Computer Networks CS348

Instructor: Joydeep Chandra

Course Outline

- Theory
  - Basics of Interworking
  - Modern Networking Applications and Technologies
  - Advanced Concepts in Design of Network based Applications
- Lab
  - Implementation of networking protocols
  - Use of simulators
  - Develop network based applications

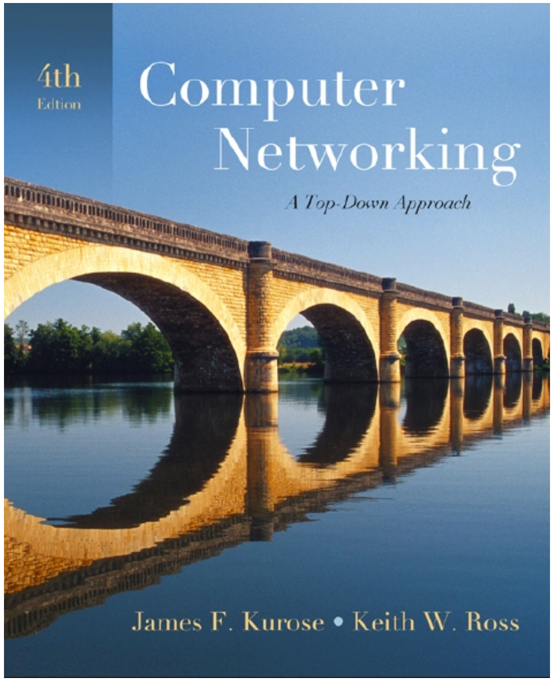
Evaluation

- Theory + Lab
  - Either 60-40 or 70-30 (TBD)
- Theory
  - Quizzes and Class Tests 20%
  - MidSem 30%
  - End Sem 50%
- Lab
  - Assignments 50%
  - MidSem 20%
  - EndSem 30%

Books and References

- Text Book
  - James F. Kurose and Keith W. Ross, Computer Networking: A Top-Down Approach
- References
  - Larry L. Peterson and Bruce S. Davie, Computer Networks, A Systems Approach
  - Tenenbaum and Wetherall, Computer Networks, Pearson India, 5^{th} Edition
  - Some research articles and papers

Chapter 1
Introduction



Computer Networking: A Top Down Approach ,
4th edition.
Jim Kurose, Keith Ross
Addison-Wesley, July 2007.

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Thanks and enjoy! JFK/KWR

Outline

- Internet architecture
- Internet history
- Today's Internet
- Internet in a nutshell (protocols in practice)

Internet Architecture

- http://www.nap.edu/html/coming_of_age/
- http://www.ietf.org/rfc/rfc1958.txt

Why did the Internet win?

- Packet switching over circuit switching
- End-to-end principle and “Hourglass” design
- Layering of functionality
- Distributed design, decentralized control
- Superior organizational process

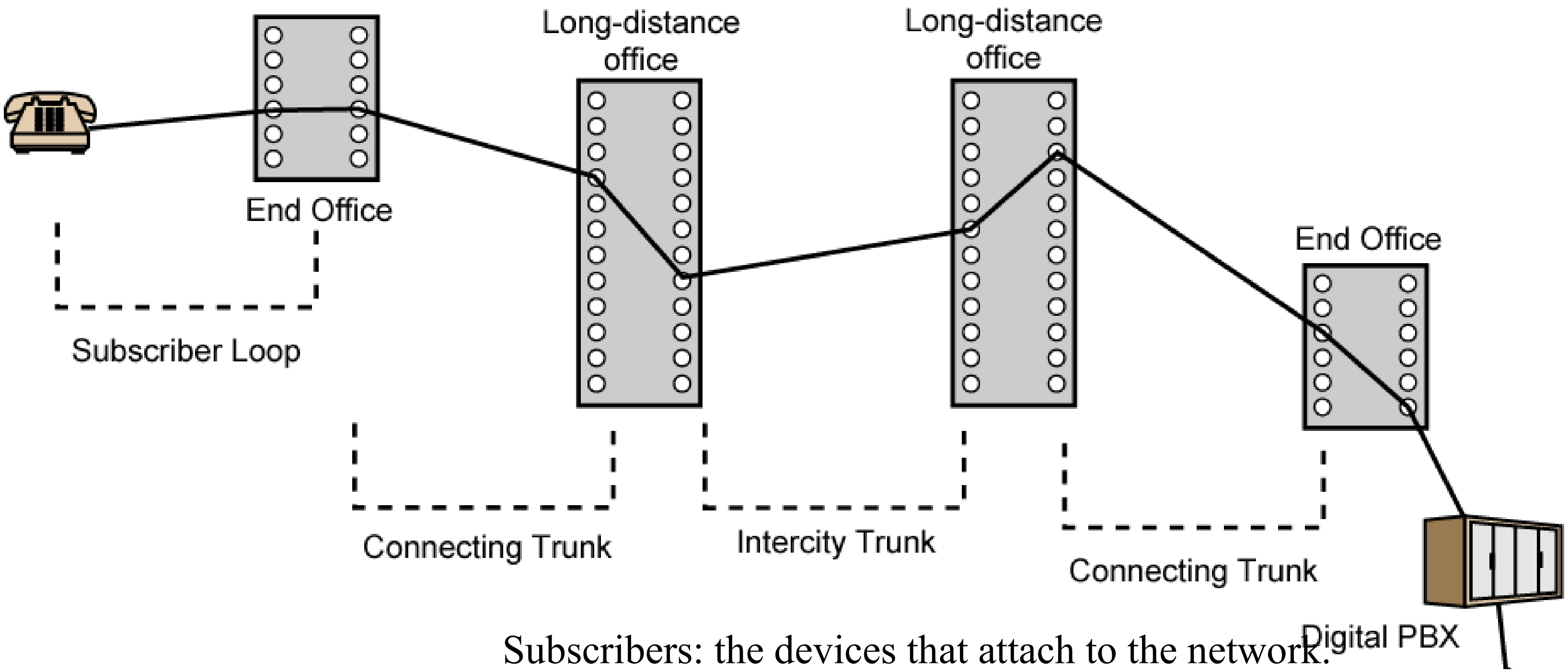
Circuit Switching

- Circuit switching:
  - There is a dedicated communication path between two stations (end-to-end)
  - The path is a connected sequence of links between network nodes. On each physical link, a logical channel is dedicated to the connection.
- Communication via circuit switching has three phases:
  - Circuit establishment (link by link)
    - Routing & resource allocation (FDM or TDM)
  - Data transfer
  - Circuit disconnect
    - Deallocate the dedicated resources
- The switches must know how to find the route to the destination and how to allocate bandwidth (channel) to establish a connection.

Circuit Switching Properties

- Inefficiency
  - Channel capacity is dedicated for the whole duration of a connection
  - If no data, capacity is wasted
- Delay
  - Long initial delay: circuit establishment takes time
  - Low data delay: after the circuit establishment, information is transmitted at a fixed data rate with no delay other than the propagation delay. The delay at each node is negligible.
- Developed for voice traffic (public telephone network) but can also applied to data traffic.
  - For voice connections, the resulting circuit will enjoy a high percentage of utilization because most of the time one party or the other is talking.
  - But how about data connections?

Public Circuit Switched Network



Subscribers: the devices that attach to the network.

Subscriber loop: the link between the subscriber and the network.

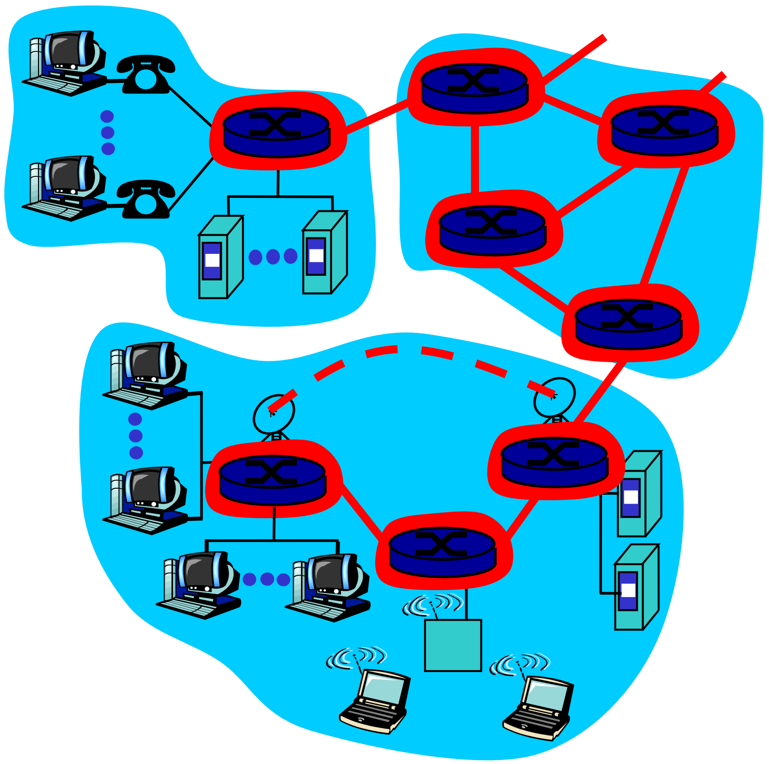
Exchanges: the switching centers in the network.

End office: the switching center that directly supports subscribers.

Trunks: the branches between exchanges. They carry multiple voice-frequency circuits using either FDM or synchronous TDM.

Packet vs. circuit switching

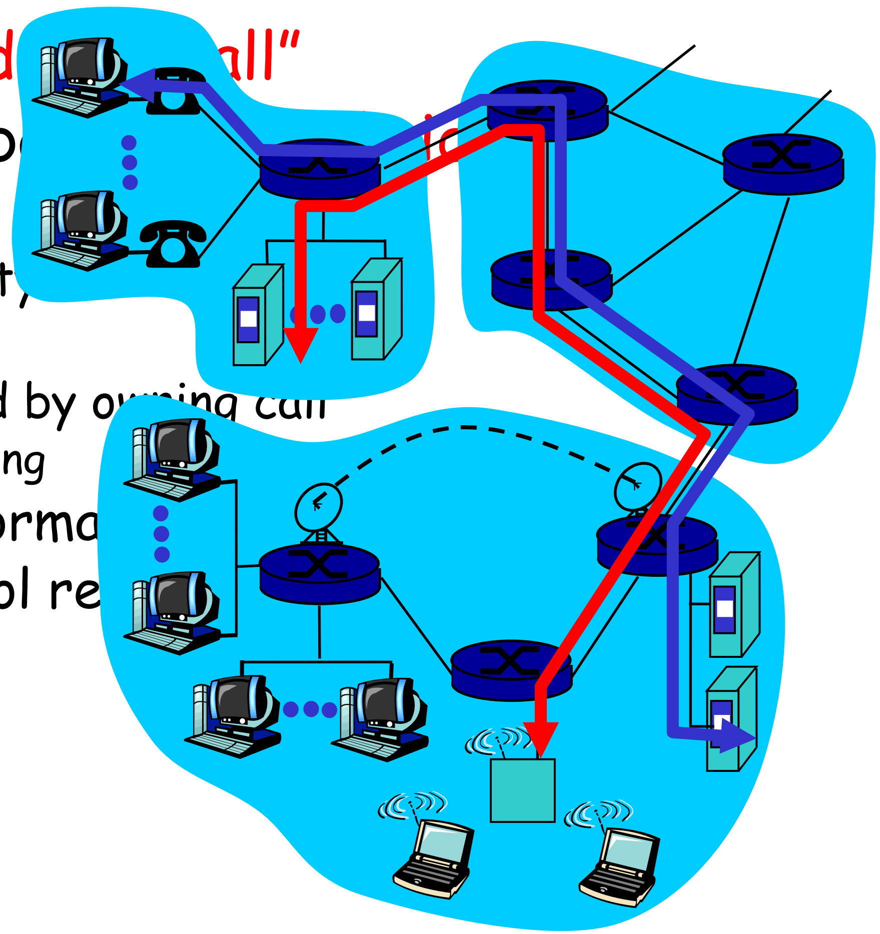
- mesh of interconnected routers
- *the* fundamental question: how is data transferred through net?
  - circuit switching: dedicated circuit per call: telephone net
  - packet-switching: data sent thru net in discrete "chunks"



Circuit Switching

End-end resources reserved … all”

- network resources (e.g., b…
  “pieces”
  - link bandwidth, switch capacit…
  - pieces allocated to calls
  - resource piece *idle* if not used by o… call
    - dedicated resources: no sharing
- circuit-like (guaranteed) performa…
- call setup and admission control re…

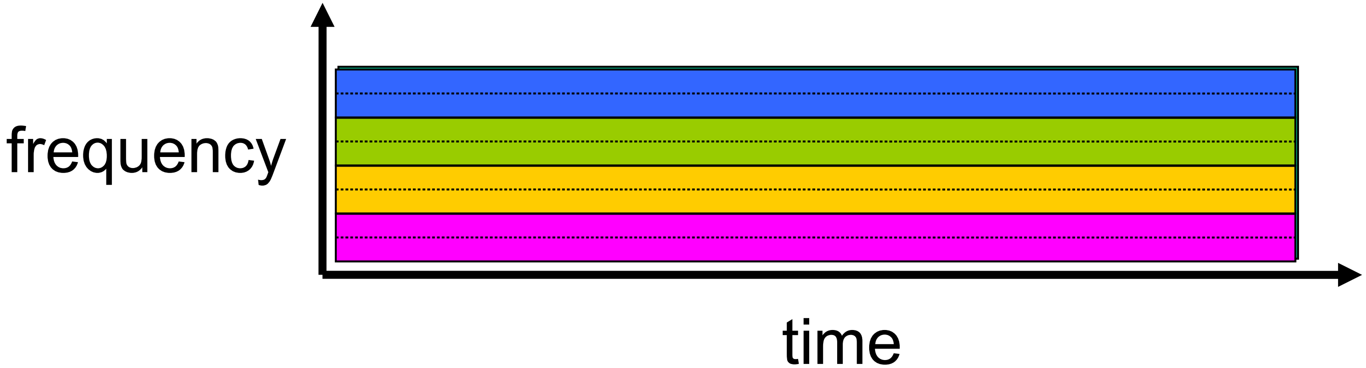


Circuit Switching: FDM and TDM

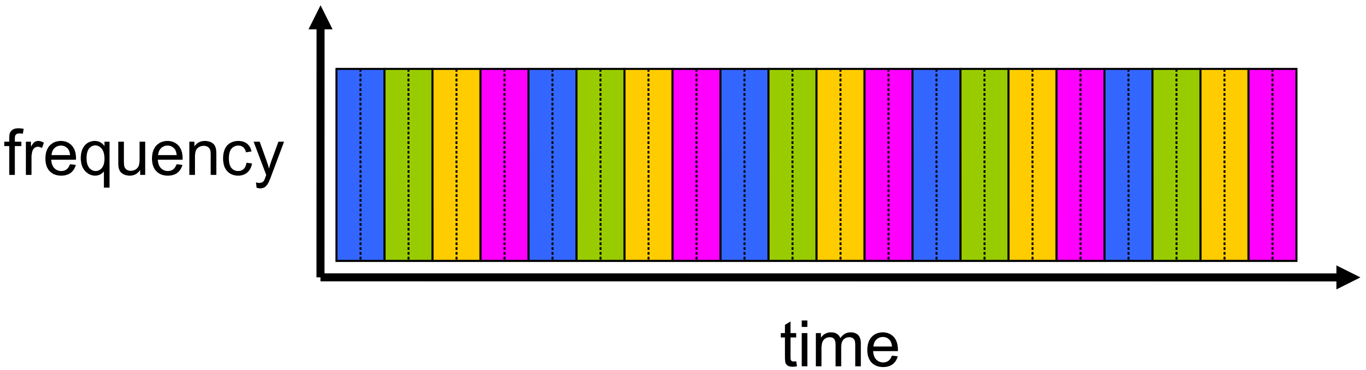
Example:

4 users

FDM



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!

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Let's work it out!

1,536,000/24 = 64000 bps per time slot

640000bits/64000bps = 10 sec.

