Chapter 4: Communication

Introduction

- In a distributed system, processes run on different machines.
- Processes can only exchange information through message passing.
  - harder to program than shared memory communication
- Successful distributed systems depend on communication models that hide or simplify message passing

Overview

- Message-Passing Protocols
  - OSI reference model
  - TCP/IP

- Higher level communication models
  - Remote Procedure Call (RPC)
  - Message-Oriented Middleware (time permitting)
  - Data Streaming (time permitting)

Introduction

- A communication network provides data exchange between two (or more) end points.

- In a computer network, the end points of the data exchange are computers and/or terminals. (nodes, sites, hosts, etc., …)

Circuit Switching vs Packet Switching

- Circuit switching is *connection-oriented* (think traditional telephone system)
  - Establish a dedicated path between hosts
  - Data can flow continuously over the connection
- Packet switching divides messages into fixed size units (packets) which are routed through the network individually.
  - different packets in the same message may follow different routes.

Protocols

- A protocol is a set of rules that defines how two entities interact.
  - For example: HTTP, FTP, TCP/IP
- Layered protocols have a hierarchical organization
- Conceptually, layer n on one host talks directly to layer n on the other host, but in fact the data must pass through all layers on both machines.

Open Systems Interconnection Reference Model (OSI)

- Supports communication between open systems
- Divides issues into 7 levels (layers) from most concrete to most abstract
- Each layer provides an interface (set of operations) to the layer immediately above
- Defines functionality – not specific protocols

Layered Protocols (1)

High level 7→

Create message, 6 → string of bits

Establish Comm. 5→

Create packets 4→

Network routing 3→

Add header/footer tag + checksum 2→

Transmit bits via 1→ comm. medium (e.g. Copper, Fiber, wireless)

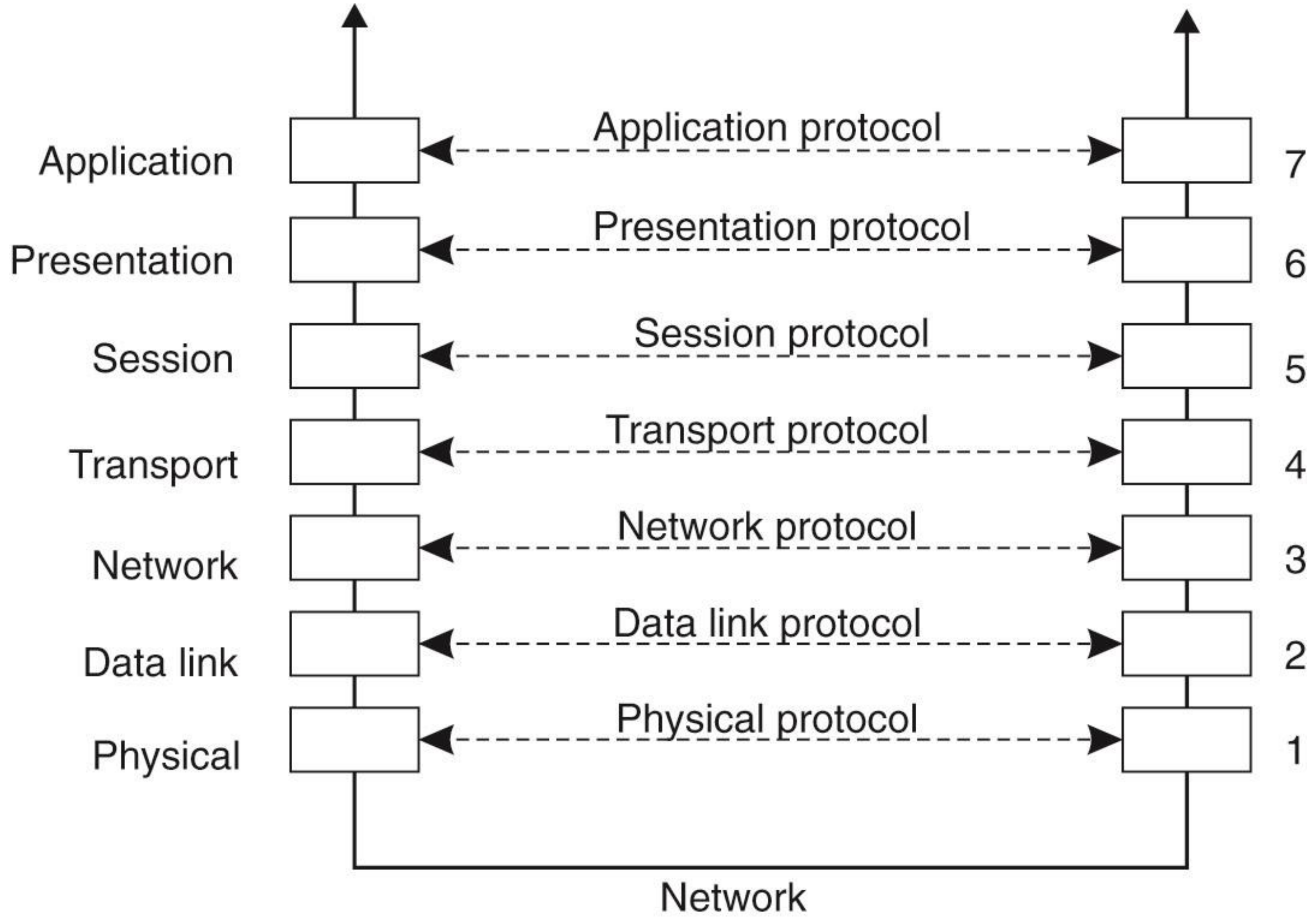


Figure 4-1. Layers, interfaces, and protocols in the OSI model.

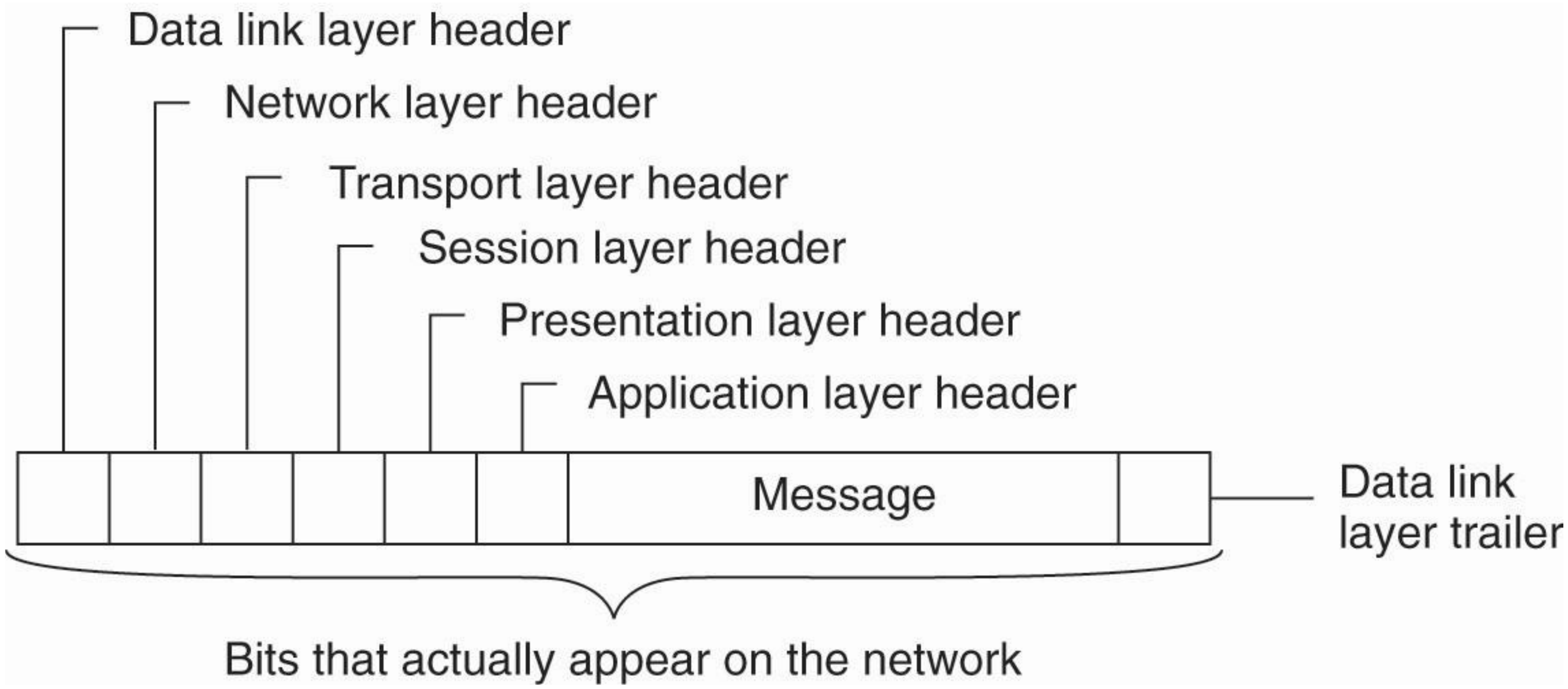


Figure 4-2. A typical message as it appears on the network

Lower-level Protocols

- **Physical**: standardizes electrical, mechanical, and signaling interfaces; e.g.,
  - # of volts that signal 0 and 1 bits
  - # of bits/sec transmitted
  - Plug size and shape, # of pins, etc.
- **Data Link**: provides low-level error checking
  - Appends start/stop bits to a frame
  - Computes and checks checksums
- **Network**: routing (generally based on IP)
  - IP packets need no setup
  - Each packet in a message is routed independently of the others

Transport Protocols

- **Transport layer, sender side**: Receives message from higher layers, divides into packets, assigns sequence #
- Reliable transport (connection-oriented) can be built on top of connection-oriented or connectionless networks
  - When a connectionless network is used the transport layer re-assembles messages in order at the receiving end.
- Most common transport protocols: TCP/IP

Higher Level Protocols

- **Session layer**: rarely supported
  - Provides dialog control;
  - Keeps track of who is transmitting
- **Presentation**: Cares about the meaning of the data
  - Record format, encoding schemes, mediates between different internal representations
- **Application**: Originally meant to be a set of basic services; now holds applications and protocols that don’t fit elsewhere

Middleware Protocols to Support Communication

- Protocols for remote procedure call (RPC)
- Protocols to
  - support message-oriented services
  - support streaming real-time data, as for multimedia applications
  - support reliable multicast service across a wide-area network

- These protocols would be built on top of low-level message passing, as supported by the transport layer.

