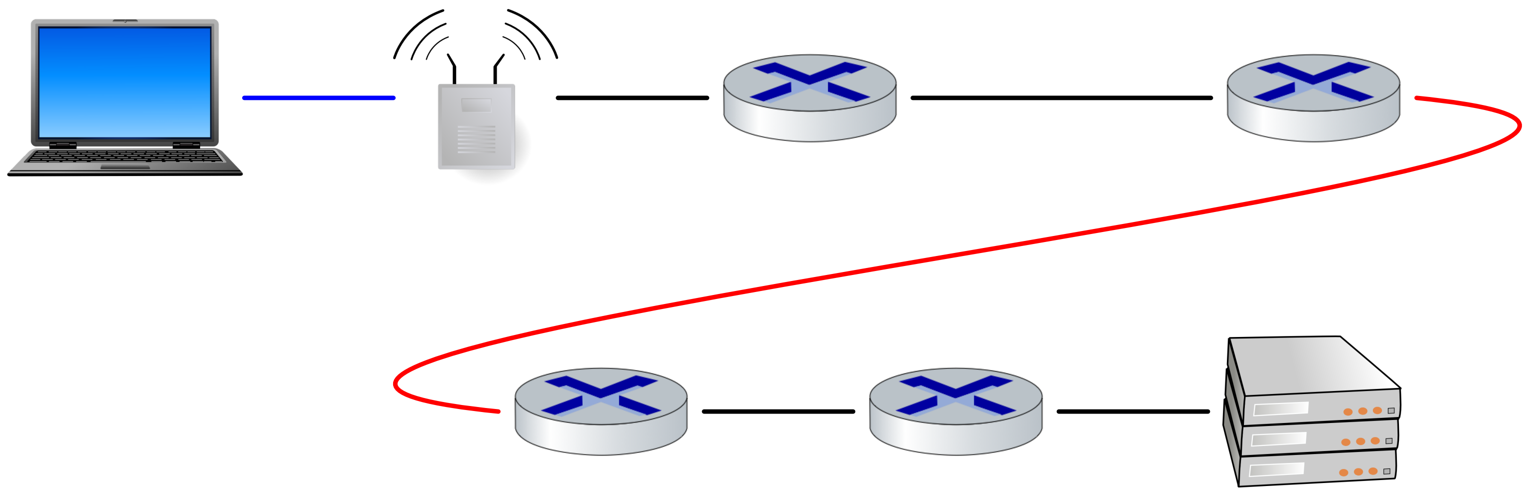
Latency Numbers Every Programmer Should Know (Dean 2009)

L1 cache reference	½ ns		
Branch mispredict	5 ns		
L2 cache reference	7 ns		
Mutex lock/unlock	25 ns		
Main memory reference	100 ns		
Compress 1 K bytes with Zippy	3,000 ns	3 μs	
Send 1 K bytes over 1 Gbps network	10,000 ns	10 μs	
Read 4 K randomly from SSD	150,000 ns	150 μs	
Read 1 MB sequentially from memory	250,000 ns	250 μs	
Round trip within same datacenter	500,000 ns	500 μs	
Read 1 MB sequentially from SSD	1,000,000 ns	1,000 μs	1 ms
Disk seek	10,000,000 ns	10,000 μs	10 ms
Read 1 MB sequentially from disk	20,000,000 ns	20,000 μs	20 ms
Send packet CA→Netherlands→CA	150,000,000 ns	150,000 μs	150 ms

How Long Will It Take to Get a Response?



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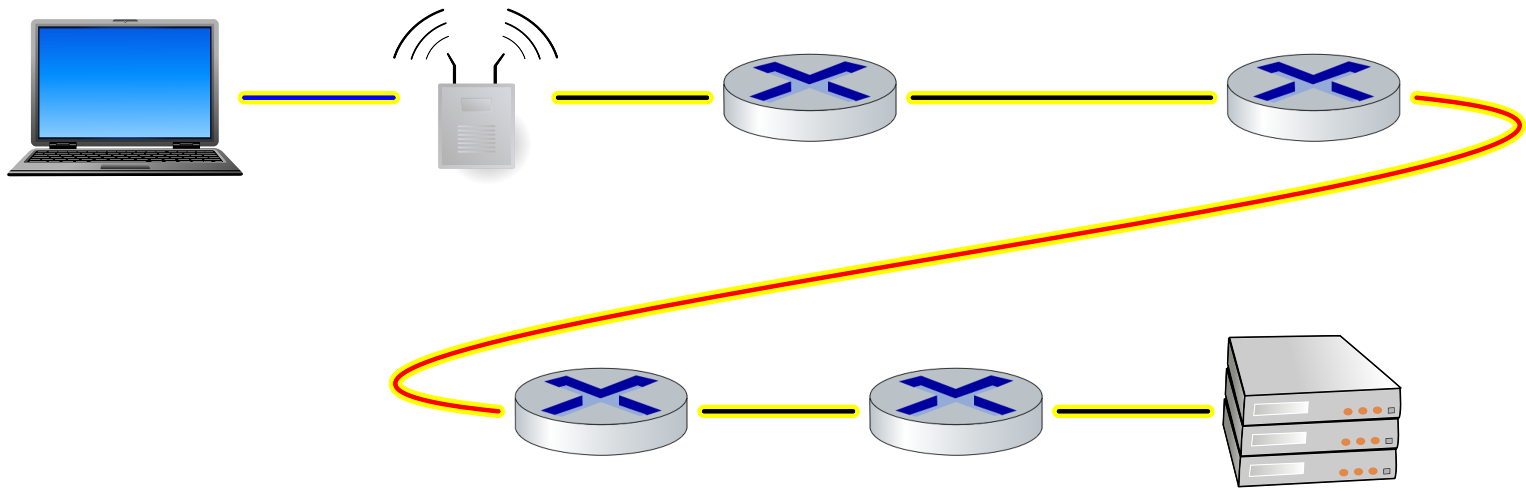

propagation delay

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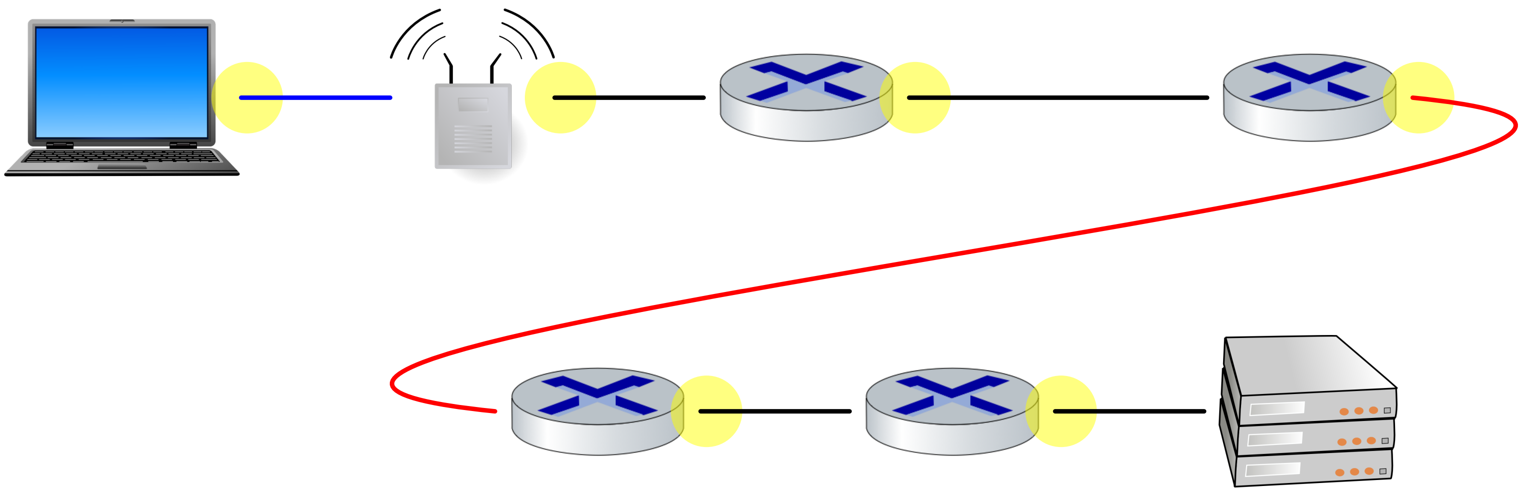

