A Taxonomy of Communication Networks

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http://zoo.cs.yale.edu/classes/cs433/

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Outline

- *Admin and recap*
- A taxonomy of communication networks

Admin

- Please check the Schedule page for links to related readings

Recap

- A protocol defines the format and the order of messages exchanged between two or more communicating entities, as well as the actions taken on the transmission or receipt of a message or other events.
- Key Internet milestones and their implications:
  - ARPANET is sponsored by ARPA →

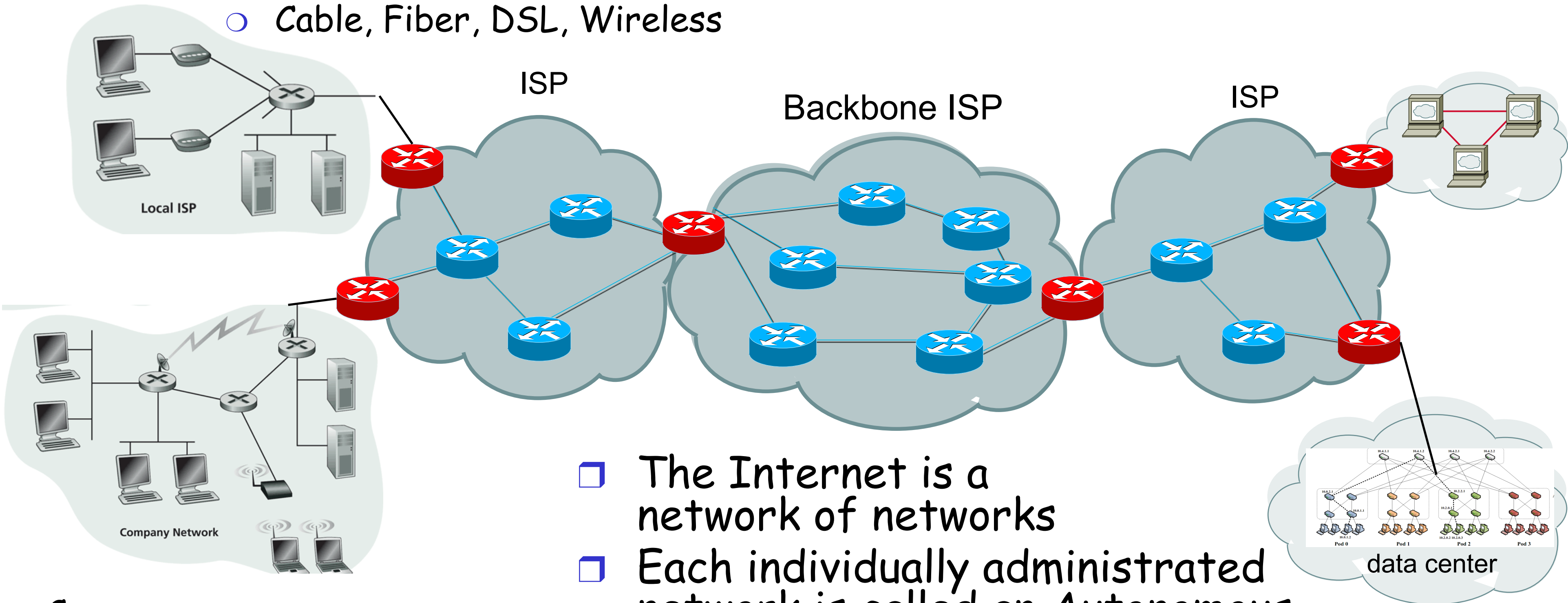
    design should survive failures
  - The initial IMPs (routers) were made by a small company → keep the network simple
  - Many networks →

    internetworking: need a network to connect networks
  - Commercialization →

    architecture supporting decentralized, autonomous systems

Recall: Internet Physical Infrastructure

Residential access, e.g.,
- Cable, Fiber, DSL, Wireless



Campus access, e.g.,
- Ethernet, Wireless

- The Internet is a network of networks
- Each individually administrated network is called an Autonomous System (AS)

  ~ 61,940 ASes; Avg 5.5 hops; (http://bgp.potaroo.net/as2.0/bgp-active.html)

Observing Internet Connectivity

- Read the manual of traceroute, and try it on a zoo machine

  % /usr/sbin/traceroute <machine_name>

  - look at the web sites of the routers you see through traceroute
  - look up info on autonomous networks (e.g., Yale) https://www.ultratools.com/tools/asnInfo

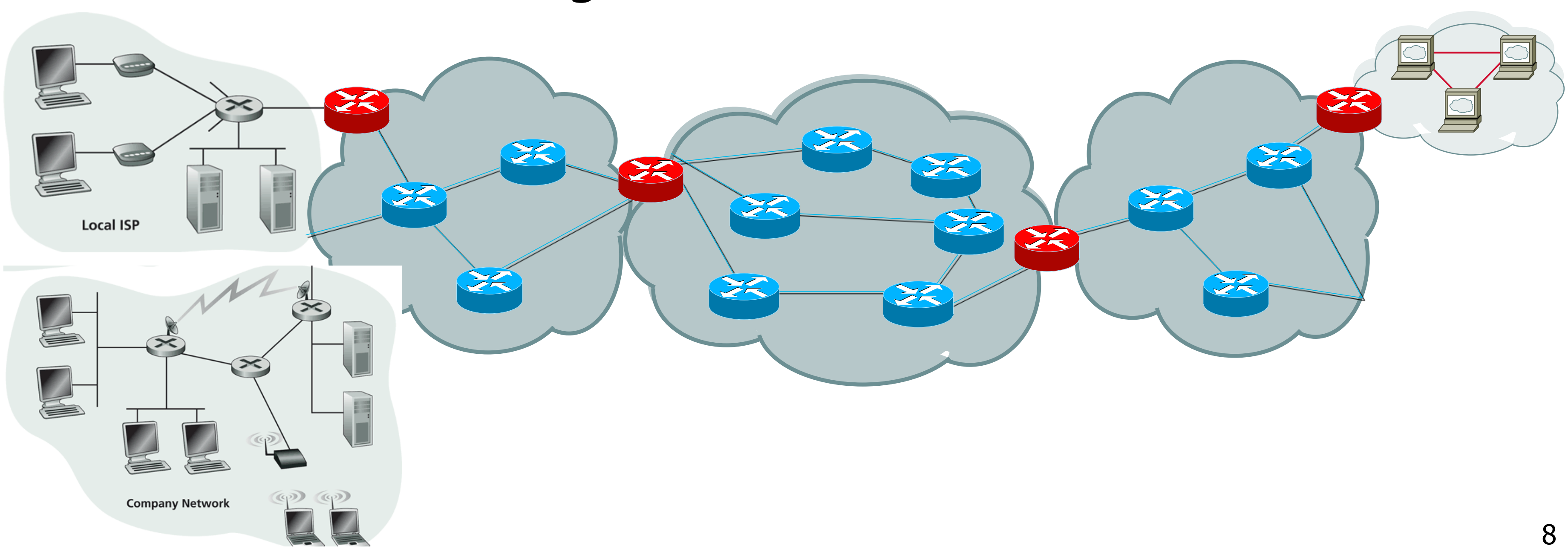
- Use routeviews to see connection info (e.g., neighbors) about a network, e.g.,
  - at a glance: https://stat.ripe.net/AS29#tabId=at-a-glance
  - routing: https://stat.ripe.net/AS29#tabId=routing

Recap: Complexity from Robustness

- Complexity in highly organized systems arises primarily from design strategies intended to create *robustness* to uncertainty in their environments and component parts.
  - Scalability
    - robustness to changes to the size and complexity of a system as a whole.
  - Evolvability
    - robustness of lineages to large changes on various (usually long) time scales.
  - Reliability
    - robustness to component failures.
  - Modularity
    - robustness to component rearrangements.
  - Asynchrony
    - robustness to uncertainty of performance.
  - Decentralization
    - robustness to single-point of failure.