Middleware Protocols

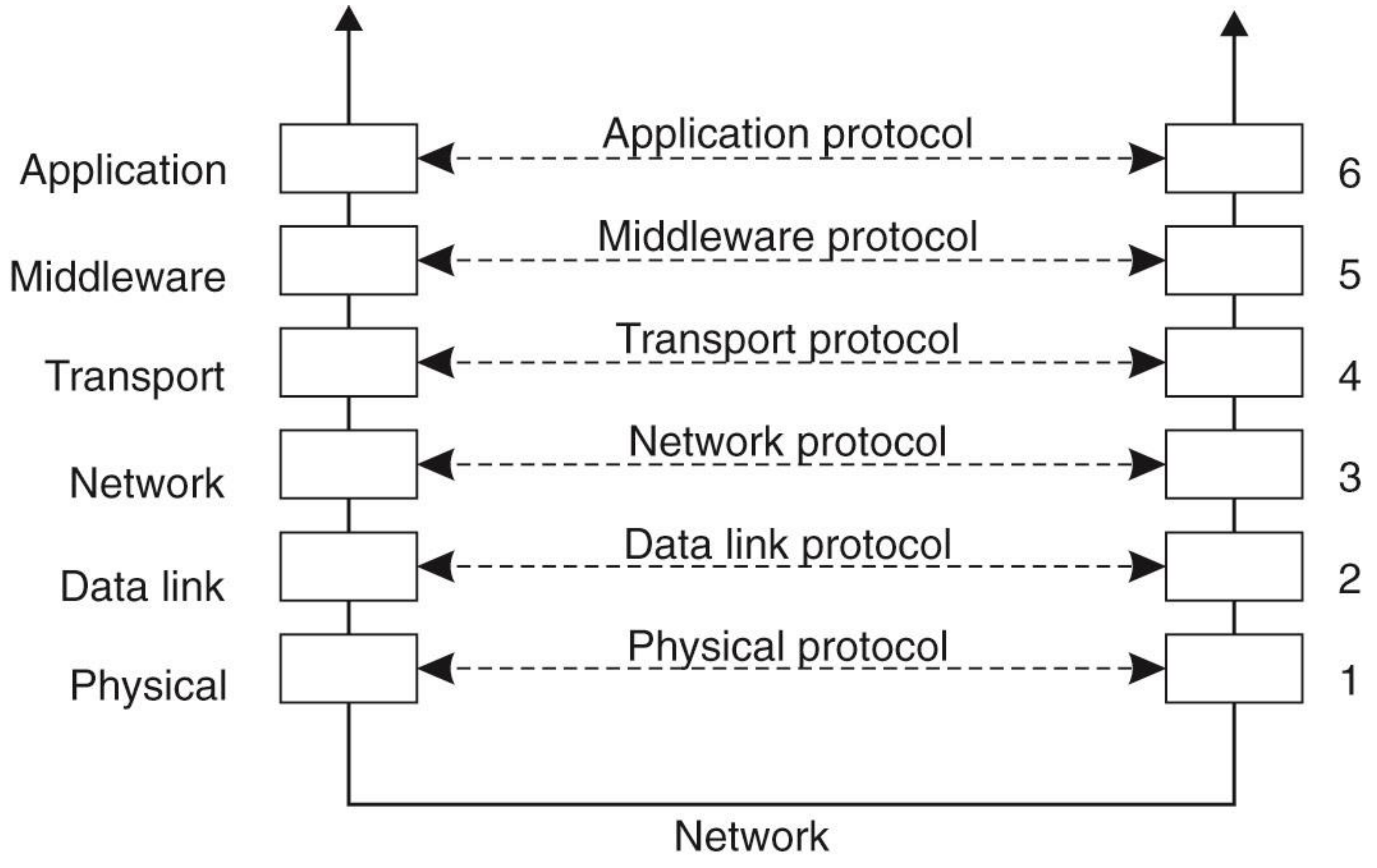


Figure 4-3. An adapted reference model for networked communication.

Messages

- Transport layer message passing consists of two types of primitives: send and receive
  - May be implemented in the OS or through add-on libraries
- Messages are composed in user space and sent via a send() primitive.
- When processes are expecting a message they execute a receive() primitive.
  - Receives are often blocking

Types of Communication

- Persistent versus Transient
- Synchronous versus Asynchronous
- Discrete versus Streaming

Persistent versus Transient Communication

- **Persistent**: messages are held by the middleware comm. service until they can be delivered. (Think email)
  - Sender can terminate after executing send
  - Receiver will get message next time it runs
- **Transient**: Messages exist only while the sender and receiver are running
  - Communication errors or inactive receiver cause the message to be discarded.
  - Transport-level communication is transient

Asynchronous v Synchronous Communication

- **Asynchronous**: (non-blocking) sender resumes execution as soon as the message is passed to the communication/middleware software
  - Message is buffered temporarily by the middleware until sent/received

- **Synchronous**: sender is blocked until
  - The OS or middleware notifies acceptance of the message, *or*
  - The message has been delivered to the receiver, *or*
  - The receiver processes it & returns a response.

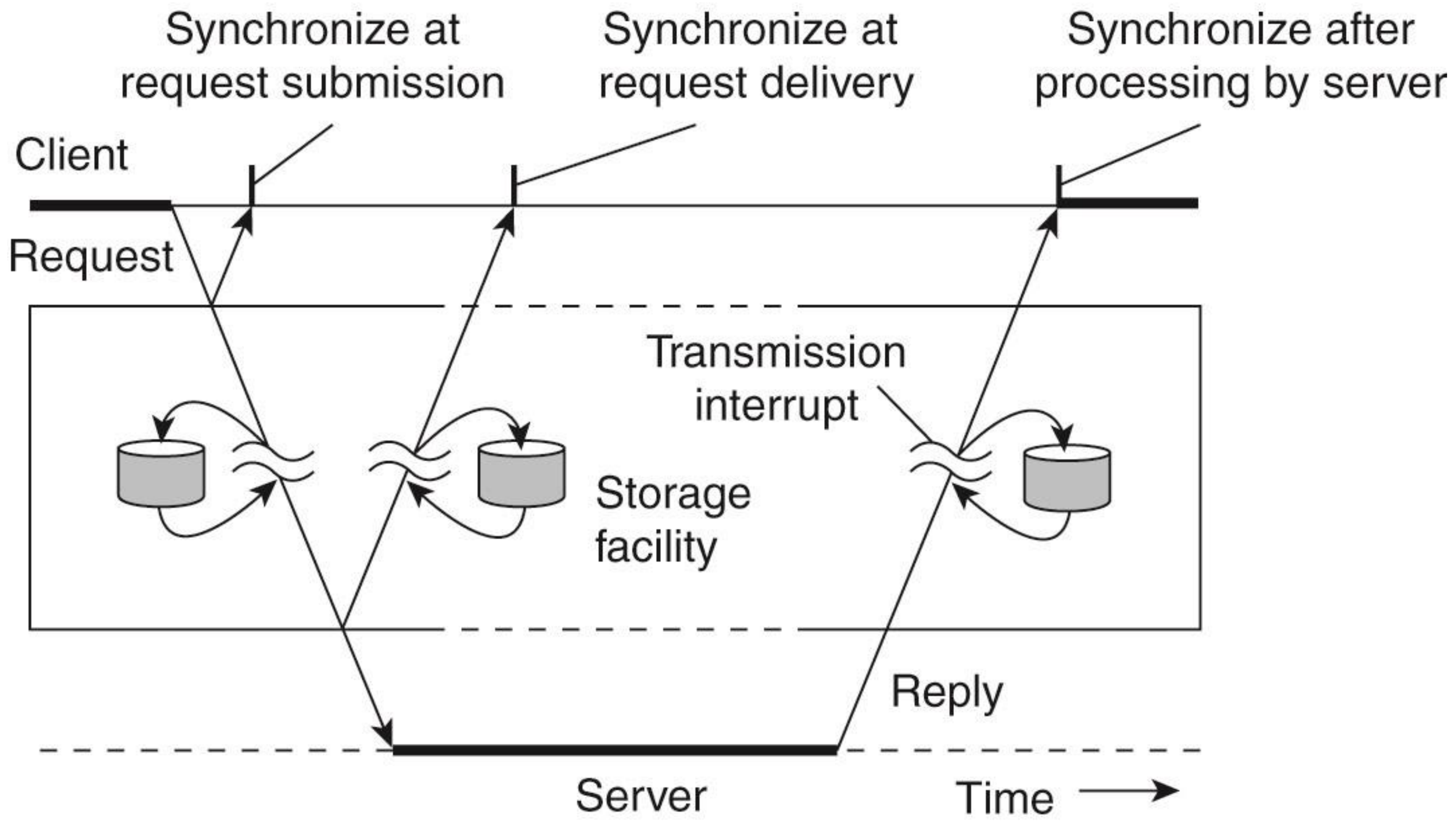

Synchronize at request submission
Synchronize at request delivery
Synchronize after processing by server
Client
Request
Transmission interrupt
Storage facility
Reply
Server
Time

Figure 4-4. Viewing middleware as an intermediate (distributed) service in application-level communication.