transmission delay

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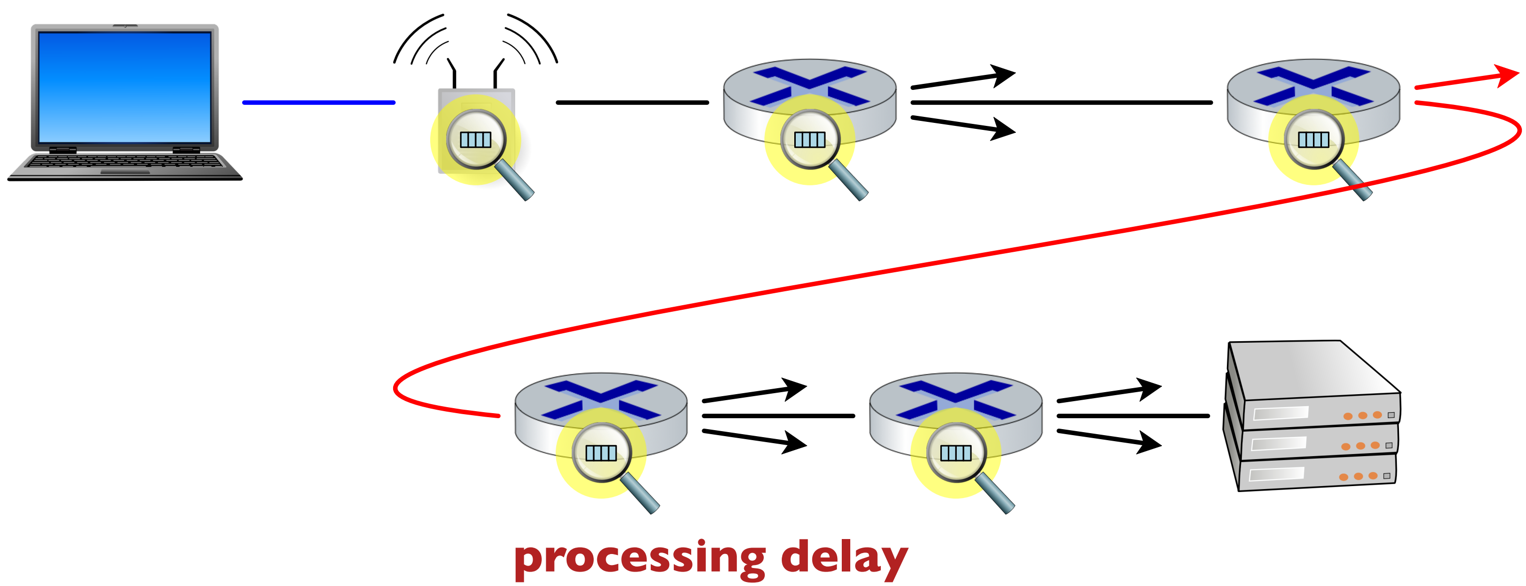

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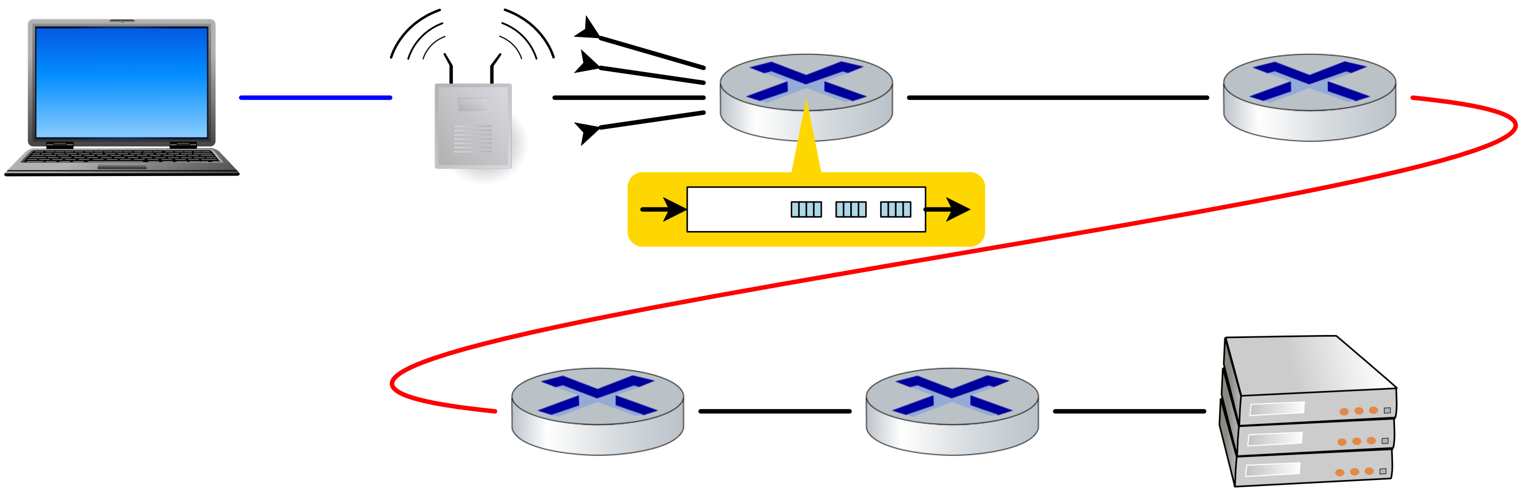
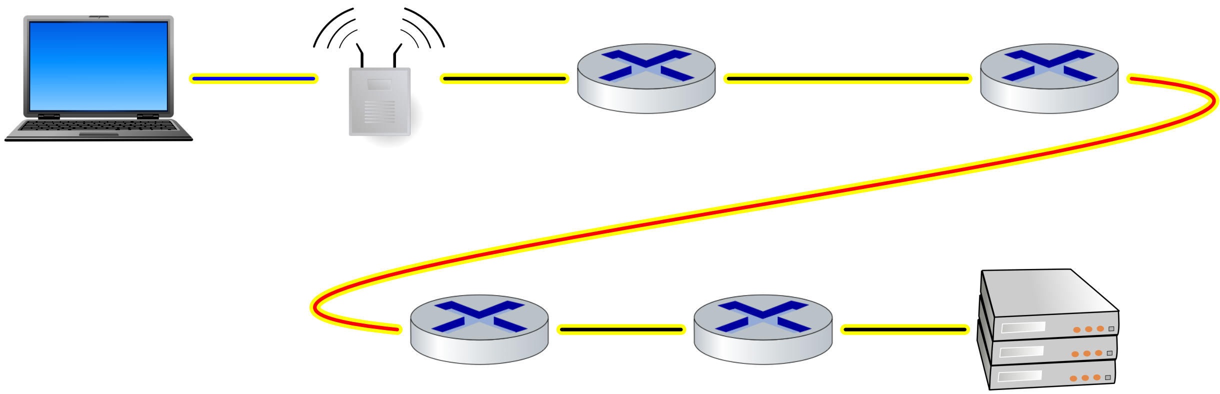


