How the Internet Works

(in about an hour)

Nick McKeown
Professor of Electrical Engineering
and Computer Science, Stanford University

Professor Nick McKeown
1964

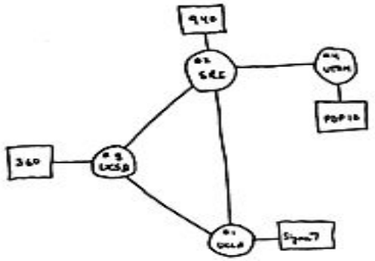
"*A network to survive nuclear attack.*"

Paul Baran

1st network connects two computers

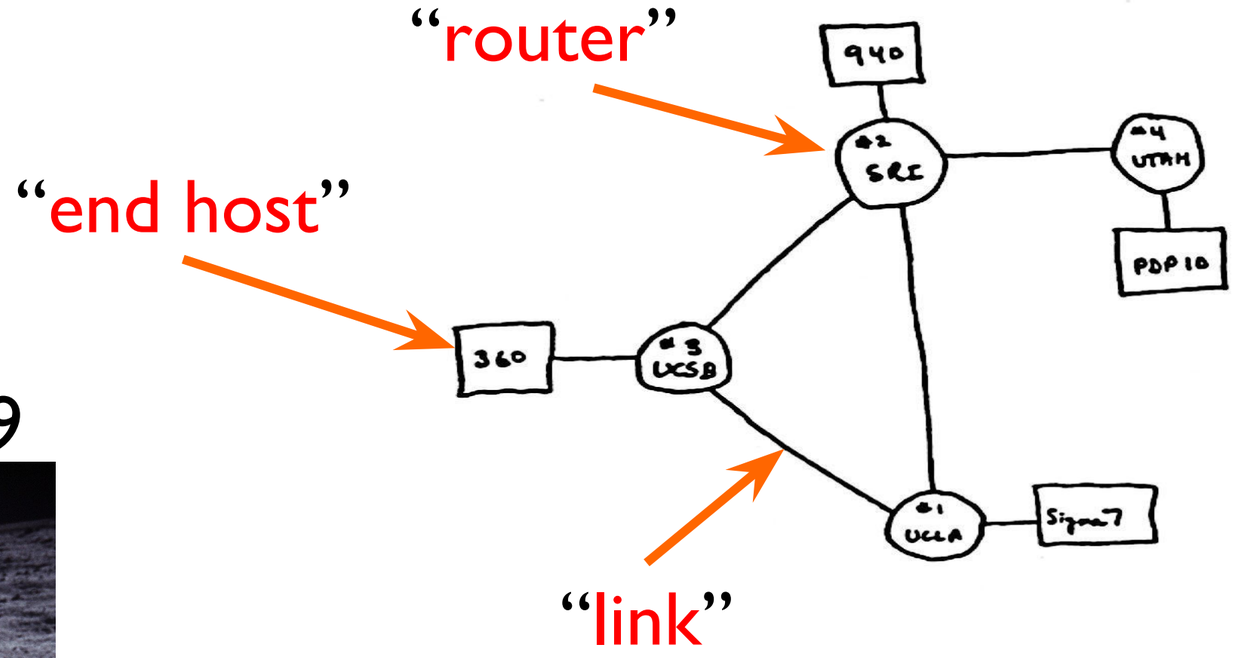
US Government starts "ARPANET" project

Four nodes connected (UCLA, SRI, UCSB, Utah)

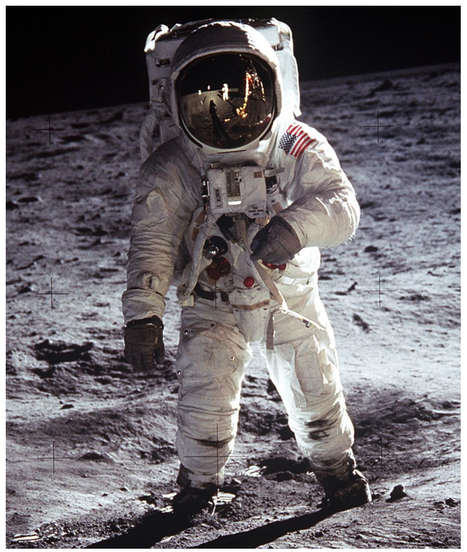


1964 1965 1966 1968 1969

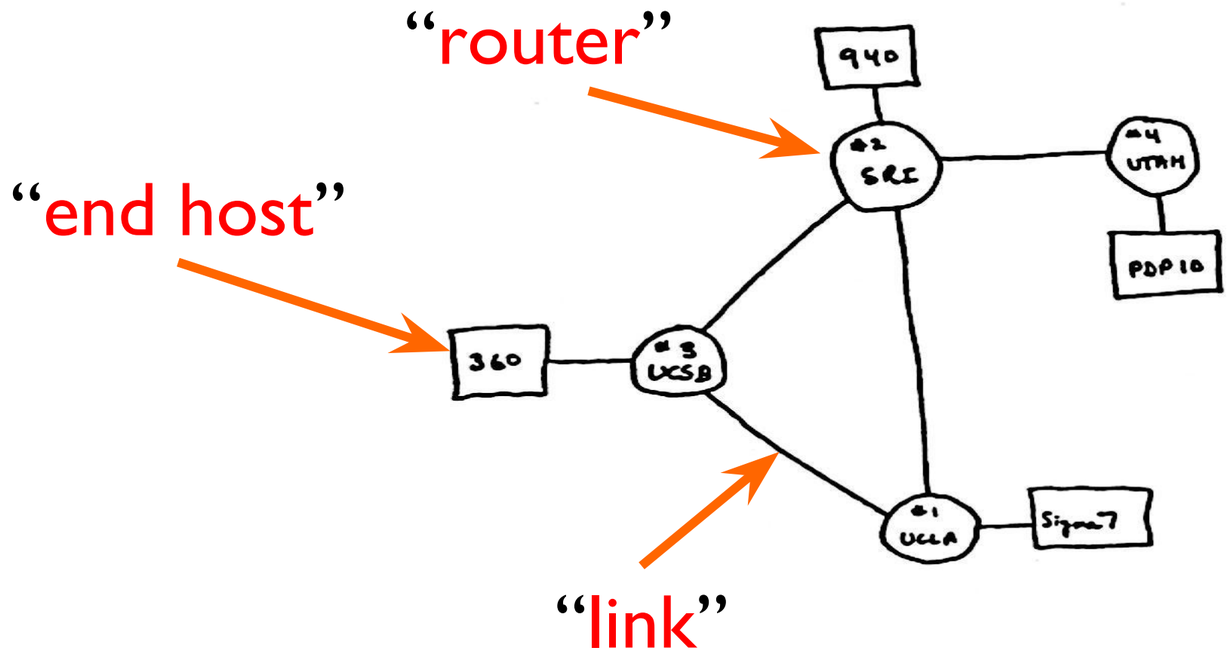
The Internet in 1969



Also in 1969

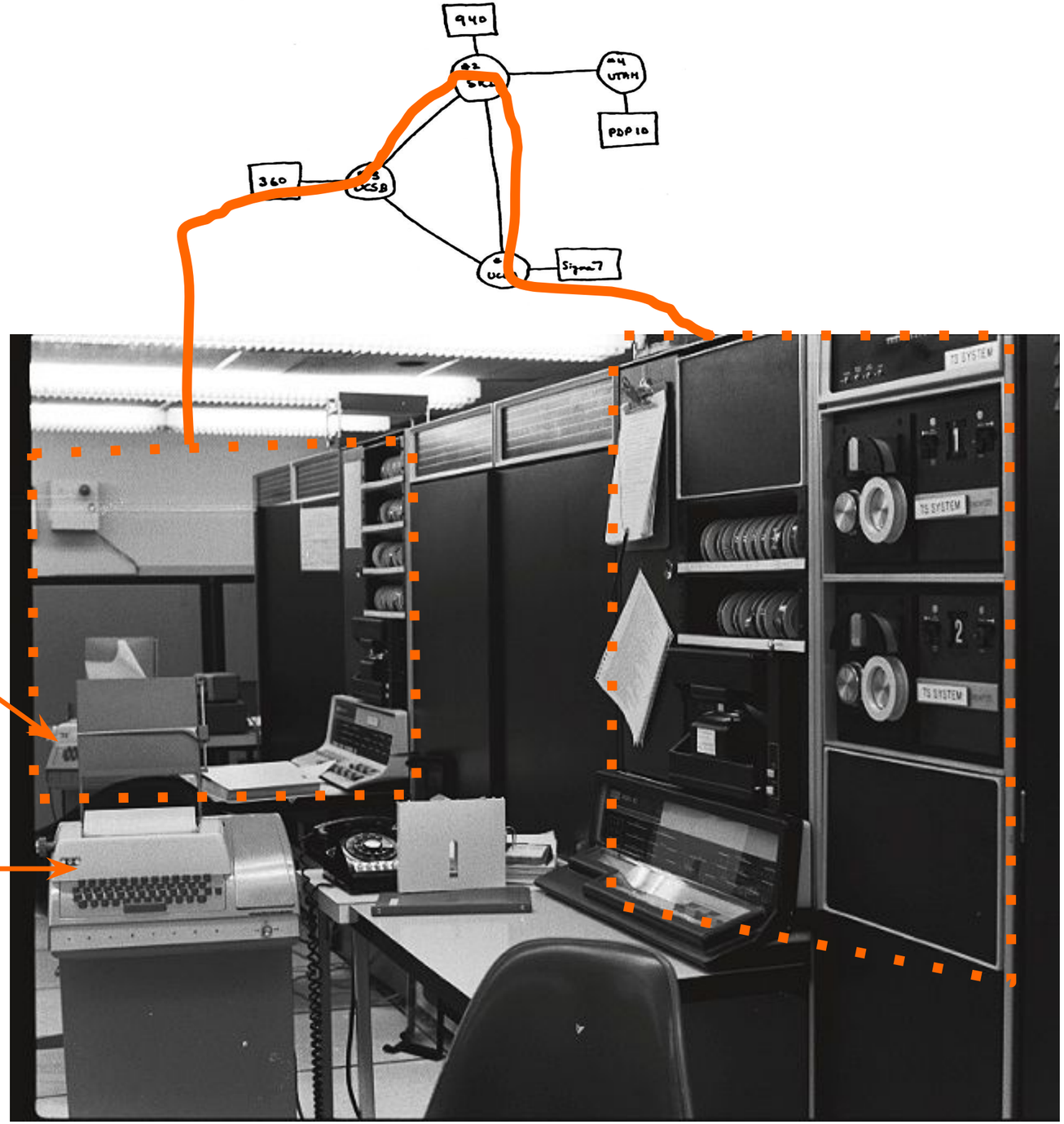


What did they use it for?



1. Sending files between scientists: "*Here is a big file of astronomy data!*"
2. Email: "*Where shall we have lunch today?*"
3. Remote login to another computer.

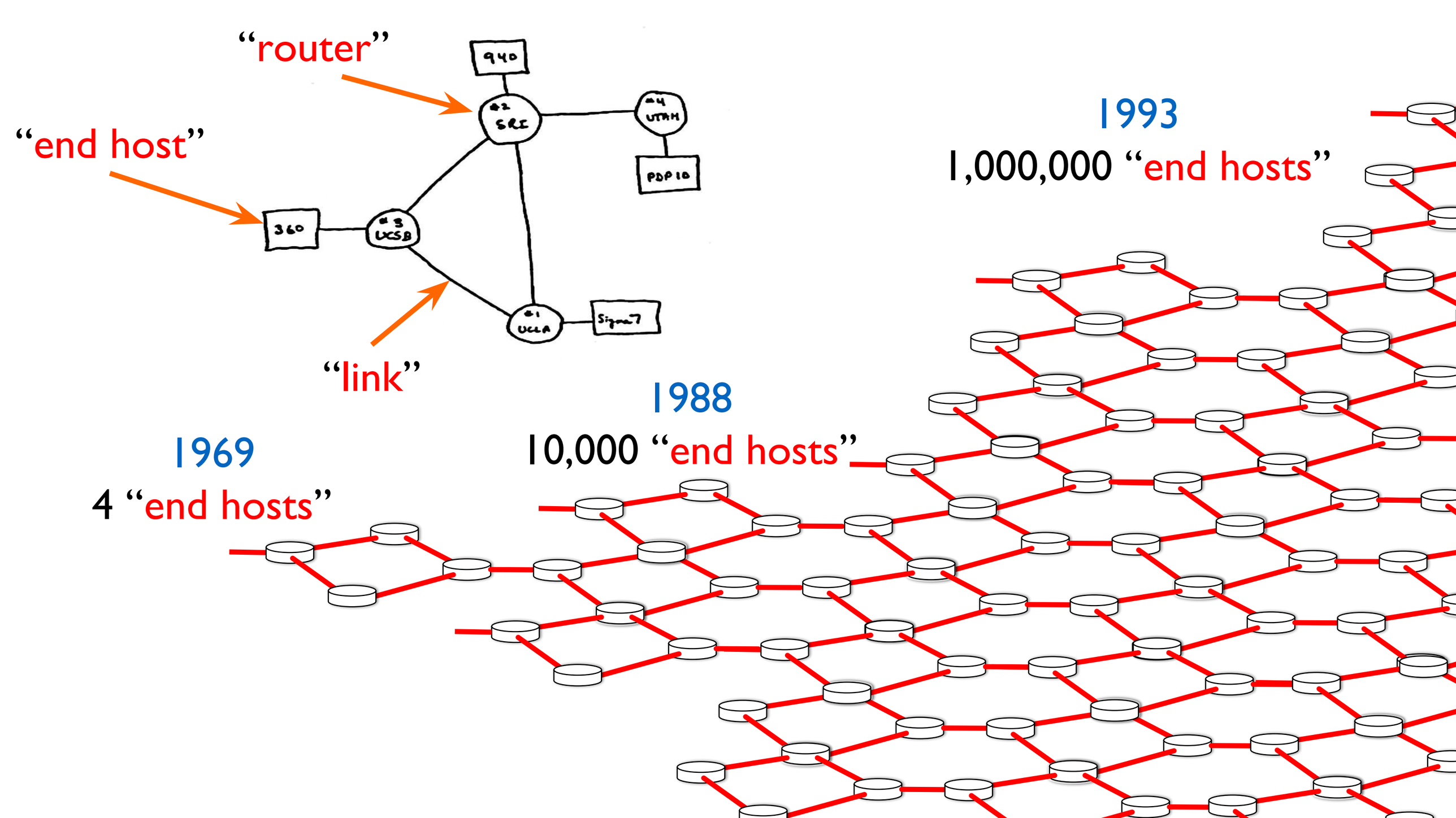
1971



First email typed here

"QWERTYUIOP"

