



DIAG



SAPIENZA  
UNIVERSITÀ DI ROMA

# Reti di Elaboratori

Corso di Laurea in Ingegneria Informatica  
Università degli Studi di Roma “La Sapienza”  
Prof.ssa Chiara Petrioli

Parte di queste slide sono state prese dal materiale associato al libro  
*Computer Networking: A Top Down Approach* , 5th edition.

All material copyright 1996-2009

J.F Kurose and K.W. Ross, All Rights Reserved

Thanks also to Antonio Capone, Politecnico di Milano, Giuseppe Bianchi and  
Francesco LoPresti, Un. di Roma Tor Vergata

# Chapter 1: roadmap

1.1 What *is* the Internet?

1.2 Network edge

- end systems, access networks, links

1.3 Network core

- circuit switching, packet switching, network structure

1.4 Delay, loss and throughput in packet-switched networks

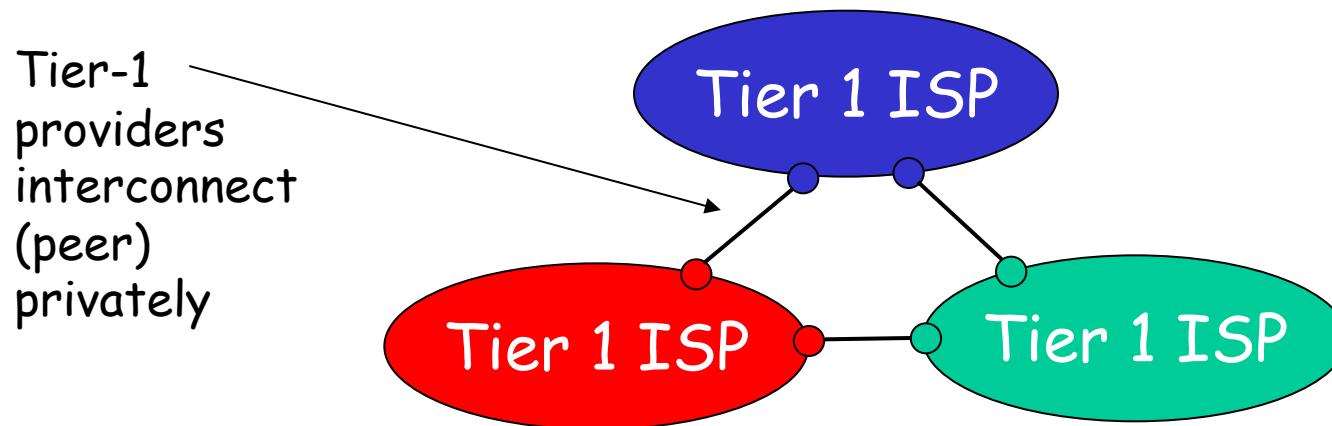
1.5 Protocol layers, service models

