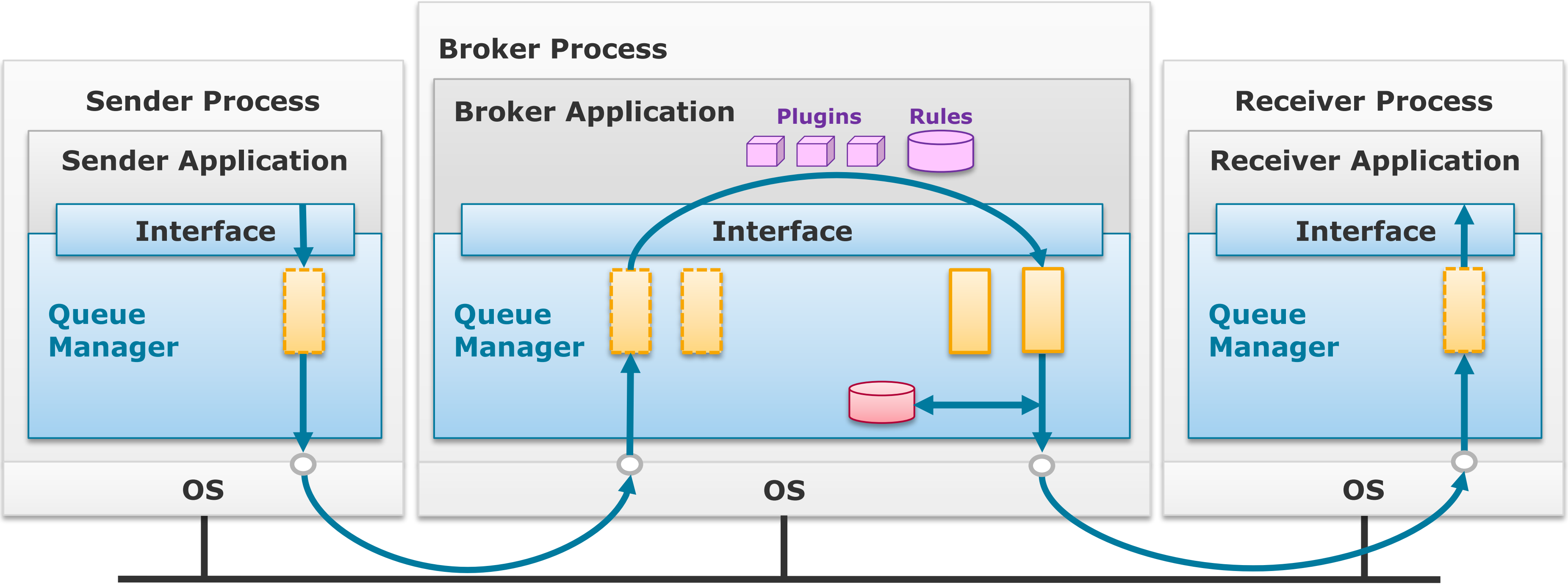
Message-Queuing Systems – Message Broker

Message Broker (cont.)

- Can add additional capabilities on top of the message-queuing system (often via plugins and rule sets), such as:
  - Message transformations/re-encodings
  - Replication of queues
  - Partitioning of queues
  - Sender and receiver group management
  - Batch processing
- Example: Apache Kafka



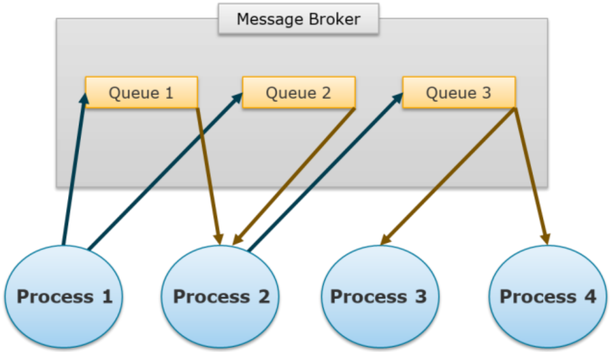
Message-Queuing Systems – Message Broker



Message-Queuing Systems – Message Broker

Publish-Subscribe

- The queue manager of the message broker maintains all message queues.
  - ➢ Any process can potentially access all queues of the broker.
  - ➢ Queues may be used in many-to-many communications.
- Publish-subscribe is a message-queuing communication pattern:
  - Senders (called publishers) address their messages to queues, which represent topics or categories, without knowing the real recipients.
  - Receivers (called subscribers) listen on one or multiple queues via subscriptions to these queues; they consume messages without knowing the sender(s).
- Subscription = registered callback function



Message-Queuing Systems – Message Broker

General message delivery

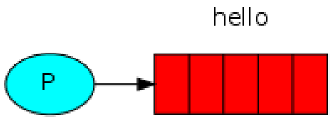
- Processes can …
  - create named message queues.
  - subscribe to existing message queues.
  - send messages to a queue.
- The message broker promises that send messages are delivered to some (1-to-1) or all (broadcasting) subscribers of a queue.

Popular message brokers

- Commercial:
  - TIBCO, IBM WebSphere, webMethods, …
- Open source:
  - Apache Kafka, RabbitMQ, ActiveMQ, HornetQ, NATS, …

Example: RabbitMQ – Sending a Message

https://www.rabbitmq.com/getstarted.html




```java
public class Send {

  private final static String QUEUE_NAME = "hello";

  public static void main(String[] argv) throws Exception {
    ConnectionFactory factory = new ConnectionFactory();
    factory.setHost("localhost");
    Connection connection = factory.newConnection();
    Channel channel = connection.createChannel();

    channel.queueDeclare(QUEUE_NAME, false, false, false, null);
    String message = "Hello World!";
    channel.basicPublish("", QUEUE_NAME, null, message.getBytes("UTF-8"));
    System.out.println(" [x] Sent '" + message + "'");

    channel.close();
    connection.close();
  }
}
```

Create a connection to the message broker running on localhost (see TCP protocol).

Create a channel to a queue; the queue is created if it does not exist yet.

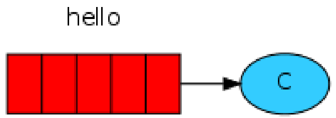
Send the message encoded as an array of bytes.

Close all channels and the connection.

Example: RabbitMQ – Receiving a Message

```java
public class Recv {

  private final static String QUEUE_NAME = "hello";

  public static void main(String[] argv) throws Exception {
    ConnectionFactory factory = new ConnectionFactory();
    factory.setHost("localhost");
    Connection connection = factory.newConnection();
    Channel channel = connection.createChannel();

    channel.queueDeclare(QUEUE_NAME, false, false, false, null);
    System.out.println(" [*] Waiting for messages. To exit press CTRL+C");

    Consumer consumer = new DefaultConsumer(channel) {
      @Override
      public void handleDelivery(String consumerTag, Envelope envelope, AMQP.BasicProperties properties, byte[] body)
          throws IOException {
        String message = new String(body, "UTF-8");
        System.out.println(" [x] Received '" + message + "'");
      }
    };
    channel.basicConsume(QUEUE_NAME, true, consumer);
  }
}
```

https://www.rabbitmq.com/getstarted.html



Create a connection to the message broker running on localhost (see TCP protocol).

Create a channel to a queue; the queue is created if it does not exist yet.

Create a callback object that can buffer and consume messages from a queue.

Special metadata for the received message:
- E.g. encoding, timestamp, sender, priority, …

Decode and print any received byte message.

Subscribe the new consumer to the queue; the broker will call it with messages of that queue.

Message-oriented Middleware

Example: RabbitMQ – Example in Python

```python
#!/usr/bin/env python
import pika

connection = pika.BlockingConnection(pika.ConnectionParameters(
        host='localhost'))
channel = connection.channel()


channel.queue_declare(queue='hello')

channel.basic_publish(exchange='',
                      routing_key='hello',
                      body='Hello World!')
print(" [x] Sent 'Hello World!'")
connection.close()
```


```python
#!/usr/bin/env python
import pika

connection = pika.BlockingConnection(pika.ConnectionParameters(
        host='localhost'))
channel = connection.channel()


channel.queue_declare(queue='hello')

def callback(ch, method, properties, body):
    print(" [x] Received %r" % body)

channel.basic_consume(callback,
                      queue='hello',
                      no_ack=True)

print(' [*] Waiting for messages. To exit press CTRL+C')
channel.start_consuming()
```

Further APIs:

Ruby, PHP, C#, JavaScript, Go, Elixir, Objective-C, Swift, …

https://www.rabbitmq.com/getstarted.html

Message-Queuing Systems – Message Broker

Advantages

- Maintainability: Decouples sender and receiver objects/threads/processes
- Asynchronicity: Buffers messages if receiver is unavailable or overloaded
- Robustness: May redirect messages if some receiver is unreachable
- Efficiency: Message routing, buffering, replication… can be optimized

