A Taxonomy of Communication Networks; Statistical Multiplexing

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https://qiaoxiang.me/courses/cnns-xmuf22/index.shtml

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This deck of slides are heavily based on CPSC 433/533 at Yale University, by courtesy of Dr. Y. Richard Yang.

Outline

- Admin. and recap
- A taxonomy of communication networks
- Layered network architecture

Admin.

- Readings from the textbook and additional suggested readings
  - All are highly recommended
  - Some are marked as required

- Assignment one to be linked on the schedule page
  - Due on Sep. 29, in class or by email to the instructor

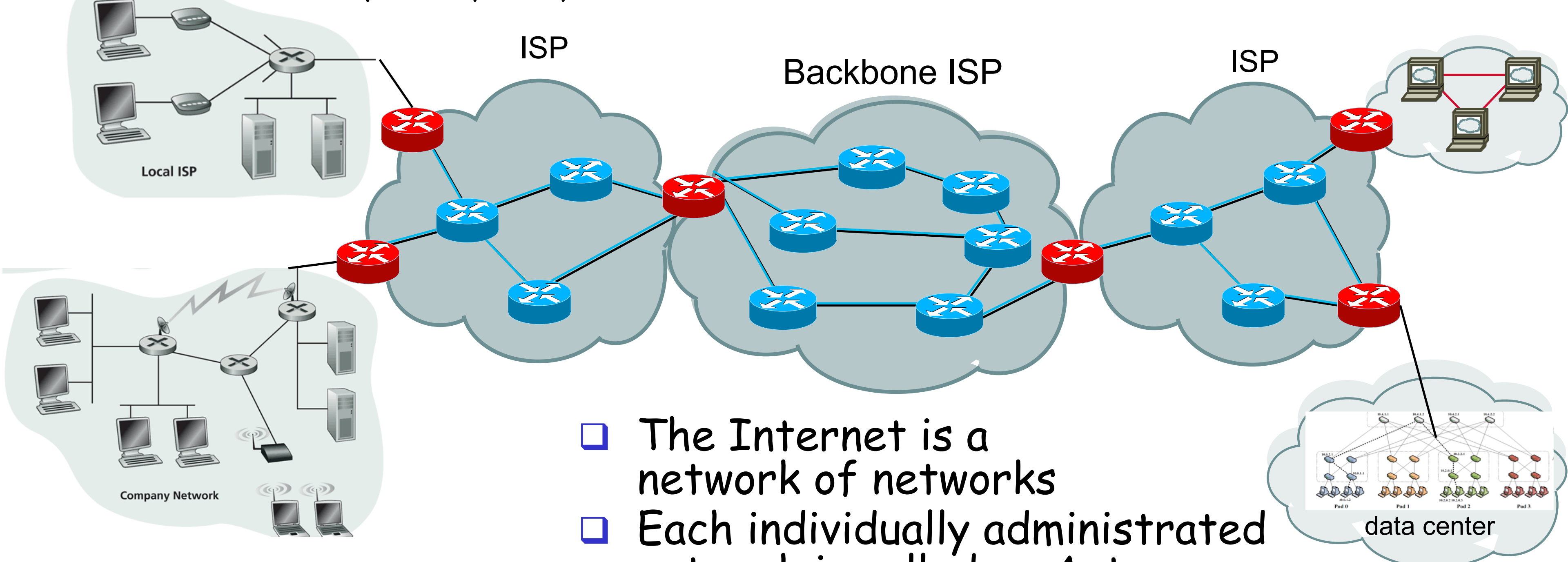
Recap

- 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)

  ~ 58000 ASes; Avg 5.7 hops; (http://bgp.potaroo.net/as2.0/bgp-active.html)

Recap: Challenges - Scale

"Developers who have worked at the small scale might be asking themselves why we need to bother when we could just use some kind of out-of the-box solution. For small-scale applications, this can be a great idea. We save time and money up front and get a working and serviceable application. The problem comes at larger scales—there are no off-the-shelf kits that will allow you to build something like Amazon... There's a good reason why the largest applications on the Internet are all bespoke creations: no other approach can create massively scalable applications within a reasonable budget."

http://www.evontech.com/symbian/55.html

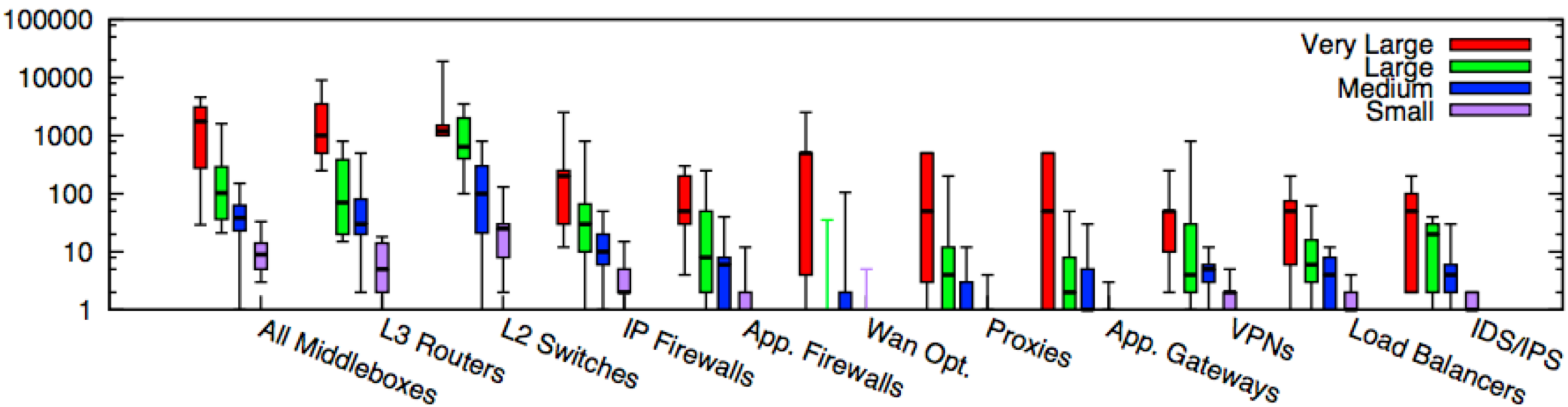
Recap: Challenges - General Complexity

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

Core: Simple Forwarding to Network Functions

- Modern networks contain diverse types of equipment beyond simple routing/forwarding

Enterprise networks



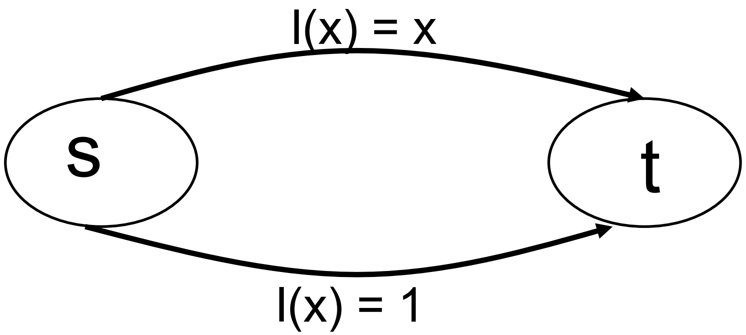
Small: <=1k hosts; Medium: 1k-10k; Large: 10k-100k; Very Large: >= 100k

Source: [Sherry, et. al SIGCOMM'12]

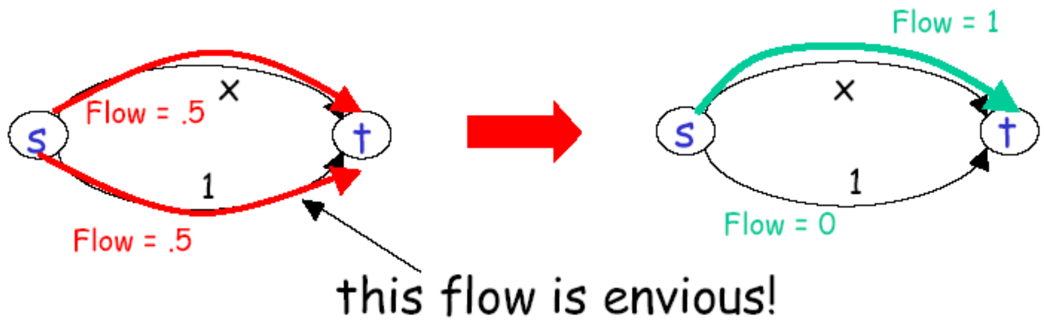
Centralized vs Decentralized (Price of Anarchy)