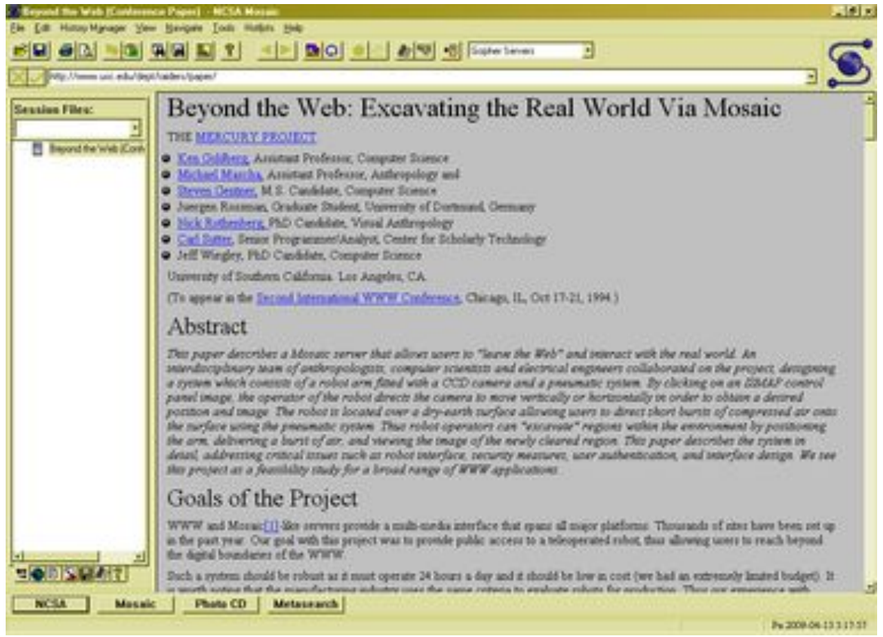
…and printed here


"router"
"end host"
"link"
940
#2 SRI
#4 UTAH
PDP 10
360
#3 UCSB
#1 UCLA
Sigma 7
1969
4 "end hosts"
1988
10,000 "end hosts"
1993
1,000,000 "end hosts"

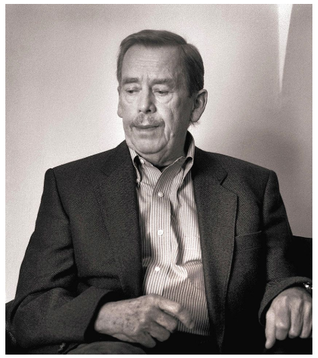
Then in 1993 something even BIGGER happened!!!

1993: The first web browser “Mosaic”

Marc Andreessen



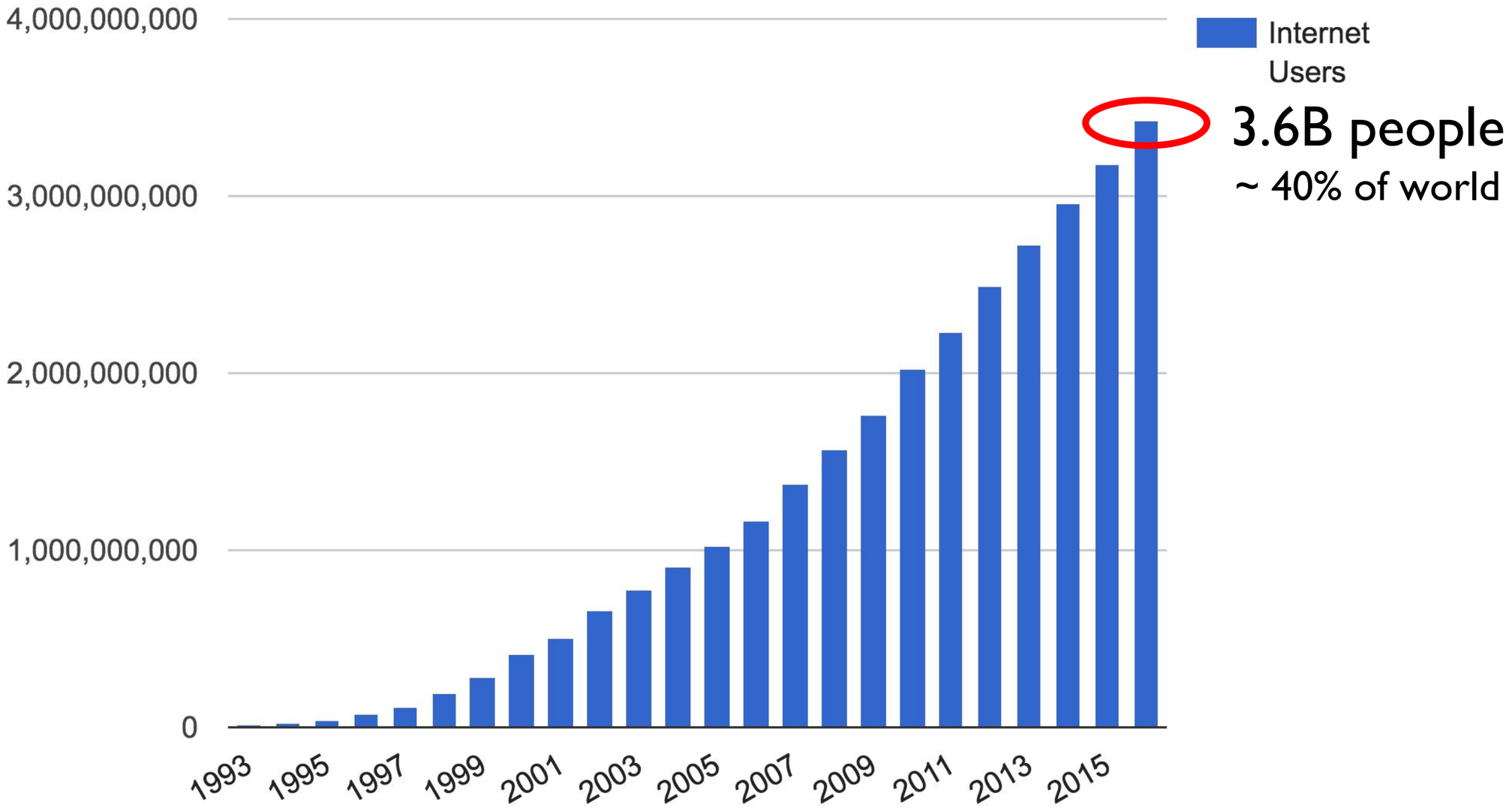
1993



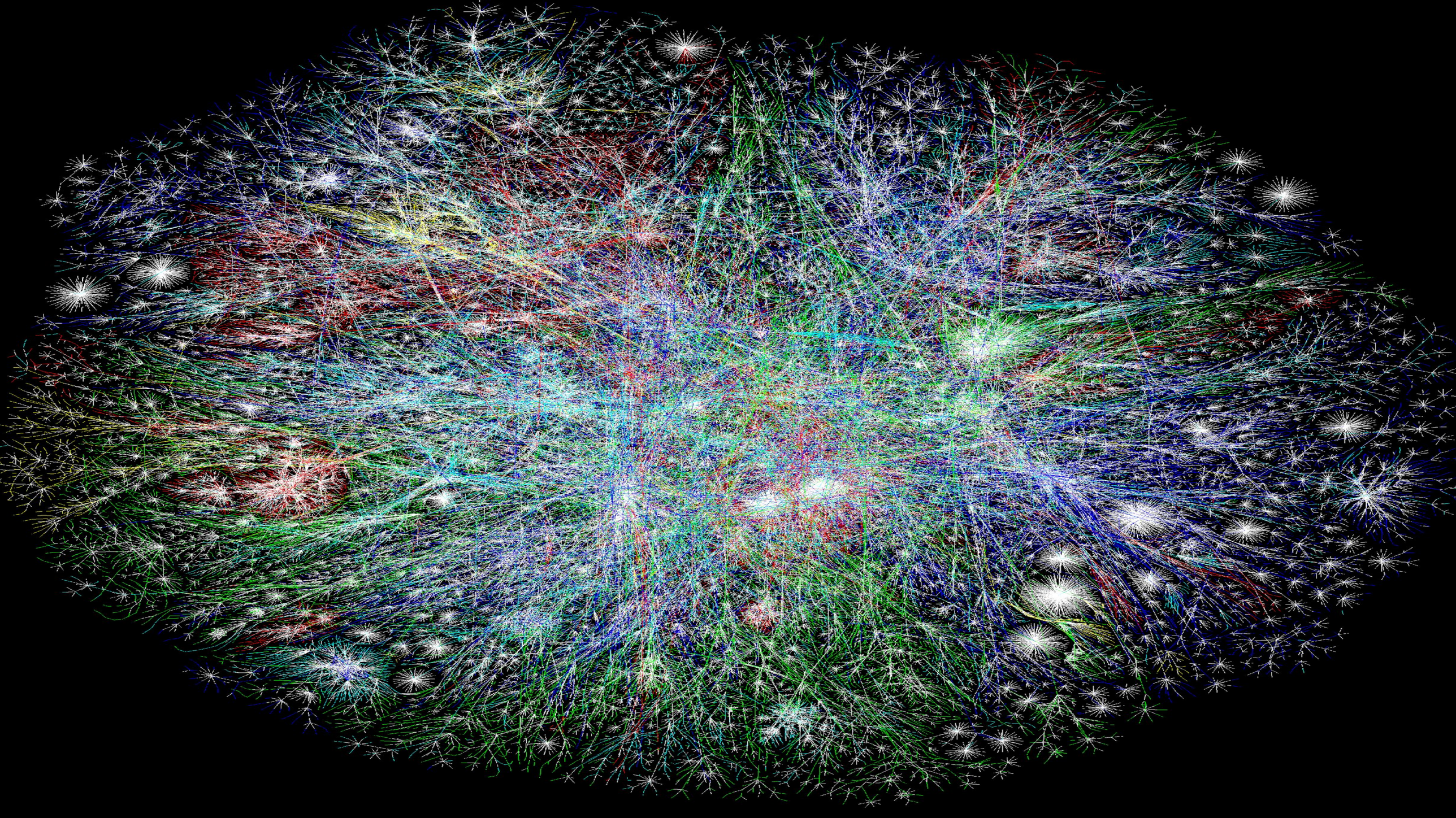
President
Václav Havel

President
Bill Clinton

The number of Internet users in the world

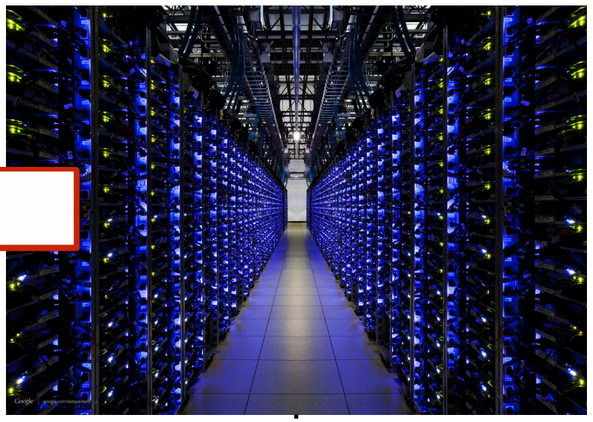


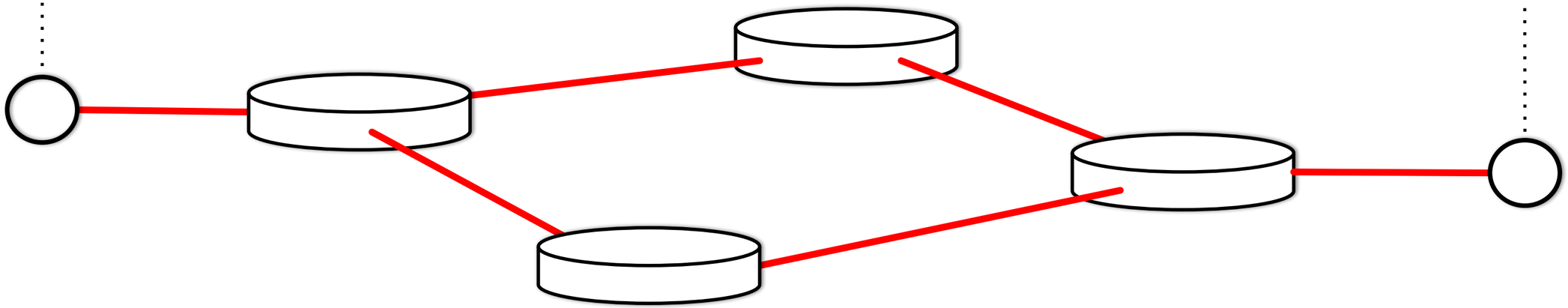
Source: http://www.internetlivestats.com/



How does it all work?