Evaluation

- Communication primitives that don’t wait for a response are faster, more flexible, but programs may behave unpredictably since messages will arrive at unpredictable times.
- Fully synchronous primitives may slow processes down, but program behavior is easier to understand.
- In multithreaded processes, blocking is not as big a problem because a special thread can be created to wait for messages.

Discrete versus Streaming Communication

- **Discrete**: communicating sections exchange discrete messages
- **Streaming**: one-way communication; a “session” consists of multiple messages from the sender that are related either by send order, temporal proximity, etc.

Middleware Communication Techniques

- Remote Procedure Call
- Message-Oriented Communication
- Stream-Oriented Communication
- Multicast Communication

RPC - Motivation

- Low level message passing is based on *send* and *receive* primitives.
- Messages lack *access transparency*.
  - Differences in data representation, need to understand message-passing process, etc.
- Programming is simplified if processes can exchange information using techniques that are similar to those used in a shared memory environment.

The Remote Procedure Call (RPC) Model

- A high-level network communication interface
- Based on the single-process procedure call model.
- Client request: formulated as a procedure call to a function on the server.
- Server’s reply: formulated as function return

Conventional Procedure Calls

- Initiated when a process calls a function or procedure
- The caller is “suspended” until the called function completes.
- Arguments & return address are pushed onto the process stack.
- Variables local to the called function are pushed on the stack

Conventional Procedure Call

count = read(fd, buf, nbytes);

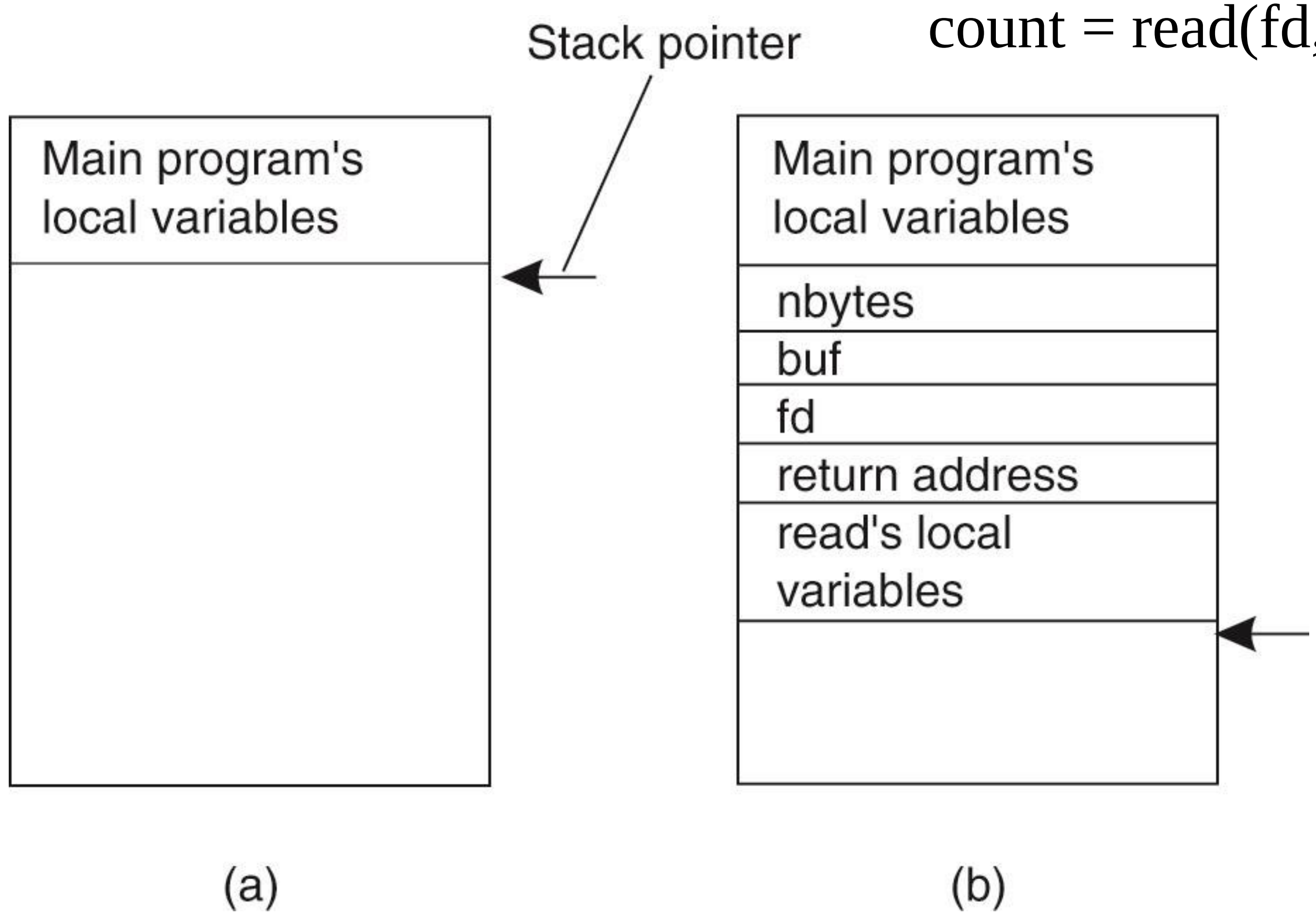


Figure 4-5. (a) Parameter passing in a local procedure call: the stack before the call to *read*. (b) The stack while the called procedure is active.

Conventional Procedure Calls

- Control passes to the called function
- The called function executes, returns value(s) either through parameters.
- The stack is popped.
- Calling function resumes executing

Remote Procedure Calls

- Basic operation of RPC parallels same-process procedure calling
- Caller process executes the remote call and is suspended until called function completes and results are returned.
- Parameters are passed to the machine where the procedure will execute.
- When procedure completes, results are passed back to the caller and the client process resumes execution at that time.

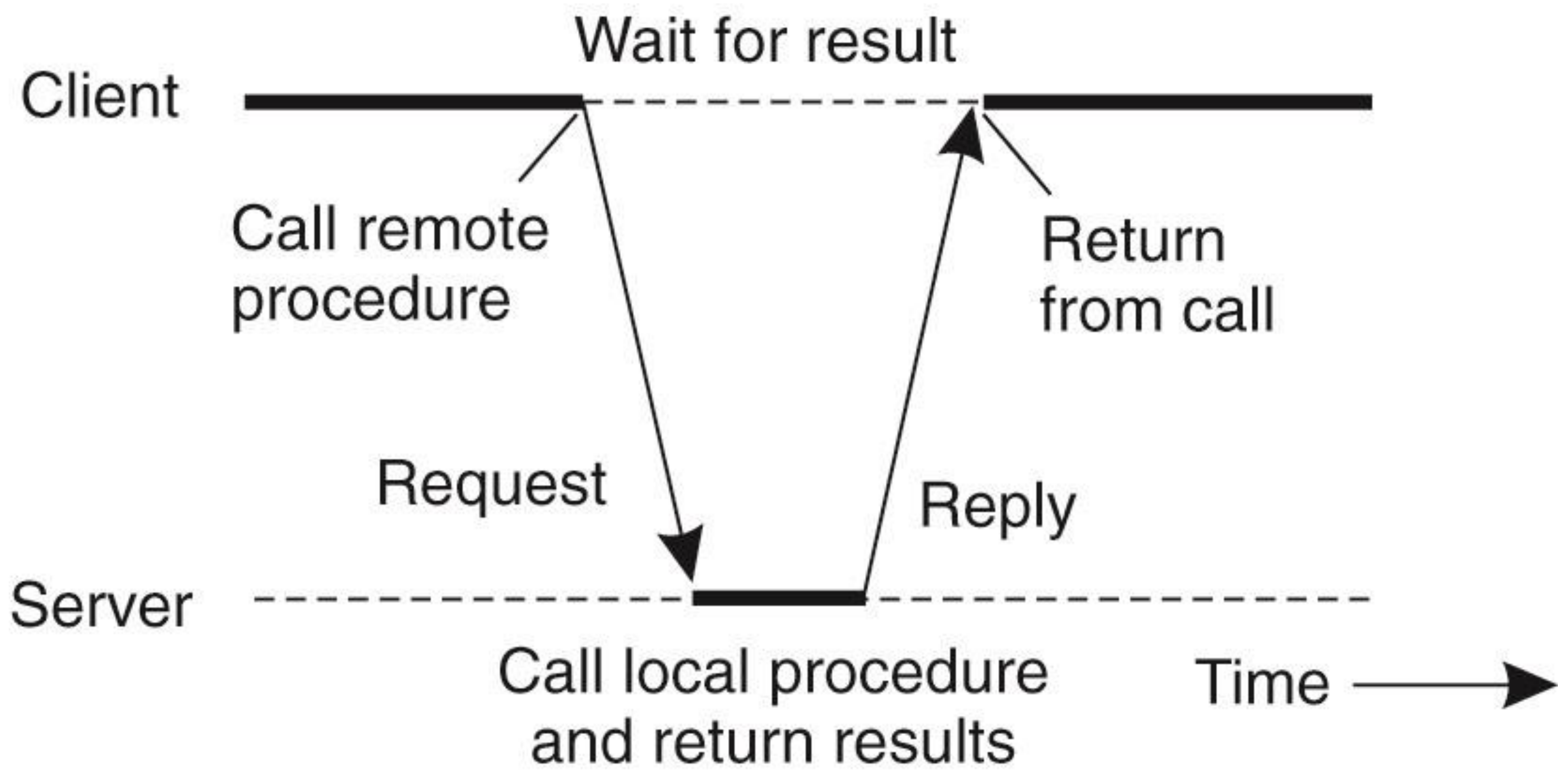


Figure 4-6. Principle of RPC between a client and server program.

