Introduction to Computer Networks

CS640

Computer Networks: Performance Analysis

https://pages.cs.wisc.edu/~mgliu/CS640/S25/index.html

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Outline

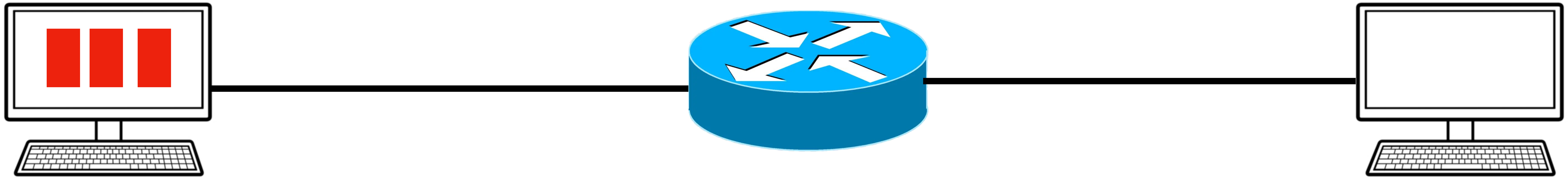
- Last
  - Computer networks: hardware infrastructure
  - Computer networks: software system

- Today
  - Delay
  - Throughput
  - RTT and BDP

- Announcements
  - Lab1 will be released this Thursday
  - No class on Thursday

Packet-Switched Networks

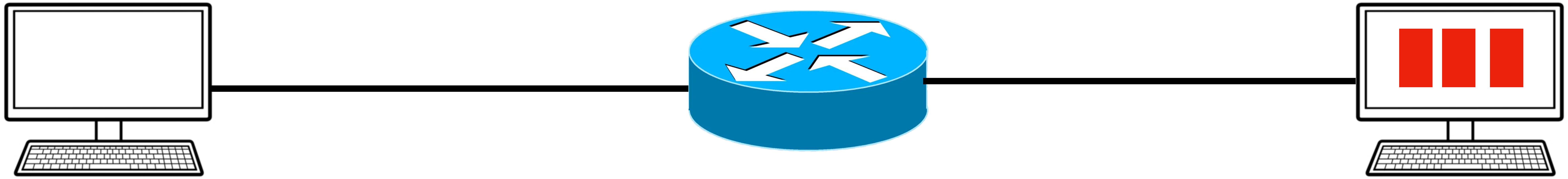
- Packet communication path
  - Host 1 —> Router A —> Router B —> … —> Host 2



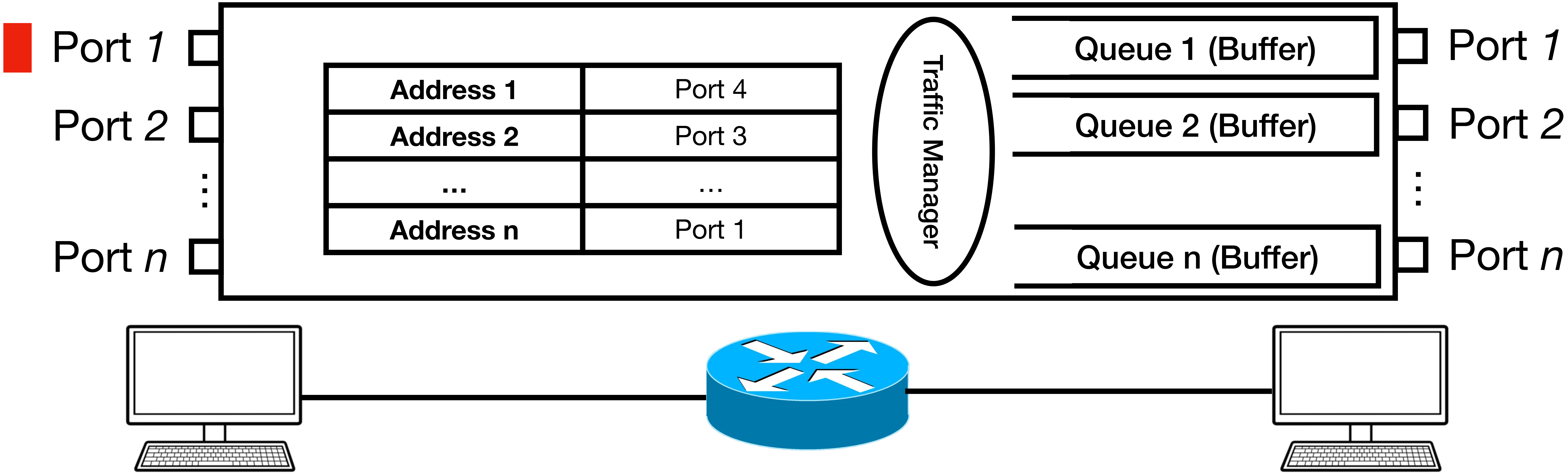
Packet-Switched Networks

- Packet communication path
  - Host 1 —> Router A —> Router B —> … —> Host 2

- Delay
  - The total amount of time transfers N bits across the packet path
  - Four types of delay

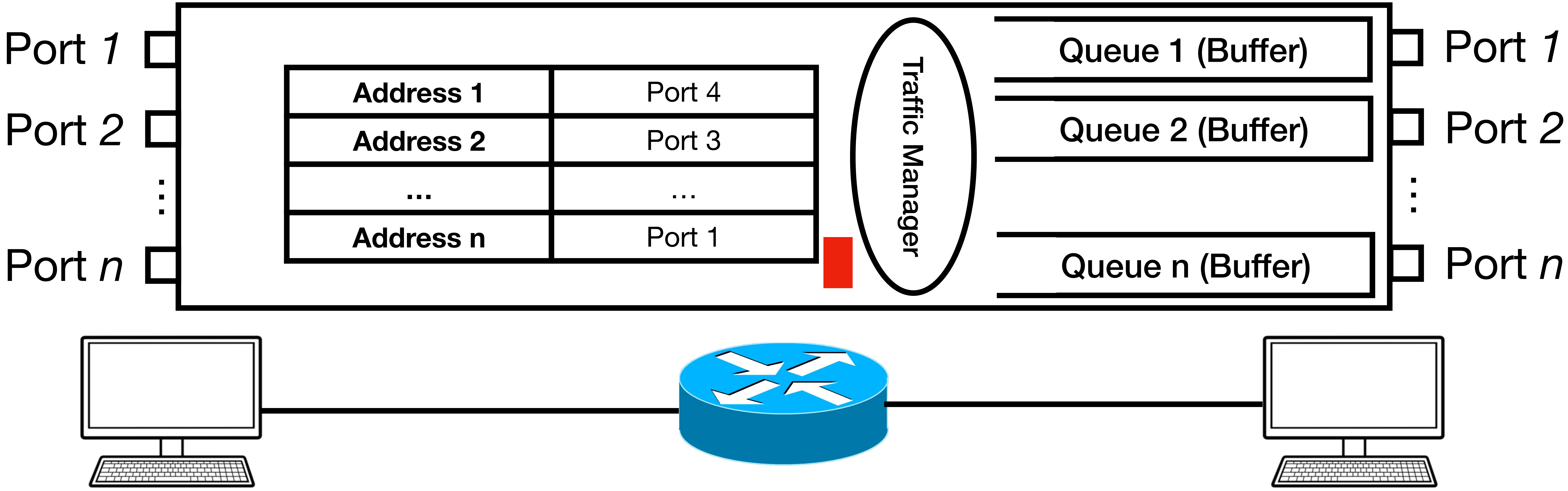


Processing Delay (T_{proc})