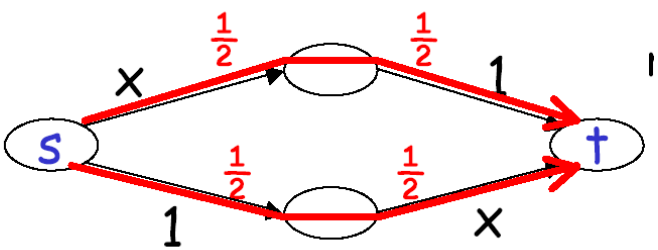
- Autonomous ("Selfish") App: Assume each link has a latency function $l_e(x)$: latency of link e when x amount of traffic goes through e:

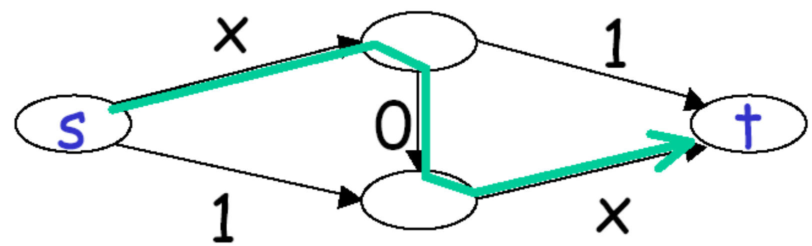
total traffic



Autonomous ("Selfish") App







Braess's paradox

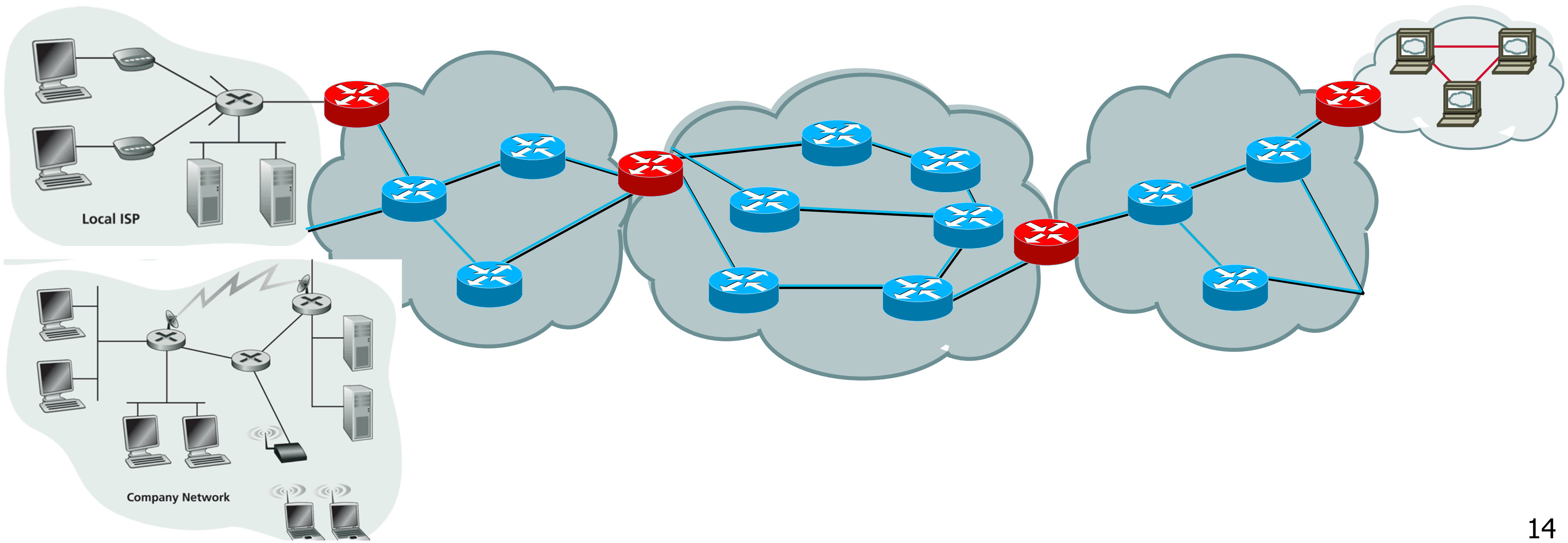
Distributed vs Centralized

- Distributed computing is hard, e.g.,
  - FLP Impossibility Theorem
  - Arrow's Impossibility Theorem

- Achieved good design for only few specific tasks (e.g., state distribution, leader election). Hence, a trend in networking is Software Defined Networking, which is a way of moving away from generic distributed computing, by focusing on utilizing the few well-understood primitives, in particular logically centralized state.

Roadmap

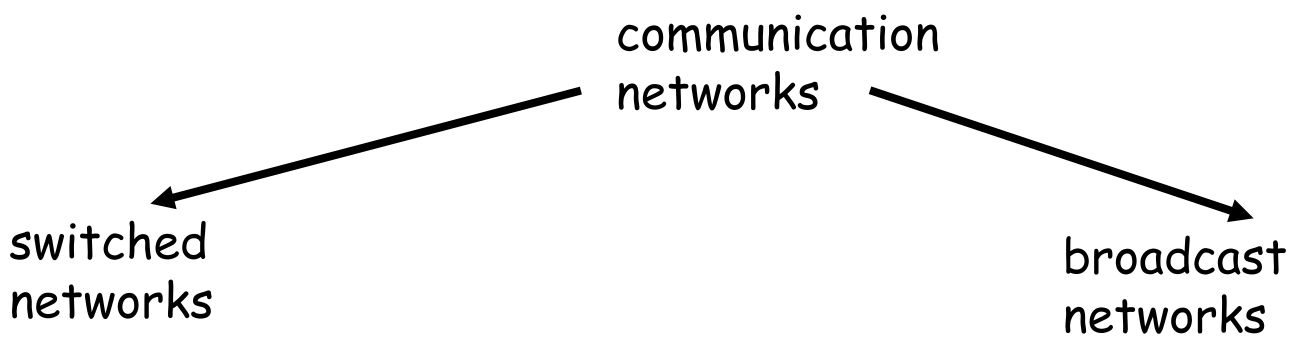
- So far we have looked at only the topology and physical connectivity of the Internet: a mesh of computers interconnected via various physical media
- A basic question: how are data (the bits) transferred through communication networks?



Outline

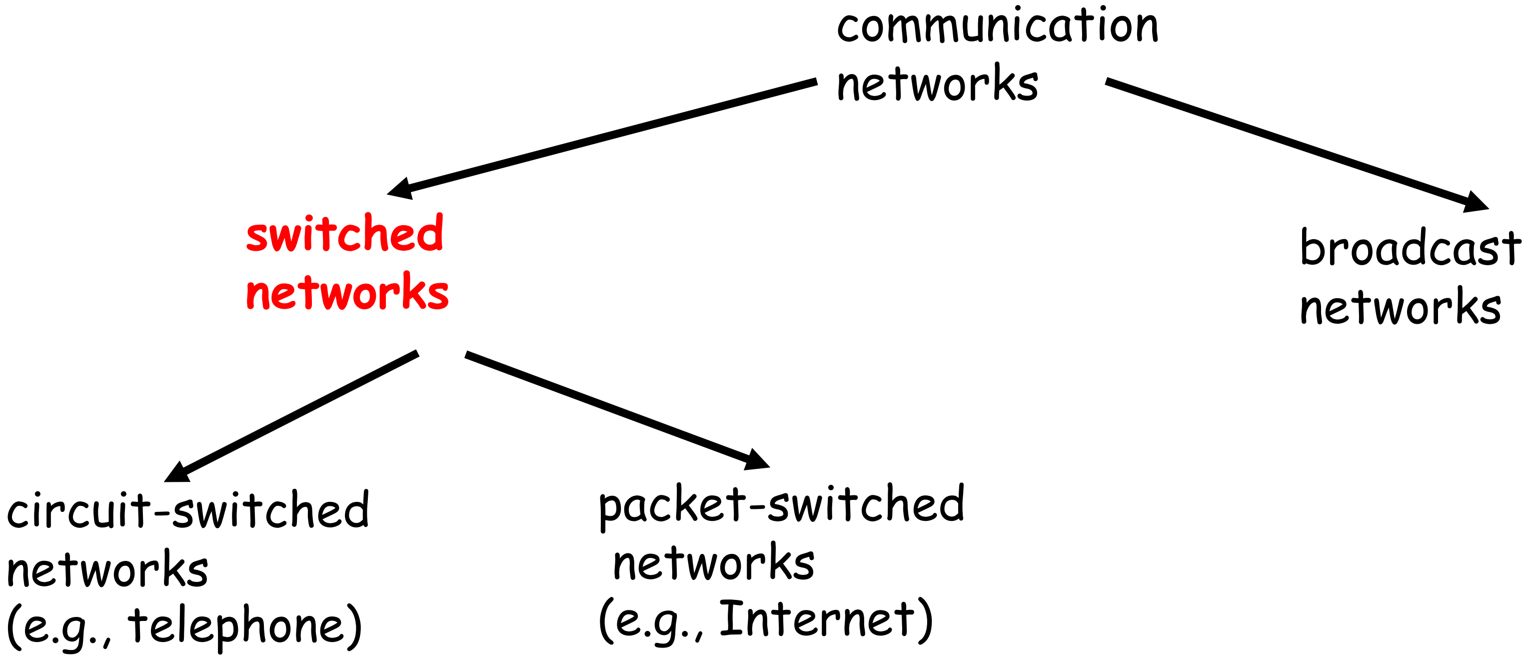
- Admin. and recaps
- Challenges of Internet networks and apps
- *A taxonomy of communication networks*