RPC and Client-Server

- RPC forms the basis of most client-server systems.
- Clients formulate requests to servers as procedure calls
- Access transparency is provided by the RPC mechanism
- Implementation?

Transparency Using **Stubs**

- Stub procedures (one for each RPC)
- For procedure calls, control flows from
  - Client application to client-side stub
  - Client stub to server stub
  - Server stub to server procedure
- For procedure return, control flows from
  - Server procedure to server-stub
  - Server-stub to client-stub
  - Client-stub to client application

Client Stub

- When an application makes an RPC the stub procedure does the following:
  - Builds a message containing parameters and calls local OS to *send* the message
  - Packing parameters into a message is called **parameter marshalling**.
  - Stub procedure calls *receive( )* to wait for a reply (blocking receive primitive)

OS Layer Actions

- Client’s OS sends message to the remote machine
- Remote OS passes the message to the server stub

Server Stub Actions

- Unpack parameters, make a call to the server
- When server function completes execution and returns answers to the stub, the stub packs results into a message
- Call OS to send message to client machine

OS Layer Actions

- Server’s OS sends the message to client
- Client OS receives message containing the reply and passes it to the client stub.

Client Stub, Revisited

- Client stub unpacks the result and returns the values to the client through the normal function return mechanism
  - Either as a value, directly or
  - Through parameters

Passing Value Parameters

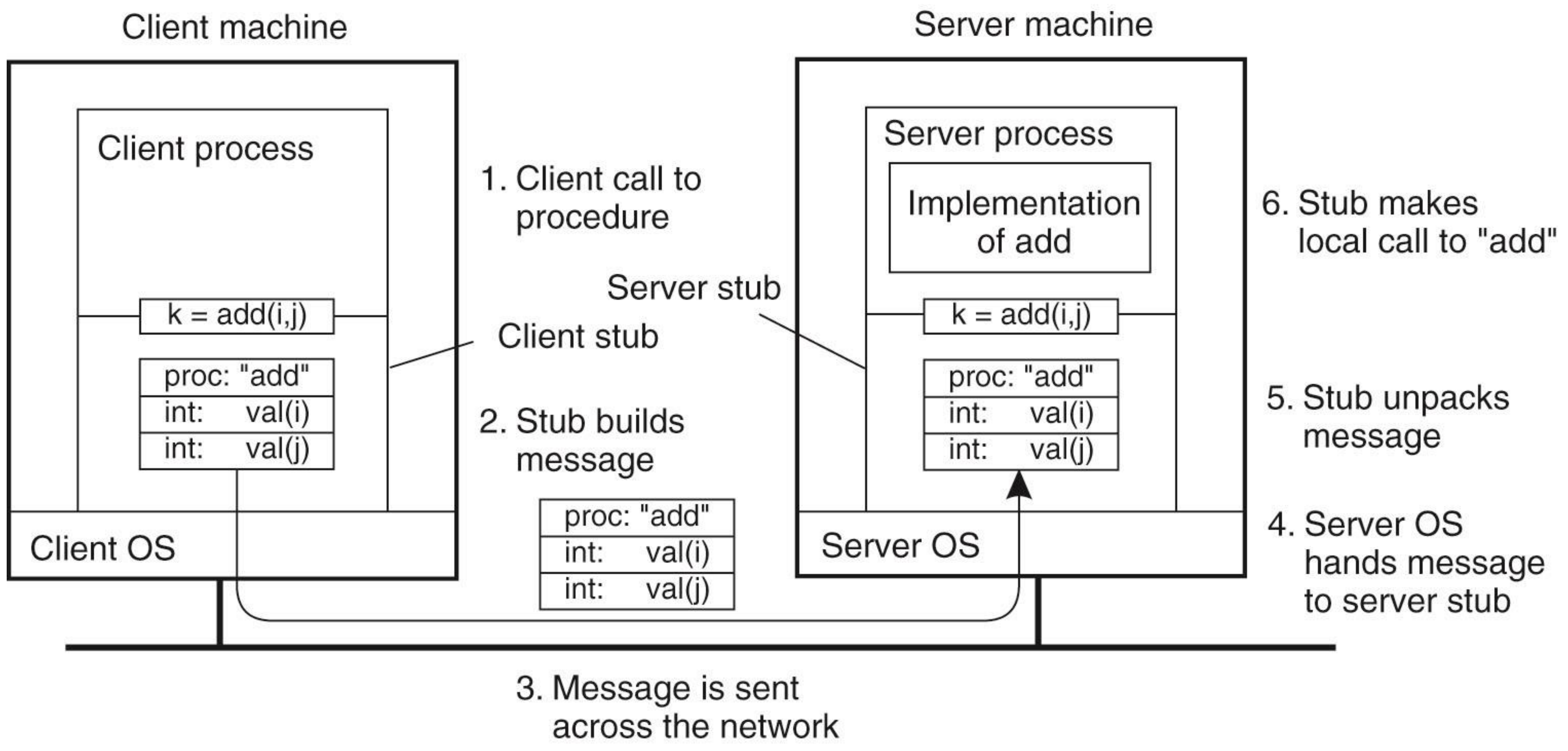


Figure 4-7. The steps involved in a doing a remote computation through RPC.

Issues

- Are parameters call-by-value or call-by-reference?
  - Call-by-value: in same-process procedure calls, parameter value is pushed on the stack, acts like a local variable
  - Call-by-reference: in same-process calls, a pointer to the parameter is pushed on the stack
- How is the data represented?
- What protocols are used?

Parameter Passing –Value Parameters

- For *value parameters*, value can be placed in the message and delivered directly, except …
    - Are the same internal representations used on both machines? (char. code, numeric rep.)
    - Is the representation big endian, or little endian? (see p. 131)

Parameter Passing – Reference Parameters

- Consider passing an array in the normal way:
  - The array is passed as a pointer
  - The function uses the pointer to directly modify the array values in the caller’s space
- Pointers = machine addresses; not relevant on a remote machine
- Solution: copy array values into the message; store values in the server stub, server processes as a normal reference parameter.

Other Issues

- Client and server must also agree on other issues
  - Message format
  - Format of complex data structures
  - Transport protocol (TCP/IP or UDP?)

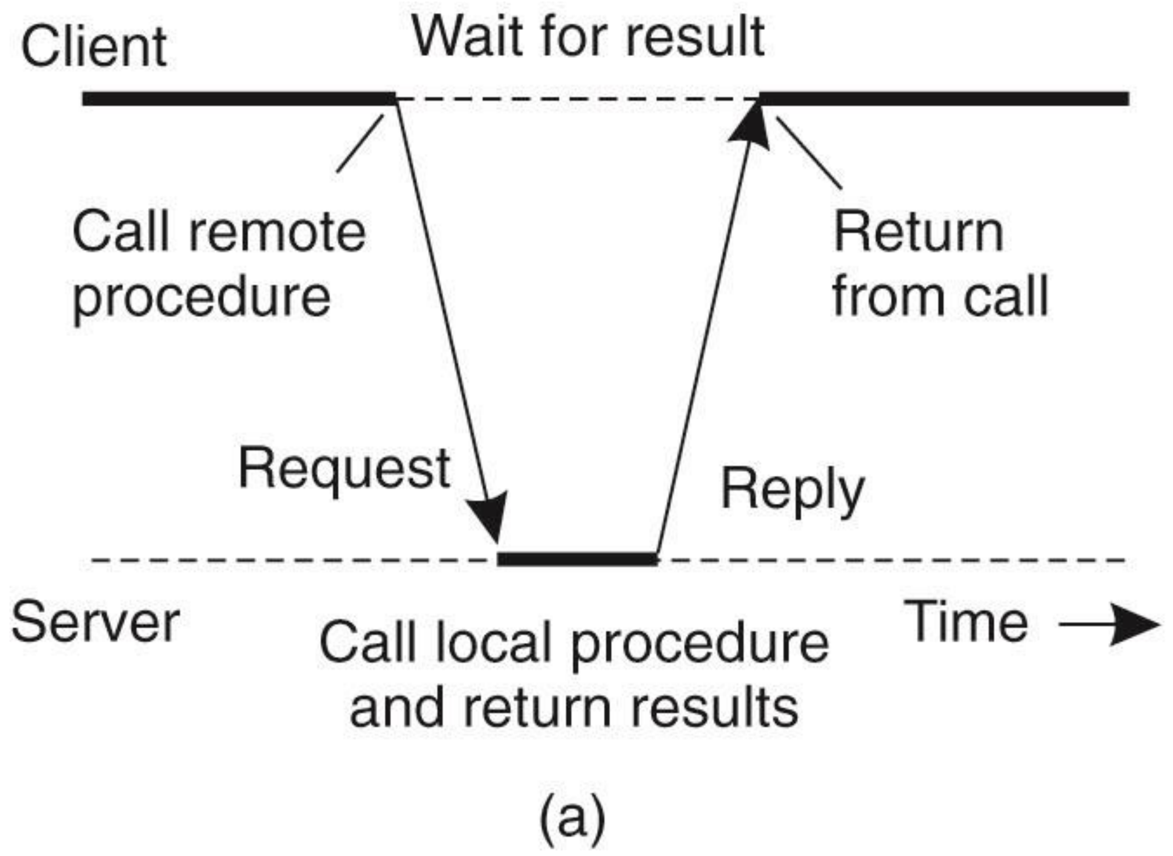
Reliable versus Unreliable RPC

- If RPC is built on a reliable transport protocol (e.g., TCP) it will behave more like a true procedure call.
- On the other hand, programmers may want a faster, connectionless protocol (e.g., UDP) or the client/server system may be on a LAN.
- How does this affect returned results?

