南京大學
NANJING UNIVERSITY

Computer Networks

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Material with thanks to James F. Kurose, Mosharaf Chowdhury, and other colleagues.

教学团队

- 李文中（一班）
- 研究方向：分布计算与并行处理、移动互联网、社交网络、大数据挖掘
- 个人主页：http://cs.nju.edu.cn/lwz/

- 田臣（二班）
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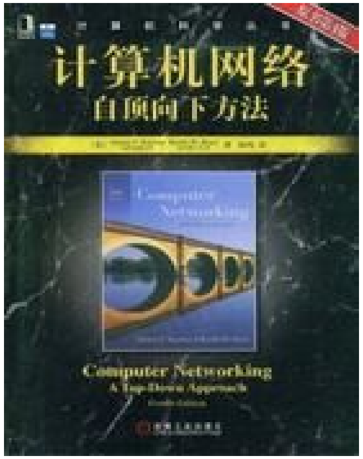
- 课程主页：http://cs.nju.edu.cn/lwz/networks/
- 助教QQ群：待公布（实验验收、作业提交、答疑）

课程概况

- 课程名称：计算机网络
- 课程编号：22010050
- 授课方式：课堂讲授+实验
  - 实验课每两周一次，共7-8次实验
- 课程考核
  - 平时成绩：15%
  - 实验: 25%
  - 期末考试: 60%

参考书籍

- James F. Kurose, Keith W. Ross. 计算机网络—自顶向下方法 (6th). 机械工业出版社，2014.



- William Stallings. 数据与计算机通信 (8th). 电子工业出版社

课程大纲

- Internet简介（教材第1章）
- 链路层（教材第5章，第6章）
- 网络层（教材第4章）
- 传输层（教材第3章，第7章）
- 网路安全（教材第8章）

- 作业习题：以教材第6版为准

Chapter 1. Introduction of Networking

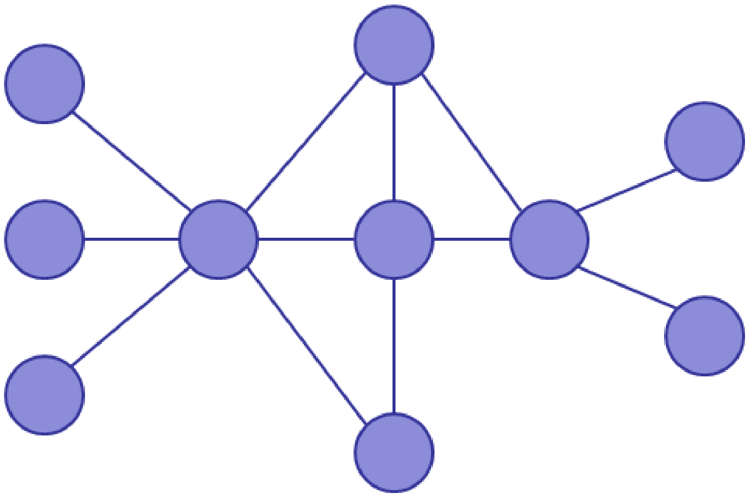
- Basic Concepts and Questions

- Internet History
- Protocol Layers and Service Model
- Network Performance

Concept: Internet

What is a network?

- A system of “links” that interconnect “nodes” in order to move “information” between nodes



- Yes, this is very vague

Different types of networks

- Internet
- Telephone network
- Wireless networks
- Optical networks
- Datacenter networks
- *Transportation networks*
- *Social networks*

We will focus primarily on *the Internet*

What is the Internet?

- [WiKi]
  - The Internet is the global system of interconnected mainframe, personal, and wireless computer networks that use the Internet protocol suite (TCP/IP) to link billions of devices worldwide.
  - It is a network of networks that consists of millions of private, public, academic, business, and government networks of local to global scope, linked by a broad array of electronic, wireless, and optical networking technologies.

The Internet is transforming everything

- The way we do business
  - E-commerce, advertising, cloud-computing
- The way we have relationships
  - Facebook friends, E-mail, IM, virtual worlds
- The way we learn
  - Wikipedia, MOOCs, search engines
- The way we govern and view law
  - E-voting, censorship, copyright, cyber-attacks

MASSIVE Scale

- 3.5 Billion users (34% of world population)
- 1 Trillion websites
- 200 Billion emails sent per day
- 2 Billion smartphones
- 1.8 Billion Facebook users
- 4 Billion YouTube videos watched per day
- Routers that switch 10 Terabits/second
- Links that carry 100 Gigabits/second

Diversity in all dimensions

- Technology
  - Optical, wireless, satellite, copper
- Endpoint devices
  - From wearable devices and cell phones to datacenters and supercomputers
- Applications
  - Video streaming, social networking, file transfer, Skype, live TV, gaming, remote medicine, IM
- Users
  - Malicious, naïve, savvy, embarrassed, paranoid

The Internet is a lesson

- In how to reason through the design of a <u>very</u> complex system
  - What are our goals and constraints?
  - What's the right prioritization of goals?
  - How do we decompose a problem?
  - Who does what? How?
  - What are the interfaces between components?
  - What are the tradeoffs between design options?

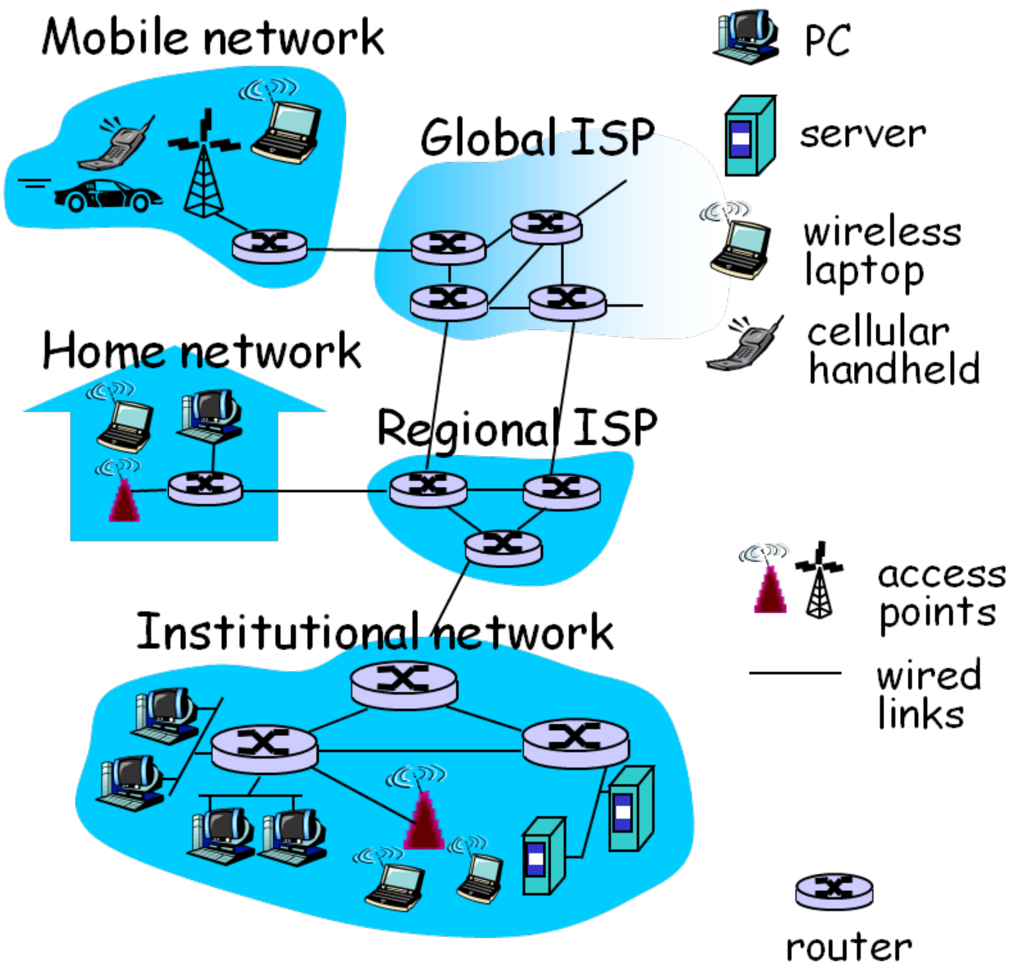
Basic questions:

Q1: What is the Internet made of?
Q2: How to connect to the Internet?
Q3: How to transfer data in the network?

Q1: What is the Internet made of?

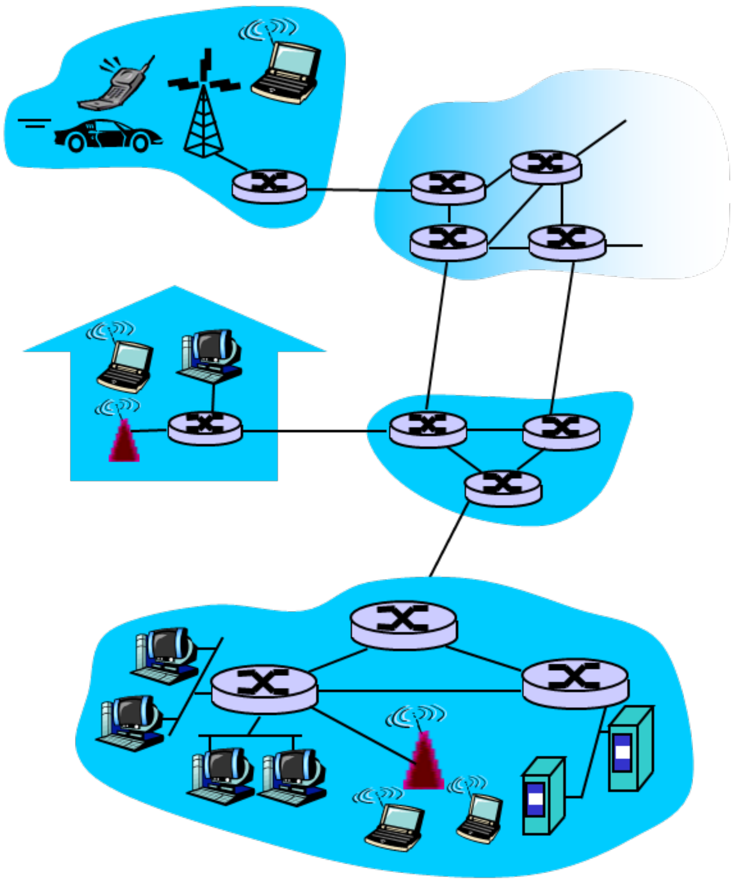
Internet – Component View

- Millions of connected computing devices
  - Hosts = End systems
  - Running network applications
- Communication links
  - Fiber, Copper, Radio, Satellite
  - Building physical networks
- Routers
  - Forward packets (chunks of data) between physical networks



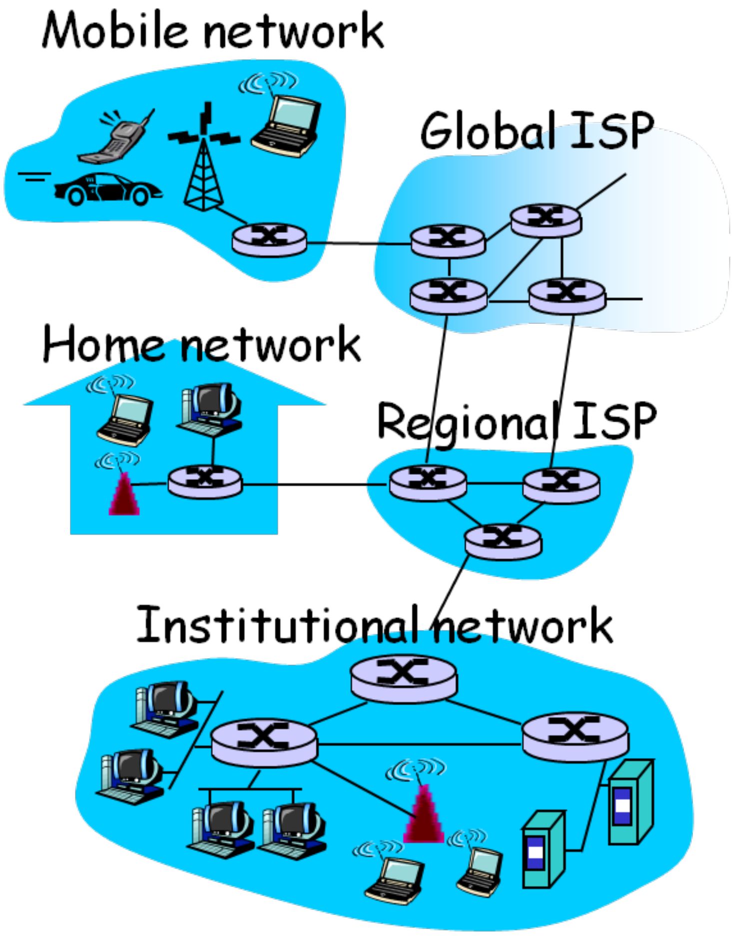
Internet – Service View

- Communication infrastructure
  - Enables distributed applications
  - Web, VoIP, email, online games, e-commerce, file sharing
- Communication services provided to Apps:
  - Reliable data delivery from source to destination
  - "best effort" (unreliable) data delivery
  - Guaranteed delay and throughput



Internet – Protocols

- Network Protocols
  - Control sending, receiving of messages
  - e.g. HTTP, Skype; TCP, IP; PPP, Ethernet
- Internet standards
  - IETF: Internet Engineering Task Force
  - RFC: Request for comments
- Internet: "network of networks"
  - Public Internet versus private Intranet
  - Loosely hierarchical



What's a protocol?

human protocols:

- "what's the time?"
- "I have a question"

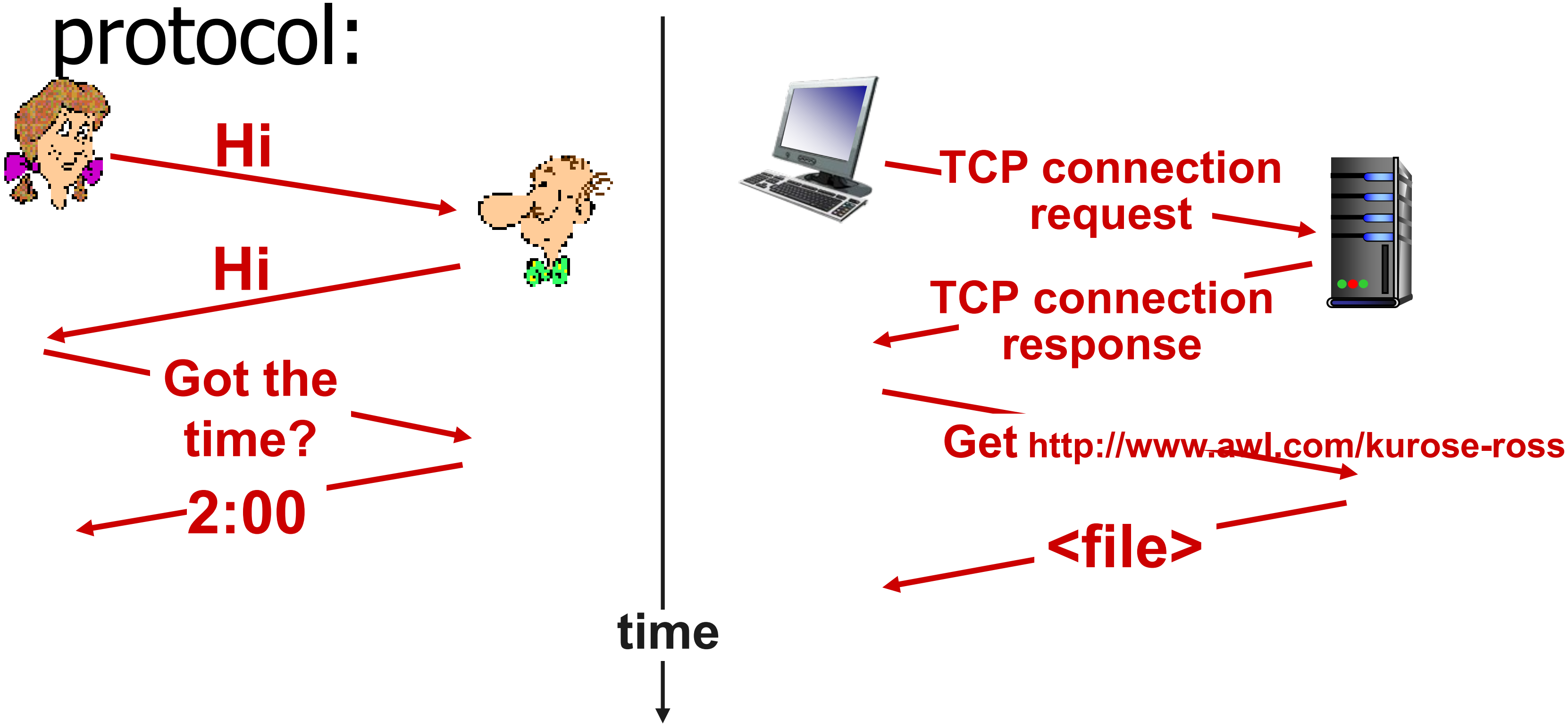
… specific msgs sent

… specific actions taken when msgs received, or other events

network protocols:

- machines rather than humans
- all communication activity in Internet governed by protocols

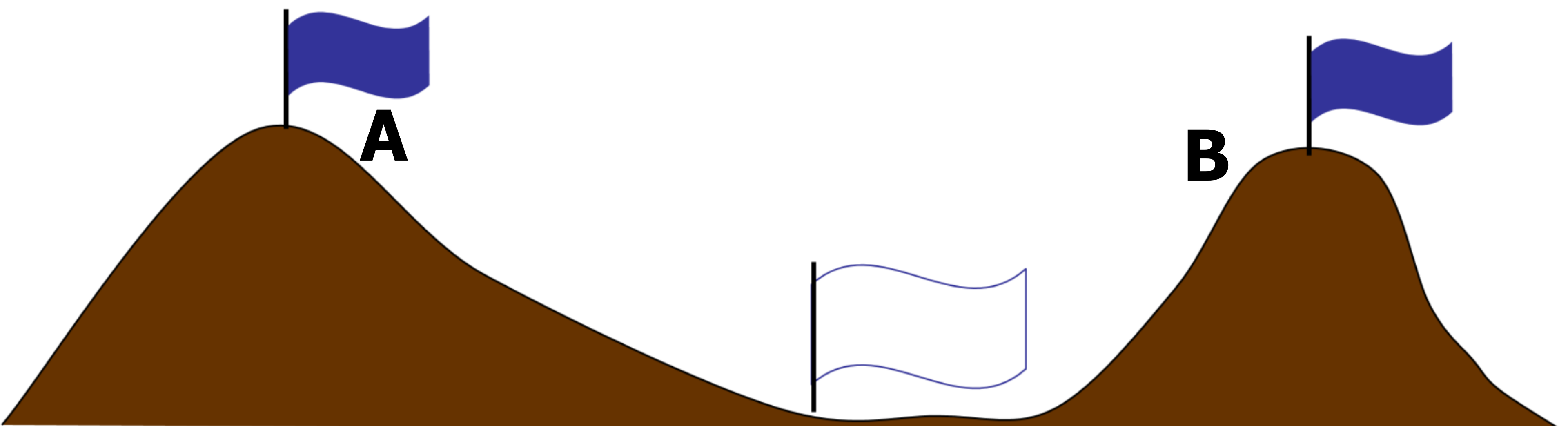
***protocols** define **format**, **order** of **msgs sent and received** among network entities, and **actions taken** on msg transmission, receipt* a human protocol and a computer network protocol:



Reliability of Communication

例子：蓝军-白军作战

- 占据东、西两个山顶的蓝军**A**和蓝军**B**与驻扎在山谷的白军作战。其力量对比是：单独的蓝军**A**或蓝军**B**打不过白军，但蓝军**A**和蓝军协同作战则可战胜白军。
  - **A**和**B**可以派遣通信兵穿过白军营地向对方发送消息，但是通信兵有可能被白军截获。
  - 现蓝军**A**拟于次日正午向白军发起攻击。有什么方法能保证蓝军取得胜利？



明日正午进攻，如何？

同意

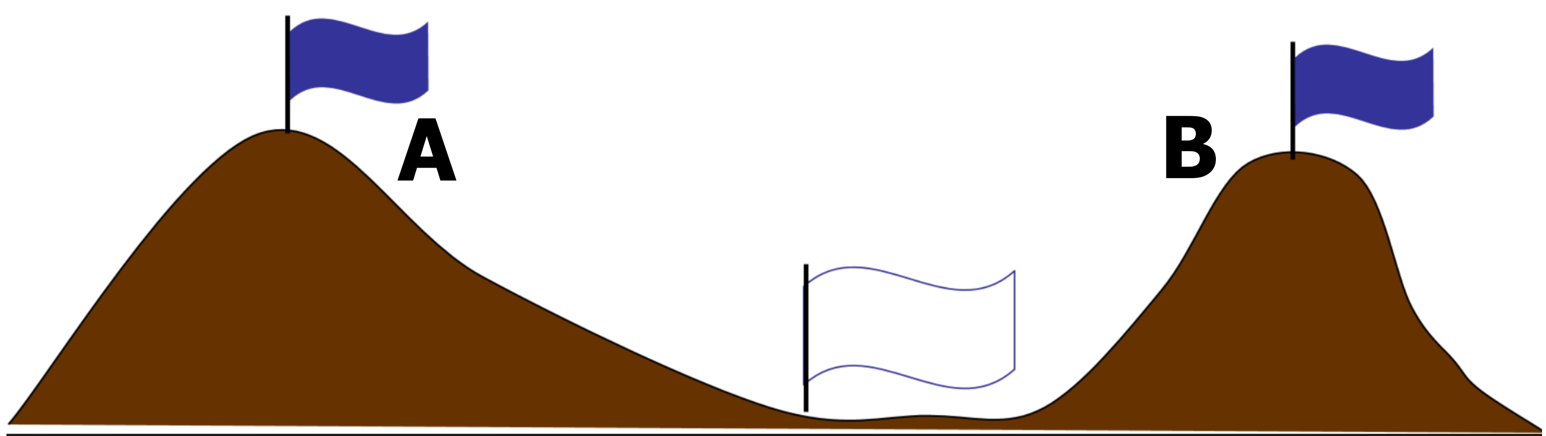
收到“同意”

收到：收到“同意”

…

…

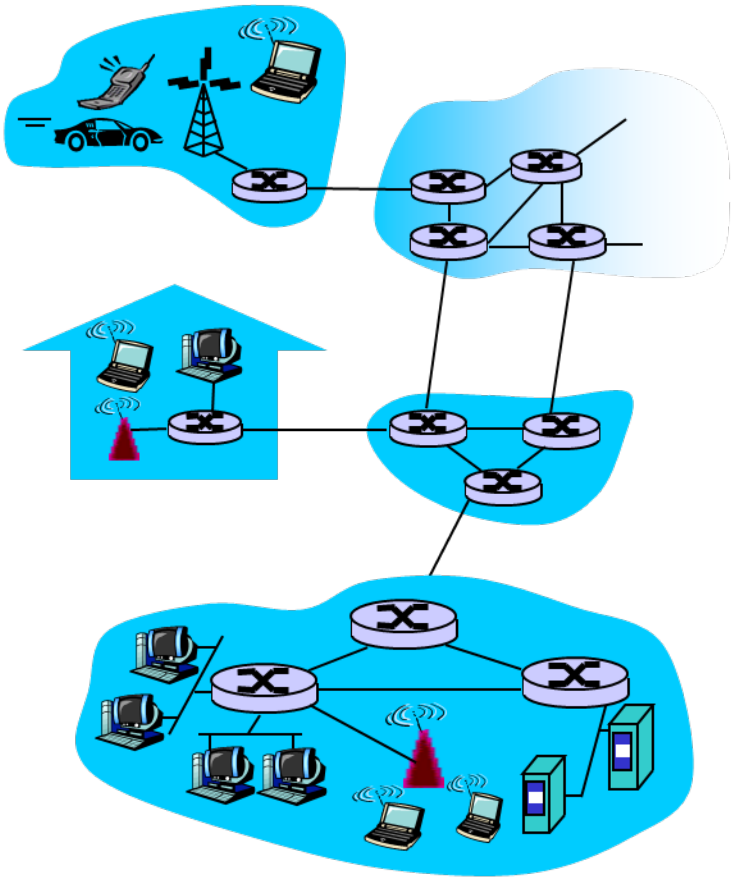
这样的协议无法实现！
没有方法能保证蓝军100%取得胜利



Q2: How to connect to the Internet?

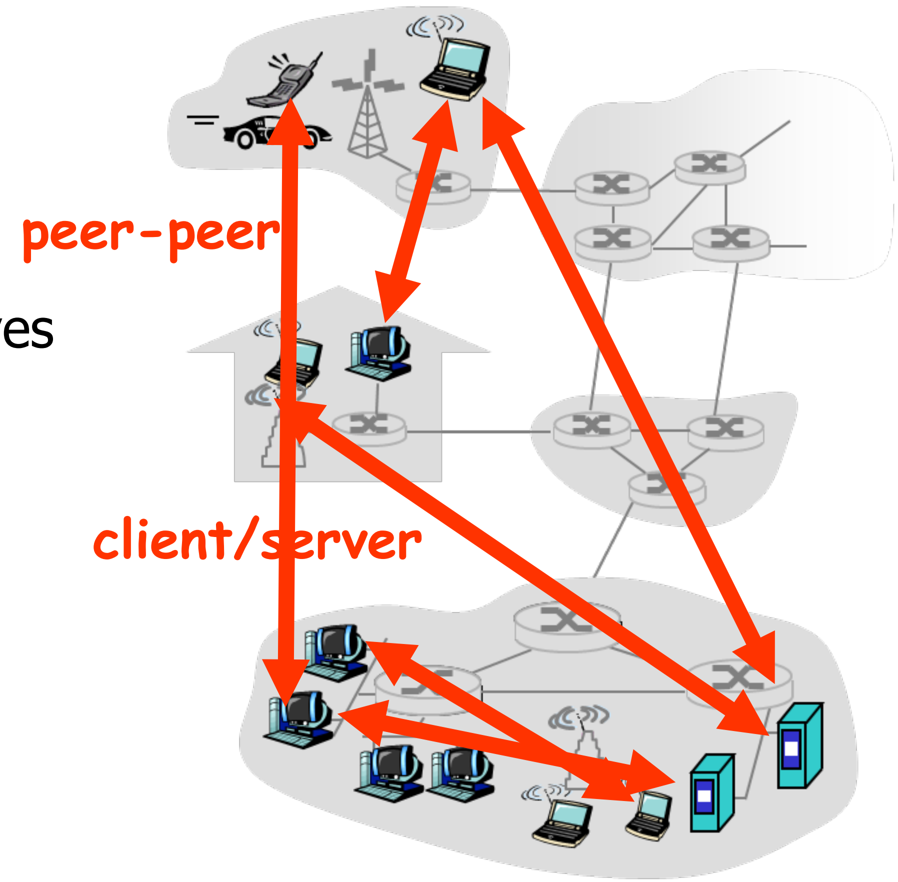
Access Internet

- Network edge
  - Applications and hosts
- Access networks
  - Physical media
  - Wired and wireless communication links
- Network core
  - Interconnected routers
  - Network of networks



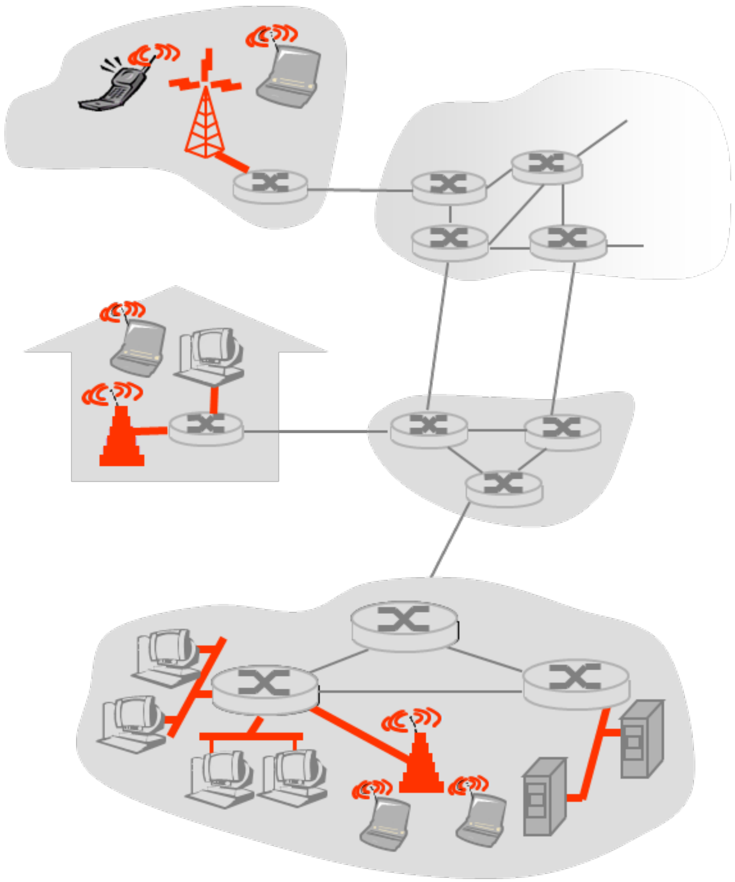
Network Edge

- End systems (hosts)
  - Run application programs
  - e.g. Web, Email
- Client/server model
  - Client host requests, receives service from always-on server
  - e.g. Web browser/server; Email client/server
- Peer-to-peer model
  - Minimal (or no) use of dedicated servers
  - e.g. Skype, BitTorrent



Access Networks

- How to connect end systems to edge router?
  - Residential (Home) access networks
  - Institutional access networks (school, company)
  - Mobile access networks



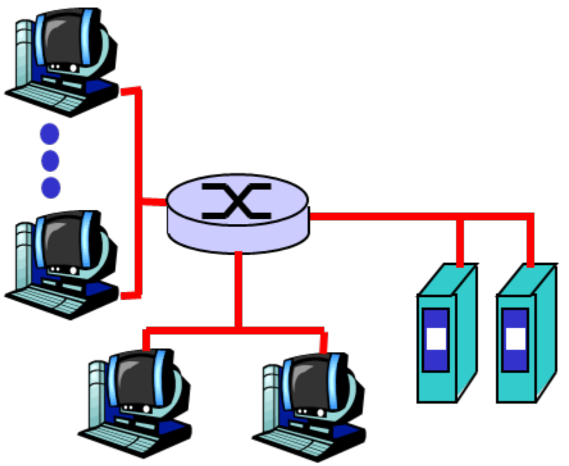
Residential Access

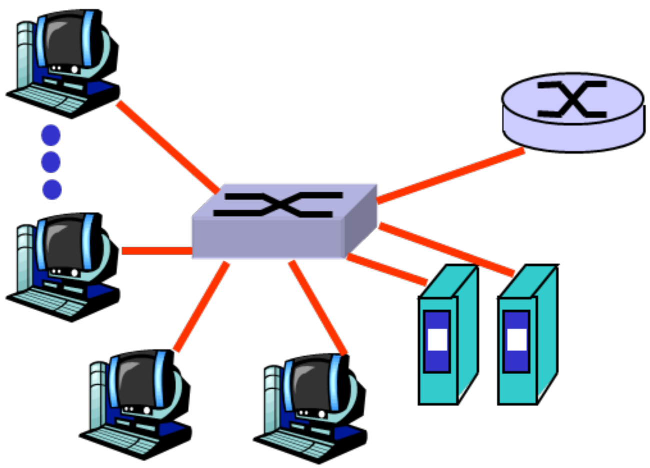
- Dialup via modem
  - Up to 56Kbps direct access to router
- DSL: digital subscriber line
  - Deployment: telephone company
  - Up to 1 Mbps upstream, and 8 Mbps downstream
  - Dedicated physical line to telephone central office
- HFC: hybrid fiber coax
  - Asymmetric: up to 30Mbps downstream, 2 Mbps upstream
  - Homes share access to ISP router
  - Deployment: cable TV companies

Company Access: Local Area Networks

- Company/University local area network (LAN) connects end systems to edge router

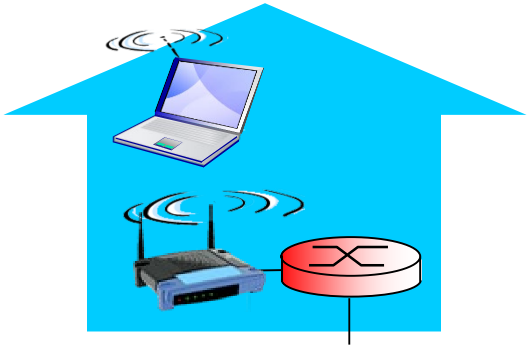
- Ethernet:
  - 10 Mbs, 100Mbps, 1Gbps, 10Gbps Ethernet
  - Modern configuration: end systems connect into backbone of Ethernet switches





Wireless Access Networks

- Shared wireless media connects end system to router
  - via base station, or "access point"
- Wireless LANs:
  - 802.11b/g (WiFi): 11 or 54 Mbps
- Wider-area wireless access
  - Provided by telecommunication operator，10's Km
  - between 1 and 10 Mbps
  - 3G, 4G: LTE, WiMax



Physical media

- bit: propagates between transmitter/receiver pairs
- physical link: what lies between transmitter & receiver
- guided media:
  - signals propagate in solid media: copper, fiber, coax
- unguided media:
  - signals propagate freely, e.g., radio

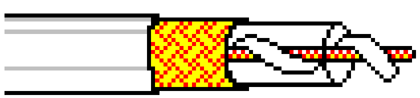
twisted pair (TP)

- two insulated copper wires
  - Category 5: 100 Mbps, 1 Gpbs Ethernet
  - Category 6: 10Gbps

Physical media: coax, fiber

coaxial cable:

- two concentric copper conductors
- bidirectional
- broadband:
  - multiple channels on cable



fiber optic cable:

- **glass fiber carrying light pulses, each pulse a bit**
- **high-speed operation:**
  - **high-speed point-to-point transmission (e.g., 10's-100's Gpbs transmission rate)**
- **low error rate:**
  - **repeaters spaced far apart**
  - **immune to electromagnetic noise**

Physical media: radio

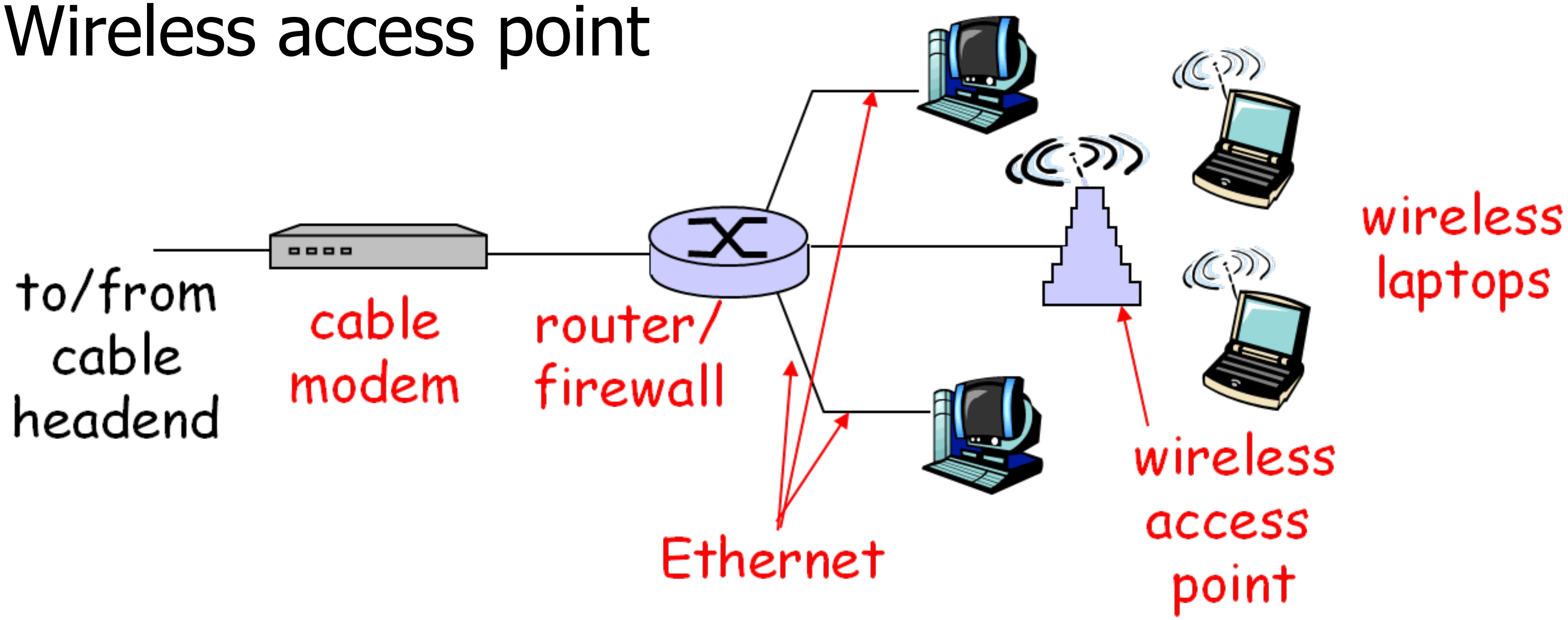
- signal carried in electromagnetic spectrum
- no physical "wire"
- bidirectional
- propagation environment effects:
  - reflection
  - obstruction by objects
  - interference

radio link types:

- **terrestrial microwave**
  - e.g. up to 45 Mbps channels
- **LAN (e.g., WiFi)**
  - 11Mbps, 54 Mbps
- **wide-area (e.g., cellular)**
  - 3G cellular: ~ 1 Mbps
- **satellite**
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - 270 msec end-end delay
  - geosynchronous versus low altitude

