Syllabus

Module III (10 Hours) Syllabus

Network Layer Protocols: Virtual circuits and datagrams, Principles of routing, internet protocol Ipv4 CIDR Routing algorithms: Link-state and distance vector routing, Routing on the internet RIP OSPF and BGP, Multicast routing. Introduction to IPV6 and software defined networks, Open flow

- Behrouz A Forouzan, Firouz Mosharraf, “Computer Networks: A top down Approach”, McGraw Hill Education, 1 st Edition (2011).
- James F Kurose and Keith W Ross, “Computer Networking: A Top - Down Approach”, Pearson Education; 6 th Edition (2017)

Network Layer

- Network layer provides host-to-host communication service.
- Unlike the transport and application layers, there is a piece of the network layer in each and every host and router in the network.
- Two important functions of the network layer are forwarding and routing.
- Forwarding involves the transfer of a packet from an incoming link to an outgoing link within a single router.
- Routing involves all of a network's routers, whose collective interactions via routing protocols determine the paths that packets take on their trips from source to destination node.

Network Layer

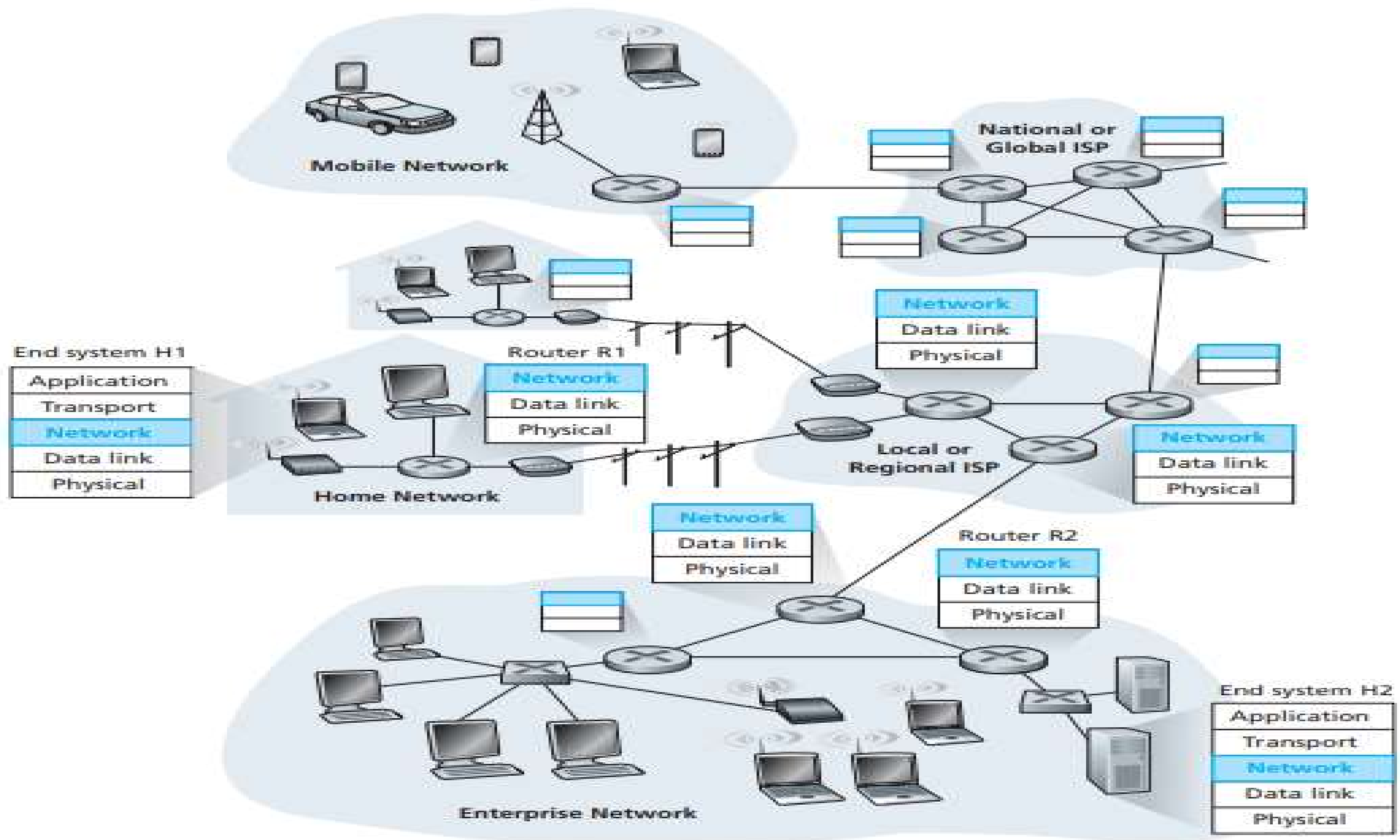


Figure 4.1 ◆ The network layer

James F Kurose and Keith W Ross, "Computer Networking: A Top - Down Approach", Pearson Education; 6 th Edition (2017)

Network Layer

- Figure shows a simple network with two hosts, H1 and H2, and several routers on the path between H1 and H2.
- Suppose that H1 is sending information to H2.
- The network layer in H1 takes segments from the transport layer in H1, encapsulates each segment into a datagram (that is, a network-layer packet), and then sends the datagrams to its nearby router, R1.
- At the receiving host, H2, the network layer receives the datagrams from its nearby router R2, extracts the transport-layer segments, and delivers the segments up to the transport layer at H2.
- The primary role of the routers is to forward datagrams from input links to output links.
- The routers are shown with a truncated protocol stack, that is, with no upper layers above the network layer, because (except for control purposes) routers do not run application and transport-layer protocols.

Network Layer Functions : Forwarding and Routing

- The role of the network layer is to move packets from a sending host to a receiving host.
- To do so, two important network-layer functions can be identified:
- **Forwarding**: When a packet arrives at a router's input link, the router must move the packet to the appropriate output link. For example, a packet arriving from Host H1 to Router R1 must be forwarded to the next router on a path to H2.
- **Routing** : The network layer must determine the route or path taken by packets as they flow from a sender to a receiver.
- The algorithms that calculate these paths are referred to as routing algorithms.
- A routing algorithm would determine the path along which packets flow from H1 to H2.

Forwarding and Routing

- **Forwarding** involves the transfer of a packet from an incoming link to an outgoing link within a single router.
- When a packet arrives at a router's input link, the router must move the packet to the appropriate output link.

- **Routing** involves all of a network's routers, whose collective interactions via routing protocols determine the paths that packets take on their trips from source to destination node.
- The network layer must determine the route or path taken by packets as they flow from a sender to a receiver.
- The algorithms that calculate these paths are referred to as routing algorithms.

Forwarding and Routing

- Every router has a forwarding table.
- A router forwards a packet by examining the value of a field in the arriving packet's header, and then using this header value to index into the router's forwarding table.
- The value stored in the forwarding table entry for that header indicates the router's outgoing link interface to which that packet is to be forwarded.
- Depending on the network-layer protocol, the header value could be the destination address of the packet or an indication of the connection to which the packet belongs.