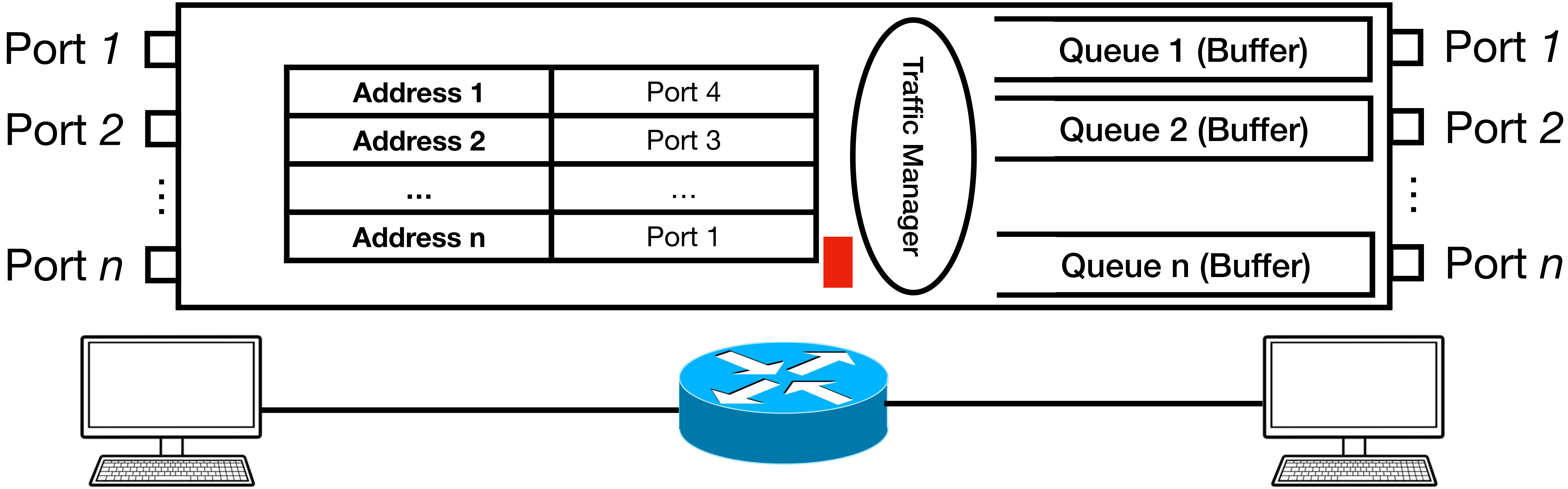


Processing Delay (T_{proc})

- The time required to examine the packet header and determine where to forward
  - Including checking bit-level errors
  - Microsecond

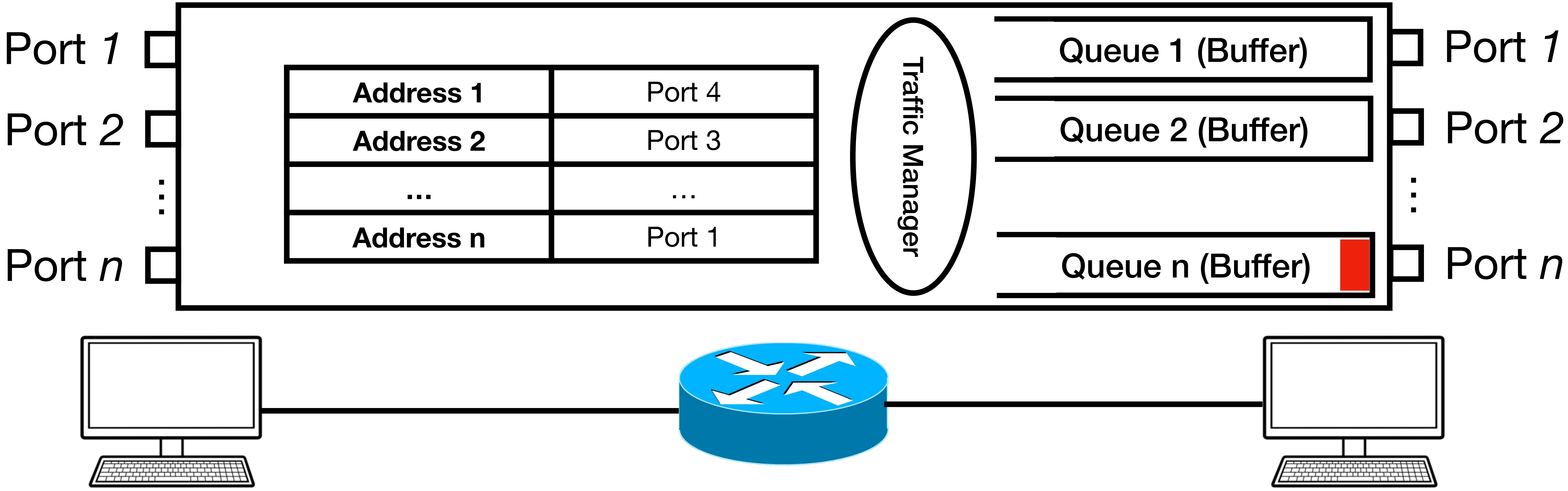


Queueing Delay (T_{queue})

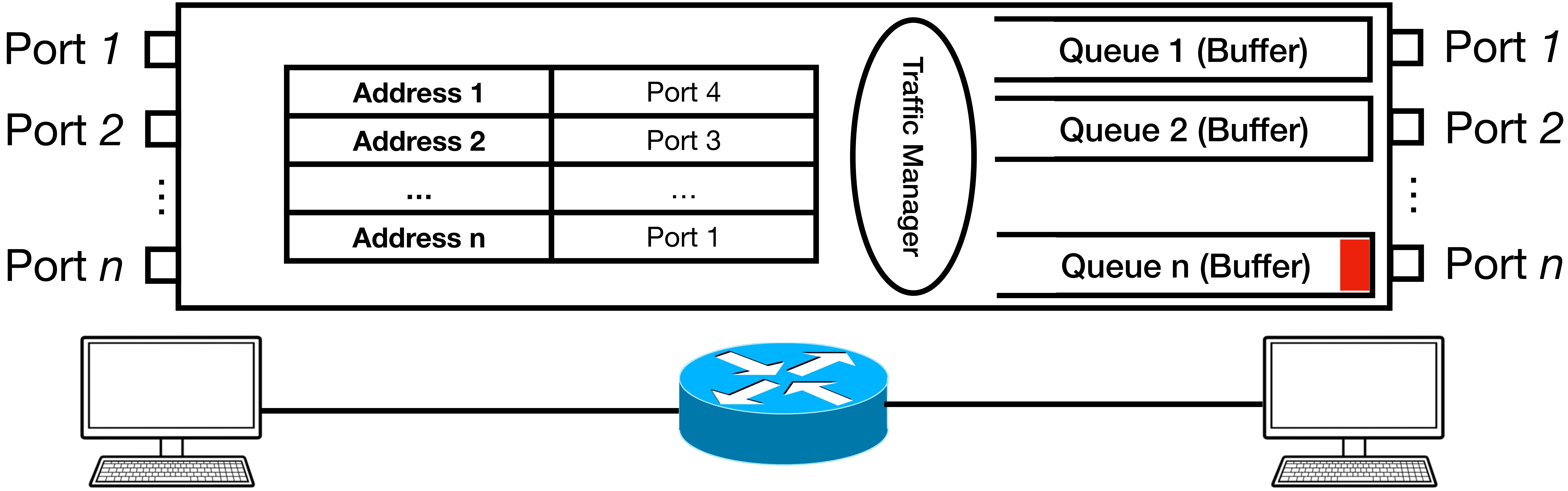


Queueing Delay (T_{queue})

- The time it takes to wait to be transmitted
  - Depend on the number of earlier-arriving packets
  - Microsecond~Millisecond