Roadmap

- So far we have looked at only the topology and physical connectivity of the Internet: a mesh of computers interconnected via various physical media
- A basic question: how are data (the bits) transferred through communication networks?



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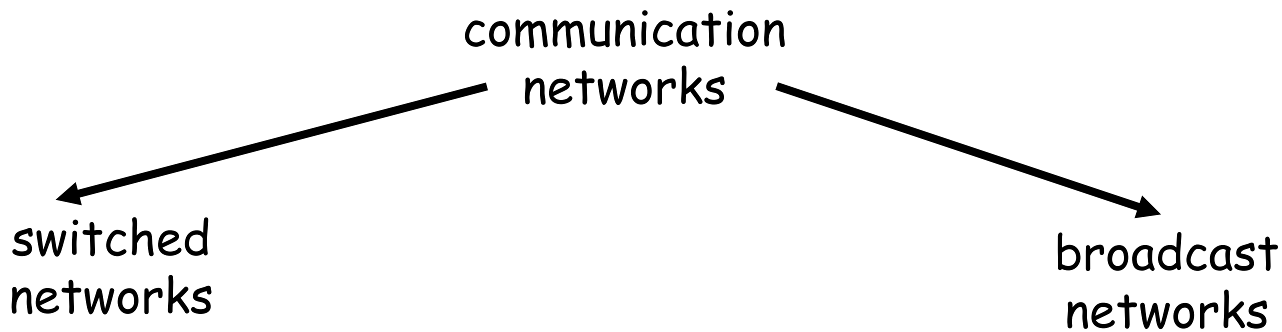
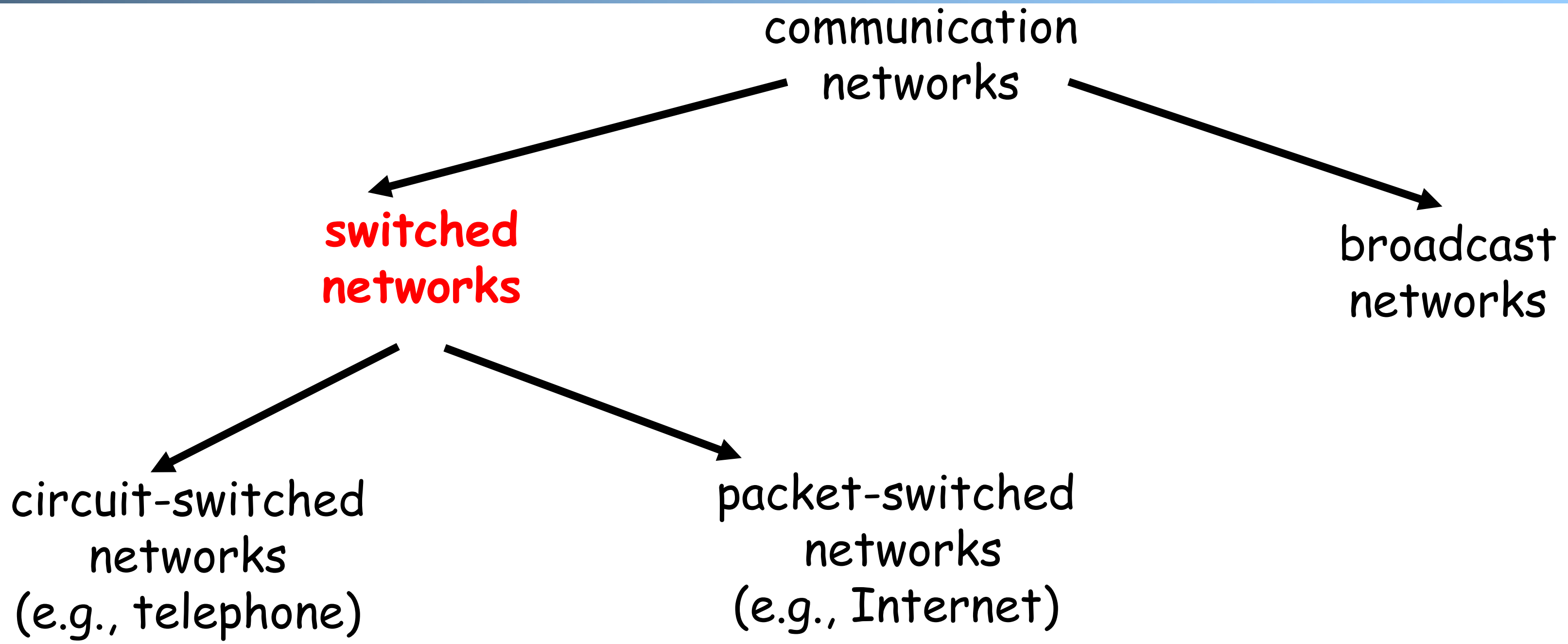
Taxonomy of Communication Networks



- Broadcast networks
  - nodes share a common channel; information transmitted by a node is received by all other nodes in the network
  - examples: TV, radio
- Switched networks
  - information is transmitted to a small sub-set (usually only one) of the nodes

A Taxonomy of Switched Networks



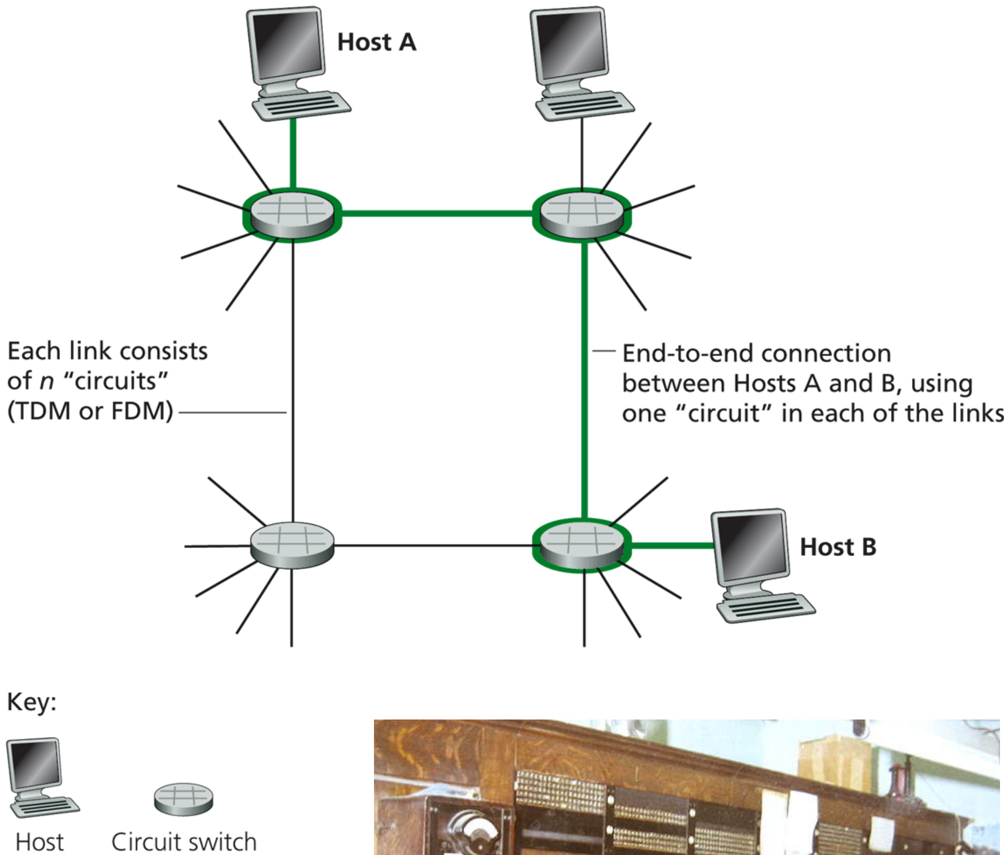
- Circuit switching: dedicated circuit per call/session:
  - e.g., telephone, cellular voice
- Packet switching: data sent thru network in discrete "chunks"
  - e.g., Internet, cellular data