Asynchronous RPC

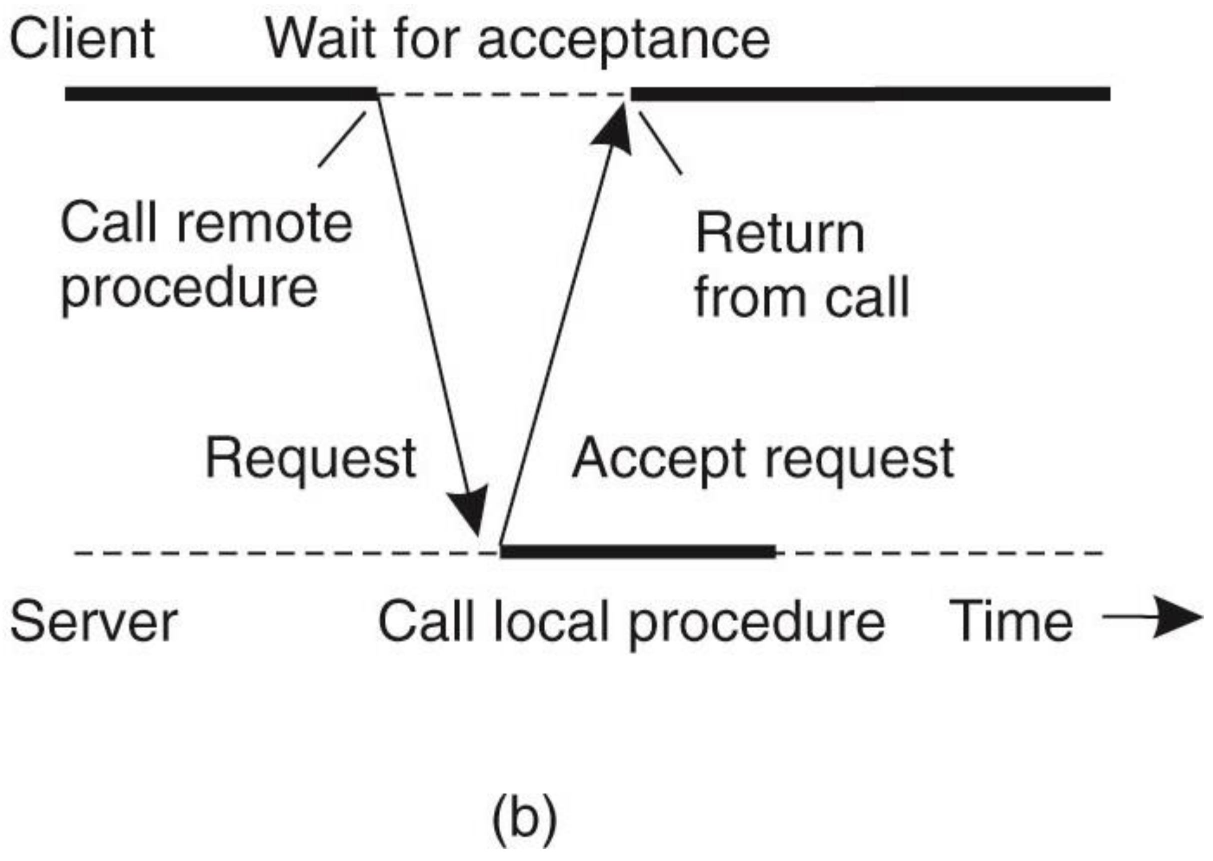
- Allow client to continue execution as soon as the RPC is issued and acknowledged, but before work is completed
  - Appropriate for requests that don’t need replies, such as a print request, file delete, etc.
  - Also may be used if client simply wants to continue doing something else until a reply is received (improves performance)
  - What are the problems with unreliable, asynchronous RPC?

Synchronous RPC



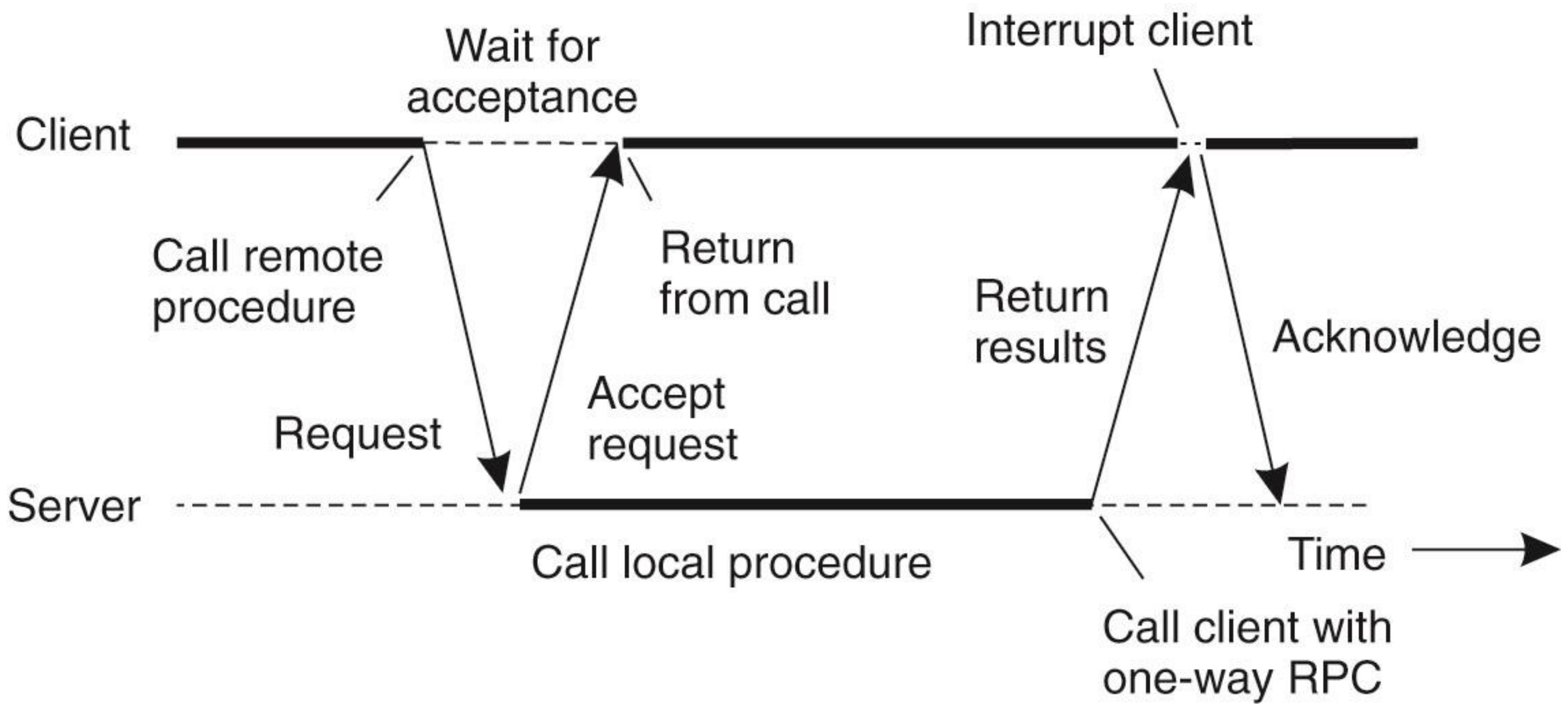
- Figure 4-10. (a) The interaction between client and server in a traditional RPC.

Asynchronous RPC



- Figure 4-10. (b) The interaction using asynchronous RPC.

Asynchronous RPC



- Figure 4-11. A client and server interacting through two asynchronous RPCs.

Synchronous or Asynchronous?