Forwarding and Routing

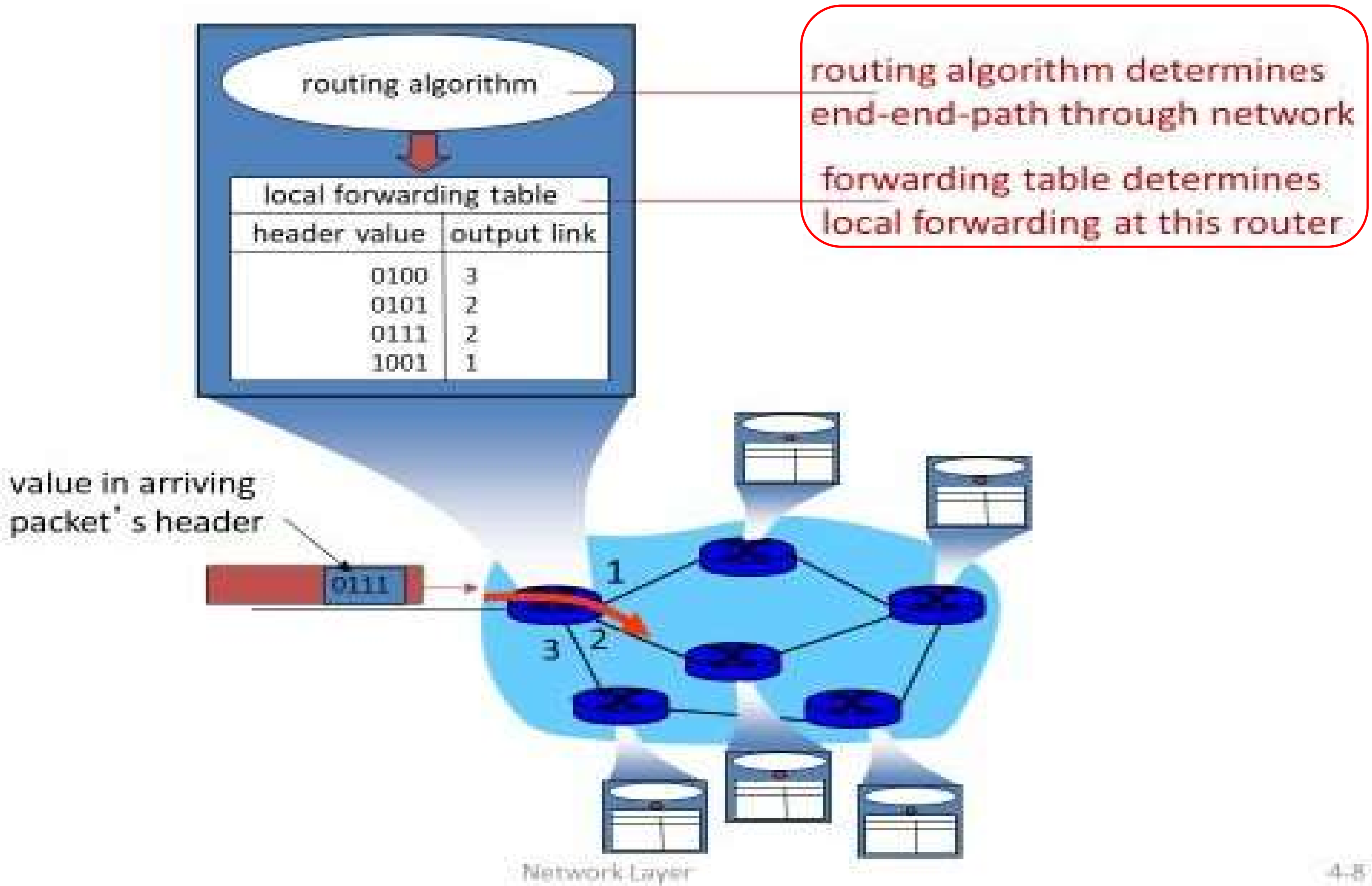


Figure 4.2 ♦ Routing algorithms determine values in forwarding tables

[James F Kurose and Keith W Ross, "Computer Networking: A Top - Down Approach", Pearson Education; 6 th Edition (2017)]

Forwarding and Routing

- A packet with a header field value of 0111 arrives to a router.
- The router indexes into its forwarding table and determines that the output link interface for this packet is interface 2.
- The router then internally forwards the packet to interface 2.
- The routing algorithm determines the values that are inserted into the routers' forwarding tables.
- The routing algorithm may be centralized (e.g., with an algorithm executing on a central site and downloading routing information to each of the routers) or decentralized (i.e., with a piece of the distributed routing algorithm running in each router).
- In either case, a router receives routing protocol messages, which are used to configure its forwarding table.

Network Layer Function : Connection setup

- Third important network-layer function is connection setup
- Some network-layer architectures—for example, ATM, frame relay, and MPLS (Multiprotocol Label Switching)—require the routers along the chosen path from source to destination to handshake with each other in order to set up state before network-layer data packets within a given source-to-destination connection can begin to flow.
- In the network layer, this process is referred to as connection setup.

Network Service Models

- The network service model defines the characteristics of end-to-end transport of packets between sending and receiving end systems.
- In the sending host, when the transport layer passes a packet to the network layer, specific services that could be provided by the network layer include:
    - Guaranteed delivery. This service guarantees that the packet will eventually arrive at its destination.
    - Guaranteed delivery with bounded delay. This service not only guarantees delivery of the packet, but delivery within a specified host-to-host delay bound (for example, within 100 msec)

Network Service Models

- The following services could be provided to a flow of packets between a given source and destination:
  - In-order packet delivery. This service guarantees that packets arrive at the destination in the order that they were sent.
  - Guaranteed minimal bandwidth As long as the sending host transmits bits (as part of packets) at a rate below the specified bit rate, then no packet is lost and each packet arrives within a prespecified host-to- host delay (for example, within 40 msec).

Network Service Models

- Furthermore, the following services could be provided to a flow of packets between a given source and destination:
  - Guaranteed maximum jitter. This service guarantees that the amount of time between the transmission of two successive packets at the sender is equal to the amount of time between their receipt at the destination.
  - Security services. Using a secret session key known only by a source and destination host, the network layer in the source host could encrypt the payloads of all datagrams being sent to the destination host.

This is only a partial list of services that a network layer could provide—there are countless variations possible

Network Service Models

Network Architecture	Service Model	Bandwidth Guarantee	No-Loss Guarantee	Ordering	Timing	Congestion Indication
Internet	Best Effort	None	None	Any order possible	Not maintained	None
ATM	CBR	Guaranteed constant rate	Yes	In order	Maintained	Congestion will not occur
ATM	ABR	Guaranteed minimum	None	In order	Not maintained	Congestion indication provided

Constant bit rate (CBR) ATM network service
Available bit rate (ABR) ATM network service

Table 4.1 ♦ Internet, ATM CBR, and ATM ABR service models

- The Internet's network layer provides a single service, known as best-effort service

[James F Kurose and Keith W Ross, "Computer Networking: A Top - Down Approach", Pearson Education; 6 th Edition (2017)]

Virtual Circuit and Datagram Networks

- A transport layer can offer applications connectionless service or connection-oriented service between two processes.
- For example, the Internet's transport layer provides each application a choice between two services: UDP, a connectionless service; or TCP, a connection-oriented service.
- A network layer can provide connectionless service or connection service between two hosts.
- Network-layer connection and connectionless services in many ways parallel transport-layer connection-oriented and connectionless services.
- For example, a network-layer connection service begins with handshaking between the source and destination hosts; and a network-layer connectionless service does not have any handshaking preliminaries

Virtual Circuit and Datagram Networks

- The network-layer connection and connectionless services have some parallels with transport-layer connection-oriented and connectionless services, there are crucial differences:
    1. In the network layer, these services are host-to-host services provided by the network layer for the transport layer. In the transport layer these services are process to-process services provided by the transport layer for the application layer.
    2. In all major computer network architectures to date (Internet, ATM, frame relay, and so on), the network layer provides either a host-to-host connectionless service or a host-to-host connection service, but not both.

Virtual Circuit and Datagram Networks

- The network-layer connection and connectionless services have some parallels with transport-layer connection-oriented and connectionless services, there are crucial differences:

  2a. Computer networks that provide only a connection service at the network layer are called virtual-circuit (VC) networks; computer networks that provide only a connectionless service at the network layer are called datagram networks.

  3. The transport-layer connection-oriented service is implemented at the edge of the network in the end systems; The network-layer connection service is implemented in the routers in the network core as well as in the end systems.

Virtual Circuit and Datagram Networks

- Virtual-circuit and datagram networks are two fundamental classes of computer networks.
- They use very different information in making their forwarding decisions.

Virtual Circuit Networks

- While the Internet is a datagram network, many alternative network architectures— including those of ATM and frame relay—are virtual-circuit networks and, therefore, use connections at the network layer.

- These network-layer connections are called virtual circuits (VCs).

Virtual Circuit Networks

VC implementation

- A VC consists of

  (1) a path (that is, a series of links and routers) between the source and destination hosts,

  (2) VC numbers, one number for each link along the path, and

  (3) entries in the forwarding table in each router along the path.

Virtual Circuit Networks

VC implementation

- A packet belonging to a virtual circuit will carry a VC number in its header.
- Because a virtual circuit may have a different VC number on each link, each intervening router must replace the VC number of each traversing packet with a new VC number.
- The new VC number is obtained from the forwarding table.