Total time = 500 msec + 10 sec = 10.5 sec

Case study: Circuit Switching

- 1890-current: Phone network
  - Fixed bit rate
  - Mostly voice
  - Not fault-tolerant
  - Components extremely reliable
  - Global application-level knowledge throughout network
  - Admission control at local switching station (dial-tone)

Network Core: Packet Switching

each end-end data stream divided into *packets*

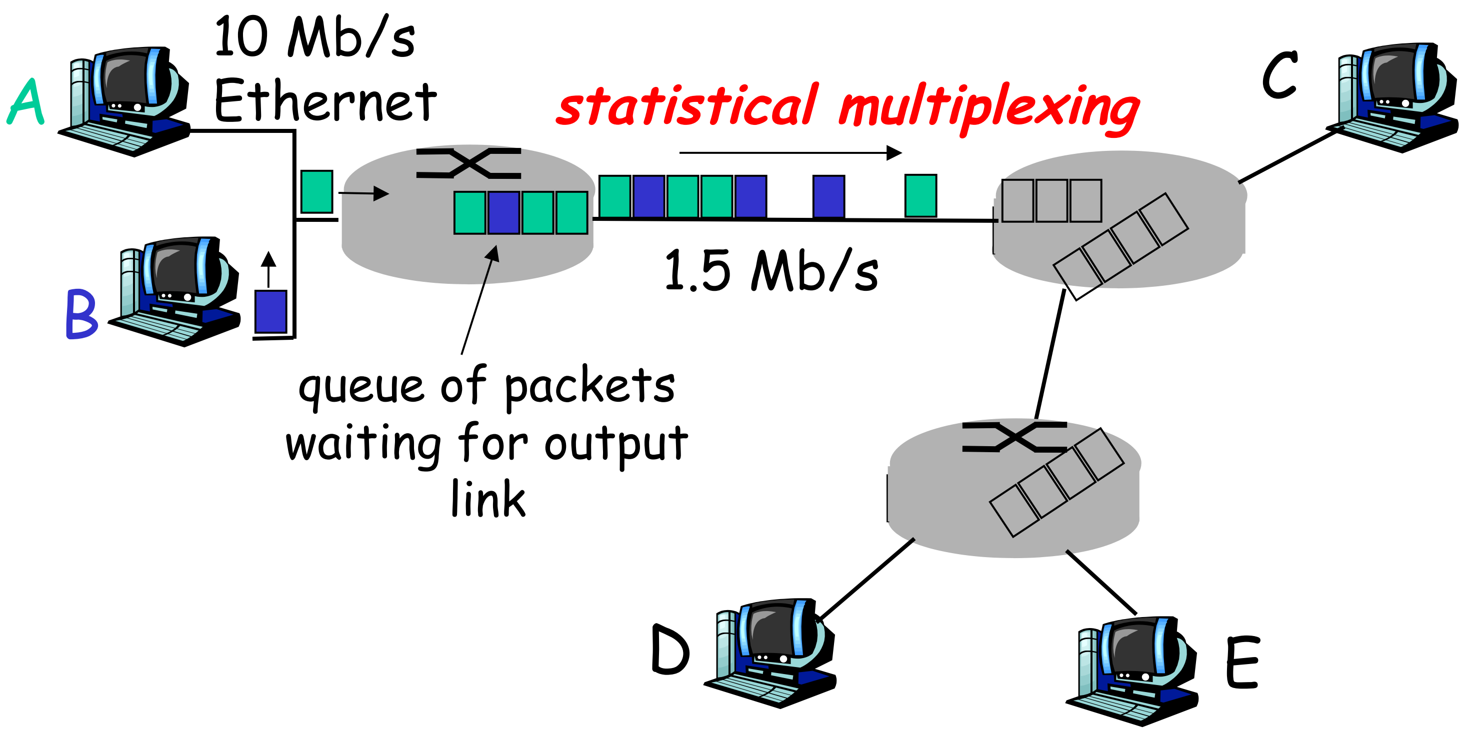
- user A, B packets *share* network resources
- each packet uses full link bandwidth
- resources used *as needed*

Bandwidth division into "pieces"
Dedicated allocation
Resource reservation

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

Packet Switching: Statistical Multiplexing



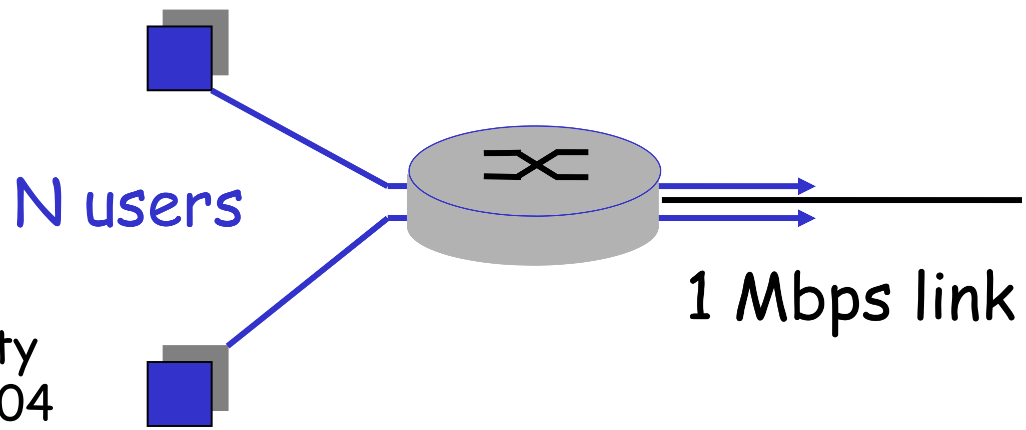
Sequence of A & B packets does not have fixed pattern, shared on demand → ***statistical multiplexing***.

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

Packet switching versus circuit switching

Packet switching allows more users to use network!

- N users over 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 less than .0004
  - Allows more users to use network
  - "Statistical multiplexing gain"



Q: how did we get value 0.0004?

Packet switching versus circuit switching

Is packet switching a "slam dunk winner?"

- Great for bursty data
  - resource sharing
  - simpler, no call setup
- Bad for applications with hard resource requirements
  - Excessive congestion: packet delay and loss
  - Need protocols for reliable data transfer, congestion control
  - Applications must be written to handle congestion

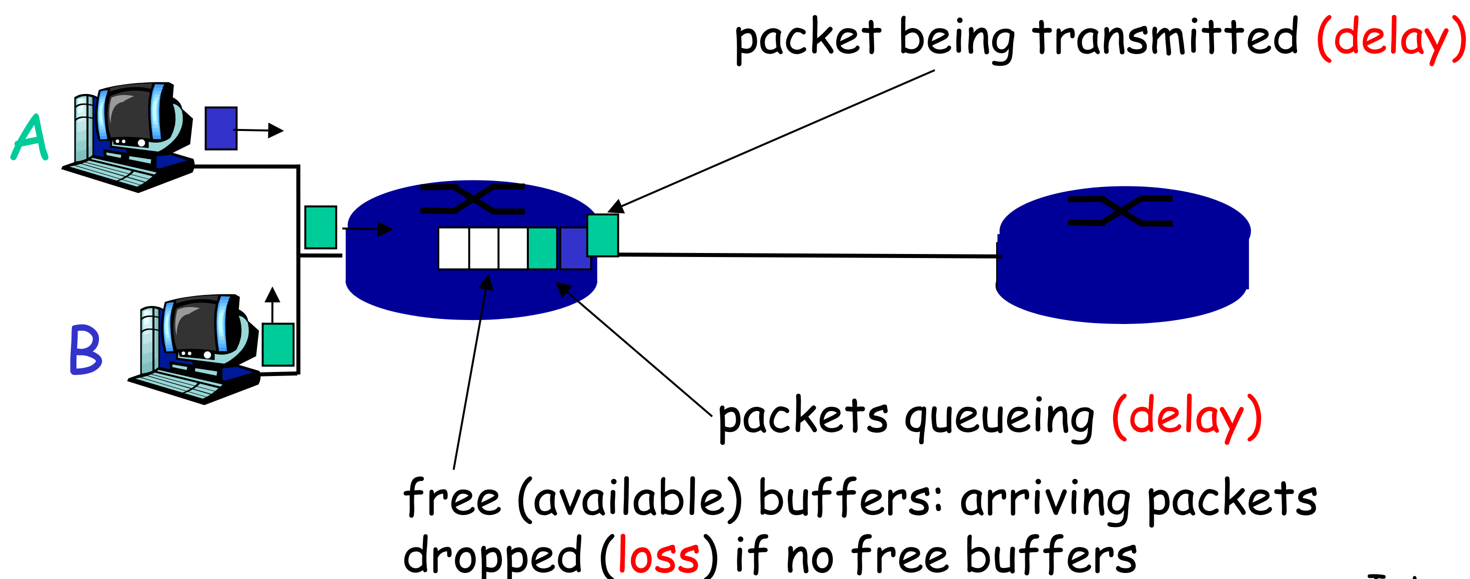
Q: How to provide circuit-like behavior?

- bandwidth guarantees needed for audio/video apps
- still an unsolved problem (chapter 7)
- Common practice: over-provision

Problems with packet switching

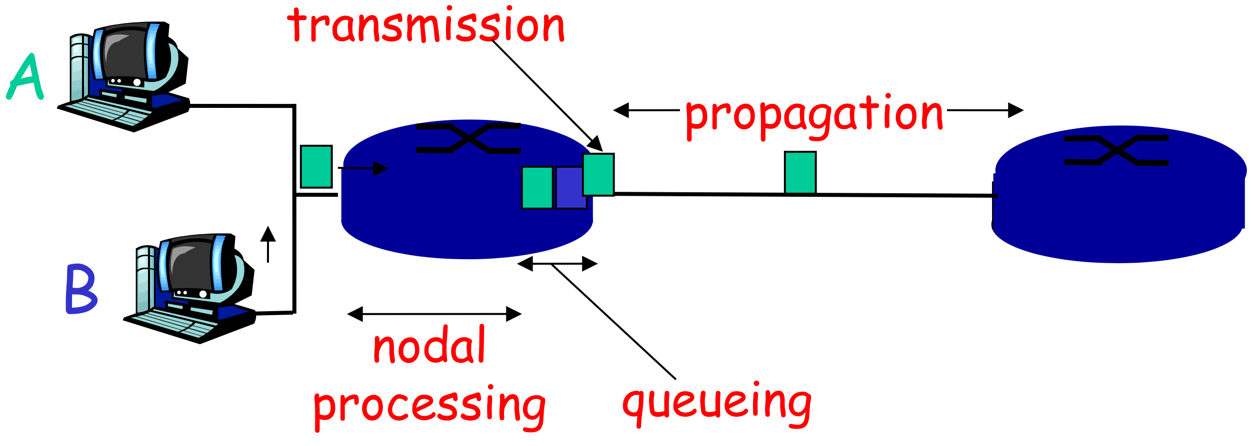
Packet loss and queuing delay
packets *queue* in router buffers

- packet arrival rate to link exceeds output link capacity
- packets queue, wait for turn
- when packet arrives to full queue, packet is dropped (aka lost)
  - lost packet may be retransmitted by previous node, by source end system, or not retransmitted at all



Four sources of packet delay

- 1. nodal processing:
  - check bit errors
  - determine output link
- 2. queueing
  - time waiting at output link for transmission
  - depends on congestion level of router



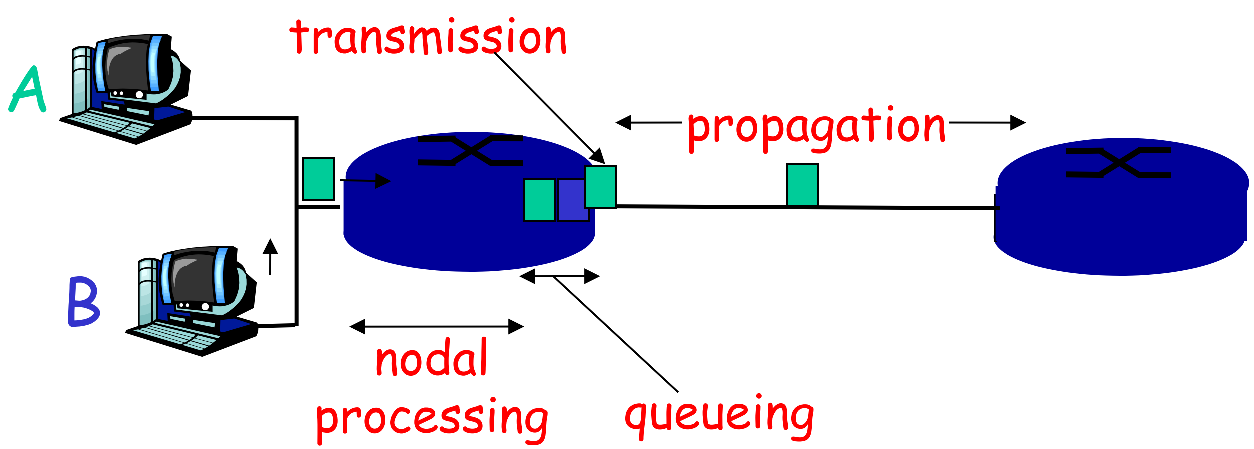
Delay in packet-switched networks

3. Transmission delay:

- R=link bandwidth (bps)
- L=packet length (bits)
- time to send bits into link = L/R

4. Propagation delay:

- d = length of physical link
- s = propagation speed in medium (~2×10^8 m/sec)
- propagation delay = d/s

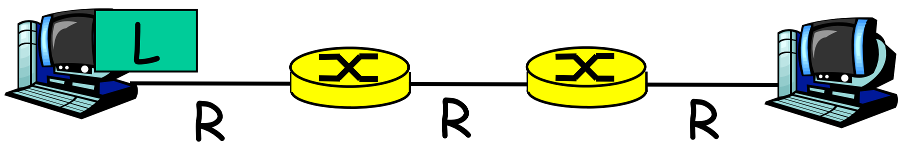


Nodal delay

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

- d_{proc} = processing delay
  - typically a few microsecs or less
- d_{queue} = queuing delay
  - depends on congestion
- d_{trans} = transmission delay
  - = L/R, significant for low-speed links
- d_{prop} = propagation delay
  - a few microsecs to hundreds of msecs

Transmission delay example



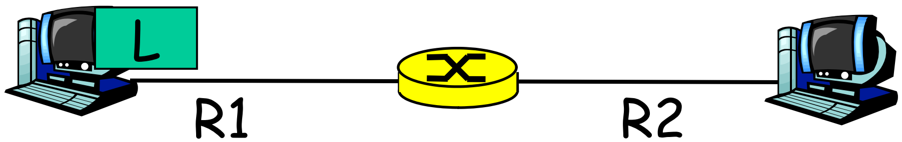
- Packet switching
  - Store-and-forward
  - Packet completely received before being transmitted to next node
- Takes L/R seconds to transmit (push out) packet of L bits on to link or R bps
- Entire packet must arrive at router before it can be transmitted on next link: *store and forward*
- delay = 3L/R (assuming zero propagation delay)

more on delay shortly …

Example:

- L = 7.5 Mbits
- R = 1.5 Mbps
- delay = 15 sec

Problem



- Consider a packet of length L that begins at system A, travels over one link to a packet switch over a second link to a destination end system.
- Let d_i, s_i and R_i denote the length, propagation speed and transmission rate of link i, for i=1,2.
- The packet switch delays each packet by d_{proc}
- Assuming no queuing delays, what is the total end-to-end delay?

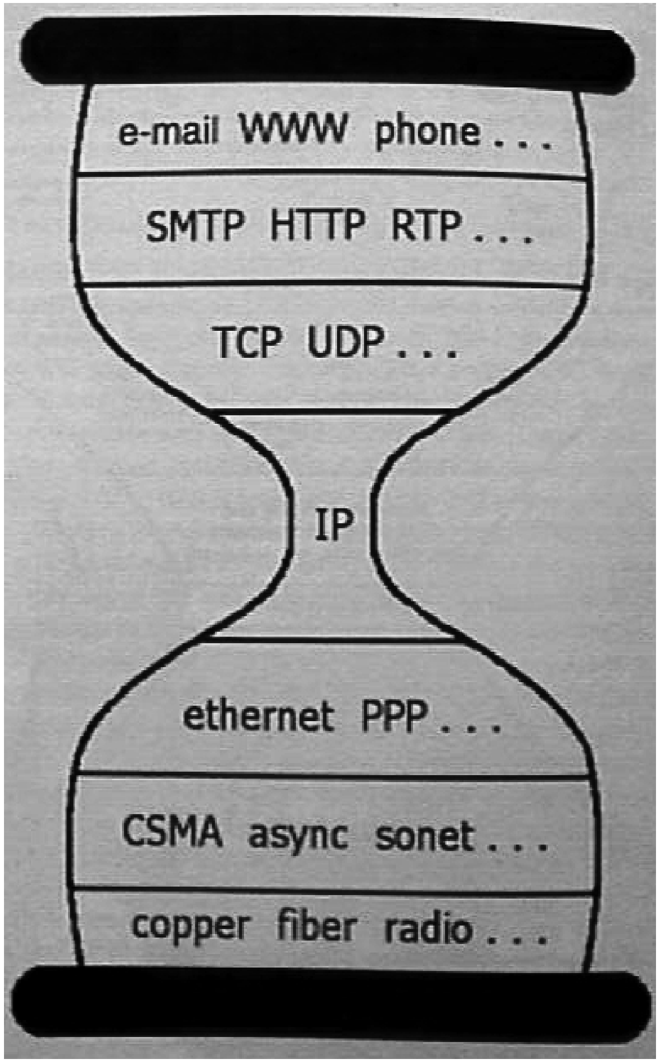
Case study: Packet Switching

- 1970/80s-current: Internet network
  - Variable bit rate
  - Mostly data
  - Fault-tolerant
  - Components not extremely reliable (versus phone components)
  - Distributed control and management

Why did the Internet win?

