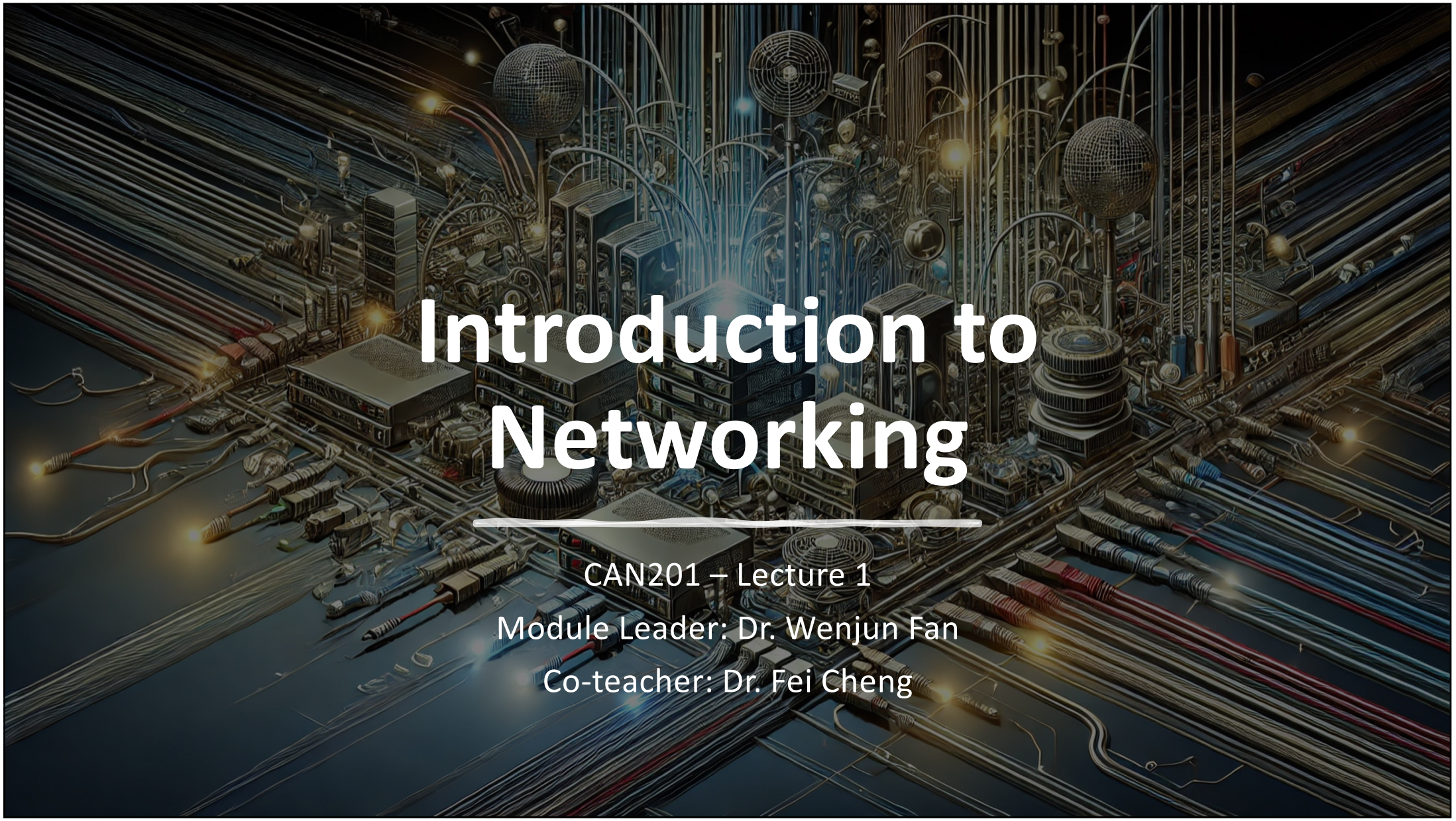


Introduction to Networking

CAN201 – Lecture 1

Module Leader: Dr. Wenjun Fan

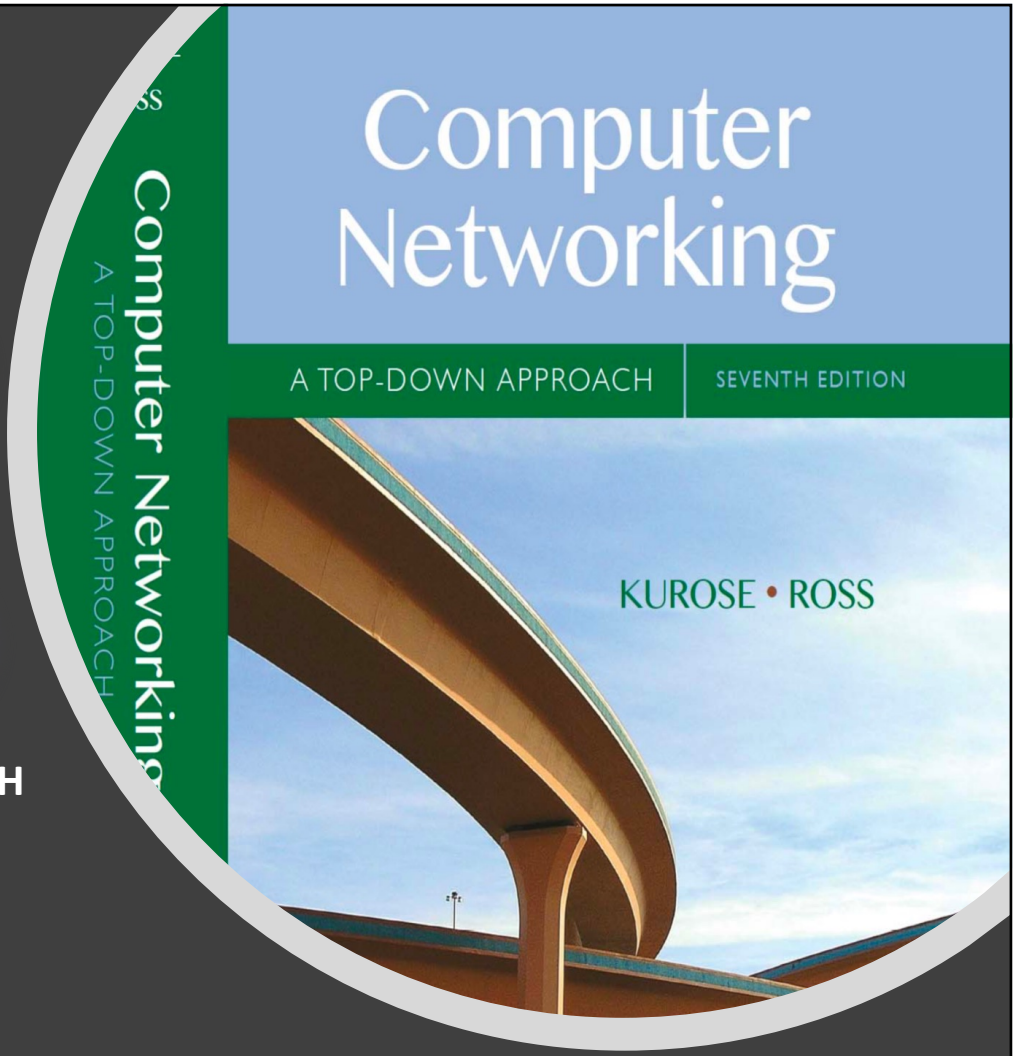
Co-teacher: Dr. Fei Cheng

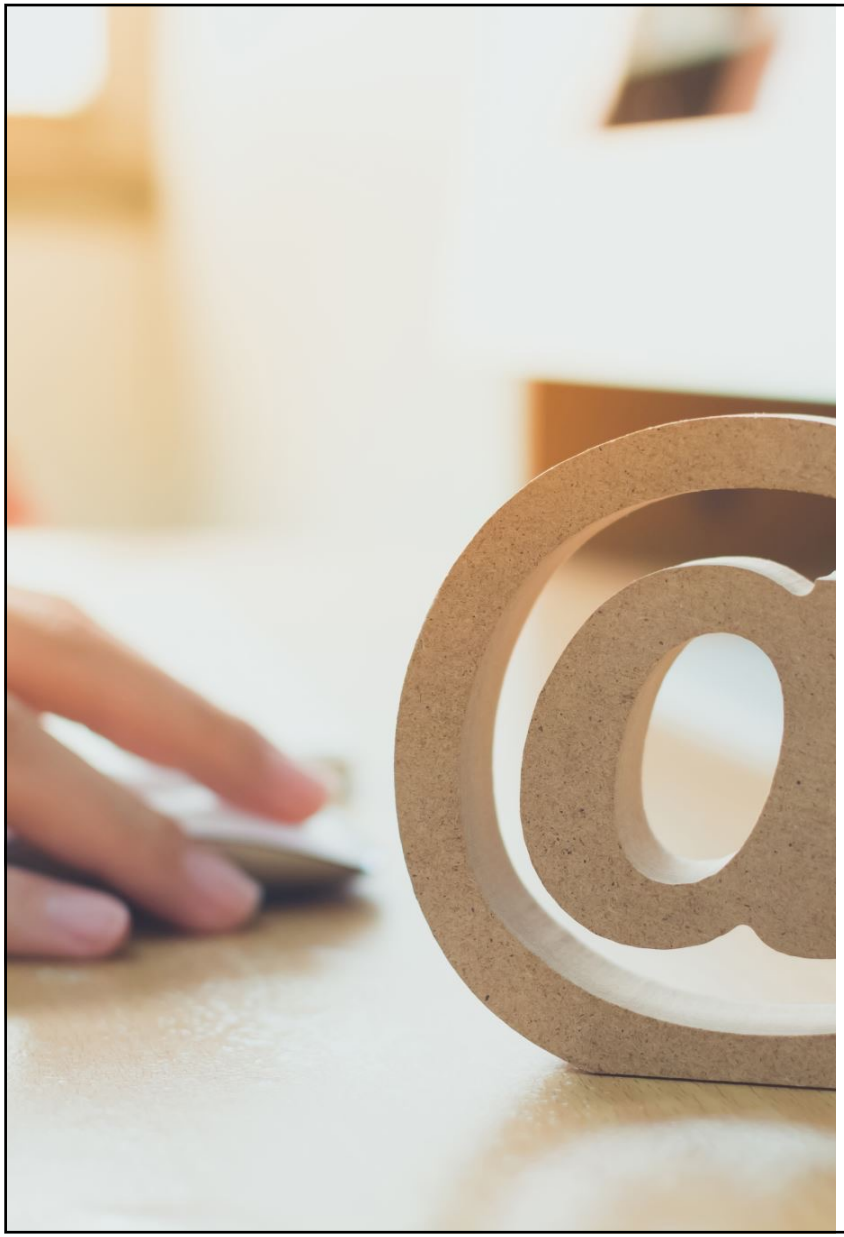
Basic Information

- **Teachers:**
  - Dr. Wenjun Fan (Module Leader), Wenjun.fan@xjtlu.edu.cn
  - Dr. Fei Cheng, fei.cheng@xjtlu.edu.cn

- **TAs:**

- **Textbook:**
  - **Computer Networking: A TOP-DOWN APPROACH**
    - Seventh Edition
    - Author: Jim Kurose, Keith Ross





TAs' emails

Aochen Zhang	zgaochen@163.com
Yuwen Zou	yuwen.zou22@student.xjtlu.edu.cn
Haotian Yin	haotian.yin23@student.xjtlu.edu.cn
Yuxin Xia	yuxin.xia2202@student.xjtlu.edu.cn
Jingyu Cheng	jingyu.cheng23@student.xjtlu.edu.cn
Jia Liu	jia.liu21@student.xjtlu.edu.cn
Dekun Peng	dekun.peng24@student.xjtlu.edu.cn
Derong Wang	derong.wang24@student.xjtlu.edu.cn
Danxiang Xue	danxiang.xue24@student.xjtlu.edu.cn
Zhiqi Wu	zhiqi.wu23@student.xjtlu.edu.cn
Pengfei Fan	pengfei.fan22@student.xjtlu.edu.cn
Yuli Zhang	yuli.zhang20@student.xjtlu.edu.cn

“Protocol” for CAN201 related email

[协议]

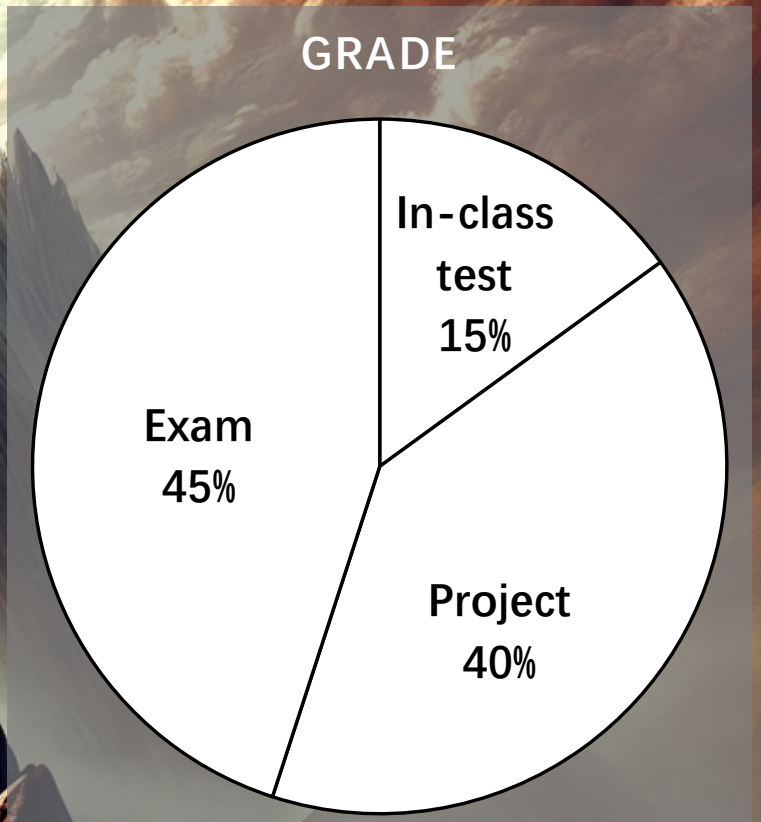
EMAIL TITLE SHOULD START WITH “[CAN201]”

WAIT 2 DAYS

IF I DON’T REPLY, SEND ME AGAIN…

Assessments

- In class test: 15% (Across the Labs)
- Project: 40% (Two Parts/Group work)
- Final Exam: 45%



In Class Test

Assessment Task	Learning Outcomes	Weighting	Release Date	Due Date	Need Submission?
Socket Programming	AB	5%	14/Oct/2024	18/Oct/2024	YES
Generative AI Permissions		No			
Requirement and Guideline of the Assessment Task					
The students are required to develop a socket client and a socket server. These will be tested by running them on two separate virtual machines (VMs) to verify that they can communicate effectively.					

Assessment Task	Learning Outcomes	Weighting	Release Date	Due Date	Need Submission?
Network Description	AB	5%	04/Nov/2024	08/Nov/2024	YES
Generative AI Permissions		No			
Requirement and Guideline of the Assessment Task					
The students are required to use Mininet to describe and create a network topology according to the network diagram given by the test.					

Assessment Task	Learning Outcomes	Weighting	Release Date	Due Date	Need Submission?
Solution to DoS Attack	AB	5%	18/Nov/2024	22/Nov/2024	YES
Generative AI Permissions		No			
Requirement and Guideline of the Assessment Task					
The students are required to provide a solution to a security problem given by the test, and also explain the solution.					

Project

Assessment Task	Learning Outcomes	Weighting	Release Date	Due Date	Need Submission?
CW Part 1	ALL	20%	07/Oct/2024	15/Nov/2024	YES
Generative AI Permissions		No			
Requirement and Guideline of the Assessment Task					
File uploading and downloading should be one of the most important network-based applications in our daily life. This part of the networking project aims to use Python Socket programming to implement a client-side application for file uploading and downloading based on a given protocol. The examiner will define and release the protocol description and the server-side application on Learning mall. However, the released server-side code might have some syntax bugs. The student should firstly fix all the bugs and run the server-side code. Then, you should implement the client-side application using Python and test your code using the server-side application.					
Assessment Task	**Learning Outcomes**	**Weighting**	**Release Date**	**Due Date**	**Need Submission?**
CW Part 2	ALL	20%	04/Nov/2024	13/Dec/2024	YES
Generative AI Permissions		No			
Requirement and Guideline of the Assessment Task					
This part of the networking project aims to use Mininet to create a simple SDN network topology and emulate a traffic control function through using the SDN flow entry. Assuming that the client side only knows the service running on server 1 and communicates with server 1 (without knowing the existence of the service on server 2). However, the SDN controller can manipulate (forward/redirect) the traffic without the awareness of the client. The student needs to develop the SDN controller application to create effective flow entry to make the incoming network traffic forward or redirected.					

Assignment Policies

Programming projects are ~ 25% of your grade

- 4 – 5 weeks for each
- Manage your time

Assignments will be done in Python 3 and other plugins/modules.

Late submission will follow the university late submission policy [1].

Academic dishonesty will not be tolerated.

[1] Item 42-43, Part F, Code of Practice on Assessment of XJTLU.

