

How the Internet Works

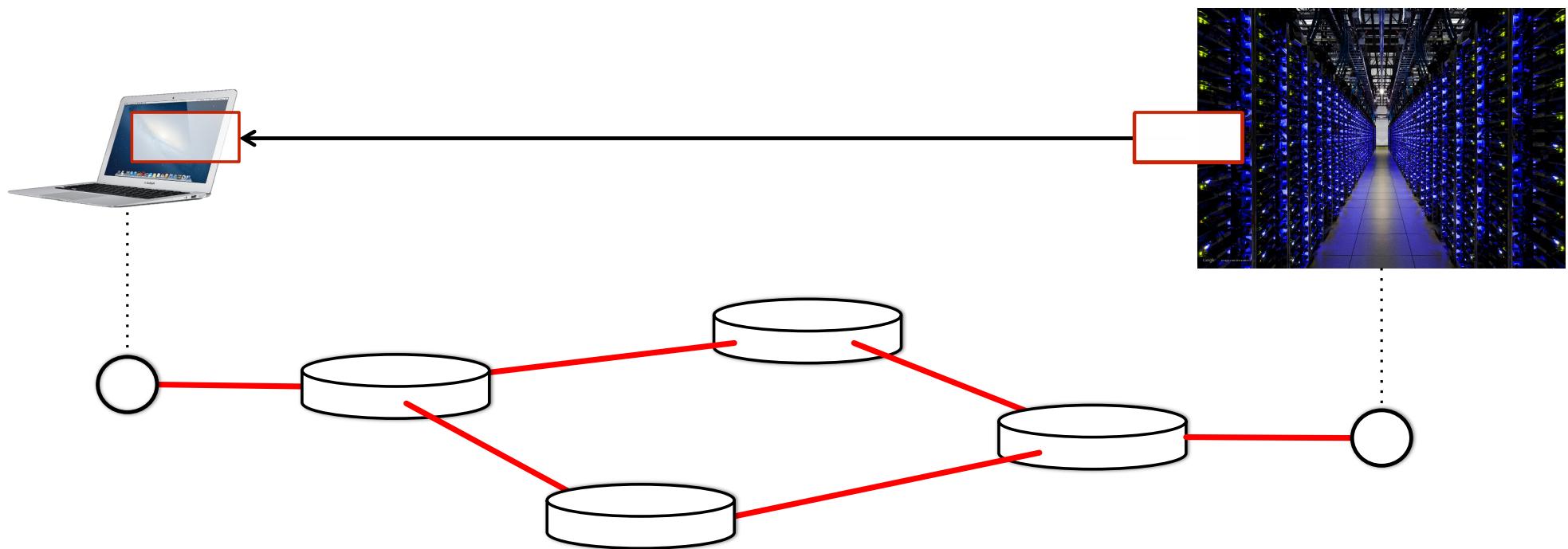
(in 50 mins)

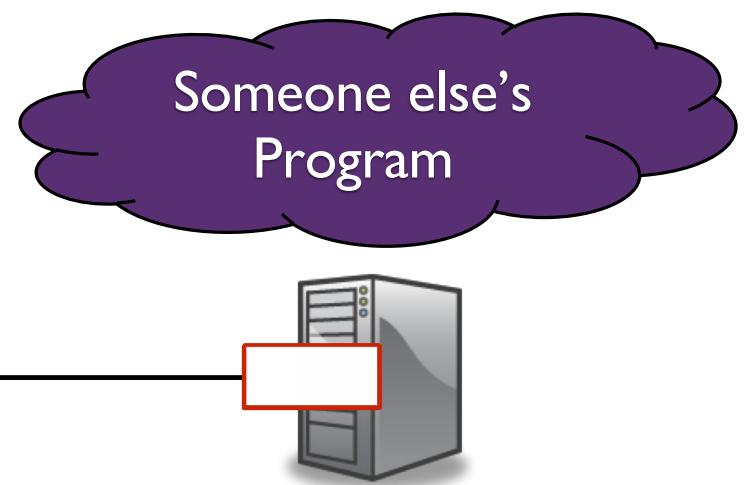
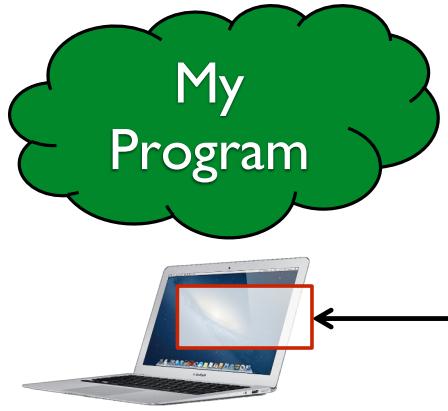


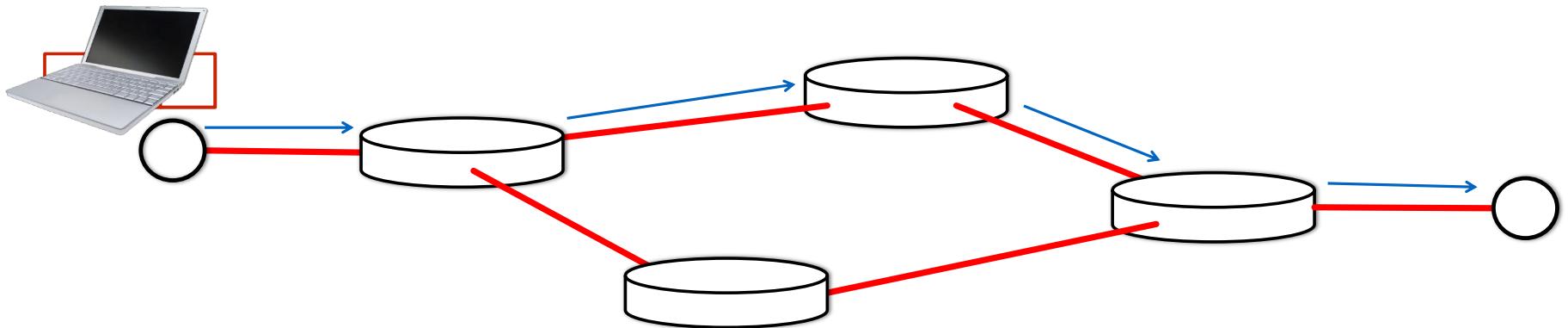
Nick McKeown

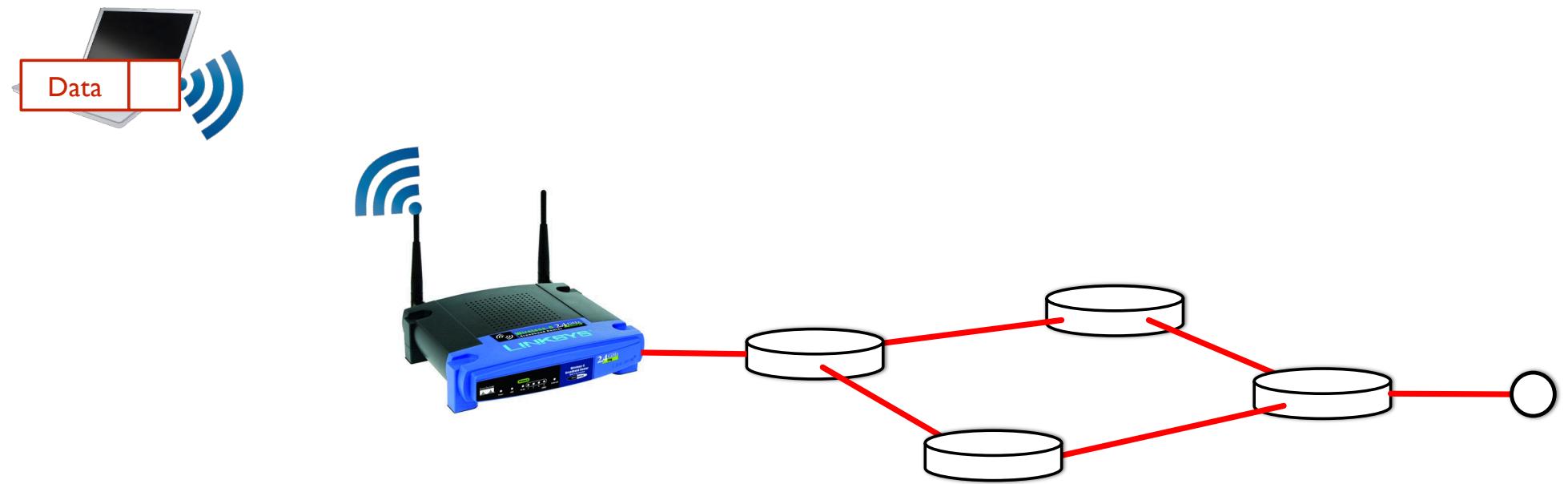
Professor of Electrical Engineering
and Computer Science, Stanford University