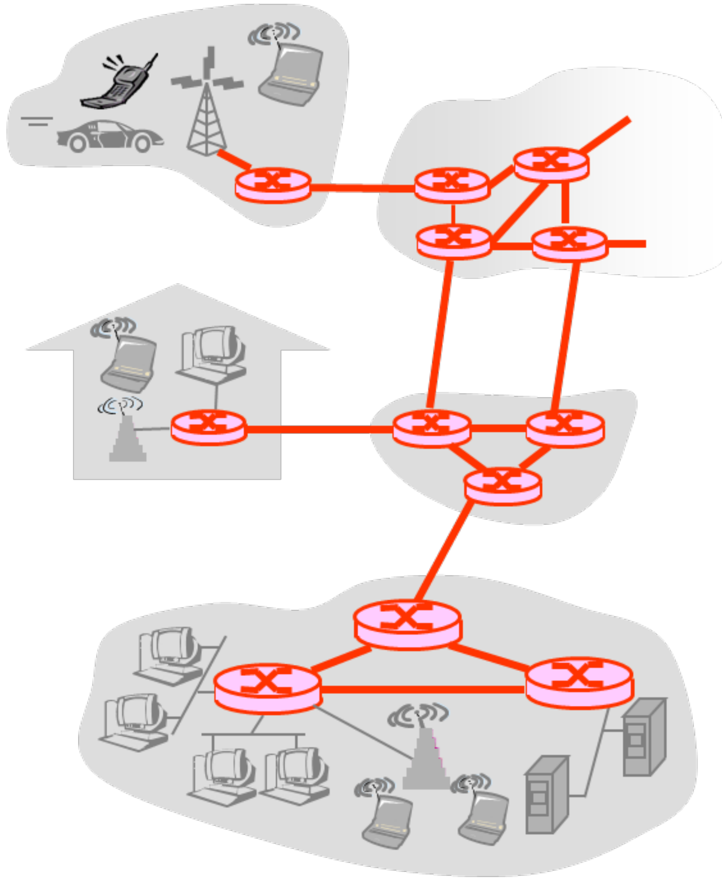
Example: A Modern Family

- A home network components:
  - DSL or cable modem
  - Router/Firewall/NAT
  - Ethernet switch
  - Wireless access point



The Network Core

- Mesh of interconnected routers
- Fundamental question
  - How is data transferred through the net?
- Circuit switching
  - Dedicated circuit per call, e.g. telephone net
- Packet-switching
  - hosts break application-layer messages into packets
  - forward packets from one router to the next, across links on path from source to destination



- 请归类：
  - 属于网络边缘的是：____________
  - 属于接入网络的是：____________
  - 属于网络核心的是：____________

A 笔记本电脑；　B 手机；　C 路由器；

D 双绞线；E 智能家具；　F 无线路由器；

G 服务器；　H 同轴电缆；　I 光纤；J 交换机

- 请归类：
  - 属于网络边缘的是：___A B E G______
  - 属于接入网络的是：___D F H I______
  - 属于网络核心的是：___C J__________

A 笔记本电脑；　B 手机；　C 路由器；

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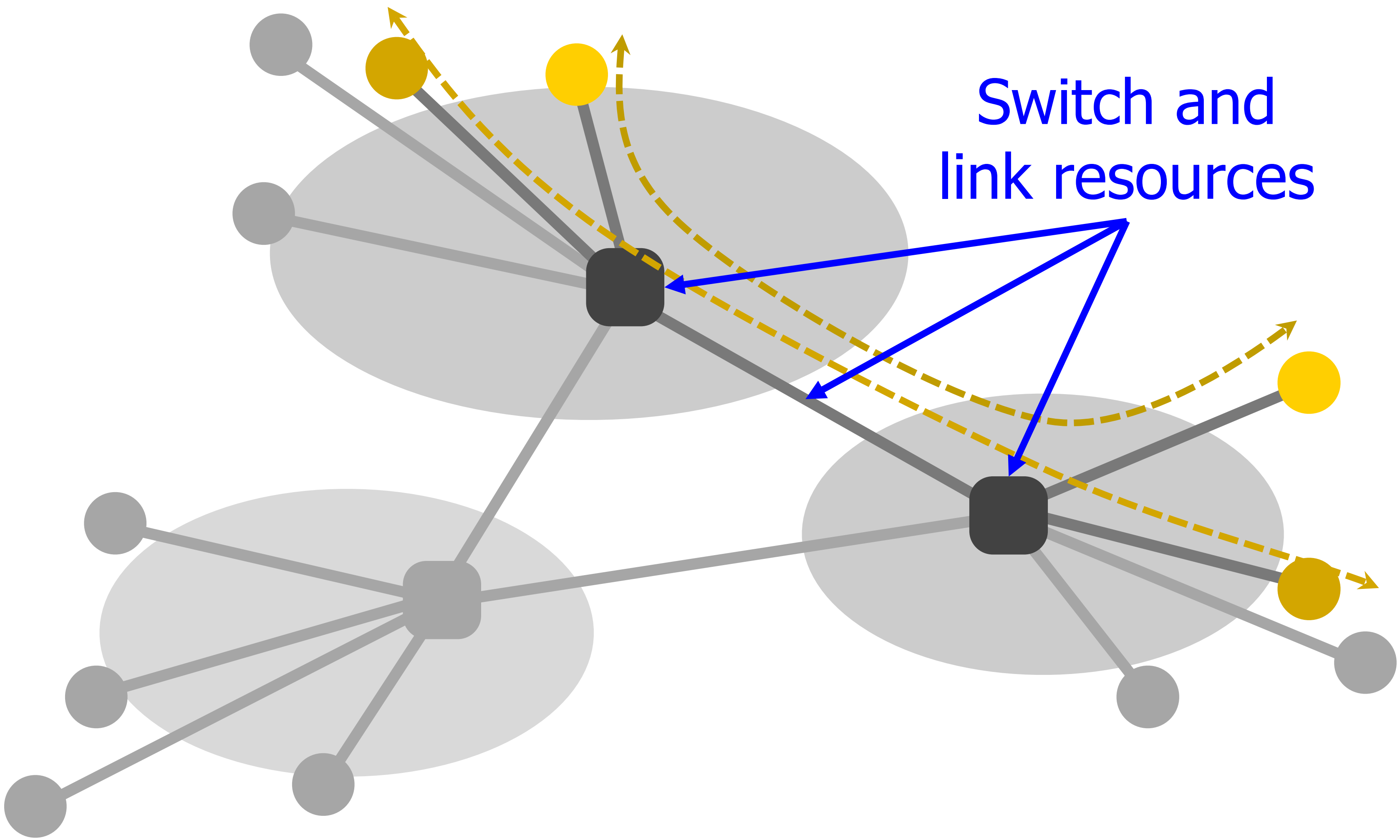
Q3: How to transfer data in the network?

Switched networks

- End-systems and networks connected by switches instead of directly connecting them
- Allows us to scale
  - For example, directly connecting N nodes to each other would require N^2 links!

When do we need to share the network?



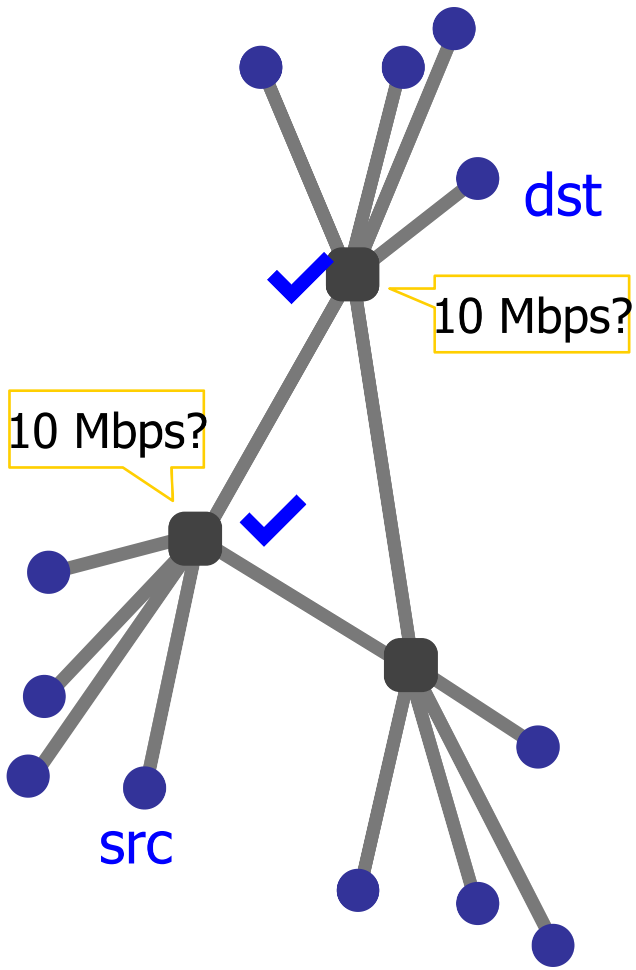
Two ways to share switched networks

- Circuit switching
  - Resource reserved per connection
  - Admission control: per connection
- Packet switching
  - Packets treated independently, on-demand
  - Admission control: per packet

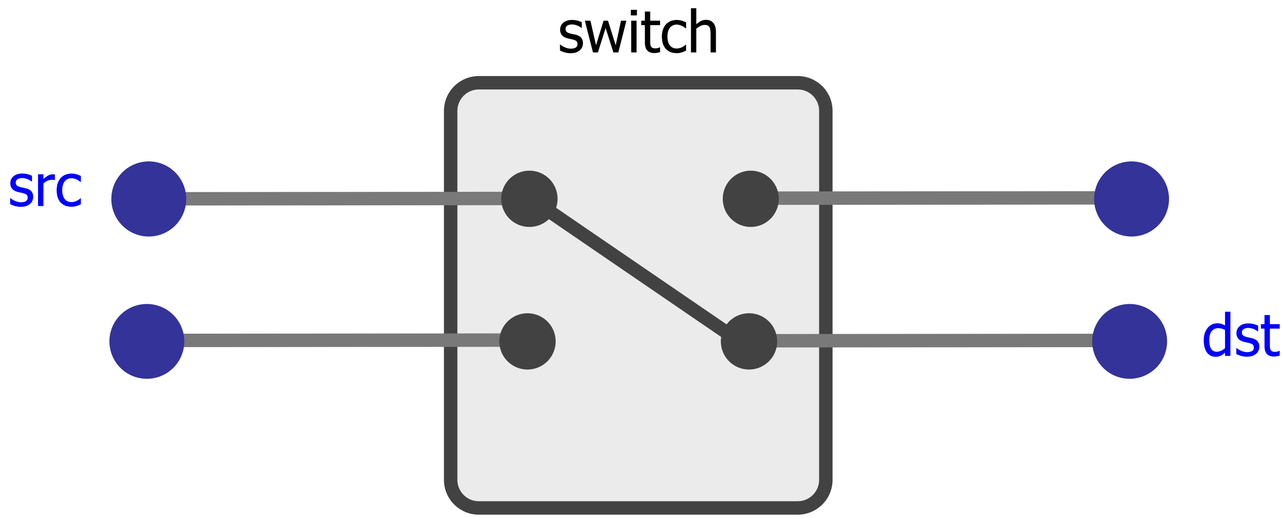
- Hybrid: virtual circuits
  - Emulating circuit switching with packets (see text)

Circuit switching

1. src sends reservation request to dst
2. Switches create circuit *after* admission control
3. src sends data
4. src sends teardown request



Circuit switching



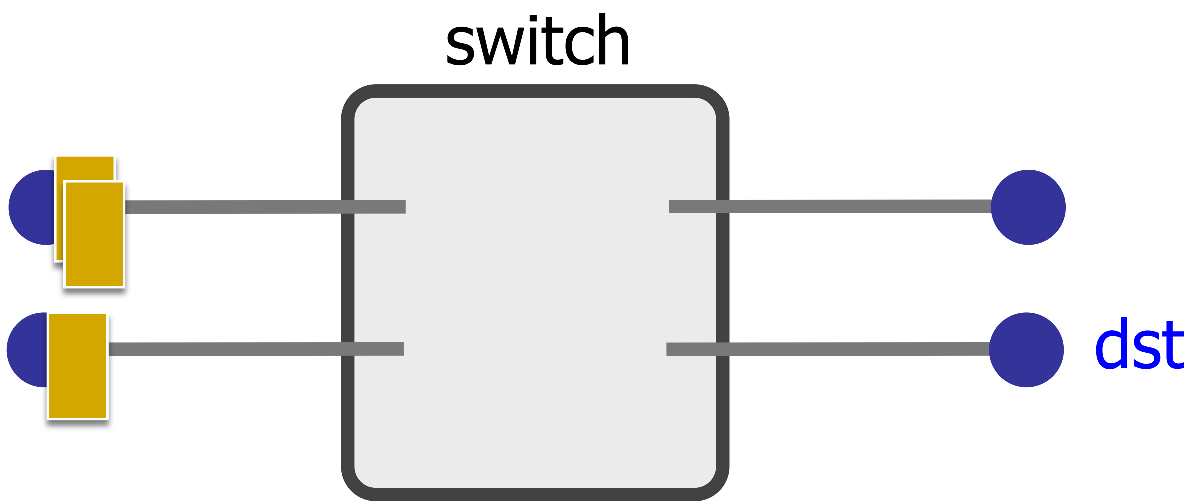
- Reservation establishes a "circuit" within a switch

Circuit switching

- Pros
  - Predictable performance
  - Simple/fast switching (once circuit established)

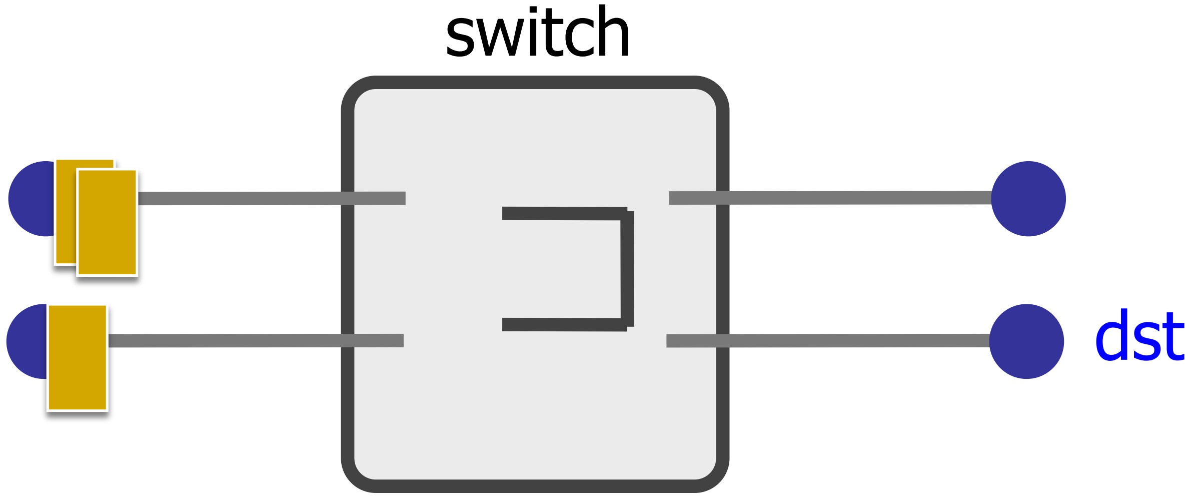
- Cons
  - Complexity of circuit setup/teardown
  - Dedicated resources: Inefficient when traffic is bursty
  - Circuit setup adds delay
  - Switch fails → its circuit(s) fails

Packet switching



- Each packet contains destination (dst)
- Each packet treated independently

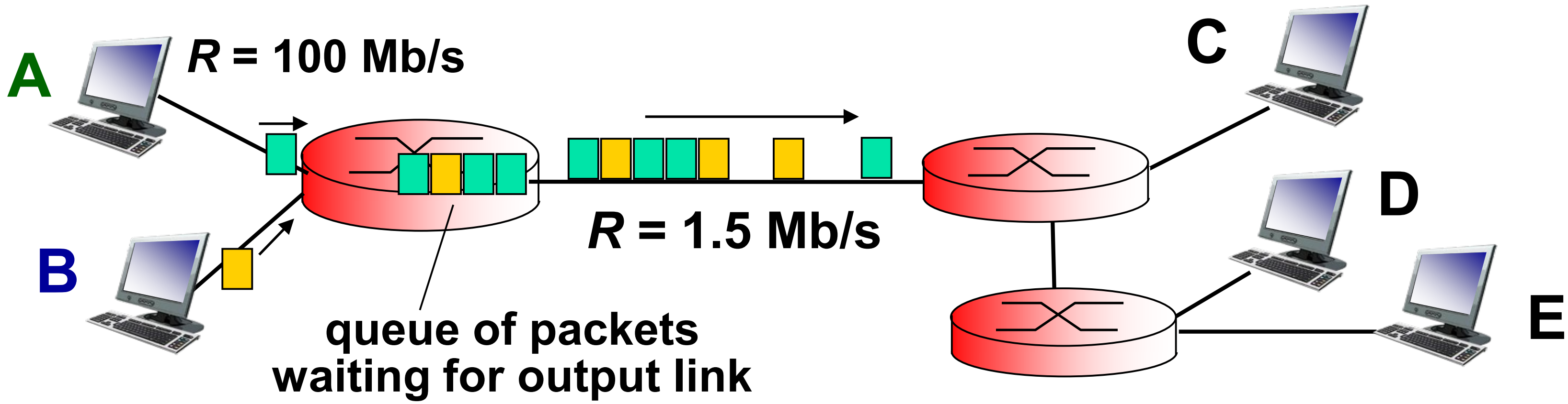
Packet switching



- Each packet contains destination (dst)
- Each packet treated independently
- With buffers to absolve transient overloads

Store and forward: packets move one hop at a time, stored (queued) at switches

Packet Switching: queueing delay, loss



- Resource contention
  - aggregate (burst-up) resource demand can exceed amount available
- Congestion:
  - packets will queue, wait for link use
  - packets can be dropped (lost) if no memory to store them

Packet switching

- Pros
  - Efficient use of network resources
  - Simpler to implement
  - Robust: can “route around trouble”
- Cons
  - Unpredictable performance
  - Requires buffer management and congestion control

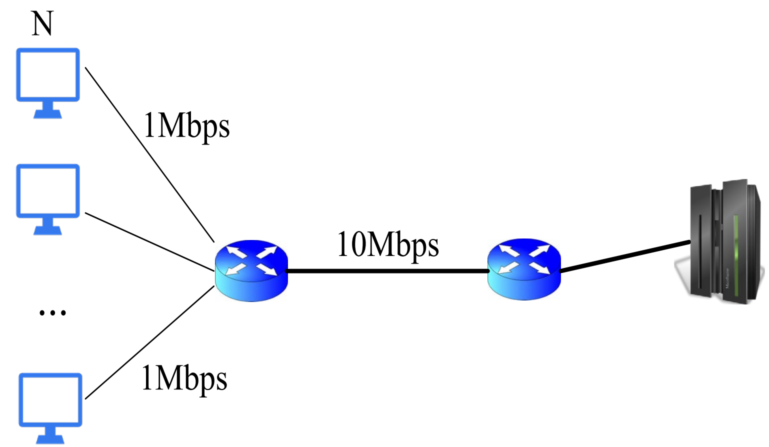
Statistical multiplexing

- Statistical Multiplexing (统计多路复用): Link bandwidth shared on demand （按需共享）
- Allowing more demands than the network can handle
  - Hoping that not all demands are required at the same time
  - Results in unpredictability
  - Works well except for the extreme cases

Example: Statistical Multiplexing

Example:
- N users share one link (10Mbps)
- Each user requires 1Mbps
- Each user: active 10%, idle 90%.

