Distributed Systems & Network Principles

Communication 1/2

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Introduction

- Previous lecture:
  - Shared memory allows multiple programs to communicate
- Today's lecture:
  - What if we don't have shared memory?
  - How to implement an alternative communication medium, like message channel?

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Outline

- Layered protocols
- Routing
- Socket
- Message passing interface (MPI)
- Message-oriented middleware (MOM)
- Stream-oriented communication

Layered Protocols

Communication problem

Communicating is about transmitting encoded information

› Problem: two computers must agree on the code (language) they use

› Open standards give rules for everyone to communicate with each other

- International Standards Organization (ISO)

  The Open Systems Interconnection (OSI) reference model names communication levels, and assigns roles to each level

- Internet Engineering Task Force (IETF)

  The Request For Comments (RFC) are a public description of internet communication protocols (e.g., TCP->RFC793, UDP->RFC768, SMTP->RFC2821, ICMP->RFC792)

› Private "closed" protocols exist

- Skype: people did reverse engineering to discover the protocol, find security issues, or to implement IM clients

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Two modes of communication

Connection oriented vs. Connectionless

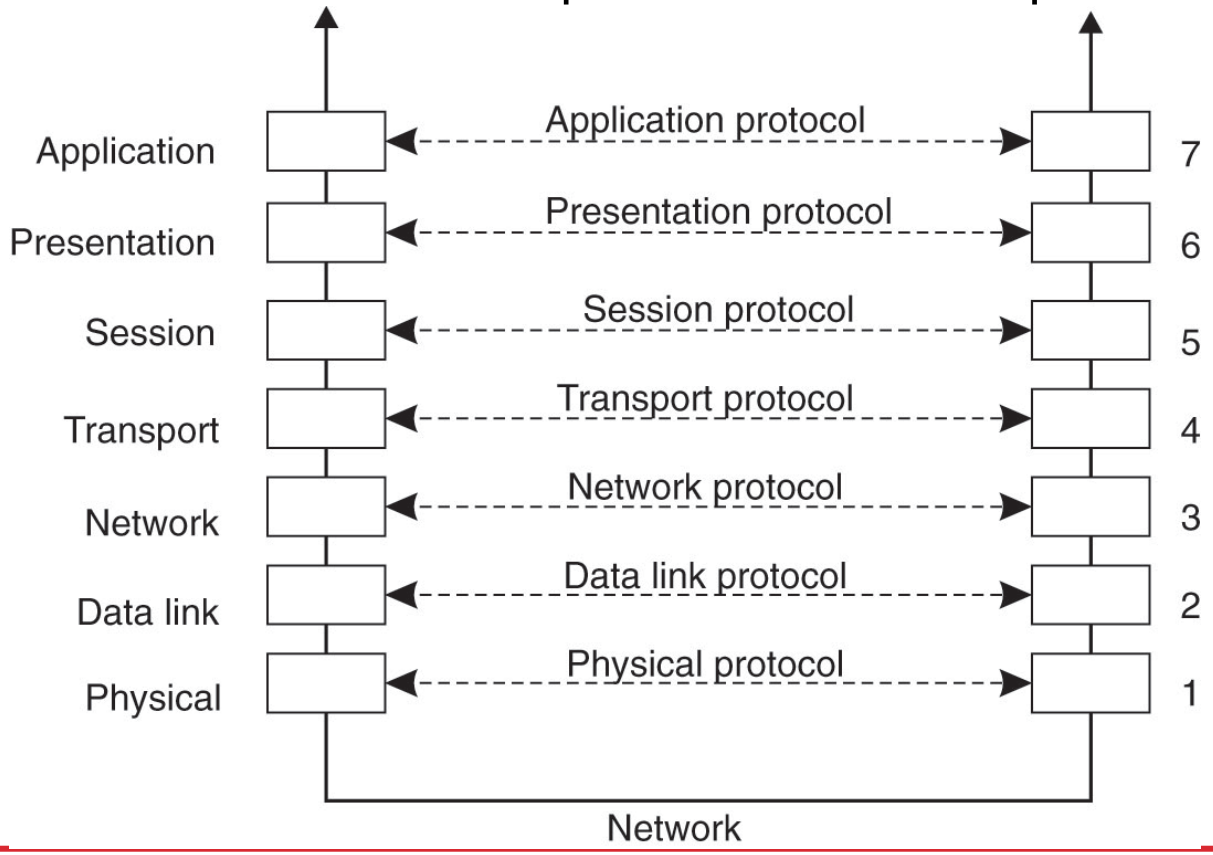
- Connection oriented
  - Establish explicitly a connection with a partner before exchanging data
  - Protocol example: Transmission Control Protocol (TCP)
  - Application usage: file transfer, web browsing, email

- Connectionless
  - No setup in advance is needed
  - Protocol example: User Datagram Packet (UDP, IP)
  - Application usage: VoIP (Skype), IPTV

Layers

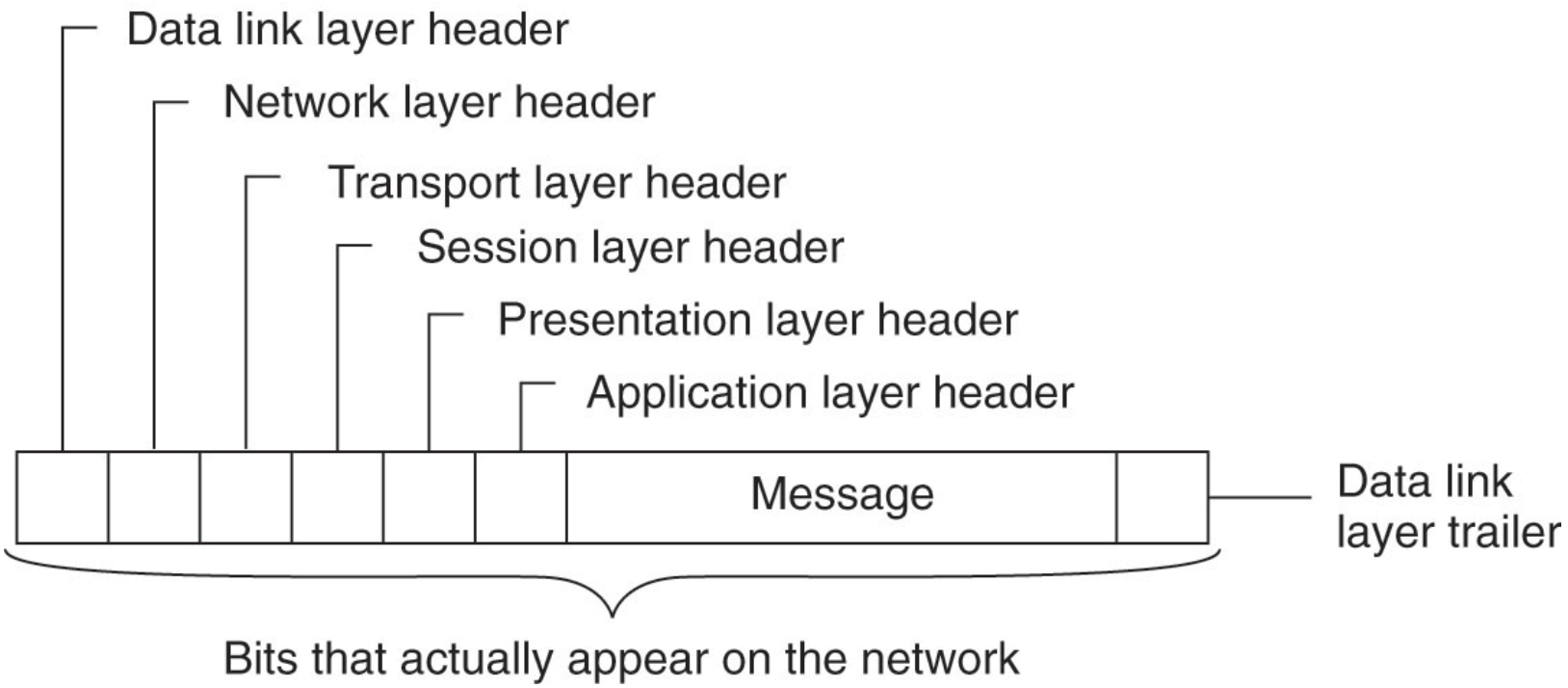
OSI layers

- Each layer deals with one specific aspect of the communication
- The problem is divided into sub-parts that can be implemented individually