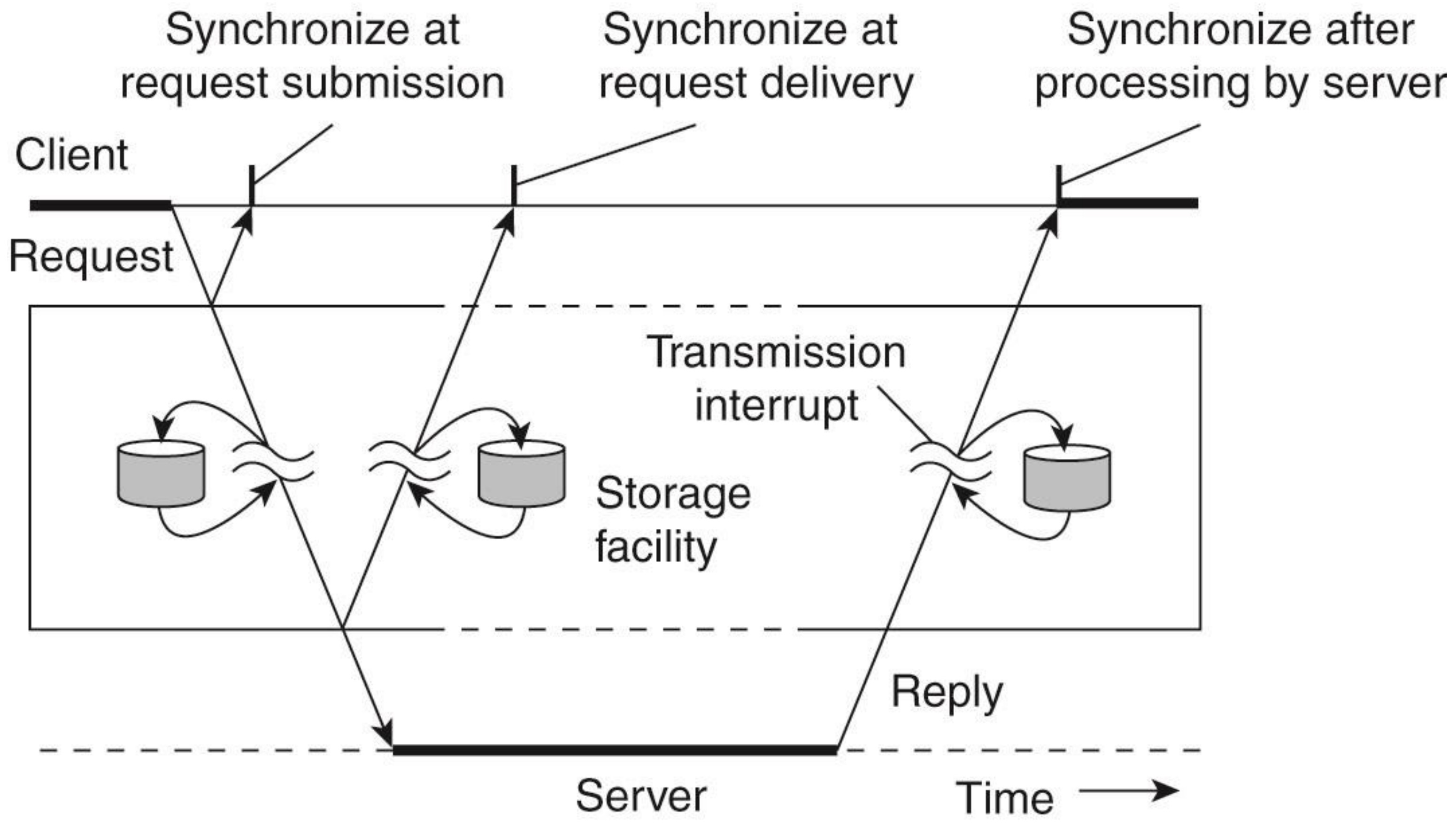

Synchronize at request submission
Synchronize at request delivery
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Figure 4-4. Viewing middleware as an intermediate (distributed) service in application-level communication.

Message Oriented Communication

- RPC support access transparency, but aren’t always appropriate
- Message-oriented communication is more flexible
- Built on transport layer protocols.

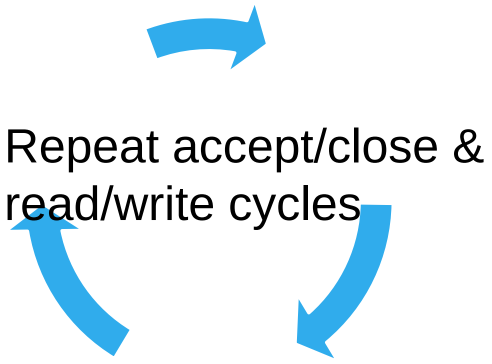
Sockets

- A communication endpoint used by applications to write and read to/from the network.
- Sockets provide a basic set of primitive operations
- Sockets are an abstraction of the actual communication endpoint used by local OS
- Socket address: IP# + port#

Primitive	**Meaning**
Socket	Create new communication end point
Bind	Attach a local address to a socket
Listen	Willing to accept *connections* (non-blocking)
Accept	Block caller until connection request arrives
Connect	Actively attempt to establish a connection
Send	Send some data over the connection
Receive	Receive some data over the connection
Close	Release the connection

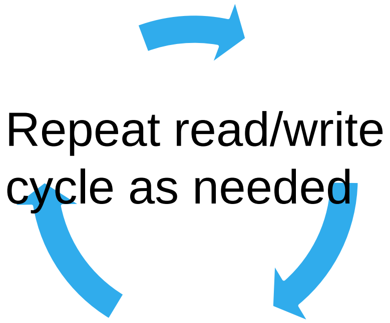
How a Server Uses Sockets

System Calls	Meaning
• Socket	• Create socket descriptor
• Bind	• Bind local IP address/ port # to the socket
• Listen	• Place in passive mode, set up request queue
• Accept	• Get the next message
• Read	• Read data from the network
• Write	• Write data to the network
• Close	• Terminate connection



How a Client Uses Sockets

System Calls	Meaning
• Socket	• Create socket descriptor
• Connect	• Connect to a remote server
• Write	• Write data to the network
• Read	• Read data from the network
• Close	• Terminate connection



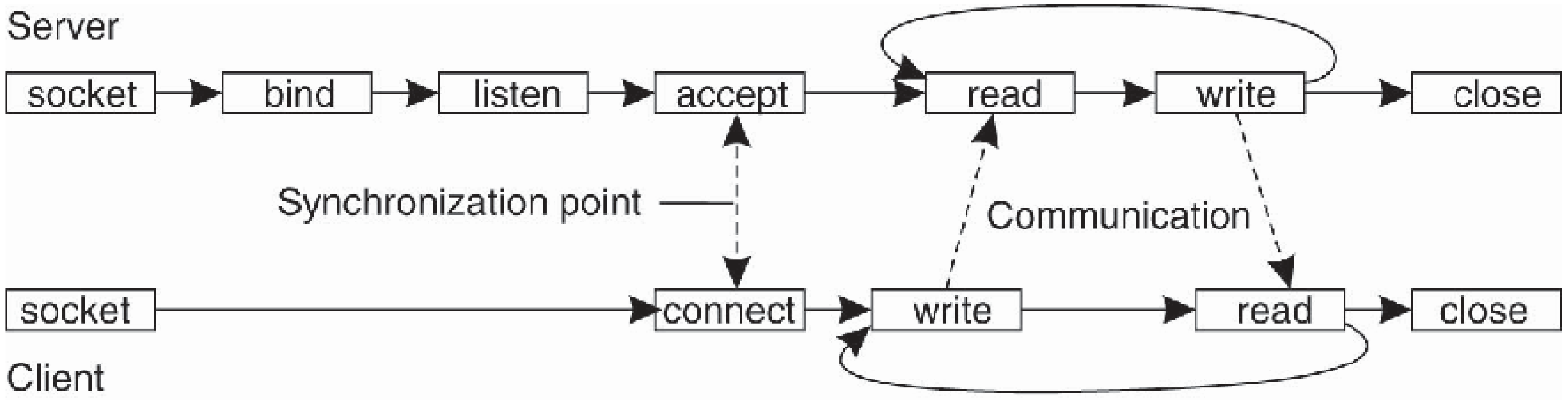


Figure 4-15. Connection-oriented communication pattern using sockets.

Socket Communication

- Using sockets, clients and servers can set up a connection-oriented communication session.
- Servers execute first four primitives (socket, bind, listen, accept) while clients execute socket and connect primitives)
- Then the processing is client/write, server/read, server/write, client/read, all close connection.

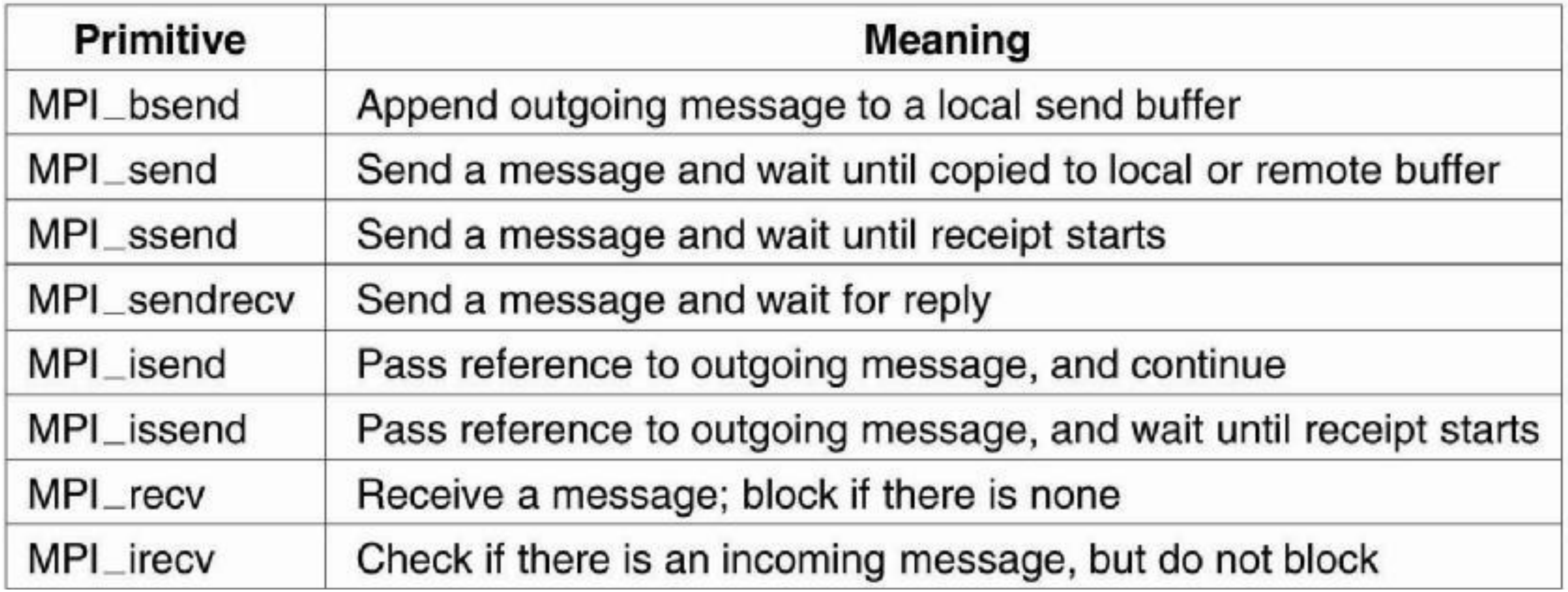
Message-Passing Interface (MPI)

- Sockets provide a low-level (send, receive) interface to wide-area (TCP/IP-based) networks
- Distributed systems that run on high-speed networks in high-performance cluster systems need more advanced protocols
- A need to be hardware/platform independent eventually led to the development of the MPI standard for message passing.

