ECE 671
Introduction to Computer Networks

Lesson 2
Networking Concepts

Rationale

- Computer networks are complex engineered systems
- Protocol details can get confusing
- Underlying principles appear all over networks
- Exploration of these concepts helps with later understanding

Objectives

- Explain engineering principles as they apply to networking
- Analyze characteristics of delay and throughput as network performance metrics

Prior Knowledge

- Last lecture
    - Networks as communication medium for distributed application
    - Billions of nodes and links in Internet
    - Nodes grouped into networks that connect to each other
    - Tiered structure of Internet

Required Resources

- Kurose, J., & Ross, K. (2017). *Computer networking: A top-down approach* (7th ed.). New York, NY: Pearson Publishing.
    - Chapter 1, “Computer Networks and the Internet” (pp. 35–67)

Orchestrated Discussion (Hand Raise): Lesson Reflection Feedback

- Discuss questions and comments on Lesson Reflection from prior lesson

Engineering Networks

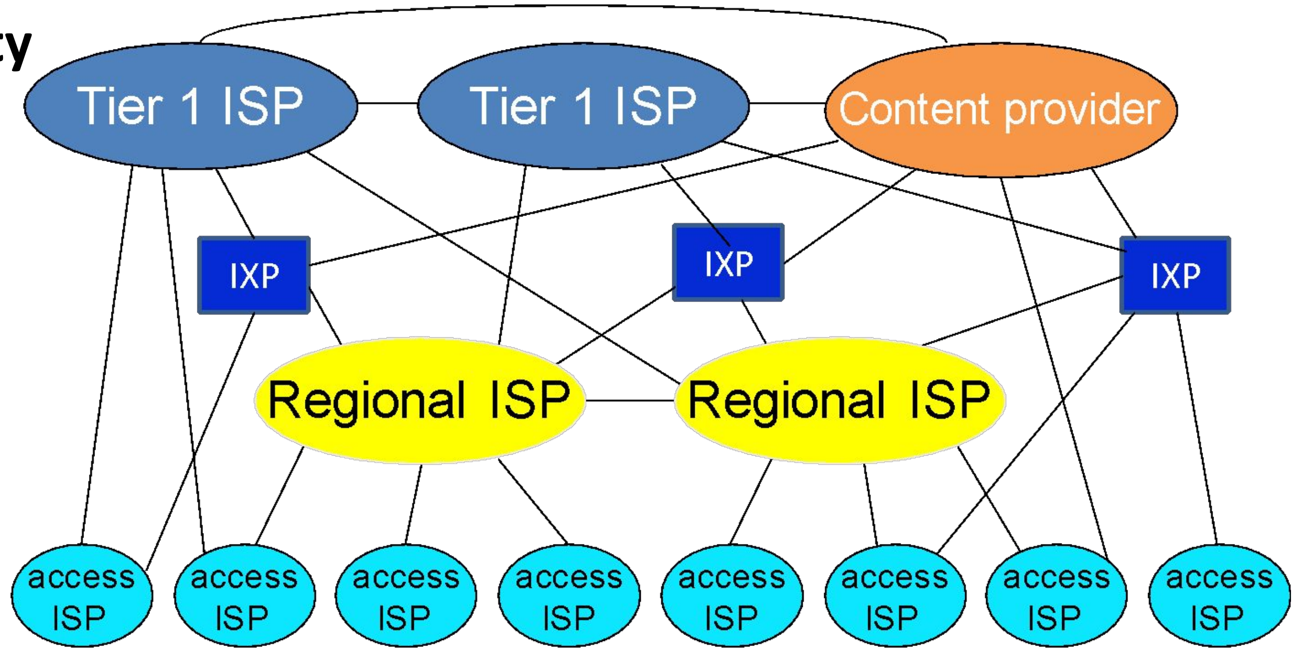
- Engineering techniques in networking
  - Hierarchies (last lecture: network of networks)
  - Layering / modularization
  - Resource sharing
  - Coordination tradeoff
- Instantiation of technique depends on context
  - Example: resource sharing
    - Sharing links vs. sharing packet buffers
- Similar concepts apply to other engineered systems

Whiteboard: Modularization

Property	Benefit	Not a Benefit
Isolation of complexity between modules		
Enforcement of clearly defined interfaces between modules		
Interchangeability of modules with same interfaces but different implementation		
Interchangeability of modules with different interfaces		
Improved performance through inter-module optimization		
Accessibility of implementation details across modules		

Document Cam: Hierarchies

- Hierarchical structuring of Internet (last lecture)
  - Tier 1 network providers: national / international connectivity
  - Regional network providers: regional connectivity
  - Access network providers: local connectivity
- Hierarchical structure reduces complexity
  - Identifies are of responsibility
  - Defines basic approach to reaching other networks
    - If destination is local area, go down, if not go up
- Internet does not have hierarchy within a tier

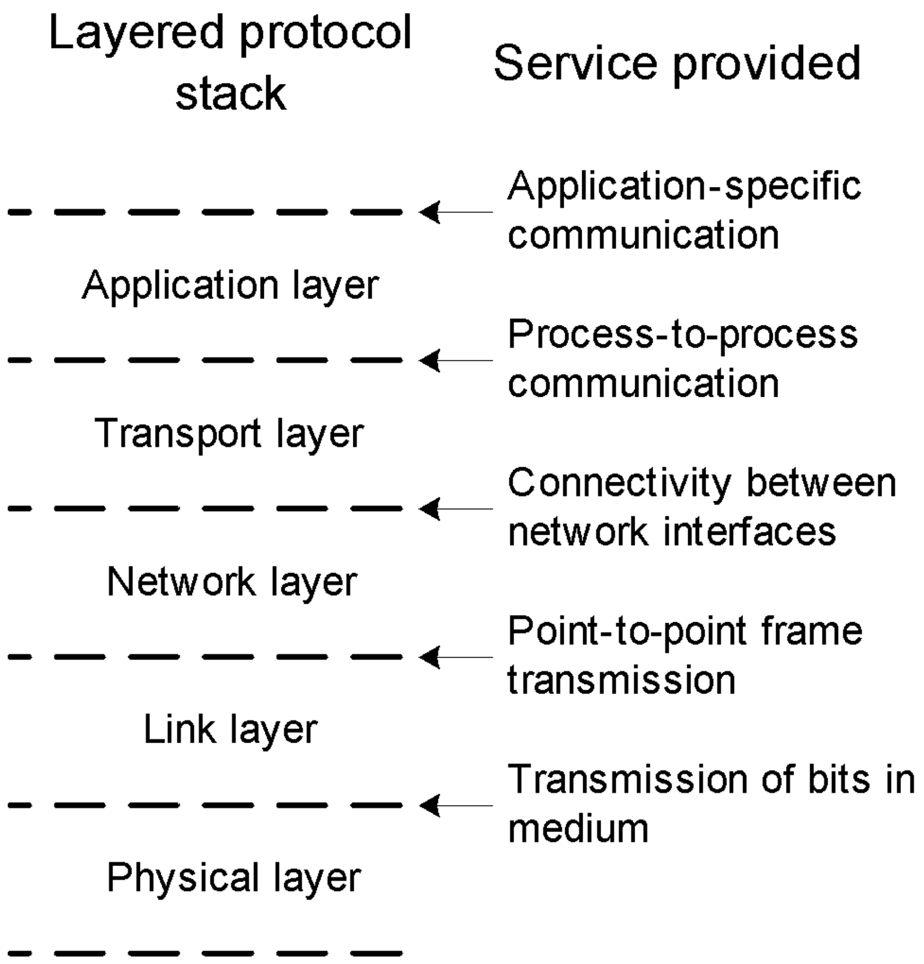


Modularization

- Breaking complex systems into smaller components
    - Modularization structures functionality
    - Interfaces describe interactions between components
- Module implementation is interchangeable
    - Change of implementation does not affect other modules
- Layered reference model of Internet
    - OSI reference model protocol stack (7 layers)
        - Session layer and presentation layer not used widely
    - Internet protocol stack (5 layers)