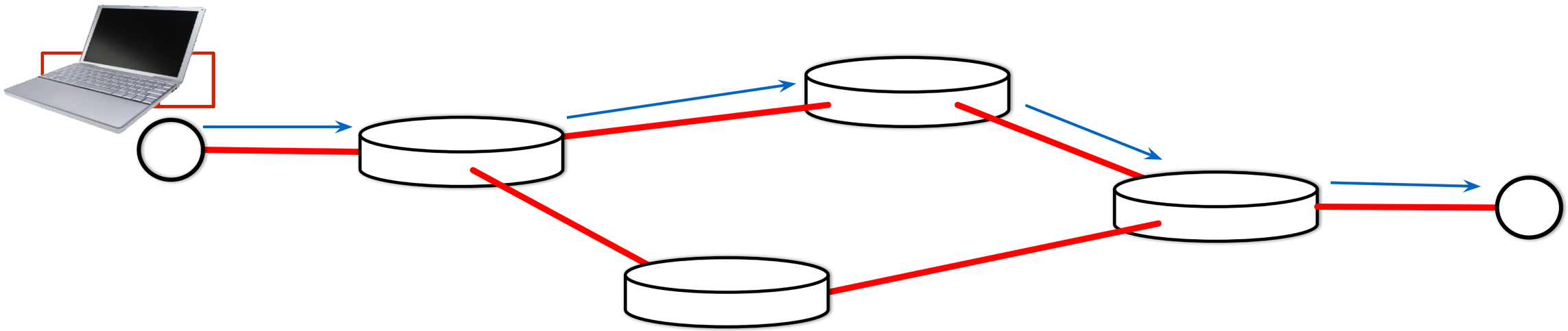
Google YouTube facebook NETFLIX

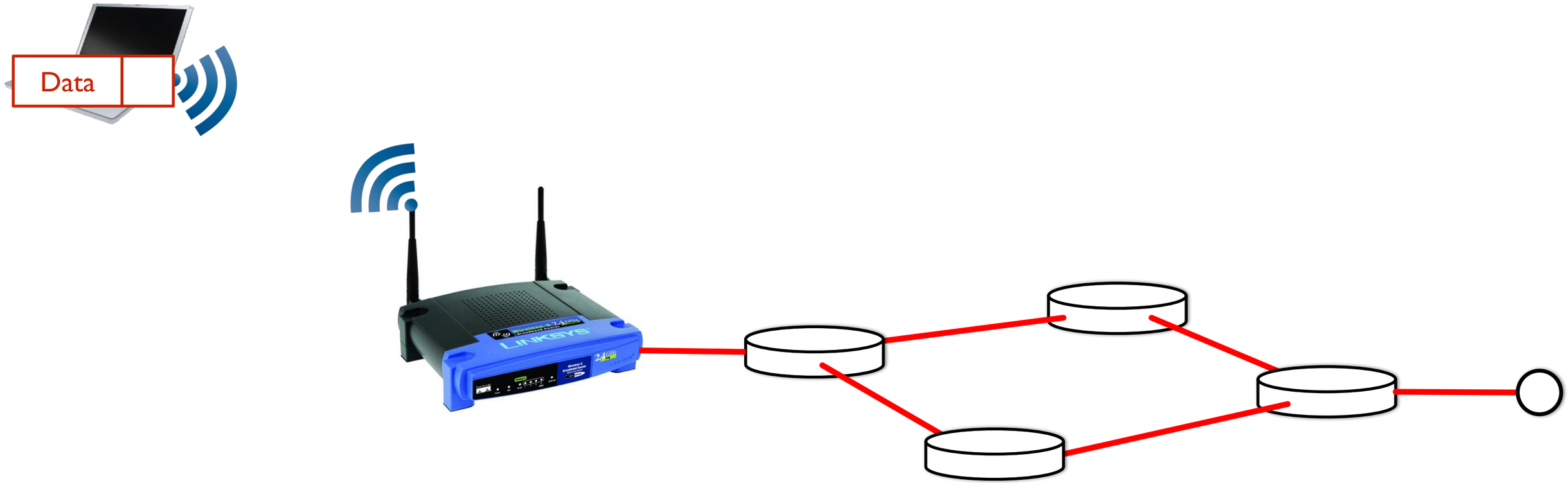


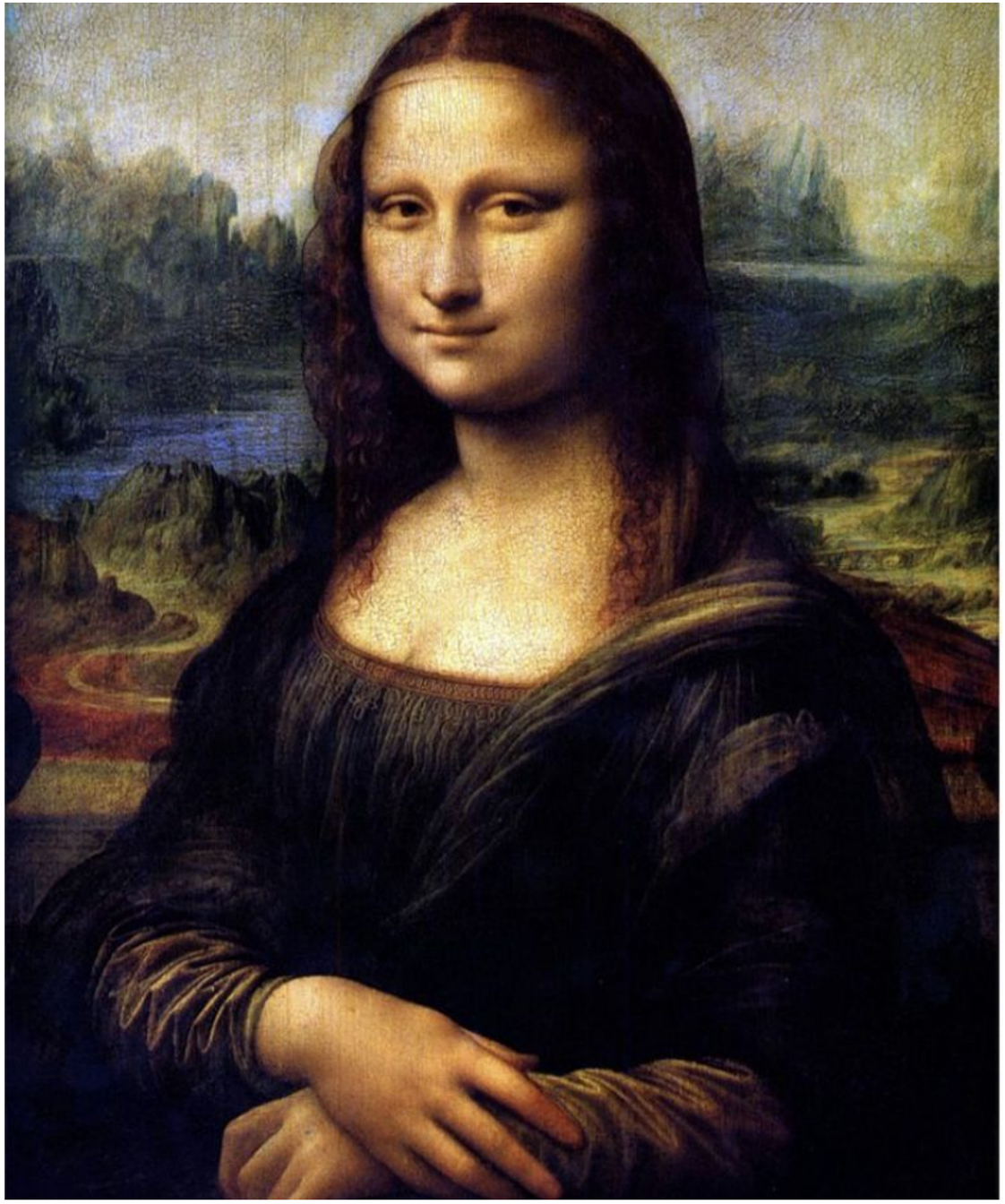


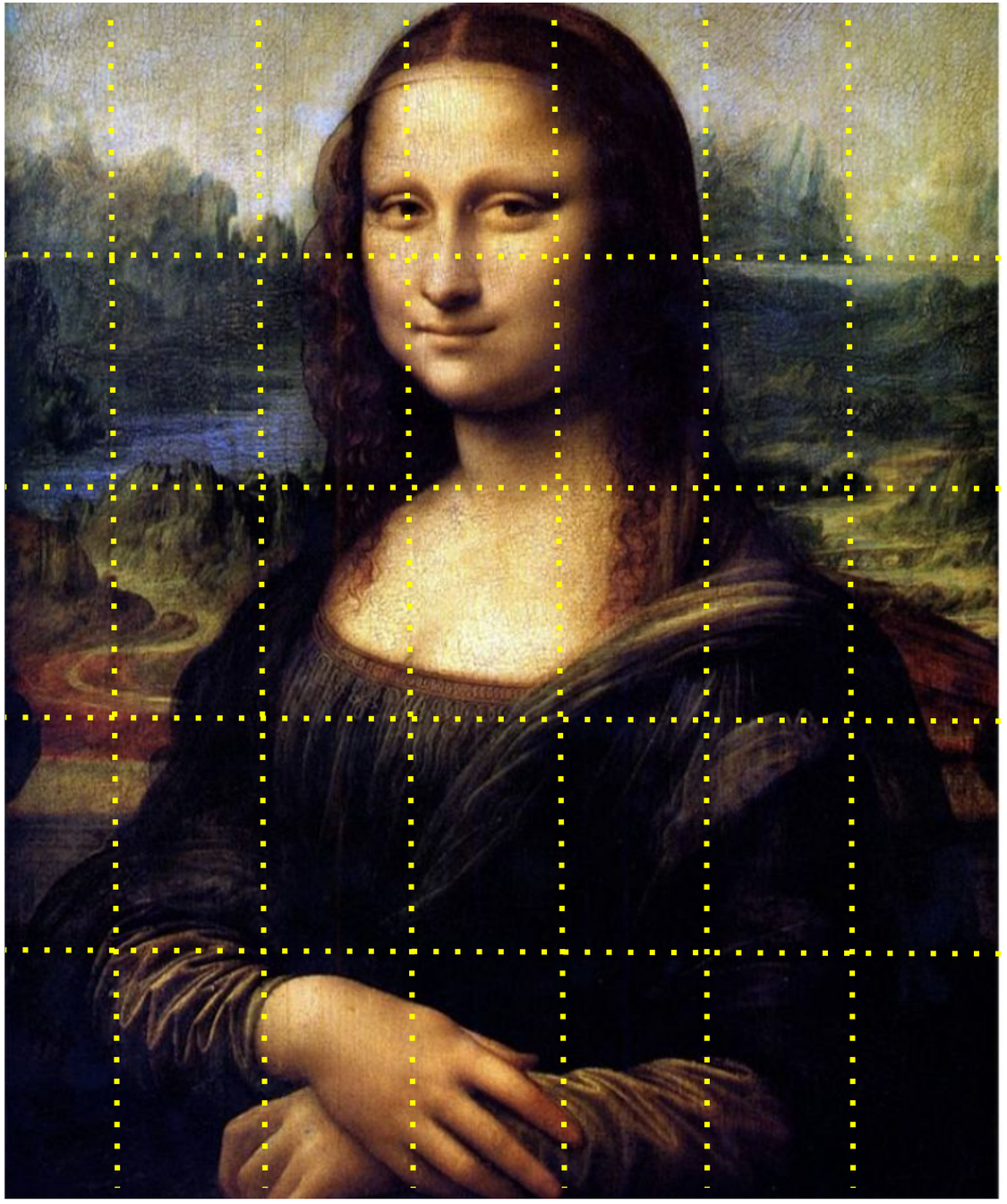
My Program

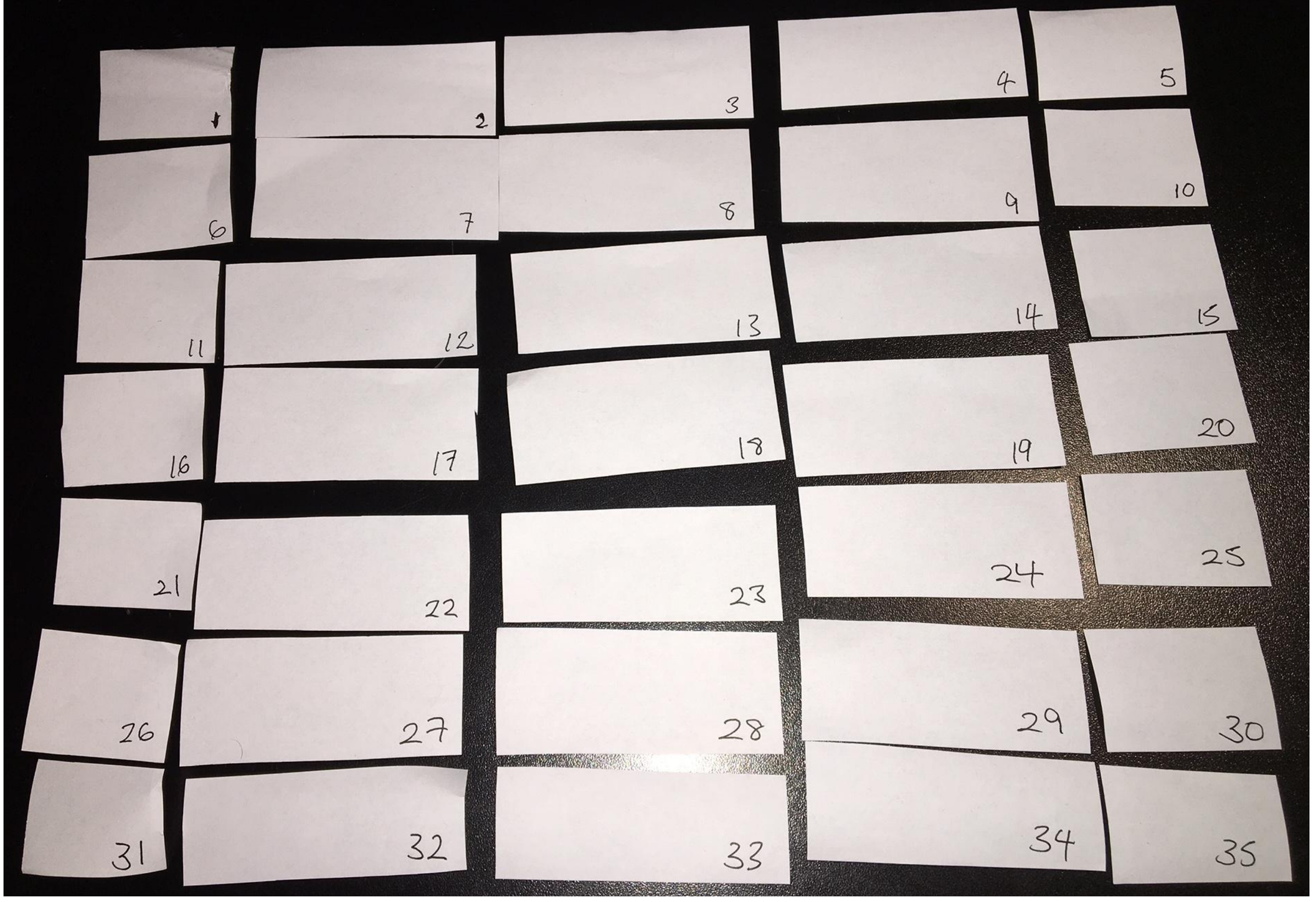
Someone else's Program




Data
LINKSYS



