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Distributed Systems

Communication

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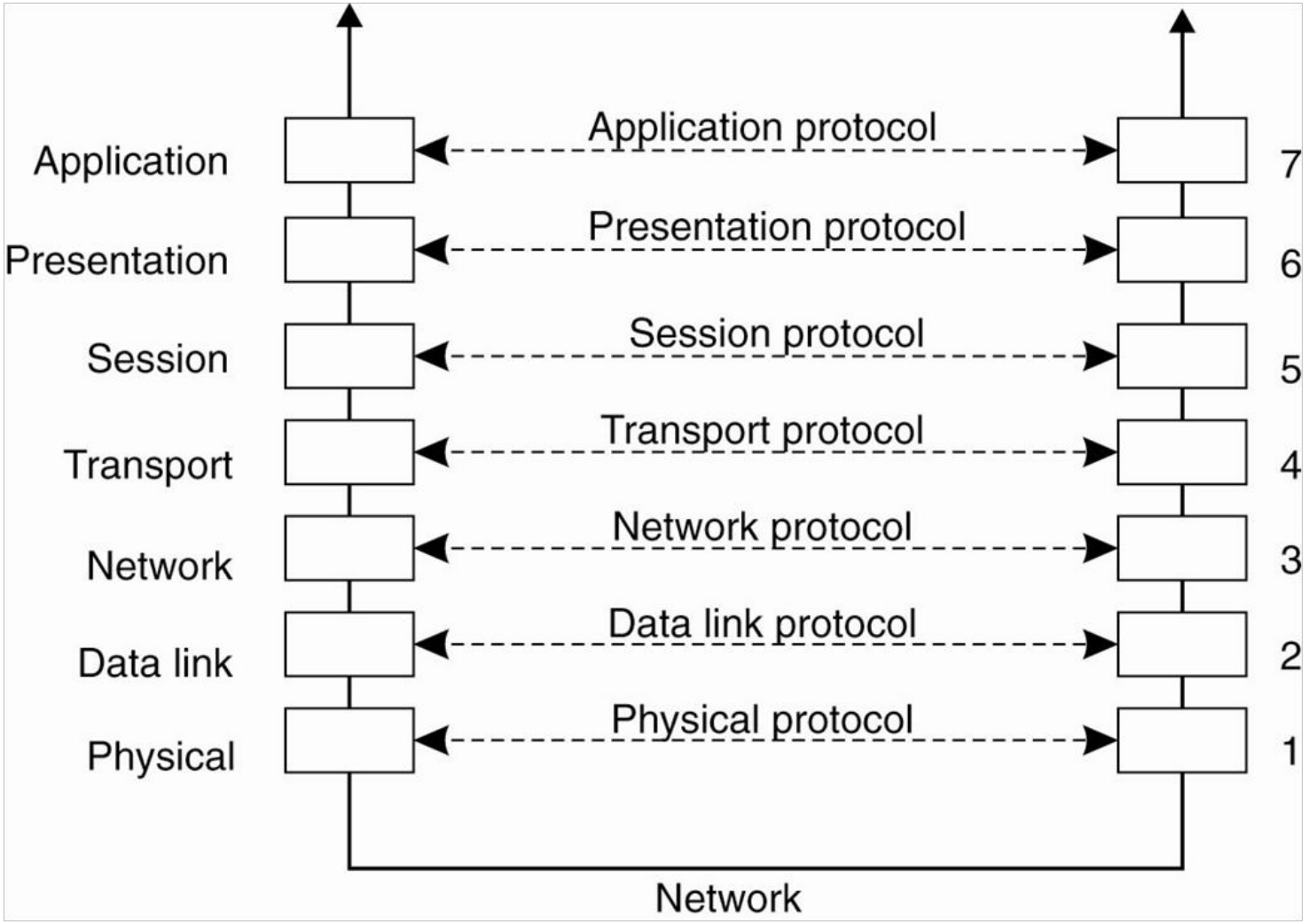
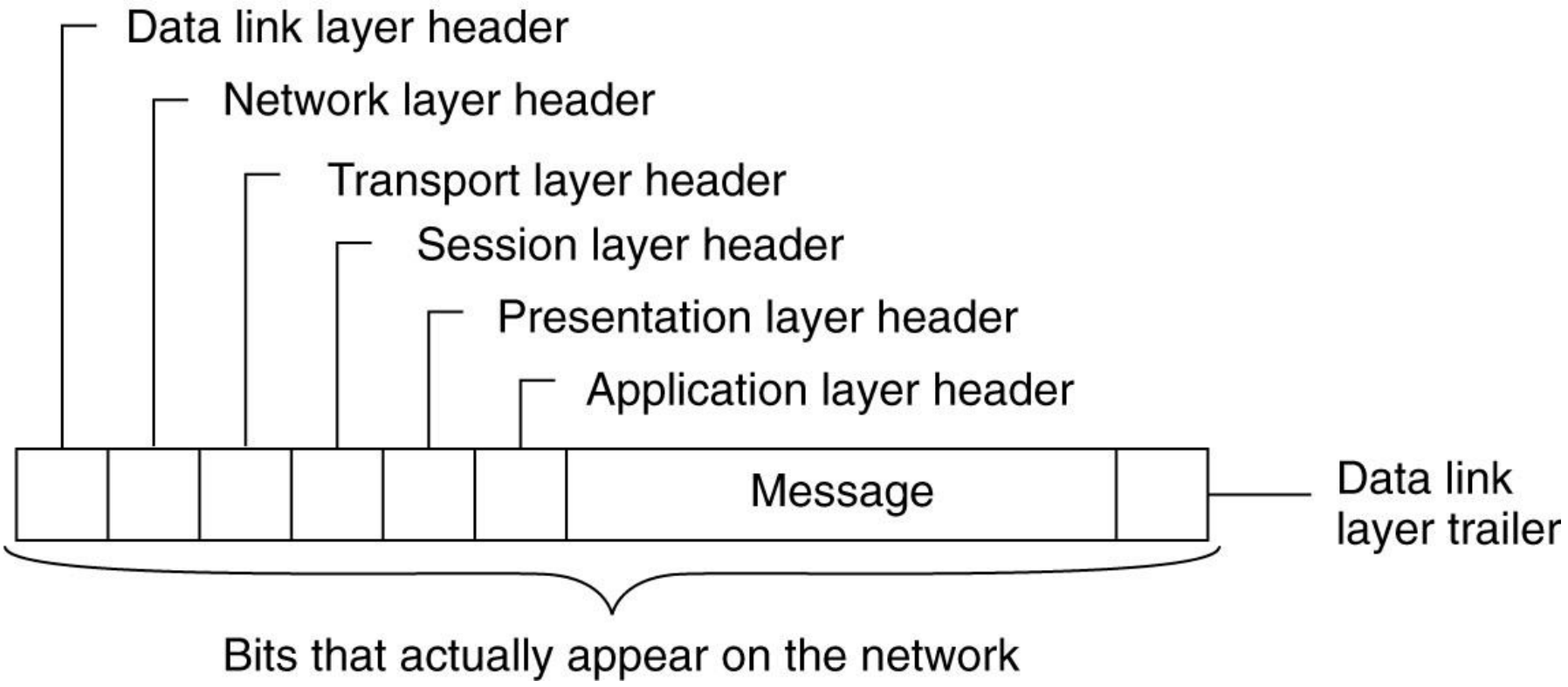
Layered protocols: The OSI model



The OSI model: Recap

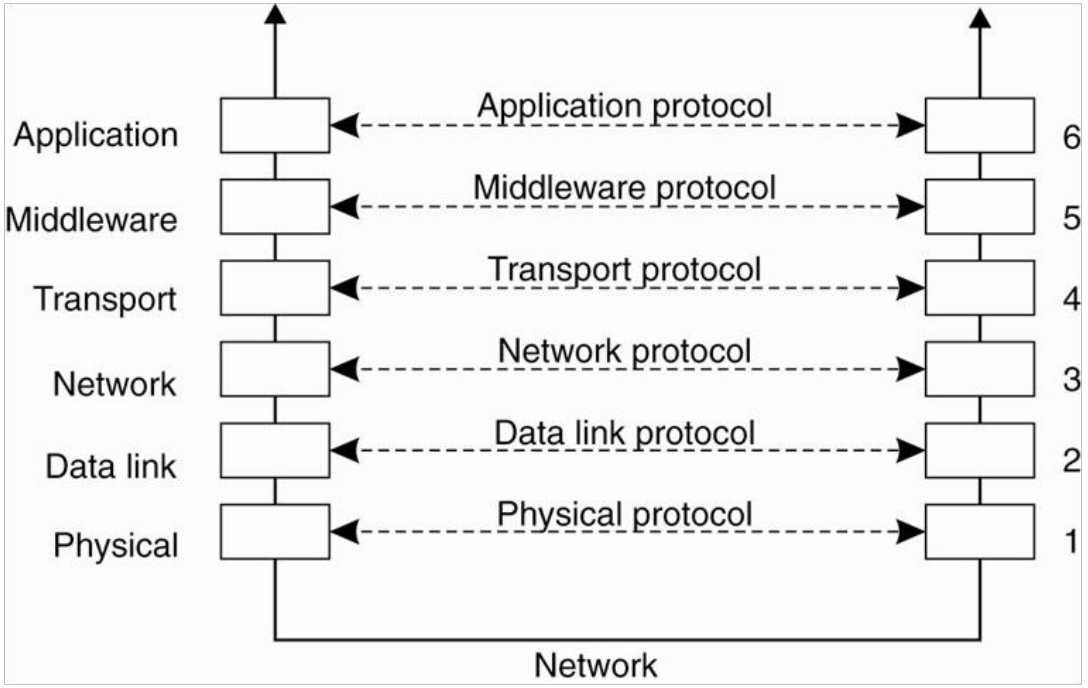
- Low level layers
  - Physical layer: describes how bits are transmitted between two directly connected nodes
  - Data link layer: describes how a series of bits is packed into a frame to allow for error and flow control
  - Network layer: describes how packets in a network of computers are to be routed
- Transport layer
  - Describes how data is transmitted among two nodes, offering a service independent from the lower layers
  - It provides the actual communication facilities for most distributed systems
  - Standard Internet protocols
    - TCP: connection-oriented, reliable, stream-oriented communication
    - UDP: unreliable (best-effort) datagram communication
- Higher level layers
  - Merged together in the current, Internet practice

Layered Protocols: Encapsulation



Middleware as a protocol layer

- Middleware includes common services and protocols that can be used by many different applications
  - (Un)marshaling of data, necessary for integrated systems
  - Naming protocols, to allow easy sharing of resources
  - Security protocols for secure communication
  - Scaling mechanisms, such as for replication and caching
- What remains are truly application-specific protocols...



Types of Communication

- Middleware may offer different form of communication:
  - Transient vs. persistent
  - Synchronous vs. asynchronous (various forms)
- Popular combinations
  - Transient communication with synchronization after processing
  - Persistent communication with synchronization at request submission

decoupling of sender and receiving in space

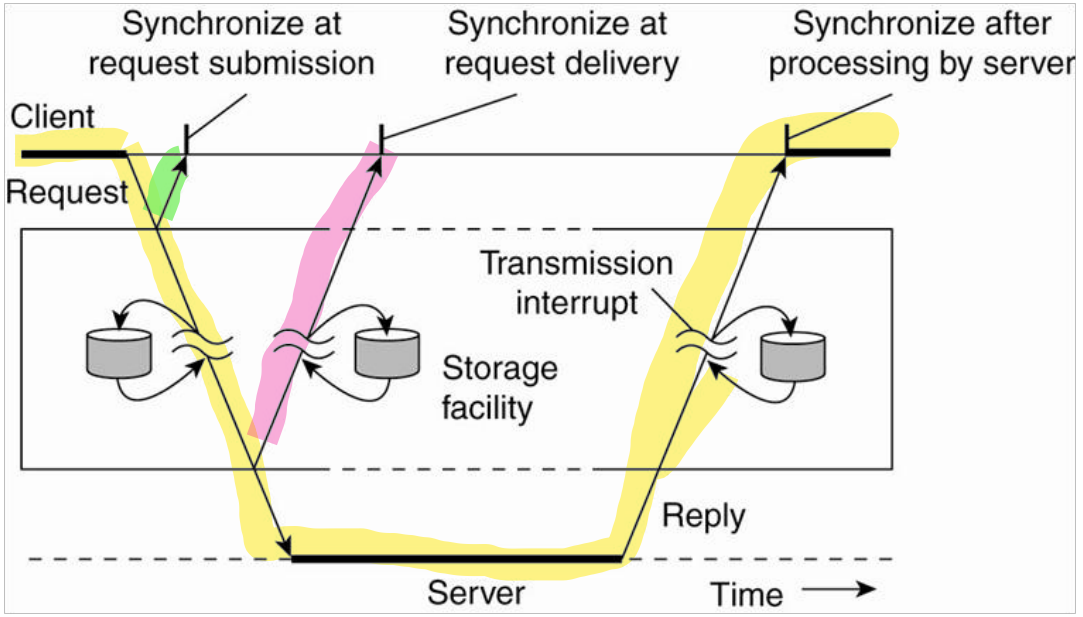
decoupling in time

-phone call is transient
-email is persistent

the invoker waits for the invokee

the invoker goes on in parallel after invoking the invokee

Notice tha transicity and synchronous and persistency and asycnronous are not the only possibility.



the stronger kind of synchronous communication

another form of synchronization happens between client and middleware, in fact the client "returns" after having delivered the message to the lower level. This is the case in TCP: when a TCP call returns with no error, it only guarantees that the call has been delivered to your operating systems

another form of synchronization regards the deliver at the server side of middleware

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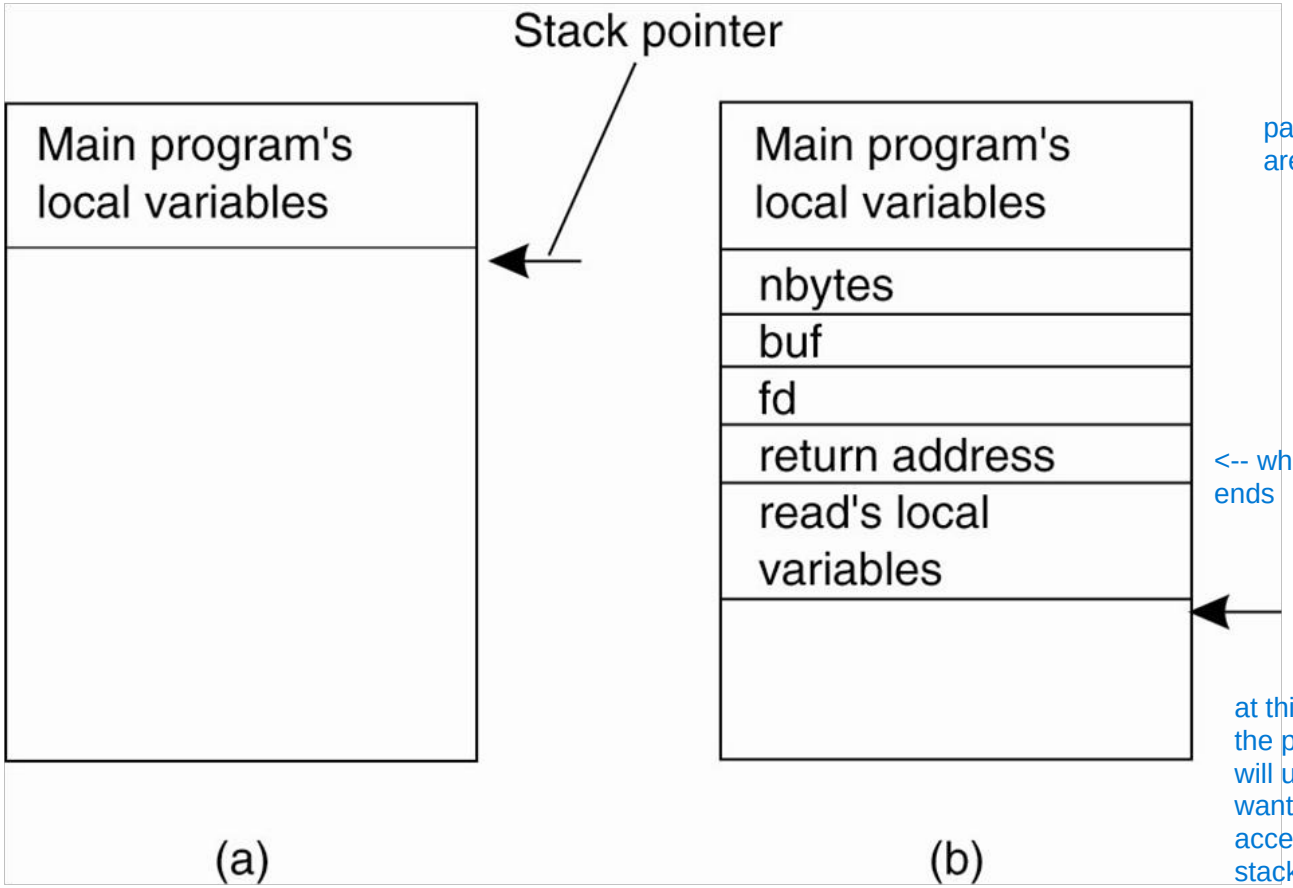
Local procedure call

- Parameter passing in a local procedure call
  - the stack before (a) and after (b) the call to:
    `count = read(fd, buf, nbytes)`



parameters of the call are saved into the stack

<-- where to go when the process ends

at this point the procedure can start, and will use this stack (es: when want to find the buffer it access the second cell of the stack).