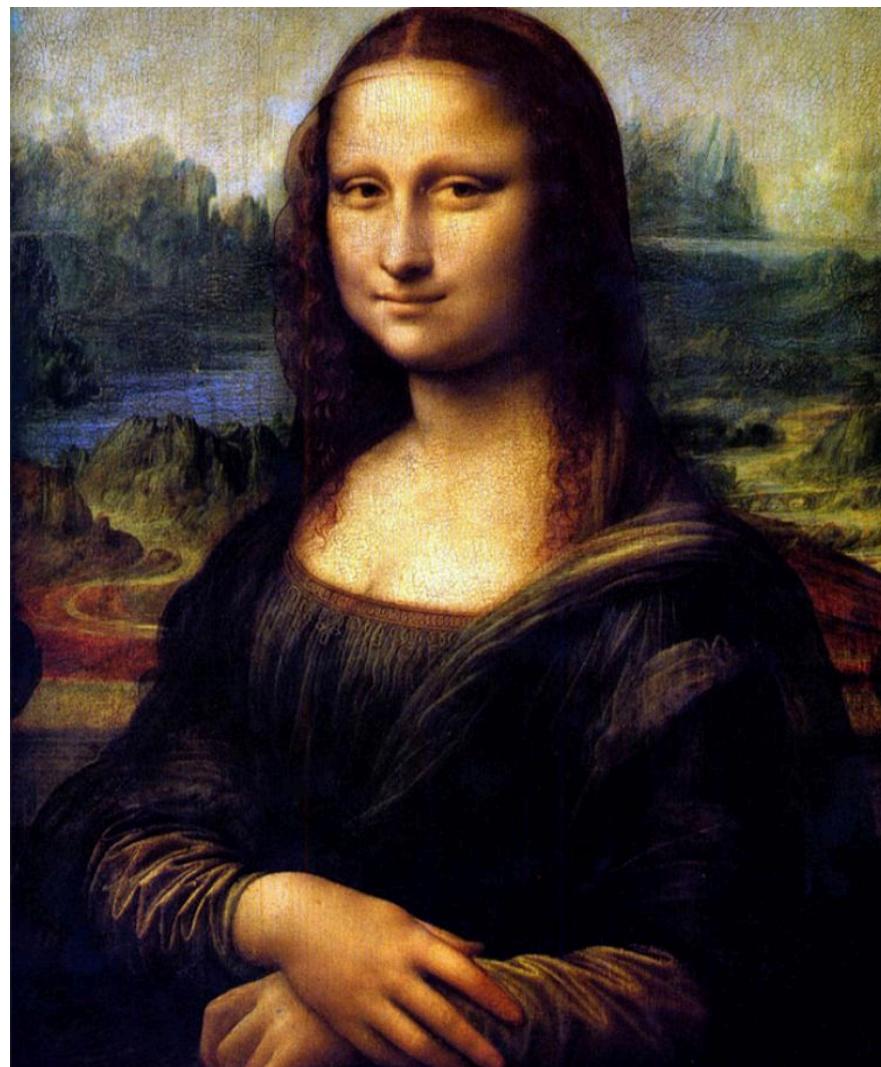
Google YouTube facebook



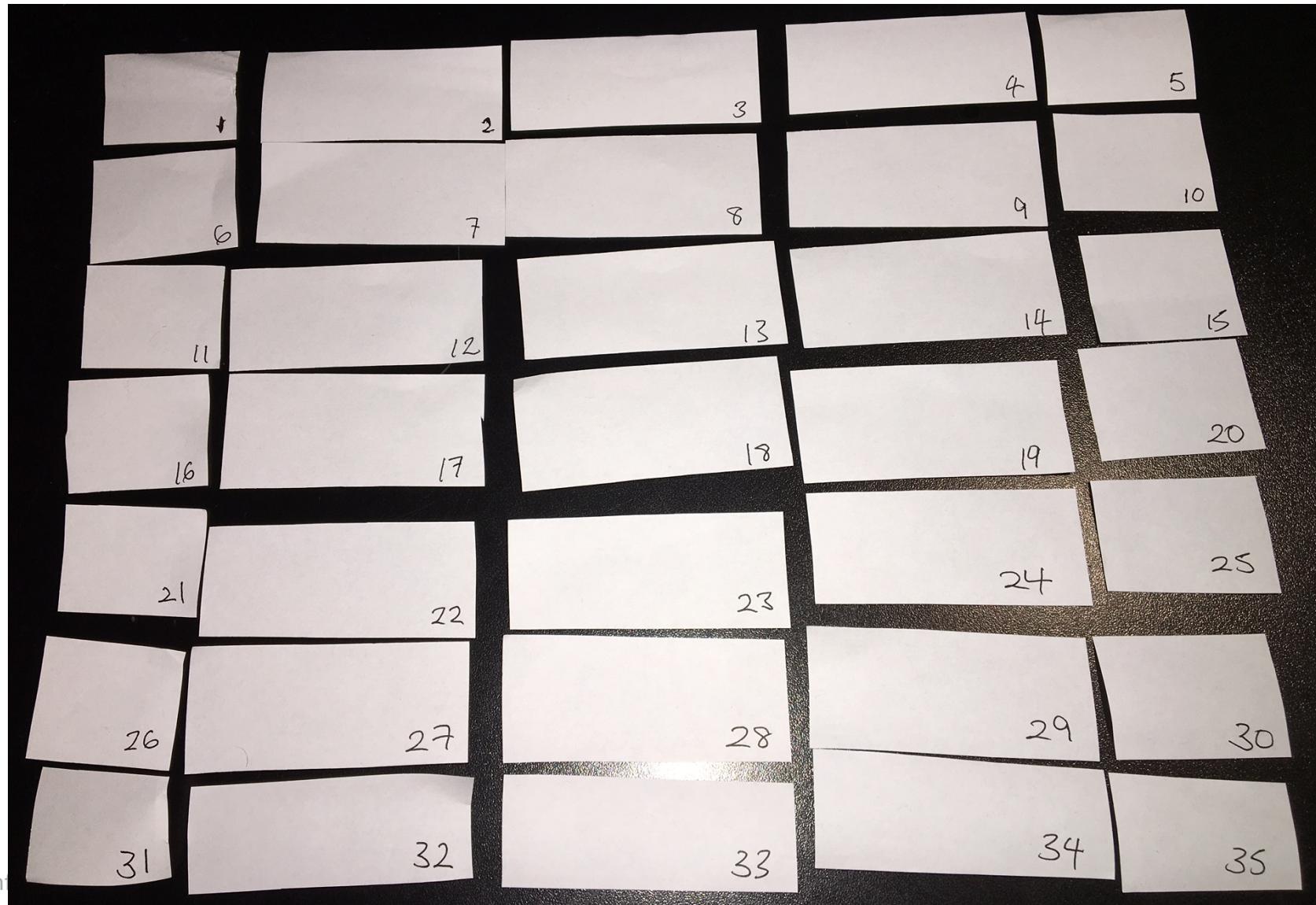




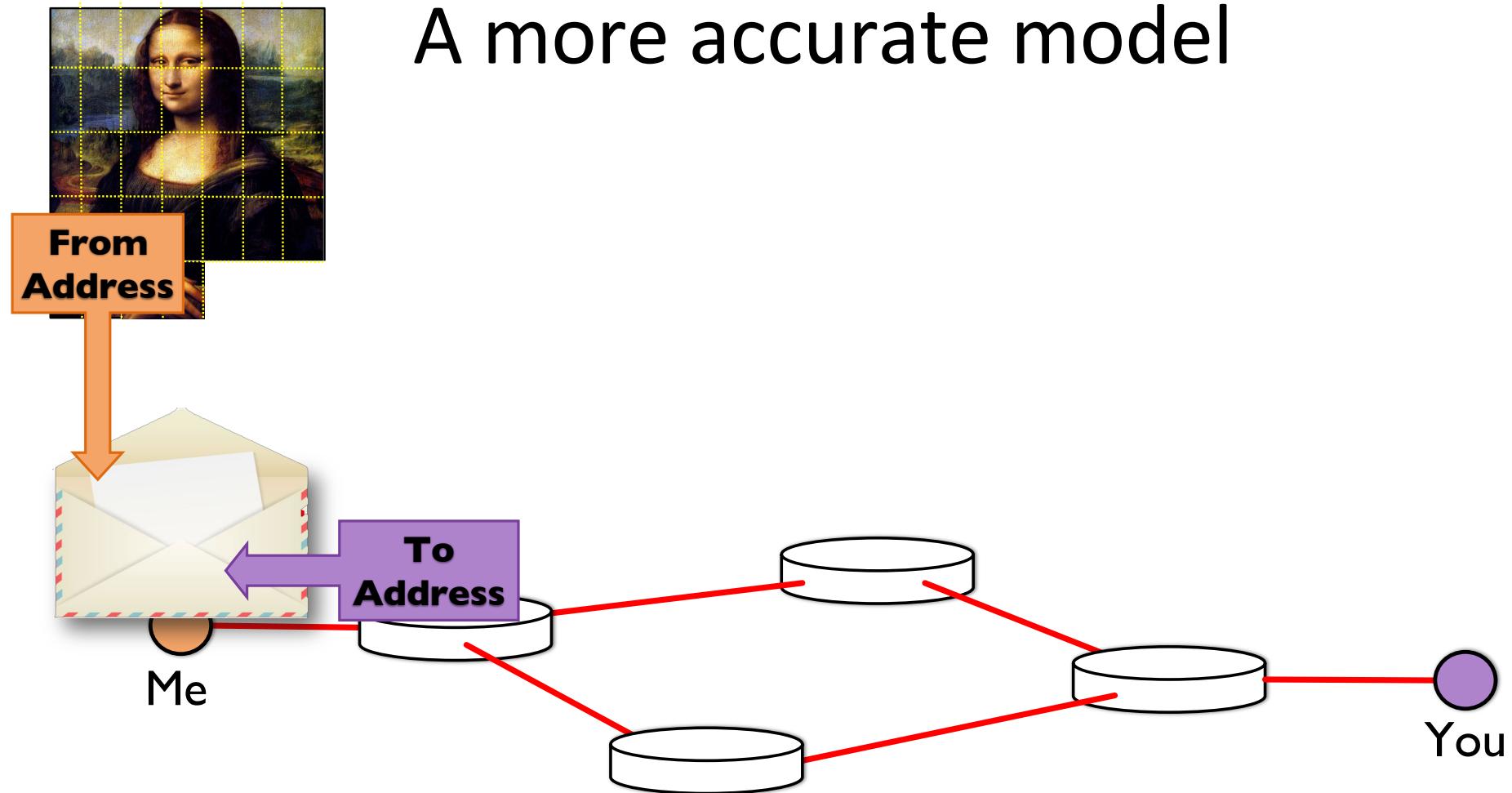


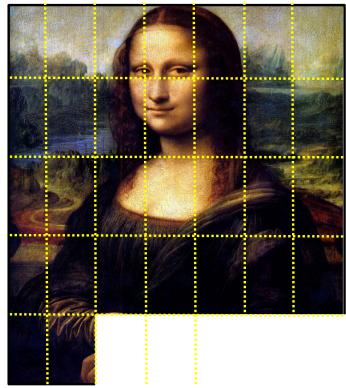


CS144, Stanford University

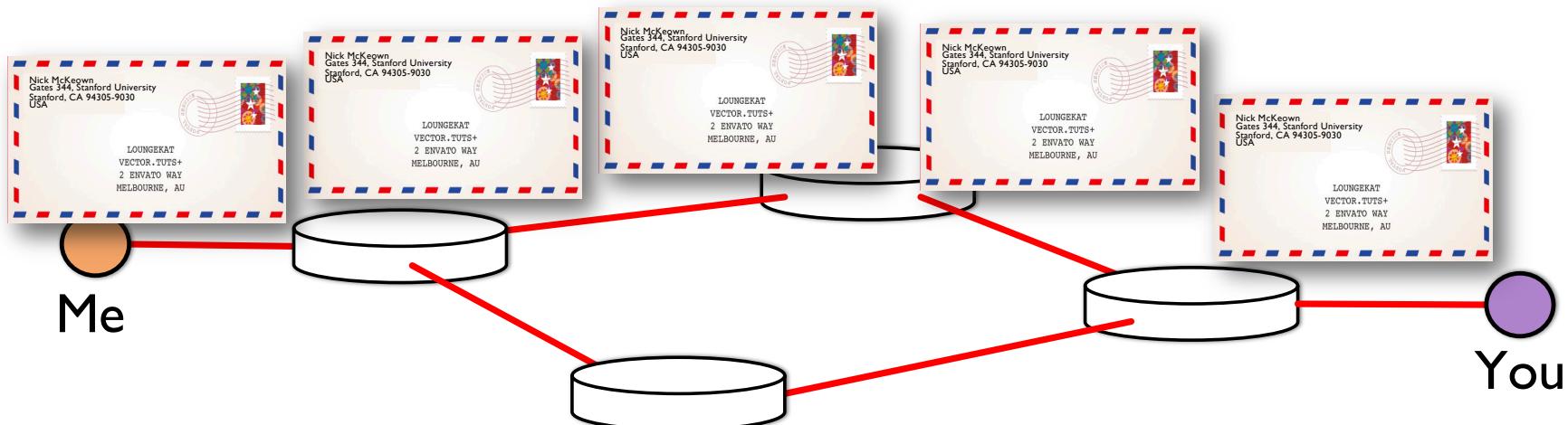


A more accurate model

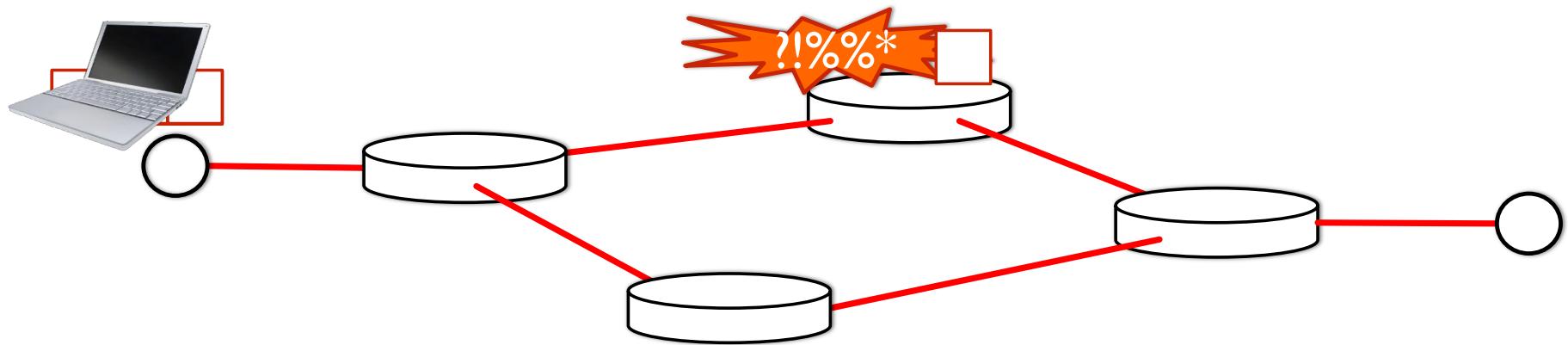