Virtual Circuit Networks

VC implementation

- Network chooses the path A-R1-R2-B and assigns VC numbers 12, 22, and 32 to the three links in this path for this virtual circuit.
- When a packet in this VC leaves Host A, the value in the VC number field in the packet header is 12; when it leaves R1, the value is 22; and when it leaves R2, the value is 32

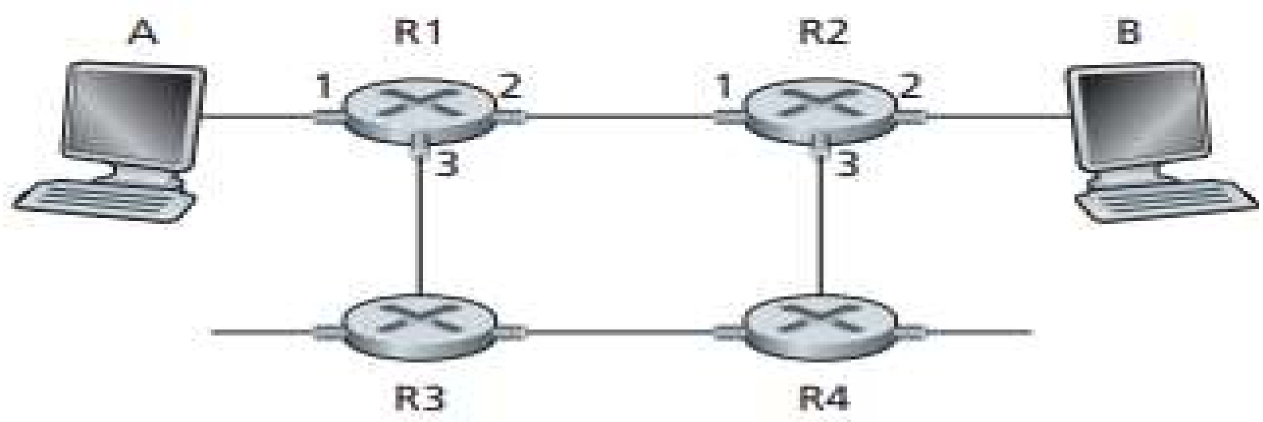


Figure 4.3 • A simple virtual circuit network

[James F Kurose and Keith W Ross, "Computer Networking: A Top - Down Approach", Pearson Education; 6 th Edition (2017)]

Virtual Circuit Networks

VC forwarding table

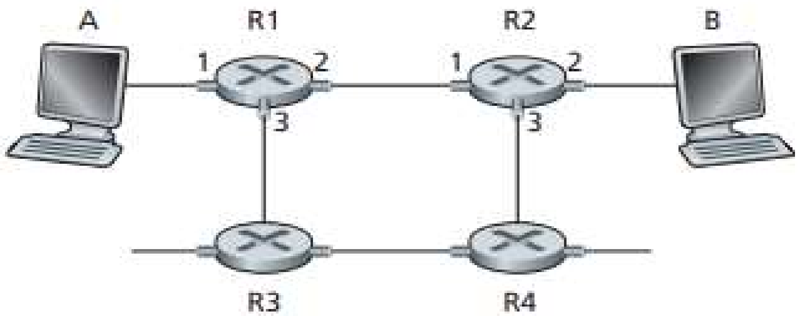


Figure 4.3 ♦ A simple virtual circuit network

forwarding table in router:

Incoming interface	Incoming VC #	Outgoing interface	Outgoing VC #
1	12	3	22
2	63	1	18
3	7	2	17
1	97	3	87
…	…	…	…

VC routers maintain connection state information!

Virtual Circuit Networks

- Why a packet doesn’t just keep the same VC number on each of the links along its route?
- First, replacing the number from link to link reduces the length of the VC field in the packet header.
- Second, VC setup is considerably simplified by permitting a different VC number at each link along the path of the VC. Specifically, with multiple VC numbers, each link in the path can choose a VC number independently of the VC numbers chosen at other links along the path.
- If a common VC number were required for all links along the path, the routers would have to exchange and process a substantial number of messages to agree on a common VC number (e.g., one that is not being used by any other existing VC at these routers) to be used for a connection.

Virtual Circuit Networks

- In a VC network, the network's routers must maintain connection state information for the ongoing connections.
- Specifically, each time a new connection is established across a router, a new connection entry must be added to the router's forwarding table; and each time a connection is released, an entry must be removed from the table.

Virtual Circuit Networks

There are three identifiable phases in a virtual circuit:

1. VC setup
2. Data transfer
3. VC teardown

Virtual Circuit Networks

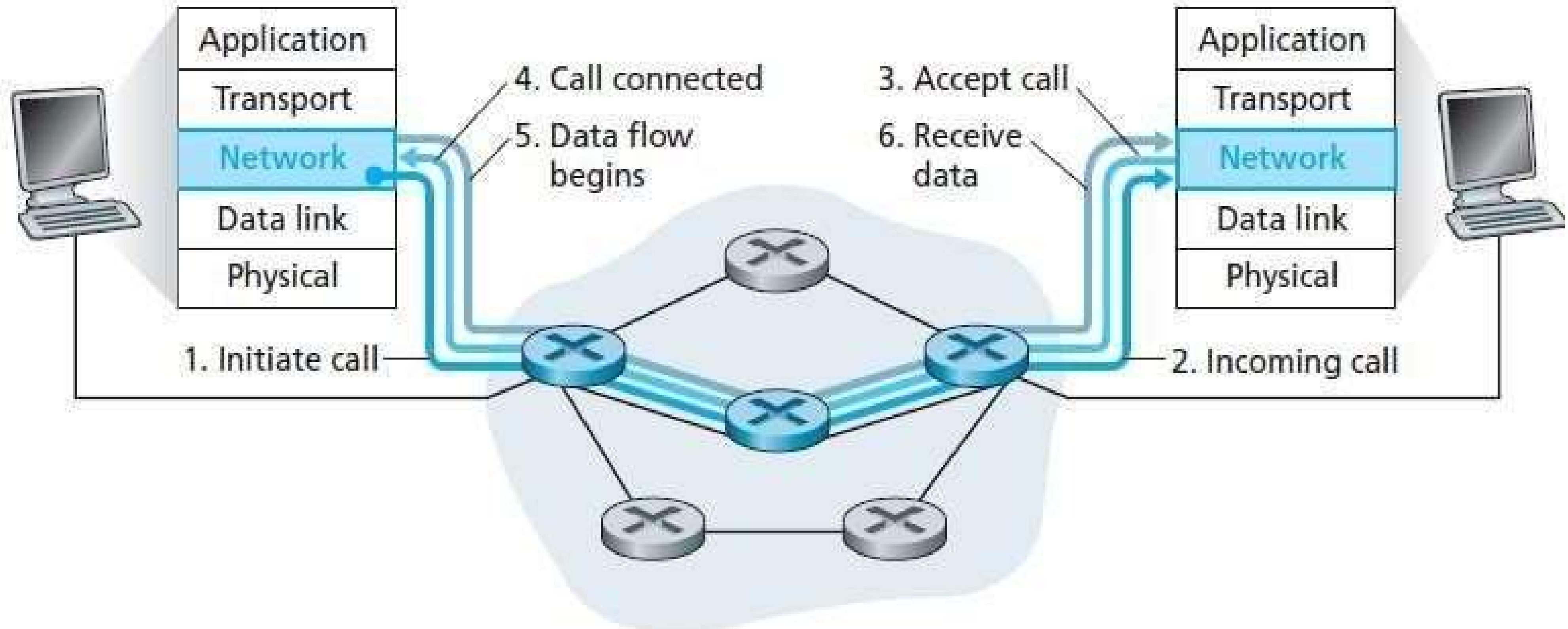


Figure 4.4 ♦ Virtual-circuit setup

[James F Kurose and Keith W Ross, "Computer Networking: A Top - Down Approach", Pearson Education; 6 th Edition (2017)]

Virtual Circuit Networks

1. VC setup

- During the setup phase, the sending transport layer contacts the network layer, specifies the receiver's address, and waits for the network to set up the VC.

- The network layer determines the path between sender and receiver, that is, the series of links and routers through which all packets of the VC will travel.

- The network layer also determines the VC number for each link along the path.

- Finally, the network layer adds an entry in the forwarding table in each router

Virtual Circuit Networks

2. Data transfer

- Once the VC has been established, packets can begin to flow along the VC.