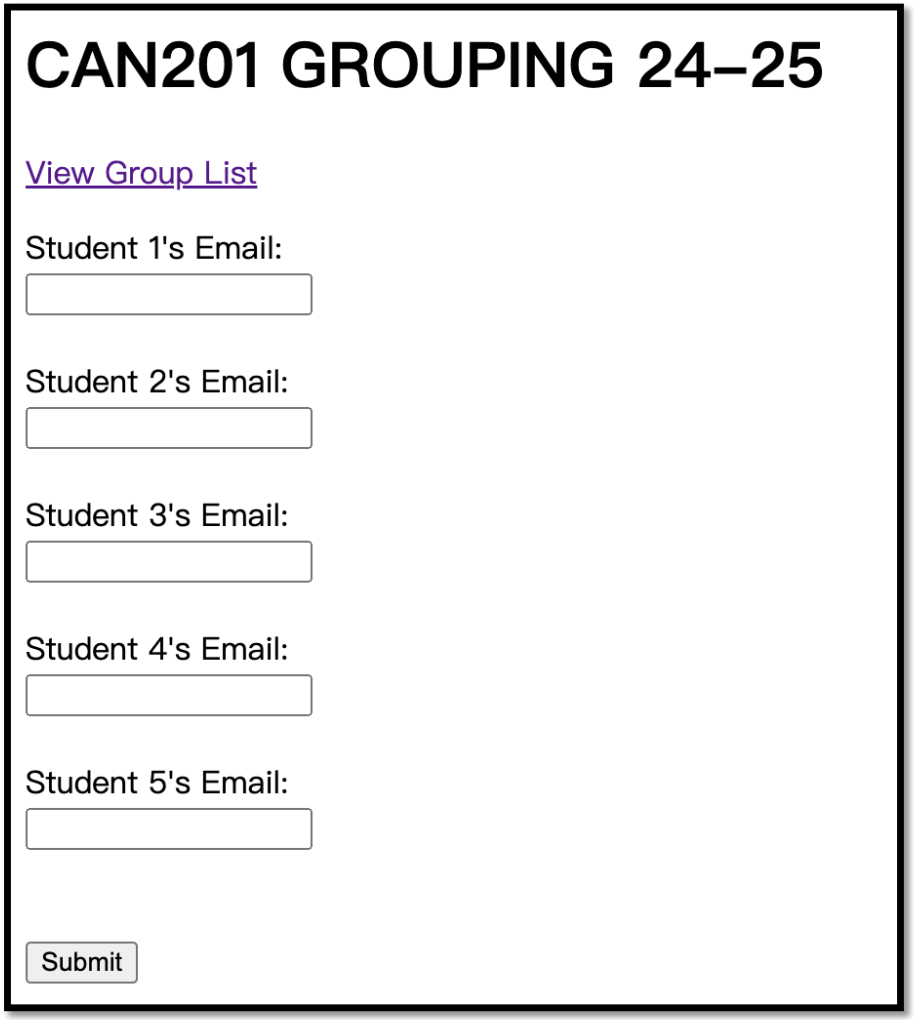
Academic Dishonesty Policy

- **Academic dishonesty is anything that involves you not doing the assignment yourself, including:**
  - Copying from your “friend”
  - Copying from an internet or other source
  - Paying someone to complete the assignment
- **Submitting a course assignment that is not your work falls under the University major plagiarism or collusion policy. The penalties for this are:**
  - Automatic failure of the course, with NO RESIT
  - A permanent mark on your transcript
  - A letter to your parents notifying them of your actions
- **The use of Generative AI for content generation is not permitted on all assessed coursework in this module.**

Register your group on this webpage:

https://group.feimax.com/

4-5 student in one group



Lecture Syllabus

Week 1

Lecture 1 - the theoretical basis for networking: protocol, layer and model…

Week 2

Lecture 2 - the application layer: principles, web and HTTP…

Week 2

Lecture 3 - the application layer: Email, DNS, P2P, multimedia protocols…

Week 4

Lecture 4 - the transport layer: multiplexing, UDP and reliable data transfer…

Week 5

Lecture 5 - the transport layer: TCP and congestion control…

Lecture Syllabus

Week 6

Lecture 6 - the network layer:
router, internet, IPv4 and IPv6 …

Week 7:
no class…

Week 8

Lecture 7 - the network layer:
routing algorithm…

Week 9

Lecture 8 - the network layer:
control plane …

Week 10

Lecture 9 - The link layer 1

Lecture Syllabus

Week 11

Lecture 10 - The link layer 2, Network Security 1

Week 12

Lecture 11 - Network Security 2

Week 13

Lecture 12 - Network Security 3 and review

Happy ending (Hopefully)

Lab Sessions

Lab time
SC464

Thu. or Fri.

Labs will be split between **Python** and **networking** experiments

Attendance to labs is required

Labs & Projects Plan

Week Number and/or Date	Lab	Topic/Theme/Title	Lecturer
Week 1	Lab 1	Linux OS, Virtual Machine and Mininet	Wenjun Fan
Week 2	Lab 2	Wireshark and Tcpdump	Wenjun Fan
Week 3	Lab 3	Python1: IDE and Interpreter	Fei Cheng
Week 4	Lab 4	Python2: Basic syntax & Data structure	Fei Cheng
Week 5	Lab 5	Python3: Network programming (Socket)	Fei Cheng
Week 6	Lab 6	Python4: Modules,Pypi,OOP,Parallel Computing	Fei Cheng
Week 8	Lab 7	Building network topology using Mininet	Wenjun Fan
Week 9	Lab 8	SDN controller application with Mininet	Wenjun Fan
Week 10	Lab 9	DoS attack on SDN	Wenjun Fan
Week 11	Lab 10	TCP connection analysis	Wenjun Fan
Week 12	Lab 11	Scanner and Firewall	Wenjun Fan
Week 13	Lab 12	Intrusion Detection System	Wenjun Fan

New Lab room Arrangement

- We will use the first Linux Computer Lab @ XJTLU!

Ubuntu

Computer Lab Disclaimer
计算机实验室免责声明

Welcome to the SC464 Computer Lab. To ensure a productive and secure environment for all users, please be aware of the following guidelines:

欢迎来到 SC464 计算机实验室。为了确保所有用户有一个高效和安全的环境，请注意以下指南：

1. **Backup Your Work**: Please save and backup your homework or task files on your own device before you shut down or leave the computer. All files stored on these computers will be **permanently removed** upon reboot.

   备份您的工作：在关闭或离开计算机之前，请将您的作业或任务文件保存在您自己的设备上并备份。这些计算机上的所有文件将在重启后被永久删除。

2. **Security and Conduct**: Do not engage in any malicious activities or violate the security policies while using these computers. Any individual found responsible for such actions will be held accountable for their behaviour and subject to disciplinary actions.

   安全和行为：在使用这些计算机时，不要从事任何恶意活动或违反安全政策。任何被发现负责此类行为的个人将对其行为负责，并将面临纪律处分。

3. **Respect Shared Resources**: Please be considerate of other users. Do not install unauthorized software, alter system settings, or use excessive bandwidth.

   尊重共享资源：请考虑其他用户的需求。不要安装未经授权的软件，修改系统设置或使用过多的带宽。

4. **Privacy Notice**: Be aware that this is a shared environment. Avoid storing sensitive personal information on these computers as it may not be secure.

   隐私注意：请注意，这是一个共享环境。出于安全考量，避免在这些计算机上存储敏感的个人信息。

5. **Report Issues**: If you encounter any technical problems or notice any suspicious activity, please report it to the lab administrator immediately.

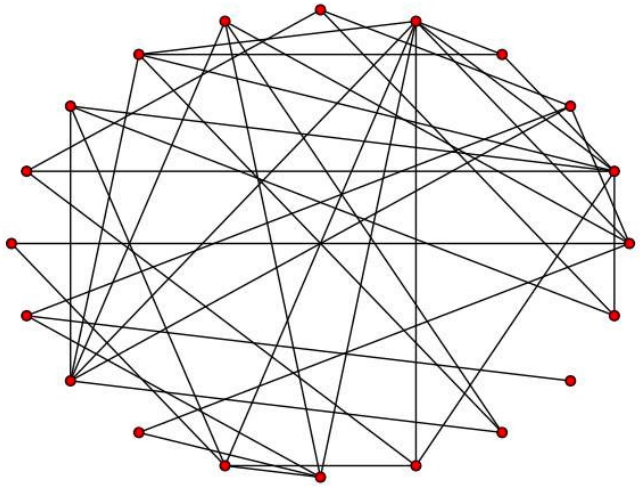
   报告问题：如果您遇到任何技术问题或注意到任何可疑活动，请立即向实验室管理员报告。

Lecture 1 - Introduction

1. What is the network?
2. How does the network work?
3. How to evaluate the performance?

Network

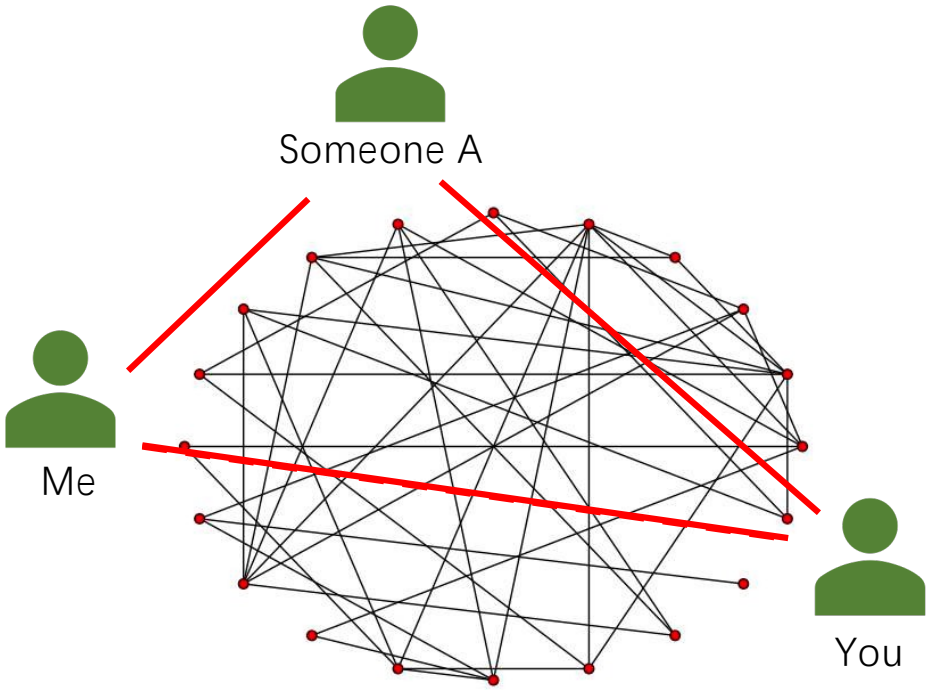
Liverpool



Suzhou

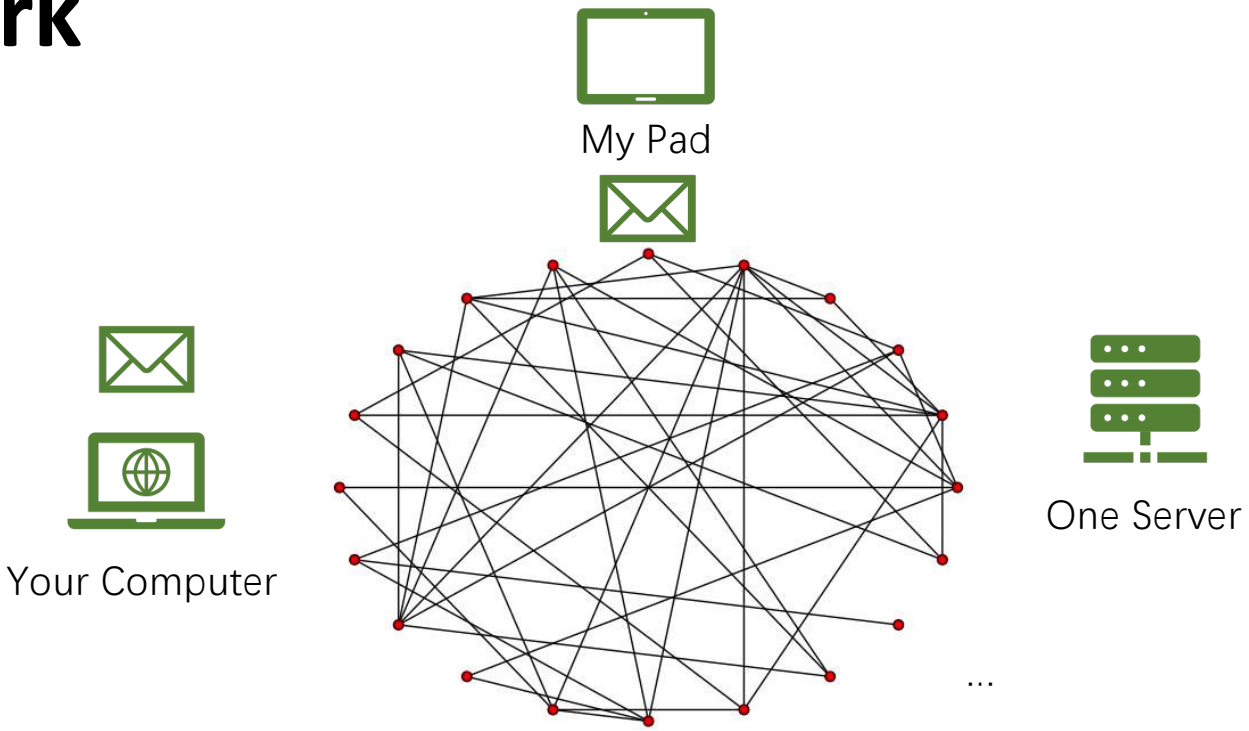
Road Network

Network



Social Network

Network



Computer Network

Network

- Enable communication between participants

Devices

Services









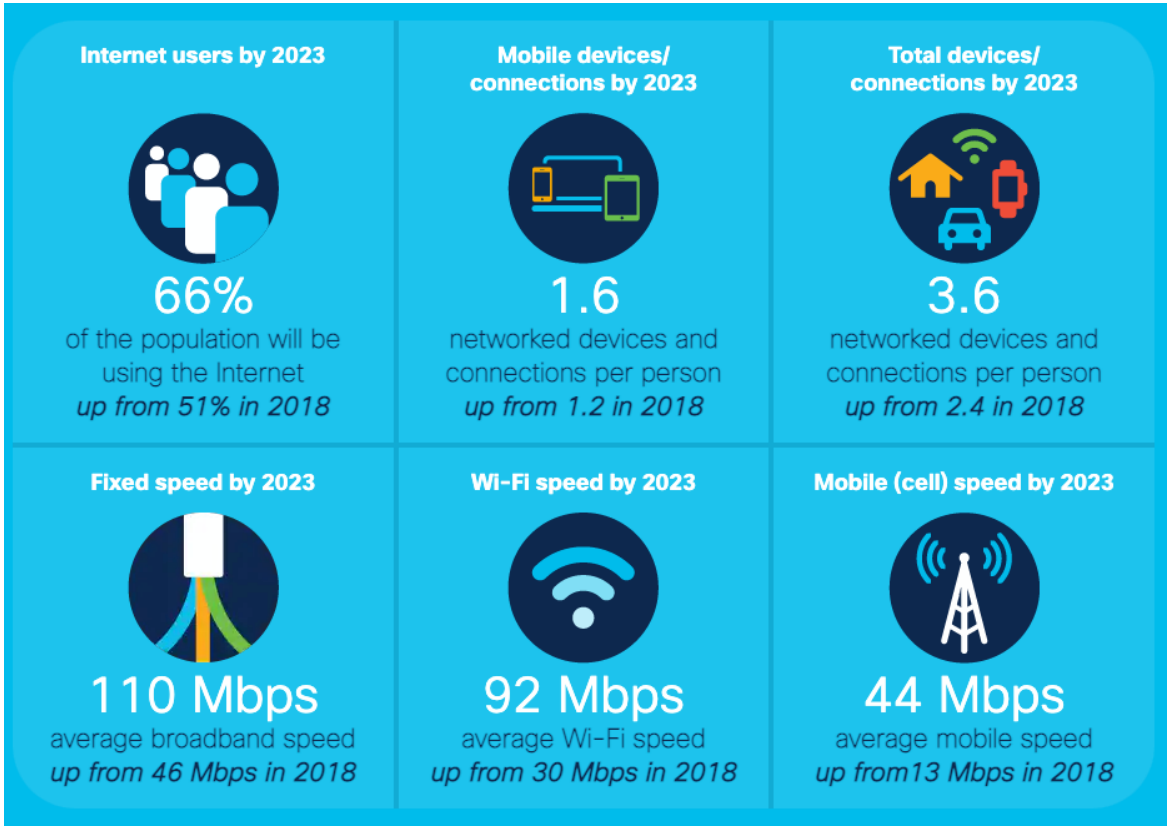
.....

Network

- Enable communication/link between participants
- **For computer network, participants are:**
  - Devices
  - Services


internet
Latin: between, among

Internet!