Locally it is a strong form of synchronous communication (invoker waits for invokee)

Passing parameters to a procedure

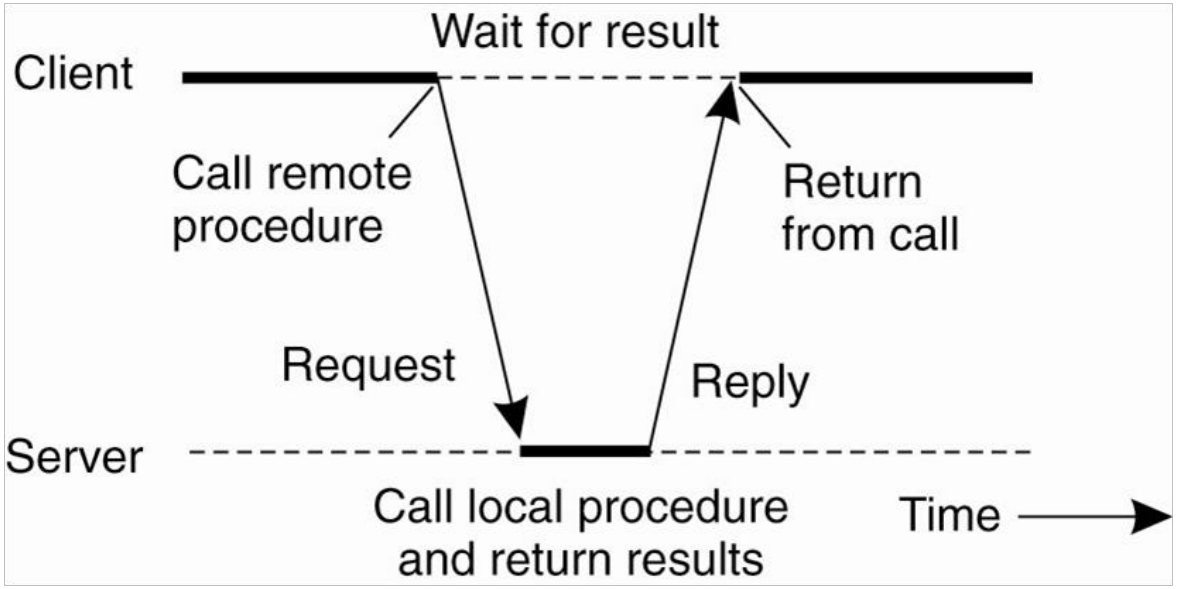
- Different mechanisms to pass parameters
  - *By value*. Like in C when passing basic data types
  - *By reference*. Like in C when passing arrays or in Java when passing objects
  - *By copy/restore*. Similar but slightly different than previous one

At first they are passed by value, but then at the end of the execution the new values are copied back to the invoker

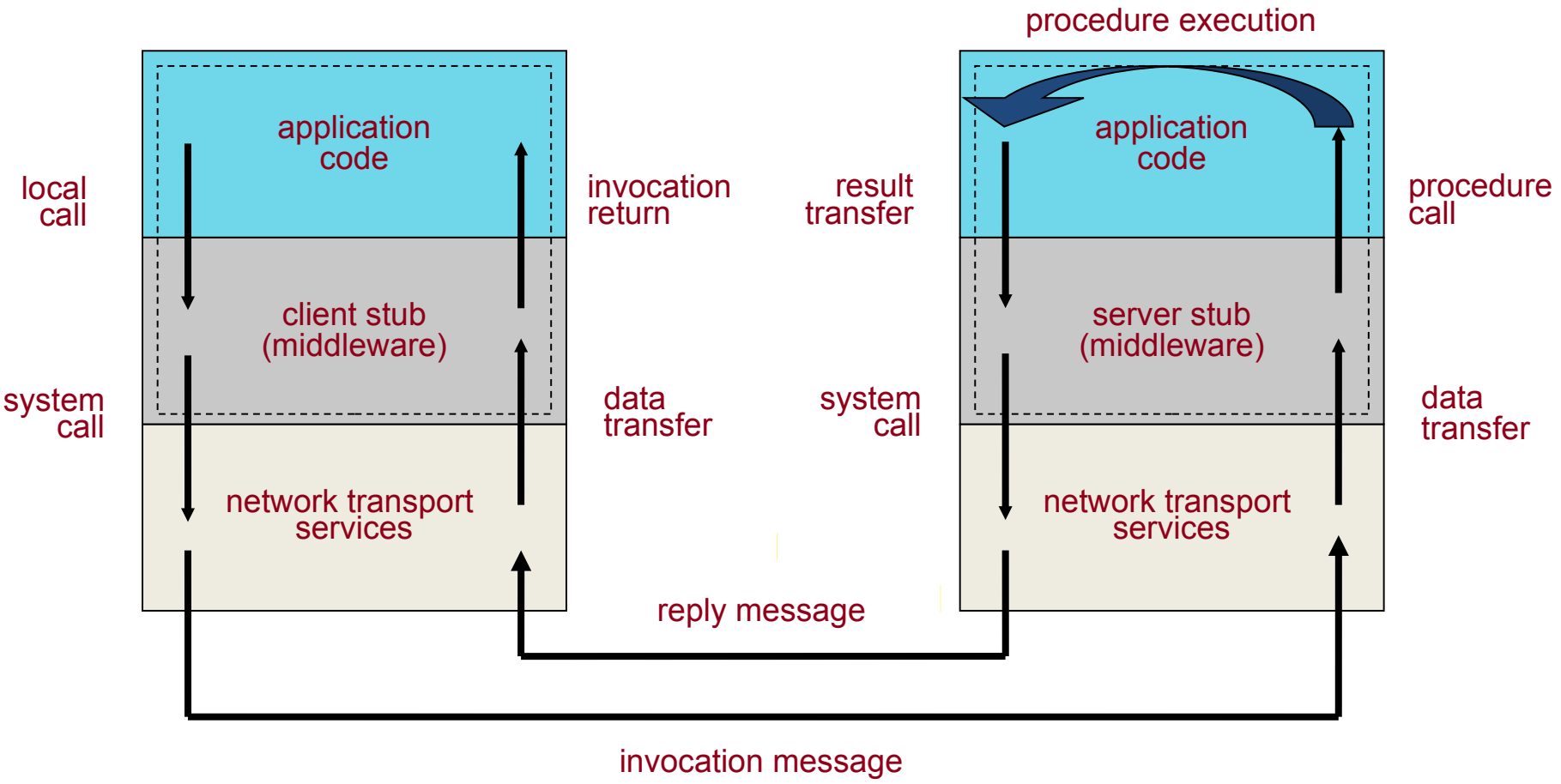
Copy/restore breaks aliasing.

From local to remote procedure call

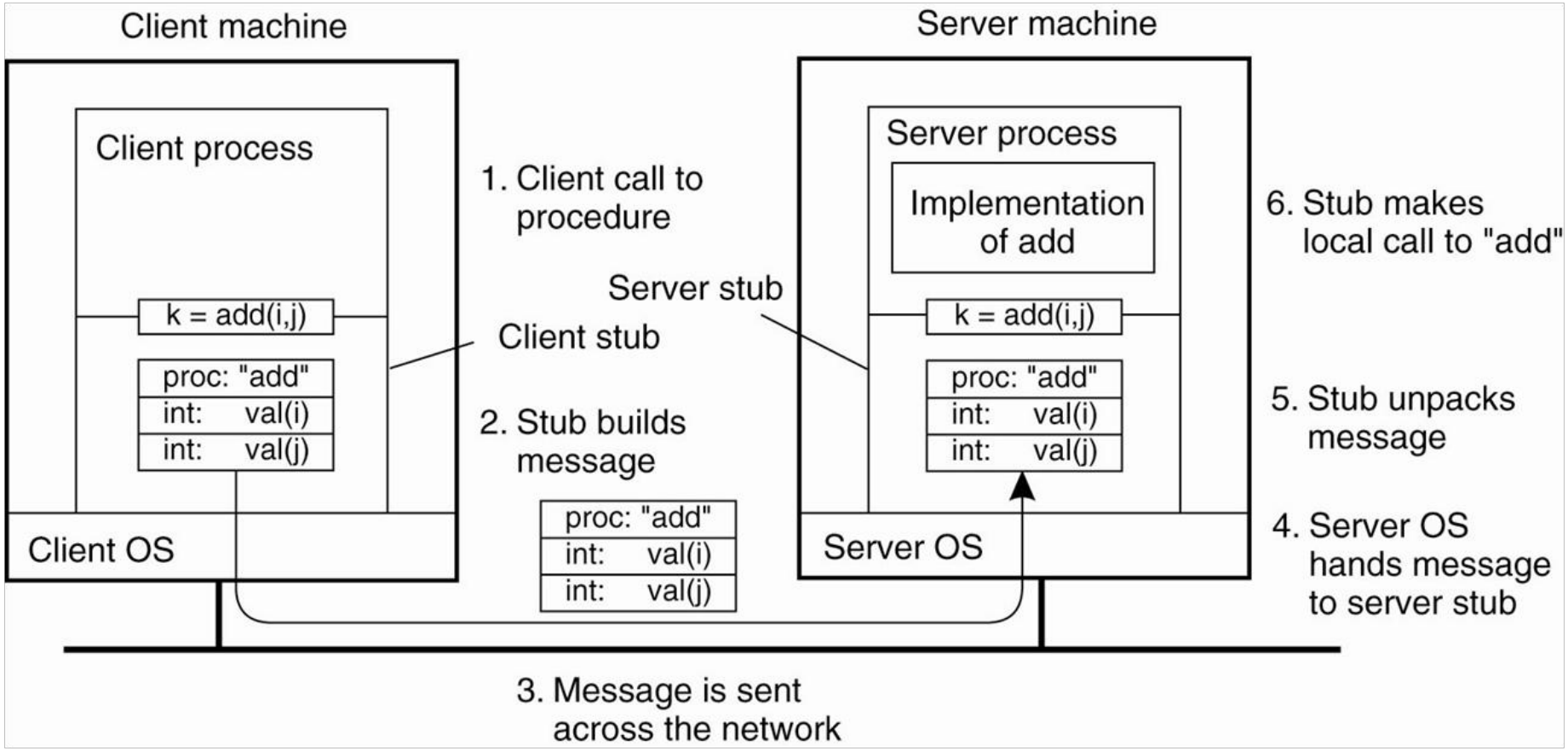
- Considerations
  - Application developers are familiar with procedure call
  - Well-engineered procedures operate in isolation (black box) helping structuring code
  - There is no fundamental reason not to execute procedures on separate machine
- Conclusion
  - Remote communication can be hidden by using procedure-call mechanism



RPC: How it works



RPC in detail
(when passing parameters by value)



Parameter passing: Marshalling and serialization

- Passing a parameter poses two problems:
  - Structured data (e.g., structs/records, objects) must be ultimately flattened in a byte stream
    - Called *serialization* (or pickling, in the context of OODBMSs)
  - Hosts may use different data representations (e.g., little endian vs. big endian, EBCDIC vs. ASCII) and proper conversions are needed
    - Called *marshalling*
- Middleware provides automated support:
  - The marshalling and serialization code is automatically generated from and becomes part of the stubs
  - Enabled by:
    - A language/platform independent representation of the procedure's signature, written using an *Interface Definition Language* (IDL)
    - A data representation format to be used during communication

The role of IDL

The middleware can recover the code of the procedure by only knowing the interface (what it does and not how it does it)

- The *Interface Definition Language* (IDL) raises the level of abstraction of the service definition
  - It separates the service *interface* from its *implementation*
  - The language comes with “mappings” onto target languages (e.g., C, Pascal, Python…)
- Advantages:
  - Enables the definition of services in a language-independent fashion
  - Being defined formally, an IDL description can be used to automatically generate the service interface code in the target language

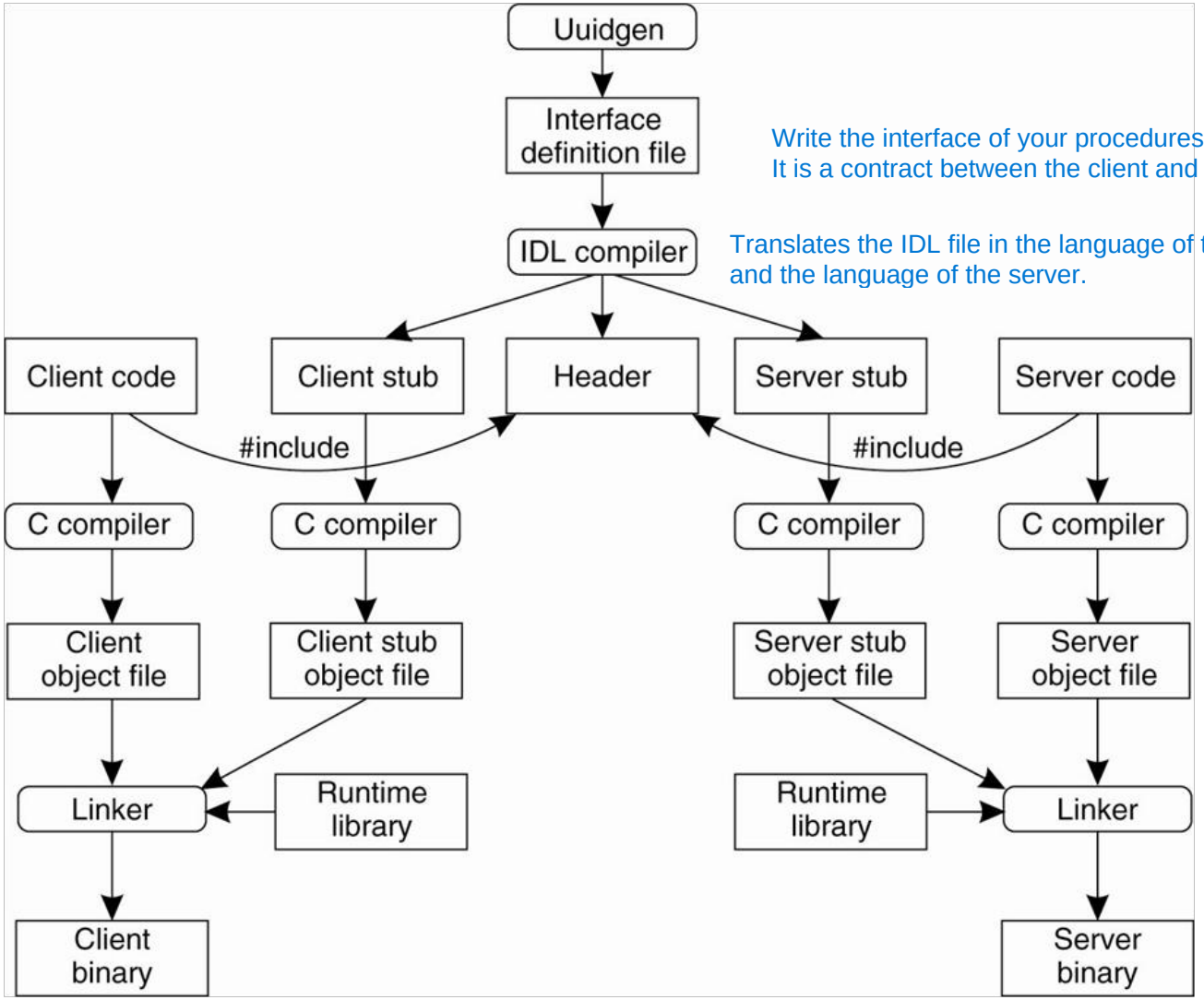
Passing parameters by reference

- How to pass a parameter by reference?
  - Many languages do not provide a notion of reference, but only of pointer
  - A pointer is meaningful only within the address space of a process…
- Often, this feature is simply not supported (as in Sun's solution)
- Otherwise, a possibility is to use call by value/result instead of call by reference
  - Semantics is different!
  - Works with arrays but not with arbitrary data structures
  - Optimizations are possible if input- or output-only

RPC in practice

- Sun Microsystems' RPC (also called Open Network Computing RPC) is the *de facto* standard over the Internet
  - At the core of NFS, and many other (Unix) services
  - Data format specified by XDR (eXternal Data Representation)
  - Transport can use either TCP or UDP
  - Parameter passing:
    - Only pass by copy is allowed (no pointers). Only one input and one output parameter
  - Provision for DES security
- The Distributed Computing Environment (DCE) is a set of specifications and a reference implementation
  - From the Open Group, no-profit standardization organization
  - Several invocation semantics are offered
    - At most once, idempotent, broadcast
  - Several services are provided on top of RPC:
    - Directory service, distributed time service, distributed file service
  - Security is provided through Kerberos
  - Microsoft's DCOM and .Net remoting are based on DCE

RPC in practice



Write the interface of your procedures in IDL.
It is a contract between the client and the server.