3. VC teardown

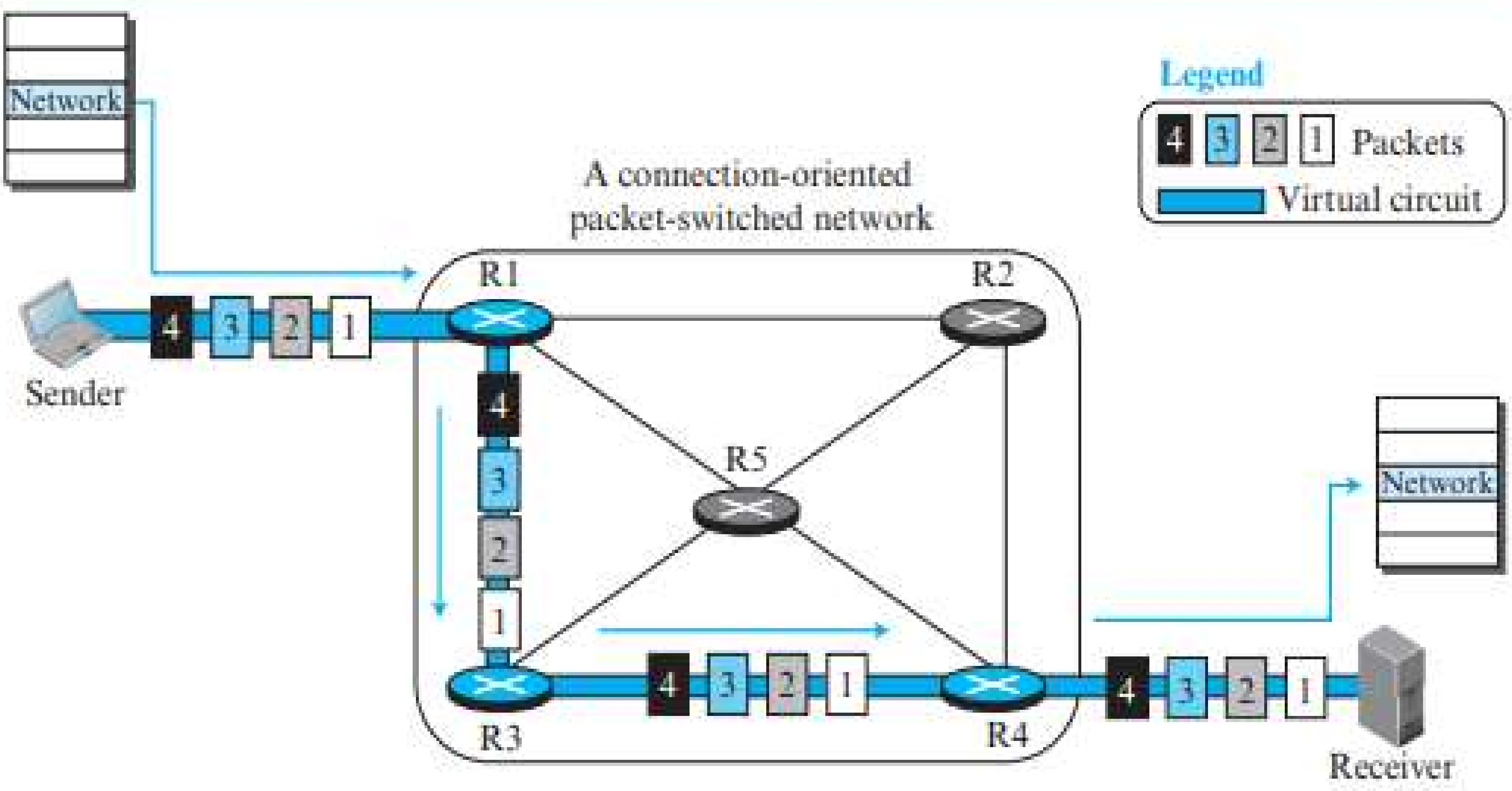
- This is initiated when the sender (or receiver) informs the network layer of its desire to terminate the VC. The network layer will then typically inform the end system on the other side of the network of the call termination and update the forwarding tables in each of the packet routers on the path to indicate that the VC no longer exists.

Virtual Circuit Networks

- With a VC network layer, routers along the path between the two end systems are involved in VC setup, and each router is fully aware of all the VCs passing through it.
- The messages that the end systems send into the network to initiate or terminate a VC, and the messages passed between the routers to set up the VC (that is, to modify connection state in router tables) are known as signaling messages, and the protocols used to exchange these messages are often referred to as signaling protocols.

Virtual Circuit Networks

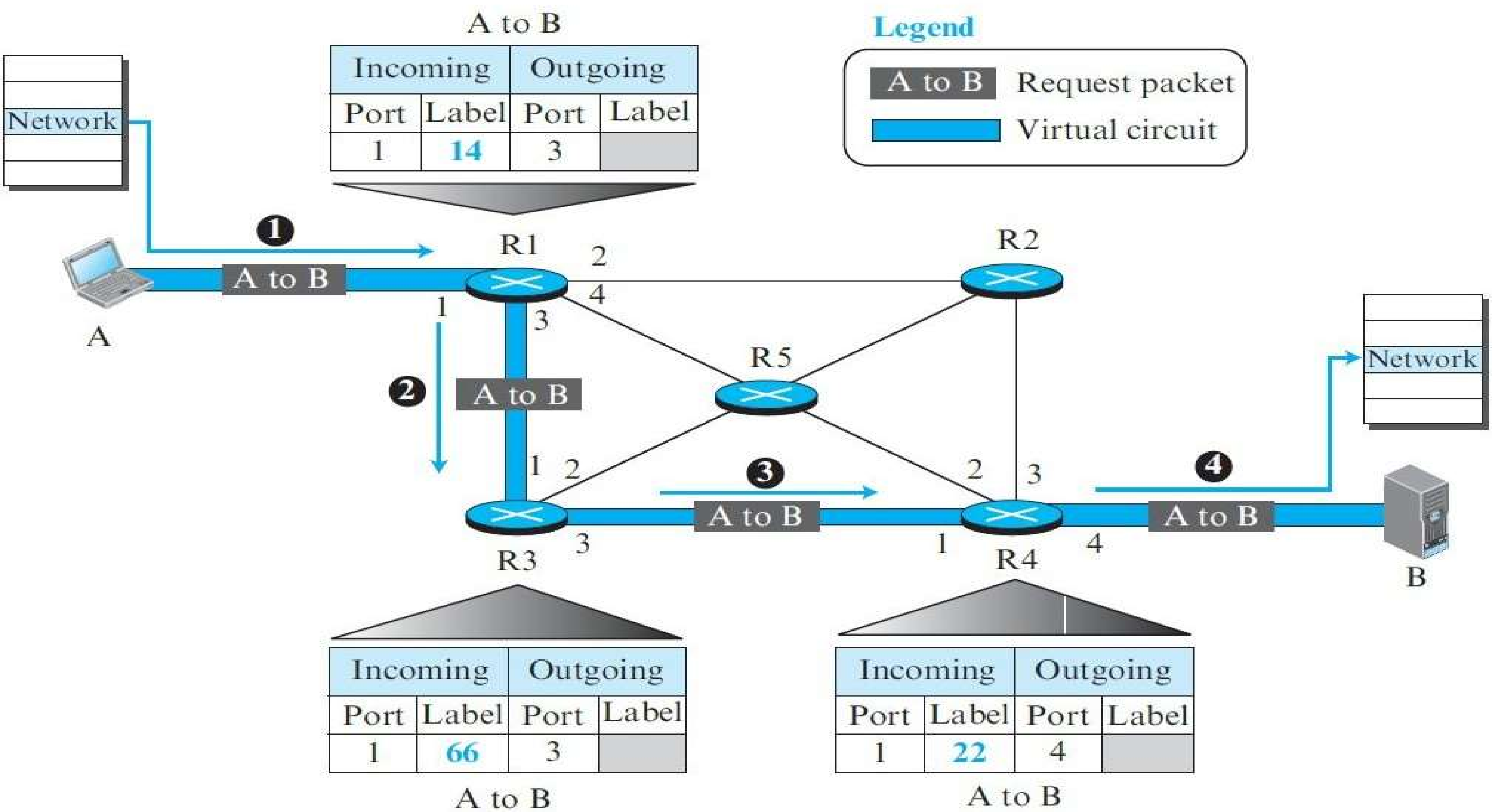
Figure 4.5 *A virtual-circuit packet-switched network*



[Behrouz A Forouzan, Firouz Mosharraf, "Computer Networks: A top down Approach", McGraw Hill Education]

