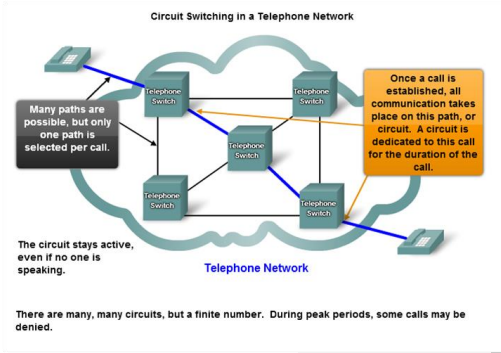
Illustration



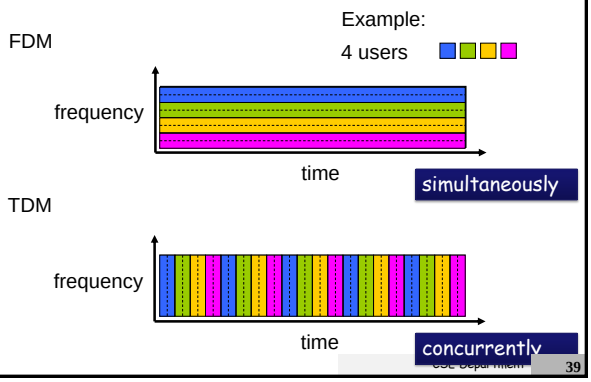
Network Core: Circuit Switching

network resources (e.g., bandwidth) divided into "pieces"

- pieces allocated to calls
- resource piece *idle* if not used by owning call *(no sharing)*

- dividing link bandwidth into "pieces"
  - frequency division (FDMA)
  - time division (TDMA)
  - code division (CDMA)

Circuit Switching: FDM and TDM



Numerical example

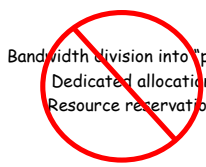
- How long does it take to send a file of 640,000 bits from host A to host B over a circuit-switched network?
  - All links are 1.536 Mbps
  - Each link uses TDM with 24 slots/sec
  - 500 msec to establish end-to-end circuit

Let's work it out!

Network Core: Packet Switching

each end-end data stream divided into *packets*

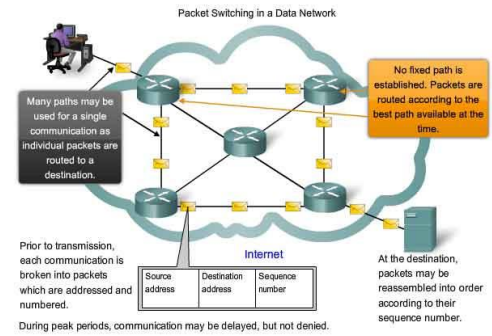
- user A, B packets *share* network resources
- each packet uses full link bandwidth
- resources used *as needed*



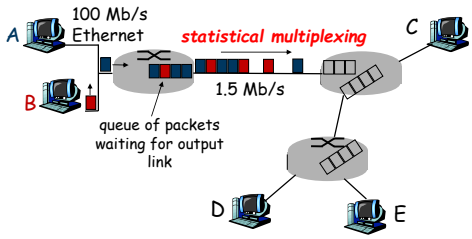
resource contention:

- aggregate resource demand can exceed amount available
- congestion: packets queue, wait for link use
- **store and forward:** packets move one hop at a time
  - Node receives complete packet before forwarding

Illustration



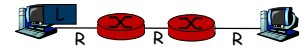
Packet Switching: Statistical Multiplexing



Sequence of A & B packets does not have fixed pattern, bandwidth shared on demand ***statistical multiplexing***.

TDM: each host gets same slot in revolving TDM frame.

Packet-switching: store-and-forward



- takes L/R seconds to transmit (push out) packet of L bits on to link at R bps
- *store and forward:* entire packet must arrive at router before it can be transmitted on next link
- delay = 3L/R (assuming zero propagation delay)

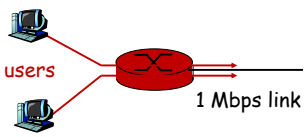
Example:
- L = 7.5 Mbits
- R = 1.5 Mbps
- transmission delay = 15 sec

more on delay shortly …

Packet switching vs. circuit switching

Packet switching allows more users to use network!

- 1 Mb/s link
- each user:
  - 100 kb/s when "active"
  - active 10% of time
- *circuit-switching:*
  - 10 users
- *packet switching:*
  - with 35 users, probability > 10 active at same time is less than .0004



Q: how did we get value 0.0004?

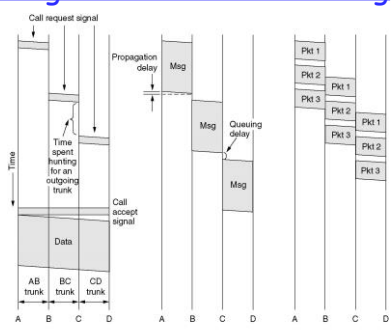
Packet switching vs. circuit switching

Is packet switching a "slam dunk winner?"

- great for bursty data
  - resource sharing
  - simpler, no call setup
- excessive congestion: packet delay and loss
  - protocols needed for reliable data transfer, congestion control
- Q: How to provide circuit-like behavior?
  - bandwidth guarantees needed for audio/video apps
  - still an unsolved problem (chapter 7)

Q: human analogies of reserved resources (circuit switching) versus on-demand allocation (packet-switching)?