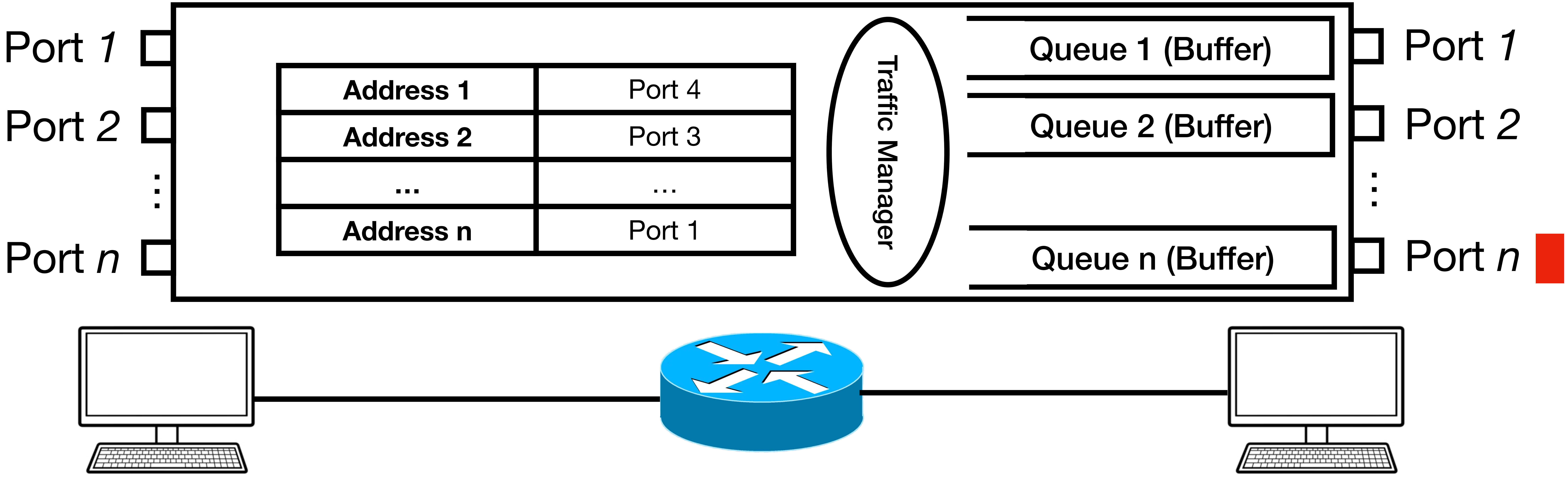


Transmission Delay (T_{trans})



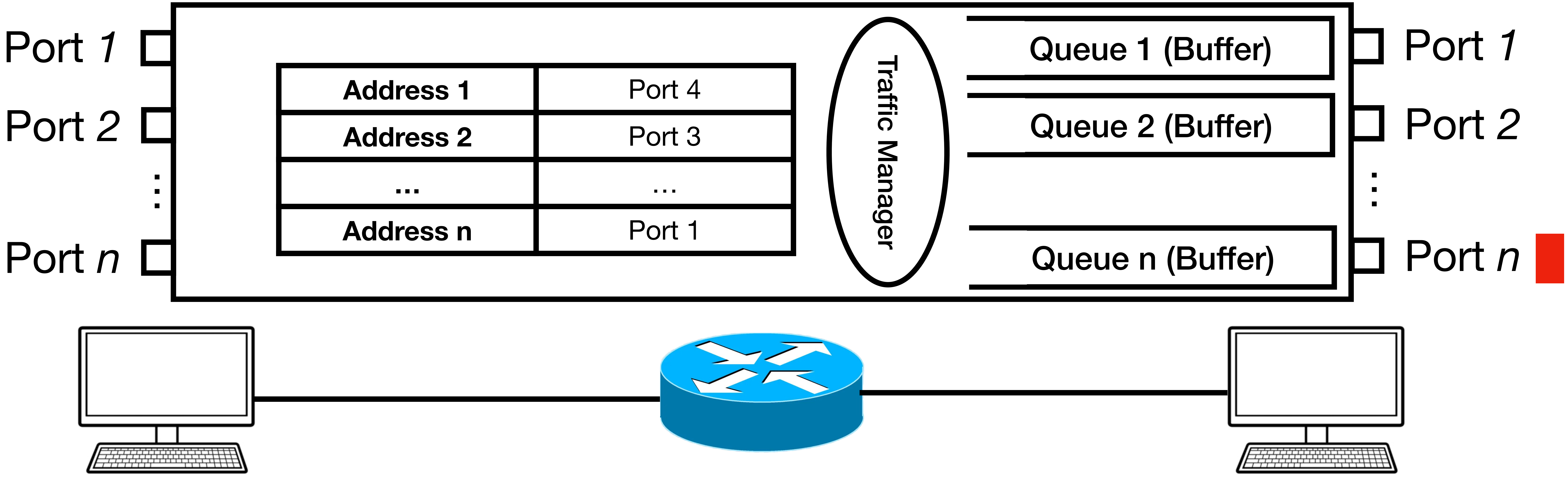
Transmission Delay (T_{trans})

- The time it takes to transmit through the communication ports
  - First-come-first-served manner
  - Depend on the packet length and transmission rate

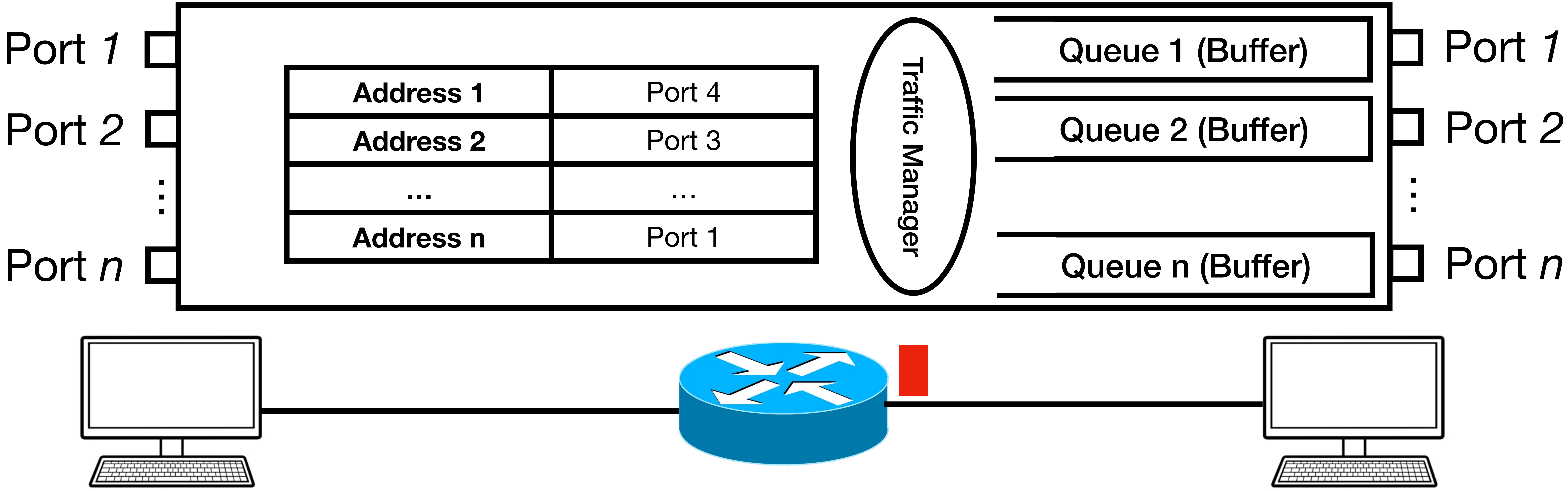


Transmission Delay Calculation

- Packet length (L bits) and Transmission Rate (R bits/sec)
  - Transmission Delay = L/R
  - Suppose L=1KB, R = 10Mbps/100Mbps, what is the transmission delay?