Message structure

- As the message go through lower layers before being sent, each layer adds its header to the message.
- Upon reception, the message is unmarshalled by the successive layers from bottom to top



Network communication

Low-level layers

- Physical layer: send bits (0 and 1)

- Data link layer :
  - groups bits into frames
  - assigns sequence numbers to frames and adds special bit at the beginning and end
  - adds a checksum (the result of some operation on the frame content)
  - If receiver disagree about the checksum, then it asks the sender to resend
  - Example: Ethernet for *Local Area Network (LAN)* or PPTP in *Virtual private network (VPN*)

- Network layer
  - Example: *Internet Protocol* (IP) for *Wide Area Network* (WAN)

Network communication

Transport and higher level layers

- Transport layer:
  - split the message from the application layer
  - number them
  - add the amounts of sent and remaining packets

- Reliable transport layer can be built on top of:
  - Connection-oriented protocol: packet would be ordered
  - Connectionless protocol: packet could be reordered

- Example of transport layer protocol: Transmission Control Protocol (TCP)
- Example of transport layer and network layer combination: TCP/IP

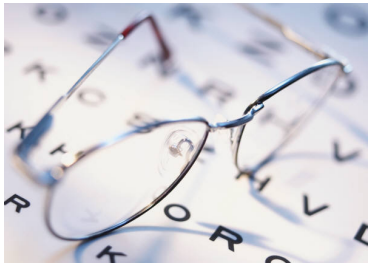
High level layers

- OSI specifies three higher level layers:
  - Session layer: dialog control, transfer check-pointing
  - Presentation layer: says how information is represented
  - Application
- Session
  - Example:
    - Domain Name Service (DNS)
    - Lightweight Directory Protocol (LDAP)
  - Sometimes the session layer is omitted: Internet protocol suite.
- Application
  - Hypertext Transfer Protocol (HTTP)
  - File Transfer Protocol (FTP)
  - TCP/IP Terminal Emulation Protocol (Telnet)
  - X-Window

Network communication

Analogy: Mail service vs. Web service

- Application (no clue of intermediary steps):
  - You post a letter with some address, the receiver reads it
  - HTTP: A user types a URL in a browser, a server sends back the web page
- Transport (error control):
  - Upon writing a wrong address on a letter, the letter will be sent back to you
  - TCP initialized a connection, checks for potential errors and may retransmit
- Internet (recipient is unknown):
  - An airplane moves letters between cities without knowing the recipients
  - IP brings packets over the WAN potentially from one LAN to another
- Data link:
  - Trucks move letters within a city
  - Ethernet handles transmission within the LAN
- Physical layer:
  - Use pen to write and glasses to read letters
  - Specifying fiber, wire, radio to transmit the one and zero encoding the message



IPv6

Internet Protocol version 6 (IPv6): new version of IP based on IPv4

- IPv6 packets are carried over Ethernet with the content type 86DD (hexadecimal) instead of IPv4's 0800.

End 2011, there were ~2.3x10^9 users

- Scalability in the number of addresses
  IPv6 increases the IP address size from 32 bits (4,294,967,296 in total) to 128 bits, to support more levels of addressing hierarchy, a much greater number of addressable nodes and simpler auto-configuration of addresses

- Scalability of multicast addresses is introduced
  A new type of address called an *anycast address* is also defined, to send a packet to any one of a group of nodes

- Efficient forwarding
  Changes in the way IP header options are encoded: Hop-by-Hop Option, Routing (Type 0), Fragment, Destination Option, Authentication, Encapsulation Payload

- Greater flexibility for additional options

Routing

Routing Problem

What are routing protocols used for?

- Related to path finding problem in graphs
- Graph nodes represent internet routers, edges are communication links
- Dijkstra thought about the shortest path algorithm in Amsterdam when trying to find his way [Frana&Misa, CACM'10]

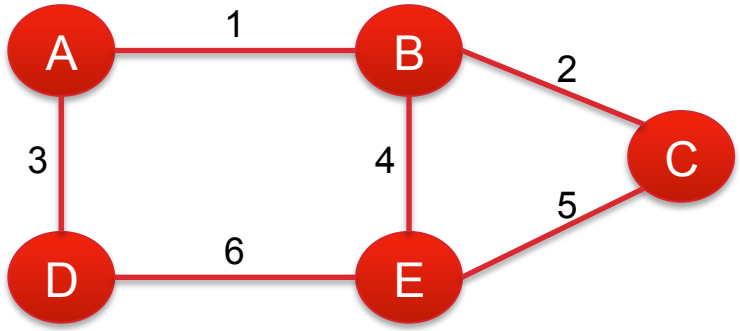
GPS clients use shortest path algorithms

- Two main classes of protocols/algorithms:
  1. Distance-vector: neighbours exchange their routing table
  2. Link-state: neighbours only exchange connectivity information
- Routing is necessary in all networks except *Local Area Networks (LANs)* where Ethernet provides direct communication between all pairs of attached hosts
- The routing protocol is implemented in the network layer of each router to determine the route for the transmission of packets to their destination
- In large networks, adaptive routing is employed: the best route for communication between two points in the network is re-evaluated periodically, taking into account the current traffic in the network

Distance-vector routing algorithm

Router Information Protocol (RIP)

- Mainly used in internet up to 1979
- Relies on Bellman-Ford algorithm: Bellman algorithm [1957] distributed by Ford and Fulkerson [1972]



Routing table of router A		
Dest.	**Dir**	**Cost**
A	local	0
B	1	1
C	1	2
D	3	1
E	1	2

- General idea: maintain a table representing the direction for each destination
  1. Every period t (=30sec) and whenever the local routing table T_L changes, send T_L to all accessible neighbours
  2. Upon reception of a table T_R with a new destination or a lower-cost route to an existing destination, update the local table T_L

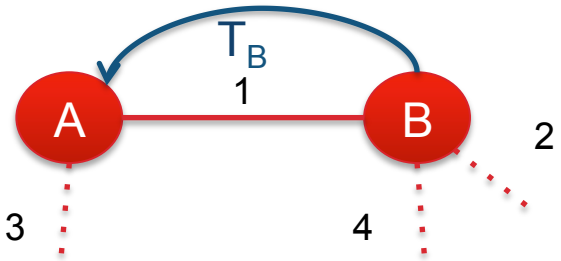
If a node detects a link failure, it sets ∞ as the associated cost of such a link and sends its local table to neighbours

Eventually (when failures stop) each router gets for each destination the direction leading to the minimal cost

Distance-vector routing algorithm

RIP (con't)

Example: A receives table T_B from B



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A	local	0
D	3	1

Received routing table T_R		
Dest.	**Dir**	**Cost**
A	1	1
B	local	0
C	2	1
D	1	2
E	4	1

Each router executes the same code:

1. Send: Each t seconds or when T_L changes, send T_L on each non-faulty outgoing link

2. Receive: Whenever a routing table T_R is received on link n:

```
for all rows R_R in T_R {
  if (R_R.dir ≠ n) {
    R_R.cost = R_R.cost + 1
    R_R.dir = n
    // add new destination to T_L
    if (R_R.dest is not in T_L) add R_R to T_L
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      if (R_R.dest = R_L.dest and
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      // R_R.cost < R_L.cost: remote node's better route
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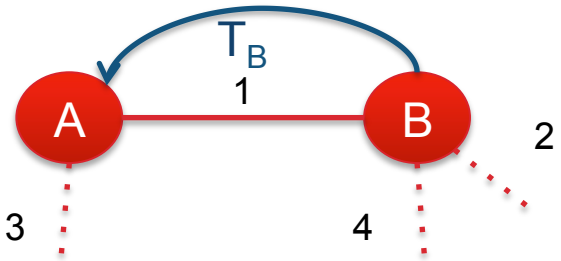

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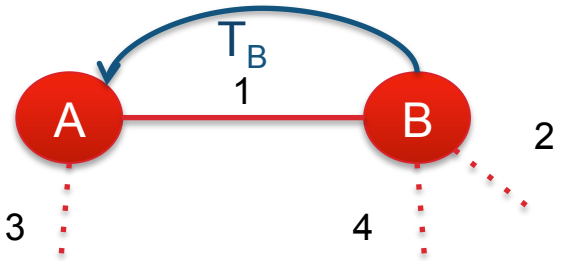

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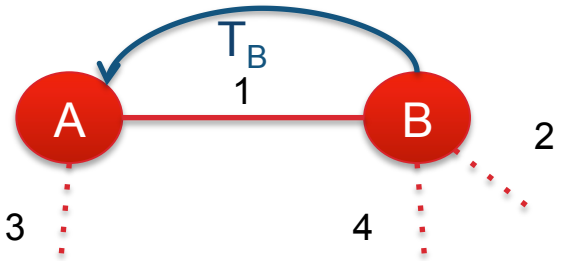

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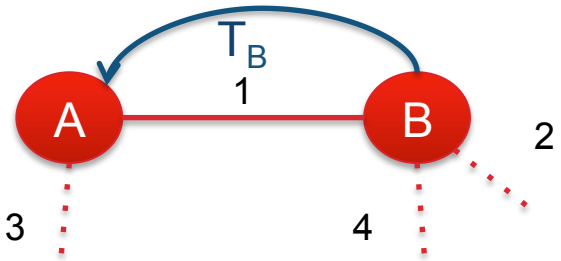

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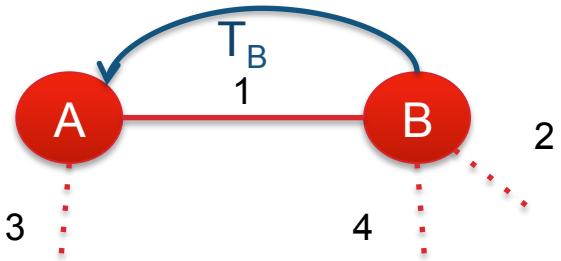

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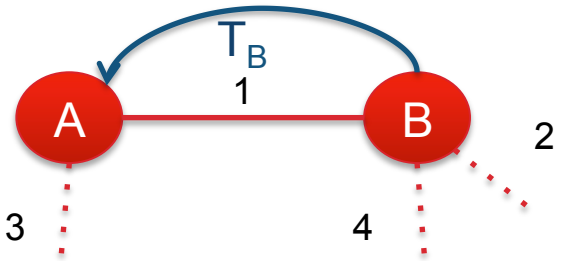

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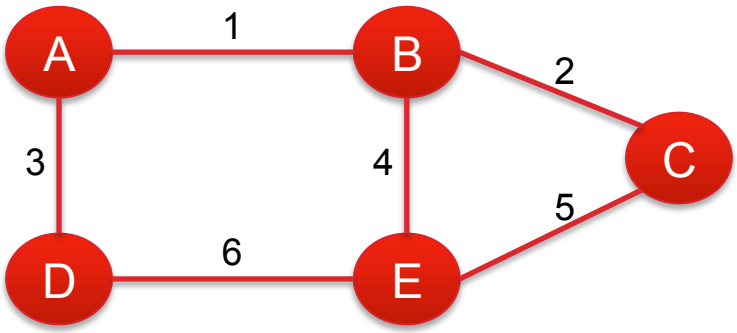
Distance-vector routing algorithm

RIP (con't)

Let's re-start the algorithm from scratch: all routing tables are empty



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A	local	0

Routing table of router B		
Dest.	**Dir**	**Cost**
B	local	0

Routing table of router C		
Dest.	**Dir**	**Cost**
C	local	0

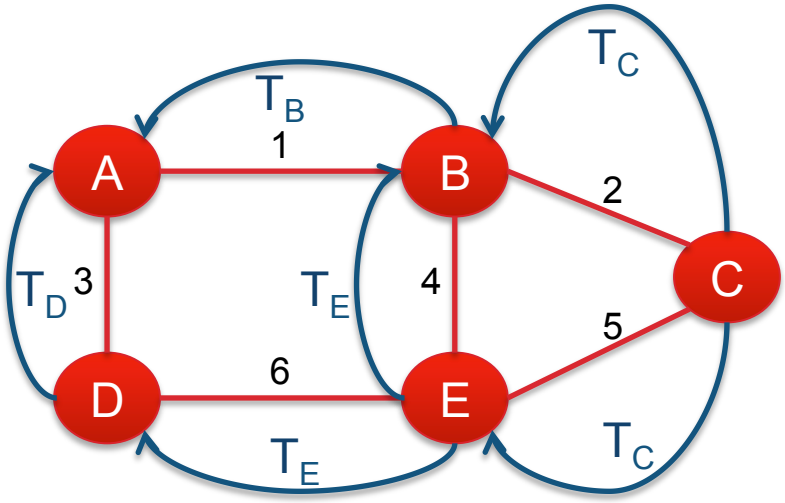
Routing table of router D		
Dest.	**Dir**	**Cost**
D	local	0

Routing table of router E		
Dest.	**Dir**	**Cost**
E	local	0

Distance-vector routing algorithm

RIP (con't)

› Example: How is routing table A built from scratch?



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Distance-vector routing algorithm

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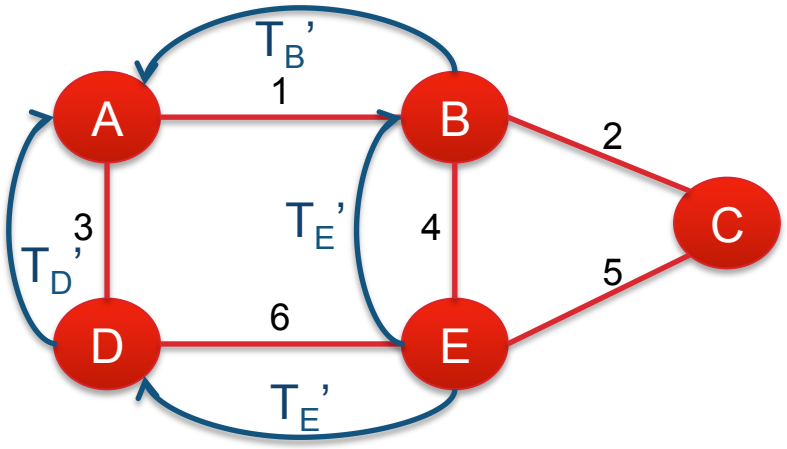

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Distance-vector routing algorithm

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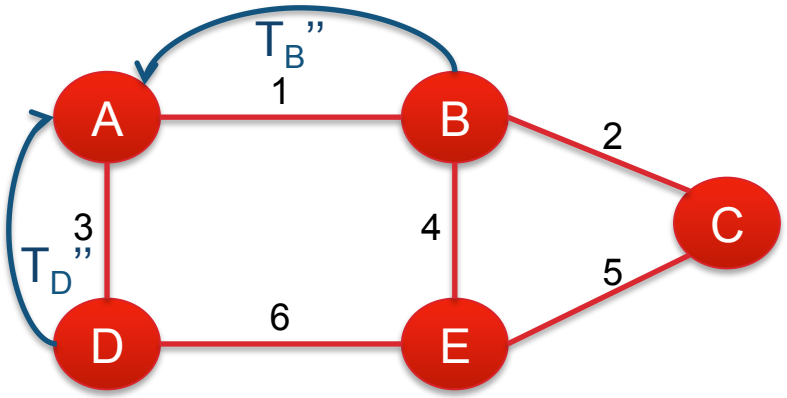

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Distance-vector routing algorithm

RIP (con't)

- Advantages:
  - Simple