Disadvantages

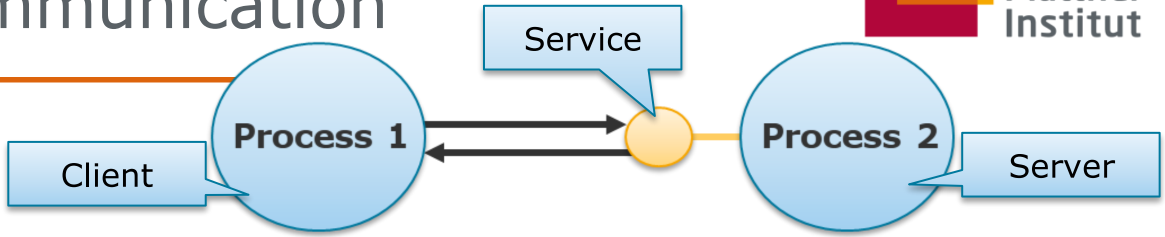
- Scalability: Message broker and shared queues can be bottlenecks
- Latency: Message broker is an additional hop for each message
- Reliability: Publishers cannot be sure that their messages will be consumed; broker will need to drop undeliverable messages eventually

Overview

Communication

- Message Passing
- OSI Model
- Socket-based Communication
- Message-oriented Middleware
- **Service-oriented Middleware**
- Database-oriented Middleware

Service-oriented Communication



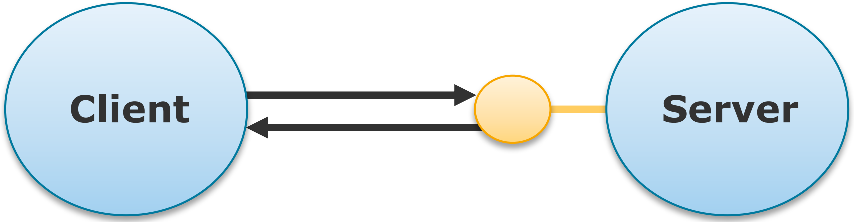
Service

- A well-defined API that can be accessed by other (remote) processes
- Identified by service protocol + IP + port
- Offers functions that may take arguments (= a send message) and return values (= a receive message)
  - Functions define **fine-grained restrictions** on what can be communicated.
  - Functions imply **clear actions** (whereas messages that imply facts).
  - Functions are **blocking** und **synchronous**

Asymmetric Communication

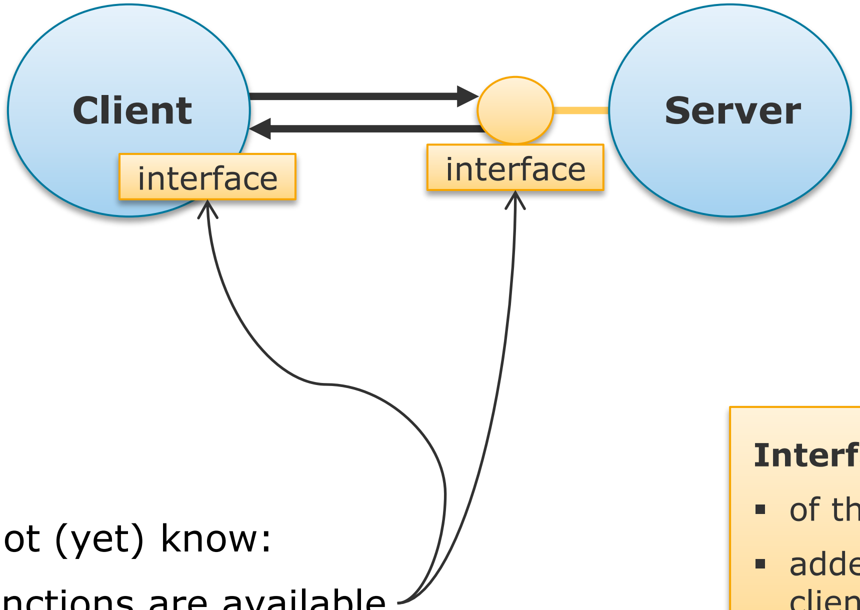
- Communicating processes have two roles:
  - Server: exposes a service that other processes can see and use.
  - Client: connects to a server's service and calls functions.

Service-oriented Communication



- Client knows:
  - How to address the server (IP + Port)
  - How to send data (serialization + packaging)
- Client does not (yet) know:
  - What functions are available
  - What data it needs to send to call a function

Service-oriented Communication

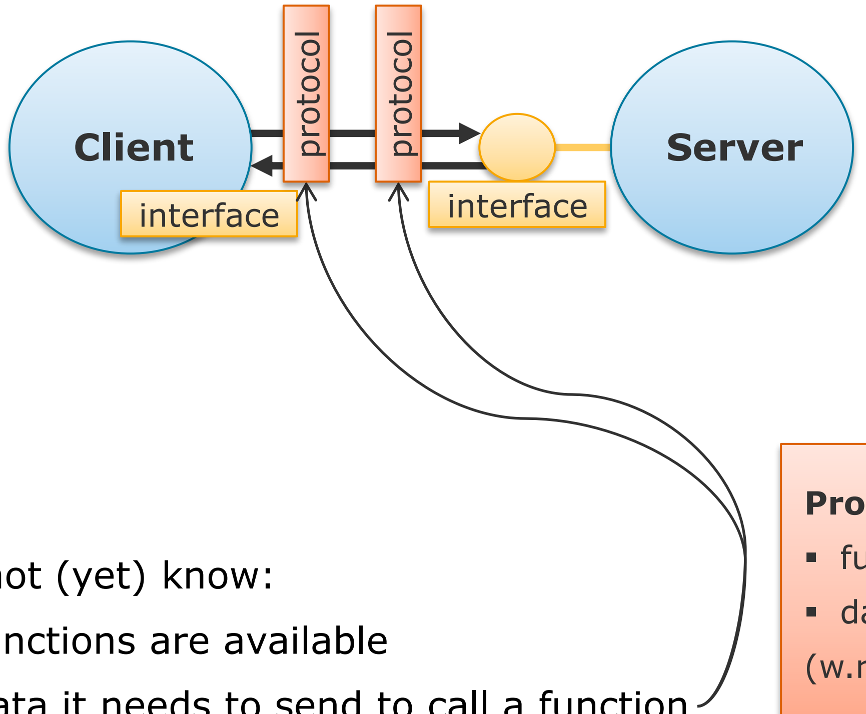


- Client does not (yet) know:
  - What functions are available
  - What data it needs to send to call a function

Interface:

- of the service functions
- added e.g. during client implementation as library

Service-oriented Communication



- Client does not (yet) know:
  - What functions are available
  - What data it needs to send to call a function

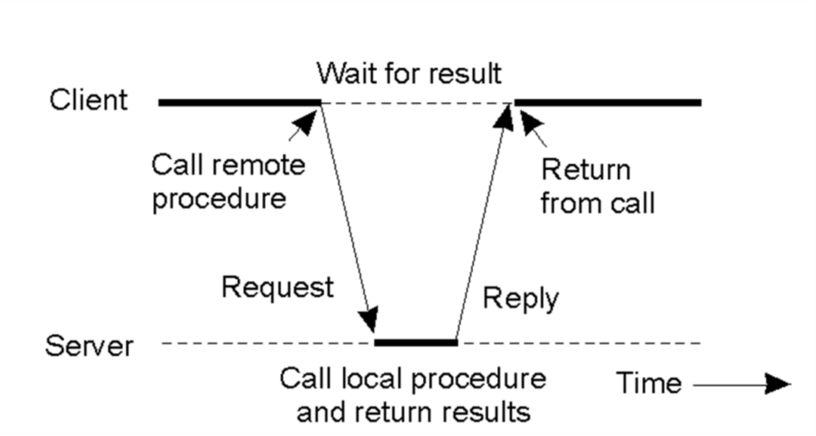
Protocol:
- function call → data
- data → function call

(w.r.t. given interface)

Remote Procedure Call (RPC)

A protocol that allows processes to directly call functions in remote processes (i.e., cause procedures to execute in different address spaces).

- The object-oriented equivalent is remote method invocation (RMI).
- Remote procedures are called like normal (local) procedures.
  - ➢ Tight coupling between processes

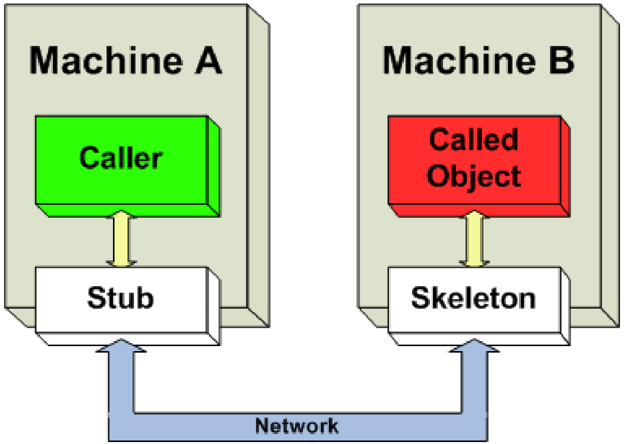


Bruce Jay Nelson
introduced the RPC idea in 1984.
[Andrew D. Birrell and Bruce Jay Nelson, "Implementing Remote Procedure Calls". ACM Transactions on Computer Systems, 1984]

