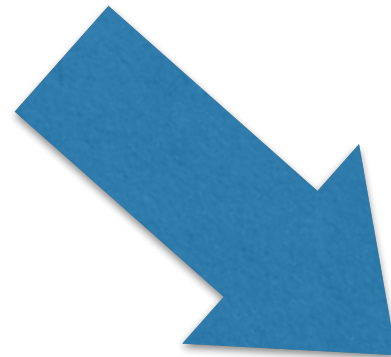


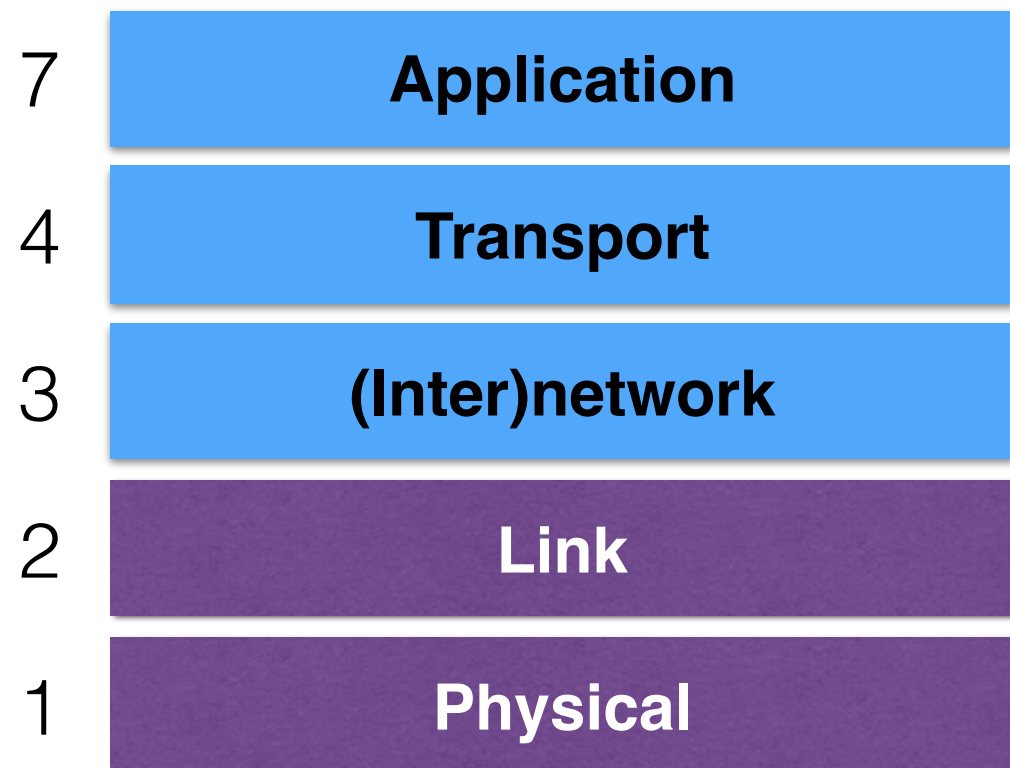
This time

Digging into
**Networking
Protocols**



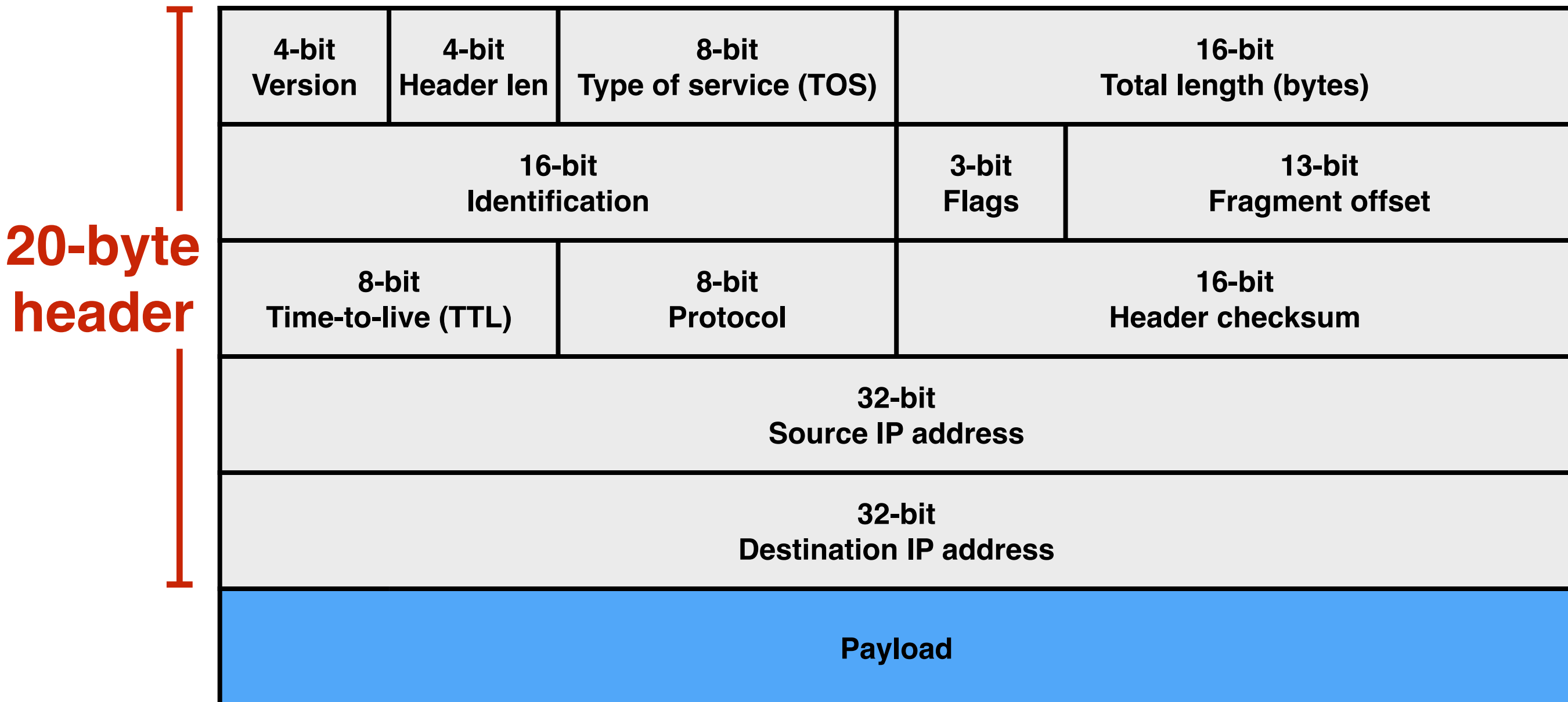
With a particular focus on
**TCP details,
attacks,
and defenses**

Layer 3: (Inter)network layer



- Bridges multiple “subnets” to provide *end-to-end* **internet** connectivity between **nodes**
- Provides **global** addressing (IP addresses)
- Only provides **best-effort** delivery of data (i.e., no retransmissions, etc.)
- Works across different link technologies

IP packet “header”



IP Packet Header Fields (1)

- **Version number** (4 bits)
 - Indicates the version of the IP protocol
 - Necessary for knowing what fields follow
 - “4” (for IPv4) or “6” (for IPv6)
- **Header length** (4 bits)
 - How many 32-bit words (rows) in the header
 - Typically 5
 - Can provide IP options, too
- **Type-of-service** (8 bits)
 - Allow packets to be treated differently based on different needs
 - Low delay for audio, high bandwidth for bulk transfer, etc.

IP Packet Header Fields (2)

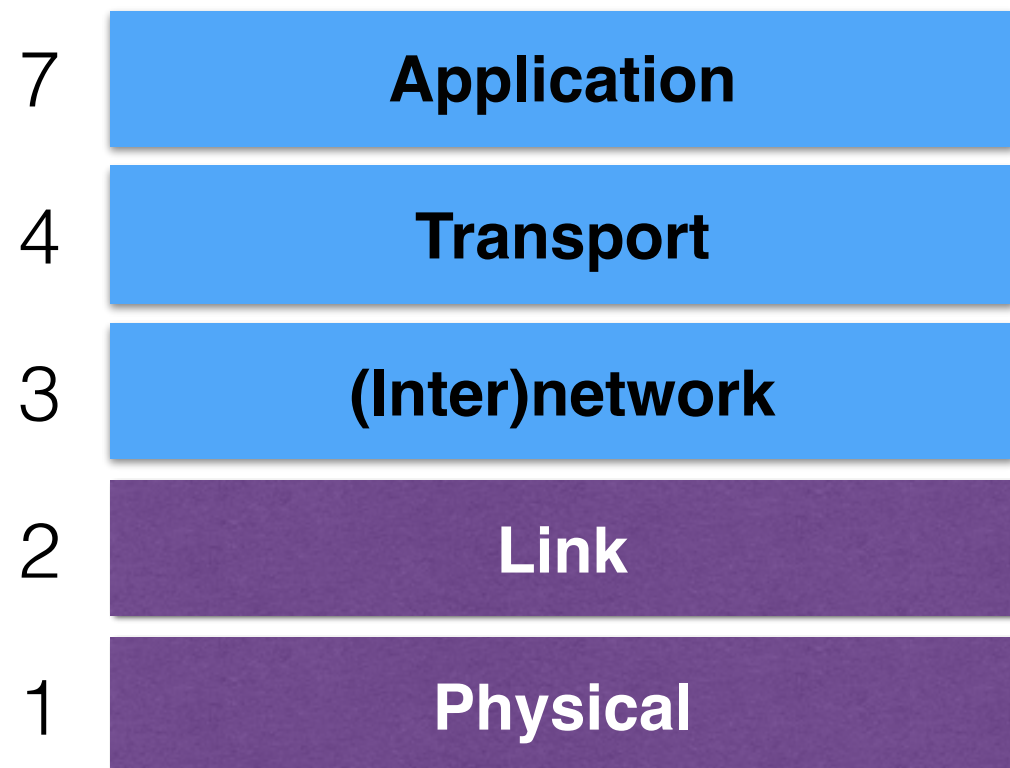
- Two IP addresses
 - Source (32 bits)
 - Destination (32 bits)
- Destination address
 - *Unique* identifier/locator for the receiving host
 - Allows each node (end-host and router) to make forwarding decisions
- Source address
 - Unique identifier/locator for the sending host
 - Recipient can decide whether to accept the packet
 - Allows destination to *reply* to the source

IP: “Best effort” packet delivery

- Routers inspect destination address, determine “next hop” in the forwarding table
- Best effort = “I’ll give it a try”
 - Packets may be lost
 - Packets may be corrupted
 - Packets may be delivered out of order

Fixing these is the job of the transport layer!

Layer 4: Transport layer



- End-to-end communication between **processes**
- Different types of services provided:
 - UDP: unreliable *datagrams*
 - TCP: *reliable* byte stream
- “Reliable” = keeps track of what data were received properly and retransmits as necessary

TCP: reliability

- Given best-effort deliver, the goal is to ensure *reliability*
 - All packets are delivered to applications
 - ... in order
 - ... unmodified (with reasonably high probability)
- Must robustly detect and retransmit lost data

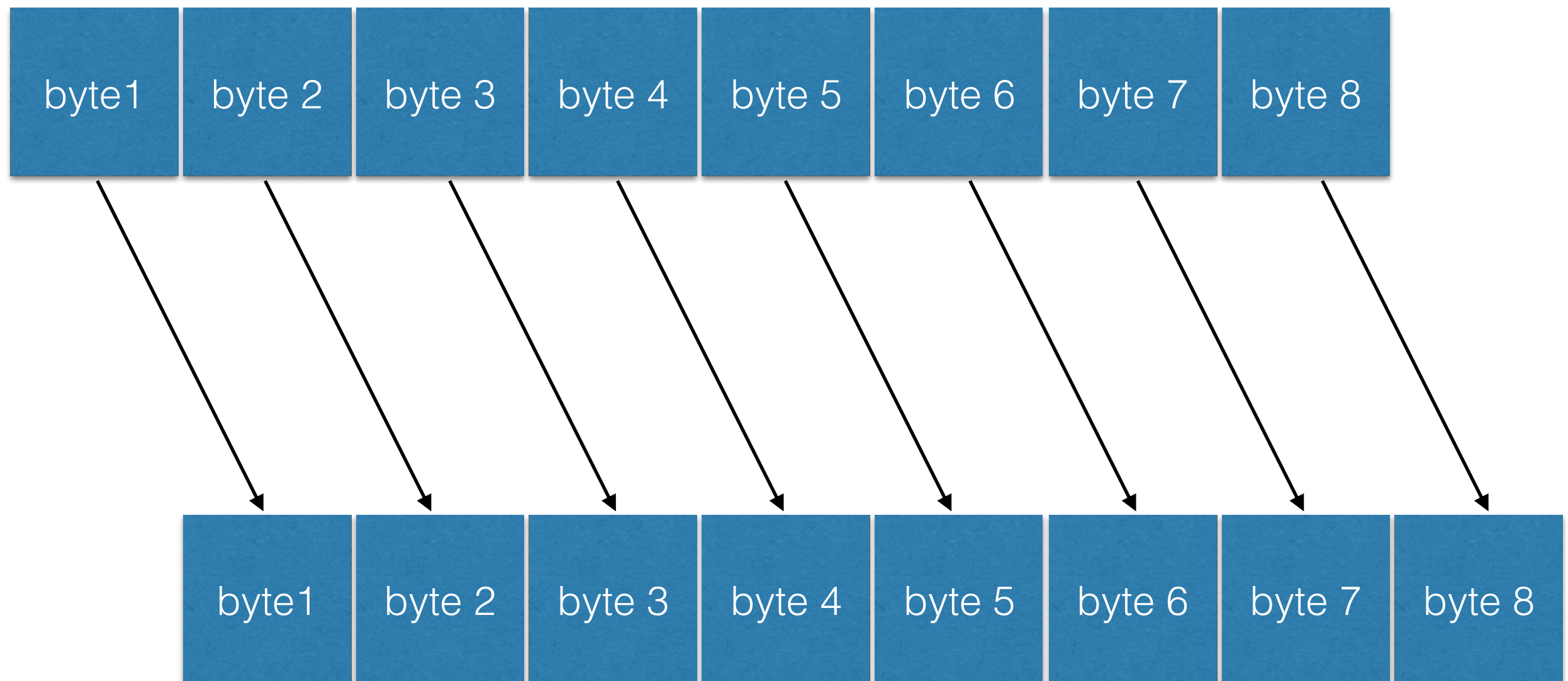
TCP's bytestream service

- Process A on host 1:
 - Send byte 0, byte 1, byte 2, byte 3, ...
- Process B on host 2:
 - Receive byte 0, byte 1, byte 2, byte 3, ...
- The applications do **not** see:
 - packet boundaries (looks like a stream of bytes)
 - lost or corrupted packets (they're all correct)
 - retransmissions (they all only appear once)

TCP bytestream service

Abstraction: Each *byte* reliably delivered in order

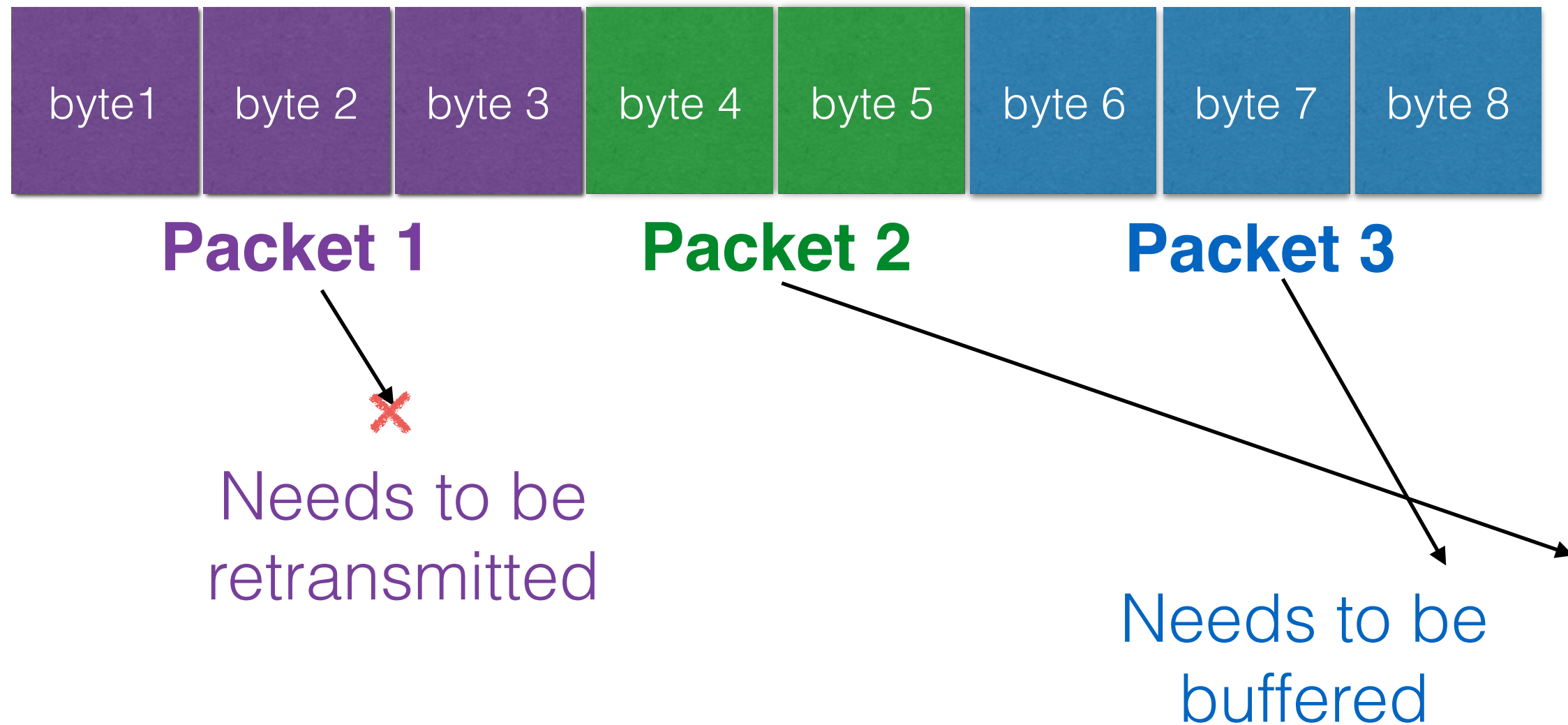
Process A on host H1



Process B on host H2

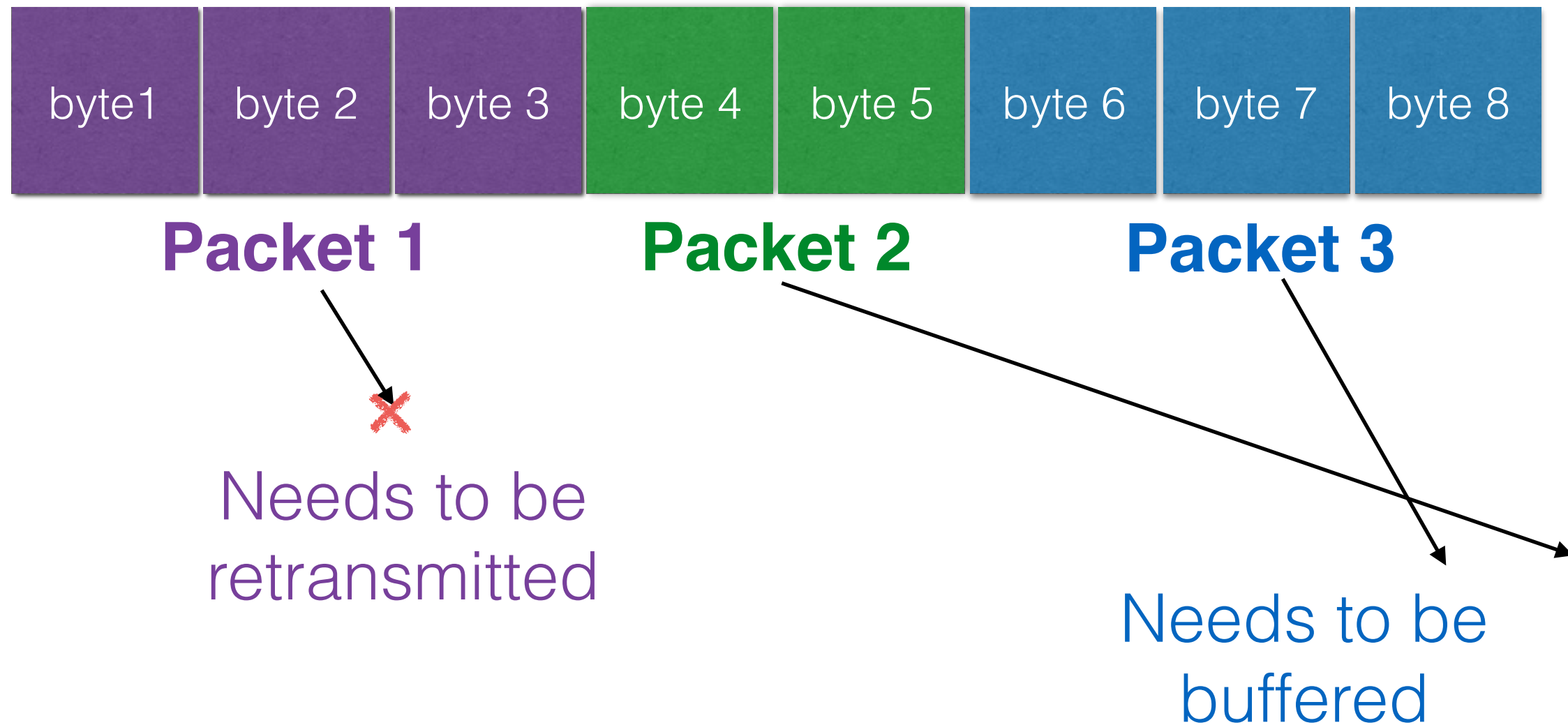
TCP bytestream service

**Reality: *Packets* sometimes retransmitted,
sometimes arrive out of order**



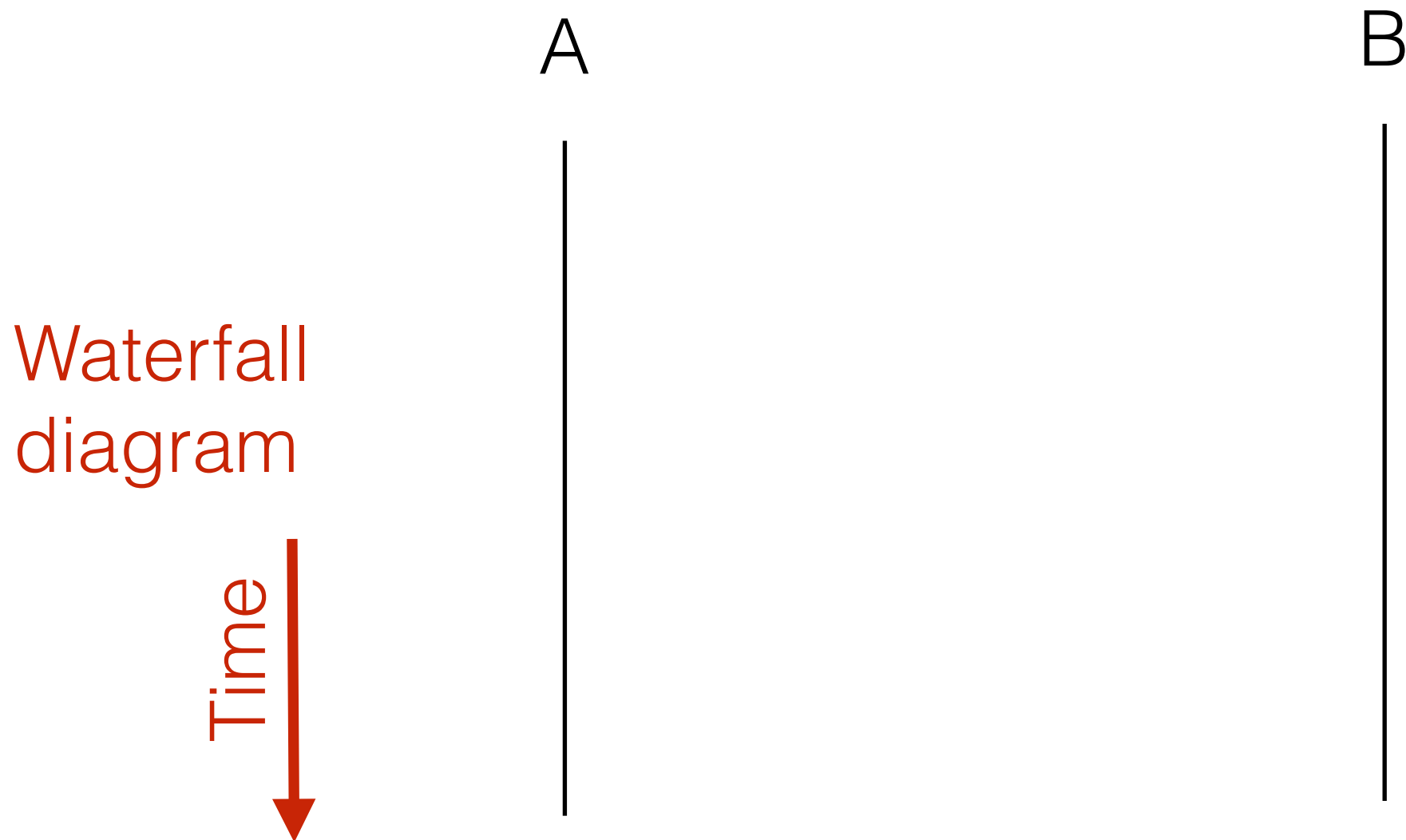
TCP bytestream service

**Reality: *Packets* sometimes retransmitted,
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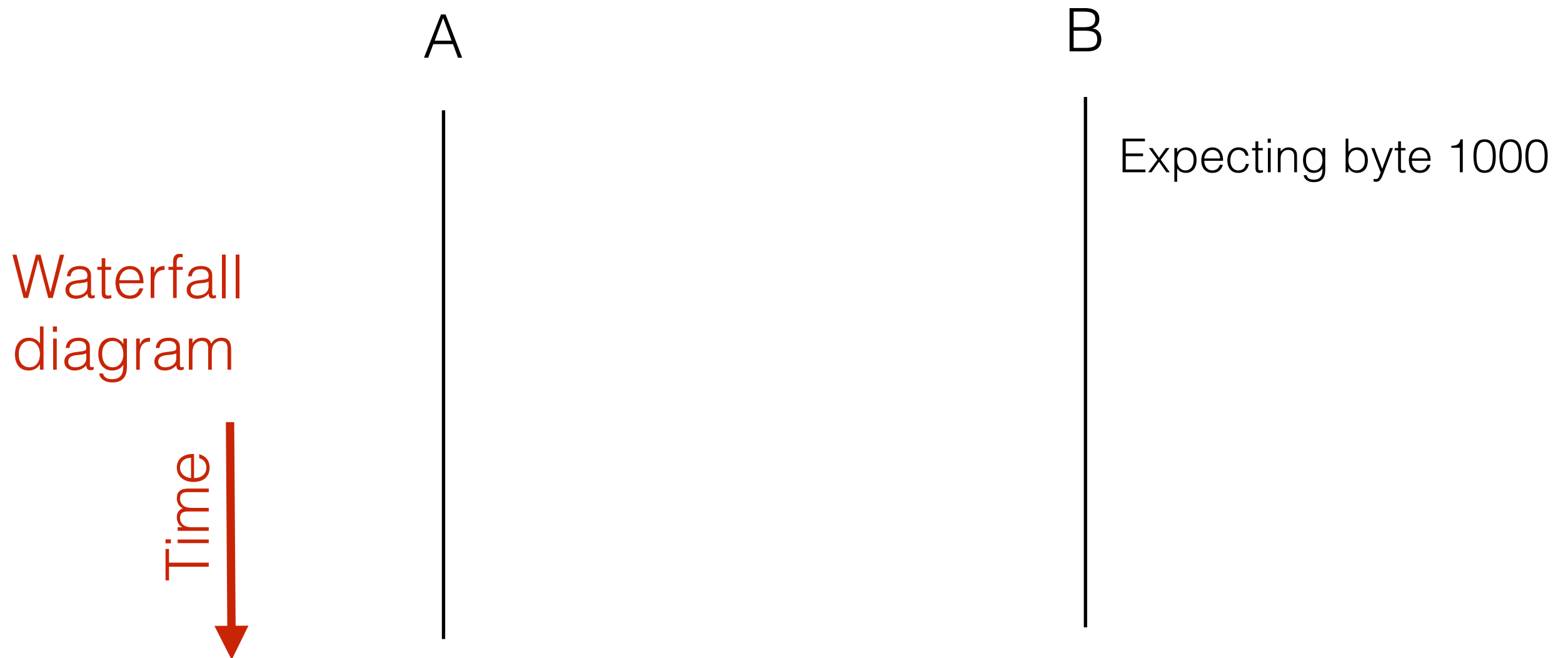


**TCP's first job: achieve the abstraction while
hiding the reality from the application**

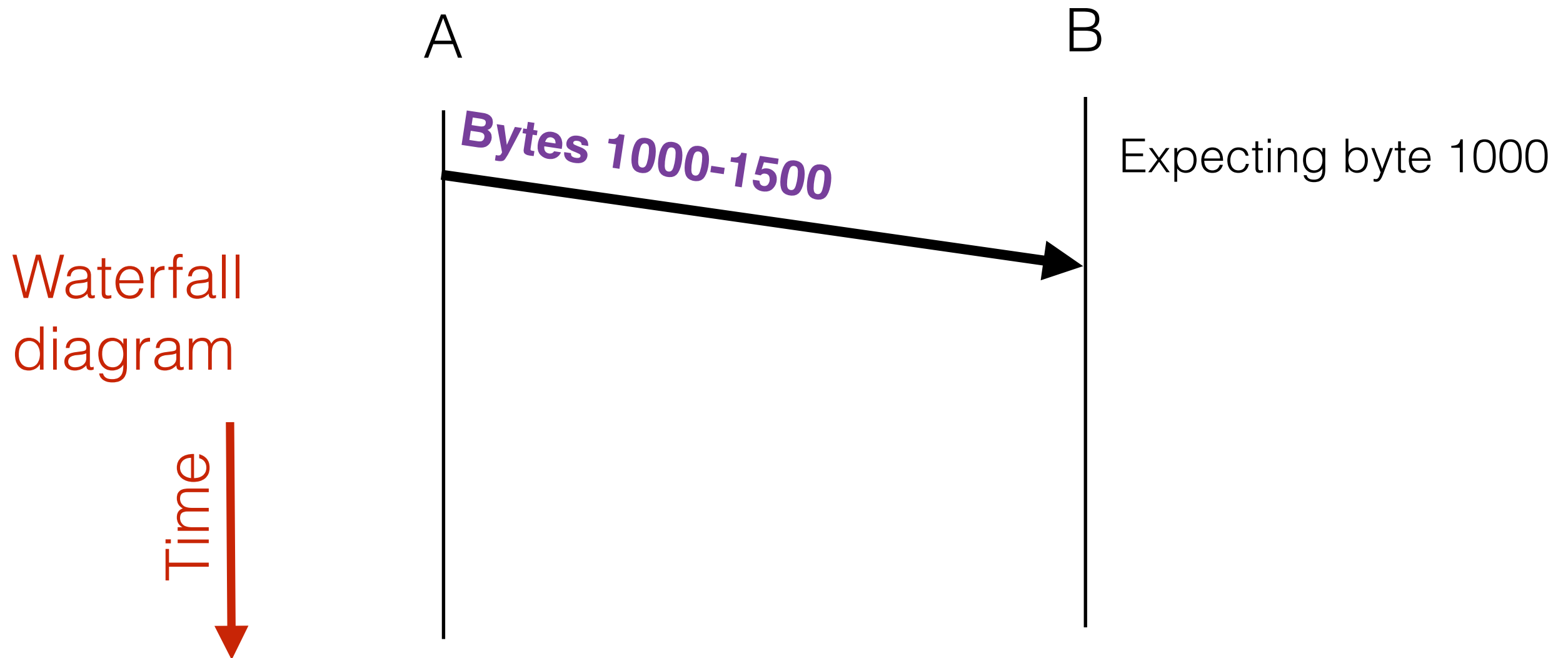
How does TCP achieve reliability?



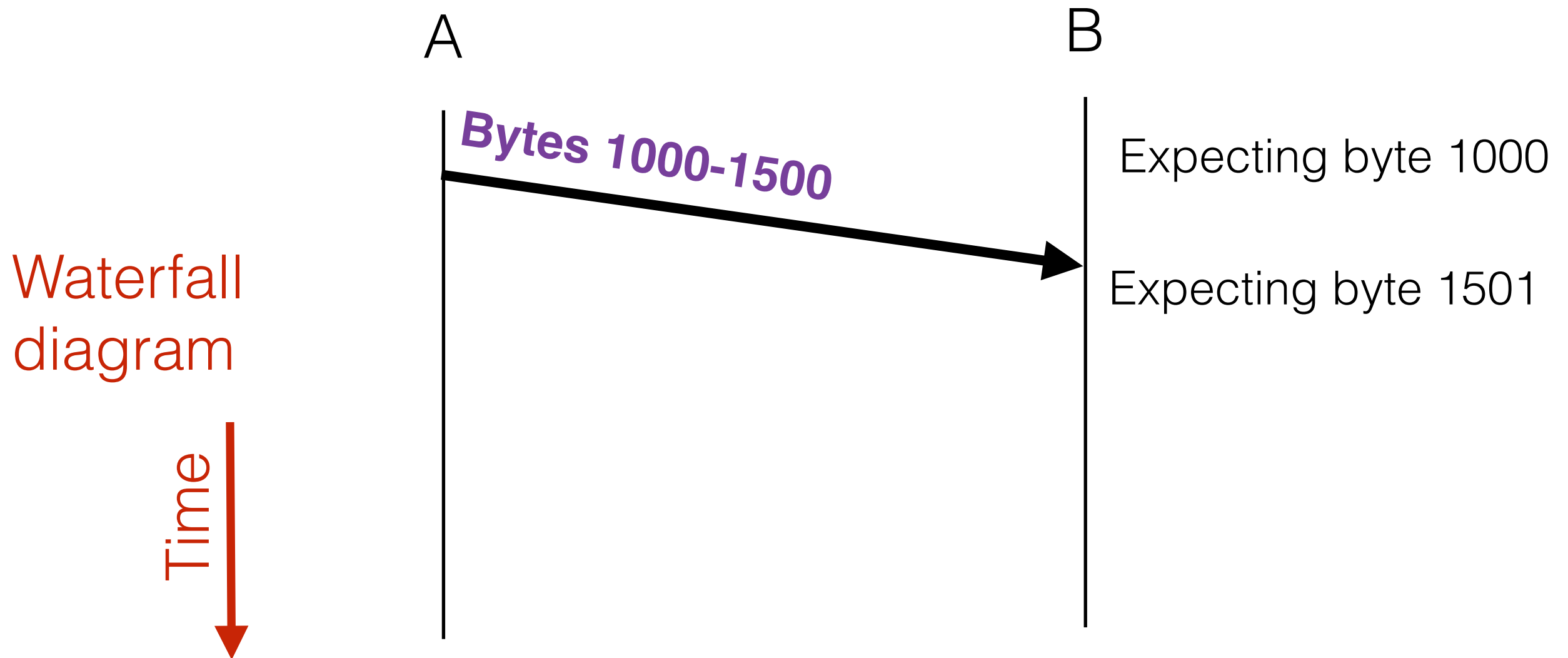
How does TCP achieve reliability?



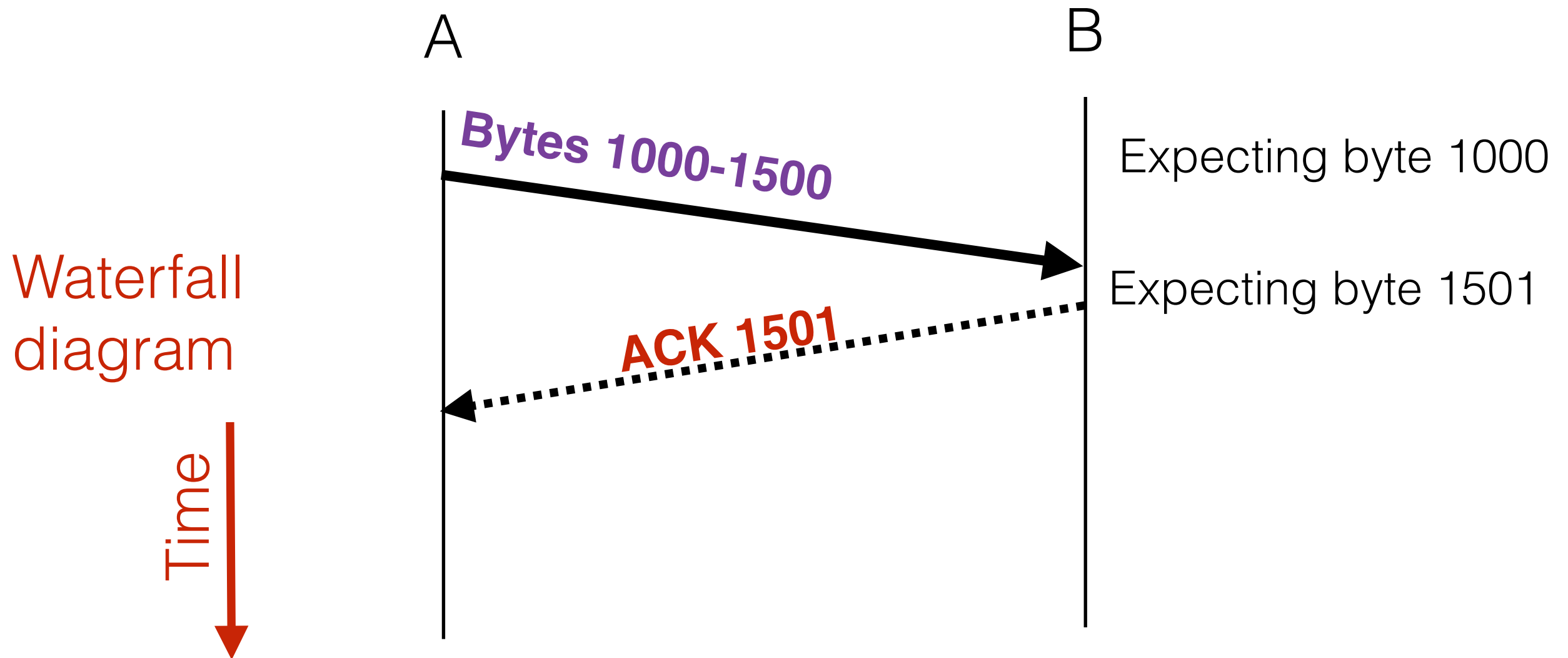
How does TCP achieve reliability?



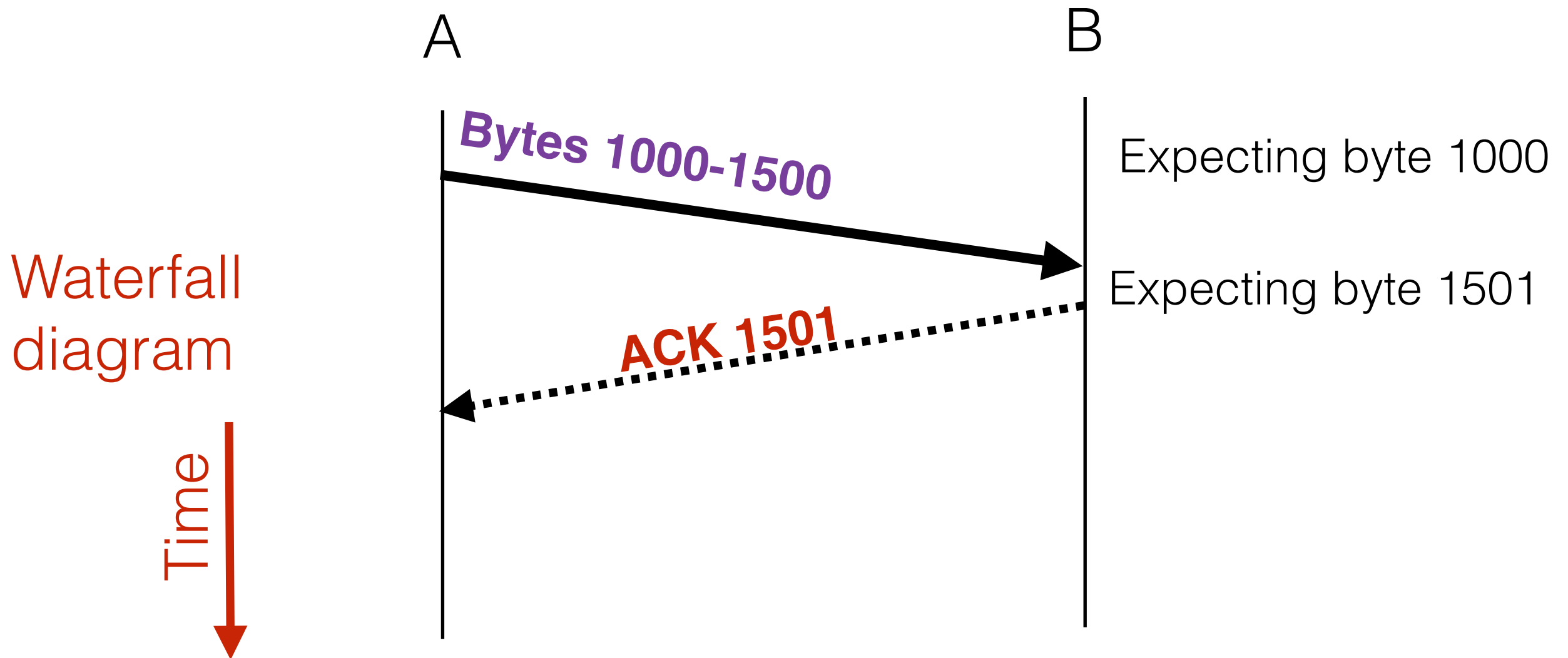
How does TCP achieve reliability?



How does TCP achieve reliability?