Translates the IDL file in the language of the client and the language of the server.

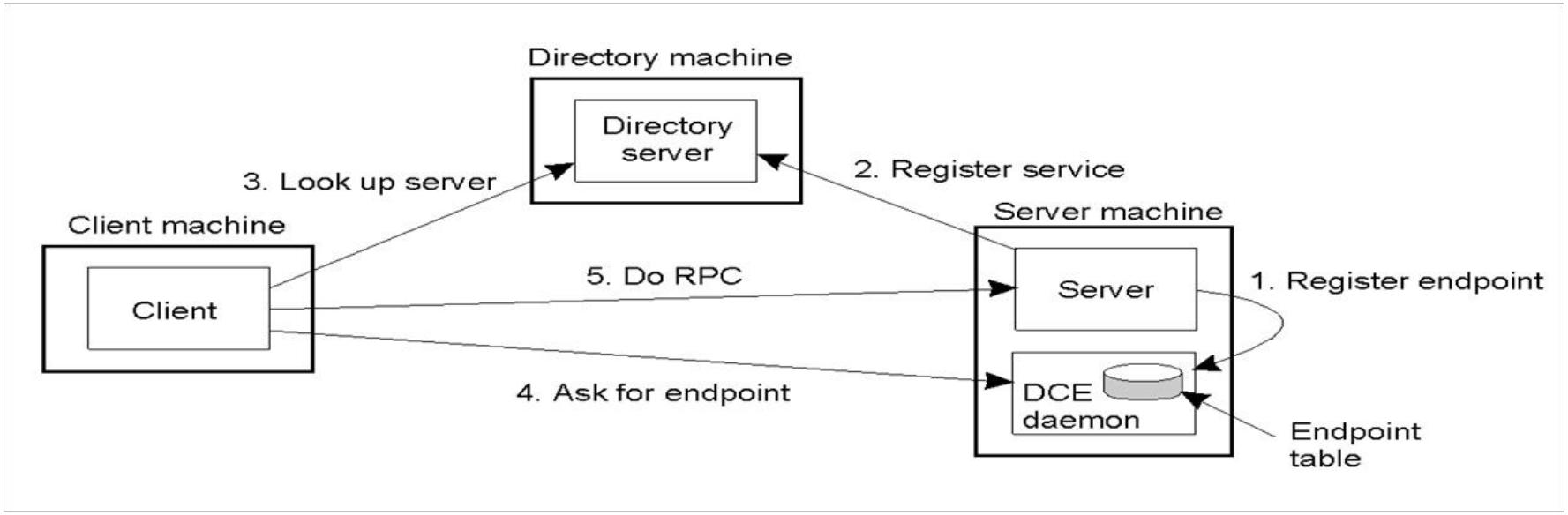
Binding the client to the server

- Problem: find out which server (process) provides a given service
  - Hard-wiring this information in the client code is highly undesirable
  - Two distinct problems:
    - Find out where the server process is
    - Find out how to establish communication with it

Sun's solution

- Introduce a daemon process (`portmap`) that binds calls and server/ports:
  - The server picks an available port and tells it to portmap, along with the service identifier
  - Clients contact a given portmap and:
    - Request the port necessary to establish communication
- `portmap` provides its services only to local clients, i.e., it solves only the second problem
  - The client must know in advance where the service resides
  - However:
    - A client can multicast a query to multiple daemons
    - More sophisticated mechanisms can be built or integrated
      - e.g., directory services

DCE's solution



- The DCE daemon works like portmap
- The directory server (aka binder daemon) enables location transparency:
  - Client need not know in advance where the service is: they only need to know where the directory service is
  - In DCE, the directory service can actually be distributed
    - To improve scalability over many servers
  - Step 3 is needed only once per session

Dynamic activation

- Problem: server processes may remain active even in absence of requests, wasting resources
- Solution: introduce another (local) server daemon that:
  - Forks the process to serve the request
  - Redirects the request if the process is already active
  - Clearly, the first request is served less efficiently
- In Sun RPC:
  - inetd daemon
  - The mapping between requested service and server process is stored in a configuration file (/etc/services)

Lightweight RPC

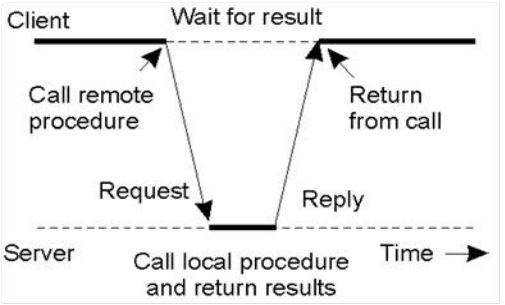
It's a form of RPC which works among processes in the same machine (es: cut and past in windows), remember that processes don't share mamory

- It is natural to use the same primitives for inter-process communication, regardless of distribution
  - But using conventional RPC would lead to wasted resources: no need for TCP/UDP on a single machine!
- Lightweight RPC: message passing using local facilities
  - Communication exploits a private shared memory region
  - Lightweight RPC invocation:
    - Client stub copies the parameters on the shared stack and then performs a system call
    - Kernel does a context switch, to execute the procedure in the server
    - Results are copied on the stack and another system call + context switch brings execution back to the client
  - Advantages:
    - Uses less threads/processes (no need to listen on a channel)
    - 1 parameter copy instead of 4 (2 x (stub→kernel + kernel→stub))
- Similar concepts used in practice in DCOM and .NET

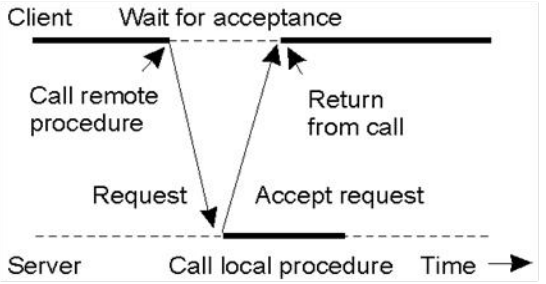
Asynchronous RPC

Only possible if the procedure is void (doesn't need to wait for return of the procedure?

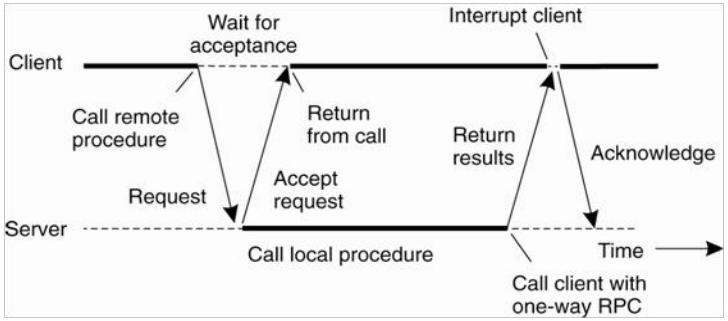
- RPC preserves the usual call behavior
  - The caller is suspended until the callee is done
- Potentially wastes client resources
  - Evident if no return value is expected
  - In general, concurrency could be increased
- Many variants of asynchronous RPC (with different semantics):
  - If no result is needed execution can resume after an acknowledgment is received from the server
    - One-way RPC returns immediately
      - May cause reliability issues: "Maybe semantics"
  - To deal with results, the callee may (asynchronously) invoke the caller back
    - Or invocation may return immediately a *promise* (or *future*), later polled by the client to obtain the result



synchronous



asynchronous
(one possible)



deferred synchronous

Batched vs. queued RPC

- Sun RPC includes the ability to perform *batched RPC*
  - RPCs that do not require a result are buffered on the client
  - They are sent all together when a non-batched call is requested (or when a timeout expires)
  - Enables yet another form of asynchronous RPC
- A similar concept can be used to deal with mobility (as in the Rover toolkit by MIT):
  - If a mobile host is disconnected between sending the request and receiving the reply, the server periodically tries to contact the mobile host and deliver the reply
  - Requests and replies can come through different channels
  - Depending on network conditions and application requirements, the network scheduler module may decide to:
    - Send requests in batches
    - Compress the data
    - Reorder requests and replies in a non-FIFO order, e.g., to suit application-specified priorities
  - Promises are used at the client

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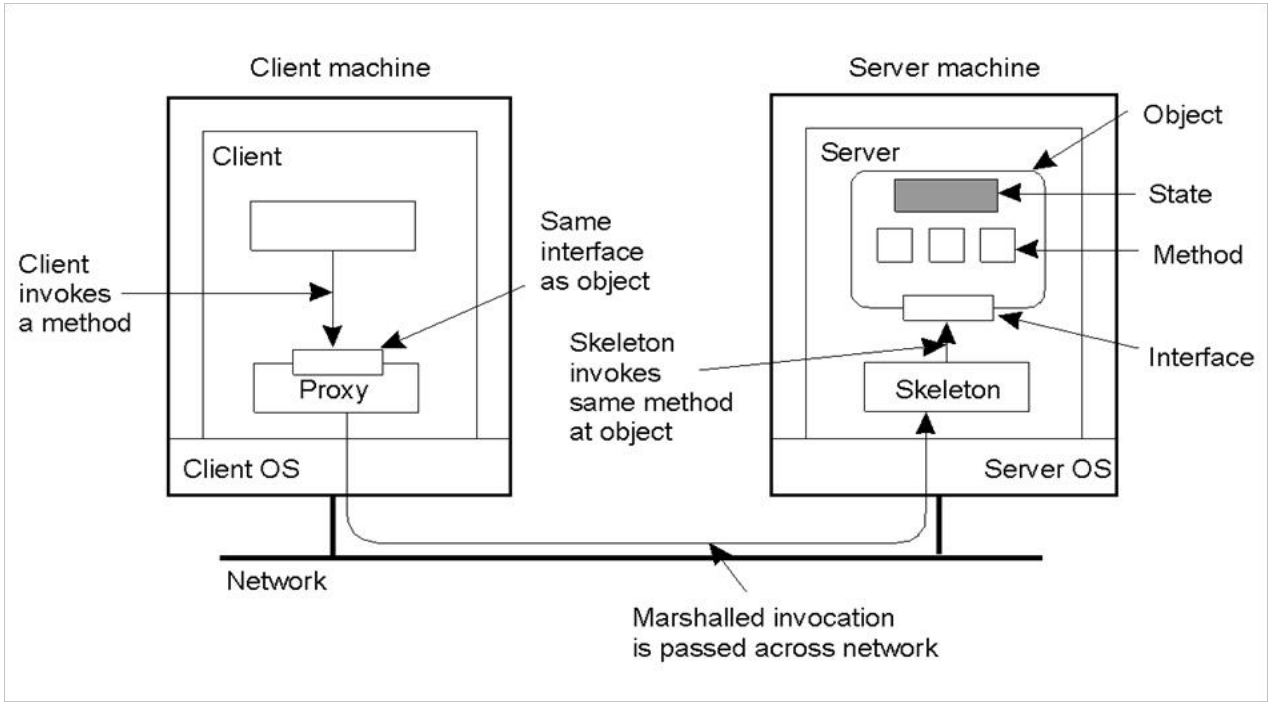
Remote method invocation

- Same idea as RPC, different programming constructs
  - The aim is to obtain the advantages of OOP also in the distributed setting
- Important difference: remote object references can be passed around
  - While passing objects by copy is hard since, in principle, it requires passing around code (the methods)
- Shares many of the core concepts and mechanisms with RPC
  - Sometimes built on top of an RPC layer

Interface definition language

- In RPC, the IDL separates the interface from the implementation
  - To handle platform/language heterogeneity
- Such separation is one of the basic OO principles
  - It becomes natural to place the object interface on one host, and the implementation on another
- The IDLs for distributed objects are much richer
  - Inheritance, exception handling, …



Remote method invocation in practice

- Java RMI
  - Single language/platform (Java and the Java Virtual Machine)
  - Easily supports passing parameters by reference or “by value” even in case of complex objects
  - Supports for downloading code (code on demand)
- OMG CORBA
  - Multilanguage/multiplatform
  - Supports passing parameters by reference or by value
    - If objects are passed by value (valuetype) it is up to the programmer to guarantee the same semantics for methods on the sender and receiver sides

middleware that offers RMi

interfaces are translated in a special language by CORBA.

(es: primitive values)

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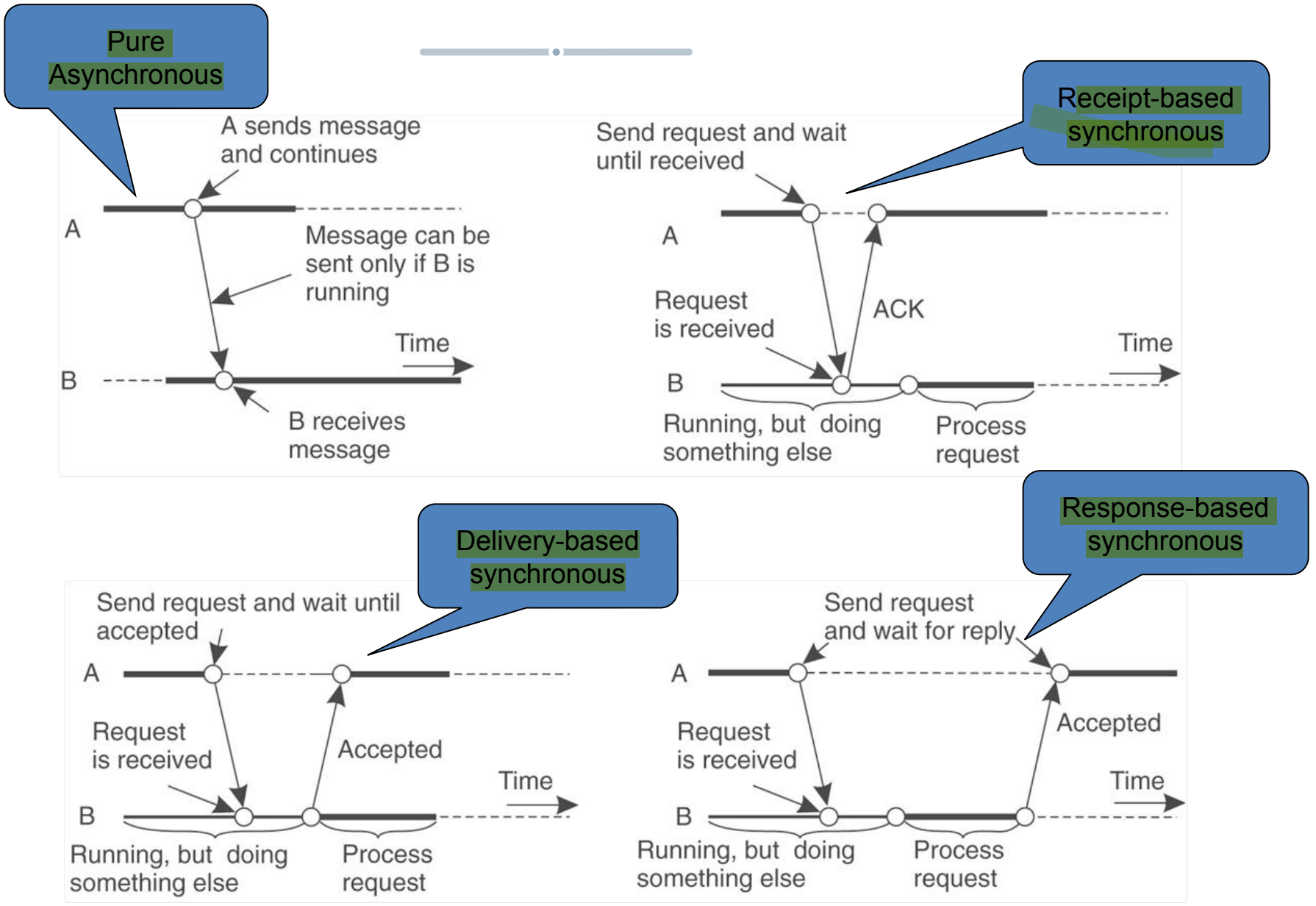
Message oriented communication

- RPC/RMI foster a synchronous model
  - Natural programming abstraction, but:
    - Supports only point-to-point interaction
    - Synchronous communication is expensive
    - Intrinsically tight coupling between caller and callee, leads to “rigid” architectures
- Message oriented communication:
  - Centered around the (simpler) notion of one-way message/event
  - Usually asynchronous (several forms)
  - Often supporting persistent communication --> guarantees our massage doesn't get lost
  - Often supporting multi-point interaction
  - Brings more decoupling among components