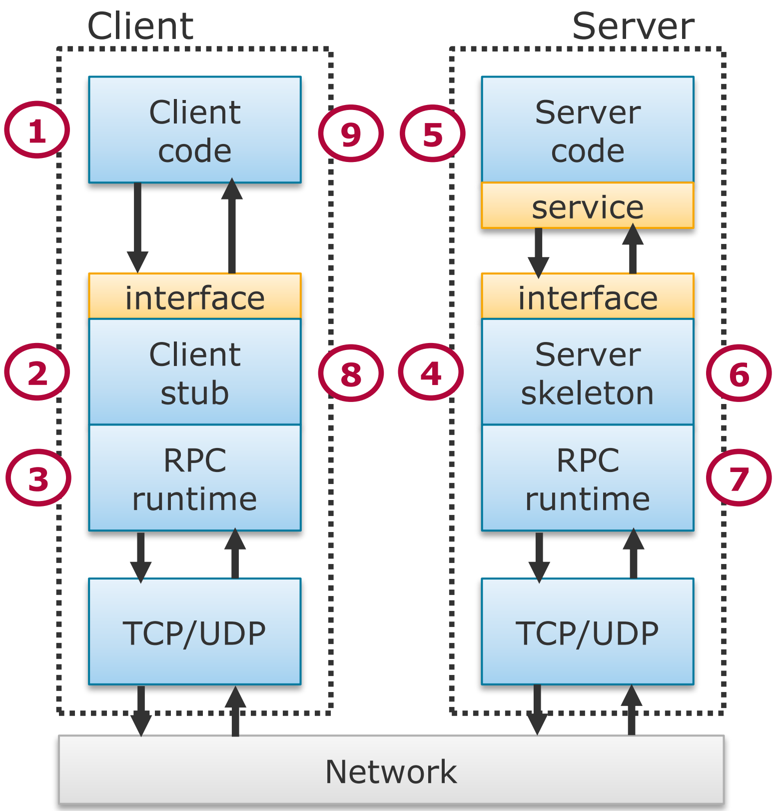
Remote Procedure Call (RPC)

The RPC middleware:

- requires the service's interface on server and client.
- implements the protocol for transmitting a function call.
- uses the interface to automatically generate two proxies:
  - Stub (function call → data)
    - Implements and offers the interface functions.
    - Translates any function call into a message and sends it to the skeleton.
      - ➢ function/parameter marshaling
  - Skeleton (data → function call)
    - Implements a messaging-based endpoint for a service.
    - Translates any message into a function call and maps it to the right local function implementation.

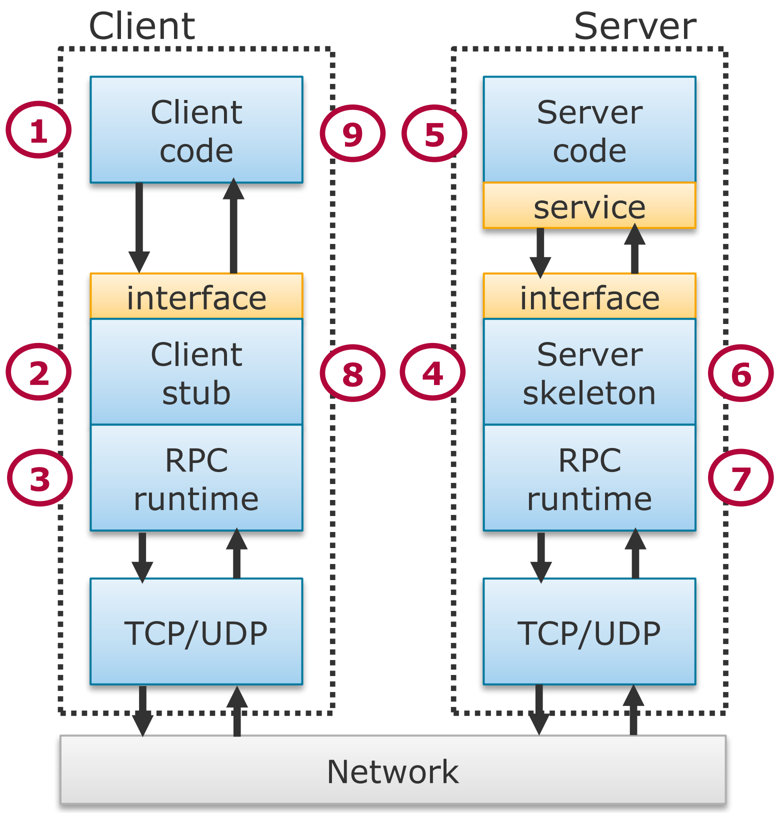


Remote Procedure Call (RPC)



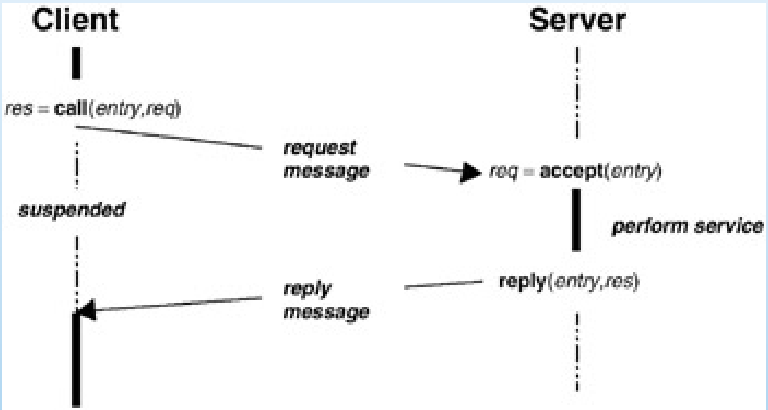
1. Client calls a remote procedure and waits.
2. Stub accepts the procedure call and serializes both the call and its parameters.
3. RPC Runtime sends the serialized call via TCP/UDP to the server.
4. Skeleton accepts procedure call, deserializes the message and calls the corresponding service procedure with the given parameters.
5. Server handles the call and returns a result.
6. Skeleton accepts the result and serializes it.
7. RPC Runtime sends the serialized result via TCP/UDP back to the client.
8. Stub accepts the result, deserializes it and forwards it to the waiting client.
9. Client awakes and accepts the result.

Remote Procedure Call (RPC)



1. Client calls a remote procedure and waits.
2. Stub accepts the procedure call and serializes both the call and its parameters.
3. RPC Runtime … via TCP/UDP
4. Skeleton acc… the message … service proce…
5. Server handl…
6. Skeleton acc… serializes it.
7. RPC Runtime … via TCP/UDP
8. Stub accepts the re… …alizes it and forwards … the waiting client.
9. Client awakes and accepts the result.

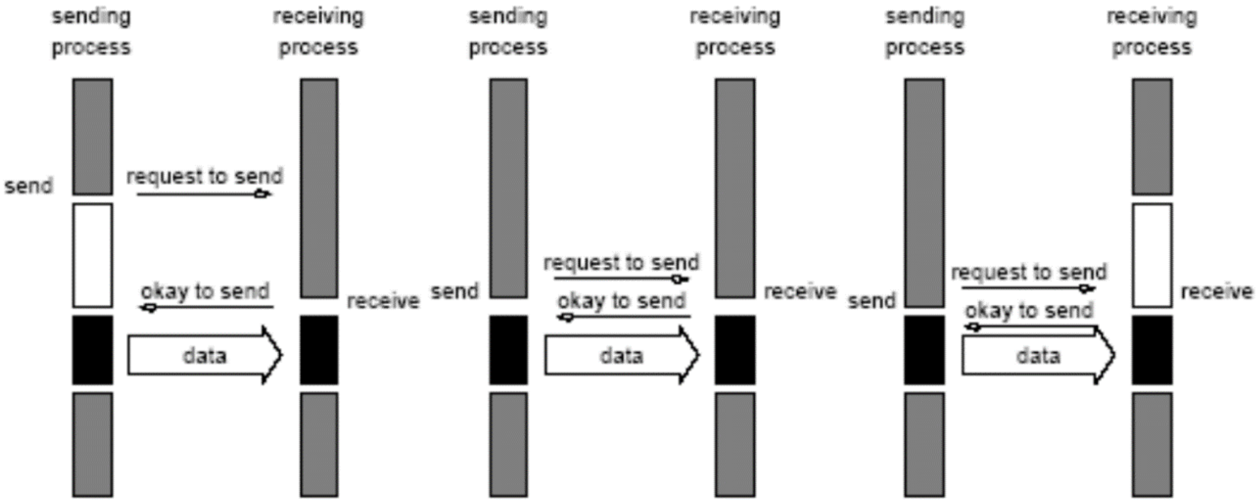
RPC calls block the client



Remote Procedure Call (RPC)

Rendezvous protocol

- Handshake protocol for sending large blocks of data via synchronous communication.
- Avoid sending data to processes that cannot accept them (at the moment).
- Before data is sent, the receiver needs to acknowledge that it is ready to accept data.