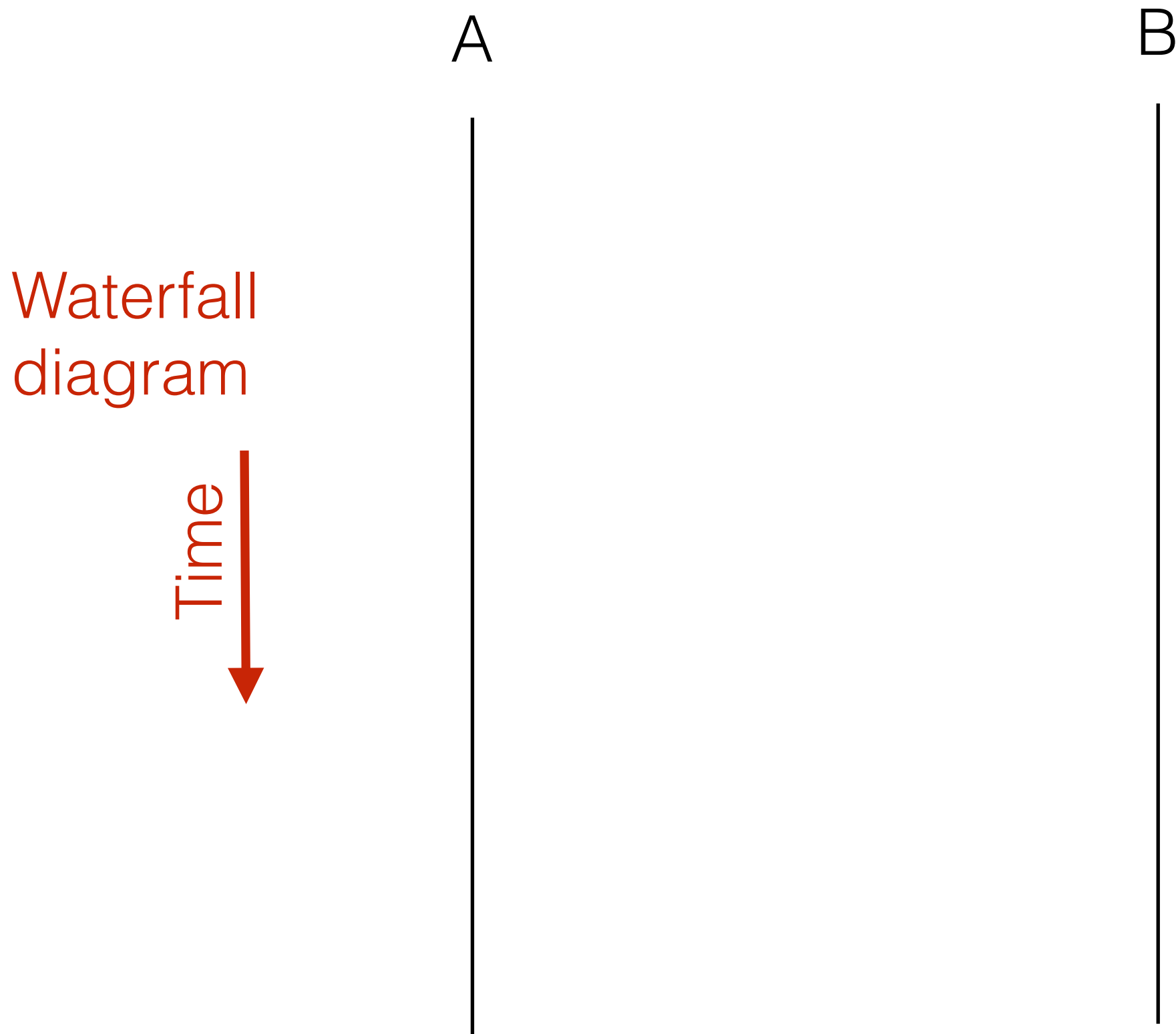


How does TCP achieve reliability?

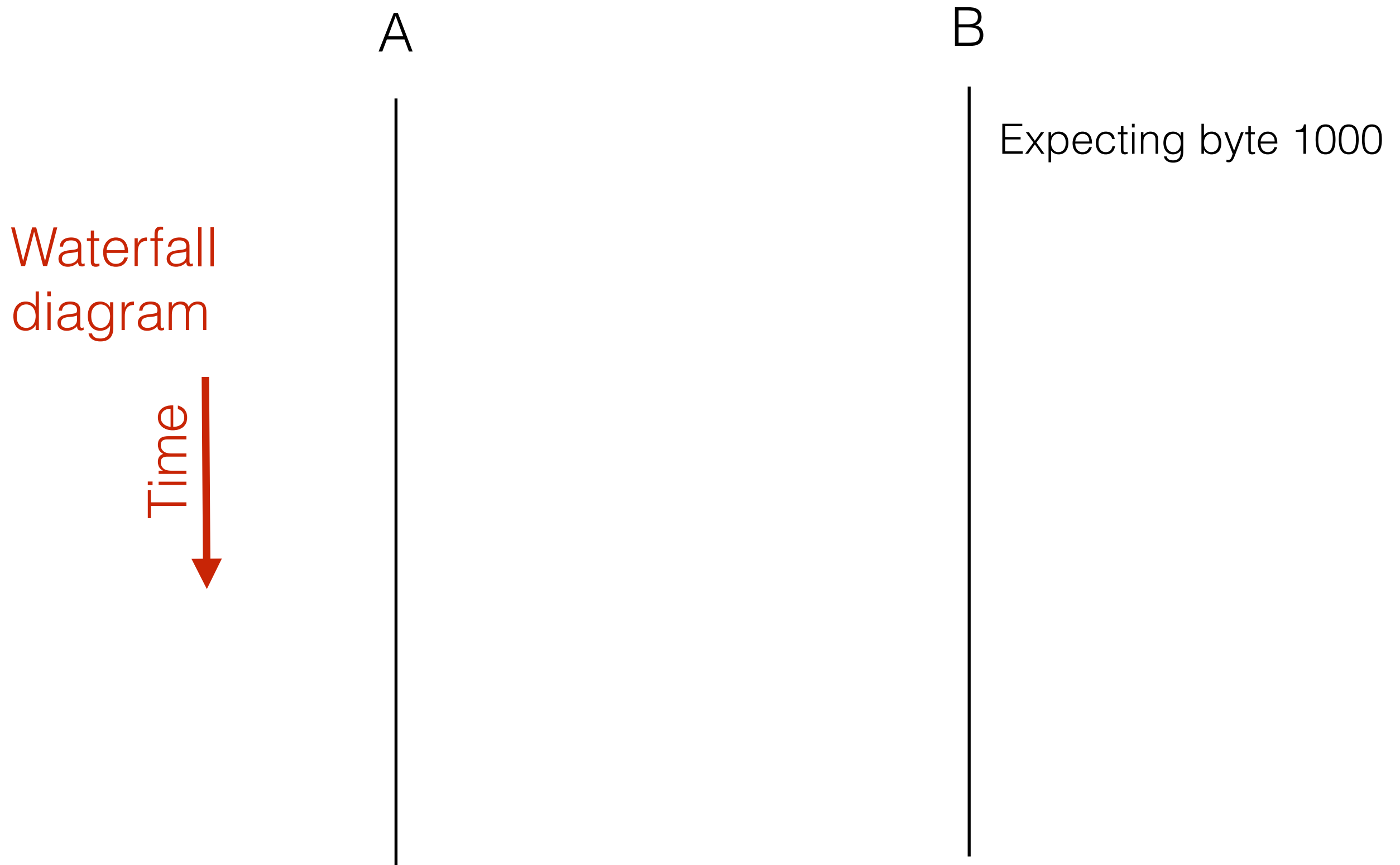


Reliability through acknowledgments
to determine whether something was received.

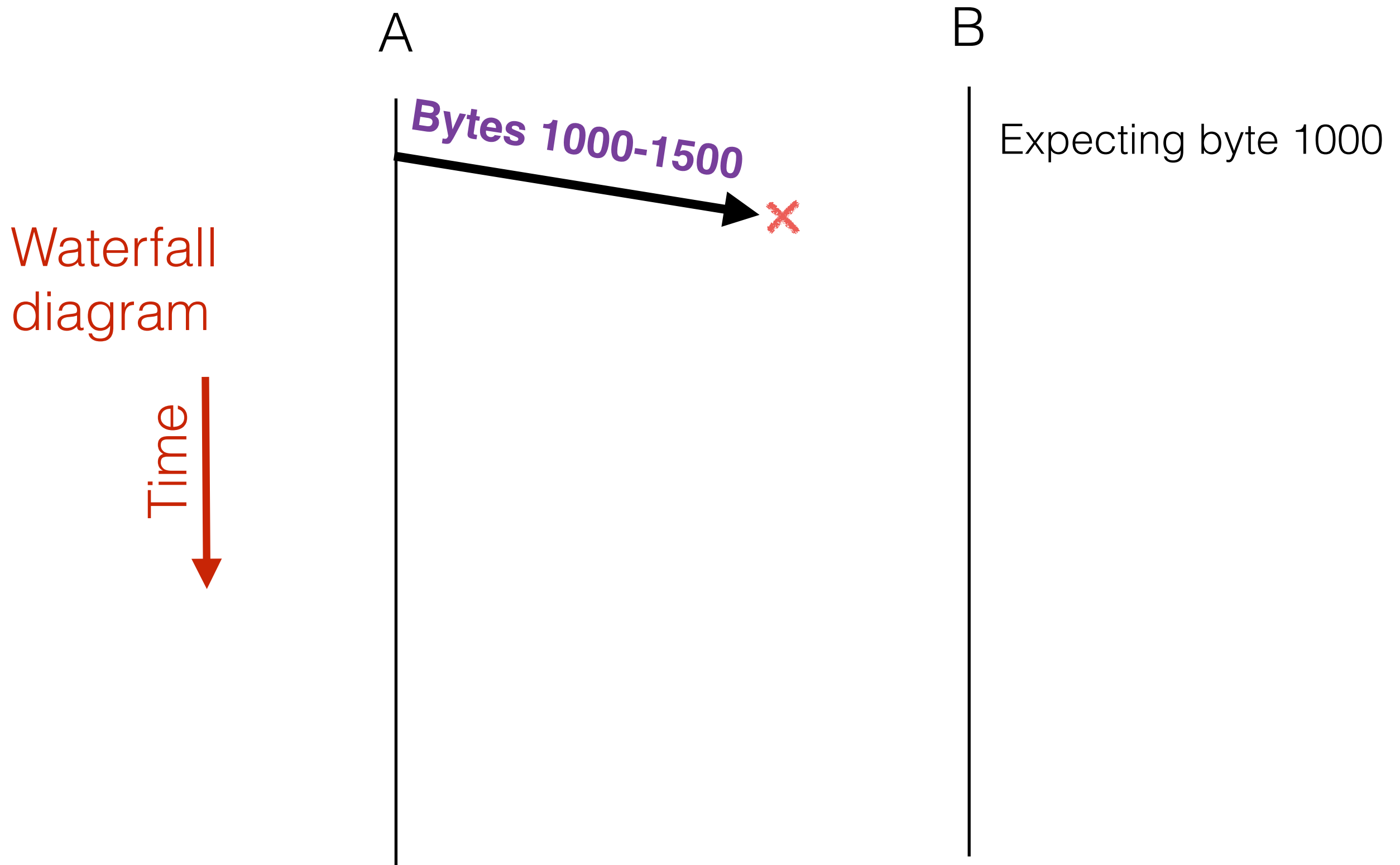
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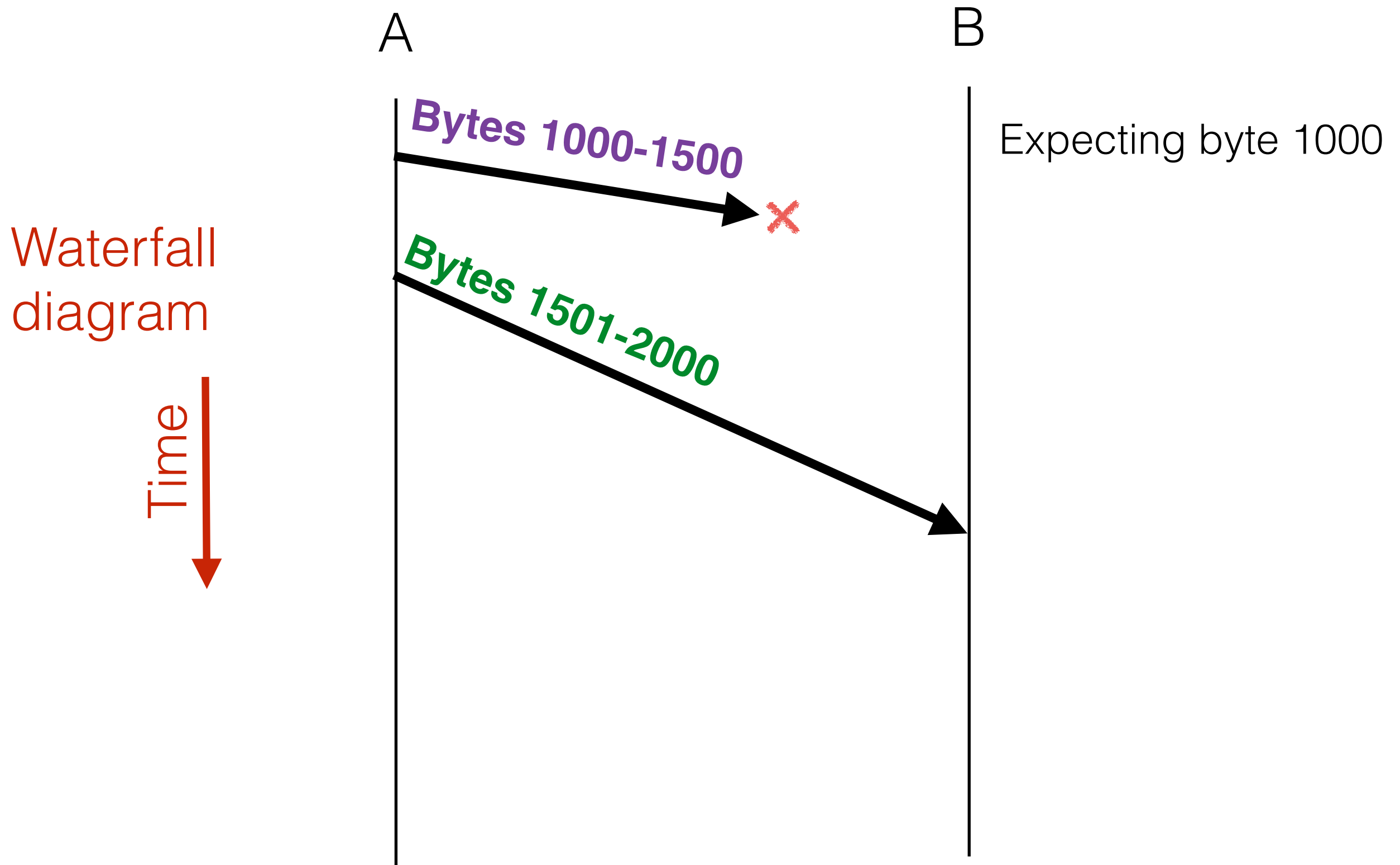
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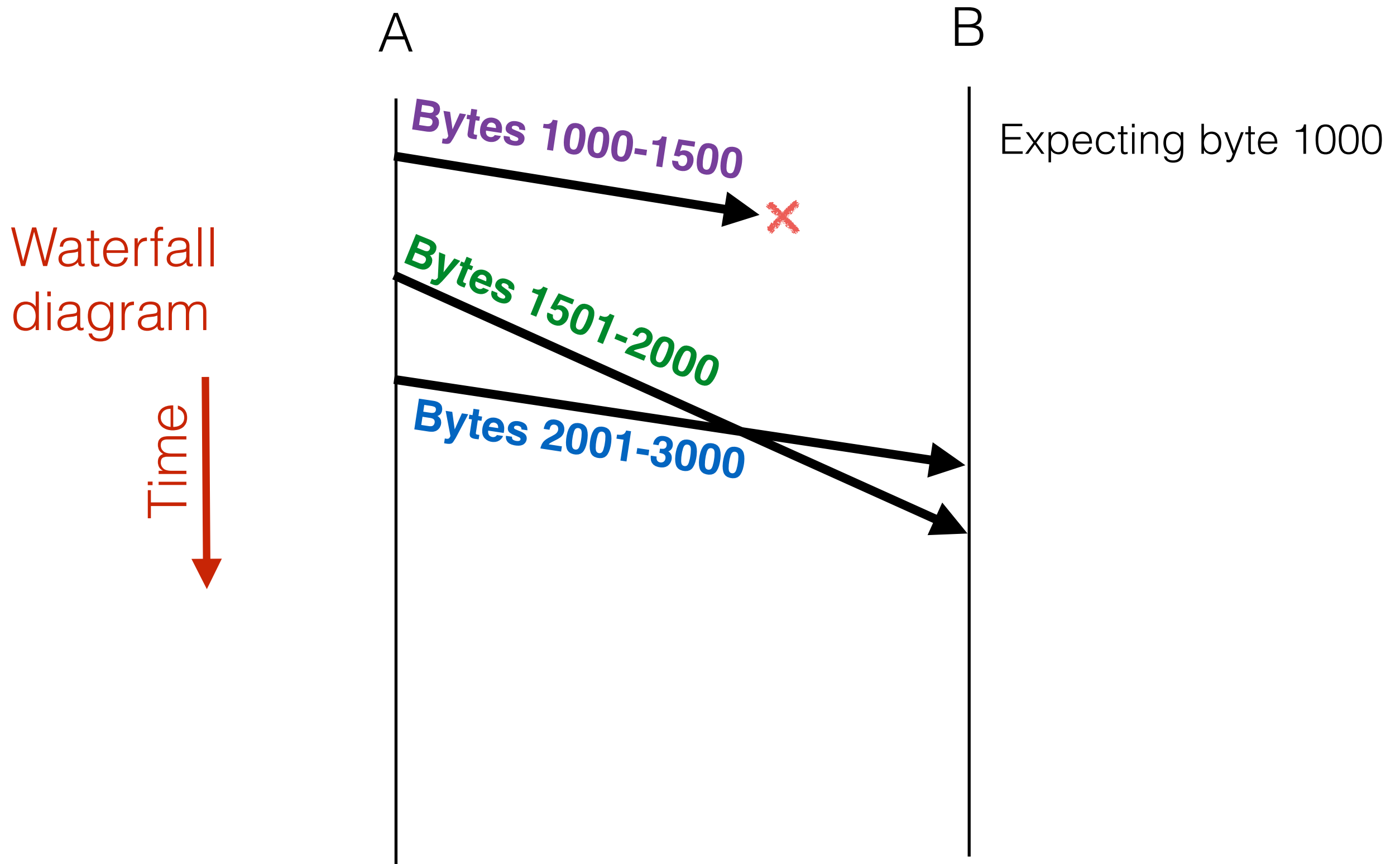
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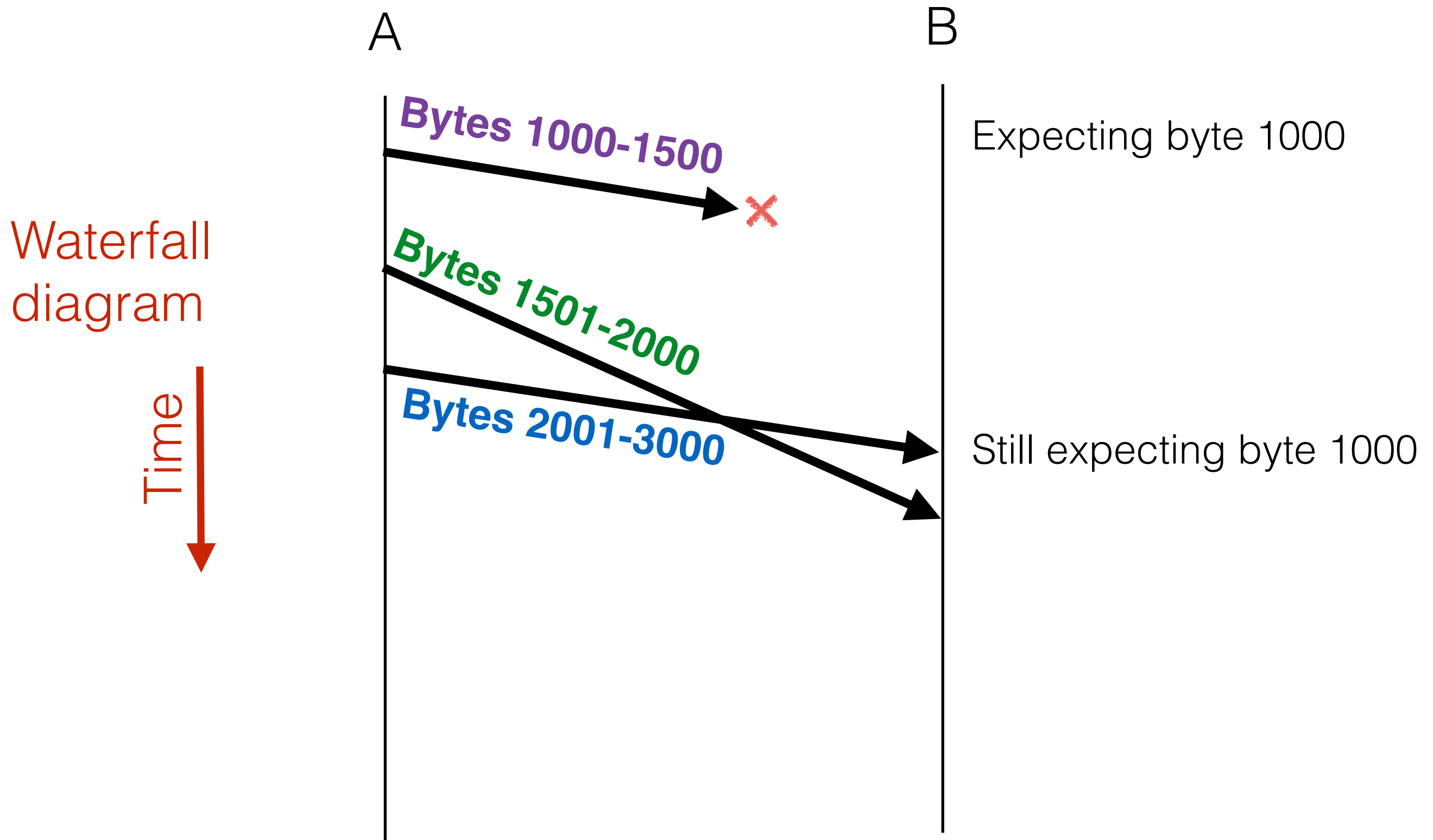
How does TCP achieve reliability?



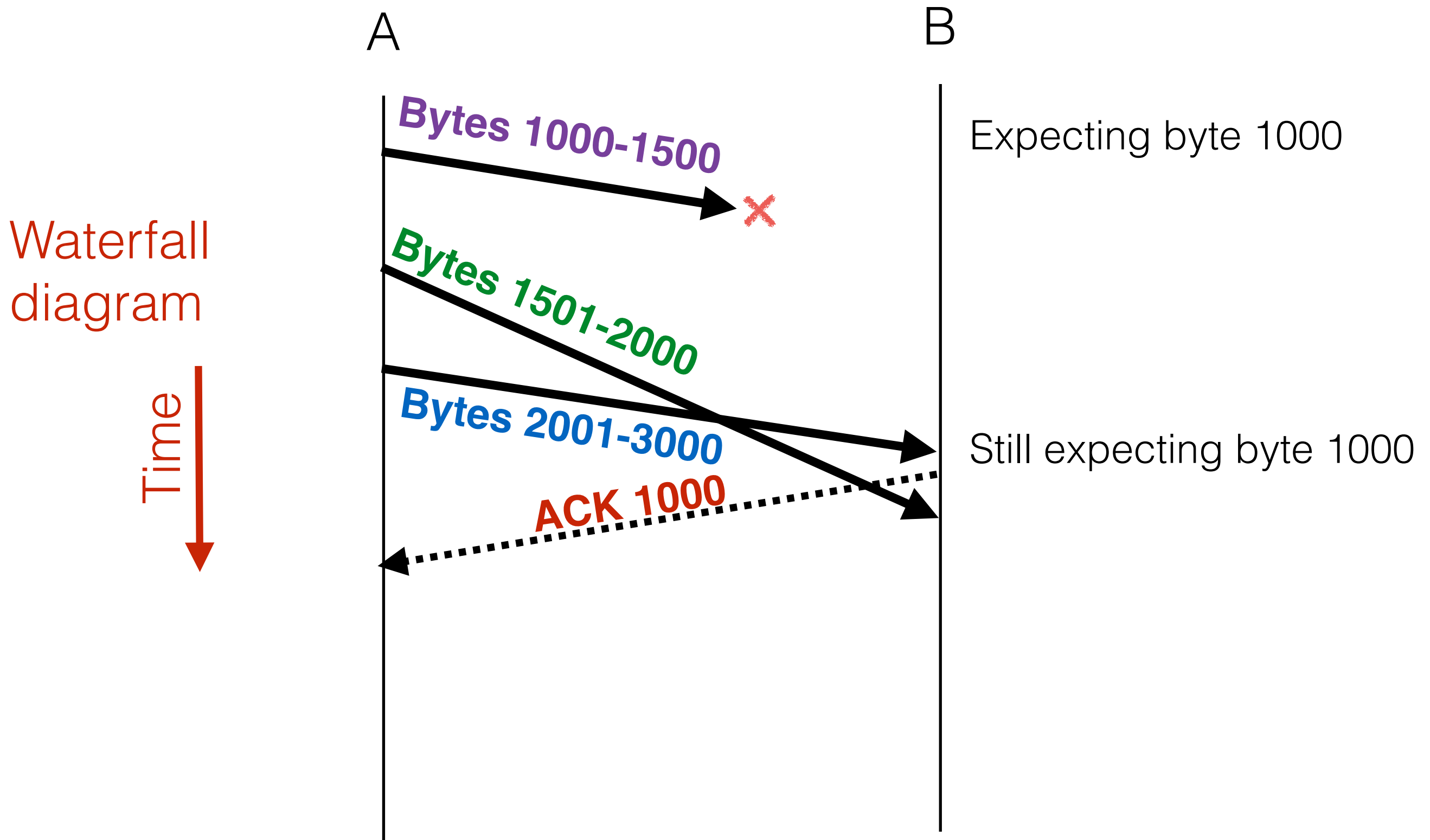
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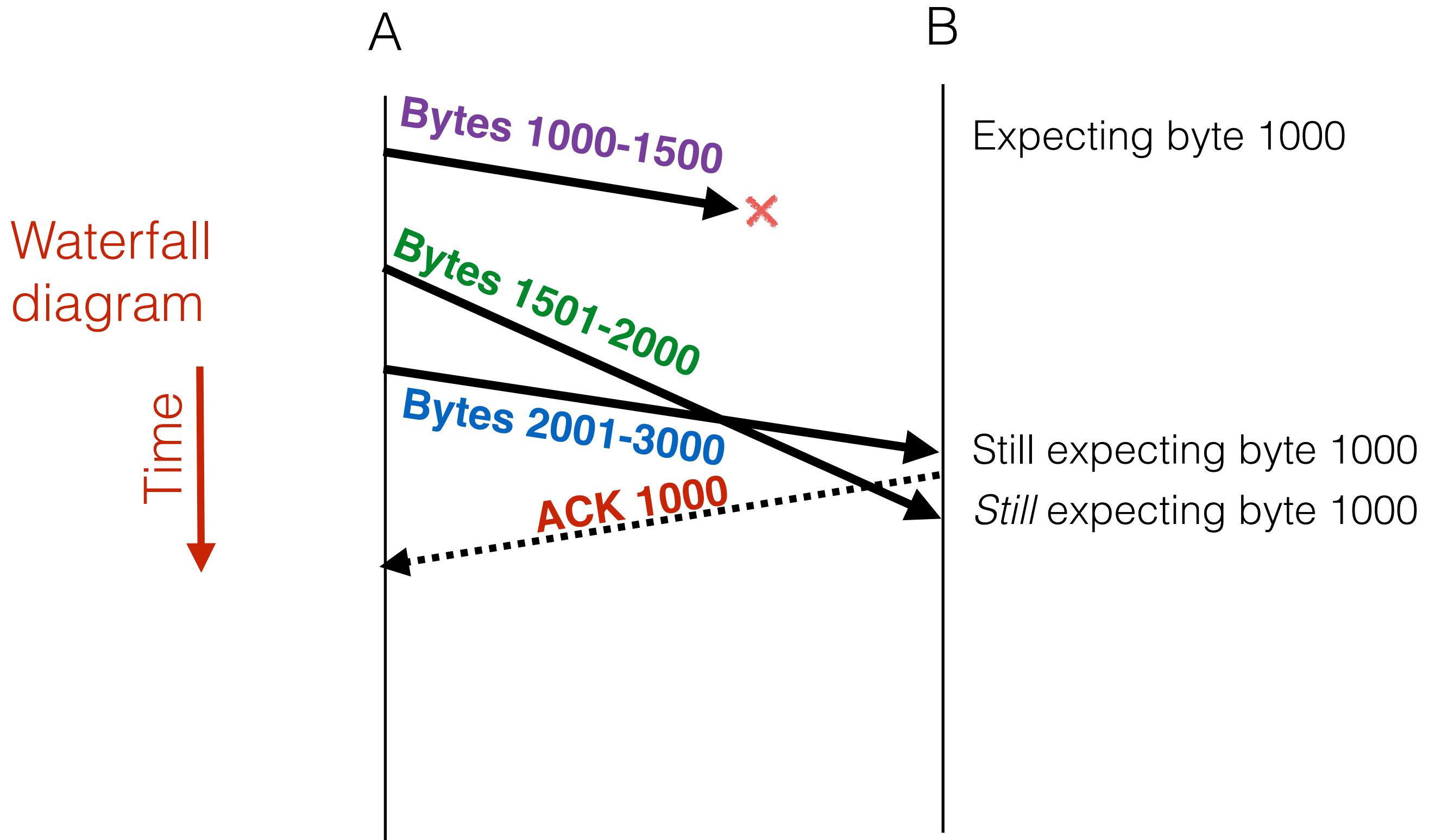
How does TCP achieve reliability?



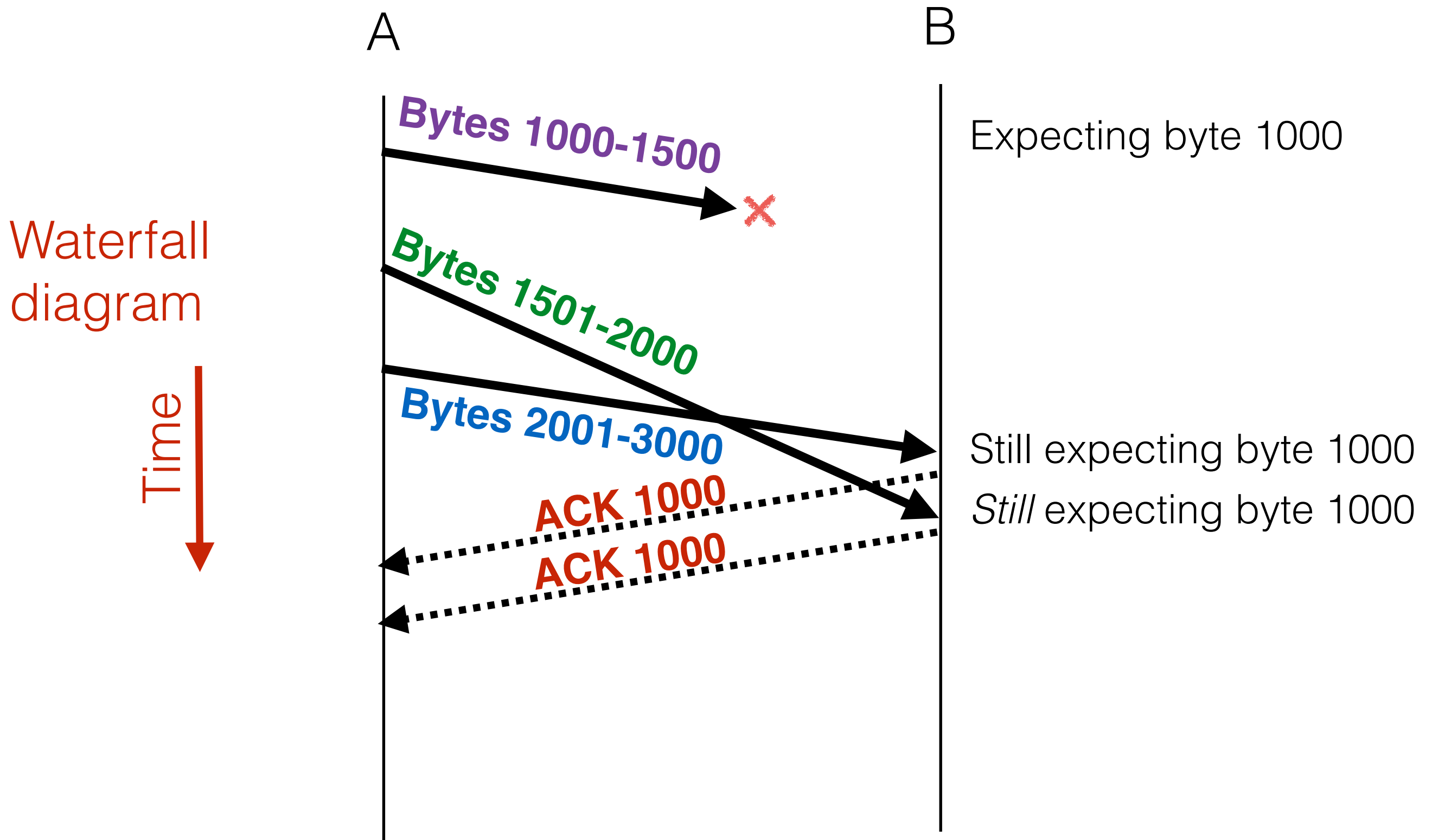
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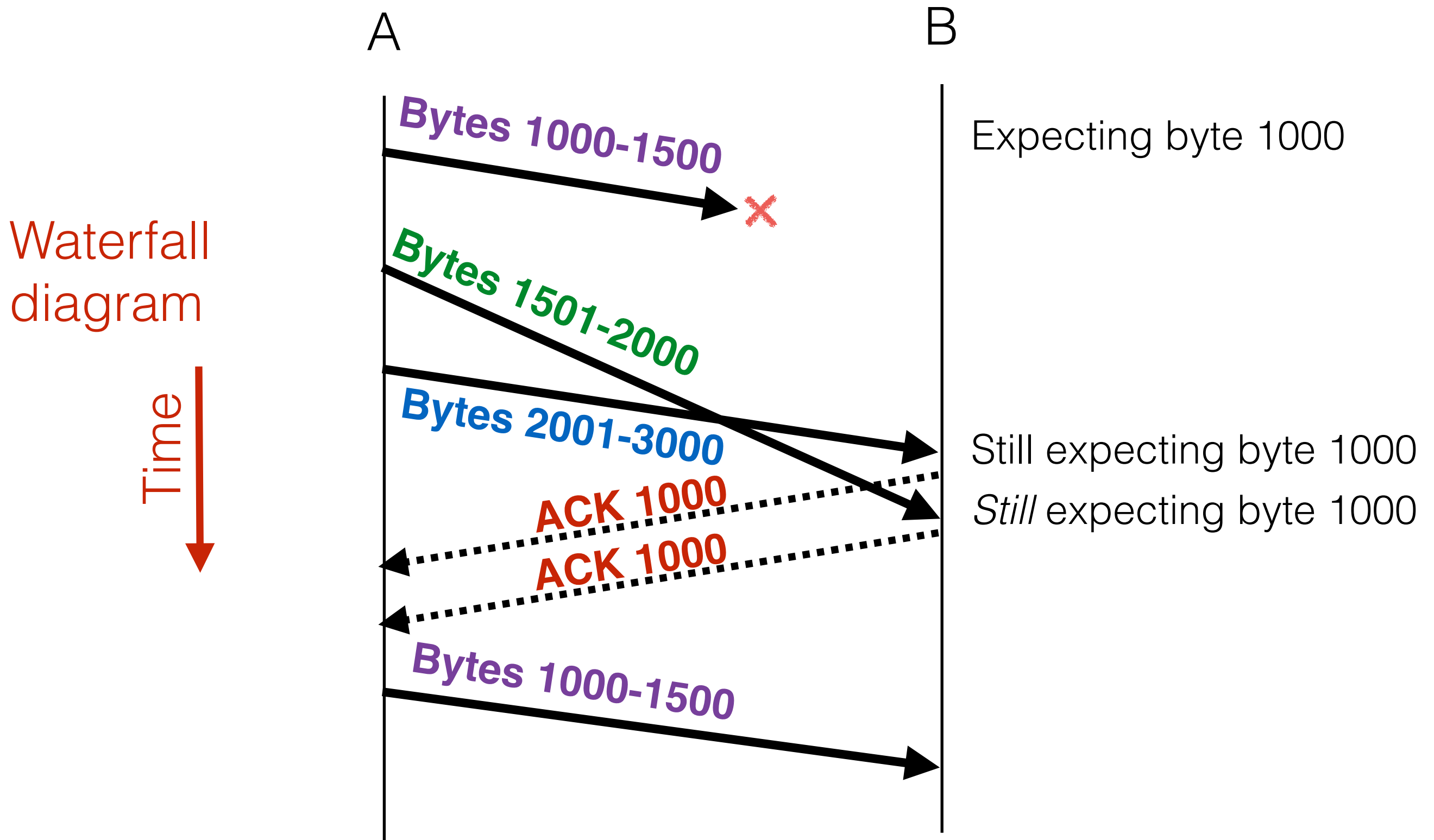
How does TCP achieve reliability?



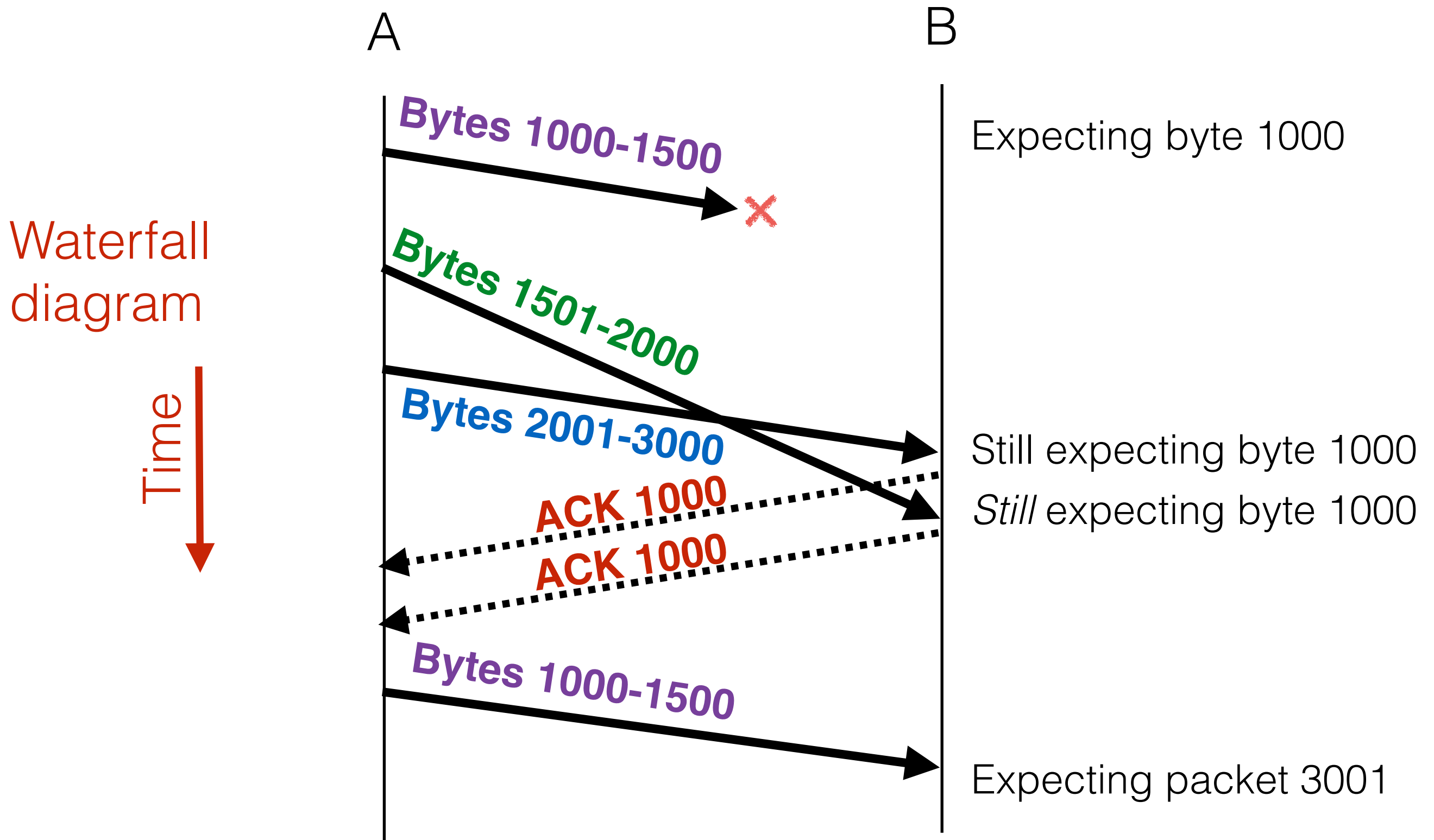
How does TCP achieve reliability?