  - Efficient in small networks

- Limitations:
  - Costs based on the number of hops is unrealistic (bandwidth of links counts)
  - No big deal: this is just a matter of defining link weights (support negative values)
  - Inefficient in large networks as loops may occur before the convergence state is reached

To address this inefficiency more scalable routing protocols, called linked state, were proposed

Link-state routing protocol

Dijkstra's Algorithm: find the shortest path from a node i to other nodes

- Edsger Dijkstra 1956
  - Assume that each link (from i to j) has an associated non-negative cost (Cij)
  - N, set of nodes
  - s, source node that starts the algo
  - V = {s}, set of visited nodes
  - Find the shortest distance Dj from s to every node j
- Used in IS-IS (IP) and OSPF protocols

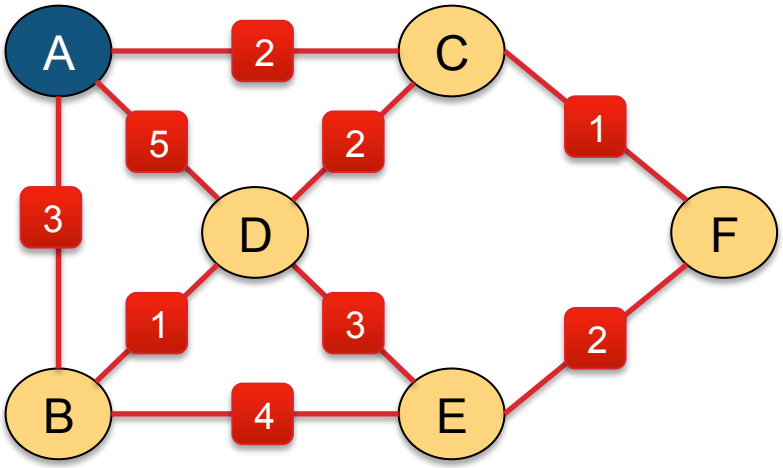
Init the routing table for node s:
  for all nodes in N:
    if j neighbor of s: Dj = Csj
    else Dj = ∞
    Ds = 0

Algo for routing table of node s:
while (V ≠ N) { *// while some nodes are unvisited*
  select node i such that
    Di = min{ Dj : j ∉ V} *// i, closer unvisited node*
  for all nodes j ∉ V: *// for all unvisited node j*
    if (Dj > Di + Cij) *// if cheaper through i*
      Dj = Di + Cij *// update the distance to j*
      Lj = i → j *// take link i to route to j*
  V = V U {i}
}

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



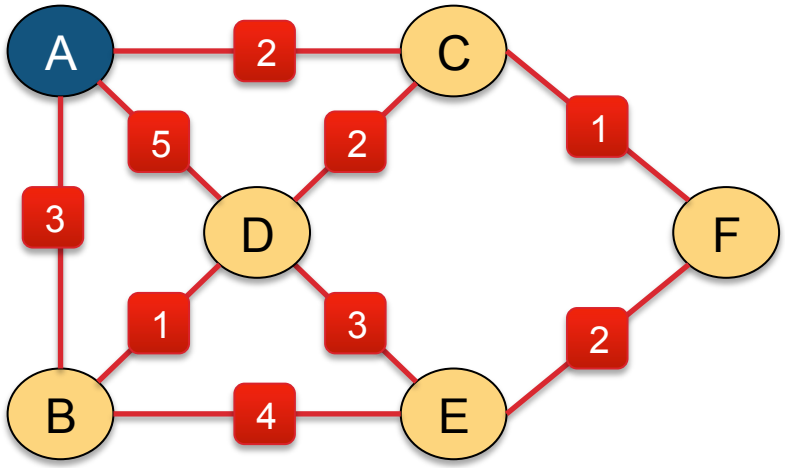
i = C

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	A→D	5
E	?	∞
F	?	∞

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



i = C

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	A→D	5
E	?	∞
F	?	∞

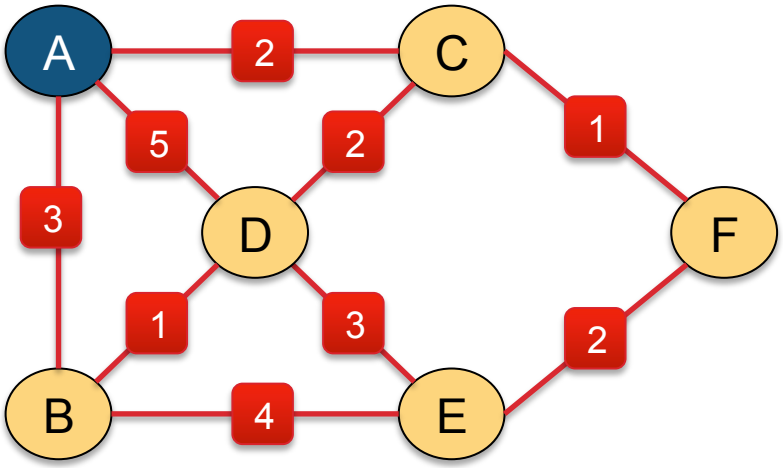
$D_D > D_C + C_{CD}$

$D_F > D_C + C_{CF}$

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



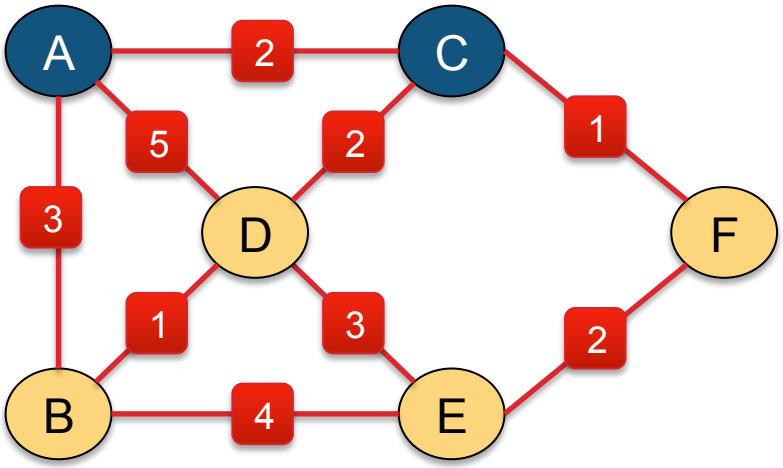
i = C

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	?	∞
F	C→F	3

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



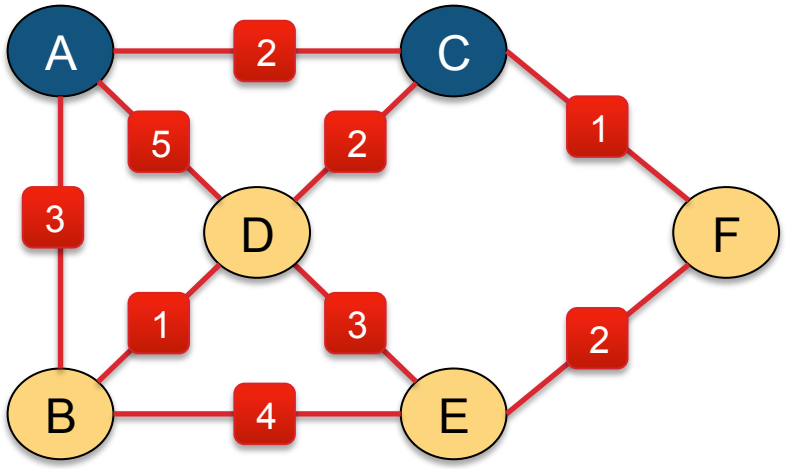
i = B

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	?	∞
F	C→F	3

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



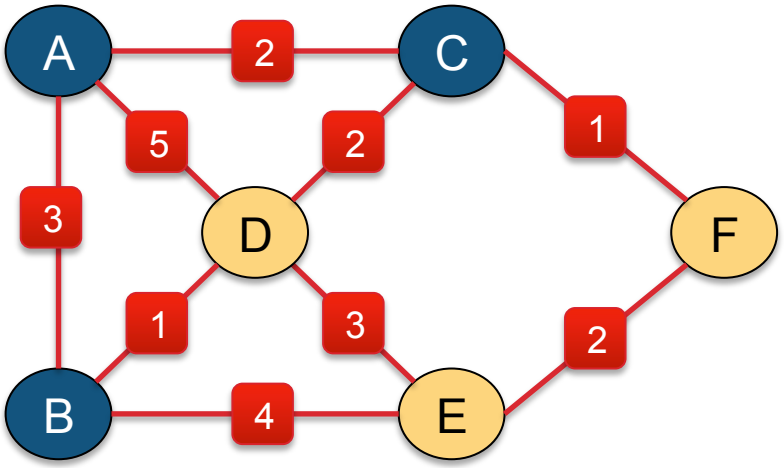
i = B

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	B→E	7