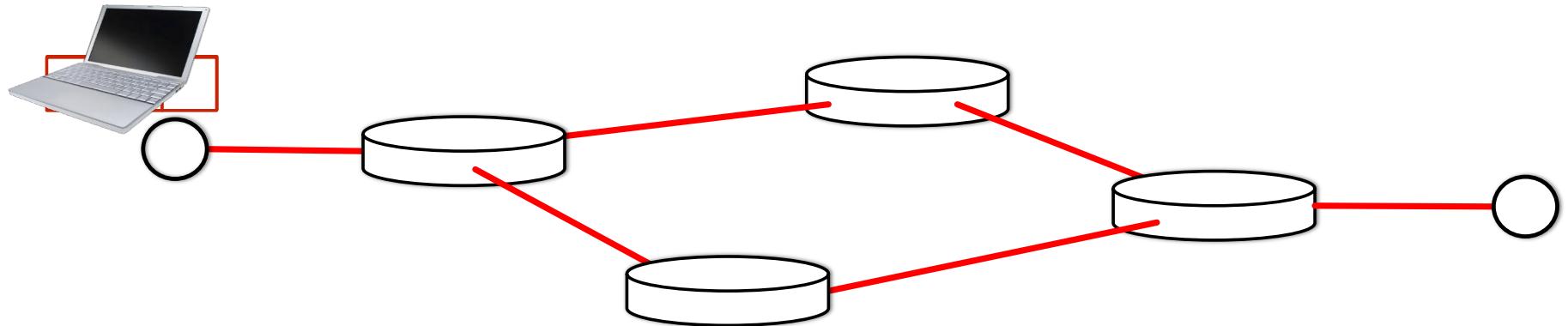
Multiple packets in pipeline at same time



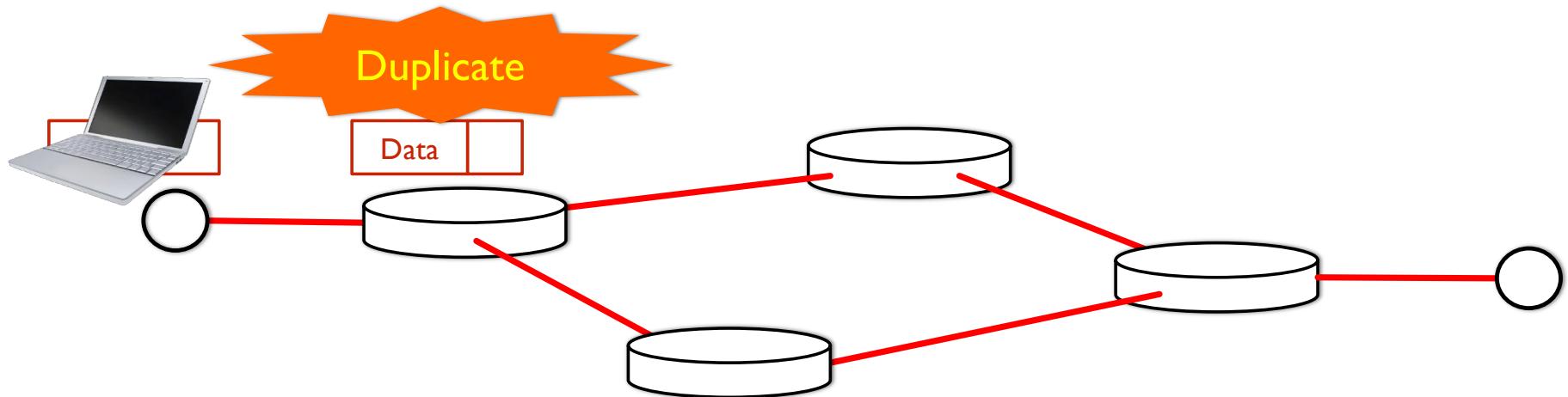
Packets may be **damaged**



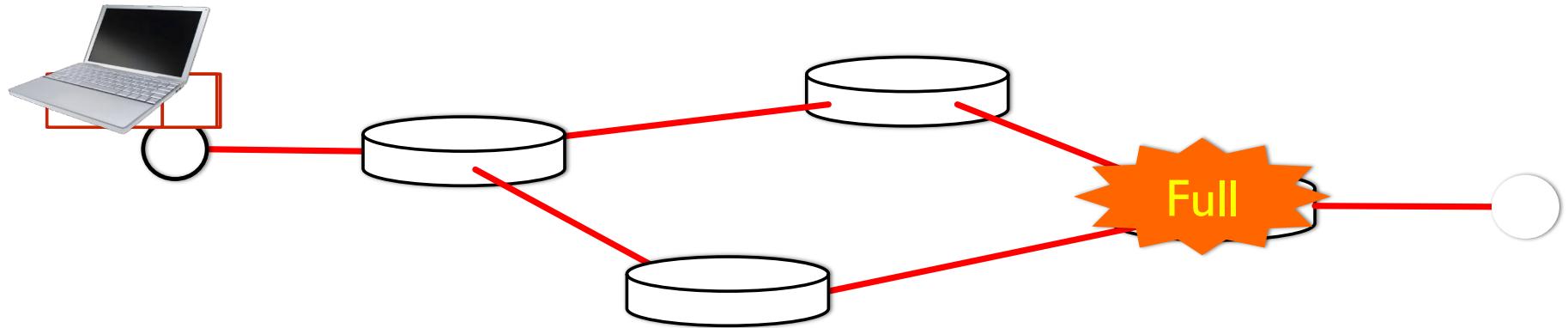
Packets may arrive out of order



Packets may be **duplicated**

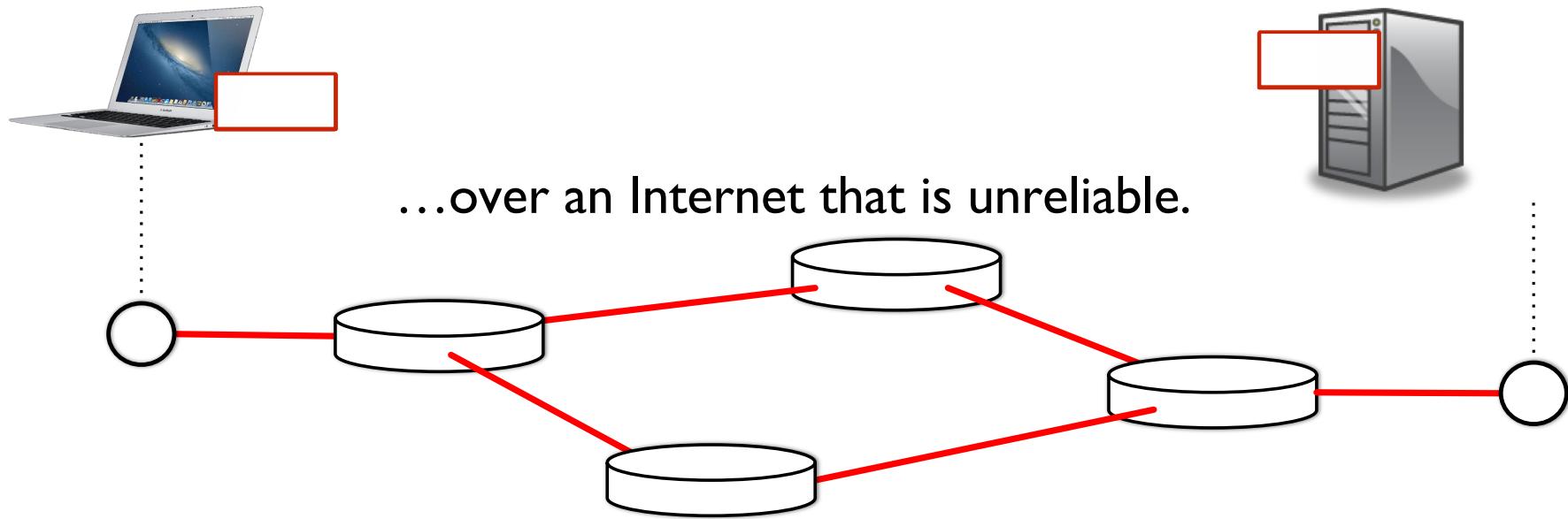


They may not arrive at all!