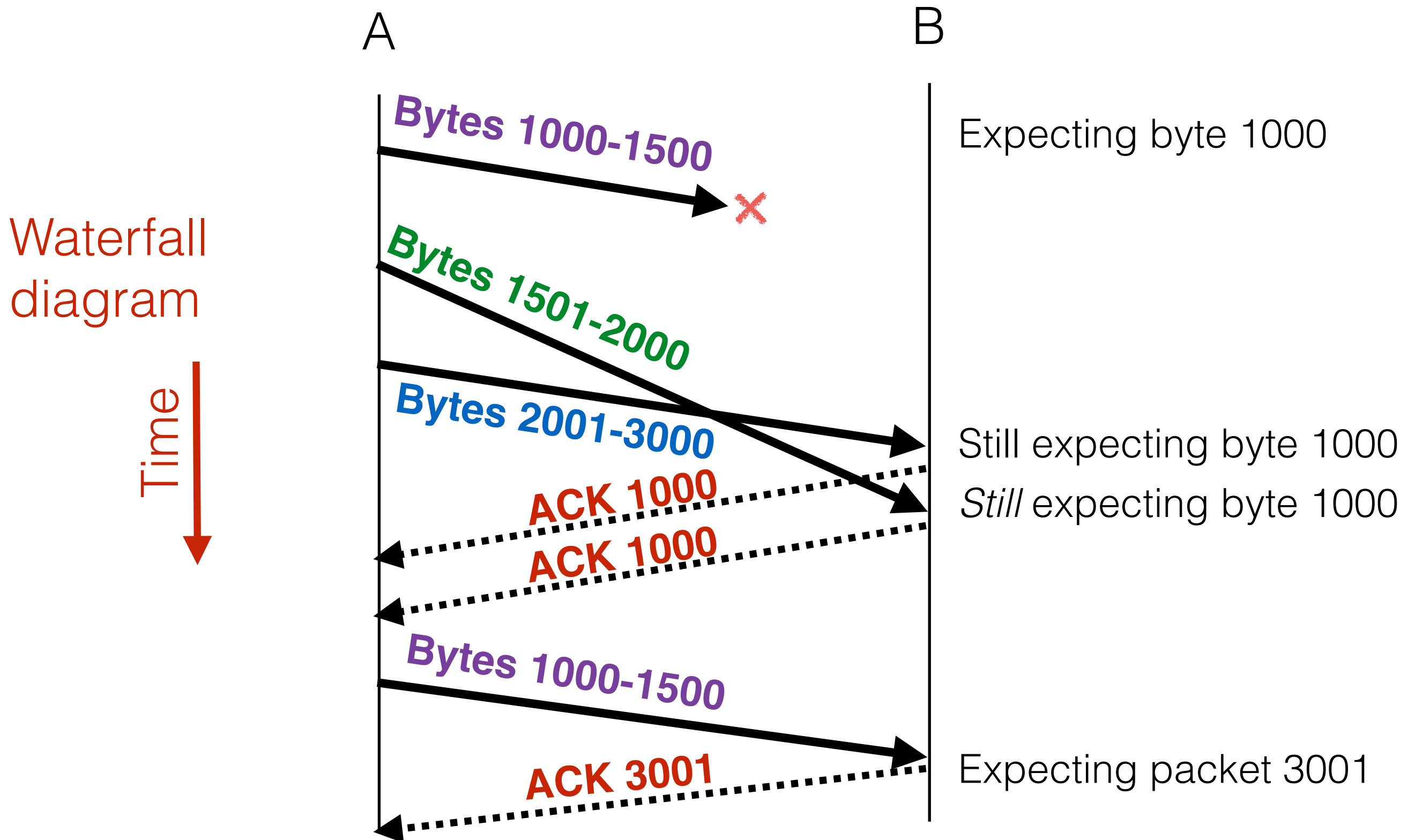
How does TCP achieve reliability?



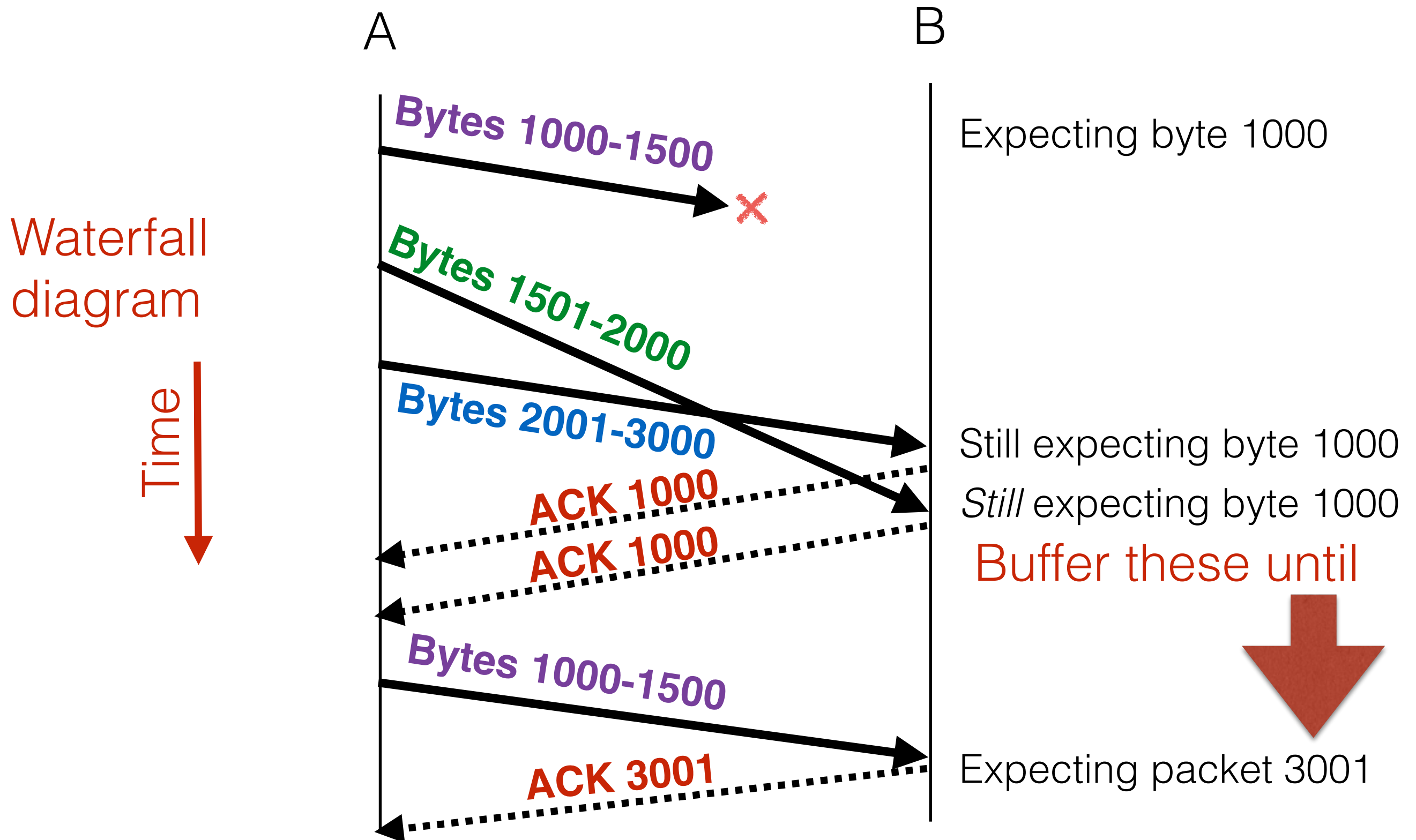
How does TCP achieve reliability?



How does TCP achieve reliability?



How does TCP achieve reliability?



TCP congestion control

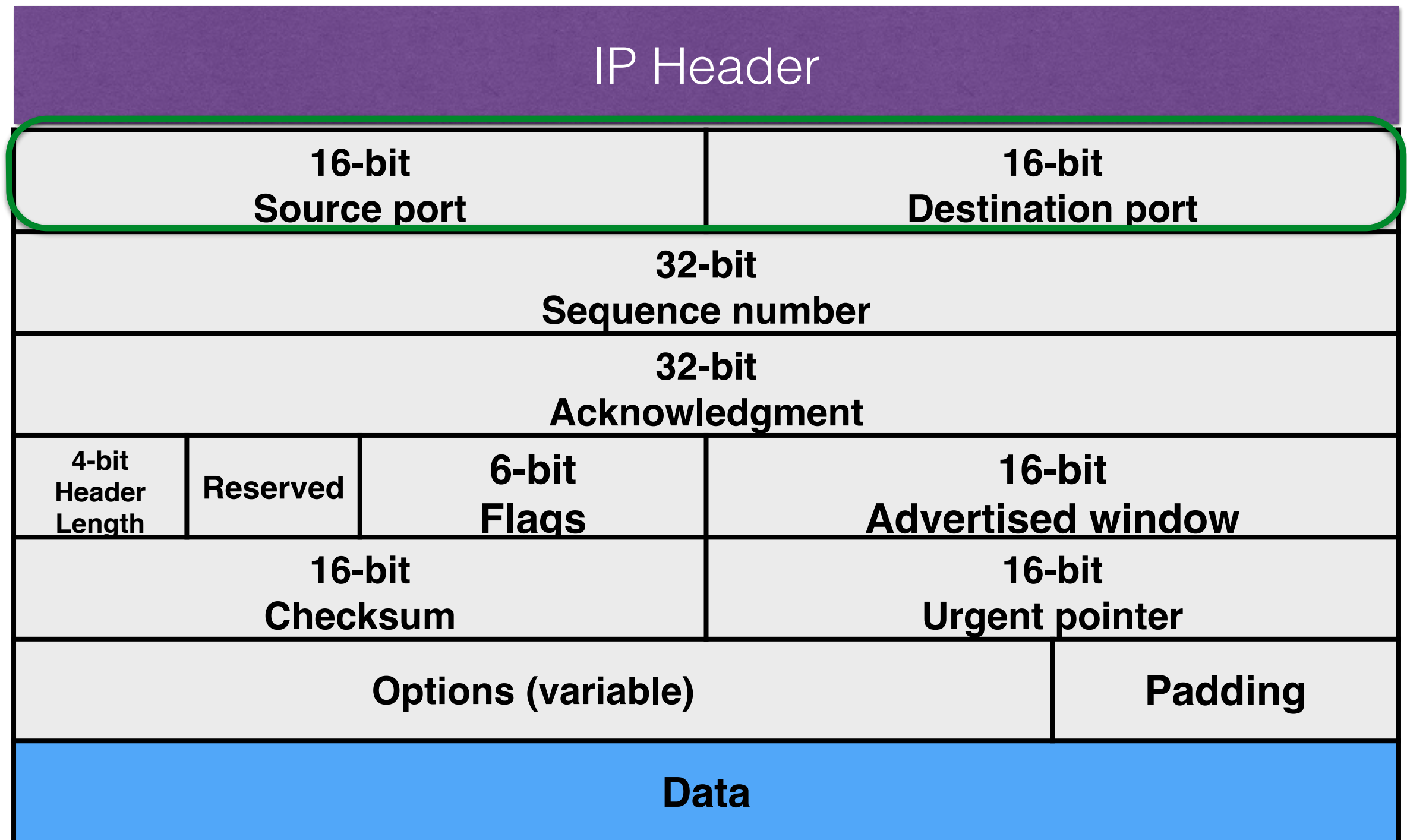
TCP's second job: don't break the network!

- Try to use as much of the network as is safe (does not adversely affect others' performance) and efficient (makes use of network capacity)
- Dynamically adapt how quickly you send based on the network path's capacity
- When an ACK doesn't come back, the network may be beyond capacity: slow down.

TCP header

16-bit Source port			16-bit Destination port		
32-bit Sequence number					
32-bit Acknowledgment					
4-bit Header Length	Reserved	6-bit Flags		16-bit Advertised window	
16-bit Checksum			16-bit Urgent pointer		
Options (variable)					Padding
Data					

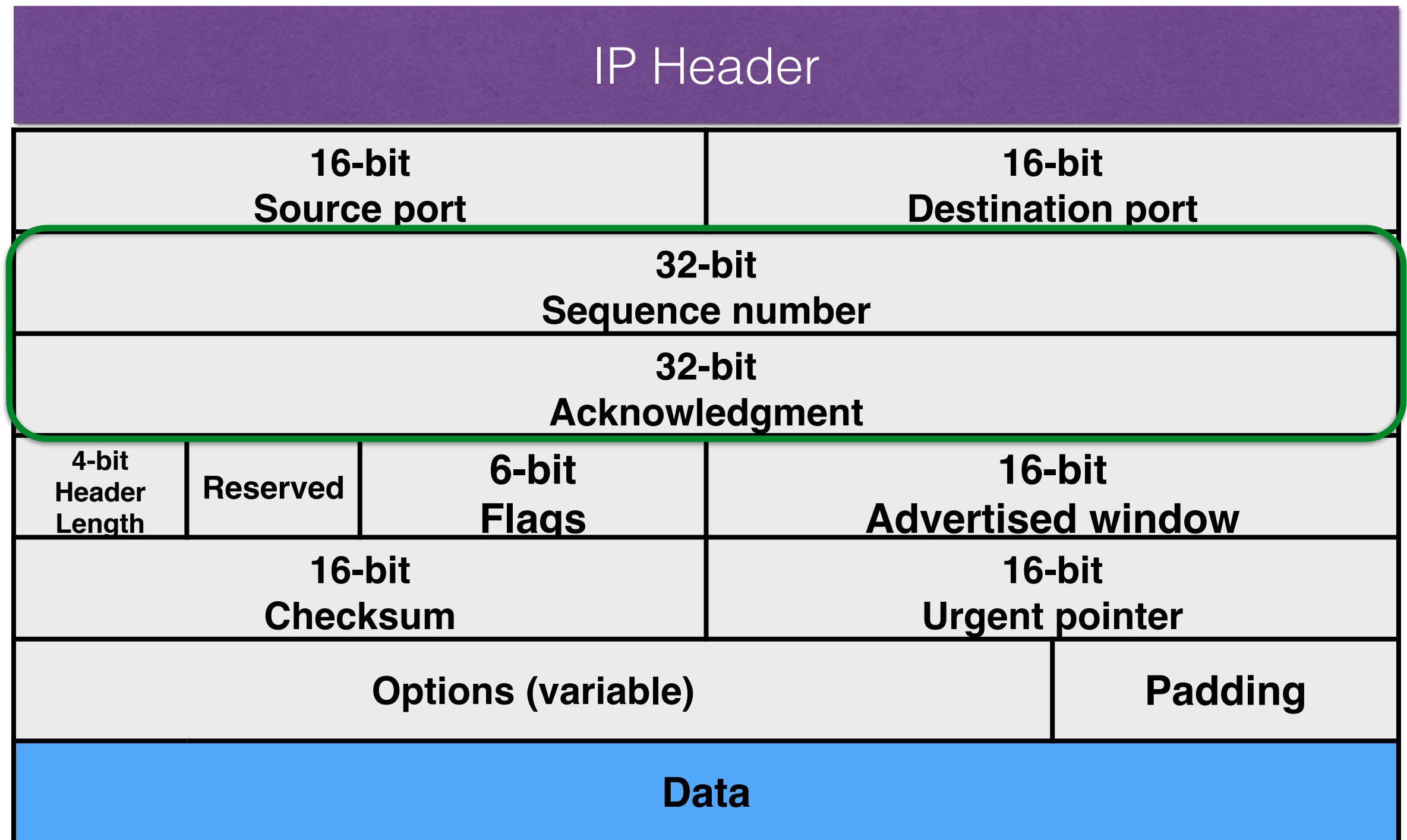
TCP header



TCP ports

- Ports are associated with **OS processes**
- Sandwiched between IP header and the application data
- {src IP/port, dst IP/port} : this 4-tuple uniquely identifies a TCP connection
- Some port numbers are well-known
 - 80 = HTTP
 - 53 = DNS

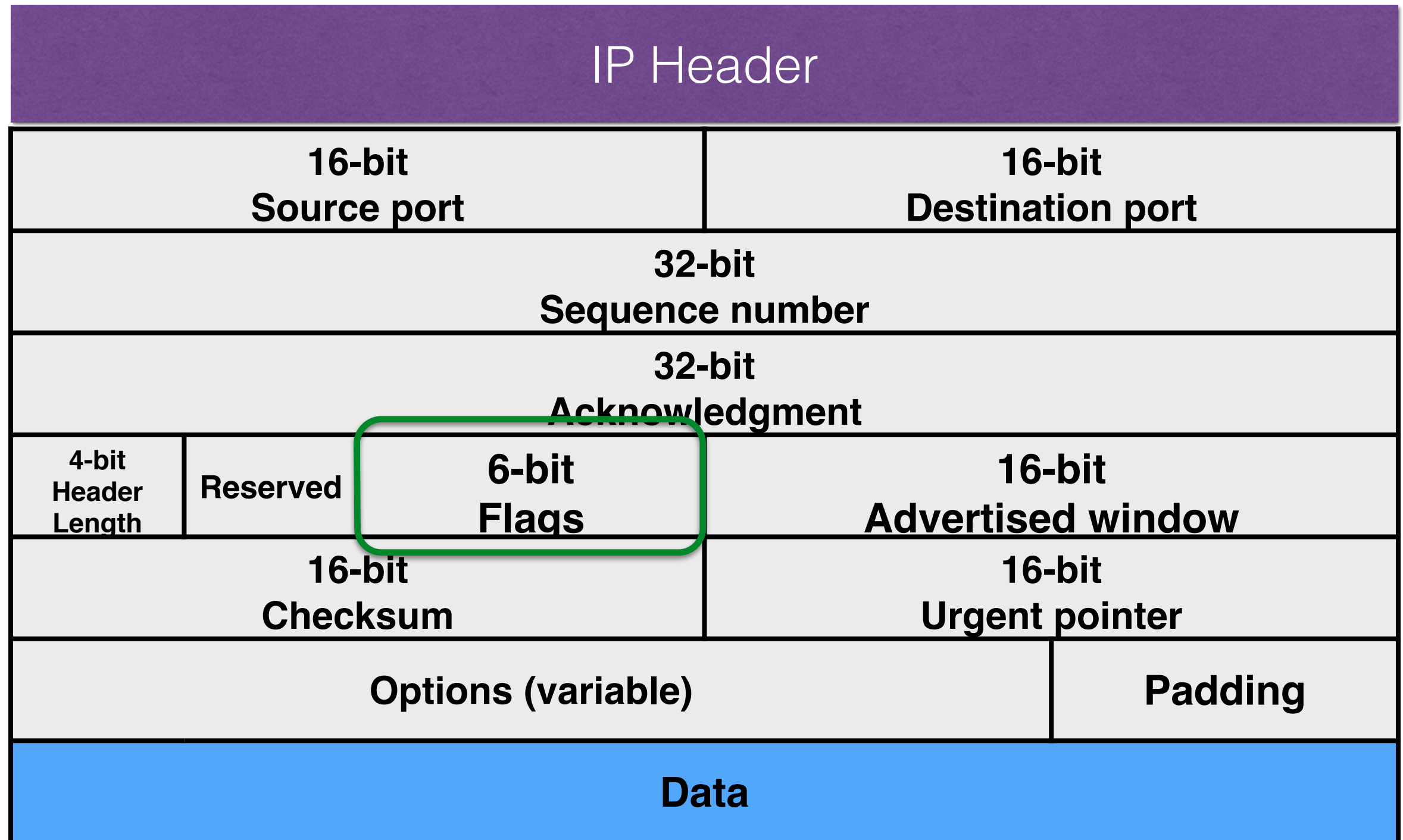
TCP header



TCP seqno

- Each byte in the byte stream has a unique “sequence number”
 - Unique for both directions
- “Sequence number” in the header = sequence number of the **first** byte in the packet’s data
- Next sequence number = previous seqno + previous packet’s data size
- “Acknowledgment” in the header = the **next** seqno you expect from the other end-host

TCP header



TCP flags

- SYN
 - Used for setting up a connection
- ACK
 - Acknowledgments, for data and “control” packets
- FIN
- RST