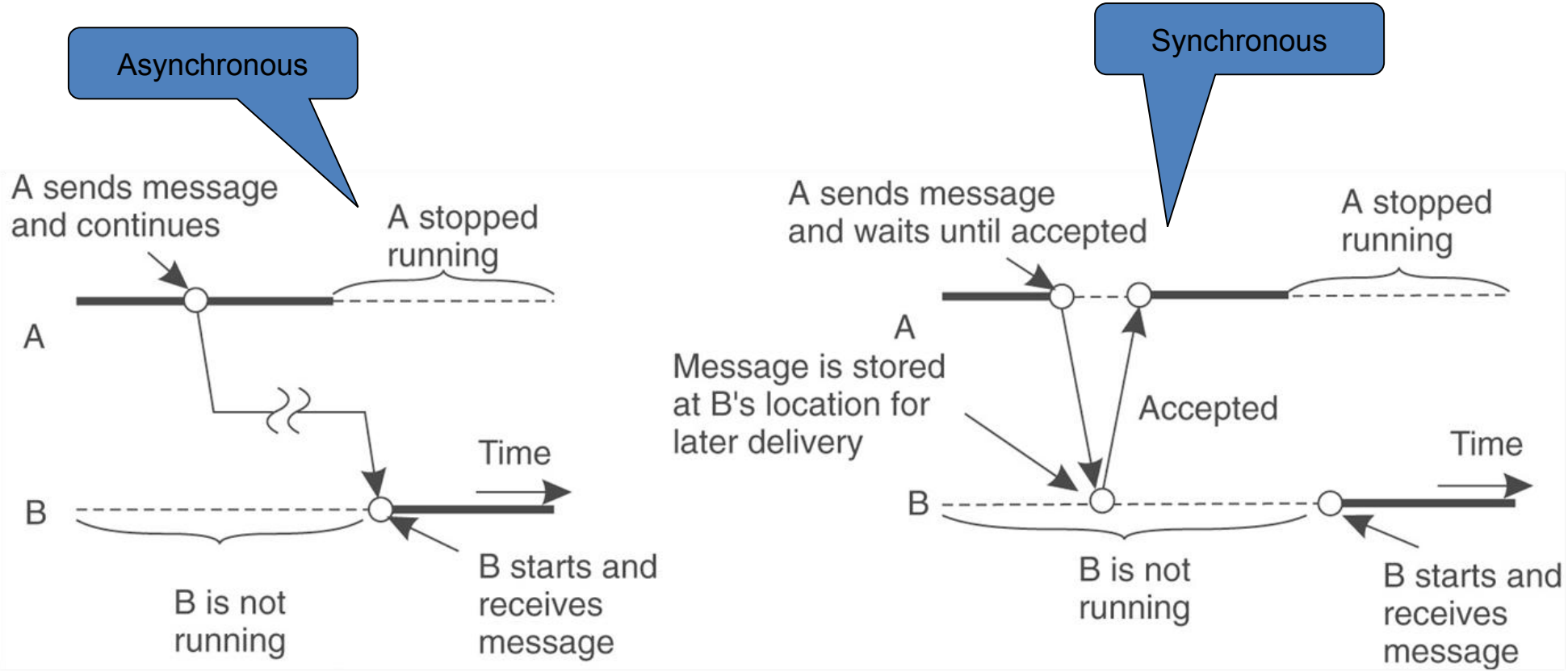
Types of communication

- Synchronous vs. asynchronous
  - Synchronous: the sender is blocked until the recipient has stored (or received, or processed) the message
  - Asynchronous: the sender continues immediately after sending the message
- Transient vs. persistent
  - Transient: sender and receiver must both be running for the message to be delivered
  - Persistent: the message is stored in the communication system until it can be delivered
- Several alternatives (and combinations) are provided in practice

Transient communication

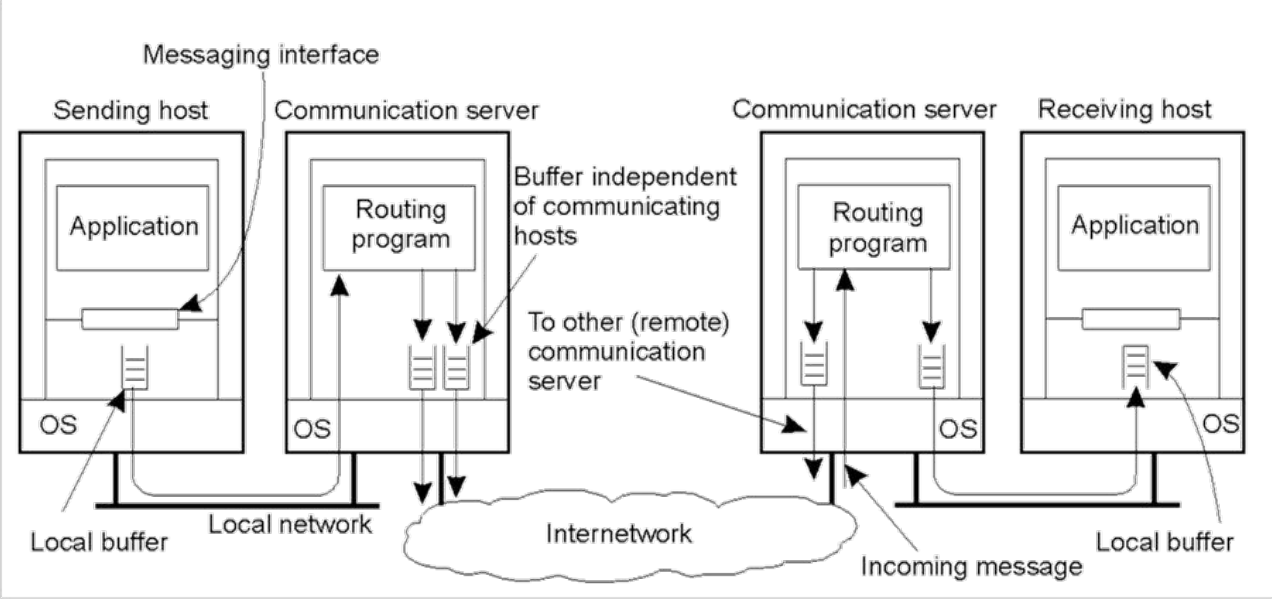


Persistent communication



Reference model

- The most straightforward form of message oriented communication is *message passing*
  - Typically directly mapped on/provided by the underlying network OS functionality (e.g., socket)
  - A (kind of) middleware provides another form of message passing called MPI
- *Message queuing* and *publish/subscribe* are two different models provided at the middleware layer
  - By several "communication servers"
  - Through what is nowadays called an *overlay network*



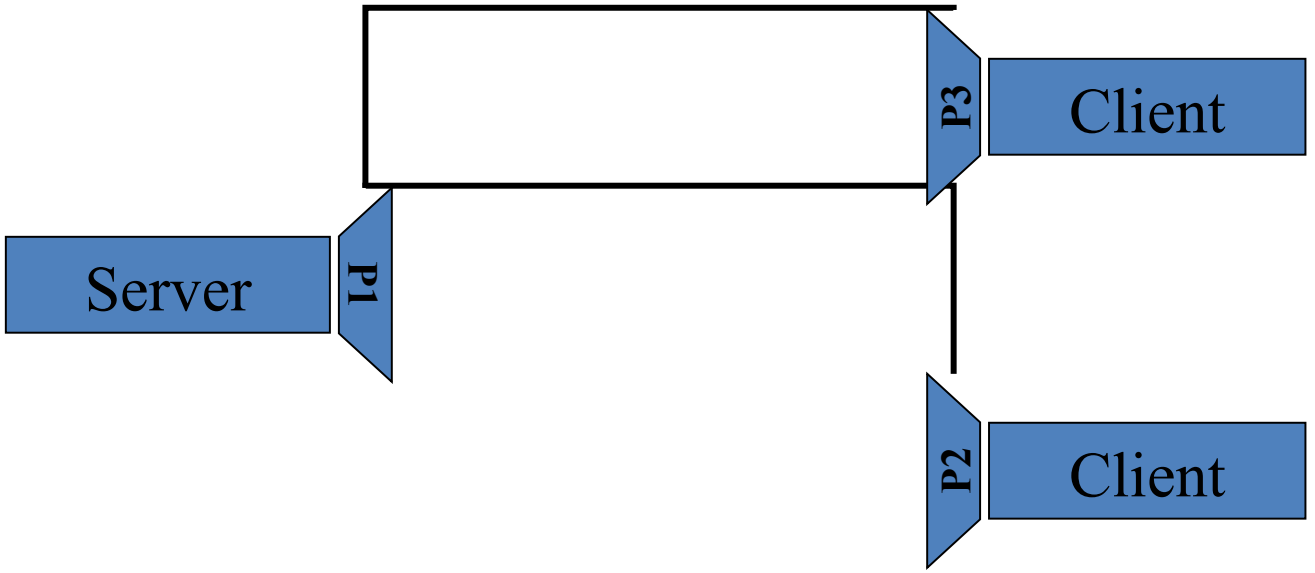
From network protocols to communication services

- Unicast TCP and UDP (and multicast IP) are well know network protocols
  - The related RFCs describe how they work in practice (on top of IP)
  - But how a poor programmer can take advantage of such protocols?
- Berkeley sockets are the answer!
  - First appeared in Unix BSD in 1982 ---> BSD is the api developers can use to use TCP and UTP.
  - Today available for every platform
- Sockets provide a common abstraction for inter-process communication
  - Unix and Internet sockets exists. Here we are interested in the latter
  - Allows for connection-oriented (stream i.e., TCP) or connectionless (datagram, i.e., UDP) communication

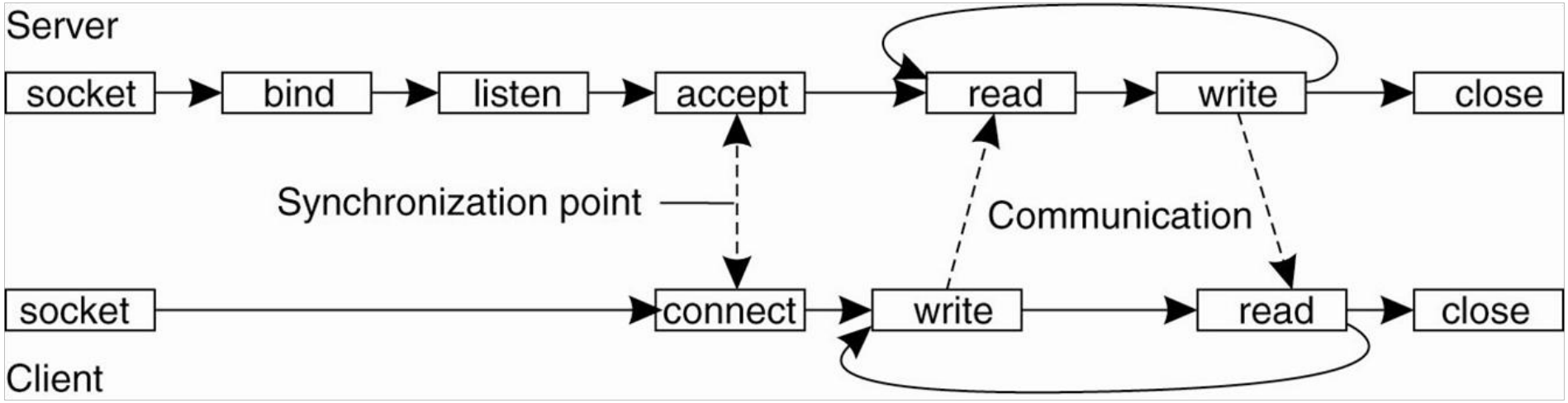
Stream sockets: Fundamentals

- The server accepts connection on a port
- The client connects to the server
- Each (connected) socket is uniquely identified by 4 numbers: The IP address of the server, its “incoming” port, the IP address of the client, its “outgoing” port

so the same port can accept more socket connection, cause socket is defined by the 4 numbers



Stream sockets in C

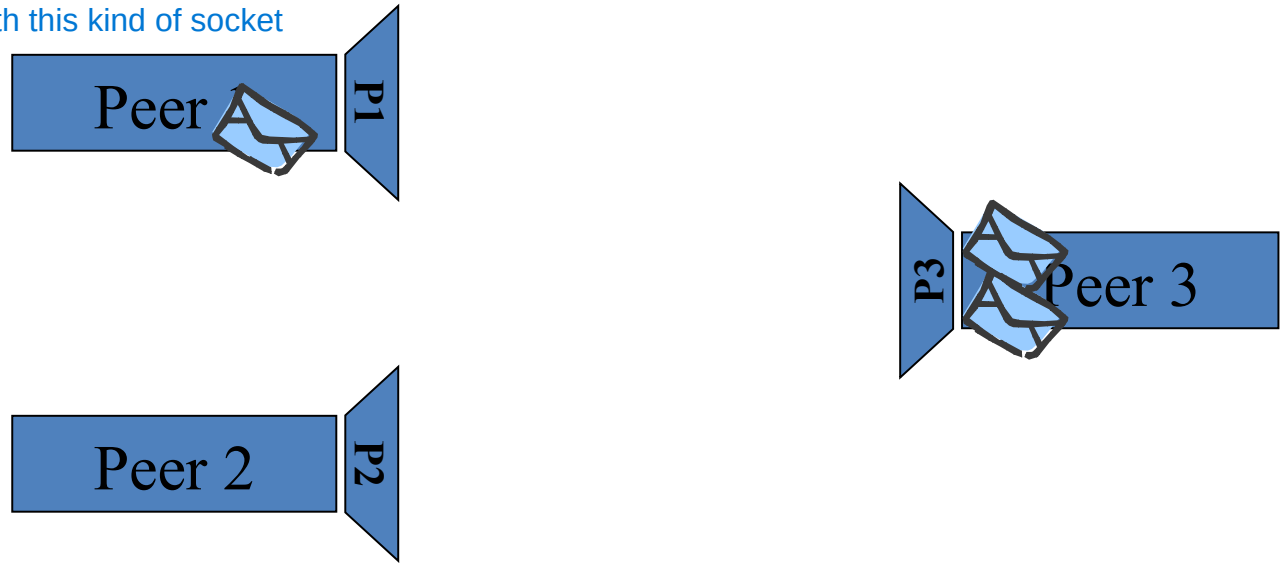


Datagram sockets: Fundamentals

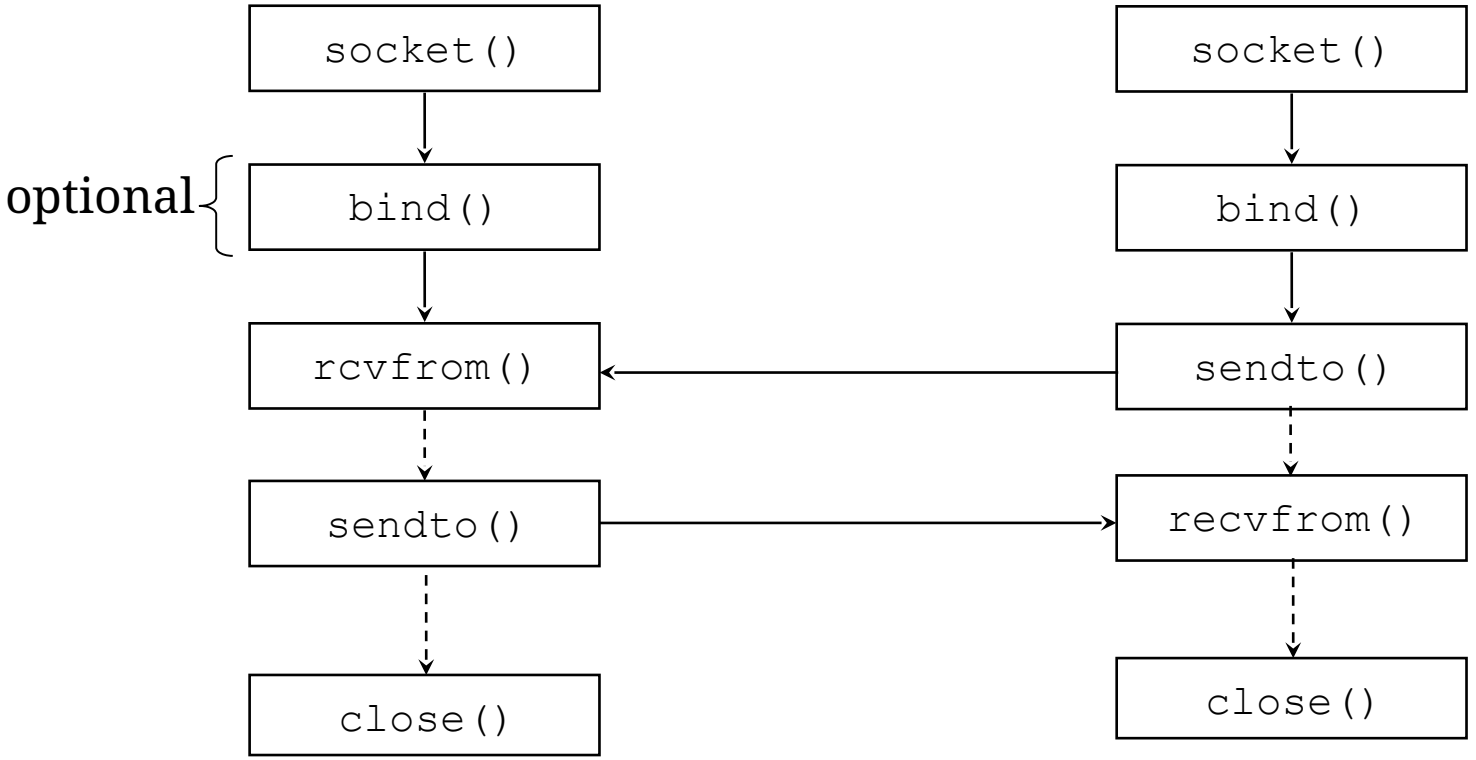
No clear distinction between client and server.