1.6 Networks under attack: security

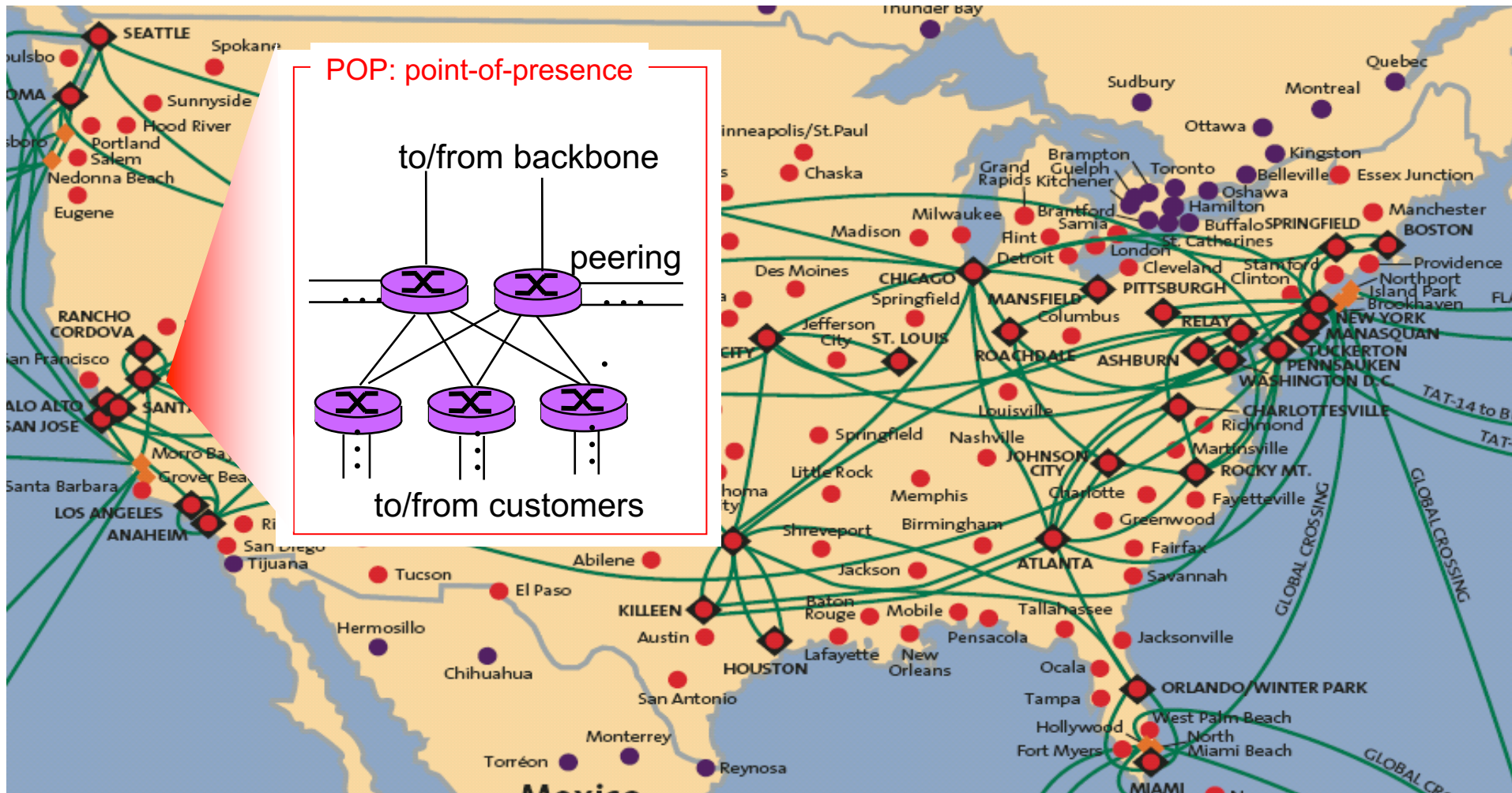
1.7 History

# 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



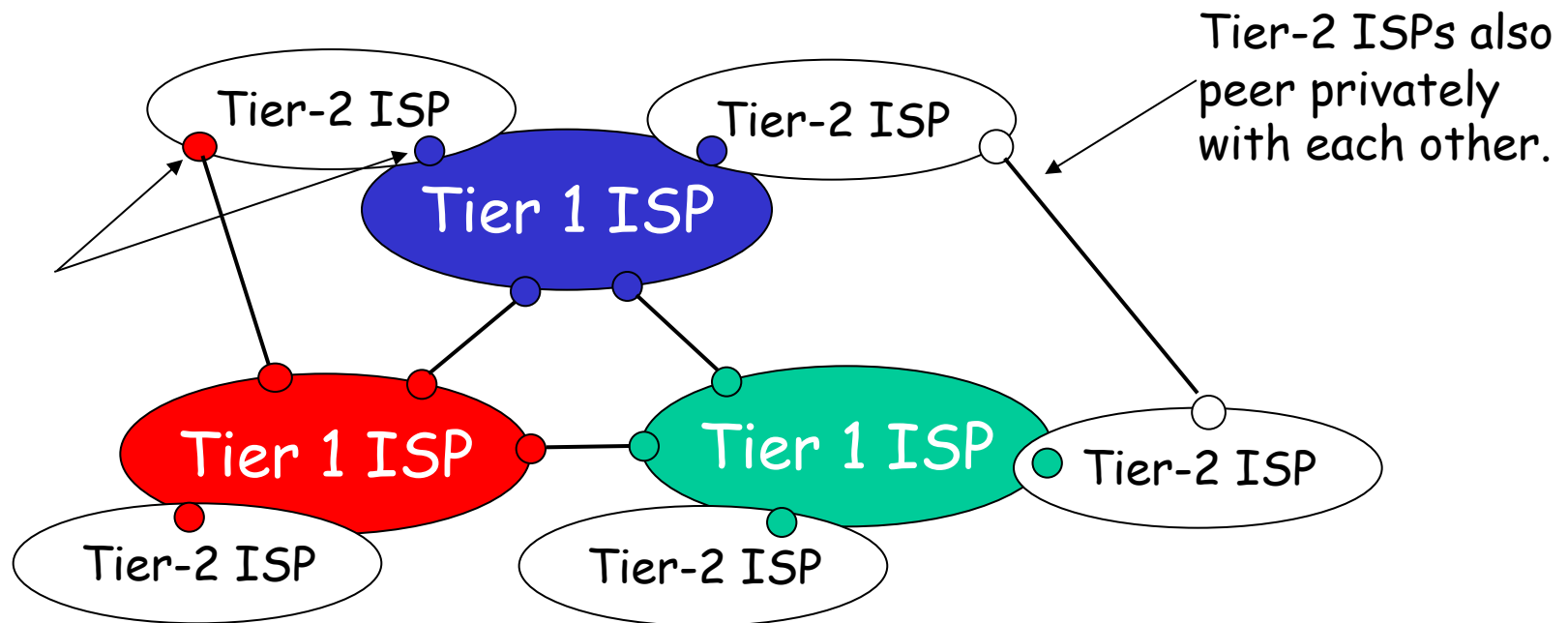
# Tier-1 ISP: e.g., Sprint



# Internet structure: network of networks

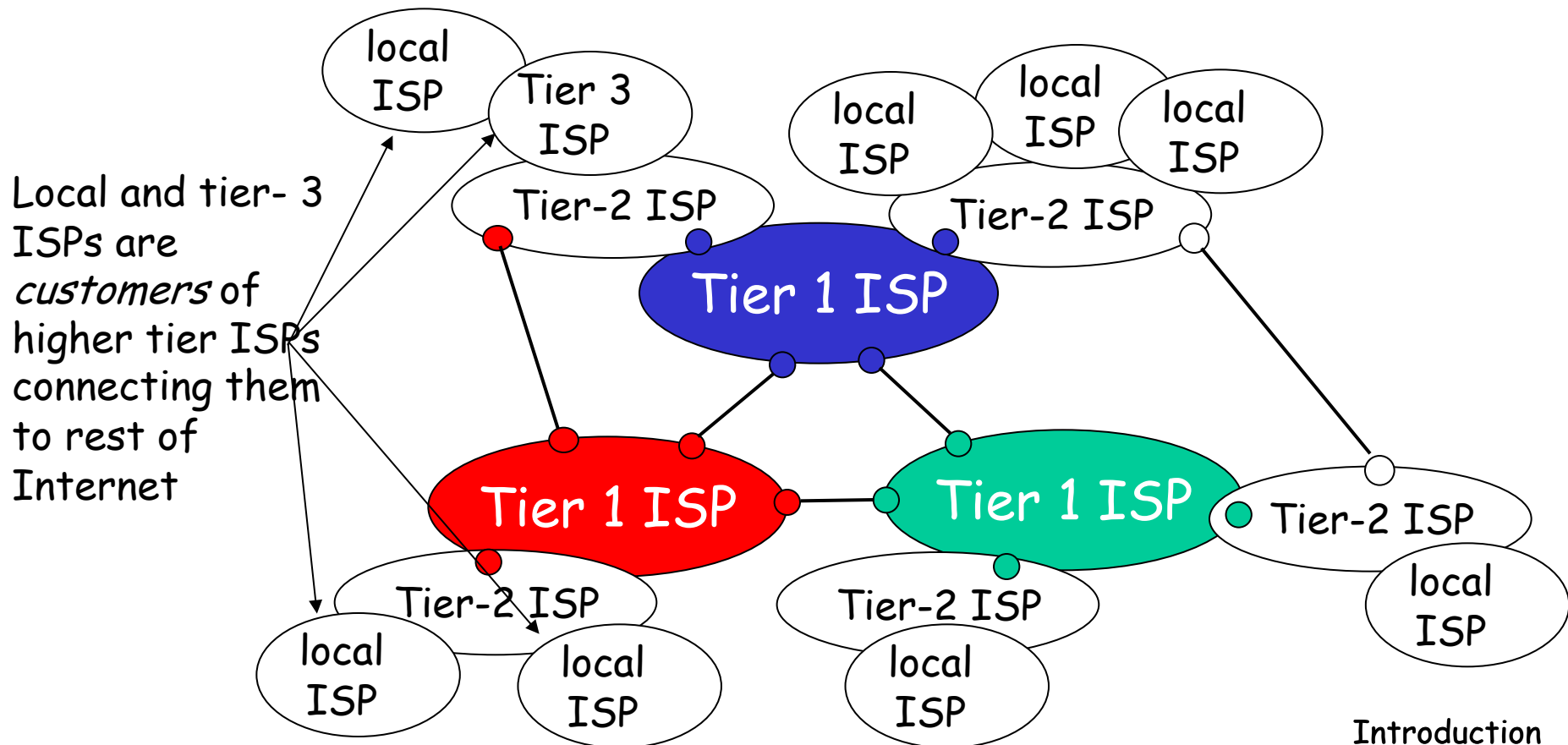
- ❑ “Tier-2” ISPs: smaller (often regional) ISPs
  - Connect to one or more tier-1 ISPs, possibly other tier-2 ISPs

Tier-2 ISP pays tier-1 ISP for connectivity to rest of Internet  
❑ tier-2 ISP is *customer* of tier-1 provider



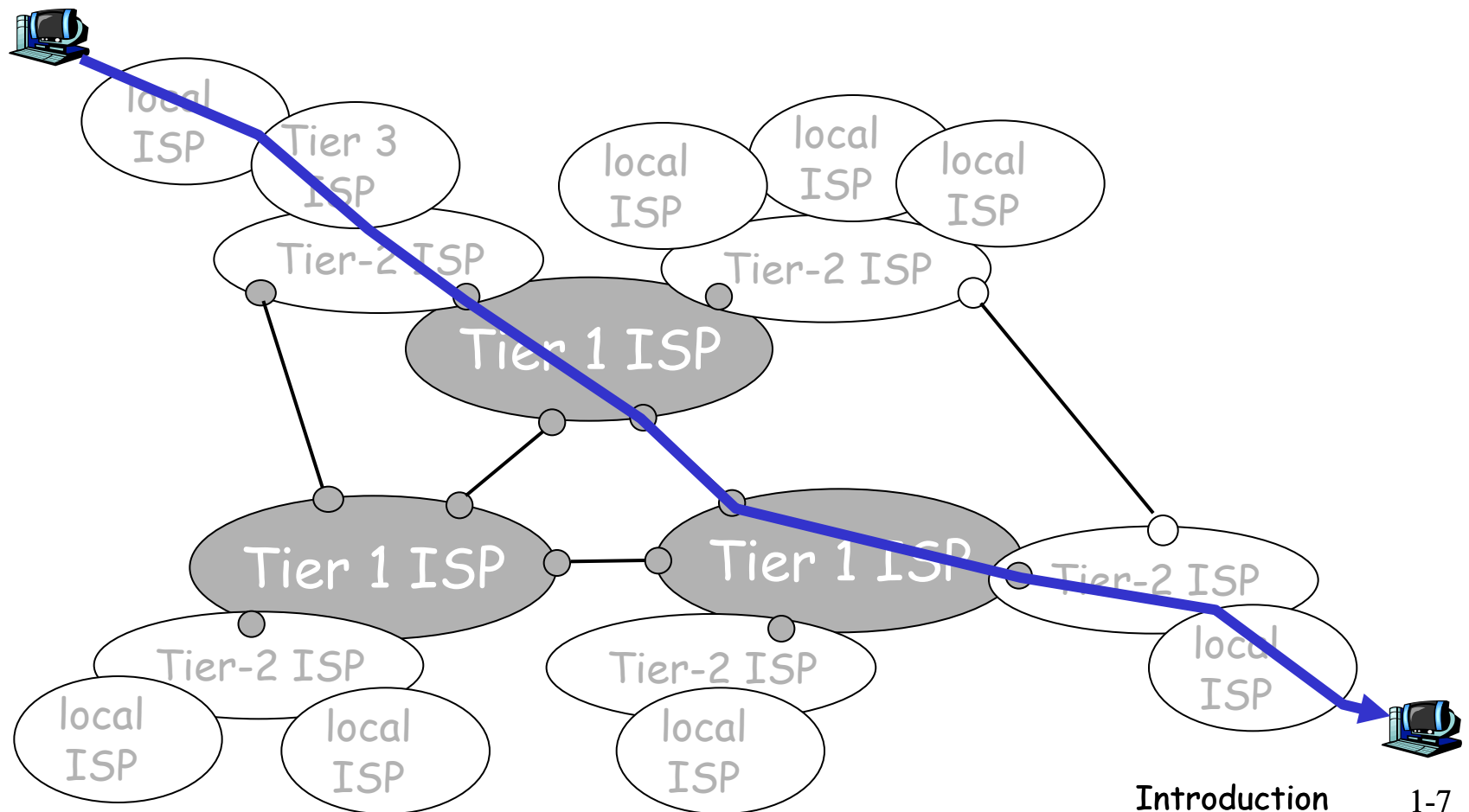
# Internet structure: network of networks

- ❑ “Tier-3” ISPs and local ISPs
  - last hop (“access”) network (closest to end systems)



# Internet structure: network of networks

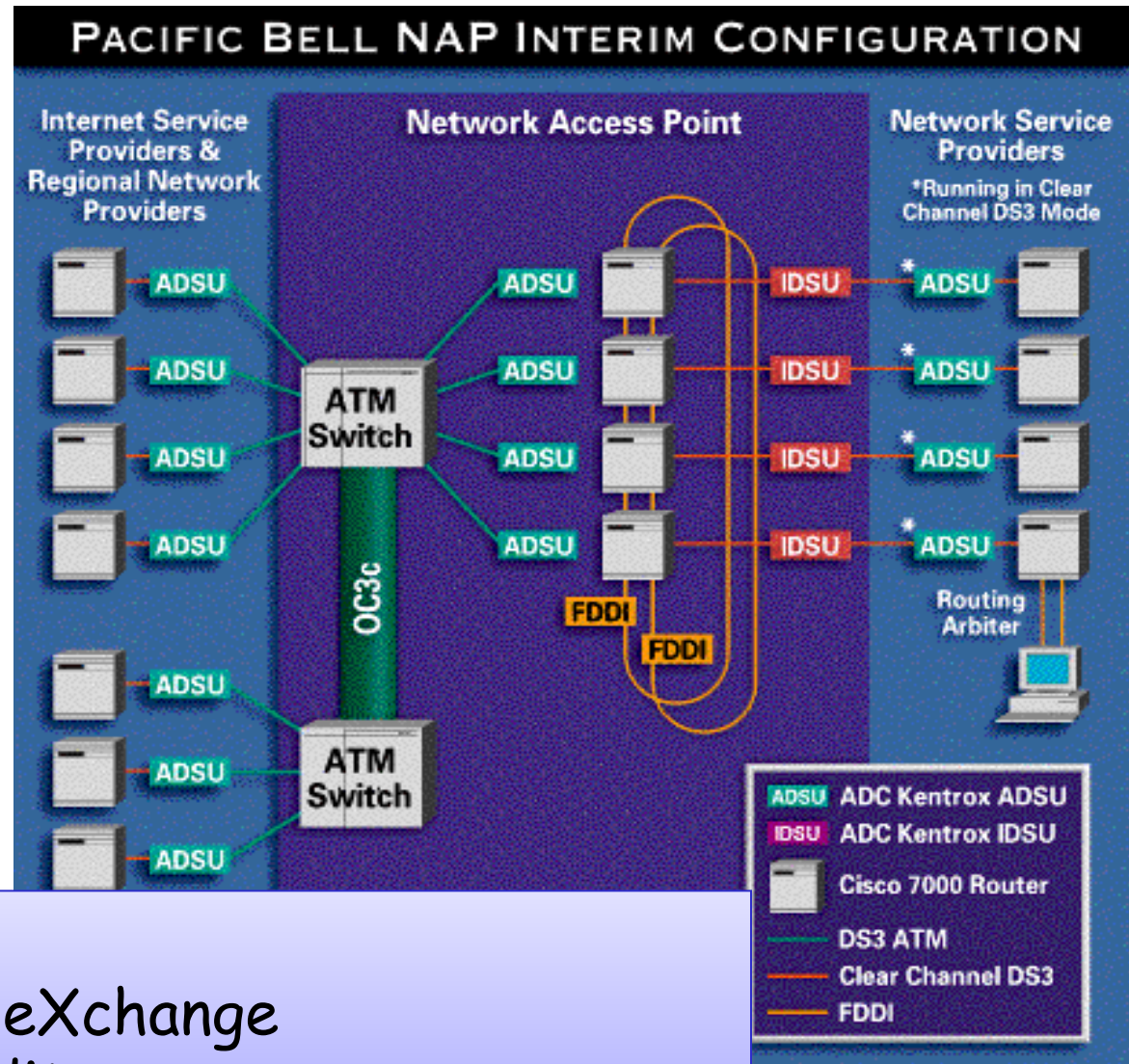
- a packet passes through many networks!