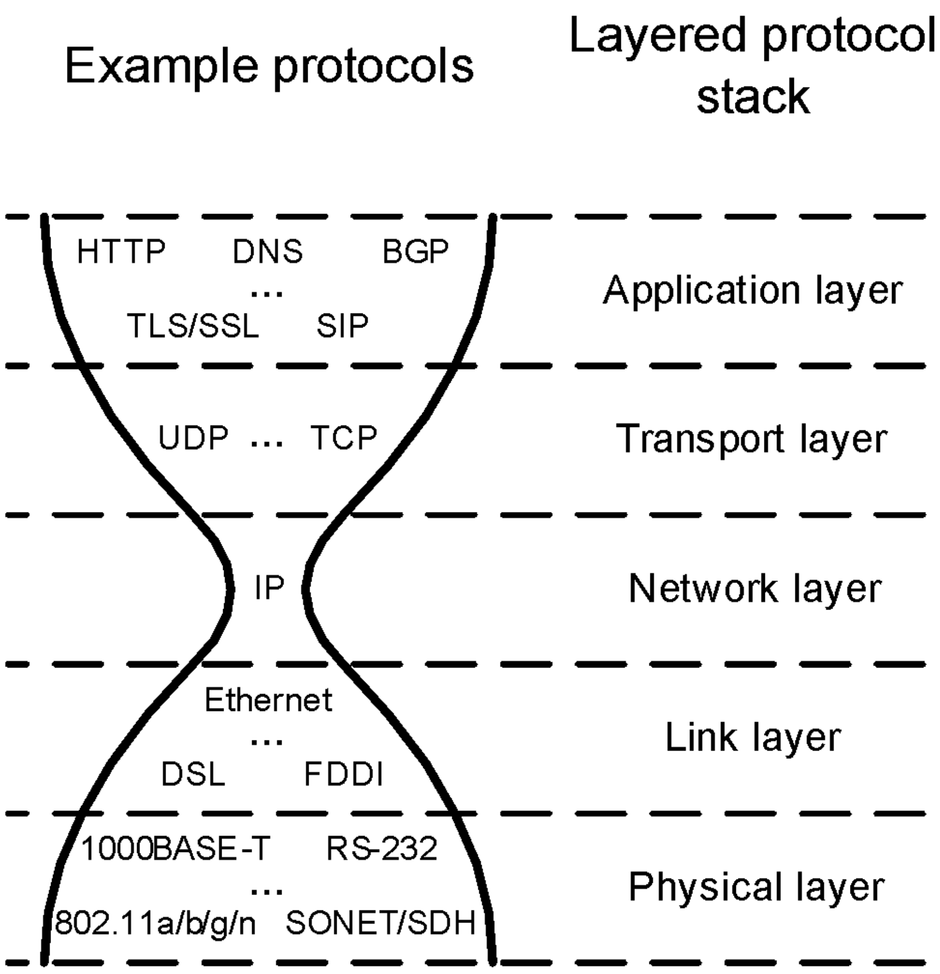
Interfaces between Layers

- Each layer in protocol stack provides a "service"
  - Uses service from lower layers
- Benefits of layering
  - Isolates complexity
  - Clearly defined interfaces
- Protocols implement functionality within layer
  - Different protocols can achieve module functionality



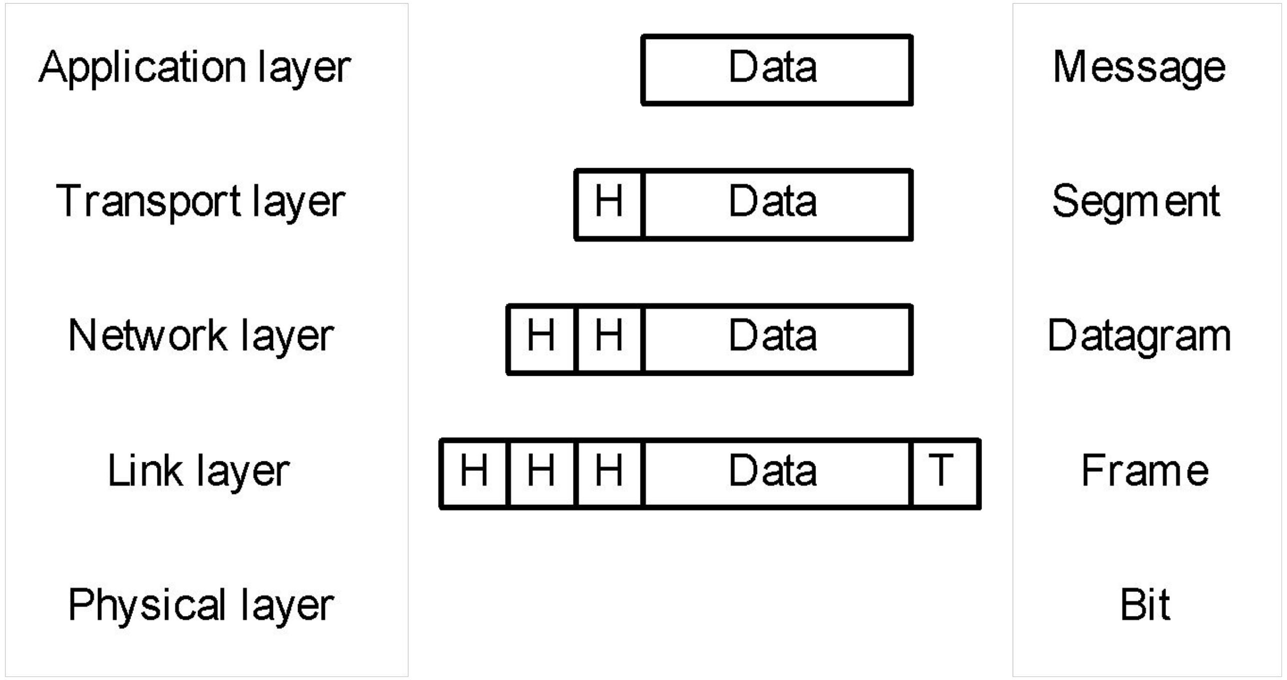
Internet Architecture

- "Hourglass architecture"
- Achieves interoperability
  - Single, common network layer protocol: Internet Protocol (IP)
  - All network nodes need to support this protocol
- Supports diversity
  - Different link/physical layer protocols below
  - Different transport/application layer protocols above