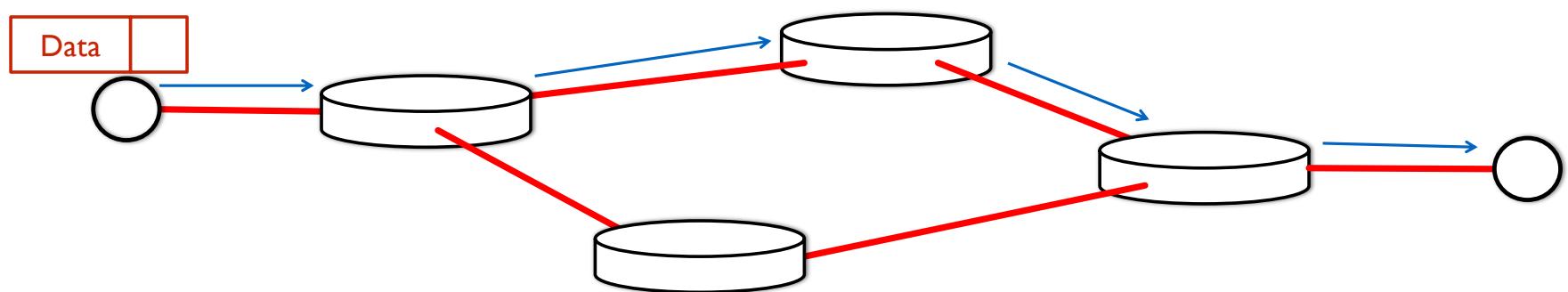
Summary so far

Applications send and receive data in packets....



How packets find their way across the Internet

Internet addresses



Internet Addresses (“IP address”)

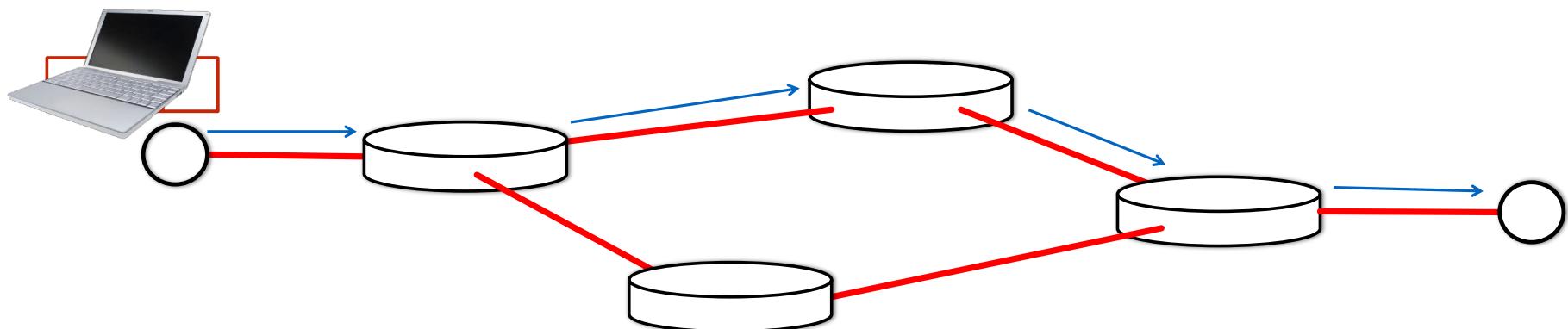


All Internet packets carry a destination IP address.
We usually write the IP address like this:

171.64.74.58

Routers forward packets one at a time.

Routers look at IP addresses, then send packets to a router closer to the destination.



IP Addresses

The IP address tells a router where to send the packet next.
IP addresses have *structure*

A network in ~~The CS department at Stanford University~~

171.64.74.58

An address managed by ~~The RIB (Router Information Base)~~

88.255.96.208

Can we see the path our packets take?

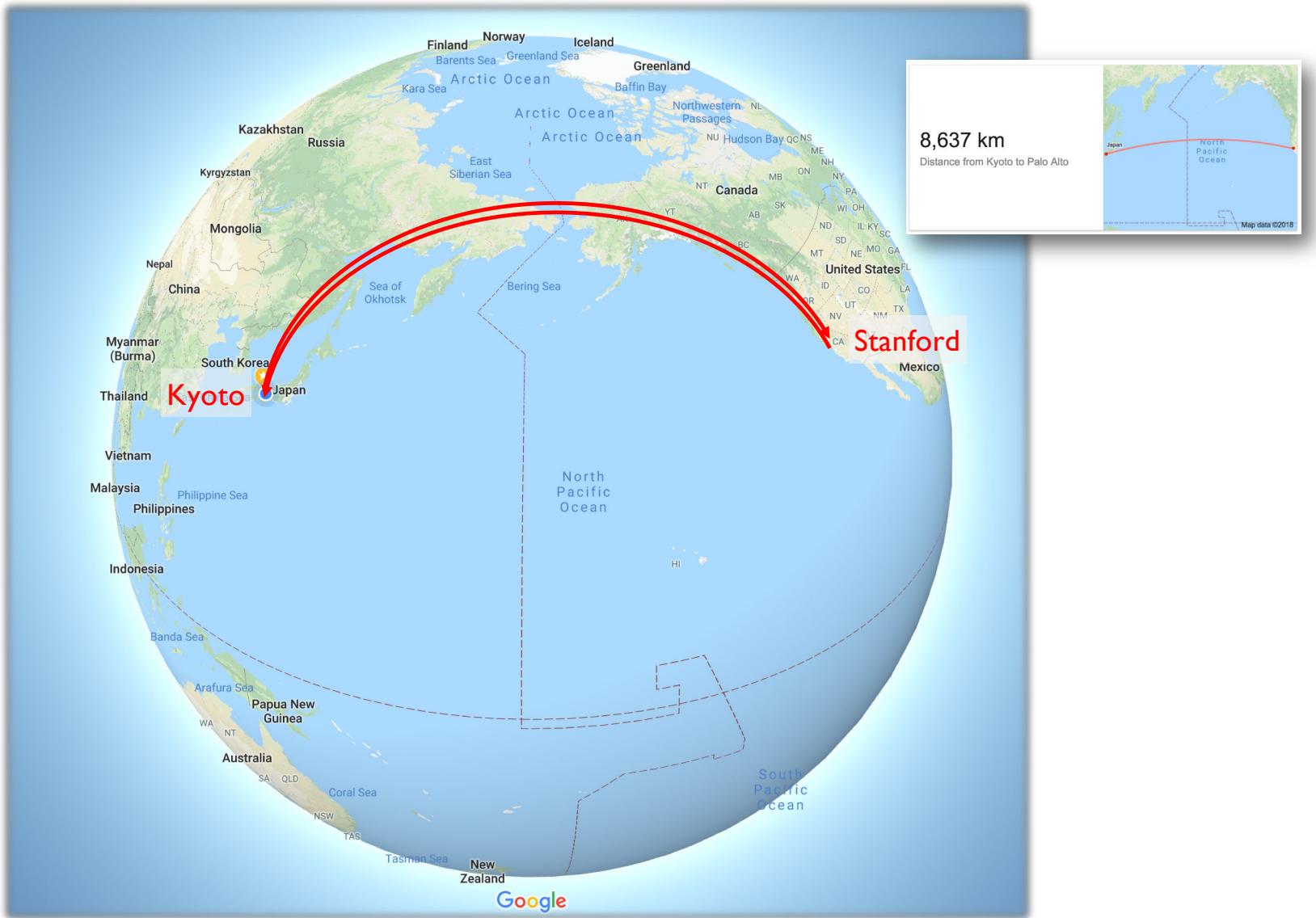
Yes!

On your computer, try: “ping yuba.stanford.edu”
and “traceroute yuba.stanford.edu”

(Windows: “tracert yuba.stanford.edu”)

ping

From yuba, it takes about 115ms to reach Japan and back again
("round-trip-time")





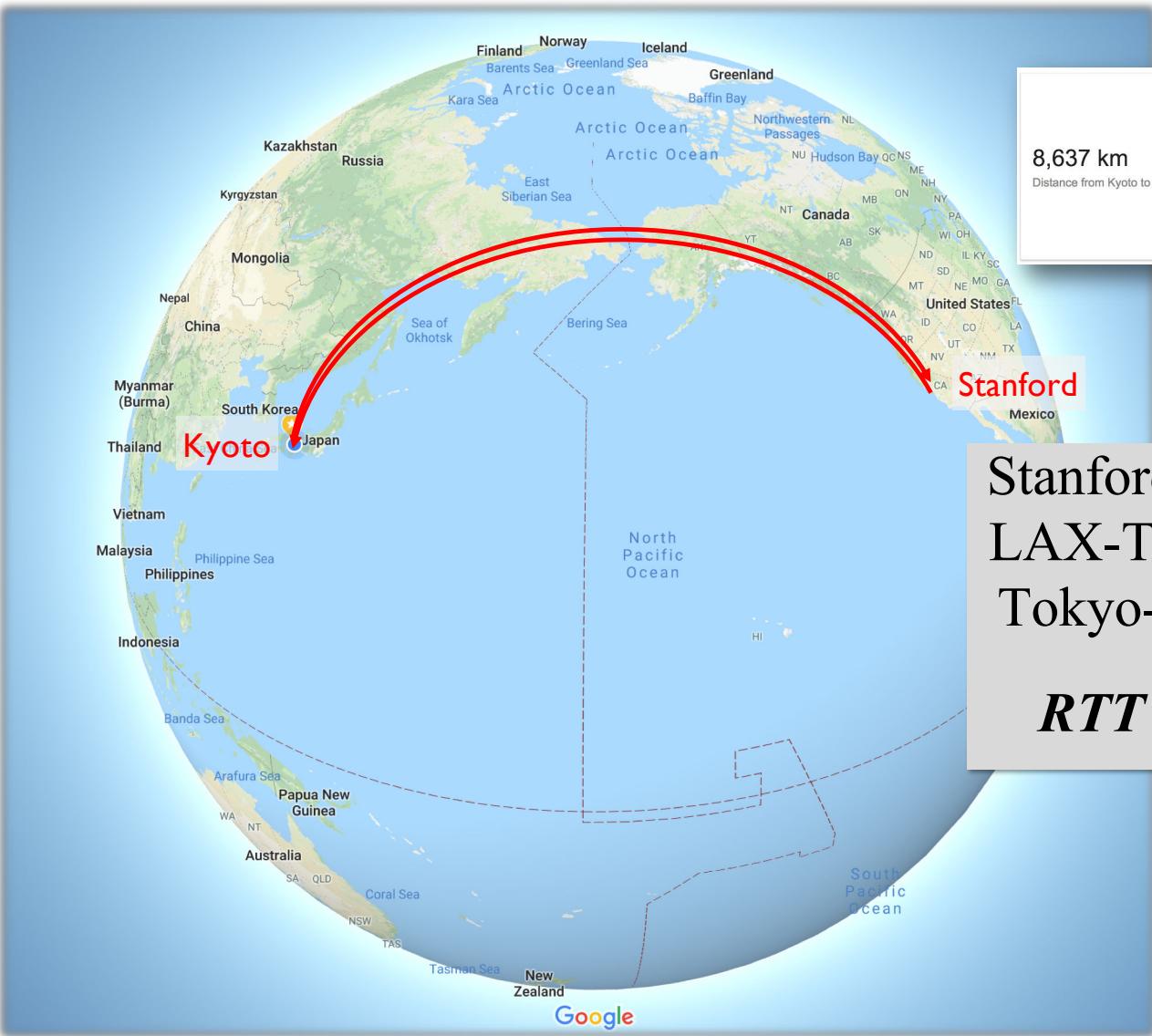
traceroute

From Stanford to Doshisha University (Kyoto)