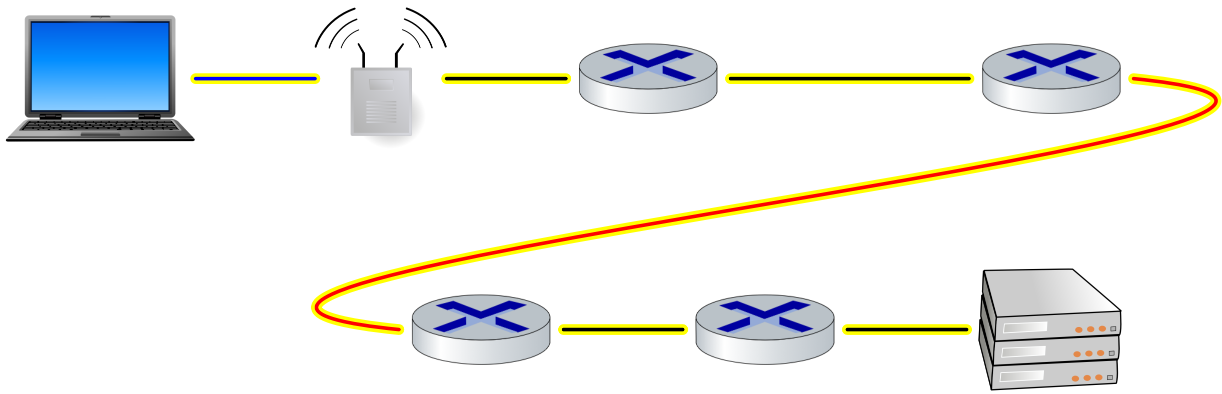
queueing delay

Propagation Delay



Time to travel along medium

Propagation Delay

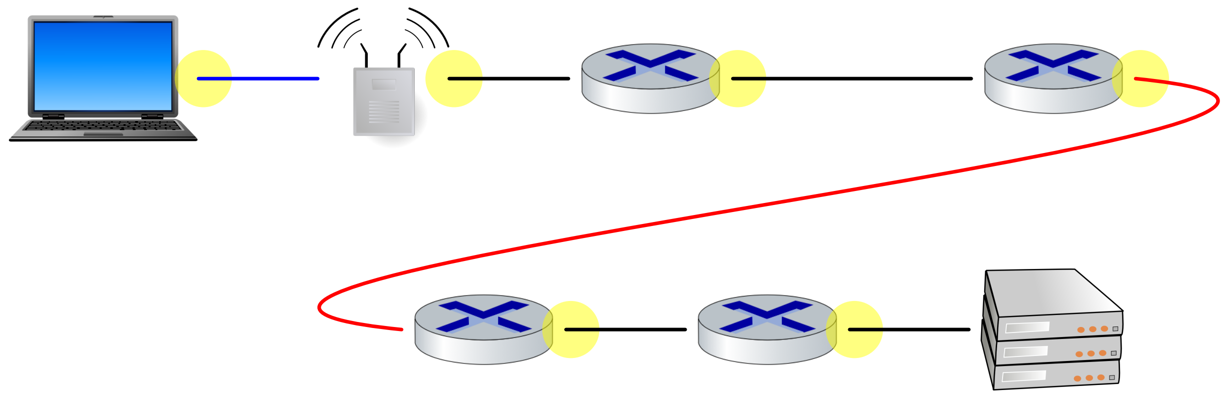


Time to travel along medium, depends on physics

- distance travelled
- speed of link — some fraction of the speed of light

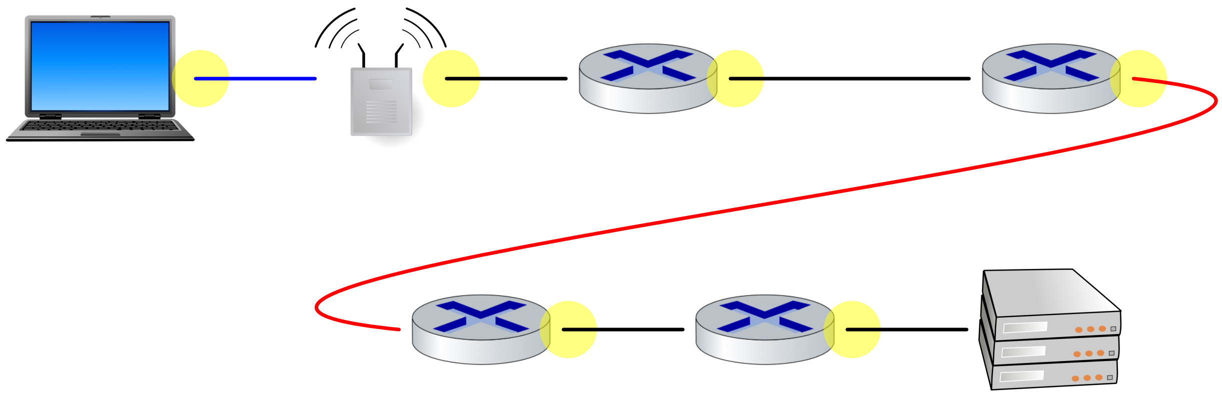
$$delay_{propagation} = \frac{scale \times distance}{speed\ of\ light}$$

Transmission Delay



Time to convert from bytes to medium

Transmission Delay

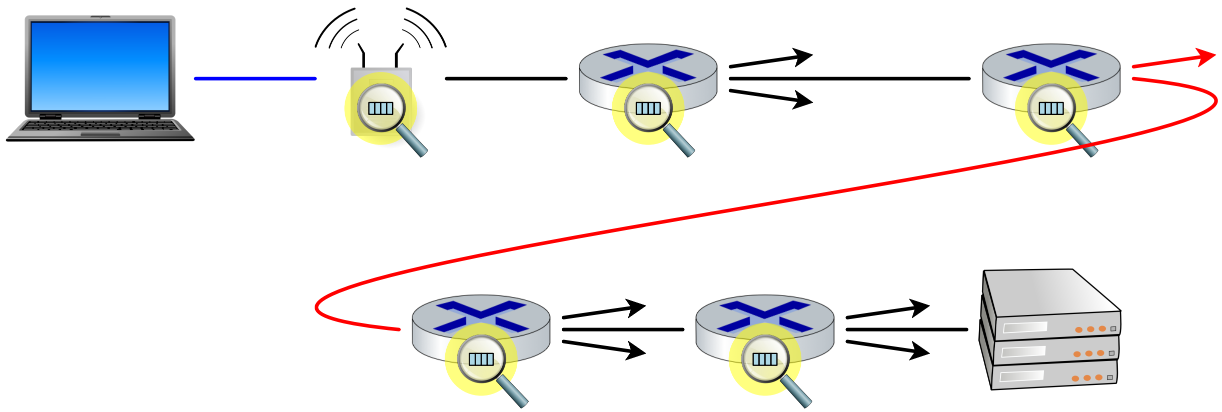


Time to convert from bytes to medium, depends on device and data

- device rate *R*
  - fiber, ethernet: 1-400 Gbps
  - WiFi: ~10 Mbps
  - dial-up: 56.6 Kbps
- packet size

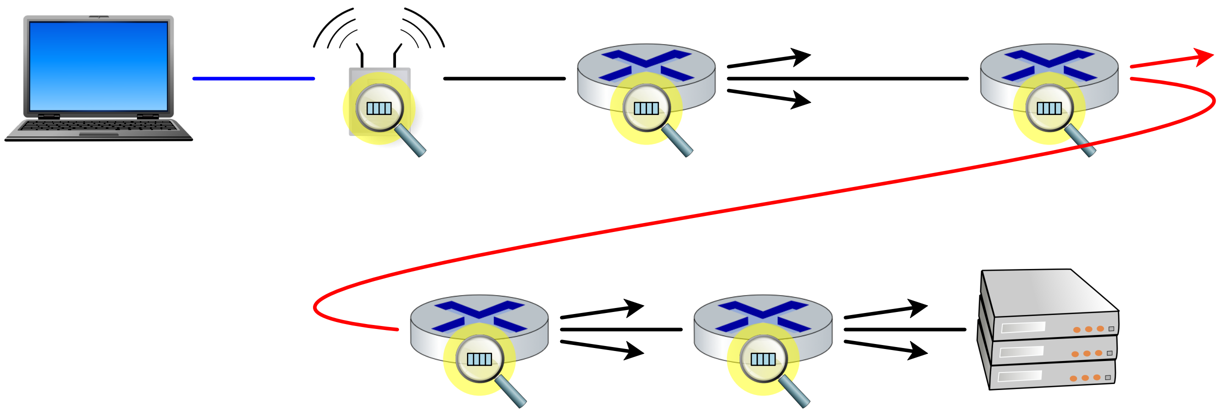
$$delay_{transmission} = \frac{size}{R}$$