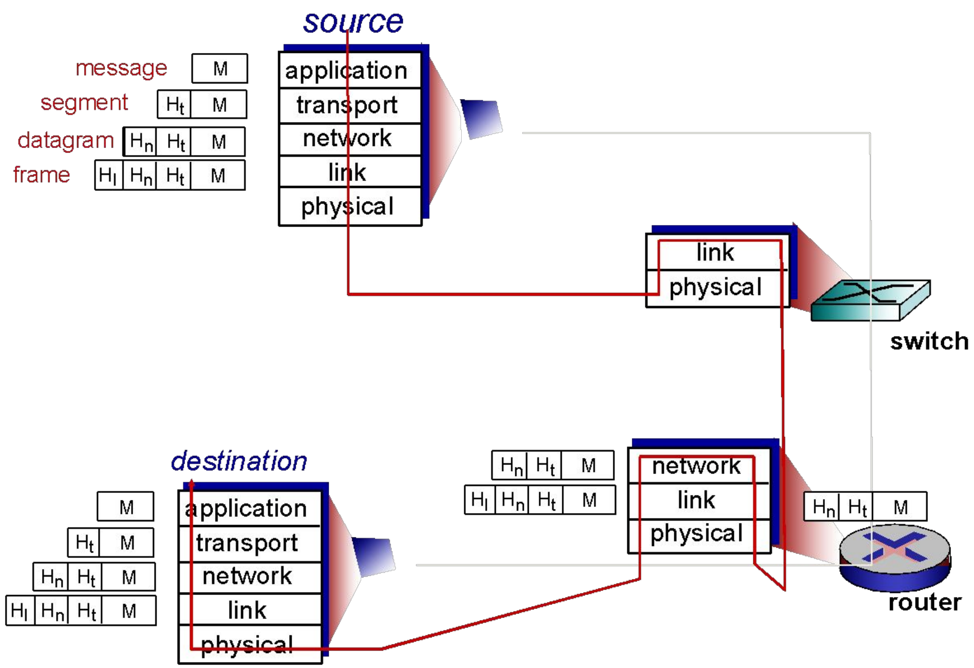
Protocols

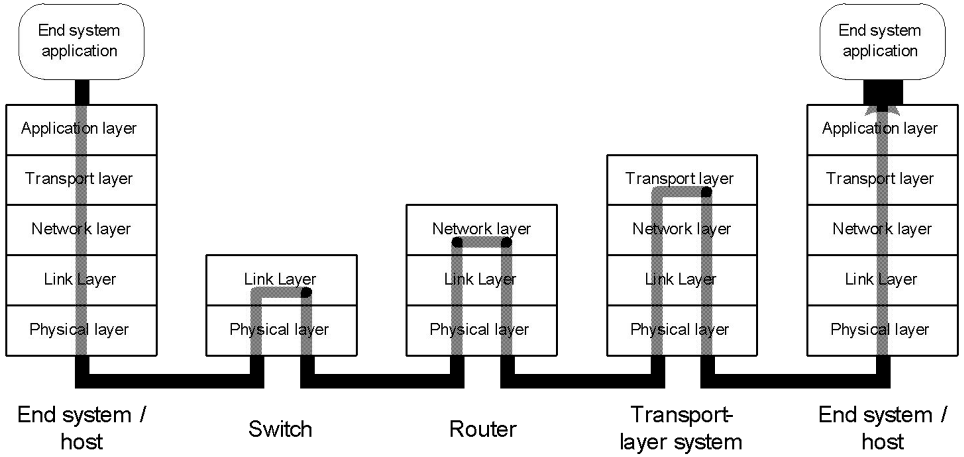
- Protocols define communication between entities
  - Format and order of messages
  - Actions taken on transmission and/or receipt of message or other event
- Protocols use headers (and trailers) for control information
  - Naming depends on layer



Network Devices

- Network devices differ by highest layer processed
  - Devices can process/modify headers up to that layer
  - Switches and routers are most common





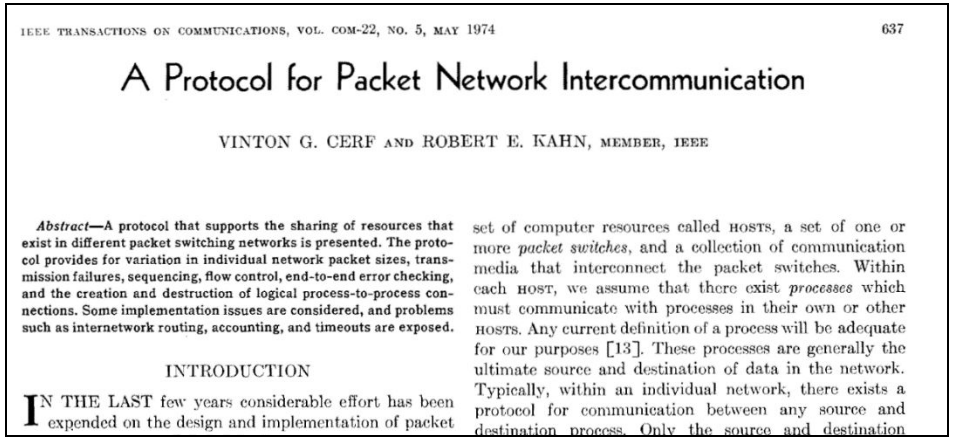
Example Protocol Stack

Layer	Example protocols
Application layer	Hypertext Transfer Protocol (HTTP)
Transport layer	Transmission Control Protocol (TCP)
Network layer	Internet Protocol (IP)
Link layer	Ethernet
Physical layer	1000BASE-T

- **We will review Application Layer through Link Layer**

Turing Award

- **Turing Award 2004: Vint Cerf and Bob Kahn**
  - **“for pioneering work on internetworking, including the design and implementation of the Internet's basic communications protocols, TCP/IP, and for inspired leadership in networking”**



IEEE TRANSACTIONS ON COMMUNICATIONS, VOL. COM-22, NO. 5, MAY 1974 637

A Protocol for Packet Network Intercommunication

VINTON G. CERF AND ROBERT E. KAHN, MEMBER, IEEE

Abstract—A protocol that supports the sharing of resources that exist in different packet switching networks is presented. The protocol provides for variation in individual network packet sizes, transmission failures, sequencing, flow control, end-to-end error checking, and the creation and destruction of logical process-to-process connections. Some implementation issues are considered, and problems such as internetwork routing, accounting, and timeouts are exposed.

INTRODUCTION

IN THE LAST few years considerable effort has been expended on the design and implementation of packet

set of computer resources called HOSTS, a set of one or more *packet switches*, and a collection of communication media that interconnect the packet switches. Within each HOST, we assume that there exist *processes* which must communicate with processes in their own or other HOSTS. Any current definition of a process will be adequate for our purposes [13]. These processes are generally the ultimate source and destination of data in the network. Typically, within an individual network, there exists a protocol for communication between any source and destination process. Only the source and destination

Group Discussion and Report Back (Short Answer): Resource Sharing

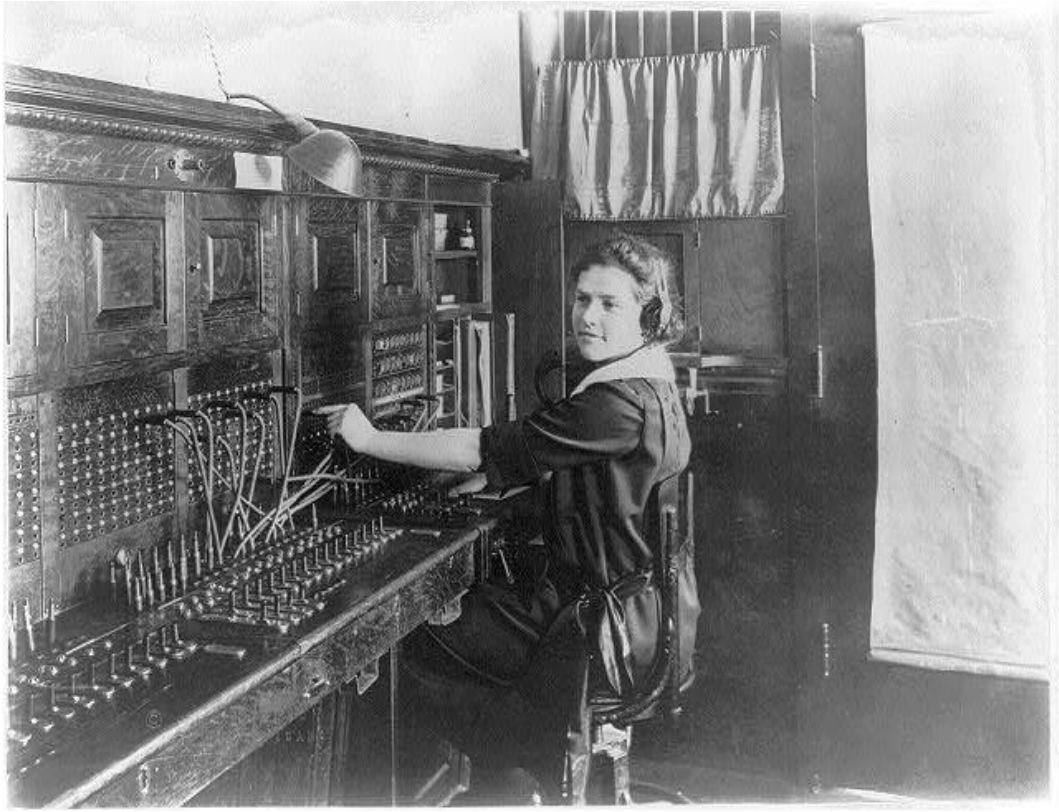
- Consider traffic from multiple sources on a link.
  - What are concerns about sharing that link?
  - What are possible approaches to sharing?