# A NAP: just another router...?

## Pacific Bell S. Francisco NAP



In Italia:

- MIX Milan Internet eXchange
- NaMeX Nautilus Mediterranean Exchange Point



# Chapter 1: roadmap

1.1 What *is* the Internet?

1.2 Network edge

1.3 Network core

1.4 Network access and physical media

1.5 Internet structure and ISPs

1.6 Delay & loss in packet-switched networks

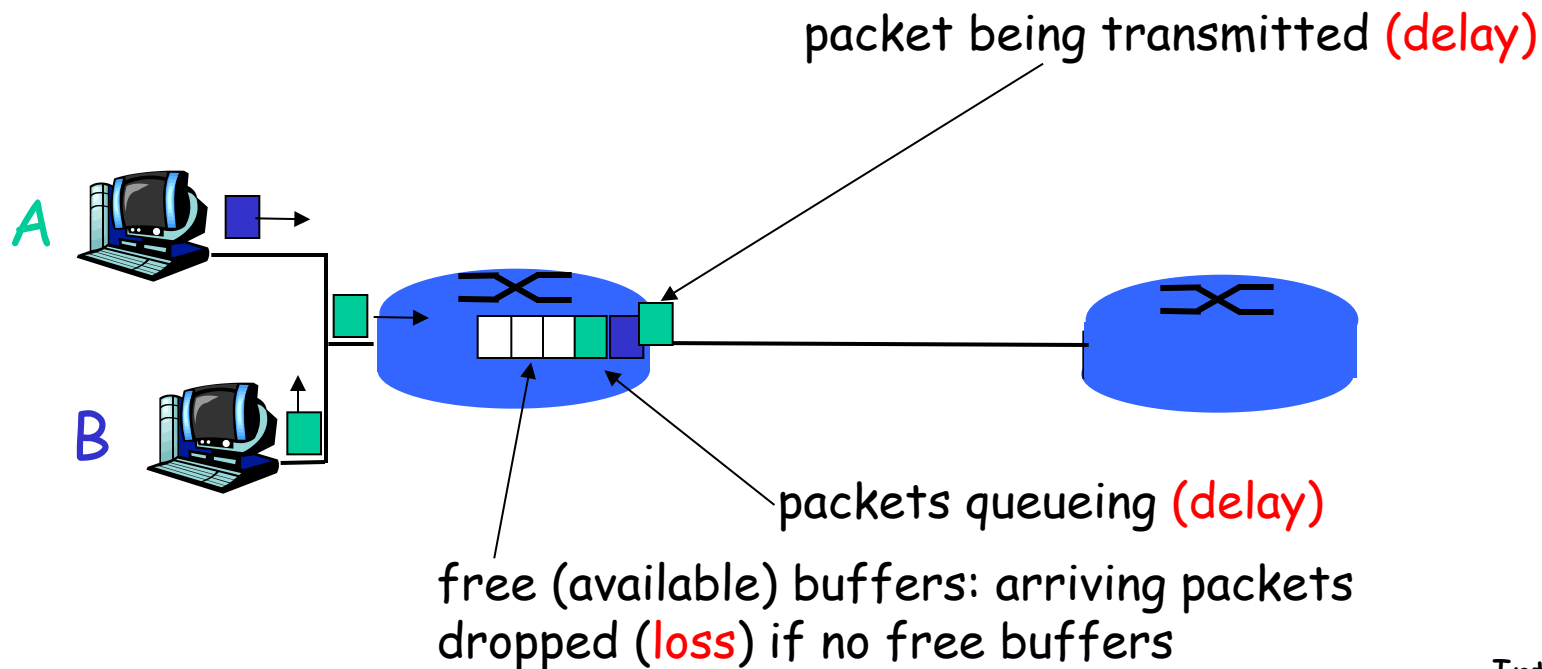
1.7 Protocol layers, service models

1.8 History

# 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



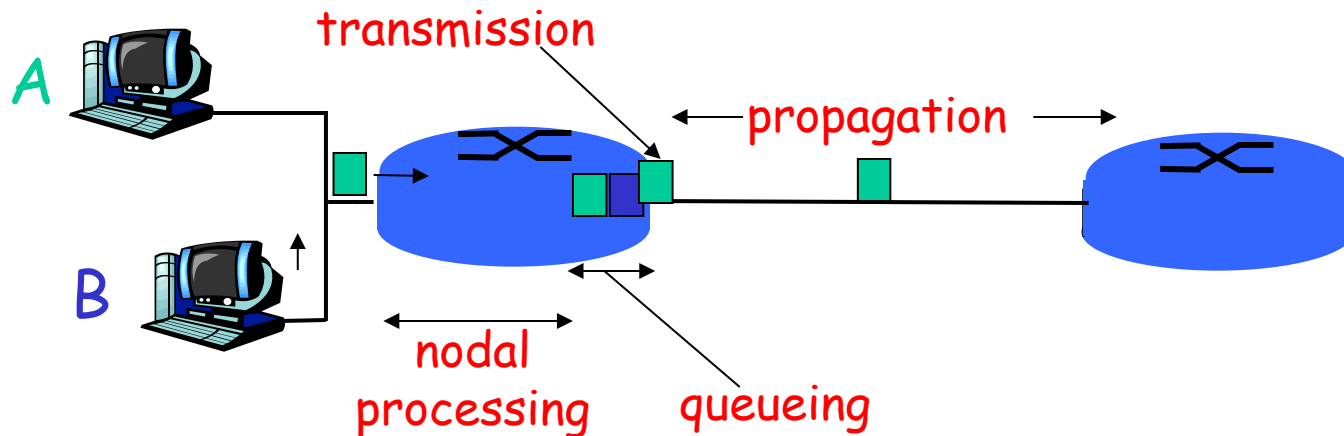
# Four sources of packet delay

## ❑ 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

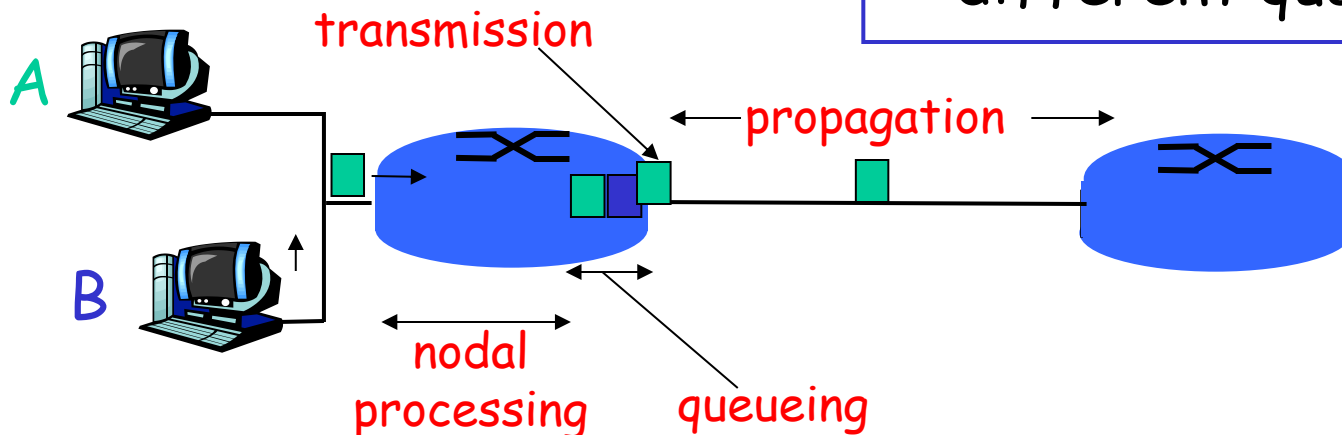
## 3. Transmission delay:

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

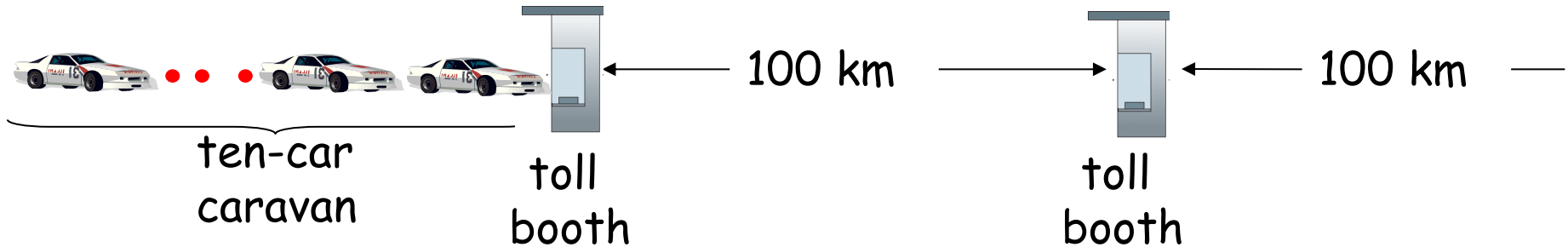
## 4. Propagation delay:

- $d$  = length of physical link
- $s$  = propagation speed in medium ( $\sim 2 \times 10^8$  m/sec)
- propagation delay =  $d/s$

**Note:**  $s$  and  $R$  are *very* different quantities!

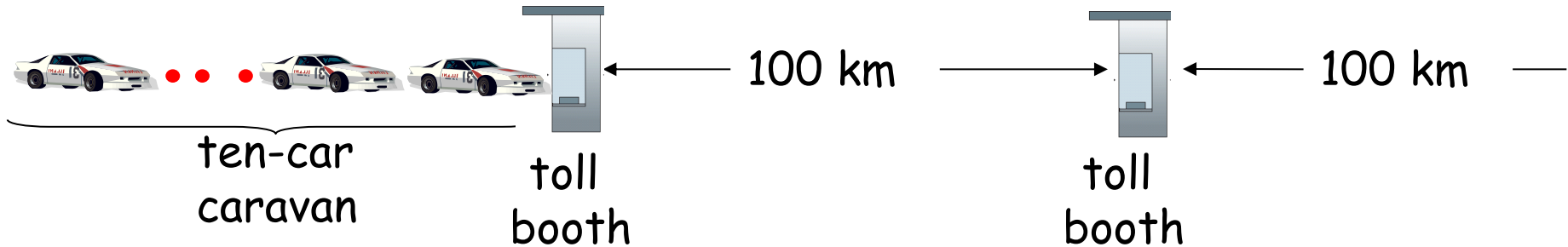


# Caravan analogy



- ❑ cars “propagate” at 100 km/hr
- ❑ toll booth takes 12 sec to service car (transmission time)
- ❑ car~bit; caravan ~ packet
- ❑ Q: How long until caravan is lined up before 2nd toll booth?
- ❑ Time to “push” entire caravan through toll booth onto highway =  $12 \times 10 = 120$  sec
- ❑ Time for last car to propagate from 1st to 2nd toll booth:  
 $100\text{km} / (100\text{km/hr}) = 1$  hr
- ❑ A: 62 minutes

# Caravan analogy (more)



- ❑ Cars now “propagate” at 1000 km/hr
- ❑ Toll booth now takes 1 min to service a car
- ❑ Q: Will cars arrive to 2nd booth before all cars serviced at 1st booth?
- ❑ **Yes!** After 7 min, 1st car at 2nd booth and 3 cars still at 1st booth.
- ❑ 1st bit of packet can arrive at 2nd router before packet is fully transmitted at 1st router!
  - See Ethernet applet at AWL Web site



# Nodal delay

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

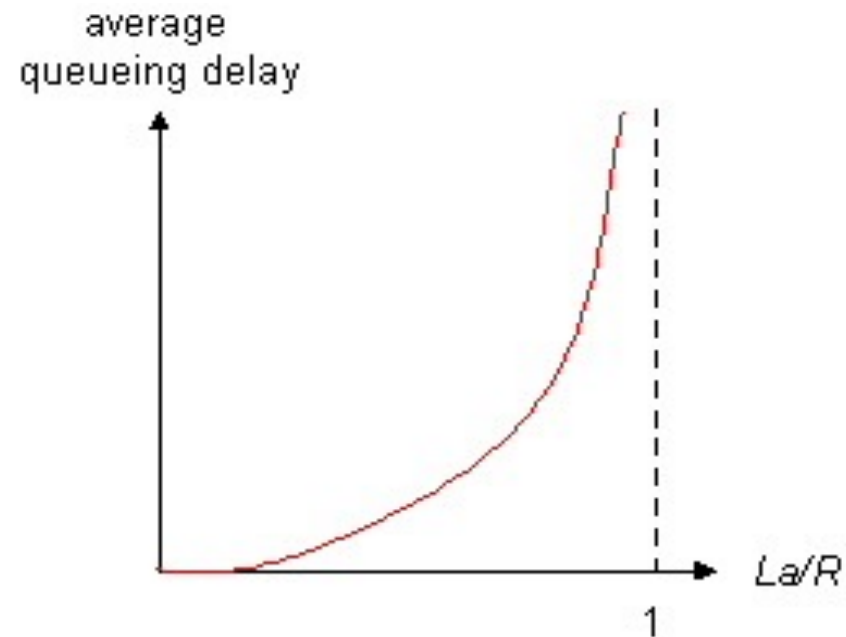
- $d_{\text{proc}}$  = processing delay
  - typically a few microsecs or less
- $d_{\text{queue}}$  = queuing delay
  - depends on congestion
- $d_{\text{trans}}$  = transmission delay
  - $= L/R$ , significant for low-speed links
- $d_{\text{prop}}$  = propagation delay
  - a few microsecs to hundreds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

Delay for each hop!!!

# Queueing delay (revisited)

- ❑  $R$ =link bandwidth (bps)
- ❑  $L$ =packet length (bits)
- ❑  $a$ =average packet arrival rate

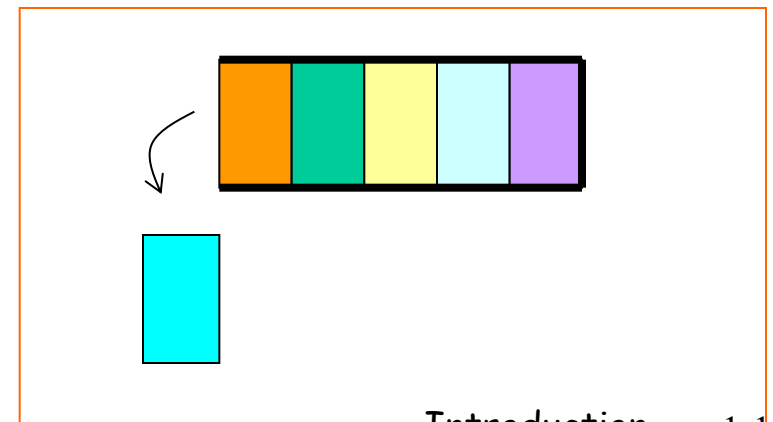
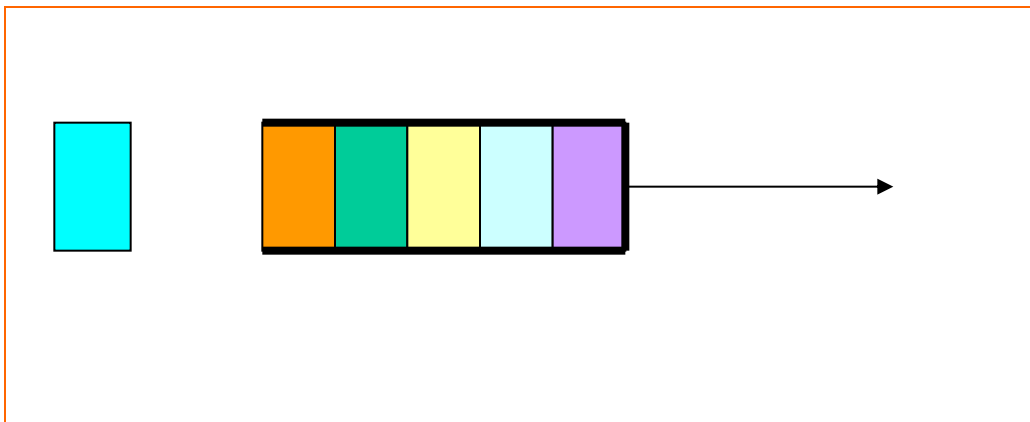
traffic intensity =  $\lambda a / R$



- ❑  $\lambda a / R \sim 0$ : average queueing delay small
- ❑  $\lambda a / R \rightarrow 1$ : delays become large
- ❑  $\lambda a / R > 1$ : more “work” arriving than can be serviced, average delay infinite!

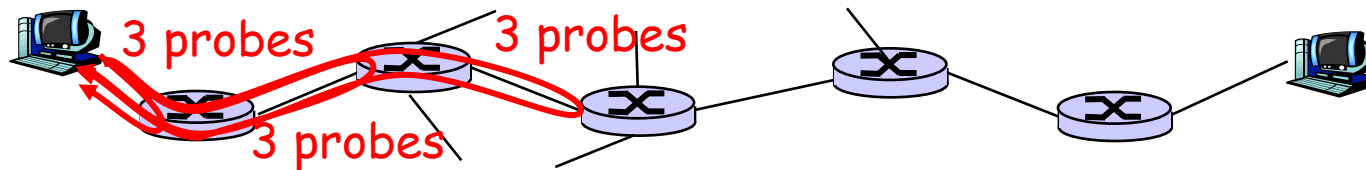
# Packet loss

- ❑ queue (→buffer) preceding link in buffer has finite capacity
- ❑ when packet arrives to full queue, packet is dropped (→lost)
- ❑ lost packet may be retransmitted by previous node, by source end system, or not retransmitted at all



# “Real” Internet delays and routes


- ❑ What do “real” Internet delay & loss look like?
- ❑ Trace route program: provides delay measurement from source to router along end-end Internet path towards destination. For all  $i$ :
  - sends three packets that will reach router  $i$  on path towards destination
  - router  $i$  will return packets to sender
  - sender times interval between transmission and reply.