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

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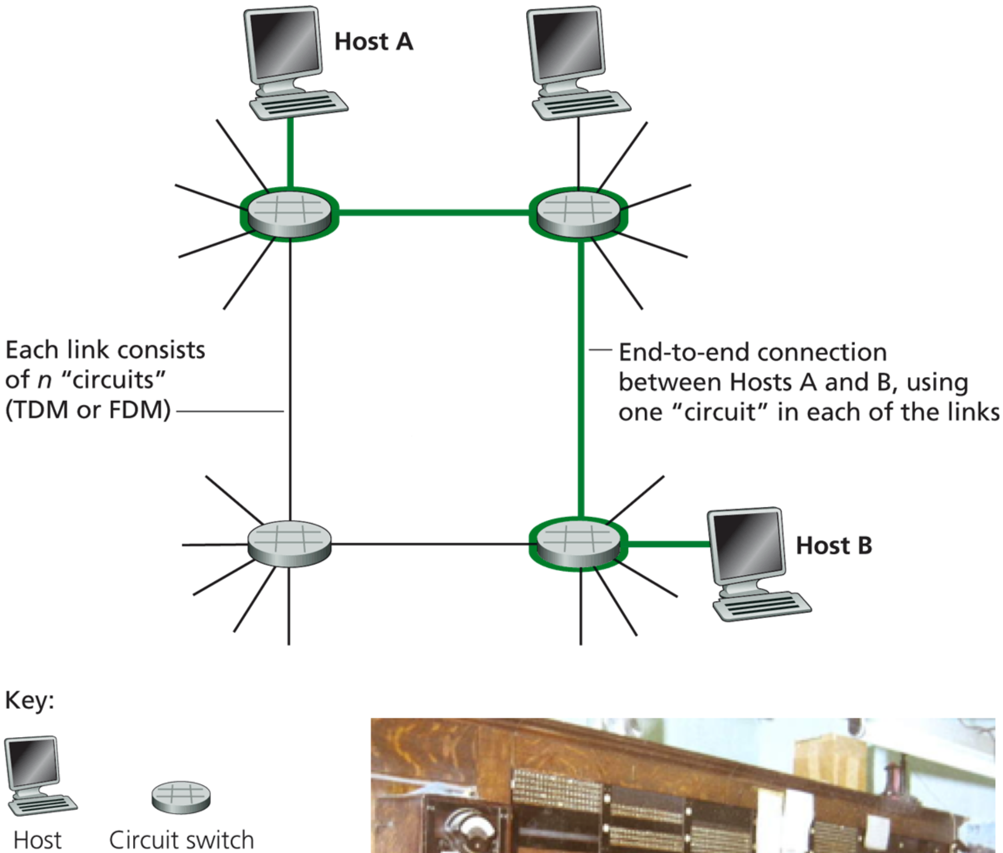
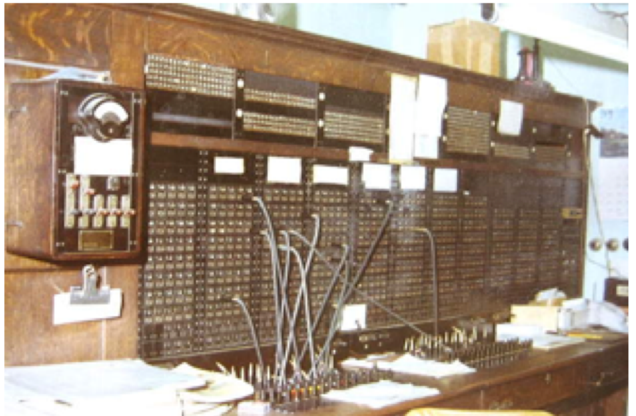
  - *circuit switched networks*

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

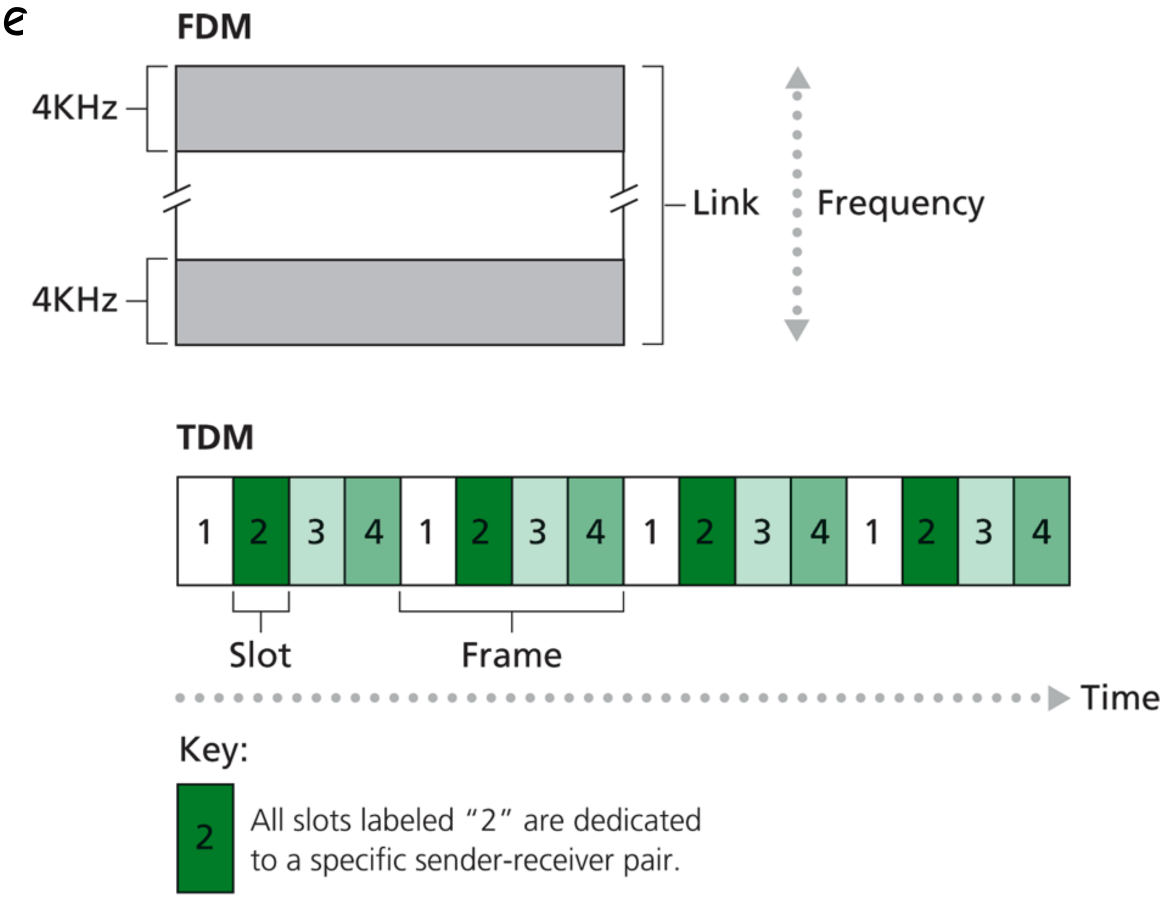




First commercial telephone switchboard was opened in 1878 to serve the 21 telephone customers in New Haven

