DATA COMMUNICATOIN NETWORKING

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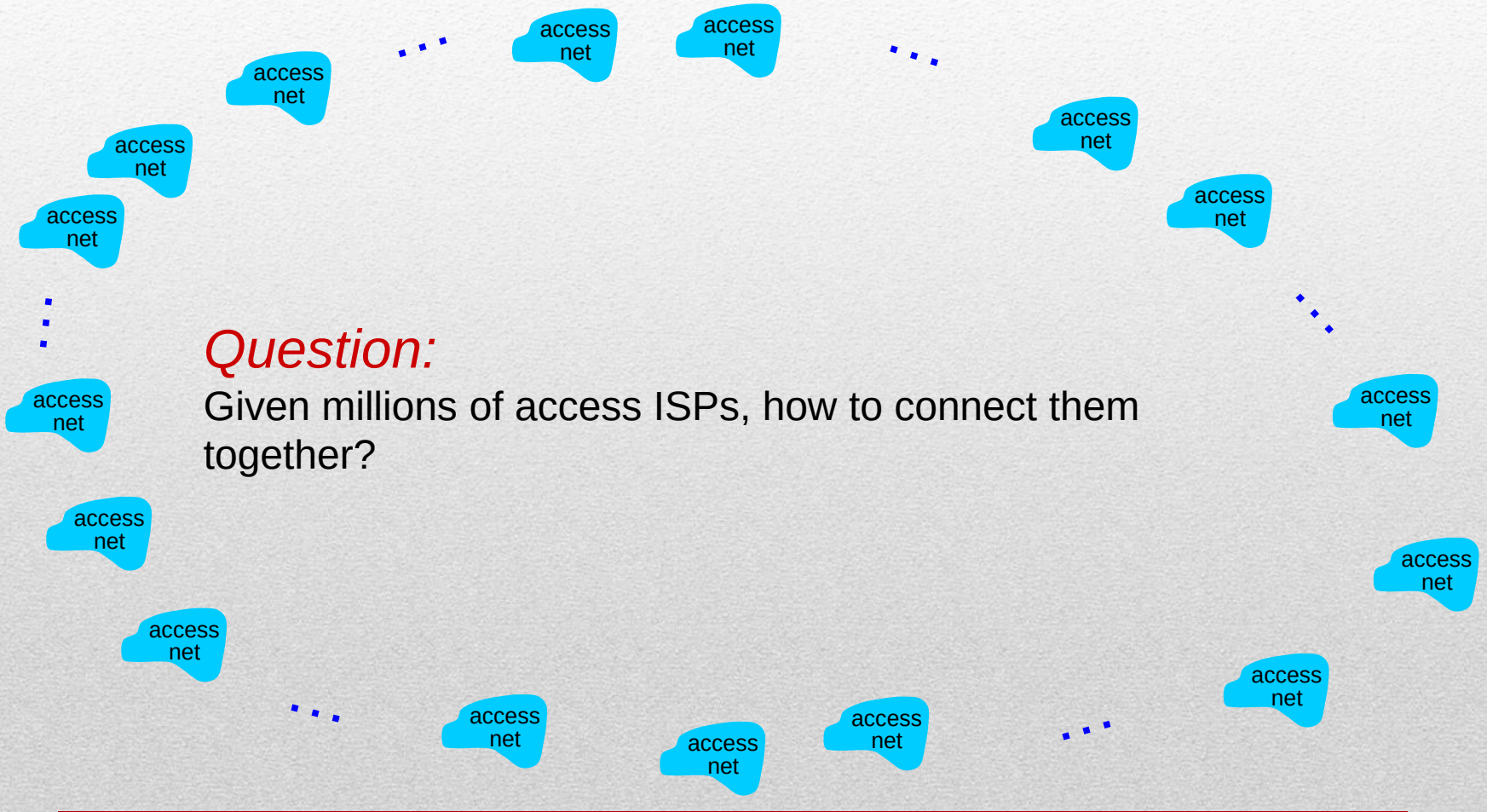
Course Textbook: Computer Networking: A Top-Down Approach
Kurose, Ross

Internet: Network of Networks

- **Internet Service Providers (ISPs)**
  - Connect the end systems to the Internet
    - Residential
    - Company
    - University
- **Access ISPs interconnected**
  - Complex connection among ISPs connected to end hosts