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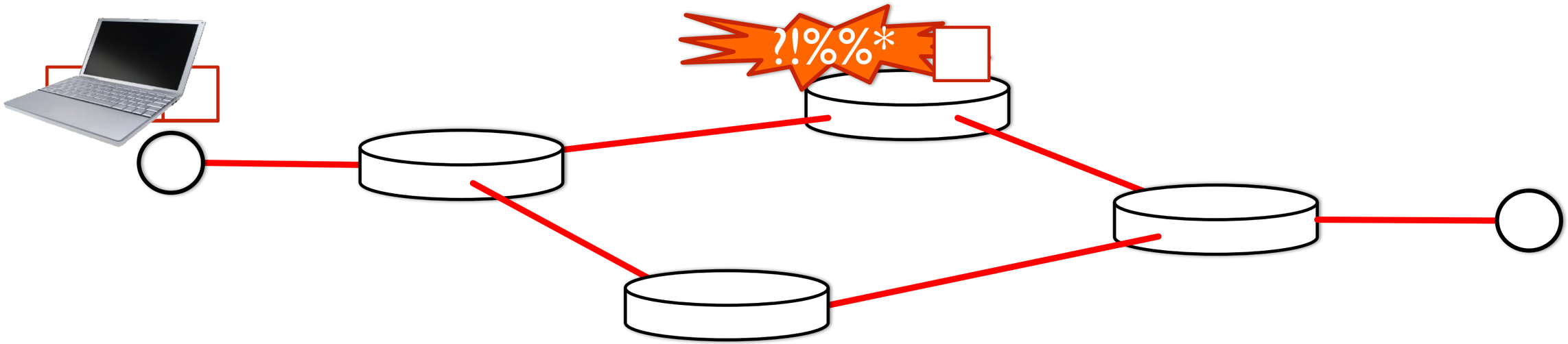
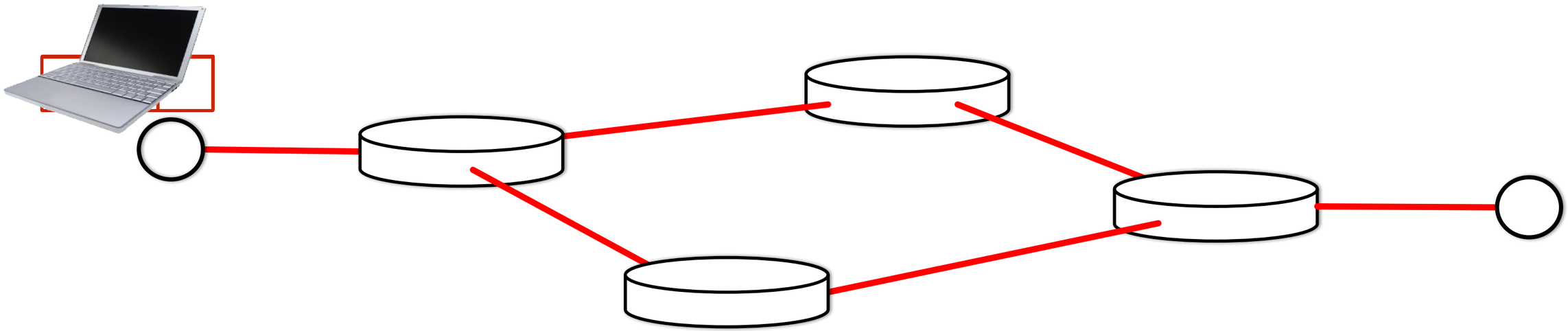
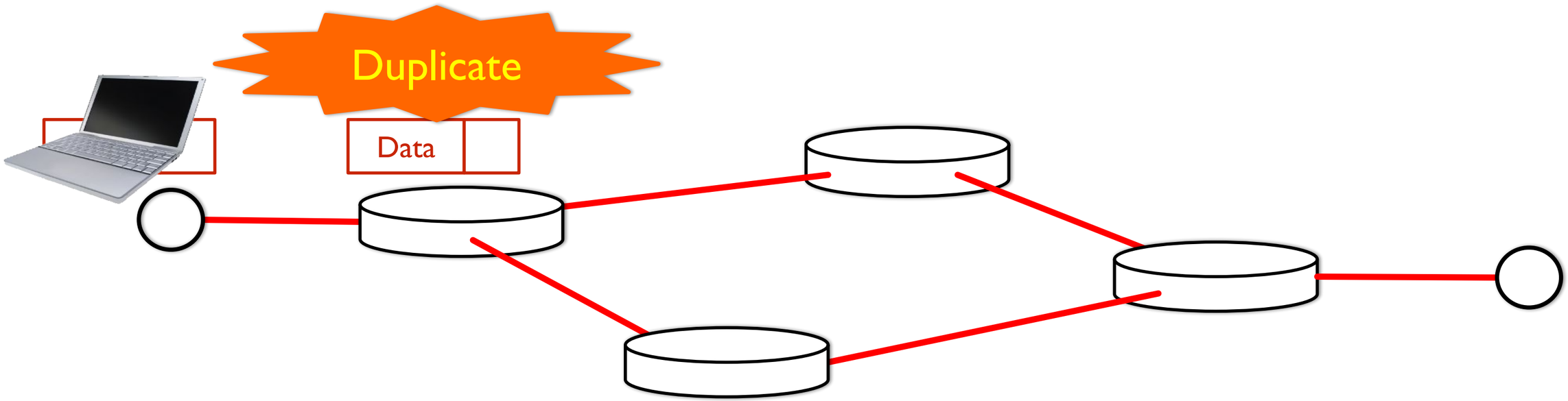
Packets may be damaged



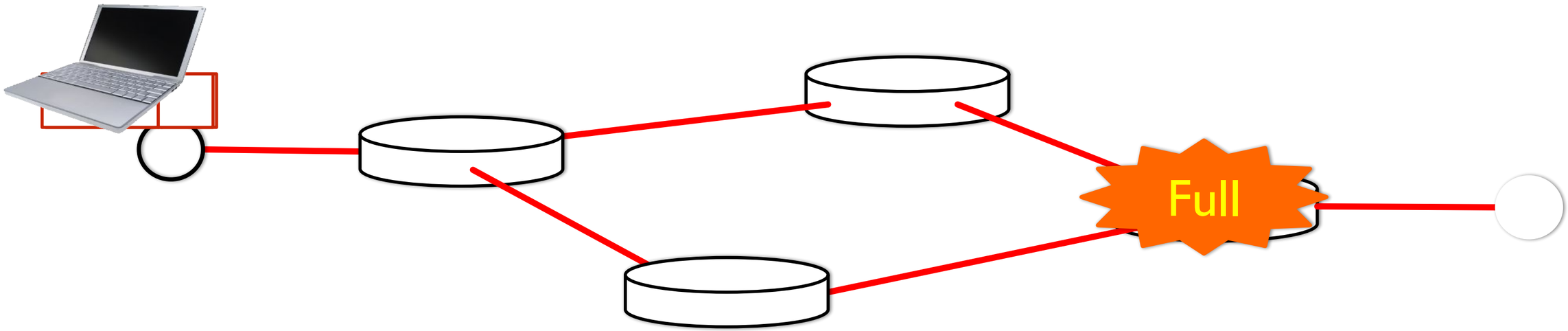
Packets may arrive out of order



Packets may be duplicated



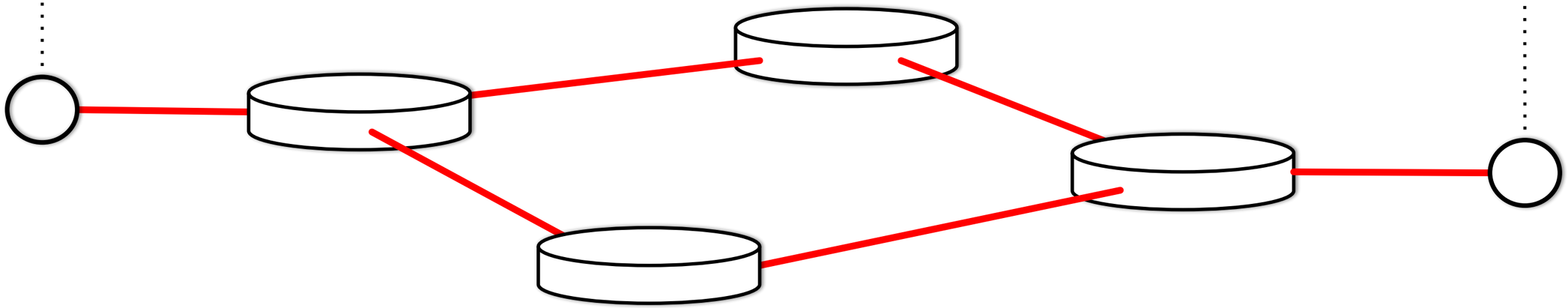
They may not arrive at all!