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

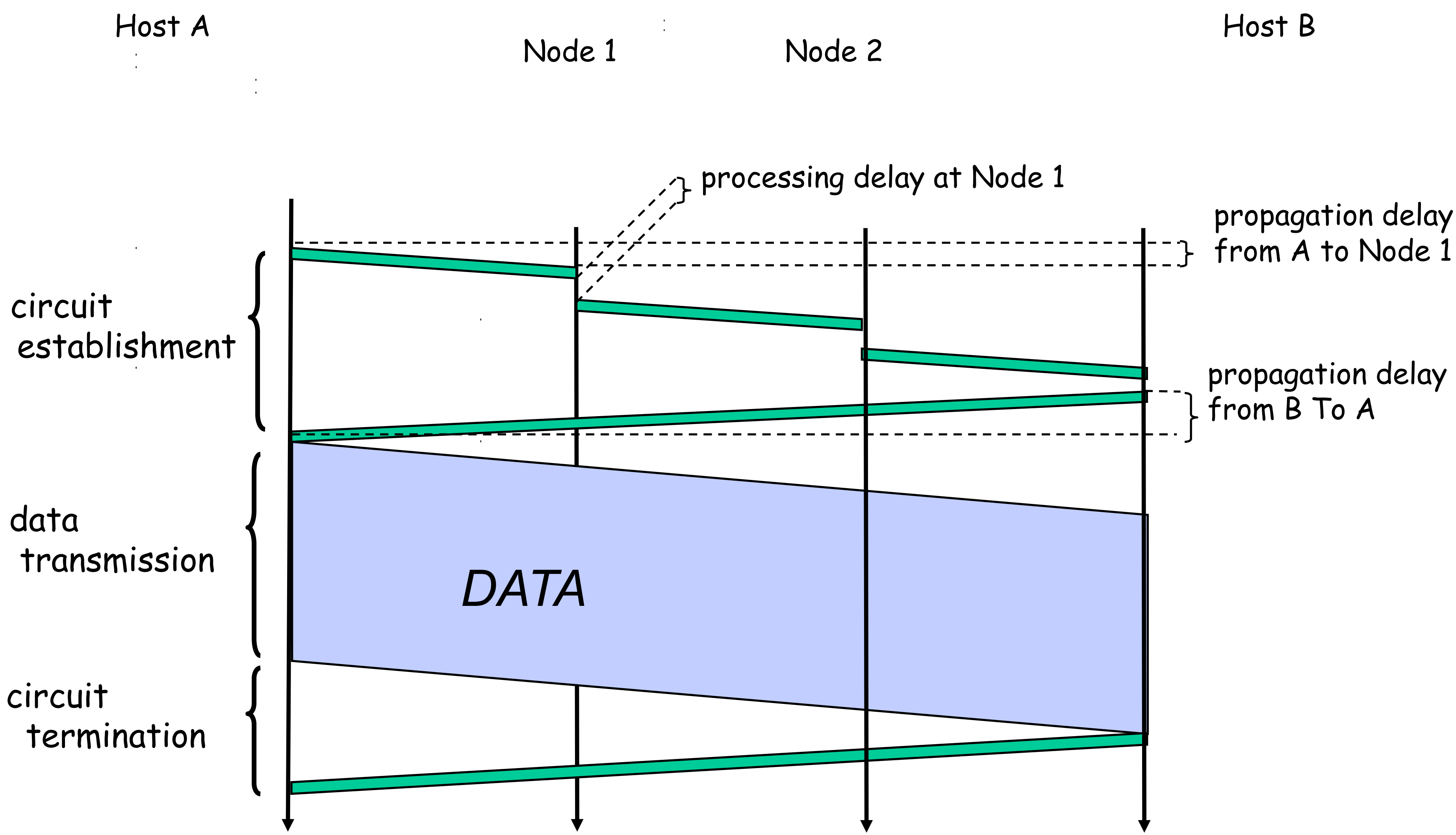
- Divide link resource into "circuits"
  - frequency division multiplexing (FDM)
  - time division multiplexing (TDM)
  - others such as code division multiplexing (CDM), color/lambda division



Circuit Switching: The Process

- Three phases
  - circuit establishment
  - data transfer
  - circuit termination

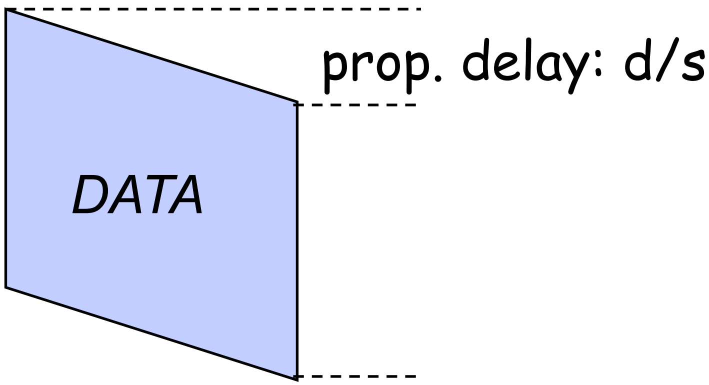
Timing Diagram of Circuit Switching



Delay Calculation in Circuit Switched Networks

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

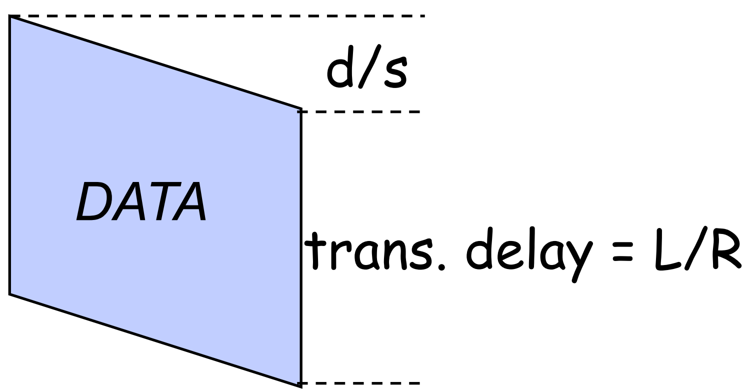
Propagation delay:
- d = length of physical link
- s = propagation speed in medium (~2×10^5 km/sec)



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:

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

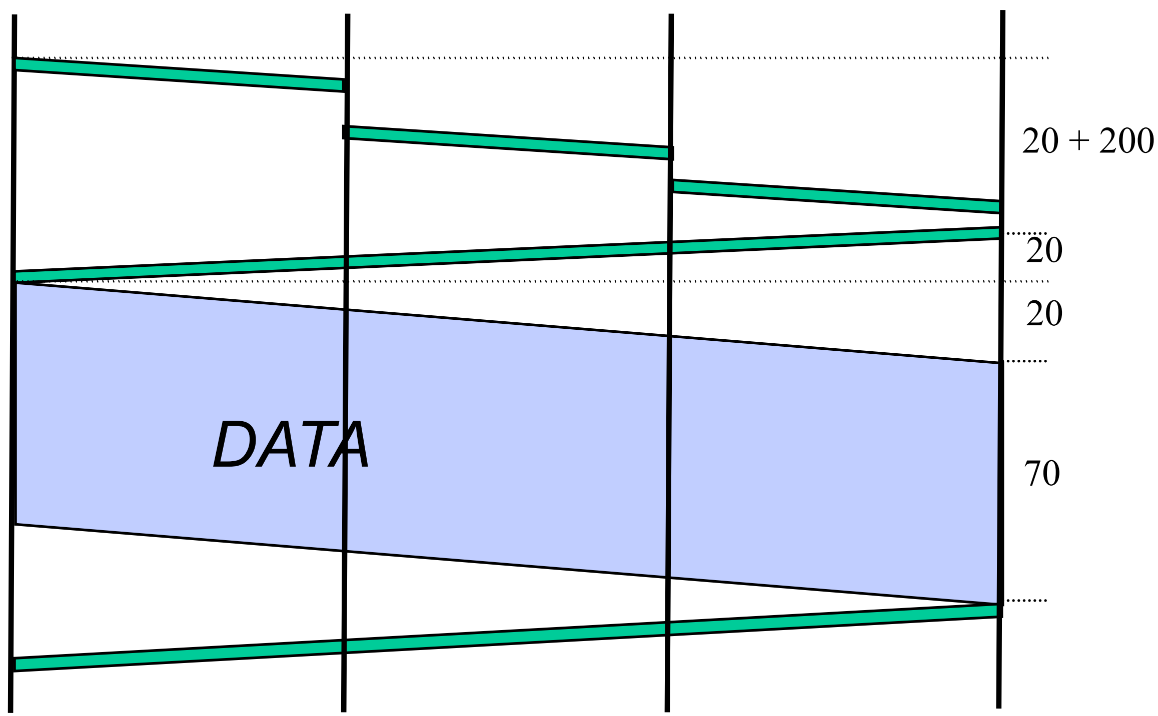
- Transmission delay
  - suppose your iphone reserves a one-slot HSCSD channel
    - each HSCSD frame can transmit about 115 kbps
    - a frame is divided into 8 slots
  - then the transmission delay of using one reserved slot for a message of 1 Kbits:

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

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

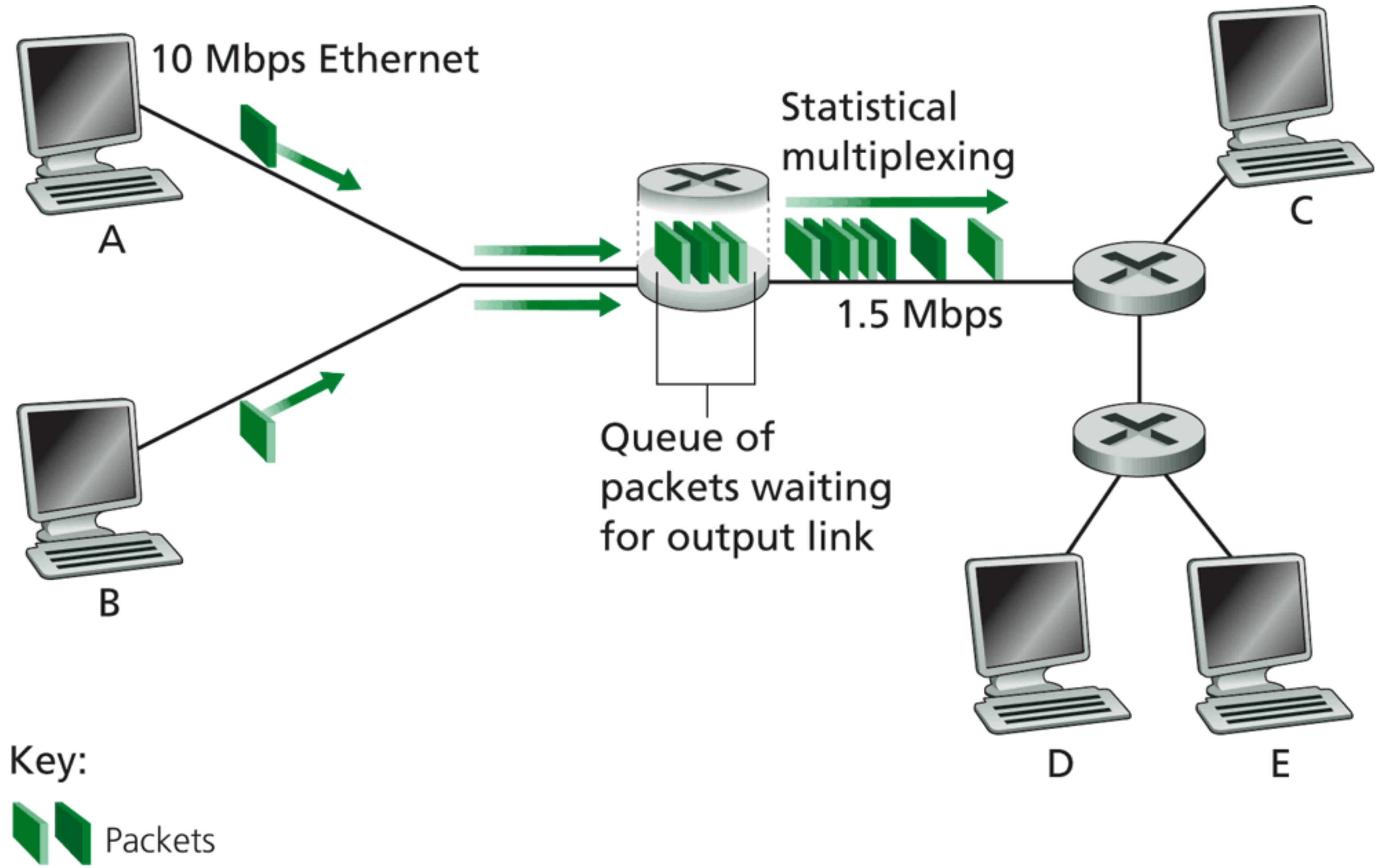
Each end-to-end data **flow** (i.e., a sender-receiver pair) divided into ***packets***

- 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?

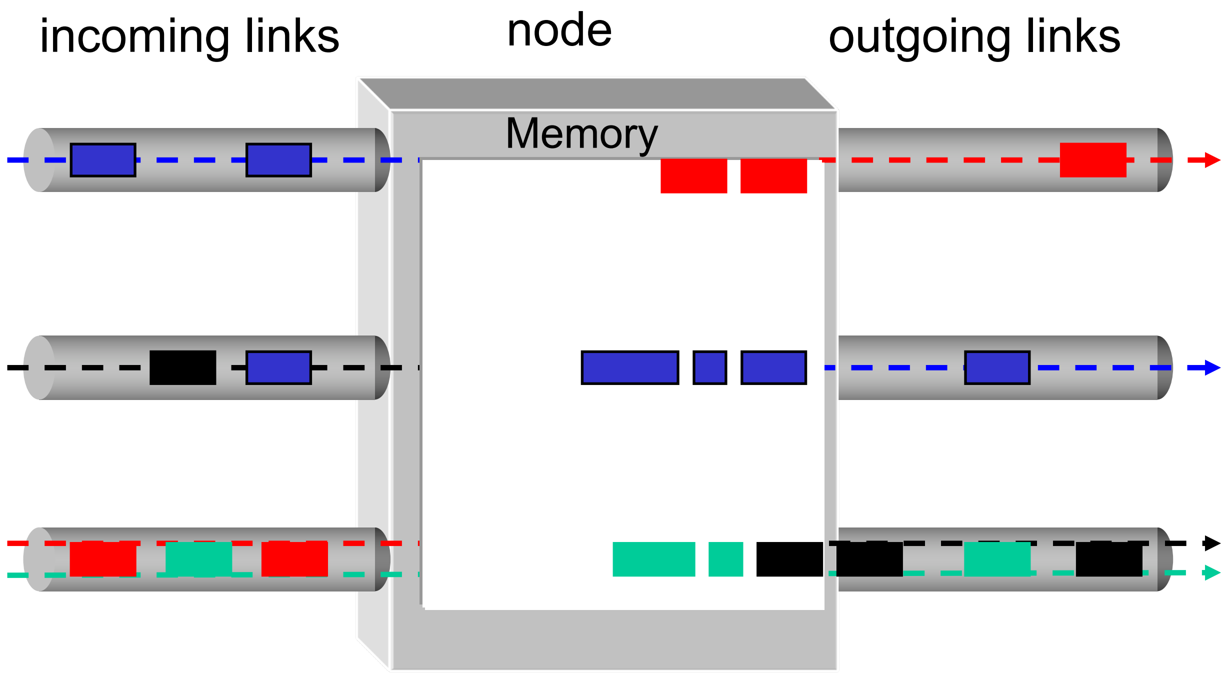
- At each node the entire packet is received, processed (e.g., routing), stored briefly, and then forwarded to the next node; thus packet-switched networks are also called **store-and-forward networks.** On its turn, a packet uses full link bandwidth