F	C→F	3

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



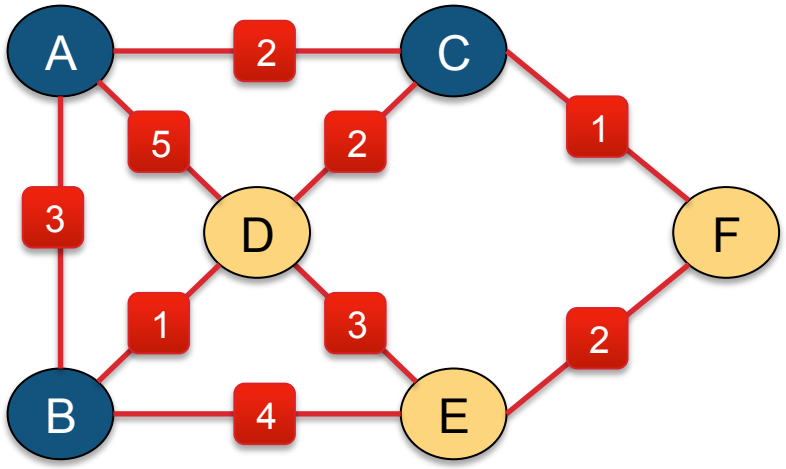
i = F

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	B→E	7
F	C→F	3

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



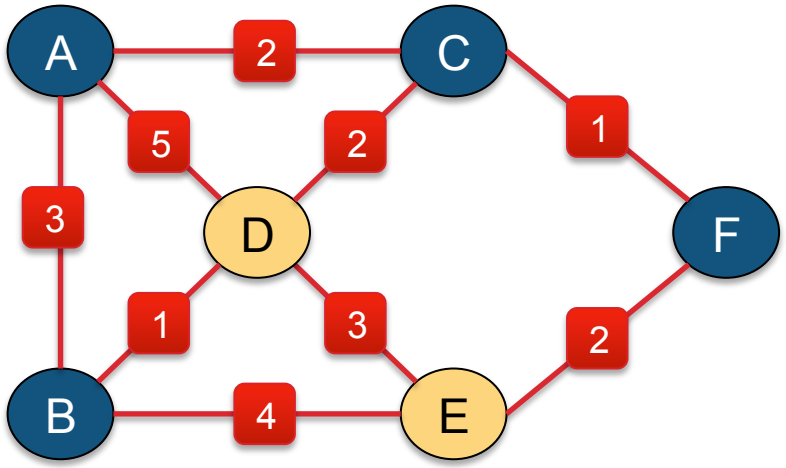
i = F

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	F→E	5
F	C→F	3

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



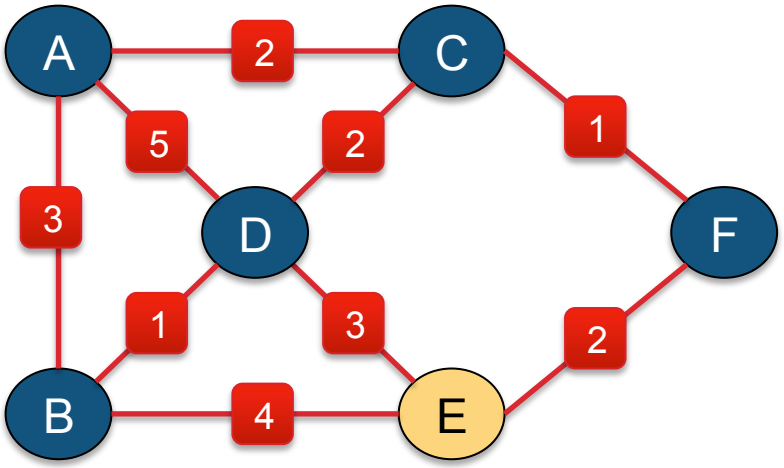
i = D

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	F→E	5
F	C→F	3

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



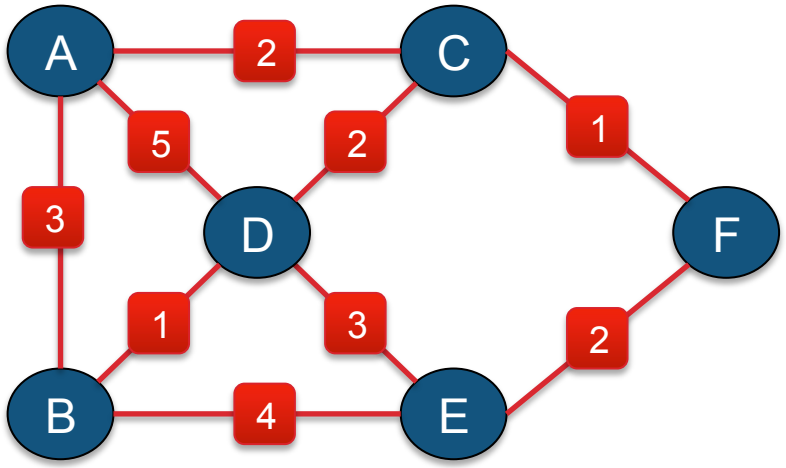
i = E

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	F→E	5
F	C→F	3

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



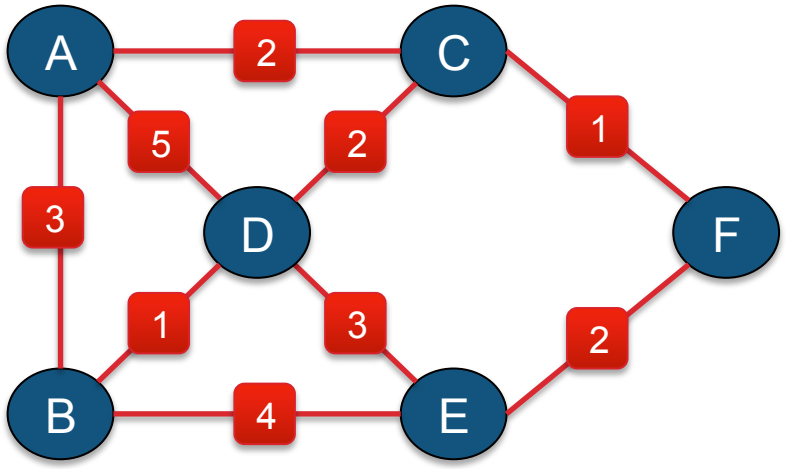
done

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	F→E	5
F	C→F	3

Link-state routing protocol

Dijkstra's Algorithm (con't)

› Example: routing table A



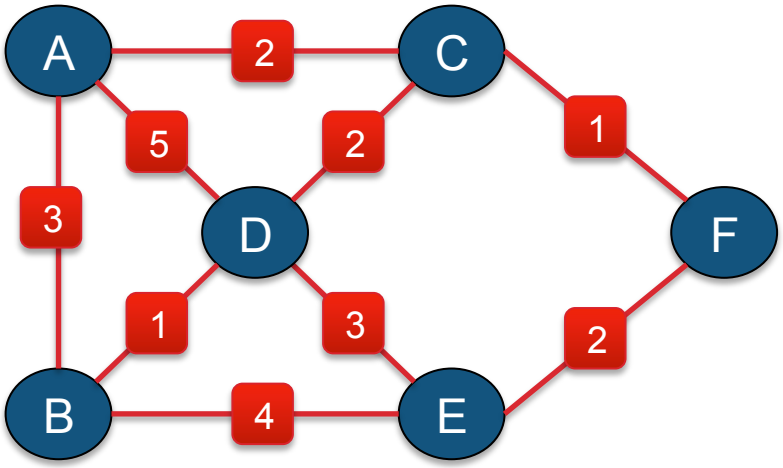
Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	F→E	5
F	C→F	3

› How to exploit such an inverted routing table?

Link-state routing protocol

How to route?

› Example: routing from A to E



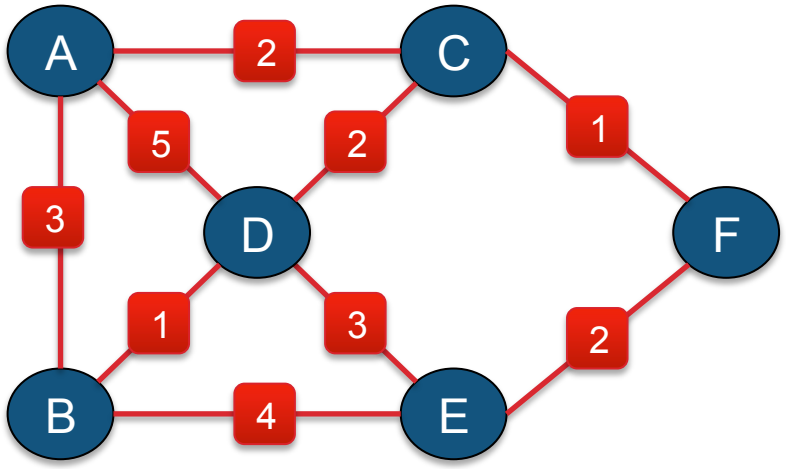
E

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	F→E	5
F	C→F	3

Link-state routing protocol

How to route?

› Example: routing from A to E



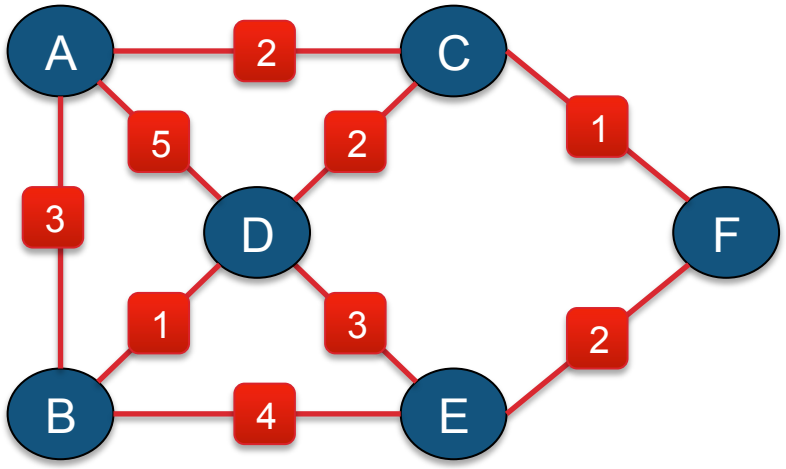
F→E

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	F→E	5
F	C→F	3

Link-state routing protocol

How to route?

› Example: routing from A to E



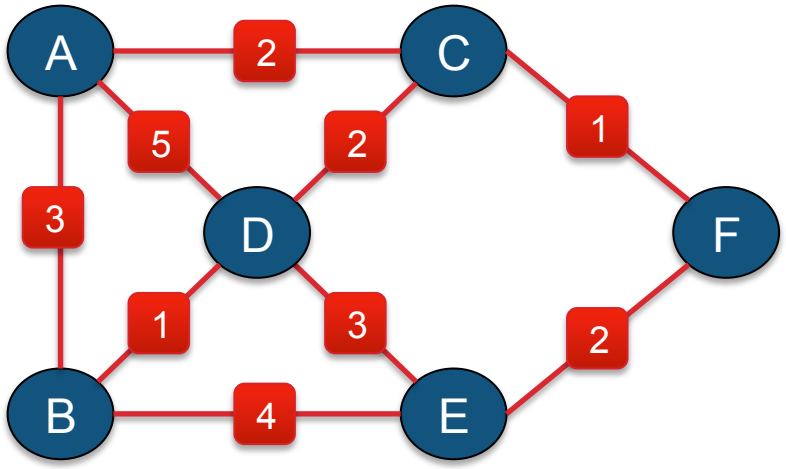
C→F→E

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	F→E	5
F	C→F	3

Link-state routing protocol

How to route?

› Example: routing from A to E



A→C→F→E

Routing table of router A		
Dest.	**L**	**D**
A	⌀	0
B	A→B	3
C	A→C	2
D	C→D	4
E	F→E	5
F	C→F	3

› A→C→F→E is the shortest path from A to E

Socket

Socket

Definition

- *Socket*: a communication end-point to which an application can write data that is to be sent out over the underlying network, and from which incoming data can be read

- A pair of processes communicating over a network employ a pair of sockets, one for each process

- A socket is identified by an IP address concatenated with a port number.