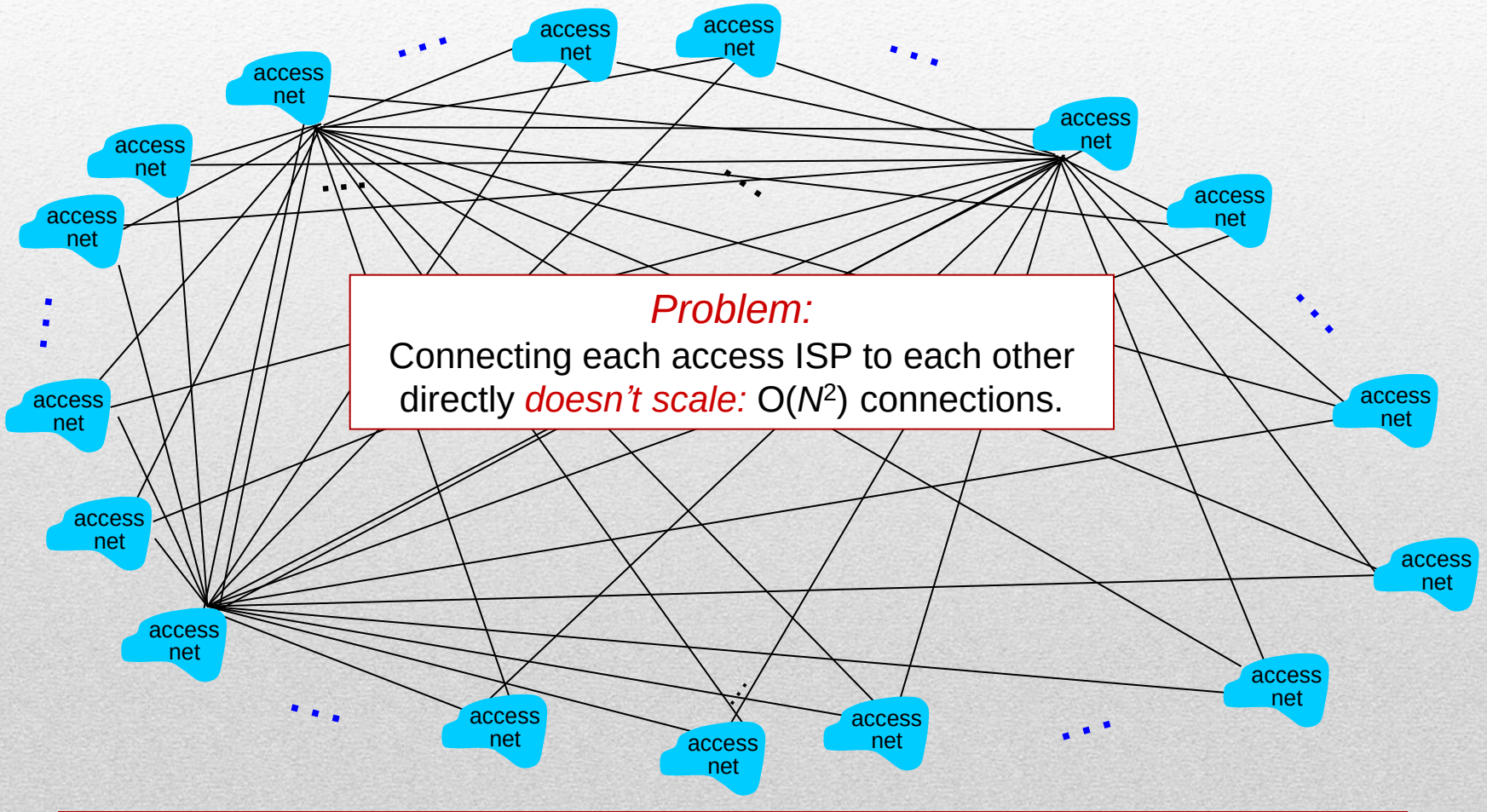
Internet: Network of Networks



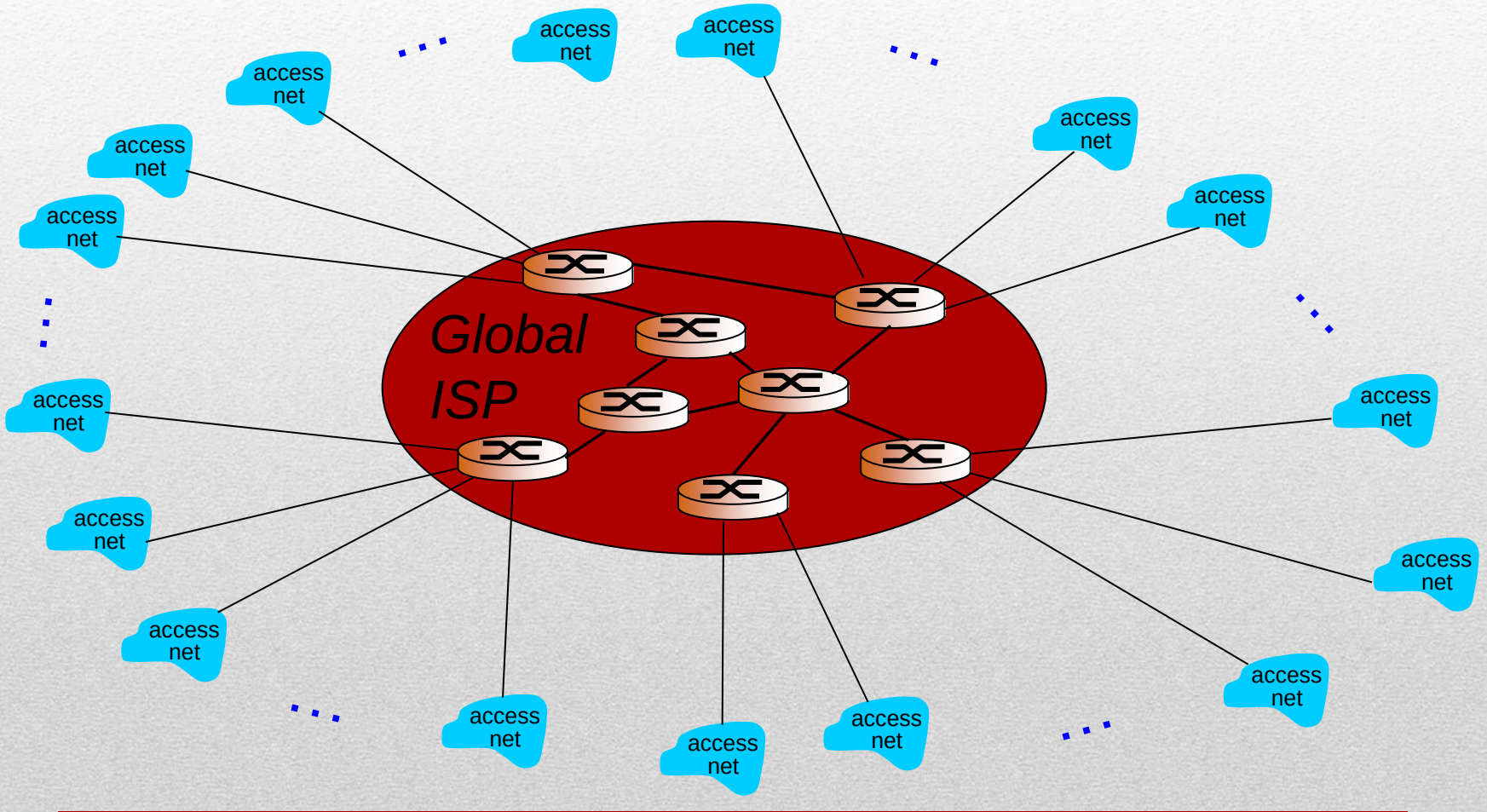
Question:

Given millions of access ISPs, how to connect them together?