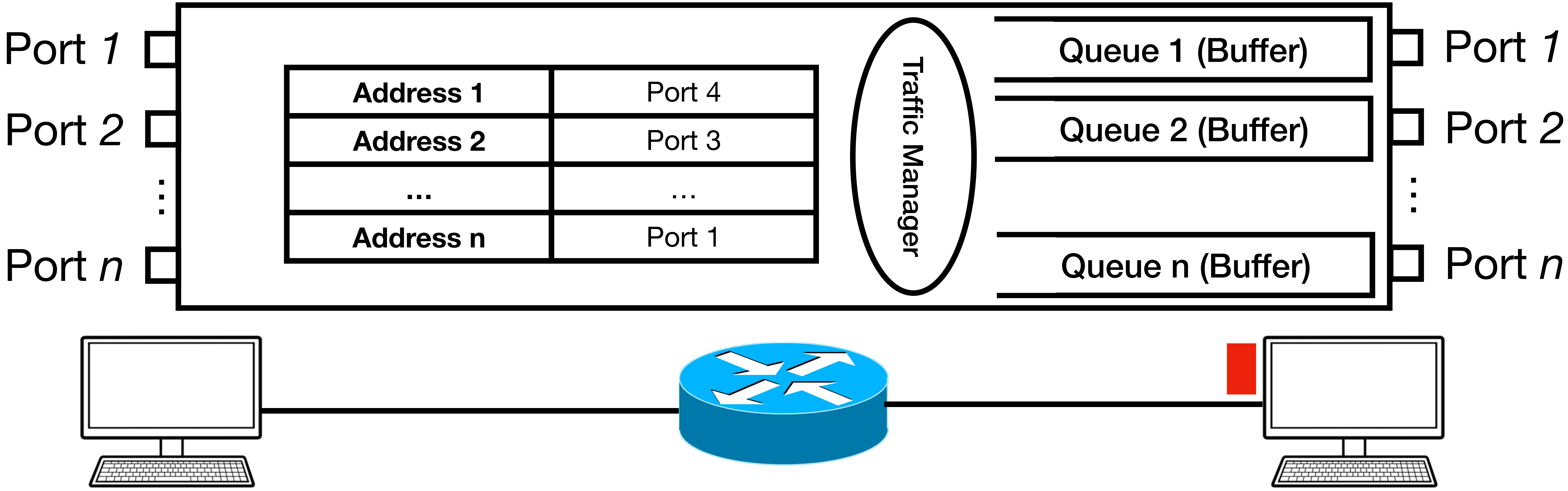


Propagation Delay (T_{prop})



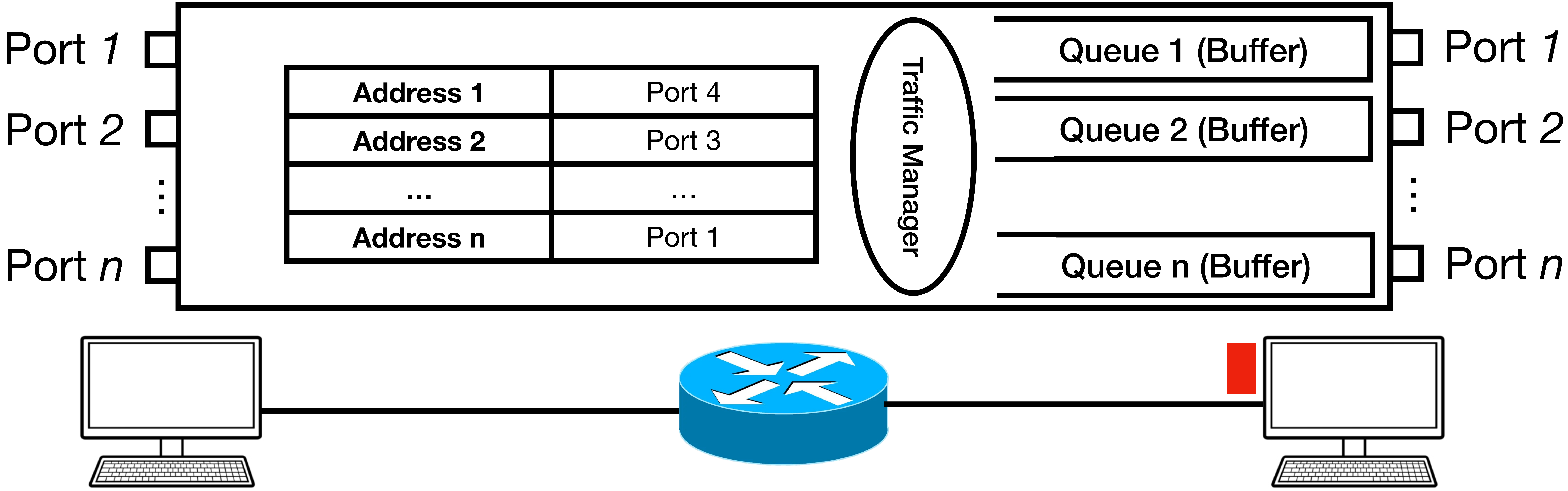
Propagation Delay (T_{prop})

- The time required to propagate over the communication link
  - Depend on the physical media (e.g., fiber optics, copper wire, etc.)
  - 2x10^8 ~ 3x10^8 meters/second



Propagation Delay Calculation

- Distance (d) and propagation speed (s)
  - Propagation delay = d/s
  - Distance matters!



Transmission Delay v.s. Propagation Delay

- Difference
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- Suppose
  - Packet length (L) = 1.5KB and transmission rate (R) = 1Mbps
  - Distance (d) = 3m and propagation speed (s) = 3^8 m/s
  - What is the transmission delay and propagation delay?

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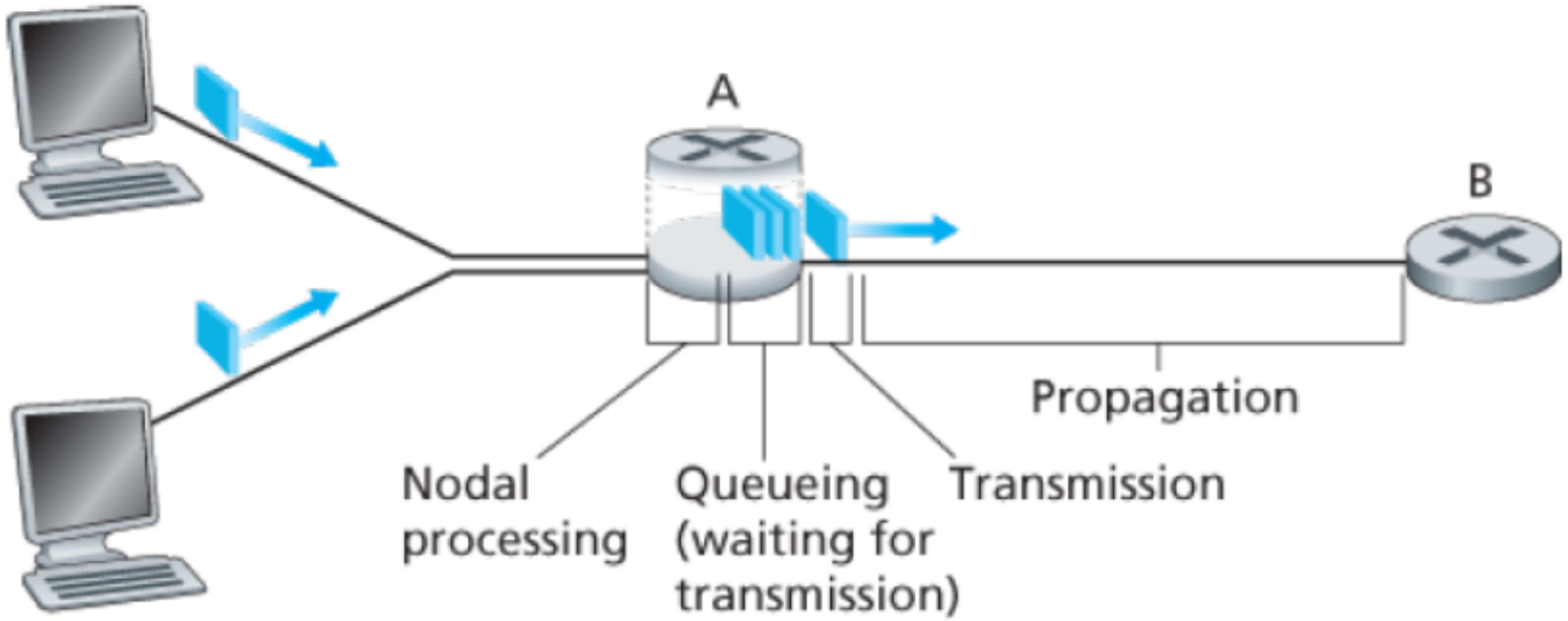
  - If we increase the distance to 3km, what happens?