How many users are supported?

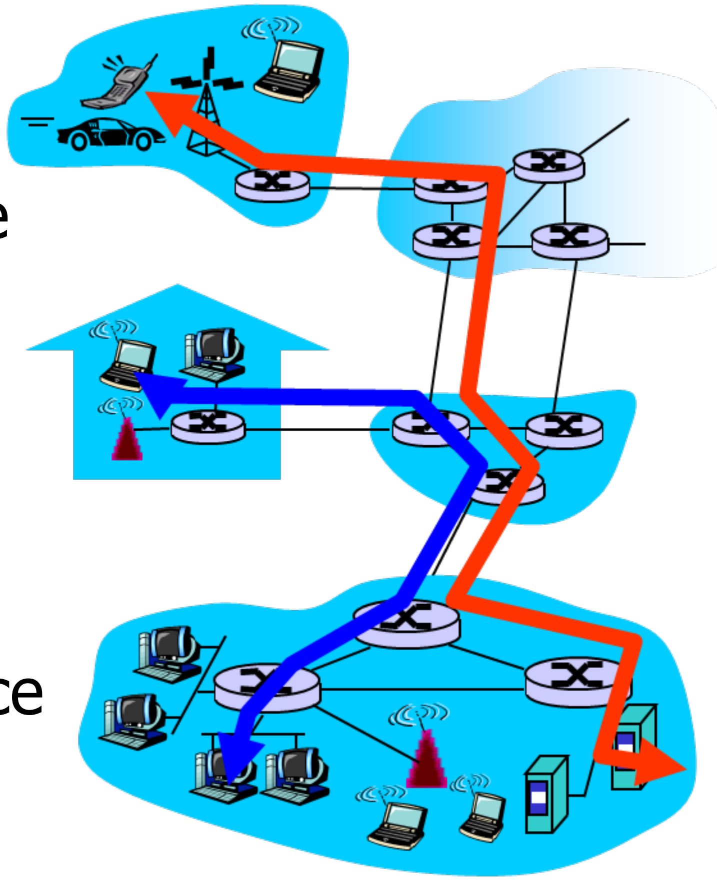


Circuit Switching:
N=10Mbps/1Mbps=10 users

Statistical Multiplexing:
Assume N=35,
Prob{active user>10}<=0.0004,
So for N=35, with probability 0.9996 a user have bandwidth larger than 1Mbps.

Virtual Circuit

- Circuit Switching + Packet Switching
  - Routes or main cross roads are fixed
  - Resources shared, congestion control needed
  - Resources can be preserved, leading to different performance
  - Connection setup/teardown needed



Comparison

	电路交换	数据报分组交换	虚电路分组交换
传输通路	专用	非专用	非专用
连续性	连续传输	分组传输	分组传输
带宽	固定	动态使用	动态使用
路由	固定	动态	固定
时延	实时（只有呼叫建立时延）	分组传输时延	分组传输时延+呼叫建立时延
扩展性	差（接入用户有上限）	好（用户数量可动态扩充）	较好（用户数量动态，由拥塞控制来保证服务质量）

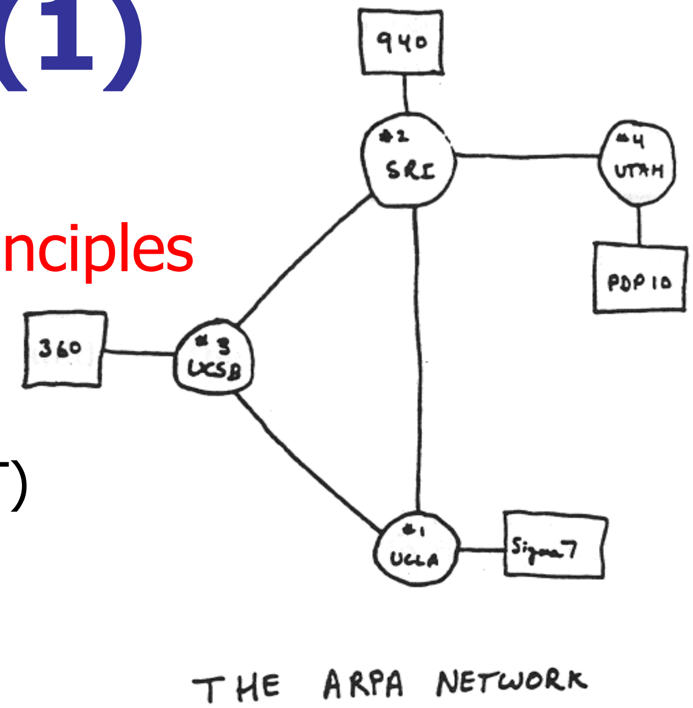
Thank You！

- Basic Concepts and Questions

- Internet History
- Protocol Layers and Service Model
- Network Performance

Internet History

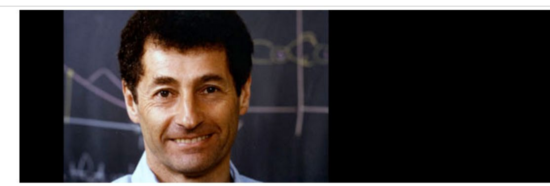
Internet History (1)



1961-1972: Early packet-switching principles

60年代：诞生-分组交换网络

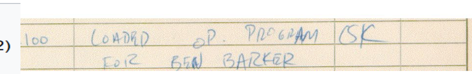
- 1961: Kleinrock – queuing theory shows effectiveness of packet-switching (PhD@MIT)
- 1964: Baran – packet-switching in military nets
- 1967: ARPAnet conceived by Advanced Research Projects Agency
- 1969: first ARPAnet node operational (UCLA, Stanford, UCSB, UTAH), Kleinrock
- 1972:
  - ARPAnet demonstrated publicly
  - NCP (Network Control Protocol) first host-host protocol [RFC001]
  - First email program
  - ARPAnet has 15 nodes



In the Press | About | Publications | History | Twitter | Students

The Day the Infant Internet Uttered its First Words

Below is a record of the first message ever sent over the ARPANET. It took place at 22:30 hours on October 29, 1969. This record is an excerpt from the "IMP Log" that was kept at UCLA. Professor Kleinrock was supervising his student/programmer Charley Kline (CSK) and they set up a message transmission to go from the UCLA SDS Sigma 7 Host computer to another programmer, Bill Duvall, at the SRI SDS 940 Host computer. The transmission itself was simply to "login" to SRI from UCLA. They succeeded in transmitting the "l" and the "o" and then the system crashed! Hence, the first message on the Internet was **"lo",** as in "lo and behold! They were able to do the full login about an hour later.



Leonard Kleinrock	
Born	June 13, 1934 (age 82) New York City
Residence	Los Angeles
Nationality	United States
Fields	Engineering Computer science
Institutions	UCLA

Internet History (2)

1972-1980: Internetworking, new and proprietary nets

70年代：成型　　单一、封闭网络 -〉开放互联网络

- 1970: ALOHAnet satellite network in Hawaii, Norman Abramson （无线分组网络）
- 1973: Robert Metcalfe's PhD thesis (@Harvard) proposes Ethernet（以太网）, at Xerox PARC in 1976（局域网诞生）
- 1974: Cerf and Kahn – architecture for interconnecting networks（Internet构架）
- Late70's:
  - Proprietary architectures: DECnet, SNA, XNA
  - Switching fixed length packets (ATM precursor)
- 1979: ARPAnet has 200 nodes

Vint Cerf, Robert E. Kahn and George W. Bush

- Cerf and Kahn's internetworking principles:
  - Minimalism, autonomy – no internal changes required to interconnect networks
  - Best effort service model
  - Stateless routers
  - Decentralized control
- Define today's Internet architecture
- Design of TCP/IP suits

Internet History (3)

1980-1990: new protocols, a proliferation of networks

80年代：持续发展
- 新协议：**NCP-〉TCP/IP**
- **DNS**：实现域名解析
- 应用：**Email，Ftp**

- 1983: deployment of TCP/IP
- 1982: SMTP email protocol defined
- 1983: DNS defined for name-to-IP-address translation
- 1985: FTP protocol defined
- 1988: TCP congestion control

- New national networks: Csnet, BITnet, NSFnet, Minitel
- 100,000 hosts connected to confederation of networks

Internet History (4)

1990's, 2000's: commercialization, the Web, new apps

90年代：因特网爆炸
- 万维网出现：**www （http，HTML，Web Server，Browser）**
- 商用化，逐渐普及
- 新型应用：**Email，Web，IM （instant messaging），MP3**文件共享

- Early 1990's: ARPAnet decommissioned
- 1991: NSF lifts restrictions on commercial use of NSFnet (decommissioned in 1995)
- Early 1990's: Web
  - Hypertext [Bush 1945, Nelson 1960's]
  - HTML, HTTP: Berners-Lee
- 1994: Mosaic, later Netscape Browser

Late 1990's: commercialization of the Web

Late 1990's ~ 2000's:

- More killer apps: instant messaging, peer2peer file sharing (e.g. Napster)
- Network security to forefront
- Est. 50 million host, 100 million+ users
- Backbone links running at Gbps

蒂姆·伯纳斯-李爵士
Sir Tim Berners-Lee

出生 1955年6月8日（61歲）[1]
英格兰伦敦

机构 万维网联盟
南安普敦大学
Plessey
麻省理工学院

知名于 发明万维网
麻省理工学院计算机科学及人工智能实验室创办主席

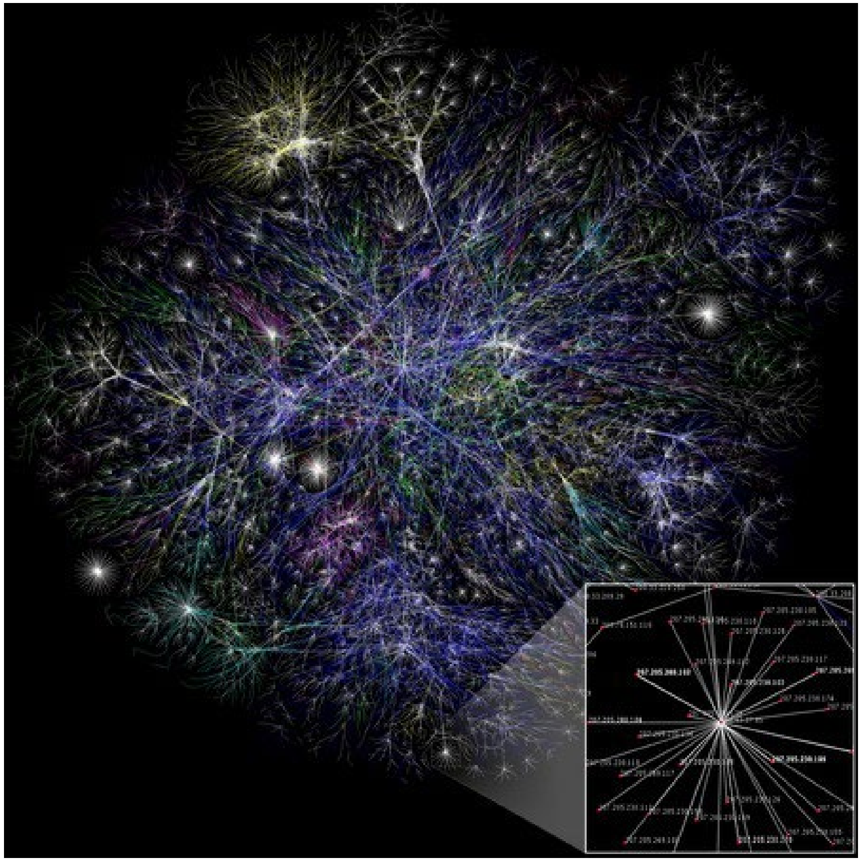
2016 Turing Award

Internet History (5)

2000年以后，新型应用涌现
- 多媒体
- **P2P**网络
- 社交网络（**Facebook**，**Twitter**，人人，微博，微信，**...**）

2007

- ~500 million hosts
- Voice, Video over IP
- P2P applications: BitTorrent (file sharing), Skype (VoIP), PPLive (video)
- More applications: YouTube, online gaming
- Wireless and mobility
- 2015- , blockchain, AINet, 5G, …




THE INTERNET AGE
中央电视台大型电视纪录片
互联网时代
CCTV2 财经
CCTV.com 央视网 经济
首页
边看边聊
主创团队
开播仪式回顾
大调查启动回顾
采访嘉宾
CCTV2
经济频道
CCTV 2 财经
CNTV
导演 石 强 孙曾田
01:07 | 49:51
高清
点播
《互联网时代》 第十集 眺望
《互联网时代》 第九集 世界
《互联网时代》 第八集 忧虑
《互联网时代》 第七集 控制
《互联网时代》 第六集 迁徙
《互联网时代》 第五集 崛起
《互联网时代》 第四集 再构
《互联网时代》 第三集 能量
《互联网时代》 第二集 浪潮
《互联网时代》 第一集 时代

Protocol Layers and Service Model

Protocol "layers"

Networks are complex, with many "pieces":

- hosts
- routers
- links of various media
- applications
- protocols
- hardware, software

Question:

is there any hope of *organizing* structure of network?

.... or at least our discussion of networks?

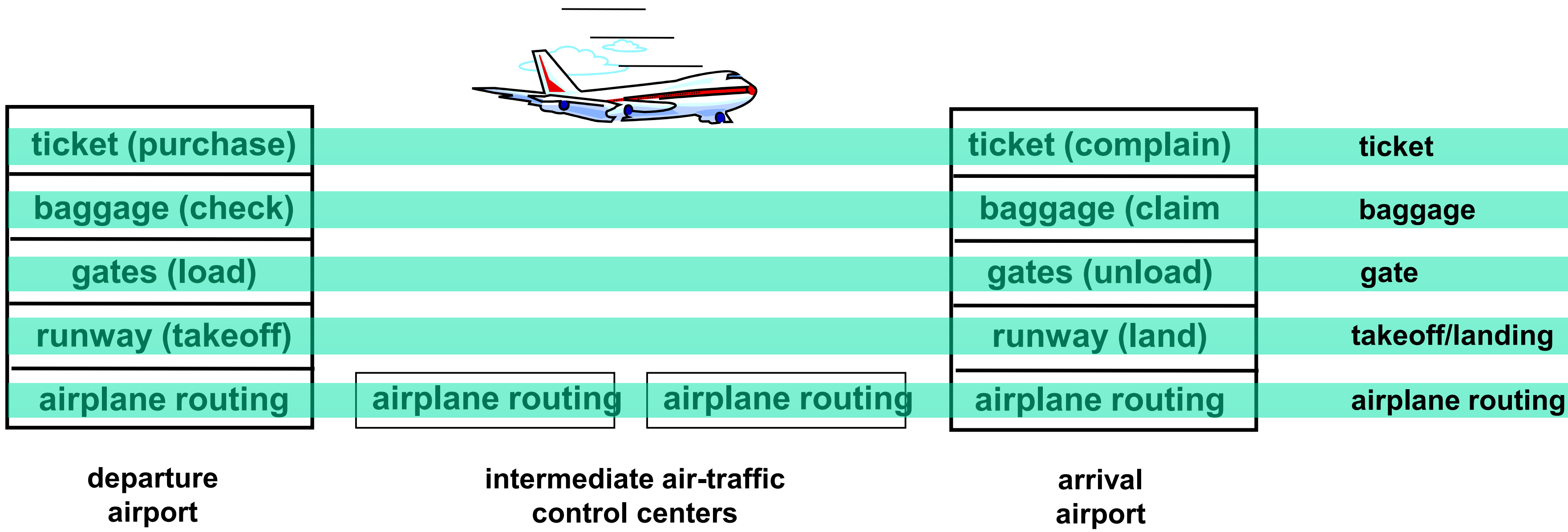
Organization of air travel

ticket (purchase)	ticket (complain)
baggage (check)	baggage (claim)
gates (load)	gates (unload)
runway takeoff	runway landing
airplane routing	airplane routing

airplane routing

- a series of steps

Layering of airline functionality



layers: each layer implements a service

- via its own internal-layer actions
- relying on services provided by layer below

Why layering?

dealing with complex systems:

- explicit structure allows identification, relationship of complex system's pieces
  - layered *reference model* for discussion
- modularization eases maintenance, updating of system
  - change of implementation of layer's service transparent to rest of system
  - e.g., change in gate procedure doesn't affect rest of system

Standard Protocol Architectures

- Two standards:
  - OSI Reference model
    - Never lived up to early promises
  - TCP/IP protocol suite
    - Most widely used

- Others
  - IBM Systems Network Architecture (SNA)
  - DECNet, Netware

ISO-OSI

- Open Systems Interconnection (OSI)
- Developed by the International Organization for Standardization (ISO)
- Seven layers structure

- A theoretical system delivered too late
- TCP/IP is the de facto standard now

OSI – The Model

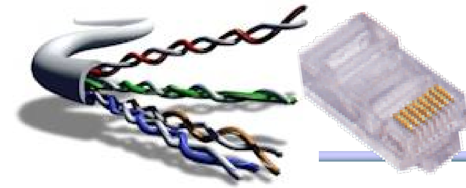
- A layer model, and flow structure
- Each layer performs a subset of the required communication functions
- Each layer relies on the next lower layer to perform more primitive functions
- Each layer provides services to the next higher layer
- Changes in one layer should not require changes in other layers

OSI Layers

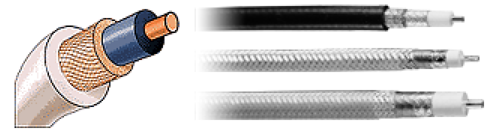
Example：Alice invite Bob to lunch

Layer	Description	Example
Application	Provides access to the OSI environment for users and al provides distributed information services.	“请客吃饭”
Presentation	Provides independence to the application processes from differences in data representation (syntax).	语言表述
Session	Provides the control structure for communication between applications; establishes, manages, and terminates connections (sessions) between cooperating applications.	听说同步
Transport	Provides reliable, transparent transfer of data between end points; provides end-to-end error recovery and flow control.	摘机拨号
Network	Provides upper layers with independence from the data transmission and switching technologies used to connect systems; responsible for establishing, maintaining, and terminating connections.	PBX中转
Data Link	Provides for the reliable transfer of information across the physical link; sends blocks (frames) with the necessary synchronization, error control, and flow control.	信号传输
Physical	Concerned with transmission of unstructured bit stream over physical medium; deals with the mechanical, electrical, functional, and procedural characteristics to access the physical medium.	插口、双绞线

Physical Layer



- Transfers bits across link



- Specification of the physical aspects of a comm link
  - Mechanical: cable, plugs, pins...
  - Electrical/optical: modulation, signal strength, voltage levels, bit times, …
  - Functional/procedural: activate, maintain, deactivate physical links…
- Physical interface between devices
  - Ethernet, DSL, cable modem, telephone modems, …
  - Twisted-pair cable, coaxial cable, optical fiber, radio, infrared, …

Data Link Layer

- Groups bits into frames
- Activation, maintenance, & deactivation of data link connections

- Transfers frames across direct connections
- Medium access control for local area networks

- Detection of bit errors; Retransmission of frames
- End-to-end flow control

- Higher layers may assume error free transmission

Network Layer

- Transfers packets across multiple links / multiple networks
- Addressing must scale to large networks