Packet Switching



Inside a Packet Switching Router

An output queueing switch



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  - *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

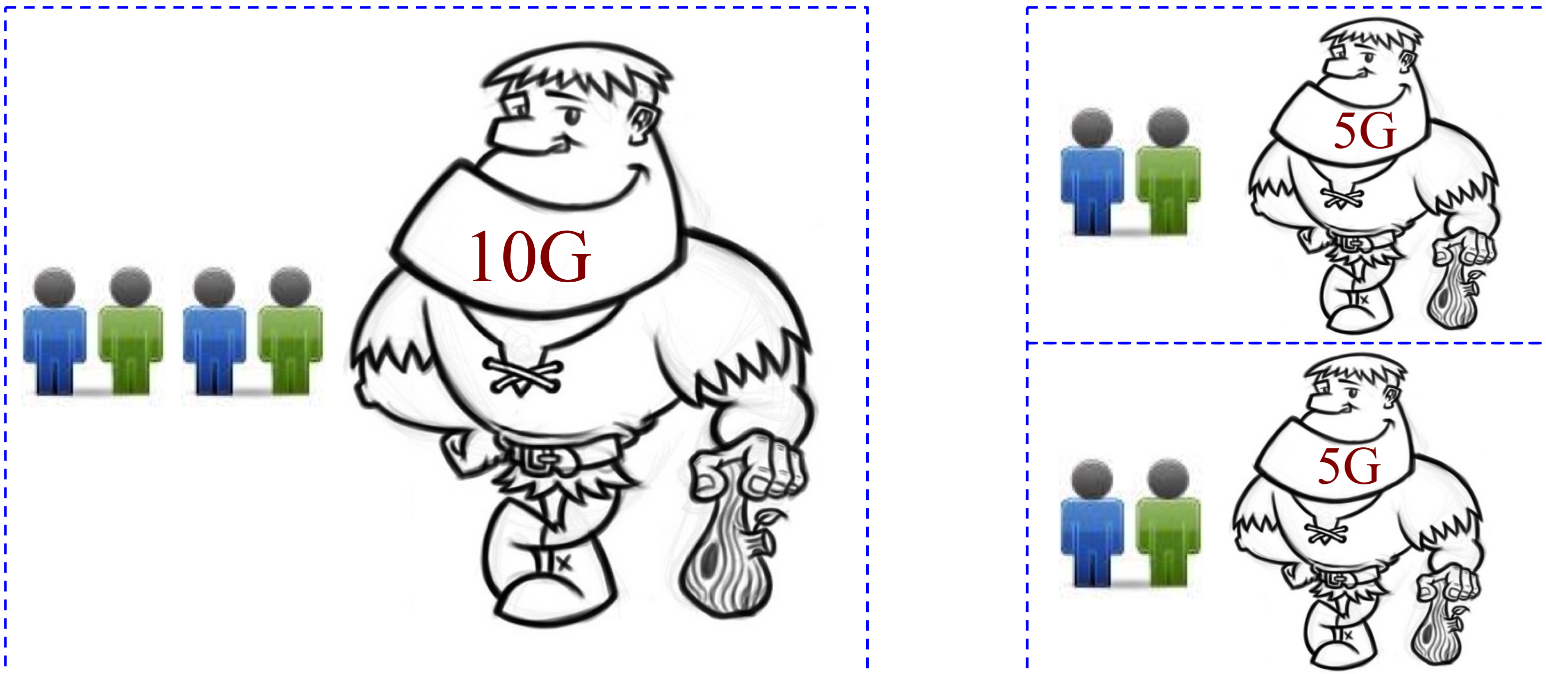
- Need to compare packet switching with circuit switching

Circuit Switching vs. Packet Switching

	circuit switching	packet switching
resource usage		
reservation/setup		
resource contention		
charging		
header		
fast path 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 basic results of queueing theory can be quite useful in many systems settings

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

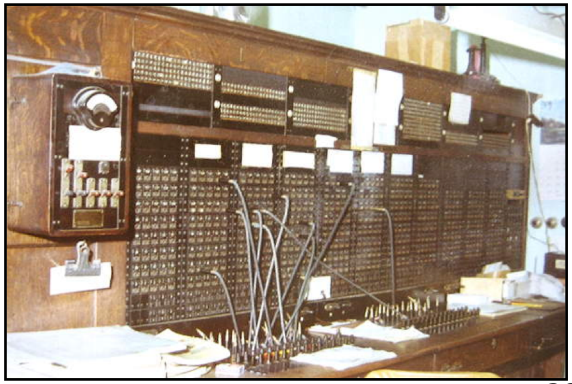
Queueing Theory

- Strategy:
  - model system state
    - if we know the fraction of time that the system spends at each state, we can get answers to many basic questions: 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 extremely precise modeling, but want quantitative 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?



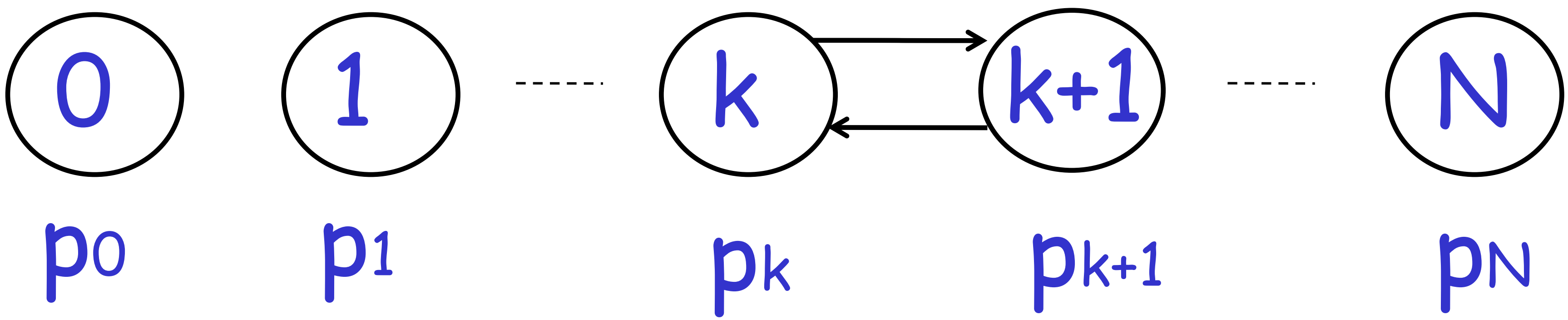
- Key parameters?

Analysis of Circuit-Switching Blocking (Busy) Time

- Consider a simple arrival pattern
  - client requests arrive at a rate of λ (lambda/second)
  - service rate: each call takes on average $1/\mu$ second
- Arrival and service patterns: 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



Q: How to characterize equilibrium?