- Client and server use the same approach to send and receive datagrams
- Both create a socket bound to a port and use it to send and receive datagrams
- There is no connection and the same socket can be used to send (receive) datagrams to (from) multiple hosts

No warranties with this kind of socket



Datagram sockets in C



Multicast sockets

Can be Open or closed: closed group multicast communication means you can send to the group only if you're part of the group. Open if it is not true.

- IP multicast is a network protocol to efficiently deliver UDP datagrams to multiple recipients
  - The Internet Protocol reserve a class D address space, from 224.0.0.0 to 239.255.255.255, to multicast *groups*
- The socket API for multicast communication is similar to that for datagram communication
  - Component interested in receiving multicast datagrams addressed to a specific group must *join* the group (using the `setsockopt` call)
    - Groups are open: It is not necessary to be a member of a group in order to send datagrams to the group
  - As usual it is also necessary to specify a *port*
    - It is used *by the OS* to decide which process on the local machine to route packets to
- Note: most routers are configured to *not* route multicast packets outside the LAN

in a multicast communication setup, the port number's role is primarily to specify which application or process on a receiving host should handle the incoming data, rather than identifying the host itself. Data is sent to a multicast group identified by a multicast IP address and a specific port number.
Multiple hosts can join this multicast group and listen to the data sent to the multicast IP address. When data reaches a host that is part of the multicast group, the port number determines which application or process on that host should receive and handle the data. This is because multiple applications or processes might be running on the same host, each potentially interested in different data streams.

MPI: Fundamentals

- Limitation of sockets
  - Low level
  - Protocol independent (and so awkward to use)
- In high performance networks (e.g., clusters of computers) we need higher level primitives for asynchronous, transient communication…
- …providing different services besides pure read and write
- MPI was the (platform independent) answer

MPI: The model and main API

- Communication takes place within a known group of processes
- Each process within a group is assigned a local id
  - The pair (groupID, processID) represents a source or destination address
  - Messages can also be sent in broadcast to the entire group (`MPI_Bcast, MPI_Reduce, MPI_Scatter, MPI_Gather`)
- No support for fault tolerance (crashes are supposed to be fatal)
- Main MPI primitives

Six forms of sending data

the simplest:

Primitive	Meaning
MPI_bsend	Append outgoing message to a local send buffer
MPI_send	Send a message and wait until copied to local or remote buffer
MPI_ssend	Send a message and wait until receipt starts
MPI_sendrecv	Send a message and wait for reply
MPI_isend	Pass reference to outgoing message, and continue
MPI_issend	Pass reference to outgoing message, and wait until receipt starts
MPI_recv	Receive a message; block if there is none
MPI_irecv	Check if there is an incoming message, but do not block

it just guarantees that after the methods return your buffer of data is saved to a buffer (don't care where is)

--> it's like a rmeote invocation

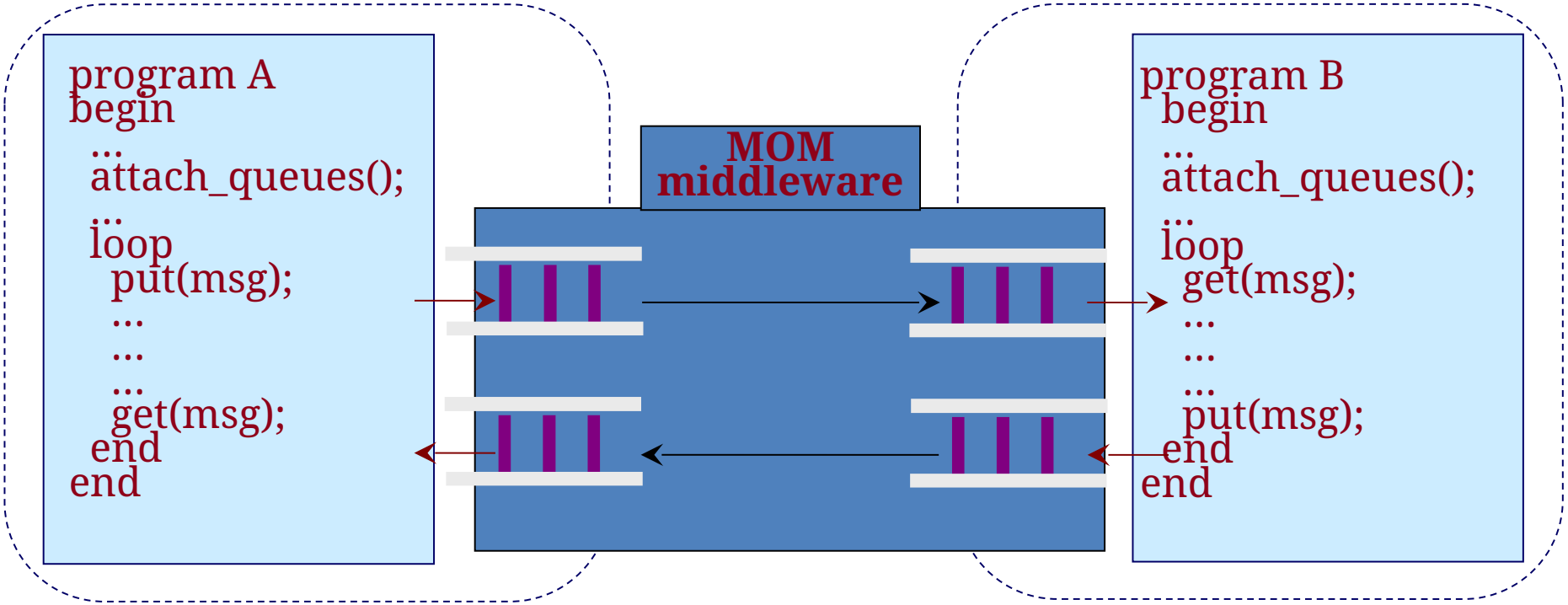
--> pass a pointer of HIS buffer to the middleware, allowing it to send data without copying data to a new buffer. It is very fast

Message queuing

- Point-to-point persistent asynchronous communication
  - Typically guarantee only eventual insertion of the message in the recipient queue (no guarantee about the recipient's behavior)
  - Communication is decoupled in time and space
  - Can be regarded as a generalization of the e-mail
- Intrinsically peer-to-peer architecture
- Each component holds an input queue and an output queue
- Many commercial systems:
  - IBM MQSeries (now WebSphere MQ), DECmessageQ, Microsoft Message Queues (MSMQ), Tivoli, Java Message Service (JMS), …

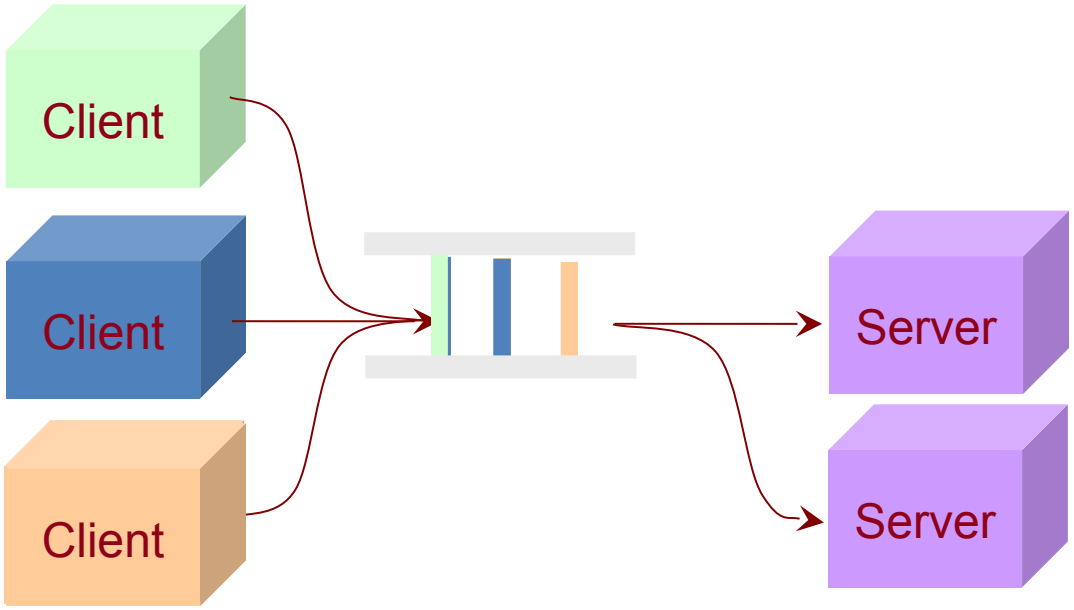
Queuing: Communication primitives

Primitive	Meaning
Put	Append a message to a specified queue
Get	Block until the specified queue is nonempty, and remove the first message
Poll	Check a specified queue for messages, and remove the first. Never block
Notify	Install a handler to be called when a message is put into the specified queue



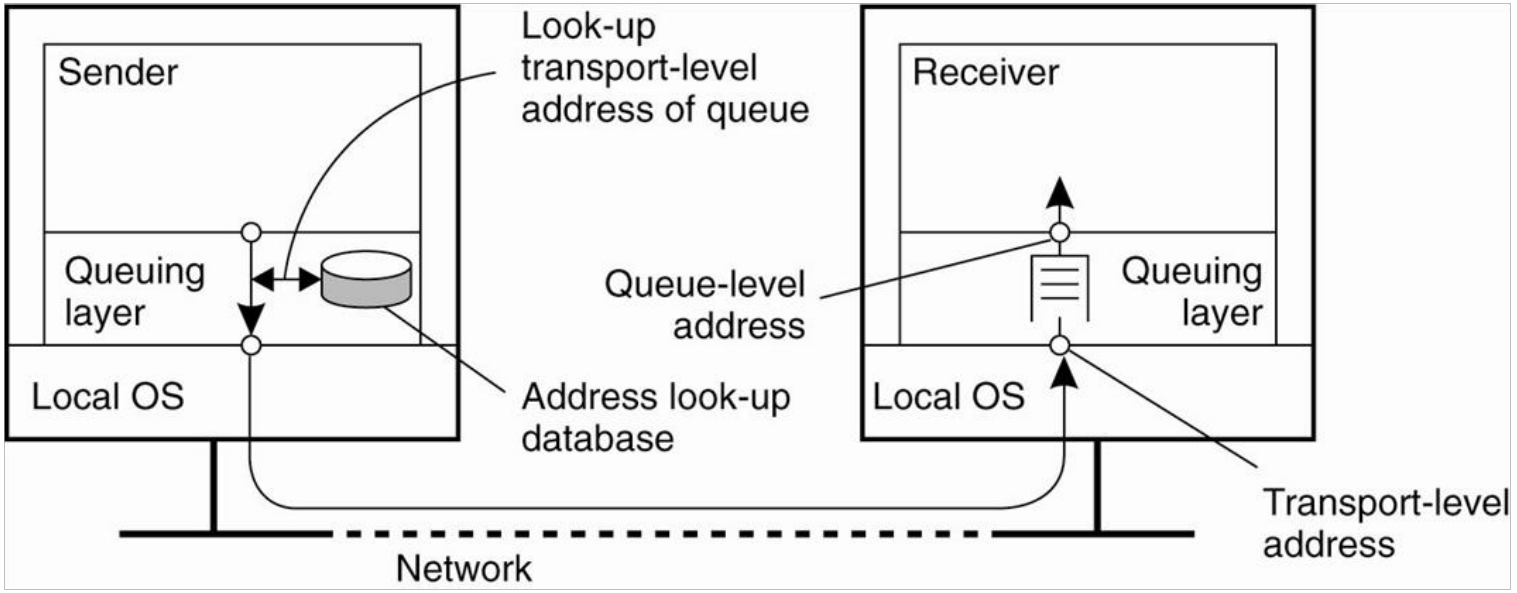
Client-Server with queues

- Clients send requests to the server's queue
- The server asynchronously fetches requests, processes them, and returns results in the clients' queues
  - Thanks to persistency and asynchronicity, clients need not remain connected
  - Queue sharing simplifies load balancing



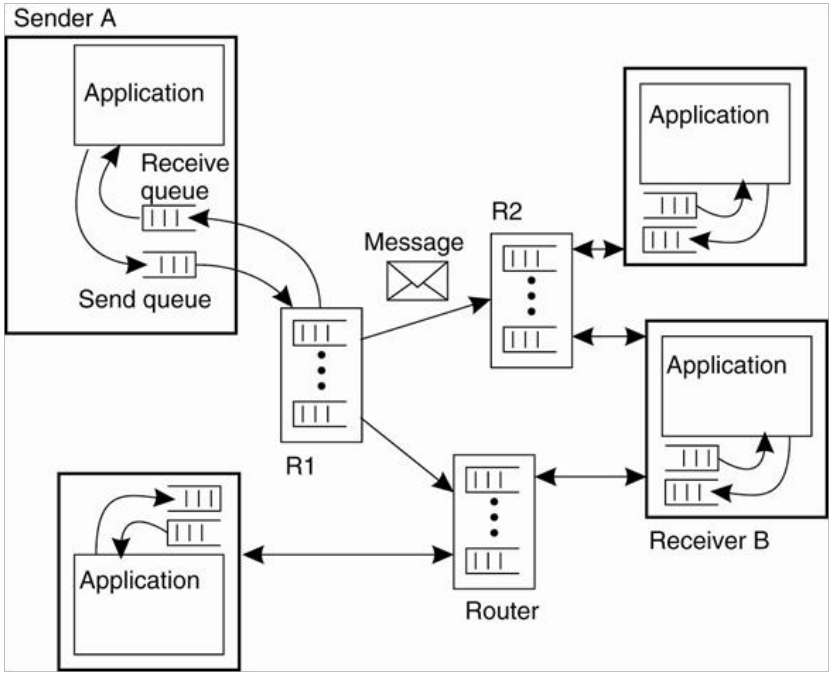
Message queuing: Architectural Issues

- Queues are identified by symbolic names
  - Need for a lookup service, possibly distributed, to convert queue-level addresses in network addresses
  - Often pre-deployed static topology/naming



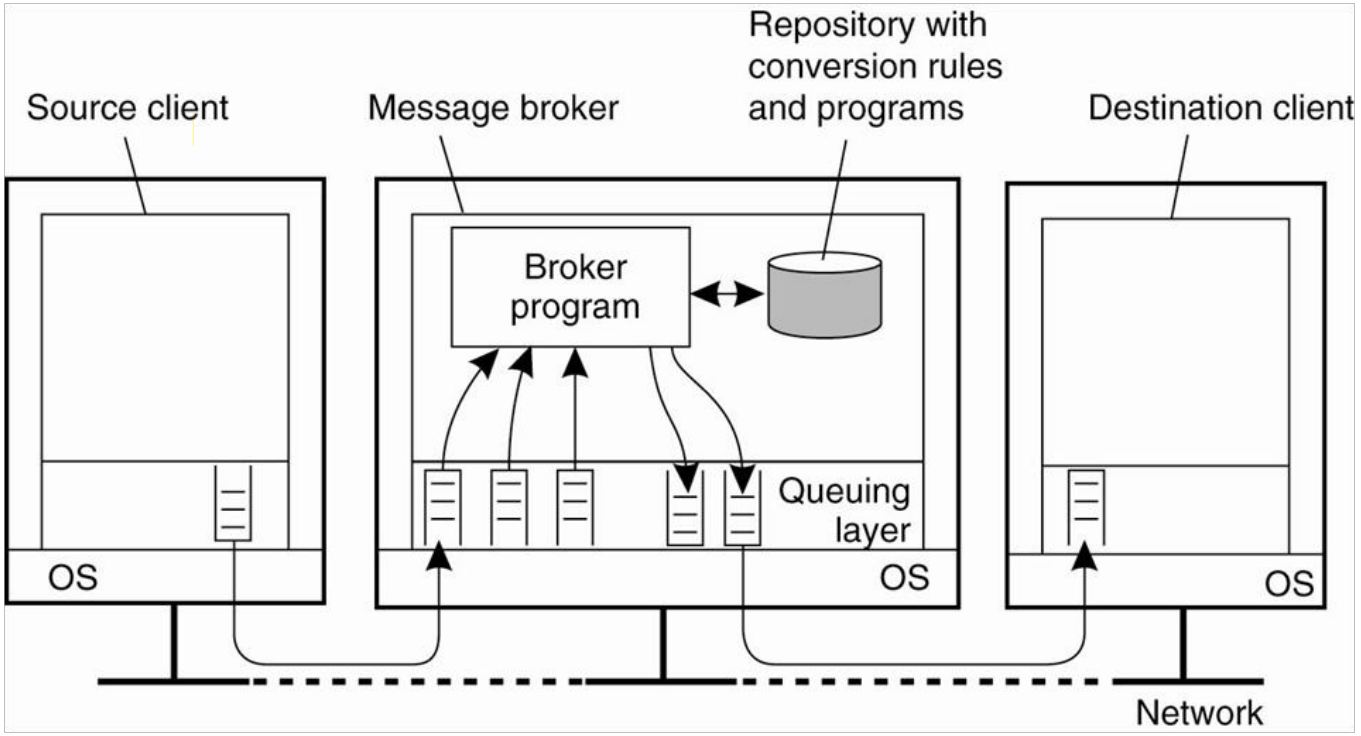
Message queuing: Architectural Issues

- Queues are manipulated by queue managers
  - Local and/or remote, acting as relays (a.k.a. applicative routers)
- Relays often organized in an overlay network
  - Messages are routed by using application-level criteria, and by relying on a partial knowledge of the network
  - Improves fault tolerance
  - Provides applications with multi-point without IP-level multicast