From
Cisco Annual Internet Report
2023


INTERNET
Largest
Project
Users
Devices
almost
Every
Everywhere
Everyday
Everything

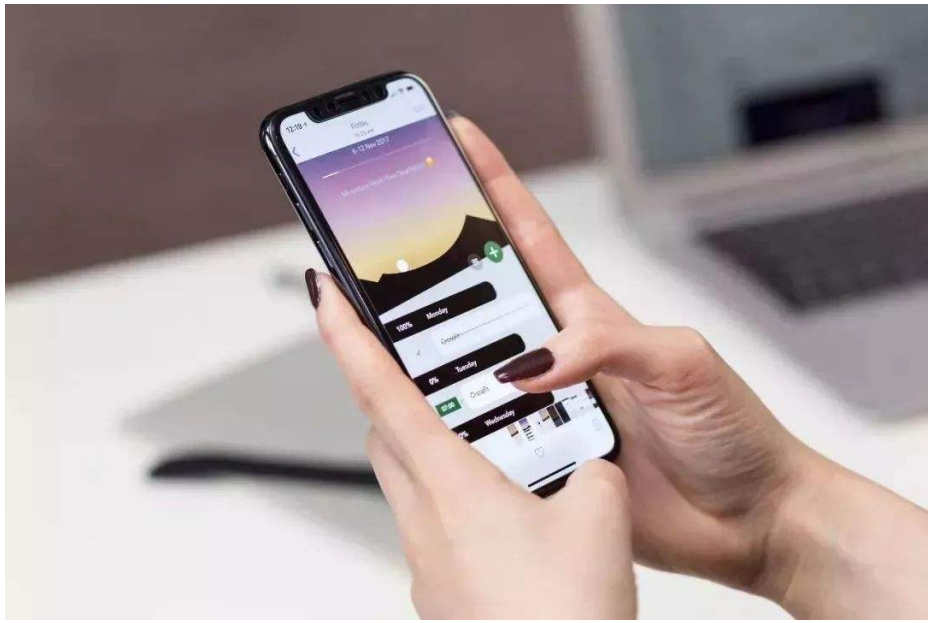

INTERNET

Network

- Enable communication/link between participants
- For computer network, participants are:
  - Devices
  - Services
- **Internet:**
  - The largest network of networks
  - Connect billions of devices worldwide
  - How it works?

Lecture 1 - Introduction

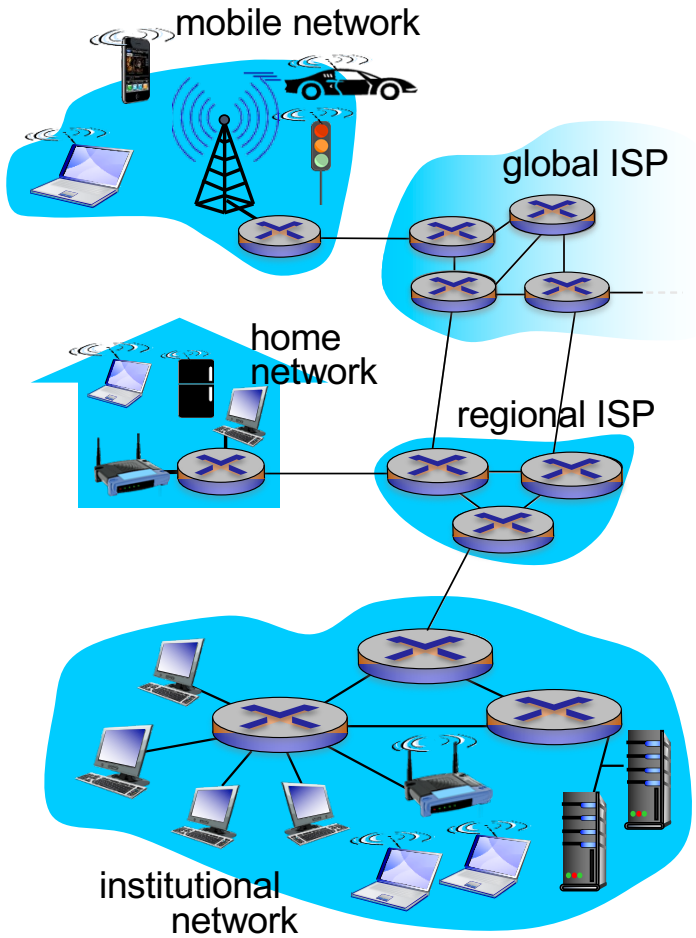
1. What is the network?
2. How does the network work?
3. How to evaluate the performance?



- **How does your message pass to the destination?**

- Hedwig will not help you deliver your messages…

The whole picture of the network / internet



Medium

Optical fiber, metal …
Radio, light…

Methods

Packet switches 分组交换
Protocols: TCP/IP, HTTP, 802.11

Framework

Layered: from global to local
ISO/OSI - 7
IP stack - 5

How to access the internet?

Medium?

Methods?

Physical media

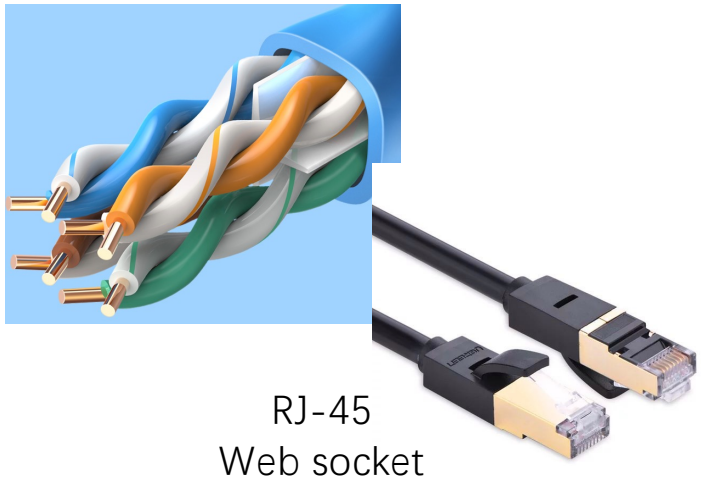
- **Guided media:**
  - signals propagate in solid media: copper, fiber, coaxial cable, glass

- **Unguided media:**
  - signals propagate freely, e.g., radio

Physical media: twisted pair, coax, fiber

Twisted pair (TP) 双绞线

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



RJ-45
Web socket

Coaxial cable: 同轴电缆

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

Fiber optic cable:

- glass fiber carrying light pulses, one pulse = a bit
- high-speed operation:
  - high-speed point-to-point transmission (e.g., 10-100 Gbps 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:

- Wireless LAN (e.g., WiFi)
  - 54 Mbps – 9.6Gbps
- Wide-area (e.g., cellular)
  - 4G cellular: ~ 100 Mbps
  - 5G cellular: ~ 1Gbps
- Satellite
  - Kbps to 45Mbps channel (or multiple smaller channels)
  - Starlink ~ 1440Mbps
  - 270 msec end-end delay

Different methods to access the internet

Early methods:

PSTN
DSL
TV Net

Modern methods:

FTTH
Wireless

1979

Dial-up Internet access (PSTN)

Dial-up Internet access is a form of Internet access that uses the facilities of the public switched telephone network (PSTN) to establish a connection to an Internet service provider (ISP) by dialing a telephone number on a conventional telephone line. Dial-up connections use modems to decode audio signals into data to send to a router or computer, and to encode signals from the latter two devices to send to another modem.

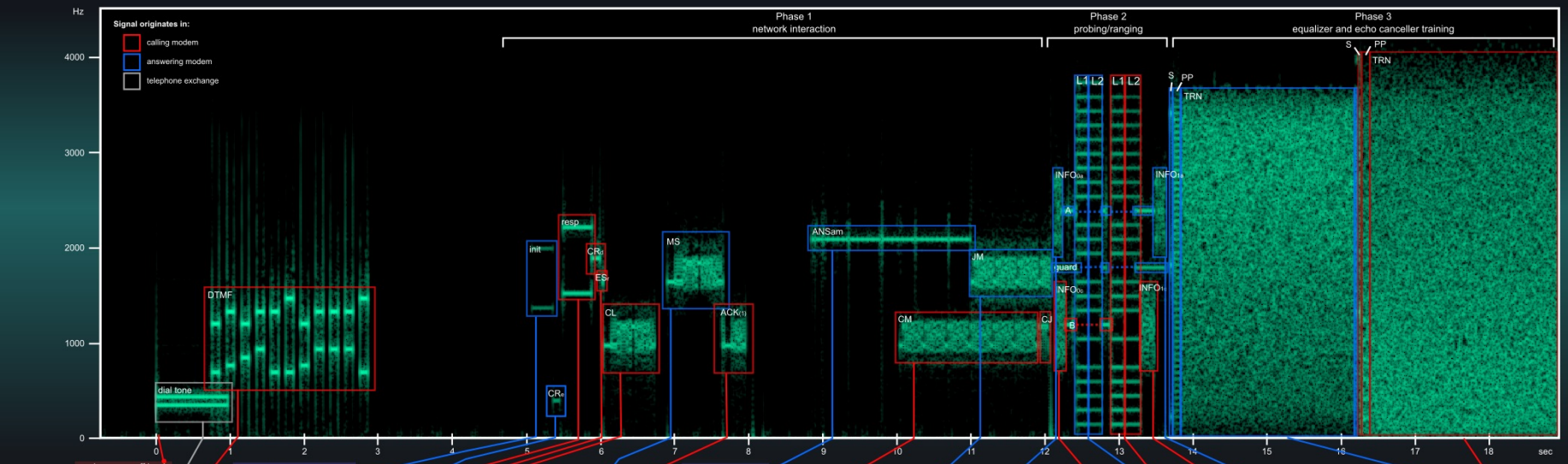
Modulator and demodulator

Bandwidth: 56 Kbps ~ 10 min for a mp3 music

https://en.wikipedia.org/wiki/Dial-up_Internet_access

Listen Please

The Sound of the Dialup: an Example Handshake



modem goes off hook

telephone exchange sends a dial tone

modem dials 1-(570)234-0003, a number in Pennsylvania

answering modem initiates a V.8 *bis* transaction

answering modem asks caller to list its capabilities

caller responds to V.8 *bis* initiation, agrees to list its capabilities

caller requests to escape from telephony into information transfer mode

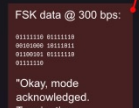
FSK data @ 300 bps:

"I'm capable of full V.8.
I can transmit ACK.
By the way,
my country is the U.S.
I was manufactured by
Net2phone Inc."

FSK data @ 300 bps:

"Why don't we use V.8 then."

FSK data @ 300 bps:



"Okay, mode acknowledged.
Terminating
V.8 bis transaction."

answering modem disables echo suppressors and cancellers in PSTN

FSK data @ 300 bps:

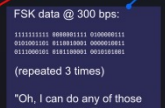
(repeated 6 times)

"Modulation modes available:
-PCM V.90/V.92 analogue
-V.34 duplex
-V.32/V.32 bis
-V.23 duplex
-V.22/V.22 bis
-V.21

V.42 LAPM is available.

PSTN connection is over a regular landline (not cellular).
My network is analogue."

FSK data @ 300 bps:



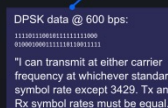
(repeated 3 times)

"Oh, I can do any of those modes as well. Except my V.90/V.92 is digital.

V.42 LAPM is available.

PSTN connection is over a regular landline (not cellular).
My network is digital."

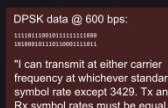
DPSK data @ 600 bps:



"I can transmit at either carrier frequency at whichever standard symbol rate except 3429. Tx and Rx symbol rates must be equal.

I can reduce power if needed.
I can support up to 1664-point signal constellations.
My clock source is internal."

DPSK data @ 600 bps:



"I can transmit at either carrier frequency at whichever standard symbol rate except 3429. Tx and Rx symbol rates must be equal.

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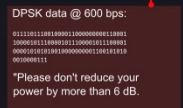
I can support up to 1664-point signal constellations.
My clock source is external."

modems send a wide-spectrum probing signal in both directions to do measurements of the telephone line

DPSK data @ 600 bps:



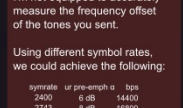
"Please don't reduce power any further.

Your tones were offset by 0 Hz.

Let's use a symbol rate of 3200. We can achieve a maximum of 4800 bps. For your pre-emphasis filter, select the parameters β = 1.0 dB and γ = 2.0 dB.

Please use carrier at 1920 Hz for transmission, I'll use 1829."

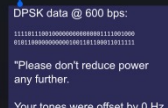
DPSK data @ 600 bps:



symrate	ur pre-emph α	bps
2400	6 dB	14400
2743	8 dB	16800
2800	8 dB	16800
3000	8 dB	16800
3200	8 dB	19200
3429	10 dB	21600

I can use the higher frequency carrier at any symbol rate."

DPSK data @ 600 bps:



"Please don't reduce power any further.

Your tones were offset by 0 Hz.

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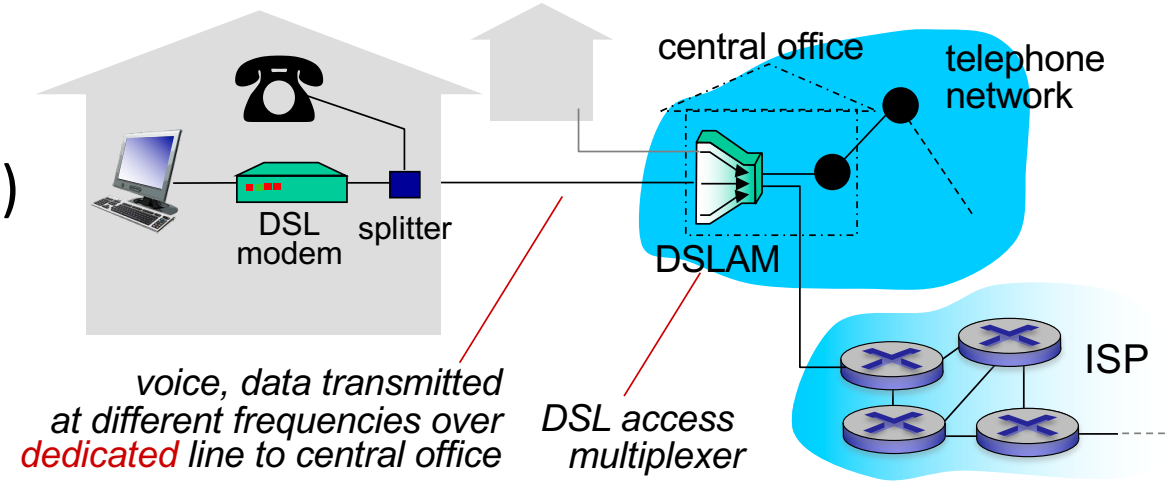
Please use carrier at 1920 Hz for transmission, I'll use 1829."

Modems go to scrambled data and learn how the other modem sounds over the channel. The final bitrate and signal constellation are also decided on.

A final training phase called Phase 4 will follow, after which the modem speaker goes mute and data can be put through the connection.

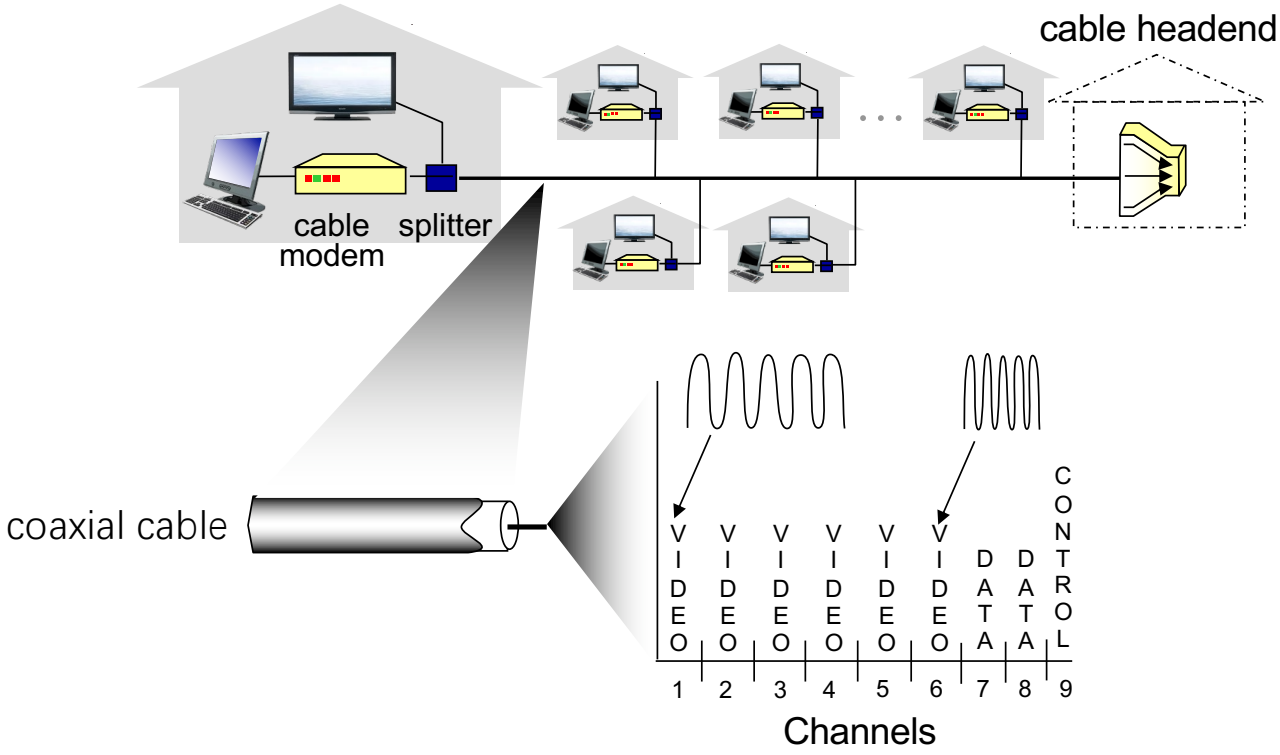
Digital subscriber line (DSL)