(a) Sender comes first; idling at sender

(b) Sender and receiver come at about the same time; idling minimized

(c) Receiver comes first; idling at receiver

Remote Procedure Call (RPC)

- RPC/RMI are protocols of which many framework implementations exist.
- RPC/RMI provide a communication interface in the programming language and hide the communication protocol in a runtime, i.e., middleware.
- RPC/RMI implementations can be:
  - language specific:
    interface is written in same language;
    often the programming language itself
  - language agnostic:
    interface is written in some RPC/RMI dialect;
    compiles to different programming languages
- The RPC/RMI protocols use blocking, synchronous communication but it is easy to turn the idea into non-blocking, asynchronous communication:
  - e.g. procedure calls may immediately return “Future” or “Promise” objects

Remote Procedure Call (RPC)

Strengths of RPC/RMI

- RPC/RMI frameworks are well suited for machine to machine communication (remote calls appear like local calls; program does not leave its own language).
- RPC/RMI frameworks are easy to use (automatic code generation and abstraction of the messaging details).
- RPC/RMI frameworks are extensive (no restrictions other than those the interface language has).
- RPC/RMI frameworks offer good performance (highly optimized messaging, because the runtime controls both ends of the communication and no third party needs to understand the messages).

Remote Procedure Call (RPC)

Weaknesses of RPC/RMI

- RPC/RMI cause a tight coupling of server and client code.
  (interface changes always concern both)

- Local and remote function calls are, in fact, very different.
  - Local function calls are predictable: they succeed or fail, throw proper exceptions or starve processing; can handle same pointers and data types than caller
  - Remote function calls are unpredictable: they fail silently, succeed but responses get lost, are unavailable; cannot handle the caller's pointers (and all data types)

- RPC/RMI code may be hard to debug and test.
  (code generation; possibly hiding of network errors)

> Good/modern RPC frameworks make differences explicit and forward errors transparently so that application code can (and should!) handle these issues.

Service-oriented Middleware
Remote Procedure Call (RPC)

https://en.wikipedia.org/wiki/Remote_procedure_call

RPC implementations

Language-specific [edit]

- Java's Java Remote Method Invocation (Java RMI) API provides similar functionality to standard Unix RPC methods.
- Modula-3's network objects, which were the basis for Java's RMI[10]
- RPyC implements RPC mechanisms in Python, with support for asynchronous calls.
- Distributed Ruby (DRb) allows Ruby programs to communicate with each other on the same machine or over a network. DRb uses remote method invocation (RMI) to pass commands and data between processes.
- Erlang is process oriented and natively supports distribution and RPCs via message passing between nodes and local processes alike.
- Elixir builds on top of the Erlang VM and allows process communication (Elixir/Erlang processes, not OS processes) of the same network out-of-the-box via Agents and message passing.

Application-specific [edit]

- Action Message Format (AMF) allows Adobe Flex applications to communicate with back-ends or other applications that support AMF.
- Remote Function Call is the standard SAP interface for communication between SAP systems. RFC calls a function to be executed in a remote system.

General [edit]

- NFS (Network File System) is one of the most prominent users of RPC
- Open Network Computing Remote Procedure Call, by Sun Microsystems
- D-Bus open source IPC program provides similar function to CORBA.
- SORCER provides the API and exertion-oriented language (EOL) for a federated method invocation
- XML-RPC is an RPC protocol that uses XML to encode its calls and HTTP as a transport mechanism.
- JSON-RPC is an RPC protocol that uses JSON-encoded messages
- JSON-WSP is an RPC protocol that uses JSON-encoded messages
- SOAP is a successor of XML-RPC and also uses XML to encode its HTTP-based calls.
- ZeroC's Internet Communications Engine (Ice) distributed computing platform.
- Etch framework for building network services.
- Apache Thrift protocol and framework.
- CORBA provides remote procedure invocation through an intermediate layer called the *object request broker*.
- Libevent provides a framework for creating RPC servers and clients.[11]
- Windows Communication Foundation is an application programming interface in the .NET framework for building connected, service-oriented applications.
- Microsoft .NET Remoting offers RPC facilities for distributed systems implemented on the Windows platform. It has been superseded by WCF.
- The Microsoft DCOM uses MSRPC which is based on DCE/RPC
- The Open Software Foundation DCE/RPC Distributed Computing Environment (also implemented by Microsoft).
- Google Protocol Buffers (protobufs) package includes an interface definition language used for its RPC protocols[12] open sourced in 2015 as gRPC.[13]
- Google Web Toolkit uses an asynchronous RPC to communicate to the server service.[14]
- Apache Avro provides RPC where client and server exchange schemas in the connection handshake and code generation is not required.
- Embedded RPC is lightweight RPC implementation developed by NXP, targeting primary CortexM cores

… Thrift-based

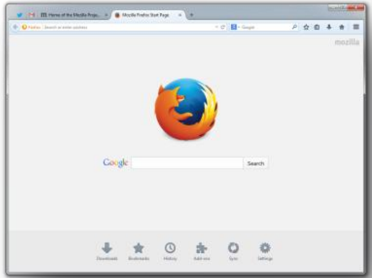
… Protocol Buffers-based

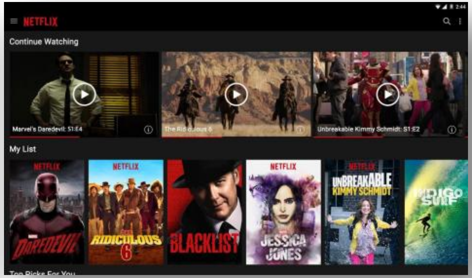
… Avro-based

Service-Oriented Architecture (SOA)

- A server process can, again, become a client to some other server.
  - ➢ (Distributed) systems of interacting processes
- Services should be self-contained black box components that represent logical activities hiding lower-level services.
- Microservice architecture:
  - Variant of SOA where services are particularly fine-grained and the protocol is lightweight

Examples


Web Browser



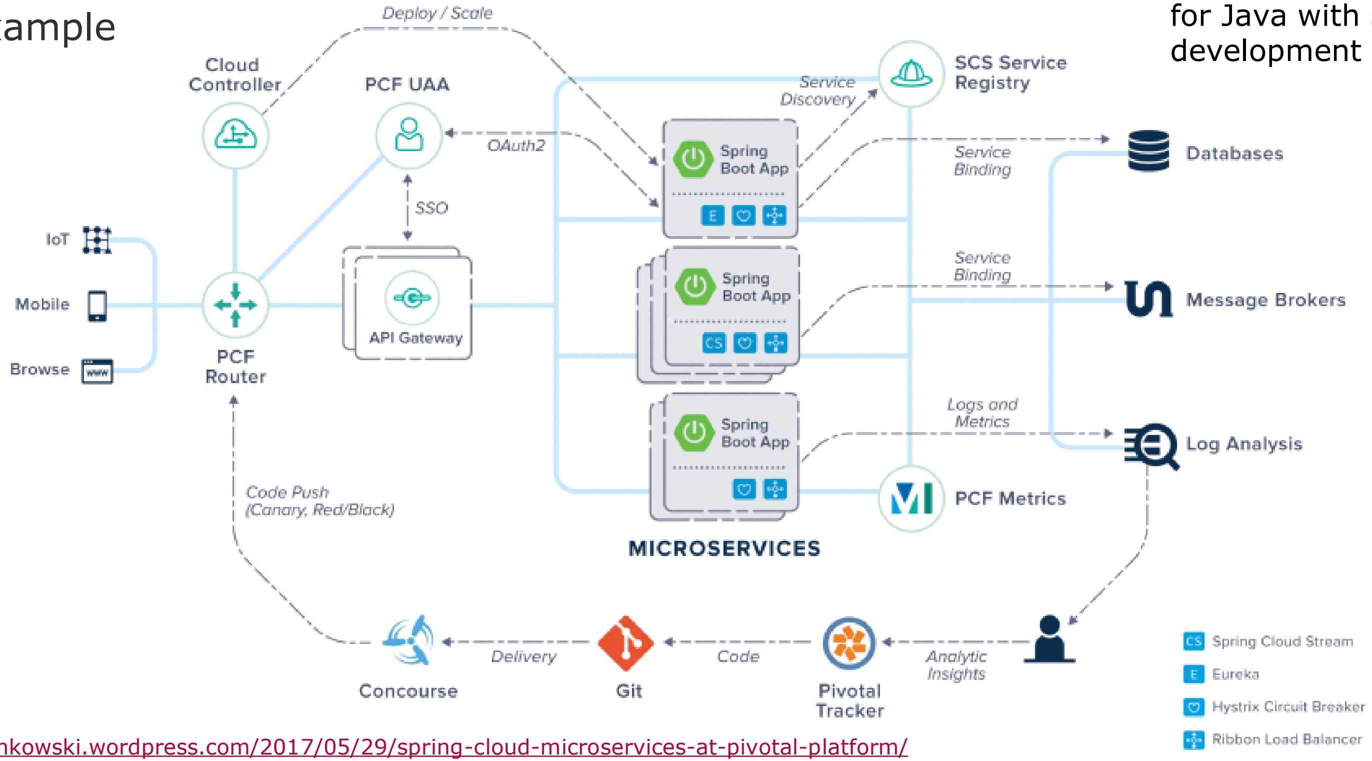
Apps


Online Games

Service-Oriented Architecture (SOA)

Microservice architecture

- Example



- A light-weight application framework for Java with support for microservice development