- In general, sockets uses the client-server model:
  - The server waits for incoming client requests by listening to a specified port
  - Once the a request is received, the server accepts a connection from the client socket to complete the connection

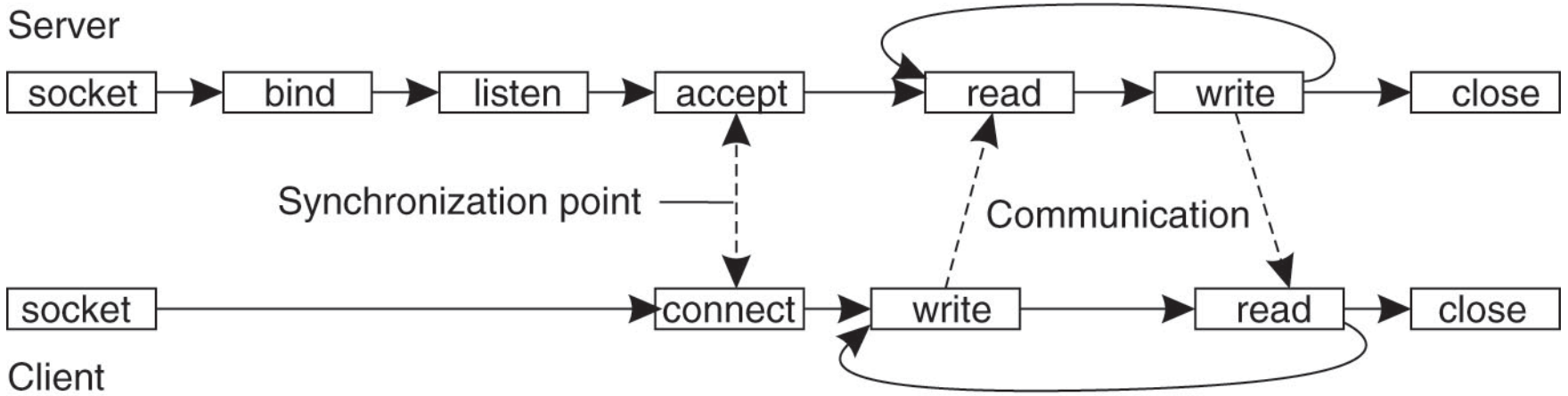
Berkley Sockets: Socket interface as proposed in Berkley UNIX in the 70's

1. Servers generally execute the first 4 primitives and block on accept
2. Bind associated the newly created socket to a local address and a port; the client binds implicitly to any available port
3. The client connects to a specified address which blocks until response
4. Once the connection is accepted by the server, the system creates a new socket with the same properties as the original one; the client and server can communicate with send and receive.

Primitive	Meaning
Socket	Create a new communication end point
Bind	Attach a local address to a socket
Listen	Announce willingness to accept connections
Accept	Block caller until a 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

Berkley Sockets: Socket interface as proposed in Berkley UNIX in the 70's

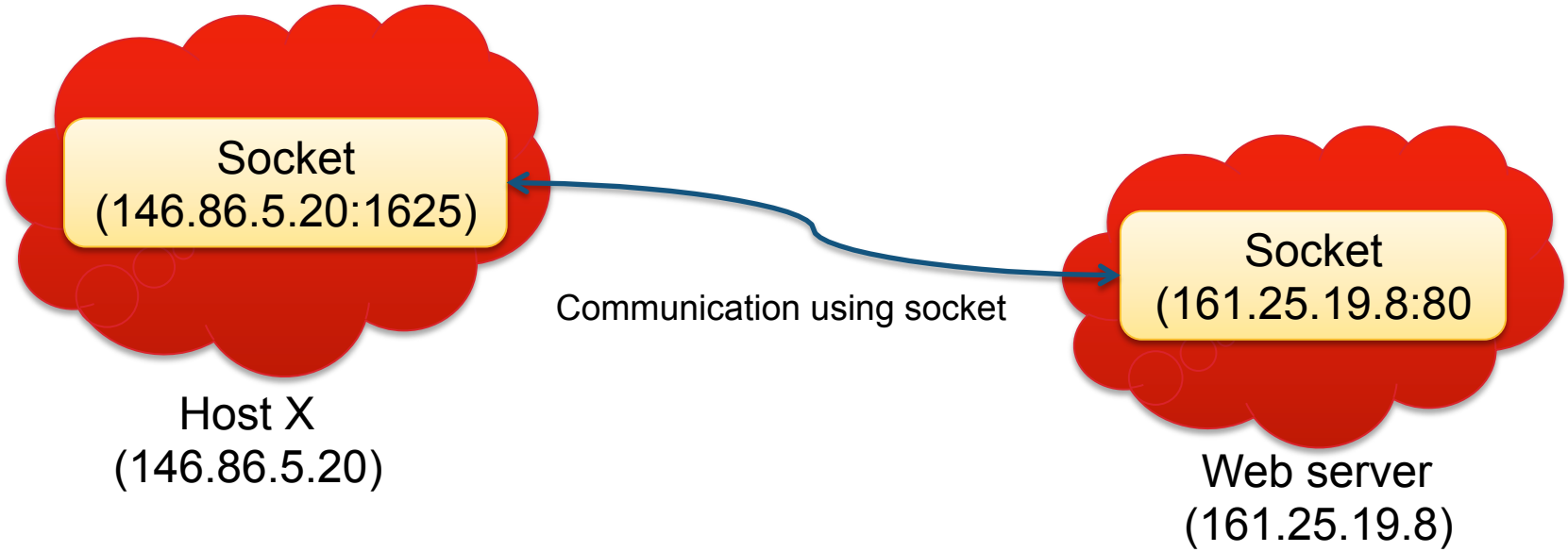
1. Servers generally execute the first 4 primitives and block on accept
2. Bind associated the newly created socket to a local address and a port; the client binds implicitly to any available port
3. The client connects to a specified address which blocks until response
4. Once the connection is accepted by the server, the system creates a new socket with the same properties as the original one; the client and server can communicate with send and receive.



Socket

Port

- Port numbers <1024 are for specific service protocols
  e.g., 80:HTTP, SSH:22, FTP:21, SMTP:25
- A client initiating a connection is assigned a free port number (>1024) by its host



Java Sockets

- Three socket classes:
  - DatagramSocket: Connectionless (UDP) socket, to open a lightweight communication favoring throughput rather than reliability
  - MulticastSocket: Multicast socket (subclass of DatagramSocket) to send data to multiple recipients
  - Socket: Connection-oriented (TCP) socket, to open a connection for reliable communication

Java TCP Sockets