Timing of Events in Switching



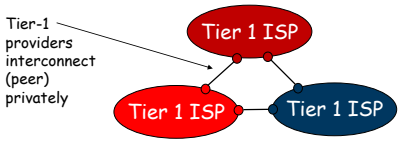
(a) Circuit switching (b) Message switching (c) Packet switching

Circuit vs. Packet Switching

- Advantages of packet switching
  - Efficient for bursty data
  - Easy to provide bandwidth on demand with variable rates
- Disadvantages of packet switching
  - Variable delays
  - Difficult to provide QoS assurances (Best-effort service)
  - Packets can arrive out-of-order

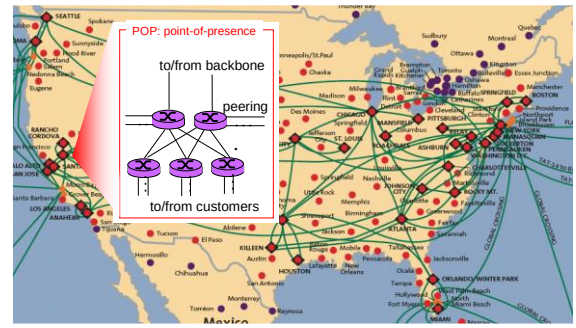
Internet structure: network of networks

- roughly hierarchical
- at center: "tier-1" ISPs (e.g., Verizon, Sprint, AT&T, Cable and Wireless), national/international coverage
  - treat each other as equals



Tier-1 ISP: e.g., Sprint

Sprint

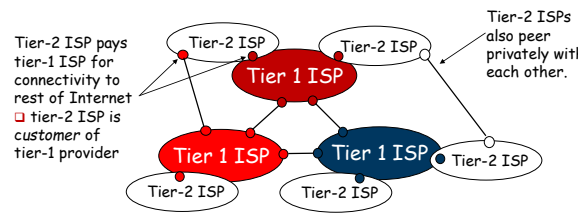


Tier 1 Networks

Name	AS number
Qwest	209
Verizon Business	701
Sprint	1239
TeliaSonera International Carrier	1299
NTT Communications	2914
Tinet	3257
Level 3 Communications (L3)	3356
Global Crossing (GBLX)	3549
Savvis	3561
AT&T	7018
Tata Communications	6453

Internet structure: network of networks

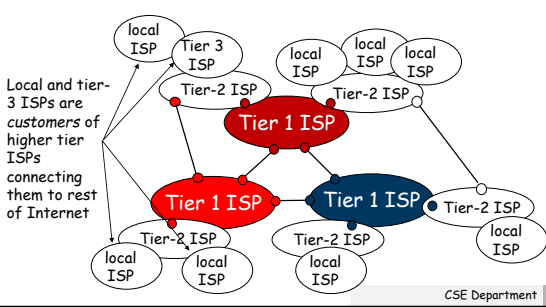
- "Tier-2" ISPs: smaller (often regional) ISPs
  - Connect to one or more tier-1 ISPs, possibly other tier-2 ISPs



Internet structure: network of networks

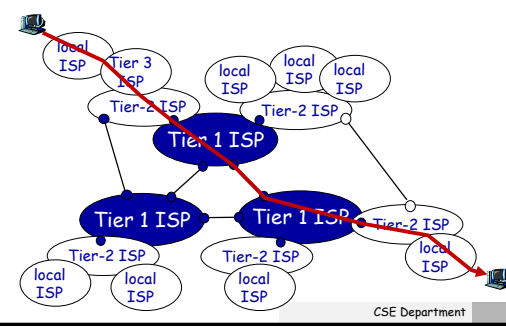
"Tier-3" ISPs and local ISPs

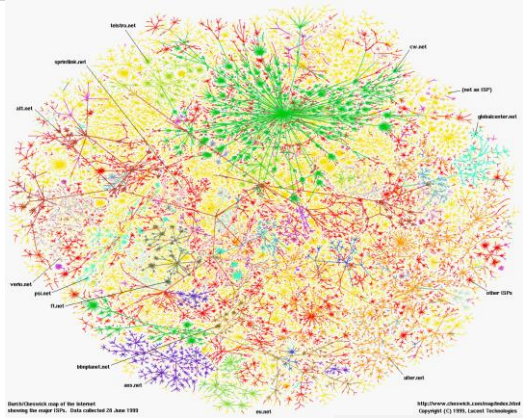
- last hop ("access") network (closest to end systems)



Internet structure: network of networks

a packet passes through many networks!





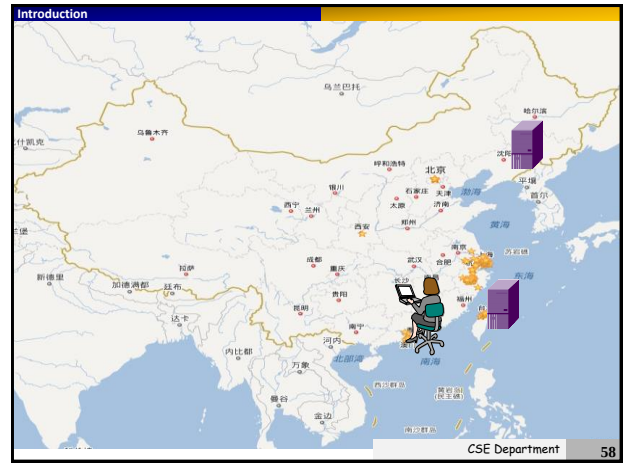
Chapter 1: roadmap

- What is the Internet?
- Network edge
  - end systems, access networks, links
- Network core
  - circuit switching, packet switching, network structure
- Delay, loss and throughput in packet-switched networks
- Protocol layers, service models
- Networks under attack: security
- History

Why Different Delays?

http://www.sjtu.edu.cn

http://www.korea-dpr.com/



Discussion!

Distance matters

Is it the only reason?

If not, any insights?

How do loss and delay occur?

packets *queue* in router buffers

- packet arrival rate to link exceeds output link capacity
- packets queue, wait for turn