CS 455/555
Intro to Networks and Communications

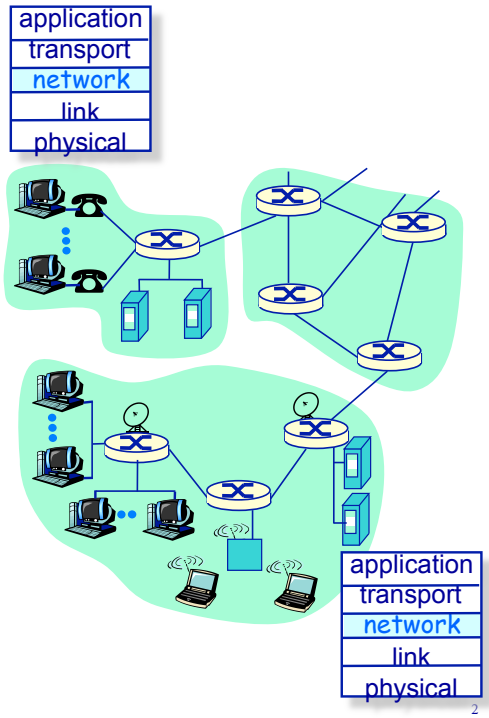
The Network Layer

Dr. Michele Weigle
Department of Computer Science
Old Dominion University
mweigle@cs.odu.edu

http://www.cs.odu.edu/~mweigle/CS455-S13/

The Network Layer: Routing & Addressing
Outline

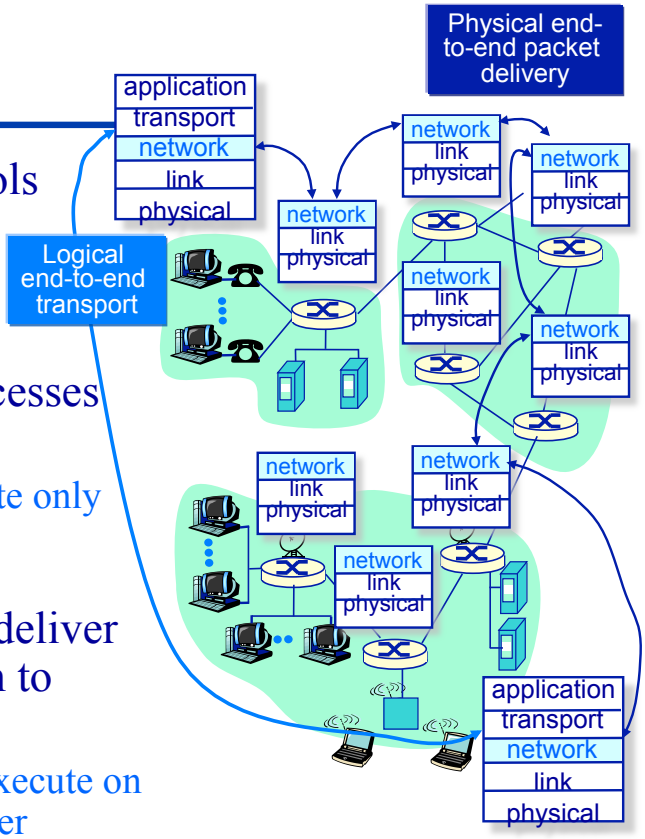
- Network layer functions
- Virtual circuits and datagram networks
- Router architecture
- IP Internet Protocol
  - » Addressing
- Routing algorithms
  - » Least cost path computation algorithms
- Hierarchical routing
  - » Connecting networks of networks
- Routing on the Internet
  - » Intra-domain routing
  - » Inter-domain routing