MPI

- Designed for parallel applications using transient communication
- Assumes communication is among a group of processes that know about each other
- Assign groupID to group, processID to each process in a group
- (groupID, processID) serves as an address

Message Primitives



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

Message-Oriented Persistent Communication

- Processes communicate through message queues
  - sender appends to queue, receiver removes from queue
- MPI and sockets support transient communication, message queuing allows messages to be stored temporarily (minutes versus milliseconds).
  - Neither the sender nor receiver needs to be on-line when the message is transmitted.
- Designed for messages that take minutes to transmit.

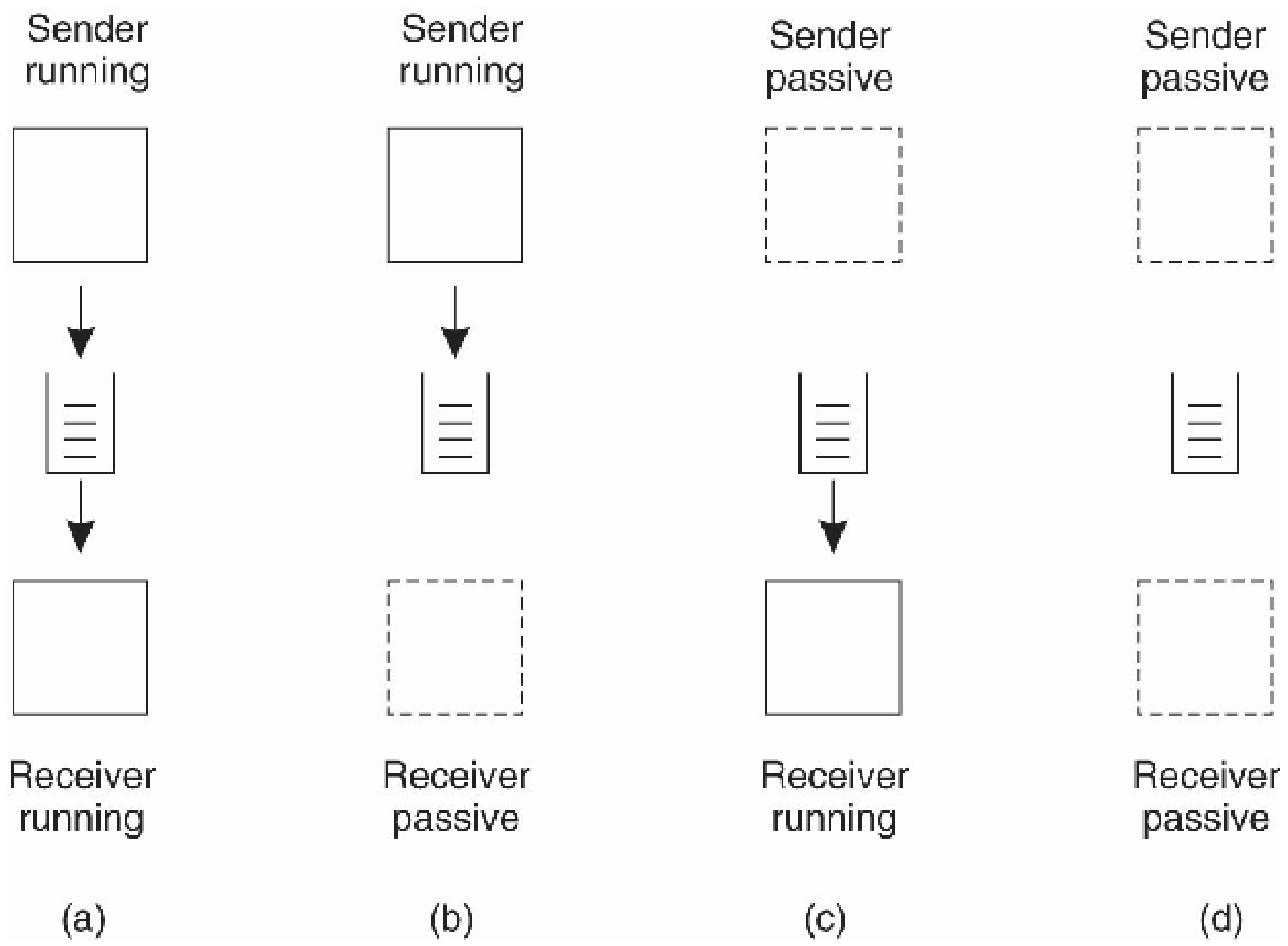
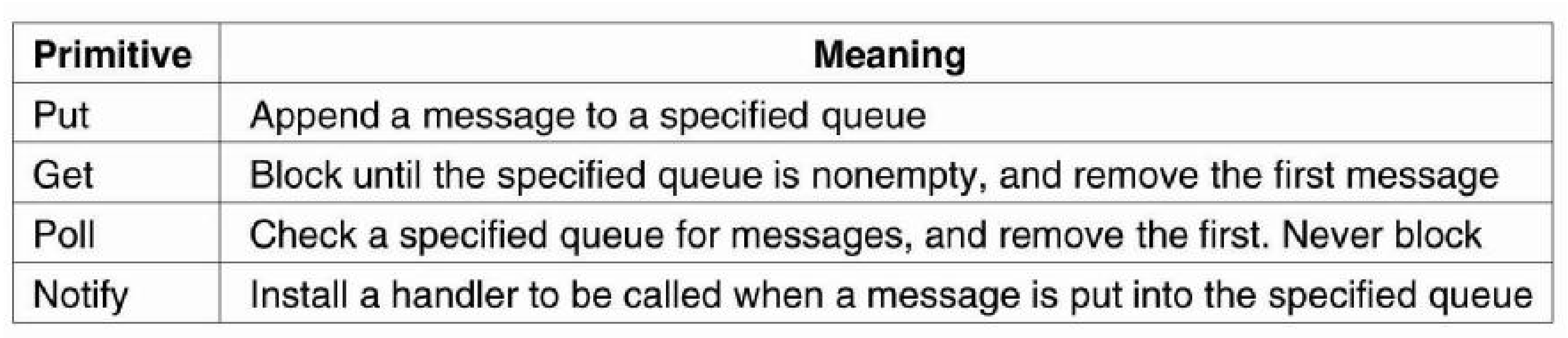


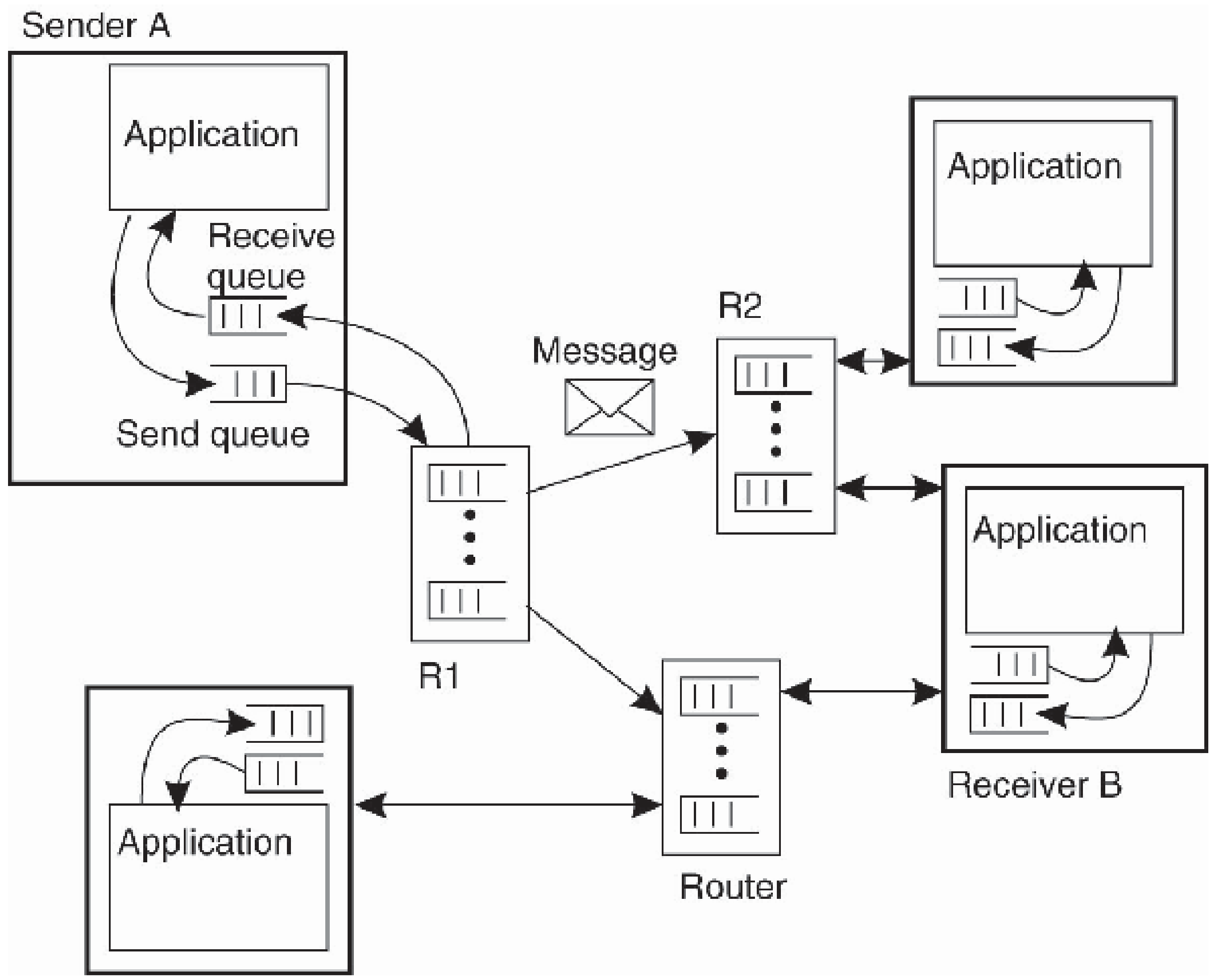
Figure 4-17. Four combinations for loosely-coupled communications using queues.