Distributed Data Management

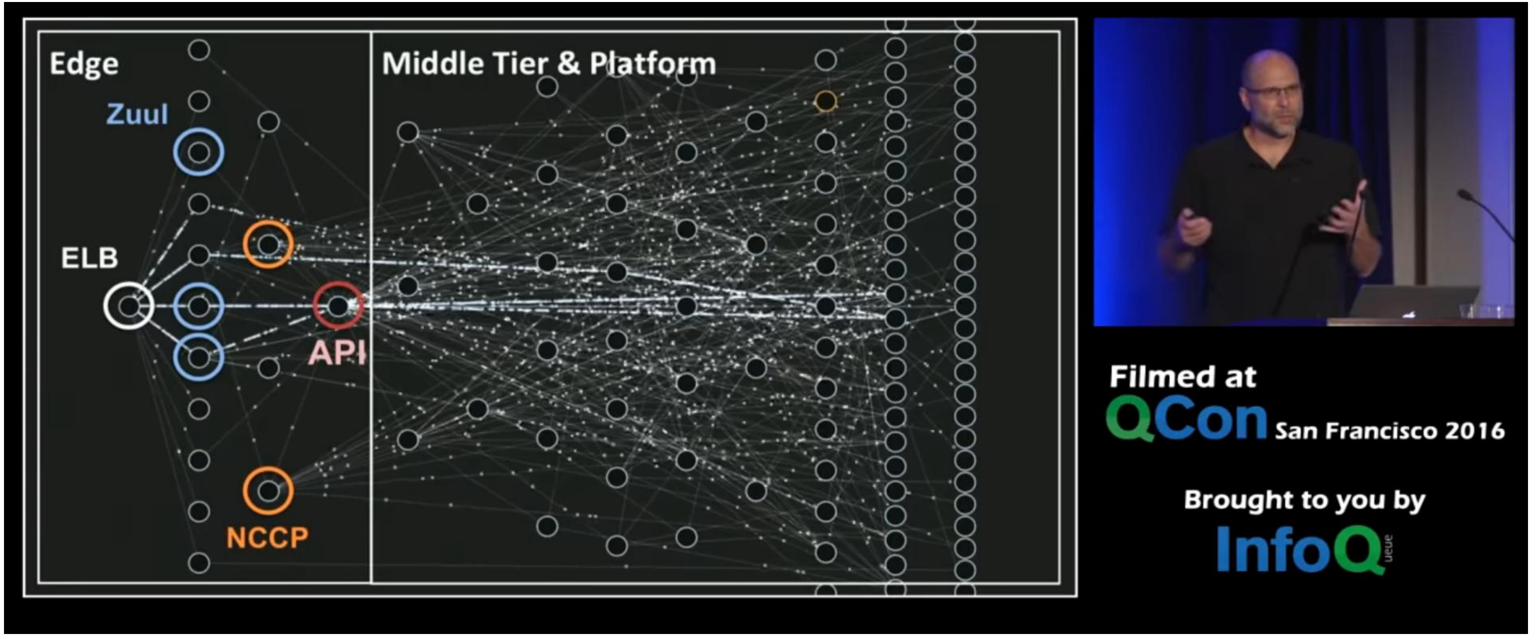
Communication

https://piotrminkowski.wordpress.com/2017/05/29/spring-cloud-microservices-at-pivotal-platform/

Service-Oriented Architecture (SOA)

Microservice architecture

- Example: **Mastering Chaos - A Netflix Guide to Microservices**



https://www.youtube.com/watch?v=CZ3wIuvmHeM

Service-Oriented Architecture (SOA)

All this contradicts an implementation with RPCs

(Micro-)Services are:

- loosely coupled
- independently deployable
- heterogeneous in their implementation (languages, libraries, resources, dependencies, …)
- dependent on only lightweight protocols
- highly maintainable and testable
- organized around business capabilities
- often owned by a small team

(Micro-)Services enable:

- rapid, frequent and reliable delivery of large, complex applications
- the evolution of an applications technology stack (at runtime).

Popular Service Protocols

HTTP

- Used by the largest SOA systems on the planet, e.g., the World Wide Web.

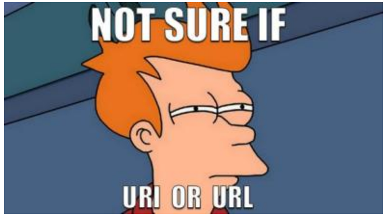
(HTTP) REST

- If you need clearer conventions for HTTP service APIs.
(e.g. to make them easier to maintain and better machine consumable)
- Used by many Web applications to connect front- and backend systems.

(HTTP + RPC) SOAP

- If you develop heterogeneous distributed systems that need to communicate not only data but also instructions (i.e., method calls).
- Used by many large scale, heterogeneous distributed systems.

Hypertext Transfer Protocol (HTTP)



Definition

- A stateless, synchronous request-response application protocol for distributed, collaborative, and hypermedia information systems
- The foundation for communication in the World Wide Web
- Hypertext: structured text that uses logical links (hyperlinks) between nodes containing text (usually HTML)

Technical Details

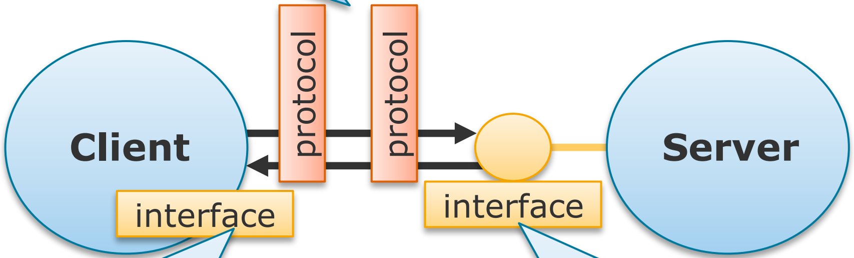
- Message format: designed for hypertext, but works for any text format
- Based on the TCP transport layer protocol
- Uniform Resource Locators (URLs) / Uniform Resource Identifier (URI) to find services and resources:

  scheme:[//[user[:password]@]host[:port]][/path]

  - E.g.: http://hpi.de/naumann/people/thorsten-papenbrock

Hypertext Transfer Protocol (HTTP)

HTTP defines the message format and protocol so that two different HTTP implementations, i.e., different runtimes can communicate.



Library/program that implements the well defined HTTP interface
(e.g. web browser, curl, libashttp, java.net.HttpURLConnection)

Well defined functions:
GET, POST, PUT, DELETE, …

Well defined messages:
header fields and text data

7. **Application layer**
NNTP · SIP · SSI · DNS · FTP · Gopher · HTTP · NFS · NTP · SMPP · SMTP · SNMP · Telnet · DHCP · Netconf · *more....*

6. **Presentation layer**
MIME · XDR · ASN.1 · ASCII · PGP

5. **Session layer**
Named pipe · NetBIOS · SAP · PPTP · RTP · SOCKS · SPDY

4. **Transport layer**
TCP · UDP · SCTP · DCCP · SPX

3. **Network layer**
IP (IPv4 · IPv6) · ICMP · IPsec · IGMP · IPX · AppleTalk · X.25 PLP

2. **Data link layer**
ATM · ARP · IS-IS · SDLC · HDLC · CSLIP · SLIP · GFP · PLIP · IEEE 802.2 · LLC · MAC · L2TP · IEEE 802.3 · Frame Relay · ITU-T G.hn DLL · PPP · X.25 LAPB · Q.922 LAPF

1. **Physical layer**
EIA/TIA-232 · EIA/TIA-449 · ITU-T V-Series · I.430 · I.431 · PDH · SONET/SDH · PON · OTN · DSL · IEEE 802.3 · IEEE 802.11 · IEEE 802.15 · IEEE 802.16 · IEEE 1394 · ITU-T G.hn PHY · USB · Bluetooth · RS-232 · RS-449

Hypertext Transfer Protocol (HTTP)

HTTPs

- HTTP over Transport Layer Security (TLS) / Secure Sockets Layer (SSL)
- Features:
  - Privacy through **symmetric encryption**
  - Authentication through **public-key cryptography**
  - Integrity through checking of **message authentication codes**

Session (HTTP/1.1)

- A sequence of network request-response transactions:
  1. Client establishes a TCP connection to server port (typically port 80).
  2. Client sends an HTTP message.
  3. Server sends back a status line with a message of its own.
  4. Client sends next HTTP message or closes the TCP connection.

Hypertext Transfer Protocol (HTTP)

Request Message Pattern

A request-line:	<method> <resource identifier> <protocol version>
Any header lines:	<header field>: <value>
An empty line	
A message-body:	<any text format> optional

Request Methods

- GET: Retrieve information from the target resource using a given URI (no side effects).
- HEAD: Like GET, but response contains only status line and header section (no content).
- POST: Send data to the target resource; the resource decides what to do with the data.
- PUT: Send data to the target resource; replace the content of the resource with that data.
- DELETE: Removes all content of the target resource.
- CONNECT: Establishes a tunnel to the server identified by a given URI.
- OPTIONS: Describe the communication options for the target resource.
- TRACE: Performs a message loop back test along with the path to the target resource.