The Network Layer

Network Layer Functions

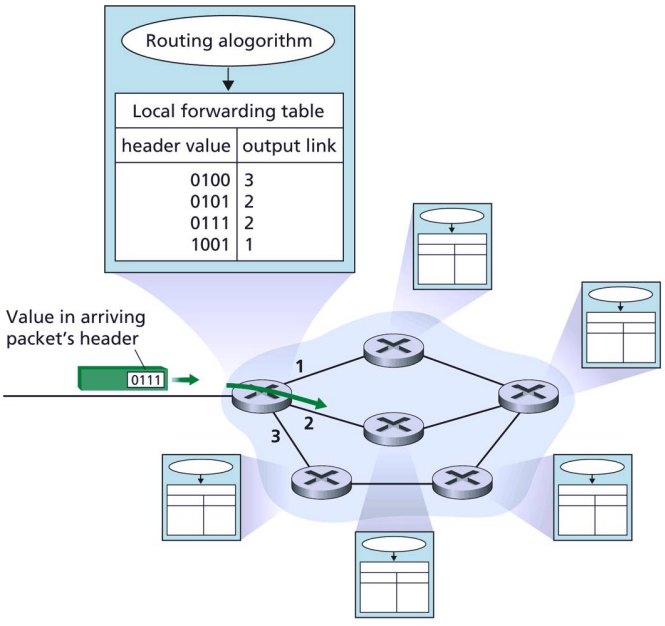
- Application-layer protocols define when and how messages are sent
- Transport-layer protocols deliver data between processes on different end-systems
  - » Transport protocols execute only on end systems
- Network-layer protocols deliver data from one end-system to another
  - » Network layer protocols execute on *every* end-system and router



The Network Layer

Network Layer Functions

- The network-layer provides two important functions:
  - » *Routing*: the route taken by packets from source to destination (involves all routers)
  - » *Forwarding (aka Switching)*: the movement of packets from an input interface to an appropriate output interface (involves a single router)
- Some architectures have a 3rd important function: *connection setup*



The Network Layer
Network Service Model

What types of services might be offered by the network layer?

Example services for individual datagrams:

- » guaranteed delivery
- » guaranteed delivery with bounded delay

Example services for a flow of datagrams:

- » in-order datagram delivery
- » guaranteed minimum bandwidth to flow
- » restrictions on changes in inter-packet spacing
- » security

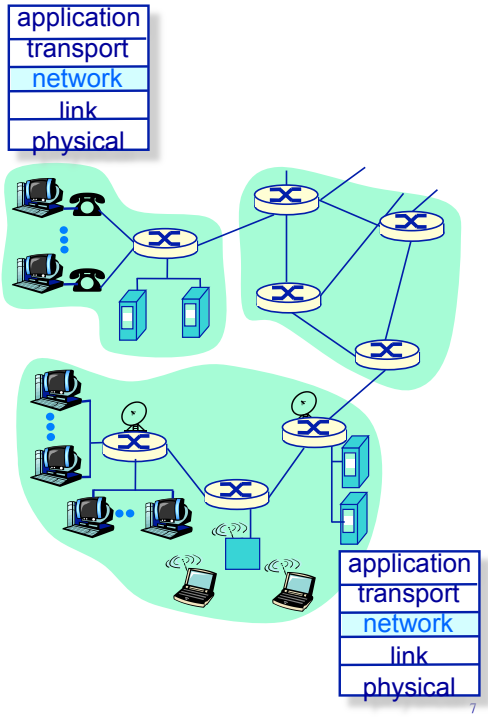
The Network Layer
Network Layer Service Models

Network Architecture	Service Model	Guarantees ?				Congestion feedback
		Bandwidth	Loss	Order	Timing	
Internet	best effort	none	no	no	no	no (inferred via loss)
ATM	CBR	constant rate	yes	yes	yes	no congestion
ATM	ABR	guaranteed minimum	no	yes	no	yes

The Network Layer: Routing & Addressing

Outline

- Network layer functions
- Virtual circuits and datagram networks
- Router architecture
- IP Internet Protocol
  - » Addressing
- Routing algorithms
  - » Least cost path computation algorithms
- Hierarchical routing
  - » Connecting networks of networks
- Routing on the Internet
  - » Intra-domain routing
  - » Inter-domain routing