- Nodes jointly execute routing algorithm to determine paths across the network
- Forwarding transfers packet across a node
- Congestion control to deal with traffic surges

- Connection setup, maintenance, and teardown when connection-based

Transport Layer

- Exchange of data between end systems
  - Transfers data end-to-end from process in one host to process in another host
- Reliable stream transfer or quick-and-simple single-block transfer
  - Error free
  - In sequence
  - No losses
  - No duplicates
- Connection setup, maintenance, and release

Upper Layers

- ~~Session~~
  - ~~Control of dialogues between applications~~
  - ~~Dialogue discipline~~
  - ~~Grouping data~~
  - ~~Checkpoint recovery~~

Incorporated into Application Layer Now

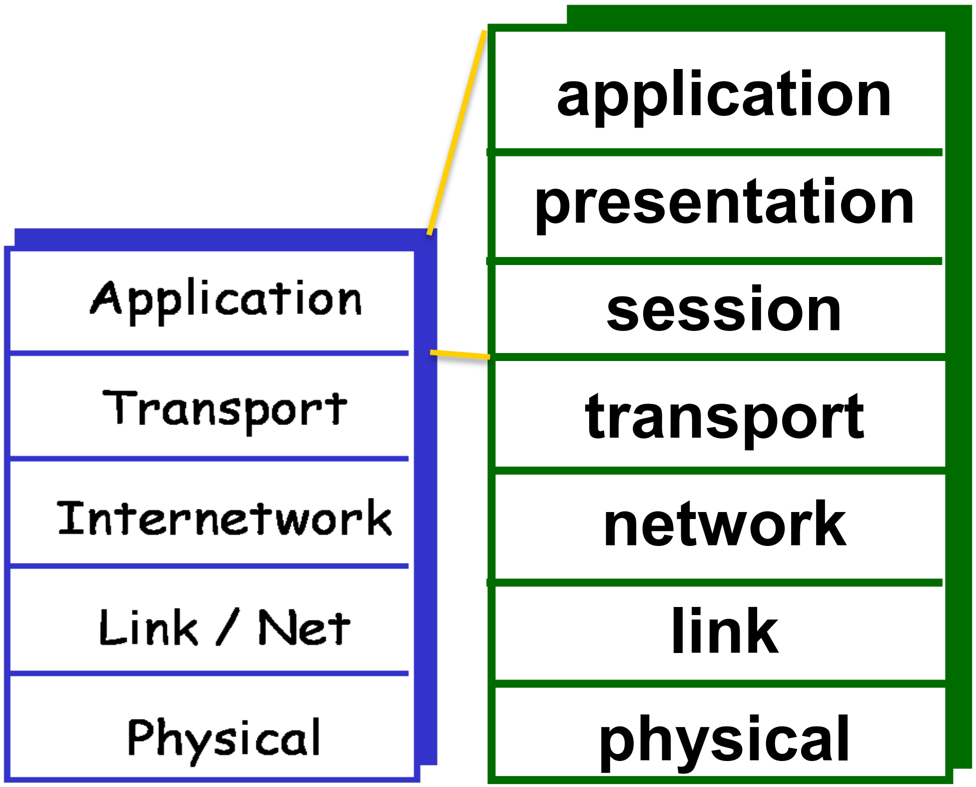
- ~~Presentation~~
  - ~~Machine-independent representation of data~~
  - ~~Data formats and coding~~
  - ~~Data compression & encryption~~
- Application
  - Means for applications to access OSI environment

TCP/IP Protocol Architecture

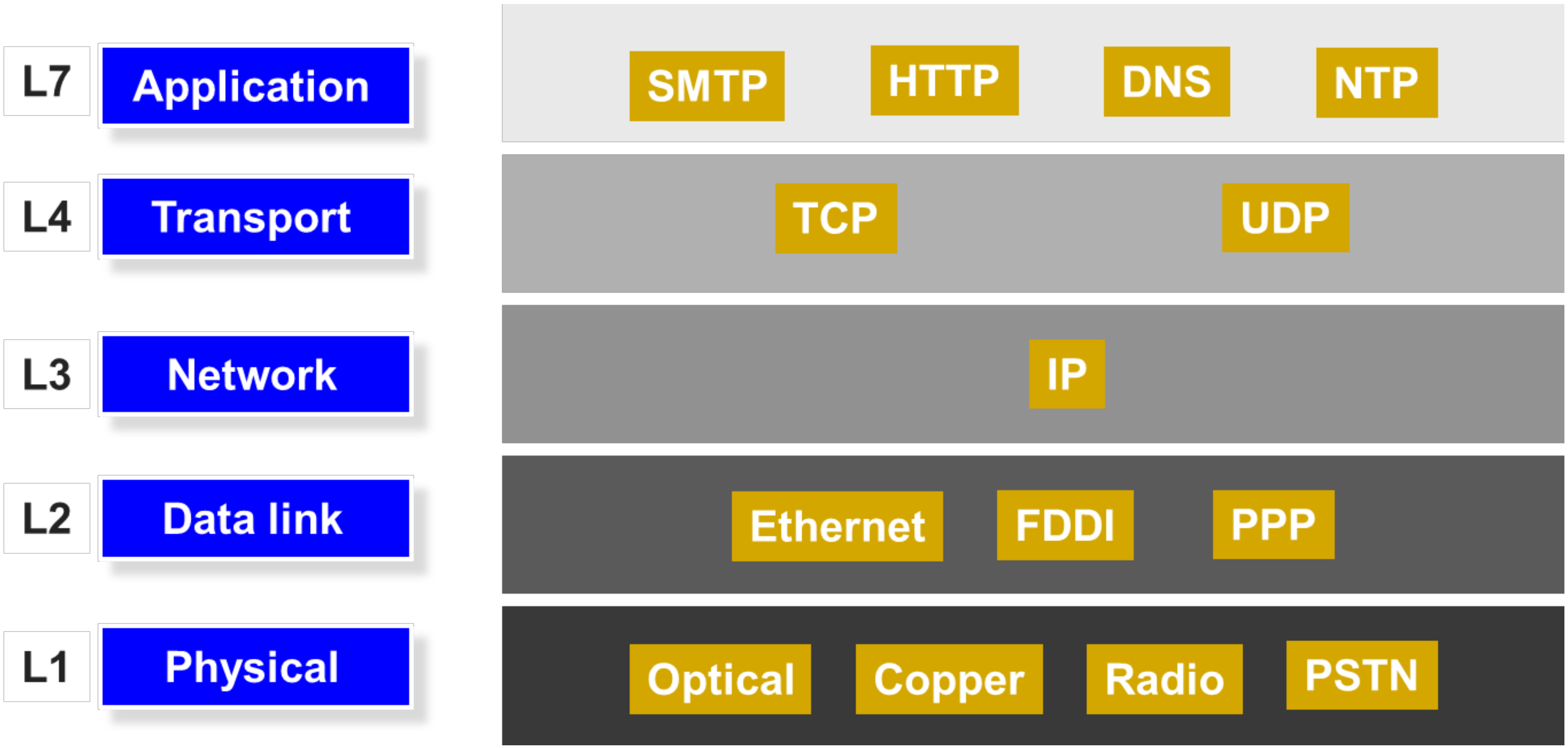
Used by the global Internet

- Application: supporting network applications
  - FTP, SMTP, HTTP
- Transport: process-process data transfer
  - TCP, UDP
- Internetwork: routing of datagrams across net of nets
  - IP, routing protocols
- Link: data transfer between neighboring routers / hosts
  - PPP, Ethernet
- Physical: bits "on the wire"

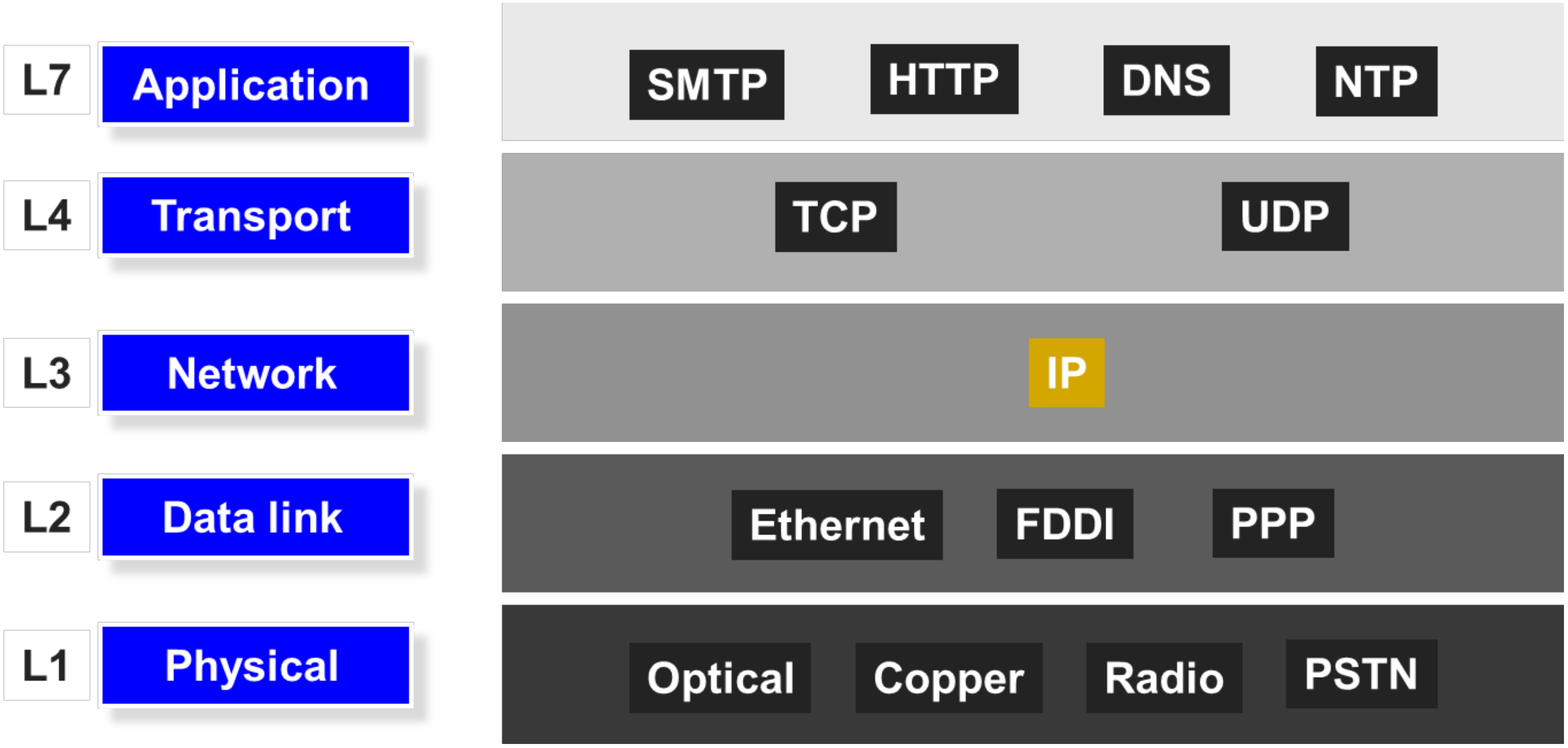
TCP/IP protocol stack vs. OSI



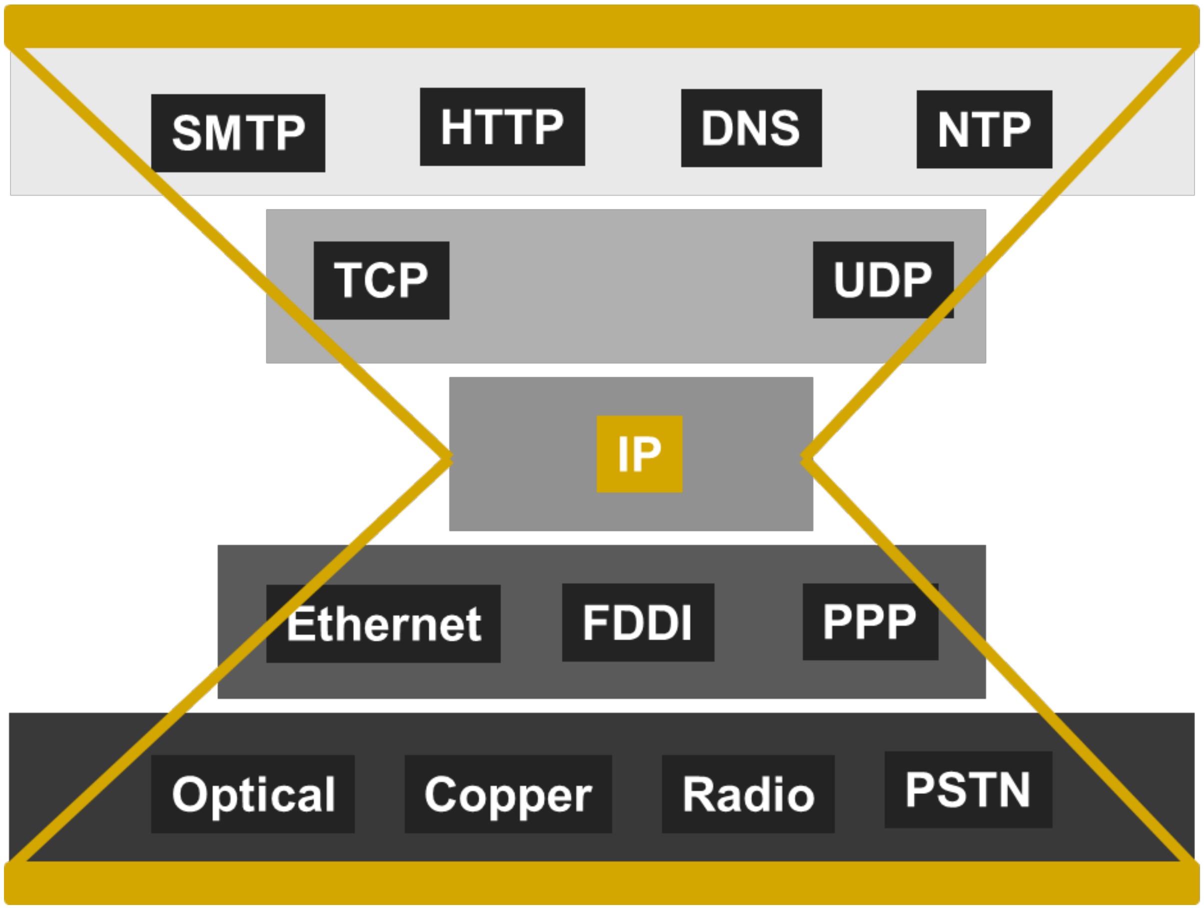
Protocols at different layers



ONE network layer protocol



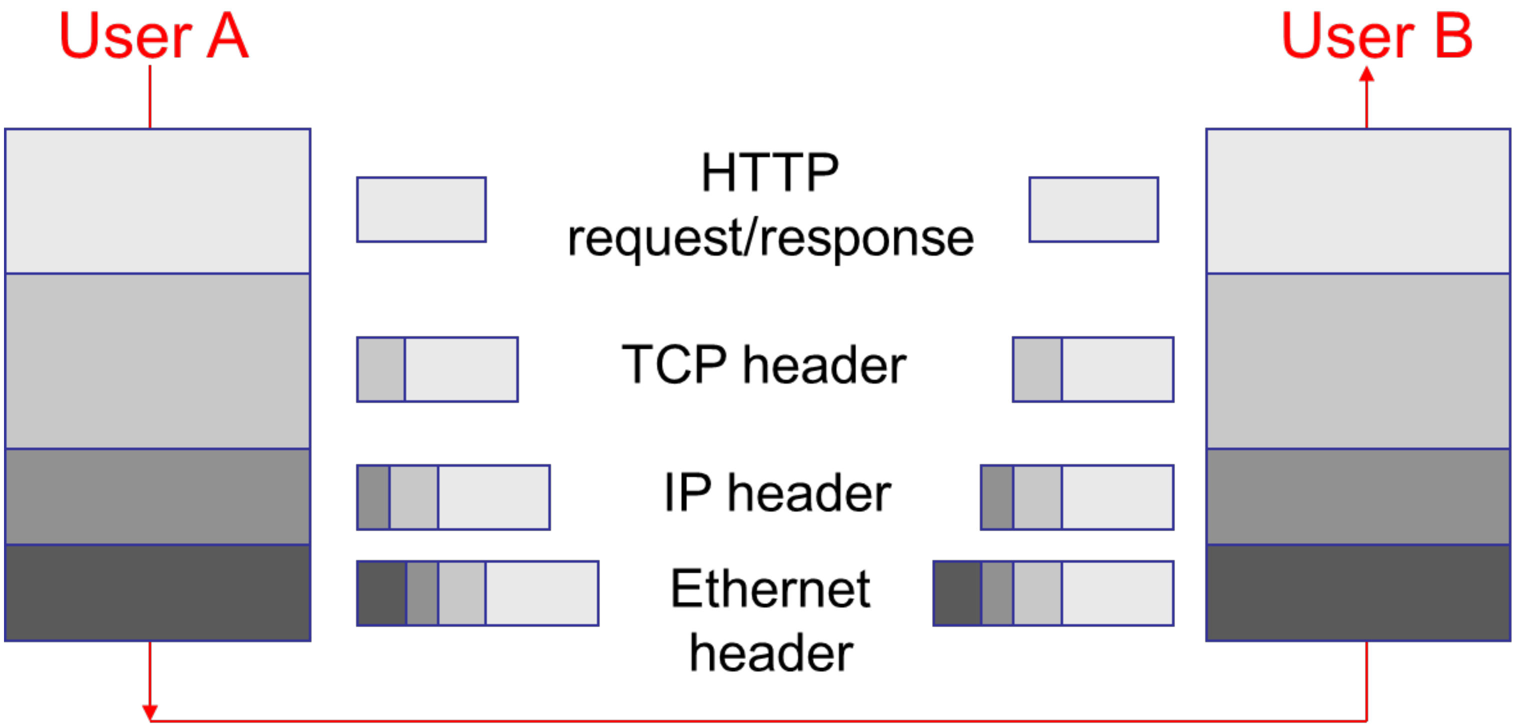
IP is the narrow waist of the layering hourglass



Implications of hourglass

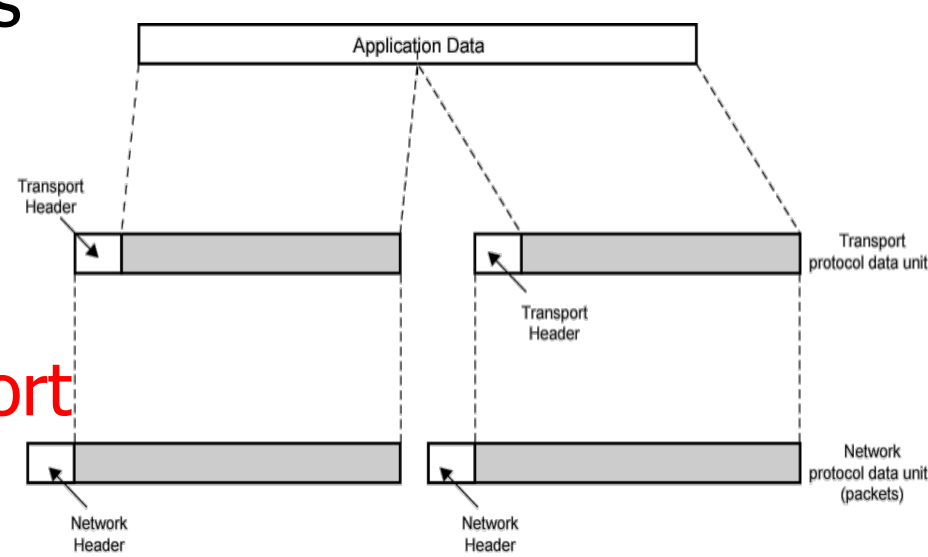
- Single network-layer protocol (IP)
- Allows arbitrary networks to interoperate
  - Any network that supports IP can exchange packets
- Decouples applications from low-level networking technologies
  - Applications function on all networks
- Supports simultaneous innovations above and below IP
- But changing IP itself is hard (e.g., IPv4 → IPv6)