Setting up a connection

Three-way handshake

A

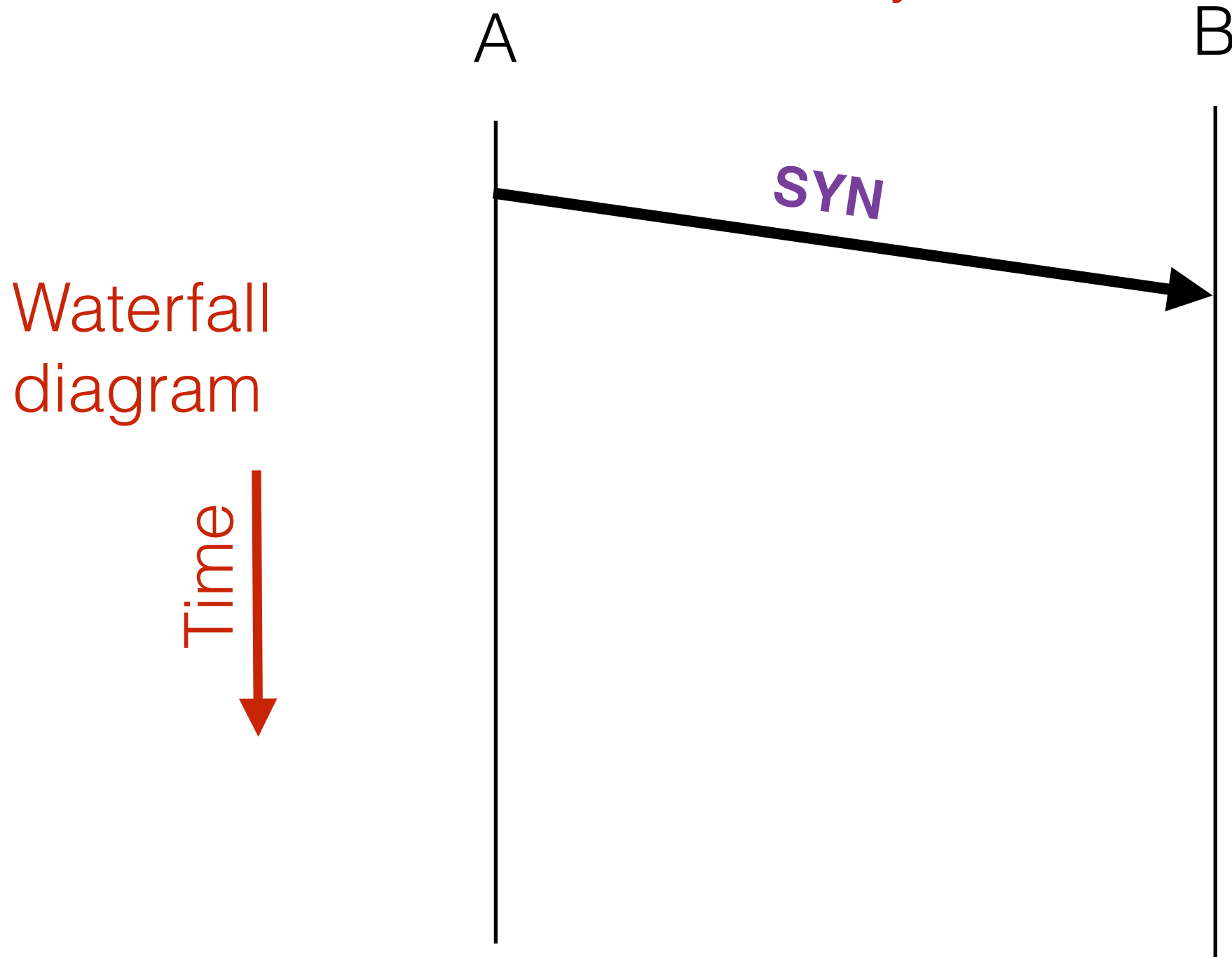
B

Waterfall
diagram



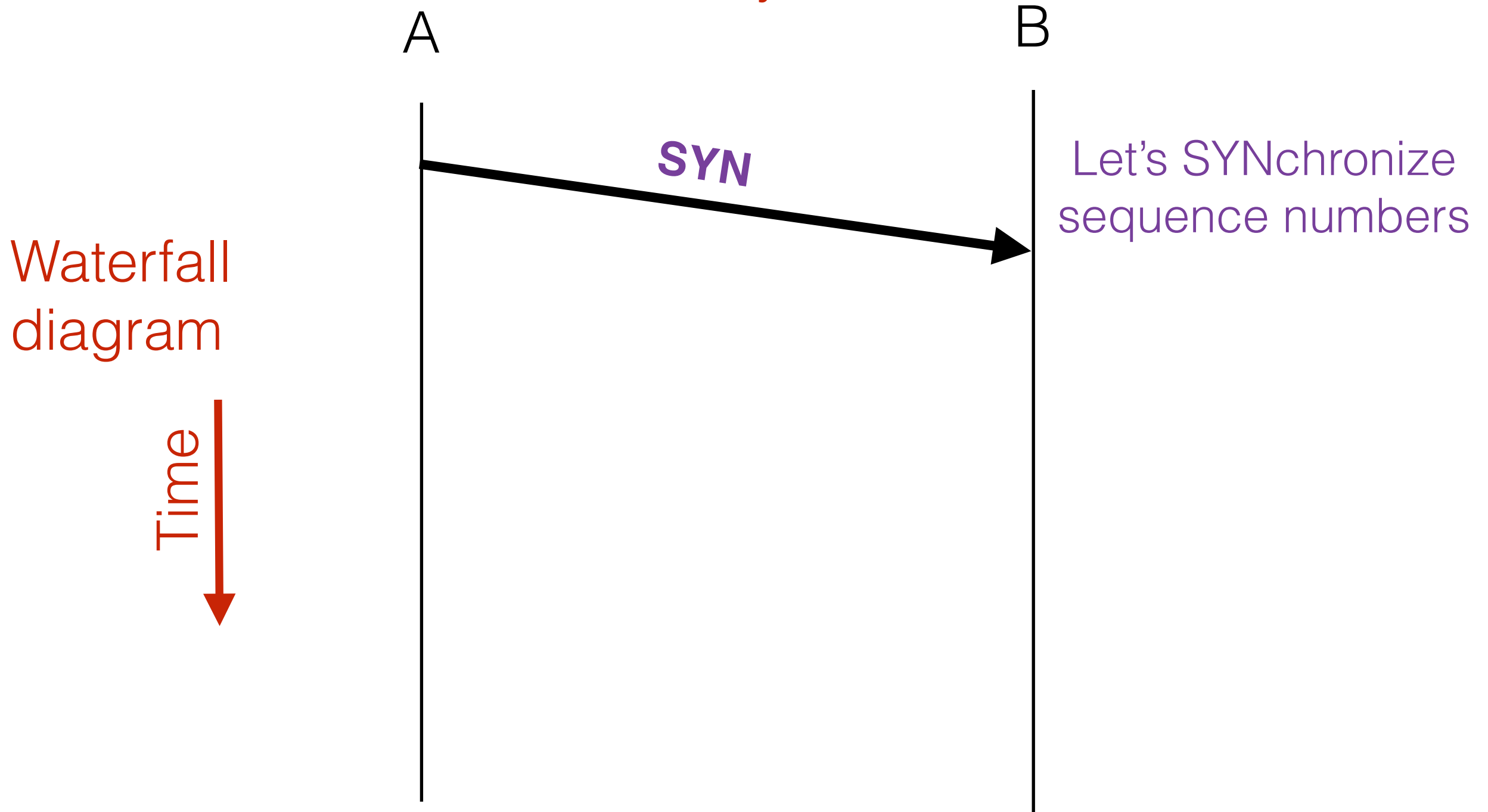
Setting up a connection

Three-way handshake



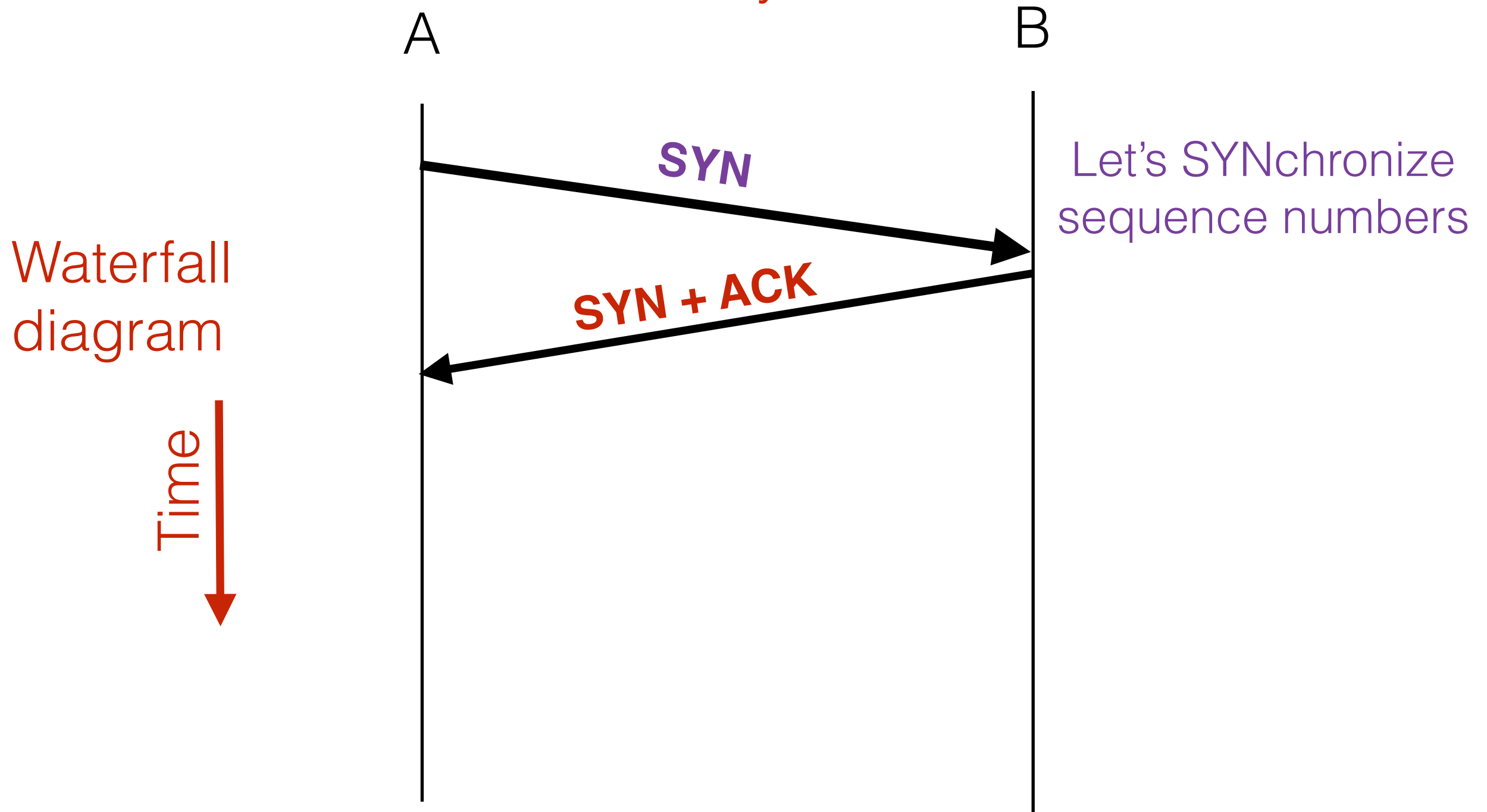
Setting up a connection

Three-way handshake



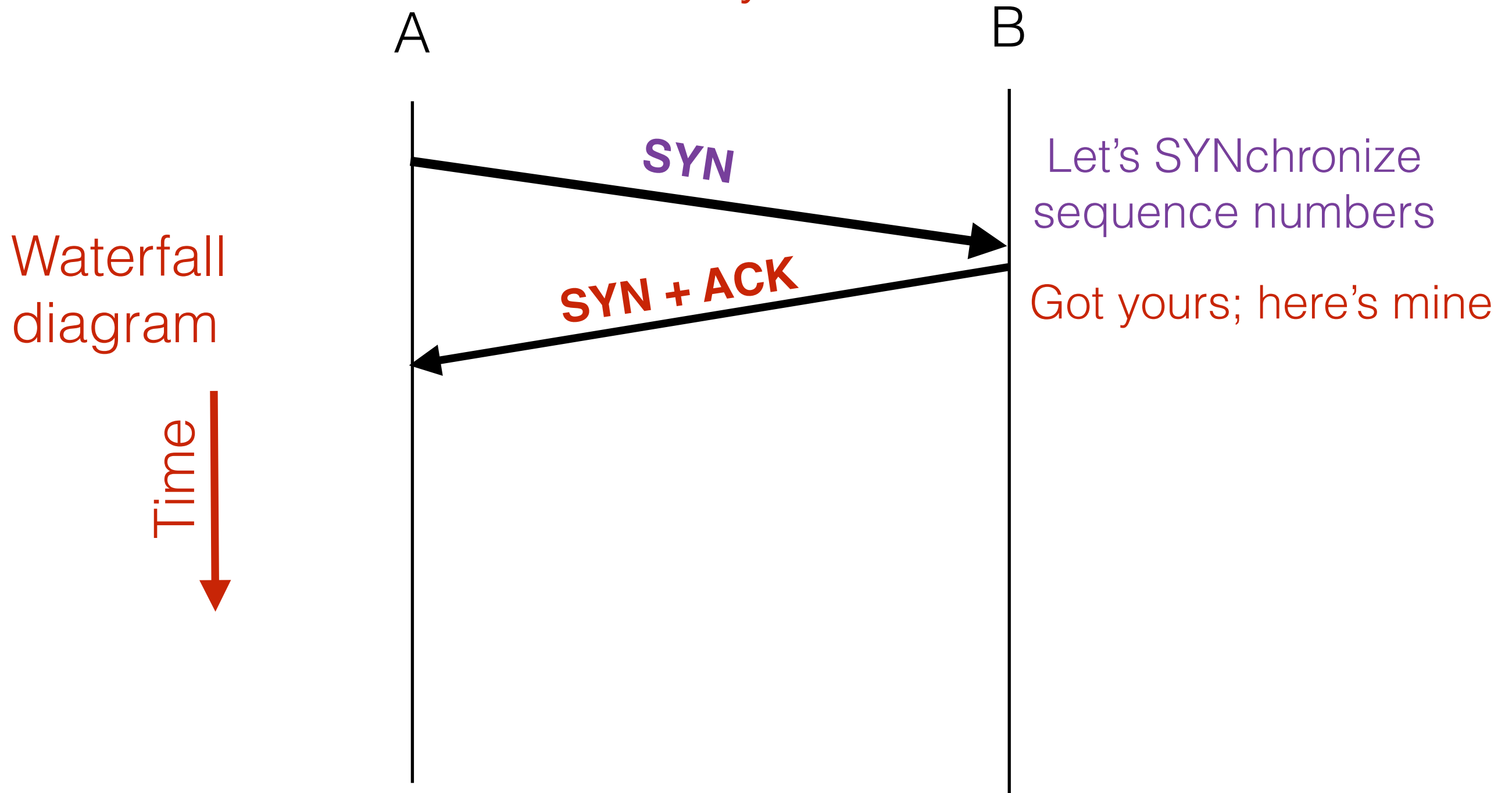
Setting up a connection

Three-way handshake



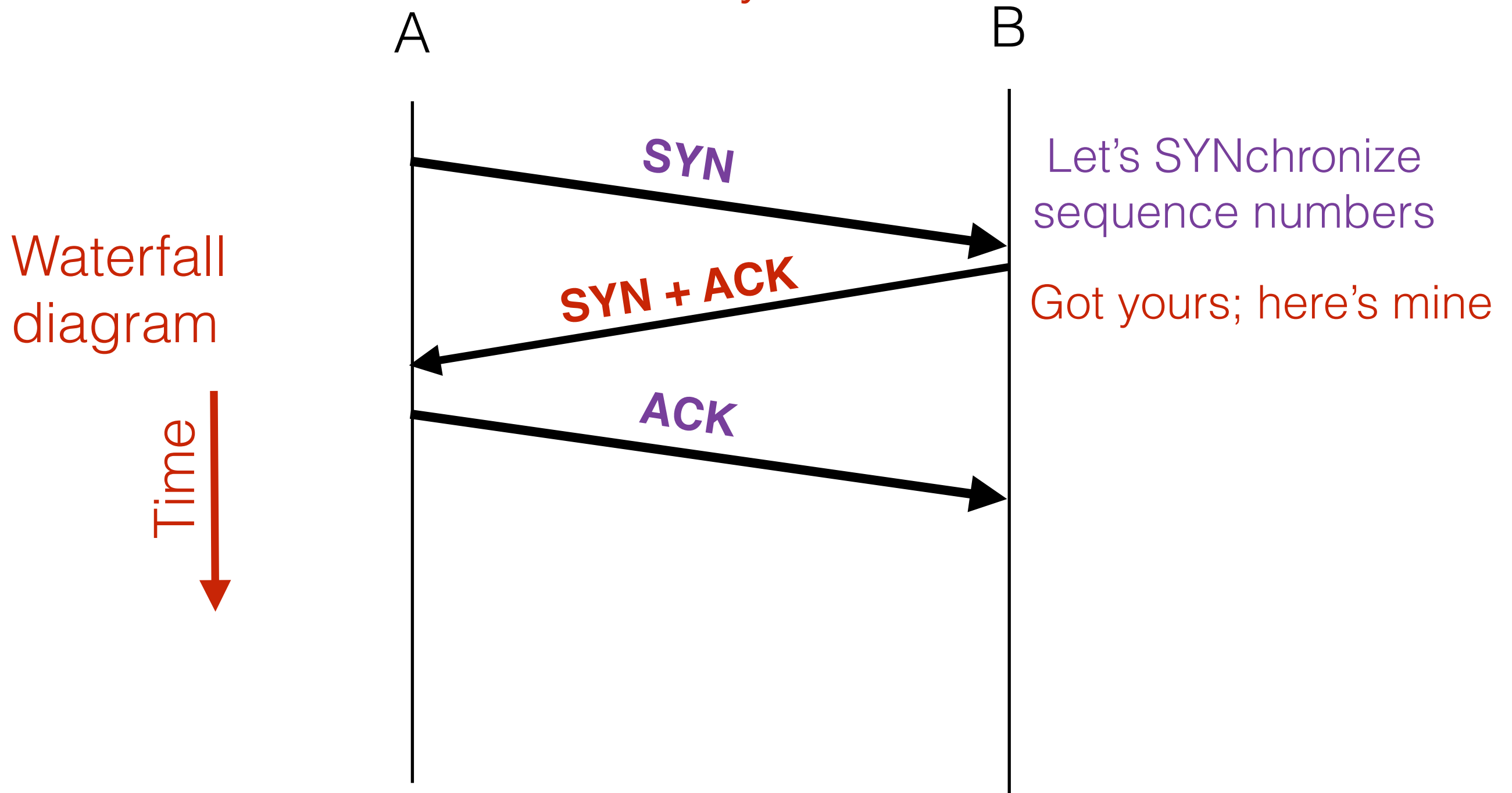
Setting up a connection

Three-way handshake



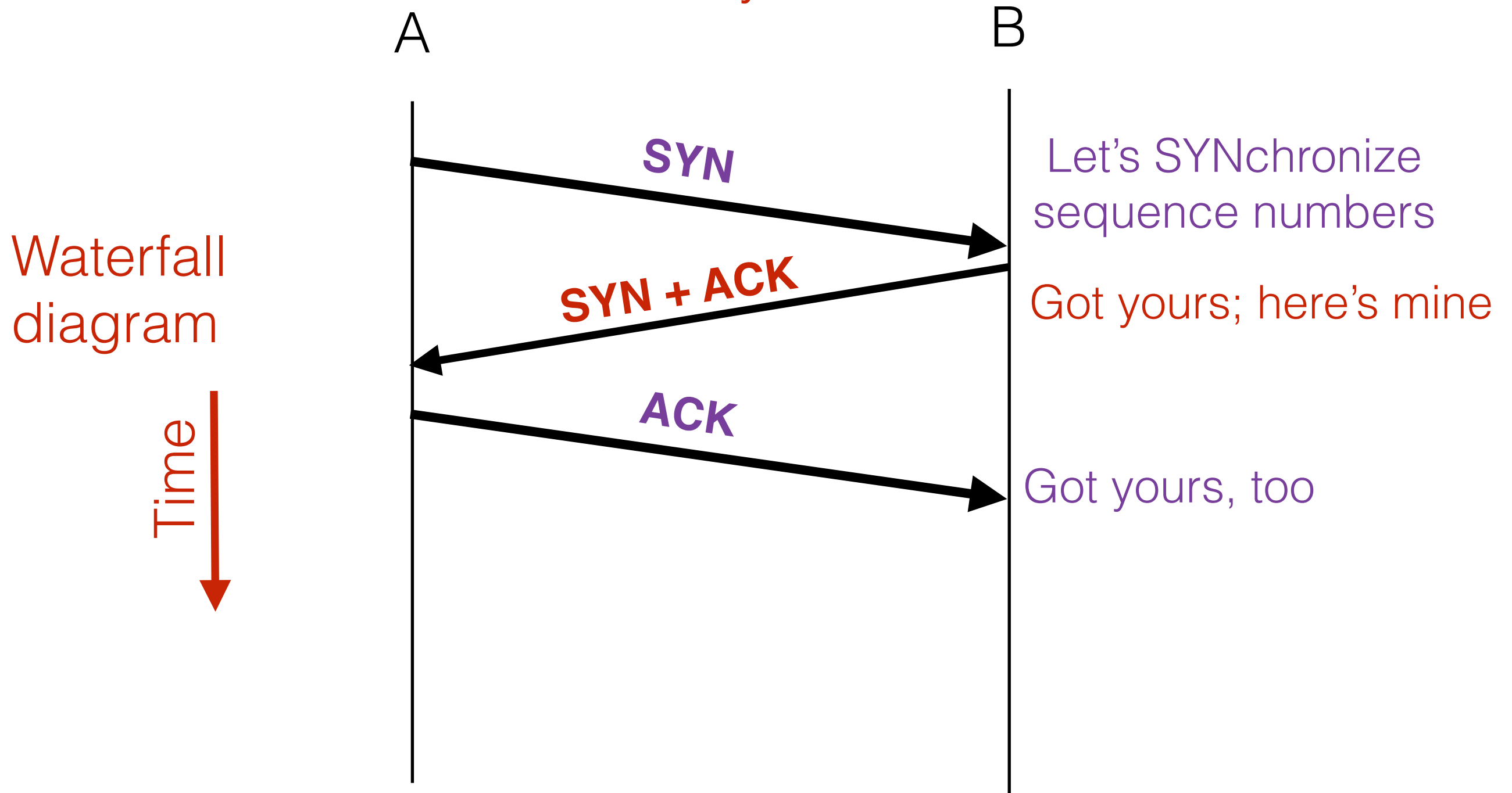
Setting up a connection

Three-way handshake



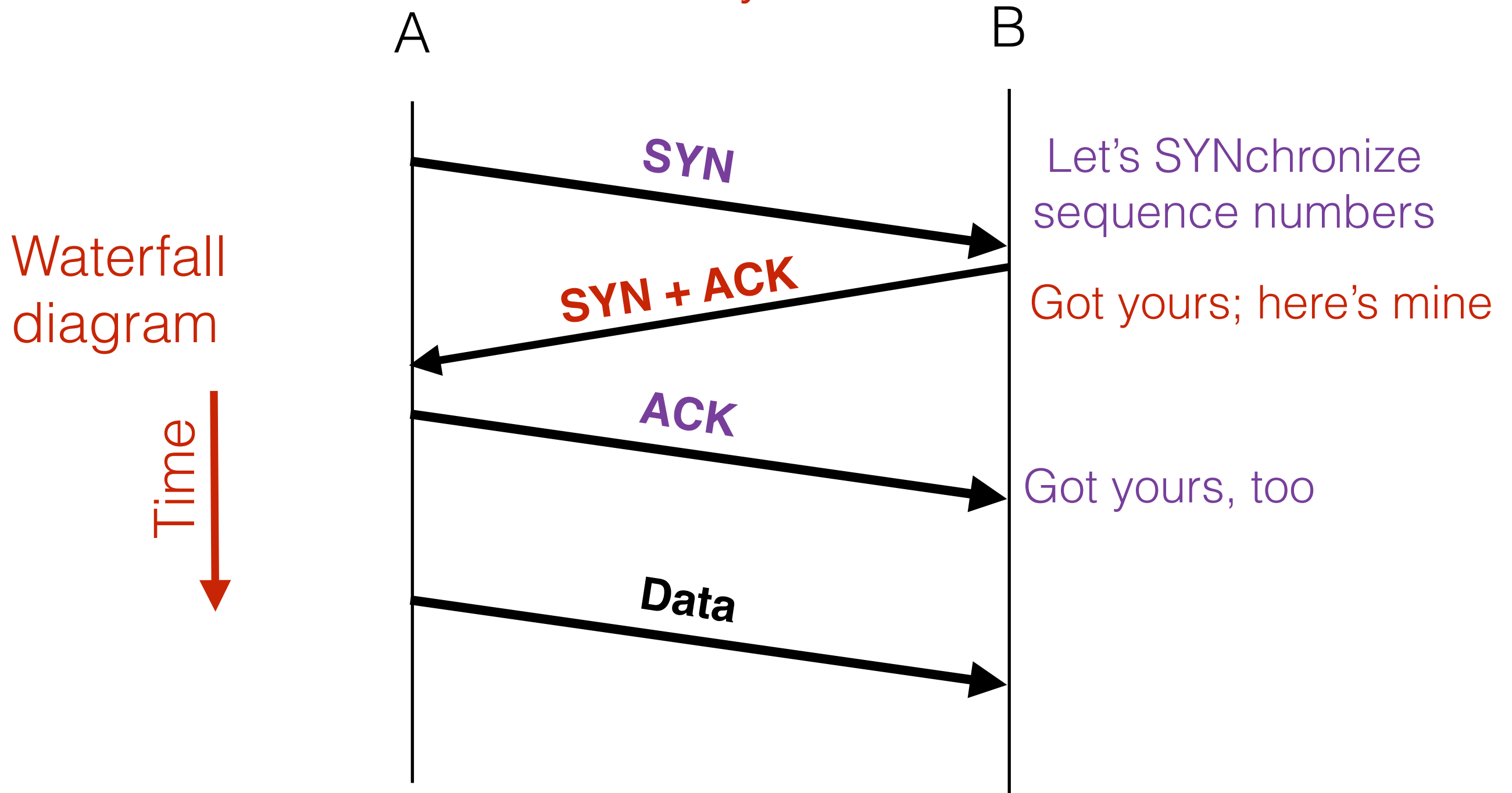
Setting up a connection

Three-way handshake



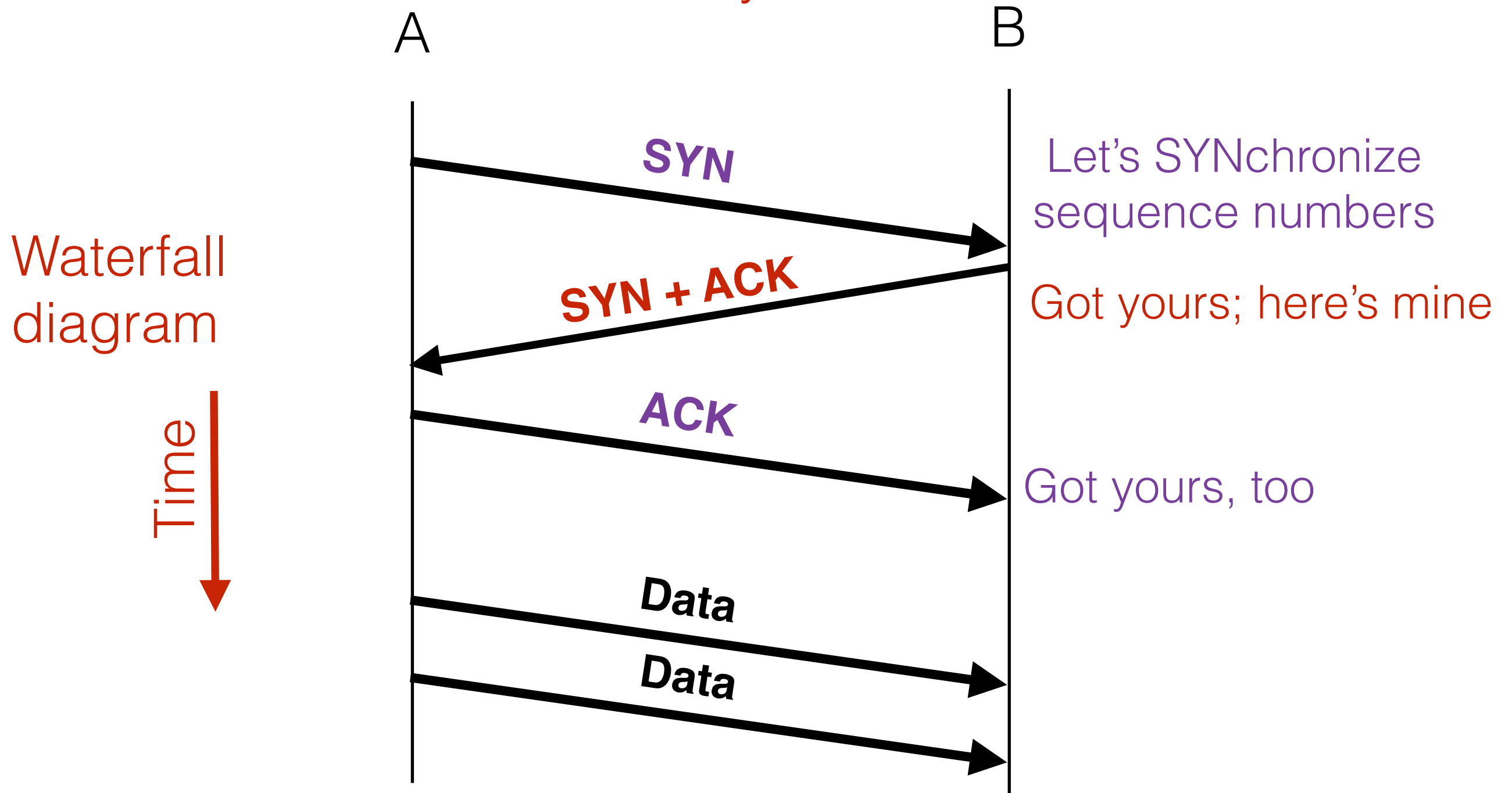
Setting up a connection

Three-way handshake



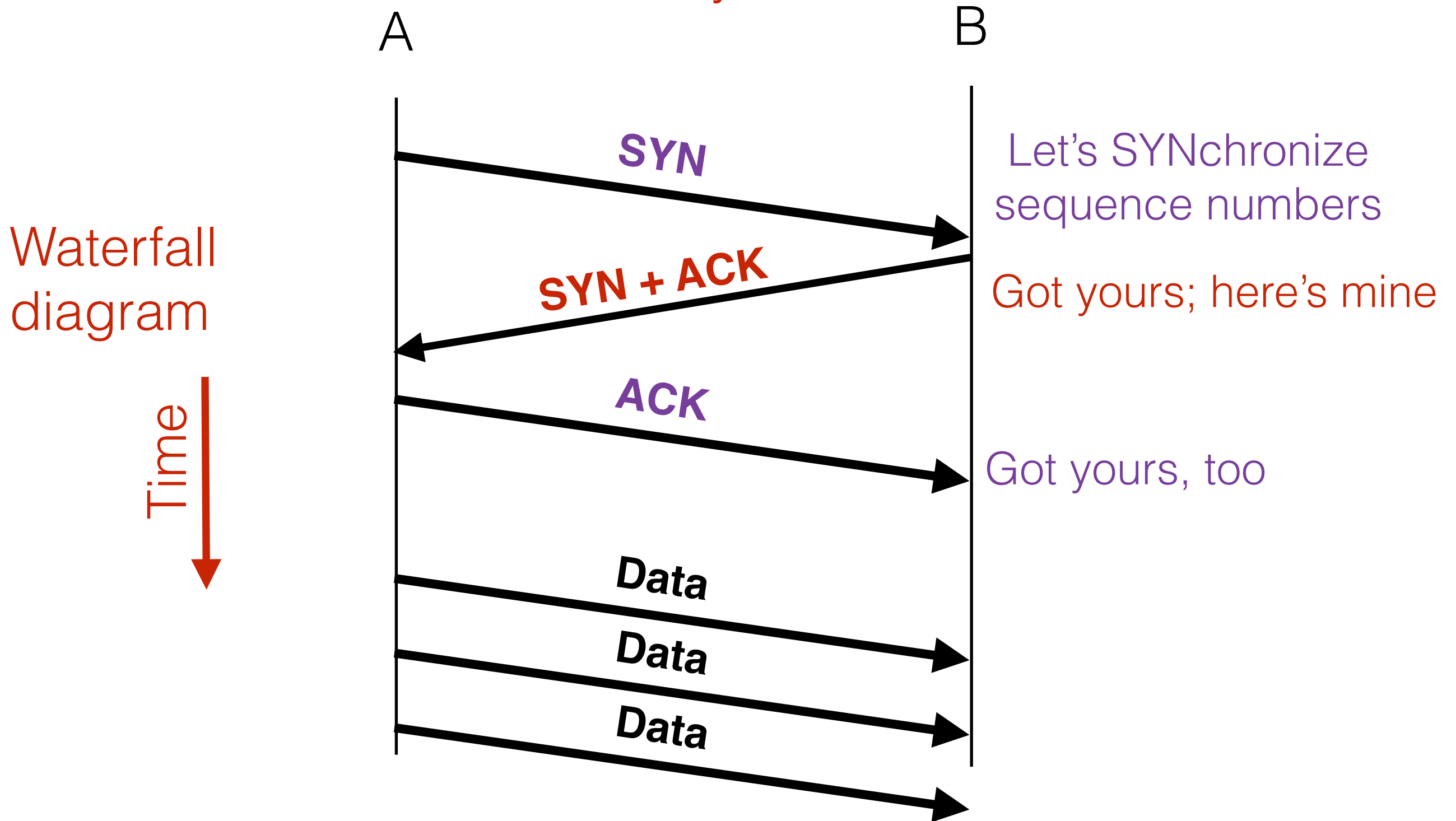
Setting up a connection

Three-way handshake



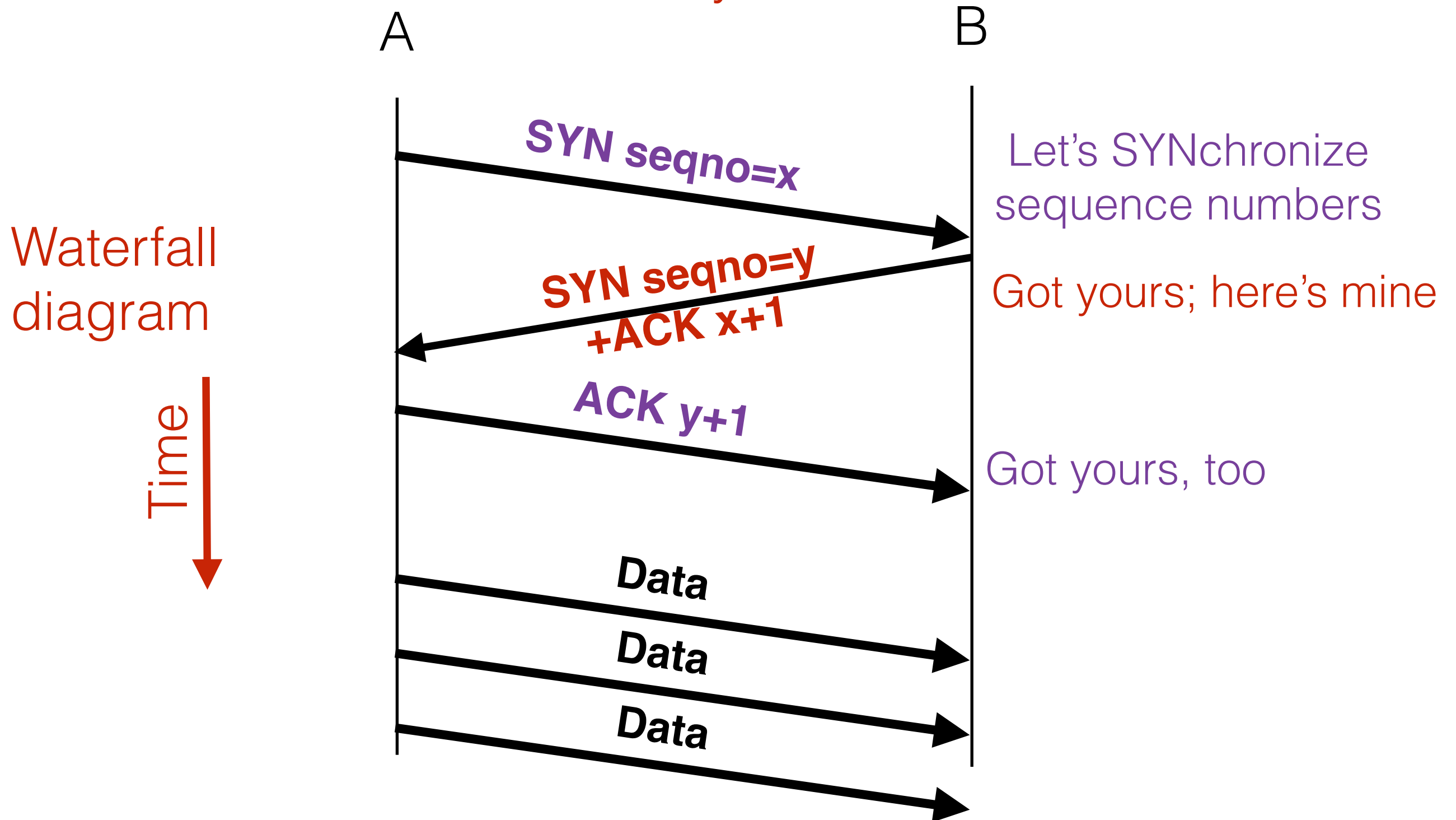
Setting up a connection

Three-way handshake



Setting up a connection

Three-way handshake



TCP flags

- SYN
- ACK
- FIN: Let's shut this down (two-way)
 - FIN
 - FIN+ACK
- RST: I'm shutting you down
 - Says "delete all your local state, because I don't know what you're talking about"

Attacks

- SYN flooding
- Injection attacks
- Opt-ack attack

SYN flooding

SYN flooding

Recall the three-way handshake:

A

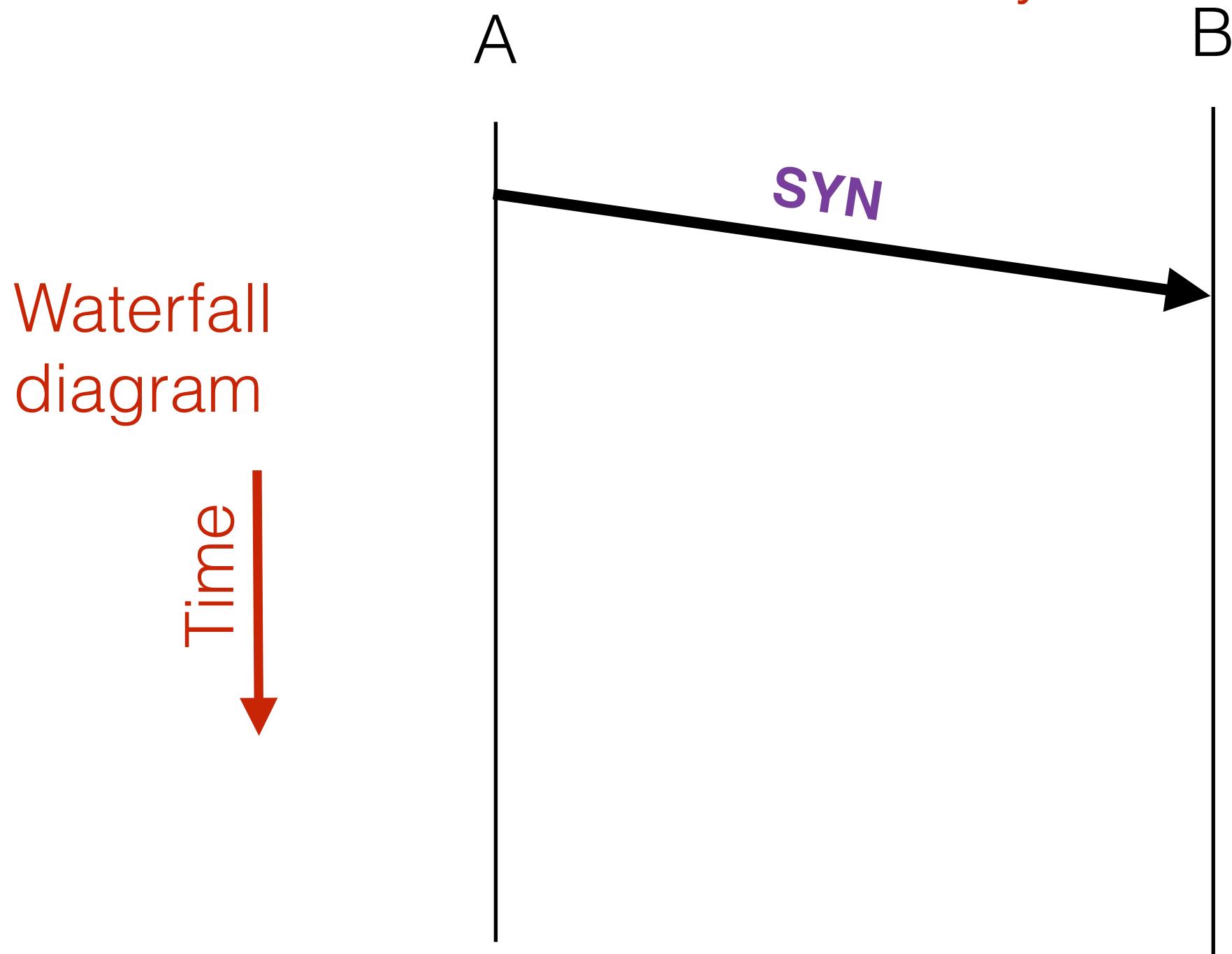
B

Waterfall
diagram



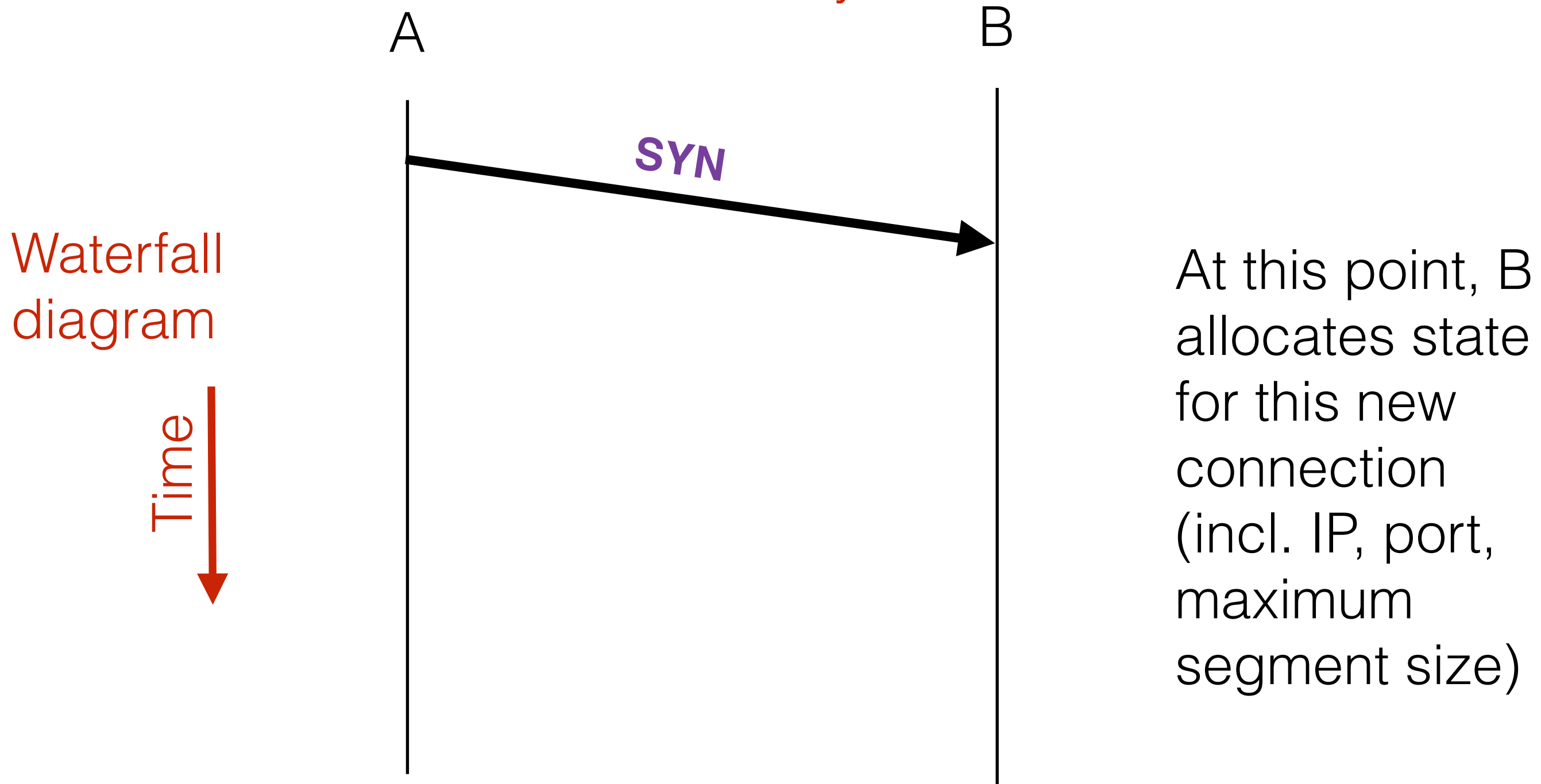
SYN flooding

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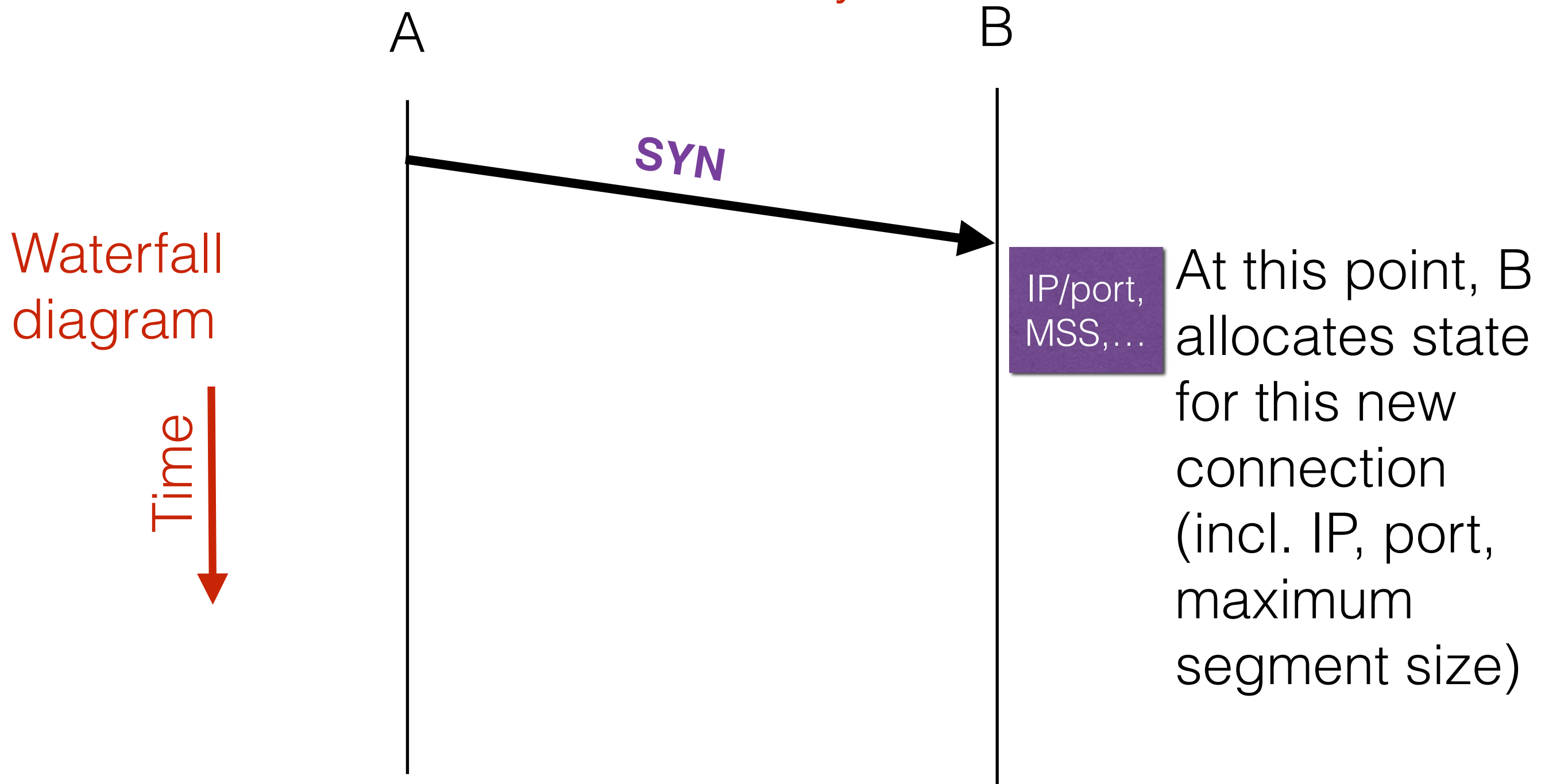
SYN flooding

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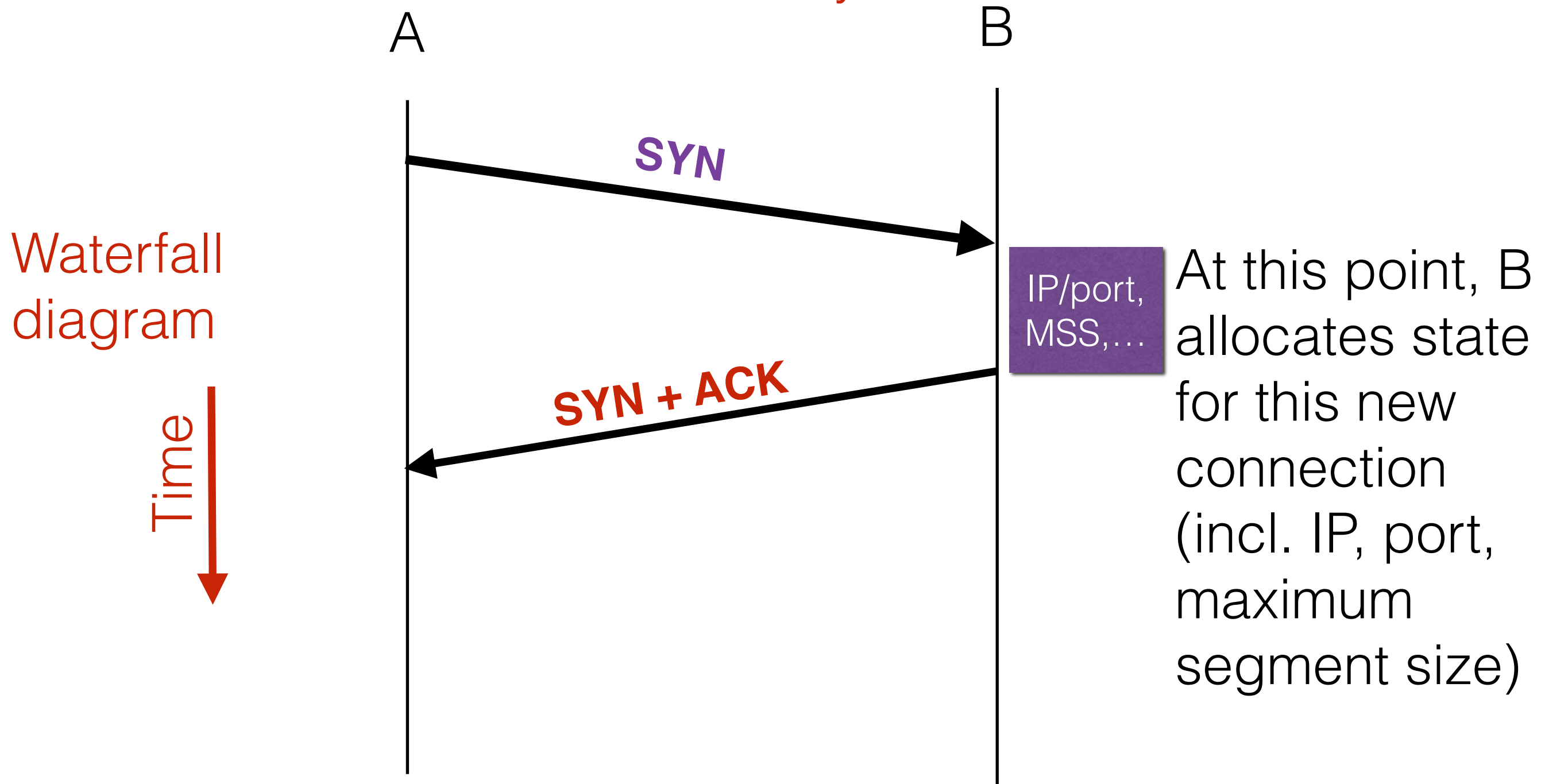
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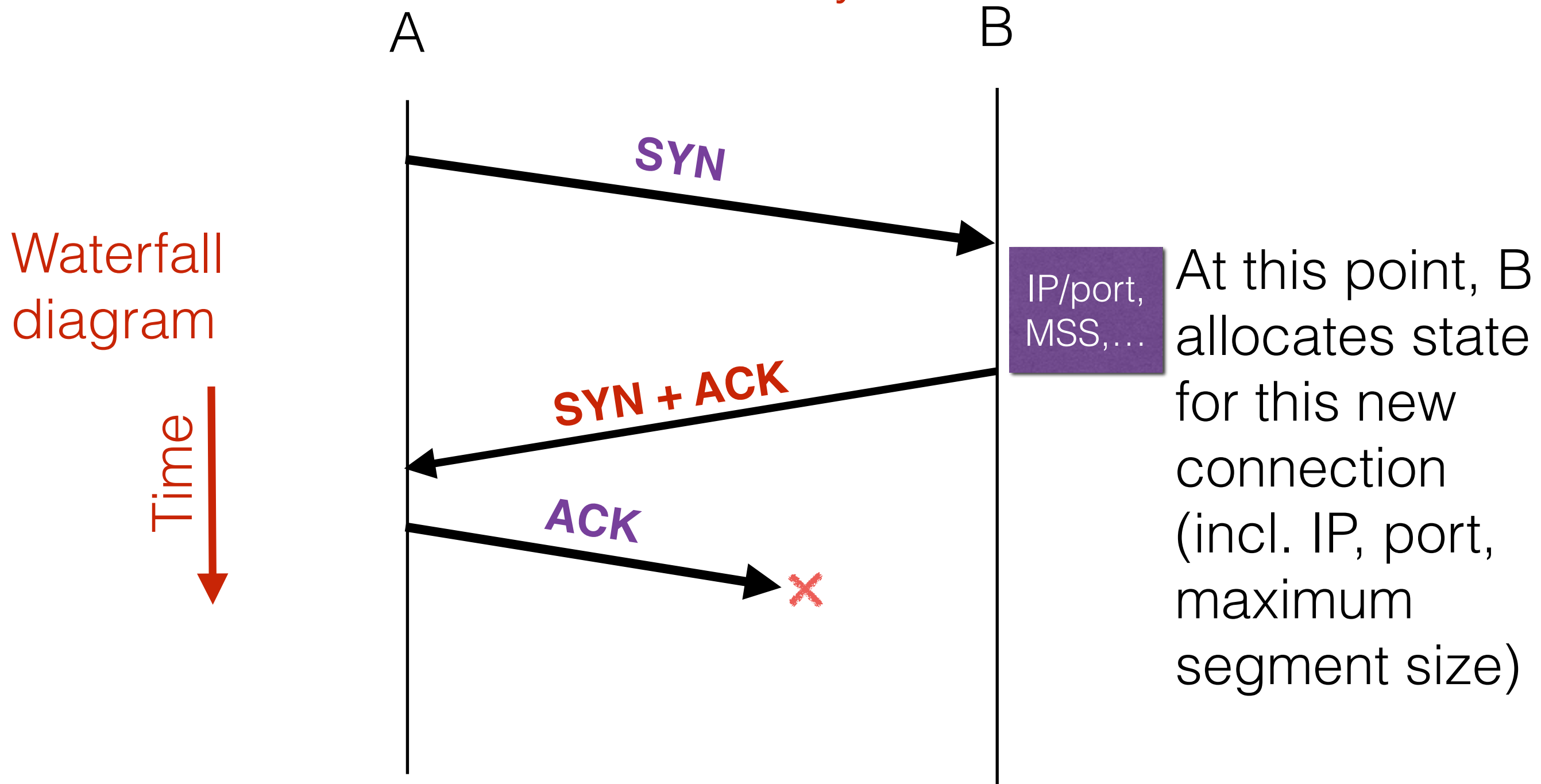
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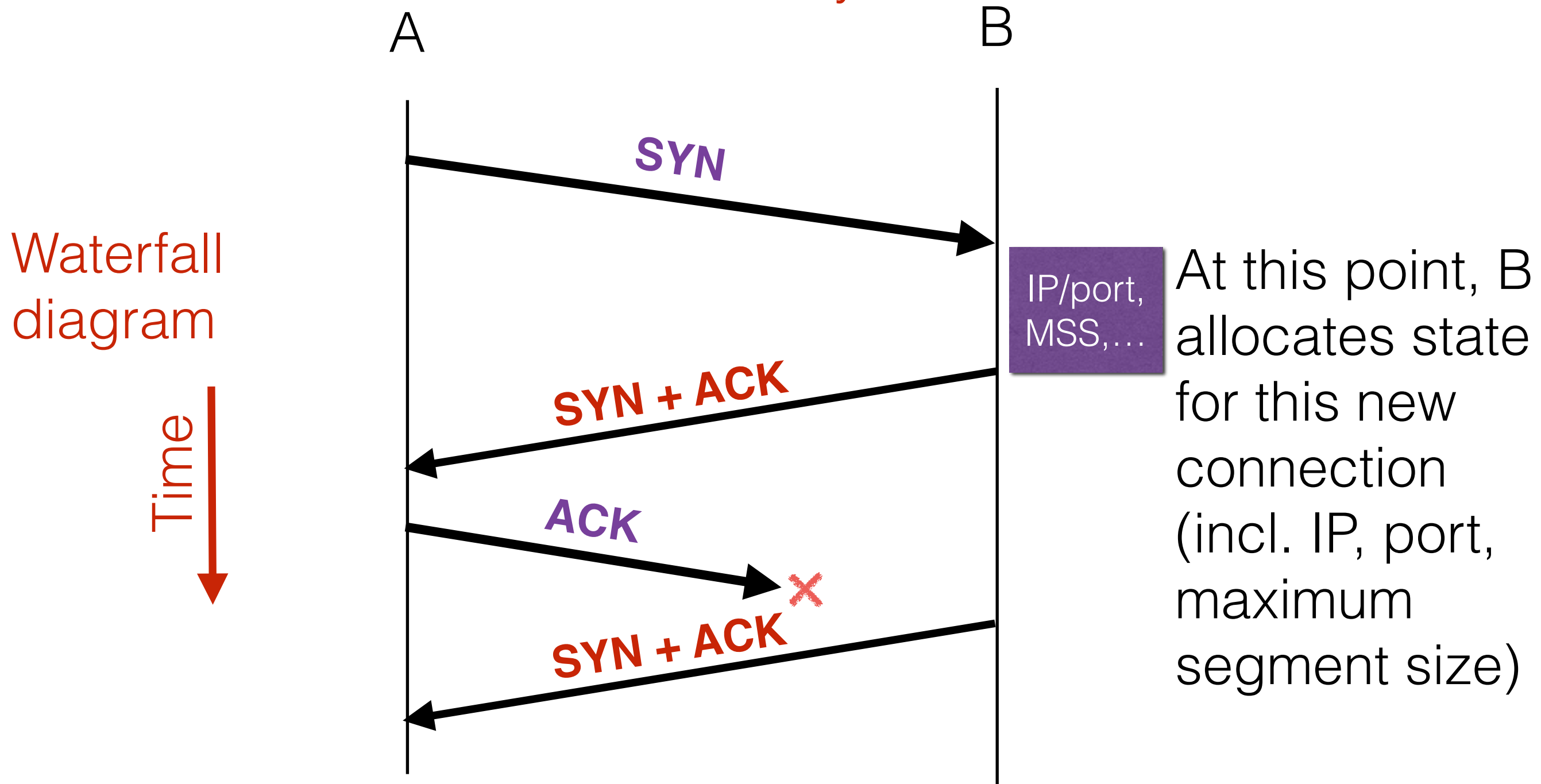
SYN flooding

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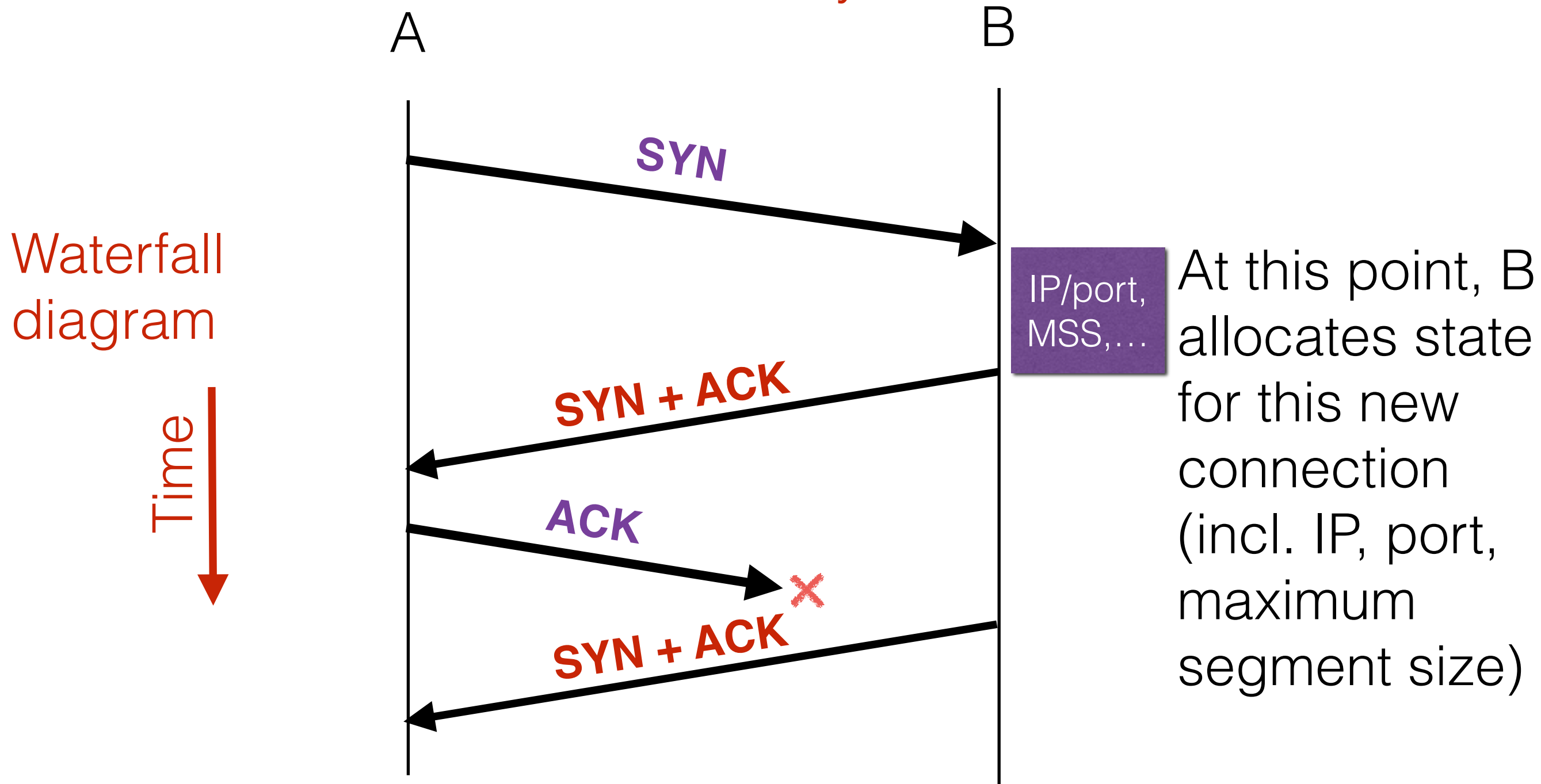
SYN flooding

Recall the three-way handshake:



SYN flooding

Recall the three-way handshake:



B will hold onto this **local state** and retransmit SYN+ACK's until it hears back or times out (up to 63 sec).