Virtual Circuits and Datagram Networks

Connection and Connection-less Service

- Datagram network provides network-layer connectionless service
- Virtual circuit (VC) network provides network-layer connection service
- Analogous to the transport-layer services, but:
  - » service: host-to-host
  - » no choice: network provides either one or the other
  - » implementation: in network core

Virtual Circuits and Datagram Networks

Virtual Circuits

"source-to-dest path behaves much like telephone circuit"
- » performance-wise
- » network actions along source-to-dest path

- Call setup, teardown for each call *before* data can flow
- Each packet carries VC identifier (not destination host address)
- *Every* router on source-dest path maintains "state" for each passing connection
- Link, router resources (bandwidth, buffers) may be *allocated* to VC (dedicated resources = predictable service)

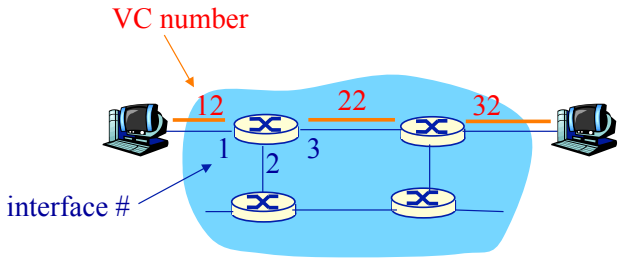
Virtual Circuits

Implementation

- A VC consists of:
  - » path from source to destination
  - » VC numbers - one number for each link along path
  - » entries in forwarding tables in routers along path
- Packet belonging to VC carries VC number (rather than destination address)
- VC number can be changed on each link
  - » New VC number comes from forwarding table

Virtual Circuits

Forwarding Table



Forwarding table in northwest router:

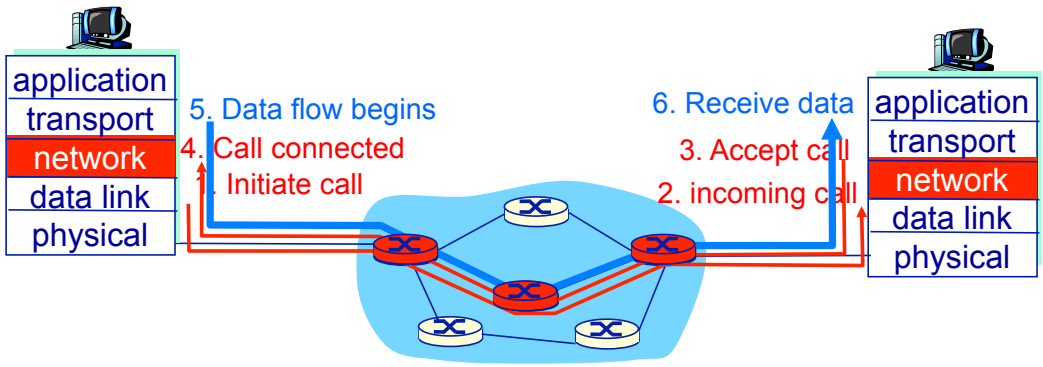
Incoming interface	Incoming VC #	Outgoing interface	Outgoing VC #
1	12	3	22
2	63	1	18
3	7	2	17
1	97	3	87
…	…	…	…

Routers maintain connection state information!