Message-Queuing Model

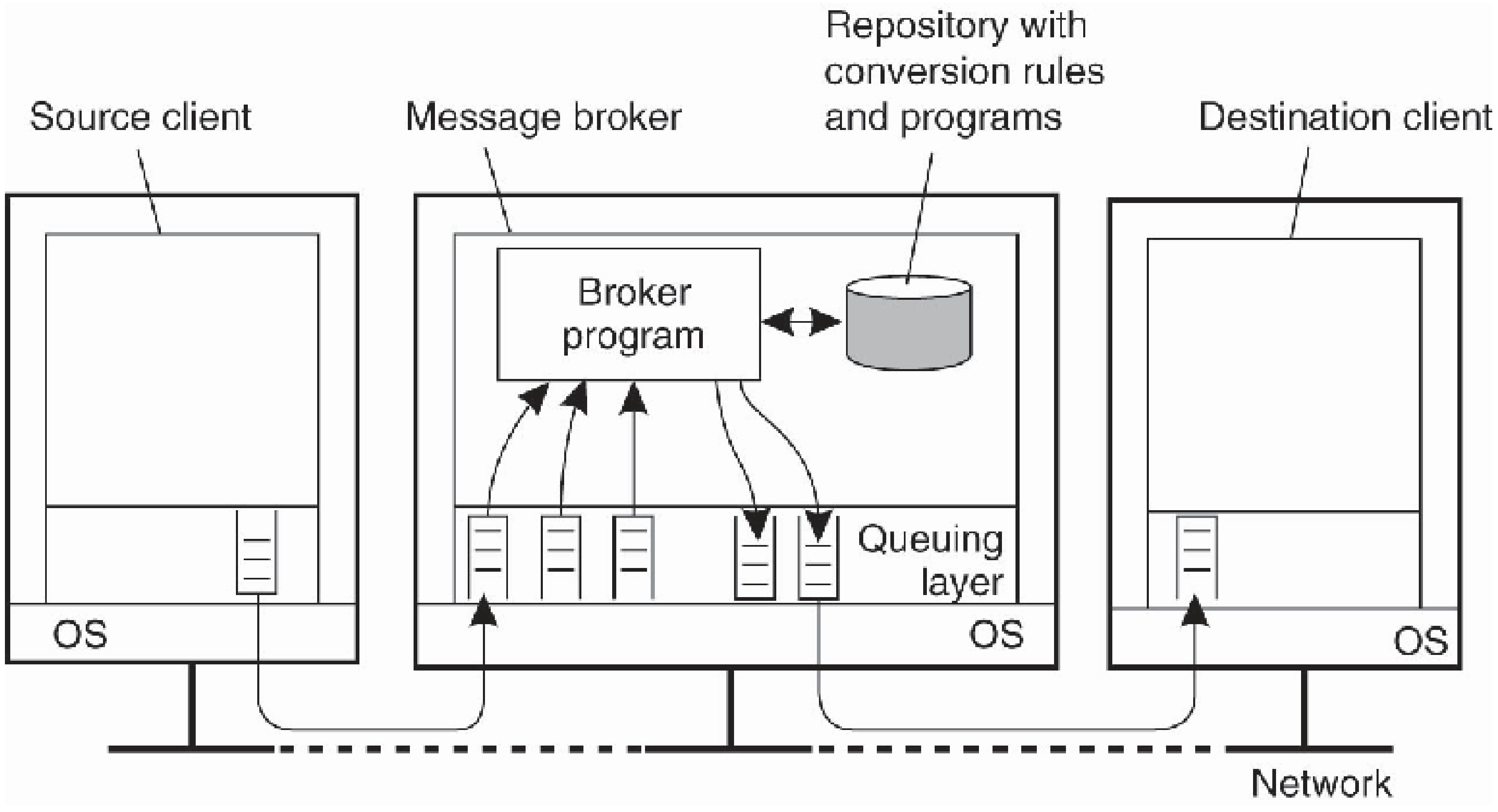


Primitive	Meaning
Put	Append a message to a specified queue
Get	Block until the specified queue is nonempty, and remove the first message
Poll	Check a specified queue for messages, and remove the first. Never block
Notify	Install a handler to be called when a message is put into the specified queue

General Architecture of a Message-Queuing System



Message Brokers



Stream-Oriented Communication

- RPC, RMI, message-oriented communication are based on the exchange of **discrete** messages
  - Timing might affect performance, but not correctness

- In stream-oriented communication the message content must be delivered at a **certain rate**, as well as correctly.
  - e.g., music or video

Data Streams

- Data stream = sequence of data items
- Can apply to discrete, as well as continuous media
- Audio and video require continuous data streams between file and device.

- **Asynchronous transmission mode:** the order is important, and data is transmitted one after the other. (file trans.)
- **Synchronous transmission** mode transmits each data unit with a guaranteed upper limit to the delay for each unit. (sensors)
- **Isochronous transmission** mode have a maximum and minimum delay. (video & audio)
  - Not too slow, but not too fast either

- Simple streams have a single data sequence
- Complex streams have several substreams, which must be synchronized with each other; for example a movie with
  - One video stream
  - Two audio streams (for stereo)
  - One stream with subtitles

Streams and Quality of Service

1. The required bit rate at which data should be transported.
2. The maximum delay until a session has been set up (i.e., when an application can start sending data).
3. The maximum end-to-end delay (i.e., how long it will take until a data unit makes it to a recipient).
4. The maximum delay variance.
5. The maximum round-trip delay.

Data Stream

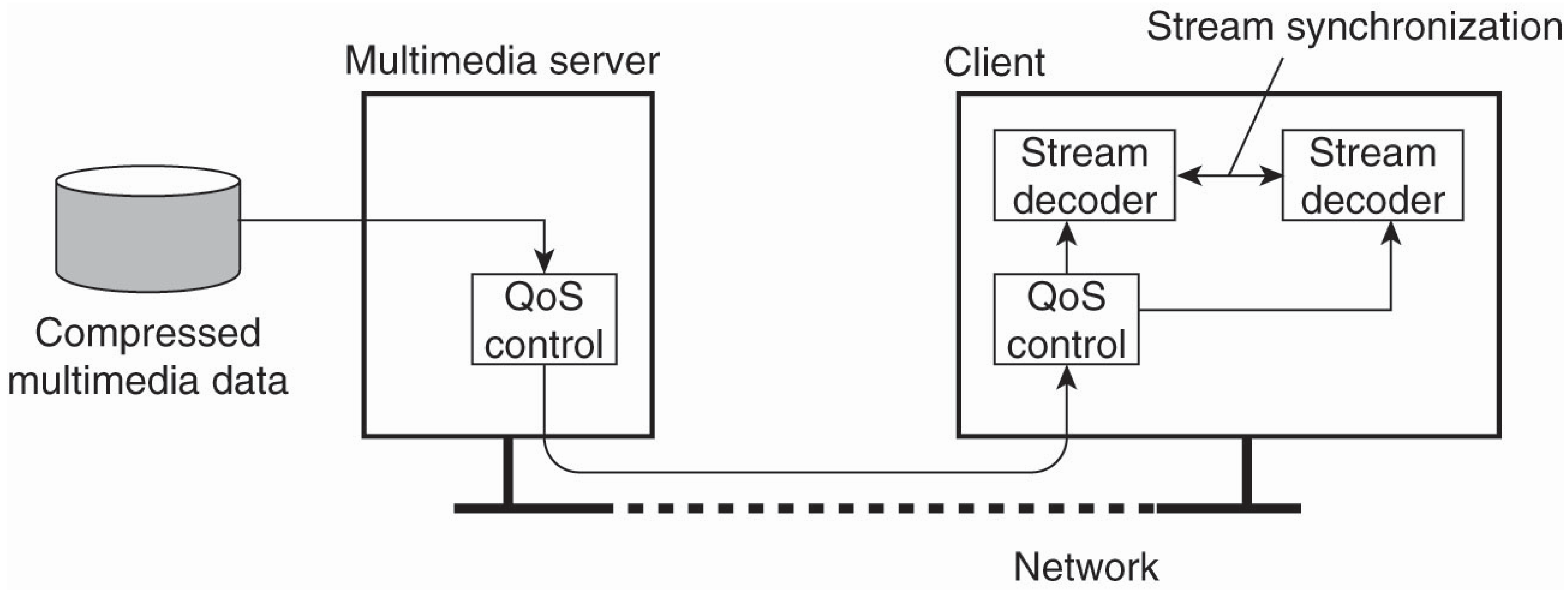


Figure 4-26. A general architecture for streaming stored multimedia data over a network.