Summary so far

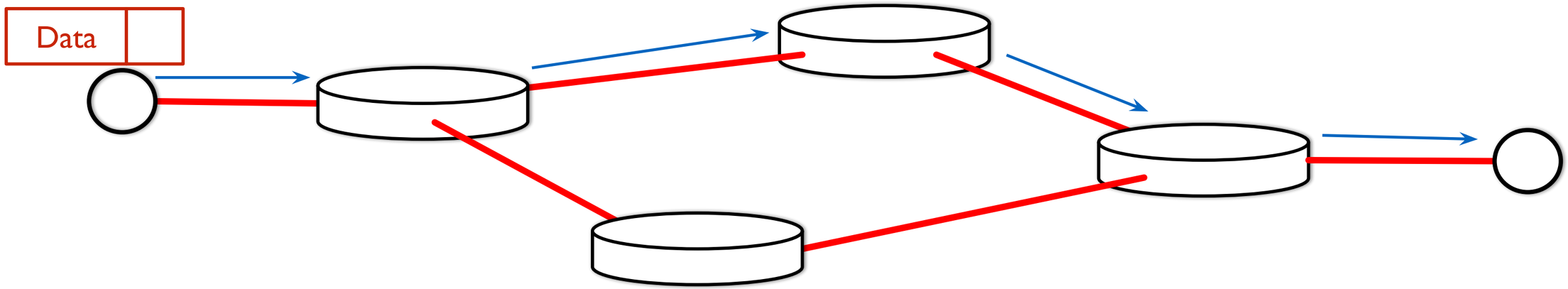
Applications send and receive data in packets….

…over an Internet that is unreliable.



What do Internet packets look like?

Internet addresses



Internet Addresses (“IP address”)

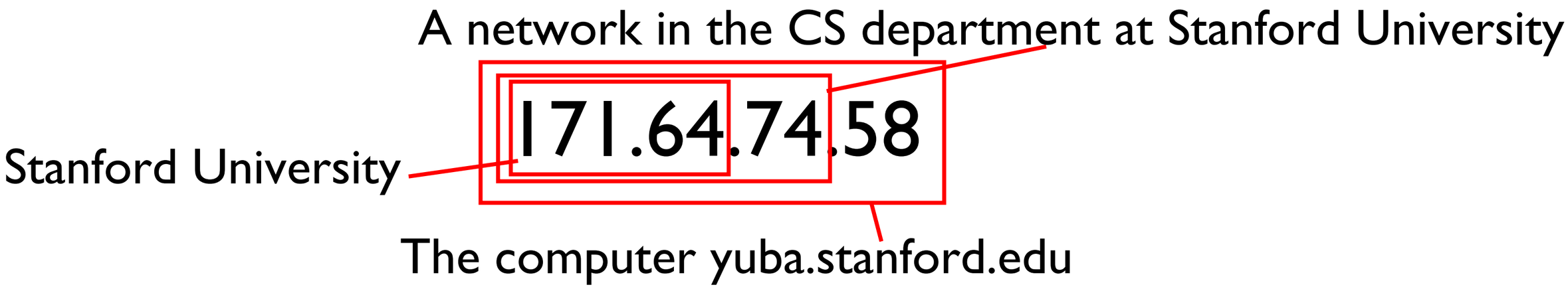
All Internet packets carry a destination IP address.

We usually write the IP address like this:

171.64.74.58

Internet “IP” Addresses

The IP address tells each router where to send the packet next.



Can we see the path our packets take?

Yes!

On a Mac or Linux , try:

“`traceroute yuba.stanford.edu`”

On Windows, try: “`tracert yuba.stanford.edu`”

nickm > **traceroute yuba.stanford.edu**

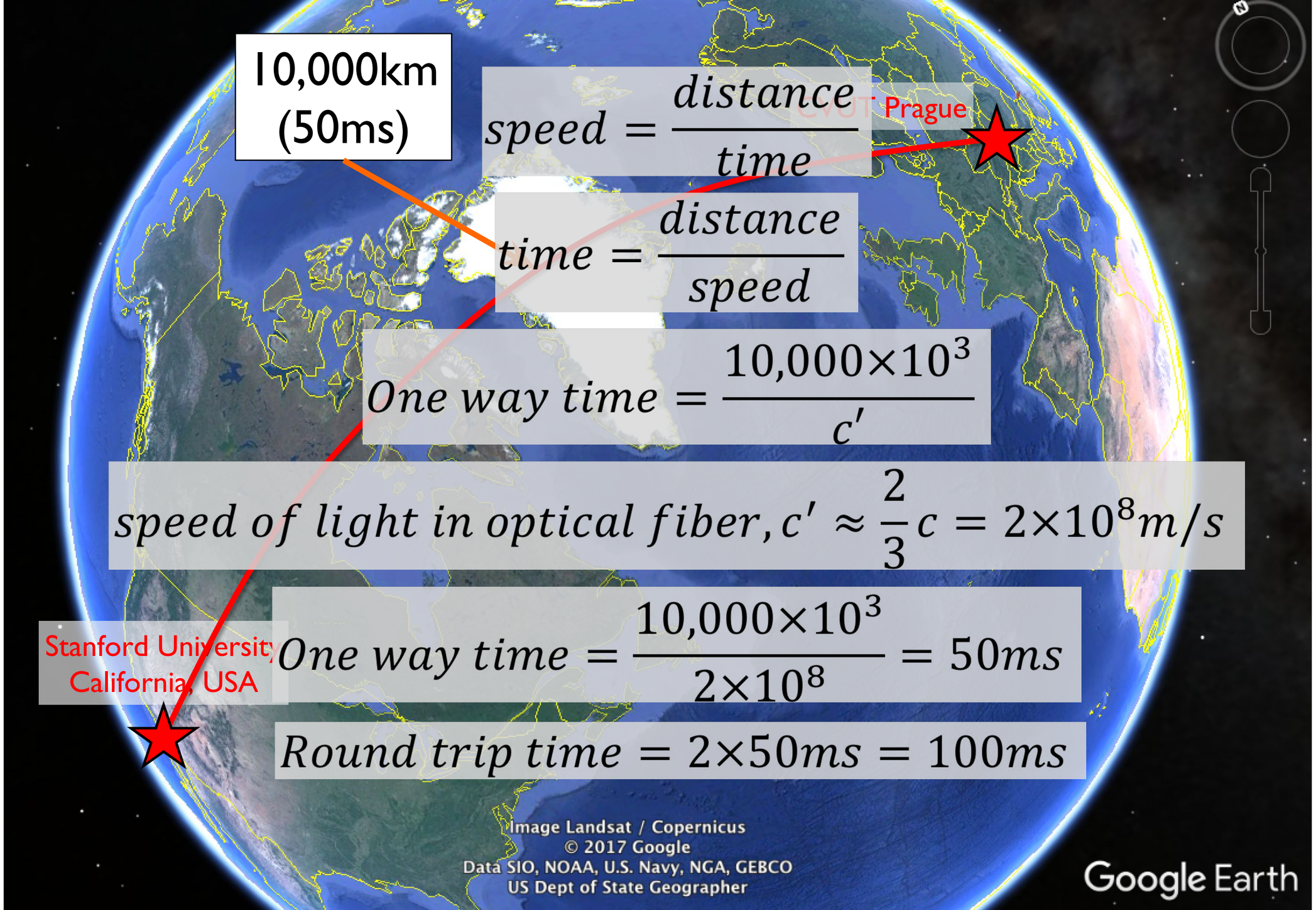
```
traceroute to yuba.stanford.edu (171.64.74.58), 64 hops max, 52 byte packets
 1  10.101.5.254 (10.101.5.254)  1.858 ms
 2  77.48.48.241 (77.48.48.241)  3.195 ms
 3  10.1.1.1 (10.1.1.1)  2.192 ms
 4  te0-6-0-2-s404.cz-pra-pop1-rb1.net.upc.cz (77.48.21.21)  4.443 ms
 5  cz-prg02a-ra2-ae5-129.aorta.net (84.116.131.153)  11.574 ms
 6  cz-prg01a-ra4-ae15-0.aorta.net (84.116.136.69)  15.949 ms
 7  de-fra04a-rc1-ae33-0.aorta.net (84.116.135.5)  13.060 ms
 8  de-fra04a-rc1-ae26-0.aorta.net (84.116.138.237)  26.720 ms
 9  de-fra01b-ri1-ae1-0.aorta.net (84.116.134.10)  11.594 ms
10  10ge10-2.core1.fra1.he.net (216.66.87.125)  45.676 ms
11  100ge1-1.core1.par2.he.net (72.52.92.13)  31.118 ms
12  100ge14-1.core1.nyc4.he.net (184.105.81.77)  95.162 ms
13  100ge13-1.core4.fmt2.he.net (184.105.81.61)  182.769 ms
14  100ge9-1.core1.pao1.he.net (184.105.222.90)  159.940 ms
15  stanford-university.10gigabitethernet1-4.core1.pao1.he.net
    (216.218.209.118)  160.110 ms
16  csee-west-rtr-vl2.sunet (171.64.255.140)  160.209 ms
17  yuba.stanford.edu (171.64.74.58)  160.372 ms
```

```
tracert yuba.stanford.edu
```

From CVUT, it takes about 160ms to reach yuba.stanford.edu
and back again (“round-trip-time”)


CVUT Prague
Stanford University
California, USA
Image Landsat / Copernicus
© 2017 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
US Dept of State Geographer
Google Earth


10,000km
(50ms)
CVUT Prague
Stanford University
California, USA
Image Landsat / Copernicus
© 2017 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
US Dept of State Geographer
Google Earth



$$speed = \frac{distance}{time}$$

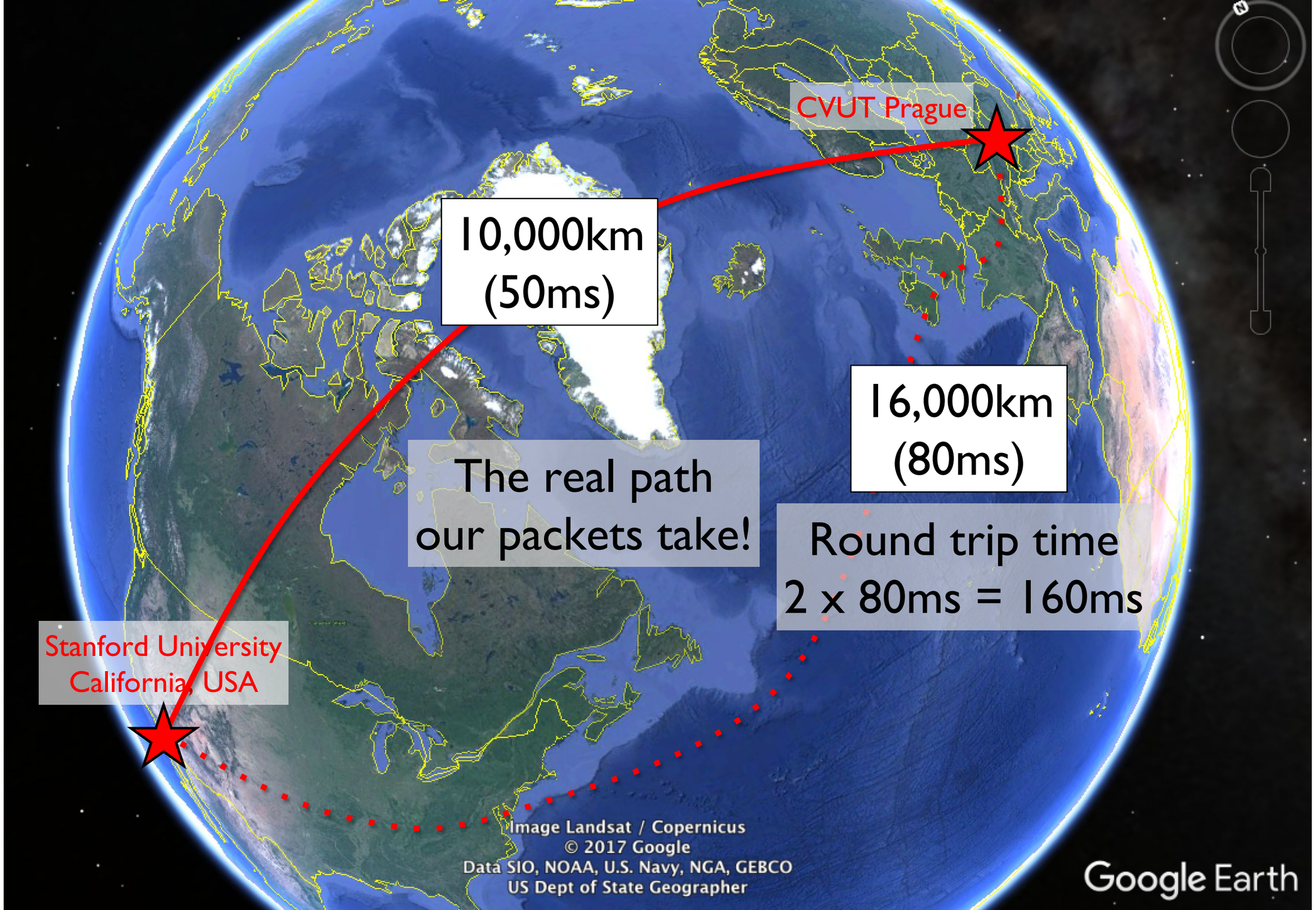
$$time = \frac{distance}{speed}$$

$$One\ way\ time = \frac{10{,}000 \times 10^3}{c'}$$

$$speed\ of\ light\ in\ optical\ fiber, c' \approx \frac{2}{3}c = 2 \times 10^8 m/s$$