Setup request in a virtual circuit

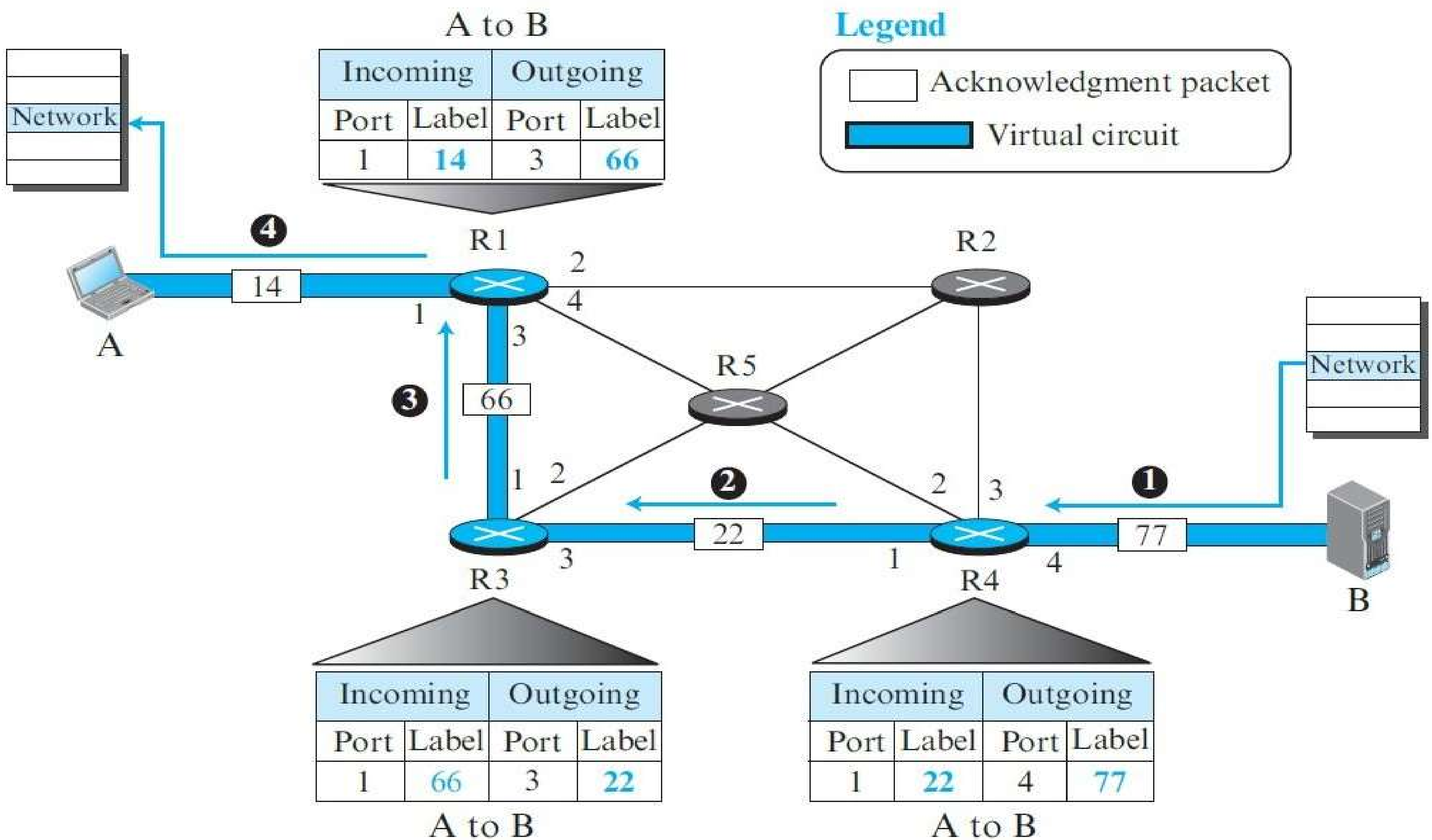
Figure 4.7 *Sending request packet in a virtual-circuit network*



[Behrouz A Forouzan, Firouz Mosharraf, "Computer Networks: A top down Approach", McGraw Hill Education]

Sending acknowledgements in a virtual circuit

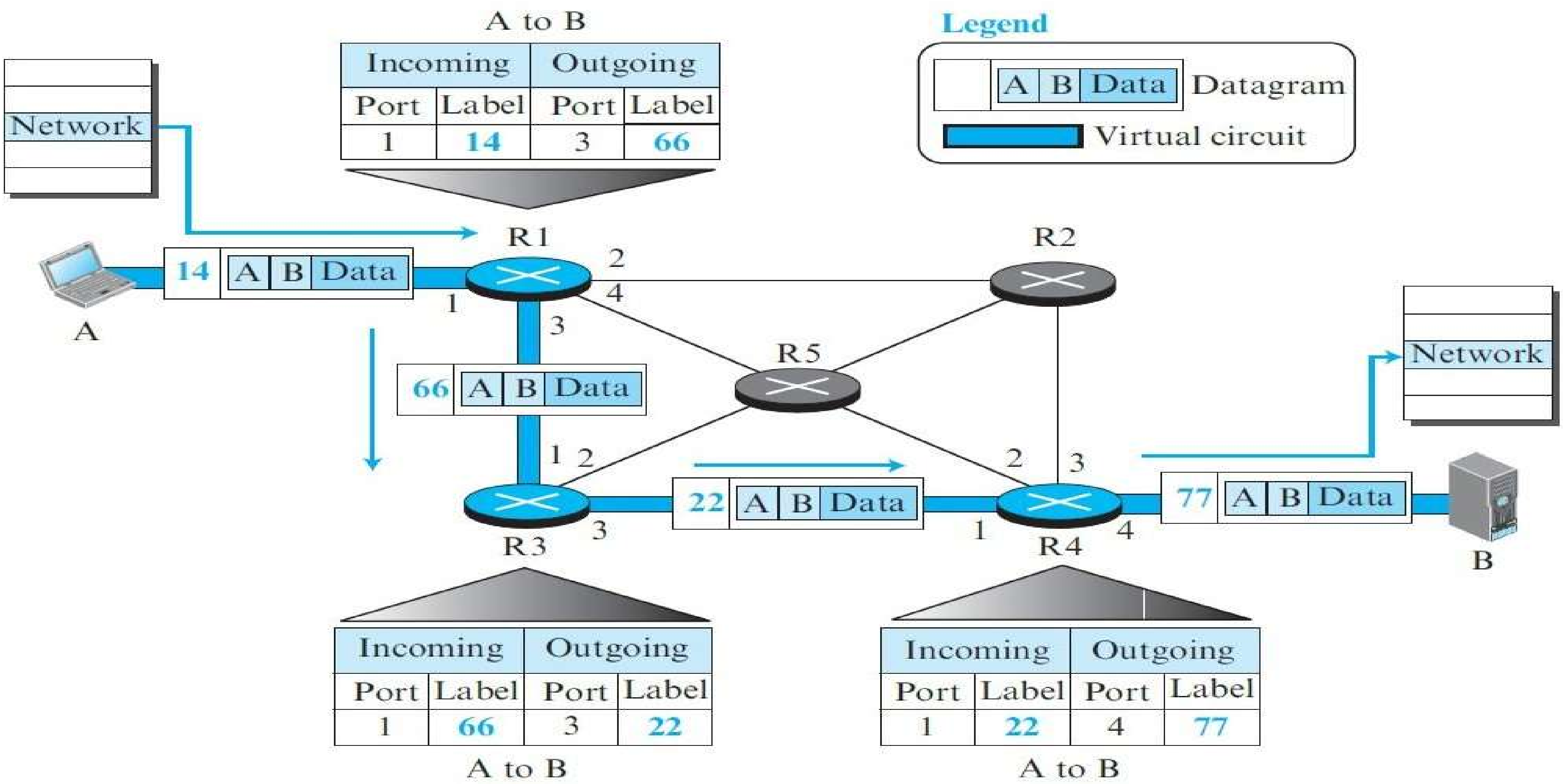
Figure 4.8 *Sending acknowledgments in a virtual-circuit network*



[Behrouz A Forouzan, Firouz Mosharraf, "Computer Networks: A top down Approach", McGraw Hill Education]

Flow of packet in a virtual circuit

Figure 4.9 *Flow of one packet in an established virtual circuit*



- *Data transfer. once the VC has been established, packets* can begin to flow along the VC.

[Behrouz A Forouzan, Firouz Mosharraf, "Computer Networks: A top down Approach", McGraw Hill Education]

VC Teardown

- VC teardown: This is initiated when the sender (or receiver) informs the network layer of its desire to terminate the VC.

- The network layer will then typically inform the end system on the other side of the network of the call termination and update the forwarding tables in each of the packet routers on the path to indicate that the VC no longer exists.