```
public class Server {

   public static void main(String[] args) {
     try {
      // Create a socket on port 6013
      ServerSocket sock = new ServerSocket(6013);
      while (true) {
        Socket client = sock.accept();
        … // communicate with the client
        client.close(); // close socket
      }
     } catch (Exception e) {
        System.err.println("I/O problem");
     }
   }
}
```

```
public class Client {

  public static void main(String[] args) {
    try {
       // Specify server address and port for socket
       Socket sock = new Socket("127.0.0.1", 6013);


       … // communicate with the server
       sock.close(); // close socket

    } catch (Exception e) {
       System.err.println("server? or I/O problem");
    }
  }
}
```

Message-Passing Interface (MPI)

MPI vs. Sockets

- Sockets
  - Limited set of primitives, providing only send and receive for communication
  - Exploits general purpose communication layered protocols (e.g., TCP/IP, UDP)
  - For example, TCP/IP aims at being tolerant to message losses

- MPI
  - Hardware and platform independent
  - Direct use of underlying network (no multiple layers)
  - Assume no failures, communication involves a group of processors

Some of the MPI communication primitives:

- Blocking synchronous send (MPI_ssend) and asynchronous send (MPI_bsend)
- RPC-like mechanism (MPI_sendrecv)
- Pointers passed as a parameter to MPI_isend and MPI_issend, MPI takes care of communication
- Blocking recv (MPI_recv) and non-blocking one (MPI_irecv)
- Variety of communication primitives allows for optimizations but makes it more complex

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

MPI is used in high-performance parallel applications

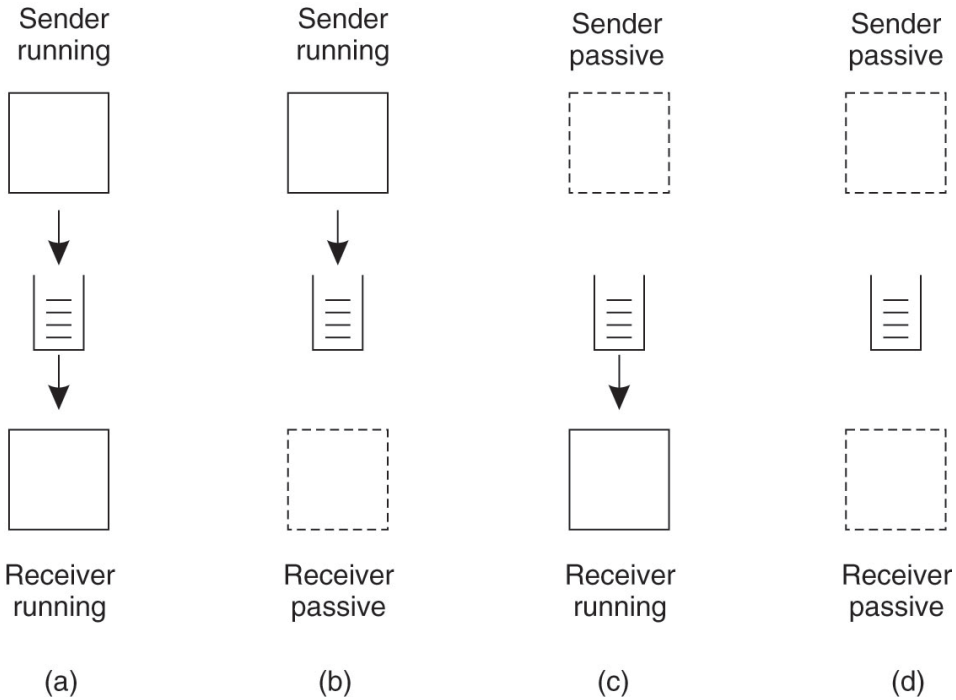
Message-Oriented Middleware (MOM)

MOM

- Characteristics:
  - Do not require sender and receiver to be active during communication
  - Offering intermediate storage capacity for messages
  - Typically target long (> minutes) message transfers

- Principles:
  - Each application maintains its local queue
  - And sends messages to other application queues
  - Unaware of the reading of its messages (recipient can be down at sending time)

Scenarios



- (a) Both sender and receiver execute during the entire transmission of a message
- (b) Only the sender is executing while the receiver is passive
- (c) The sender is passive while the receiver is active
- (d) The system is storing message (and potentially sending to intermediate servers) while sender and receiver are passive

Interface

- The sender uses put to enqueue a message in a non-blocking way
- The get primitive returns the longest pending message of the queue or may be tuned to return the highest priority message (in a priority queue)
- poll is the non-blocking variant of the get
- Callbacks can be used to automatically fetch new messages from the receiver side via notify

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

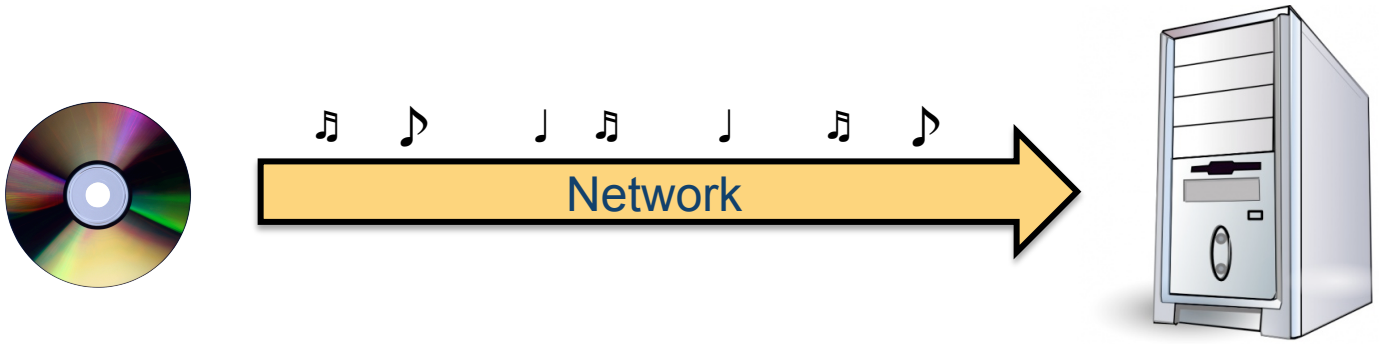
Stream-Oriented Communication

Stream-oriented communication