- Packet switching over circuit switching
- End-to-end principle and "Hourglass" design
- Layering of functionality
- Distributed design, decentralized control
- Superior organizational process

End-to-end principle and Hourglass design



End-to-end principle

- J. H. Saltzer, D. P. Reed and D. D. Clark "End-to-end arguments in system design", Transactions on Computer Systems, Vol. 2, No. 4, 1984
- http://www.acm.org/pubs/citations/journals/tocs/1984-2-4/p277-saltzer/

Hourglass design

- D. Clark, “The design philosophy of the DARPA Internet”, SIGCOMM 1988, August 16 - 18, 1988.

http://www.acm.org/pubs/citations/proceedings/comm/52324/p106-clark/

End-to-end principle

- Where to put the functionality?
  - In the network? At the edges?
- End-to-end functions best handled by end-to-end protocols
  - Network provides basic service: data transport
  - Intelligence and applications located in or close to devices at the edge
  - Violate principle as a performance enhancement
- Leads to innovation at the edges
  - Phone network: dumb edge devices, intelligent network
  - Internet: dumb network, intelligent edge devices

Hourglass design

- End-to-end principle leads to "Hourglass" design of protocols
- Only one protocol at the Internet level
  - Minimal required elements at narrowest point
- IP - Internet Protocol
  - http://www.rfc-editor.org/rfc/rfc791.txt
  - http://www.rfc-editor.org/rfc/rfc1812.txt
  - Unreliable datagram service
  - Addressing and connectionless connectivity
  - Fragmentation and assembly

Hourglass design

- Simplicity allowed fast deployment of multi-vendor, multi-provider public network
  - Ease of implementation
  - Limited hardware requirements (important in 1970s)
    - Is it relevant now with today's semiconductor speeds?
  - Eventual economies of scale
- Designed independently of hardware
  - No link-layer specific functions
  - Hardware addresses decoupled from IP addresses
  - IP header contains no data/physical link specific information
  - Allows IP to run over any fabric

Hourglass design

- Waist expands at transport layer
- Two dominant services layered above IP
- TCP – Transmission Control Protocol
  - Connection-oriented service
  - http://www.rfc-editor.org/rfc/rfc793.txt
- UDP – User Datagram Protocol
  - Connectionless service
  - http://www.rfc-editor.org/rfc/rfc768.txt

Hourglass design

- TCP – Transmission Control Protocol
  - Reliable, in-order byte-stream data transfer
    - Acknowledgements and retransmissions
  - Flow control
    - Sender won't overwhelm receiver
  - Congestion control
    - Senders won't overwhelm network
- UDP – User Datagram Protocol
  - Unreliable data transfer
  - No flow control
  - No congestion control

Hourglass design

- What uses TCP?
  - HTTP, FTP, Telnet, SMTP, NNTP, BGP, IMAP, POP
- What uses (mainly) UDP?
  - SNMP, NTP, NFS, RTP (streaming media, IP telephony, teleconferencing), multicast applications
  - Many protocols can use both
- Check out /etc/services on *nix or C:\WIN*\system32\services
- IANA
  - http://www.iana.org/assignments/port-numbers

Hourglass design

- Question?
  - Are TCP, UDP, and IP enough?
  - What other functionality would applications need?

Hourglass design

- Security?
  - IPsec/SSL/TLS
- Quality-of-service?
  - RSVP, int-serv, diff-serv
- Reliable, out-of-order delivery service?
  - SCTP
- Handling greedy sources?
- Accounting and pricing support?

End-to-end principle and the Hourglass design

- The good
  - Basic network functionality allowed for extremely quick adoption and deployment using simple devices
- The bad
  - New network features and functionality are impossible to deploy, requiring widespread adoption within the network
  - IP Multicast, QoS

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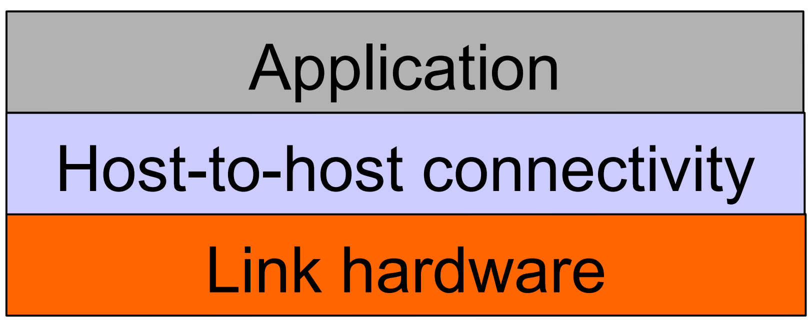
Layering

- Modular approach to network functionality
  - Simplifies complex systems
    - Each layer relies on services from layer below and exports services to layer above
  - Hides implementation
  - Eases maintenance and updating of system
    - Layer implementations can change without disturbing other layers (black box)

Layering

- Examples:
  - Topology and physical configuration hidden by network-layer routing
    - *Applications require no knowledge of routes*
    - New applications deployed without coordination with network operators or operating system vendors

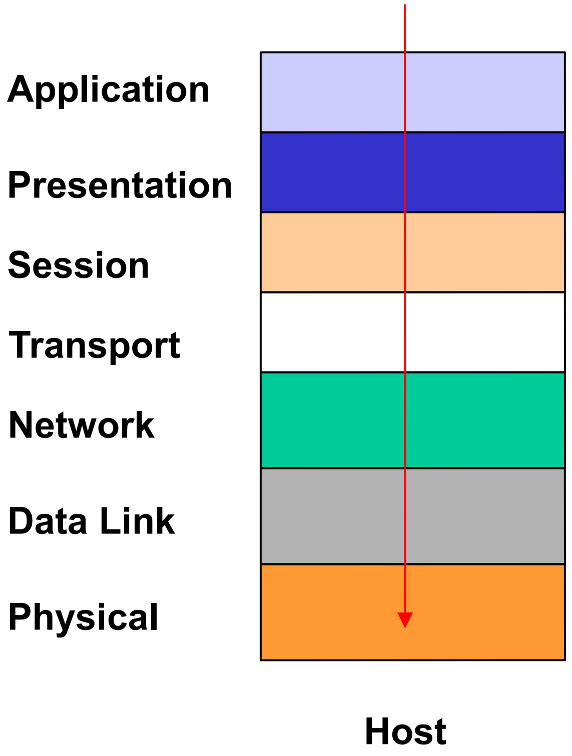


Layering essential in Protocols

- Set of rules governing communication between network elements (applications, hosts, routers)
- Protocols specify:
  - Interface to higher layers (API)
  - Interface to peer
    - Format and order of messages
    - Actions taken on receipt of a message
  - Interface defines interaction

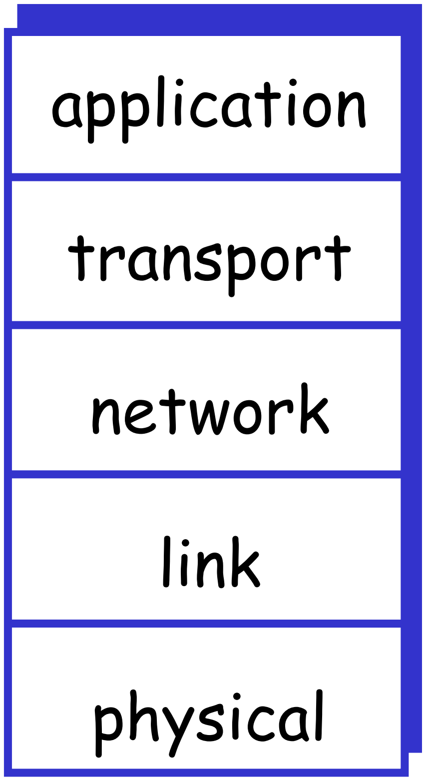
Layering: OSI Model

- Physical
  - how to transmit bits
- Data link
  - how to transmit frames
- Network
  - how to route packets host-to-host
- Transport
  - how to send packets end2end
- Session
  - how to tie flows together
- Presentation
  - byte ordering, formatting
- Application: everything else

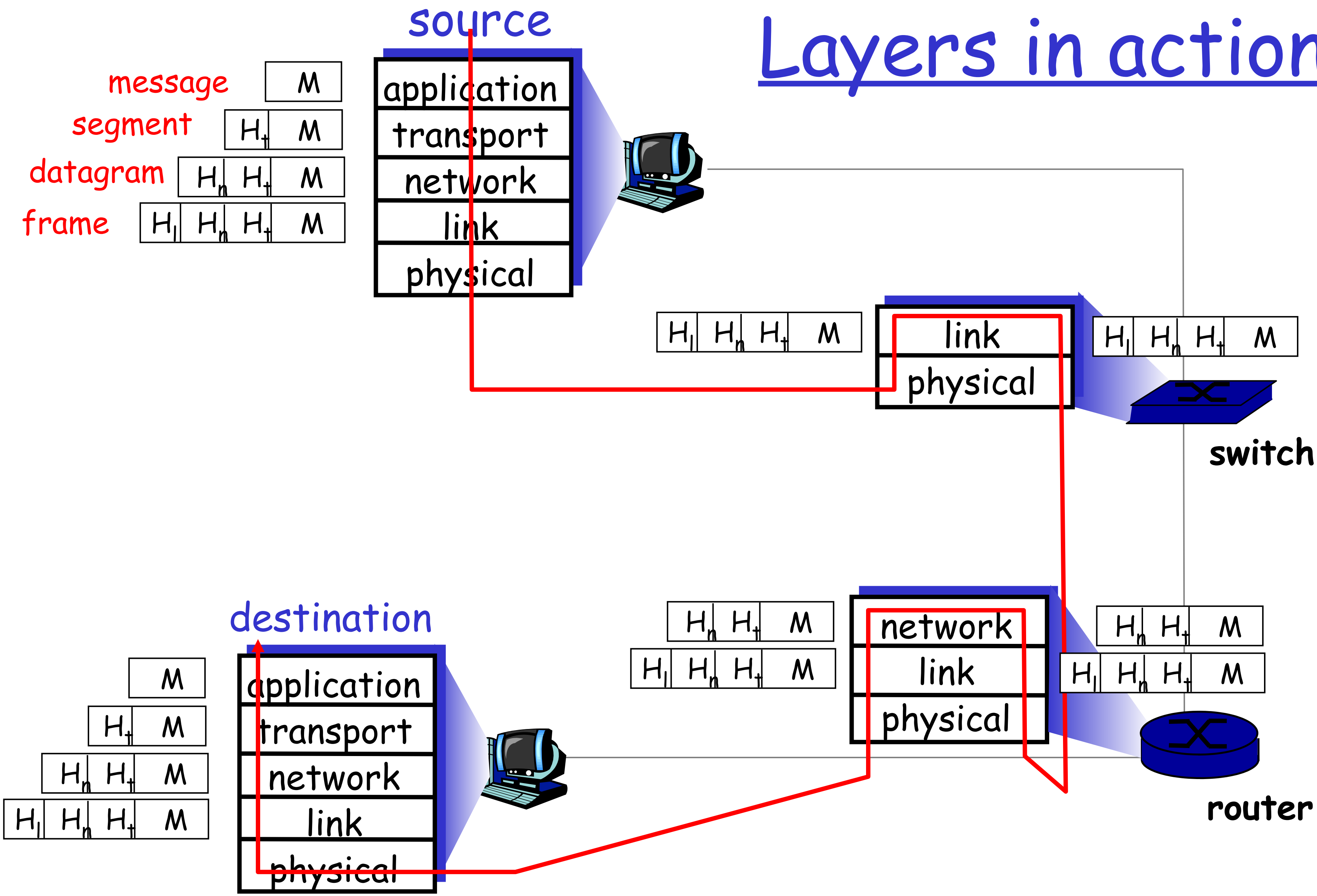


Layering: Internet protocols

- application: (L7 & L6 of OSI) supporting network applications
  - FTP, SMTP, HTTP
- transport: (L5 & L4 of OSI) host-host data transfer
  - TCP, UDP
- network: routing of datagrams from source to destination
  - IP, routing protocols
- link: data transfer between neighboring network elements
  - PPP, Ethernet
- physical: bits "on the wire"



Layers in action



Layering

- Is Layering always good?
  - Sometimes not..
    - Layer N may duplicate lower level functionality (e.g., error recovery)
    - Layers may need same info (timestamp, MTU)
    - Strict adherence to layering may hurt performance

Why did the Internet win?

- Packet switching over circuit switching
- End-to-end principle and "Hourglass" design
- Layering of functionality
- Distributed design, decentralized control
- Superior organizational process

Distributed design and control

- Requirements from DARPA
  - Must survive a nuclear attack
- Reliability
  - Intelligent aggregation of unreliable components
  - Alternate paths, adaptivity
- Distributed management & control of networks
  - Allows individual networks to independently develop without large amounts of coordination
  - Exceptions: TLDs and TLD servers, IP address allocation (ICANN)

Superior organizational process

- IAB/IETF process allowed for quick specification, implementation, and deployment of new standards
  - Free and easy download of standards
  - Rough consensus and running code
  - 2 interoperable implementations
  - Bake-offs
  - http://www.ietf.org/
- ISO/OSI
  - Comparison to IETF left as an exercise

Problem 1

- Consider the queuing delay in a router buffer (preceding an outbound link). Suppose all packets are L bits, the transmission rate is R bps and that N packets simultaneously arrive at the buffer every LN/R seconds. Find the average queuing delay of a packet

Internet history

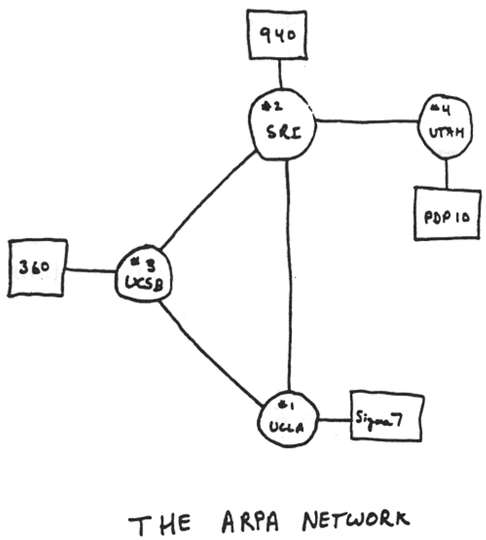
How old is the Internet?

- Guesses?
- Hint
  - It used to be the case that everyone in this class remembered the “pre-Internet” days

Internet History

1961-1972: Early packet-switching principles

- 1961: Kleinrock - queueing theory shows effectiveness of packet-switching
- 1964: Baran - packet-switching in early military nets
- 1967: ARPAnet conceived by Advanced Research Projects Agency
- 1969: first ARPAnet node operational
- 1972:
  - ARPAnet public demonstration
  - NCP (Network Control Protocol) first host-host protocol
  - first e-mail program
  - ARPAnet has 15 nodes



Internet History

1972-1980: Internetworking, new and proprietary nets

- 1970's: proprietary network architectures developed: DECnet, SNA, XNA
- 1974: Cerf and Kahn - architecture for interconnecting networks
- 1976: Ethernet at Xerox PARC
- 1979: ARPAnet has 200 nodes

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

Internet History

1980-1990: new protocols, a proliferation of networks

- 1983: deployment of TCP/IP
- 1983: smtp e-mail protocol defined
- 1983: DNS defined for name-to-IP-address translation
- 1985: ftp protocol defined
- 1988: TCP congestion control

- Late 1980s, Early 1990s: new national networks: Csnet, BITnet, NSFnet, Minitel
  - 100,000 hosts connected to confederation of networks

Internet History

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

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

Late 1990's – 2000's:

- more killer apps: instant messaging, P2P file sharing
- network security to forefront
- est. 50 million host, 100 million+ users
- backbone links running at Gbps

Internet History

2007:

- ~500 million hosts
- Voice, Video over IP
- P2P applications: BitTorrent (file sharing) Skype (VoIP), PPLive (video)
- more applications: YouTube, gaming
- wireless, mobility

Internet in a nutshell (protocols in practice)

A day in the life of an Internet host…

- Booting
  - Dynamically configure network settings
    - DHCP request
      - UDP (unreliable datagrams)
      - IP and data-link broadcast

Datalink broadcast header	IP broadcast 255.255.255.255	UDP header	DHCP request Host's datalink (MAC) address 00:50:7e:0d:30:20

    - DHCP response from listening server
      - IP address of host
      - Netmask (i.e. 255.255.255.0) to determine network ID
      - Default router

Datalink header 00:50:7e:0d:30:20	IP of Host	UDP Header	DHCP reply Host's network settings

A day in the life of an Internet host…

- Web request http://www.yahoo.com/index.html
  - Step #1: Locate DNS server

    if (netmask & IP_{Host} == netmask & IP_{DNS}) {

      DNS server on local network

      ARP for hardware address of IP_{DNS}

    } else {

      DNS server on remote network

      ARP for hardware address of $IP_{DefaultRouter}$

    }

    - ARP (Address Resolution Protocol)
      - IP address to hardware address mapping
      - Request broadcast for all hosts on network to see
      - Reply broadcast for all hosts to cache

A day in the life of an Internet host…

- Step #2: ARP request and reply

Datalink header broadcast	ARP request: Who has MAC address of IP addr "X"? (X=next-hop router, dns server) MAC address of requestor

Datalink header MAC of requestor or broadcast addr	ARP reply: MAC address of "X" is a:b:c:d:e:f

A day in the life of an Internet host…

- Step #3: DNS request/reply
  - UDP, IP, data-link header
  - DNS request to local DNS server from host

Datalink header (DNS server or next-hop router)	IP of DNS Server	UDP Header	DNS request www.yahoo.com "A" record request

  - DNS reply from local DNS server to host

Datalink header (host)	IP of host	UDP Header	DNS reply www.yahoo.com is 216.115.105.2

A day in the life of an Internet host…

- Step #4: TCP connection establishment
  - TCP 3-way handshake (SYN, SYN-ACK, ACK)
  - Session establishment to support reliable byte stream

Datalink header (next-hop router)	IP of 216.115.105.2	TCP Header SYN

Datalink header (host)	IP of host	TCP Header SYN-ACK

Datalink header (next-hop router)	IP of 216.115.105.2	TCP Header ACK

A day in the life of an Internet host…

- Step #5: HTTP request and reply
  - HTTP (application data), TCP, IP, data-link header
  - HTTP request