$$One\ way\ time = \frac{10{,}000 \times 10^3}{2 \times 10^8} = 50ms$$

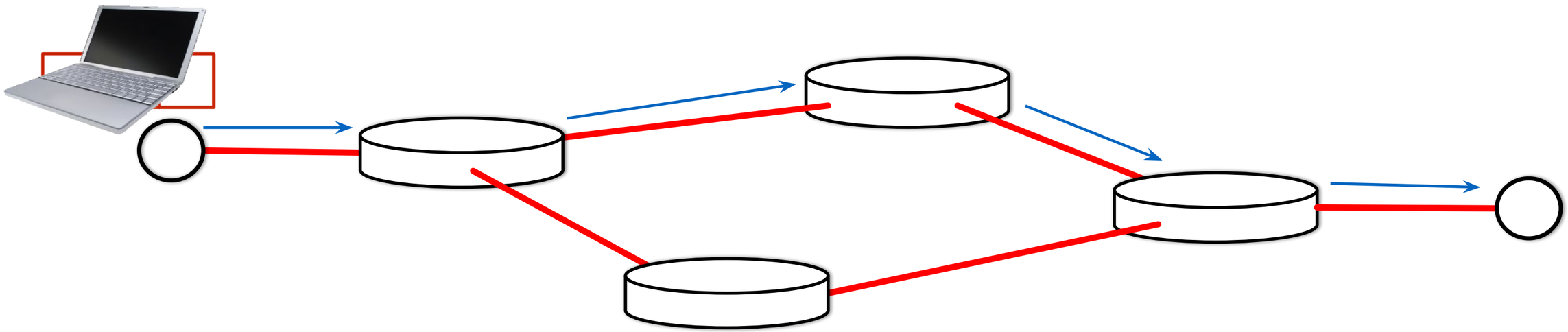
$$Round\ trip\ time = 2 \times 50ms = 100ms$$


CVUT Prague
10,000km
(50ms)
16,000km
(80ms)
The real path
our packets take!
Round trip time
2 x 80ms = 160ms
Stanford University
California, USA
Image Landsat / Copernicus
© 2017 Google
Data SIO, NOAA, U.S. Navy, NGA, GEBCO
US Dept of State Geographer
Google Earth

How do packets find their way across the Internet?

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*

Stanford University
A network in the CS department at Stanford University
The computer yuba.stanford.edu

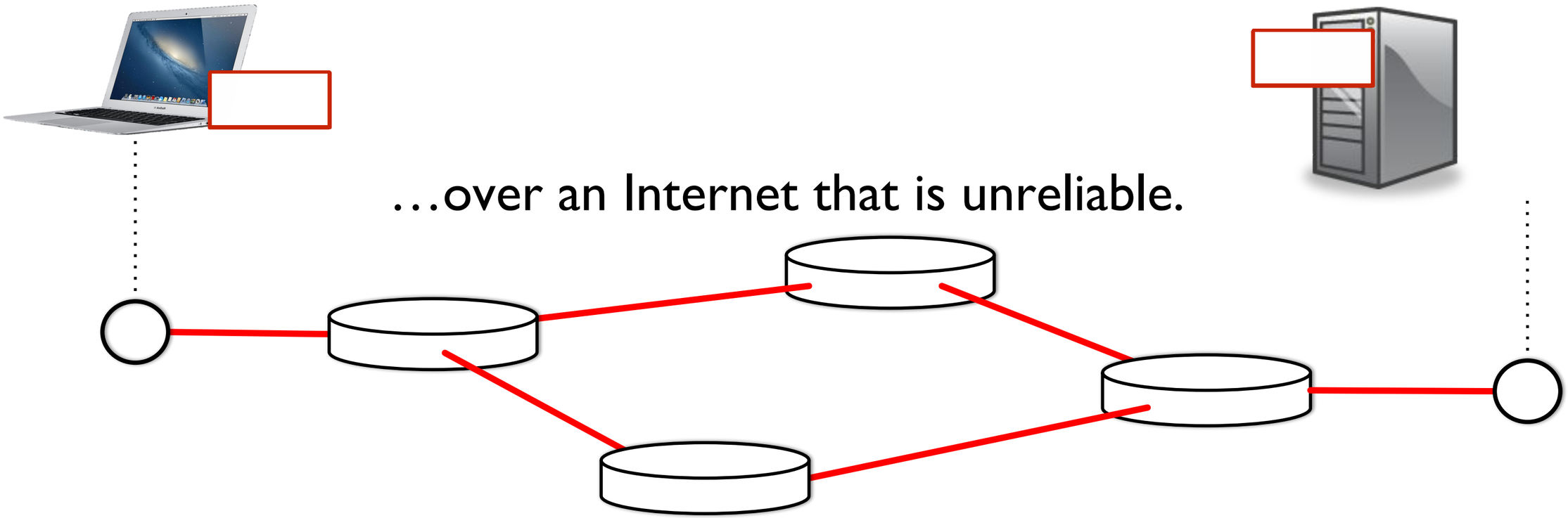
171.64.74.58

An address owned by CVUT Prague
The computer www.cvut.cz

147.32.3.202

Summary so far

Applications send and receive data in packets….



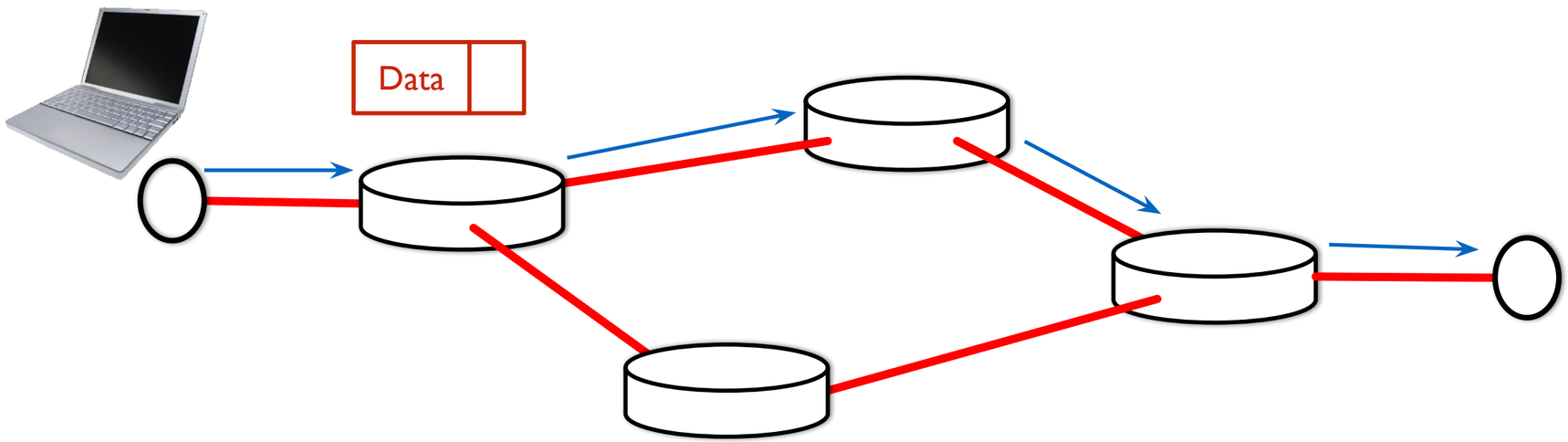
…over an Internet that is unreliable.

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

The Internet cannot be trusted!!

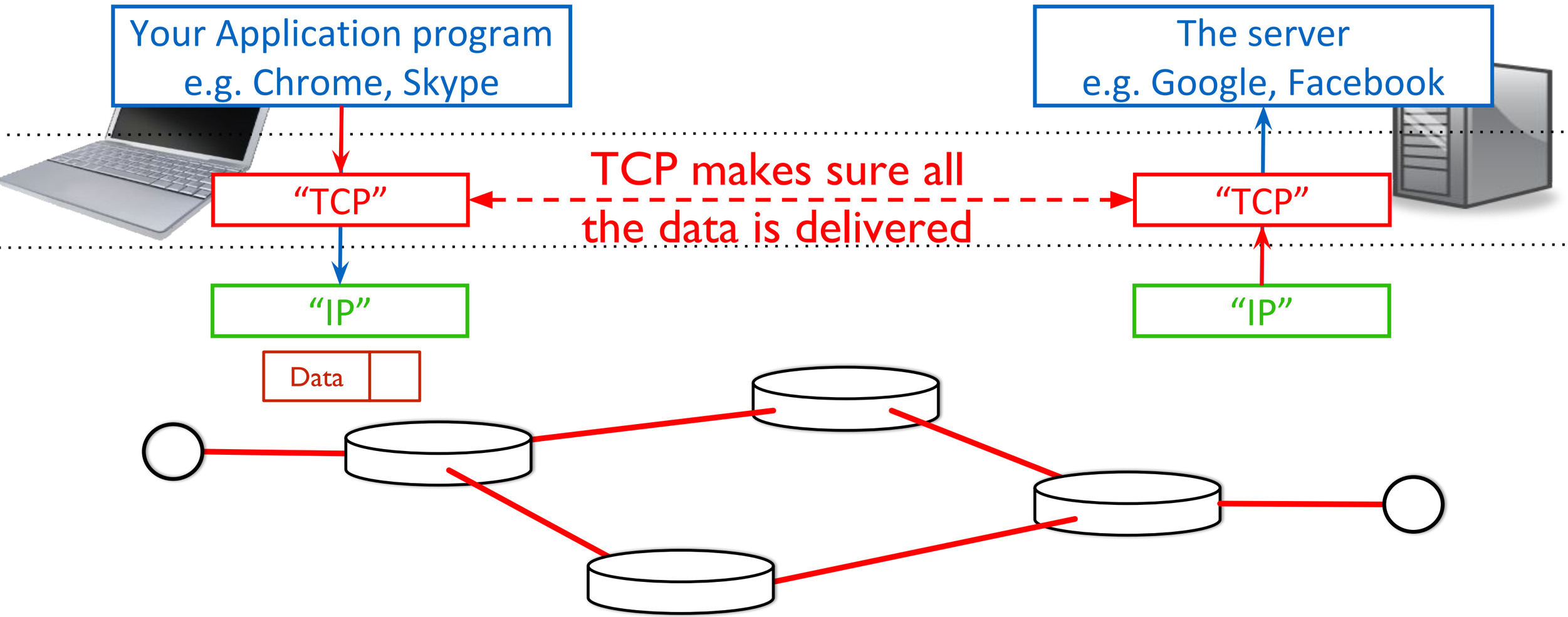
The Internet doesn't promise to deliver packets in order.
It doesn't promise to deliver packets quickly, or on time.
It doesn't even promise to deliver them at all!

It just makes a "best-effort" attempt.



How can we send data reliably over an Internet that is unreliable?