nickm@yuba.Stanford.EDU > traceroute -q1 istc.doshisha.ac.jp

traceroute to istc.doshisha.ac.jp (202.23.190.159), 30 hops max, 40 byte packets

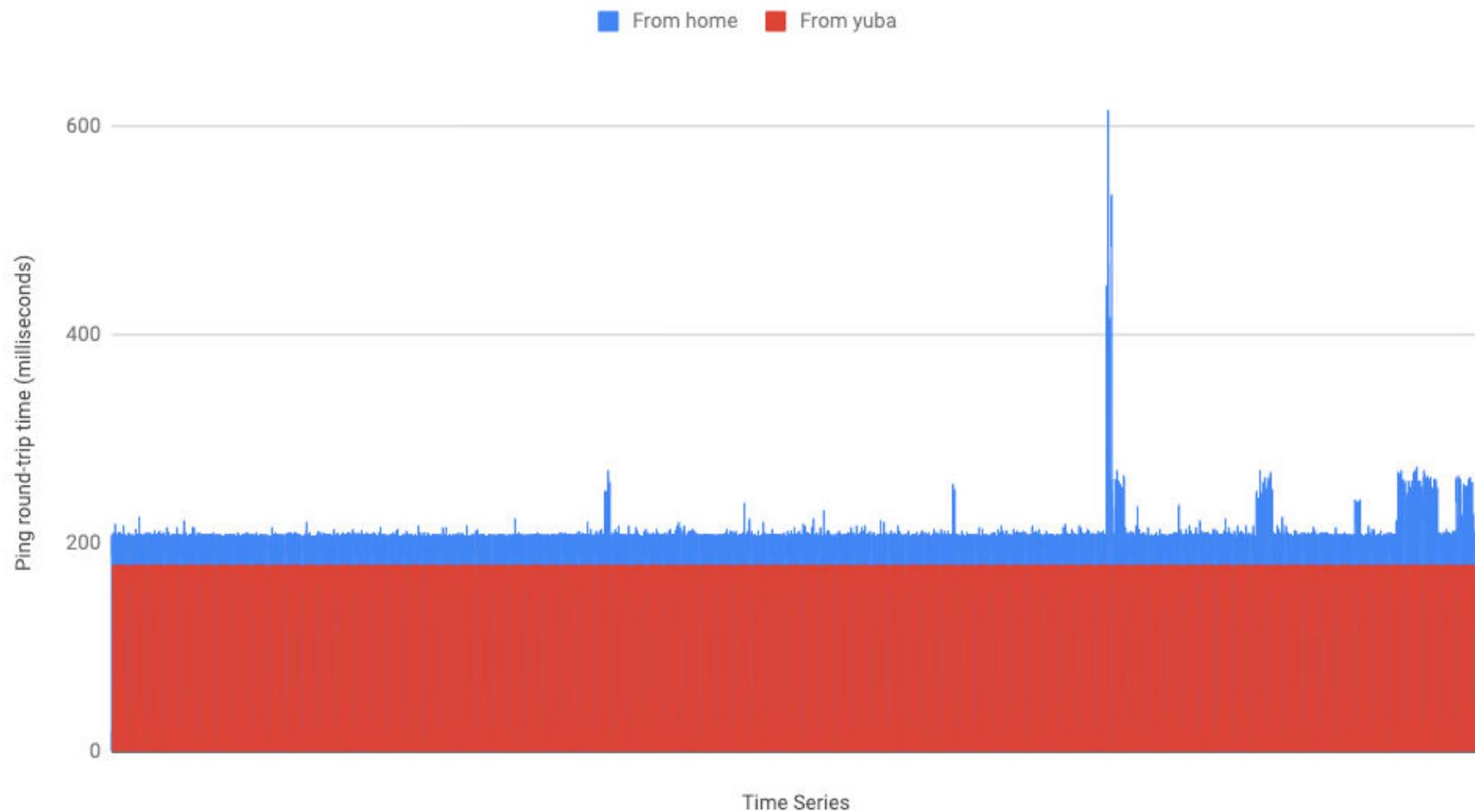
```
1 csmx-west-rtr.SUNet (171.64.74.2)  0.234 ms
2 hpr-svl-rtr-vlan3.SUNet (171.66.255.186)  0.423 ms
3 hpr-svl-hpr2--stan-ge.cenic.net (137.164.27.161)  0.779 ms
4 hpr-lax-hpr3--svl-hpr3-100ge.cenic.net (137.164.25.73)  8.627 ms
5 sinet-1-lo-jmb-702.lsanca.pacificwave.net (207.231.240.135)  8.793 ms
6 tokyo1-GM-ET-8-3-0-100.s5.sinet.ad.jp (150.99.89.242)  108.852 ms
7 kyoto-RM-ET-7-1-0-1151.s5.sinet.ad.jp (150.99.89.184)  114.829 ms
8 doshisha-LAN.gw.sinet.ad.jp (150.99.196.66)  115.249 ms
9 ***
```



Stanford-LAX: 500km
LAX-Tokyo: 8,800km
Tokyo-Kyoto: 500km

$RTT \approx 100ms$

Ping times to Tsinghua University, Beijing (Jan 21, 2019)



Try traceroute to....

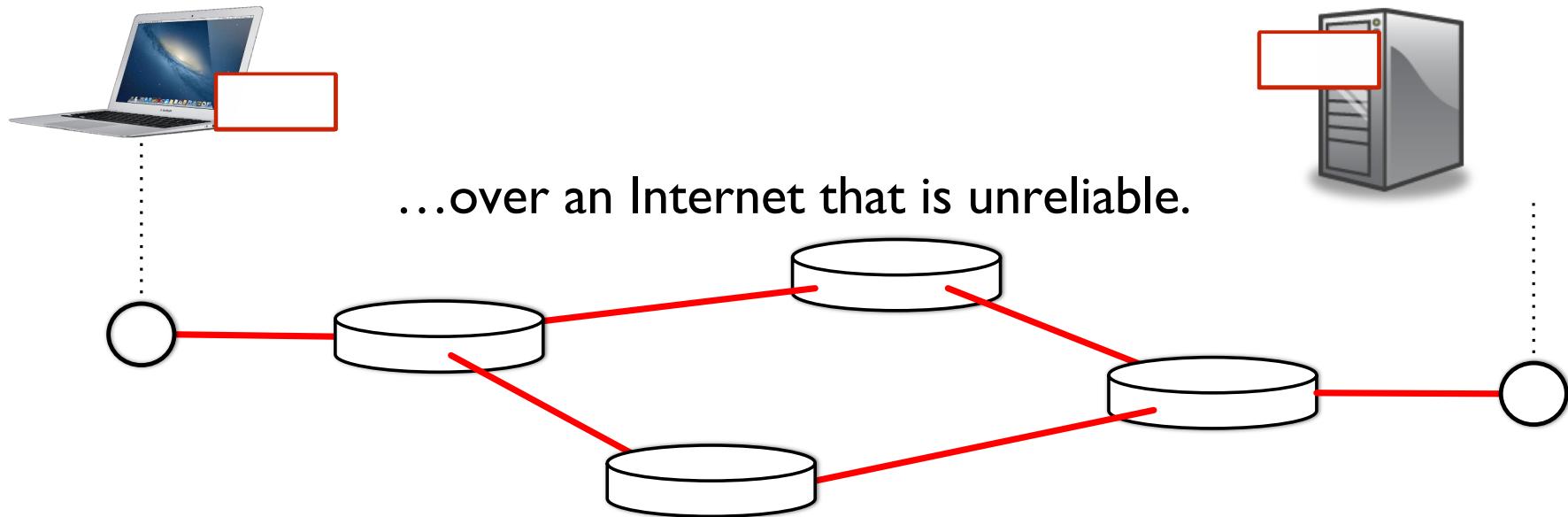
yuba.stanford.edu, www.google.com, www.ntua.gr, ...

```
nickm @ home on Comcast network $ traceroute -ql www.ntua.gr
traceroute to www.ntua.gr (147.102.224.101), 64 hops max, 52 byte packets
 1 testwifi.here (192.168.86.1) 0.921 ms
 2 96.120.91.229 (96.120.91.229) 8.491 ms
 3 be-20052-rur02.santaclara.ca.sfba.comcast.net (68.87.196.49) 10.237 ms
 4 162.151.78.129 (162.151.78.129) 8.857 ms
 5 be-232-rar01.santaclara.ca.sfba.comcast.net (162.151.78.253) 8.941 ms
 6 be-3651-cr02.sunnyvale.ca.ibone.comcast.net (68.86.91.73) 9.485 ms
 7 be-11083-pe02.529bryant.ca.ibone.comcast.net (68.86.84.14) 10.357 ms
 8 50.248.118.238 (50.248.118.238) 9.467 ms
 9 be2016.ccr22.sfo01.atlas.cogentco.com (154.54.0.177) 11.134 ms
10 be3110.ccr32.slc01.atlas.cogentco.com (154.54.44.142) 35.123 ms
11 be3038.ccr22.den01.atlas.cogentco.com (154.54.42.98) 35.458 ms
12 be3036.ccr22.mci01.atlas.cogentco.com (154.54.31.90) 53.296 ms
13 be2832.ccr42.ord01.atlas.cogentco.com (154.54.44.170) 58.615 ms
14 be2718.ccr22.cle04.atlas.cogentco.com (154.54.7.130) 65.101 ms
15 be2994.ccr32.yyz02.atlas.cogentco.com (154.54.31.234) 73.458 ms
16 be3260.ccr22.ymq01.atlas.cogentco.com (154.54.42.90) 85.407 ms
17 be3043.ccr22.lpl01.atlas.cogentco.com (154.54.44.165) 150.394 ms
18 be2183.ccr42.ams03.atlas.cogentco.com (154.54.58.70) 156.881 ms
19 be2814.ccr42.fra03.atlas.cogentco.com (130.117.0.142) 162.831 ms
20 be2960.ccr22.muc03.atlas.cogentco.com (154.54.36.254) 169.709 ms
21 be3462.ccr52.vie01.atlas.cogentco.com (154.54.59.181) 173.362 ms
22 149.6.175.250 (149.6.175.250) 173.362 ms
23 ae1.mx1.ath2.gr.geant.net (62.40.98.146) 200.320 ms
24 grnet-ias-grnet-gw.mx1.ath2.gr.geant.net (83.97.88.66) 206.457 ms
25 eier-kolettir-ae.backbone.grnet.gr (62.217.100.63) 208.703 ms
26 ntua-zogr-3.eier.access-link.grnet.gr (62.217.96.169) 201.891 ms
27 *
```

```
nickm@yuba.Stanford.EDU > traceroute -ql www.ntua.gr
traceroute to www.ntua.gr (147.102.224.101), 30 hops max, 40 byte packets
 1 csee-west-rtr-vl3874.SUNet (171.64.74.2) 0.289 ms
 2 hpr-svl-rtr-vlan2.SUNet (171.64.255.147) 0.637 ms
 3 hpr-svl-hpr3--stan-100ge.cenic.net (137.164.27.60) 0.657 ms
 4 hpr-lax-hpr3--svl-hpr3-100ge.cenic.net (137.164.25.73) 8.558 ms
 5 hpr-i2--lax-hpr3-r-and-e.cenic.net (137.164.26.201) 8.723 ms
 6 ae-5.4079.rtsw.wash.net.internet2.edu (162.252.70.158) 68.694 ms
 7 internet2-gw.mx1.lon.uk.geant.net (62.40.124.44) 143.377 ms
 8 ae6.mx1.lon2.uk.geant.net (62.40.98.37) 144.475 ms
 9 ae5.mx1.par.fr.geant.net (62.40.98.179) 151.959 ms
10 ae5.mx1.gen.ch.geant.net (62.40.98.182) 158.004 ms
11 ae4.mx1.mil2.it.geant.net (62.40.98.89) 164.868 ms
12 ae3.mx2.ath.gr.geant.net (62.40.98.151) 187.210 ms
13 grnet-gw.mx2.ath.gr.geant.net (62.40.124.90) 186.227 ms
14 ntua-zogr-3.eier.access-link.grnet.gr (62.217.96.169) 188.246 ms
15 *
```

Summary so far

Applications send and receive data in packets....