Internet: Network of Networks



Internet: Network of Networks



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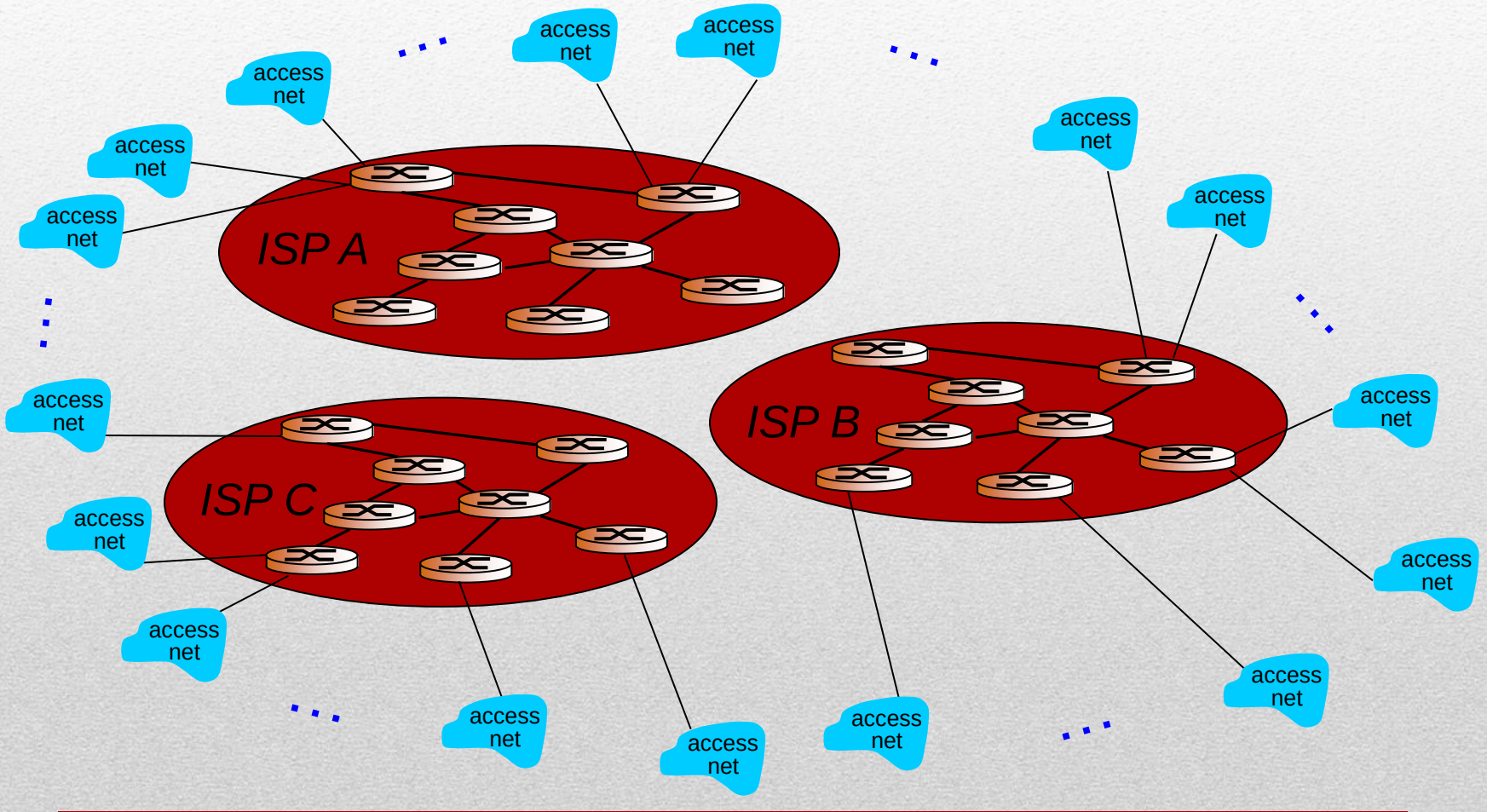
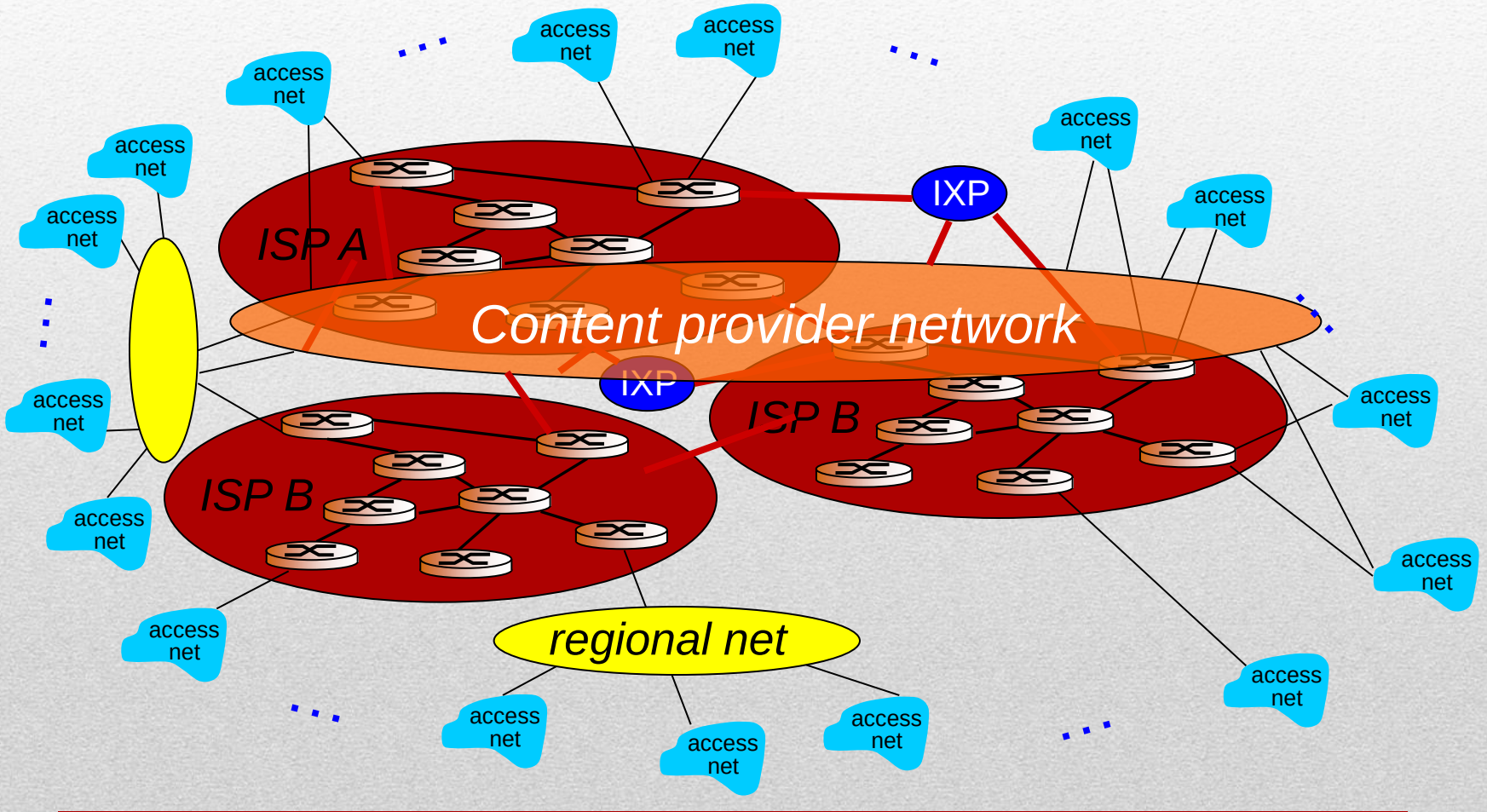