Hypertext Transfer Protocol (HTTP)

Request Message Pattern

▪ A request-line:	<method> <resource identifier> <protocol version>
▪ Any header lines:	<header field>: <value>
▪ An empty line	
▪ A message-body:	<any text format> optional

Examples

- GET http://hpi.de/naumann/people/thorsten-papenbrock/publications HTTP/1.1
  → absolute URI: for requests to a proxy, which should forward the request
  → no additional header fields
- GET /naumann/people/thorsten-papenbrock/publications HTTP/1.1
  User-Agent: Mozilla/4.0 (compatible; MSIE5.01; Windows NT)
  Host: www.hpi.de:80
  Accept-Language: en-us
  → relative URI: for request to origin server
  → some header fields as example

Hypertext Transfer Protocol (HTTP)

Request Message Pattern

▪ A request-line:	<method> <resource identifier> <protocol version>
▪ Any header lines:	<header field>: <value>
▪ An empty line	
▪ A message-body:	<any text format> optional

Examples

- POST /naumann/people/thorsten-papenbrock/publications HTTP/1.1
  Host: www.hpi.de:80
  Content-Type: text/xml; charset=utf-8
  Accept-Language: en-us
  Accept-Encoding: gzip, deflate
  Connection: Keep-Alive

  <publication>A Hybrid Approach to Functional Dependency Discovery</publication>
  → post a new publication entry to the publications resource (should be appended)
  → flags indicate utf-8 formatted xml content and ask to keep the connection open

PUT would replace all publi-cations with the new one

Hypertext Transfer Protocol (HTTP)

Response Message Pattern

▪ A status-line:	<protocol version> <status code> <reason-phrase>
▪ Any header lines:	<header field>: <value>
▪ An empty line	
▪ A message-body:	<any text format> optional

Status codes

- 1xx: Informational: the request was received and the process is continuing.
- 2xx: Success: the action was successfully received, understood, and accepted.
- 3xx: Redirection: further action must be taken in order to complete the request.
- 4xx: Client Error: the request contains incorrect syntax or cannot be fulfilled.
- 5xx: Server Error: the server failed to fulfill an apparently valid request.

Hypertext Transfer Protocol (HTTP)

Response Message Pattern

- A status-line: <protocol version> <status code> <reason-phrase>
- Any header lines: <header field>: <value>
- An empty line
- A message-body: <any text format> optional

Example

- GET http://www.my-host.com/my-new-homepage.html

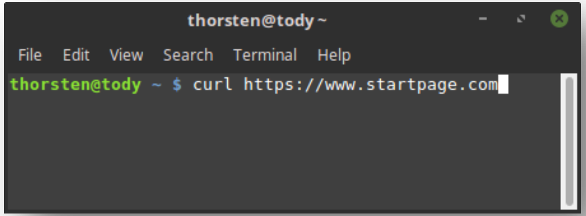
```
HTTP/1.1 200 OK
Date: Mon, 24 Jul 2017 12:28:53 GMT
Server: Apache/2.2.14 (Win32)
Last-Modified: Sat, 22 Jul 2017 13:15:56 GMT
Content-Length: 98
Content-Type: text/html
Connection: Closed

<html><body><h1>Welcome to my homepage!</h1></body></html>
```

Service-oriented Middleware

Hypertext Transfer Protocol (HTTP)

The cURL Program

- Library and command-line tool for transferring data using various protocols
- Originally developed as “see url” in 1997
- Examples:
  - curl -i -X GET http://localhost:8080/datasets
  - curl -i -X GET http://localhost:8080/datasets/by/csv
  - curl -i -X POST -d '{"name":"Planets","ending":"csv","path":"datasets"}'
    -H 'Content-Type:application/json;charset=UTF-8‘
    http://localhost:8080/datasets
  - curl -i -X DELETE http://localhost:8080/datasets/1
  - curl -i -X GET http://localhost:8080/datasets/1
  - curl -i -X PUT -d '{"name":"Planets","ending":"csv","path":"datasets"}'
    -H 'Content-Type:application/json;charset=UTF-8‘
    http://localhost:8080/datasets/1



Popular Service Protocols

HTTP

- Used by the largest SOA systems on the planet, e.g., the World Wide Web.

(HTTP) REST

- If you need clearer conventions for HTTP service APIs.
(e.g. to make them easier to maintain and better machine consumable)
- Used by many Web applications to connect front- and backend systems.

(HTTP + RPC) SOAP

- If you develop heterogeneous distributed systems that need to communicate not only data but also instructions (i.e., method calls).
- Used by many large scale, heterogeneous distributed systems.

Representational State Transfer (REST)

- A design philosophy for HTTP services:
  - Resources are the main concept
  - CRUD (create, read, update, delete) operations on resources should use their corresponding HTTP methods
- Focus on simplicity

No method miss-use like
GET ...publications/?delete_id=42
which is typical for many HTTP services

- OpenAPI Specification:
  - Creates the RESTful contract for your API.
  - RESTful contract describes all resources and their supported methods.
    - ➢ a language-agnostic interface description for the RESTful API
  - Implemented in, e.g., the Swagger framework (see https://swagger.io/)

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(HTTP + RPC) SOAP

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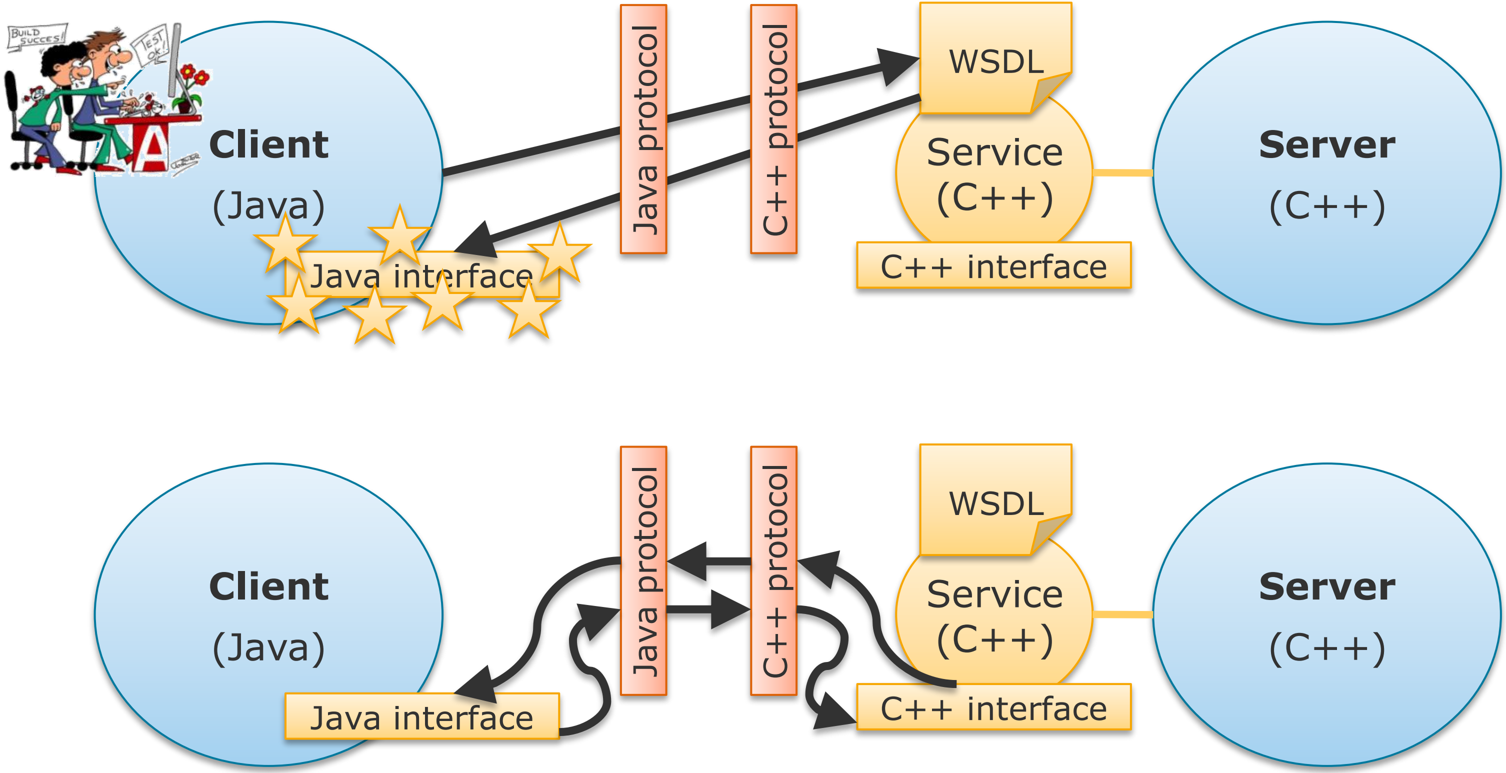
Simple Object Access Protocol (SOAP)

- An XML-based RPC protocol for making network API requests.
- Uses functions as main concepts (in contrast to resources in REST).
- Often implemented on top of HTTP but waiving most of its features.
  - ➢ Comes with its own standards (the web service framework WS[…]).
- Idea:
  - A server describes the API of its service in a WSDL document (Web Service Description Language; an XML dialect).
  - A client can use the WSDL document to generate the API code in its own programming language and then call the API functions.
    - ➢ Both server and client can access the API in their own language.
- Both programming languages and their IDEs must support SOAP for code and message generation.
  - ➢ Interoperability without this support is difficult.