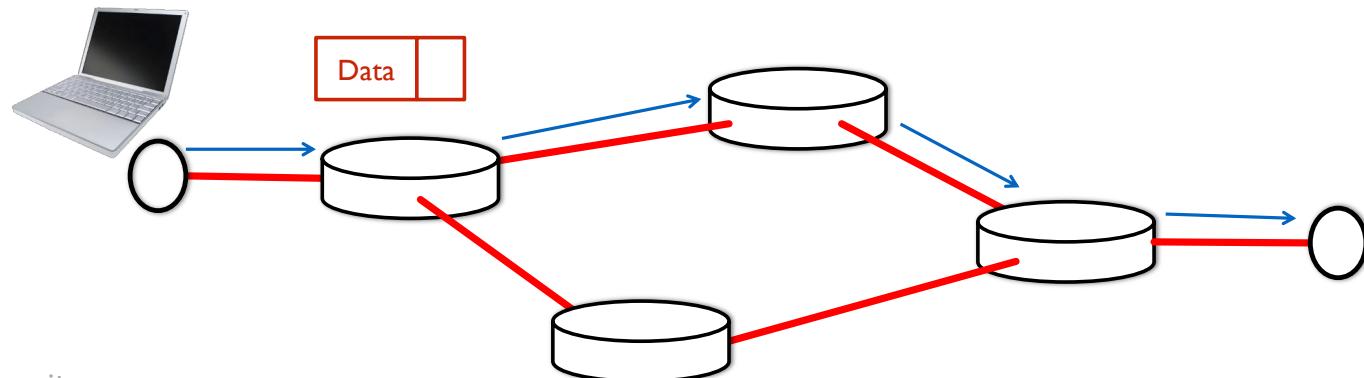


Packets are forwarded hop-by-hop based on the final destination address.

The Internet cannot be trusted!!

The Internet doesn't promise to deliver packets in order.
It doesn't promise to deliver packets quickly, or on time.
It doesn't even promise to deliver them at all!

It just makes a “best-effort” attempt.



Sending data reliably over an Internet that is
unreliable

How Network Applications Communicate



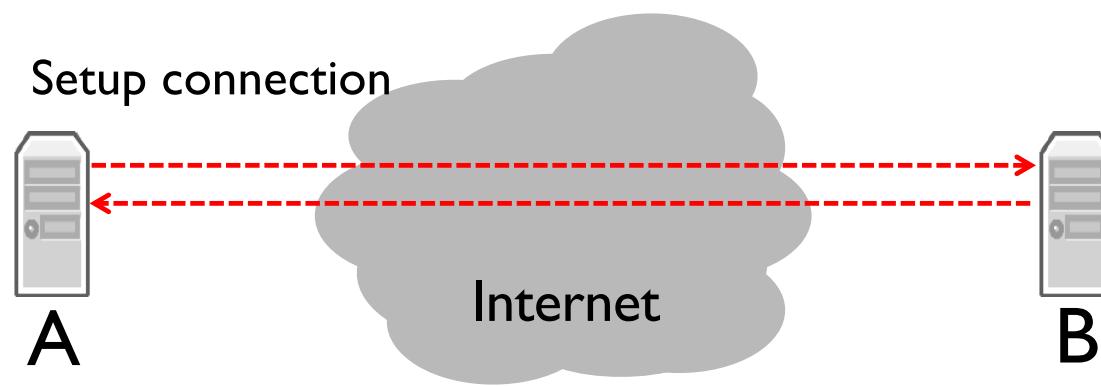
The most common method:

- ▶ Communication is in both directions – “bidirectional”.
- ▶ Communication is reliable
(if there is a working path between the two computers).

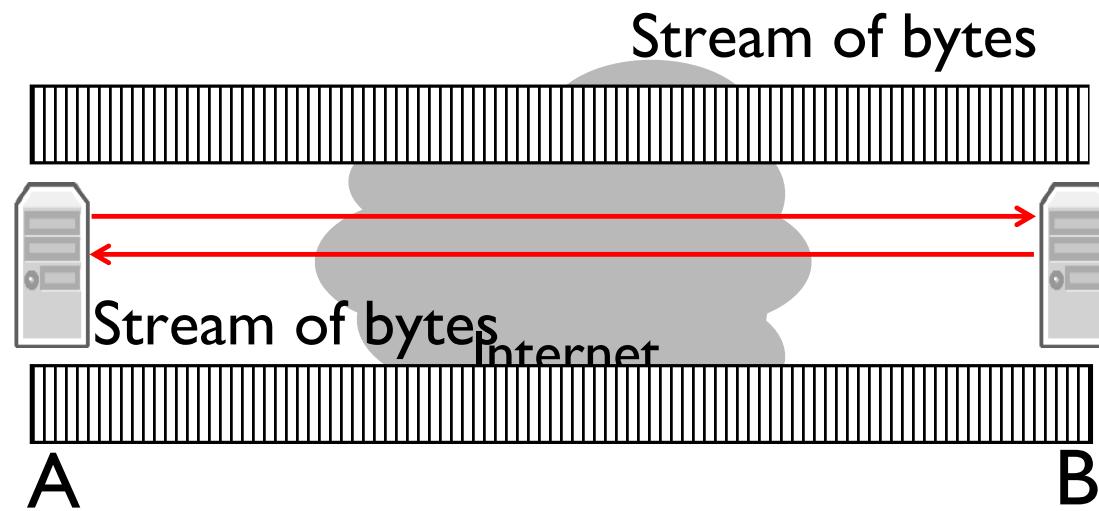
It's like an unformatted pipe:

- ▶ You push data in at one end, and it pops out correctly at the other end.
- ▶ The applications decide how the data is formatted inside the pipe.