Message queuing: Architectural Issues

- Message brokers provide application-level gateways supporting message conversion
  - Useful when integrating sub-systems



Publish-subscribe

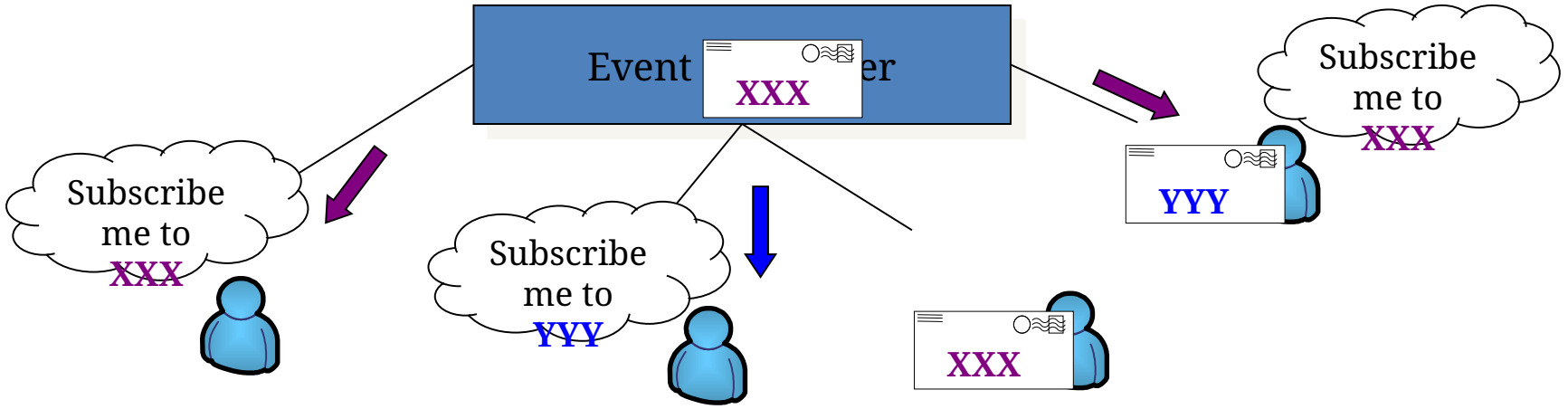
- Application components can *publish* asynchronous *event notifications*, and/or declare their interest in event classes by issuing a *subscription*
  - extremely simple API: only two primitives (`publish`, `subscribe`)
  - event notifications are simply messages
- Subscriptions are collected by an *event dispatcher* component, responsible for routing events to all matching subscribers
  - Can be centralized or distributed
- Communication is:
  - Transiently asynchronous
  - Implicit
  - Multipoint
- High degree of decoupling among components
  - Easy to add and remove components
  - Appropriate for dynamic environments

Subscription Language

- The expressiveness of the subscription language allows one to distinguish between:
  - *Subject-based* (or topic-based) --> easy to implement
    - The set of subjects is determined a priori
    - Analogous to multicast
    - e.g., subscribe to all events about “Distributed Systems”
  - *Content-based*
    - Subscriptions contain expressions (event filters) that allow clients to filter events based on their content
    - The set of filters is determined by client subscriptions
    - A single event may match multiple subscriptions
    - e.g., subscribe to all events about a “Distributed System” class with date greater than 16.11.2004 and held in classroom D04
- The two can be combined
- Tradeoffs:
  - Complexity of the implementation vs. expressiveness
  - However, expressiveness allows additional filtering!

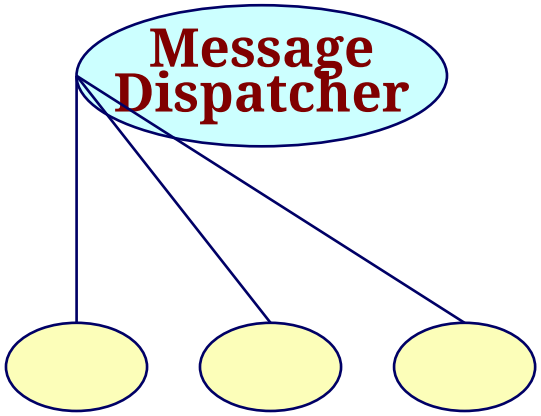
The event dispatcher

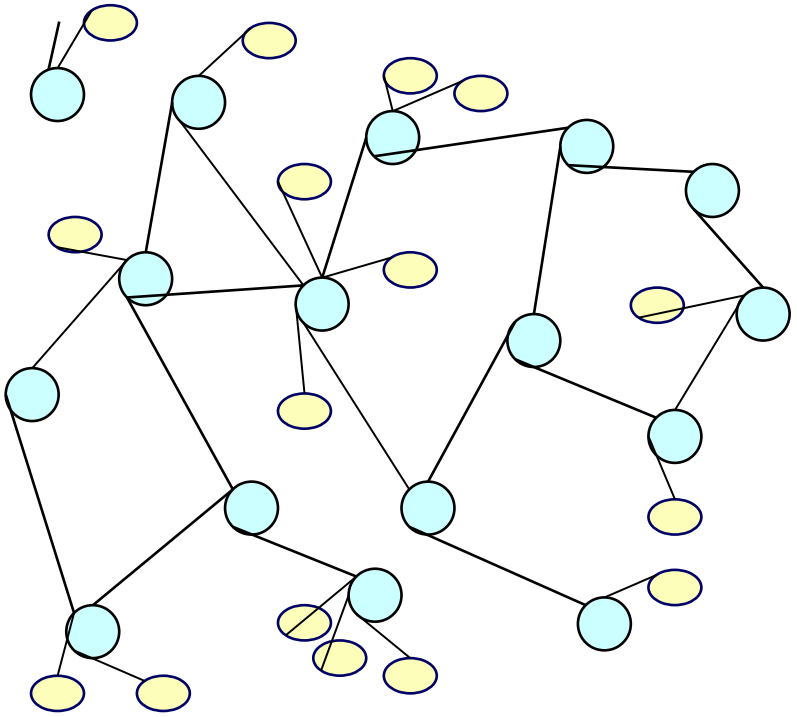
- In event-based systems a special component of the architecture, the *event dispatcher*, is in charge of collecting subscriptions and routing event notifications based on such subscriptions
  - For scalability reasons, its implementation can be distributed



Architecture of the Dispatcher

- Centralized
  - A single component is in charge of collecting subscriptions and forward messages to subscribers
- Distributed
  - A set of *message brokers* organized in an *overlay network* cooperate to collect subscriptions and route messages
  - The topology of the overlay network and the routing strategy adopted may vary
    - Acyclic vs. cyclic overlay



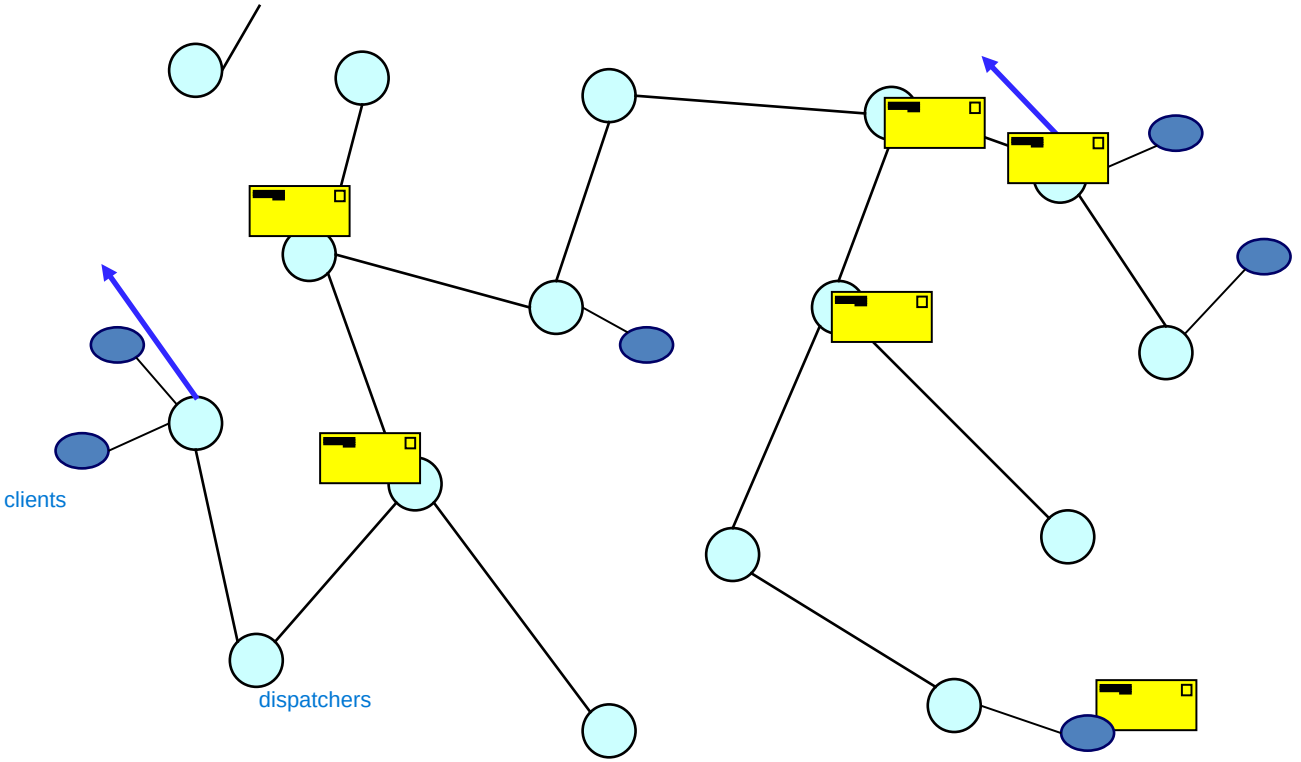


The following implementations are for content based

Message forwarding on an acyclic graph

Here we are in a content based system, matching takes a lot of time so it's good to have a distributed dispatcher

- Every broker stores only subscriptions coming from directly connected clients
- Messages are forwarded from broker to broker...
- ...and delivered to clients only if they are subscribed

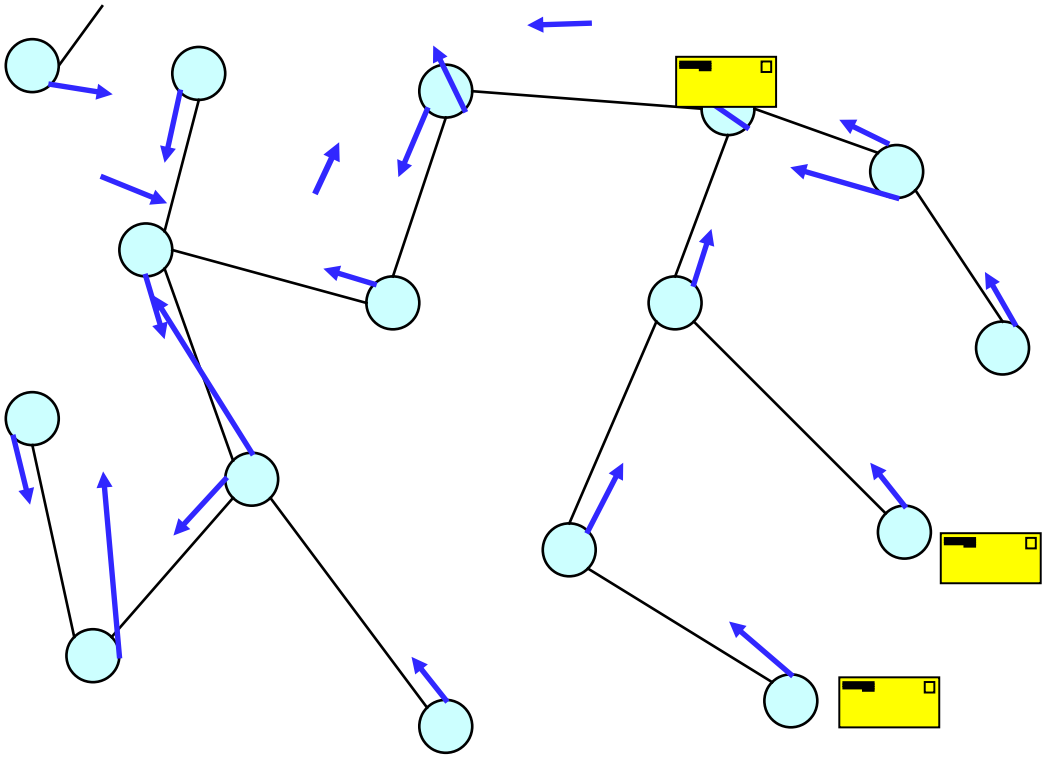


Message travel around the network, then when it reach a dispatcher he decides if forwarding it to the attached clients based on the content of the message and the subscription table. Each subscription table is small, so this process is not so costy in term of checking subscribers, but it is costy on the network

Subscription forwarding on an acyclic graph

In this alternative way, subscription table traver around the network between dispatchers, so the message only travels the "right way", cause every dispatcher can forward the message on the right way

- Every broker forwards subscriptions to the others
- Subscriptions are never sent twice over the same link
- Messages follow the routes laid by subscriptions
- Optimizations may exploit coverage relationships
  - E.g., "`Distributed *`" > "`Distributed systems`"
  - Fusion, subsumption, summarization



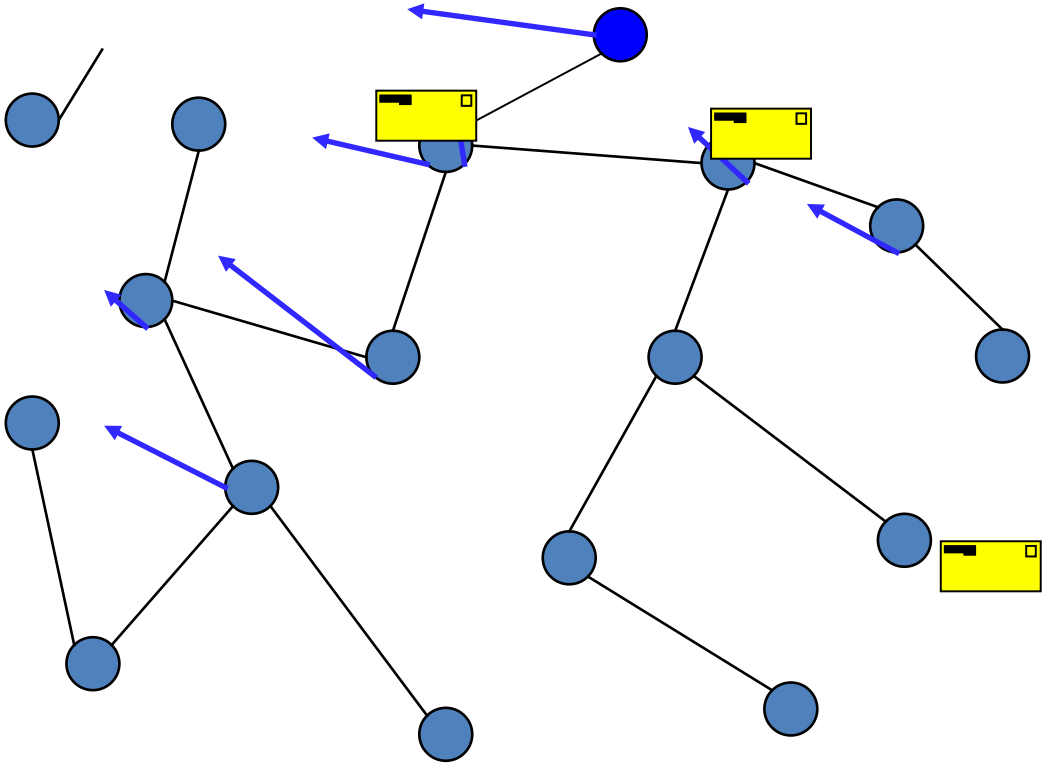
In terms of subscription forwarding it is costy, but less costy when publishing (cause message only follow one route)