Datagram Networks

- There is no VC setup and routers do not maintain any VC state information (because there are no VCs!)
- Routers: no state about end-to-end connections
  - no network-level concept of “connection”
- Packets forwarded using destination host address

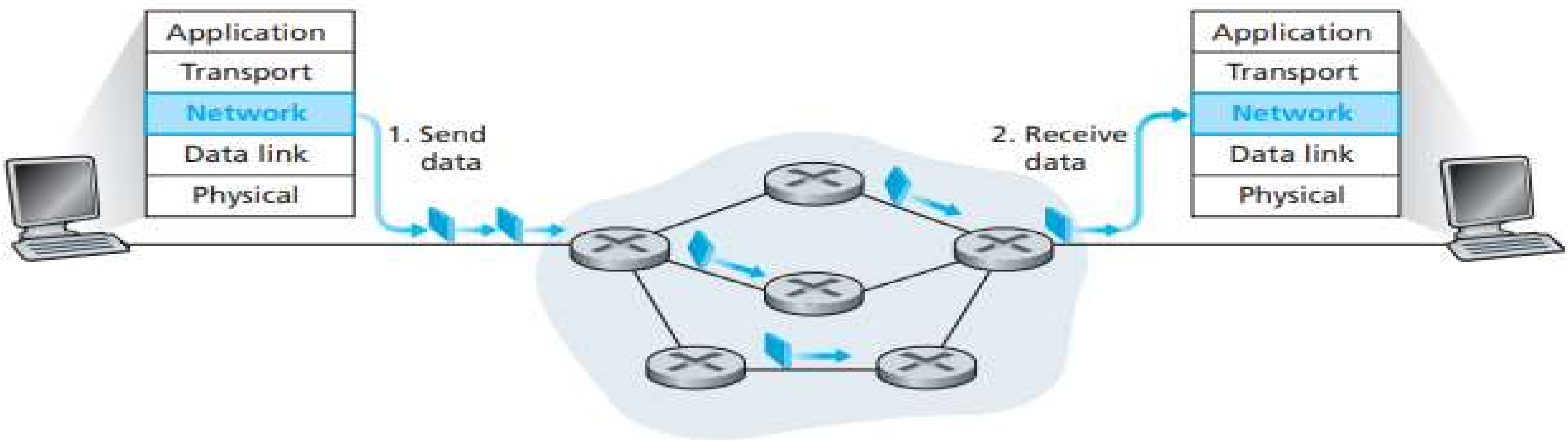
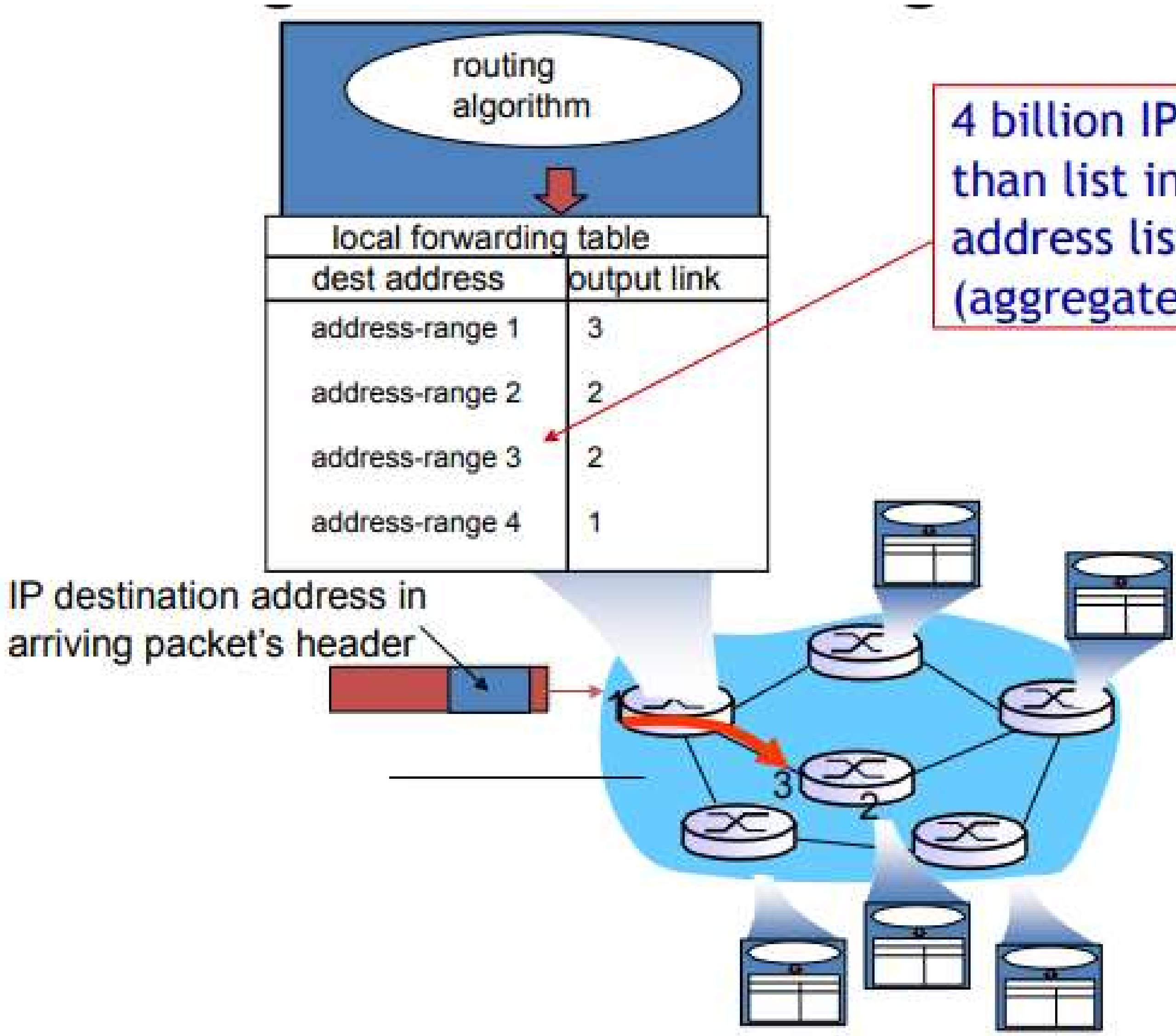


Figure 4.5 ♦ Datagram network

[James F Kurose and Keith W Ross, “Computer Networking: A Top - Down Approach”, Pearson Education; 6 th Edition (2017)]

Datagram Forwarding Table



4 billion IP addresses, so rather than list individual destination address list *range* of addresses (aggregate table entries)

Datagram Networks

- Suppose that our router has four links, numbered 0 through 3, and that packets are to be forwarded to the link interfaces as follows:

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111	0
11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111	1
11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111	2
otherwise	3

Datagram Networks

- With this style of forwarding table, the router matches a prefix of the packet's destination address with the entries in the table; if there's a match, the router forwards the packet to a link associated with the match.
- For example, suppose the packet's destination address is 11001000 00010111 00010110 10100001; because the 21-bit prefix of this address matches the first entry in the table, the router forwards the packet to link interface 0.
- If a prefix doesn't match any of the first three entries, then the router forwards the packet to interface 3.

Datagram Networks

Prefix Match	Link Interface
11001000 00010111 00010	0
11001000 00010111 00011000	1
11001000 00010111 00011	2
otherwise	3

Datagram Networks

- It is possible for a destination address to match more than one entry.
- When there are multiple matches, the router uses the longest prefix matching rule; that is, it finds the longest matching entry in the table and forwards the packet to the link interface associated with the longest prefix match.

Datagram Networks

• For example, the first 24 bits of the address 11001000 00010111 00011000 10101010 match the second entry in the table, and the first 21 bits of the address match the third entry in the table.

11001000 00010111 00011000 10101010

11001000 00010111 00011000 10101010

Destination Address Range	Link Interface
11001000 00010111 00010000 00000000 through 11001000 00010111 00010111 11111111	0
11001000 00010111 00011000 00000000 through 11001000 00010111 00011000 11111111	1
11001000 00010111 00011001 00000000 through 11001000 00010111 00011111 11111111	2
otherwise	3

Datagram Networks

- Although routers in datagram networks maintain no connection state information, they nevertheless maintain forwarding state information in their forwarding tables.

- However, the time scale at which this forwarding state information changes is relatively slow.