SYN flooding

The attack

A

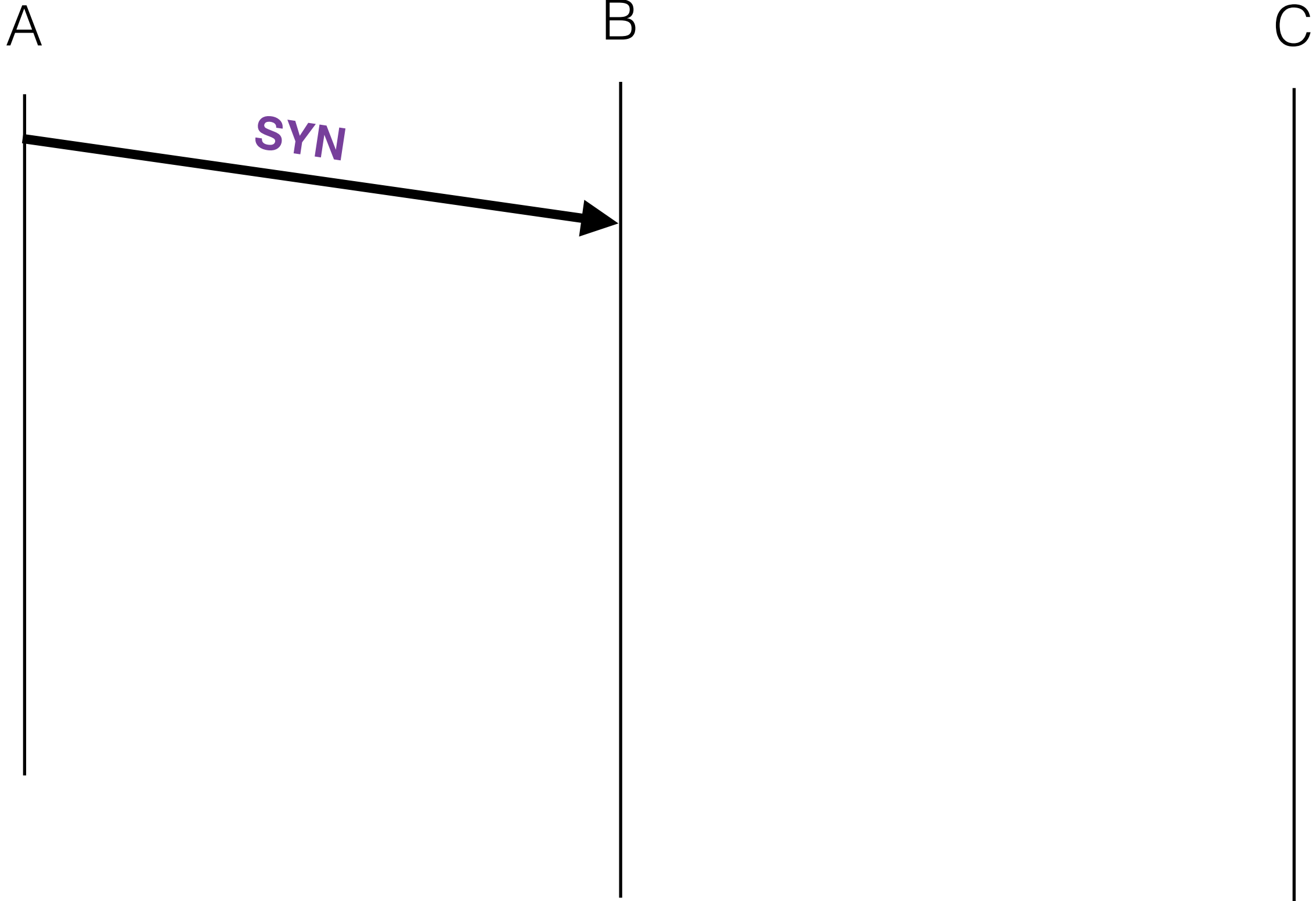
B

C



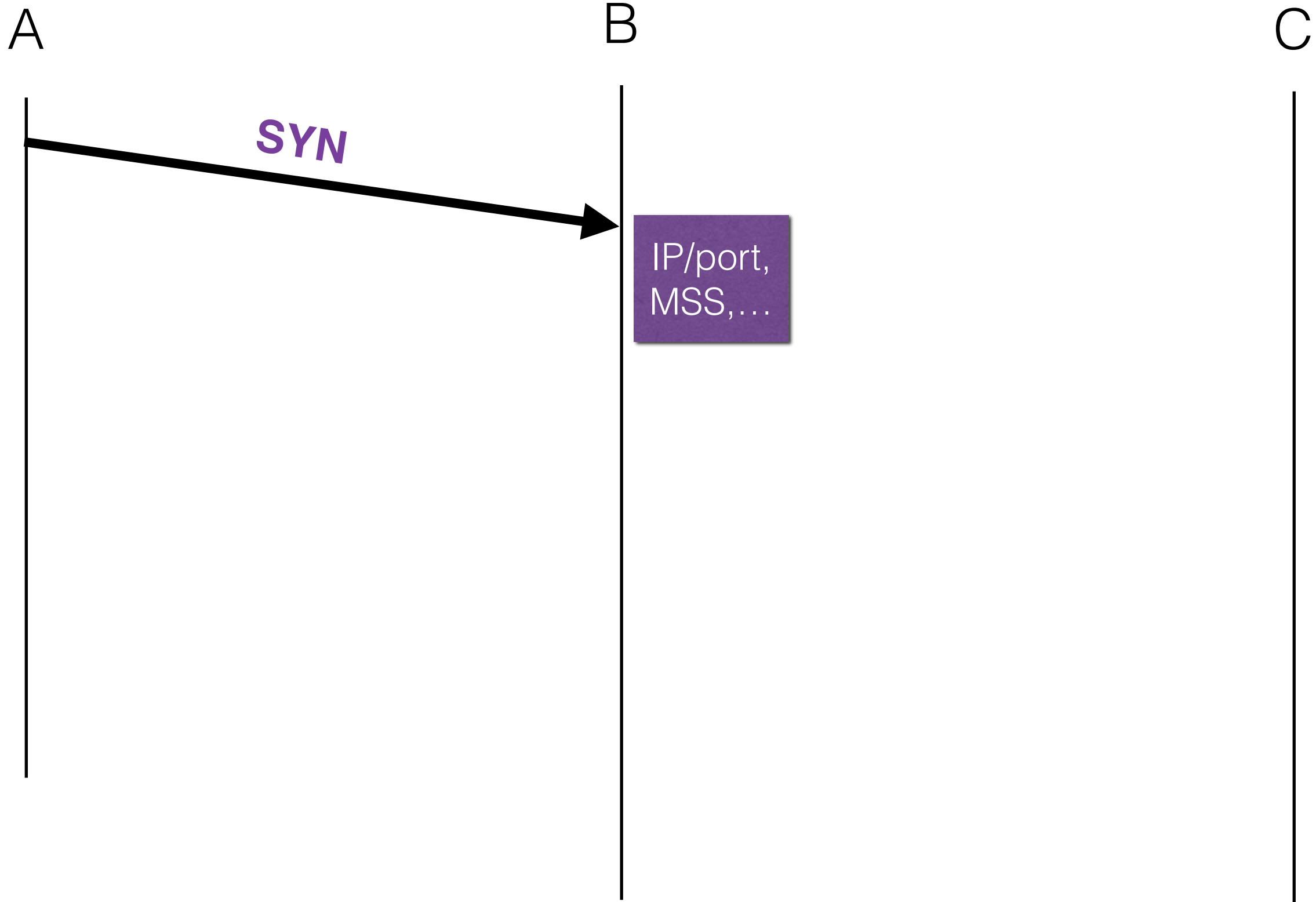
SYN flooding

The attack



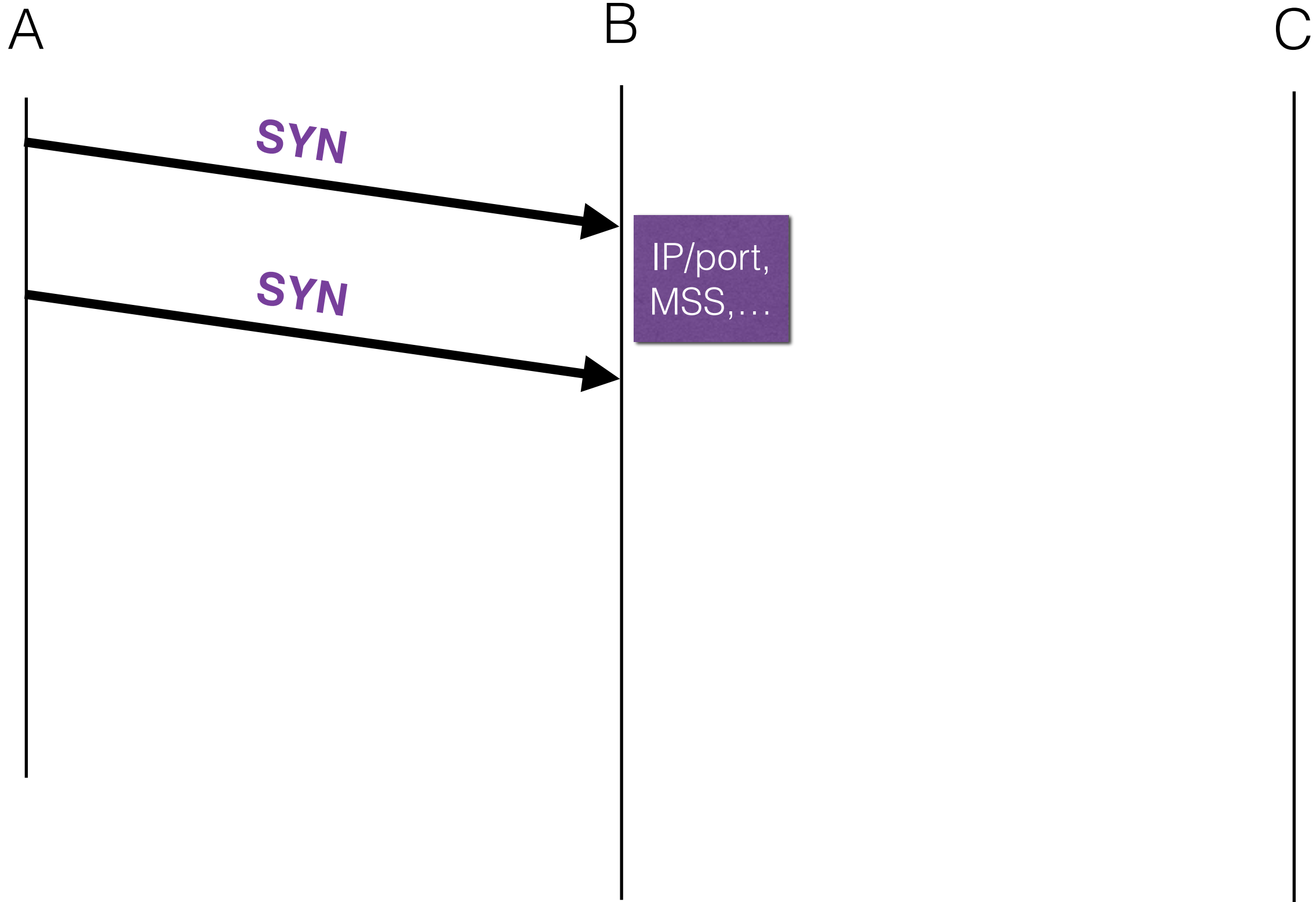
SYN flooding

The attack



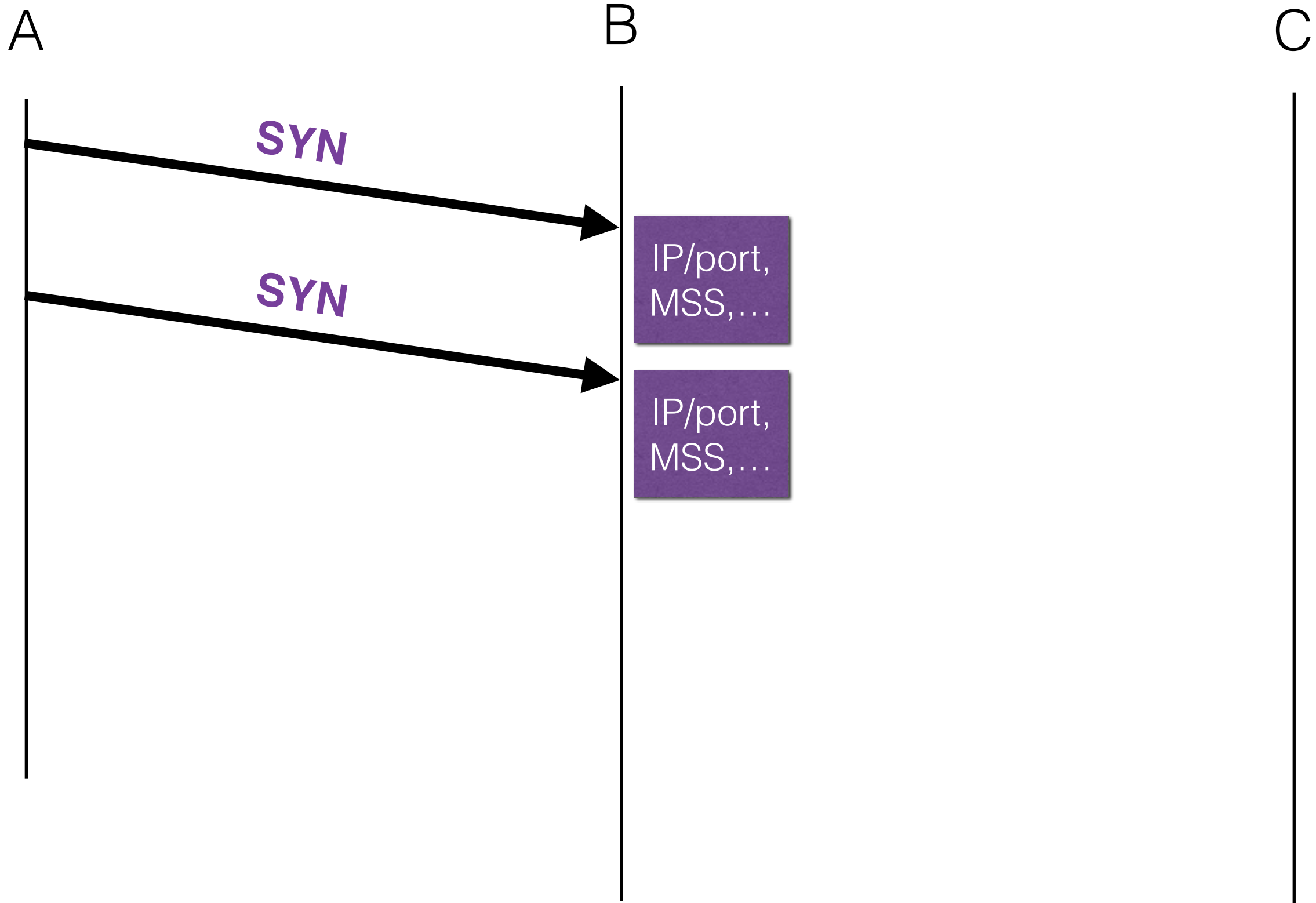
SYN flooding

The attack



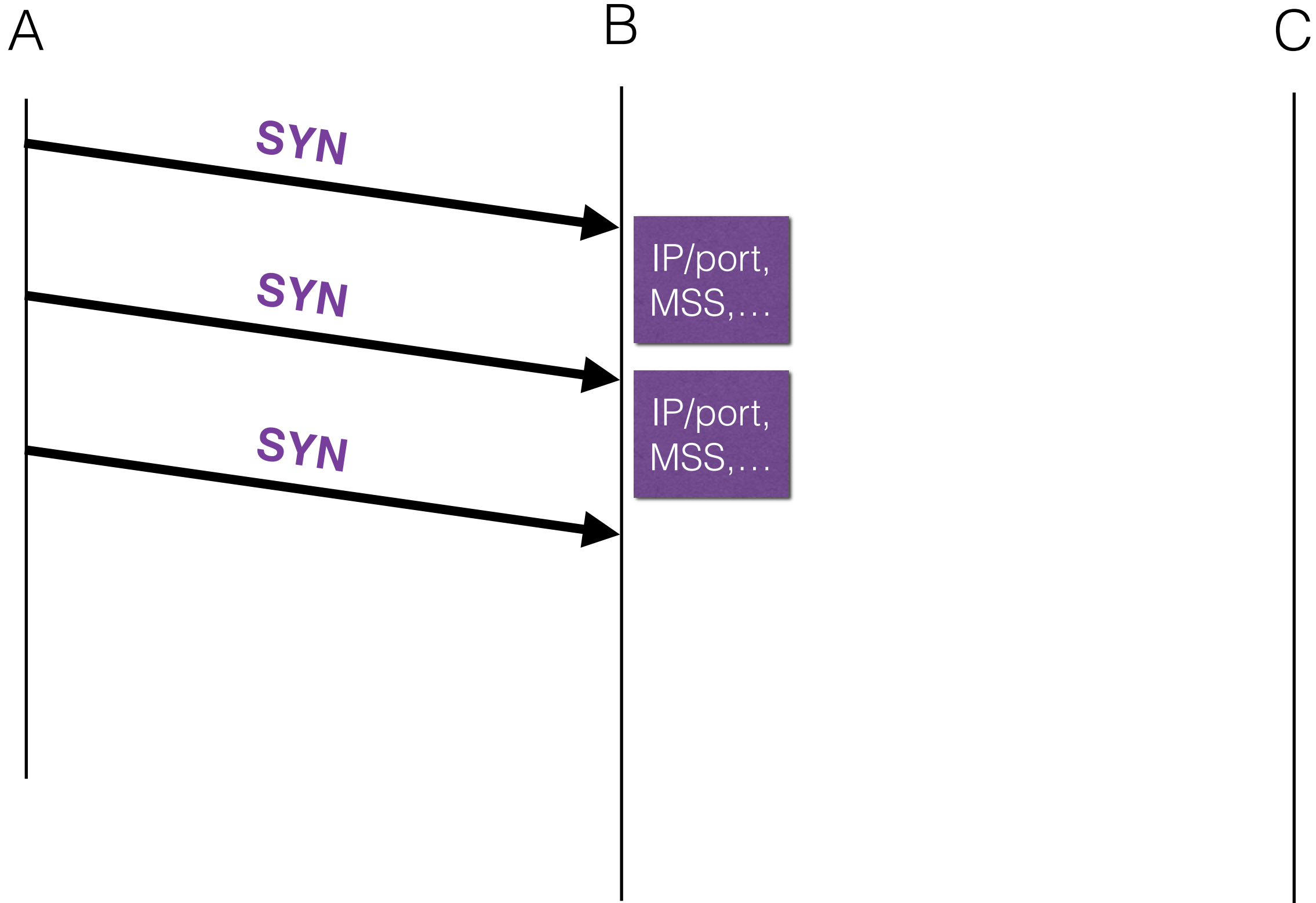
SYN flooding

The attack



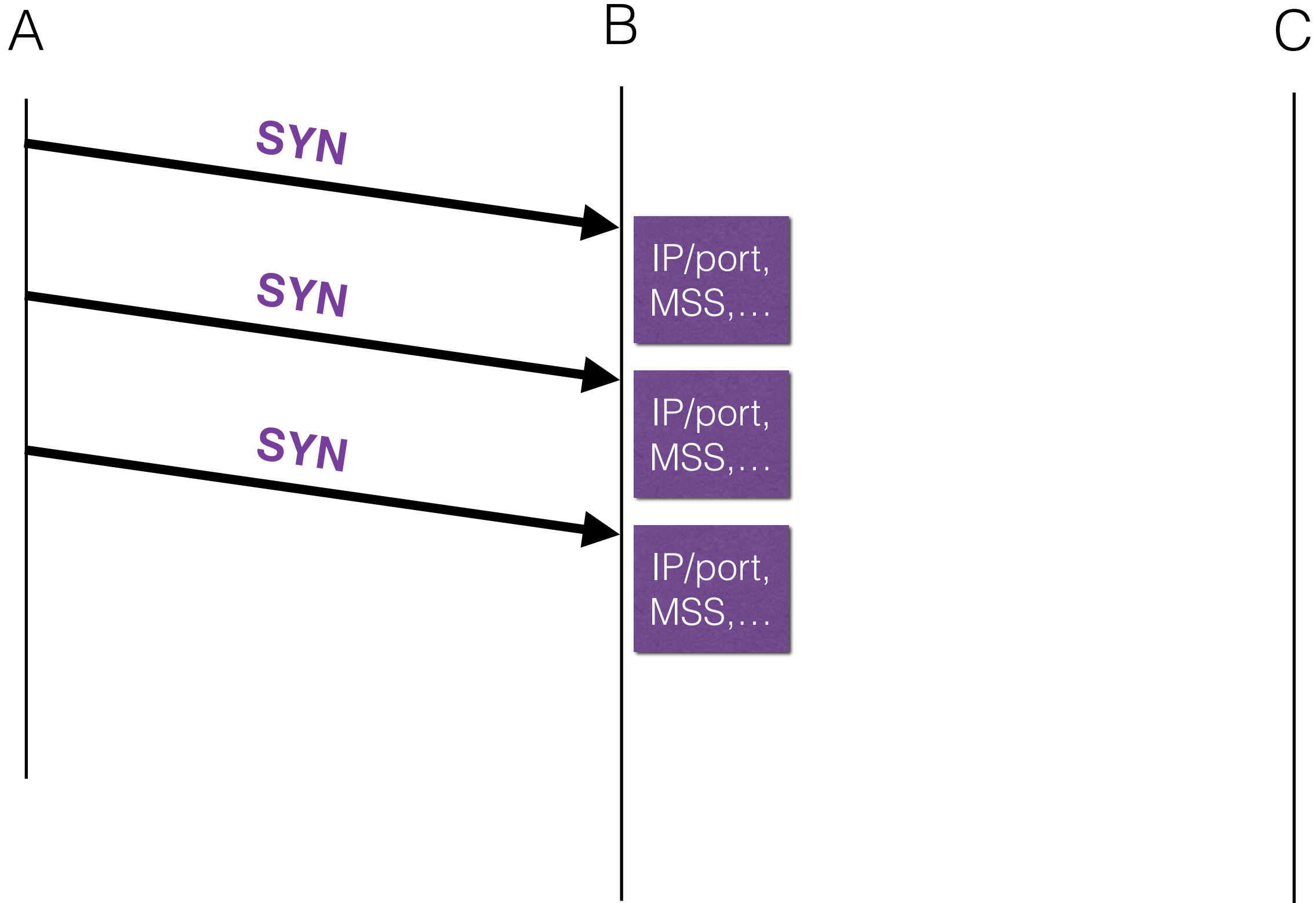
SYN flooding

The attack



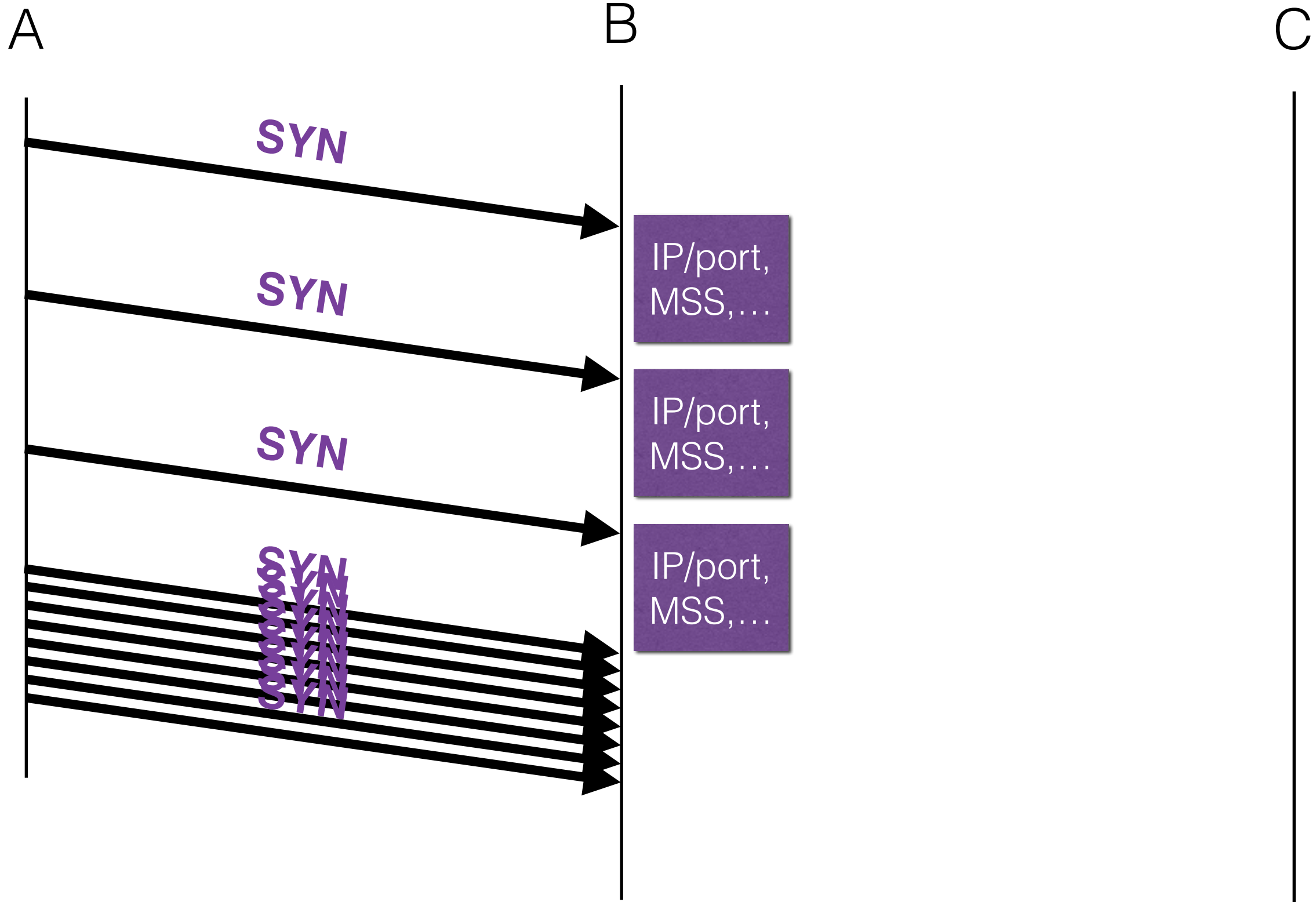
SYN flooding

The attack



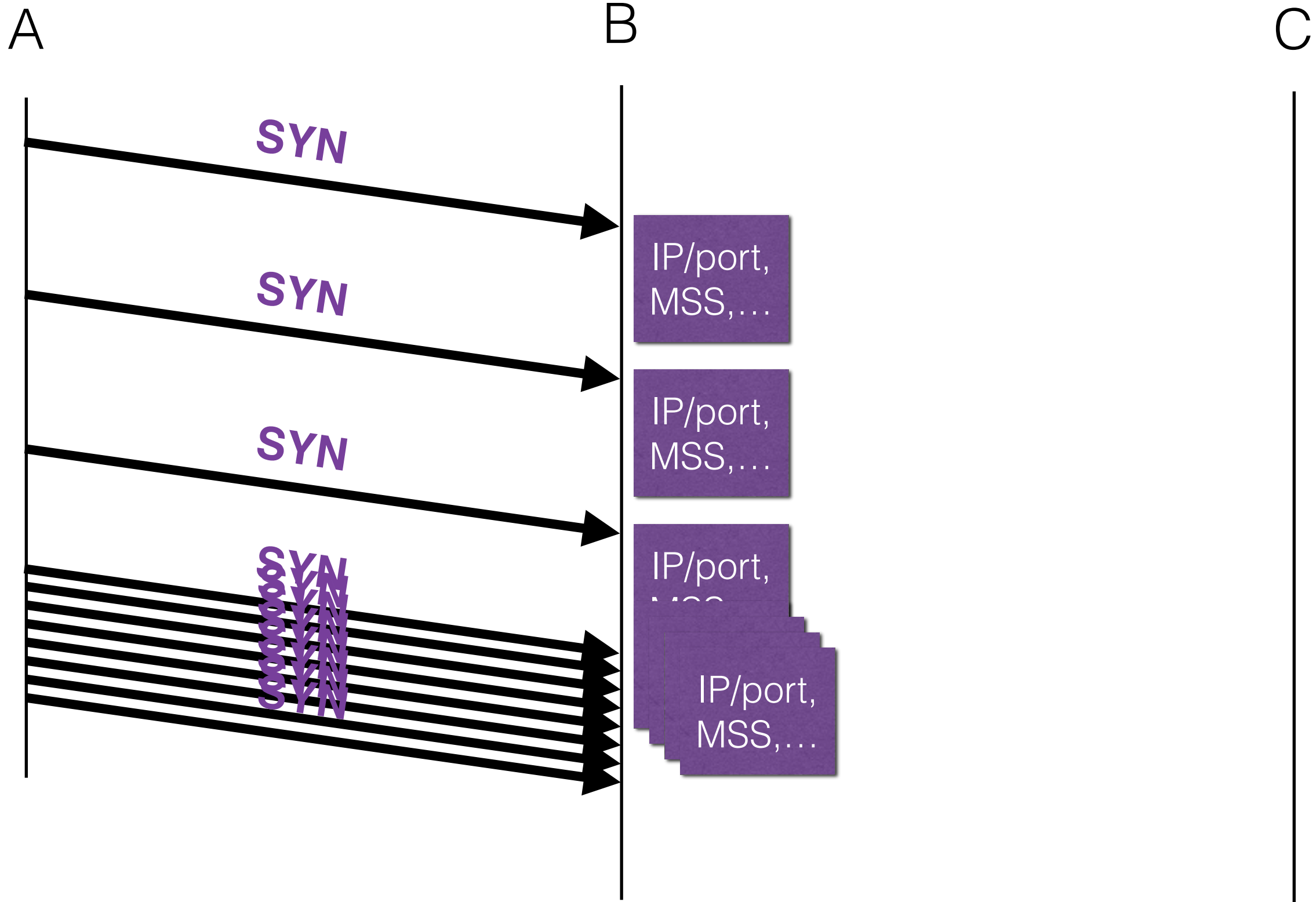
SYN flooding

The attack



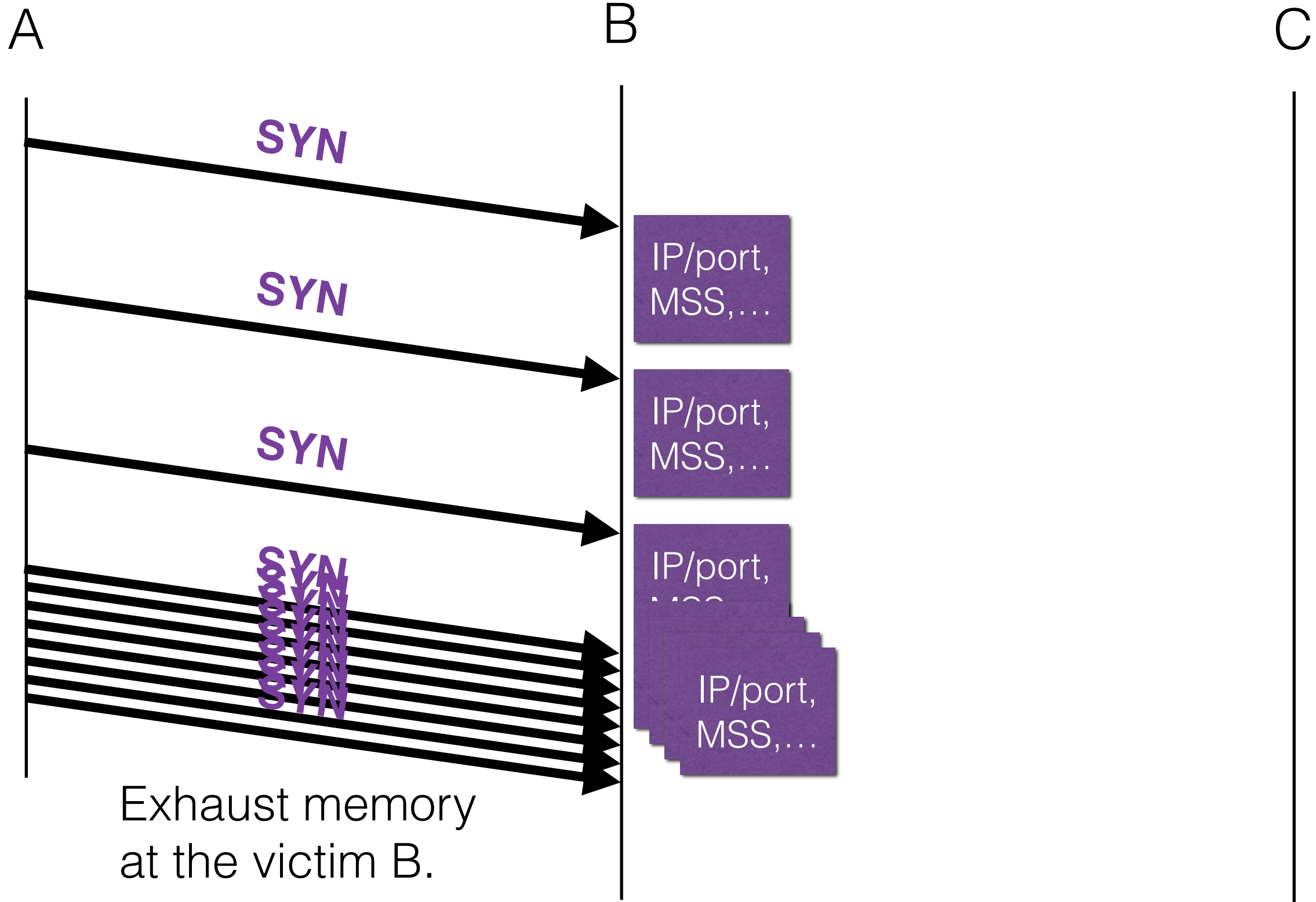
SYN flooding

The attack



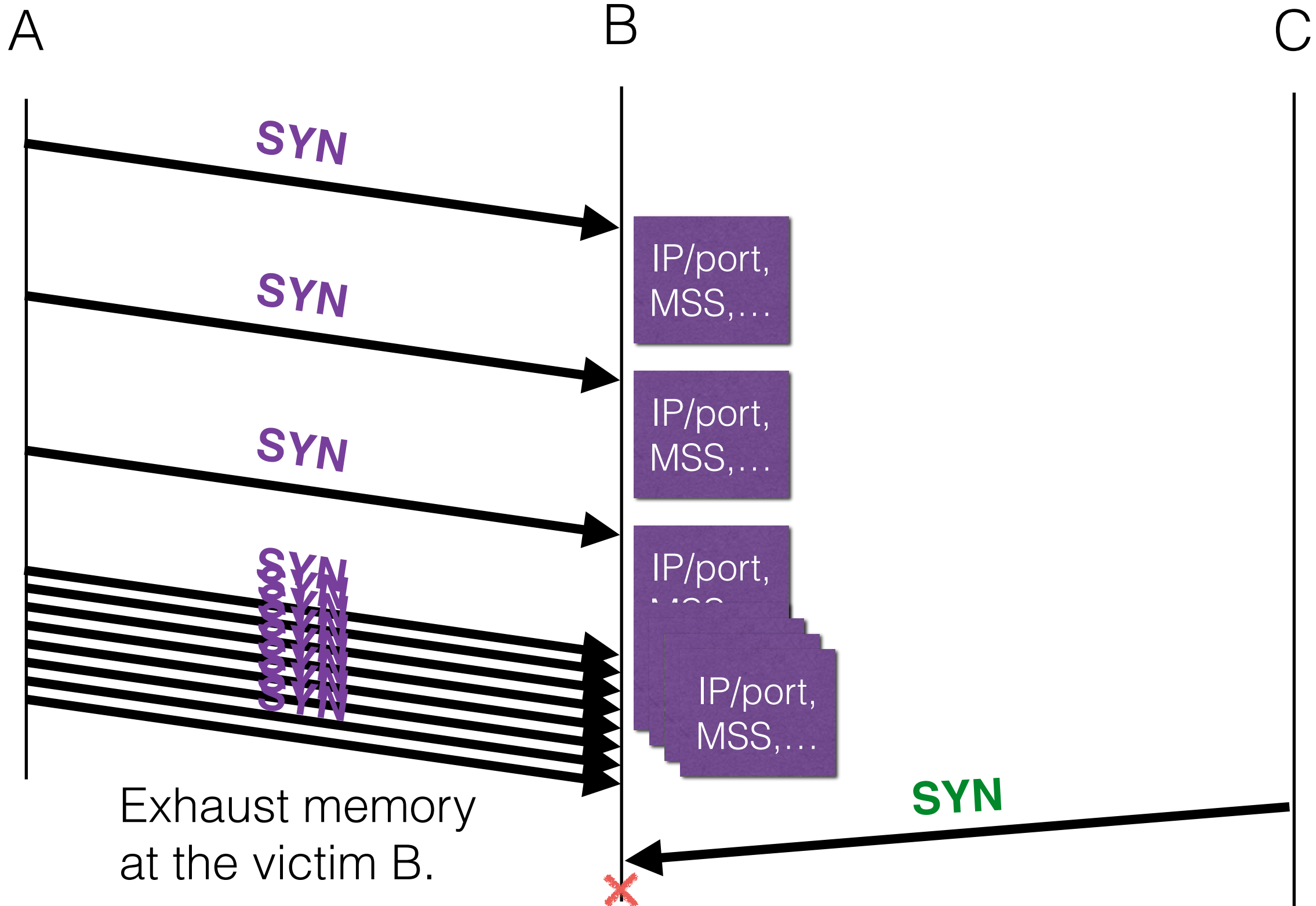
SYN flooding

The attack



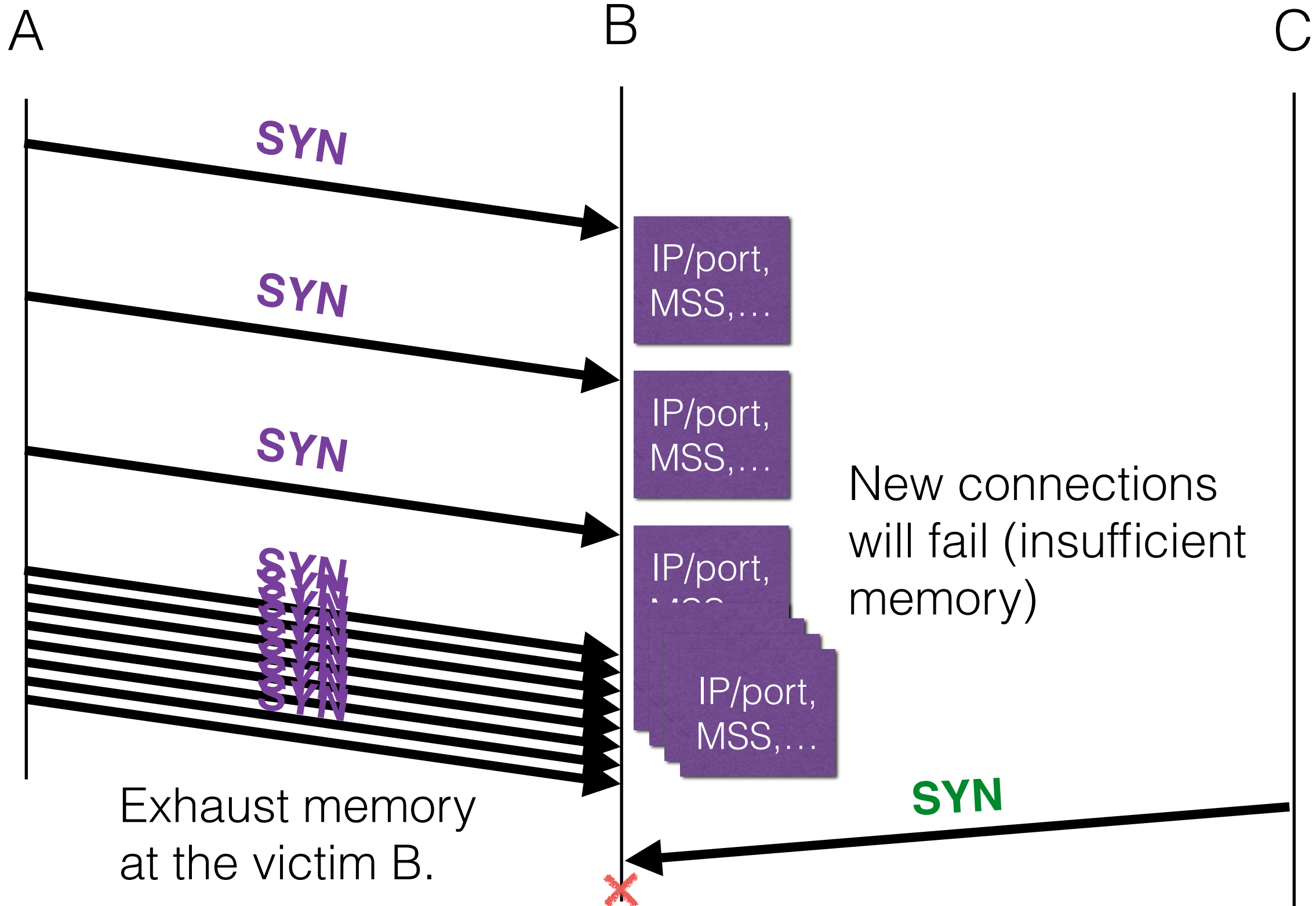
SYN flooding

The attack



SYN flooding

The attack



SYN flooding details

- Easy to detect many incomplete handshakes from a single IP address
- *Spoof* the source IP address
 - It's just a field in a header: set it to whatever you like
- Problem: the host who really owns that spoofed IP address may respond to the SYN+ACK with a RST, deleting the local state at the victim
- Ideally, spoof an IP address of a host you know won't respond