Processing Delay



Time to inspect bytes and choose next step

Processing Delay

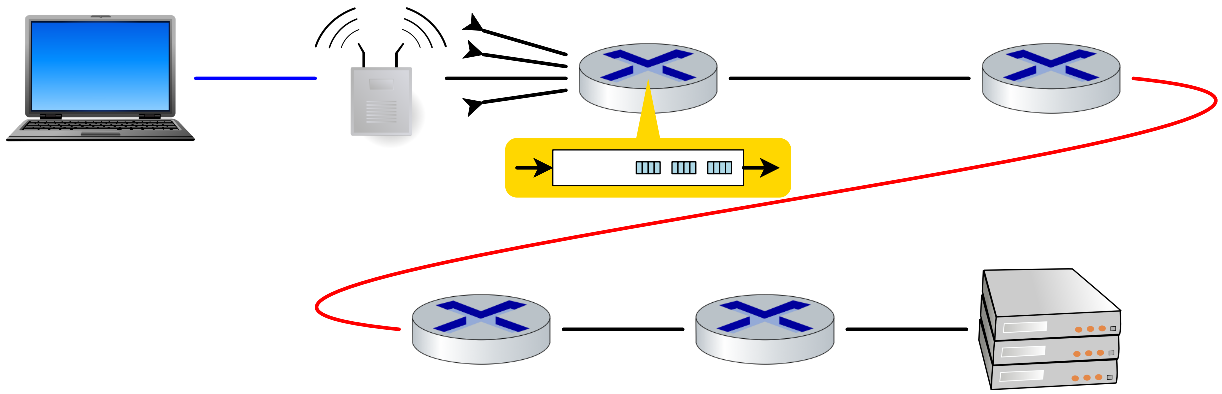


Time to inspect bytes and choose next step, depends on device speed

Typically a few nanoseconds, so we ignore it

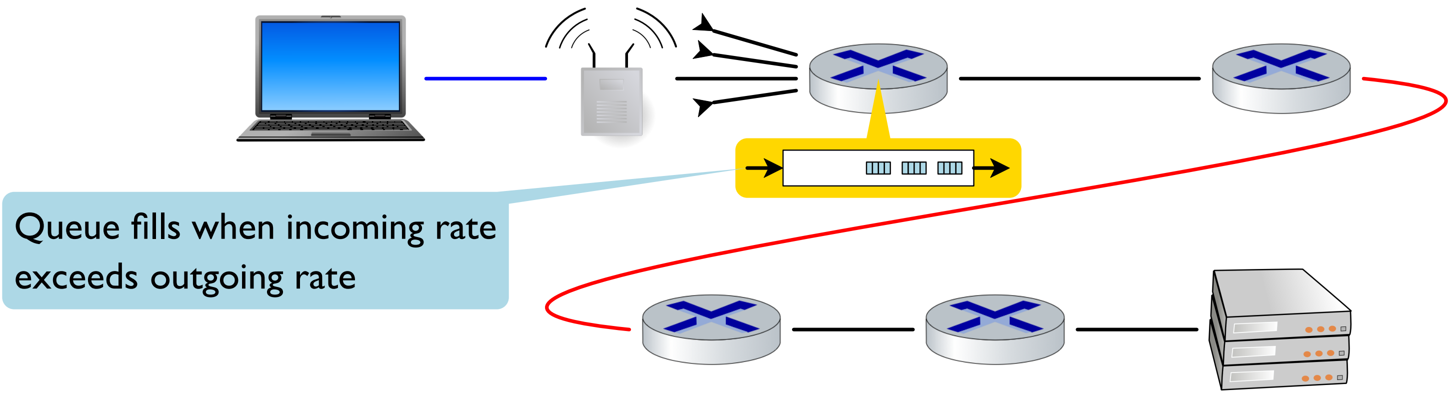
$$delay_{processing} = 0$$

Queueing Delay



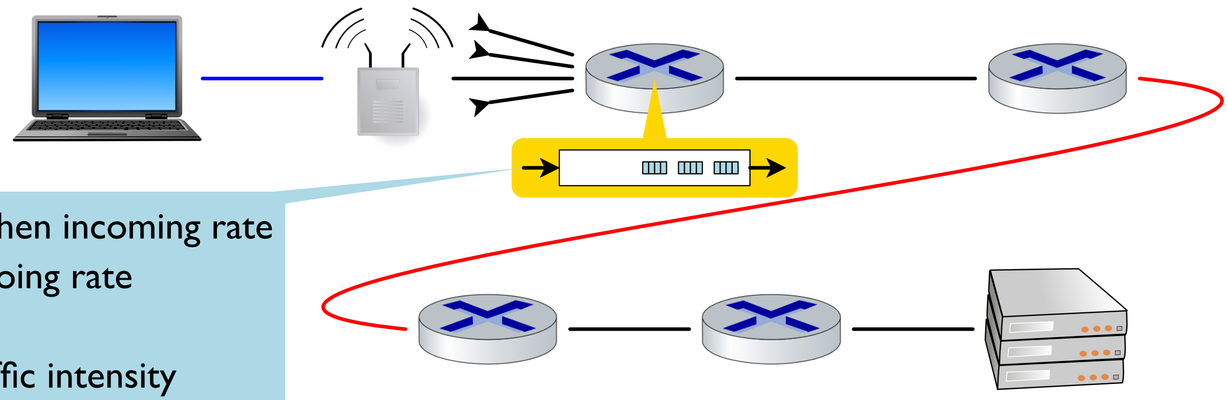
Time packets bytes are held in a queue

Queueing Delay



Time packets bytes are held in a queue, depends on traffic

Queueing Delay

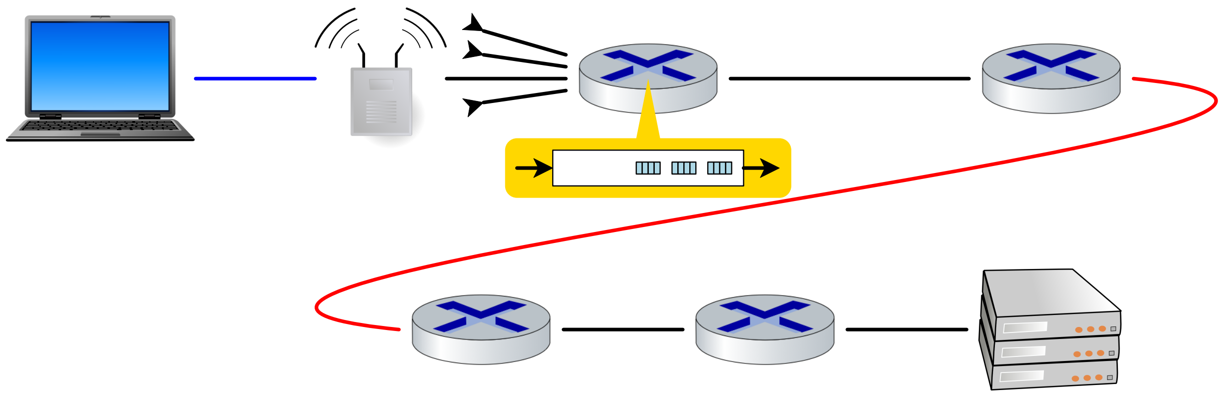


Queue fills when incoming rate exceeds outgoing rate

Sustained traffic intensity
⇒ packets get dropped

Time packets bytes are held in a queue, depends on traffic

Queueing Delay



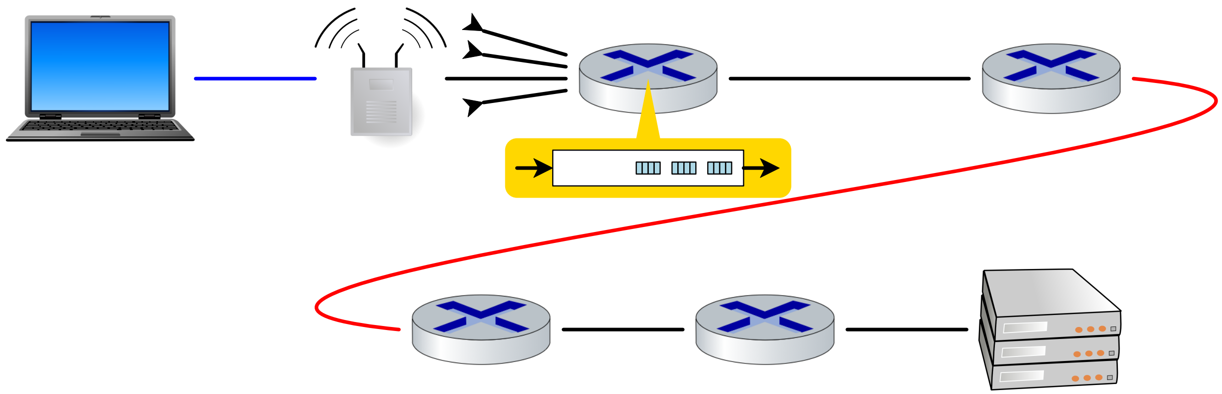
Time packets bytes are held in a queue, depends on traffic

$$\textit{incoming data rate} = \textit{average packet size} \times \textit{incoming packet rate}$$

$$\textit{traffic intensity} = \frac{\textit{incoming data rate}}{R}$$

$\textit{traffic intensity} \leq 1 \;\Rightarrow$ no delay

Queueing Delay



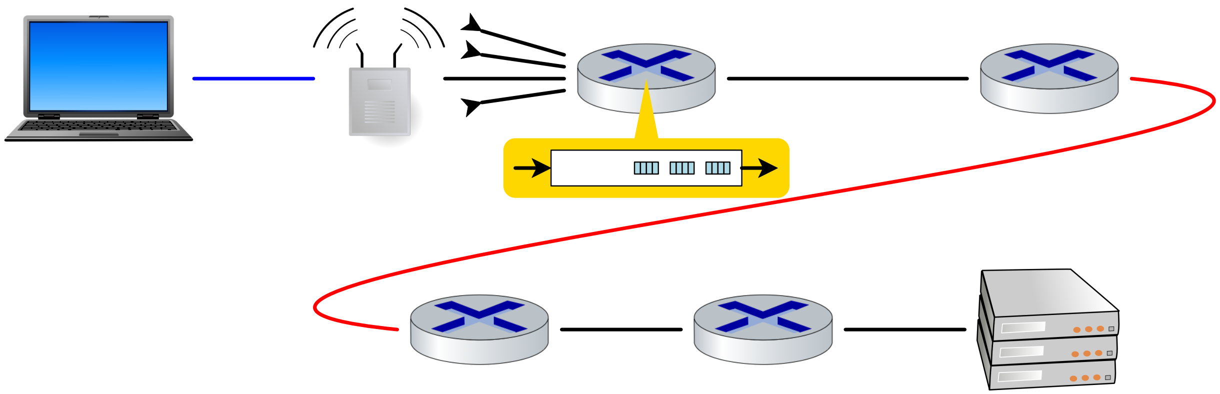
Time packets bytes are held in a queue, depends on traffic

$$\textit{incoming data rate} = \textit{average packet size} \times \textit{incoming packet rate}$$

$$\textit{traffic intensity} = \frac{\textit{incoming data rate}}{R}$$

$\textit{traffic intensity} > 1 \Rightarrow$ delay growing

Queueing Delay



Time packets bytes are held in a queue, depends on traffic

$$delay_{queue} = ???$$

Total Delay

$$delay = delay_{\text{propagation}} + delay_{\text{transmission}} + delay_{\text{processing}} + delay_{\text{queueing}}$$

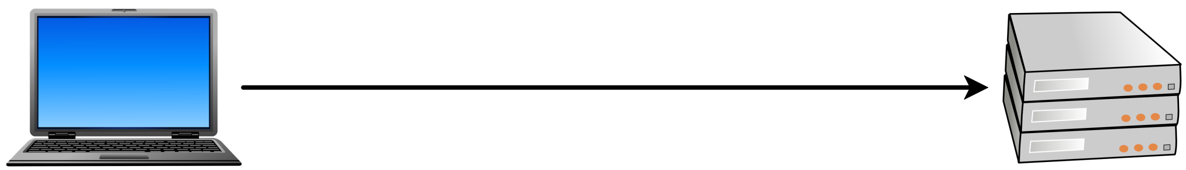
$$delay_{propagation} = \frac{scale \times distance}{speed\ of\ light}$$

$$delay_{transmission} = \frac{size}{R}$$

$$delay_{processing} = 0$$

$$delay_{queue} = ???$$

What Can We Measure?