# “Real” Internet delays and routes

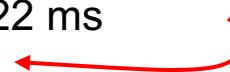
traceroute: gaia.cs.umass.edu to www.eurecom.fr

Three delay measurements from  
gaia.cs.umass.edu to cs-gw.cs.umass.edu



```
1 cs-gw (128.119.240.254) 1 ms 1 ms 2 ms
2 border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145) 1 ms 1 ms 2 ms
3 cht-vbns.gw.umass.edu (128.119.3.130) 6 ms 5 ms 5 ms
4 jn1-at1-0-0-19.wor.vbns.net (204.147.132.129) 16 ms 11 ms 13 ms
5 jn1-so7-0-0-0.wae.vbns.net (204.147.136.136) 21 ms 18 ms 18 ms
6 abilene-vbns.abilene.ucaid.edu (198.32.11.9) 22 ms 18 ms 22 ms
7 nycm-wash.abilene.ucaid.edu (198.32.8.46) 22 ms 22 ms 22 ms
8 62.40.103.253 (62.40.103.253) 104 ms 109 ms 106 ms
9 de2-1.de1.de.geant.net (62.40.96.129) 109 ms 102 ms 104 ms
10 de.fr1.fr.geant.net (62.40.96.50) 113 ms 121 ms 114 ms
11 renater-gw.fr1.fr.geant.net (62.40.103.54) 112 ms 114 ms 112 ms
12 nio-n2.cssi.renater.fr (193.51.206.13) 111 ms 114 ms 116 ms
13 nice.cssi.renater.fr (195.220.98.102) 123 ms 125 ms 124 ms
14 r3t2-nice.cssi.renater.fr (195.220.98.110) 126 ms 126 ms 124 ms
15 eurecom-valbonne.r3t2.ft.net (193.48.50.54) 135 ms 128 ms 133 ms
16 194.214.211.25 (194.214.211.25) 126 ms 128 ms 126 ms
17 * * *
18 * * *
19 fantasia.eurecom.fr (193.55.113.142) 132 ms 128 ms 136 ms
```

trans-oceanic  
link



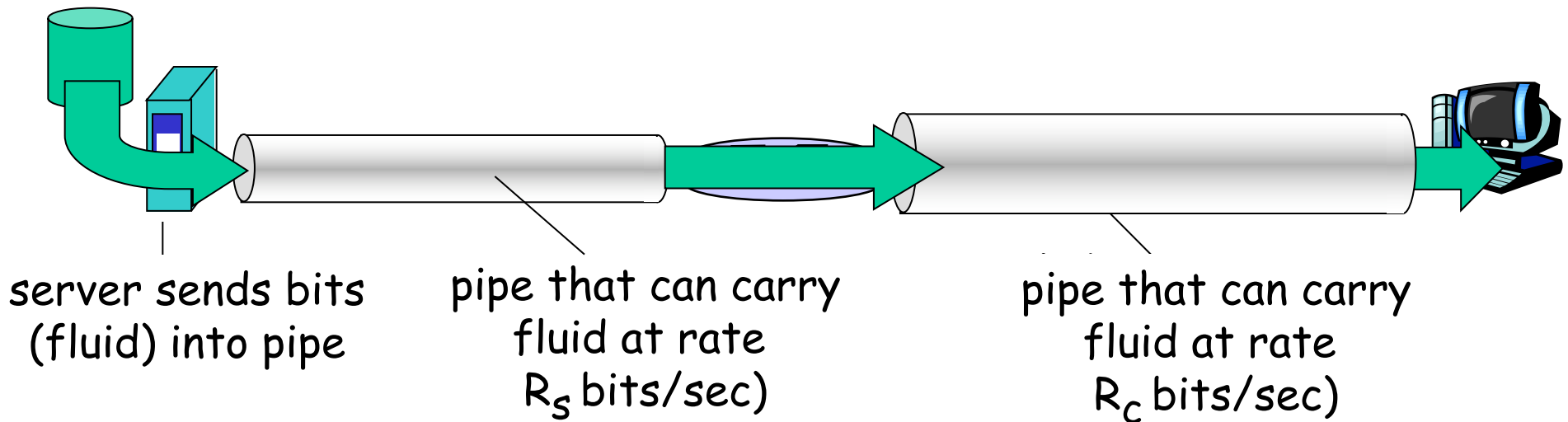
\* means no response (probe lost, router not replying)



Name and address of router, round trip delays (3 samples)

# Throughput

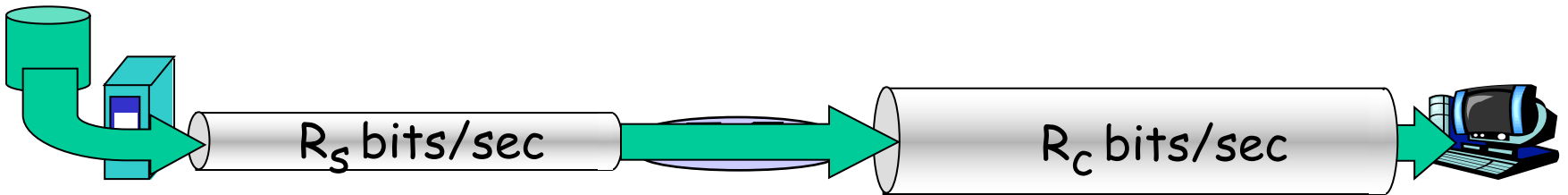
- *throughput*: rate (bits/time unit) at which bits transferred between sender/receiver
  - *instantaneous*: rate at given point in time
  - *average*: rate over longer period of time