Simple Object Access Protocol (SOAP)



Simple Object Access Protocol (SOAP)

Simple Object Access Protocol (SOAP)

- Simple example:

```
<?xml version="1.0"?>
<definitions name="Booking">
  <message name="getBookingRequest">
    <part name="user" type="xs:string"/>
    <part name="house" type="xs:string"/>
  </message>
  <message name="getAvailabilityResponse">
    <part name="available" type="xs:boolean"/>
  </message>
  <portType name="BookingPort">
    <operation name="processBooking">
      <input message="getBookingRequest"/>
      <output message="getAvailability Response"/>
    </operation>
  </portType>
```

WSDL File

```
public interface BookingPort {
  public boolean processBooking(String user, String house);
}
```

A (simple), language-agnostic interface definition

Simple Object Access Prot

Binding of an interface to concrete HTTP SOAP calls

Simple Object Access Protocol (SOAP)

- Simple example:

```
<?xml version="1.0"?>
<definitions name="Booking">
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    <part name="user" type="xs:string"/>
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  </message>
  <message name="getAvailabilityResponse">
    <part name="available" type="xs:boolean"/>
  </message>
  <portType name="BookingPort">
    <operation name="processBooking">
      <input message="getBookingRequest"/>
      <output message="getAvailability Response"/>
    </operation>
  </portType>
```

WSDL File

Bundling of service calls to a SOAP service

```
<binding name="BookingBinding" type="BookingPort">
  <soap:binding
      style="document"
      transport="http://schemas.xmlsoap.org/soap/http"/>
  <operation name="processBooking">
    <soap:operation
        soapAction="http://example.com/processBooking "/>
    <input>
      <soap:body use="literal"/>
    </input>
    <output>
      <soap:body use="literal"/>
    </output>
  </operation>
</binding>
<service name="BookingService">
  <documentation>A SOAP booking service</documentation>
  <port
      name="BookingPort"
      binding="BookingBinding">
    <soap:address location="http://example.com/booking"/>
  </port>
</service>
</definitions>
```

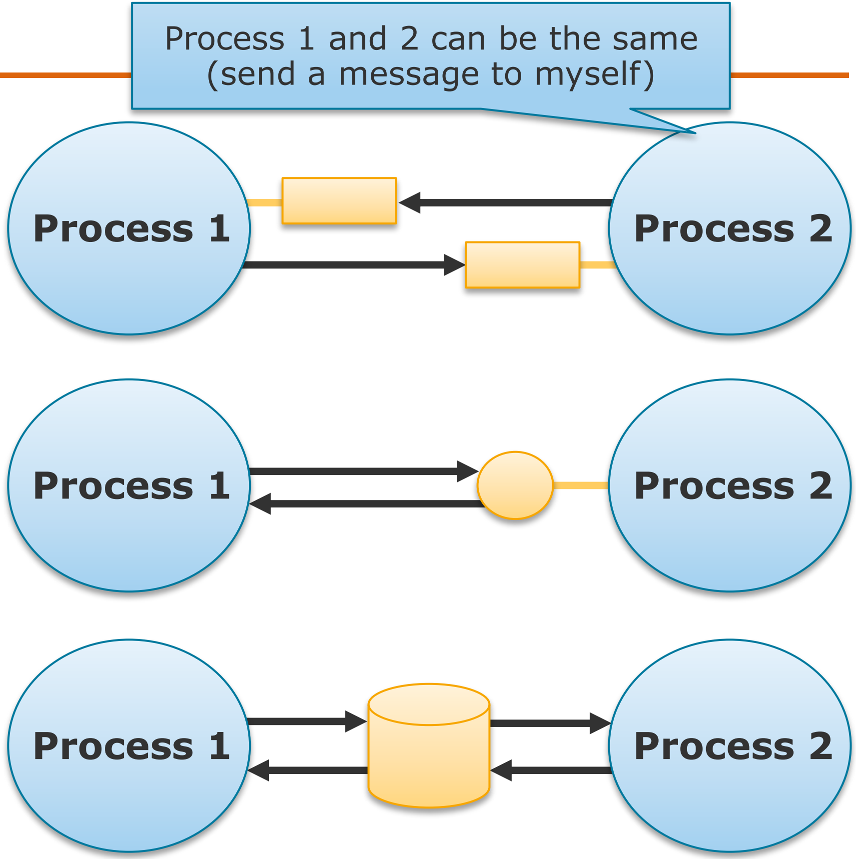
WSDL File (cont.)

Overview

Communication

- Message Passing
- OSI Model
- Socket-based Communication
- Message-oriented Middleware
- Service-oriented Middleware
- **Database-oriented Middleware**

Models of Dataflow



Message-Passing Dataflow

- Sending and receiving of messages

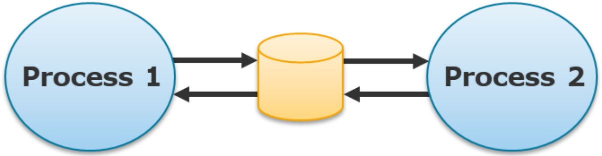
Dataflow through Services

- Calling services and waiting for responses

Dataflow through Databases

- Storage and retrieval of data

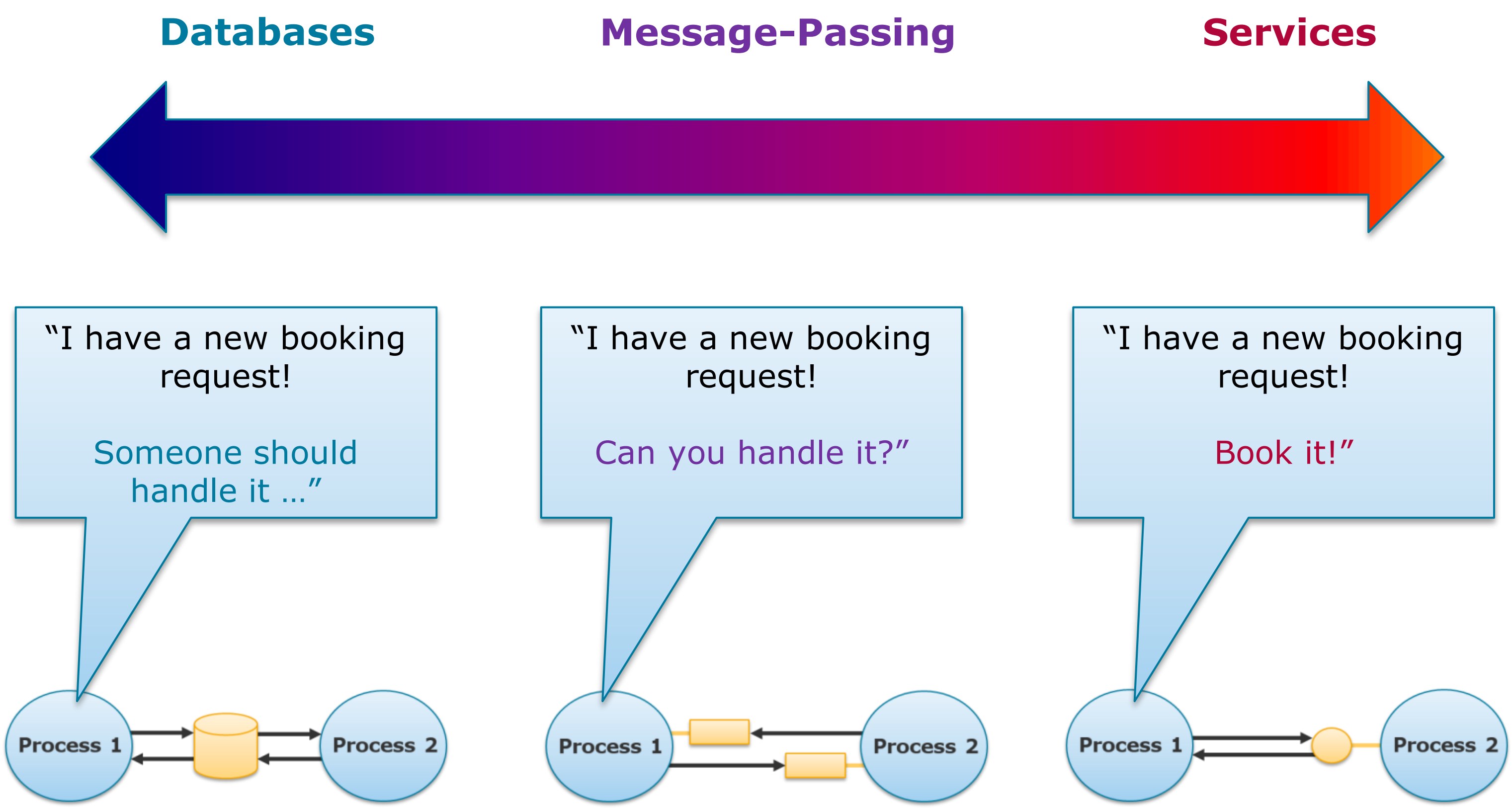
Communication Principle



- Processes write data to and read data from a database:
  - Communication through manipulation of (persistent) global state
- Requires commonly understood model, schema, and encoding:
  - Model: relational, key-value, wide-column, document, graph, …
  - Schema: either schema-on-read or schema-on-write
  - Encoding: Unicode, binary, …
- Implicit message exchange:
  - No explicit sender or receiver (think of broadcast messages)
- Varying message lifetimes:
  - Data can quickly be overwritten (= overwritten message is lost).
  - Data can stay forever (known as: data outlives code).
- Shared memory parallel applications are very similar w.r.t. this model.