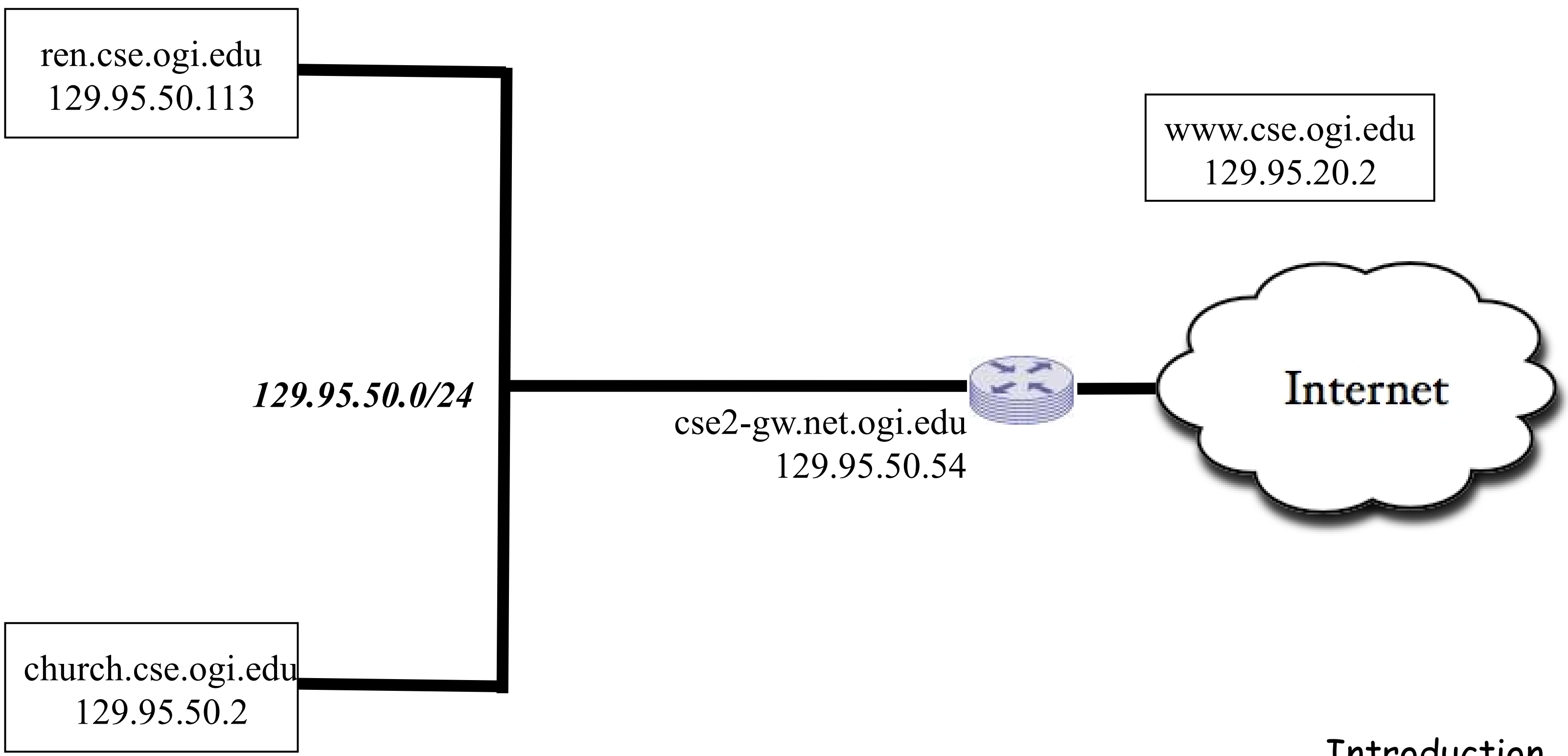
Datalink header (next-hop router)	IP of 216.115.105.2	TCP Header	HTTP request GET /index.html HTTP/1.0

  - HTTP reply

Datalink header (host)	IP of host	TCP Header	HTTP reply HTTP/1.0 200 OK Date: Mon, 24 Sep 2001 Content-Type: text/html <html> …. </html>

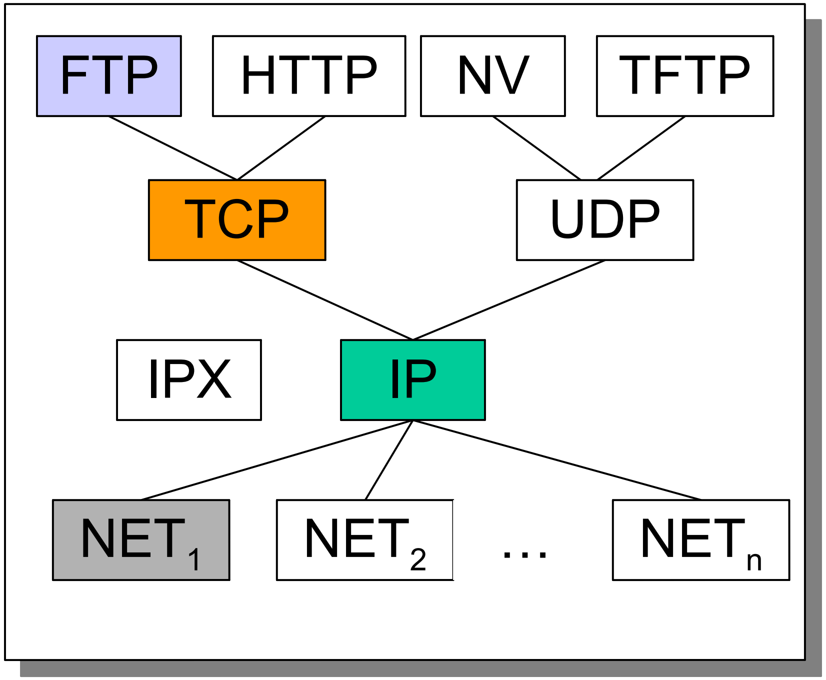
tcpdump example

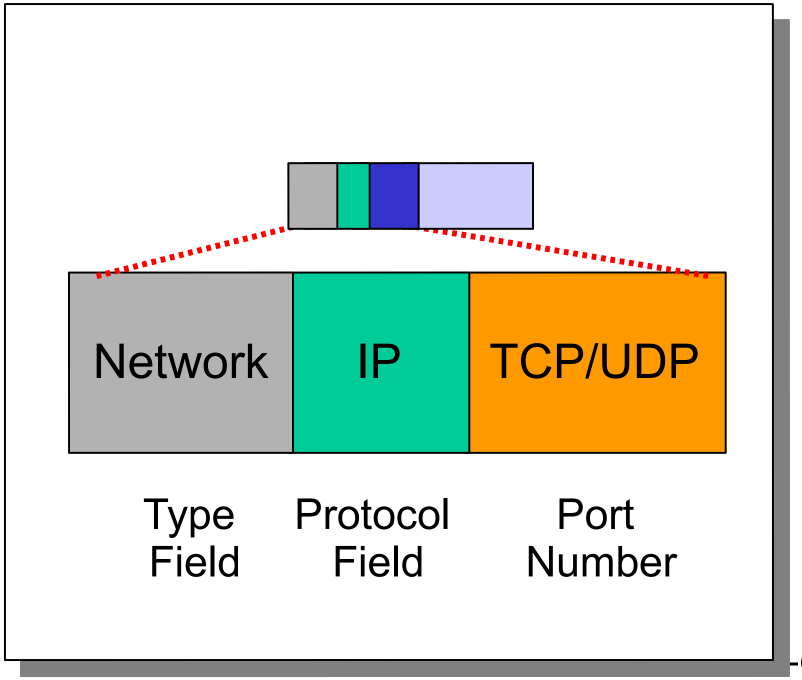
- http://thefengs.com/wuchang/work/courses/cs594/trace.txt



A day in the life of an Internet host…

- Role of TCP and UDP?
- Demultiplex at end hosts.
  - Which process gets this request?





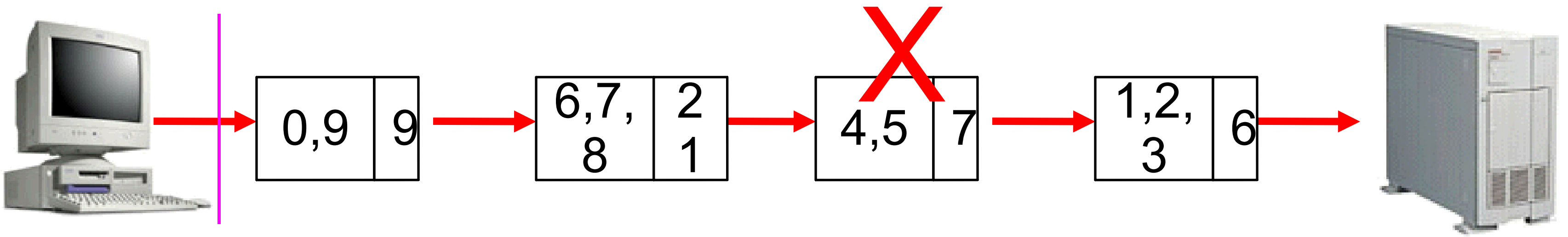
A day in the life of an Internet host….

- What about….
  - Reliability
    - Corruption
    - Lost packets
  - Flow and congestion control
  - Fragmentation
  - Out-of-order delivery
- The beauty of TCP, IP, and layering
  - All taken care of transparently

What if the Data is Corrupted?

Problem: Data Corruption

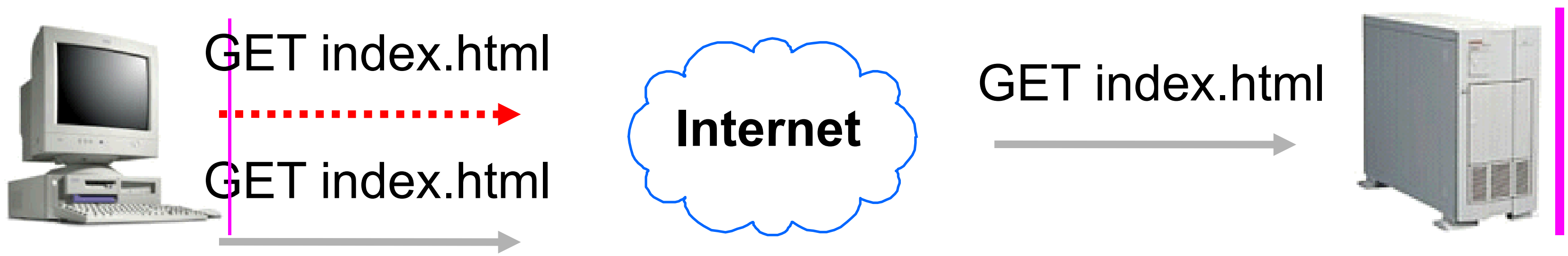
Solution: Add a *checksum*



What if the Data is Lost?

Problem: Lost Data

Solution: Timeout and Retransmit

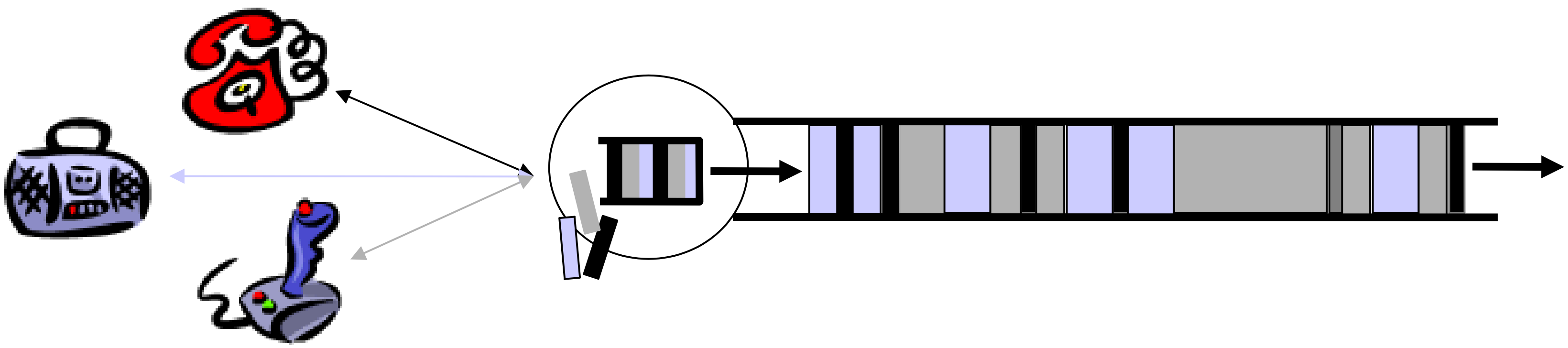


What if receiver has no resources (flow control)?

Problem: Overflowing receiver buffers

Solution: Receiver advertised window

What if Network is Overloaded?



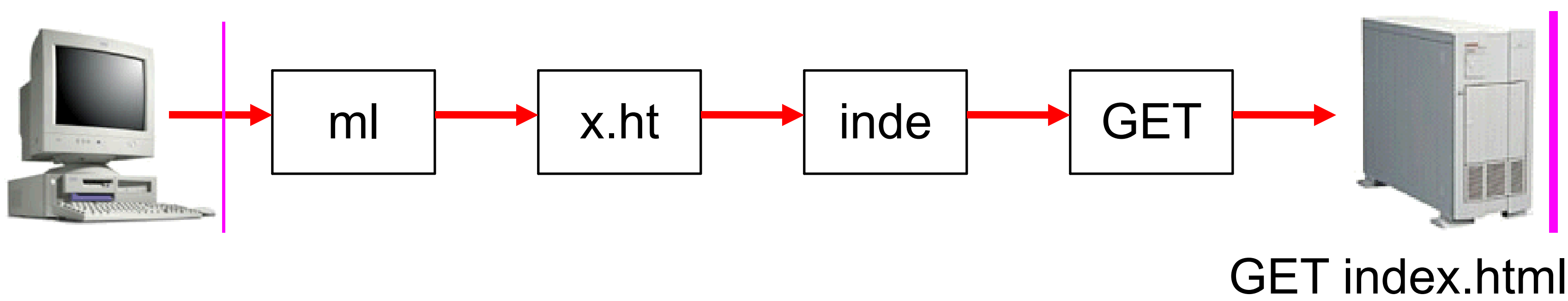
- Short bursts: buffer
- What if buffer overflows?
  - Packets dropped and retransmitted
  - Sender adjusts rate until load = resources
- Called "Congestion control"

What if the Data Doesn't Fit?

Problem: Packet size

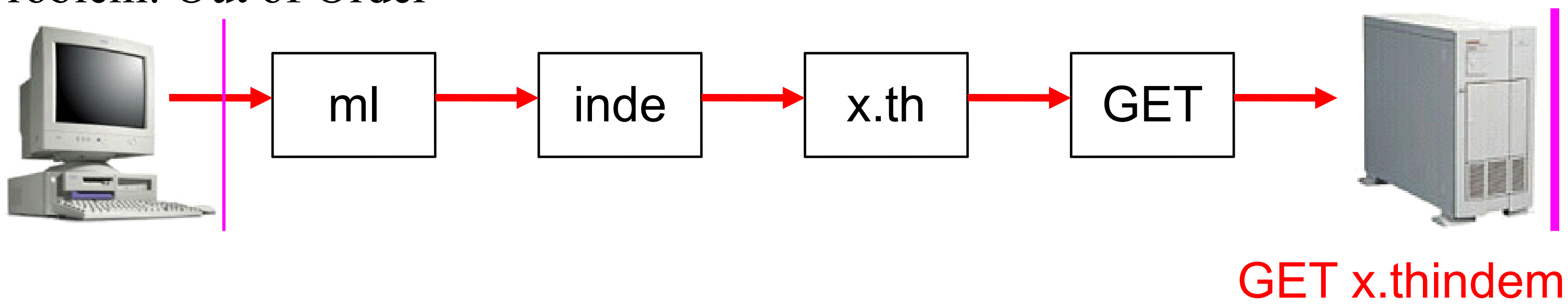
- On Ethernet, max IP packet is 1.5kbytes
- Typical web page is 10kbytes

Solution: Fragment data across packets

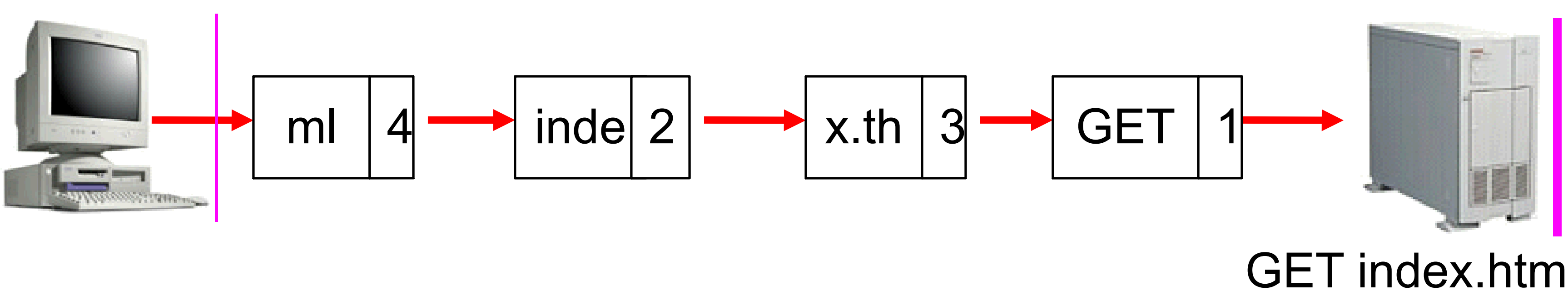


What if the Data is Out of Order?