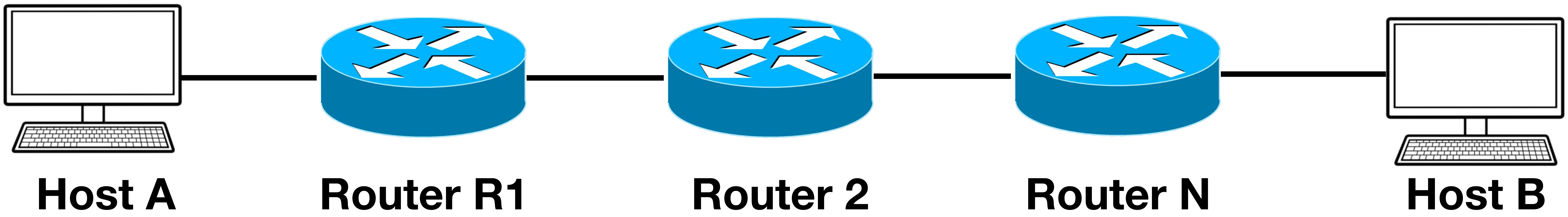
Total (Nodal) Delay

- $T_{total} = T_{proc} + T_{queue} + T_{trans} + T_{prop}$
  - Per-node, also called total nodal delay



End-to-End Delay

- Suppose
  - Host A can send a packet infinitely fast
  - Host B can receive a packet infinitely fast
- What is the end-to-end delay for a packet from host A to host B?
  - $T_{end\text{-}to\text{-}end} = N\,(T_{proc} + T_{queue} + T_{trans} + T_{prop}) + T_{prop}$



Queueing Delay

- The most complicated and interesting one
  - Varying packet to packet and scenario to scenario
- Statistical metrics
  - Average queueing delay
  - Variance of queueing delay
  - Tail queueing delay
  - The probability that the queuing delay exceeds some value

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- Unit: packets/second

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- Packet arrival rate **a**
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- Transmission rate **R**
- Unit: bits/second

When the Queue is built up?

- Given time T, incoming traffic load> outgoing traffic load
  - Incoming traffic load = $\sum_{i=1}^{N} pkt\_size_i$
  - Out going traffic load = R * T

- Packet arrival rate **a**
- Unit: packets/second

- Transmission rate **R**
- Unit: bits/second

Traffic Intensity

- We define the ratio (La/R) as the traffic intensity
  - Suppose all packets consist of L bits

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Traffic Intensity

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Design your system so that the traffic intensity is no greater than 1!

Traffic Intensity

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- La/R > 1: queue built up!
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Can we see queueing when La/R <=1?

Traffic Arrival process

- Suppose one packet arrives every L/R seconds

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  - No queueing

- Suppose N packets arrive every (L/R)N seconds

Traffic Arrival process

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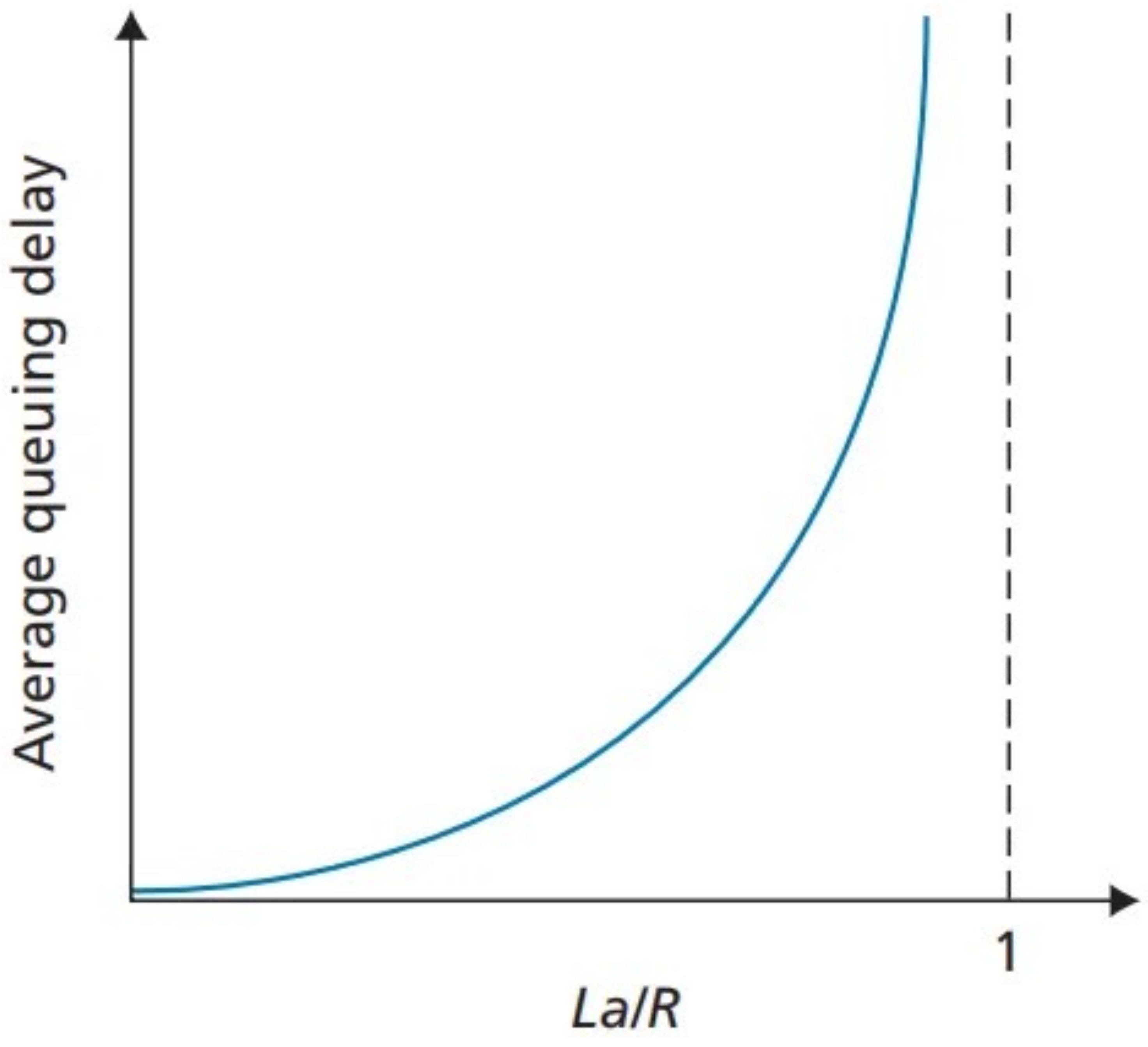
- Suppose N packets arrive every (L/R)N seconds
  - The 1st packet has no queueing delay, $T_{queue} = 0$
  - The 2nd packet has to wait for the 1st one, $T_{queue} = L/R \times 1$
  - The 3nd packet has to wait for the 1st and 2nd ones, $T_{queue} = L/R \times 2$
  - The nth packet has to wait for the (n-1) ones, $T_{queue} = L/R \times (n-1)$