SYN cookies

The defense

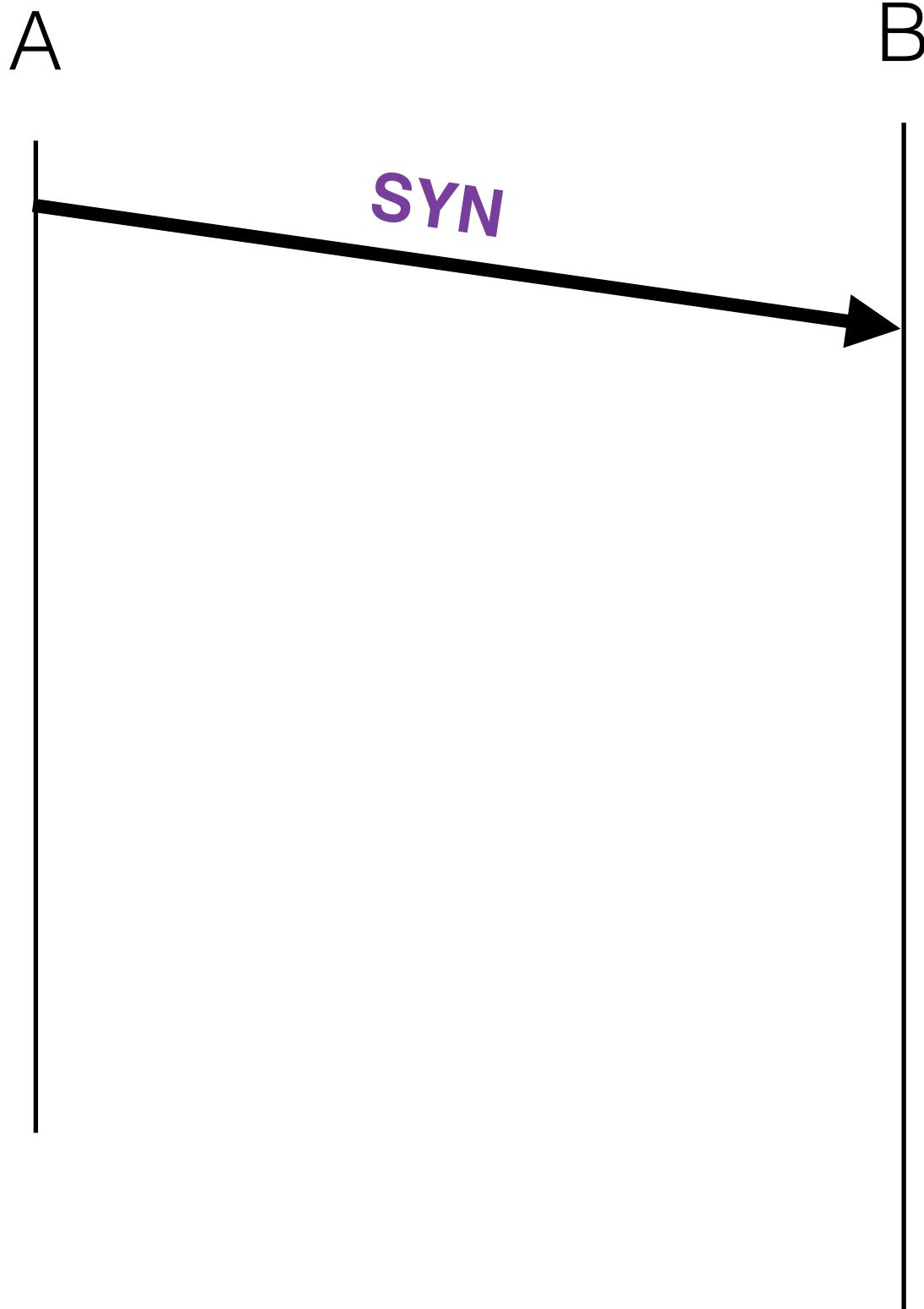
A

B



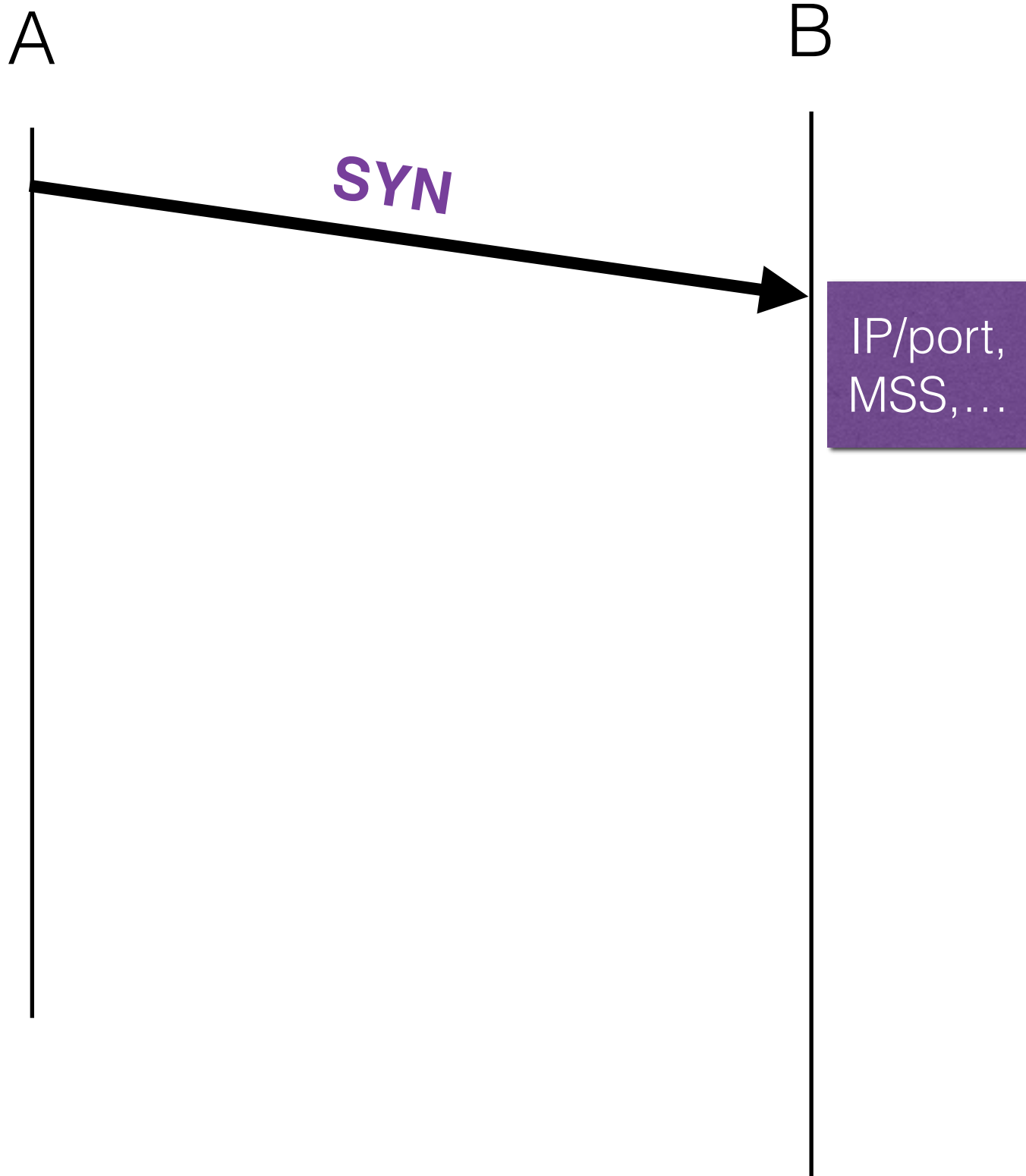
SYN cookies

The defense



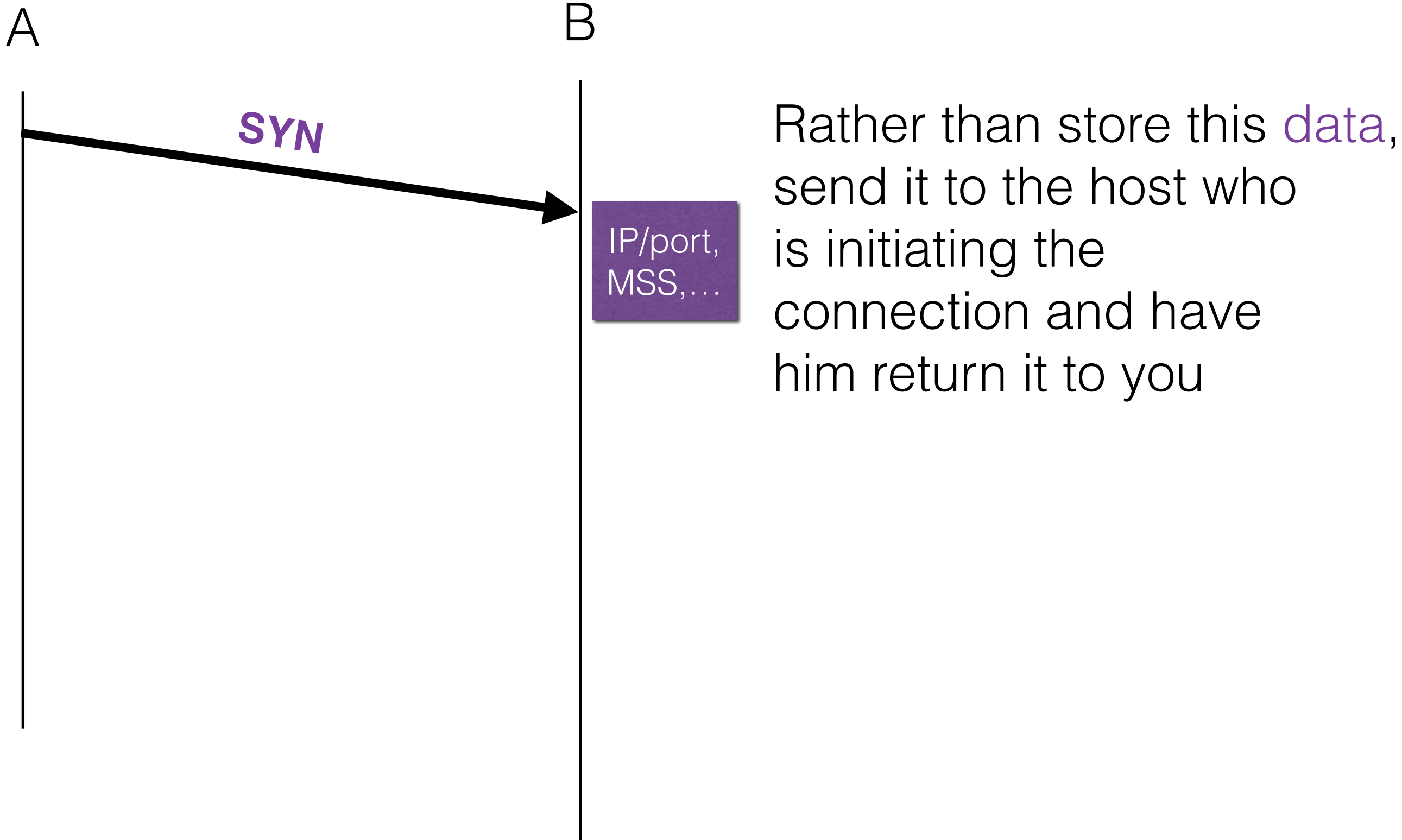
SYN cookies

The defense



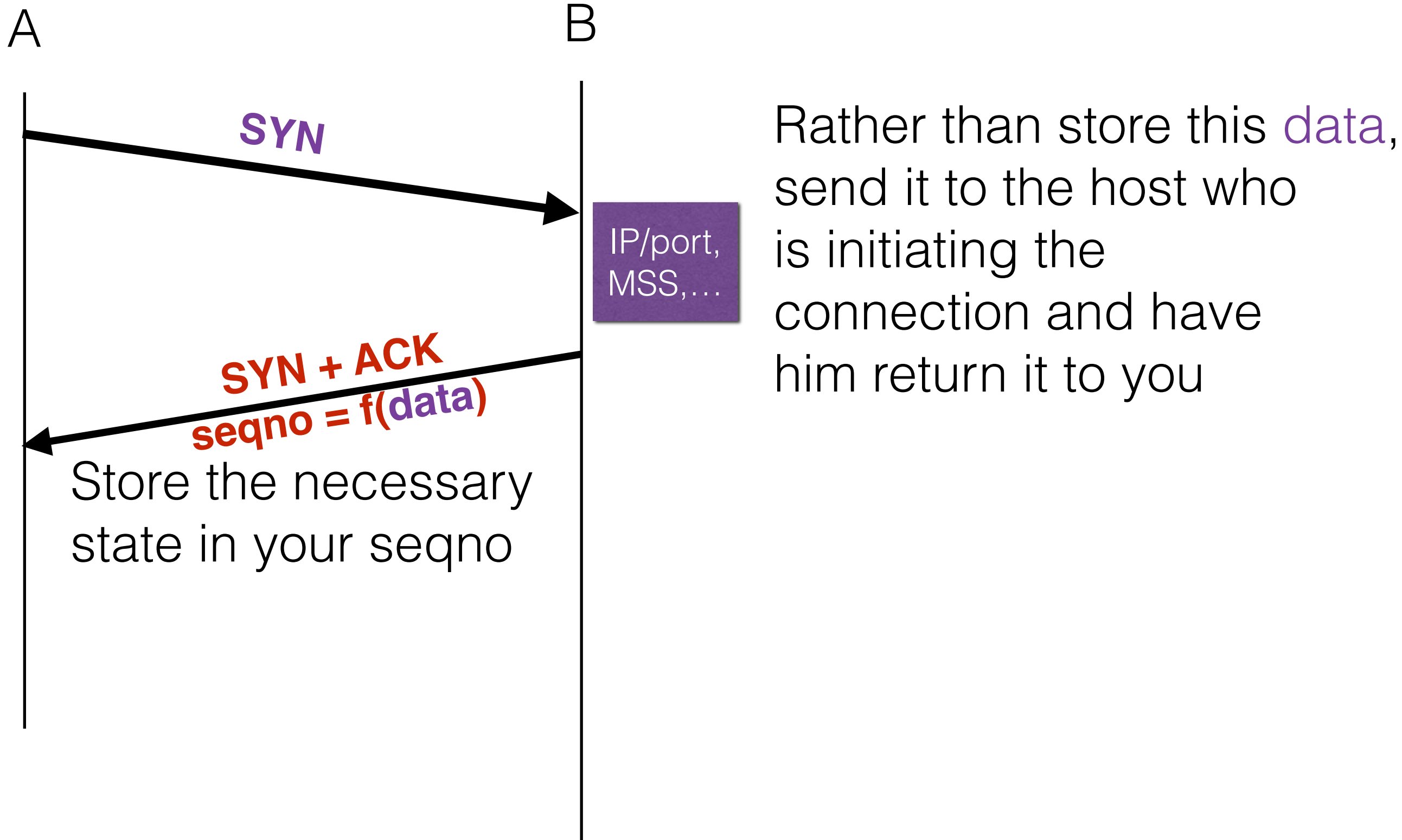
SYN cookies

The defense



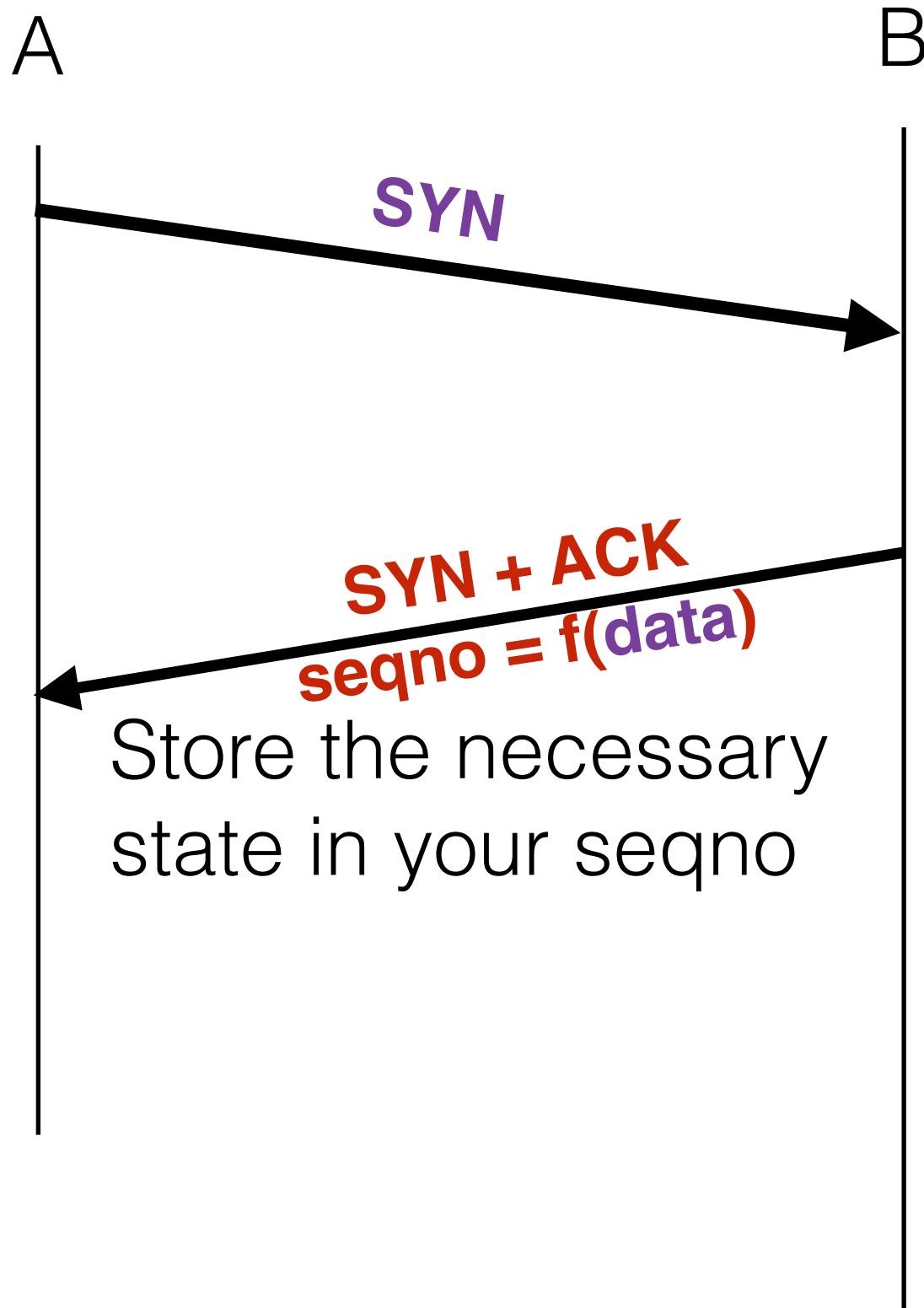
SYN cookies

The defense



SYN cookies

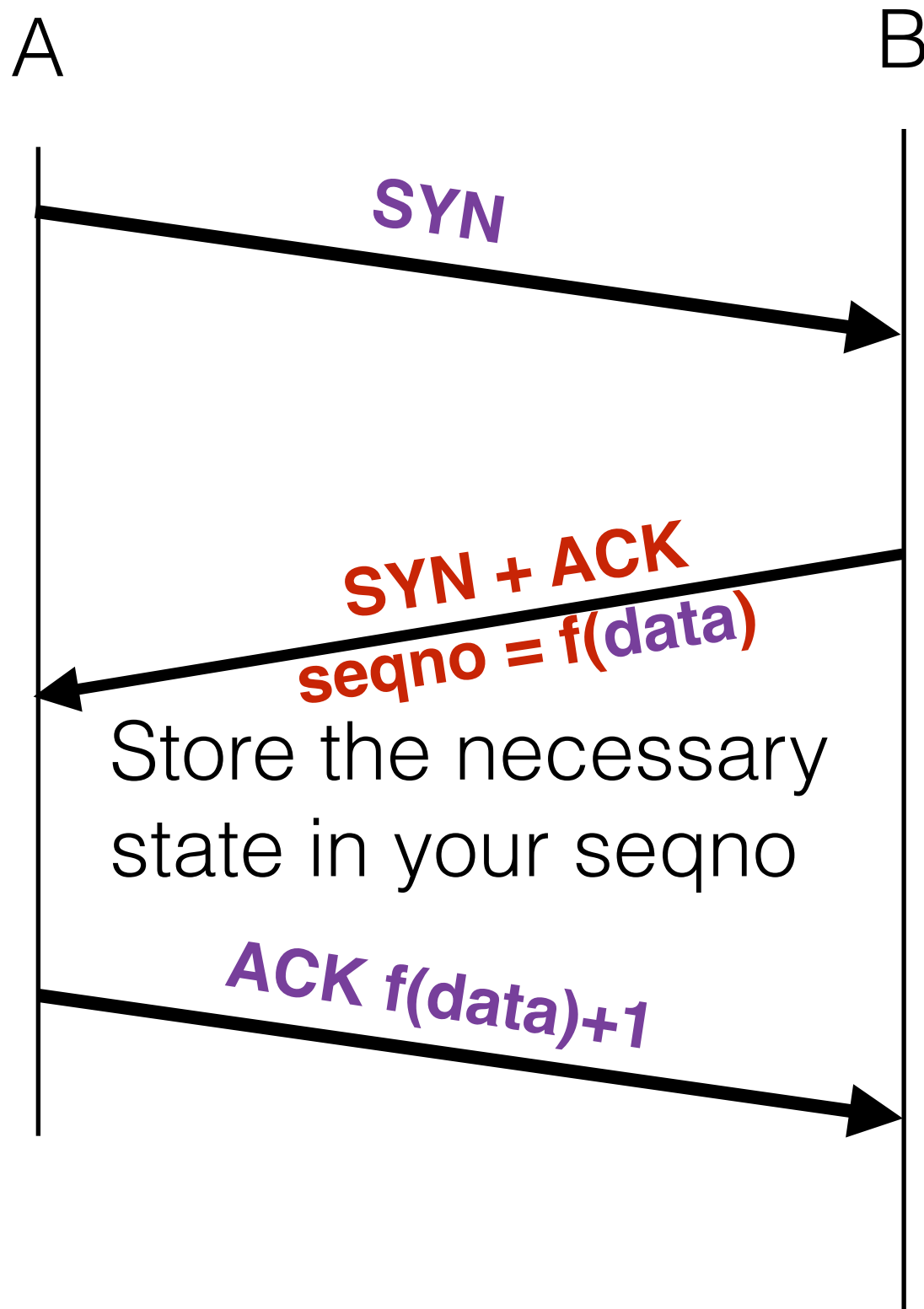
The defense



Rather than store this **data**, send it to the host who is initiating the connection and have him return it to you

SYN cookies

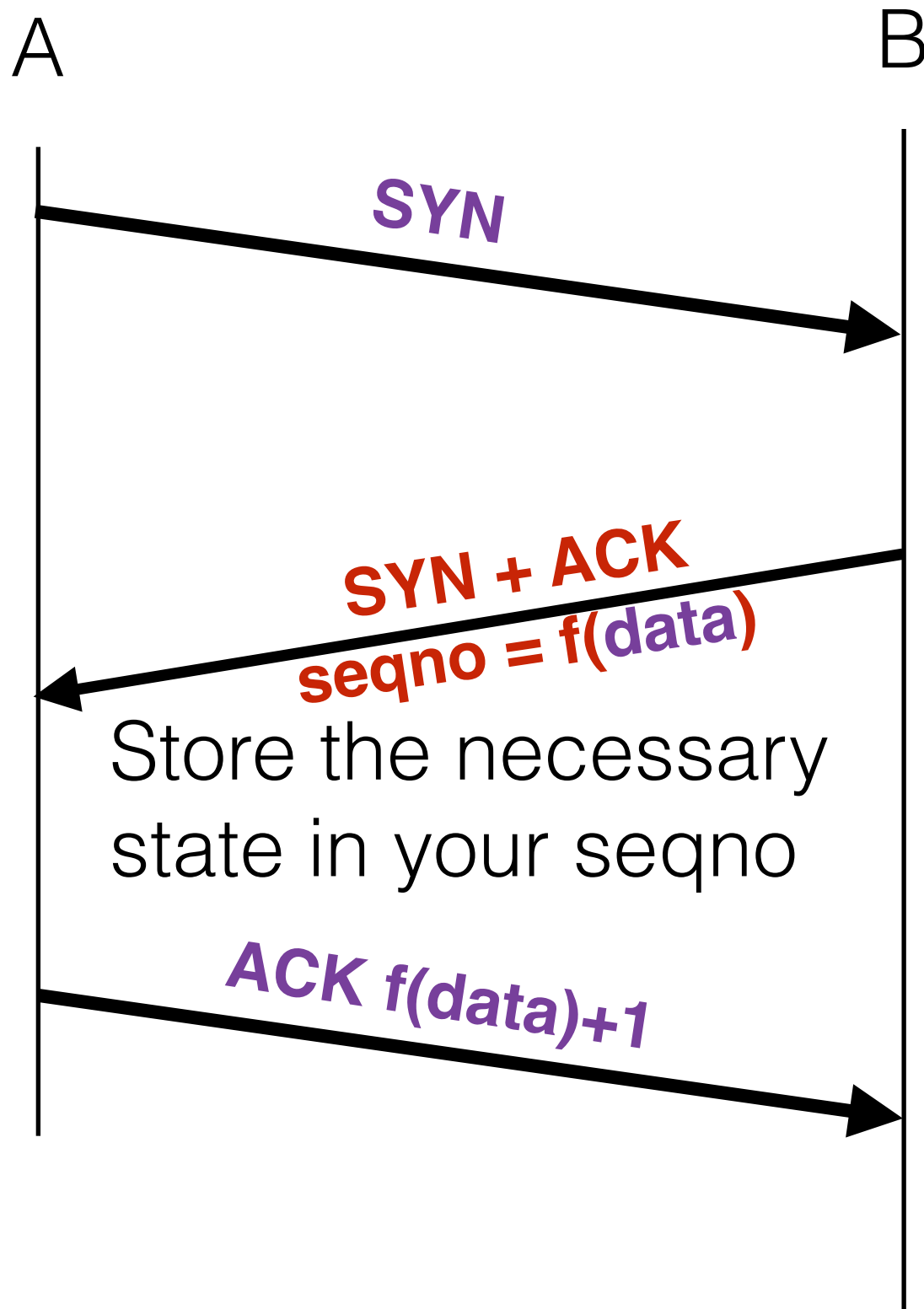
The defense



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SYN cookies

The defense

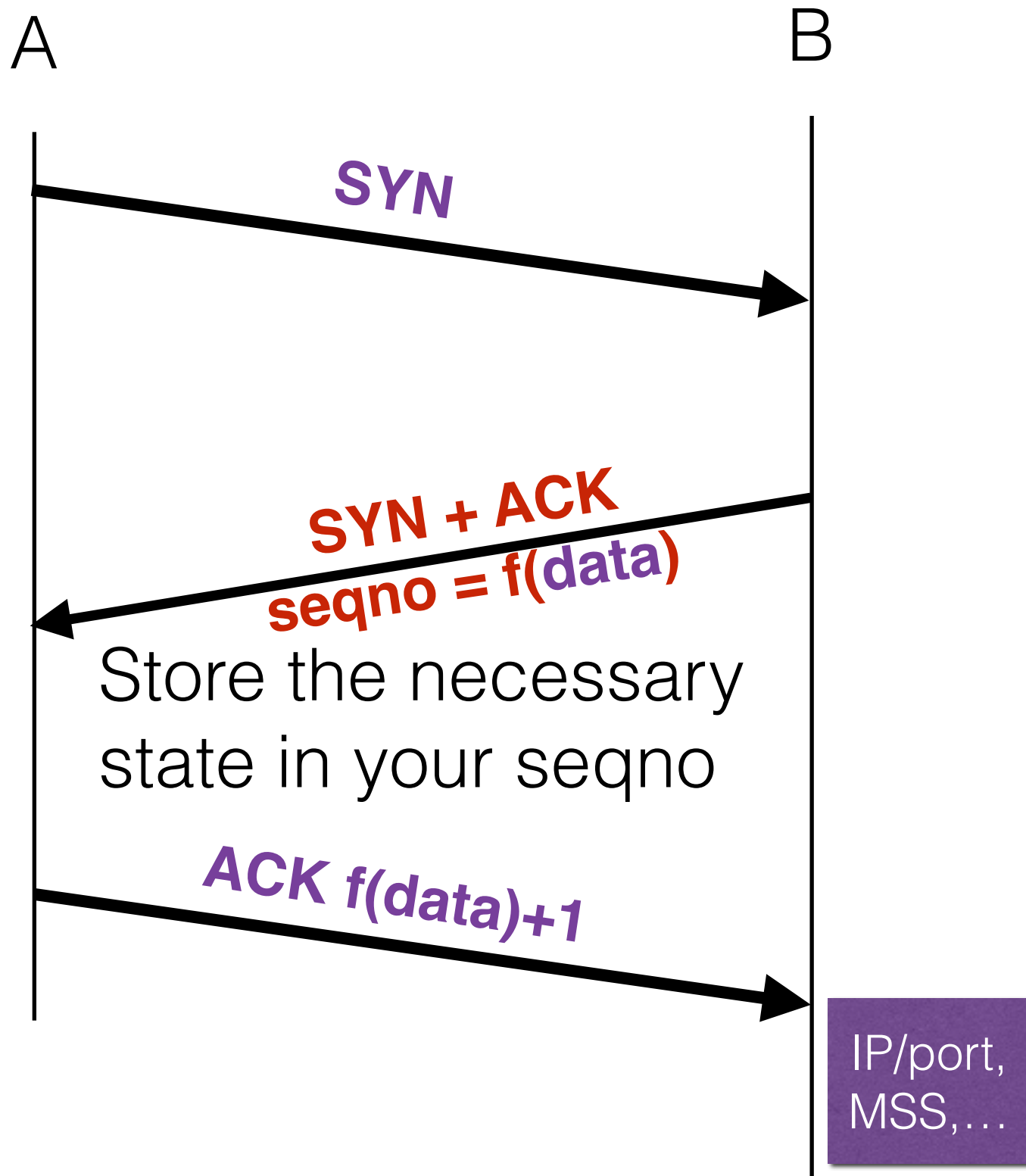


Rather than store this **data**, send it to the host who is initiating the connection and have him return it to you

Check that $f(\text{data})$ is valid for this connection. Only at that point do you allocate state.

SYN cookies

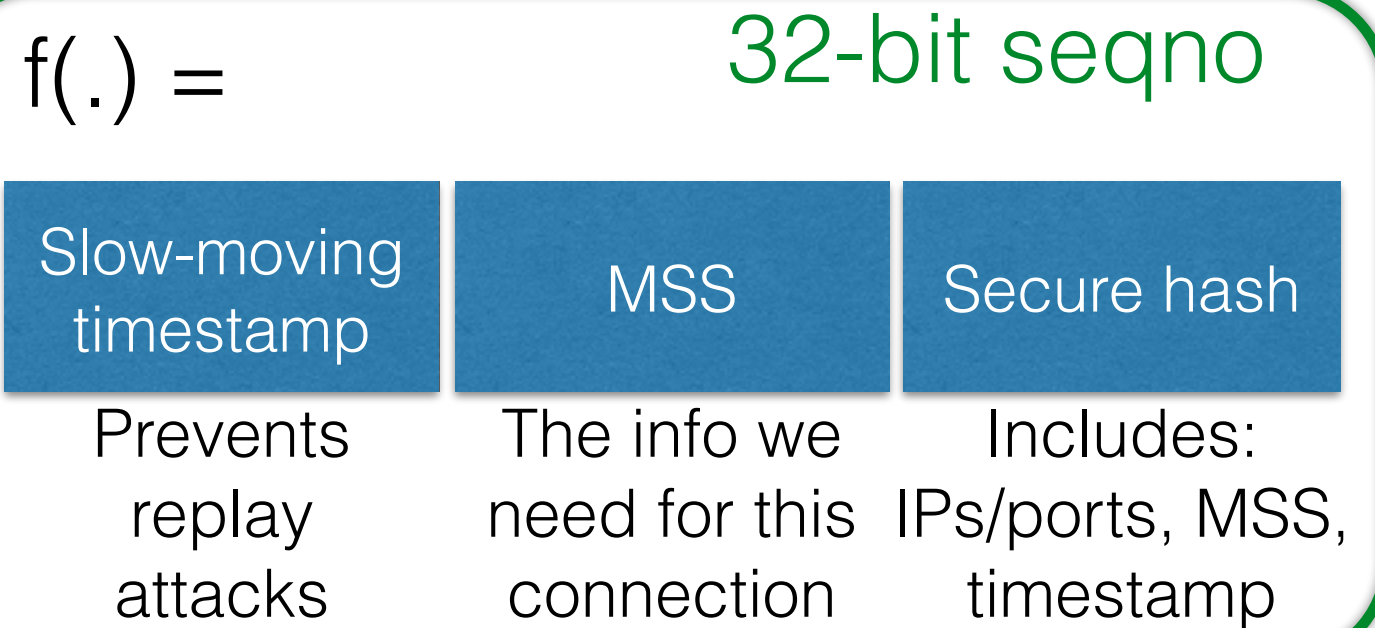
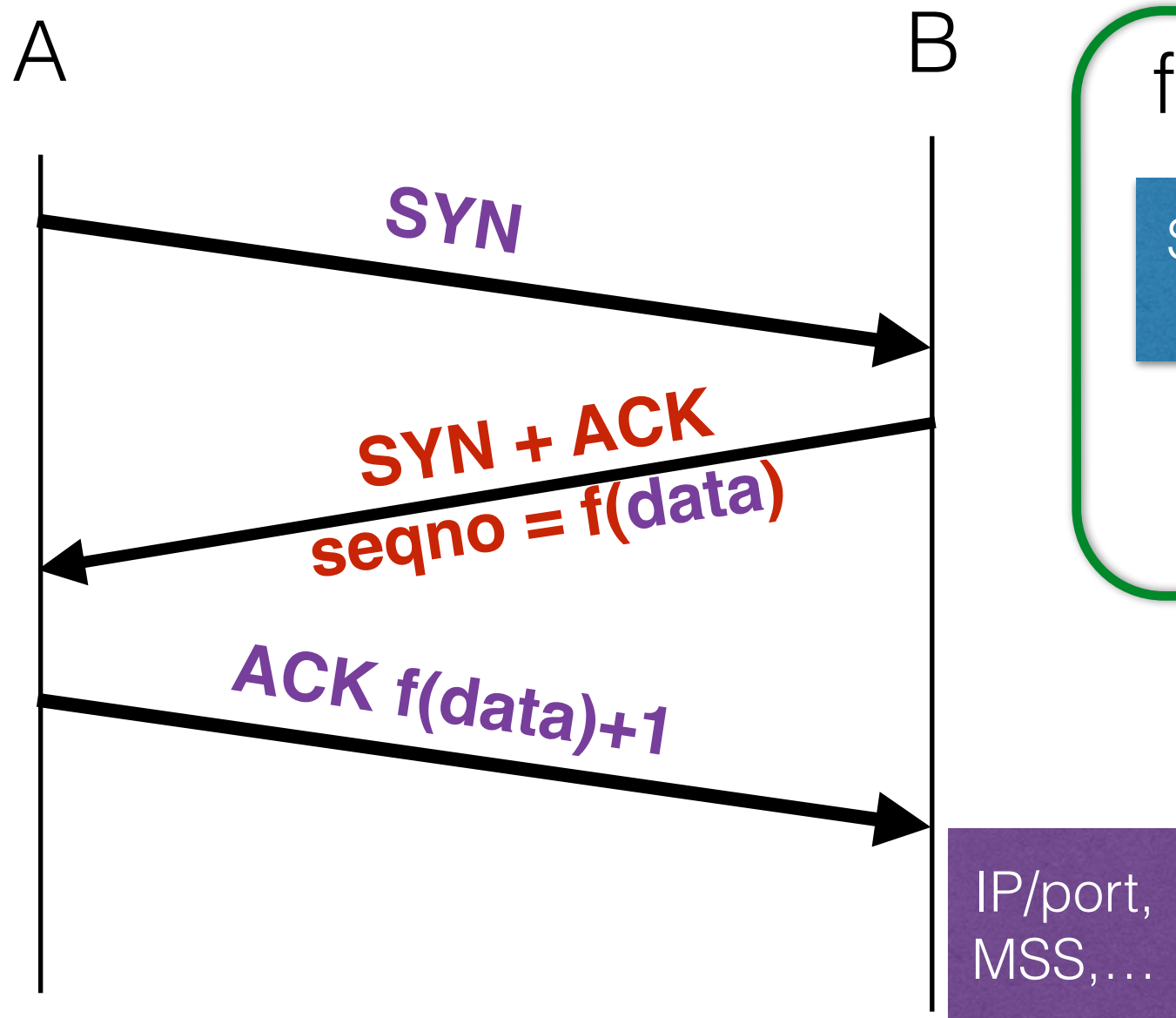
The defense



Rather than store this **data**, send it to the host who is initiating the connection and have him return it to you

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SYN cookie format



The secure hash makes it difficult for the attacker to guess what $f()$ will be, and therefore the attacker cannot guess a correct ACK if he spoofs.

Injection attacks

- Suppose you are on the path between src and dst; what can you do?
 - Trivial to inject packets with the correct sequence number
- What if you are not on the path?
 - Need to guess the sequence number
 - Is this difficult to do?

Initial sequence numbers

- Initial sequence numbers used to be deterministic
- What havoc can we wreak?
 - Send RSTs
 - Inject data packets into an existing connection (TCP veto attacks)
 - *Initiate and use an entire connection without ever hearing the other end*

Mitnick attack

X-terminal
server

Server that X-
term trusts

Any connection initiated
from this IP address is
allowed access to the
X-terminal server

Attacker

Mitnick attack

X-terminal
server

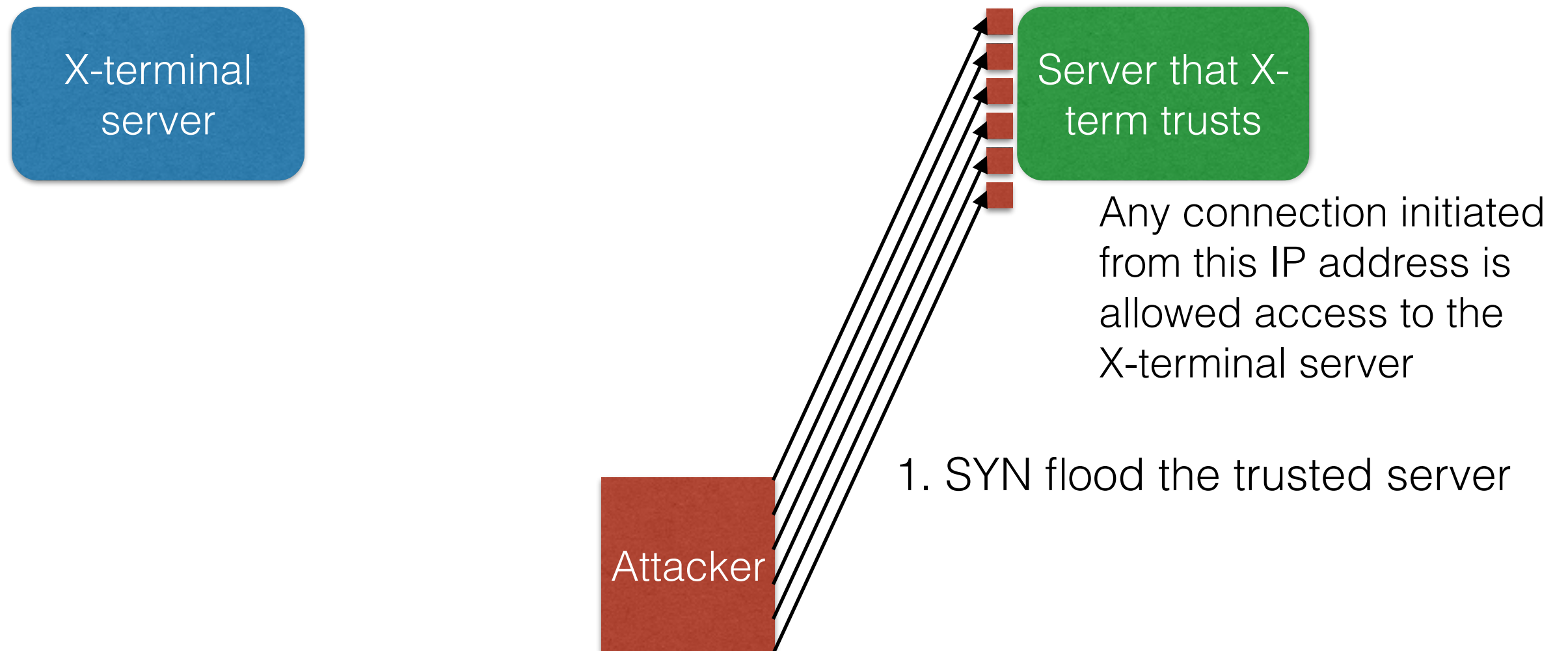
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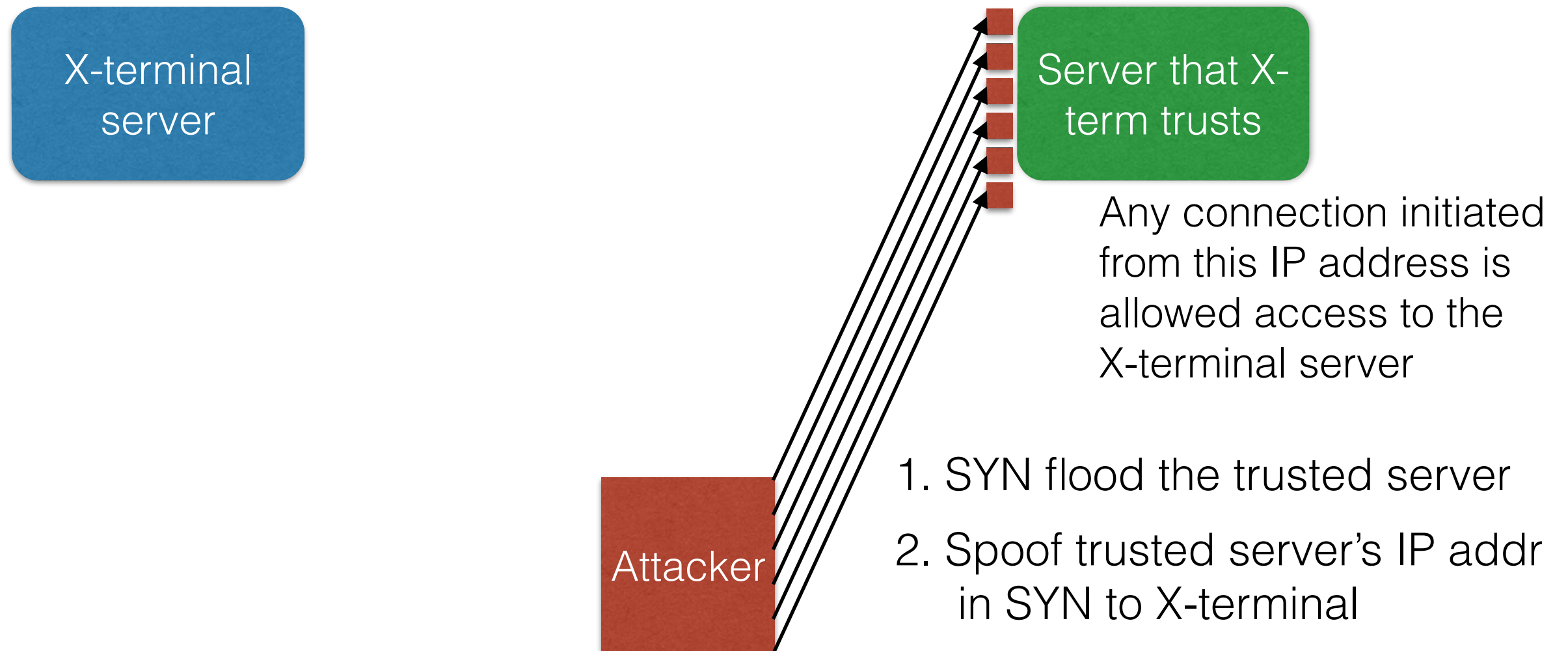
Attacker