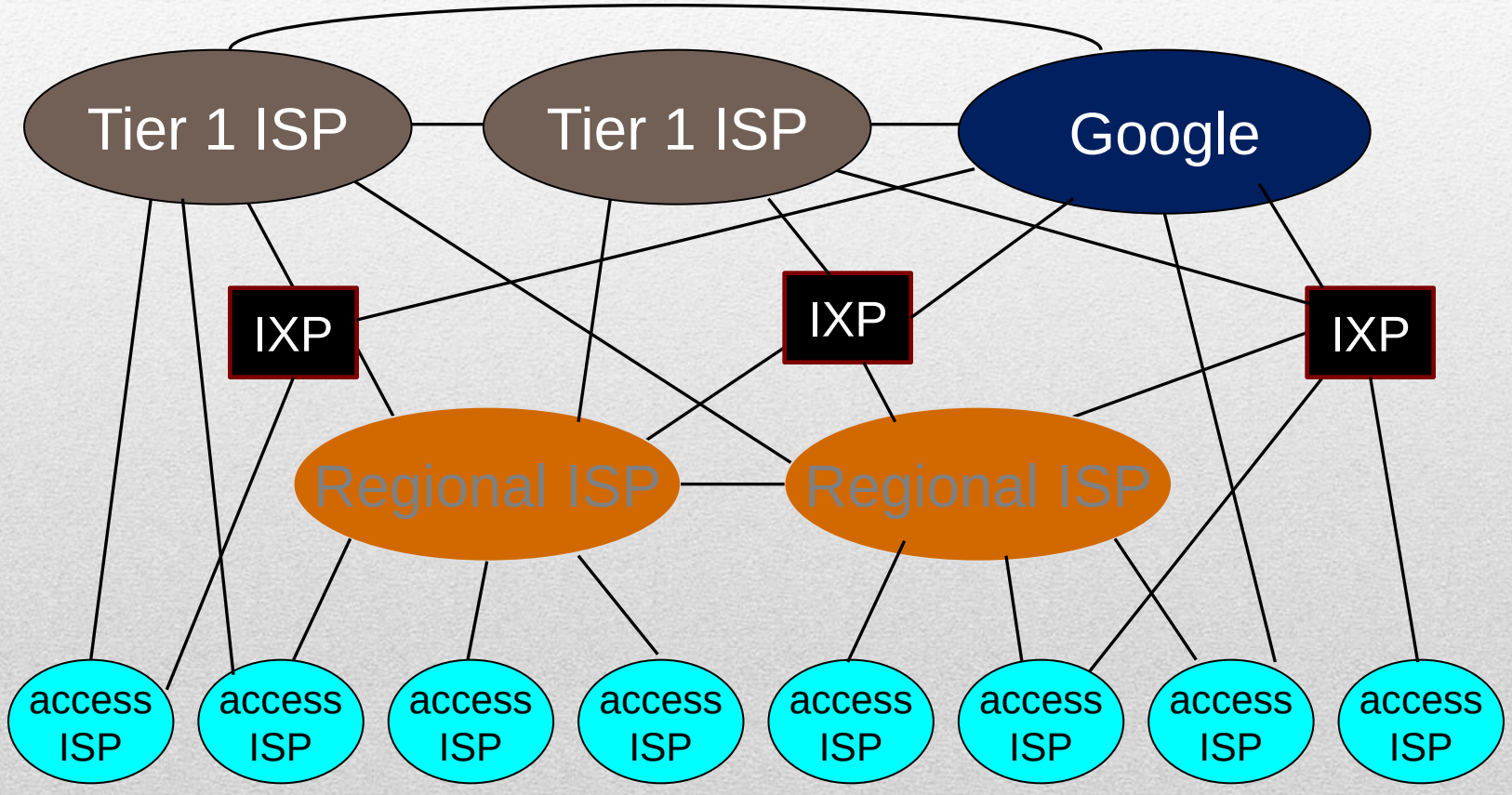
Internet: Network of Networks

- **Global Transit ISP**
  - Customer and Provider ISPs have economic agreements
  - Competitor Global Transit ISPs will start
    - Competitors must be connected
      - Internet Exchange Points(IXPs) and Peering Links
- **Regional Networks**
  - Regional ISPs to connect access networks to ISPs
- **Content Provider Networks**
  - Microsoft, Google, Akamai
  - Bring servicers close to end user