Link Sharing in the Internet

- Circuit switching
  - Fixed end-to-end connection
  - Link resources are reserved
  - Similar to telephony network
- Packet switching
  - Each data packet travels through network on its own
  - Buffering on nodes to handle contention for link
  - No guarantees for resources
- Hybrid approaches
  - E.g., virtual circuit switching

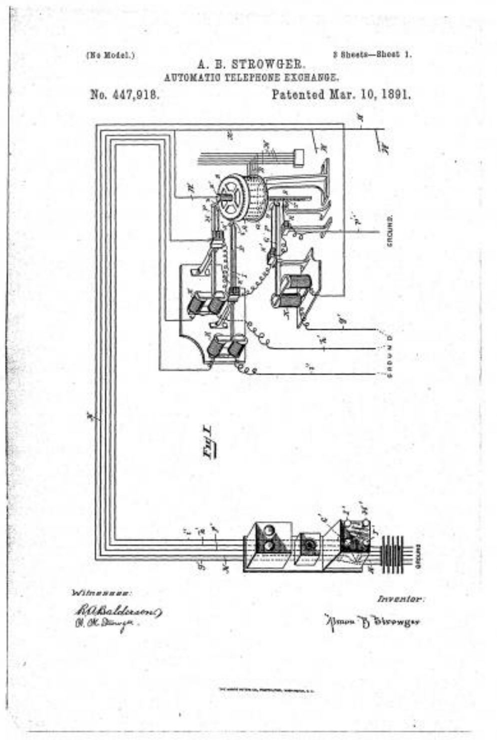
Side Note: Telephone Network

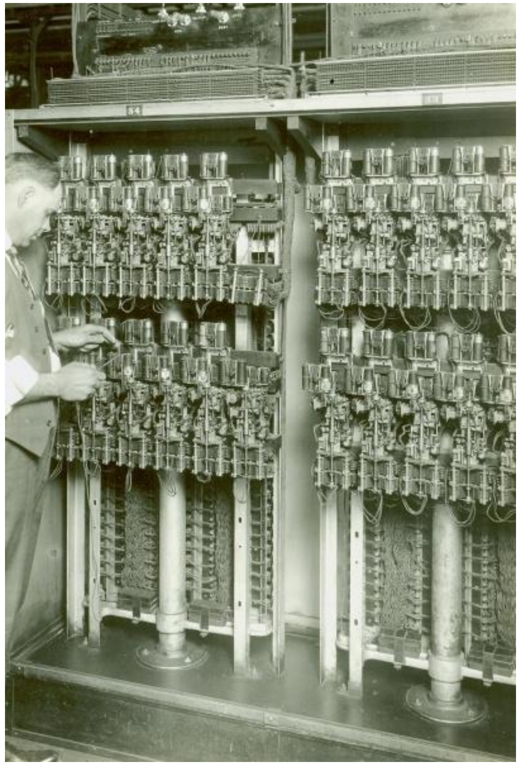
- Two phones need to be connected to each other
  - “Circuit switching” in the true sense of the word
- First generation technology: human



Side Note: Telephone Network

- **Second generation technology: electromechanical switching**





From: http://ethw.org/Electromechanical_Telephone-Switching

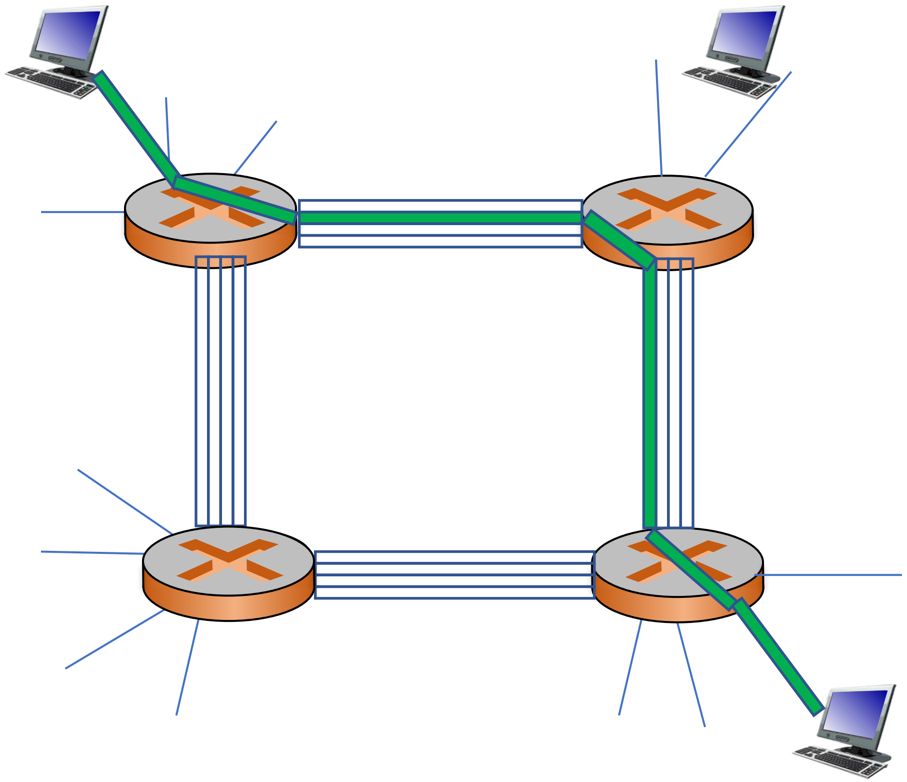
Side Note: Telephone Network

- Third generation: fully electronic switching

https://en.wikipedia.org/wiki/Number_One_Electronic_Switching_System

Circuit Switching in the Internet

- Links have multiple (four) circuits
  - Connection reserves a circuit during setup phase
- End-to-end connection by connecting circuits between switches
- Guaranteed access to reserved circuit
  - Cannot be used by other connection
- Same principle as telephony network



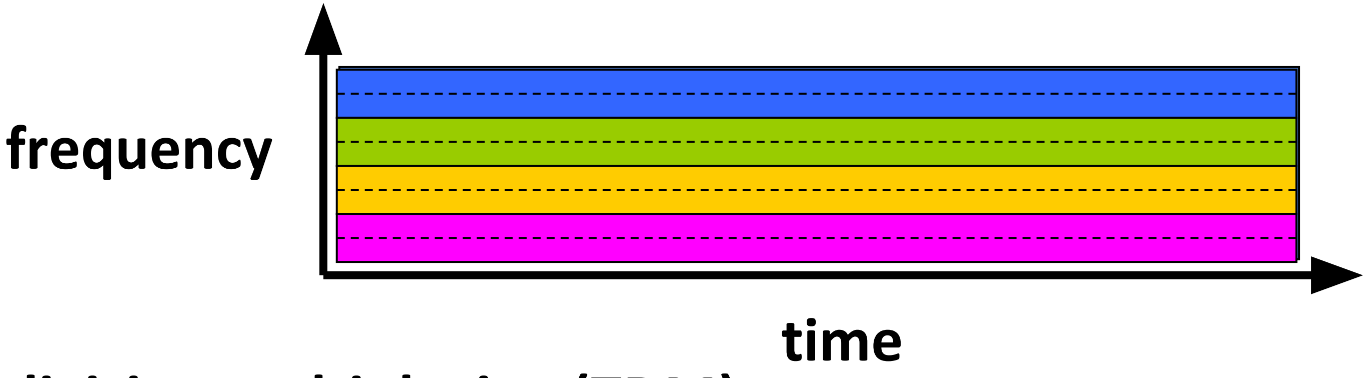
Link Sharing in Circuit Switching

- Approaches to divide link resources:

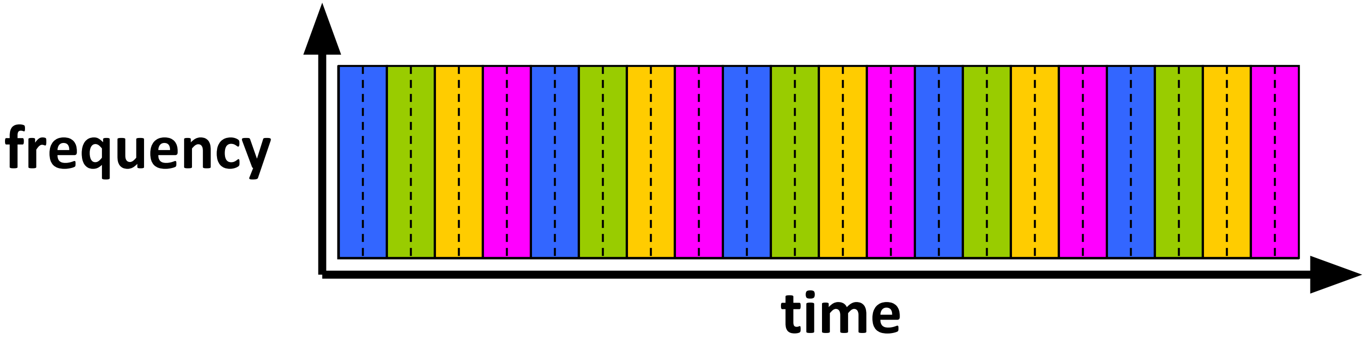
Example:

4 users

Frequency division multiplexing (FDM)

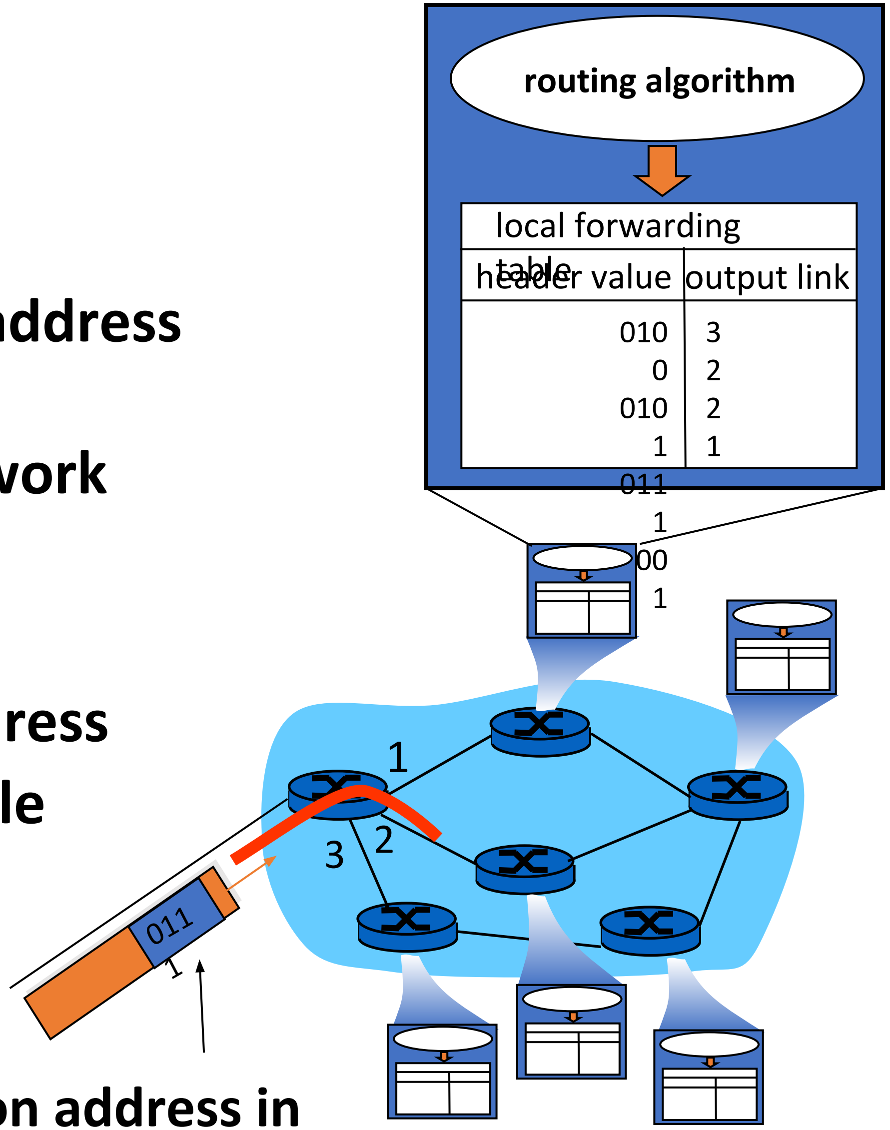


Time division multiplexing (TDM)



Packet Switching

- Traffic is divided into packets
  - Packets carry destination address in header
  - Each packet traverses network independently
- Nodes forward packets
  - Lookup on destination address
  - Each nodes needs to be able to forward to any destination address



destination address in arriving packet's header

Whiteboard: Circuit Switching vs. Packet Switching

Which property do you associate with circuit switching vs. packet switching? (Why?)

Property	Circuit Switching	Packet Switching	Depends
Better resource utilization			
Guaranteed bandwidth performance			
Easier to implement			
Less end-to-end delay variation			
Fairer			
More robust under failure			
Cheaper			

Circuit Switching vs. Packet Switching

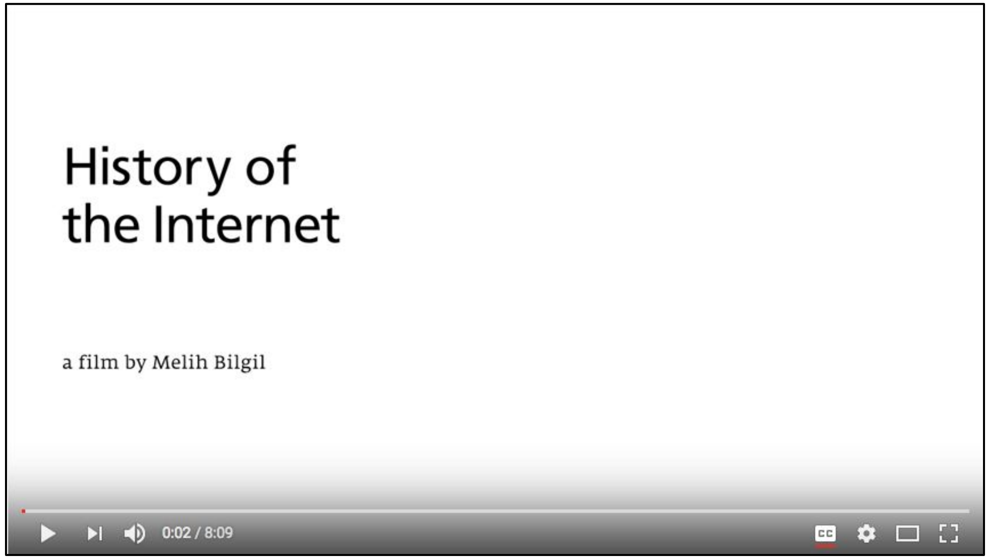
- Which property do you associate with circuit switching vs. packet switching? (Why?)
  - Better resource utilization (packet switching)
  - Guaranteed bandwidth performance (circuit switching)
  - Easier to implement (depends)
  - Less end-to-end delay variation (circuit switching)
  - Fairer (depends)
  - More robust under failure (packet switching)
  - Cheaper (depends)

Coordination Tradeoff

- Circuit switching vs. packet switching is example of engineering tradeoff
  - Coordination vs. best-effort
- Circuit switching requires more coordination, but provides better guarantees
  - Call setup necessary to reserve resources
- Packet switching requires no coordination, but provides no guarantees
  - Any end-system can send to any other at any time