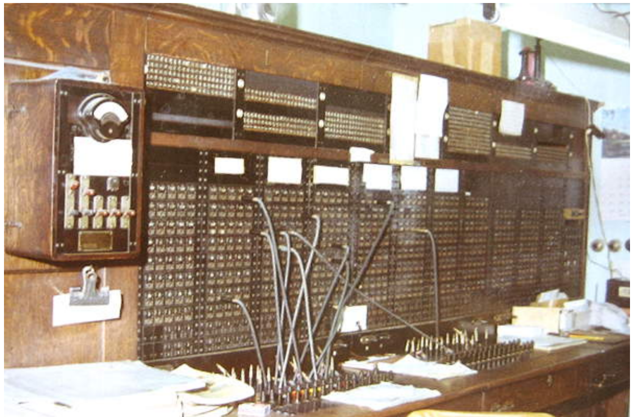
Outline

- Admin. and review
- *A taxonomy of communication networks*
  - *circuit switched networks*

Circuit Switching

- Each link has a number of "circuits"
  - sometime we refer to a "circuit" as a channel or a line
- An end-to-end connection reserves one "circuit" at each link

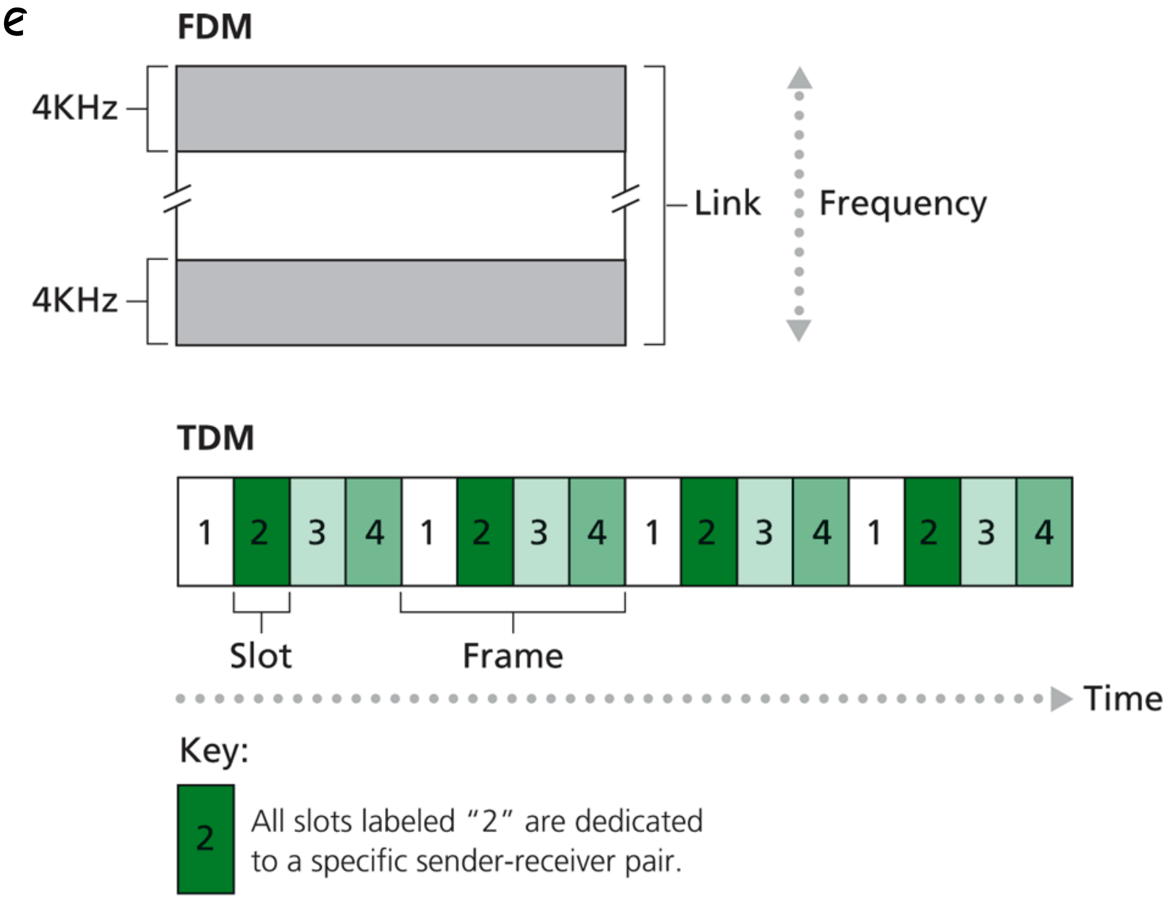




First commercial telephone switchboard was opened in 1878 to serve the 21 telephone customers in New Haven

Circuit Switching: Resources/Circuits (Frequency, Time and others)