- **Telephone line based:**
  - To central office DSL Access Multiplexer (DSLAM)
  - Data over DSL phone line goes to Internet
  - Voice over DSL phone line goes to telephone net



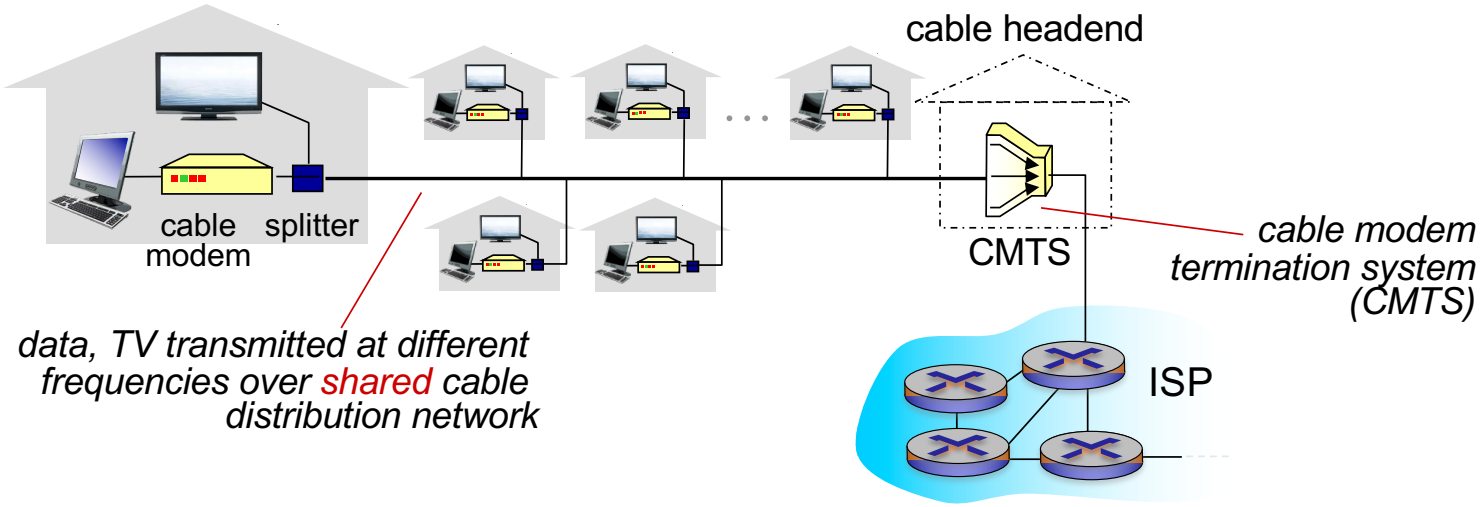
- **Bandwidth**
  - Upstream transmission rate < 2.5 Mbps (typically < 1Mbps)
  - Downstream transmission rate < 24 Mbps (typically < 10Mbps)
  - ADSL = Asymmetric Digital Subscriber Line

TV net



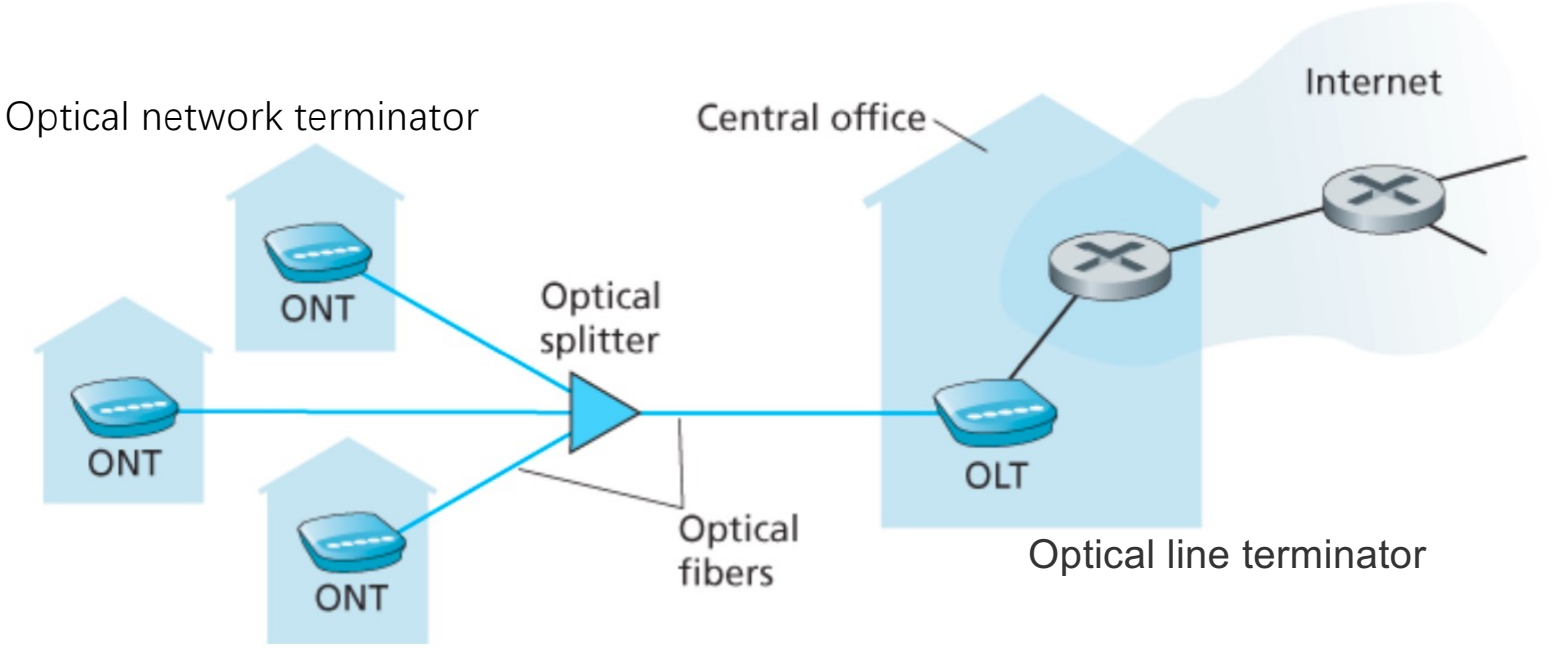
- **Key technology: Frequency division multiplexing (FDM)**
  - Different channels transmitted in different frequency bands

TV net



- **HFC: hybrid fiber coax**
  - Asymmetric: 30Mbps downstream transmission rate, 2 Mbps upstream transmission rate

FTTH: fiber to the home



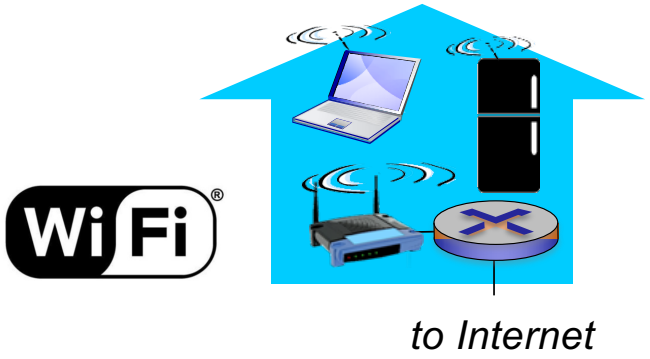
FTTH using the passive optical networks (PONs) distribution architecture

Wireless access networks

- **Base Stations should be used to provide the signal!**

Wireless LANs:

- within building (30 m)
- 802.11b/g/n (WiFi): 11, 54, 450 Mbps transmission rate
- 802.11ax : 9.6 Gbps (MIMO)

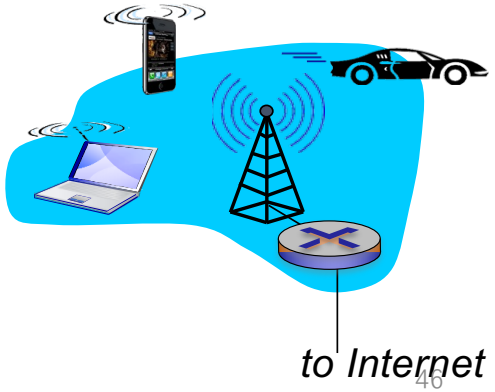


Li-Fi（in the future）

- up to 10Gbps
- over the visible light, ultraviolet, and infrared spectrums

Wide-area wireless access

- provided by ISP
- Up to 1Gbps or More
- 3G, 4G-LTE, 5G, Starlink



Wireless access networks

STARLINK

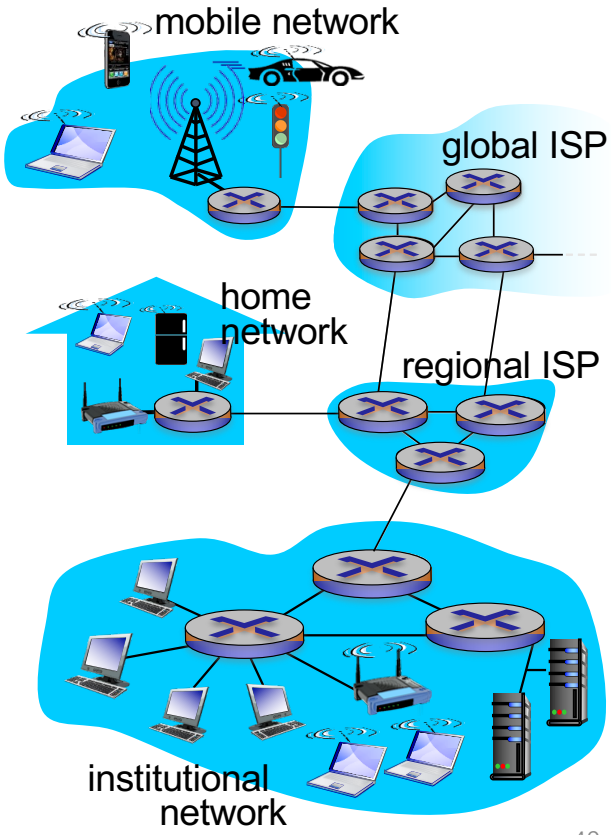
- 100 Mbps to 120 Mbps

How to deliver the data via the Internet?

Who “carries” a message?
How to pass a message?
The basic idea of the internet.

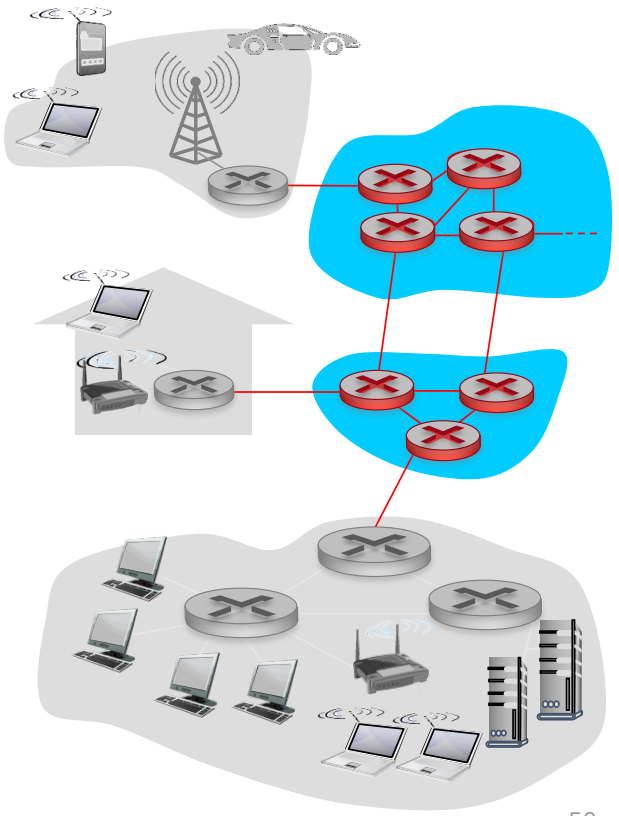
A closer look at network structure

- **Network edge = Host:**
  - Clients: PCs, Mobile phones, Smart Devices
  - Servers: normally hosted in data centers
- **Physical media to access networks:**
  - Wired or wireless communication links



Network Core

- **Mesh of interconnected routers**
- **Packet-switching:**
  - Hosts break application-layer messages into small packets
  - Packages are forwarded from one router to the next, across links on path from source to destination

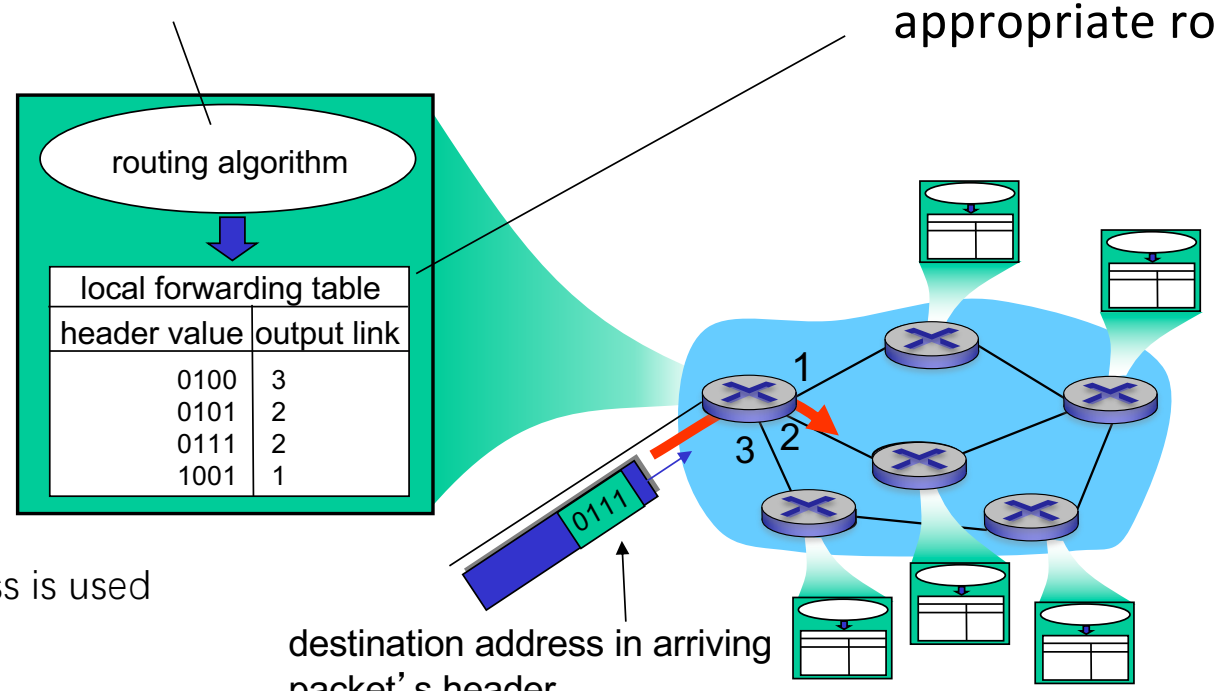


Two key network-core functions

Routing: determines source-destination route taken by packets

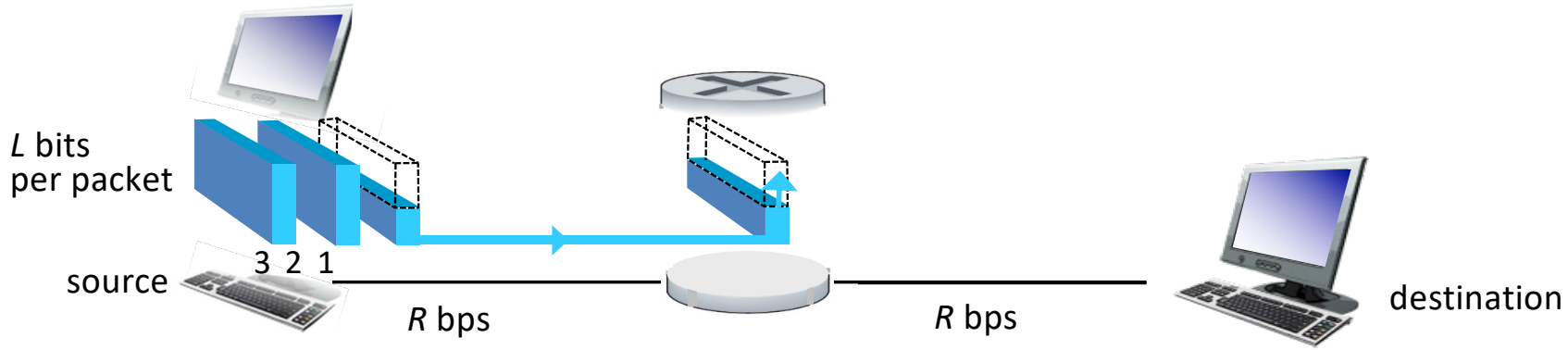
- *routing algorithms*

Forwarding: move packets from router's input to appropriate router output



*IP address is used

Packet Switching: store-and-forward

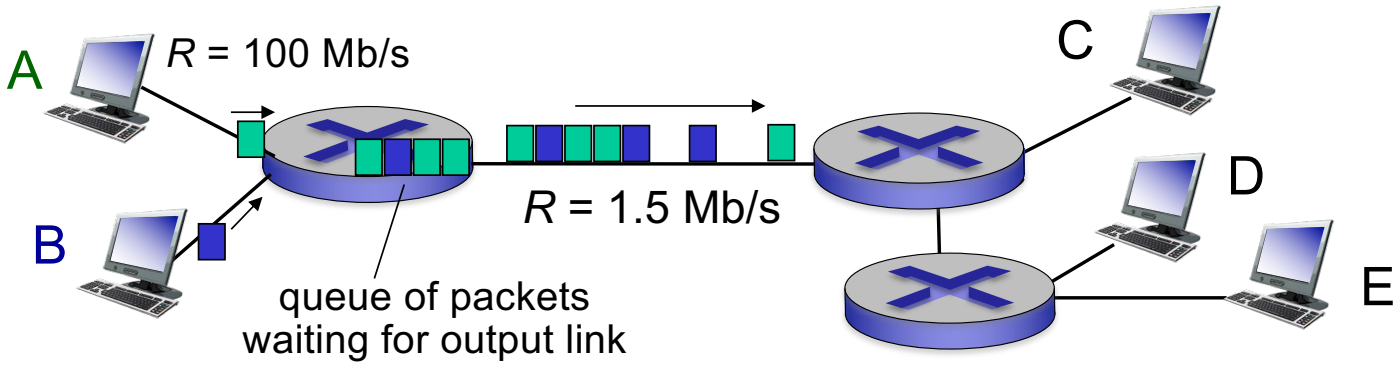


- Takes L/R seconds to transmit (push out) L-bit packet into link at R bps
- *Store and forward:* entire packet must arrive at router before it can be transmitted on next link
- End-end delay = $2L/R$ (assuming zero propagation delay)