Video: History of the Internet

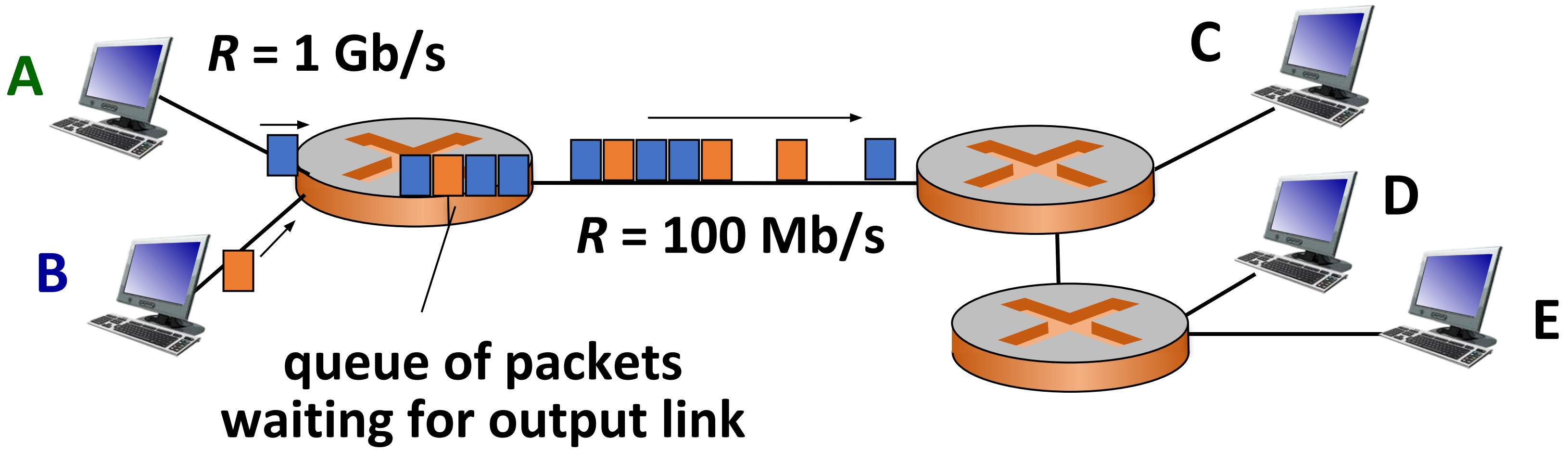
- Illustration of how concepts developed over time



- Internet today is a network of networks, has layered protocol stack, is packet switched (shared links with statistical operation)

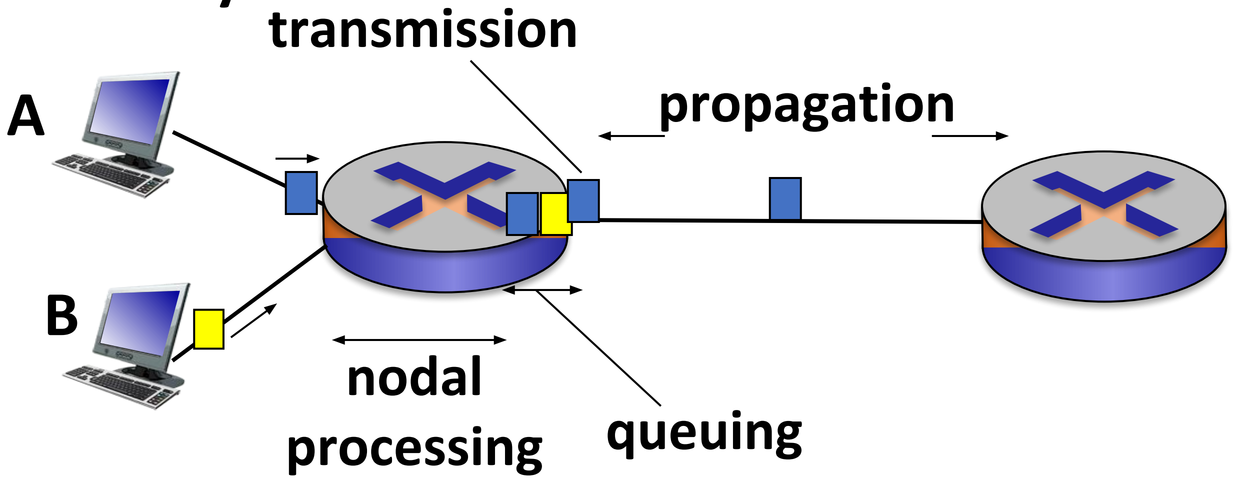
Packet Loss and Delays

- Packet switching can lead to packet loss and delays
- Traffic from A and from B have to share buffer on output link of router
  - Delay variation: depending on buffer level
  - Packet loss: if buffer is already full



Packet Delay

- Four sources of packet delay:



$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

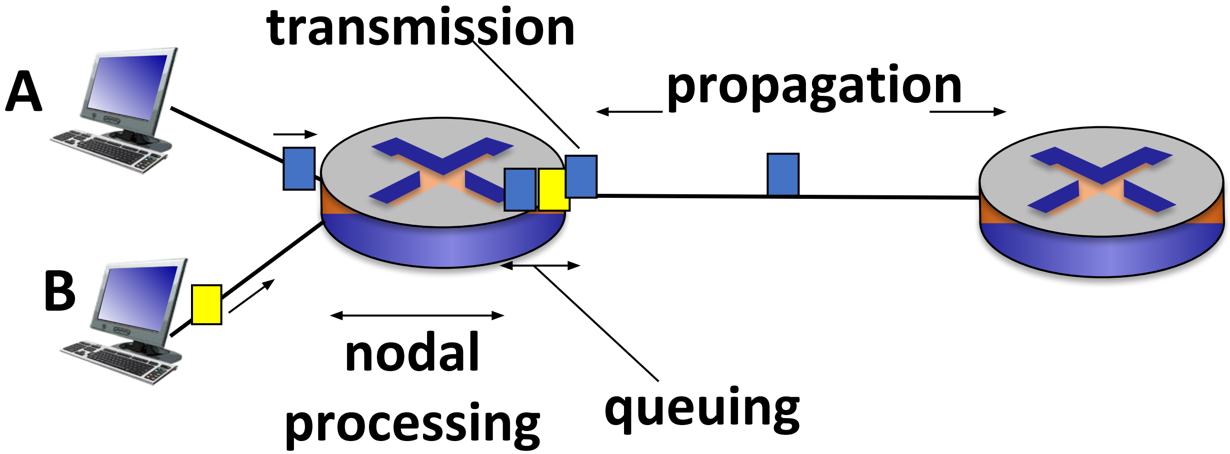
d_{proc}: nodal processing

- check bit errors
- determine output link
- typically < msec

d_{queue}: queuing delay

- time waiting at output link for transmission
- depends on congestion level of router

Packet Delay



$$d_{nodal} = d_{proc} + d_{queue} + d_{trans} + d_{prop}$$

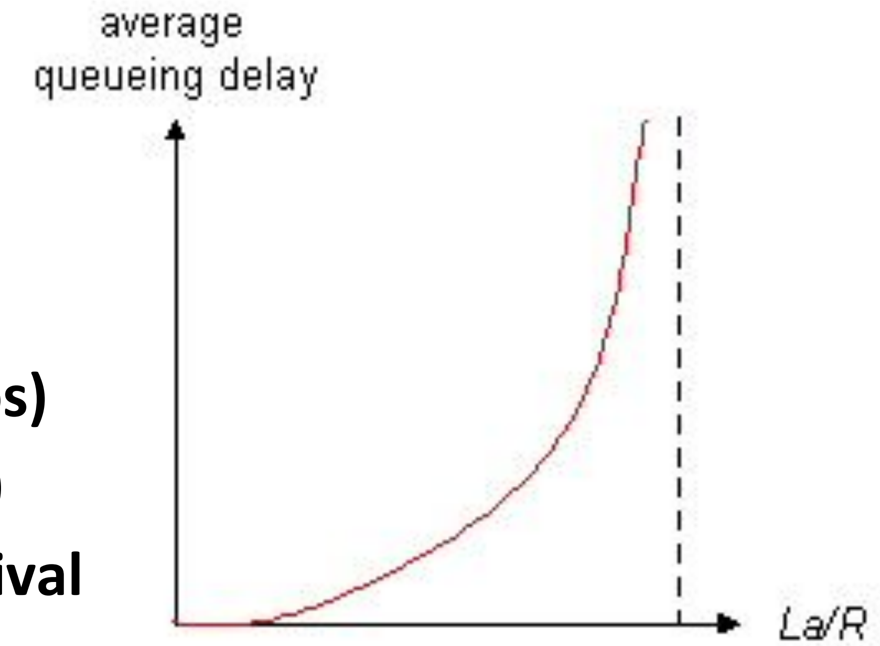
d_{trans}: transmission delay
- *L*: packet length (bits)
- *R*: link *bandwidth (bps)*
- $d_{trans} = L/R$

d_{trans} and d_{prop} *very* different

d_{prop}: propagation delay
- *d*: length of physical link
- *s*: propagation speed (~2×10^8 m/sec)
- $d_{prop} = d/s$

Queuing Delay

- We will study queuing later in the course
  - *R:* link bandwidth (bps)
  - *L:* packet length (bits)
  - a: average packet arrival rate



- *La/R* ~ 0: avg. queueing delay small
- *La/R* -> 1: avg. queueing delay large
- *La/R* > 1: more "work" arriving than can be serviced, average delay infinite!