Virtual Circuits

Signaling Protocols

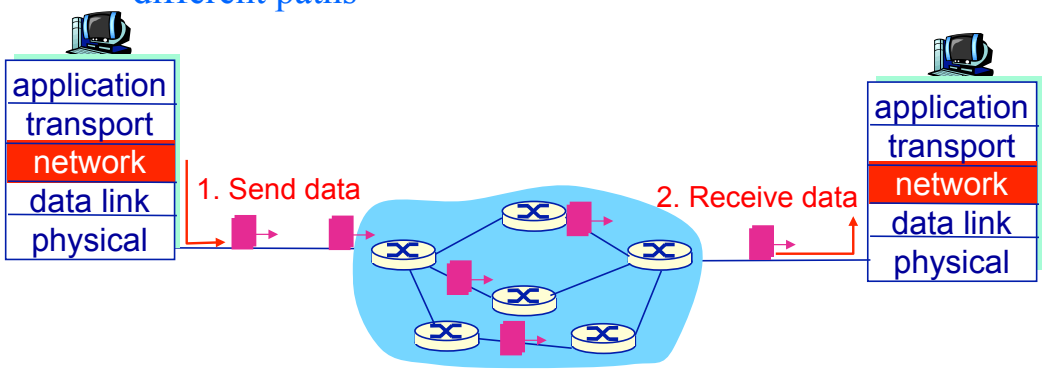
- Used to setup, maintain, and teardown VC
- Used in ATM, frame-relay, X.25
- Not used in today's Internet



Virtual Circuits and Datagram Networks

Datagram Networks

- No call setup at network layer
- Routers: no state about end-to-end connections
  - » no network-level concept of "connection"
- Packets forwarded using destination host address
  - » packets between same source-dest pair may take different paths



Datagram Networks

Forwarding Table Example

4 billion possible entries

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
Longest Prefix Matching

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

Examples

Destination Addr: 11001000 00010111 00010110 10100001 Which interface?

Destination Addr: 11001000 00010111 00011000 10101010 Which interface?

Datagram or VC network
Why?

Internet (datagram)

- Data exchange among computers
  - » "elastic" service, no strict timing req.
- "Smart" end systems (computers)
  - » can adapt, perform control, error recovery
  - » simple inside network, complexity at "edge"
- Many link types
  - » different characteristics
  - » uniform service difficult

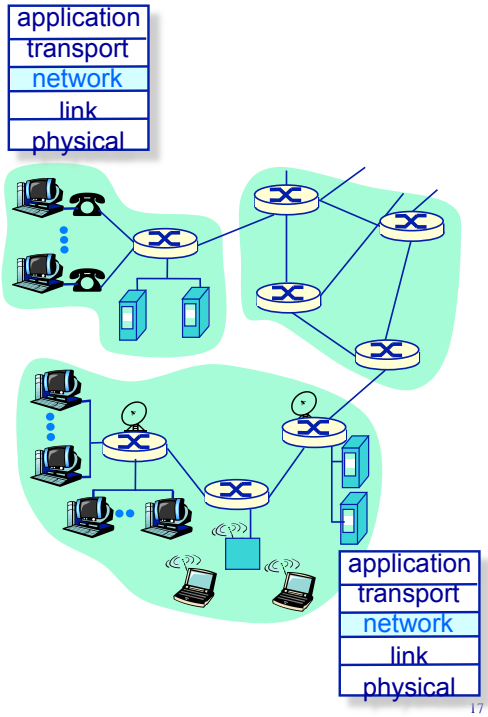
ATM (VC)

- Evolved from telephony
- Human conversation:
  - » strict timing, reliability requirements
  - » need for guaranteed service
- "Dumb" end systems
  - » telephones
  - » complexity inside network