One-hop example:

- L = 7.5 Mbits
- R = 1.5 Mbps
- one-hop transmission delay = 5 sec

Packet Switching: queueing delay, loss



Queuing and loss:

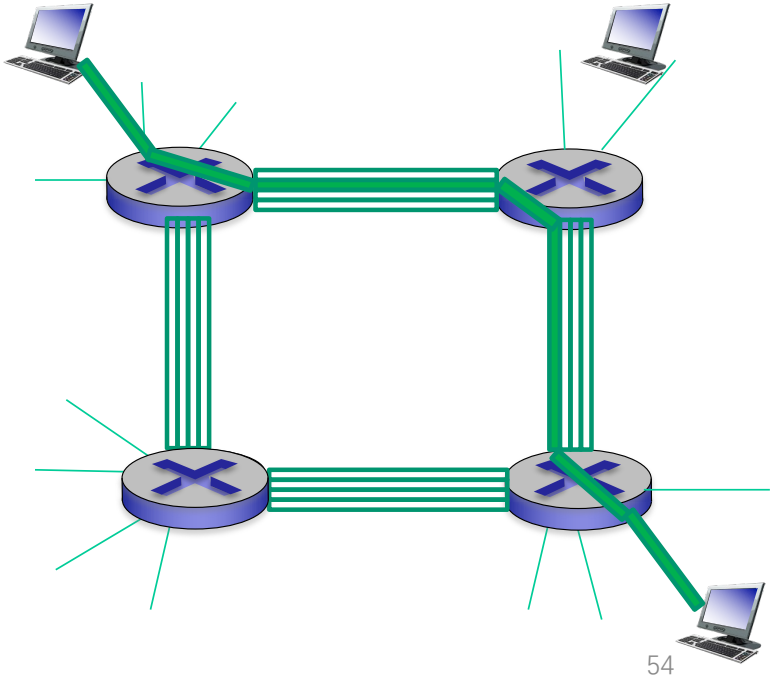
- If arrival rate (in bits) to link exceeds transmission rate of link for a period of time:
  - packets will queue, wait to be transmitted on link
  - packets can be dropped (lost) if memory (buffer) fills up

Circuit switching

- Dedicated resources: no sharing
  - circuit-like (guaranteed) performance
- Circuit segment is idle if not used by call *(no sharing)*
- Commonly used in traditional telephone networks

Operator
接线员

manually circuit switching

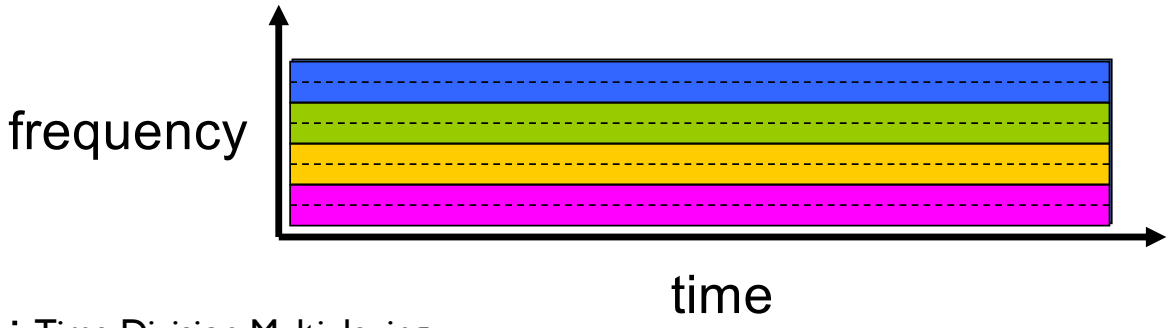


Circuit switching: FDM versus TDM

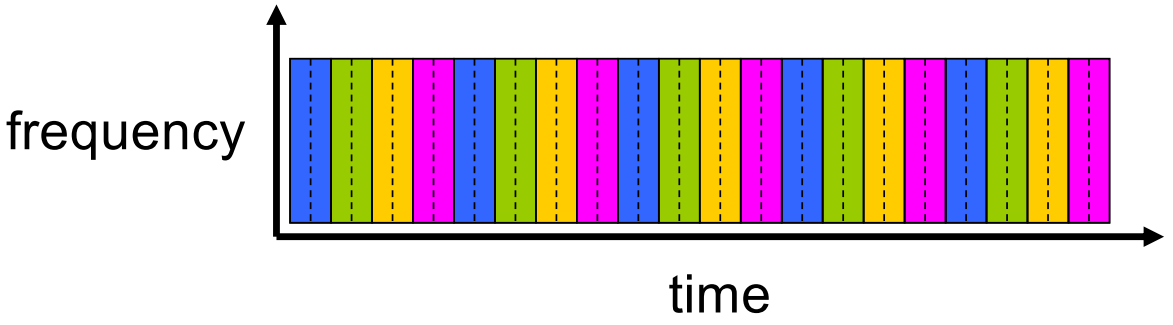
FDM : Frequency Division Multiplexing

Example:

4 users



TDM : Time Division Multiplexing

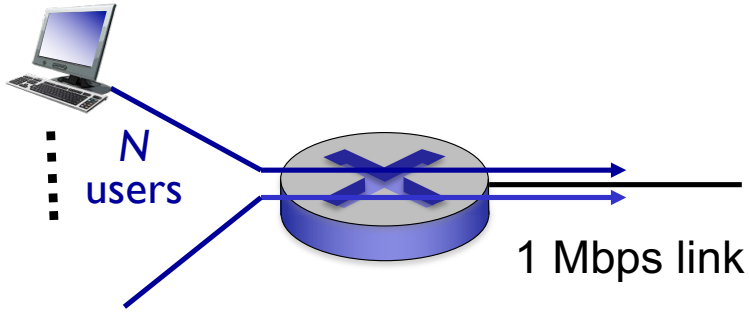


Packet switching VS circuit switching

Packet switching allows more users to use network!

Example:

- 1 Mb/s link
- each user:
  - 100 kb/s
  - aka, active 10% of time



- *Circuit-switching:*
  - 10 users
- *Packet switching:*
  - with 35 users, probability > 10 active at same time is less than 0.0004

$$\sum_{i=11}^{35} C_{35}^{i} p^{i} (1-p)^{35-i}$$

Q: how did we get value 0.0004?

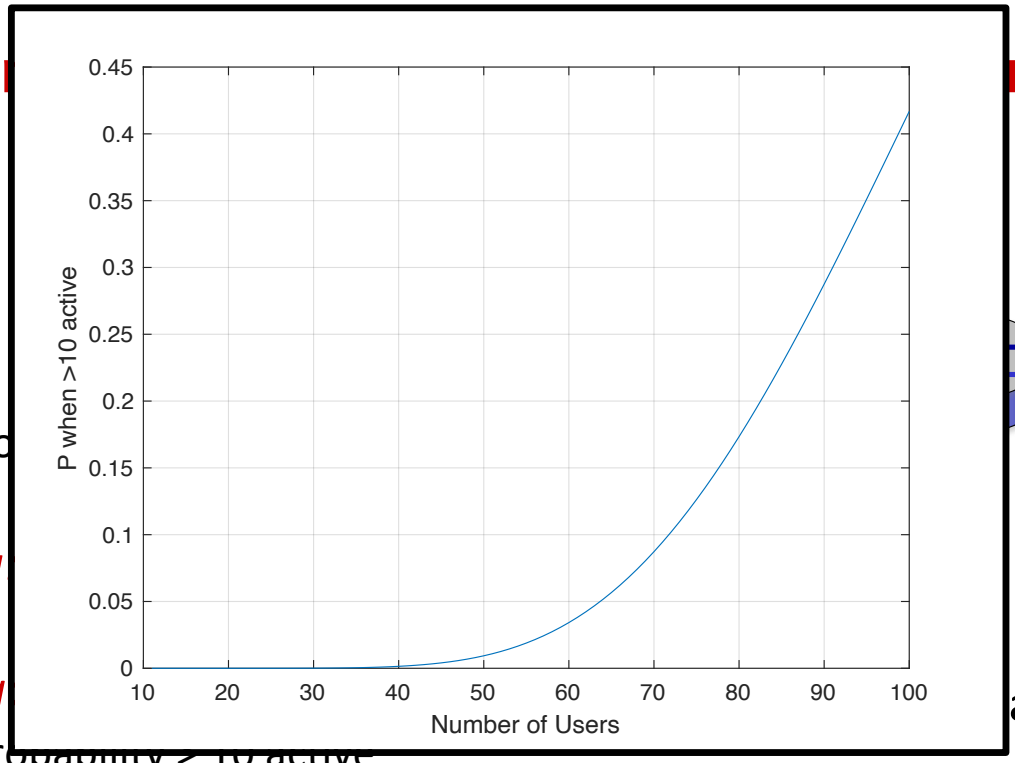
Q: what happens if > 35 users ?

Packet switching VS circuit switching

Packet switchi **rk!**

Example:

- 1 Mb/s link
- each user:
  - 100 kb/s
  - aka, active 10% o
- *Circuit-switching*
  - 10 users
- *Packet switching*
  - with 35 users, probability > 10 active at same time is less than 0.0004



1 Mbps link

$$\sum_{i=11}^{35} C_{35}^{i} p^{i} (1-p)^{35-i}$$

alue 0.0004?

Q: what happens if > 35 users ?

Packet switching VS circuit switching

- **Is packet switching (PS) a "winner?"**
  - PS advantages:
    - resource sharing
    - simpler, no call setup
  - PS drawbacks:
    - excessive congestion possible: delay and loss
      - protocols needed for reliable data transfer, congestion control
  - How to provide circuit-like behavior PS?
    - Bandwidth guarantees
    - New methods should be developed

Protocols (协议)

Human protocols:

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

… specific messages sent

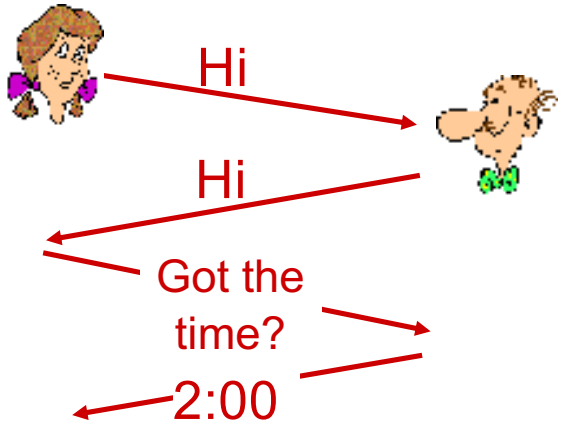
… specific actions taken when messages received, or other events

Network protocols:

- Machines rather than humans
- All communication activity in Internet governed by protocols

A set of rules for how data is transmitted across the network

Protocols define format, order of messages sent and received among network entities; and actions taken on message transmission, receipt


Hi
Hi
Got the time?
2:00

time

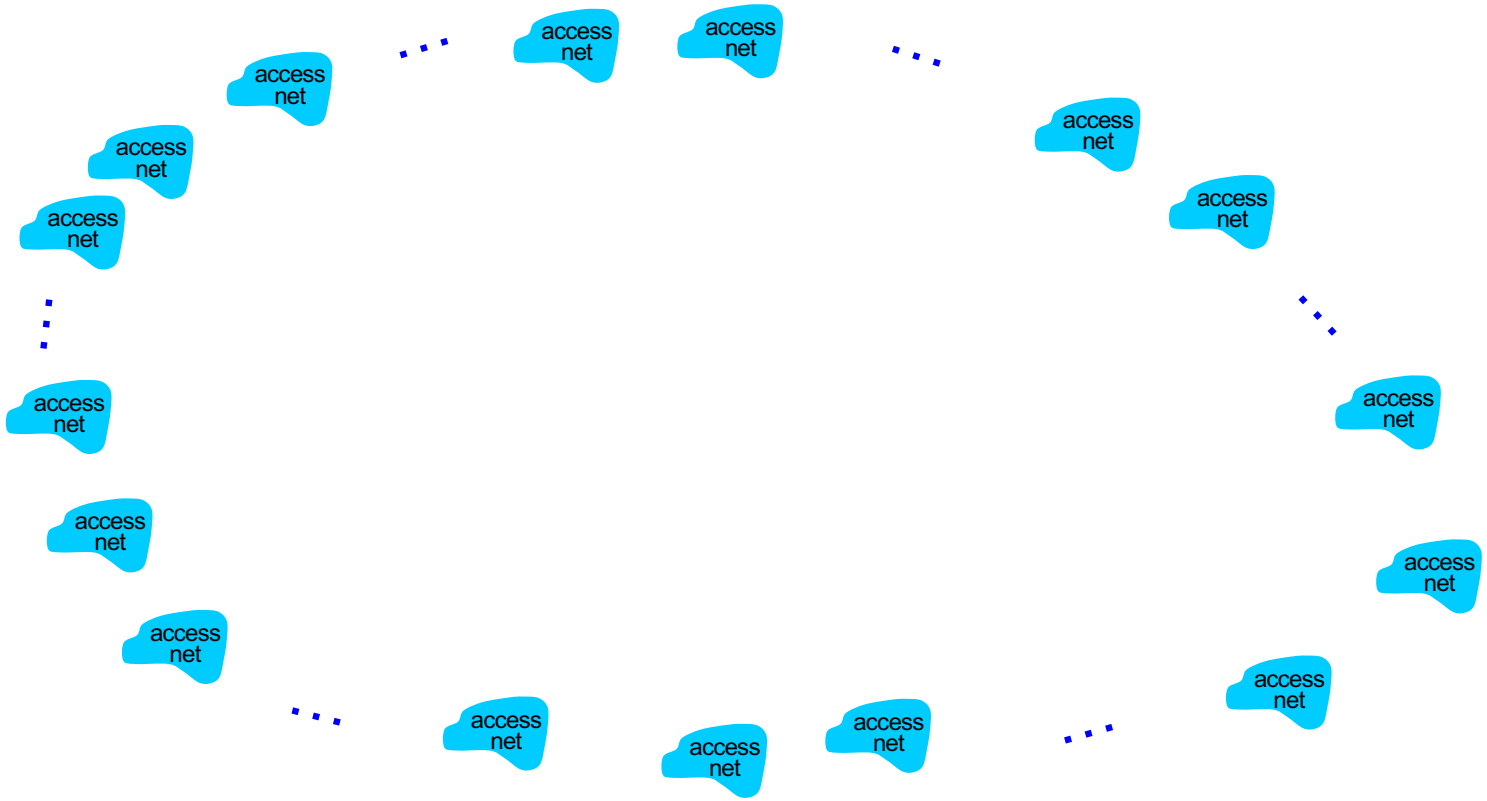

TCP connection request
TCP connection response
Get https://www.xjtlu.edu.cn
<HTML>

Internet: Network of networks

- **End systems connect to Internet via access ISPs (Internet Service Providers)**
  - residential, company and university ISPs
- **Access ISPs in turn must be interconnected.**
  - so that any two hosts can send packets to each other
- **Resulting network of networks is very complex**
  - evolution was driven by economics and national policies
- **Let's take a stepwise approach to describe current Internet structure:**