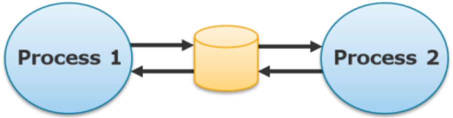
Every data value is a message

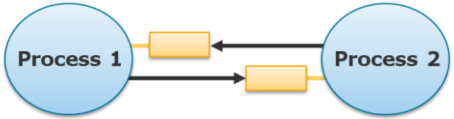
Models of Dataflow

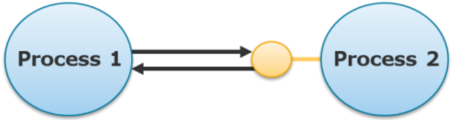


Models of Dataflow

Databases	Message-Passing	Services
Data	Messages	Function calls
No response	Maybe response	Response
Non-blocking	Usually non-blocking	Blocking
Asynchronous	Usually asynchronous	Synchronous
No addressing	Addressing recipient or queue/mailbox/topic	Addressing recipient

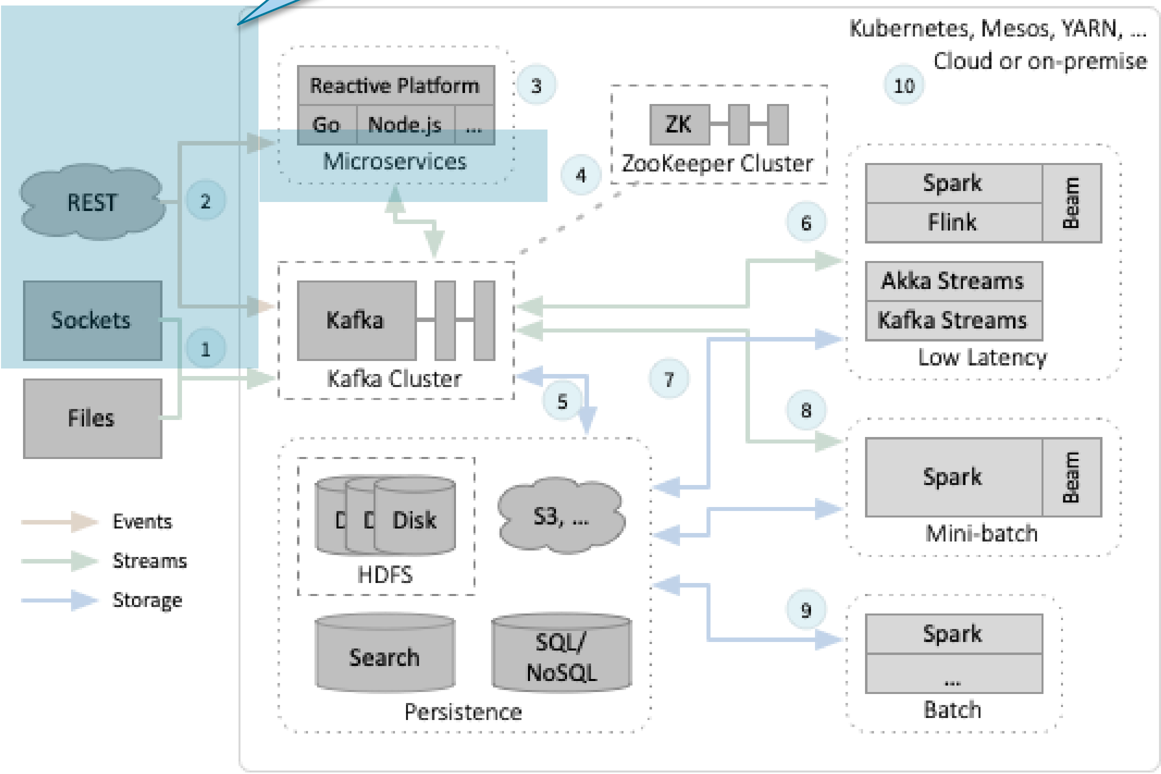




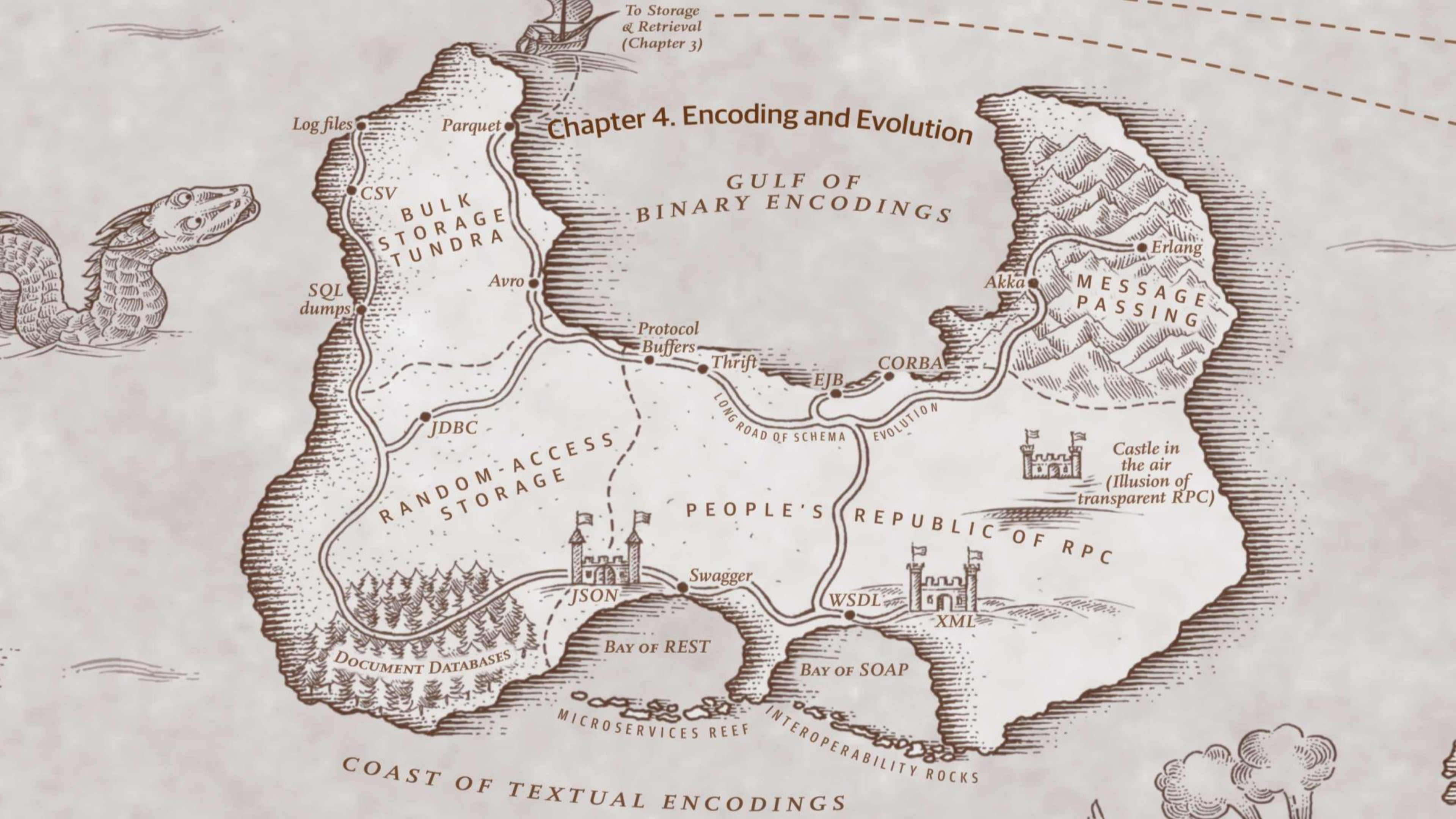


Communication
Outlook

About what we have seen so far.



https://www.lightbend.com/blog/cloud-native-streaming-data-with-akka-streams-kafka-steams


Chapter 4. Encoding and Evolution
To Storage
& Retrieval
(Chapter 3)
Log files
Parquet
CSV
BULK
STORAGE
TUNDRA
GULF OF
BINARY ENCODINGS
SQL
dumps
Avro
Protocol
Buffers
Thrift
EJB
CORBA
Akka
Erlang
MESSAGE
PASSING
JDBC
LONG ROAD OF SCHEMA EVOLUTION
RANDOM-ACCESS
STORAGE
Castle in
the air
(Illusion of
transparent RPC)
PEOPLE'S REPUBLIC OF RPC
JSON
Swagger
WSDL
XML
Bay of REST
Bay of SOAP
Document Databases
MICROSERVICES REEF
INTEROPERABILITY ROCKS
COAST OF TEXTUAL ENCODINGS