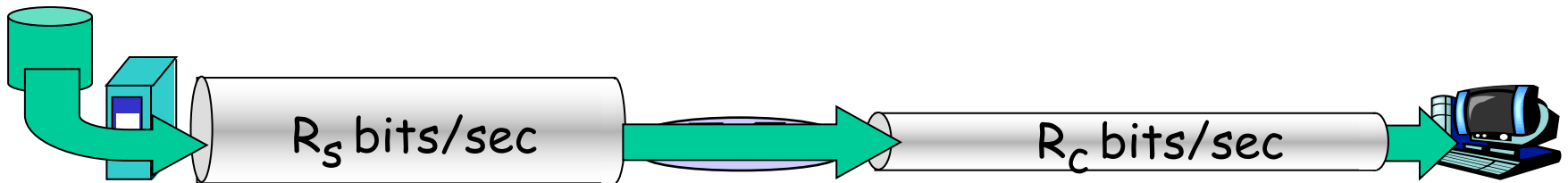


# Throughput (more)

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



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

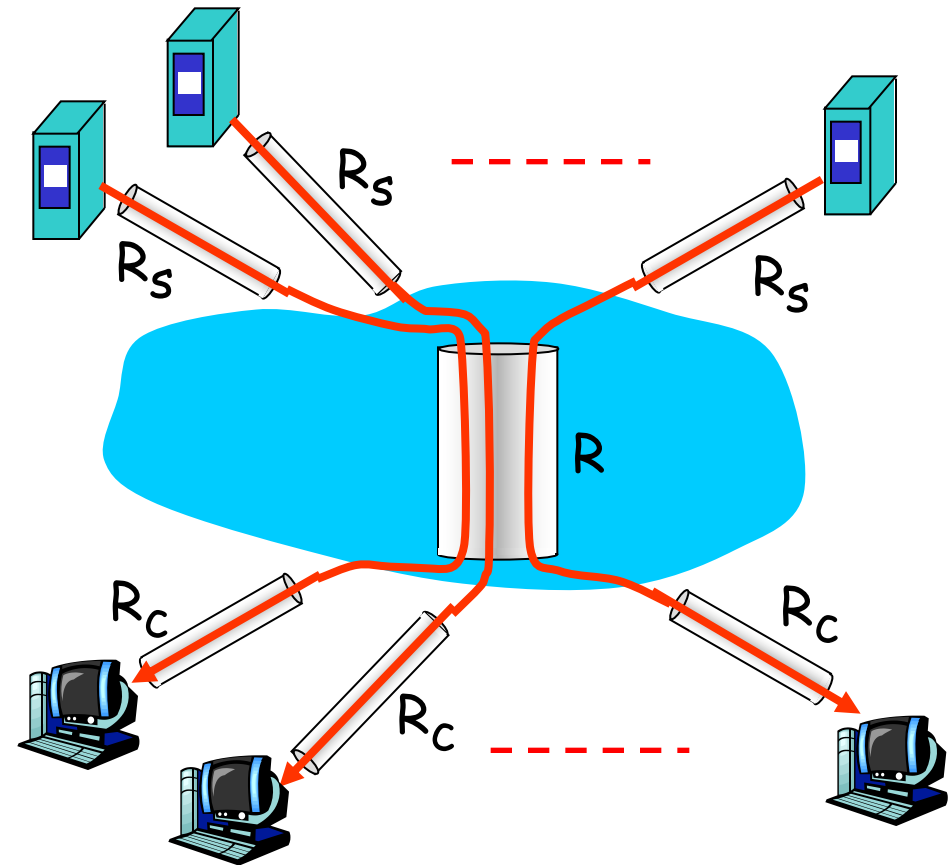


*bottleneck link*

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

# Chapter 1: roadmap

1.1 What *is* the Internet?

1.2 Network edge

1.3 Network core

1.4 Network access and physical media

1.5 Internet structure and ISPs

1.6 Delay & loss in packet-switched networks

1.7 Protocol layers, service models

1.8 History

# Protocol “Layers”

## Networks are complex!

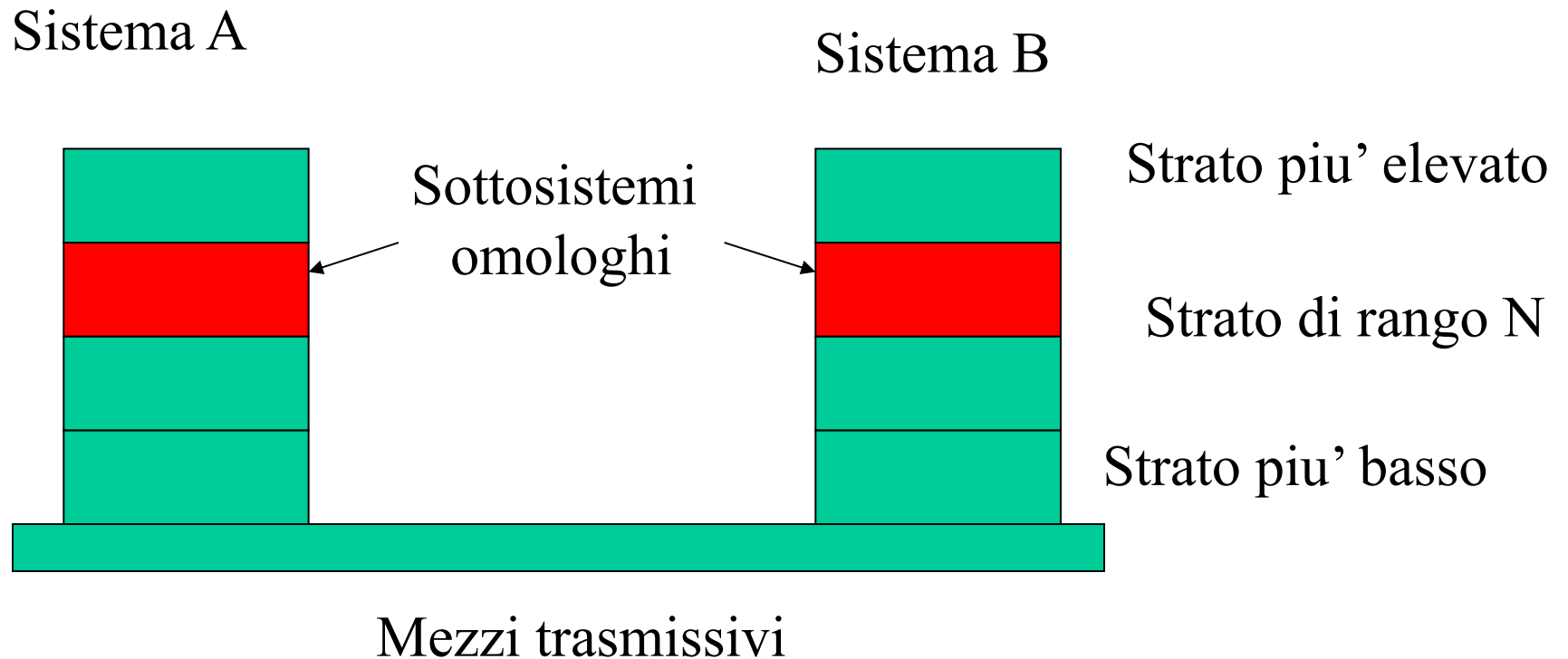
- many “pieces”:
  - hosts
  - routers
  - links of various media
  - applications
  - protocols
  - hardware, software

## Question:

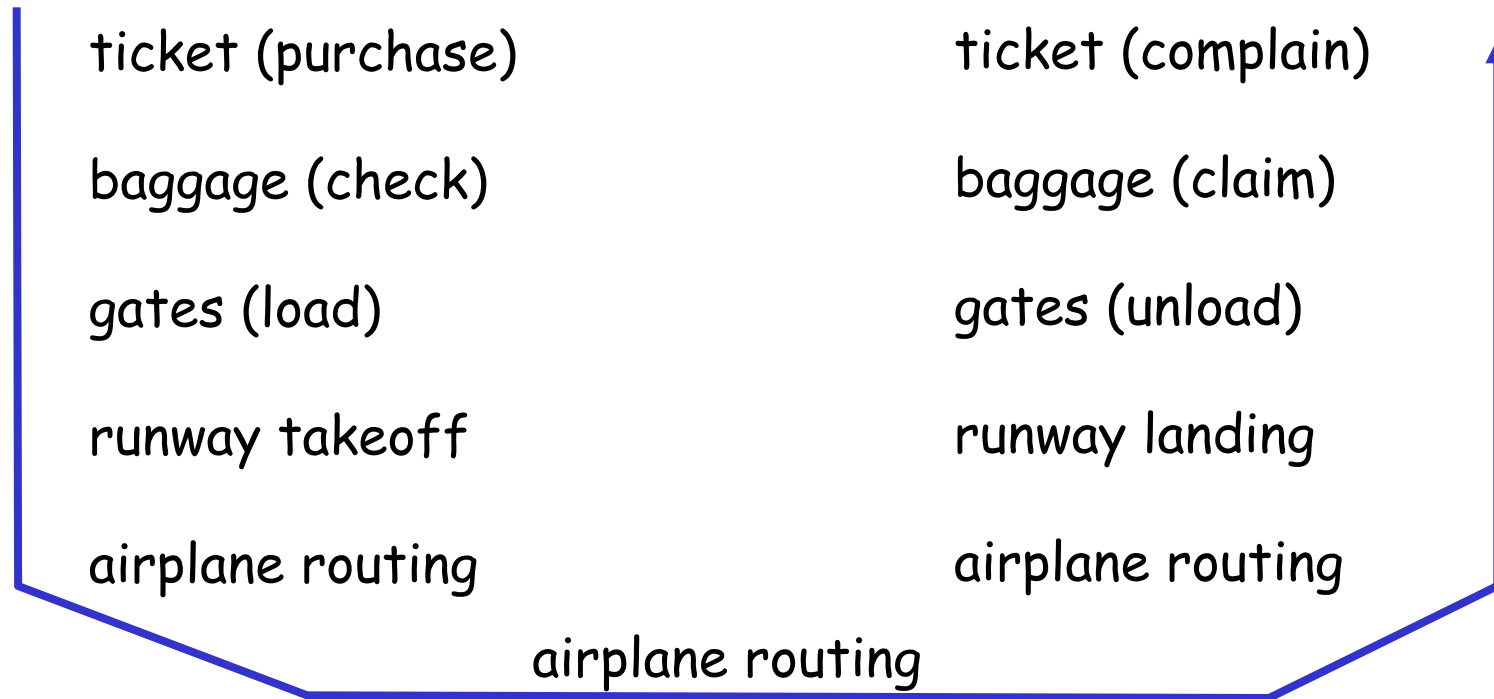
Is there any hope of  
*organizing* structure of  
network?

Or at least our discussion of  
networks?

# Layering



# Organization of air travel



□ a series of steps



# Organization of air travel: a different view

ticket (purchase)	ticket (complain)
baggage (check)	baggage (claim)
gates (load)	gates (unload)
runway takeoff	runway landing
airplane routing	airplane routing
airplane routing	

**Layers:** each layer implements a service

- via its own internal-layer actions
- relying on services provided by layer below

# Layered air travel: services

Counter-to-counter delivery of person+bags

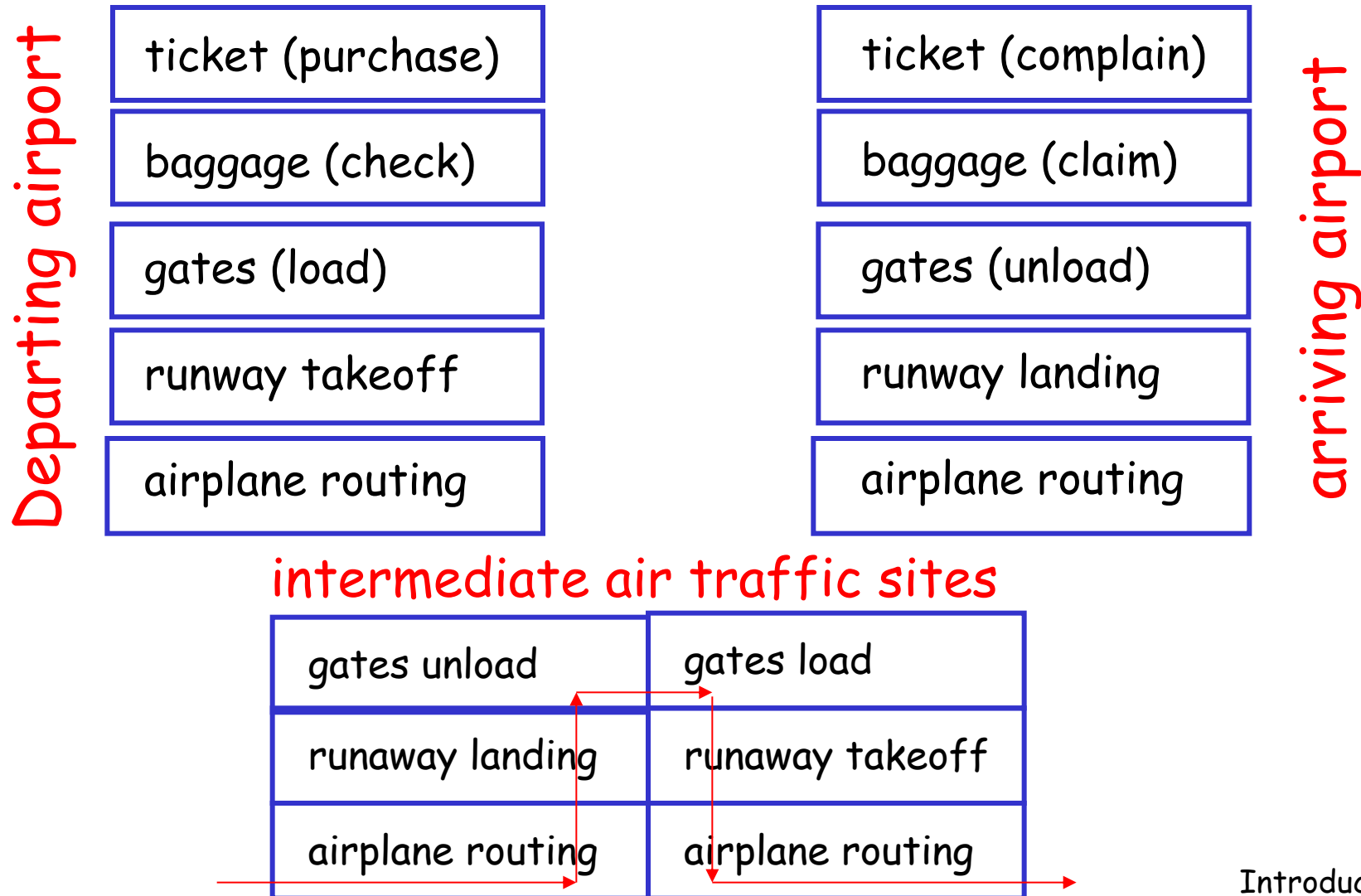
baggage-claim-to-baggage-claim delivery

people transfer: loading gate to arrival gate

runway-to-runway delivery of plane

airplane routing from source to destination

# Distributed implementation of layer functionality



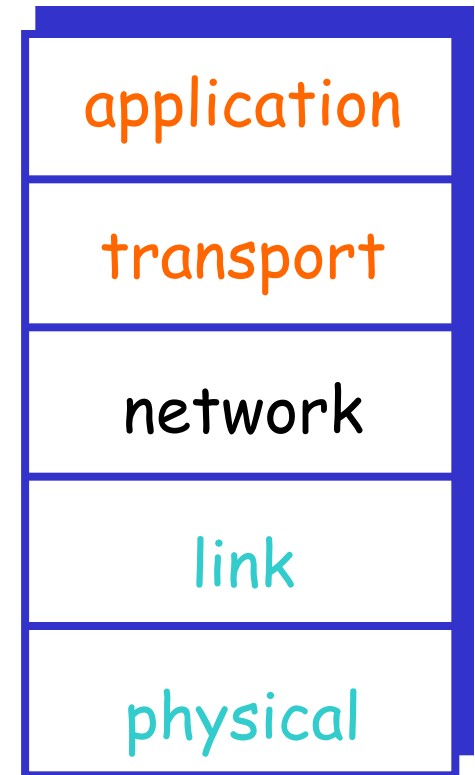
# Why layering?