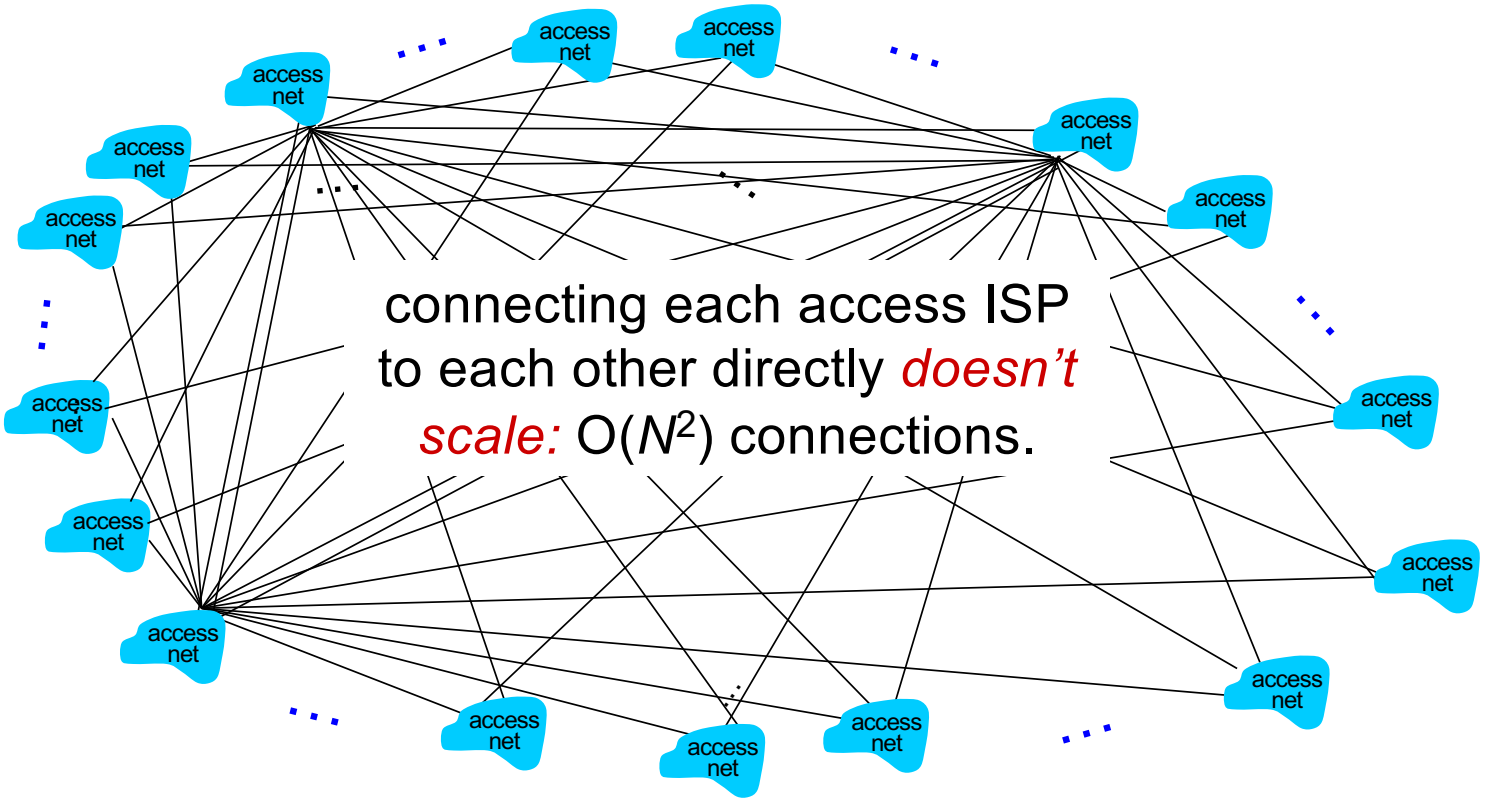
Network of networks

Question: given *millions* of access ISPs, how to connect them together?



Network of networks

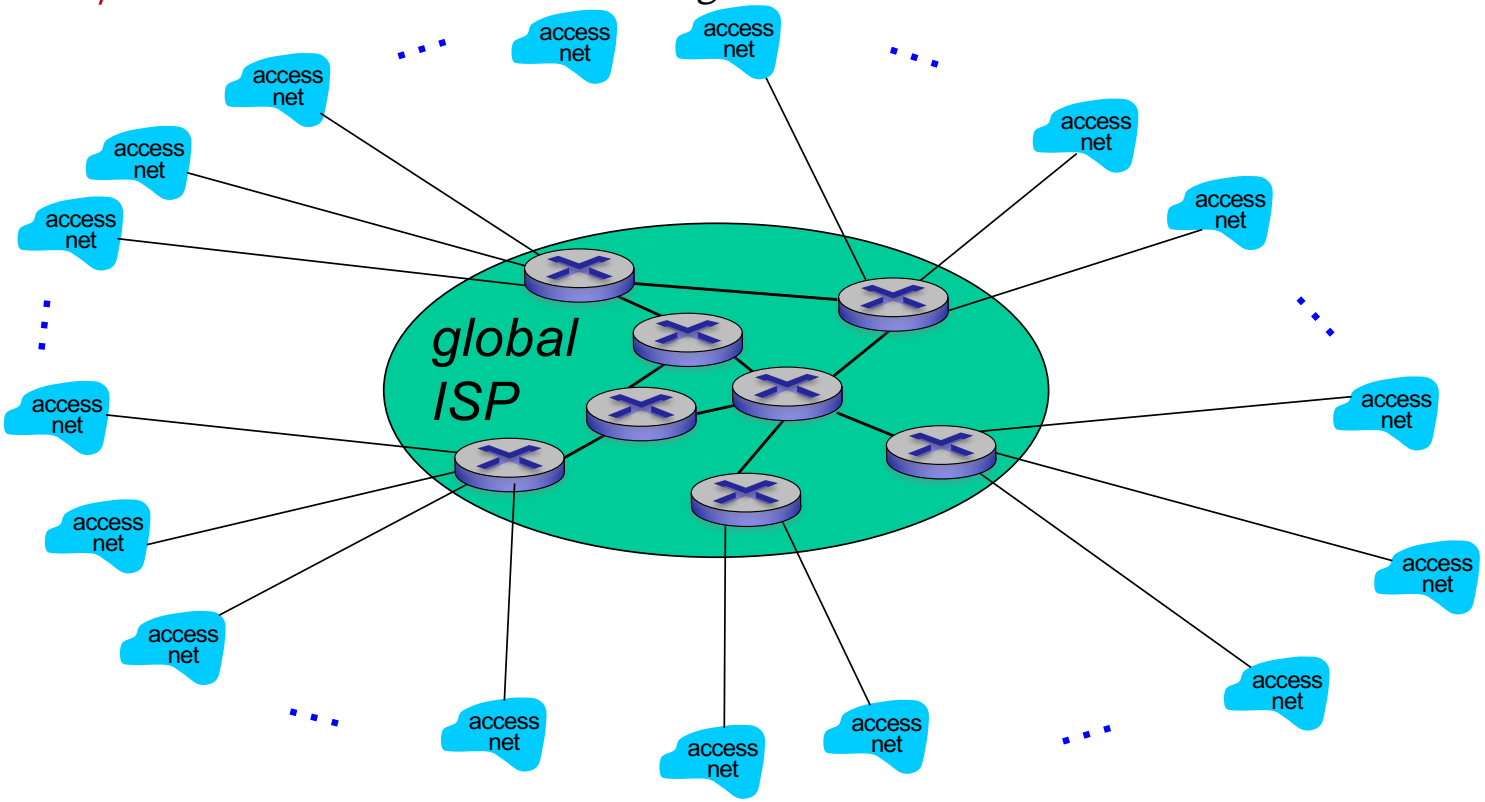
Option: connect each access ISP to every other access ISP?



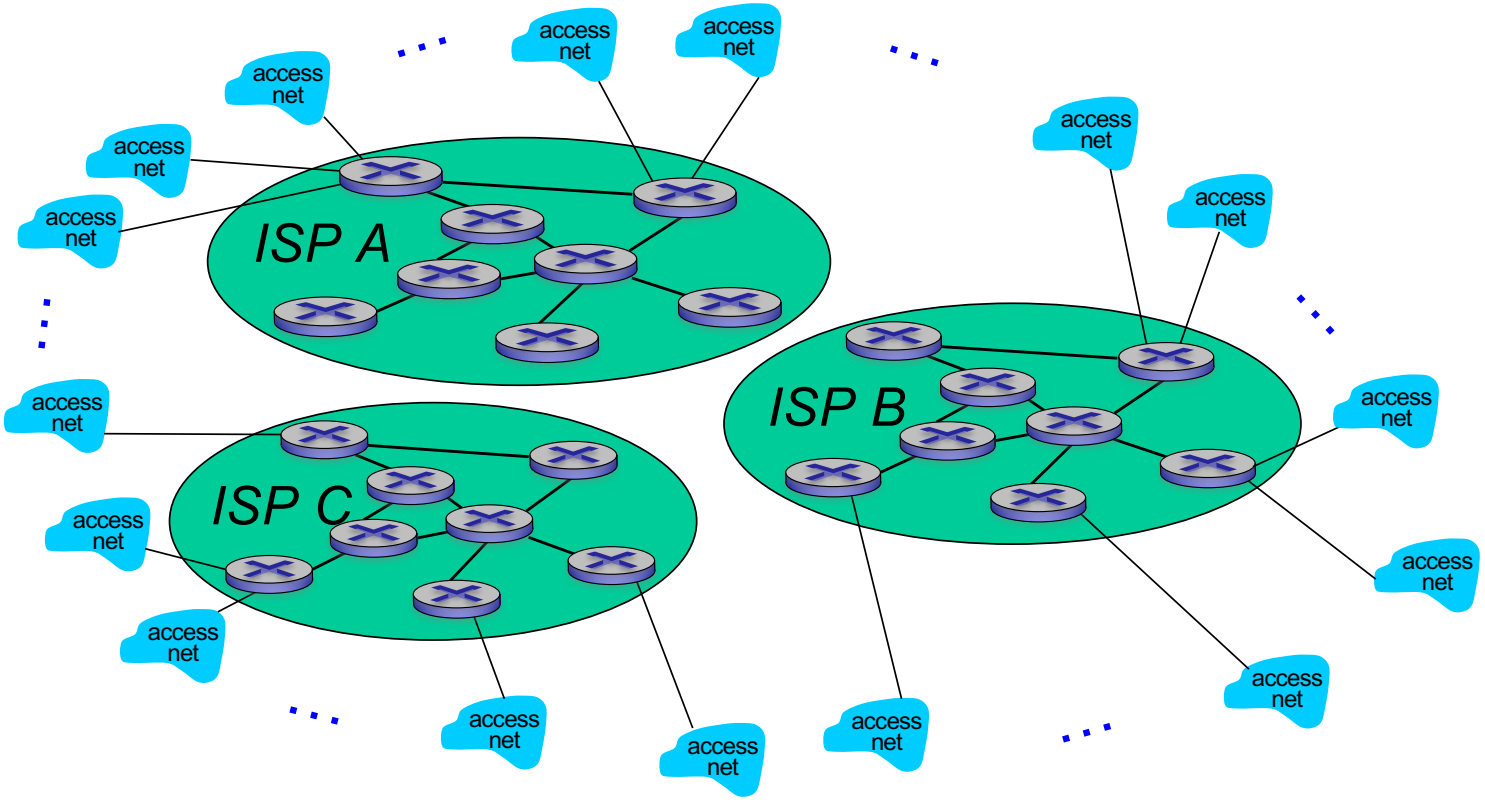
Network of networks

Option: connect each access ISP to one global transit ISP?

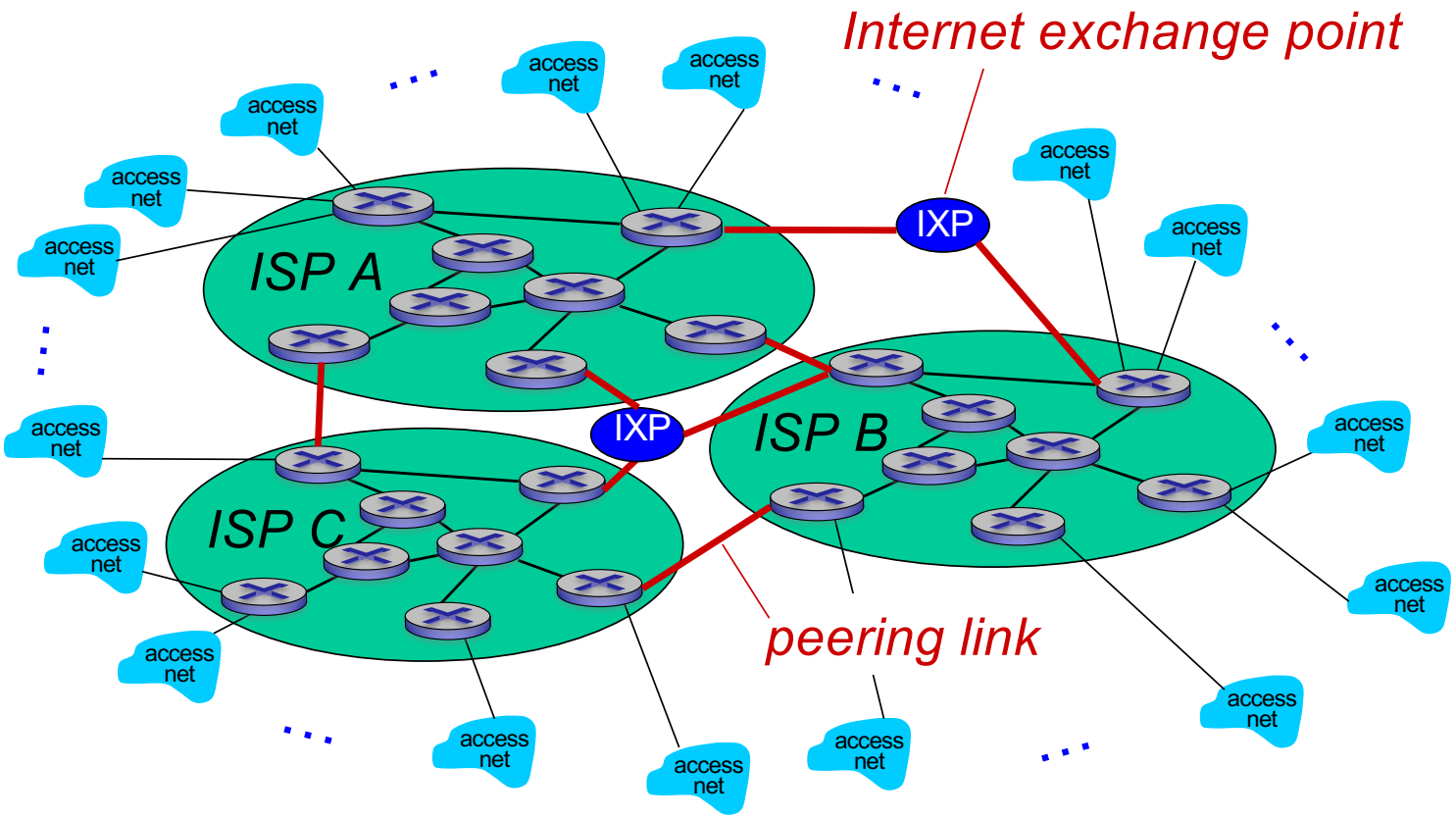
Customer and *provider* ISPs have economic agreement.