Subscription forwarding on an acyclic graph: Details

- Each time a broker receives a message it must match it against the list of received filters to determine the list of recipients
- The efficiency of this process may vary, depending on the complexity of the subscription language, but also on the forwarding algorithm chosen
  - It greatly influences the overall performance of the system

Hierarchical forwarding

- Assumes a rooted overlay tree
- Both messages and subscriptions are forwarded by brokers towards the root of the tree
- Messages flow “downwards” only if a matching subscription had been received along that route



distributed hash table is a data structure equivalent to an hash table table (key-value). The DHT is so big that you split and give a split of the table to different nodes

Until now we assumed that the network doesn't had cycles

Cyclic topologies: a DHT based approach

If we have cyclic topologies and we have a topic based message system we can use a distributed hash table

- A DHT organizes nodes in a structured overlay allowing efficient routing toward the node having the smaller ID greater or equal than any given ID (the successor)
- To subscribe for messages having a given subject *S*
  - Calculate a hash of the subject *Hs*
  - Use the DHT to route toward the node *succ(Hs)*
  - While flowing toward *succ(Hs)* leave routing information to return messages back
- To publish messages having a given subject *S*
  - Calculate a hash of the subject *Hs*
  - Use the DHT to route toward the node *succ(Hs)*
  - While flowing toward *succ(Hs)* follow back routes toward subscribers

Either the table is very big or it has a good protocol to collaborate to other (either it has the key or knows who has the key ecc...). In publish subscriber you can use the DHT to find the node who's publishing what you're interest in or to find the subscribers to who are interested in what you're publishing

Several strategies possible

Cyclic topologies: Content-based routing

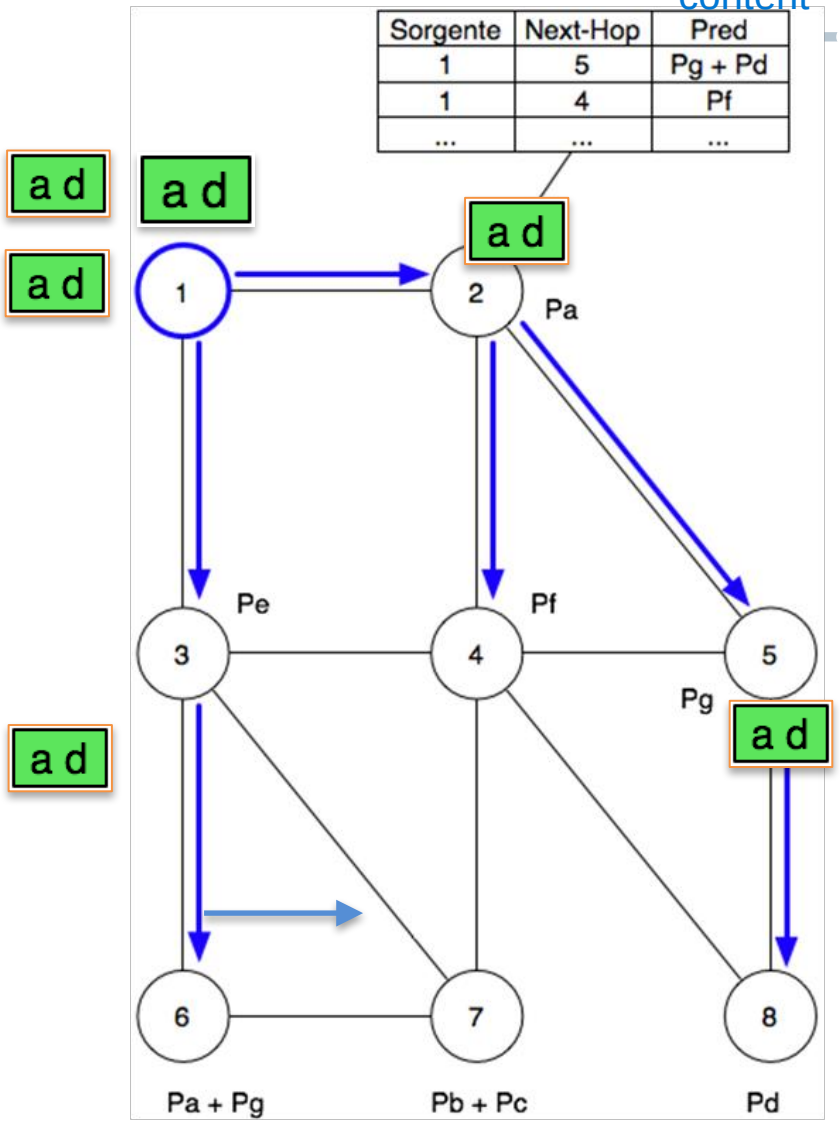
- Useful to differentiate between *forwarding* and *routing*
- Different forwarding strategies:
  - Per source forwarding (PSF)
  - Improved per source forwarding (iPSF)
  - Per receiver forwarding (PRF)
- Different strategies to build paths…
  - Distance Vector (DV)
  - Link-State (LS)
- … and populate forwarding tables
  - We will skip this!

Brokers connected to a cyclic network

PSF: Per-Source Forwarding

content

For each source a spanning tree is defined, a message is sent to the leaves of the spanning tree and then every node attaches is predicates (meaning the content he is interested in) to that message up back to the root. This result in the building of the subscribing table

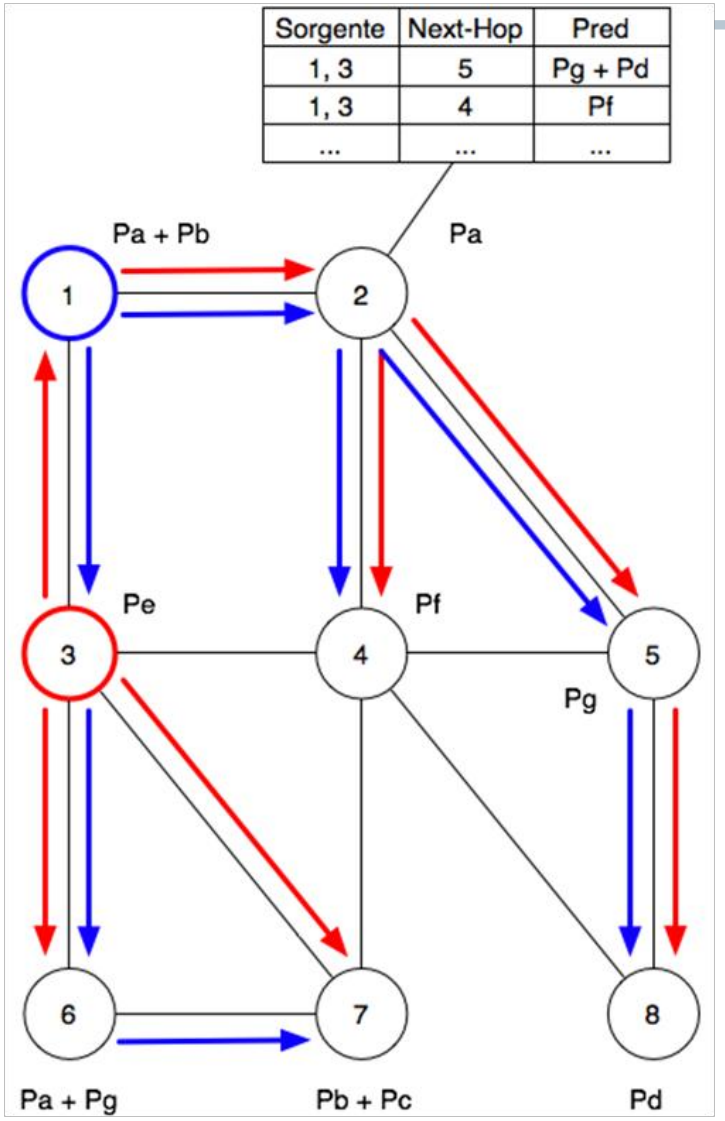


- Every source defines a shortest path tree (SPT)
- Forwarding table keeps information organized per source
  - For each source v the children in the SPT associated with v
  - For each children u a predicate which joins the predicates of all the nodes reachable from u along the SPT

At each hop you redo the predicate checking.
Smaller tables wrt per receiver forwarding (cause here every broker only knows about the next one)

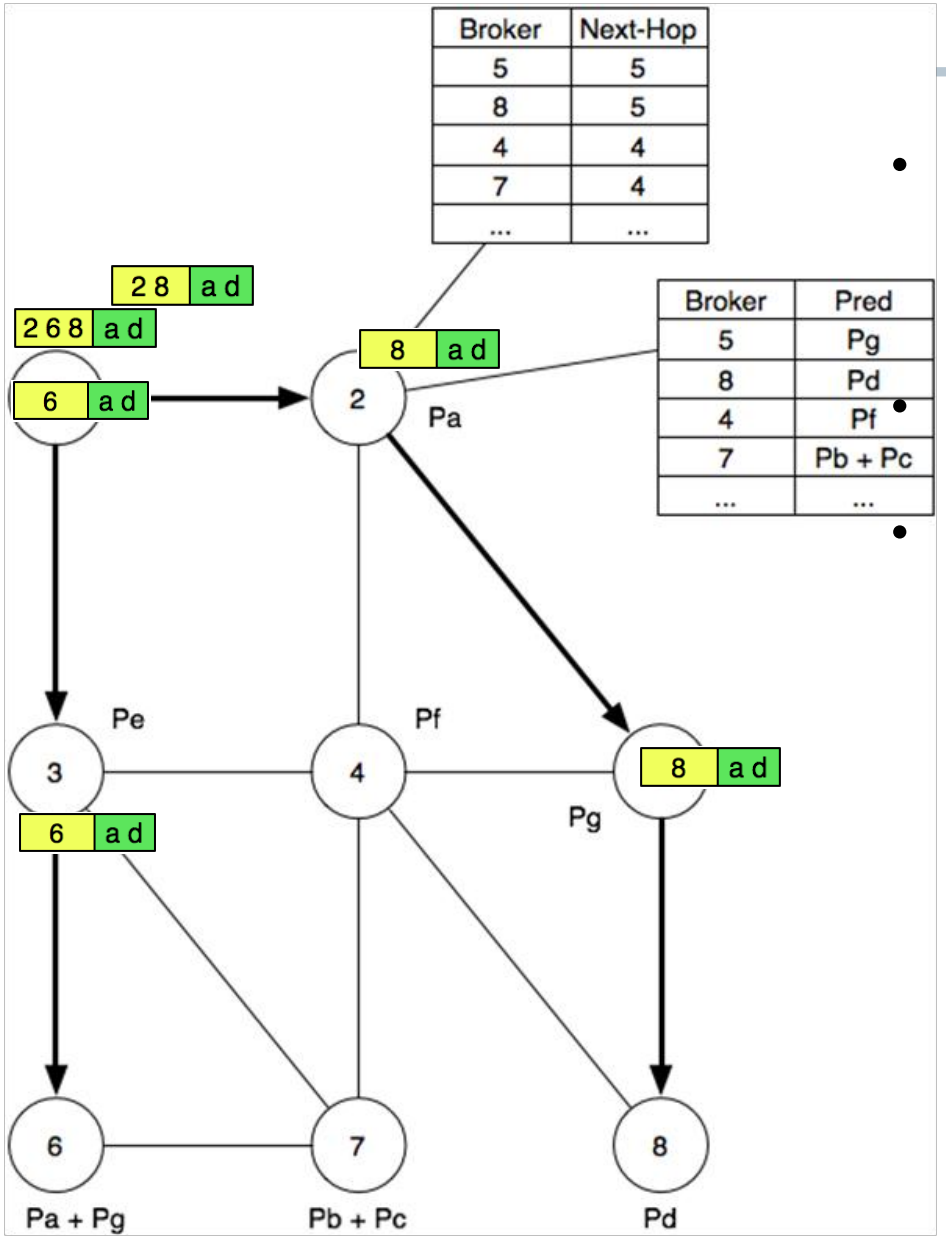
iPSF: improved PSF

skip



- Same as PSF but leveraging the concept of *indistinguishable sources*
- Two sources A e B with SPT T(A) and T(B) are indistinguishable from a node *n* if *n* has the same children for T(A) and T(B) and reaches the same nodes along those children
- This concept brings several advantages
  - Smaller forwarding tables
  - Easier to build them

PRF: Per-Receiver Forwarding

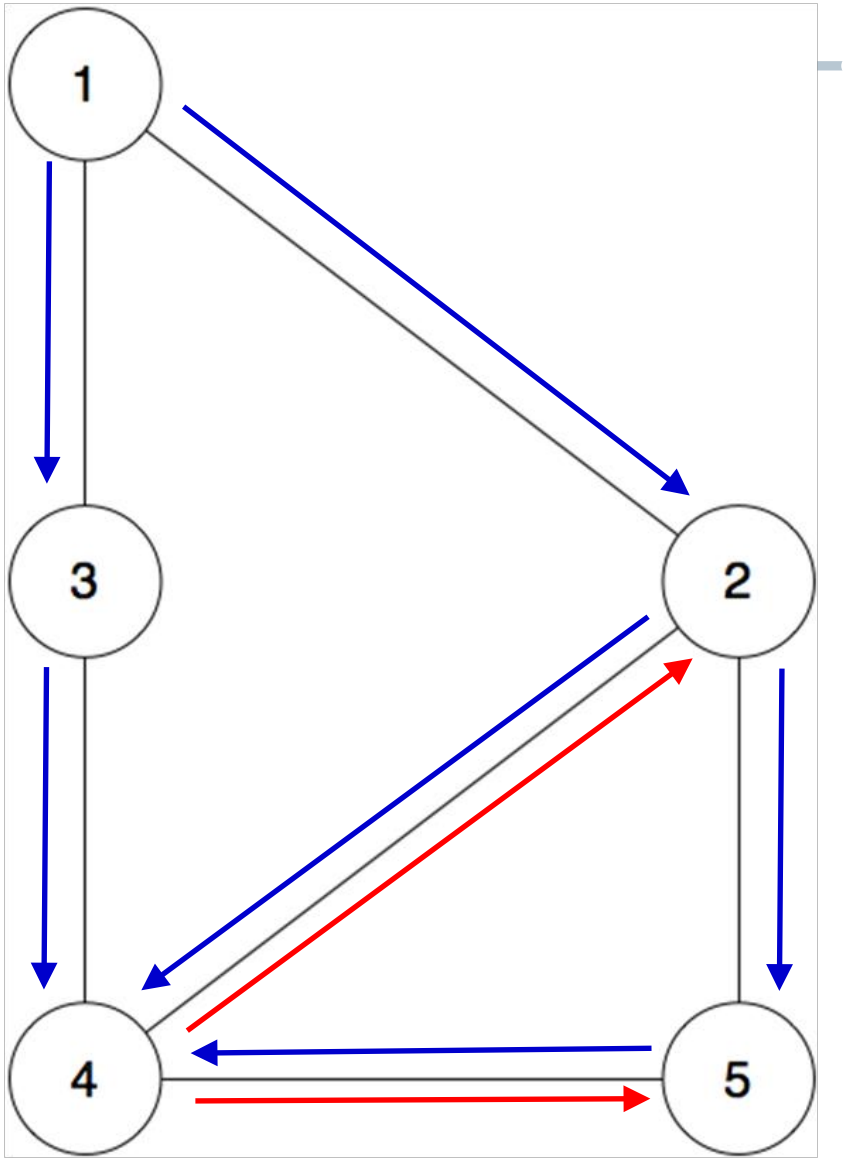


- The source of a message calculates the set of receivers and add them to the header of the message
- At each hop the set of recipients is partitioned
- Two different tables:
  - The unicast routing table
  - A forwarding table with the predicate for each node in the network

Each broker broadcast to the other its own predicate so every broker knows the predicate of all the others. So when a broker gets a message it can understand which brokers can be interested in it so attach the receivers to the message,