Traffic Intensity Curve

- Close to 1, the average queueing delay increases
  - A small percentage increase causes a significant delay increase
  - In reality, queue is fixed-sized ==> **Packet Loss**

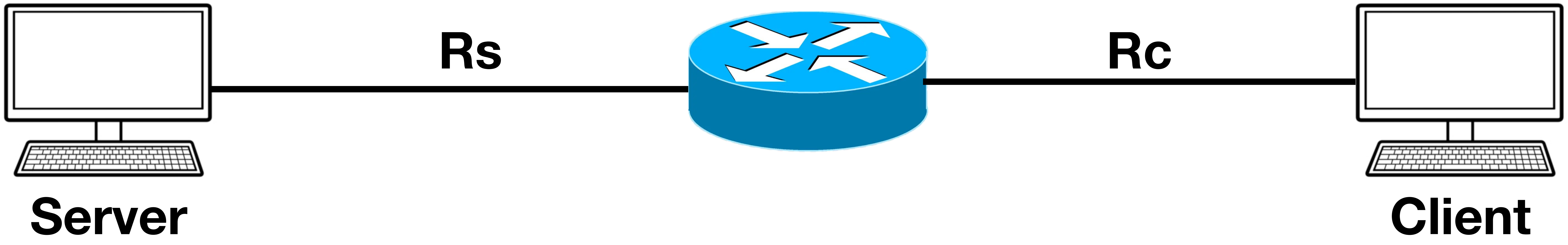


Throughput

- Bandwidth: the number of bits transmitted per second at a communication port and link
  - bps, Kbps, Mbps, Gbps, Tbps, …
- Throughput: the number of bits transmitted from A to B
  - A and B can be host, switch, etc.
  - bps, Kbps, Mbps, Gbps, Tbps, …

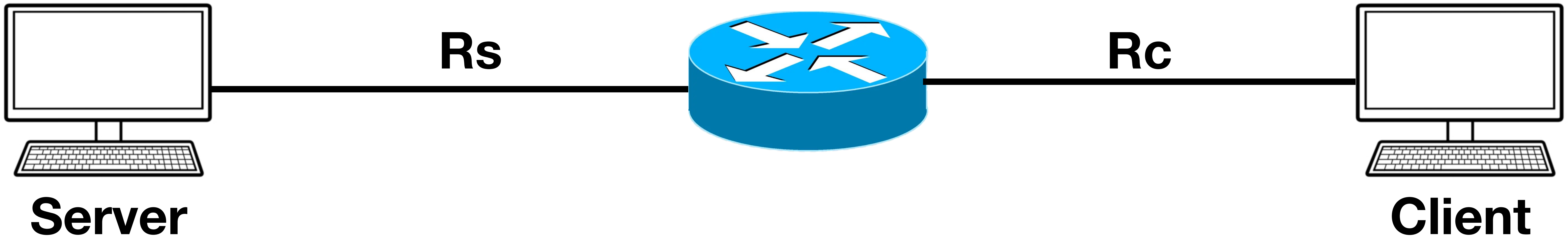
A Simple Throughput Example

- A file transferring from a server to a client



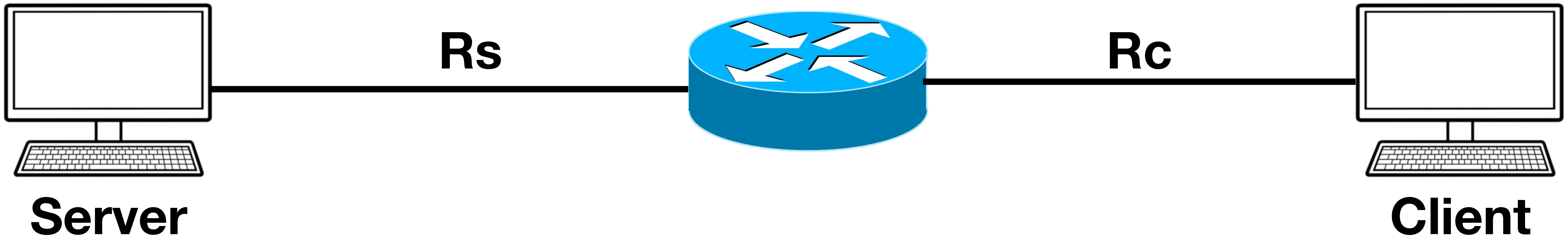
A Simple Throughput Example

- A file transferring from a server to a client
  - If Rs < Rc ==> The client receives the file at Rs
  - If Rs > Rc ==> The client receives the file at Rc, but router is queued



A Simple Throughput Example

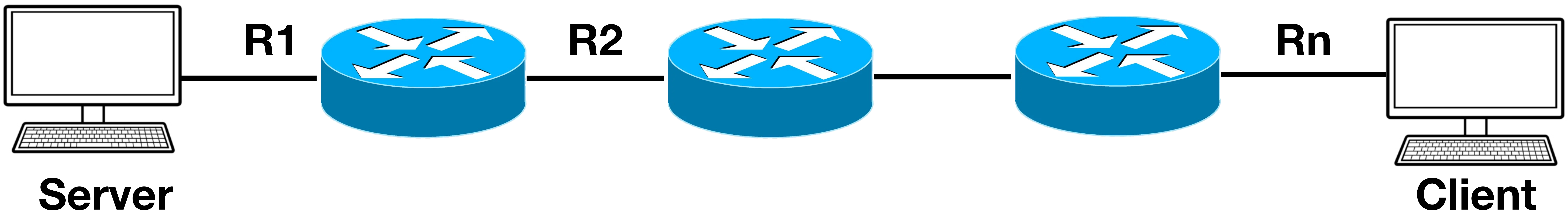
- A file transferring from a server to a client
  - If Rs < Rc ==> The client receives the file at Rs
  - If Rs > Rc ==> The client receives the file at Rc, but router is queued
- Throughput = min {Rs, Rc}
  - Depend on the bottleneck link
- A log file = 32M bits, Rs = 2Mbps, Rc = 1Mbps
  - Transfer time is 32 seconds



Another Throughput Example

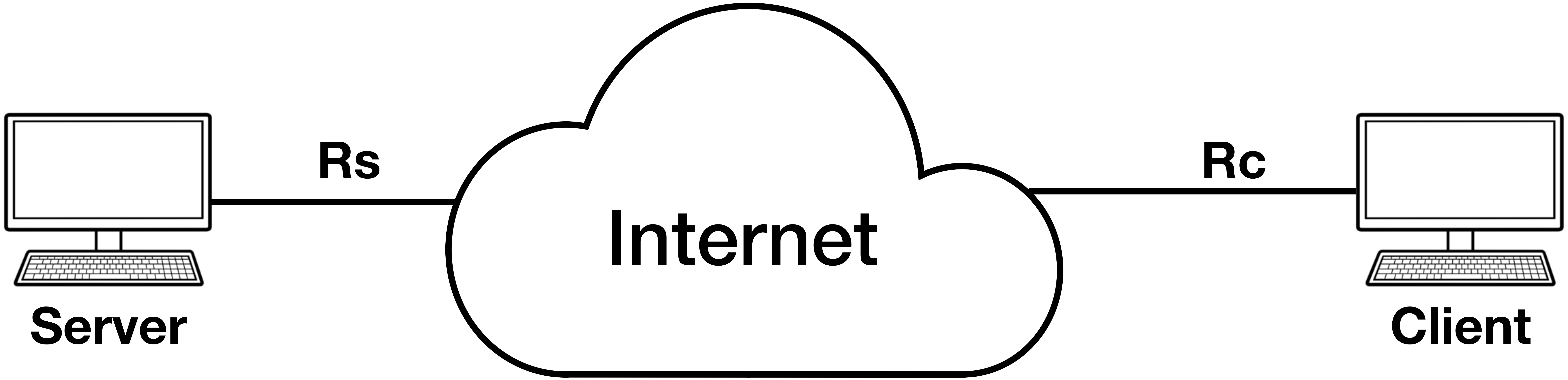
- Communication path: server -> a list of routers -> Client