The Network Layer: Routing & Addressing

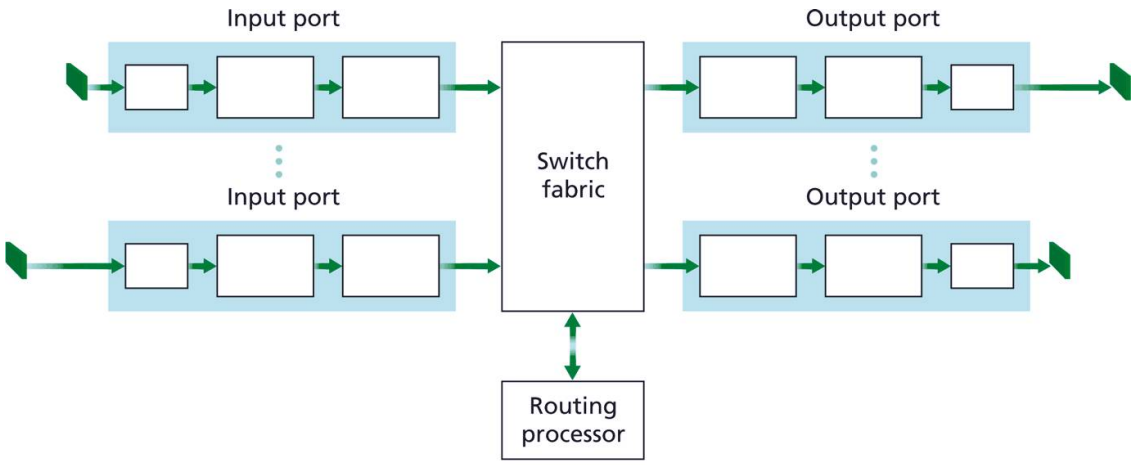
Outline

- Network layer functions
- Virtual circuits and datagram networks
- Router architecture
- IP Internet Protocol
  - » Addressing
- Routing algorithms
  - » Least cost path computation algorithms
- Hierarchical routing
  - » Connecting networks of networks
- Routing on the Internet
  - » Intra-domain routing
  - » Inter-domain routing



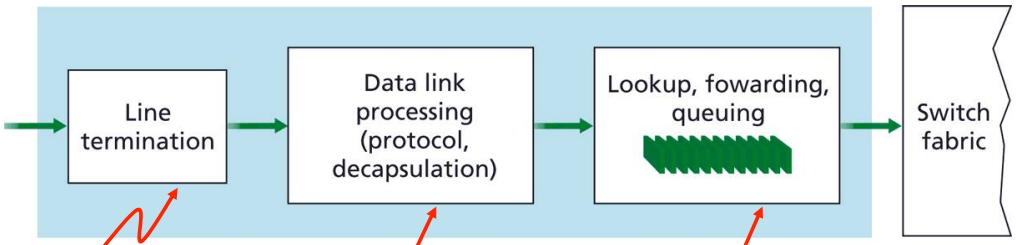
Router Architecture

Overview



Router Architecture

Input Port Functions



Physical layer:
bit-level reception

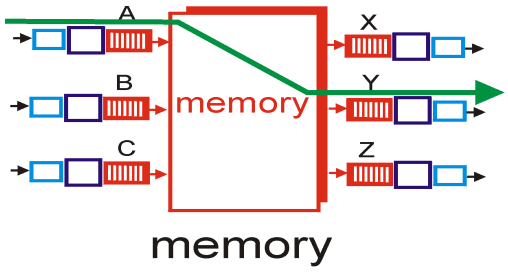
Data link layer:
e.g., Ethernet
see chapter 5

Decentralized switching:

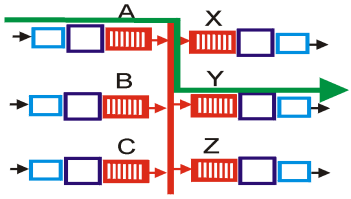
- Given datagram destination, lookup output port using forwarding table in input port memory (forwarding table copied to input port)
- **Goal:** complete input port processing at 'line speed'
  - » Lookup should take less time than time to receive next packet at input port
- **Queuing:** if datagrams arrive faster than forwarding rate into switch fabric