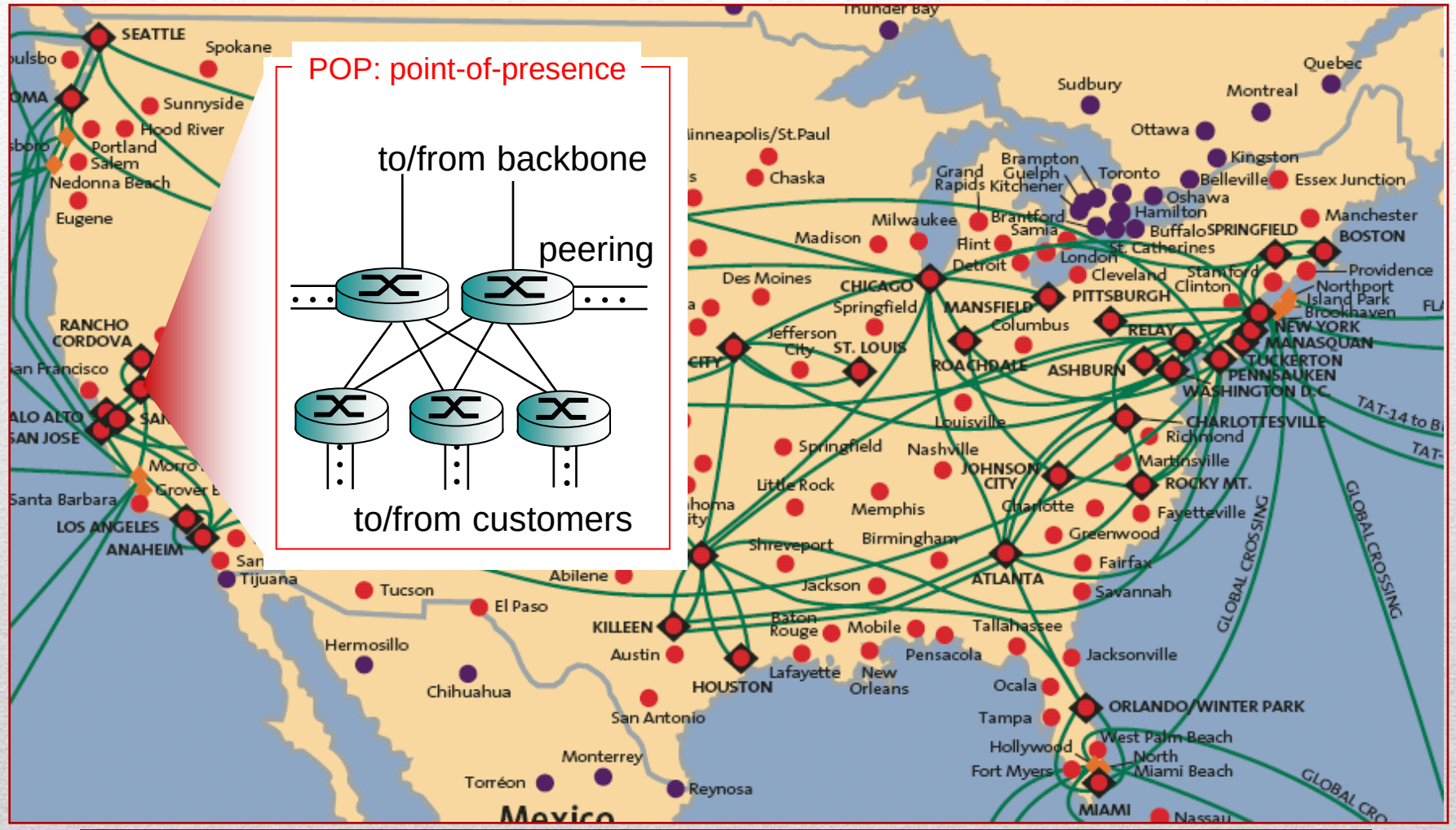
Internet: Network of Networks



Internet: Network of Networks



Tier-1 ISP

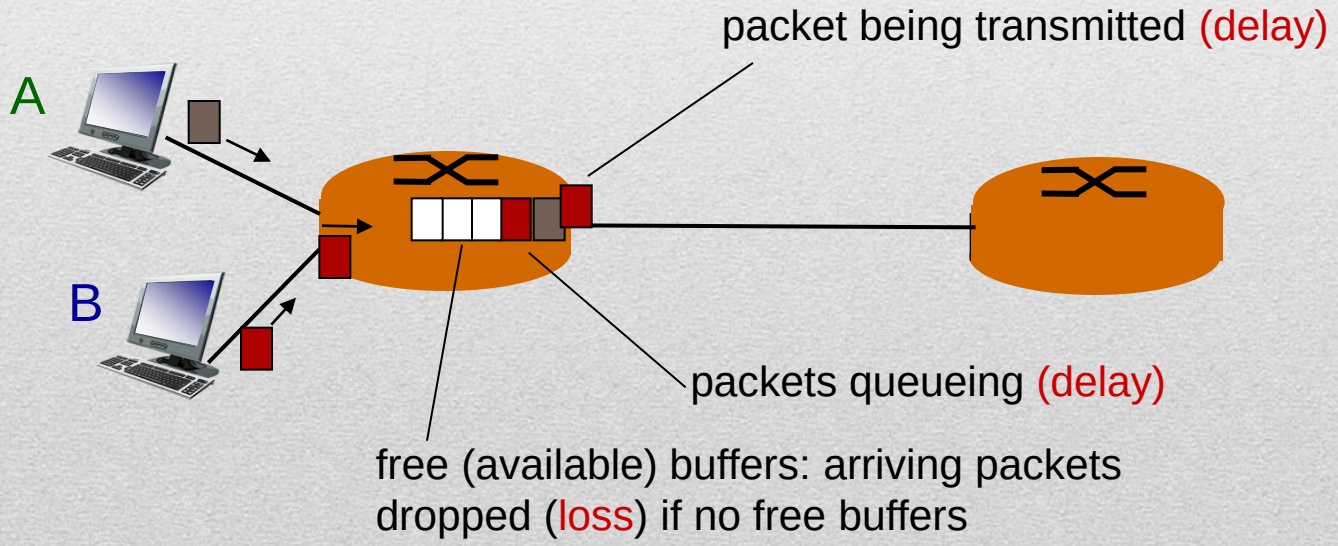

POP: point-of-presence
to/from backbone
peering
to/from customers
SEATTLE
Spokane
Sunnyside
Hood River
Portland
Salem
Nedonna Beach
Eugene
RANCHO CORDOVA
SAN JOSE
Santa Barbara
LOS ANGELES
ANAHEIM
Tijuana
Tucson
El Paso
Hermosillo
Chihuahua
Monterrey
Torréon
Reynosa
Mexico
Abilene
KILLEEN
Austin
HOUSTON
San Antonio
Lafayette
Baton Rouge
New Orleans
Mobile
Tallahassee
Pensacola
Jackson
Shreveport
Little Rock
Memphis
Birmingham
ATLANTA
Jacksonville
Ocala
Tampa
ORLANDO/WINTER PARK
Hollywood
West Palm Beach
Fort Myers
North Miami Beach
MIAMI
Nassau
Thunder Bay
Sudbury
Ottawa
Montreal
Quebec
Kingston
Belleville
Essex Junction
Toronto
Brampton
Guelph
Kitchener
Grand Rapids
Oshawa
Hamilton
Buffalo
Brantford
Samia
Milwaukee
Madison
Flint
Detroit
London
St. Catherines
Cleveland
Stamford
Clinton
SPRINGFIELD
BOSTON
Manchester
Providence
Northport
Island Park
Brookhaven
NEW YORK
MANASQUAN
TUCKERTON
PENNSAUKEN
WASHINGTON D.C.
CHARLOTTESVILLE
Richmond
Martinsville
ROCKY MT.
Fayetteville
Greenwood
Fairfax
Savannah
Charlotte
JOHNSON CITY
Nashville
Louisville
Springfield
CHICAGO
Springfield
Des Moines
Jefferson City
ST. LOUIS
MANSFIELD
Columbus
PITTSBURGH
RELAY
ROACHDALE
ASHBURN
Chaska
Minneapolis/St.Paul
TAT-14 to B
GLOBAL CROSSING

Introduction to networks & the Internet

- **Internet**
  - Network of networks
    - Network Edge
      - Access Networks
    - Network Core
      - Packet Switching
      - Circuit Switching
    - ISP Structure
      - Access ISPs
      - Regional Networks
      - Global ISPs
      - IXPs
- **Loss, Delay,…**
- **Protocol Stack**
- **Service Model**

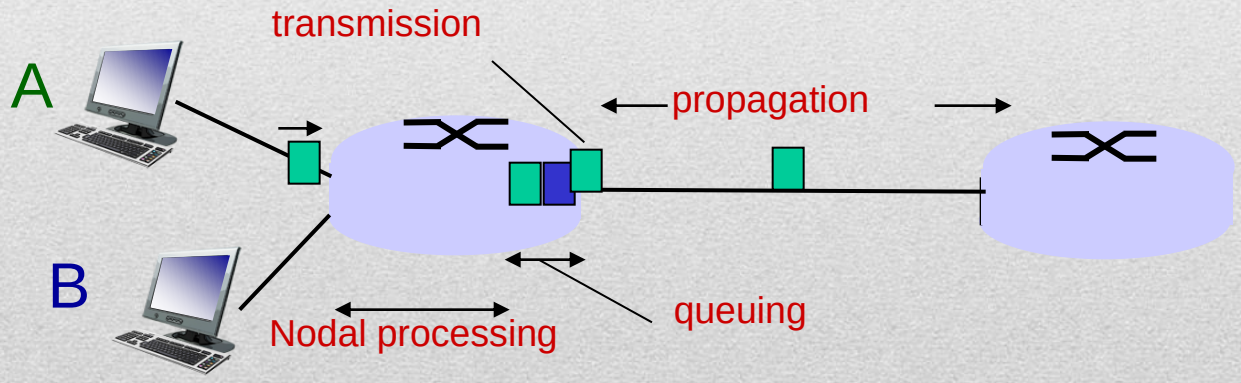
Packet Delay & Loss

- **Queue in router buffers**
  - Packet arrival rate to link temporarily exceeds output link capacity
    - Waiting packets in buffer → Delay
    - Full Buffer: Packets Dropped → Loss