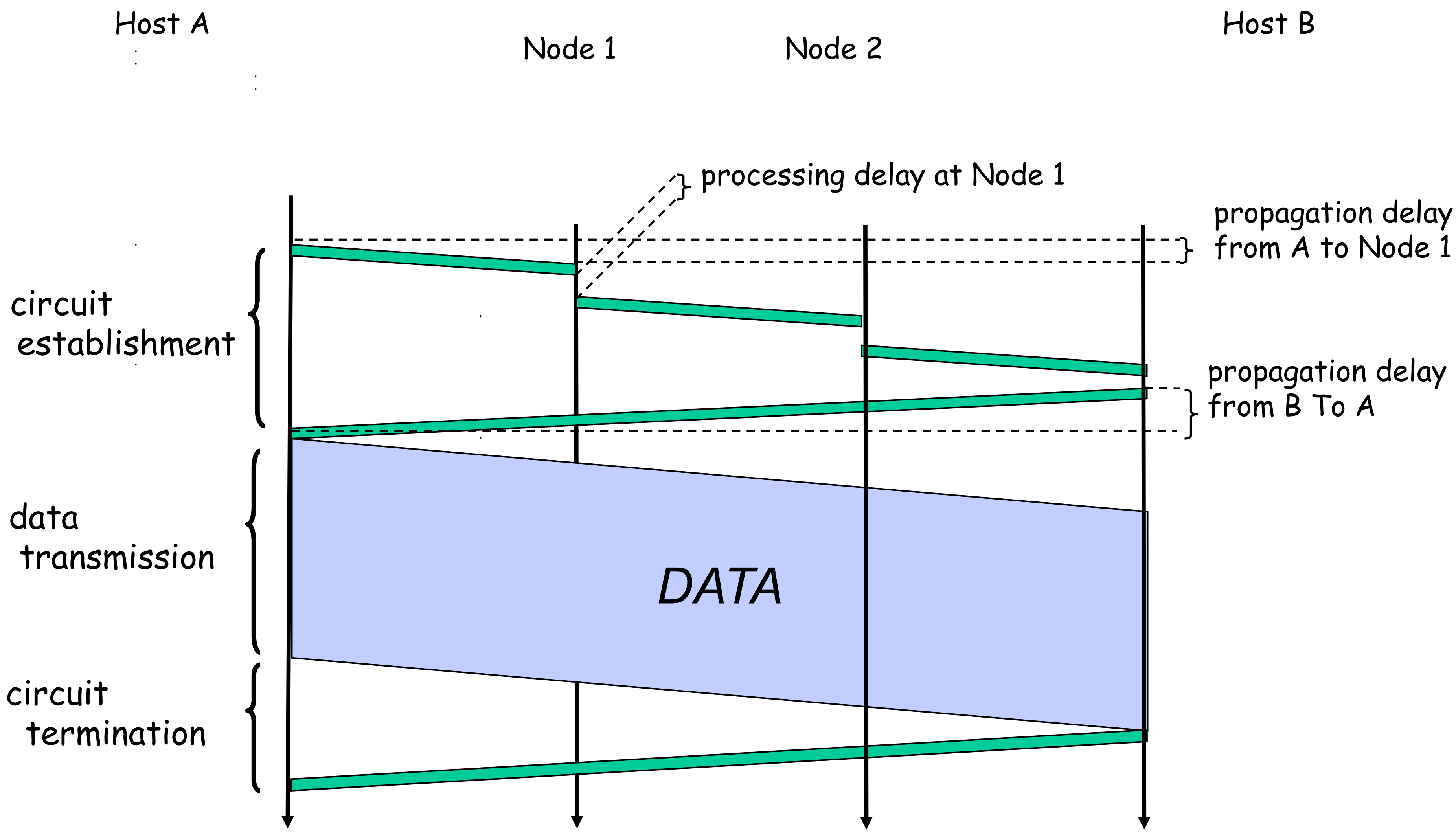
- Divide link resource into "circuits"
  - frequency division multiplexing (FDM)
  - time division multiplexing (TDM)
  - others such as code division multiplexing (CDM), color/lambda division



Circuit Switching: The Process

- Three phases
  1. circuit establishment
  2. data transfer
  3. circuit termination

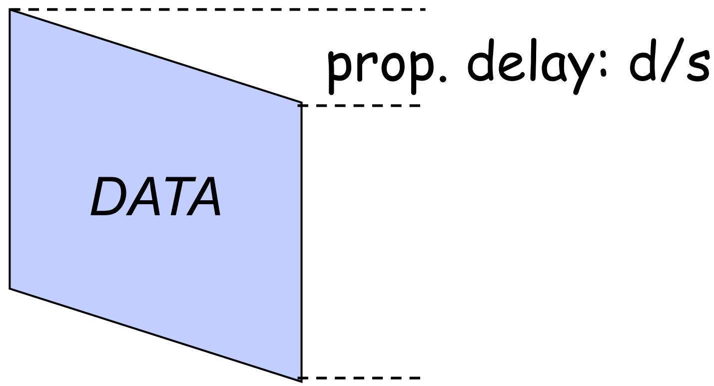
Timing Diagram of Circuit Switching



Delay Calculation in Circuit Switched Networks

- Propagation delay: delay for the first bit to go from a source to a destination

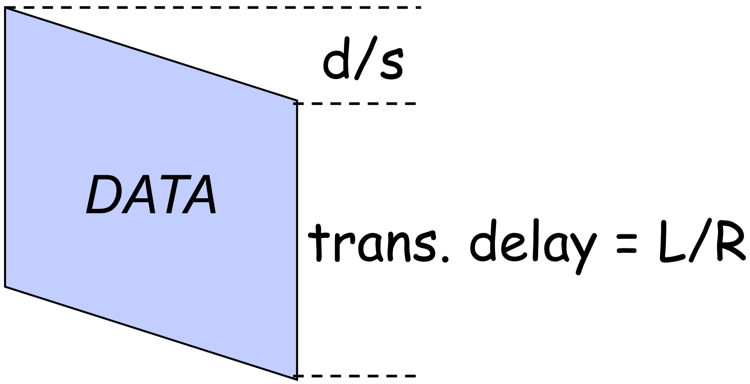
Propagation delay:
- d = length of physical link
- s = propagation speed in medium (~$2\text{x}10^5$ km/sec)



Delay Calculation in Circuit Switched Networks

- Transmission delay: time to pump data onto link at *line* rate

Transmission delay:
- R = reserved bandwidth (bps)
- L = message length (bits)



An Example

- Propagation delay
  - suppose the distance between A and B is 4000 km, then one-way propagation delay is:

$$\frac{4000\,km}{200{,}000\,km/s} = 20ms$$

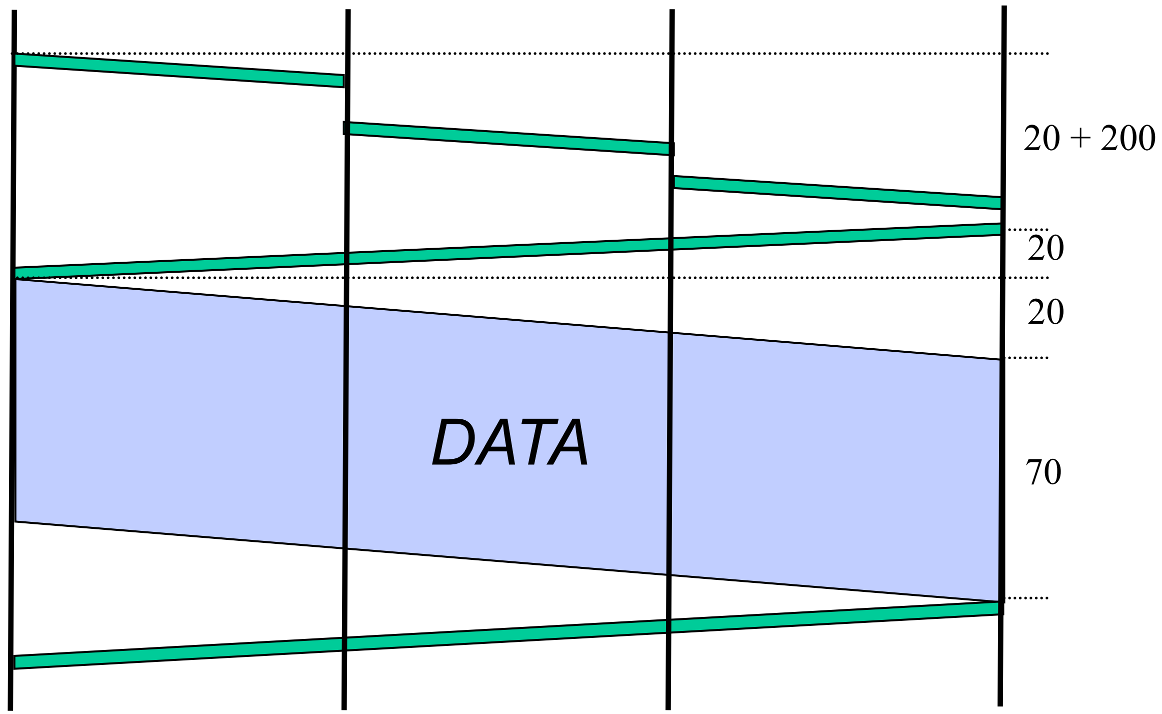
- Transmission delay
  - suppose your iphone reserves a one-slot HSCSD channel
    - each HSCSD frame can transmit about 115 kbps
    - a frame is divided into 8 slots
  - then the transmission delay of using one reserved slot for a message of 1 Kbits:

$$\frac{1kbits}{14kbps} \approx 70ms$$

An Example (cont.)