Router Architecture

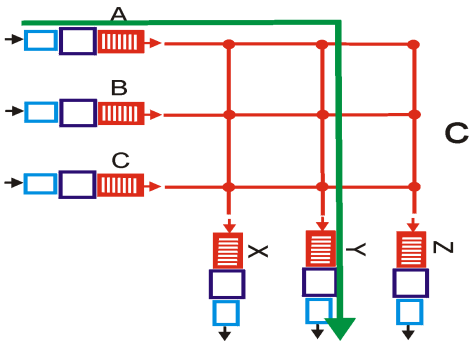
Three Types of Switching Fabrics



memory

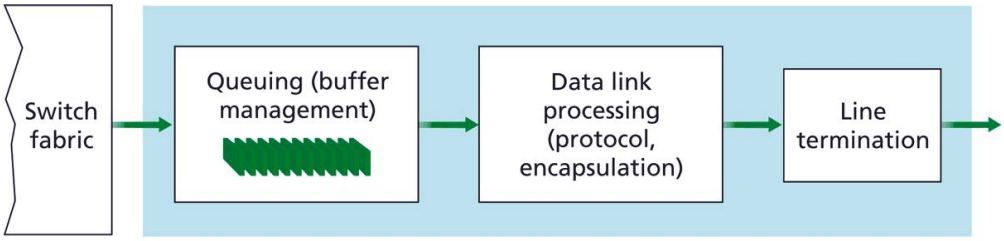


bus



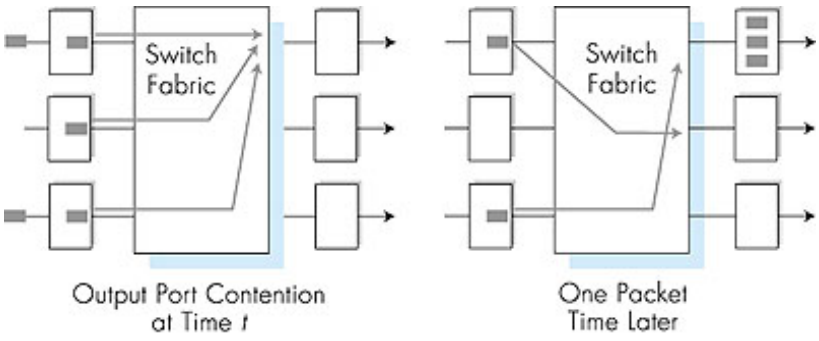
crossbar

Router Architecture
Output Ports



- *Buffering* required when datagrams arrive from fabric faster than the transmission rate
- *Scheduling discipline* chooses among queued datagrams for transmission

Output Ports
Queuing



- Buffering occurs when arrival rate via switch exceeds output line speed
- *Queuing (delay) and loss due to output port buffer overflow*

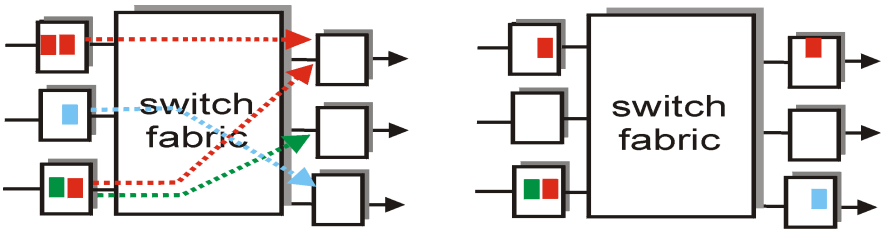
Queuing
How much buffering?

- RFC 3439 rule of thumb: average buffering equal to "typical" RTT (say 250 ms) times link capacity *C*
  - » e.g., *C* = 10 Gbps link: 2.5 Gbit buffer

- Recent recommendation: with *N* flows, buffering equal to $\frac{RTT \cdot C}{\sqrt{N}}$

Queuing
At the Input Port

- Switching fabric slower than input ports combined
  - » queuing may occur at input queues
- Head-of-the-Line (HOL) blocking
  - » queued datagram at front of queue prevents others in queue from moving forward
- ***Queuing delay and loss due to input buffer overflow***



output port contention at time t - only one red packet can be transferred

green packet experiences HOL blocking

The Network Layer: Routing & Addressing

Outline

- Network layer functions
- Virtual circuits and datagram networks
- Router architecture
- IP Internet Protocol
  - » Addressing
- Routing algorithms
  - » Least cost path computation algorithms
- Hierarchical routing
  - » Connecting networks of networks
- Routing on the Internet
  - » Intra-domain routing
  - » Inter-domain routing