Internet applications use something called “TCP” to send data reliably


Your Application program
e.g. Chrome, Skype
The server
e.g. Google, Facebook
"TCP"
TCP makes sure all
the data is delivered
"TCP"
"IP"
"IP"
Data

TCP’s job

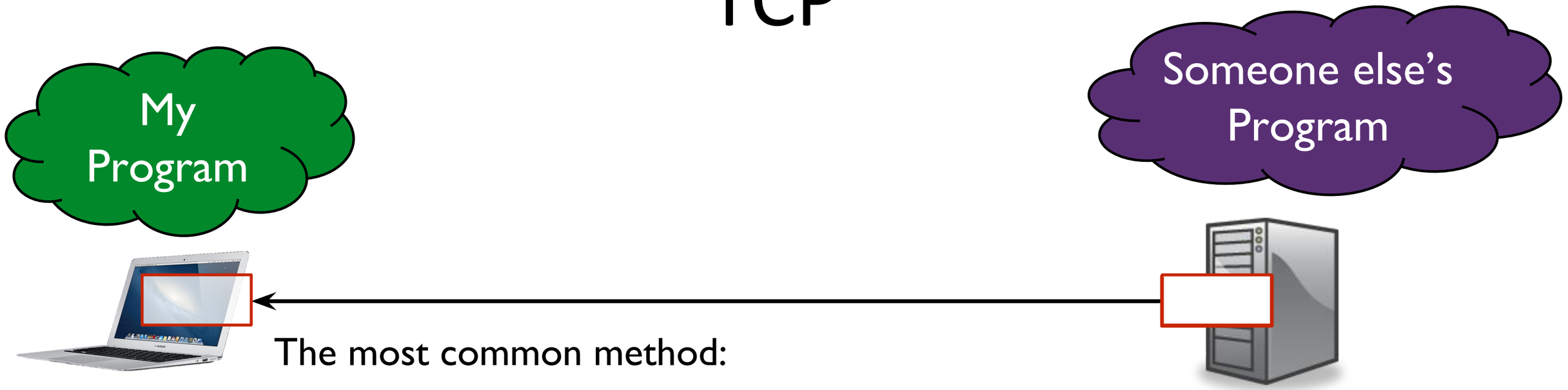
Makes sure all data is delivered correctly.

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

TCP



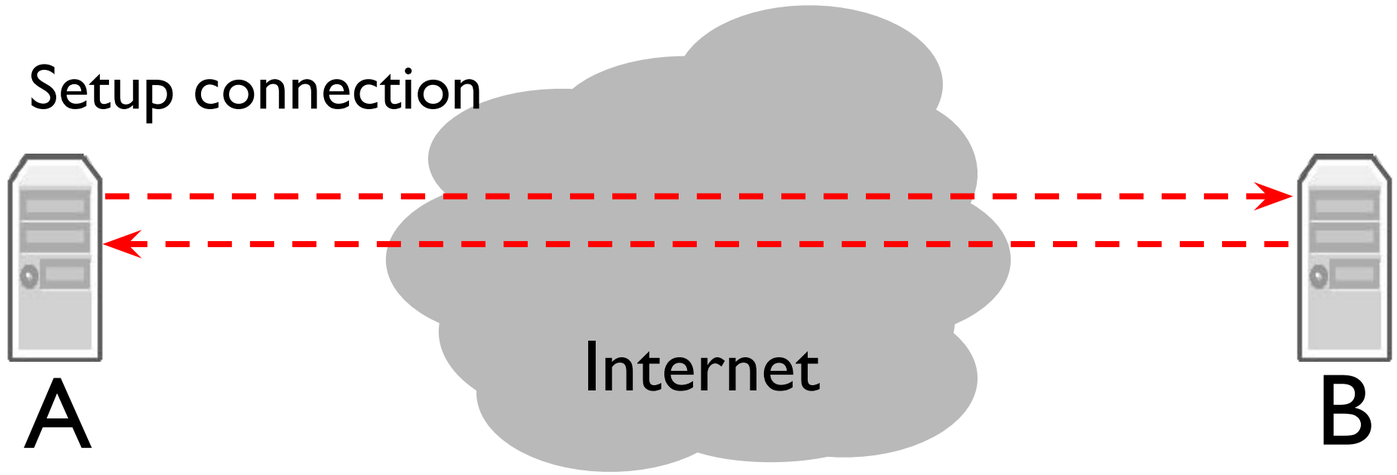
The most common method:

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

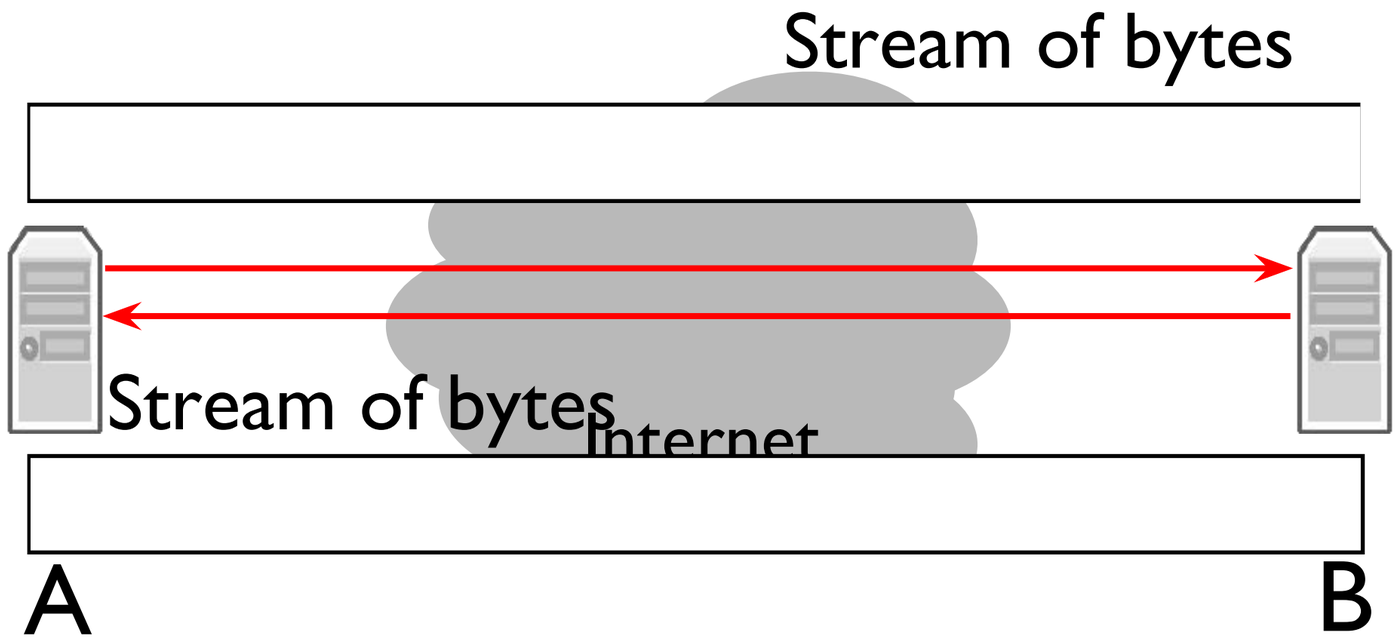
It's like an unformatted pipe:

- Your application pushes data in at one end, and it pops out correctly at the other end.
- The applications agree how the data is formatted inside the pipe.

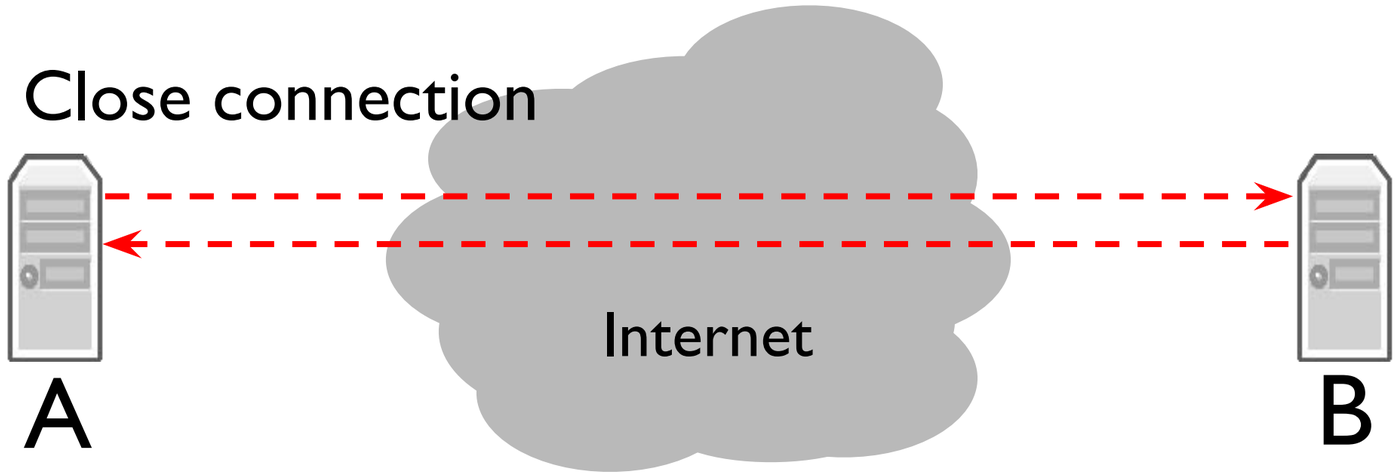
Byte Stream Model



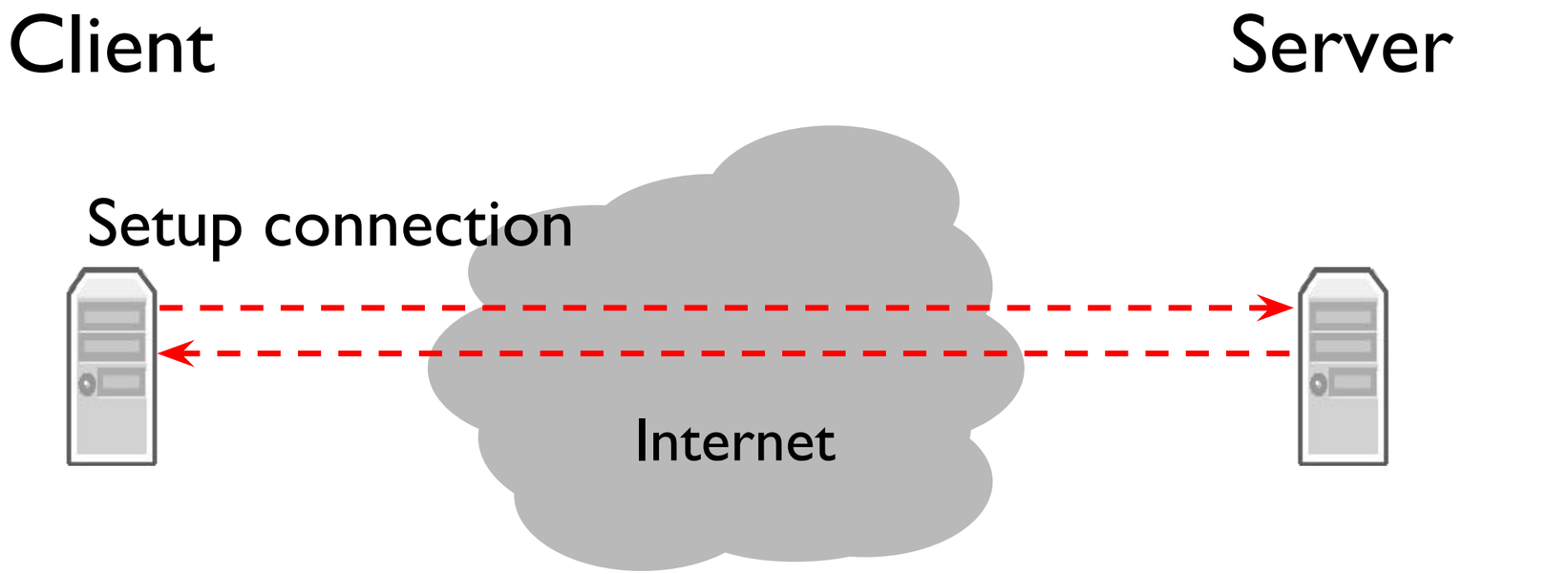
Byte Stream Model



Byte Stream Model

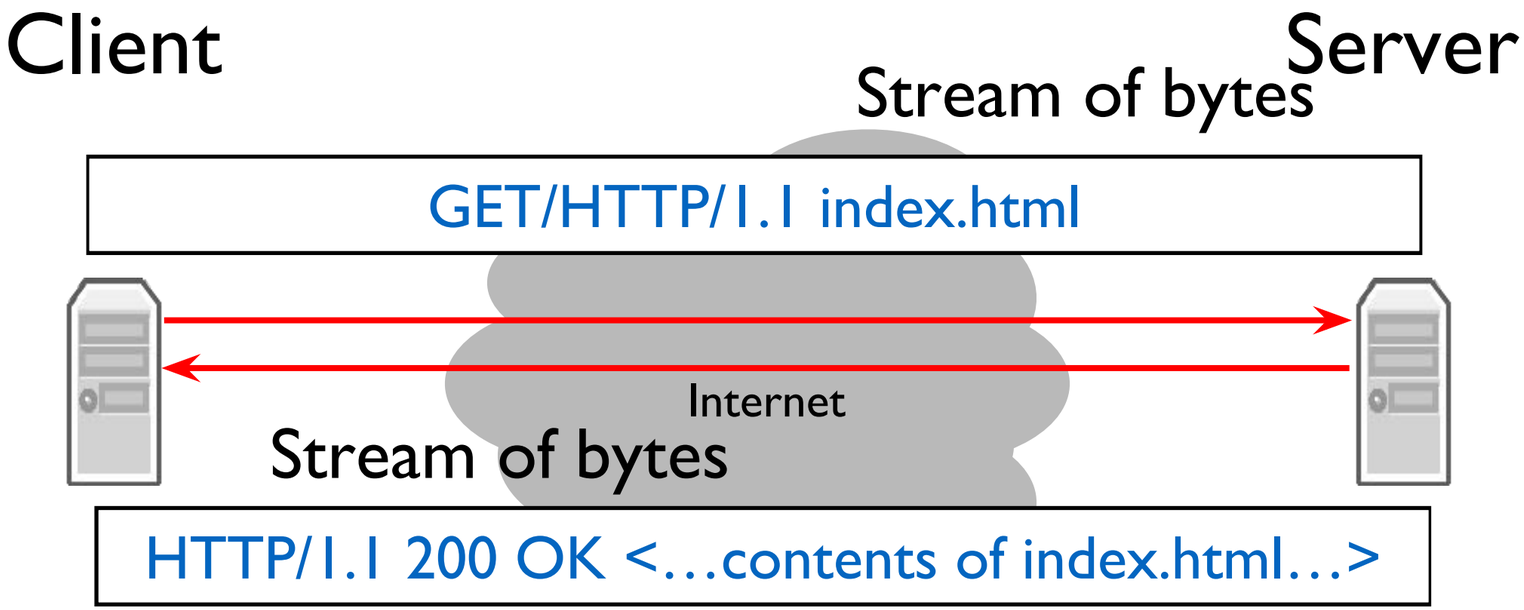


World Wide Web (HTTP)