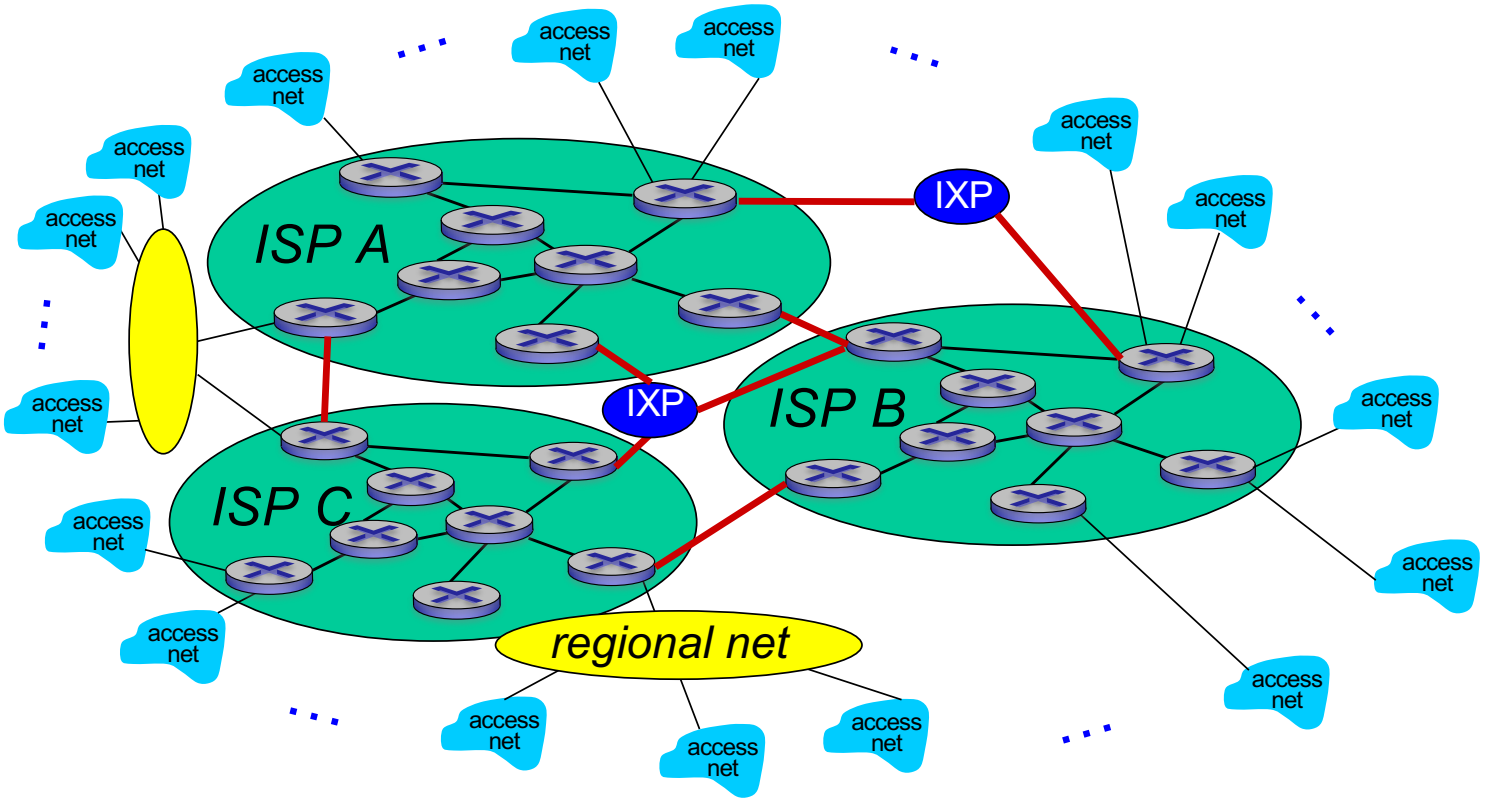
Network of networks



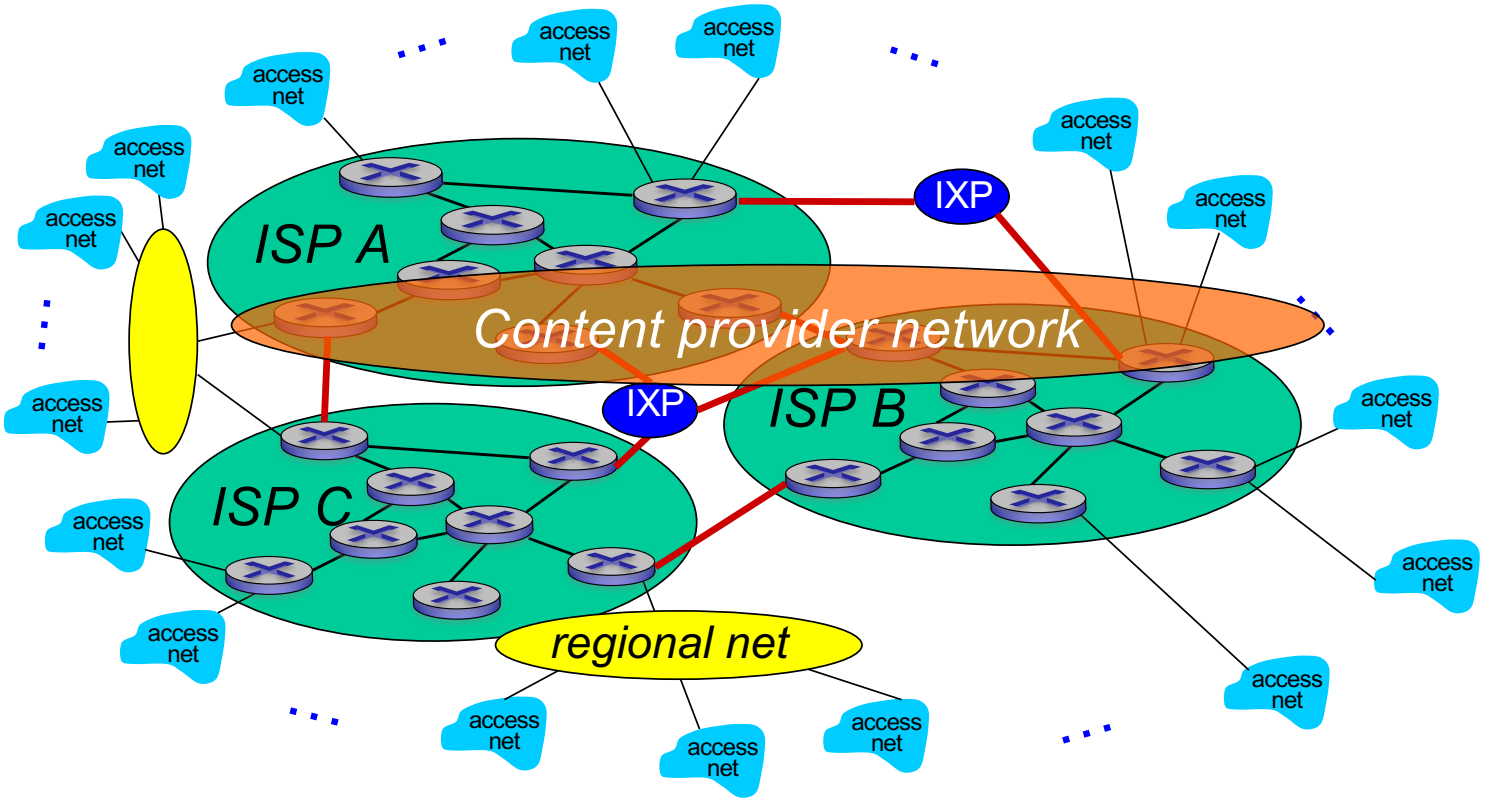
Network of networks

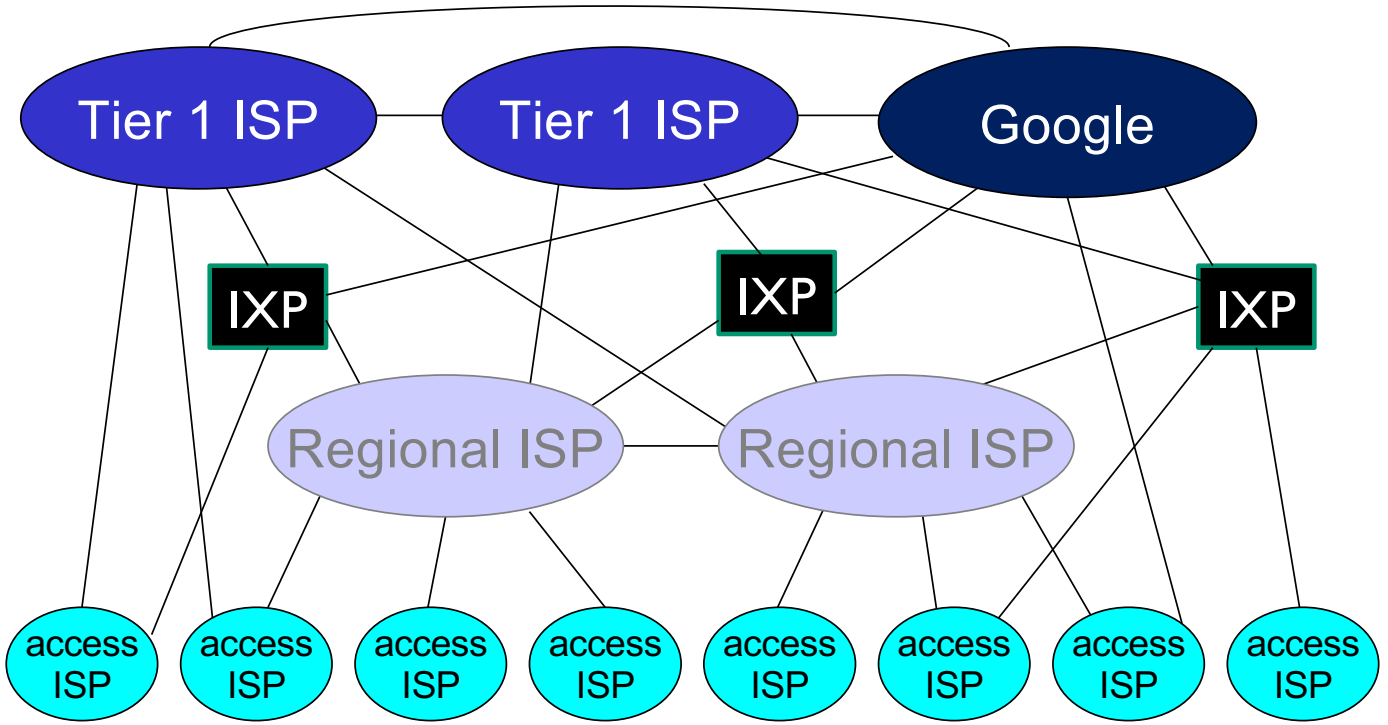


Network of networks



Network of networks





- Small view of well-connected large networks
  - "tier-1" commercial ISPs (e.g., ChineTel, Sprint, AT&T, NTT), national & international coverage
  - content provider network (e.g., Google): private network that connects it data centers to Internet, often bypassing tier-1, regional ISPs

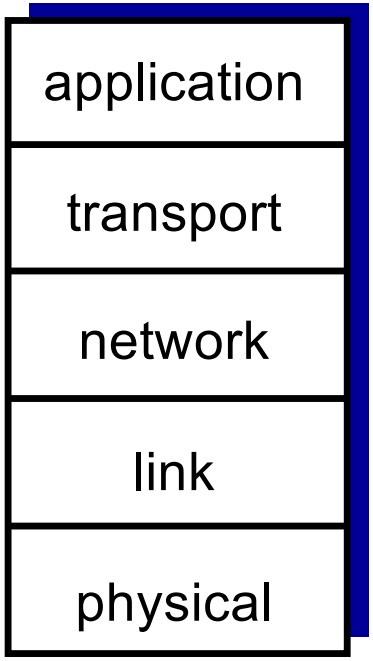
Service models

IP stack

ISO/OSI reference model

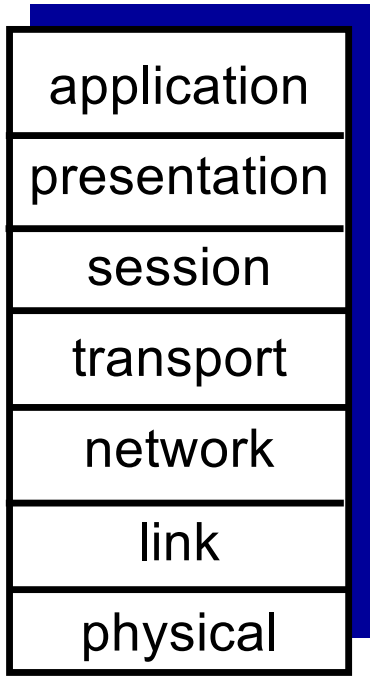
Internet protocol stack

- ***application:*** **supporting network applications**
  - FTP, SMTP, HTTP
- ***transport:*** **process-process data transfer**
  - TCP, UDP
- ***network:*** **routing of datagrams from source to destination**
  - IP, routing protocols
- ***link:*** **data transfer between neighboring network elements**
  - Ethernet, 802.11 (WiFi), PPP
- ***physical:*** **bits "on the wire"**

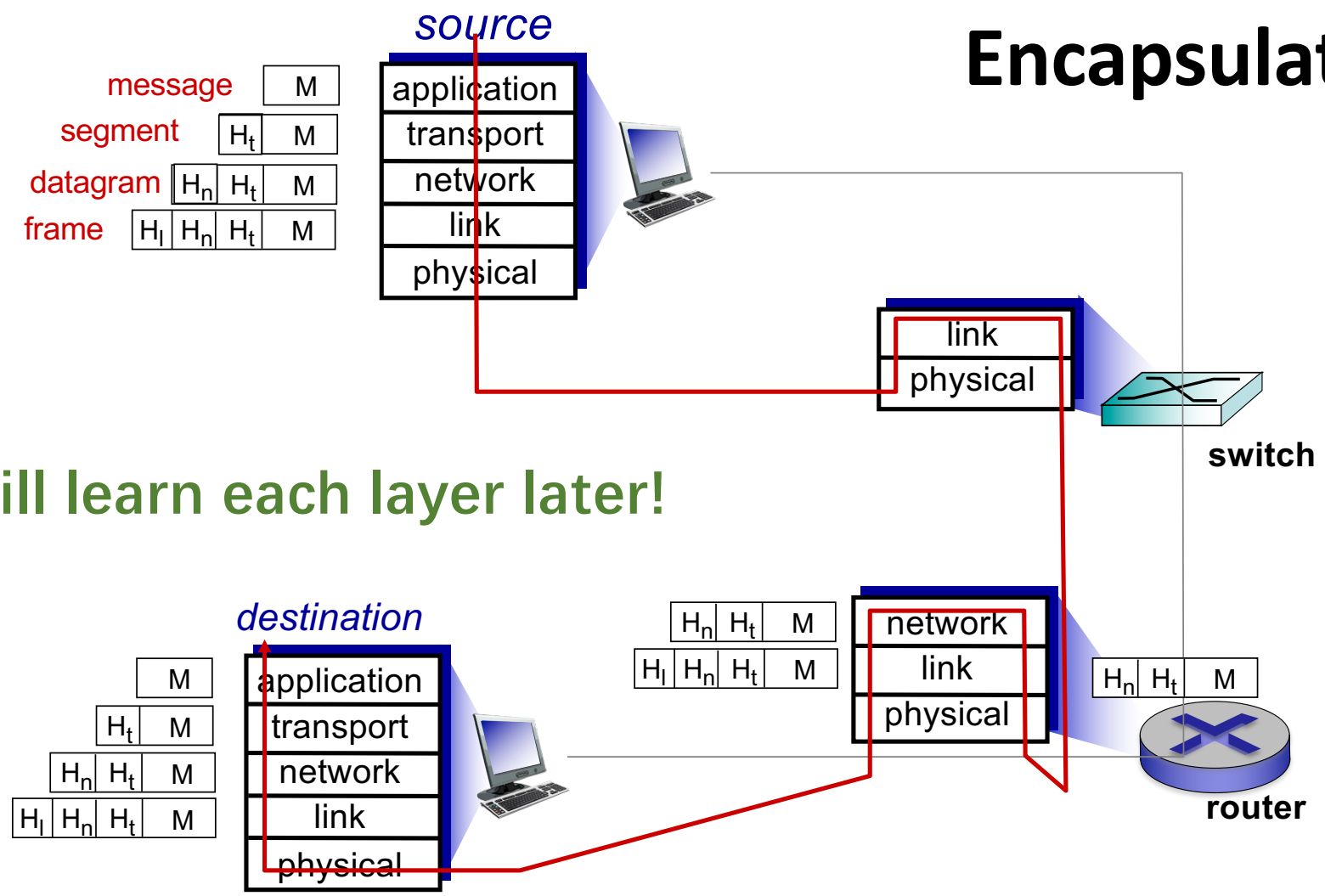


ISO/OSI reference model

- **ISO/OSI = ISO/**Open System Interconnection
- ***presentation:*** **allow applications to interpret meaning of data, e.g., encryption, compression, machine-specific conventions**
- ***session:*** **synchronization, checkpointing, recovery of data exchange**
- **Internet stack "missing" these layers!**
  - these services, *if needed,* must be implemented in application



Encapsulation



We will learn each layer later!

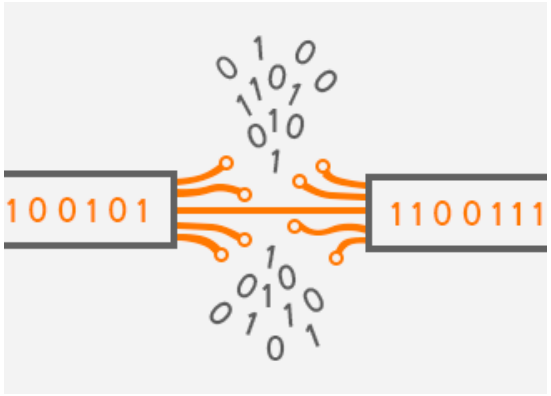
Why layering?

- Divide complex systems to simple components
- Easy for maintenance
- Flexible for updating

Lecture 1 - Introduction

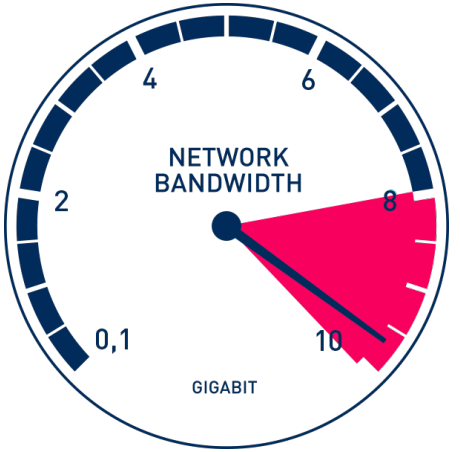
1. What is the network?
2. How does the network work?
3. How to evaluate the performance?