1. SYN flood the trusted server

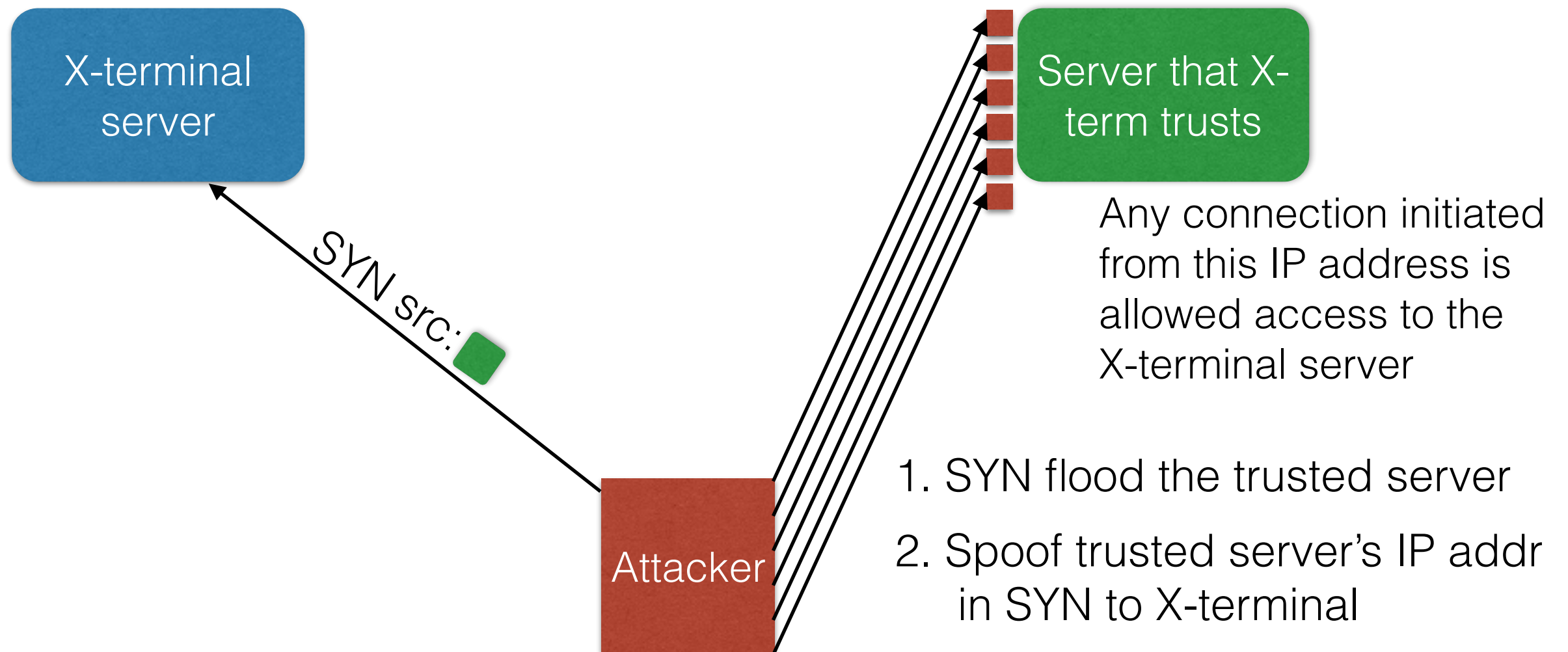
Mitnick attack



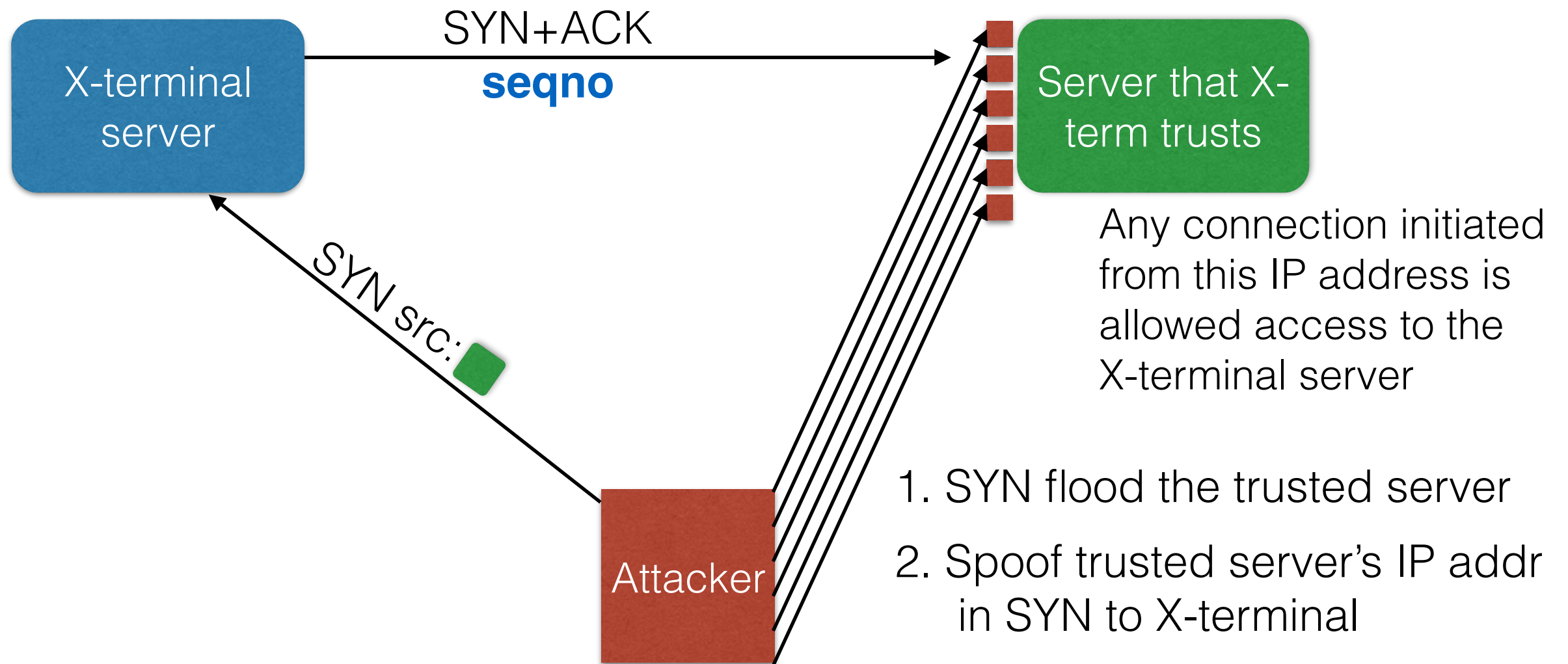
Mitnick attack



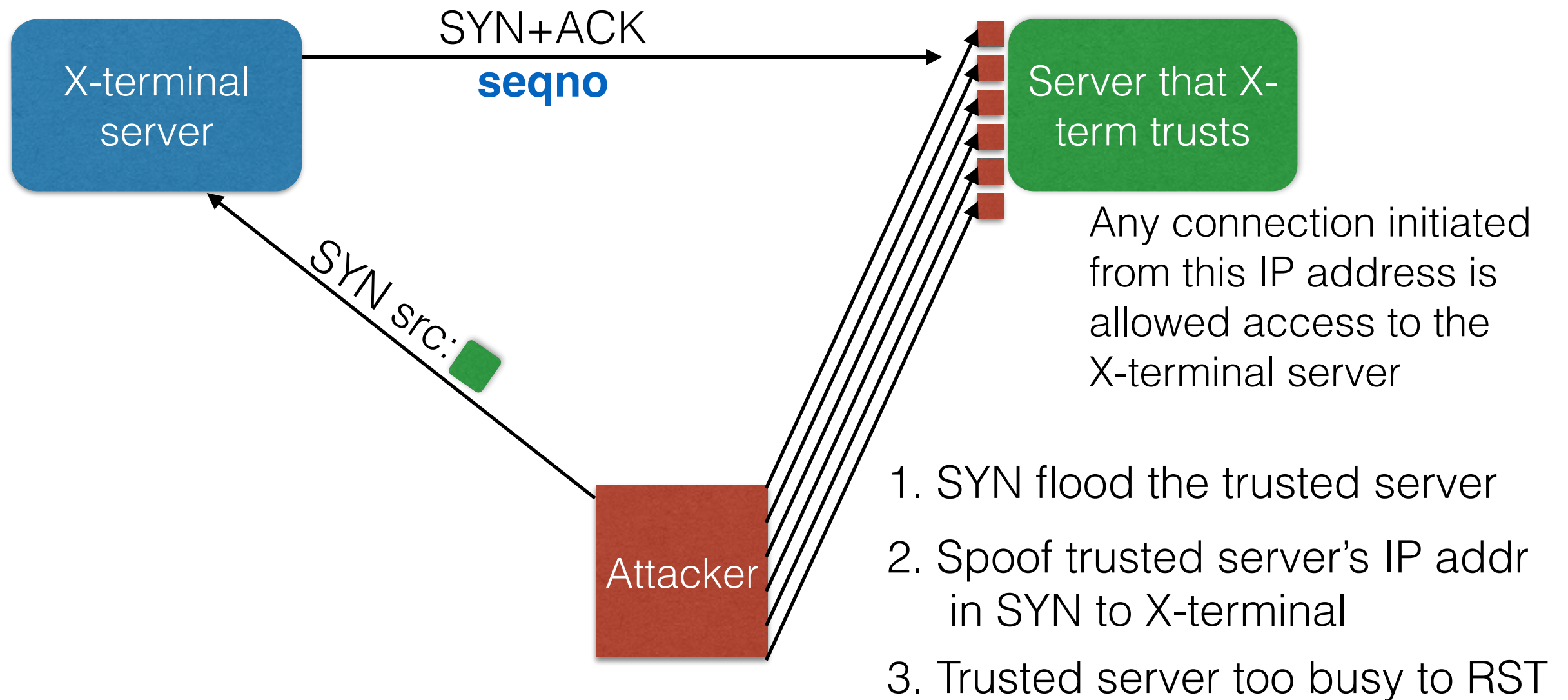
Mitnick attack



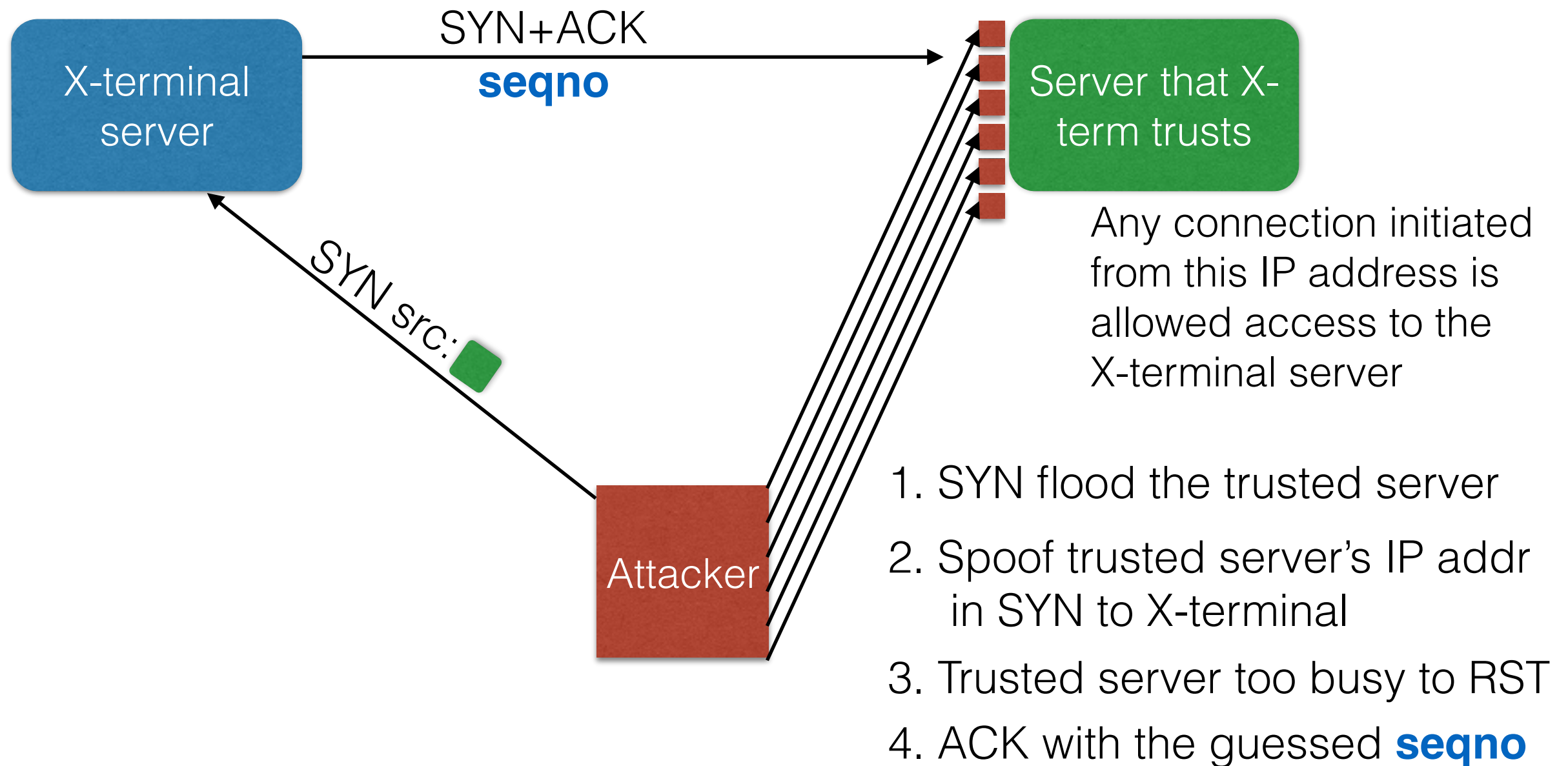
Mitnick attack



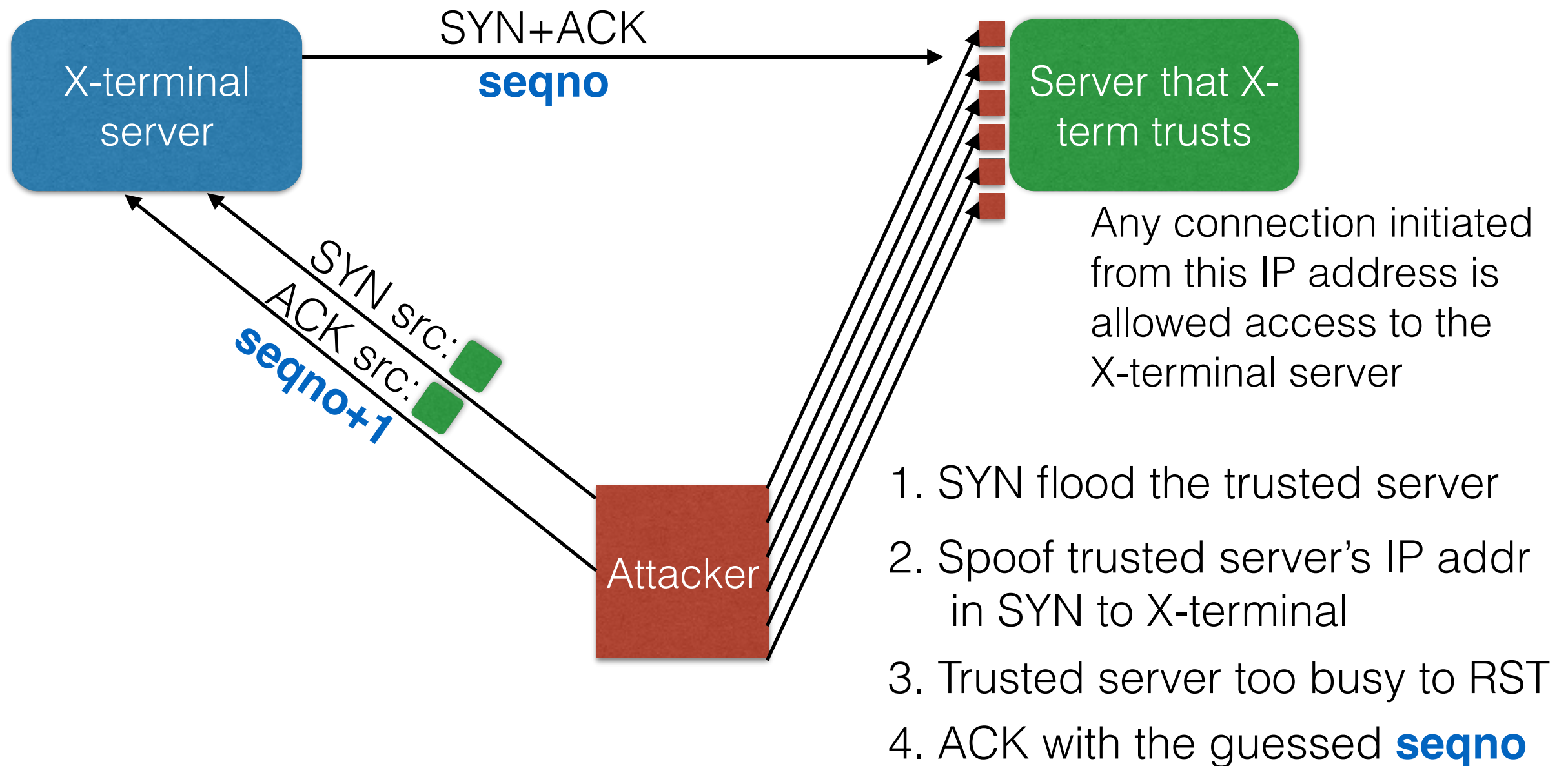
Mitnick attack



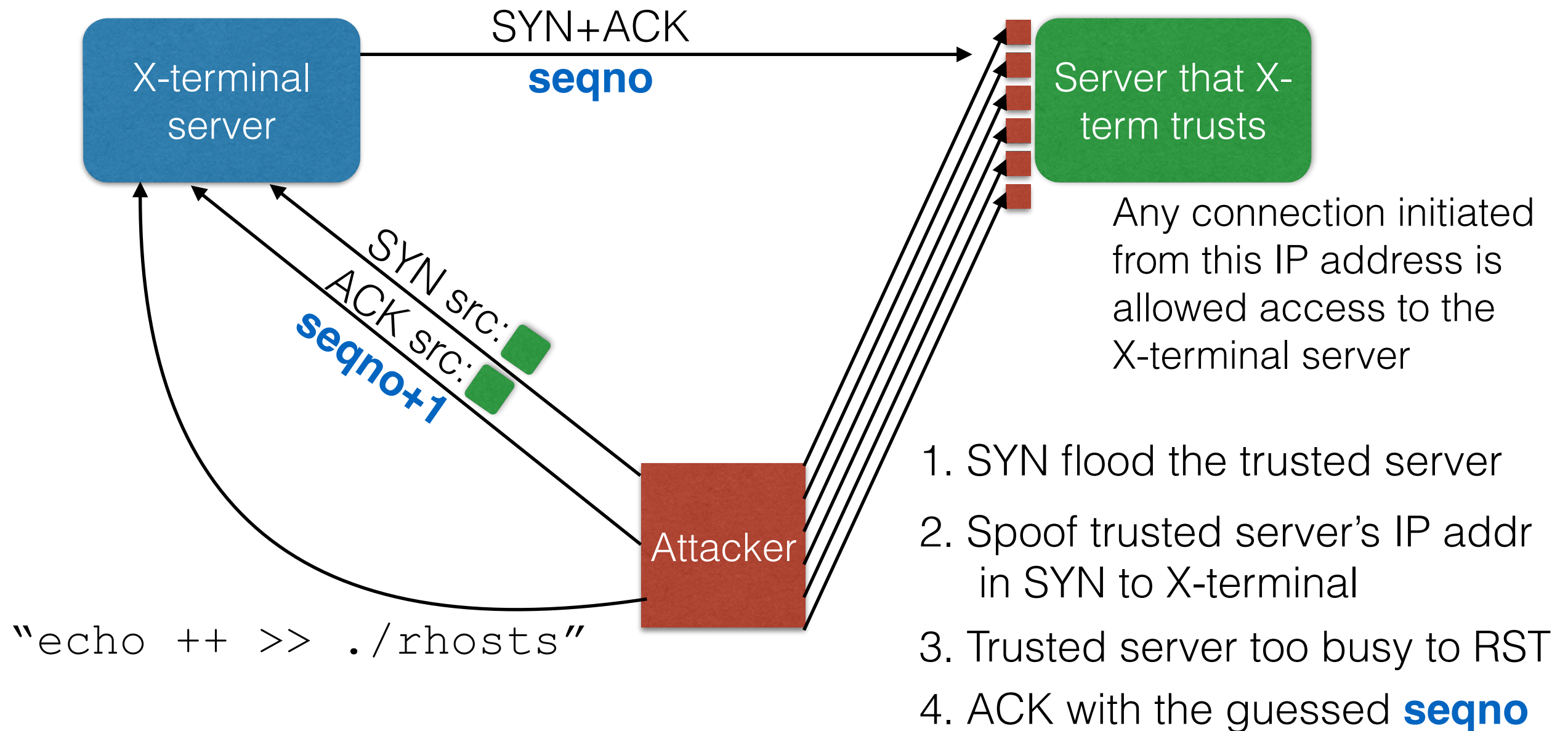
Mitnick attack



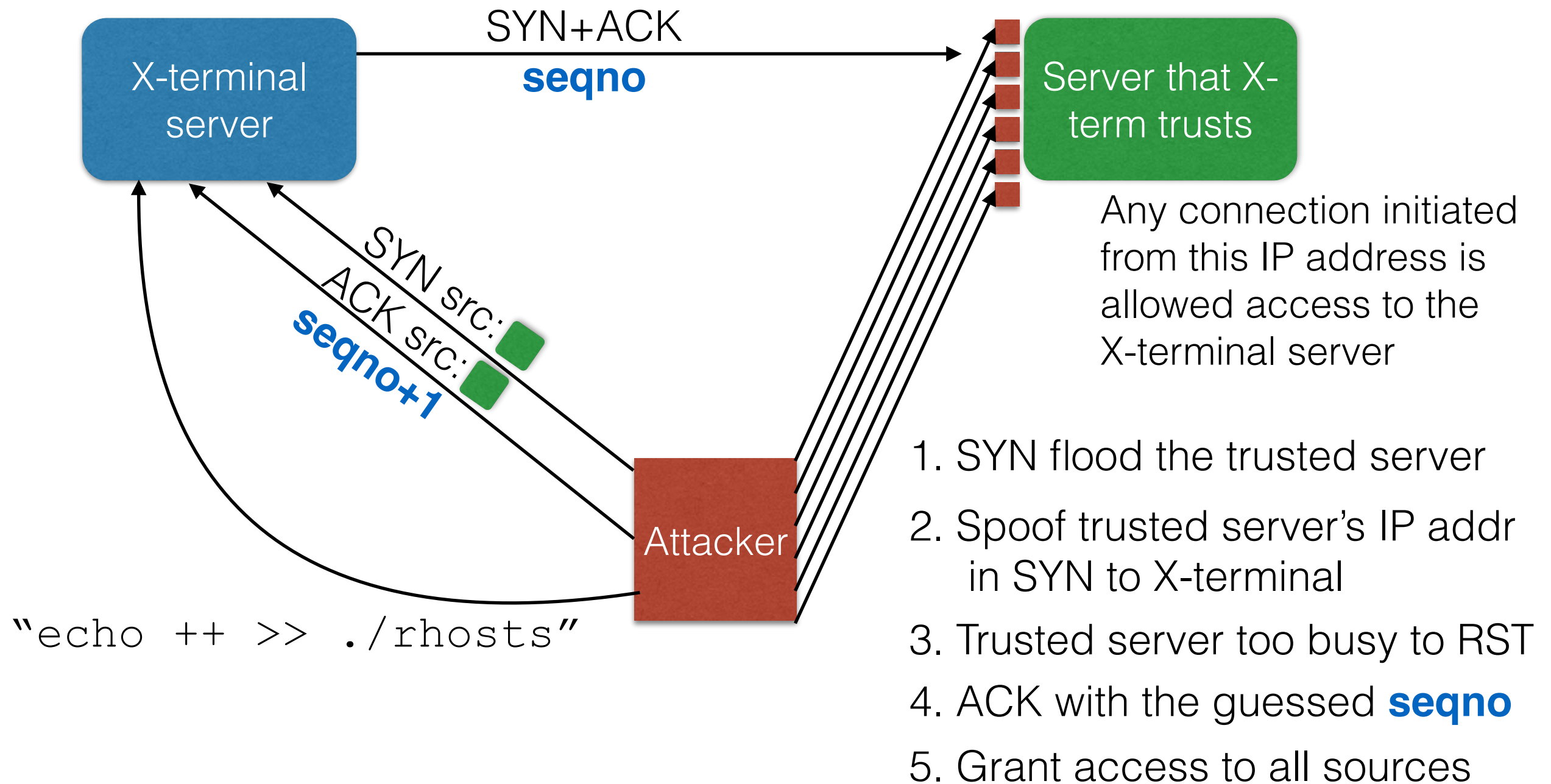
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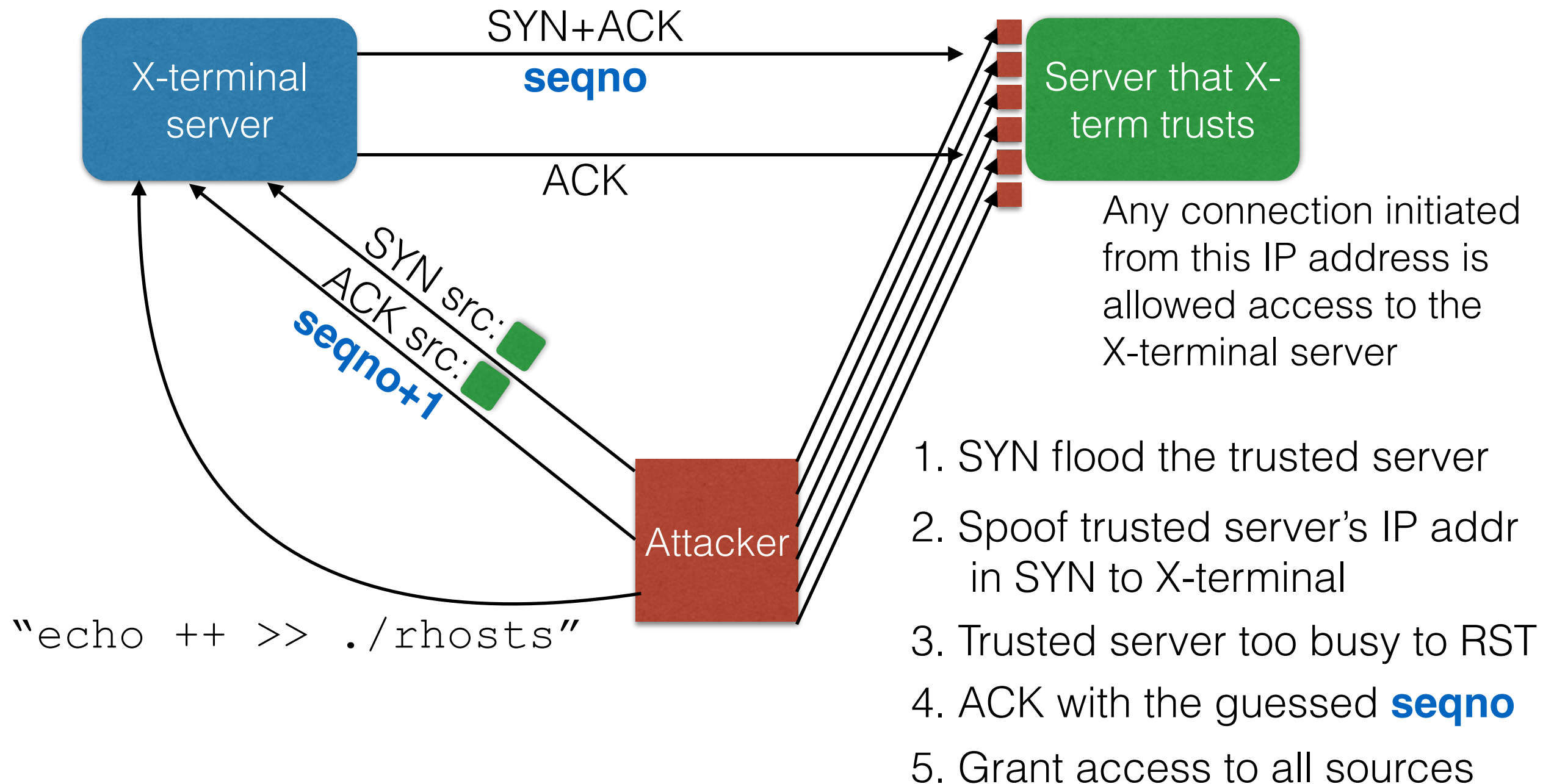
Mitnick attack



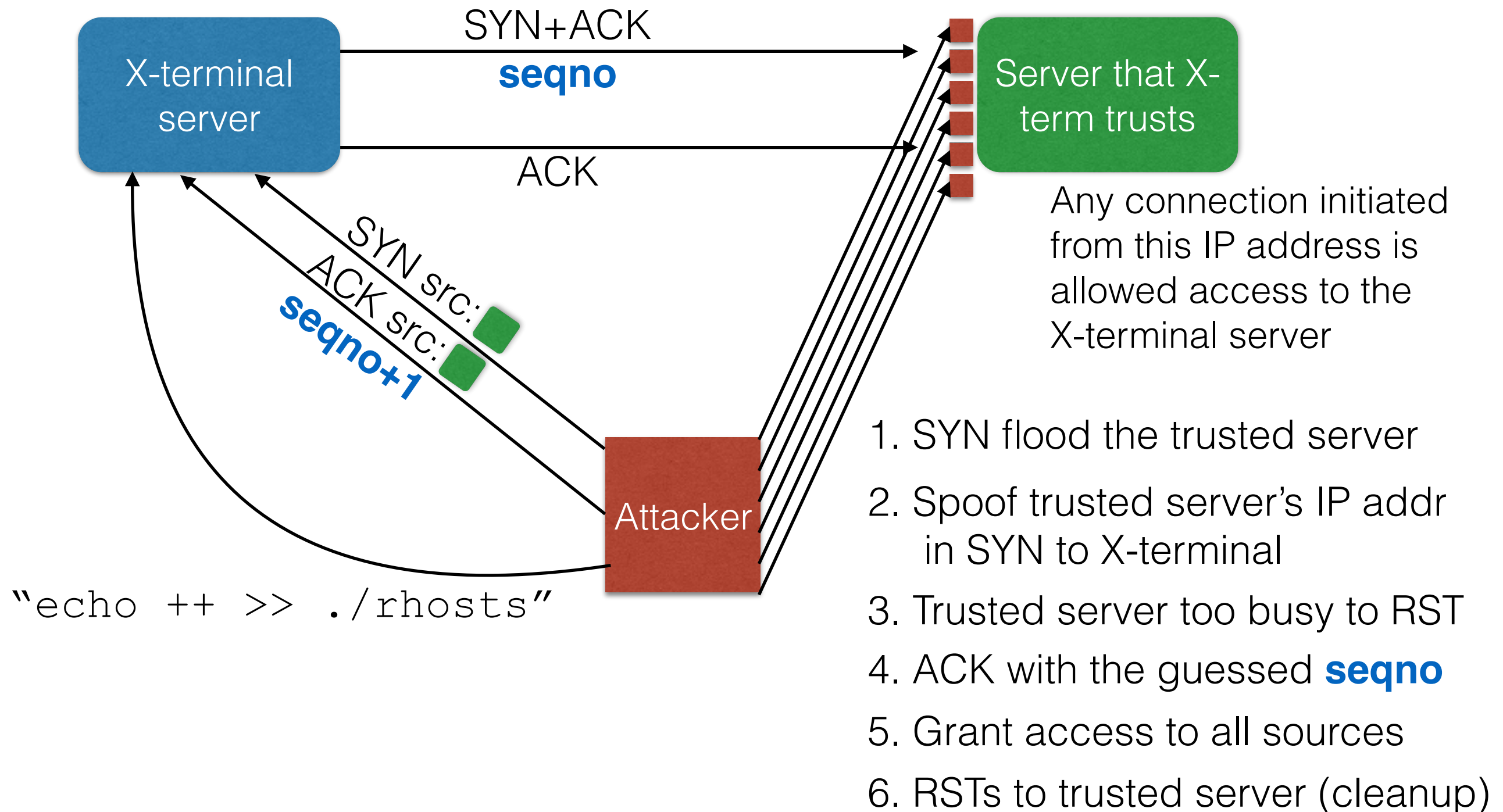
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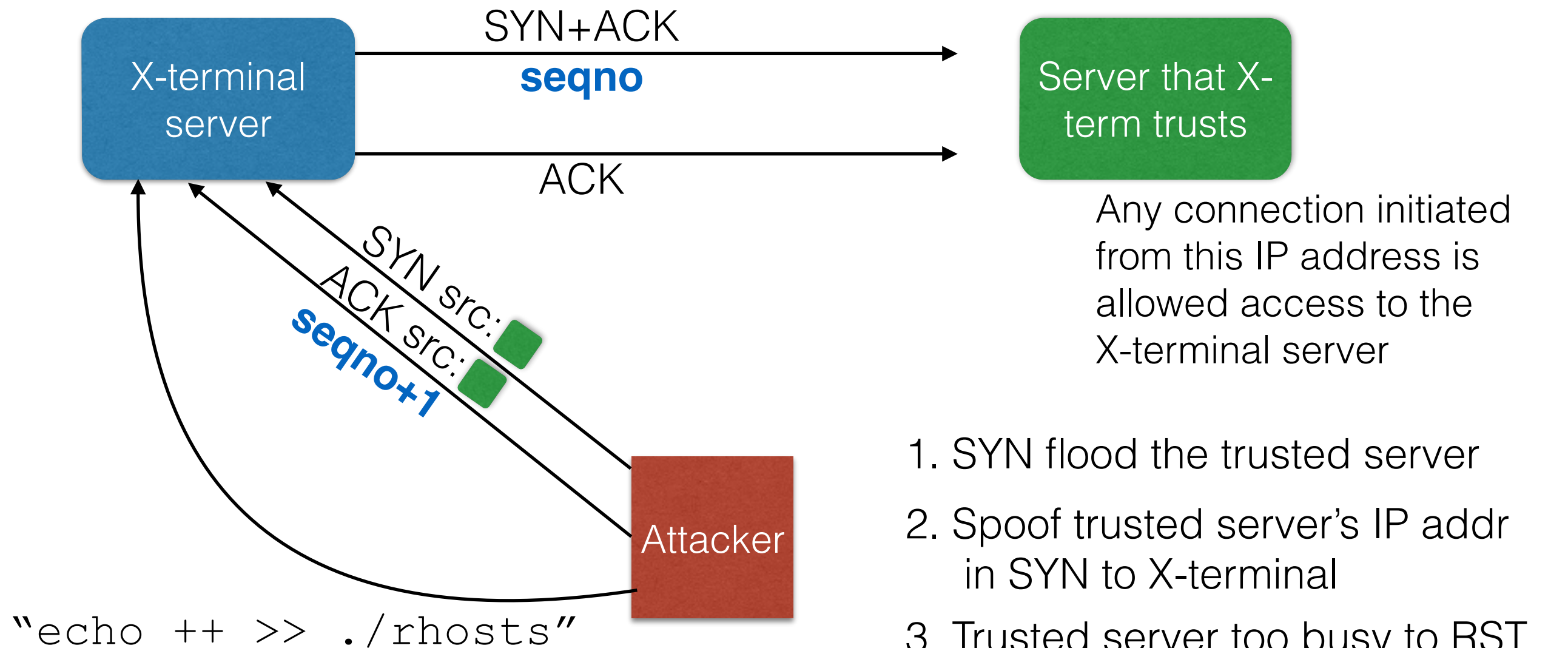
Mitnick attack



Mitnick attack



Mitnick attack



1. SYN flood the trusted server
2. Spoof trusted server's IP addr in SYN to X-terminal
3. Trusted server too busy to RST
4. ACK with the guessed **seqno**
5. Grant access to all sources
6. RSTs to trusted server (cleanup)

Defenses

- Initial sequence number must be difficult to predict!