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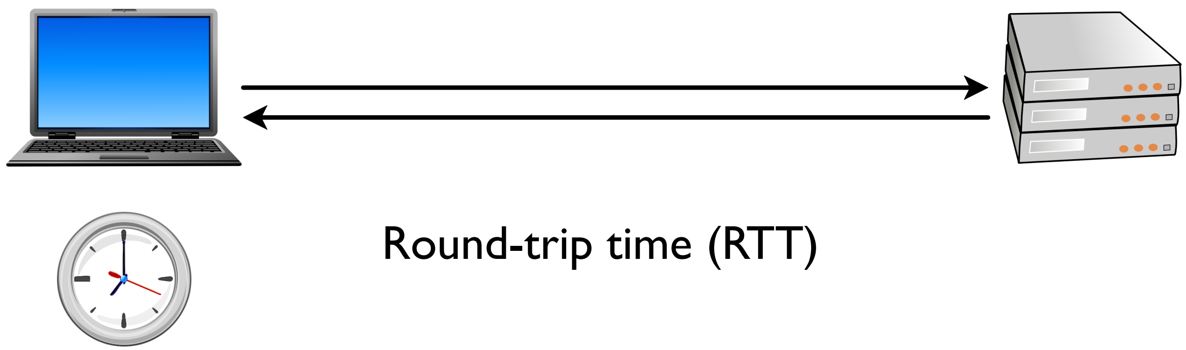
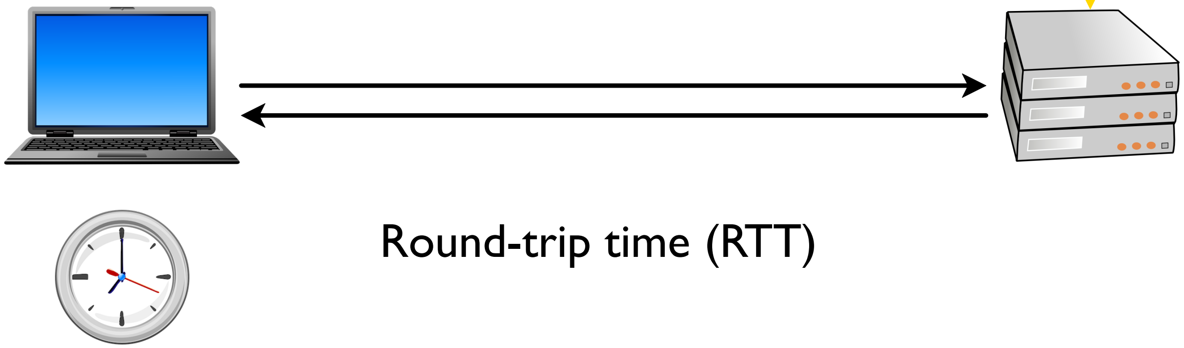


What Can We Measure?

Need a protocol that will bounce data to a client



Round-trip time (RTT)

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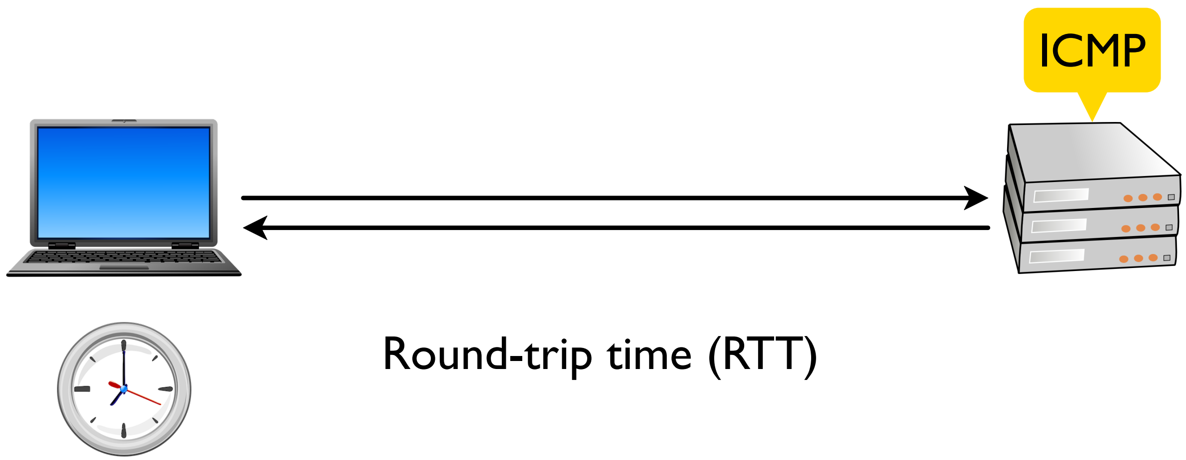

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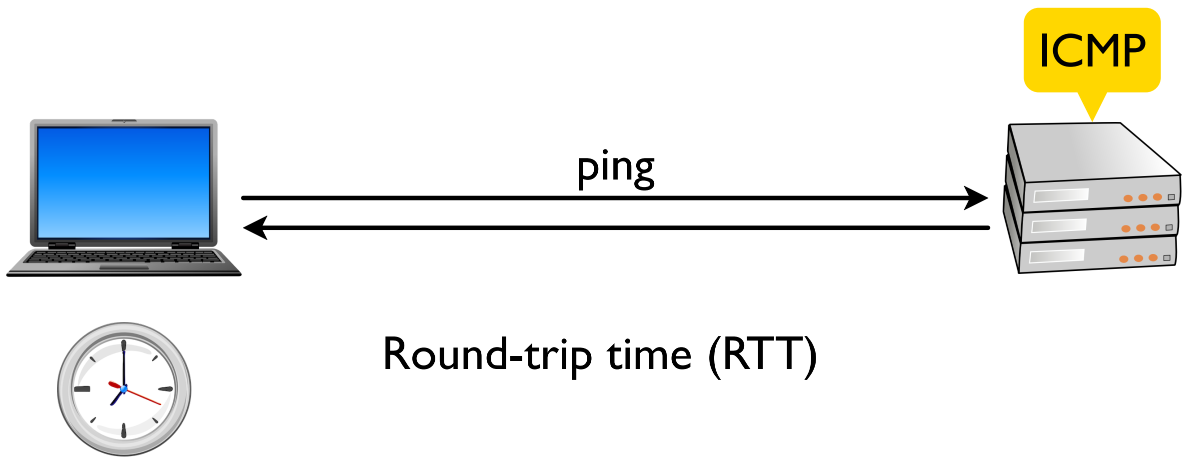

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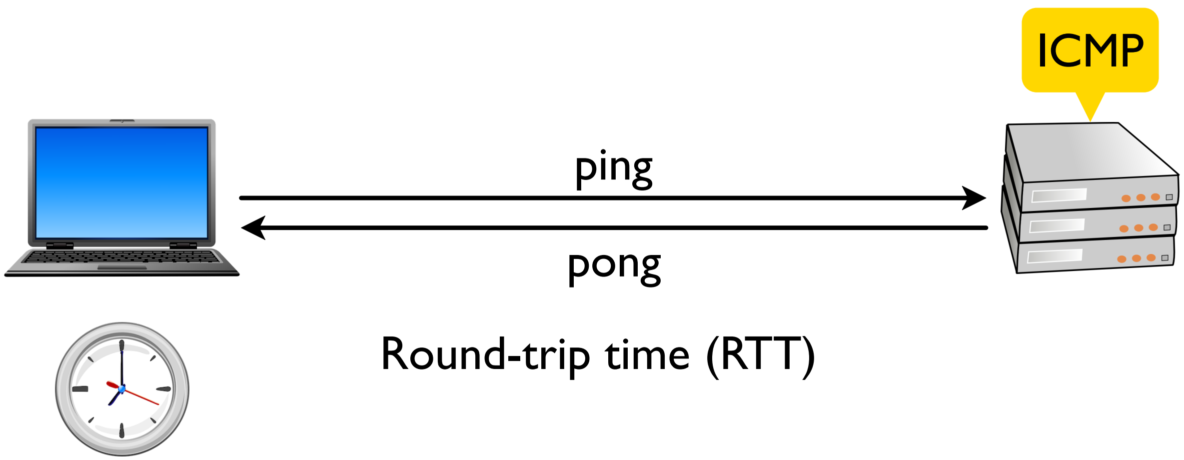

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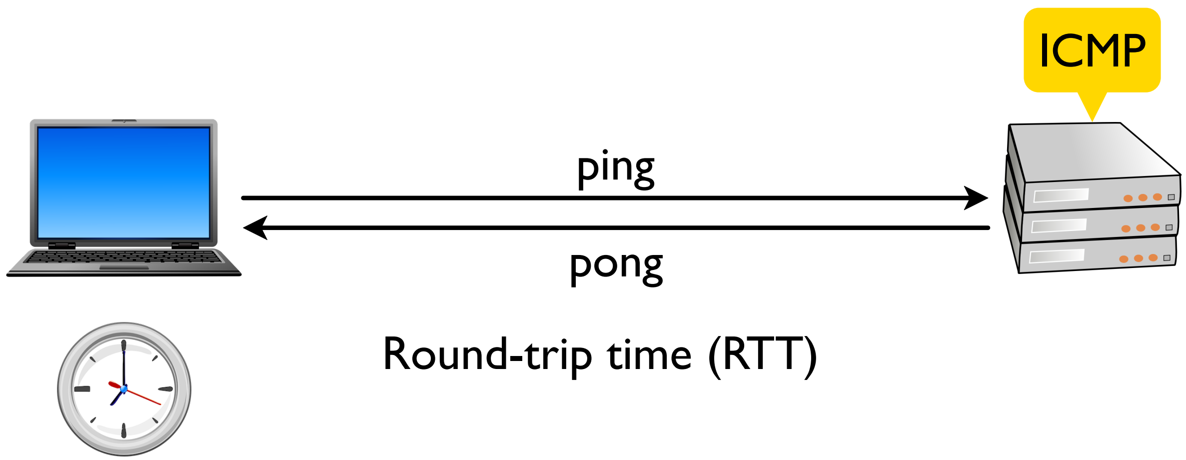
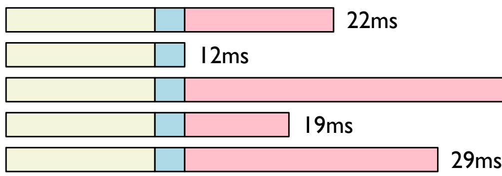