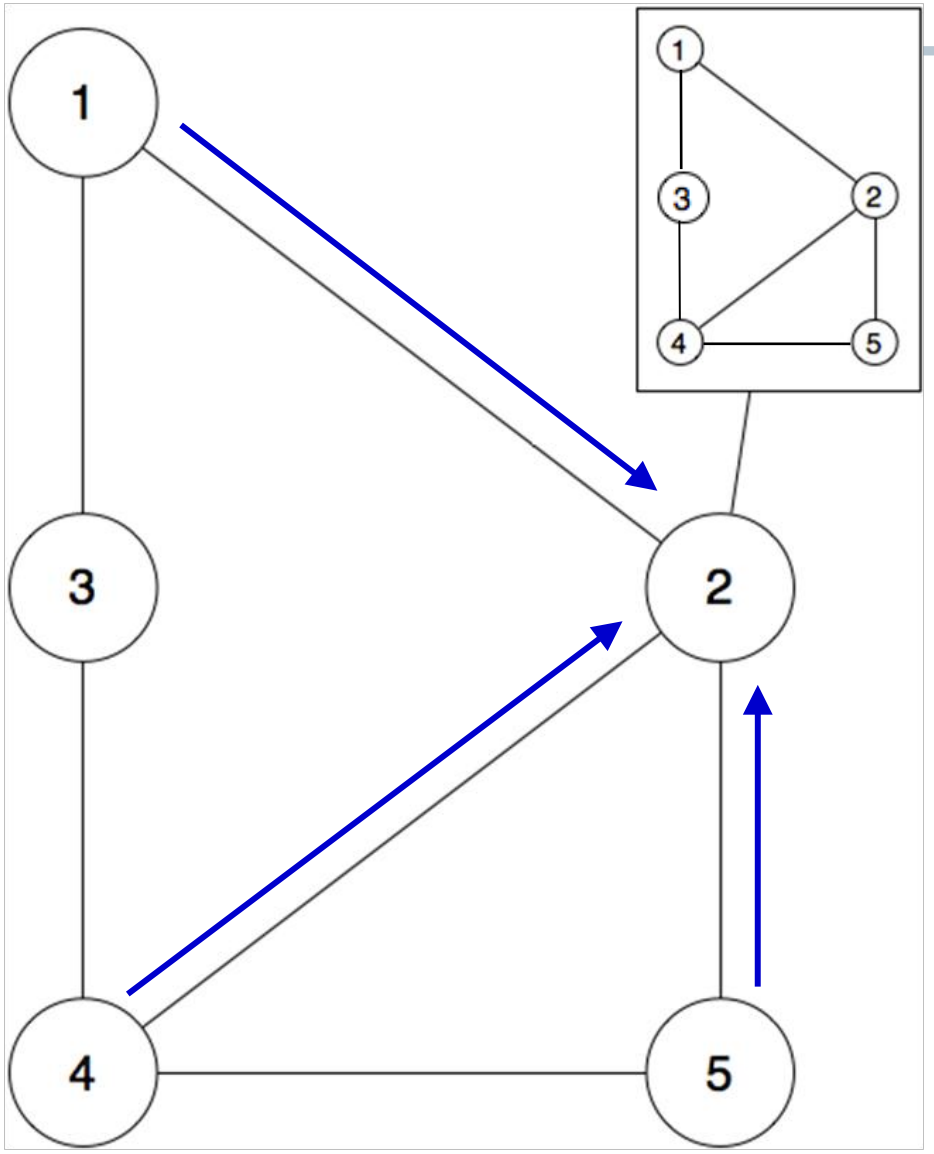
-Bigger table wrt per source forwarding.
-The predicate matching happens only once

Distance Vector (DV)



- Builds minimum latency SPTs
- Use request packets (config) and reply ones (config response).
- Every node acquire a local view of the network (its neighbors in the SPT)

Link-State (LS)

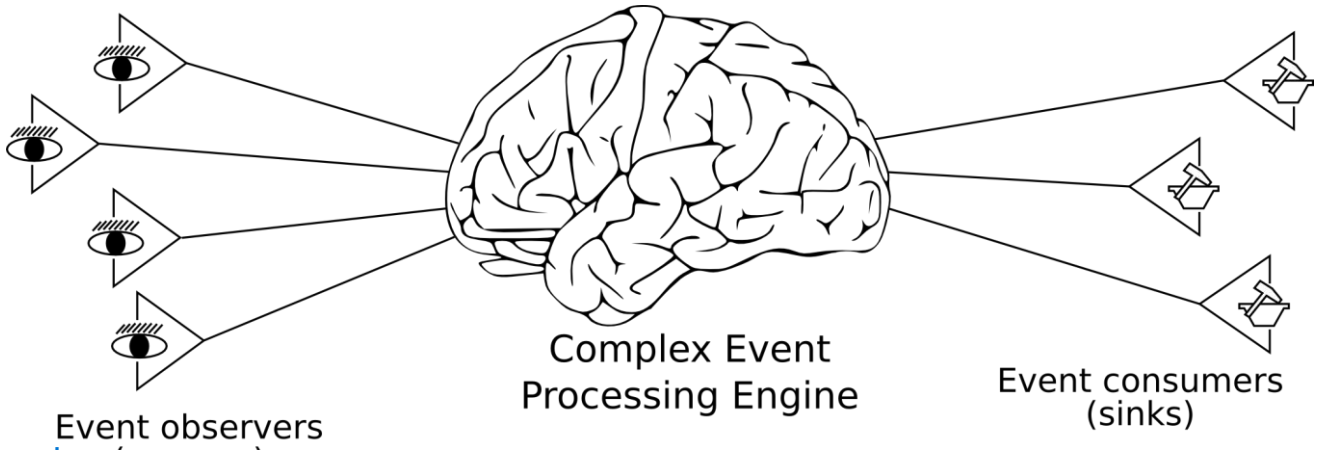


- Allows to build SPTs based on different metrics
- Use packets carrying information about the known state of the network (Link-State Packet - LSP) forwarded when a node acquire new information
- Every node discovers the topology of the whole network
- SPTs are calculated locally and independently by every node

Complex event processing

Put application code into the event bus to achieve "intelligence"

- CEP systems adds the ability to deploy rules that describe how composite events can be generated from primitive (or composite) ones
  - Recently a number of languages and systems have been proposed to support such architecture (both under the CEP and DSMS labels)

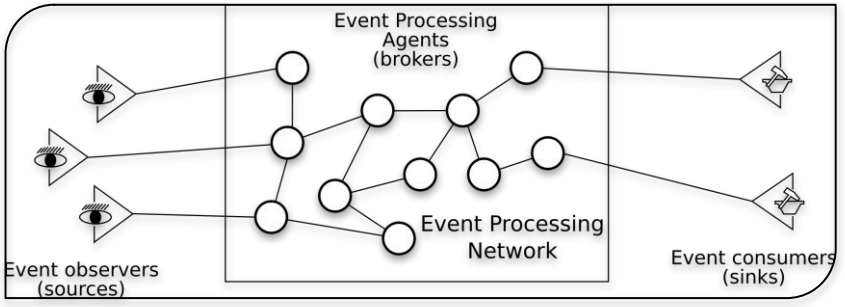


Es:
event 1 says there's smoke
event 2 says the temperature is rising

fire!

CEP: Open issues

- The rule language
  - Find a balance between expressiveness and processing complexity
- The processing engine
  - How to efficiently match incoming (primitive) events to build complex ones
- Distribution
  - How to distribute processing
    - Clustered vs. networked solutions



Contents

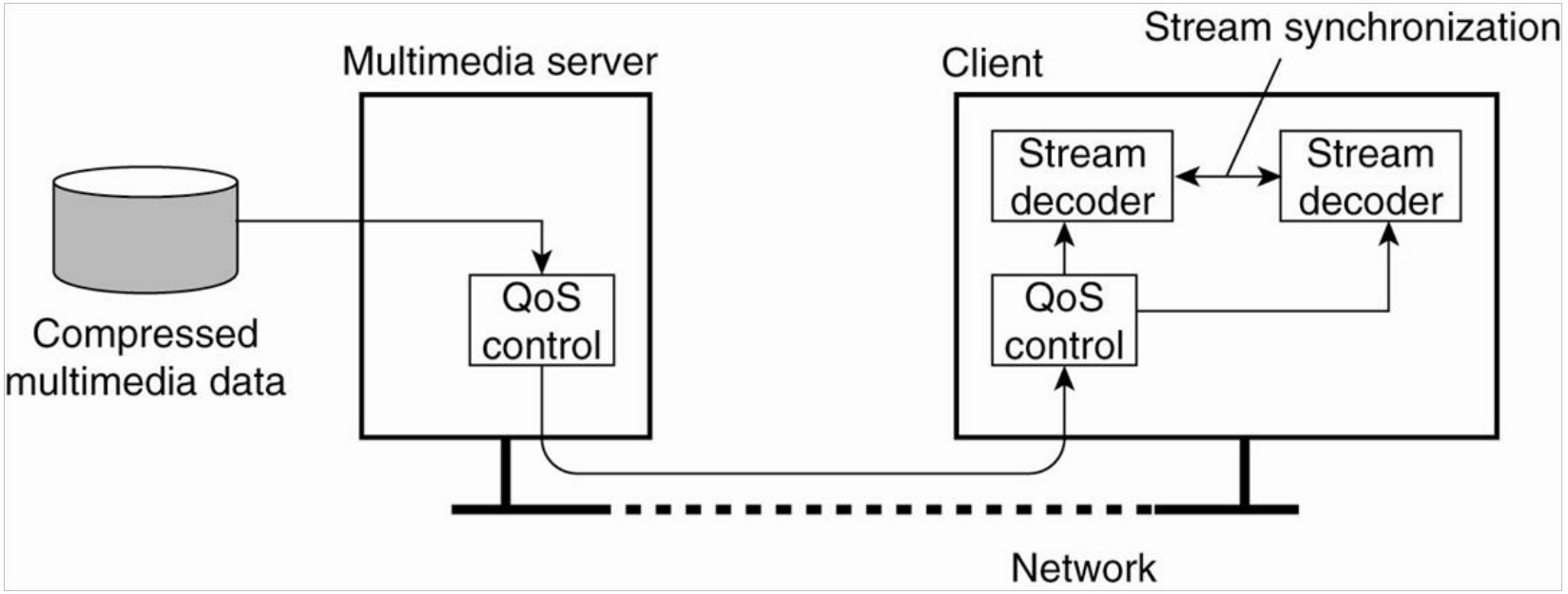
- Fundamentals
  - Protocols and protocol stacks
  - Middleware
- Remote procedure call
  - Fundamentals
  - Discovering and binding
  - Sun and DCE implementations
- Remote method invocation
  - Fundamentals
- Message oriented communication
  - Fundamentals
  - Message passing (sockets and MPI)
  - Message queuing
  - Publish/subscribe
- **Stream-oriented communication**
  - **Fundamentals**
  - **Guaranteeing QOS**

Stream-oriented communication

- Data stream: A sequence of data units
  - Information is often organized as a sequence of data units. E.g., text, audio,...
- Time usually does not impact the *correctness* of the communication
  - Just its performance
- In some cases this is not the case
  - E.g., when sending a video “in streaming”, i.e., to be played “on-line”
- Transmission modes
  - *Asynchronous*: The data items in a stream are transmitted one after the other without any further timing constraints (apart ordering)
  - *Synchronous*: There is a max end-to-end delay for each unit in the data stream
  - *Isochronous*: There is max and a min end-to-end delay (bounded jitter)
- Stream types: Simple vs. complex streams (composed of substreams)

Streaming stored data

- Non-functional requirements are often expressed as *Quality of Service* (QoS) requirements
  - Required bit rate
  - Maximum delay to setup the session
  - Maximum end-to-end delay
  - Maximum variance in delay (jitter)



QoS and the Internet: The DiffServ architecture

- IP is a best effort protocol!
  - So much for QoS :-)

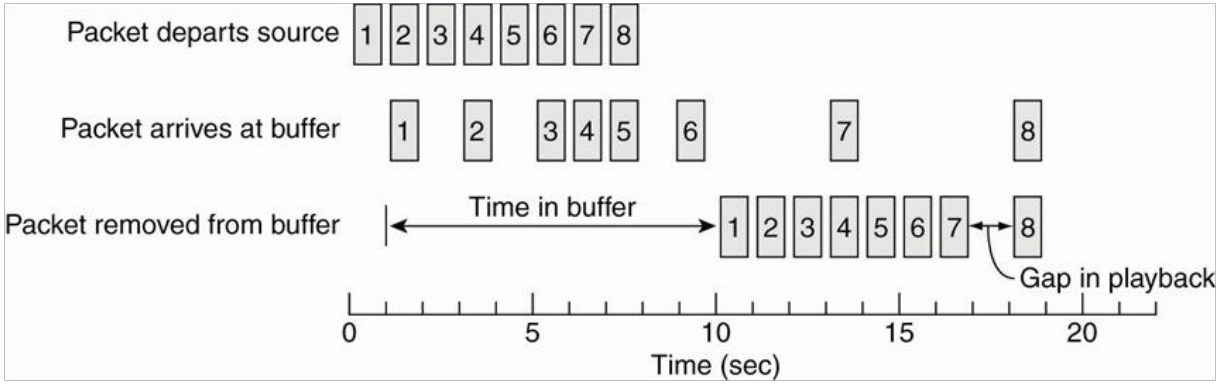
-> does its best to provide certain performances but it doesn't guarantees you anything

- Actually it offers a Differentiated Services field (aka Type Of Service - TOS) into its header
  - 6 bits for the Differentiated Services Code Point (DSCP) field
  - 2 bits for the Explicit Congestion Notification (ECP) field
  - The former encodes the Per Hop Behaviour (PHB)
    - Default
    - Expedited forwarding. Usually less than 30% of traffic and often much less
    - Assured forwarding (further divided into 4 classes)
- Not necessarily supported by Internet routers

Enforcing QoS at the application layer

- Buffering
  - Control max jitter by sacrificing session setup time

---> tries to resolve the variation on the speed of the network by creating a buffer

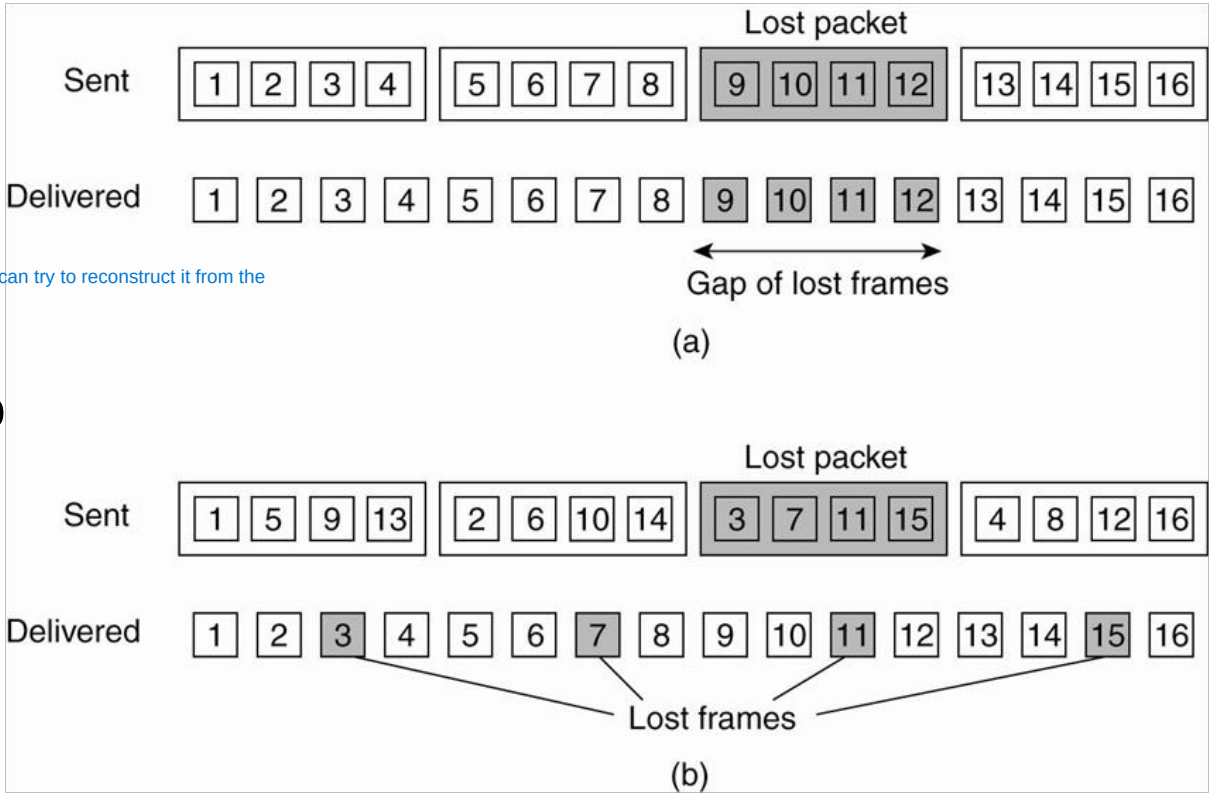


- Forward error correction

you reach a state which is incorrect one, two solutions:
- go back to a previous state: backward correction --> not the best approach for this kind of service
-try to go to the right state: forward correction. In the case of videos, you have the main frame and then deltas from the previous and the next, if you lost a delta, you can try to reconstruct it from the next deltas

- Interleaving data
  - To mitigate the impact o lost packets

Notice that you need multiple packet to reconstruct the sequence (cause frame 1 is in the first, 2 is in the second ecc...), but using a BUFFER where you save frames, you can fix the lost of a packet by doing FORWARD error connection.



Stream synchronization

- Synchronizing two or more streams (es: video and audio tracks) is not easy
- It could mean different things
  - Left and right channels at CD quality → each sample must be synchronized → 23 μsec of max jitter
  - Video and audio for lip synch → each audion interval must be in synch with its frame → at 30 fps 33 msec of max jitter
- Synchronization may take place at the sender or the receiver side
  - In the former case the different streams can be merged together
- It may happen at different layers (application vs. middleware)