La/R ~ 0

La/R -> 1

Typical Delays

- What is a typical range of each delay?
  - Assumption:
    - 1 Gbps link speed
    - 1250-byte packet
    - 1000 km distance
    - 200000 km/s propagation speed
  - Transmission delay: 10 microseconds (per hop)
  - Propagation delay: 5 milliseconds
  - Processing delay: low microseconds (per hop)
  - Queuing delay: transmission delay of queued packets (per hop)

Packet Delays in Practice

- Demo: “traceroute” tool to measure delays
  - Three packets to each hop along the path
  - Delay to that hop is reported
  - Hop name can give clue about location
  - Some routers do not respond
- What do you observe for different destinations?
  - What is the end-to-end delay?
  - How many hops?
  - Where are the links with long delays?
  - Are the measurement results consistent?

Connected Device: Packet Delays in Practice

- **traceroute Amherst to Berlin:**

wolf — -bash — 87×22

```
Aegnor:~ wolf$ traceroute www.tu-berlin.de
traceroute to www.tu-berlin.de (130.149.7.201), 64 hops max, 52 byte packets
 1  192.168.42.1 (192.168.42.1)  1.713 ms  0.933 ms  1.404 ms
 2  support.spfdma.lmlp.crocker.net (161.77.202.2)  4.298 ms  4.248 ms  3.515 ms
 3  199.188.233.81.lightower.net (199.188.233.81)  10.618 ms  11.494 ms  9.727 ms
 4  ae5-whplnywpj91.lightower.net (104.207.214.79)  14.829 ms  10.691 ms  10.390 ms
 5  ae0-nycmny83j91.lightower.net (104.207.214.142)  11.566 ms  10.440 ms  9.741 ms
 6  ae5-nycmny83j41.lightower.net (104.207.214.182)  9.953 ms  8.950 ms  9.300 ms
 7  ae2-nycmnyzrj91.lightower.net (104.207.214.179)  9.401 ms  15.148 ms  15.278 ms
 8  ae2-nycmnyzrj42.lightower.net (64.72.64.111)  10.444 ms  11.317 ms  10.121 ms
 9  10ge3-2.core1.nyc5.he.net (216.66.50.105)  9.677 ms  8.423 ms  13.372 ms
10  10ge5-7.core1.nyc4.he.net (184.105.213.217)  14.790 ms  10.423 ms  12.535 ms
11  100ge4-1.core1.par2.he.net (184.105.81.78)  85.553 ms  88.076 ms  80.052 ms
12  100ge5-2.core1.fra1.he.net (72.52.92.14)  88.761 ms  88.519 ms  94.234 ms
13  cr-fra1-be1.x-win.dfn.de (80.81.192.222)  96.278 ms  94.996 ms  94.681 ms
14  cr-erl2-be8.x-win.dfn.de (188.1.144.221)  94.755 ms  95.039 ms
    cr-tub2-be10.x-win.dfn.de (188.1.146.210)  95.710 ms
15  kr-tub87-2.x-win.dfn.de (188.1.235.118)  95.137 ms  94.365 ms  94.941 ms
16  e-ns-e-n.gate.tu-berlin.de (130.149.126.78)  342.205 ms  198.481 ms  98.405 ms
17  tu-berlin.de (130.149.7.201)  94.101 ms
    e-ns-e-n.gate.tu-berlin.de (130.149.126.78)  130.398 ms  299.683 ms
Aegnor:~ wolf$
```