Performance



Package Loss

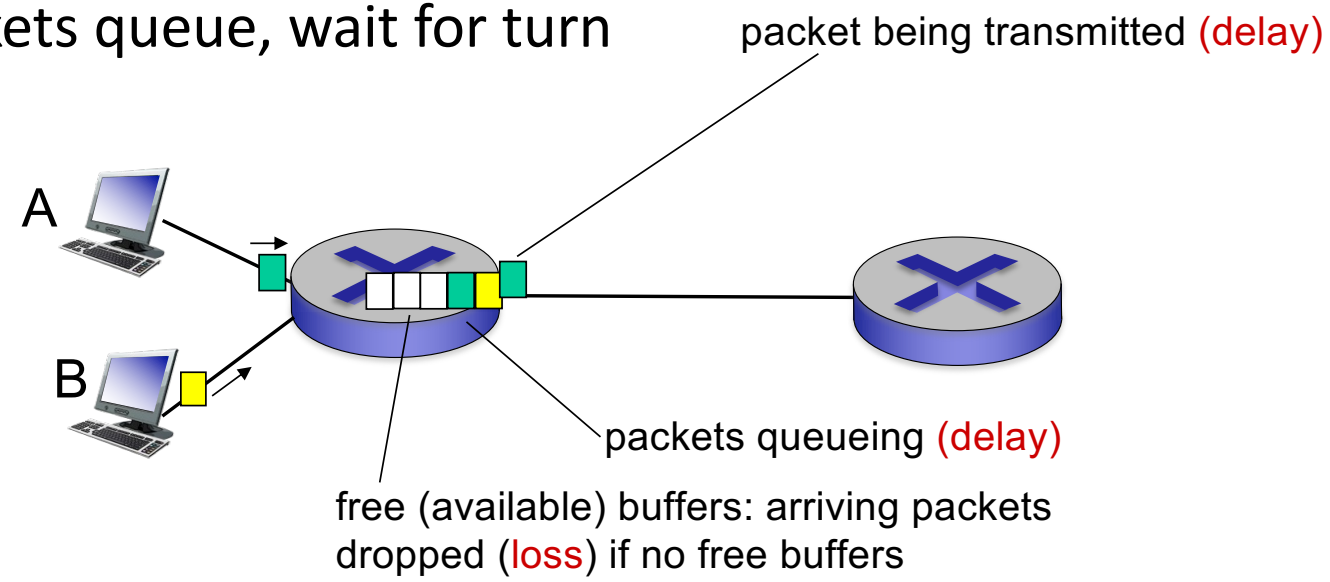
Delay



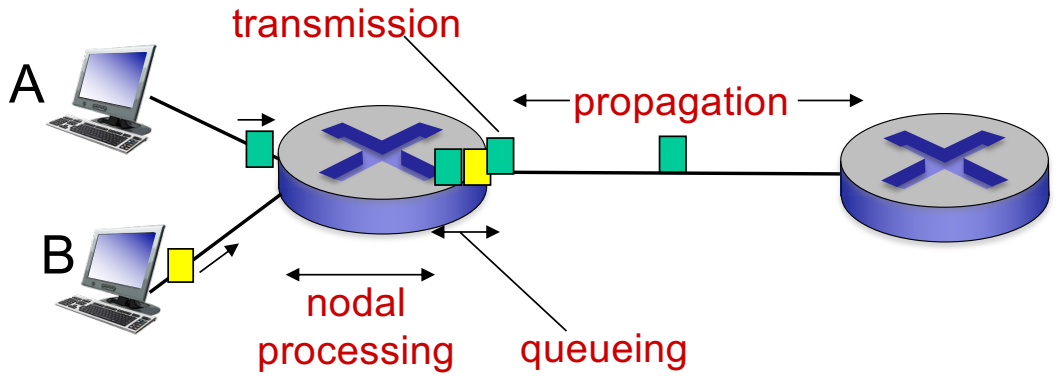
Bandwidth

How do loss and delay occur?

- **Packages queue in router buffers**
  - packet arrival rate to link (temporarily) exceeds output link capacity
  - then, packets queue, wait for turn



Four sources of packet delay



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

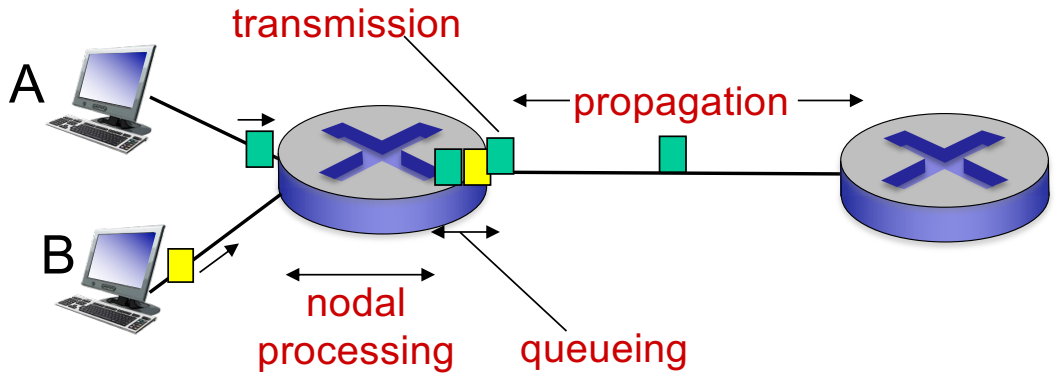
d_{proc}: nodal processing

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

d_{queue}: queueing delay

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

Four sources of packet delay



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

d_{trans}: transmission delay:

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

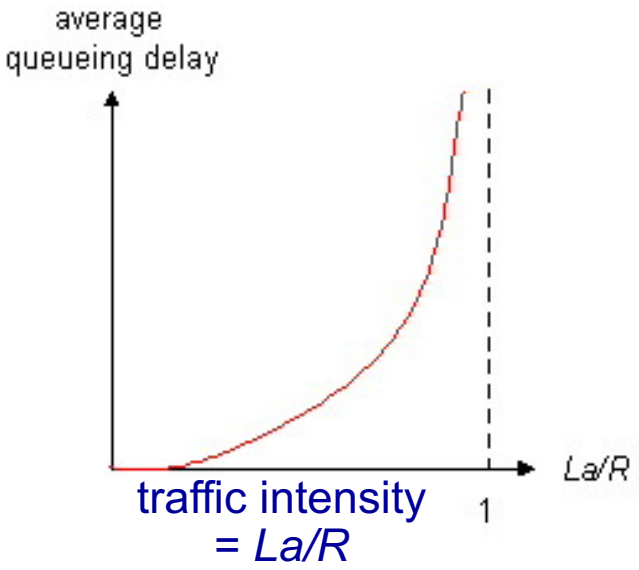
d_{trans} and d_{prop} *very* different

d_{prop}: propagation delay:

- d: length of physical link
- s: propagation speed (~2.9×10^8 m/sec)
- $d_{prop} = d/s$

Queueing delay

- *R:* link bandwidth (bps)
- *L:* packet length (bits)
- a: average packet arrival rate



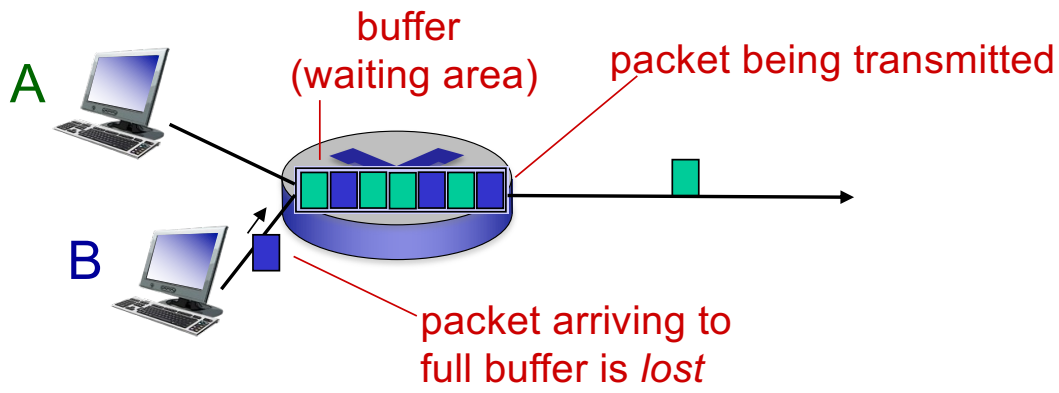
- *La/R* ~ 0: avg. queueing delay small
- *La/R* -> 1: avg. queueing delay large
- *La/R* > 1: more "work" arriving than can be serviced, average delay infinite!

La/R ~ 0

La/R -> 1

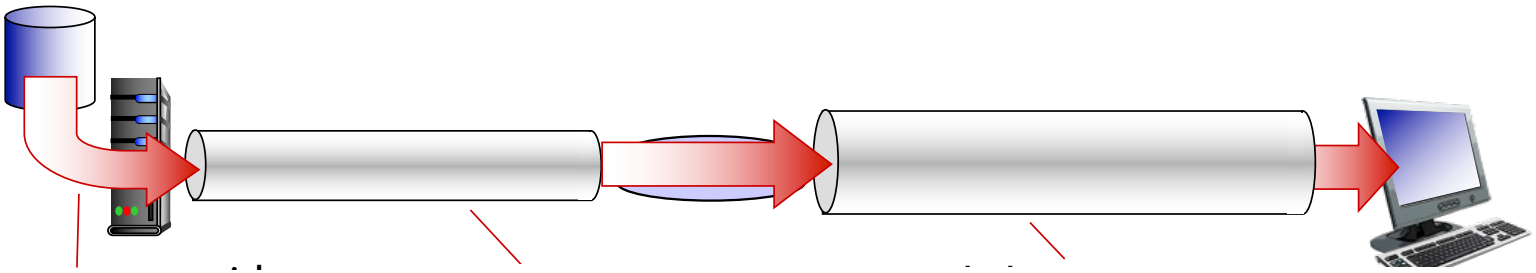
Packet loss

- Queue (aka buffer) preceding link in buffer has finite capacity
- Packet arriving to full queue dropped (aka lost)
- Lost packet may be retransmitted by previous node, by source end system, or not at all



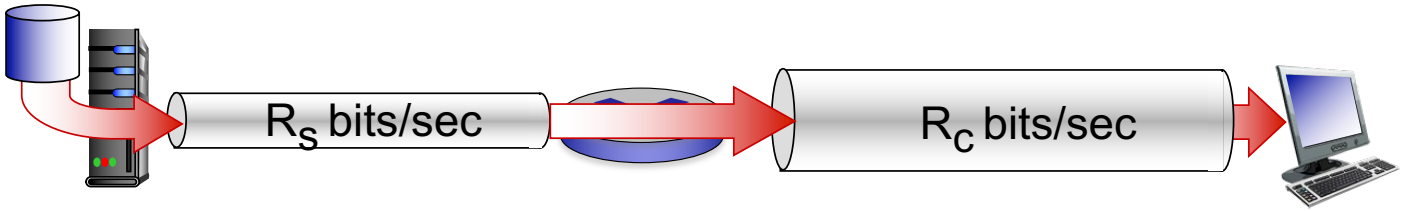
Throughput

- ***Throughput:*** **rate (bits/time unit) at which bits transferred between sender/receiver**
  - *instantaneous:* rate at given point in time
  - *average:* rate over longer period of time

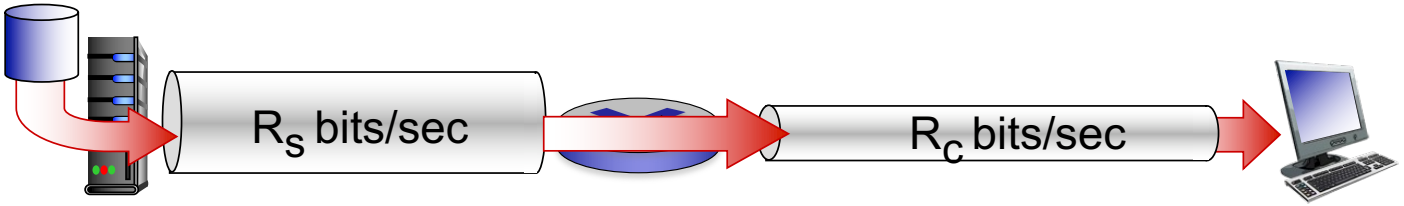


Throughput

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



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



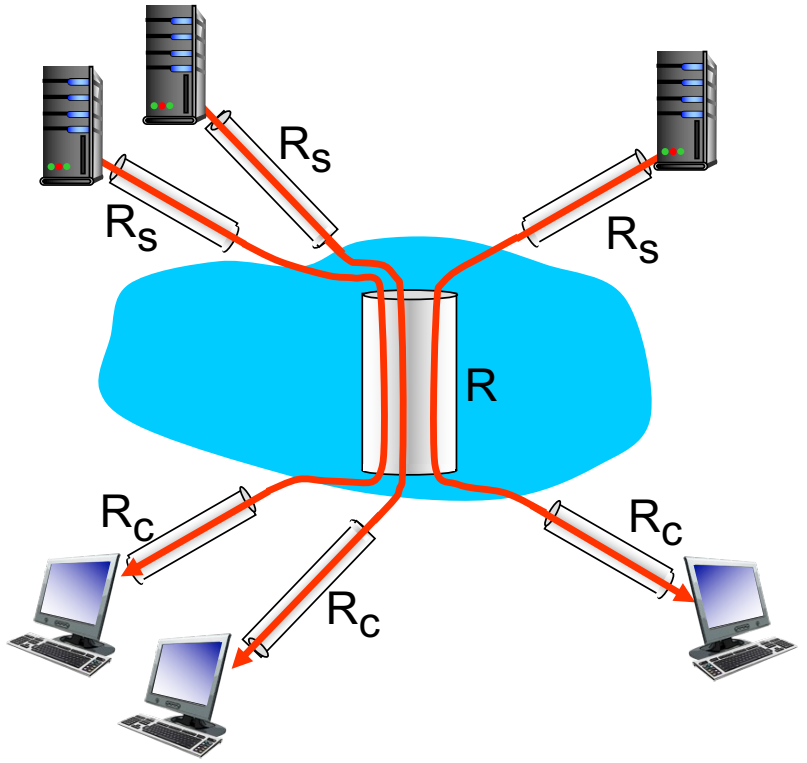
bottleneck link

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

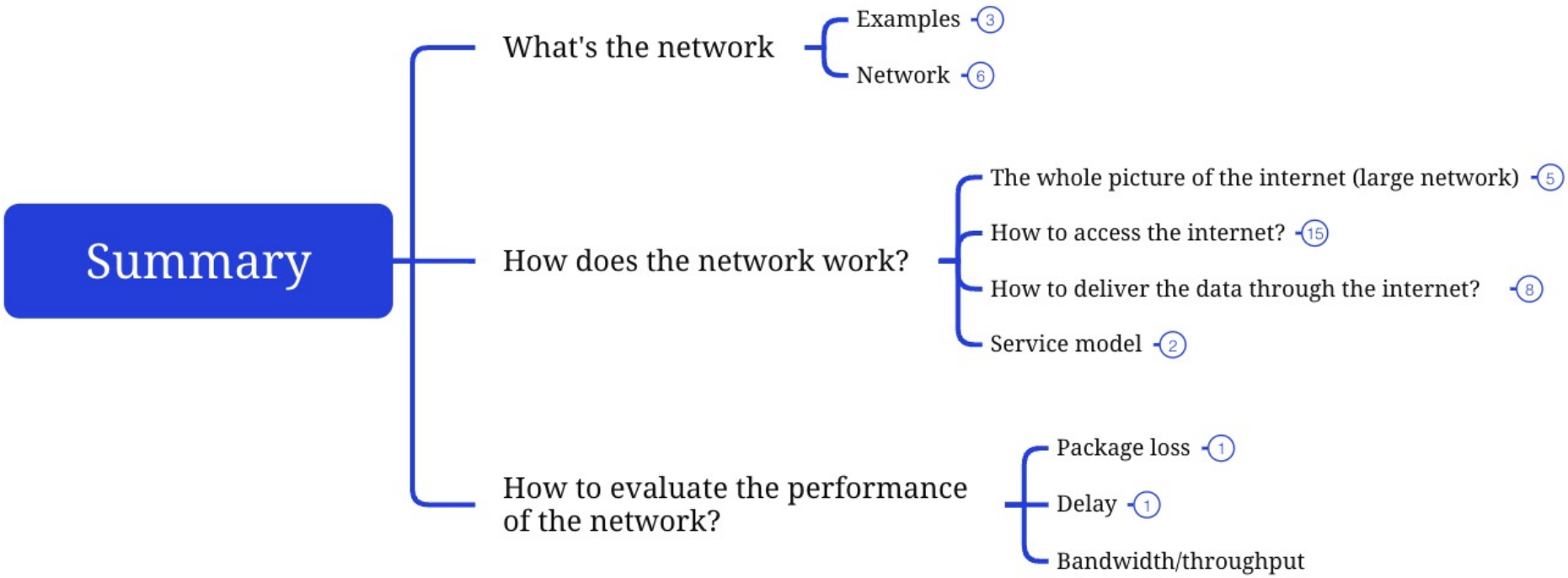
Throughput: Internet scenario

- Per-connection end-end throughput: *min{R_c, R_s, R/10}*

- In practice: R_c or R_s is often bottleneck



10 connections (fairly) share backbone bottleneck link *R* bits/sec


Summary
What's the network
Examples 3
Network 6
How does the network work?
The whole picture of the internet (large network) 5
How to access the internet? 15
How to deliver the data through the internet? 8
Service model 2
How to evaluate the performance of the network?
Package loss 1
Delay 1
Bandwidth/throughput

- **Thanks**