Problem: Out of Order



Solution: Add Sequence Numbers



The rest of the course

- From birds-eye view, we will now focus on specific components
- Review these lectures for perspective when looking at the components
- Mostly classical material with some references to newer technologies

Acknowledgements

- Material taken from course slides by Srini Seshan's Computer Networking course at http://www.cs.cmu.edu/~srini/15-744/S01/

Extra slides

Layering

- Need for exposing underlying layers for optimal application performance
  - D. Tennenhouse and D. Clark. Architectural Considerations for a New Generation of Protocols. SIGCOMM 1990.
  - Application Layer Framing (ALF)
    - Enable application to process data as soon as it can
    - Expose application processing unit (ADU) to protocols
  - Integrated Layer Processing (ILP)
    - Layering convenient for architecture but not for implementations
    - Combine data manipulation operations across layers

Residential access: cable modems

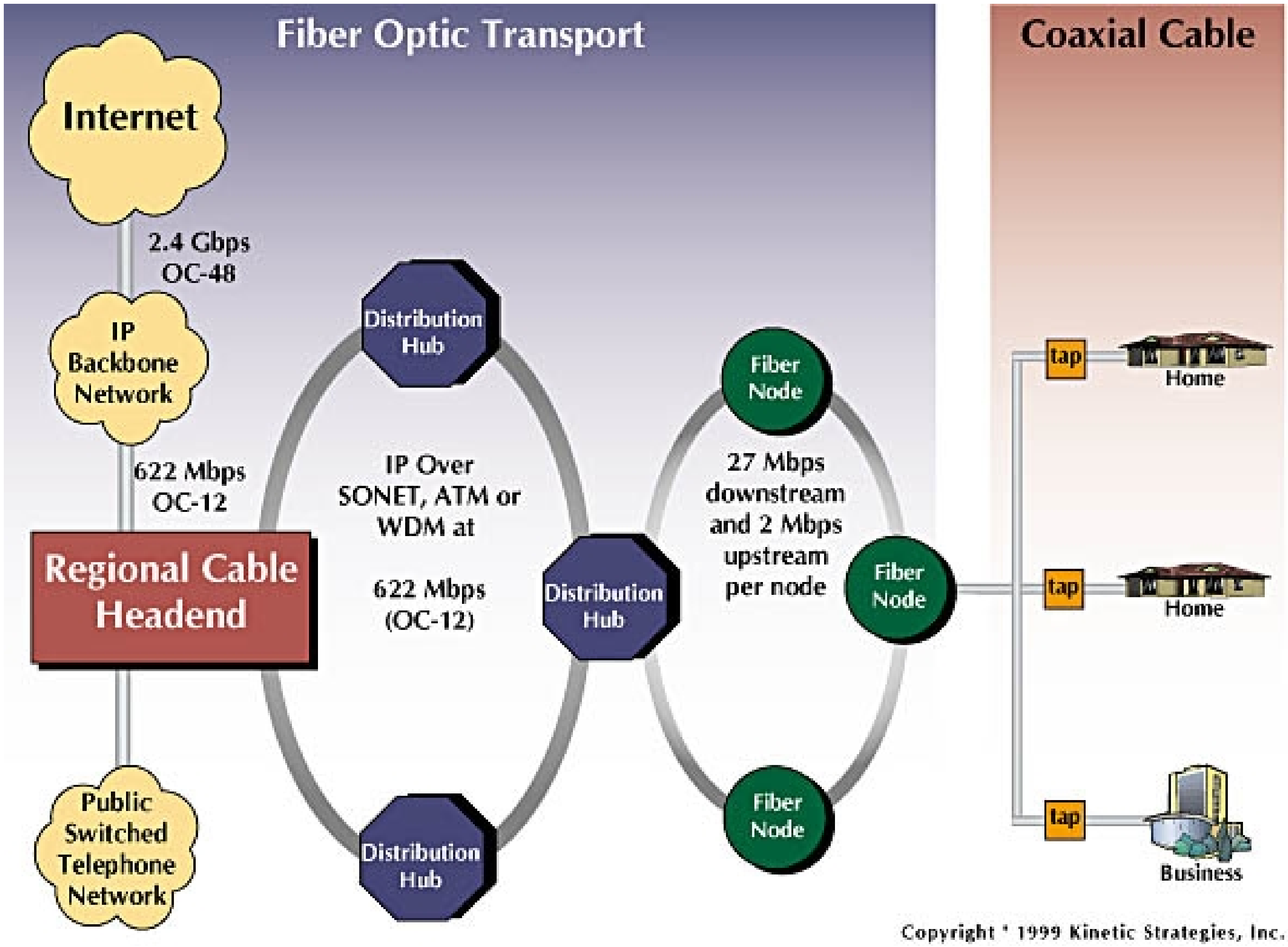
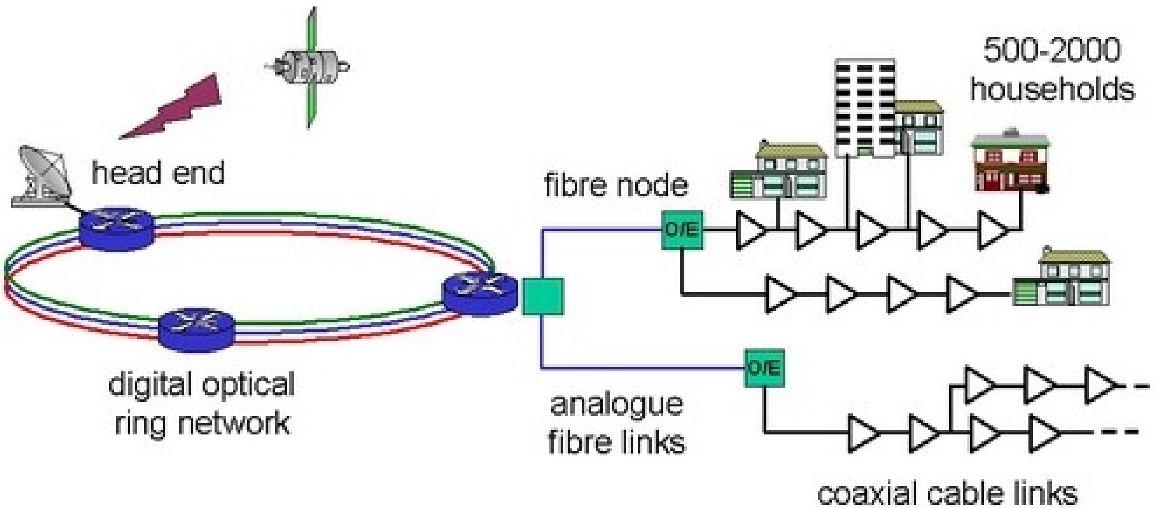
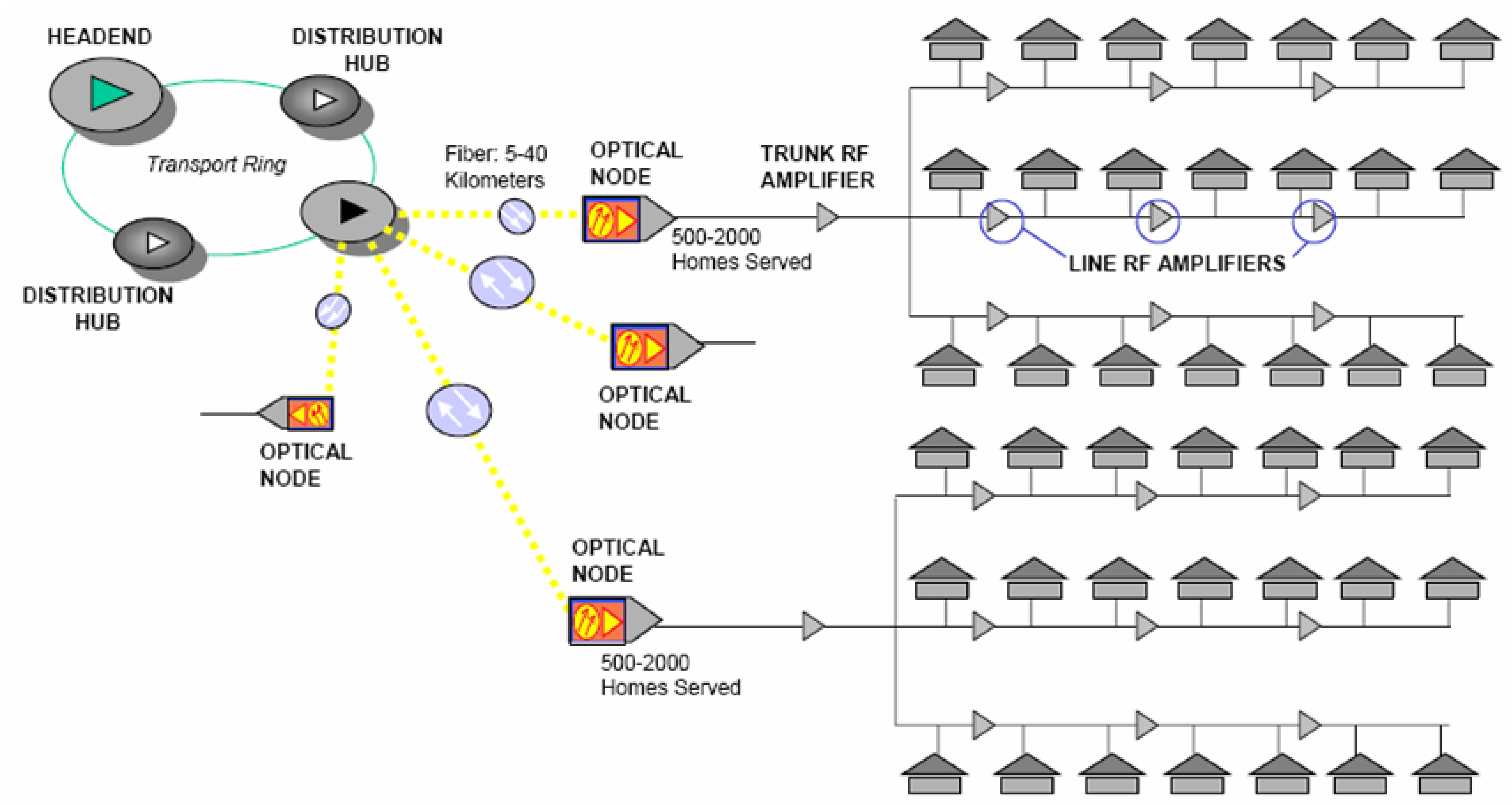


Diagram: http://www.cabledatacomnews.com/cmic/diagram.html

Cable Network Architecture: Overview



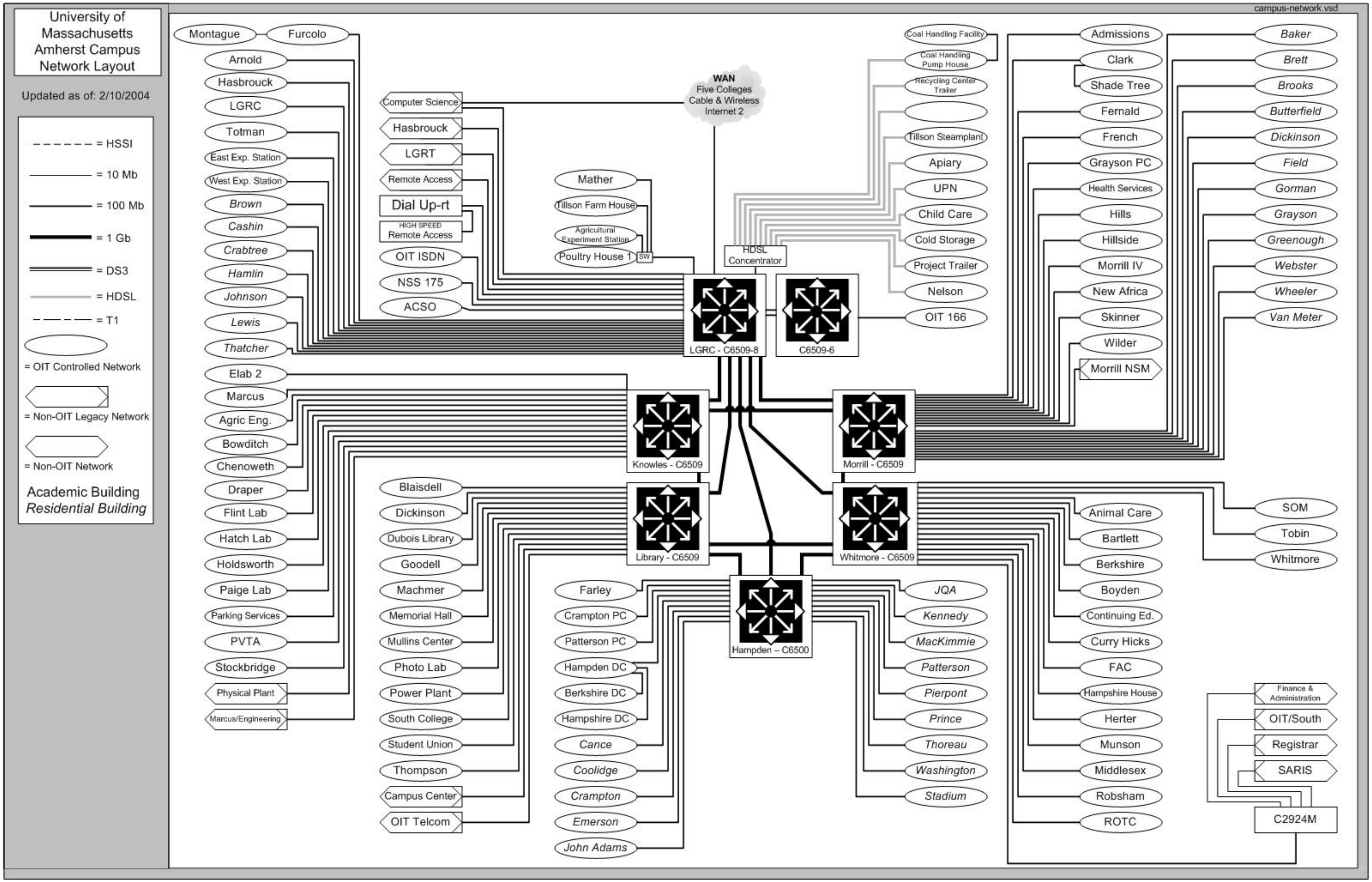
Residential access: cable modems



Residential access: cable modems

- HFC: hybrid fiber coax
  - asymmetric: up to 27Mbps downstream, 2 Mbps upstream
  - Limited upstream bandwidth due to multiple noise sources vs. downstream case with one controllable noise source (headend)
- network of cable and fiber attaches homes to ISP router
  - homes share access to router
- deployment: available via cable TV companies

UMass Campus Network



Internet History

- Those who ignore the past are doomed to repeat it
  http://www.worldcom.com/about_the_company/cerfs_up/
- Where did it come from?
- Who built it?
- Why does it work?
- Most of the original designers (old-timers) still around and active…
  - internet-history-request@postel.org

Internet timeline

- 1961 Kleinrock proposes packet switching
- 1962 Licklider proposes “galactic” network
  - Goes to DARPA as head of CS research
- 1966 Roberts proposes galactic network using packet switching
  - Goes to ARPA to build it (ARPANET)
- 1968 RFQs to build routers (Interface Message Processors)
- 1968 Kahn separates hardware addresses from network addresses
  - ARPANET to run over any hardware
- 1969 Crocker initiates RFC notes to document protocols
  - Freely available
- 1969 First node of ARPANET UCLA (September)
- 1969 4-node ARPANET at UCLA, SRI, Utah, UCSB (December)
  - Initial hosts.txt name database
- 1970 Crocker develops NCP (host-to-host protocol for applications)
  - Precursor to TCP
- 1972 Tomlinson develops e-mail (@)

Internet timeline

- 1972 Issues with NCP and ARPANET arise
  - NCP relied on ARPANET for end2end reliability (assumed no packet loss)
    - Can not work over satellite or packet radio links
  - NCP addressing tied to ARPANET
- 1973 Kahn redesigns protocols
  - Communication on a “best-effort” basis
    - Least-common denominator
    - End points in charge of retransmission, reassembly, flow control
  - No per-flow state in gateways between networks
    - Simple, avoids adaptation and recovery from failure
  - Addressing
    - 8-bit network number, 24 bit host number
    - Fails to forsee development of the LAN
    - Later split into Class A (national), B (regional), and C (LAN)
- 1974 Kahn, Cerf develop TCP (with IP included) (December)
  - IP later separated for unreliable applications, UDP added
- 1981 RFCs for TCP and IP
  - Initial applications: file transfer, e-mail, voice/video, login

Internet timeline

- 1978-1983: NCP replaced by TCP/IP
  - Implementations of TCP/IP on many platforms (Clark)
  - Mandate from to switch all users on ARPANET from NCP to TCP/IP (1980)
    - Not well received
    - One-day shutoff of NCP in mid-1982 makes people angry, but not sufficiently convincing
    - January 1983: NCP banned from ARPANET "Flag Day" -> The Internet is born
    - Some older computers allowed to operate with old NCP for a short time
    - Full transition takes several months, finishes at end of 1983
    - "I survived the TCP/IP transition" buttons (Y2K bug?)
  - Will there be an "IPv6 day?"