Packet Delay

- **Delay**
  - **Transmission:** Transmission using the limited capacity medium
  - **Propagation:** Propagation in the medium
  - **Processing:** Checking the bit error, determining output link,…
  - **Queuing:** Waiting to be sent at the output link
    - depends on the congestion level of the router



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

Packet Delay

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d_{trans}: transmission delay:

- *L*: packet length (bits)
- *R*: link *bandwidth (bps)*
- $d_{trans} = L/R$

d_{prop}: propagation delay:

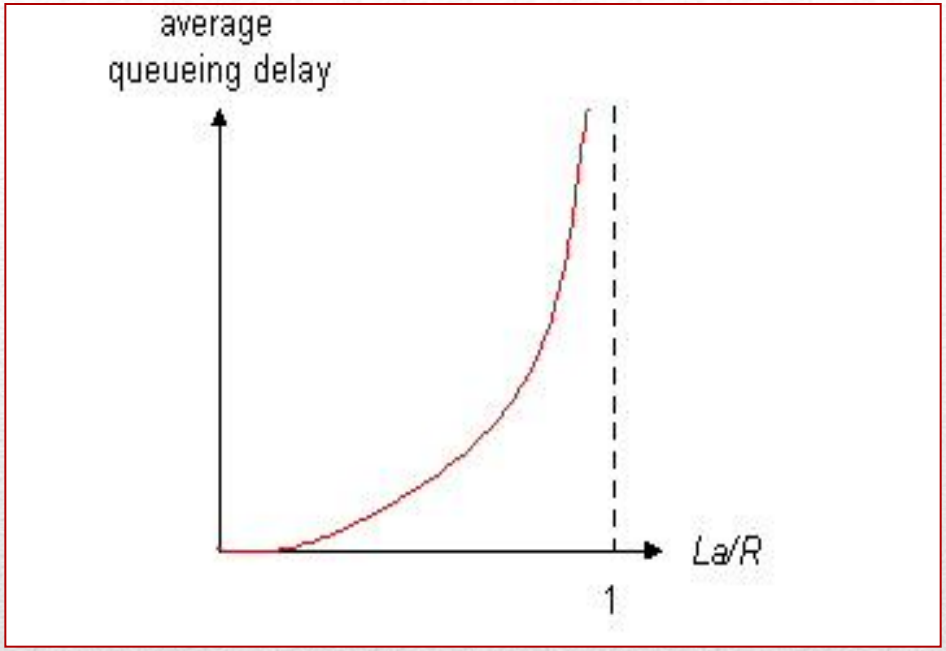
- *d*: length of physical link
- *s*: propagation speed in medium ($\sim 2 \times 10^8$ m/sec)
- $d_{prop} = d/s$

Queuing Delay

R: link bandwidth (bps)

L: packet length (bits)

a: average packet arrival rate



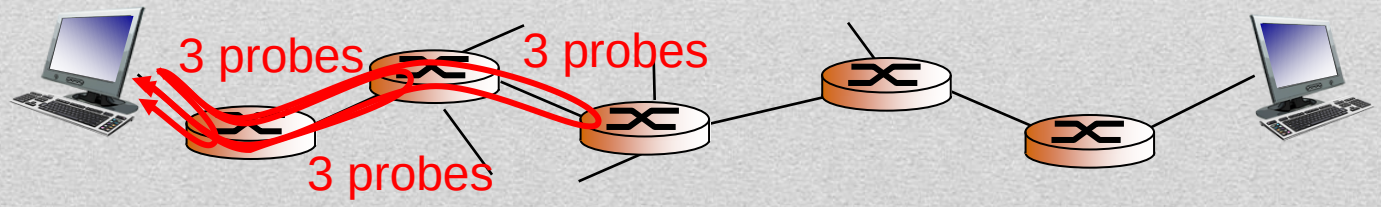
- *La/R* ~ 0: avg. queuing delay small
- *La/R* -> 1: avg. queuing delay large
- *La/R* > 1: more "work" arriving than can be serviced, average delay infinite!

La/R ~ 0

La/R -> 1

Real Internet Delays & Routes

- **Traceroute**
  - E.g. "Traceroute cs.sfu.ca"
  - www.traceroute.org
  - 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 & Routes