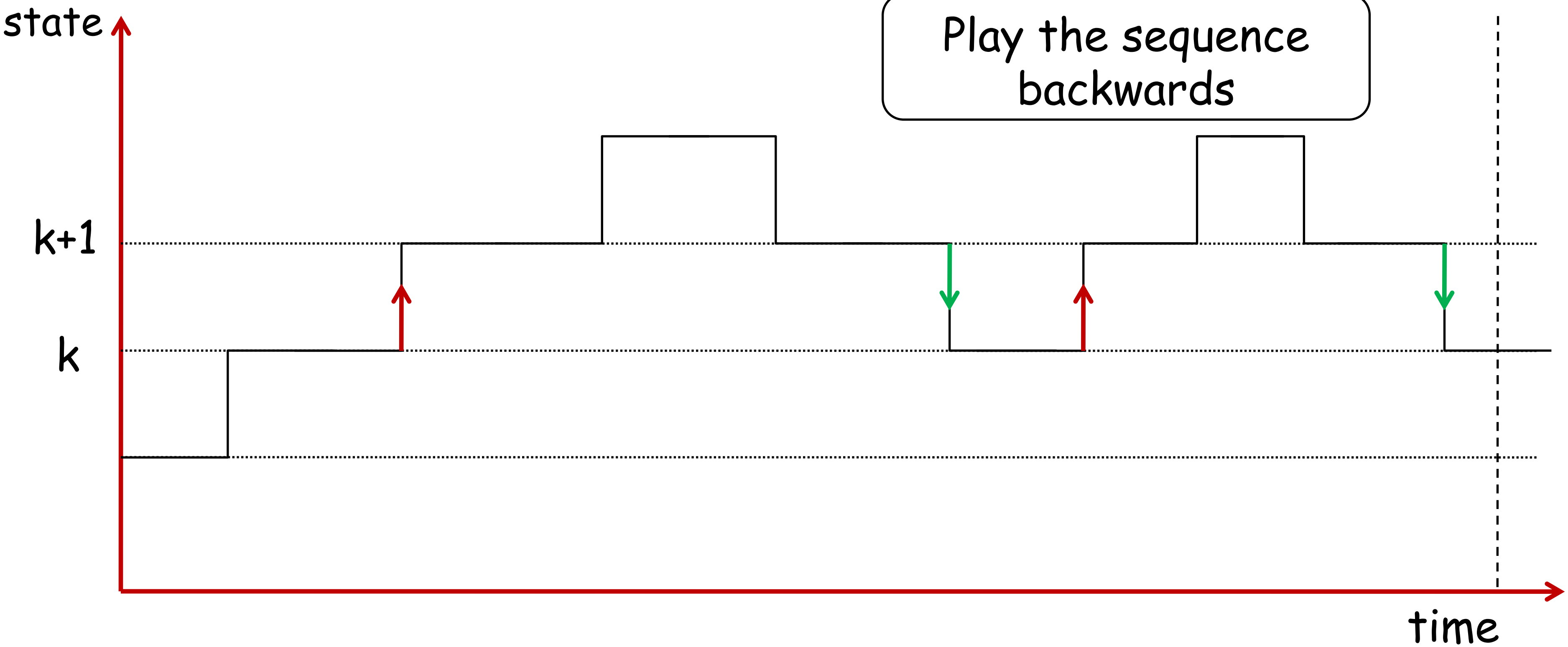
Equilibrium = Time Reversibility [Frank Kelly]

- Statistically cannot distinguish

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

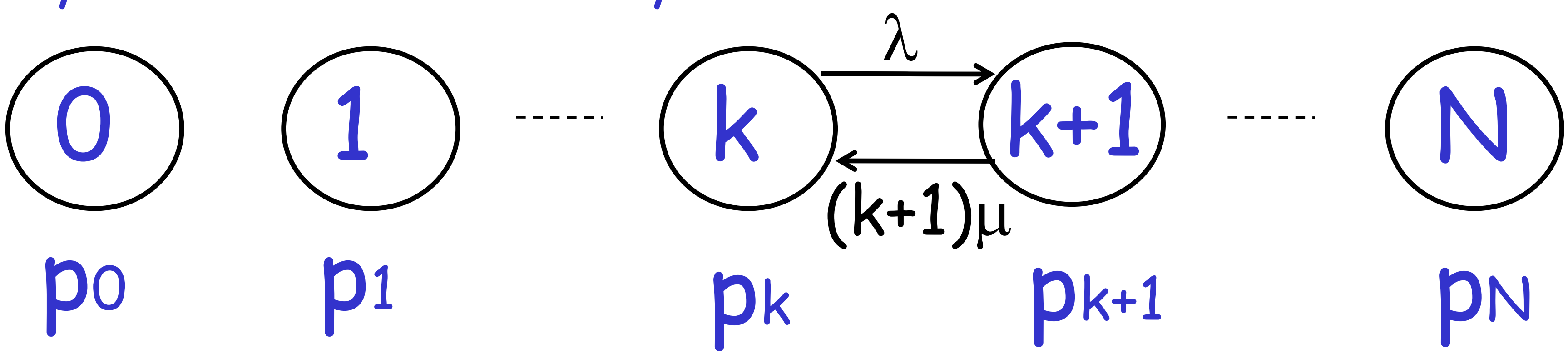
$$\#b_{k\to k+1},\ \#b_{k+1\to k}$$

Play the sequence backwards



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)

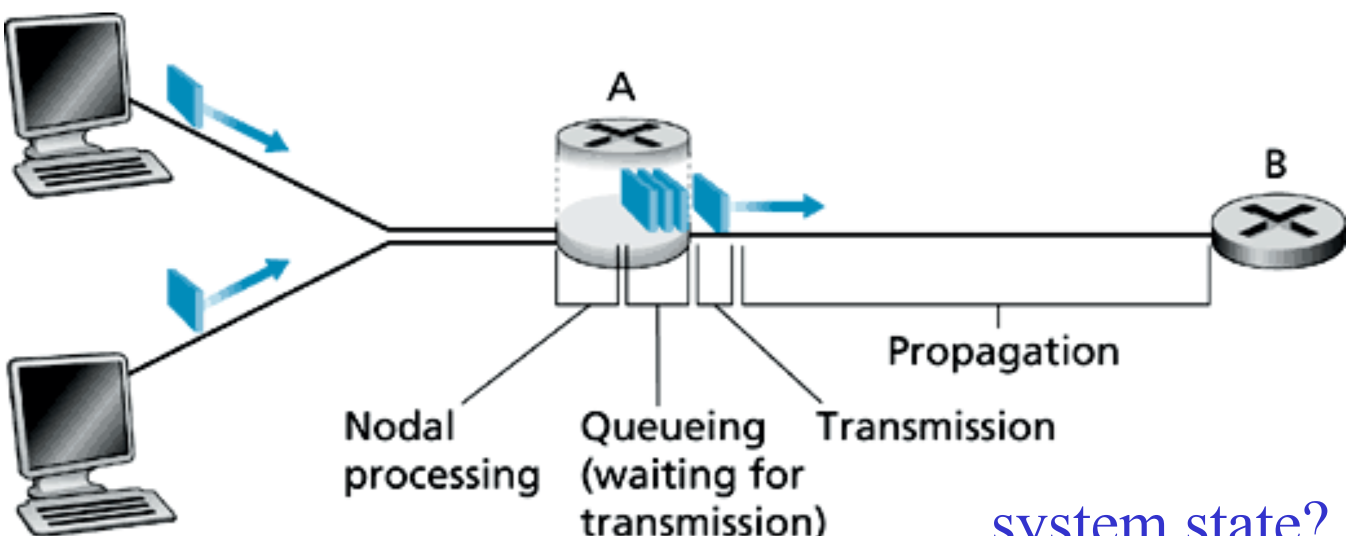
$$\boxed{p_k \lambda = p_{k+1}(k+1)\mu}$$

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

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

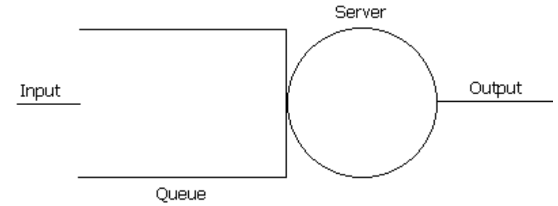
Queueing Analysis: Packet Switching Delay

- 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

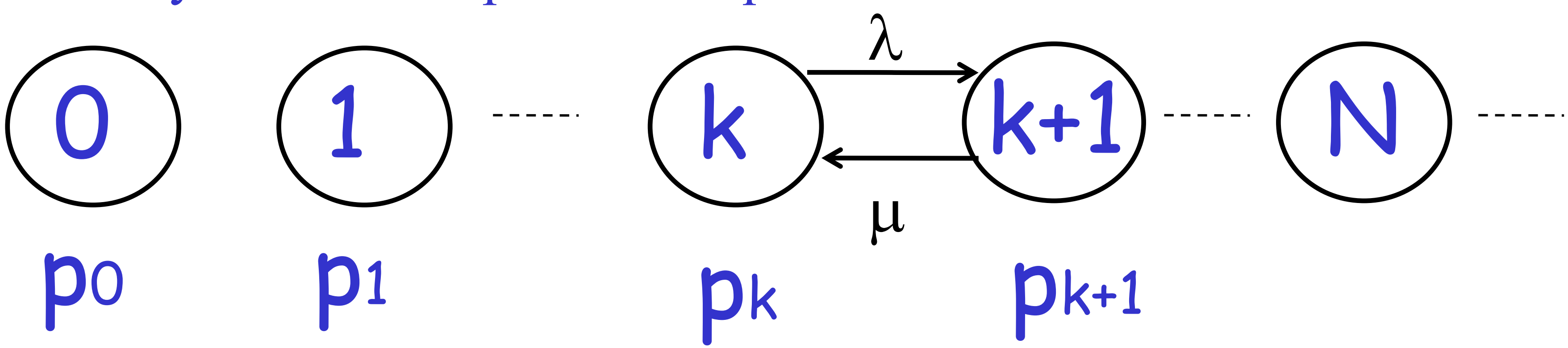


system state?