Run as the `ping` command

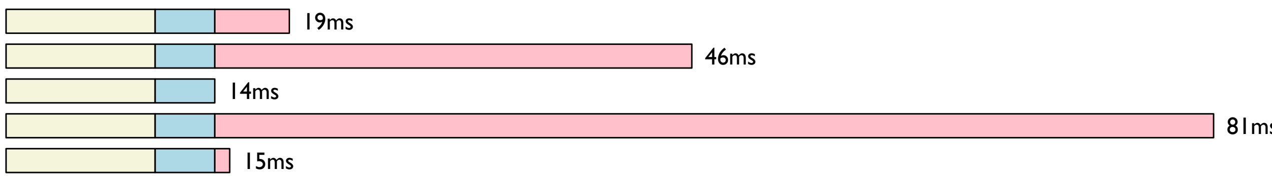
```
laptop$ ping www.cs.utah.edu
PING wp.wpenginepowered.com (141.193.213.10): 56 data bytes
64 bytes from 141.193.213.10: icmp_seq=0 ttl=51 time=35.962 ms
64 bytes from 141.193.213.10: icmp_seq=1 ttl=51 time=28.266 ms
64 bytes from 141.193.213.10: icmp_seq=2 ttl=51 time=34.257 ms
64 bytes from 141.193.213.10: icmp_seq=3 ttl=51 time=37.075 ms
64 bytes from 141.193.213.10: icmp_seq=4 ttl=51 time=135.983 ms
^C
--- wp.wpenginepowered.com ping statistics ---
5 packets transmitted, 5 packets received, 0.0% packet loss
round-trip min/avg/max/stddev = 28.266/54.309/135.983/40.950 ms
```

Inferring Delay Components

Suppose that we take 5 pings using a packet of size 100:



and for the same destination, 5 pings using a packet of size 200:



Each measurement is a *delay*

$$delay = delay_{\text{propagation}} + delay_{\text{transmission}} + delay_{\text{processing}} + delay_{\text{queueing}}$$

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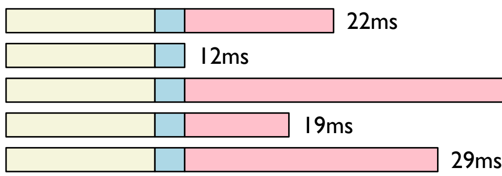

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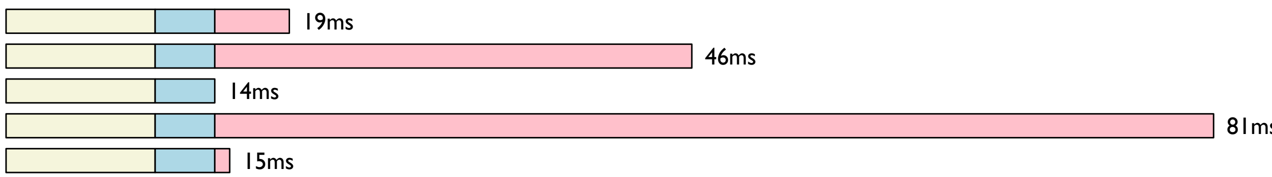


Each measurement is a *delay*

the same for every packet

treat as 0

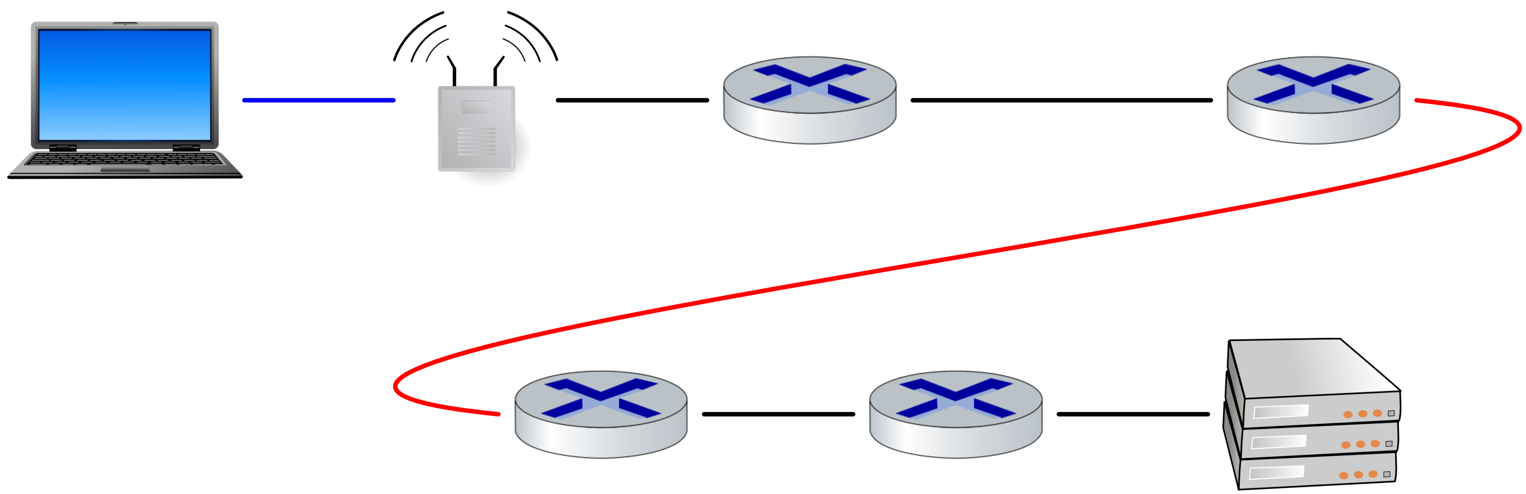
$$delay = delay_{\text{propagation}} + delay_{\text{transmission}} + delay_{\text{processing}} + delay_{\text{queueing}}$$

proportional to packet length

assume 0 in shortest

application	Firefox, `ping`, ...
transport	TCP, UDP, ICMP, ...
network	IP
link	ethernet, WiFi, ...
physical	electrons, photons, ...

Can We Get Any Information About a Route?



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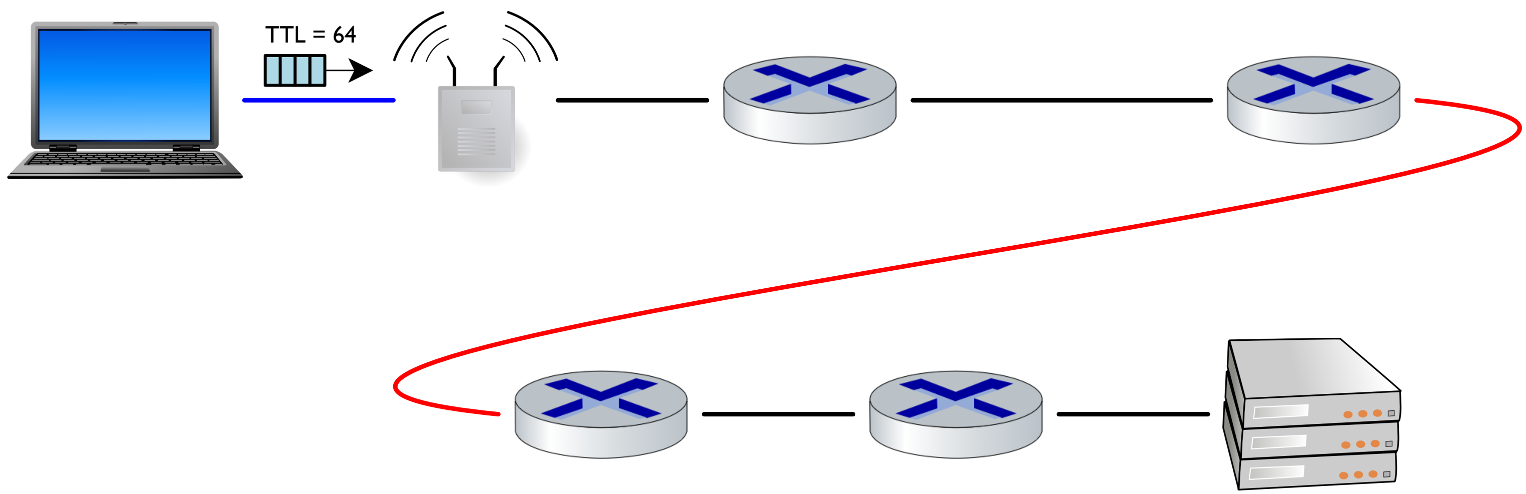