Internet timeline

- 1982-1985 Application protocols
  - SMTP (1982)
  - Mockapetris develops DNS (1983)
  - telnet (1983)
  - ftp (1985)
- 1980s Jealous non-interoperable competitors
  - DOE: MFENet (Magnetic Fusion Energy scientists)
  - DOE: HEPNet (High Energy Physicists)
  - NASA: SPAN (Space physicists)
  - NSF: CSNET (CS community)
  - NSF: NSFNet (Academic community) 1985
  - AT&T: USENET with Unix, UUCP protocols
  - Academic networks: BITNET (Mainframe connectivity)
  - Xerox: XNS (Xerox Network System)
  - IBM: SNA (System Network Architecture)
  - Digital: DECNet
  - UK: JANET (Academic community in UK) 1984

Internet timeline

- 1986-1995 NSFNet (Jennings/Wolff with funding assist from Al Gore)
  - Network for academic/research community
  - Selects TCP/IP as mandatory for NSFNet
  - Builds out wide area networking infrastructure
  - Develops strategy for developing and handing it over eventually to commercial interests
    - Prohibit commercial use of NSFNet to encourage commercial backbones
    - Leads to PSINet, UUNET, ANS, CO+RE backbone development
- 1989 WWW
  - Tim Berners-Lee develops initial web browser supporting URLs, HTTP, HTML

Internet timeline

- Early 1990s Privatization
  - ARPANET decommissioned (1990)
  - NSFNet decommissioned (1995) ($200 million spent from 1986-1995)
- Early 1990s Architectural issues
  - Address depletion
    - Multi-class addressing to break 8/24 network/host split in address bits
  - Routing table explosion
    - Hierarchy and CIDR
  - Congestion
    - TCP congestion control
- 1994 Andreessen
  - Mosaic web browser

Packet switching

- Kleinrock, MIT (July 1961)
  - Theoretical feasibility of communications using packets instead of circuits
  - L. Kleinrock, "Information Flow in Large Communication Nets", RLE Quarterly Progress Report, July 1961.
  - L. Kleinrock, Communication Nets: Stochastic Message Flow and Delay, Mcgraw-Hill (New York), 1964.

Conceptual "Internet"

- J.C.R. Licklider, W. Clark, MIT (August 1962)
  - "On-line Man Computer Communication"
  - "Galactic network" concept of globally interconnected set of computers
  - Licklider goes to DARPA as head of computer research program (Oct. 1962)

ARPANET

- Roberts, (1966)
  - Puts idea of galactic computer network and packet switching together
  - Goes to DARPA as program manager
    - Plans for building “ARPANET” based on system
    - L. Roberts, "Multiple Computer Networks and Intercomputer Communication", ACM Gatlinburg Conf., October 1967.

ARPANET

- Structure and specification (August 1968)
  - RFQ to build IMPs (Interface Message Processors)
    - Packet switches which route packets
    - BBN (Bolt, Beranek, and Newman) wins contract
  - Kahn at BBN updates ARPANET design
    - Run over any fabric (separation of hardware and network addresses)
    - Support for multiple independent networks
- First node UCLA (Sept. 1969)
  - 4 node ARPANET (Dec. 1969) SRI, UCSB, Utah
  - Initial hostname/address database (flat file: hosts.txt)

RFCs

- 1969: Crocker establishes RFC series of notes
  - Official protocol documentation
    - Printed on paper and snail mailed at first
    - Then available via ftp and now http
    - Open and free access to RFCs mandated
    - Effective, positive feedback loop
    - Key to quick development process ("time-to-market")
    - Has changed considerably as of late...
- Jon Postel RFC editor and protocol number assignment

NCP

- Crocker
  - Connectivity implemented
  - Require a host-to-host protocol standard for two ends to talk to each other
  - NCP (Network Control Protocol) defined (Dec. 1970)
  - Precursor to TCP
  - Deployed from 1971-1972
  - Allows applications to be developed on top of network

E-mail

- BBN's Tomlinson (Mar. 1972)
  - Time-shared systems at the time allow users to leave messages for each other
  - Extended to remote systems
  - Writes first e-mail application to send and read
  - Infamous "@" used

Internetting

- ARPANET not the only network in town...
  - International Network Working Group (Sept. 1973)
  - Goal: run protocols over packet satellite net, packet radio net, and wired ARPANET
  - Problems
    - NCP can only address networks connected to IMPs on ARPANET
    - NCP relied on ARPANET for end2end reliability
    - NCP assumed no packet loss: applications halt upon loss
    - NCP had no end-end host error control
  - Kahn redesigns protocols for internetworking

Internetting

- Kahn's Architecture
  - Each network stands alone
    - No changes required to connect to Internet
    - Communication between networks handled by gateways
  - Communication on a "best-effort" basis
    - Least-common denominator
    - Source in charge of retransmission
    - Host-to-Host flow control (sliding windows and acks)
  - Black boxes interconnecting networks (gateways and routers) have no per-flow information
    - Simple, avoids complicated adaptation and recovery from failure
  - No global control at the operations level

Internetting

- Other issues
  - Host-to-Host data pipelining (multiple packets en route)
  - Gateway interprets IP headers for routing and performs fragmentation to other networks
  - end2end checksums, reassembly of fragments, duplicate detection at end-hosts (much of TCP's virtual circuit model)
  - Global addressing via 32-bit address (IP's limitation)
    - 8-bit network number, 24 bit host number
    - Fails to forsee development of the LAN
      - Later split into Class A (national), B (regional), and C (LAN)
  - Interfaces to operating systems
    - R. Kahn, Communications Principles for Operating Systems. Internal BBN memo, Jan. 1972.

Internetting

- Kahn brings in Cerf (Stanford) to help implement ideas on multiple OS platforms
  - V. Cerf, R. Kahn "A protocol for packet network intercommunication" IEEE Transactions on Communications, May 1974
  - TCP draft produced (includes IP) Dec. 1974
- ARPA sponsors 3 groups to implement on hosts
  - Stanford (Cerf), BBN (Tomlinson), UCL (Kirstein)
  - All interoperate
- IP later separated (not all apps need reliability)
  - UDP added

Internetting

- IP
  - Internet Protocol (Sept. 1981) Postel
  - http://www.rfc-editor.org/rfc/rfc791.txt
- TCP
  - Transmission Control Protocol (Sept. 1981) Postel
  - http://www.rfc-editor.org/rfc/rfc793.txt
- Initial applications
  - Goal is resource sharing of systems on ARPANET
    - File transfer
    - Remote login (telnet)
    - E-mail
    - Packet voice, packet video (late 1970s)

Application protocols

- SMTP
  - Simple Mail Tranfer Protocol (Aug. 1982) Postel
    - http://www.rfc-editor.org/rfc/rfc821.txt
- DNS
  - Hostnames server, SRI (Mar. 1982) Harrenstien
    - http://www.rfc-editor.org/rfc/rfc811.txt
  - Current hierarchical architecture (Aug. 1982) Su, Postel
    - http://www.rfc-editor.org/rfc/rfc819.txt
  - Domain Name System standard (Nov. 1983) Mockapetris
    - http://www.rfc-editor.org/rfc/rfc882.txt
    - http://www.rfc-editor.org/rfc/rfc882.txt

Application protocols

- Telnet
  - Telnet protocol (May 1983) Postel, Reynolds
    - http://www.rfc-editor.org/rfc/rfc854.txt
- FTP
  - File transfer protocol (Oct. 1985) Postel, Reynolds
    - http://www.rfc-editor.org/rfc/rfc959.txt

NSFNet

- Structure
  - 6 nodes with 56kbs links
    - Jointly managed exchange points
    - Statistical, non-metered peering agreements
    - Cost-sharing of infrastructure
  - Seek out commercial, non-academic customers
    - Help pay for and expand regional academic facilities
    - Economies of scale
    - Prohibit commercial use of NSFNet to encourage commercial backbones
    - Leads to PSINet, UUNET, ANS, CO+RE backbone development

TCP/IP software proliferation

- Widespread dispersal leads to critical mass
- Case study: Berkeley Unix
  - Unix TCP/IP available at no cost (DoD)
  - Incorporates BBN TCP/IP implementation
  - Large-scale dissemination of code base
  - Eventual economies of scale

Privatization

- Commercial interconnection
  - US Federal Networking Council (1988-1989)
  - MCI Mail allowed
- ARPANET decommissioned (1990)
- NSFNet decommissioned (1995)
  - 21 nodes with multiple T3 (45Mbs) links
  - Regional academic networks forced to buy national connectivity from private long haul networks
  - TCP/IP supplants and marginalizes all others to become THE bearer service for the Internet
  - Total cost of NSF program?

$200 million from 1986-1995

Growing pains

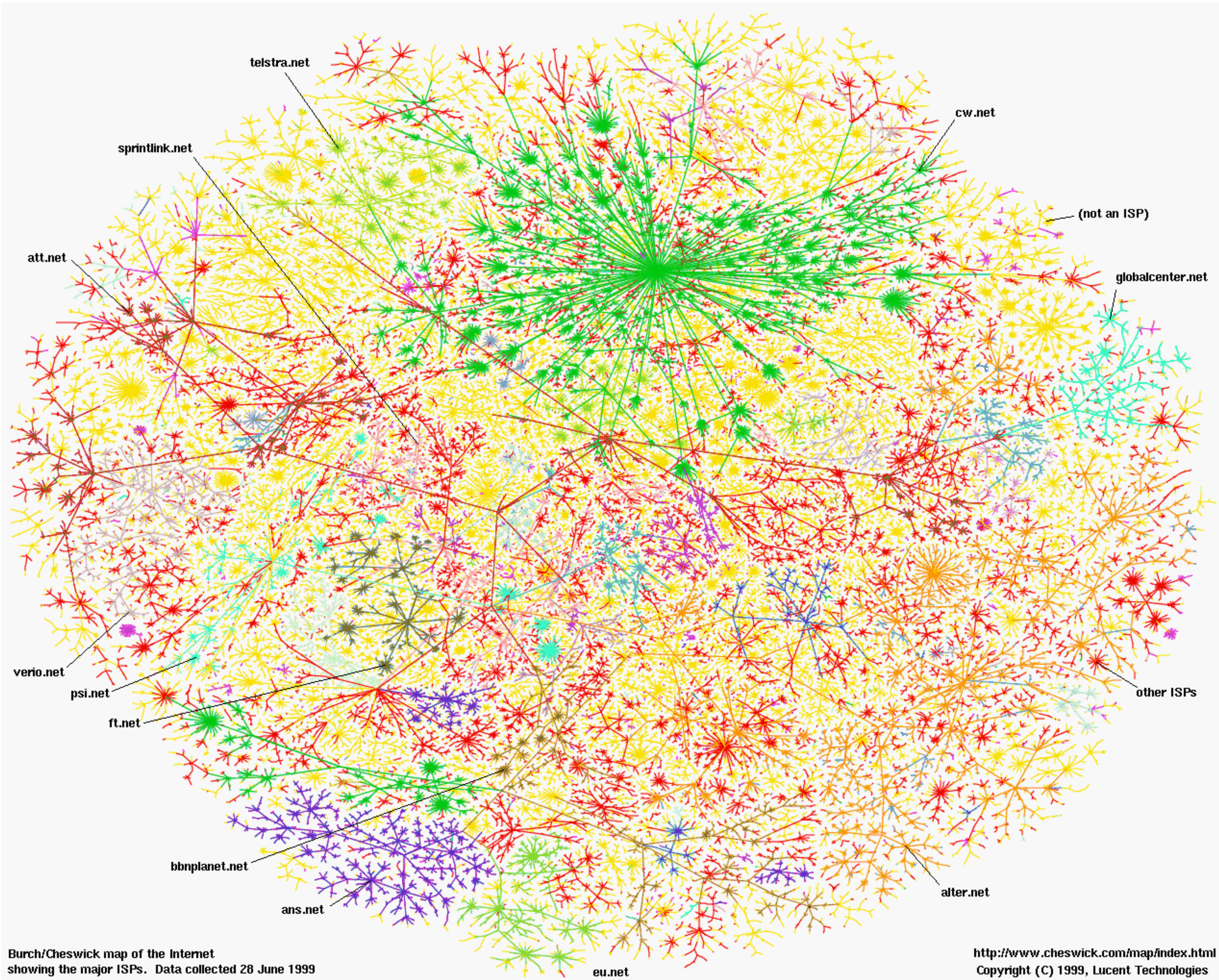
- Address depletion
  - Multi-class addressing to break up 8-bit network/24-bit host
- Explosion of networks
  - Routing initially flat, each node runs the same distributed routing algorithm
  - Moved to hierarchical model to match commercial reality (IGP, EGP)
    - Reduces table size, distributes control (a bit)
  - Classless addressing (CIDR)
    - Reduces table size
- Congestion
  - Network "brown-outs", congestion collapse
  - Add congestion control to TCP protocol, not IP

WWW

- CERN (European Organization for Nuclear Research)
  - Berners-Lee, Caillau work on WWW (1989)
  - First WWW client (browser-editor running under NeXTStep)
  - Defines URLs, HTTP, and HTML
  - Berners-Lee goes to MIT and LCS to start W3C
    - Responsible for evolving protocols and standards for the web
  - http://www.w3.org/People

WWW

- NCSA (National Center for Supercomputing Applications)
  - Federally funded research center at University of Illinois at Urbana-Champaign
  - Andreessen: Mosaic and eventually Netscape (1994)
  - http://www.dnai.com/~thomst/marca.html


telstra.net
cw.net
sprintlink.net
(not an ISP)
att.net
globalcenter.net
verio.net
psi.net
ft.net
other ISPs
bbnplanet.net
ans.net
alter.net
Burch/Cheswick map of the Internet
showing the major ISPs. Data collected 28 June 1999
eu.net
http://www.cheswick.com/map/index.html
Copyright (C) 1999, Lucent Technologies

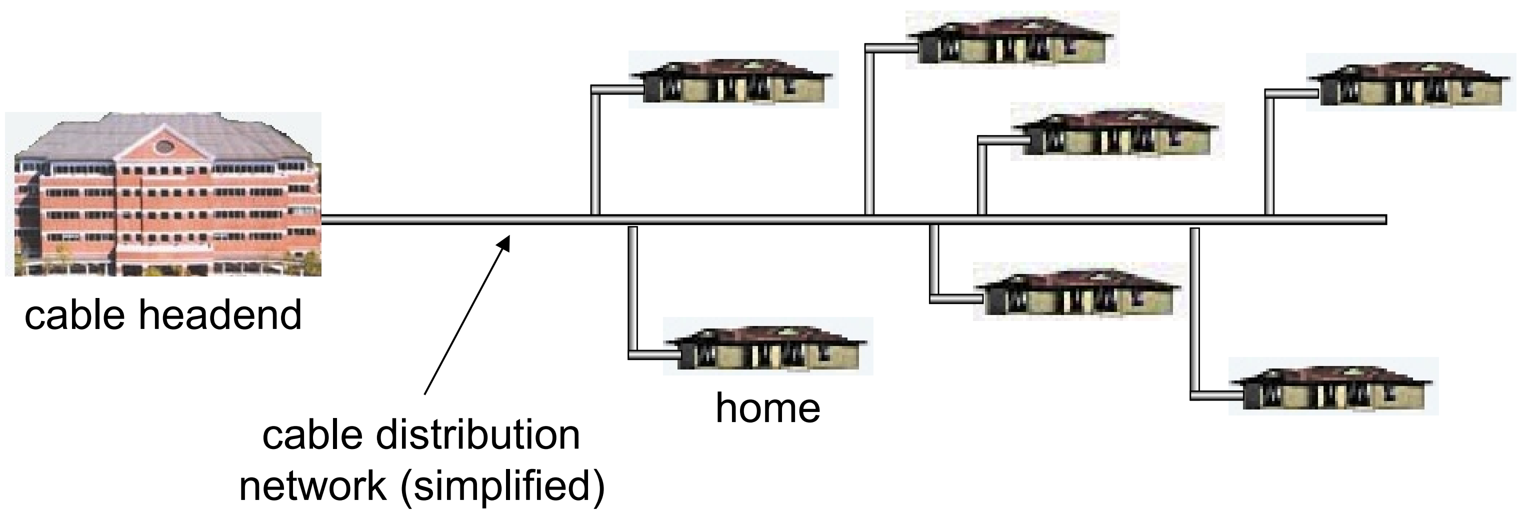
Today's Internet

Residential access

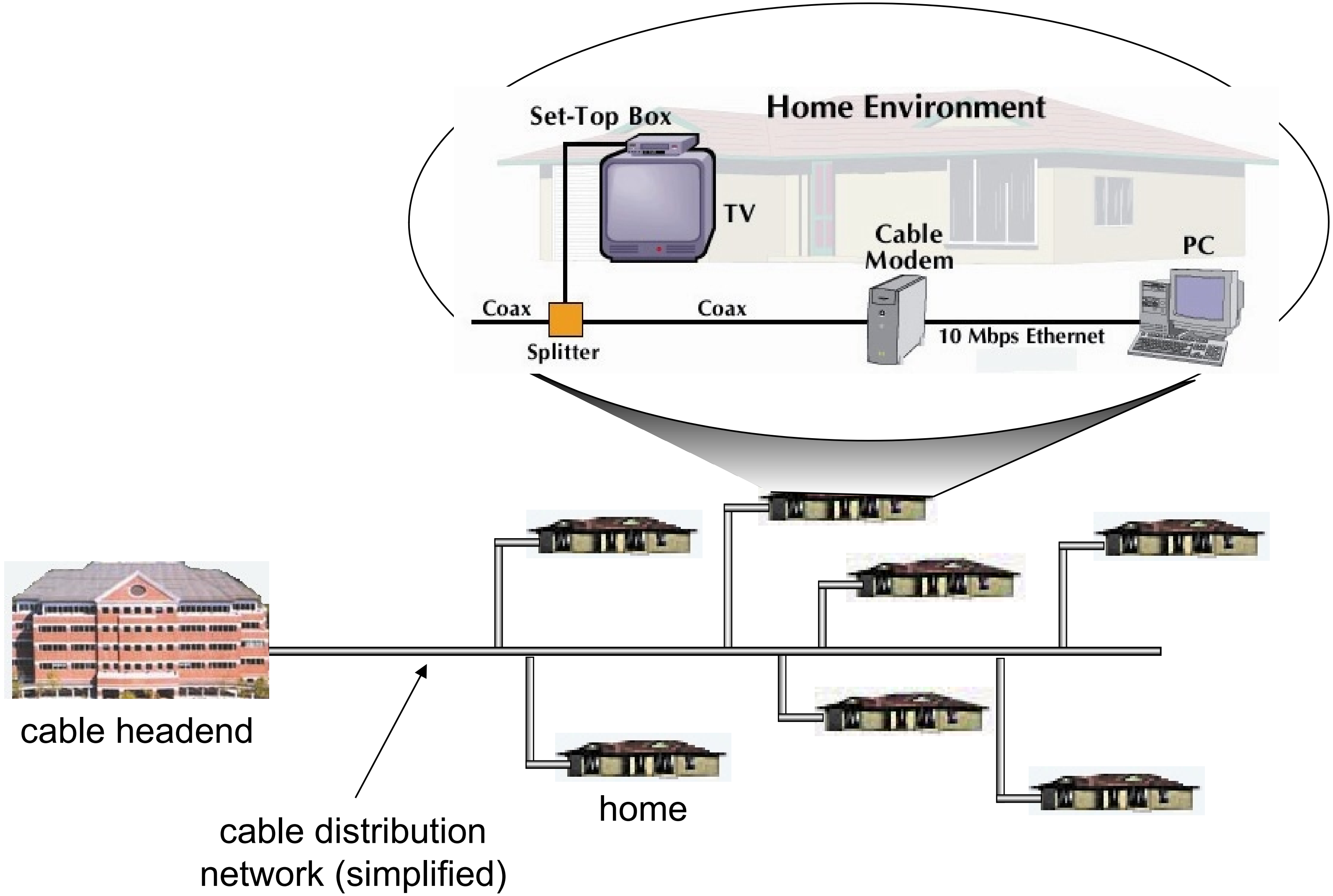
- Driven by networks already in place to the home
  - Most common
    - Cable TV lines
    - Phone lines
  - Less common
    - Satellite television
    - Power lines