## Dealing with complex systems:

- ❑ explicit structure allows identification, relationship of complex system's pieces
  - layered **reference model** for discussion
- ❑ modularization eases maintenance, updating of system
  - change of implementation of layer's service transparent to rest of system
  - e.g., change in gate procedure doesn't affect rest of system (I.e. if baggage check and claim procedures changed due to Sept 11<sup>th</sup> or if the boarding rules change, boarding people by age)
- ❑ layering considered harmful?

# Internet protocol stack

- ❑ **application:** supporting network applications
  - FTP, SMTP, HTTP
- ❑ **transport:** 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”

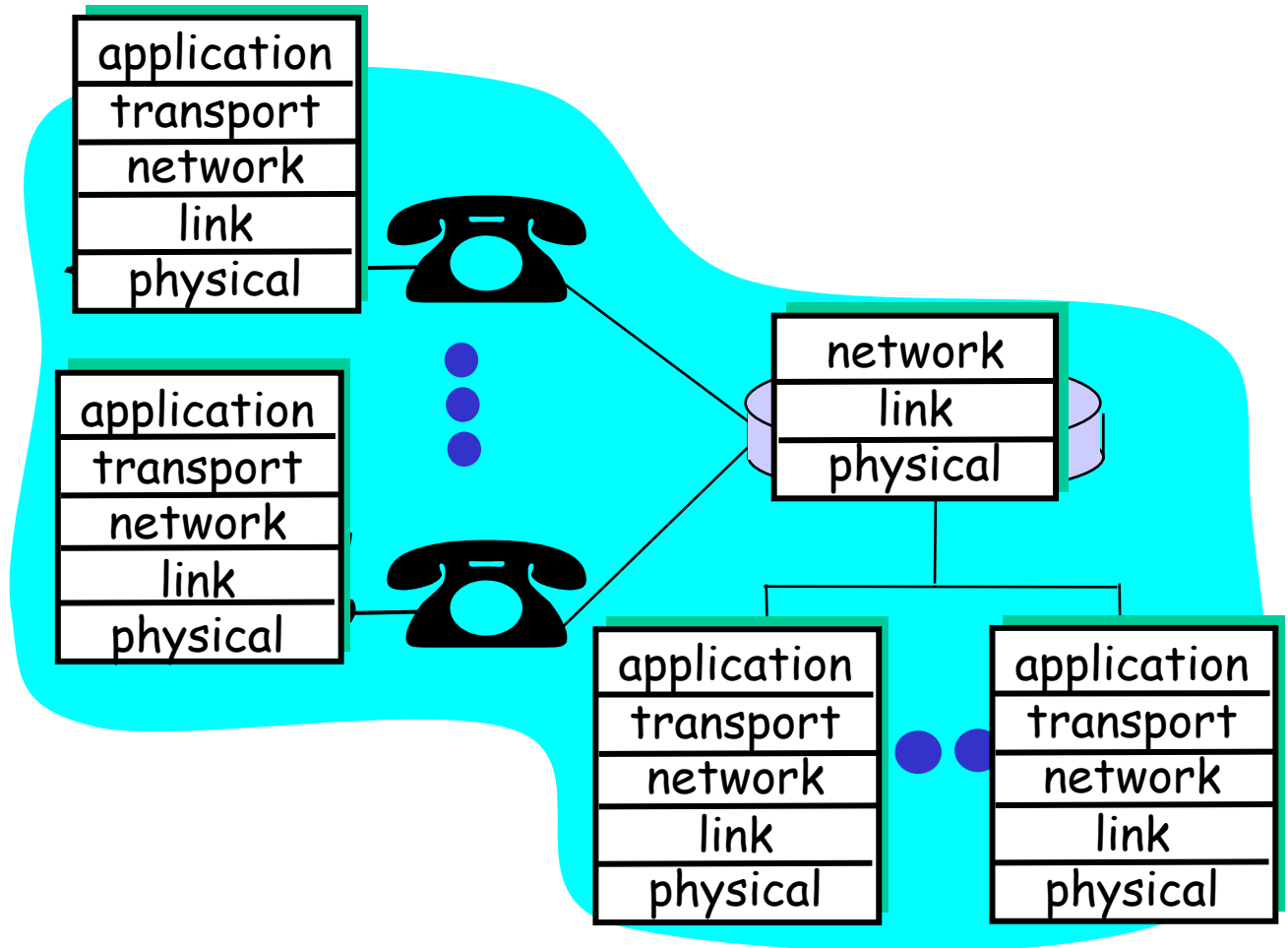


Typically in HW  
Typically SW

# Layering: logical communication

Each layer:

- ❑ distributed
- ❑ “entities” implement layer functions at each node
- ❑ entities perform actions, exchange messages with peers