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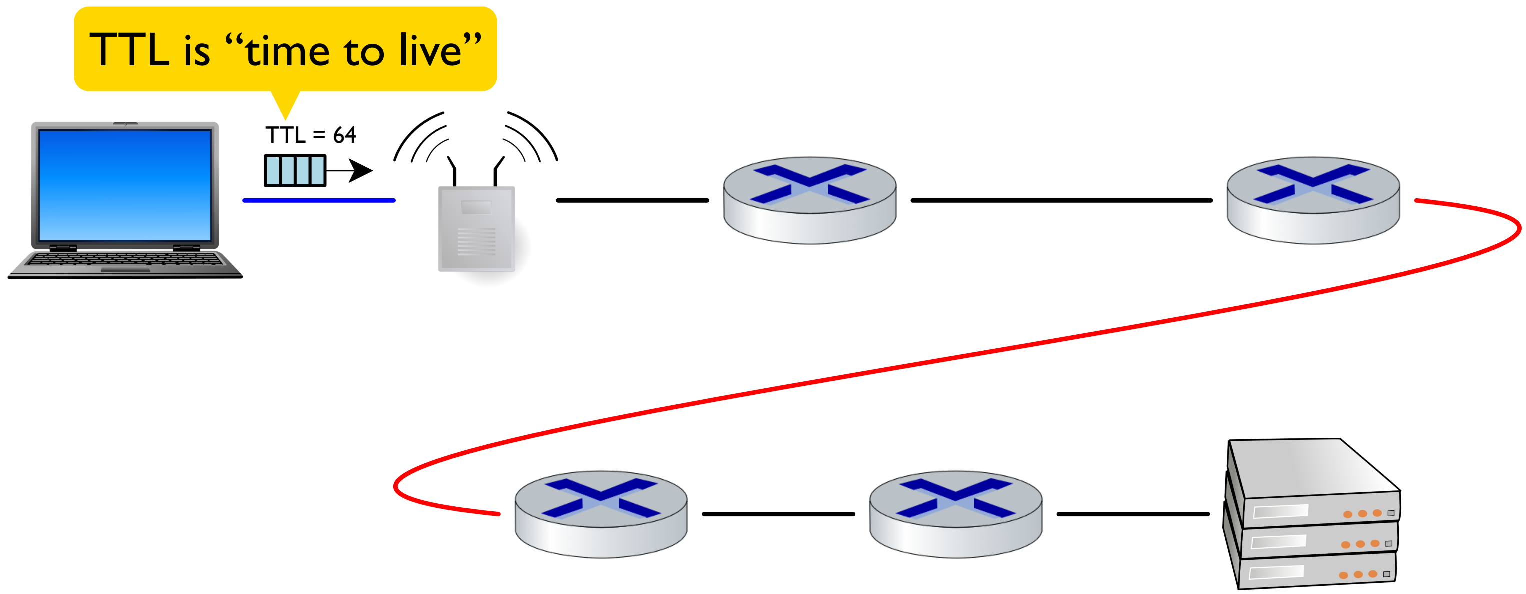

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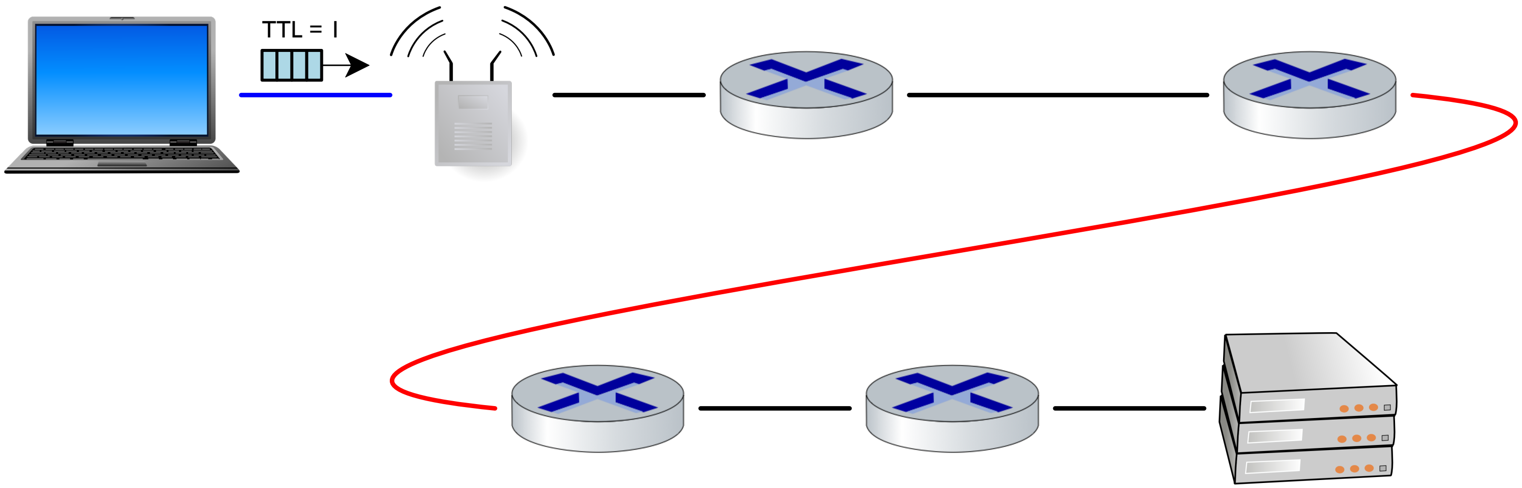

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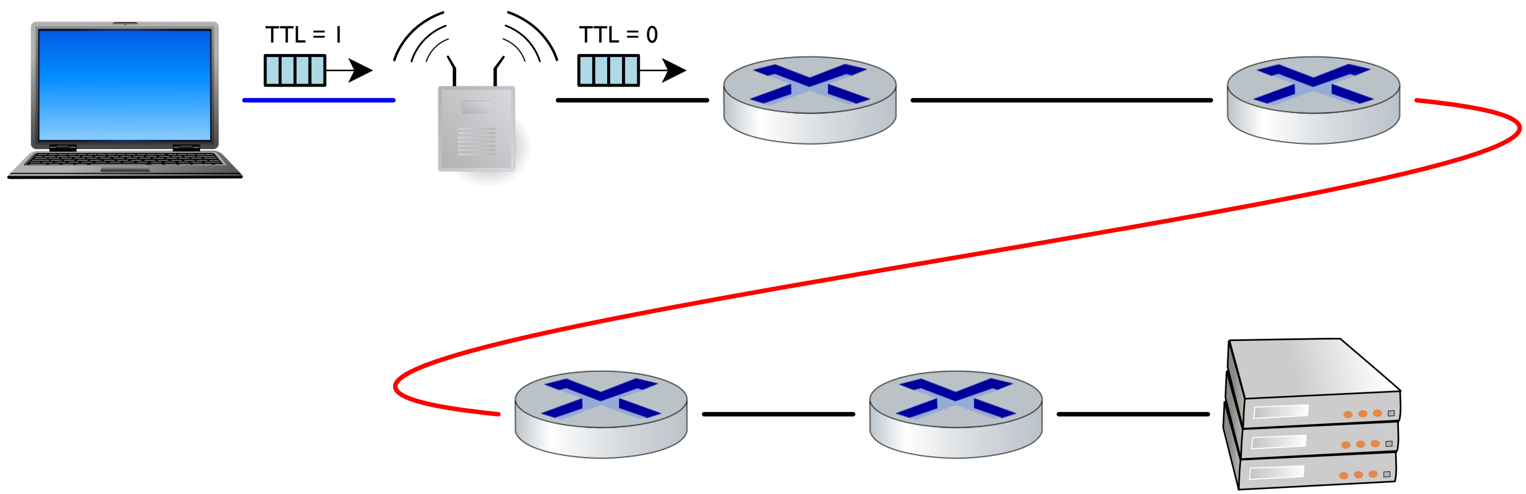

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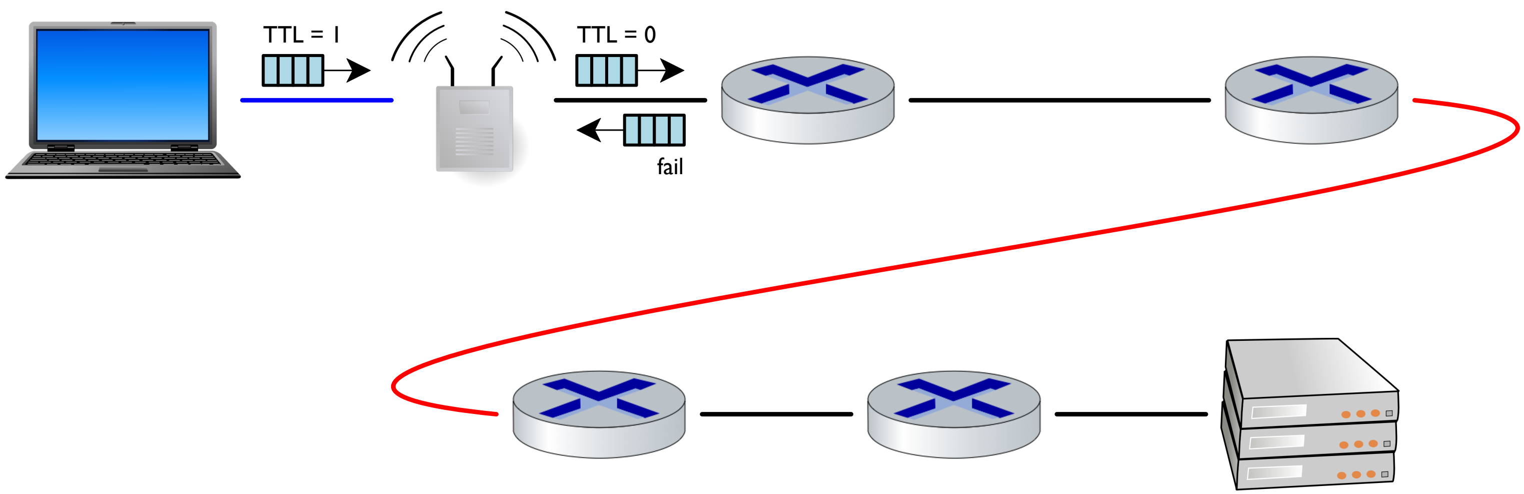