- Suppose the setup message is very small, and the total setup processing delay is 200 ms
- Then the delay to transfer a message of 1 Kbits from A to B (from the beginning until host receives last bit) is:

$$20 + 200 + 20 + 20 + 70 = 330ms$$



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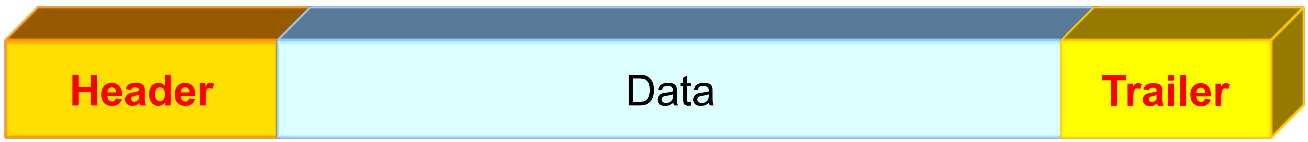
  - circuit switched networks
  - *packet switched networks*

Packet Switching

Each end-to-end data **flow** (i.e., a sender-receiver pair) divided into ***packets***

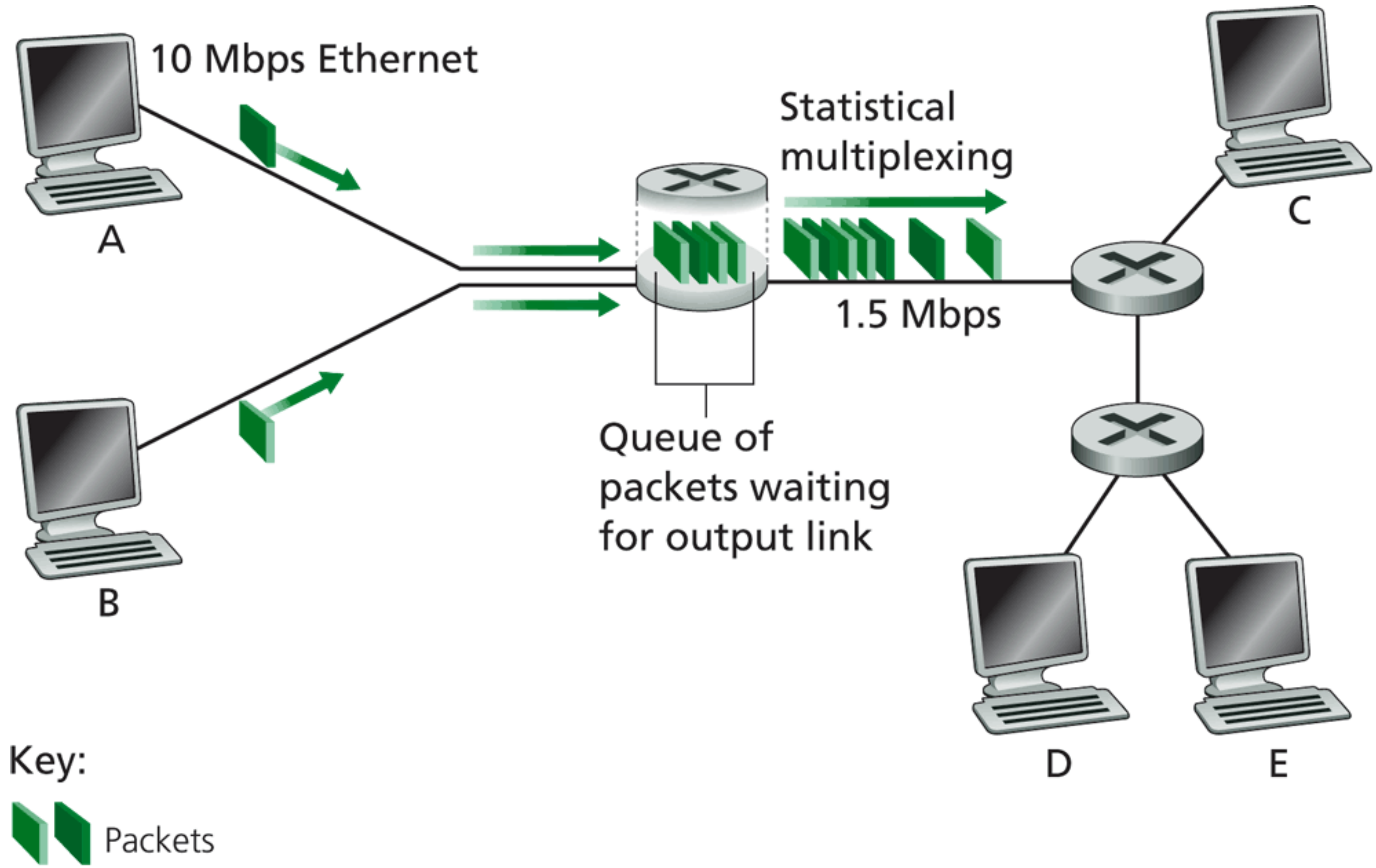
- Packets have the following structure:



  - header and trailer carry control information (e.g., destination address, check sum)
  - where is the control information for circuit switching?

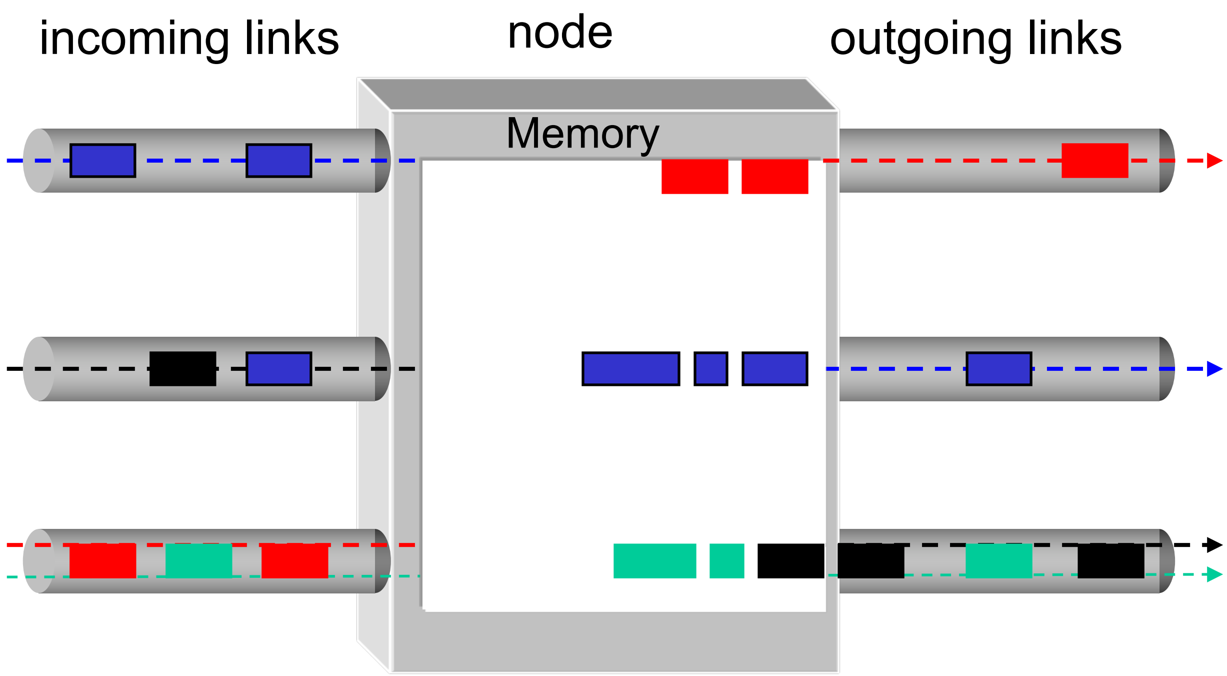
- At each node the entire packet is received, processed (e.g., routing), stored briefly, and then forwarded to the next node; thus packet-switched networks are also called **store-and-forward networks.** On its turn, a packet uses full link bandwidth