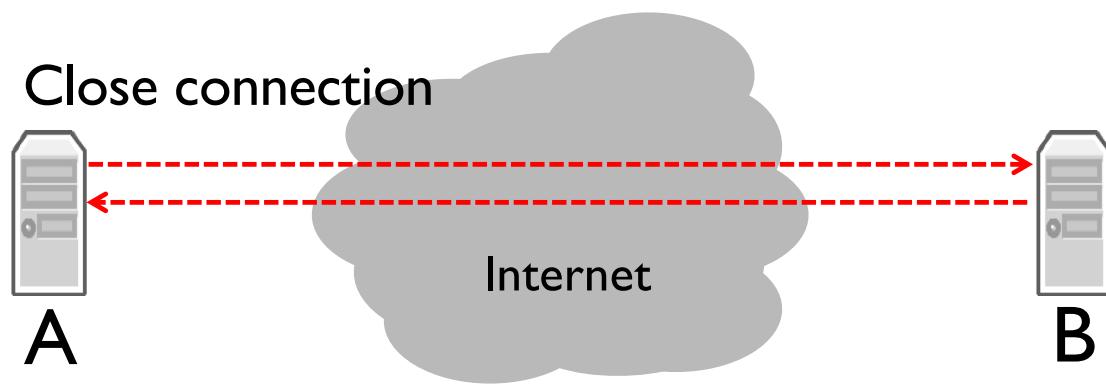
Byte Stream Model



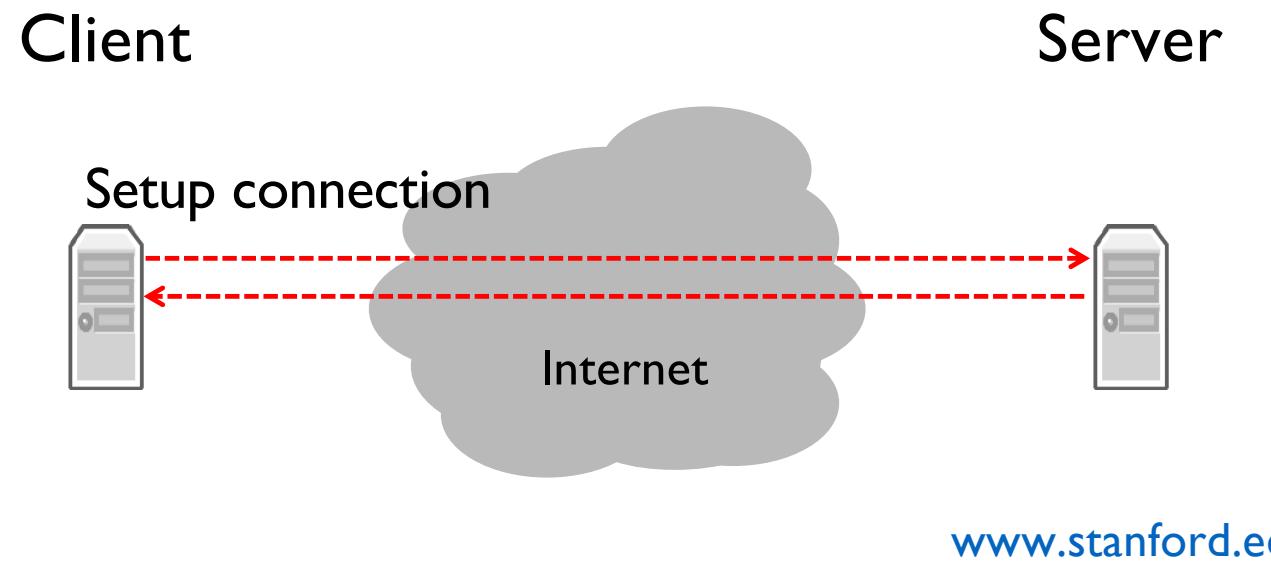
Byte Stream Model



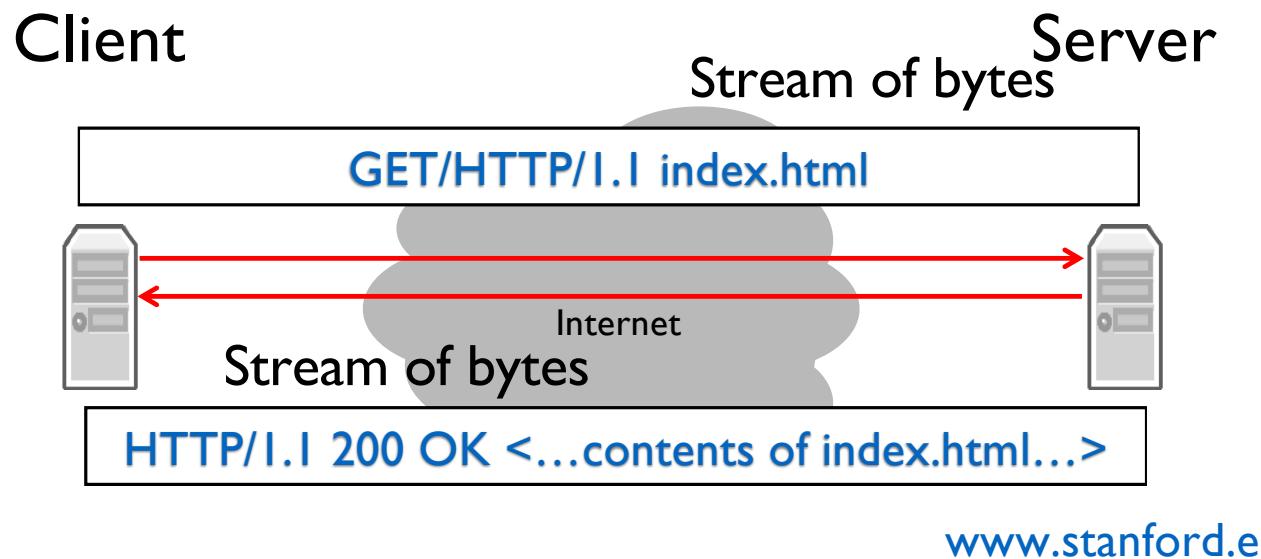
Byte Stream Model



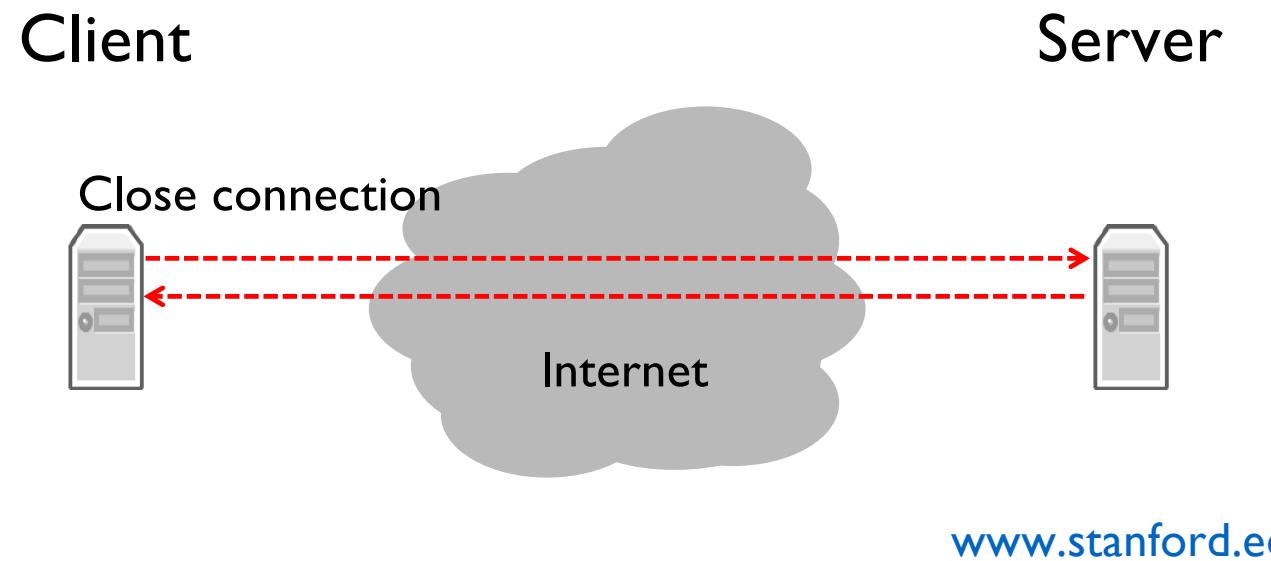
World Wide Web (HTTP)

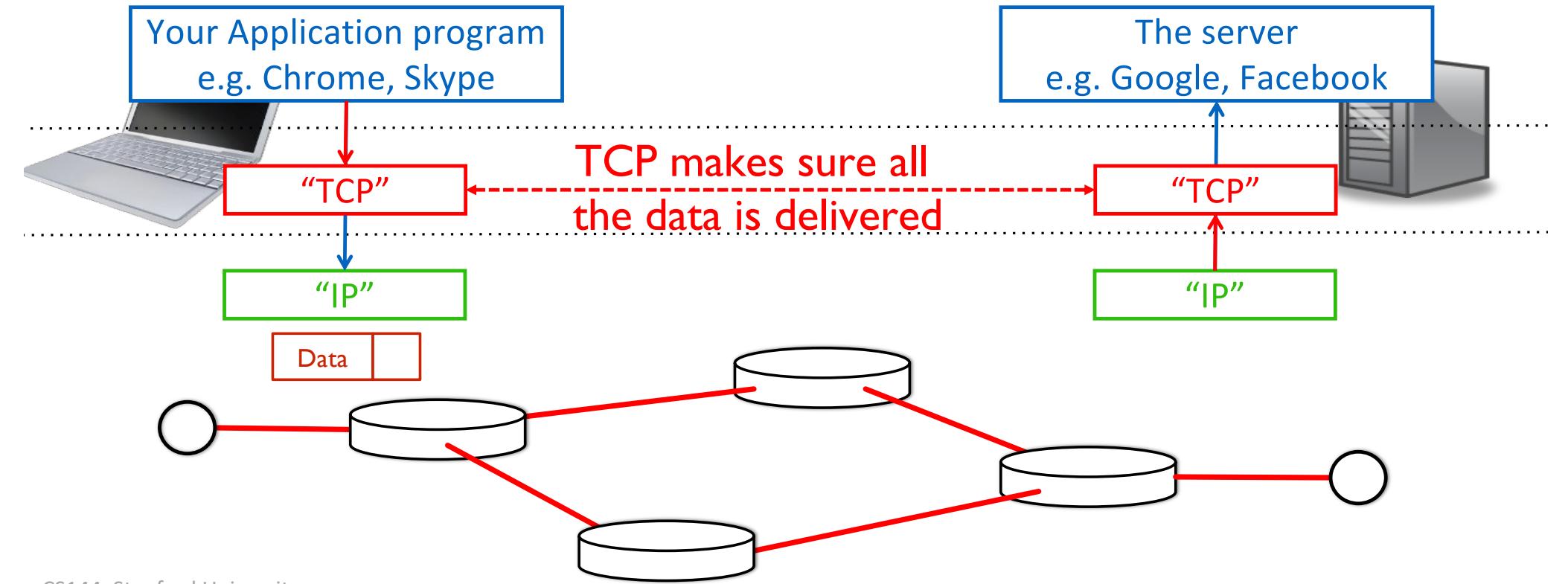


World Wide Web (HTTP)



World Wide Web (HTTP)





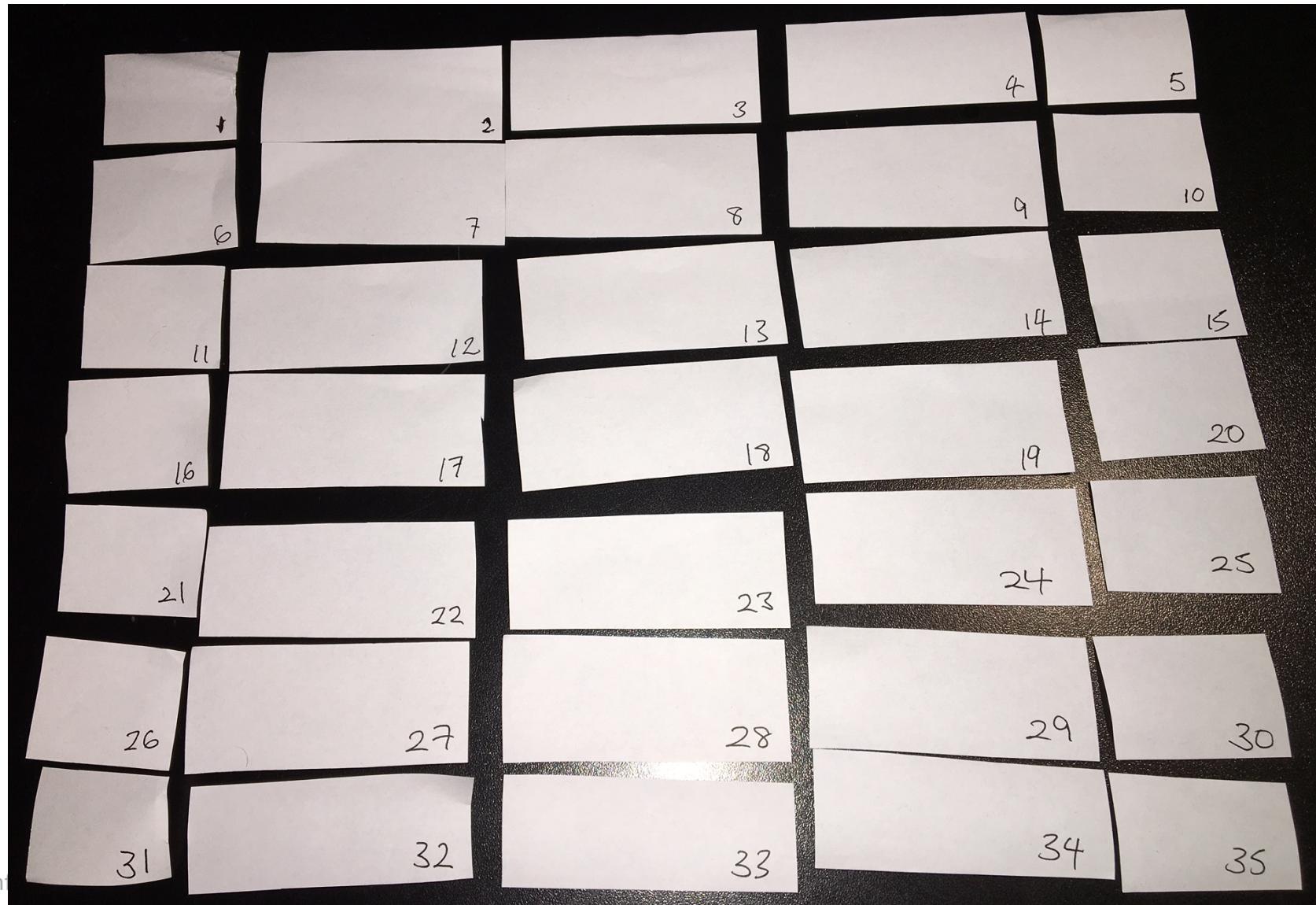
TCP's job

Makes sure all data is delivered correctly.