Packet Switching Delay



system state: #packets in queue



at equilibrium (time reversibility) in one unit time:

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

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

$$\boxed{\sum_{k=0}^{\infty} p_k = 1}$$

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

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

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

Summary: Queueing Theory

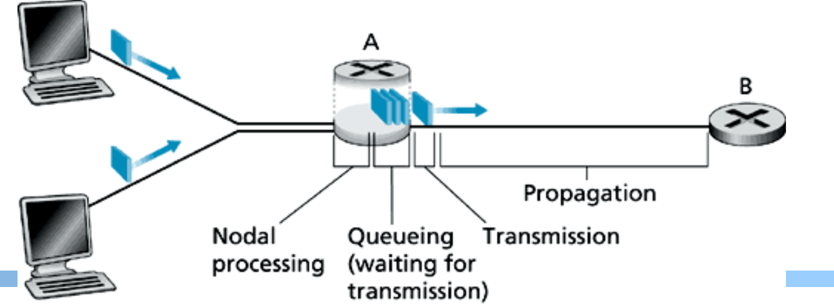
- Model system state
- Introduce state transition diagram
- Focus on equilibrium: state trend neither growing nor shrinking

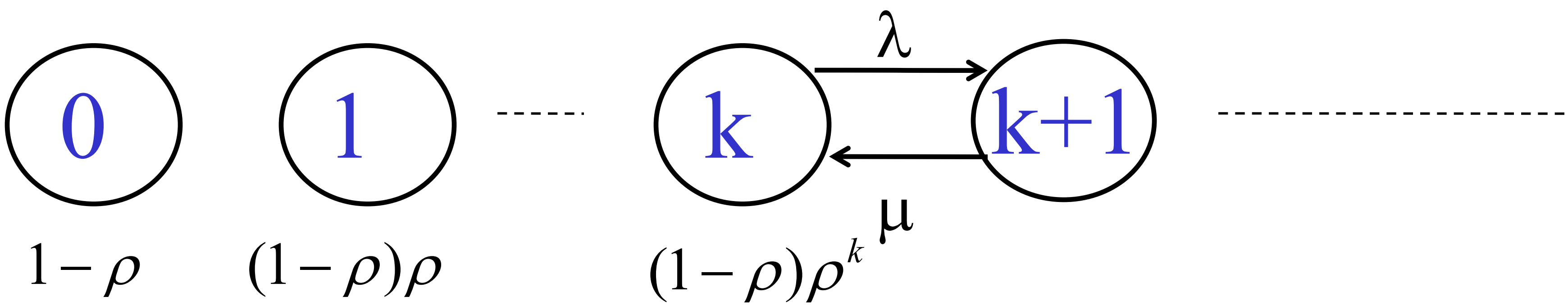
Example

- Assume requests (packets) come in at a rate of one request per 50 ms λ=1/50ms =20/s
- Each request (packet) takes on average 20 ms $1/\mu$=20 ms, μ=50/s

- What is the fraction of time that the system is empty? P_0
- What is the chance that a packet newly arrived needs to wait for 3 early packets? P_3

Analysis of Delay (cont')





- Average queueing delay:

$$\sum_{k=0}^{\infty} p_k \cdot k \cdot \frac{1}{\mu} = \sum_{k=0}^{\infty} \rho^k (1-\rho)\, k \frac{1}{\mu}$$

- Transmission delay: $\boxed{S = \frac{1}{\mu}}$

- Queueing + transmission:

Delay

$$\rho = \frac{\lambda}{\mu}$$

$$S = \frac{1}{\mu}$$

$$\text{average queueing delay: } w = S\frac{\rho}{1-\rho}$$

$$queueing + trans = S\frac{\rho}{1-\rho} + S = S\frac{1}{1-\rho}$$

For a demo of M/M/1, see:
http://www.dcs.ed.ac.uk/home/jeh/Simjava/queueing/mm1_q/mm1_q.html

Queueing Delay as a Function of Utilization

Assume:

R = link bandwidth (bps)

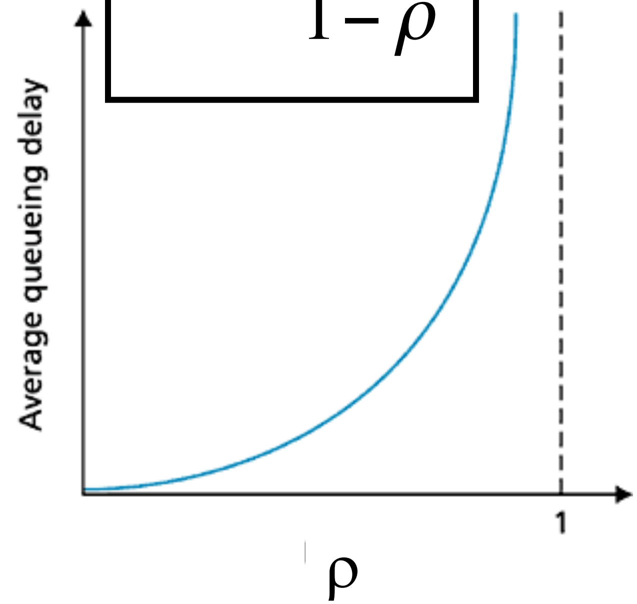
L = packet length (bits)

S = L / R

a = average packet arrival rate (pkt/sec)

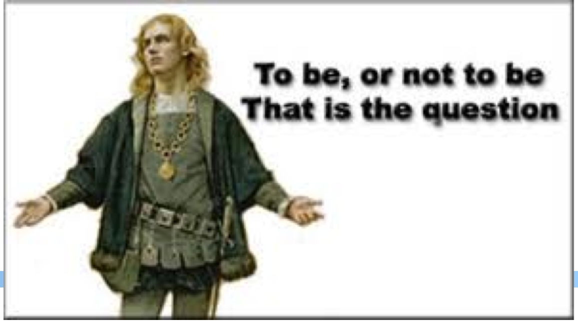
$$utilization:\ \rho = \frac{a}{1/S} = aS$$

$$w = S\frac{\rho}{1-\rho}$$



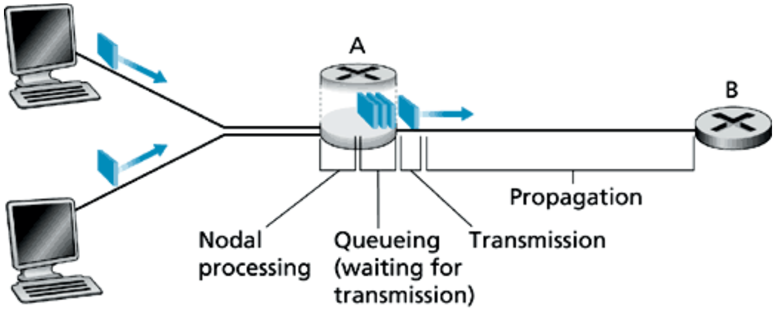
- ρ ~ 0: average queueing delay small
- ρ -> 1: delay becomes large
- ρ > 1: more "work" arriving than can be serviced, average delay infinite !

Statistical Multiplexing



A simple model to compare bandwidth efficiency of
- reservation/dedication (aka circuit-switching) vs
- no reservation (aka packet switching)

setup
- a single bottleneck link with service rate μ
- n flows; each flow has an arrival rate of λ/n



- no reservation: all arrivals into the single link, the queueing delay + transmission delay:

$$\boxed{S \frac{1}{1-\rho}}$$

- reservation: each flow uses its own reserved (sub)link with rate μ /n, the queueing delay + transmission delay:

For each flow i:

$$\rho_i = \frac{\lambda/n}{\mu/n} = \rho \Rightarrow \boxed{n S \frac{1}{1-\rho}}$$

$$S_i = \frac{1}{\mu/n} = nS$$