Packet Switching



Inside a Packet Switching Router

An output queueing switch



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  - packet switched networks
  - *circuit switching vs. packet switching*

Packet Switching vs. Circuit Switching

- The early history of the Internet was a heated debate between Packet Switching and Circuit Switching
  - the telephone network was the dominant network

- Need to compare packet switching with circuit switching

Circuit Switching vs. Packet Switching

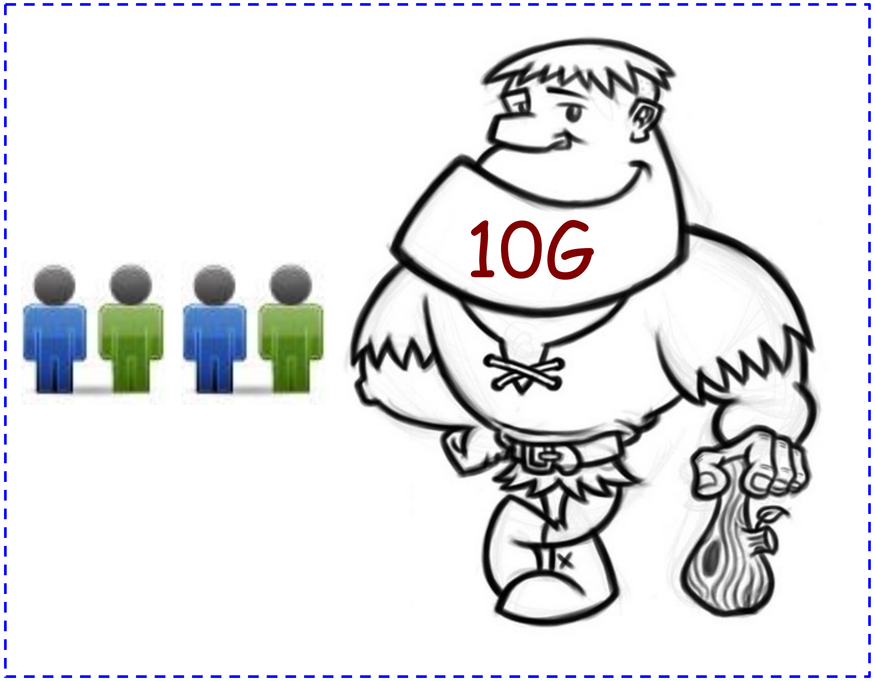
	circuit switching	packet switching
resource usage		
reservation/setup		
resource contention effect		
charging		
header		
fast path processing		

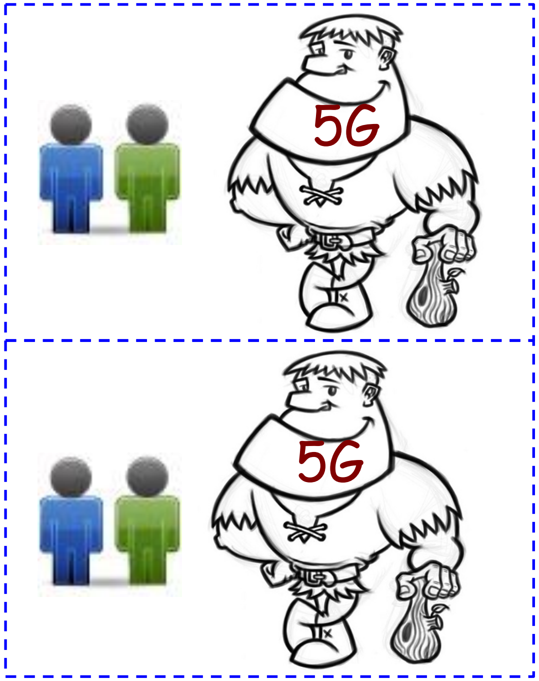
Circuit Switching vs. Packet Switching

	circuit switching	packet switching
resource usage	use a single partition bandwidth	use whole link bandwidth
reservation/setup	need reservation (setup delay)	no reservation
resource contention	busy signal (session loss)	congestion (long delay and packet losses)
charging	time	packet
header	no per-pkt header	per packet header
fast path processing	fast	per packet processing

Key Issue to be Settled

- A key issue: what is the efficiency of resource partition?





- Tool used to analyze the issue: queueing theory
  - Some fundamental insight, techniques, and results in queueing theory can be quite useful in understanding systems.

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  - packet switched networks
  - circuit switching vs. packet switching
  - *M/M queues and statistical multiplexing*

Queueing Theory

- Strategy:
  - model system state
    - if we know the fraction of time that a system spends at each state, we can get answers to many basic questions about the system: how long does a new request need to wait before being served?
- System state changes upon events:
  - introduce state transition diagram
  - focus on equilibrium: state trend neither growing nor shrinking (key issue: how to define equilibrium)

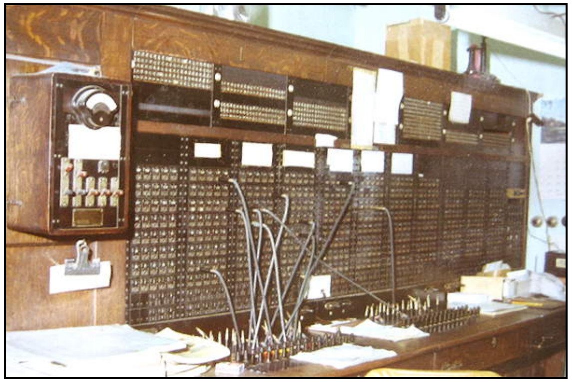
- Our approach: We are not interested in mathematical-oriented derivation; rather, we use analytical techniques providing intuition

Warm up: Analysis of Circuit-Switching Blocking (Busy) Time

- Assume a link has only a finite number of N circuits

- Objective: compute the percentage of time that a new session (call) is blocked

- Analogy in a more daily-life scenario?
- Key parameters?