Residential access: cable

- Originally one-way distribution

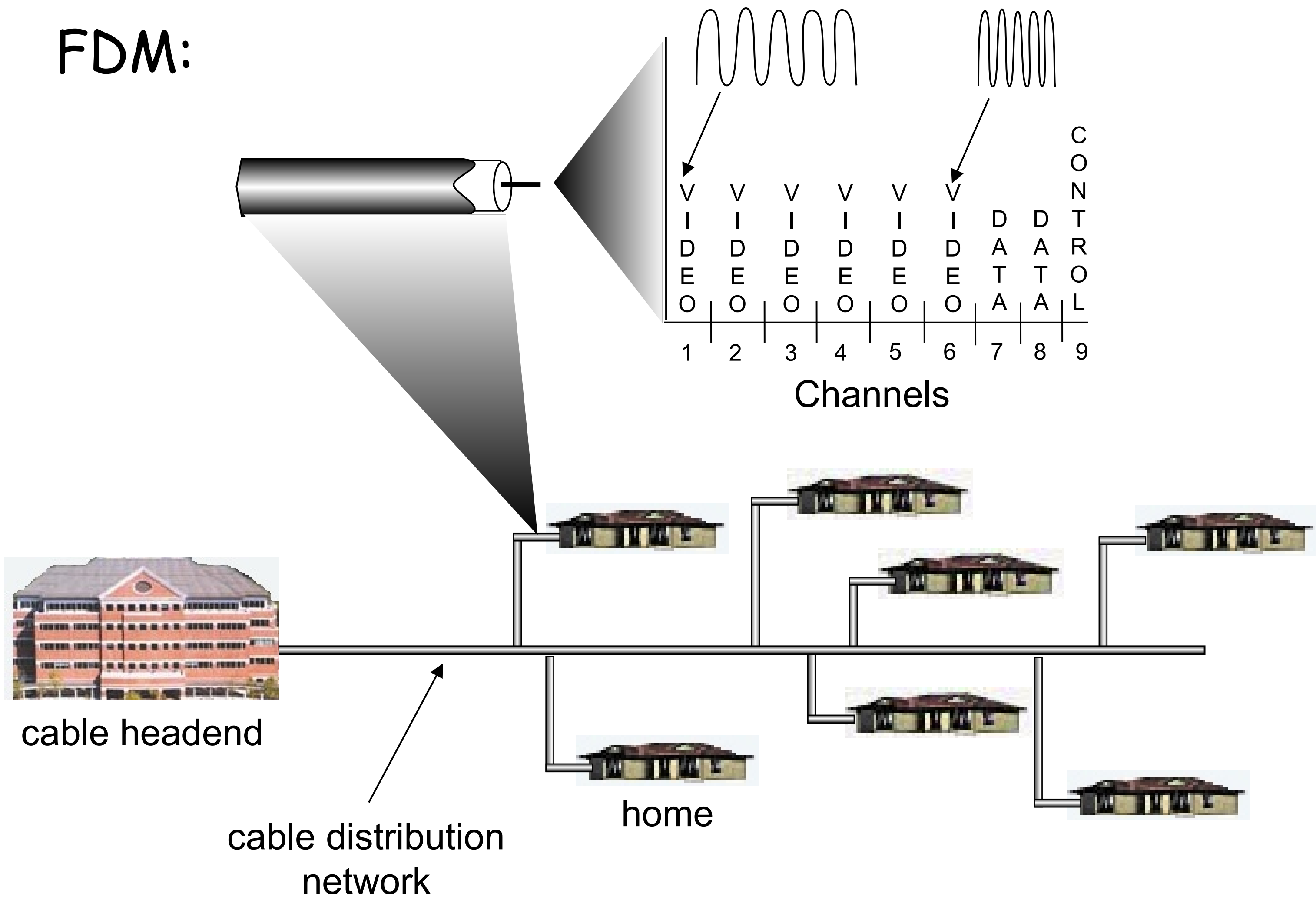


Residential access: cable



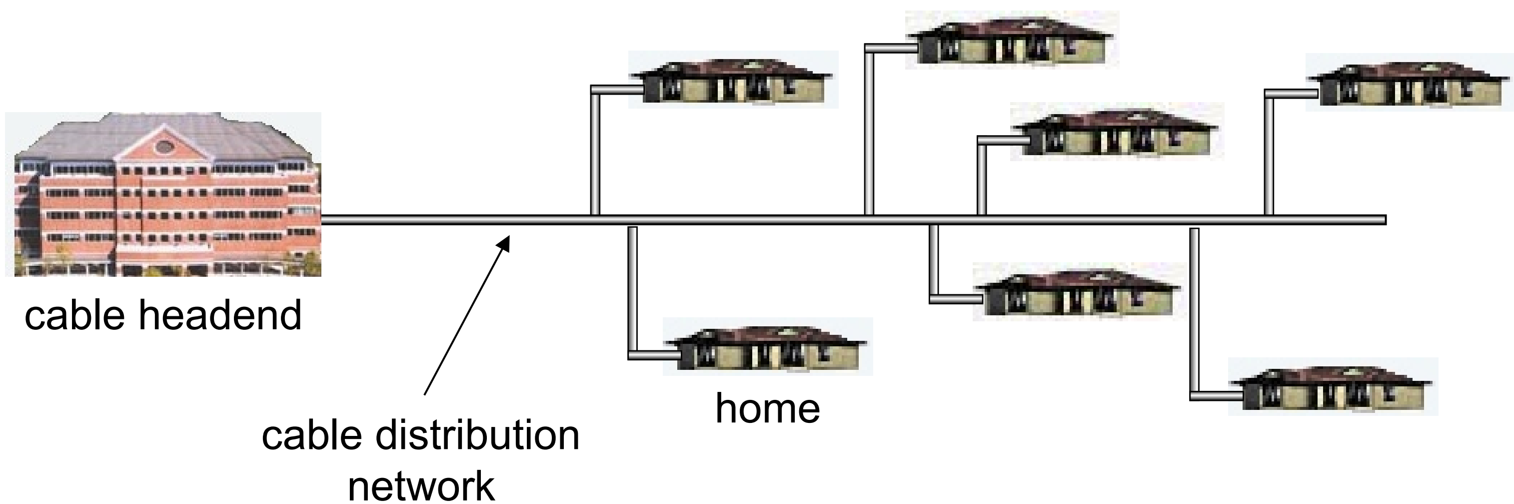
Residential access: cable

FDM:

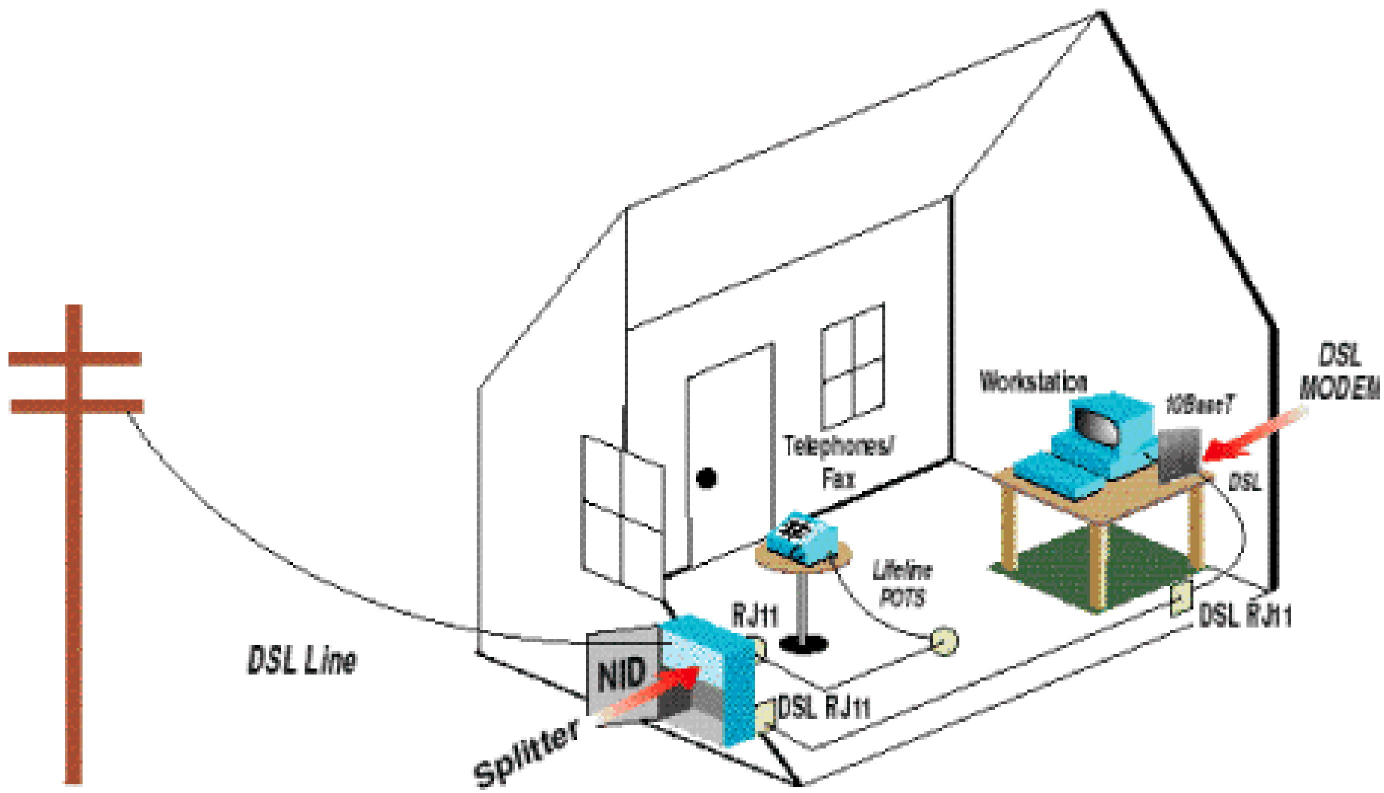


Residential access: cable

- Download faster than upload
  - Noise issues with one source vs. many



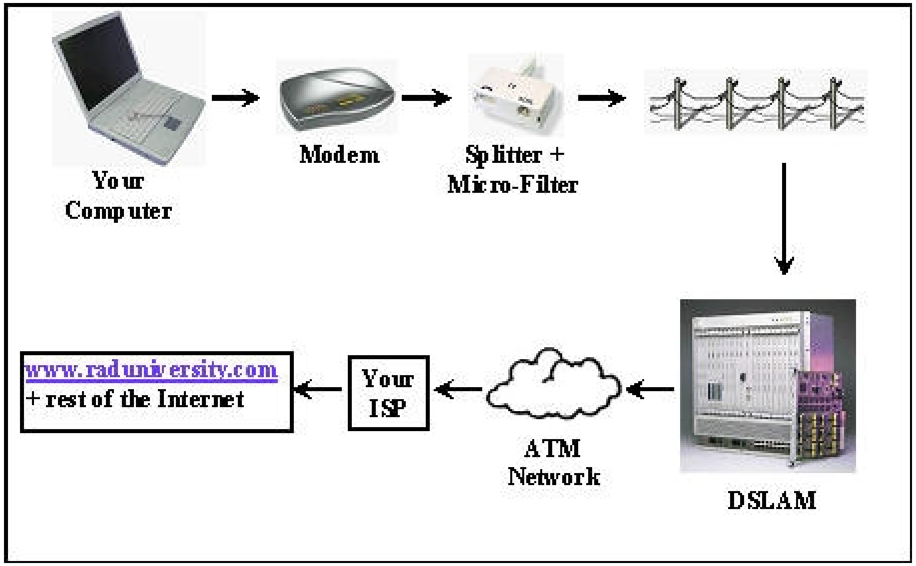
Residential access: DSL

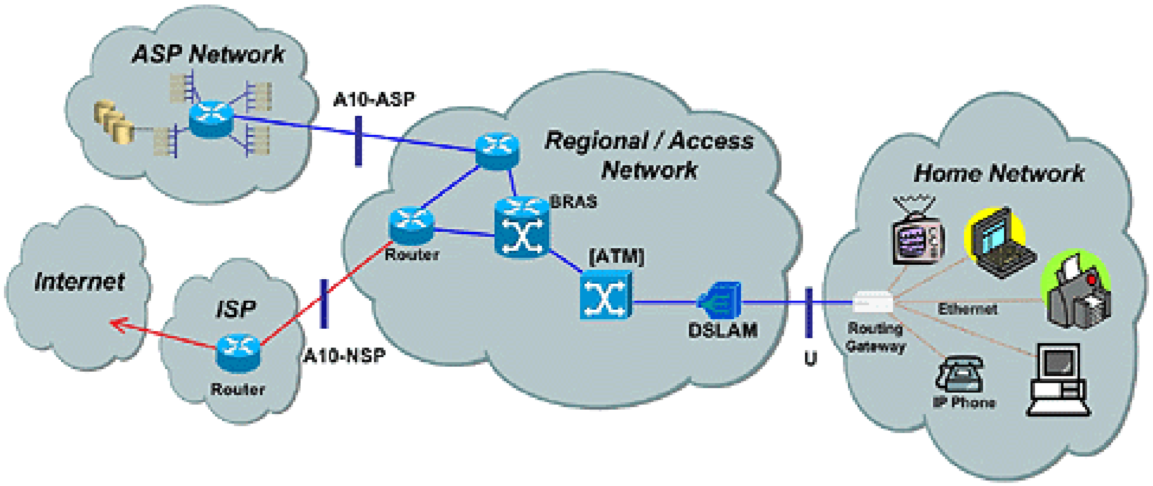


Residential access: DSL

- Uses high-frequency spectrum
  - Data superimposed onto voice using high-frequencies on existing telephone line
  - Voice transmitted in low-frequency spectrum
  - Transmissions may disrupt each other
    - Low-pass filters typically added to protect legacy devices and DSL modems from each other