Layer encapsulation: Protocol headers

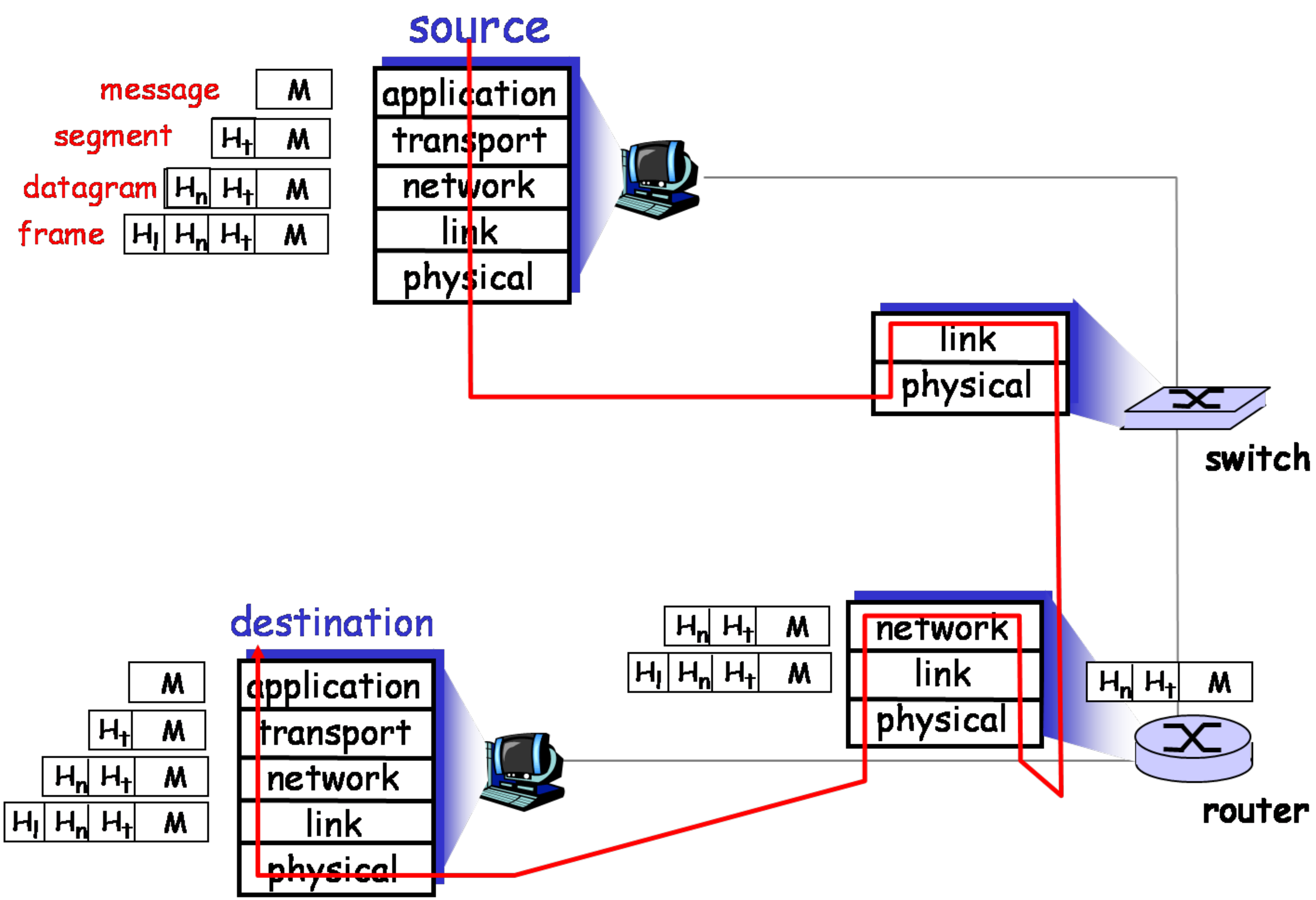


Protocol Data Units

- At each layer, Control info is added to user data to ease communication, e.g.
- Transport layer segments application data
- Each segment has a transport header added
  - Destination port
  - Sequence number
  - Error detection code
- This gives a transport protocol data unit (PDU)



Encapsulation



Pros and cons of layering

Why layers?

- Reduce complexity
- Improve flexibility

Why not?

- Higher overheads
- Cross-layer information often useful

Network Performance

How to evaluate the performance of a network?

Performance metrics

- Delay
- Loss
- Throughput

Delay

- How long does it take to send a packet from its source to destination?

Delay

- Consists of four components
  - Transmission delay
  - Propagation delay
  - Queuing delay
  - Processing delay

due to link properties

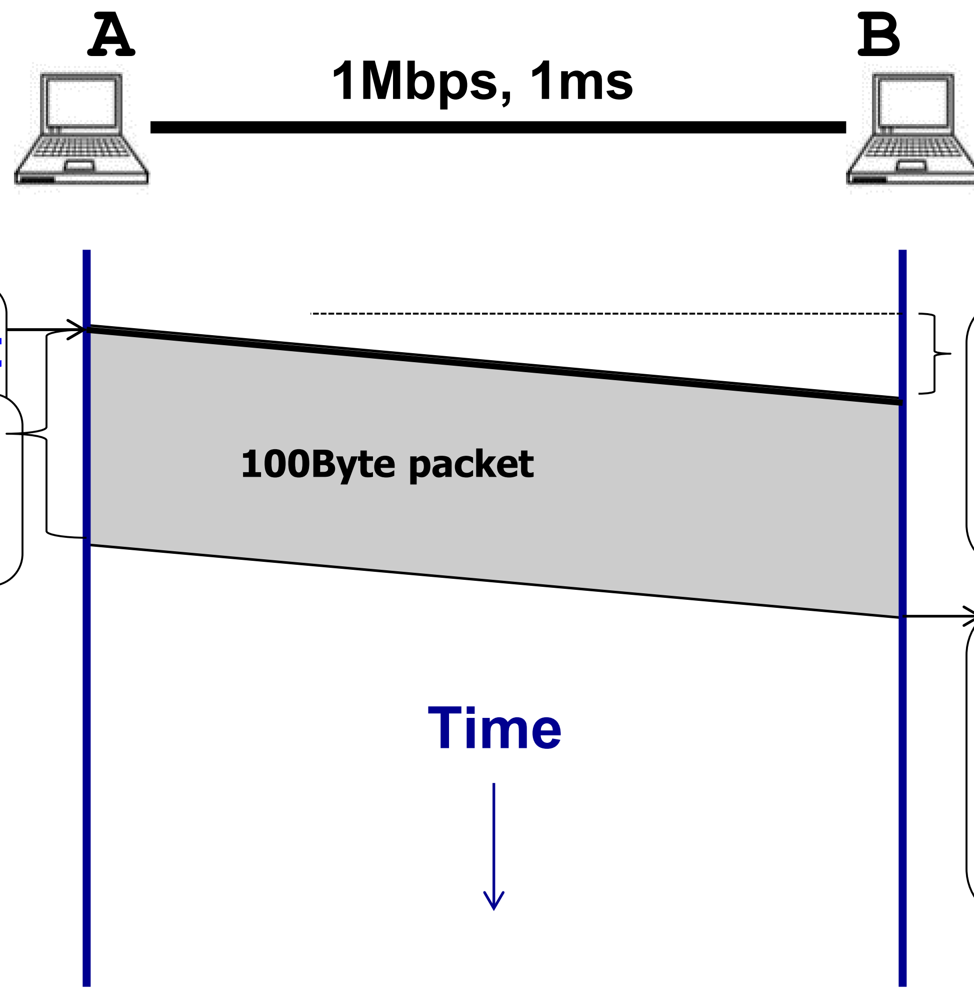
due to traffic mix and switch internals

A network link

- Transmission delay (传输时延)
  - How long does it take to push all the bits of a packet into a link?
  - Packet size / Transmission rate of the link
    - e.g., 1000 bits / 100 Mbits per sec = 10^{-5} sec

- Propagation delay
  - How long does it take to move one bit from one end of a link to the other?
  - Link length / Propagation speed of link
    - E.g., 30 kilometers / $3*10^8$ meters per sec = 10^{-4} sec

Packet delay
Sending a 100-byte packet



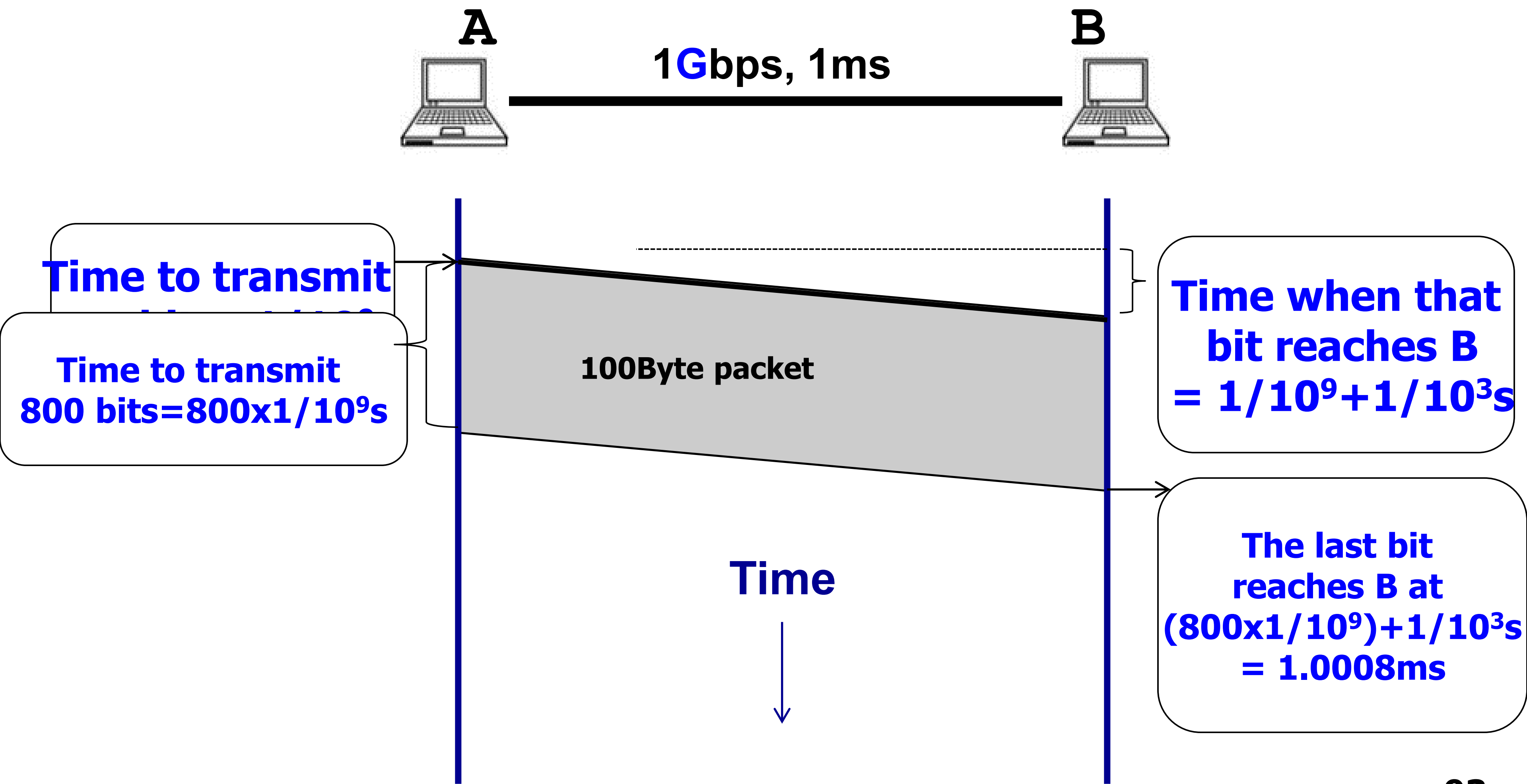
Time to transmit

Time to transmit
800 bits=800x1/10^6s

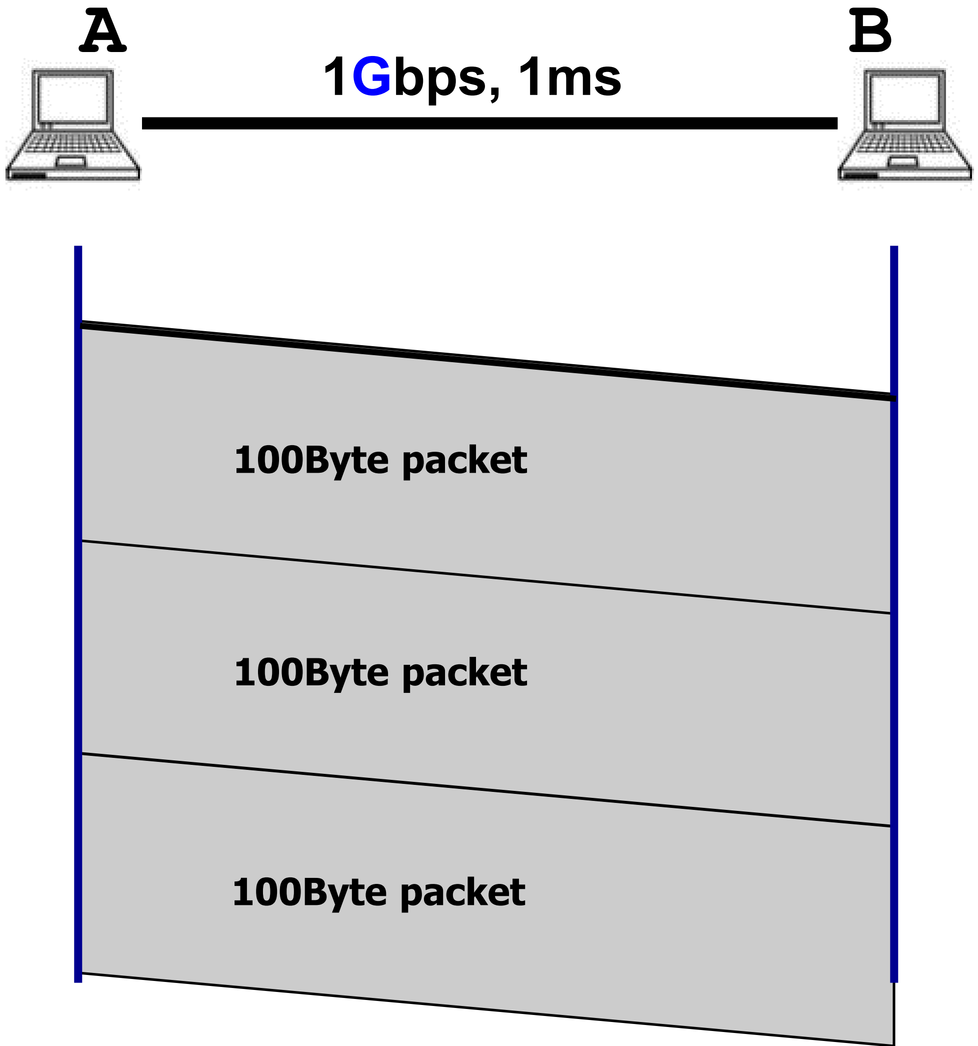
Time when that bit reaches B
= $1/10^6+1/10^3$s