Analysis of Circuit-Switching Blocking (Busy) Time

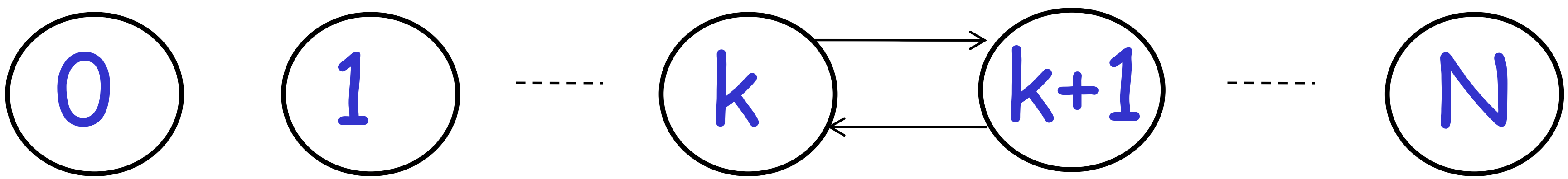
- Key parameters
  - client requests arrive at a rate of λ (lambda/second)
  - service rate: each call takes on average $1/\mu$ second

- Single arrival and service pattern: memoryless (Markovian)
  - During a small interval Δt, the number of expected new arrivals is: $\lambda \Delta t$
  - During a small interval Δt, the chance (fraction) of a current call finishes is: $\mu \Delta t$

- This model is also called an M/M/N model

Analysis of Circuit-Switching Blocking (Busy) Time: State

system state: # of busy lines



Goal: computes fraction of time at each state k in 0 to N

p_0 p_1 p_k p_{k+1} p_N

A Pure Math-Oriented Approach

- Write down differential equation

Assume stationary $p_{i,j}(t) = p(X(s+t) = j) \mid p(X(s) = i \}$

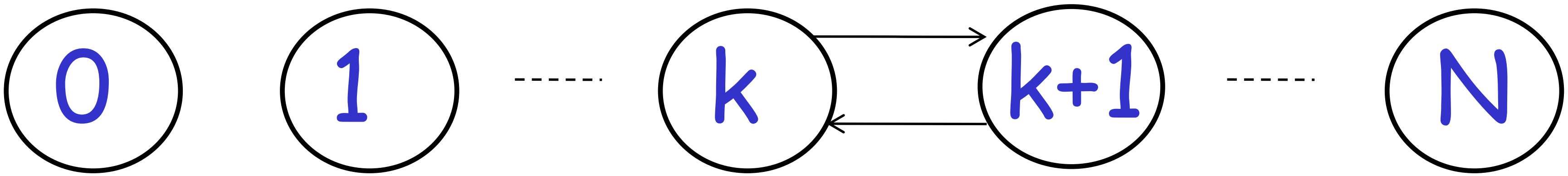
Consider as birth and death process

$$p_{k,k+1}(t) = \lambda_k t,\ t \to 0$$
$$p_{k+1,k}(t) = \mu_{k+1} t,\ t \to 0$$
$$p_{k,k}(t) = 1-(\lambda_k + \mu_{k+1})t,\ t \to 0$$

Solve the equations to obtain solution.

Analysis of Circuit-Switching Blocking (Busy) Time: State

system state: # of busy lines



Goal: computes fraction of time at each state k in 0 to N

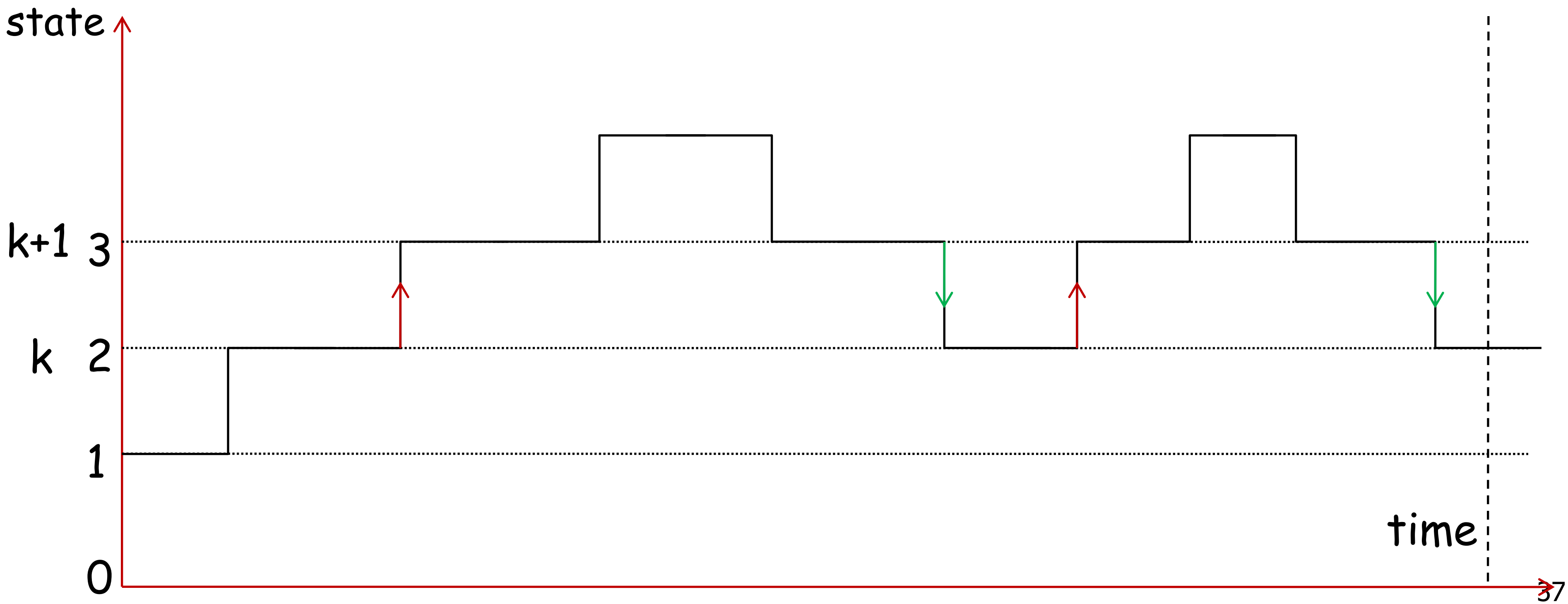
p_0 p_1 p_k p_{k+1} p_N

Approach: Compute $\{p_k\}$ at equilibrium, by characterizing equilibrium using relationship among $\{p_k\}$.

Equilibrium = Time Reversibility [Frank Kelly]

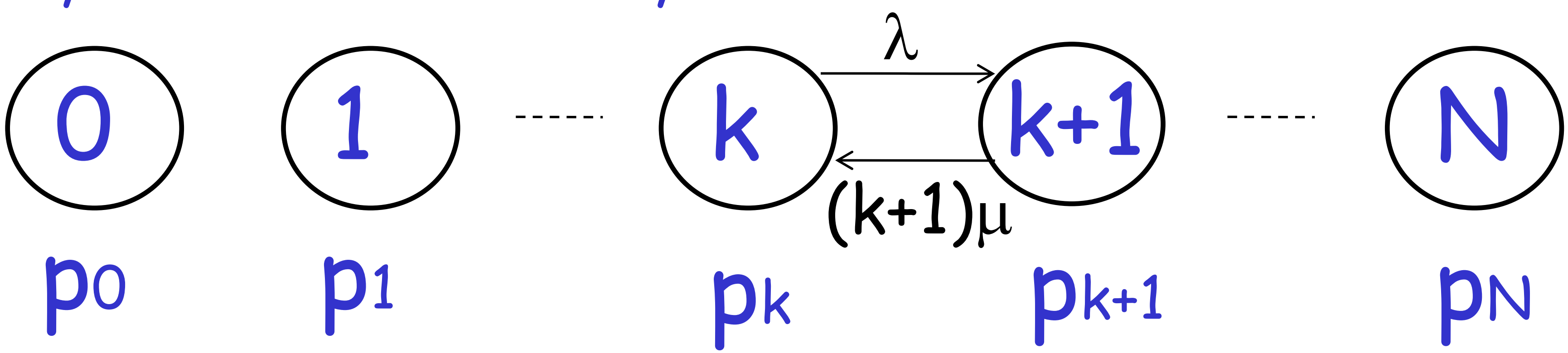
- Statistically cannot distinguish forward play vs backward play
- For example, pick statistics: the numbers of transitions between neighboring states in unit time, e.g., for each k

$$\boxed{\# f_{k\to k+1},\quad \# f_{k+1\to k}} = \boxed{\# b_{k\to k+1},\quad \# b_{k+1\to k}}$$