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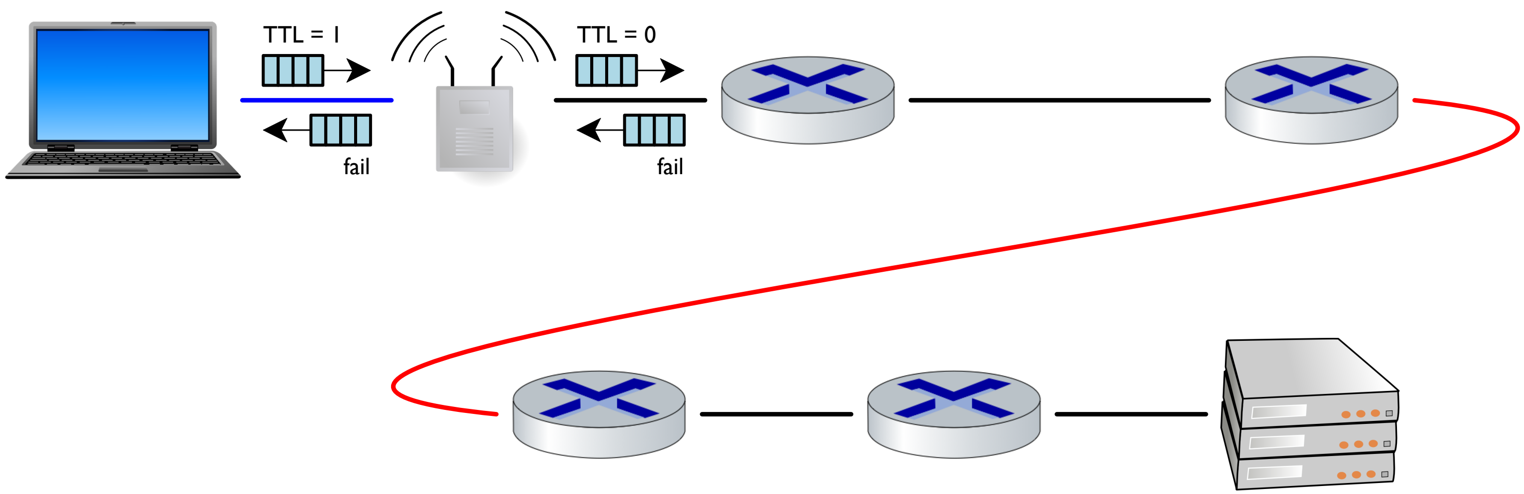

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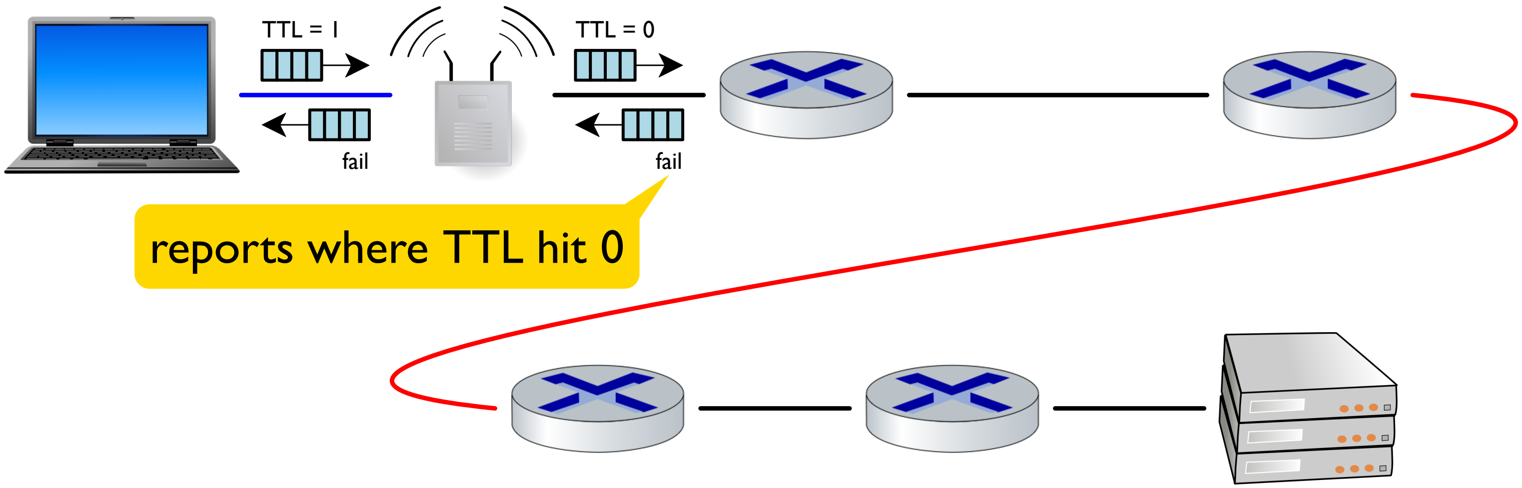

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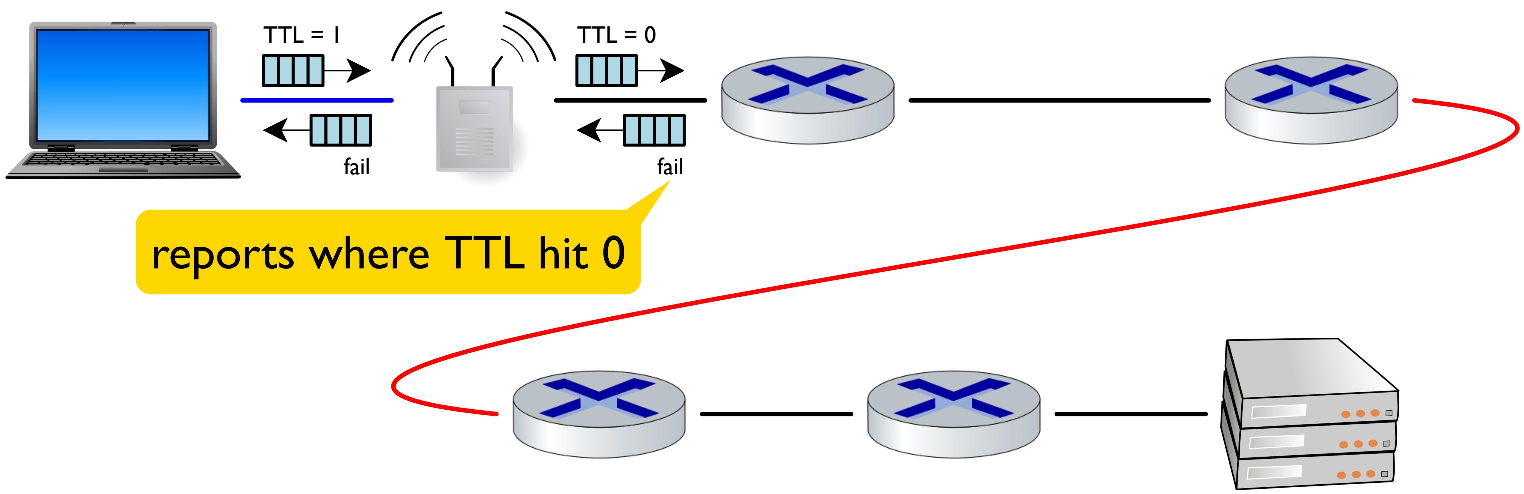

`traceroute` uses this trick systematically to explore the network

```
laptop$ traceroute www.cs.utah.edu
traceroute: Warning: www.cs.utah.edu has multiple addresses; using 141.193.213.10
traceroute to wp.wpenginepowered.com (141.193.213.10), 64 hops max, 52 byte packets
 1  10.0.0.1 (10.0.0.1)  11.987 ms  4.197 ms  4.602 ms
 2  100.93.170.195 (100.93.170.195)  15.651 ms
    100.93.170.194 (100.93.170.194)  18.858 ms
    100.93.170.195 (100.93.170.195)  16.754 ms
 3  po-333-417-rur501.saltlakecity.ut.utah.comcast.net (96.216.76.73)  16.825 ms
    po-333-418-rur502.saltlakecity.ut.utah.comcast.net (96.216.76.81)  15.903 ms
    po-333-417-rur501.saltlakecity.ut.utah.comcast.net (96.216.76.73)  18.208 ms
....
15  50.242.151.238 (50.242.151.238)  33.149 ms
    172.69.132.4 (172.69.132.4)  39.945 ms
    66.208.229.106 (66.208.229.106)  42.951 ms
16  141.193.213.10 (141.193.213.10)  33.762 ms
    172.71.156.2 (172.71.156.2)  60.377 ms
    141.193.213.10 (141.193.213.10)  32.911 ms
```

Latency vs. Throughput

- **Latency** ⇒ how long you have to wait for one small thing

  a time, such as milliseconds

  RTT can help us understand latency

- **Throughput** ⇒ how long you have to wait for everything

  a rate, such as bytes per second

  Mailing a box of flash drives can have very high throughput, but also high latency

Summary

Network delays are largely beyond our control, but we can reason about them

Four kinds of delay add up:

- **propagation** — depends on distance
- **transmission** — depends on size and medium
- **processing** — practically 0
- **queuing** — random