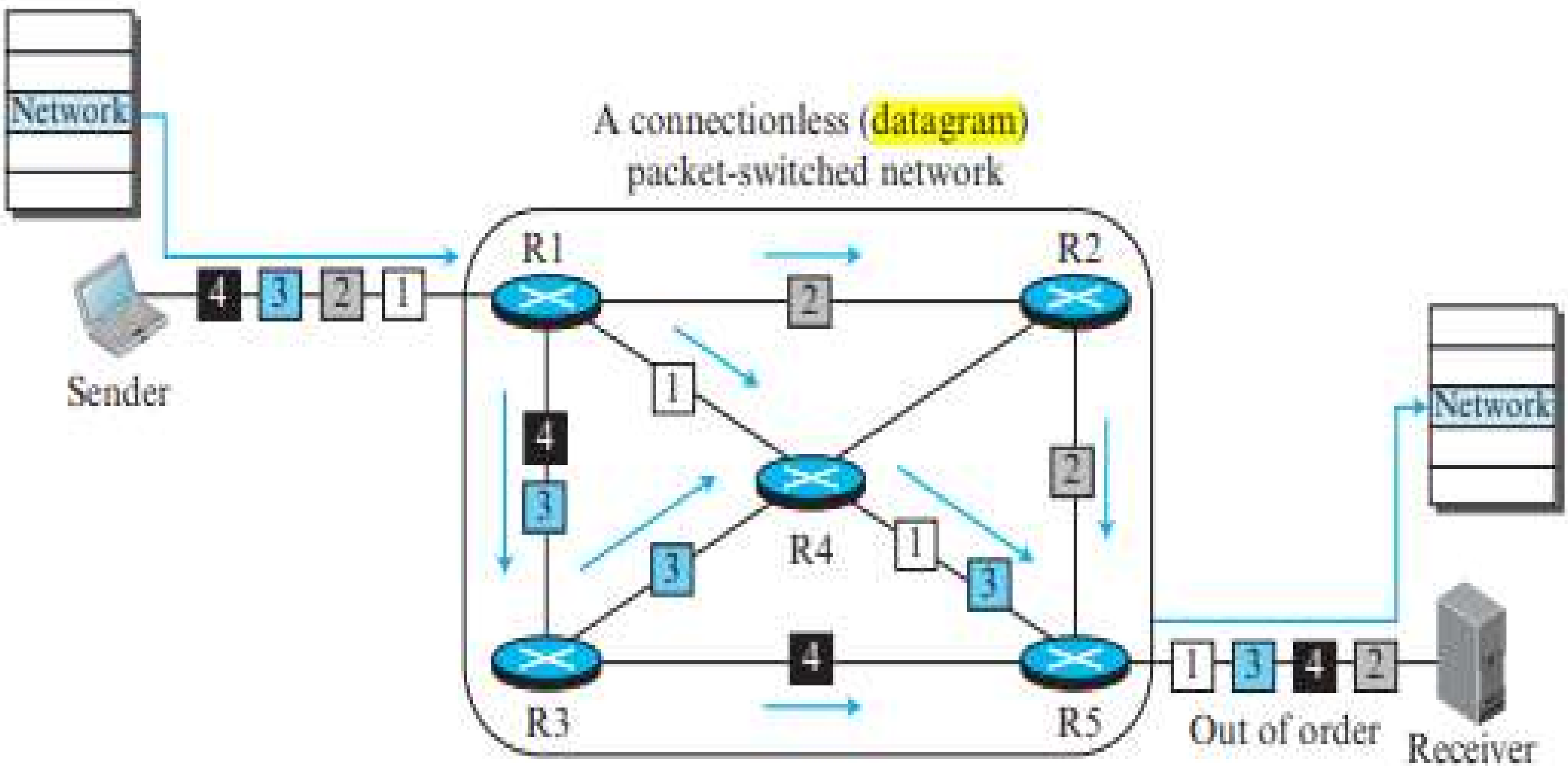
- Indeed, in a datagram network the forwarding tables are modified by the routing algorithms, which typically update a forwarding table every one-to five minutes or so.

Datagram Networks

- In a VC network, a forwarding table in a router is modified whenever a new connection is set up through the router or whenever an existing connection through the router is torn down. This could easily happen at a microsecond timescale in a backbone, tier-1 router.
- Because forwarding tables in datagram networks can be modified at any time, a series of packets sent from one end system to another may follow different paths through the network and may arrive out of order.

Datagram network

Figure 4.3 *A connectionless packet-switched network*



[Behrouz A Forouzan, Firouz Mosharraf, “Computer Networks: A top down Approach”, McGraw Hill Education]

Router

- A high-level view of a generic router architecture

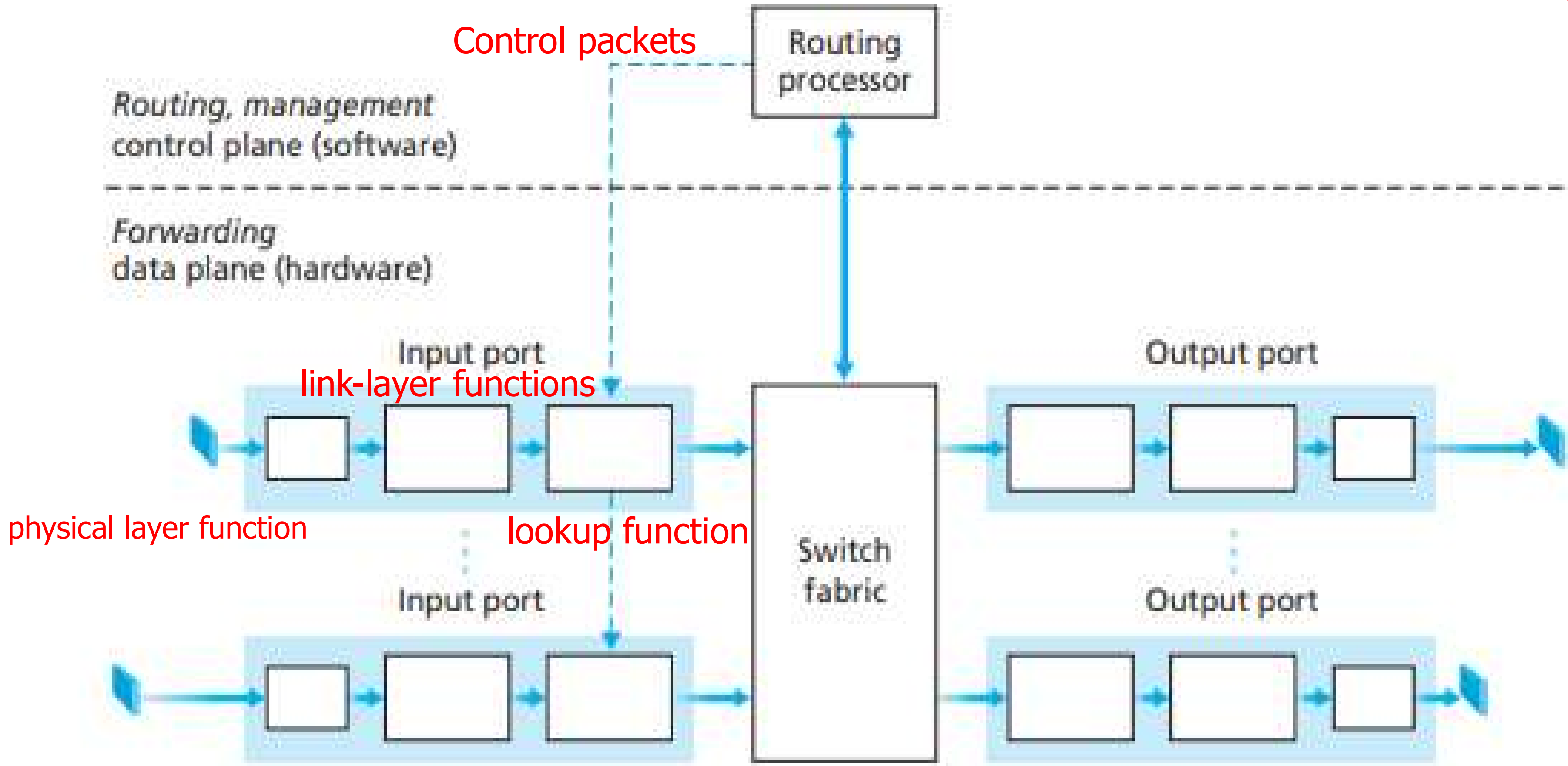


Figure 4.6 ♦ Router architecture

[James F Kurose and Keith W Ross, "Computer Networking: A Top - Down Approach", Pearson Education; 6 th Edition (2017)]

Router

- Four router components can be identified:

1. Input ports
    - An input port performs several key functions.
    - It performs the physical layer function of terminating an incoming physical link at a router.
    - An input port also performs link-layer functions needed to interoperate with the link layer at the other side of the incoming link; this is represented by the middle boxes in the input and output ports.
    - The lookup function is also performed at the input port; this will occur in the rightmost box of the input port.

Router

- Four router components can be identified:

1. Input ports
   - Forwarding table is consulted to determine the router output port to which an arriving packet will be forwarded via the switching fabric.
   - Control packets (for example, packets carrying routing protocol information) are forwarded from an input port to the routing processor.
   - Note that the term port here— referring to the physical input and output router interfaces

Router

- Four router components can be identified:

2. Switching fabric

- The switching fabric connects the router’s input ports to its output ports.
- This switching fabric is completely contained within the router— a network inside of a network router!

Router

- Four router components can be identified:

3. Output ports

- An output port stores packets received from the switching fabric and transmits these packets on the outgoing link by performing the necessary link-layer and physical-layer functions.

Router

- Four router components can be identified:

4. Routing processor

- The routing processor executes the routing protocols, maintains routing tables and attached link state information, and computes the forwarding table for the router.
- It also performs the network management functions.