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

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

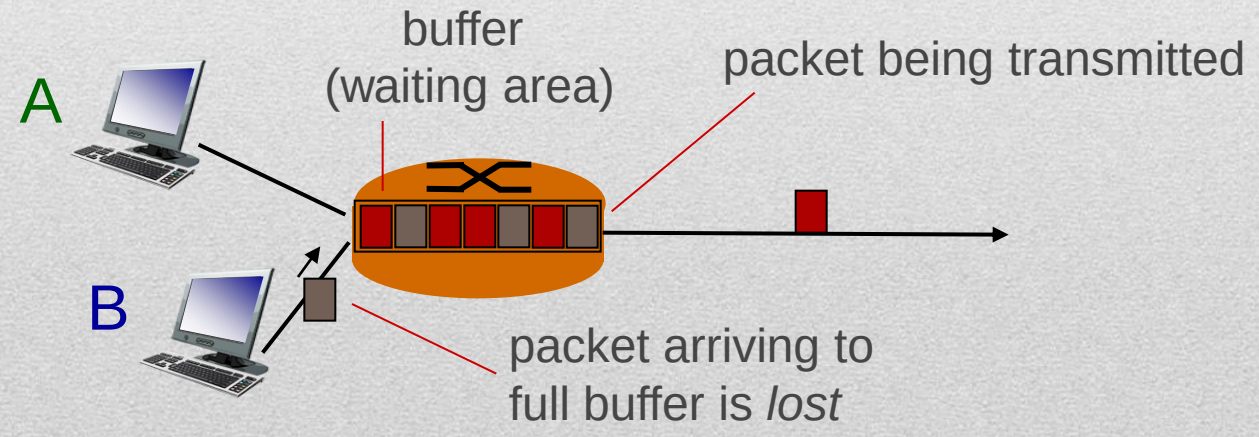
```
1  cs-gw (128.119.240.254)  1 ms  1 ms  2 ms
2  border1-rt-fa5-1-0.gw.umass.edu (128.119.3.145)  1 ms  1 ms  2 ms
3  cht-vbns.gw.umass.edu (128.119.3.130)  6 ms 5 ms 5 ms
4  jn1-at1-0-0-19.wor.vbns.net (204.147.132.129)  16 ms 11 ms 13 ms
5  jn1-so7-0-0-0.wae.vbns.net (204.147.136.136)  21 ms 18 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)

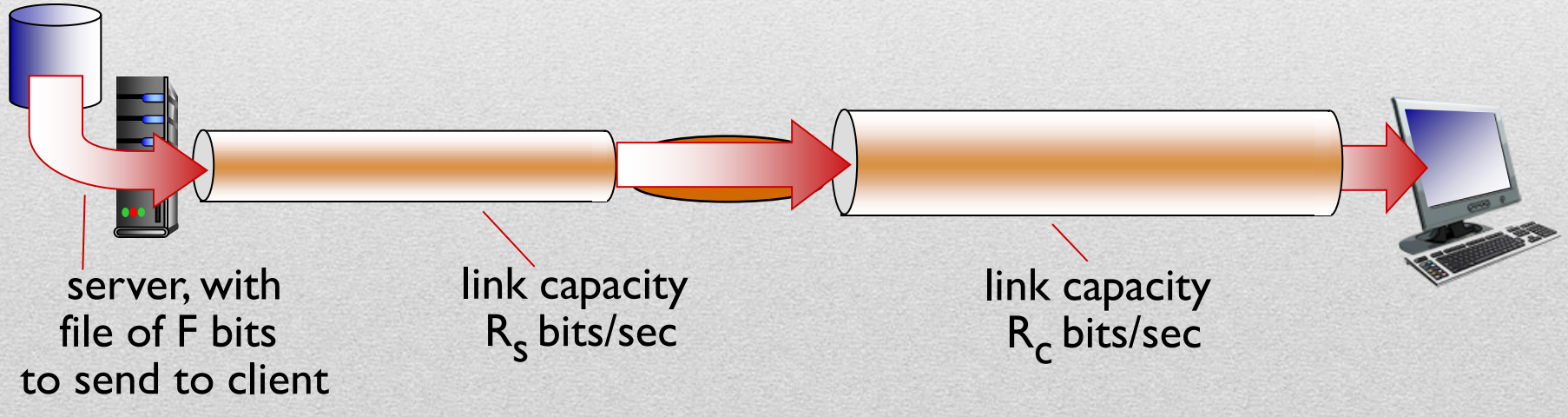
Packet Loss

- Queue (buffer) preceding link in buffer has finite capacity
- Packet arriving to full queue dropped (lost)
- Lost packet may be retransmitted by previous node, by source end system, or not at all



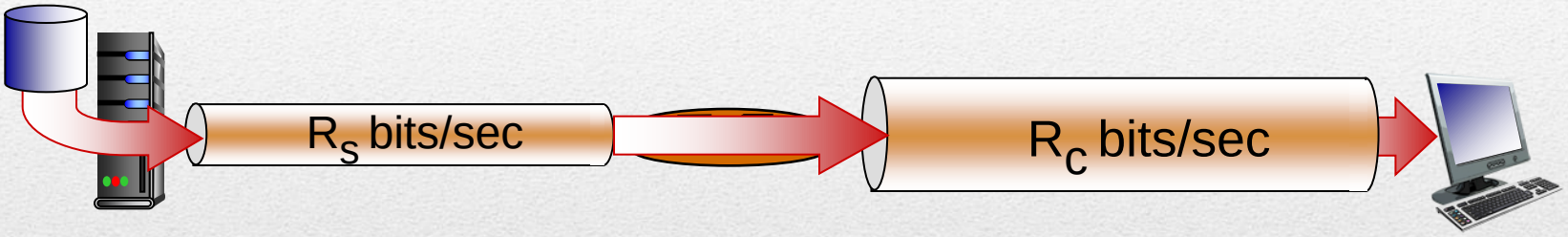
Throughput

- *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

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



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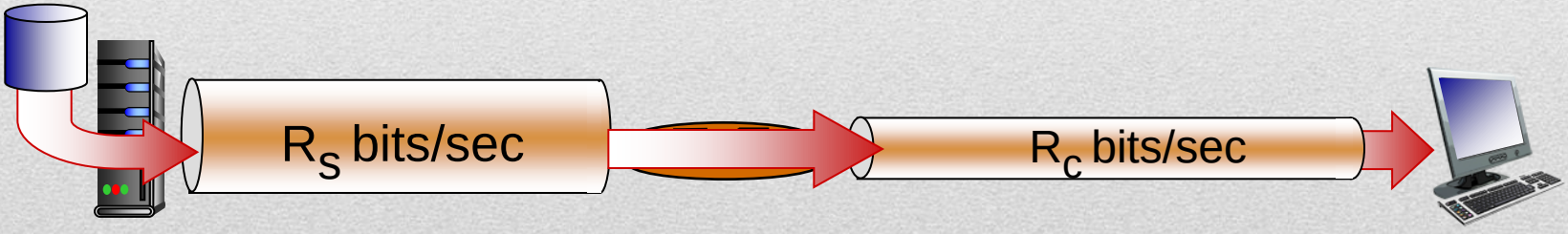
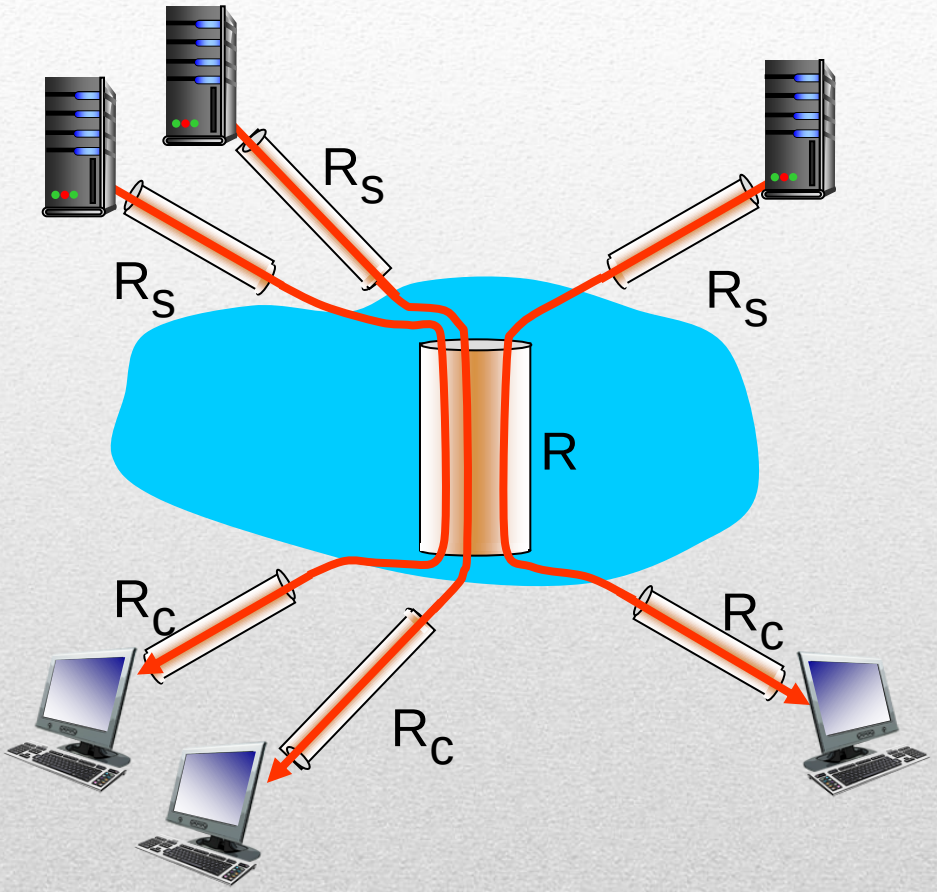


Bottleneck Link: Link on end-end path that constrains end-end throughput

Throughput

- Per-connection end-end throughput:
  $\min(R_c, R_s, R/10)$
- In practice: R_c or R_s is often bottleneck

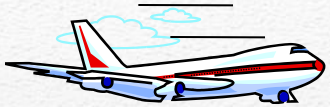


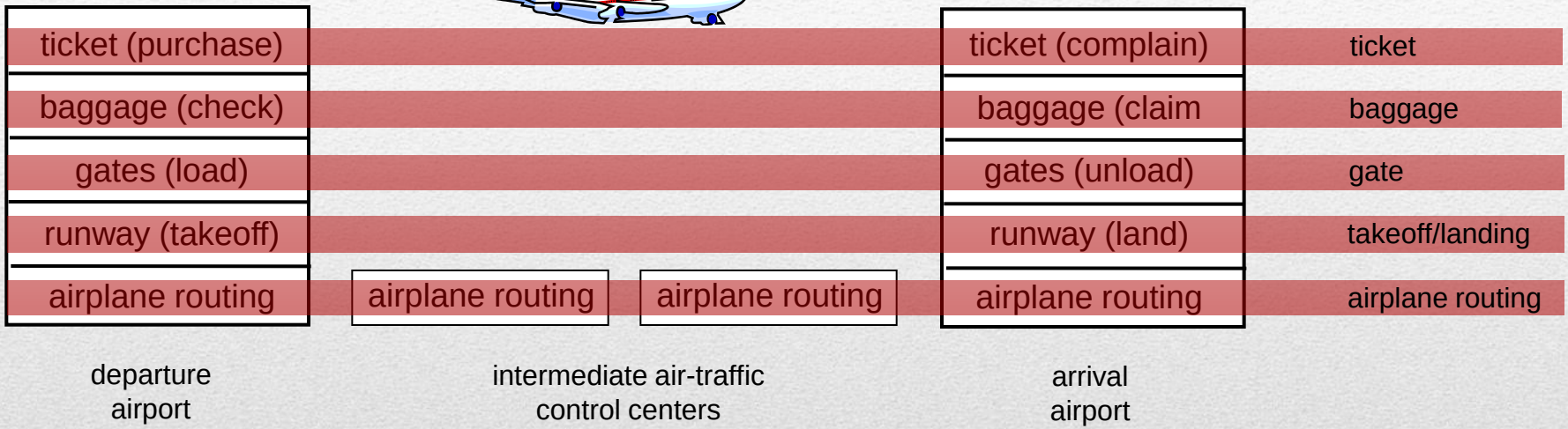
10 connections (fairly) share backbone bottleneck link R bits/sec

Protocol Layers

- **Dealing with a complex system**
  - Different components with different functionalities
- **Organization**
  - Layered reference model for discussion