- Throughput = min {R1, R2, R3, …, Rn}
  - Depend on the bottleneck link



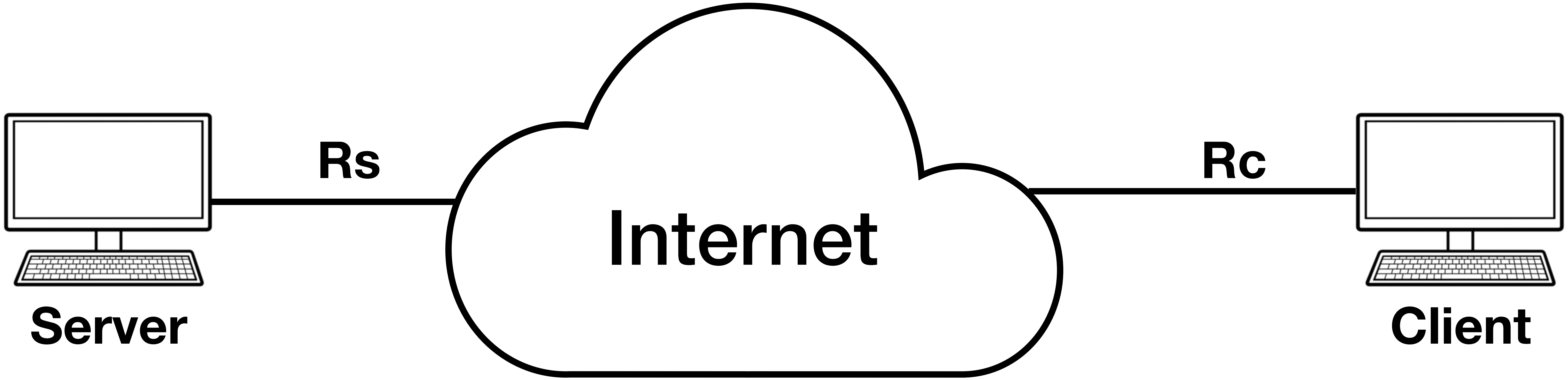
Throughput in a Shared Network

- Impossible to know the communication path details
- What is the throughput to transfer a file from a server to a client?



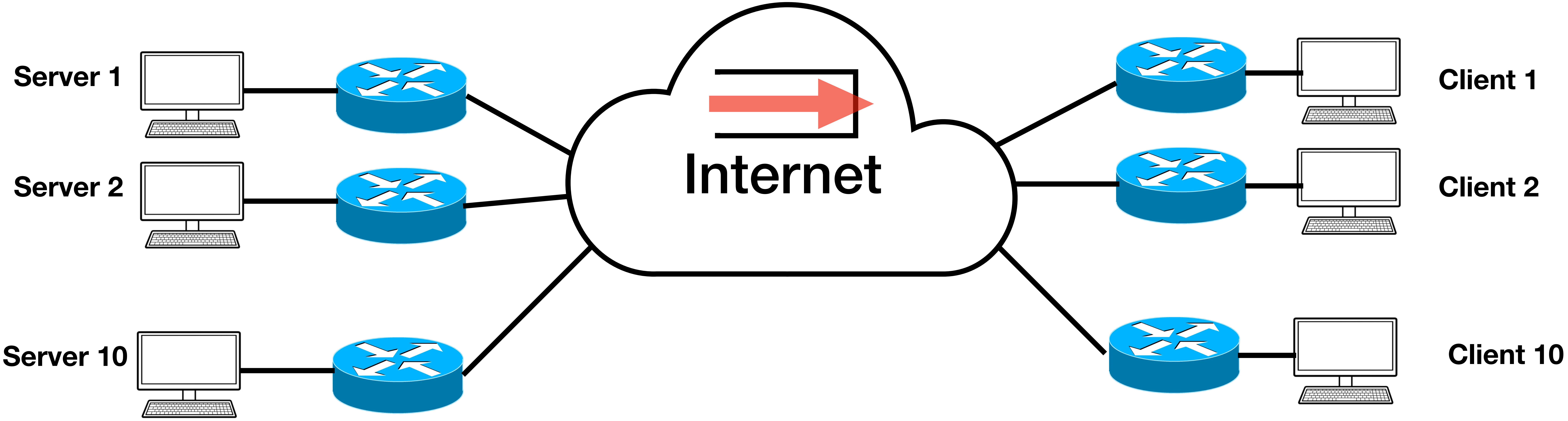
Throughput in a Shared Network

- Impossible to know the communication path details
- What is the throughput to transfer a file from a server to a client?
  - Actual Throughput = File Size / Total Transfer Time
  - Actual Throughput <= min {Rs, Rc}



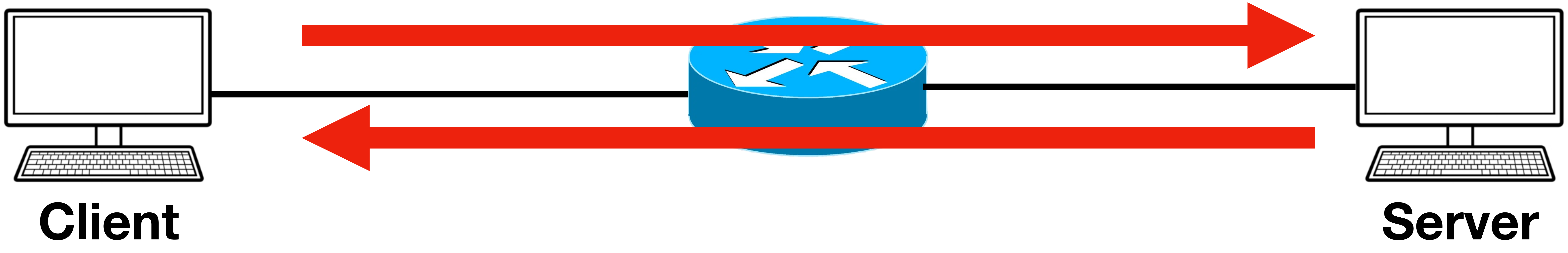
Throughput under Concurrent Transmissions

- Throughput also depends on intervening traffic



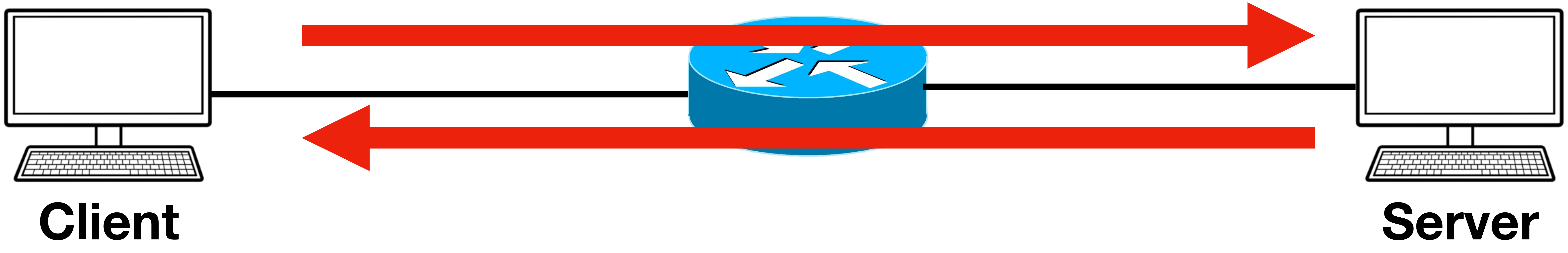
RTT (Round-Trip Time)