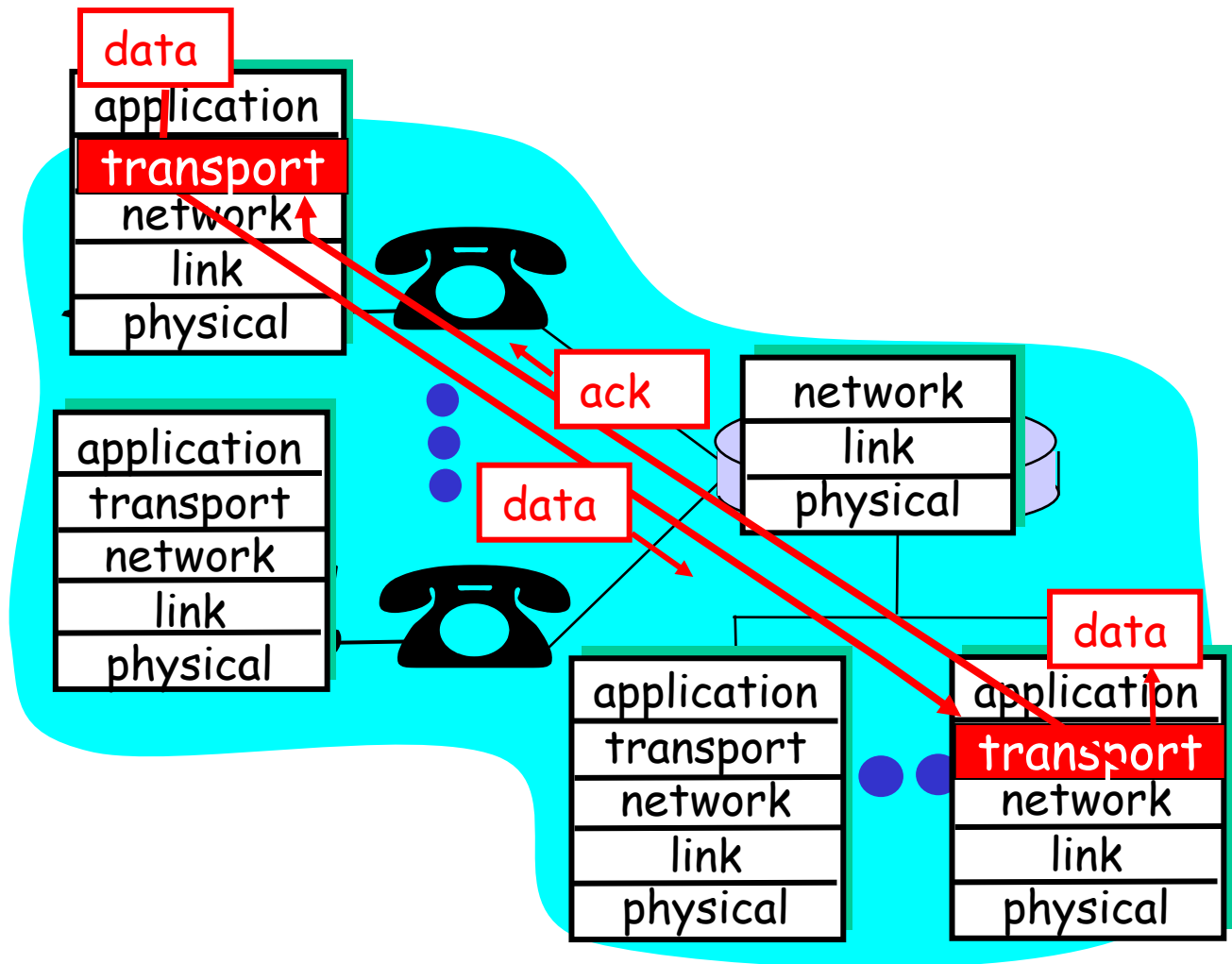




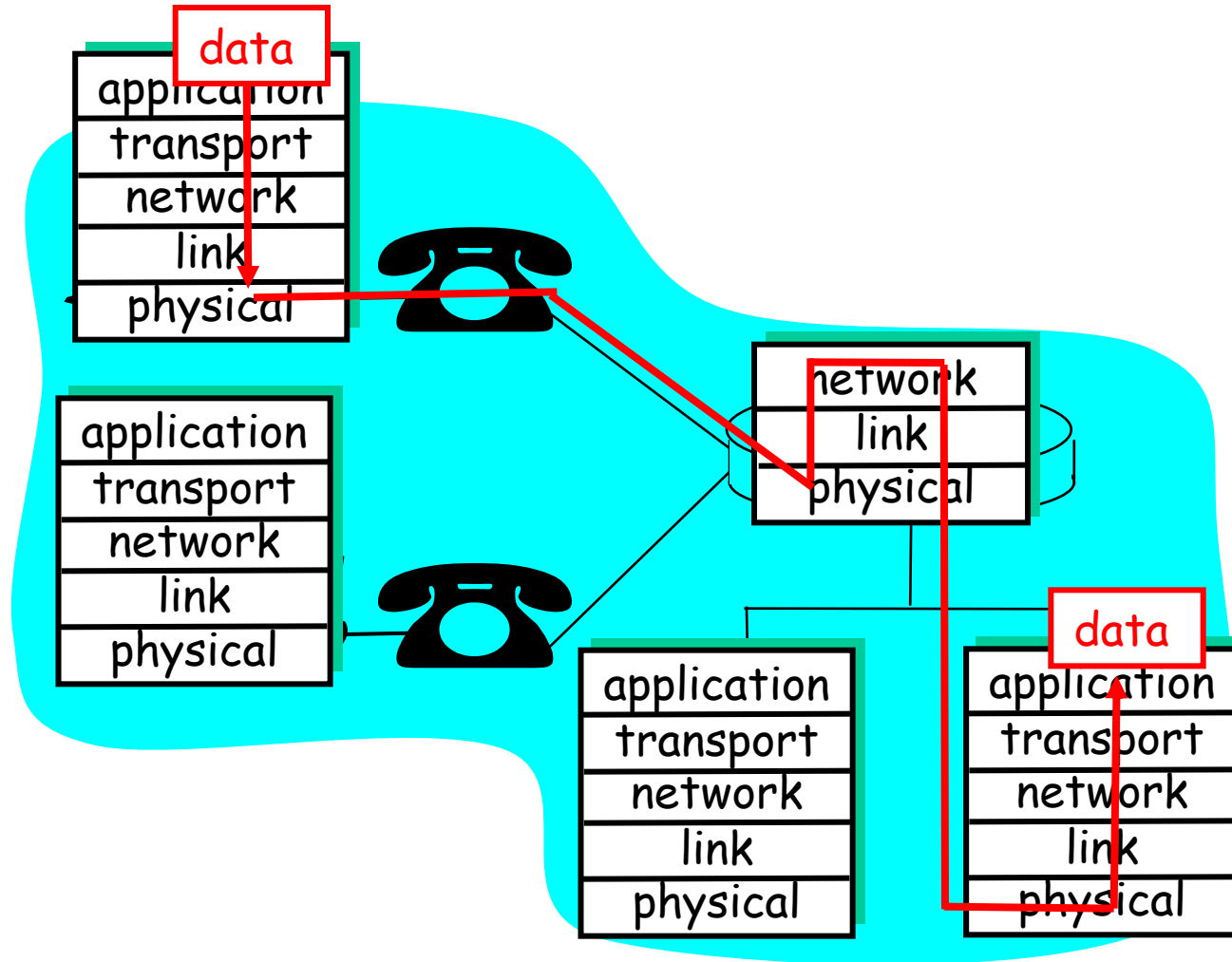
# Layering: logical communication

## E.g.: transport

- ❑ take data from app
- ❑ add addressing, reliability check info to form “datagram”
- ❑ send datagram to peer
- ❑ wait for peer to ack receipt
- ❑ analogy: post office



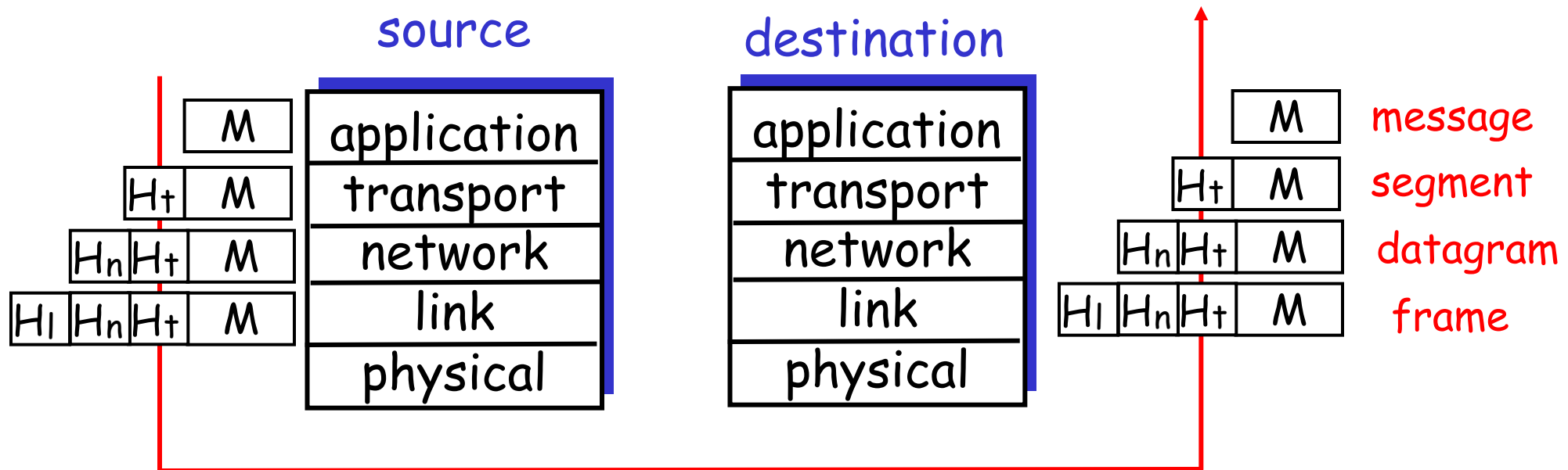
# Layering: physical communication



# Protocol layering and data

Each layer takes data from above

- adds header information to create new data unit
- passes new data unit to layer below



# Layering: pros

## ❑ Vantaggi della stratificazione

### ○ Modularita'

- Semplicita' di design
- Possibilita' di modificare un modulo in modo trasparente se le interfacce con gli altri livelli rimangono le stesse
- Possibilita' per ciascun costruttore di adottare la propria implementazione di un livello purché requisiti su interfacce soddisfatti

### ○ Gestione dell'eterogeneita'

- Possibili moduli 'diversi' per realizzare lo stesso insieme di funzioni, che riflettano l'eterogeneita' dei sistemi coinvolti (e.g. diverse tecnologie trasmissive, LAN, collegamenti punto-punto, ATM etc.)
- Moduli distinti possibili/necessari anche se le reti adottassero tutte la stessa tecnologia di rete perche' ad esempio le applicazioni possono avere requisiti diversi (es. UDP e TCP). All'inizio TCP ed IP erano integrati. Perche' adesso sono su due livelli distinti?

# Layering: cons

## ❑ Svantaggi della stratificazione

- A volte modularita' inficia efficienza
- A volte necessario scambio di informazioni tra livelli non adiacenti non rispettando principio della stratificazione

# Internet History

## *1961-1972: Early packet-switching principles*

- ❑ 1961: Kleinrock - queueing theory shows effectiveness of packet-switching (MIT)
  - ❑ 1964: Baran - packet-switching in military nets
  - ❑ Davies at the National Physical Laboratory, UK was also developing ideas on packet switching
  - ❑ 1967: ARPAnet conceived by Advanced Research Projects Agency
  - ❑ 1969: first ARPAnet node operational
- Packet switches dubbed Interface Message Processors (IMP)
- ❑ 1972:
    - ARPAnet demonstrated publicly by Robert Kahn
    - NCP (Network Control Protocol) first host-host protocol
    - first e-mail program
    - ARPAnet has 15 nodes



- Leonard Kleinrock with first IMP

Kleinrock's students:  
**Vinton Cerf**  
John Postel...

Network measurement  
center UCLA

# Internet History

## *1972-1980: Internetworking, new and proprietary nets*

- ❑ 1970: ALOHAnet satellite network in Hawaii (Abramson)
- ❑ 1973: Metcalfe's PhD thesis proposes Ethernet
- ❑ 1974: Cerf and Kahn - architecture for interconnecting networks
- ❑ late70's: proprietary architectures, e.g. IBM SNA (Schwartz)
- ❑ late 70's: switching fixed length packets (ATM precursor)
- ❑ 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
- ❑ 1982: SMTP e-mail protocol defined
- ❑ 1983: DNS defined for name-to-IP-address translation
- ❑ 1985: FTP protocol defined
- ❑ 1988: TCP congestion control
- ❑ 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, peer2peer file sharing (e.g., Napster)
- ❑ network security to forefront
- ❑ est. 50 million host, 100 million+ users
- ❑ backbone links running at Gbps

Significant late developments: P2P, broadband access, wireless Internet

# Recent trends (2000-today)

- ❑ Intense evolution
- ❑ Aggressive deployment of broadband Internet access to homes
  - enabler of distribution of user generated videos, on demand streaming videos, multi-person video conferencing services
- ❑ Ubiquitous deployment of high speed wireless access
  - number of wireless devices connected to Internet > wired devices from 2011
- ❑ Development of social networks
- ❑ Companies such as Google and Microsoft have developed extensive private networks
- ❑ Internet commerce companies and institutions run their applications on the cloud

A short digression:

where is Internet standardized?

Who controls the Internet?

- ❑ No single administrative organization
- ❑ IETF - Internet Engineering Task Force (since 86)
  - Developement of current protocols and specifications for standardization.
    - International community, open to everyone
    - Most of the work via mailing lists
    - Meets three times/year
  - organized in areas and working groups
    - Dynamically activated & deactivated on need
    - group coordination: IESG (Internet Engineering Steering Group). Area directors are members of the IESG. Responsible for the actions associated with entry into and movement along the Internet "standards track," including final approval of specifications as Internet Standards.
- ❑ Industry also preemptively determine standards