The last bit reaches B at
($800x1/10^6$)+$1/10^3$s
= 1.8ms

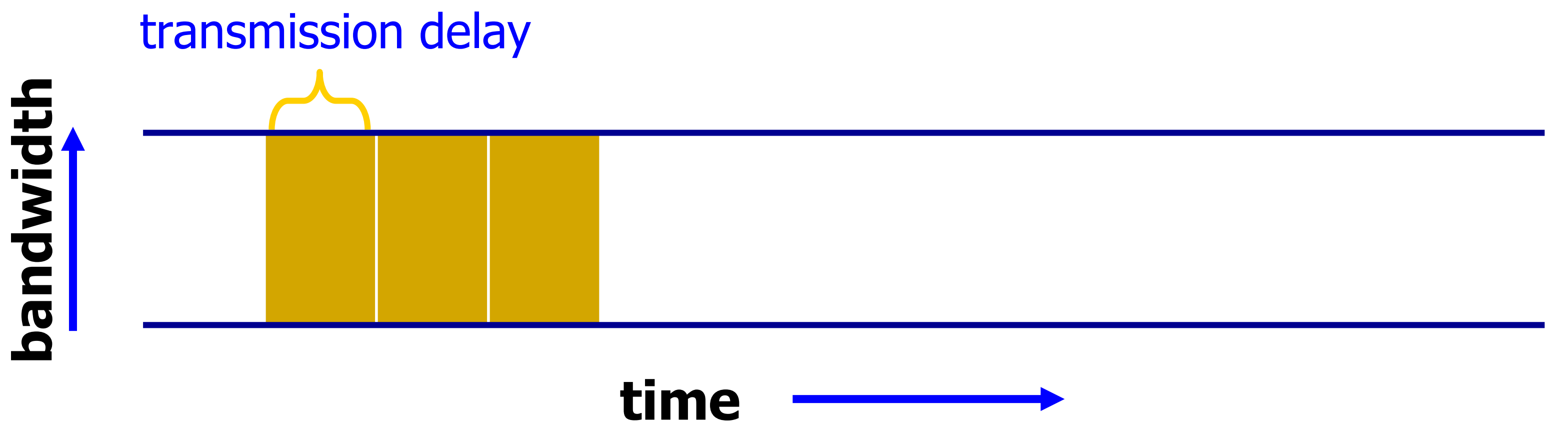
Packet delay
Sending a 100-byte packet



Sending a large file using 100-byte packets



Pipe view of a link

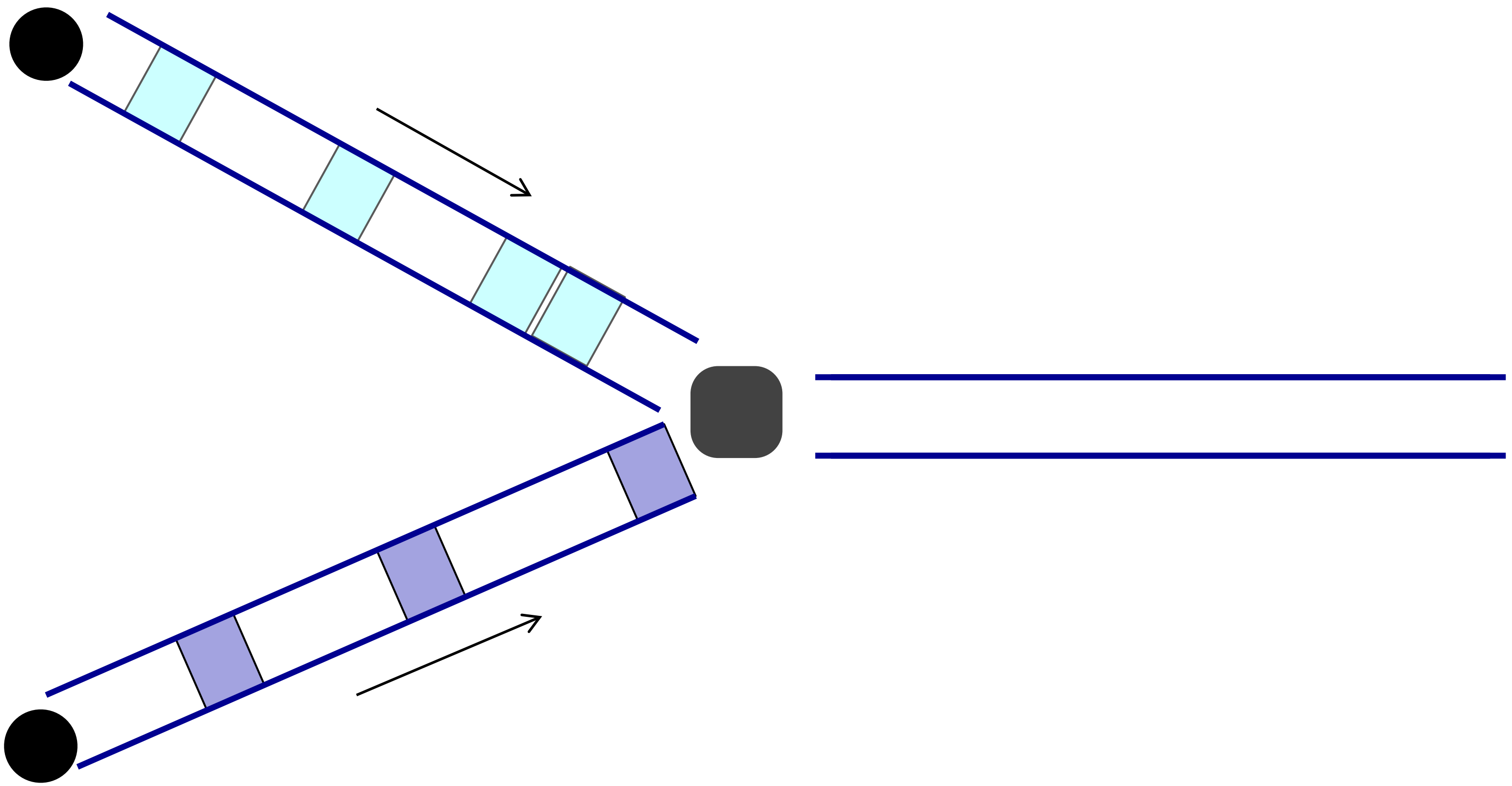


- Transmission delay decreases as bandwidth increases

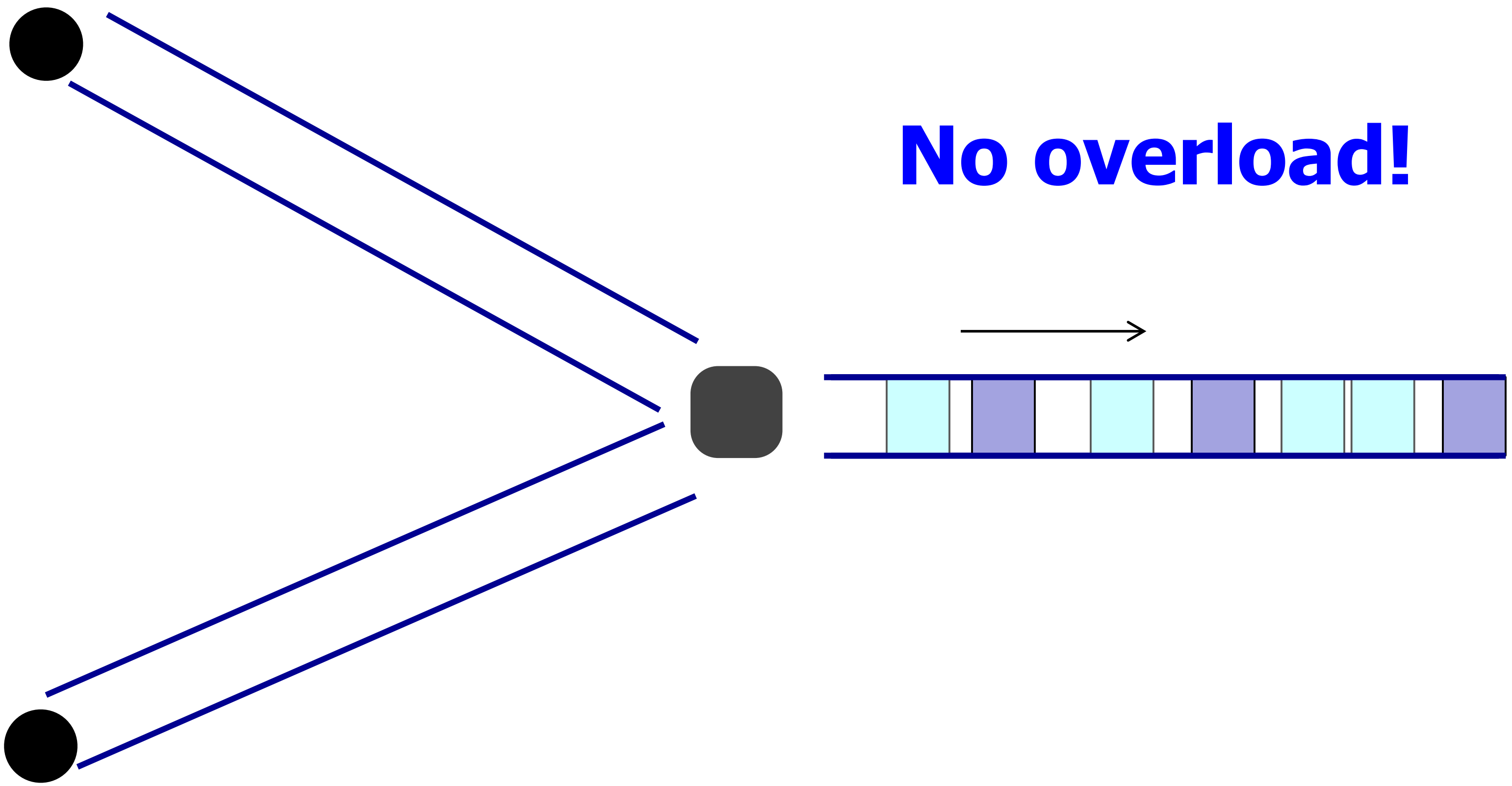
Queuing delay

- How long does a packet have to sit in a buffer before it is processed?

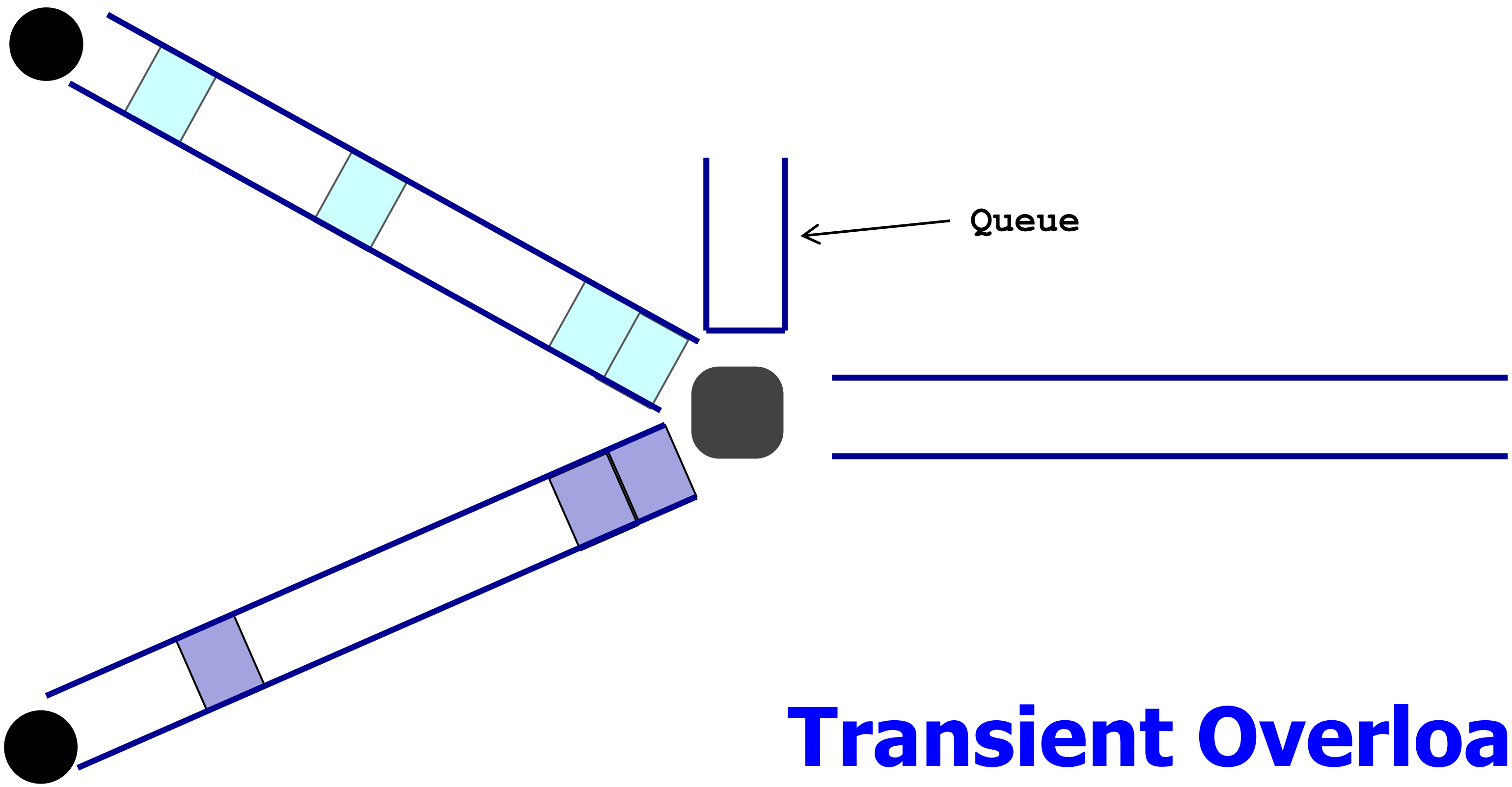
Queueing delay: “pipe” view



Queueing delay: “pipe” view



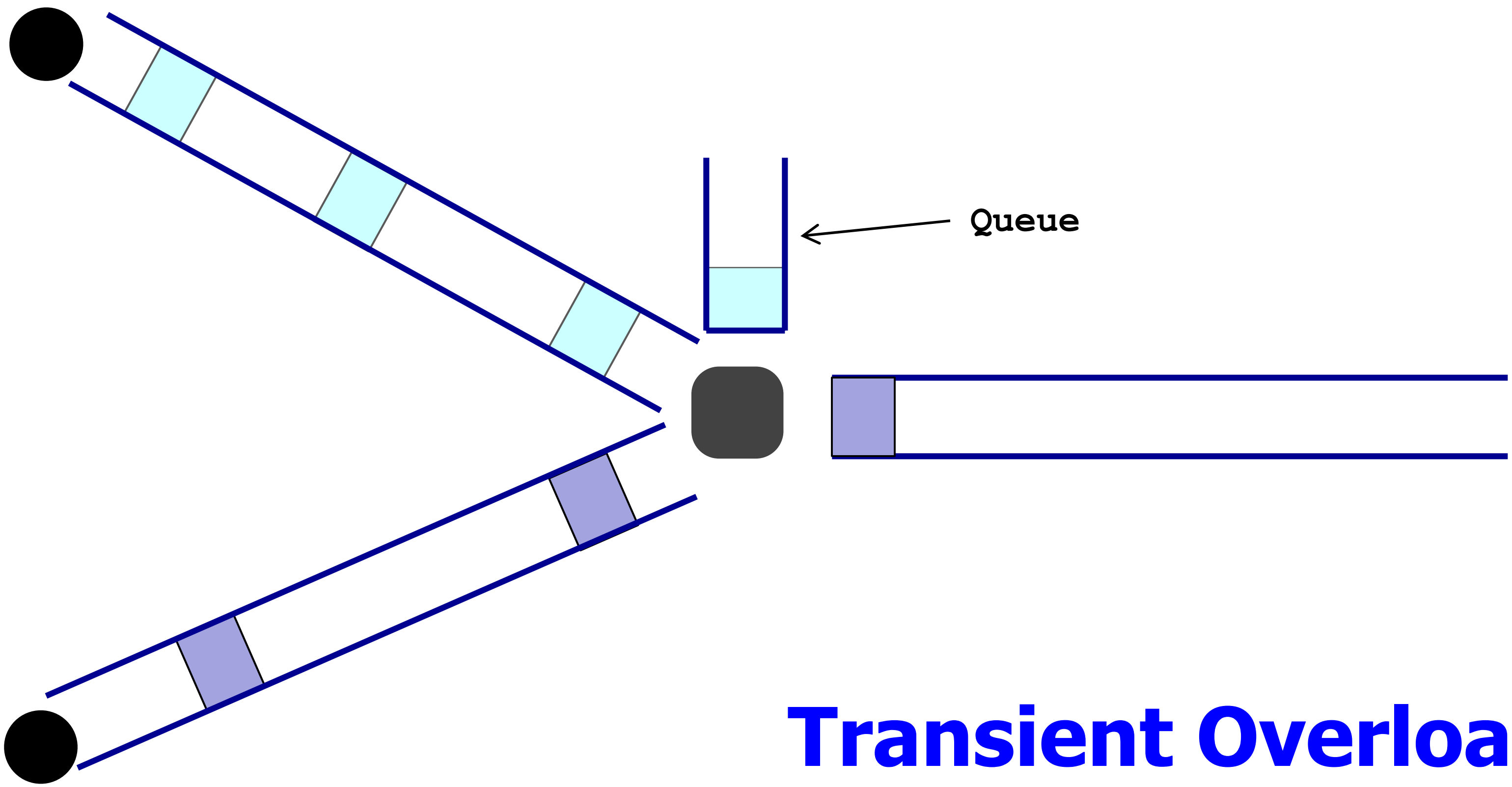
Queueing delay: "pipe" view



Transient Overload

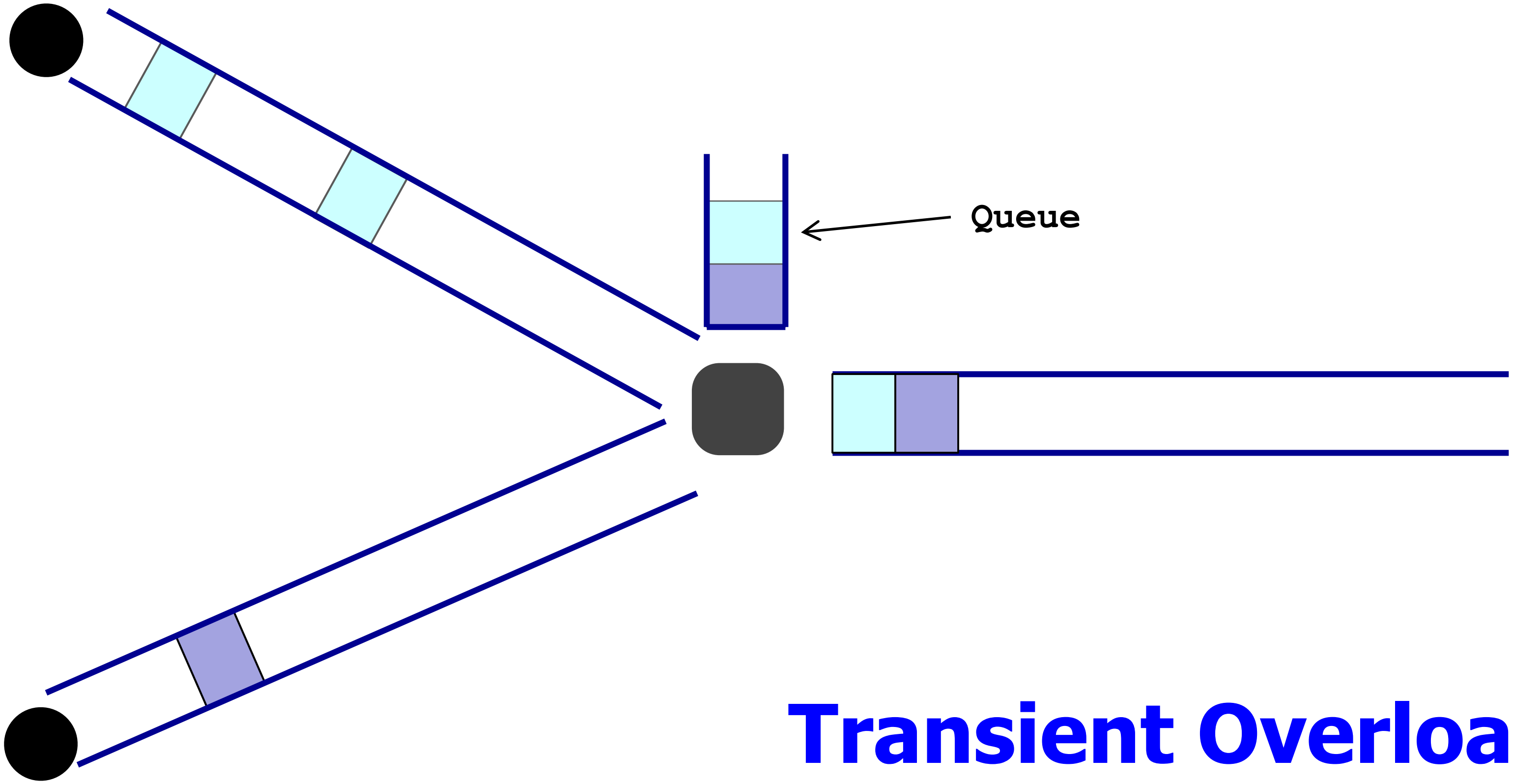
Not a rare event!