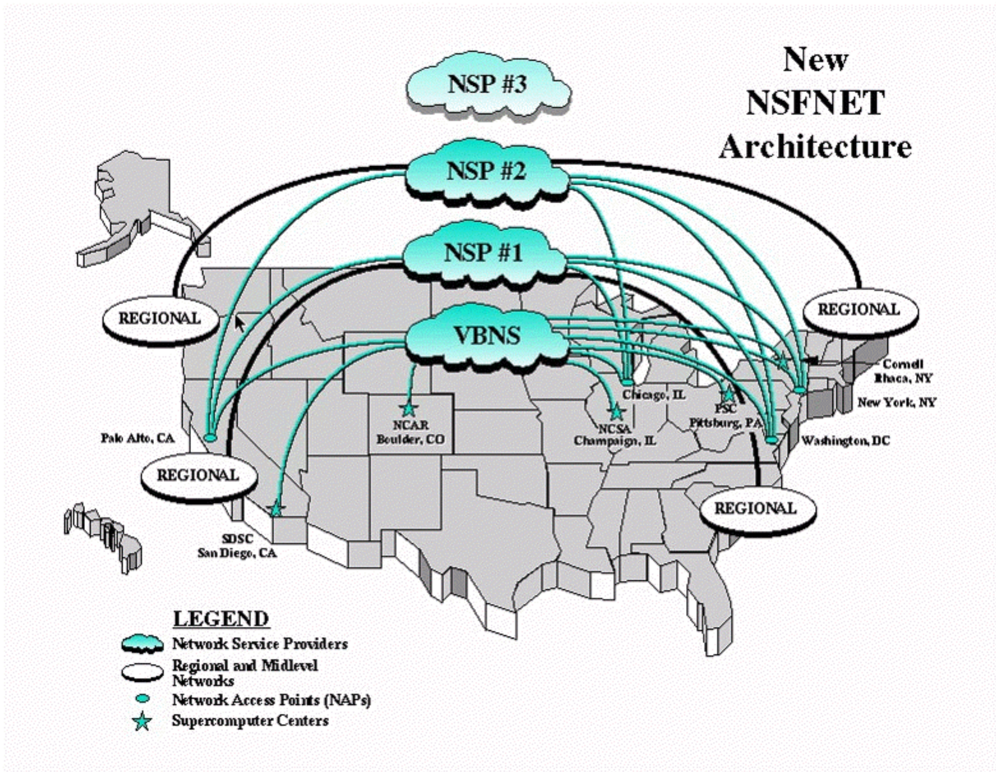
Residential access: DSL





Internet structure: network of networks

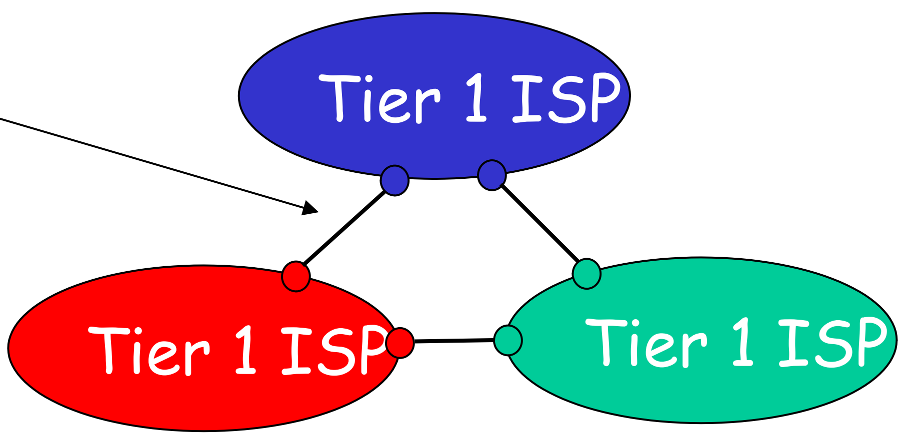
- Influenced by decommissioning of NSFNet
  - Academic network connecting NSF's supercomputing sites
  - NSF wanted out of the ISP business
  - Provided peering points for multiple competing commercial ISPs



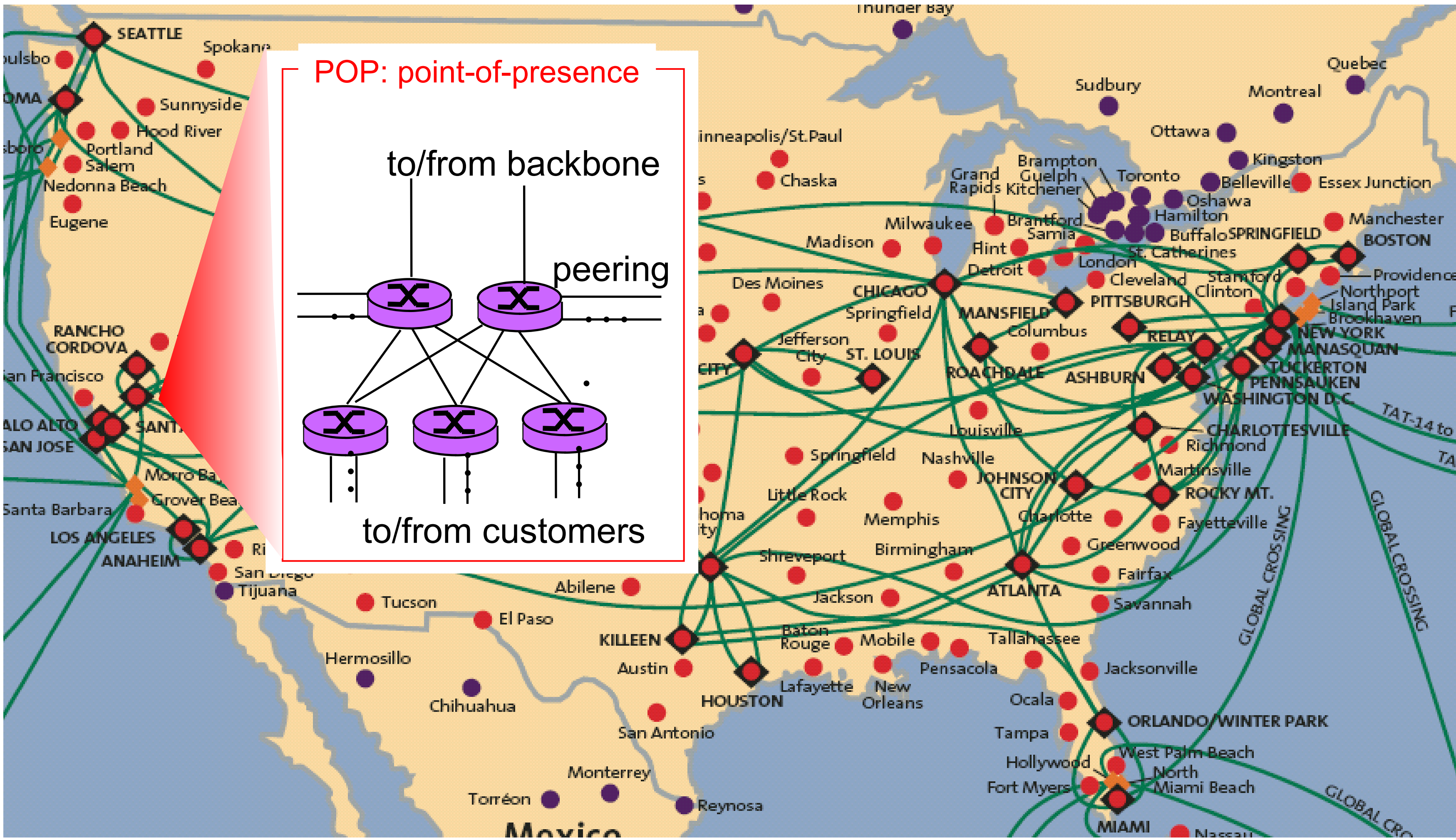
Internet structure: network of networks

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

Tier-1 providers interconnect (peer) privately



Tier-1 ISP: e.g., Sprint

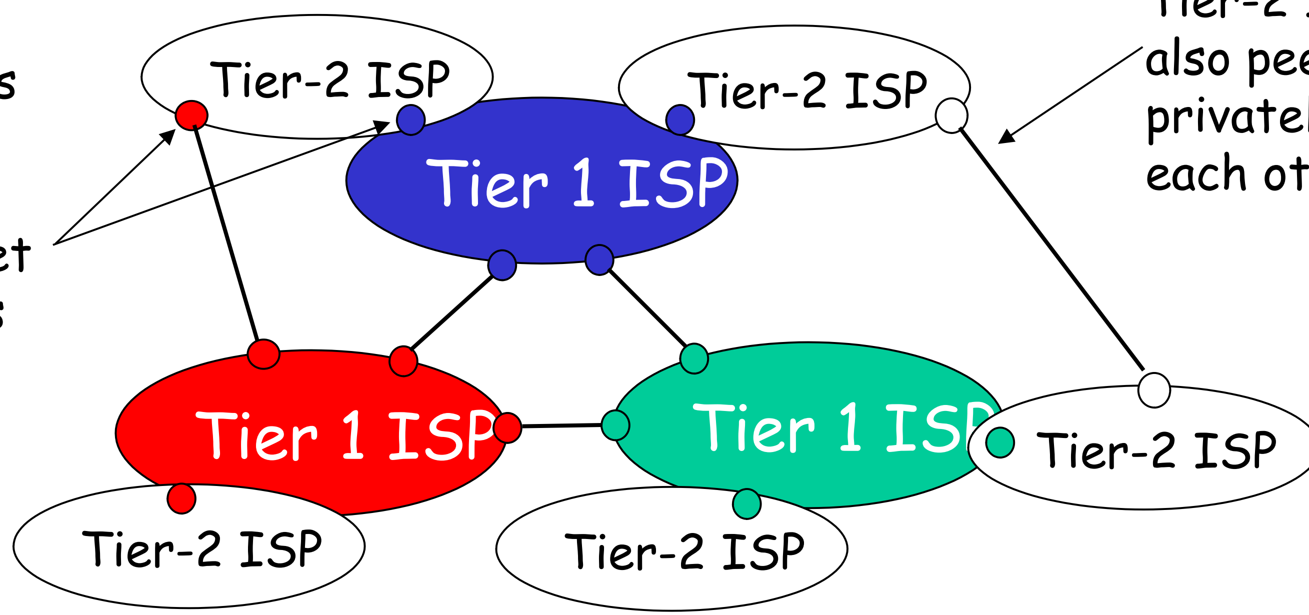


Internet structure: network of networks

- "Tier-2" ISPs: smaller (often regional) ISPs
  - Peers with some networks, but still purchases IP transit from tier-1 ISP to reach some portion of the Internet

Tier-2 ISP pays tier-1 ISP for connectivity to rest of Internet

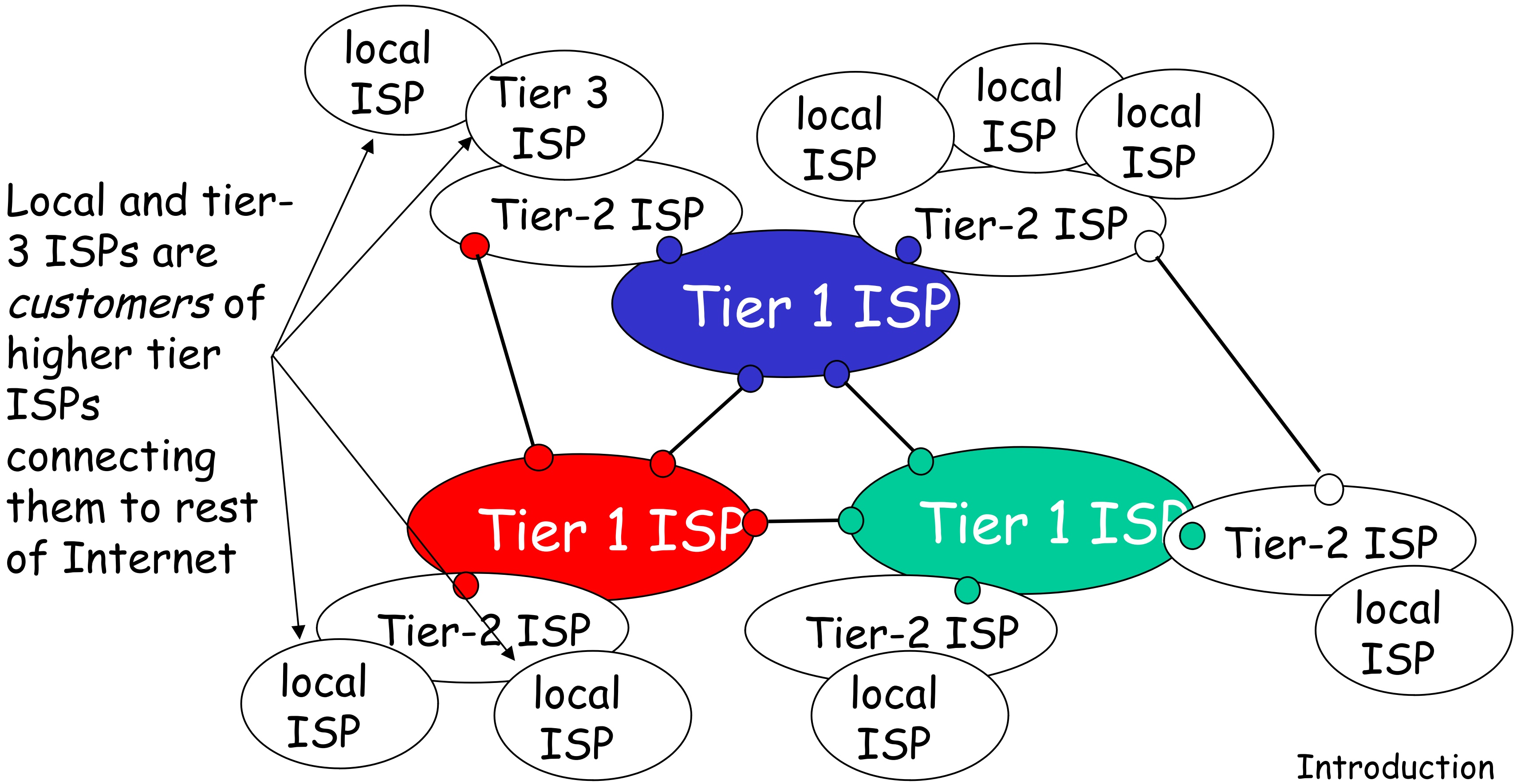
- tier-2 ISP is *customer* of tier-1 provider



Tier-2 ISPs also peer privately with each other.

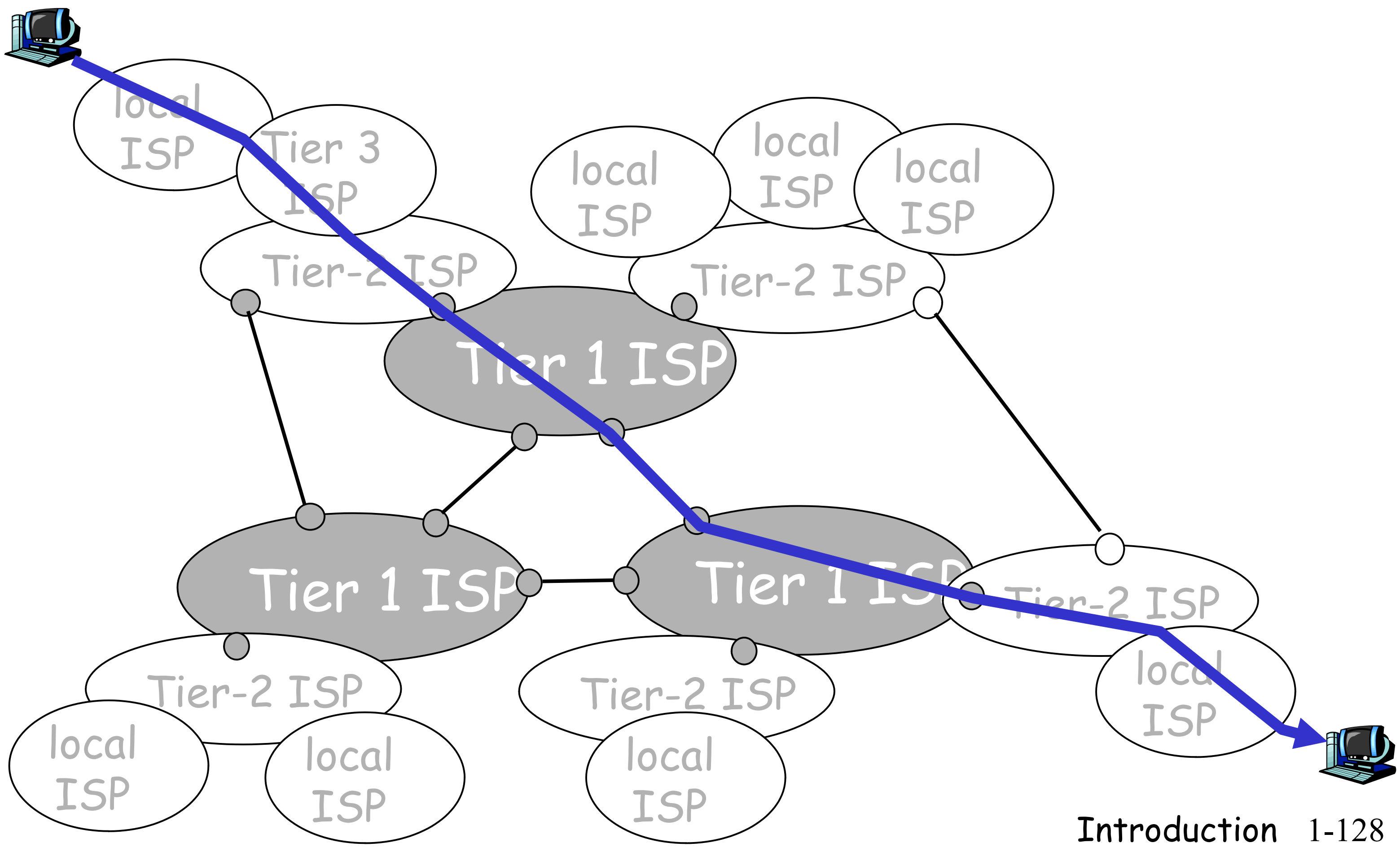
Internet structure: network of networks

- "Tier-3" ISPs and local ISPs
  - last hop ("access") network (closest to end systems)
  - solely purchases transit from other networks to reach Internet



Internet structure: network of networks

- a packet passes through many networks!



Introduction: Summary

Covered a "ton" of material!

- Internet overview
- what's a protocol?
- network edge, core, access network
  - packet-switching versus circuit-switching
- Internet/ISP structure
- performance: loss, delay
- layering and service models
- history

You now have:

- context, overview, "feel" of networking
- more depth, detail *to follow!*