Analysis of Circuit-Switching Blocking (Busy) Time: Sketch

system state: # of busy lines



at equilibrium (time resersibility) in one unit time:

#(transitions k → k+1) = #(transitions k+1 → k)

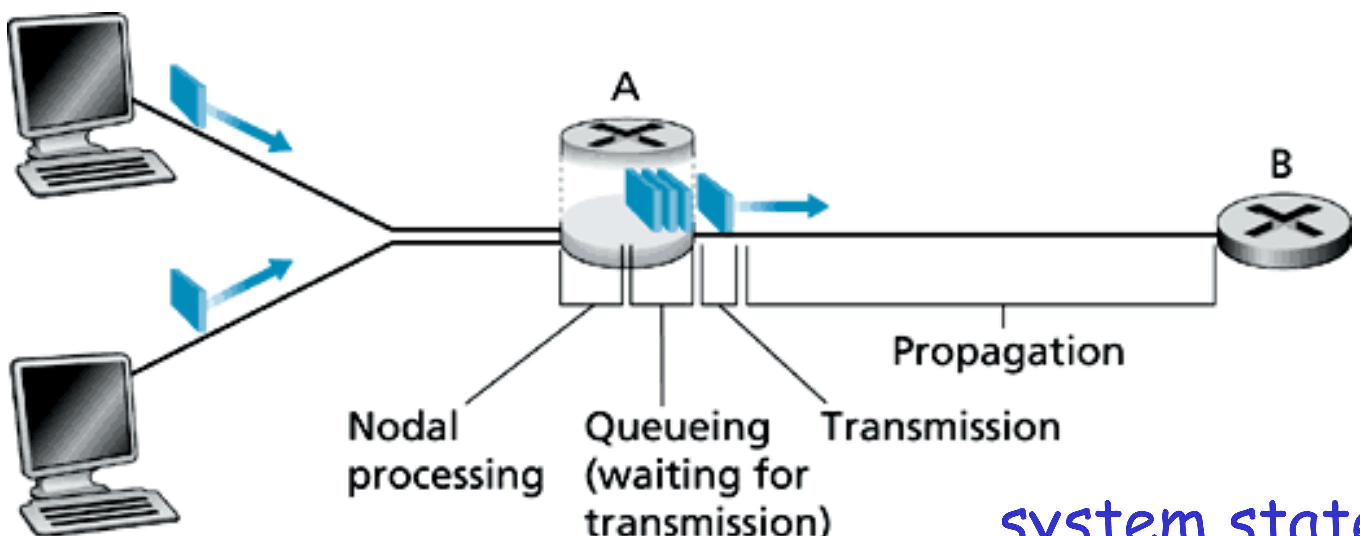
$$\boxed{p_k \lambda = p_{k+1}(k+1)\mu}$$

$$\boxed{p_{k+1} = \frac{1}{k+1}\frac{\lambda}{\mu} p_k = \frac{1}{(k+1)!}\left(\frac{\lambda}{\mu}\right)^{k+1} p_0}$$

$$\boxed{p_0 = \frac{1}{1 + \frac{1}{1!}\frac{\lambda}{\mu} + \frac{1}{2!}\left(\frac{\lambda}{\mu}\right)^2 + \ldots + \frac{1}{N!}\left(\frac{\lambda}{\mu}\right)^N}}$$

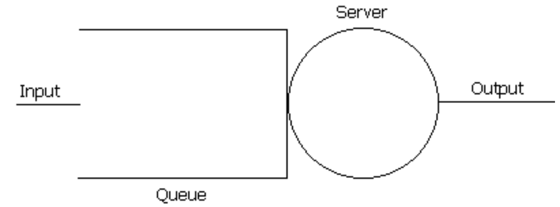
Queueing Analysis: Packet Switching Delay

- Four types of delay at each hop
  - nodal processing delay: check errors & routing
  - queueing: time waiting for its turn at output link
  - transmission delay: time to pump packet onto a link at link speed
  - propagation delay: router to router propagation
- The focus is on queueing and transmission delay

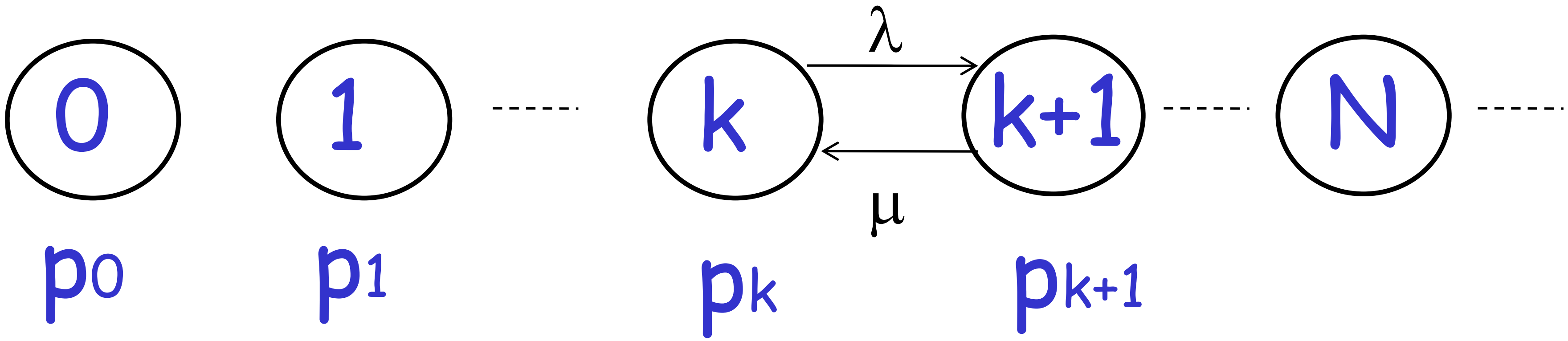


system state?

Packet Switching Delay



system state: #packets in queue



at equilibrium (time reversibility) in one unit time:

#(transitions k → k+1) = #(transitions k+1 → k)

$$\boxed{p_k \lambda = p_{k+1} \mu}$$

$$\boxed{p_{k+1} = \tfrac{\lambda}{\mu} p_k = \left(\tfrac{\lambda}{\mu}\right)^{k+1} p_0 = \rho^{k+1} p_0}$$

$$\boxed{p_0 = 1 - \rho}$$

$$\boxed{\rho = \tfrac{\lambda}{\mu}}$$

Example

- Assume requests (packets) come in at a rate of one request per 50 ms
- Each request (packet) takes on average 20 ms

- What is the fraction of time that the system is empty?
- What is the chance that a packet newly arrived needs to wait for 3 early packets?