Queueing delay: “pipe” view



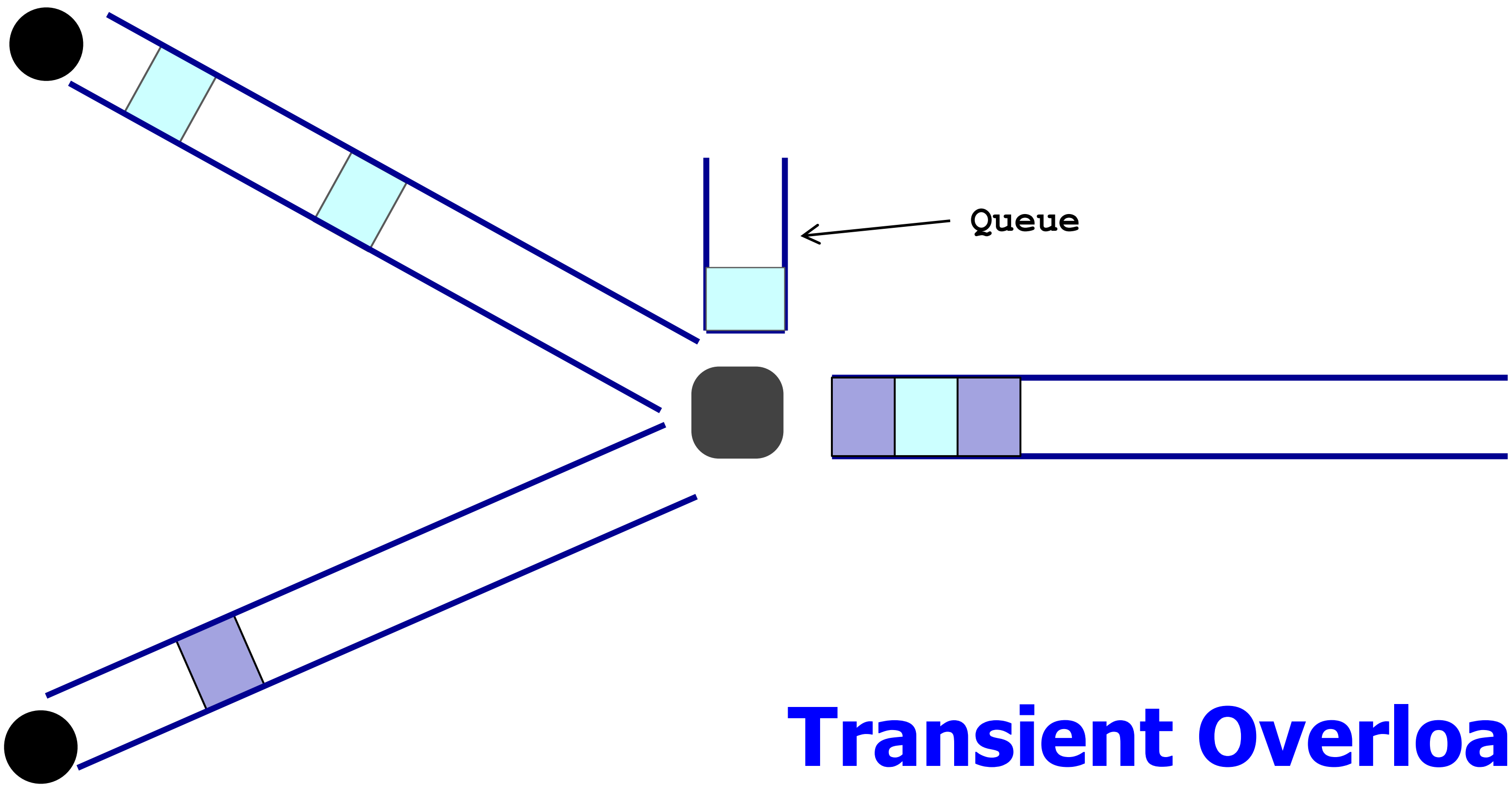
Transient Overload

Queueing delay: "pipe" view



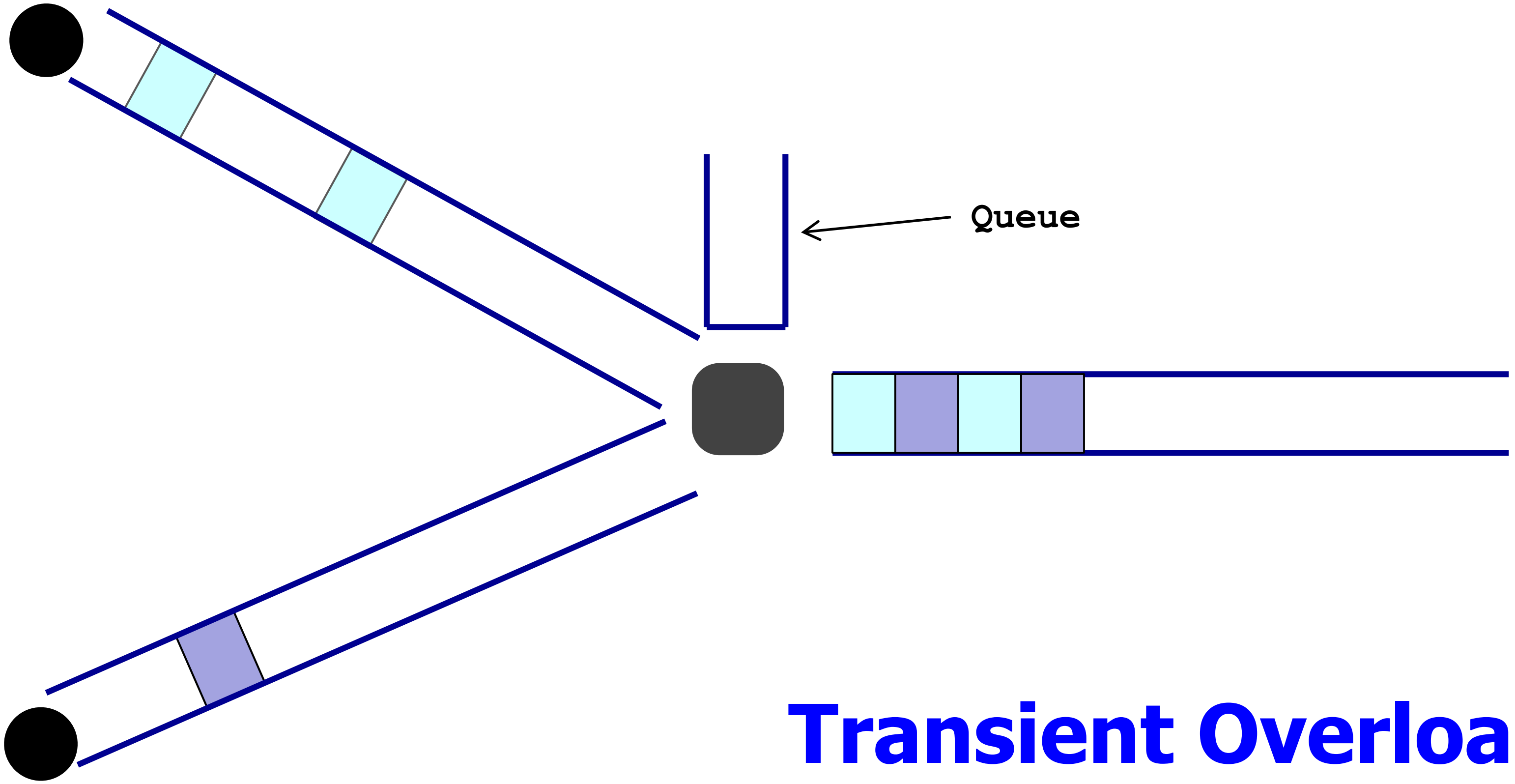
Transient Overload

Queueing delay: "pipe" view



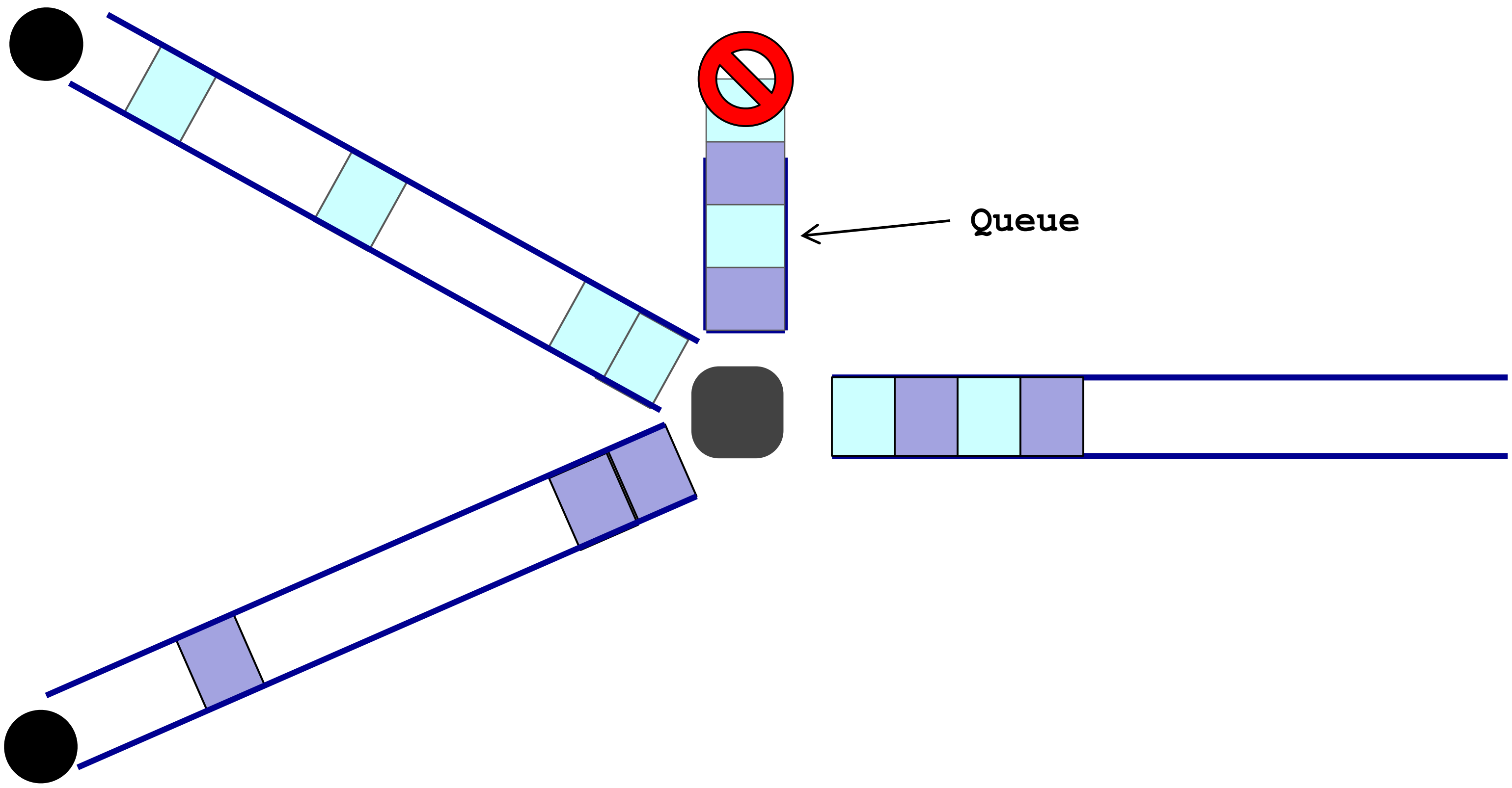
Transient Overload

Queueing delay: "pipe" view



Transient Overload

Persistent overload leads to packet loss



Queueing delay

- How long does a packet have to sit in a buffer before it is processed?

- Depends on traffic pattern
  - Arrival rate at the queue
  - Nature of arriving traffic (bursty or not?)
  - Transmission rate of outgoing link

Queueing delay

- How long does a packet have to sit in a buffer before it is processed?
- Characterized with statistical measures
  - Average queuing delay
  - Variance of queuing delay
  - Probability delay exceeds a threshold value

Basic queueing theory terminology

- Arrival process: how packets arrive
  - Average rate A
  - Peak rate P
- W: average time packets wait in the queue
  - W for "waiting time"
- L: average number of packets waiting in the queue
  - L for "length of queue"

Little's Law (1961)

- $L = A \times W$

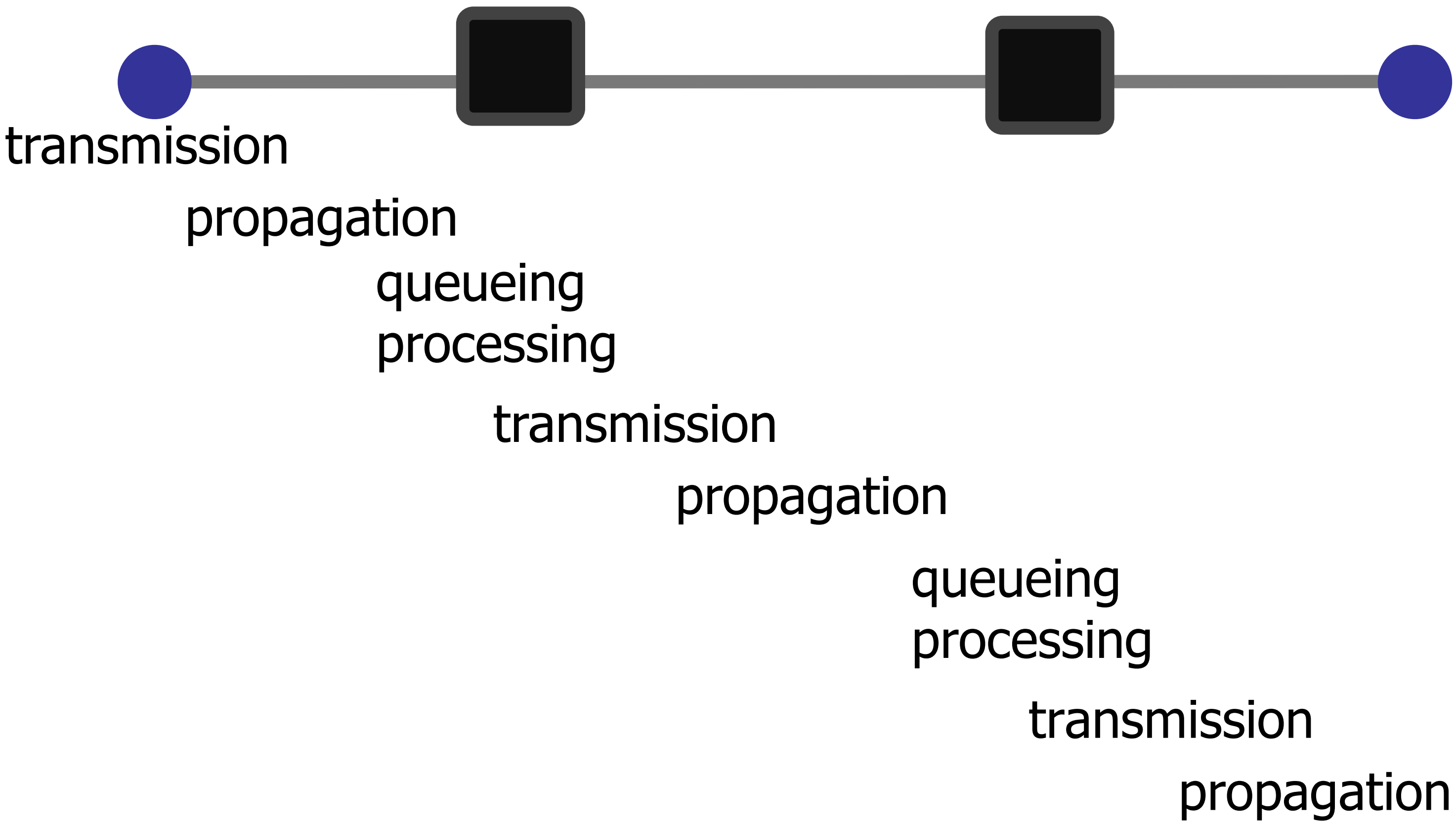
- Compute L: count packets in queue every second
  - How often does a single packet get counted? W times

- Why do you care?
  - Easy to compute L, harder to compute W

Processing Delay

- How long does the switch take to process a packet?
  - Negligible

End-to-end delay



Loss

- What fraction of the packets sent to a destination are dropped?

Throughput

- At what rate is the destination receiving data from the source

Throughput

Transmission rate R bits/sec

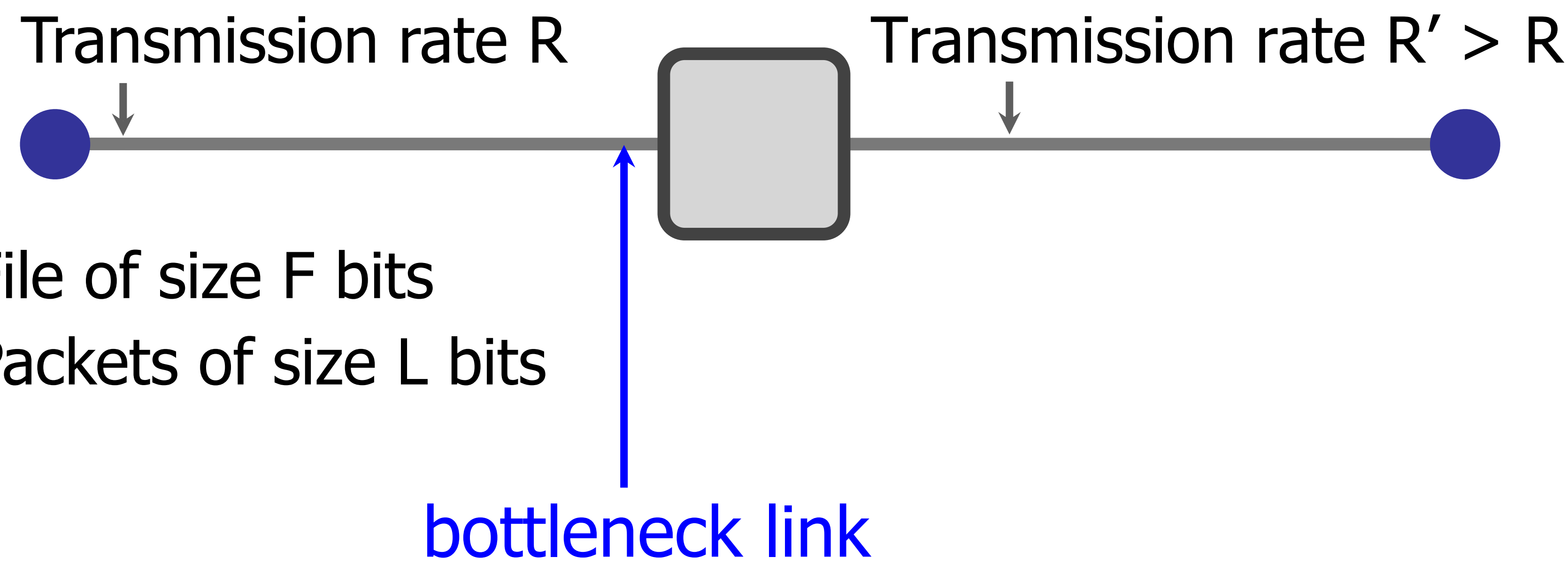
File of size F bits

Packets of size L bits

Transfer time (T) = F/R + propagation delay

Average throughput = F/T ≈ R

End-to-end throughput



Average throughput = min{R, R′} = R

Summary

- Internet基本概念
  - 什么是Internet
    - 组成、服务、协议
  - 网络边缘
  - 网络接入
    - 家庭、公司、无线
  - 网络核心
    - 电路交换、分组交换、虚电路
- Internet历史

- 协议层次及模型
  - OSI七层模型
  - TCP/IP协议栈五层模型
- 网络安全基本概念
- Internet应用
  - C/S构架
  - P2P构架

Homework

- 阅读书本第1章
- 书第1章习题：R12, R23, R24, R25