When timing is crucial

› Previous communication modes do not guarantee transmission rate

› In stream-oriented communication, the stream should not be interrupted, i.e., messages should kept being received at regular (typically small) time intervals



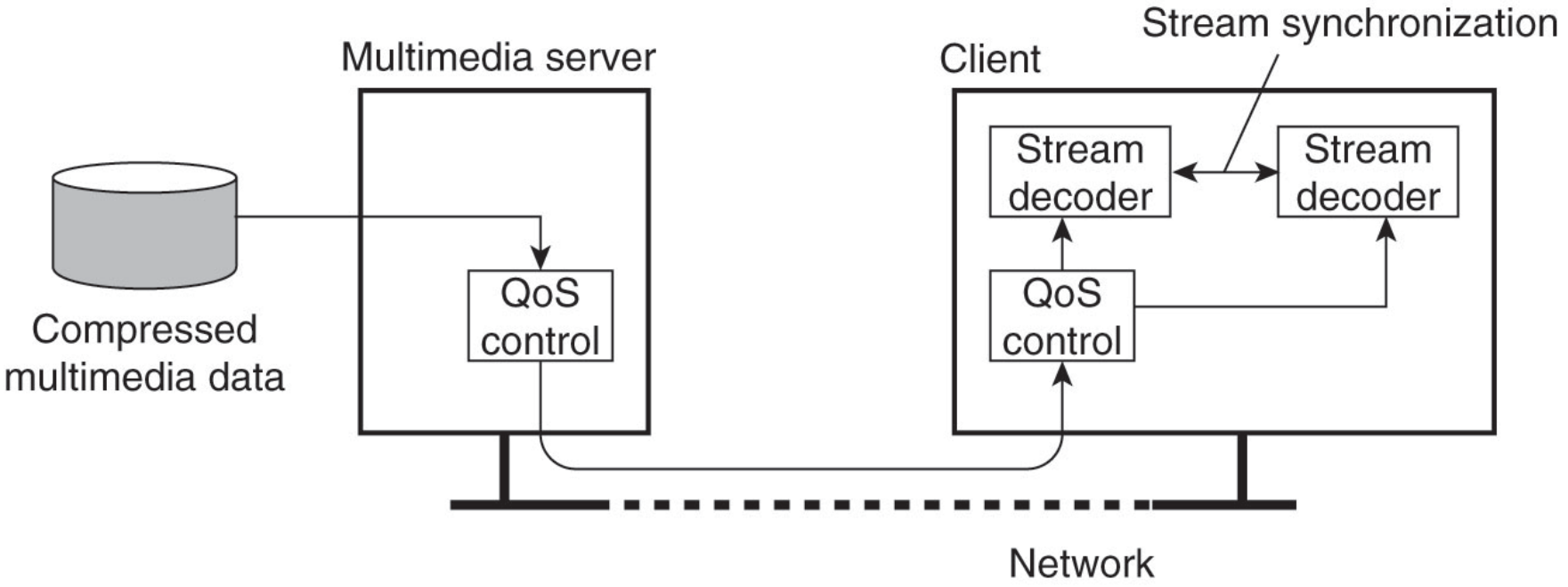
› Example: an *audio stream* in CD quality w/ sound wave at 44,100Hz

- Destination starts reading before the entire information has been transmitted
- Each piece of data should be read in order at fixed rate: every 1/44,100 seconds.

Stream-oriented communication

Supporting streams in a distributed system

› Example: architecture for streaming stored multimedia data over a network



› The streaming of live data leaves less opportunity for tuning the stream

Stream-oriented communication

Quality of Service (QoS)

› Requirements to ensure that the temporal relationships in a stream can be preserved:

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

Stream-oriented communication

Best effort protocols do not guarantee delivery of QoS

› Problem: how to stream over internet?

- Internet Protocol (IP) is best effort, it drops packet
- IP rarely implements QoS

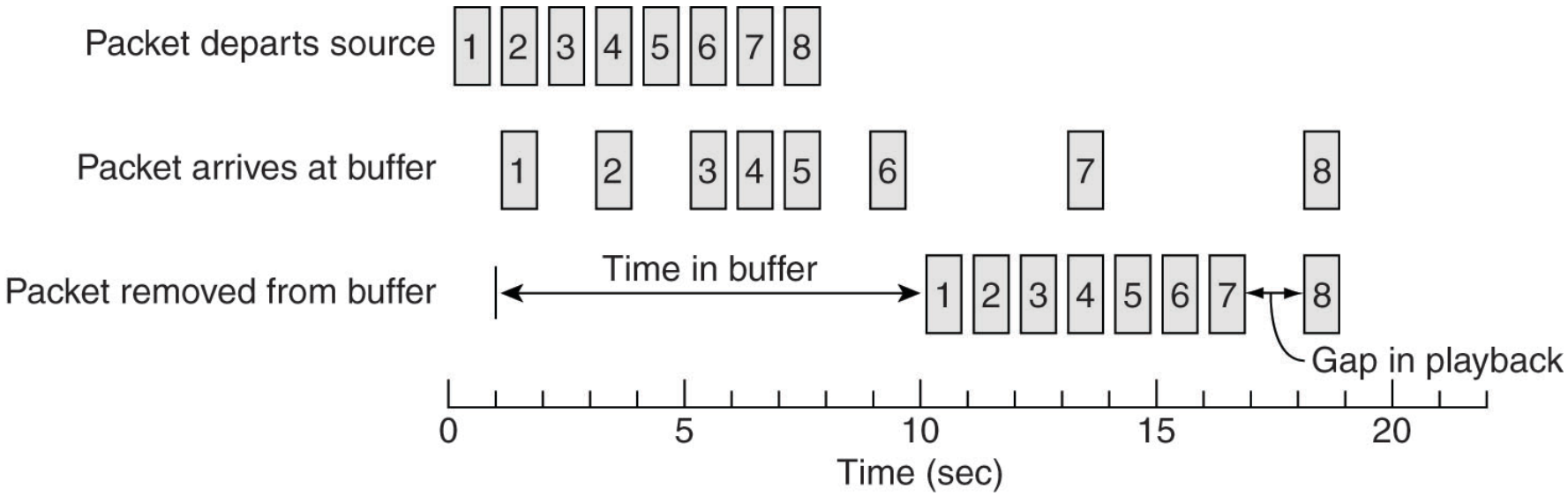
› But packets can be marked as belonging to one of several classes

- Expedited forwarding class: packet should be forwarded with absolute priority
- Assured forwarding class: defines a range of priority on packets to be dropped

Stream-oriented communication

Buffer to cope with variable delays

- Use a buffer to store several data in advance at the receiver
- If packets are delayed with a certain variance but the average rate is sustainable
- The receiver can pass packets to the application at regular time intervals

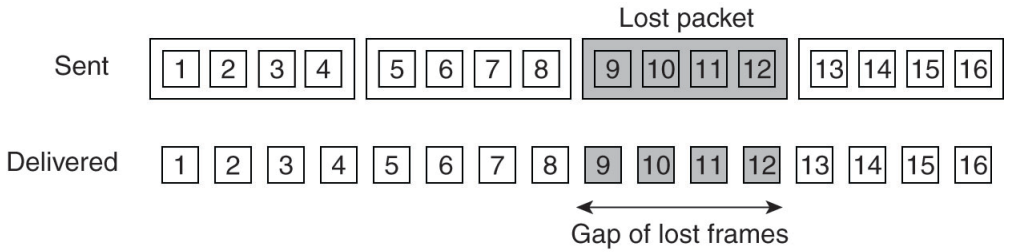


- The size of the receiver buffer is 9 seconds of packets to pass, unfortunately packet #8 took 11 seconds to reach the receiver at which time the buffer was empty.

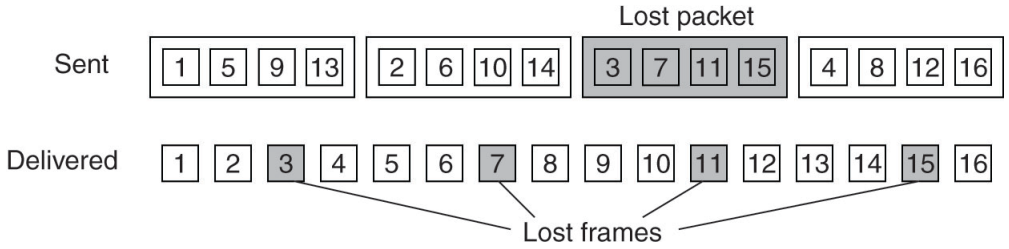
Stream-oriented communication

Error correction and interleaving to cope with message losses

- With best effort protocols, packets can be dropped
- TCP/IP retransmit drops packets, yet this is too heavy for streaming application
- Forward error correction: k out of n packets are enough to reconstruct k packets
- Interleaving circumvents dropped packet to contain multiple consecutive audio and video frame



(a)



(b)

- The effect of packet loss in (a) non-interleaved transmission and (b) interleaved transmission

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Conclusion

- Network protocols are divided into layers
- IPv6 is necessary for the Internet Protocol scalability

- Routing protocols are
  - simple but not scalable (distance-vector) or
  - more complex but scalable (link-state)

- There are various ways of communicating depending on the needs:
  - General-purpose communication (Socket)
  - High performance parallel communication (MPI)
  - Very long message transmission (MOM)
  - Timely constrained communication (Streaming communication)