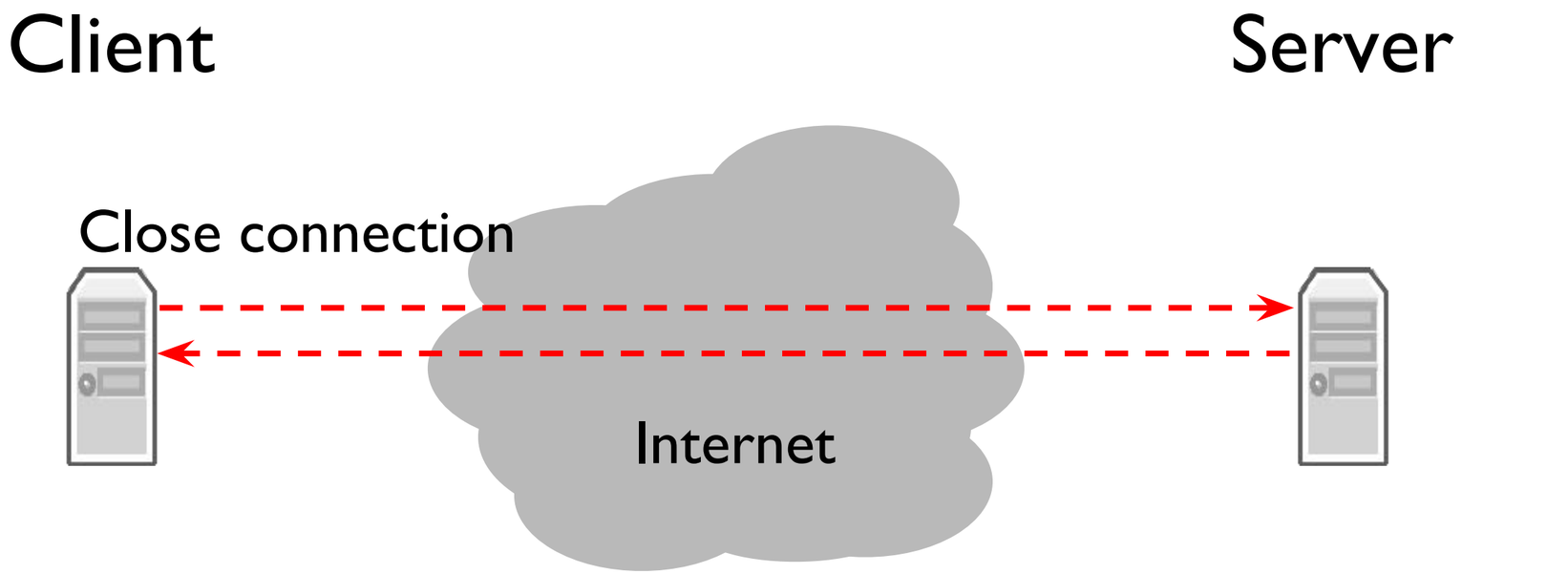
www.stanford.edu

World Wide Web (HTTP)



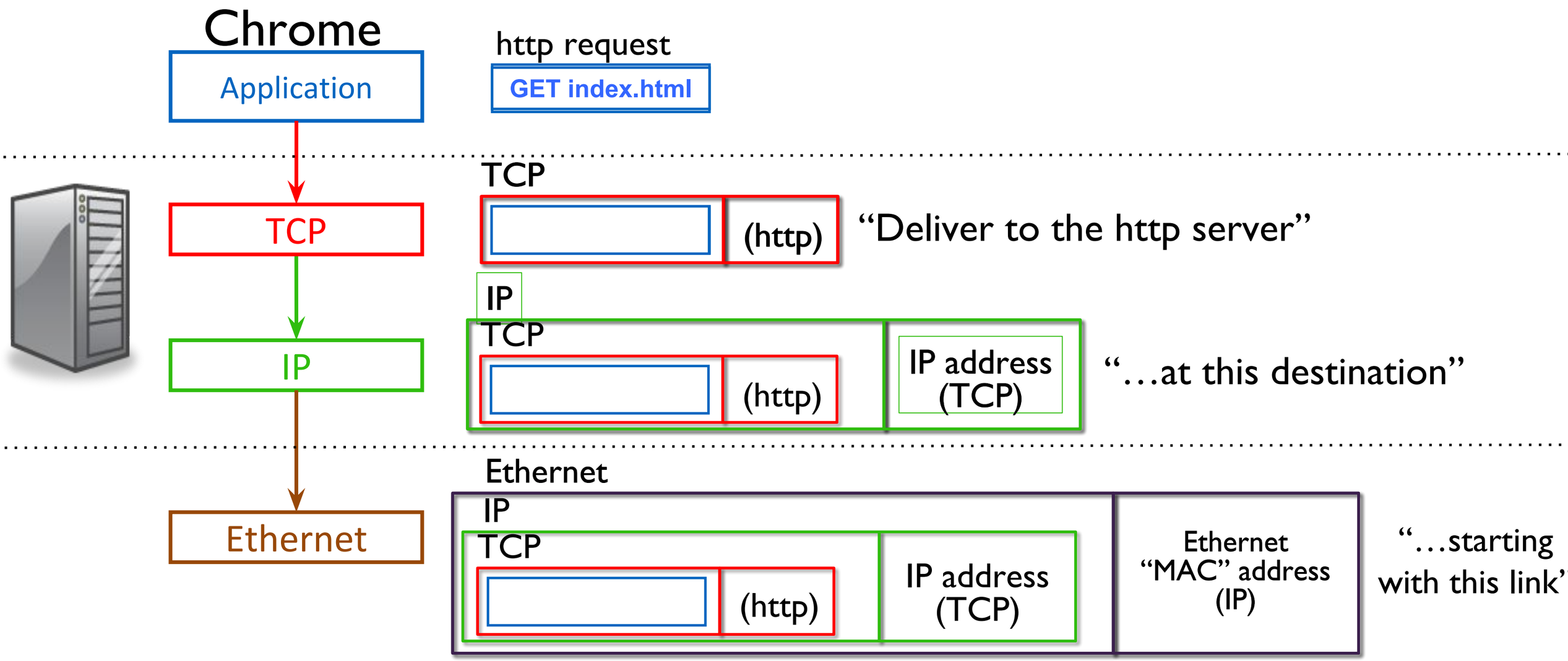
www.stanford.edu

World Wide Web (HTTP)

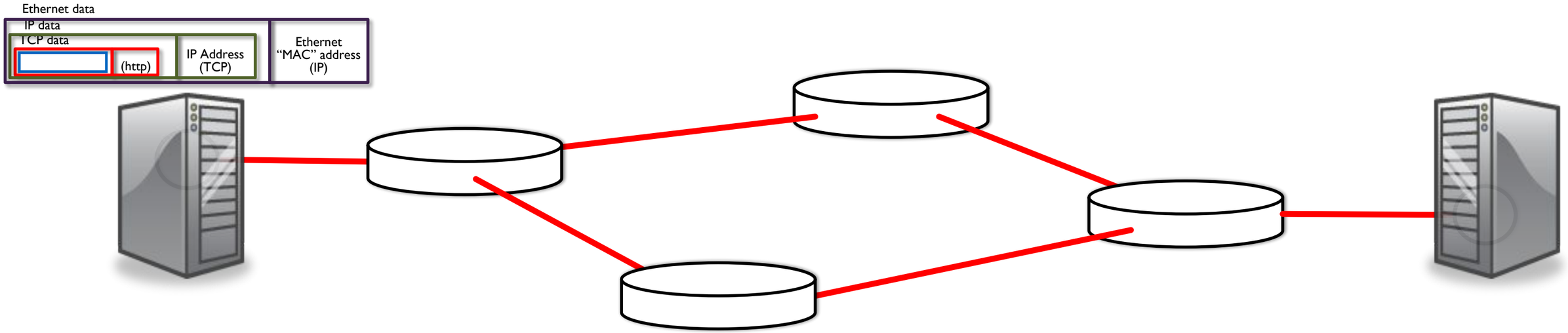


www.stanford.edu

http client (e.g. Chrome)



Here it goes….


Ethernet data
IP data
TCP data
(http)
IP Address
(TCP)
Ethernet
“MAC” address
(IP)

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

http request

GET file

"Deliver to the http server"

TCP

(http)

"Deliver to TCP"

Ethernet

IP

TCP

(http)

IP address (TCP)

Ethernet "MAC" address (IP)

http server

Application

TCP

IP

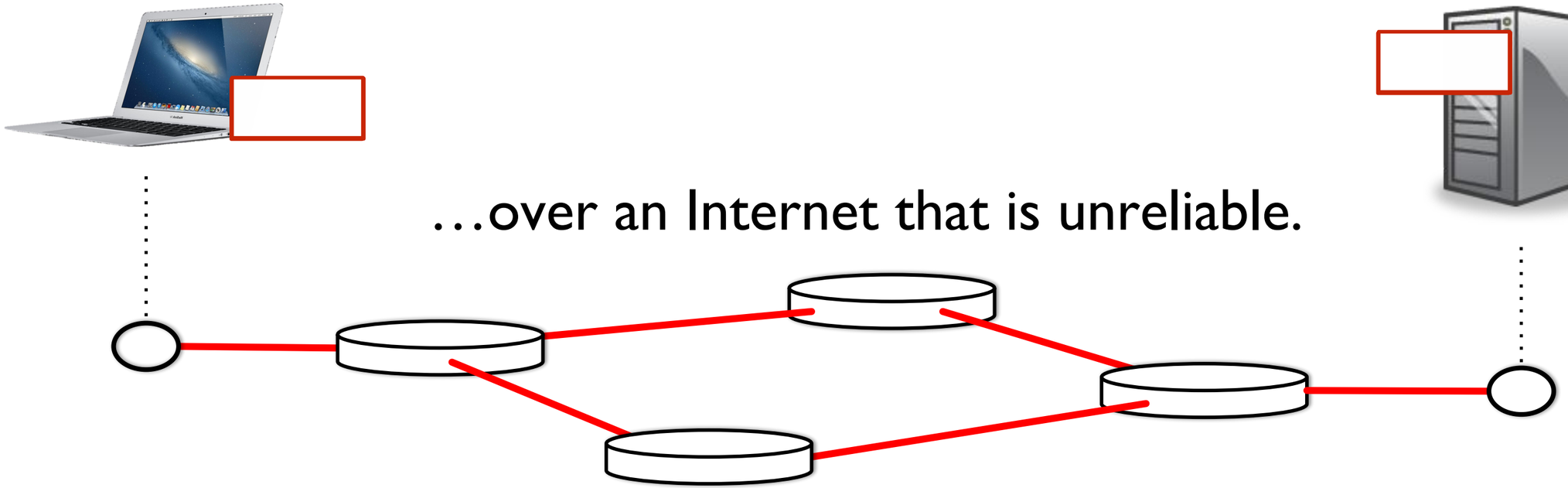
Ethernet

Summary of what we

My Program

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.