  - Explicit structure for identification, relationship of pieces
  - Modularizations for maintenance and update
    - Change of each layer service transparent to the rest of the system
  - Is it also harmful?

Protocol Layers : An Example



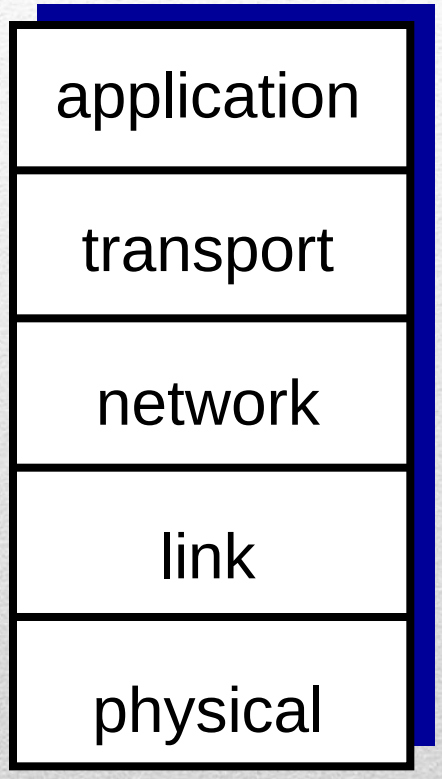


Layers: each layer implements a service

- Via its own internal-layer actions
- Relying on services provided by layer below

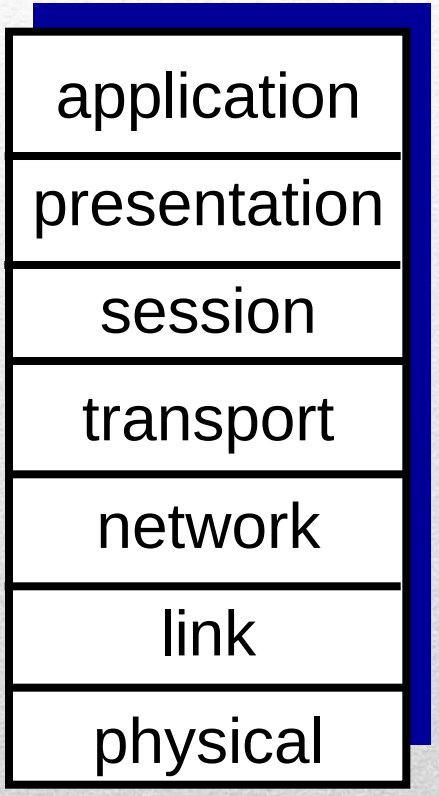
Internet Protocol Stack

- *Application:* supporting network applications
  - FTP, SMTP, HTTP
- *Transport:* process-process data transfer
  - TCP, UDP
- *Network:* routing of datagrams from source to destination
  - IP, routing protocols
- *Link:* data transfer between neighboring network elements
  - Ethernet, 802.111 (WiFi), PPP
- *Physical:* bits "on the wire"



ISO/OSI Reference Model

- *Presentation:* allow applications to interpret meaning of data
  - e.g., encryption, compression, machine-specific conventions
- *Session:* synchronization, check-pointing, recovery of data exchange
- Internet stack "missing" these layers!
  - These services, *if needed,* must be implemented in application



Network Security

- Network security
  - How bad guys can attack computer networks
  - How we can defend networks against attacks
  - How to design architectures that are immune to attacks
- Internet not originally designed with security in mind
  - *Original vision:* "a group of mutually trusting users attached to a transparent network"
  - Internet protocol designers playing "catch-up"
  - Security considerations in all layers!