- The time it takes to send a request from a client to a server and receive the response back
  - RTT = Total delay (Client -> Server) + Total Delay (Server -> Client)



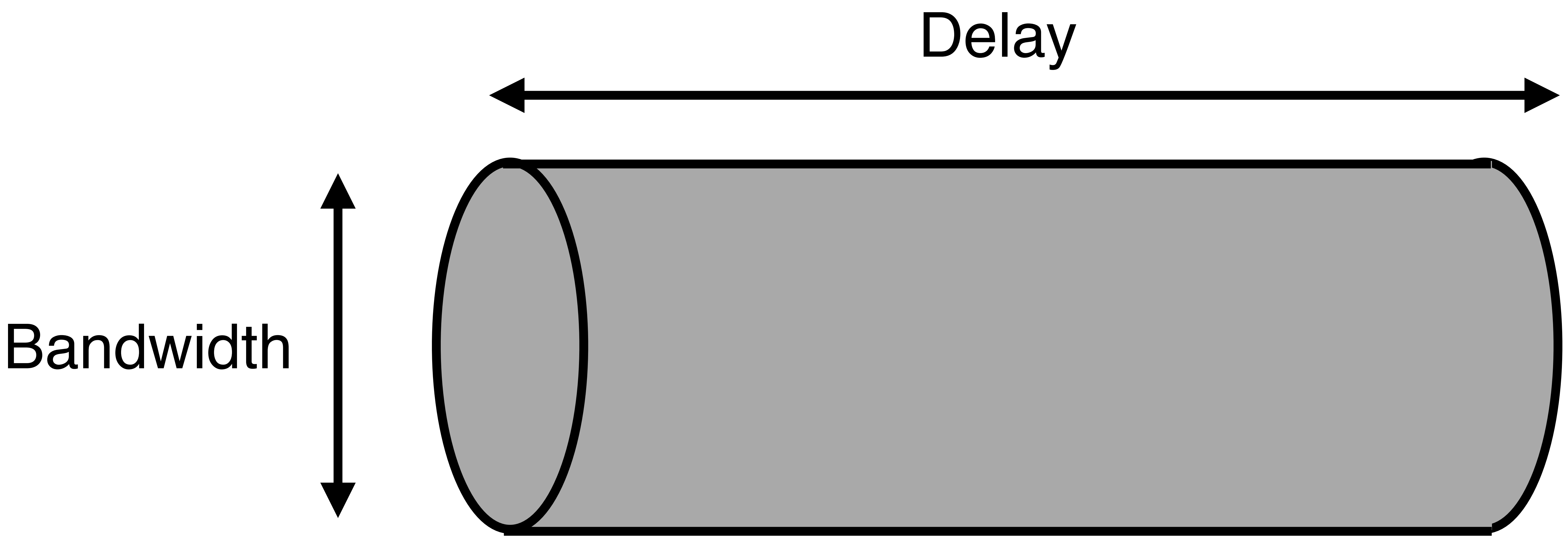
RTT (Round-Trip Time)

- The time it takes to send a request from a client to a server and receive the response back
  - RTT = Total delay (Client -> Server) + Total delay (Server -> Client)
- RTT is application-dependent
  - Web browsing: page download time (time to retrieve the first object)
  - Cloud gaming: interactive latency
  - Video conferencing and streaming: Time to First Frame
  - LLM: Time to first token



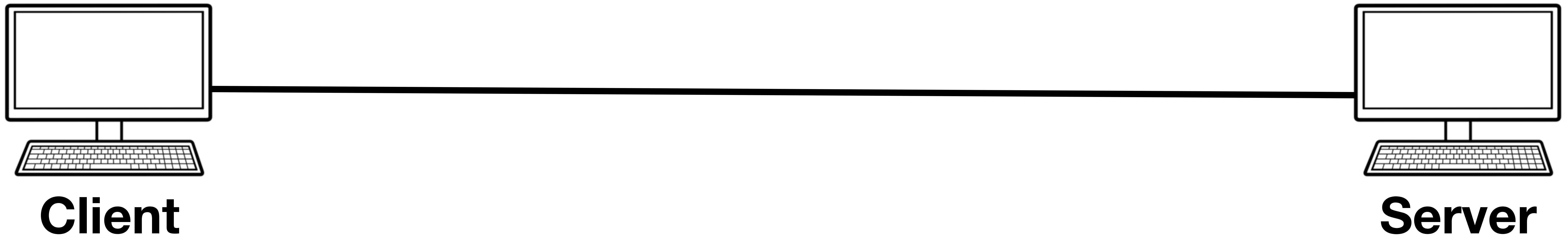
BDP (Bandwidth-Delay Product)

- The volume of a data pipe for one transmission
  - Bandwidth * Delay
  - The number of bits have left the sender and are yet to reach the receiver



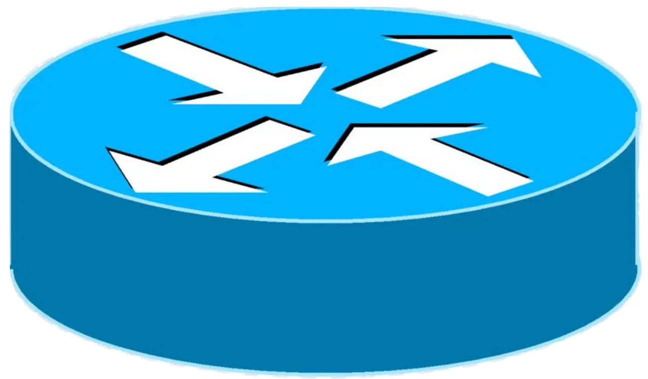
BDP of a Communication Link

- Delay=Propagation delay ==> Link BDP
  - The number of bits over the wire



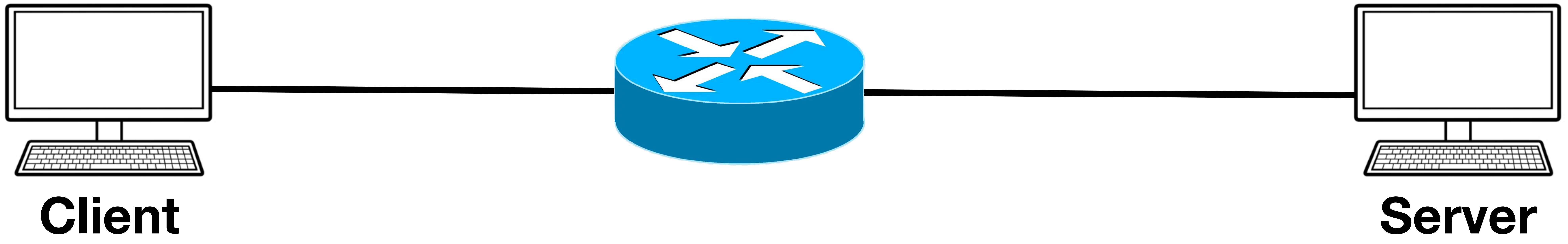
BDP of a Router

- Delay=Propagation delay ==> Link BDP
  - The number of bits over the wire
- Delay=Processing + Queueing + Transmission ==> Router BDP
  - The number of bits a router can hold



BDP of Client —> Server

- Delay=Propagation delay ==> Link BDP
  - The number of bits over the wire
- Delay=Processing + Queueing + Transmission ==> Router BDP
  - The number of bits a router can hold
- Delay=Total delay ==> End-to-End BDP
  - The number of bits that stay in-flight between two hosts



Summary

- Today
  - Computer networks: performance analysis

- Next lecture
  - Physical Layer: Encoding