Connected Device: Packet Delays in Practice

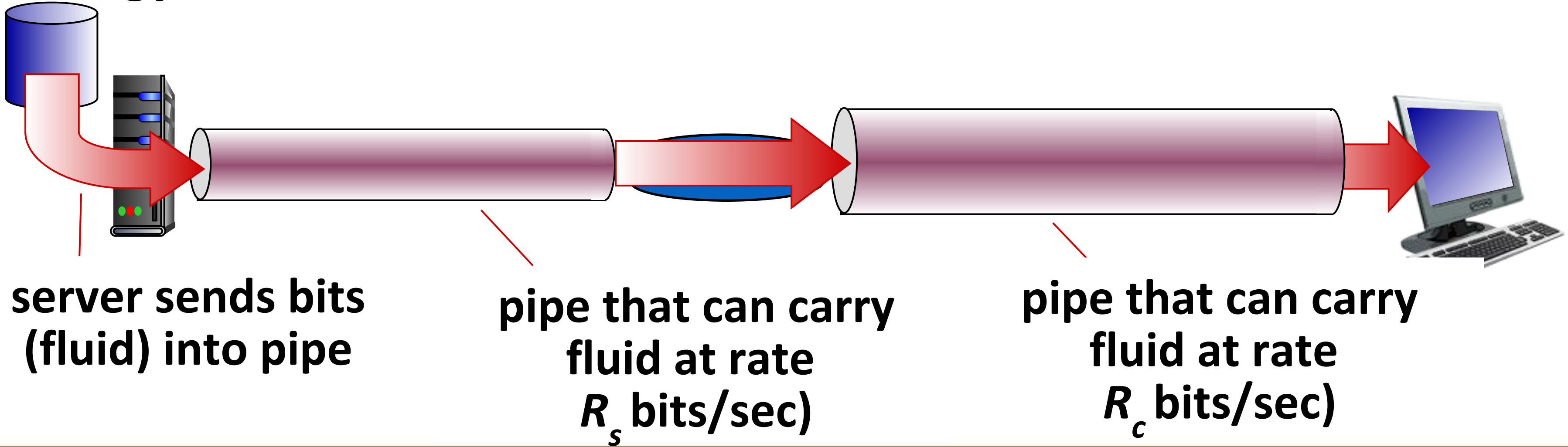
- **traceroute Amherst to Sydney:**

wolf — -bash — 97×23

```
traceroute to sydney.edu.au (129.78.5.8), 64 hops max, 52 byte packets
 1  192.168.42.1 (192.168.42.1)  1.425 ms  1.488 ms  1.624 ms
 2  support.spfdma.lmlp.crocker.net (161.77.202.2)  4.374 ms  3.440 ms  5.787 ms
 3  199.188.233.81.lightower.net (199.188.233.81)  11.364 ms  9.819 ms  9.352 ms
 4  ae5-whplnywpj91.lightower.net (104.207.214.79)  10.042 ms  11.165 ms  21.597 ms
 5  ae0-nycmny83j91.lightower.net (104.207.214.142)  11.253 ms  10.562 ms  10.396 ms
 6  ae5-nycmny83j41.lightower.net (104.207.214.182)  9.891 ms  10.355 ms  10.350 ms
 7  ae2-nycmnyzrj91.lightower.net (104.207.214.179)  11.138 ms  11.247 ms  10.152 ms
 8  ae2-nycmnyzrj42.lightower.net (64.72.64.111)  9.634 ms  9.894 ms  10.079 ms
 9  10ge3-2.core1.nyc5.he.net (216.66.50.105)  12.820 ms  10.246 ms  14.232 ms
10  10ge5-7.core1.nyc4.he.net (184.105.213.217)  18.102 ms  11.032 ms  13.382 ms
11  100ge5-1.core1.chi1.he.net (184.105.223.161)  35.716 ms  73.323 ms  35.694 ms
12  100ge14-2.core1.msp1.he.net (184.105.223.178)  33.647 ms  34.376 ms  33.147 ms
13  100ge4-1.core1.sea1.he.net (184.105.223.193)  68.048 ms  65.666 ms  68.728 ms
14  gigabitethernet3-0.bb1.b.sea.aarnet.net.au (206.81.80.112)  64.672 ms  64.520 ms
    as7575.seattle.megaport.com (206.53.171.12)  77.487 ms
15  xe-1-0-1.pe2.brwy.nsw.aarnet.net.au (202.158.194.120)  408.804 ms  409.352 ms  409.053 ms
16  et-3-1-0.pe1.brwy.nsw.aarnet.net.au (113.197.15.146)  410.389 ms  409.223 ms  216.409 ms
17  gw1.vl216.ae11.pe1.brwy-pe1.aarnet.net.au (138.44.5.47)  399.973 ms  218.473 ms  387.651 ms
18  * * *
19  * * *
20  scilearn.sydney.edu.au (129.78.5.8)  292.144 ms  409.944 ms  409.558 ms
Aegnor:~ wolf$
```

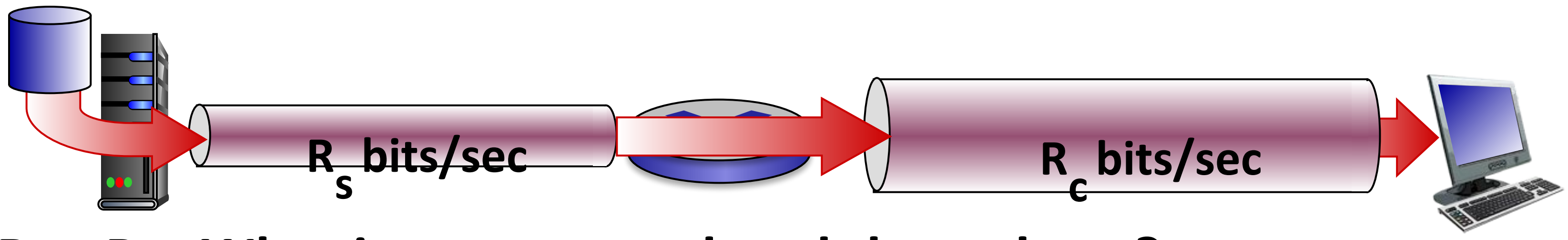
Throughput

- Throughput is rate (bits/time unit) at which data are transferred between sender/receiver
  - Instantaneous throughput: rate at given point in time
  - Average throughput: rate over longer period of time
- Fluid analogy:

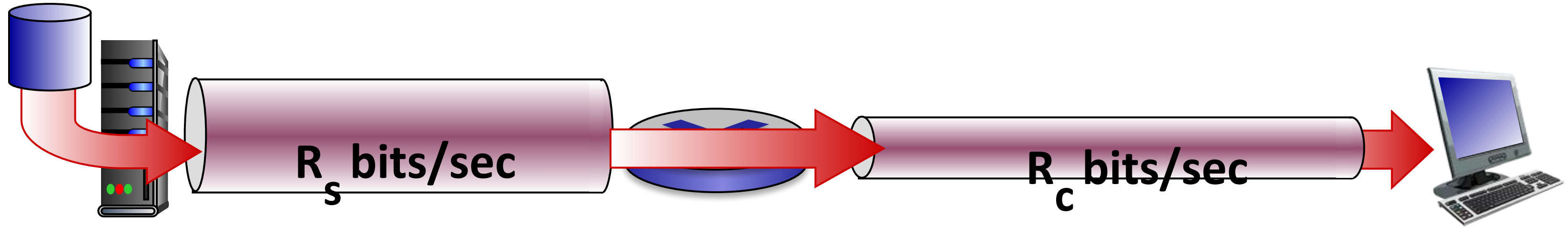


Throughput

- $R_s < R_c$: What is average end-end throughput?



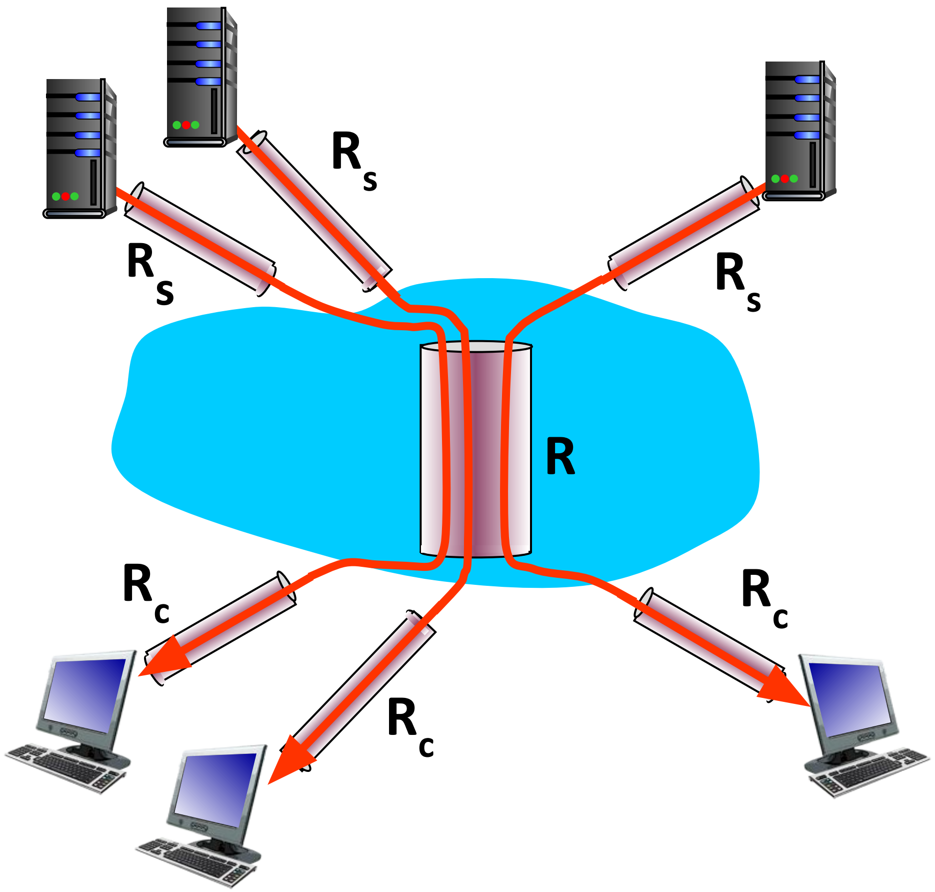
- $R_s > R_c$: What is average end-end throughput?



- Bottleneck link
  - Link on end-end path that constrains end-end throughput

Throughput and Fairness

- What if traffic from multiple connections share link?
  - Will fair sharing occur?
- No answer (yet)
  - We will see this again in congestion control and fair scheduling



Connected Device: Traceroute Activity

- To do from home: Observe Packet Delays in practice
  - Experiment with Traceroute
    - Go to website
    - Choose any country
    - Trace the route from that source to your computer

Summary of Lesson

- Engineering principles
    - Hierarchy
    - Layering/modularization
    - Resource sharing
    - Statistical operation
- Delay and throughput

Post-work for Lesson 2

Homework #1

- **After the Live Lecture, you will complete and submit a homework assignment. Go to the online classroom to view and submit the assignment.**

Homework (Tracerout)

- **After the Live Lecture, you will complete and submit a homework assignment. Go to the online classroom to view and submit the assignment.**

To Prepare for the Next Lesson

- Complete and submit the Post-work for Lesson 2.
- Read the Required Readings for Lesson 3.
- Complete the Pre-work for Lesson 3.

Go to the online classroom for details.