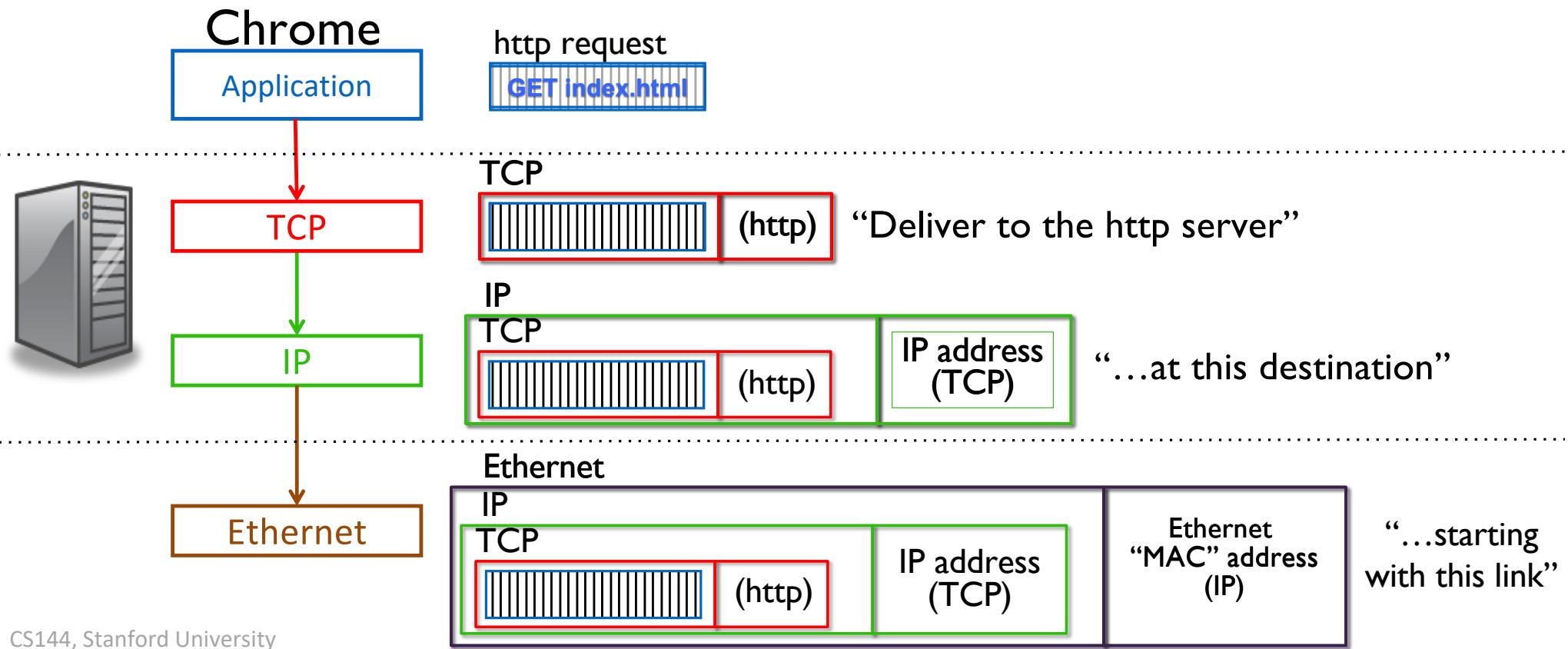
Delivers data to the application in the right order.

How?

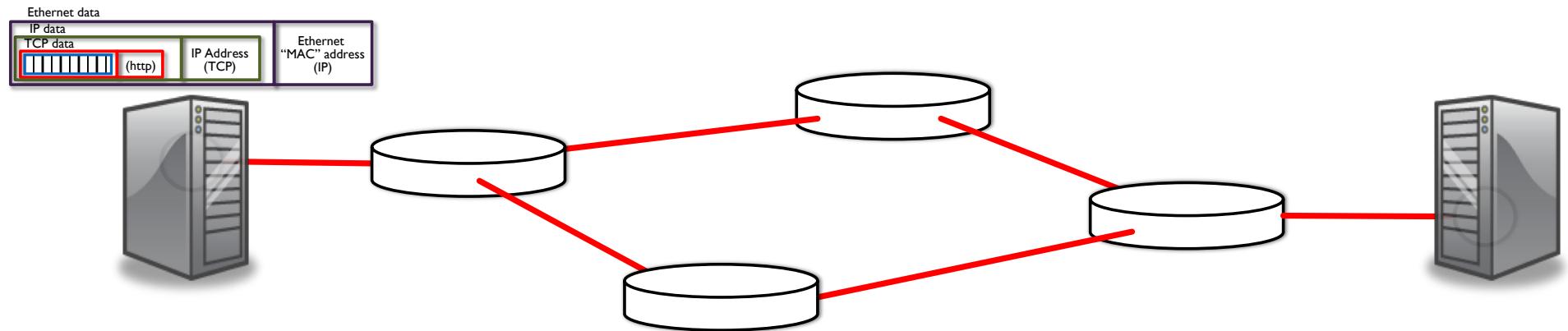
- ▶ Add sequence numbers to every packet (so the receiver can check if any are missing, and put them in right order)
- ▶ When a packet arrives, send an **acknowledgment of receipt** or “ACK” back to the sender
- ▶ If no acknowledgment is received, resend the data



http client (e.g. Chrome)

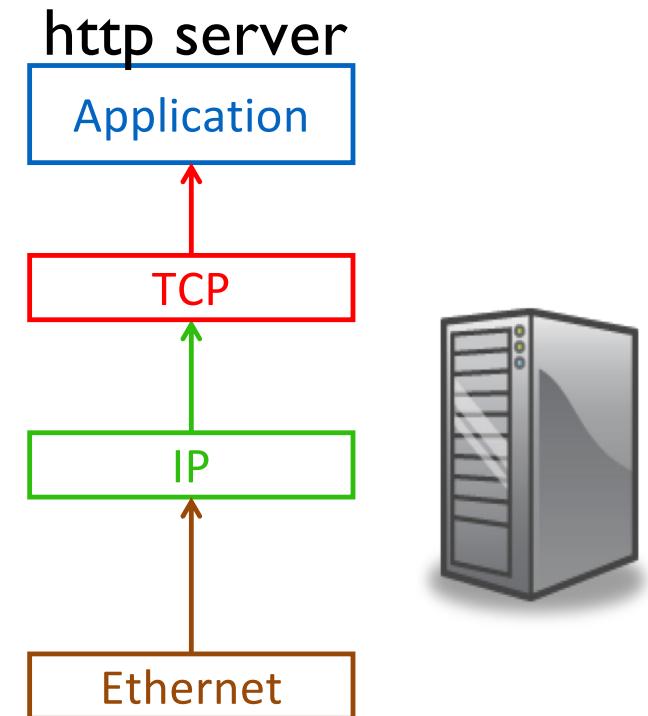
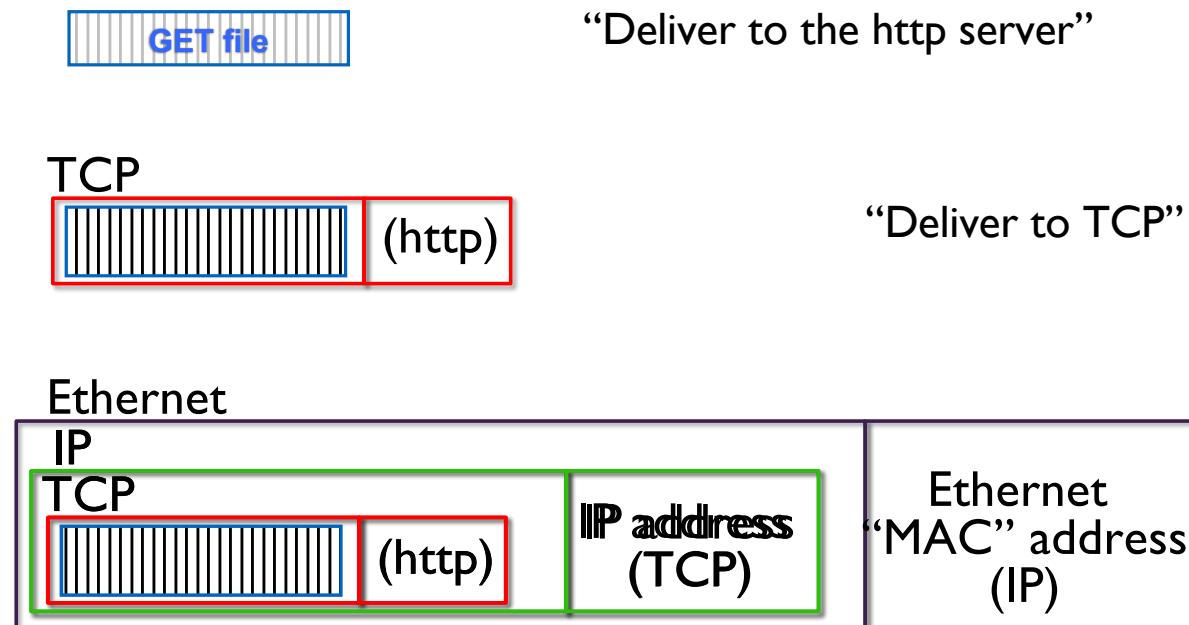


Here it goes....



http server (e.g. www.google.com)

http request



My
Program

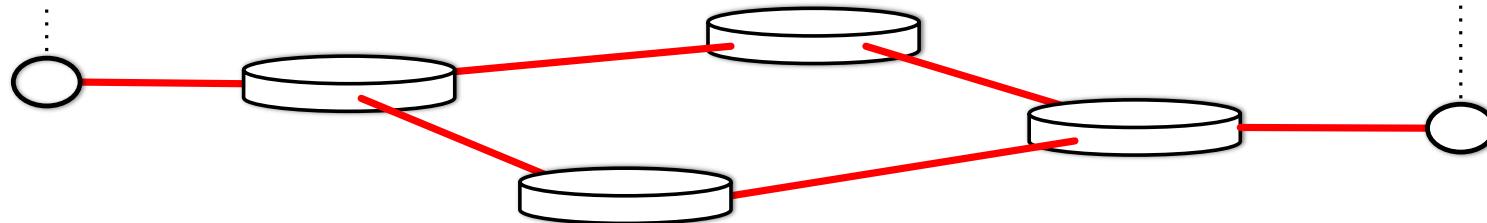
Summary of what we've learned

Someone else's
Program

Applications send and receive data in packets....



...over an Internet that is unreliable.



Packets are forwarded hop-by-hop using the IP destination address.

Our applications use TCP to make sure they are delivered and put back in the correct order.