Router

- A router's input ports, output ports, and switching fabric together implement the forwarding function and are almost always implemented in hardware.
- These forwarding functions are sometimes collectively referred to as the router forwarding plane.
- A router's control functions—executing the routing protocols, responding to attached links that go up or down, and performing management functions.
- These router control plane functions are usually implemented in software and execute on the routing processor (typically a traditional CPU).

Router

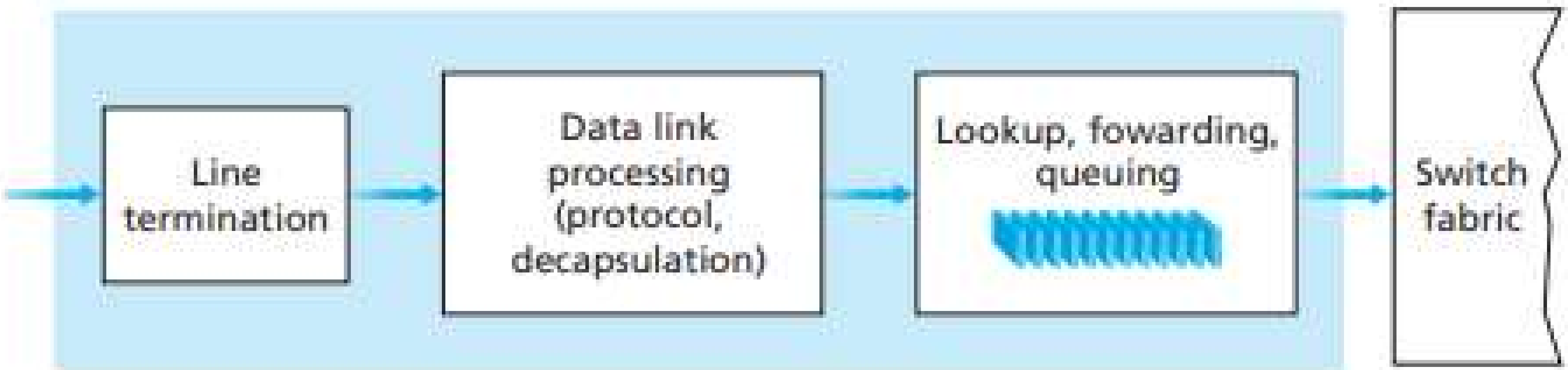
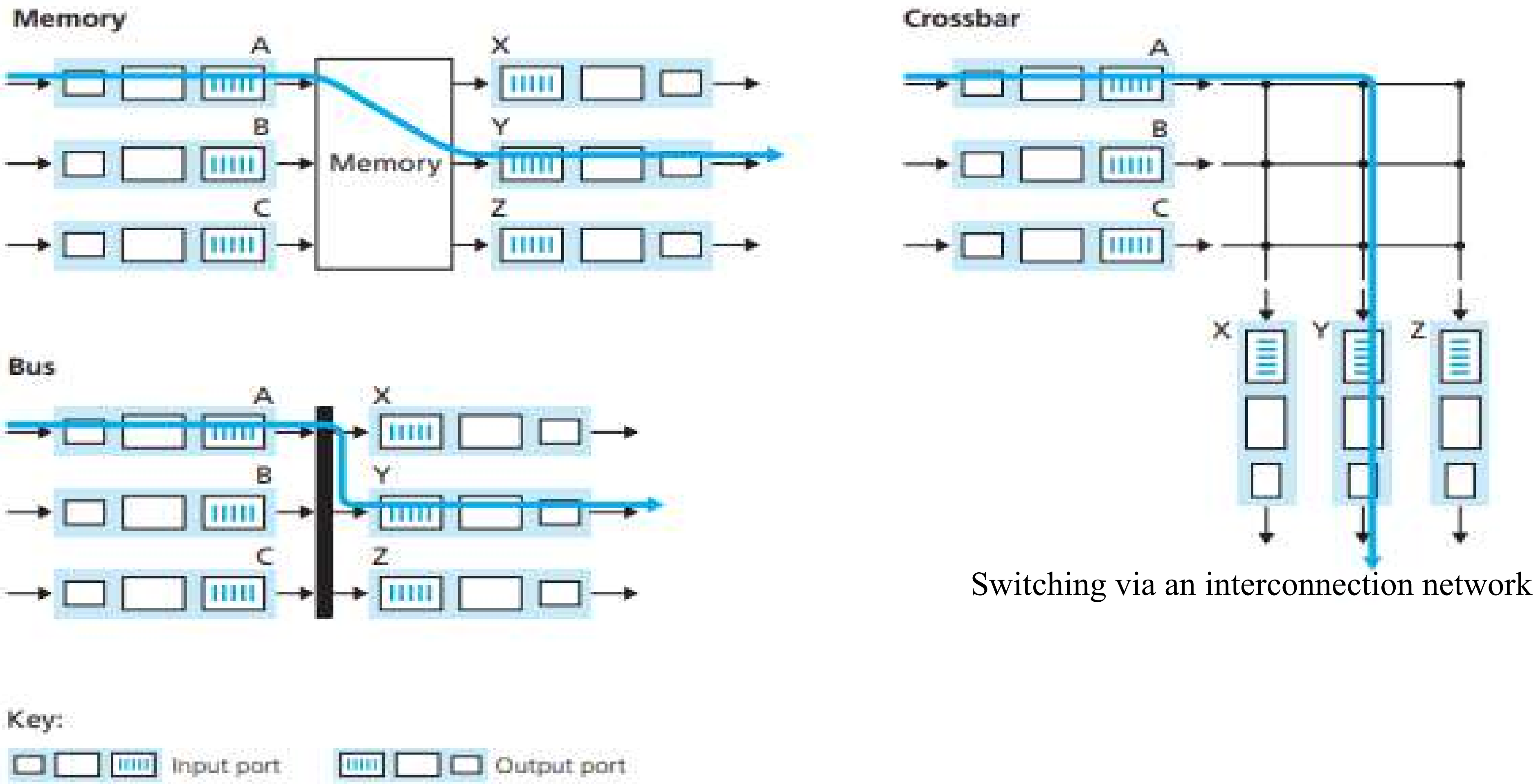


Figure 4.7 ♦ Input port processing

[James F Kurose and Keith W Ross, “Computer Networking: A Top - Down Approach”, Pearson Education; 6 th Edition (2017)]

Router



Switching via an interconnection network

Figure 4.8 ♦ Three switching techniques

[James F Kurose and Keith W Ross, “Computer Networking: A Top - Down Approach”, Pearson Education; 6 th Edition (2017)]

Router

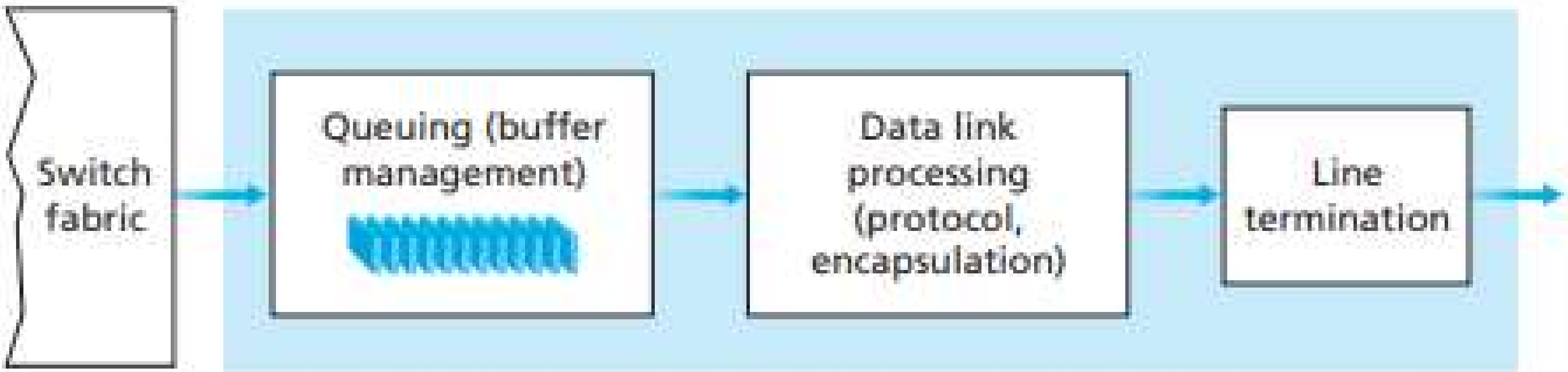


Figure 4.9 ♦ Output port processing

[James F Kurose and Keith W Ross, “Computer Networking: A Top - Down Approach”, Pearson Education; 6 th Edition (2017)]