Opt-ack attack

A



B



TCP uses ACKs not only for reliability, but also for
congestion control:
the more ACKs come back, the faster I can send

Opt-ack attack

A



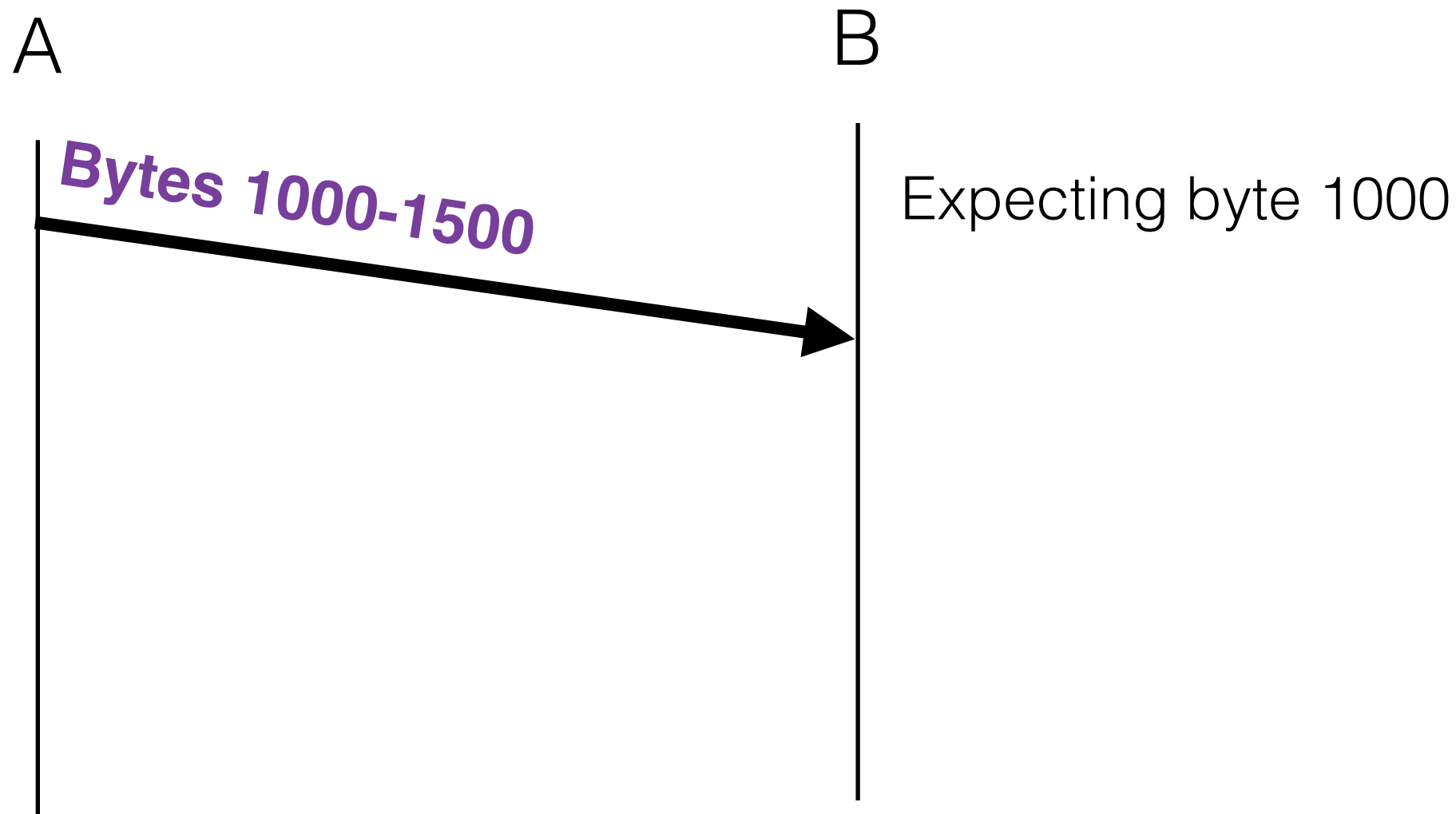
B



Expecting byte 1000

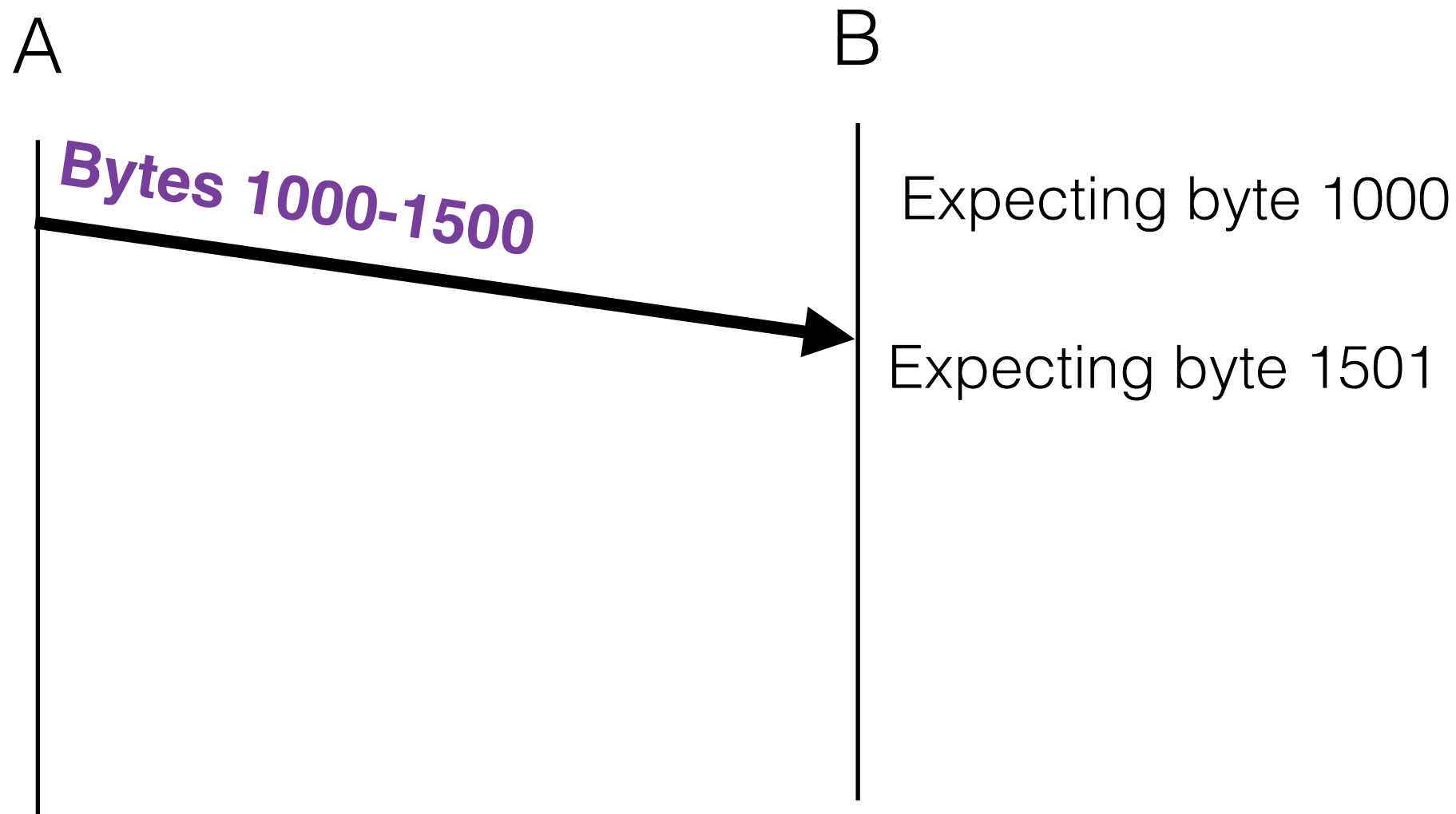
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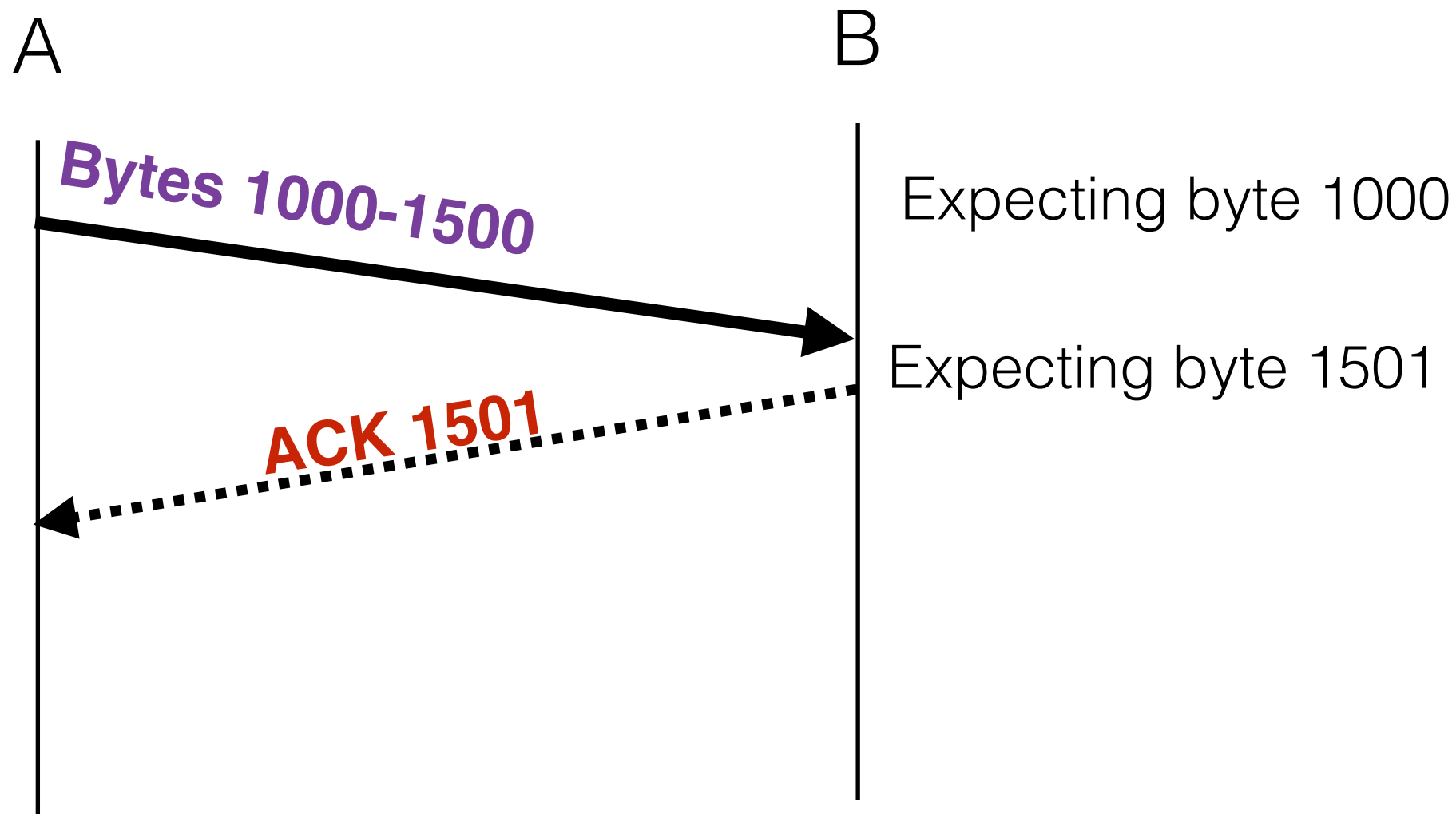
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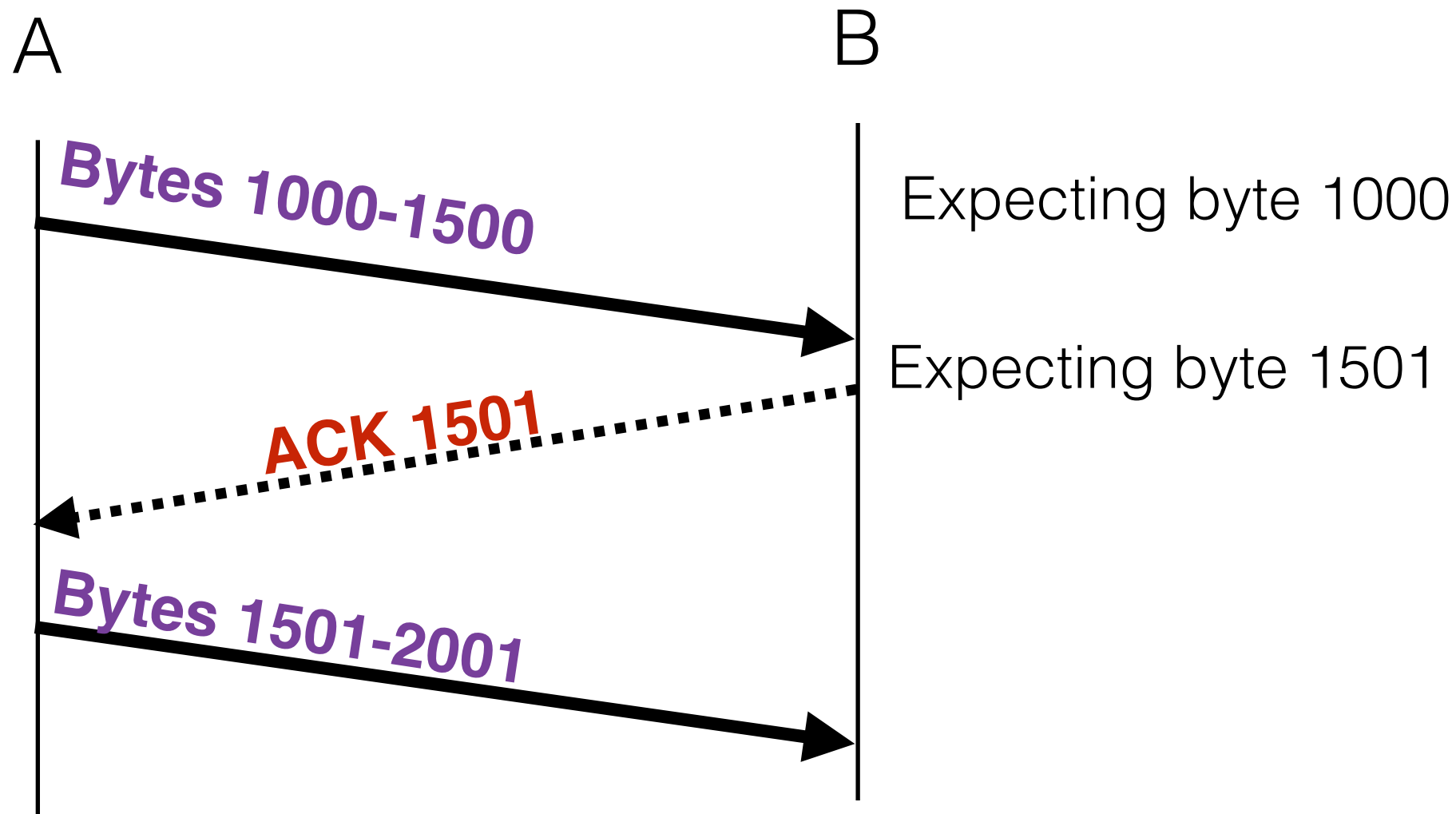
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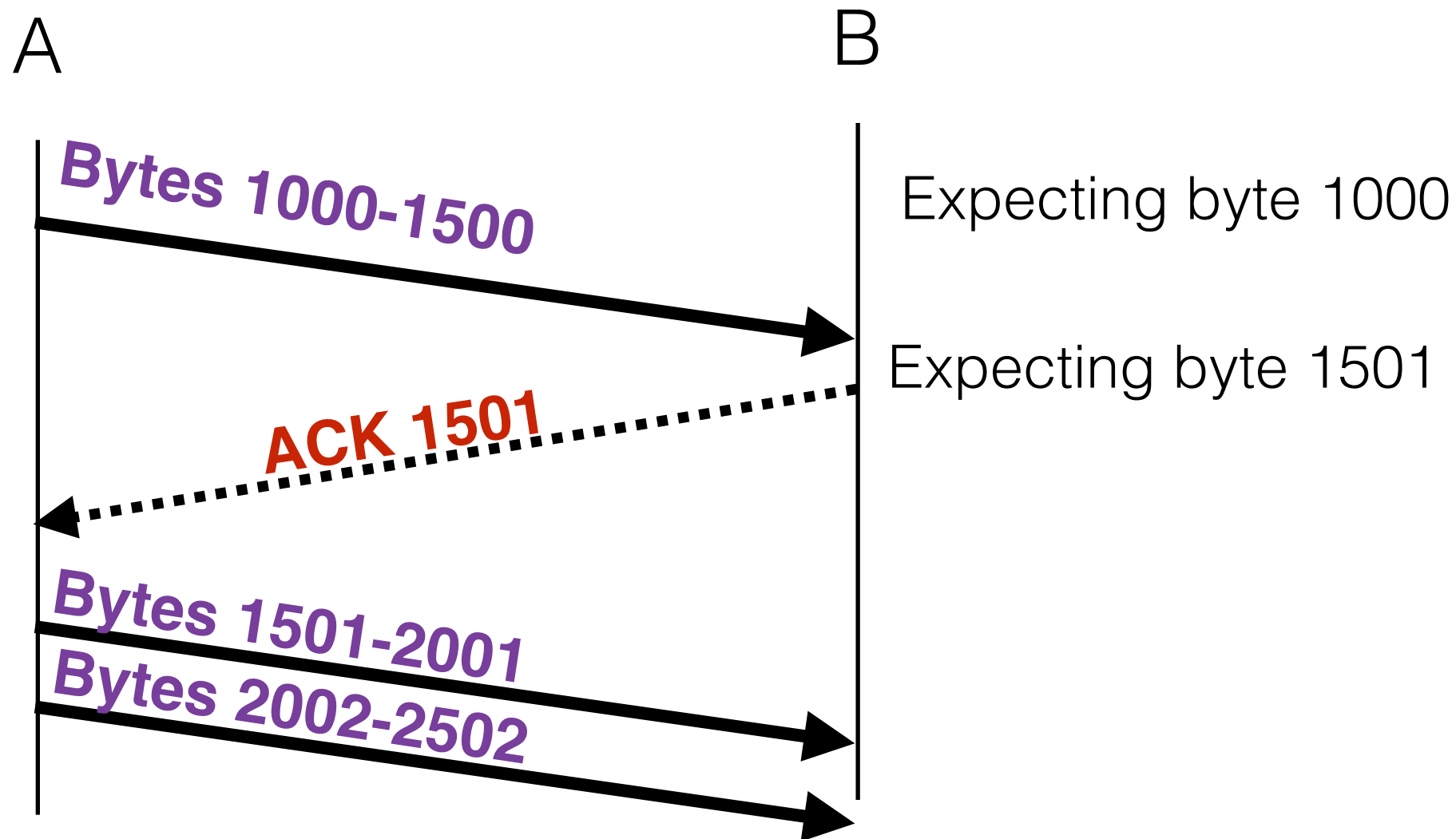
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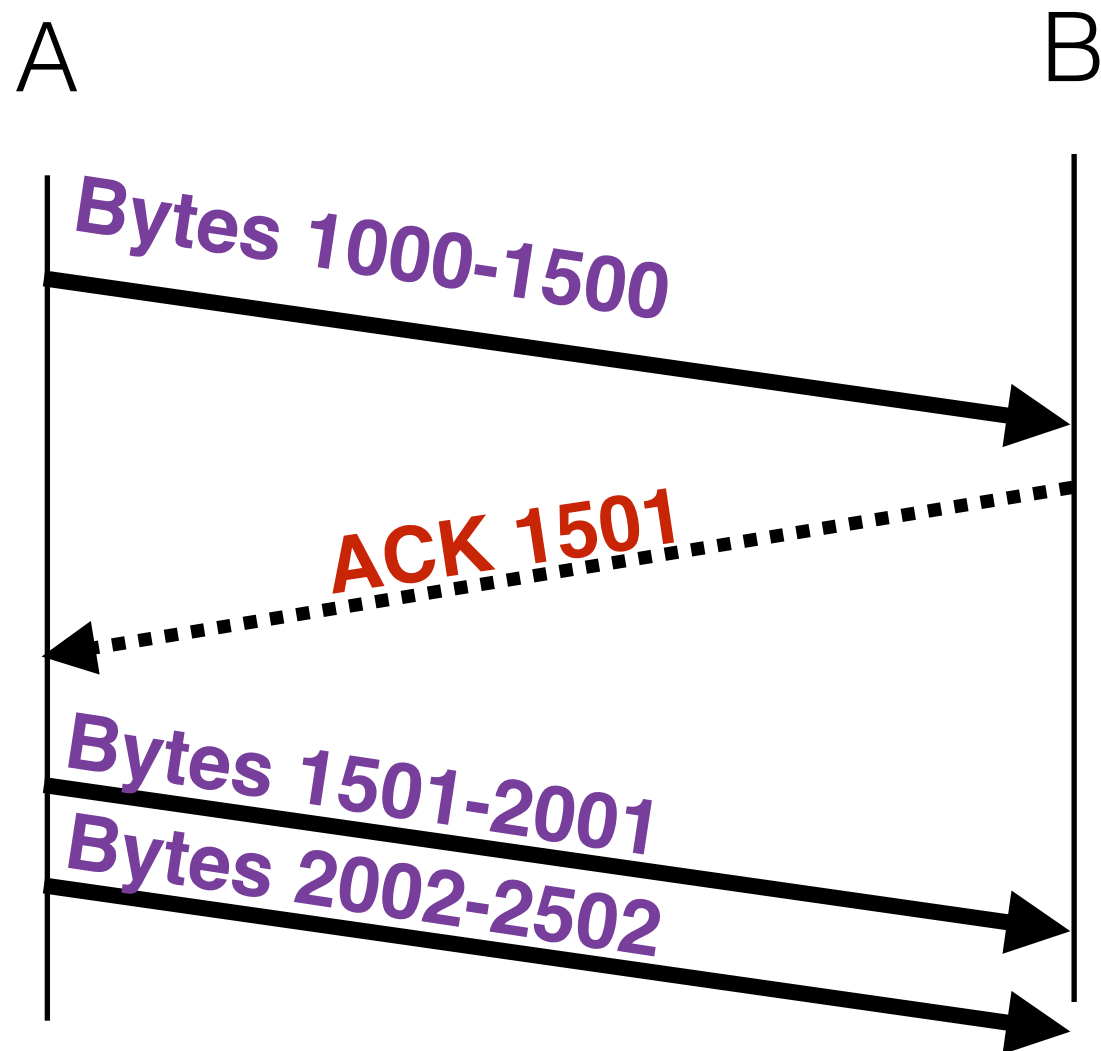
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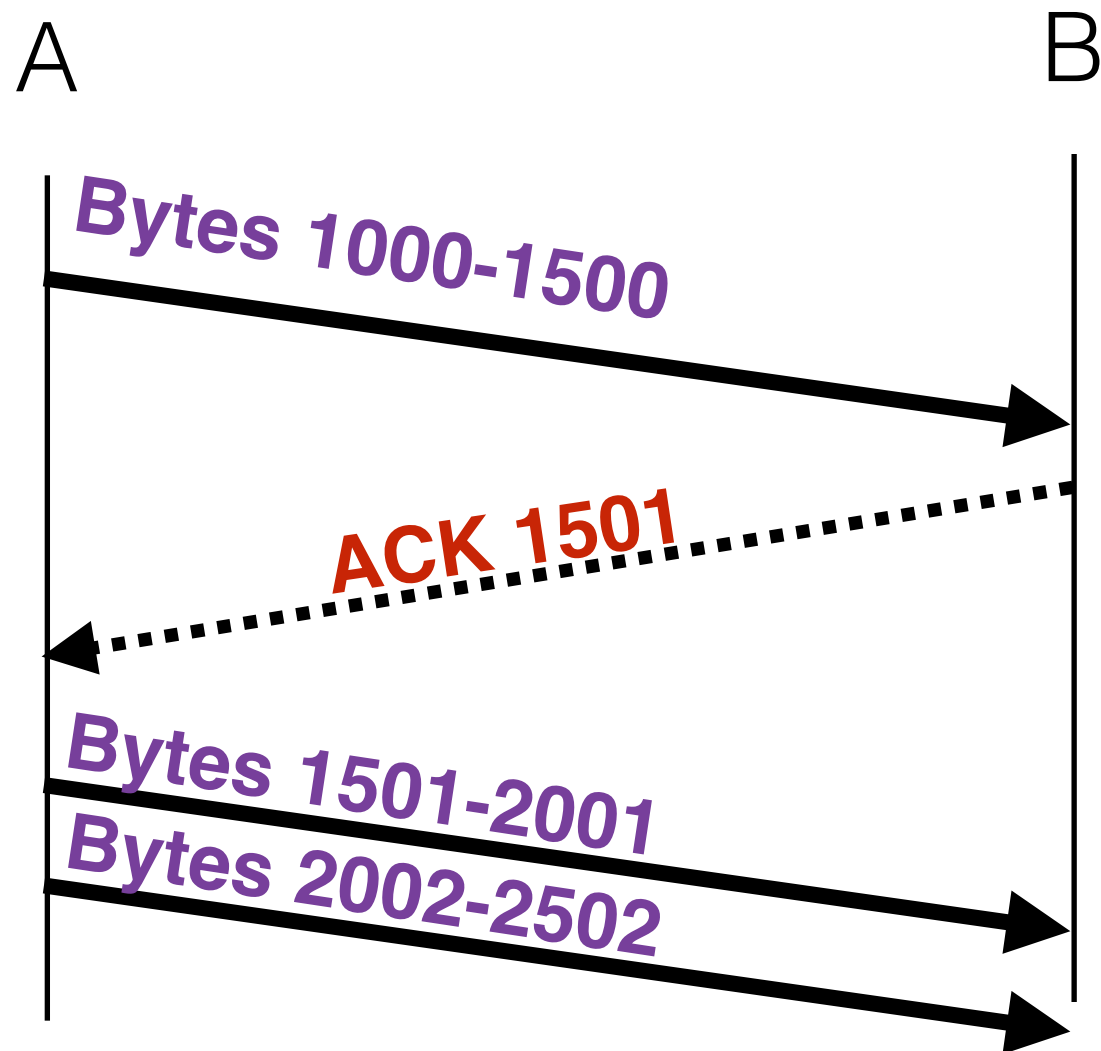


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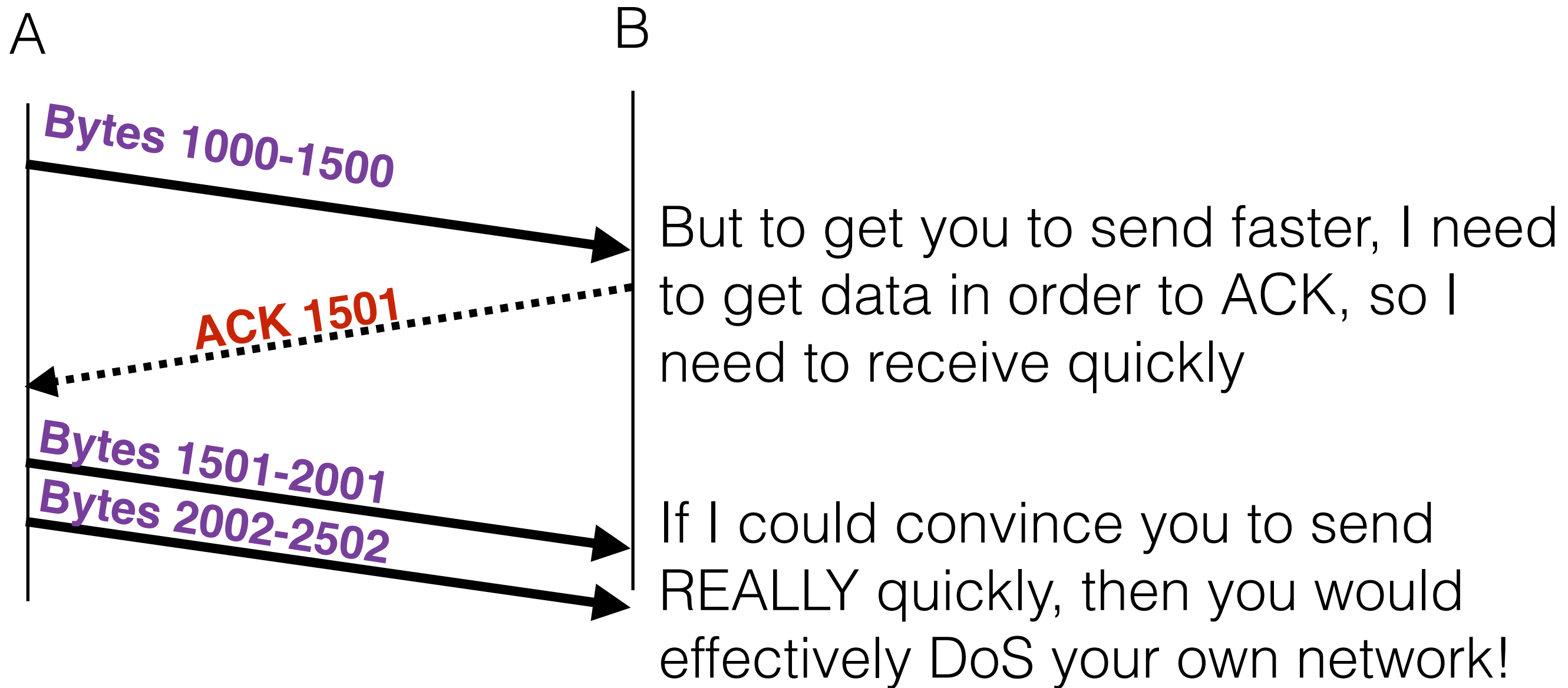


Opt-ack attack

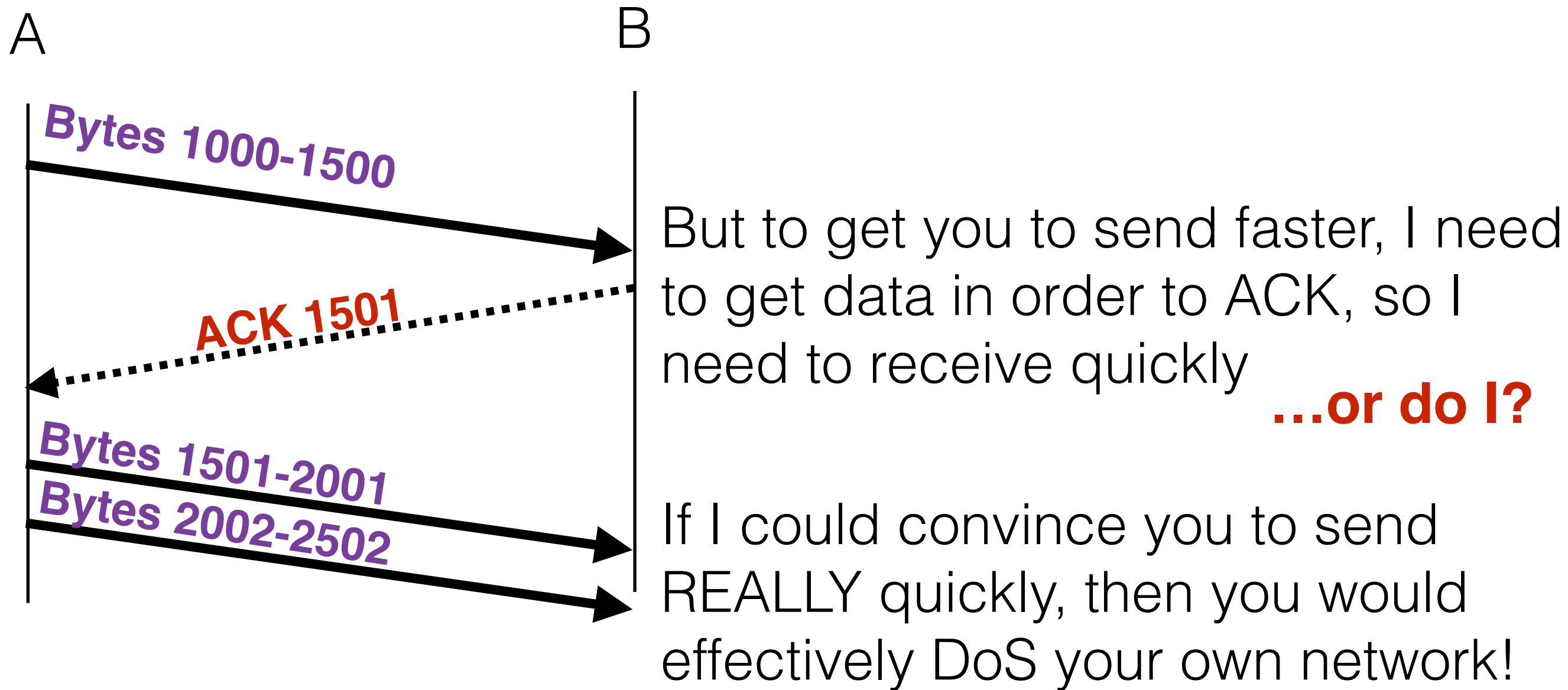


If I could convince you to send REALLY quickly, then you would effectively DoS your own network!

Opt-ack attack



Opt-ack attack



Opt-ack attack

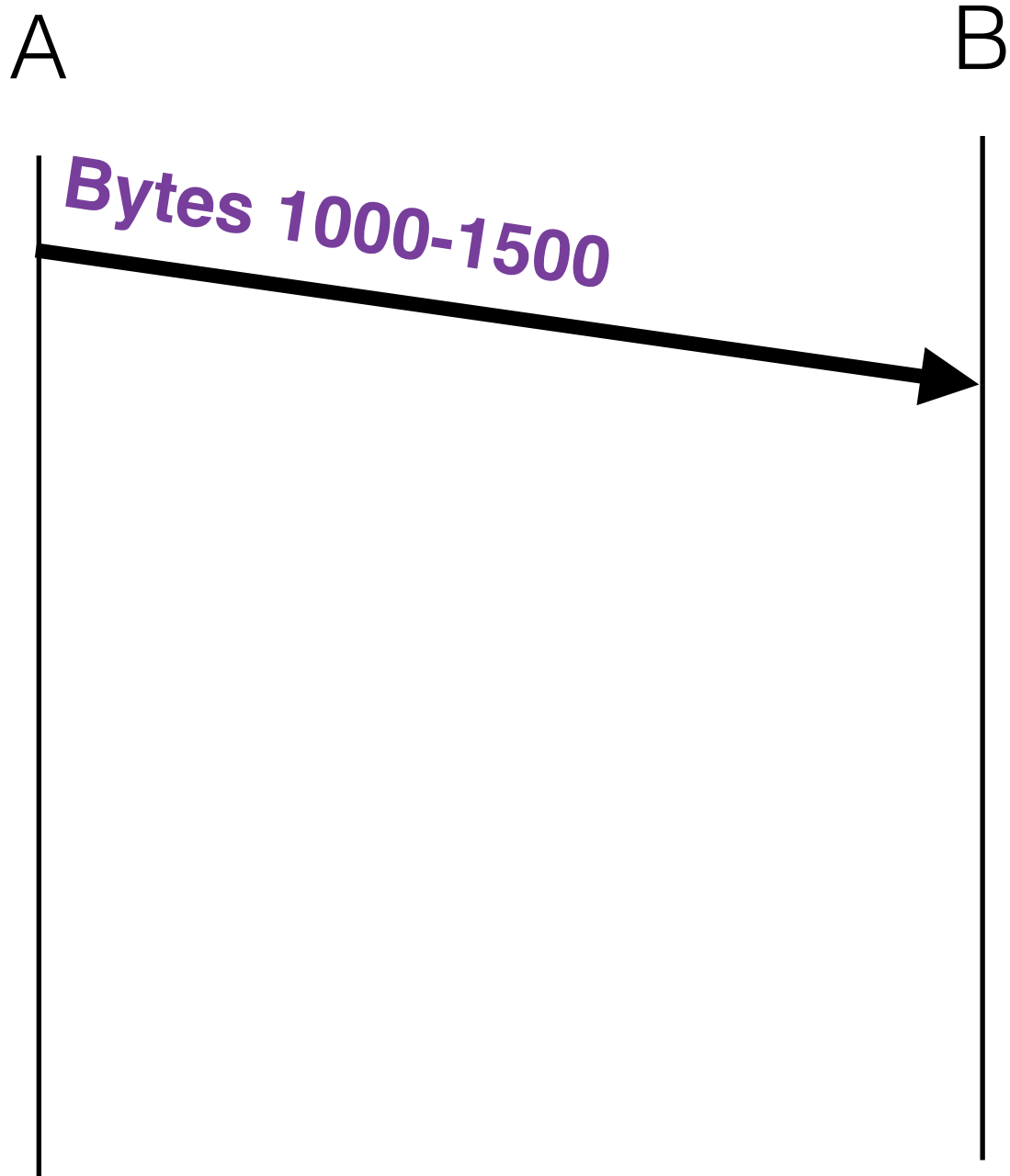
A



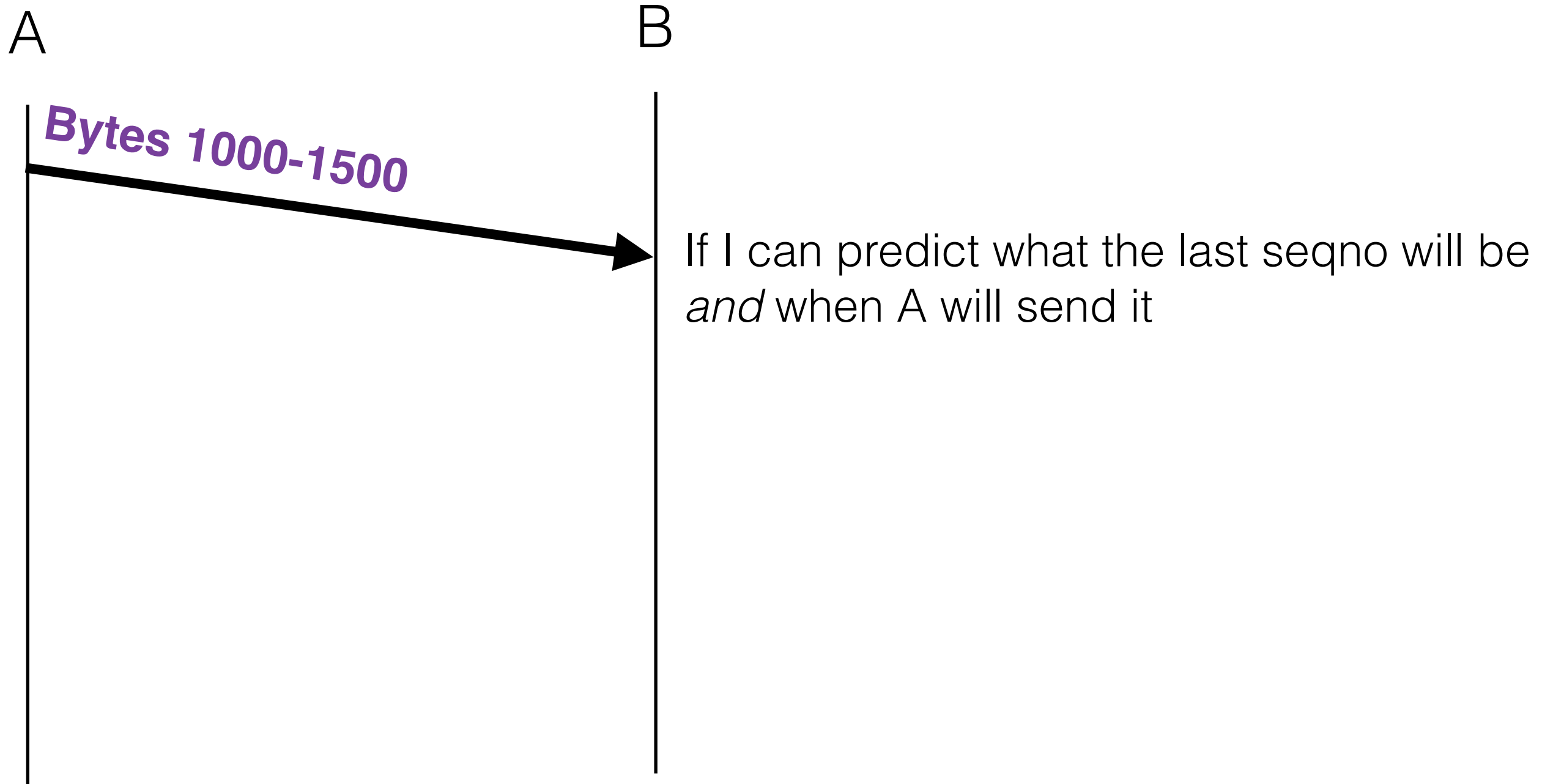
B



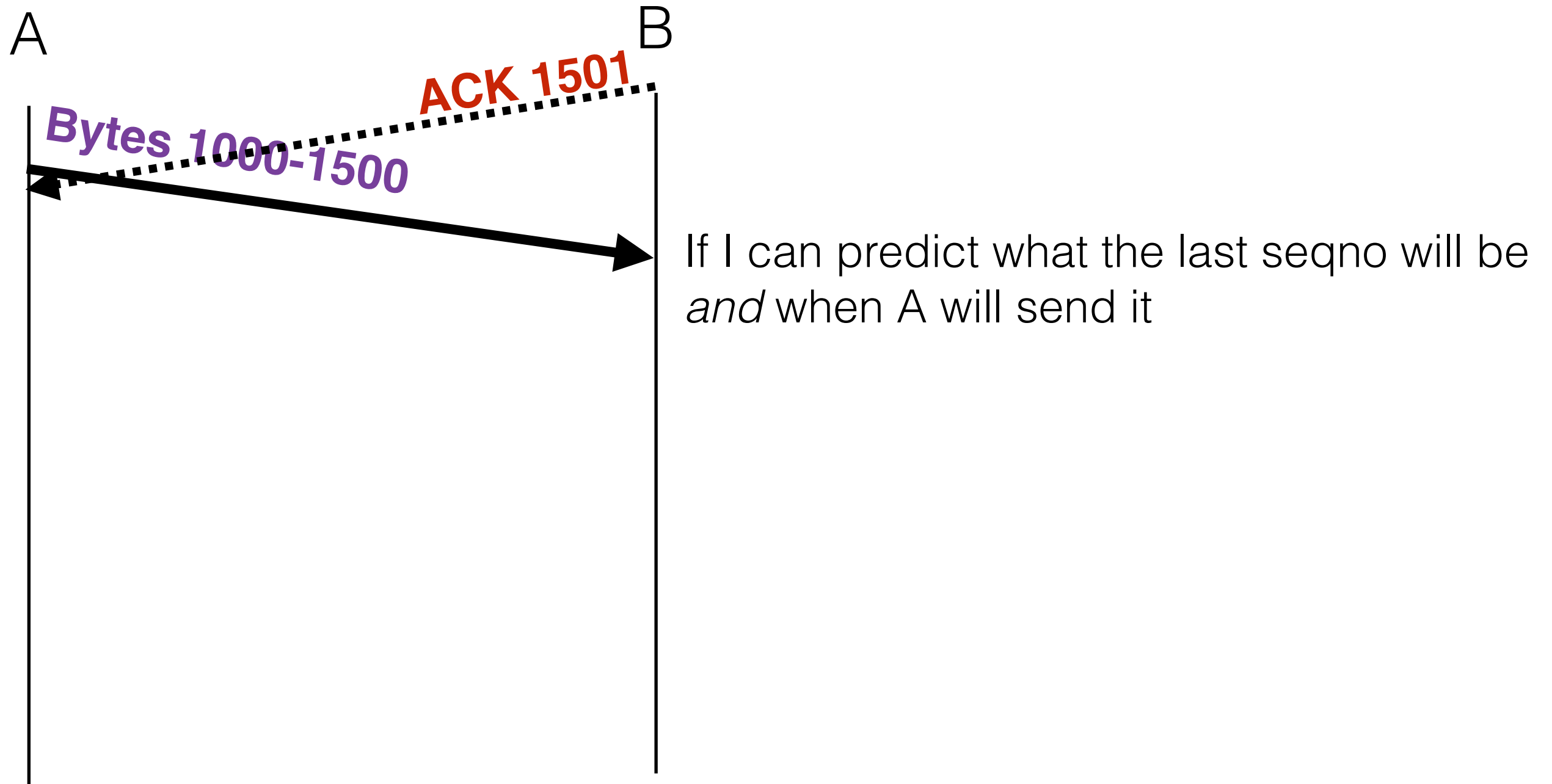
Opt-ack attack



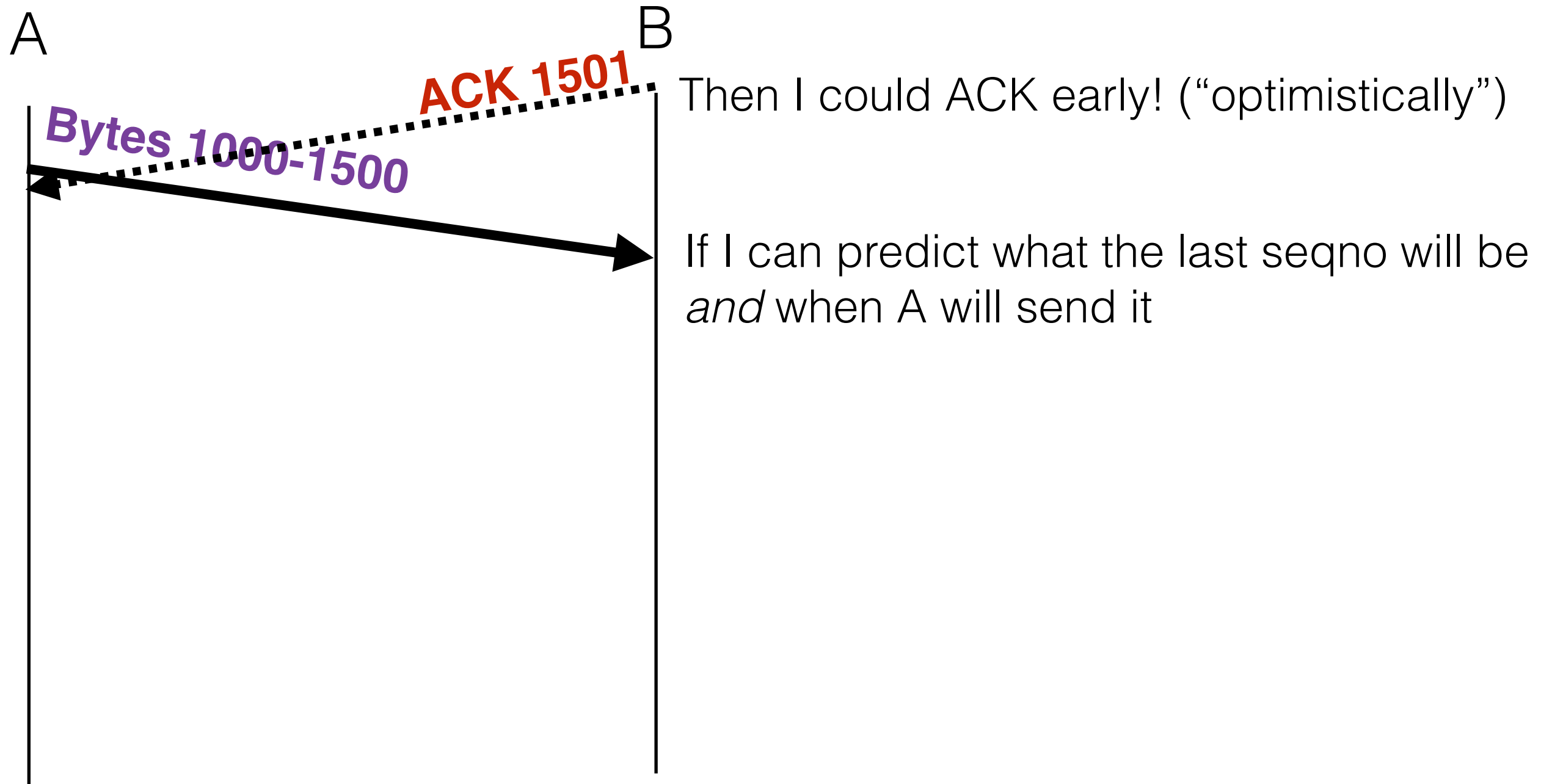
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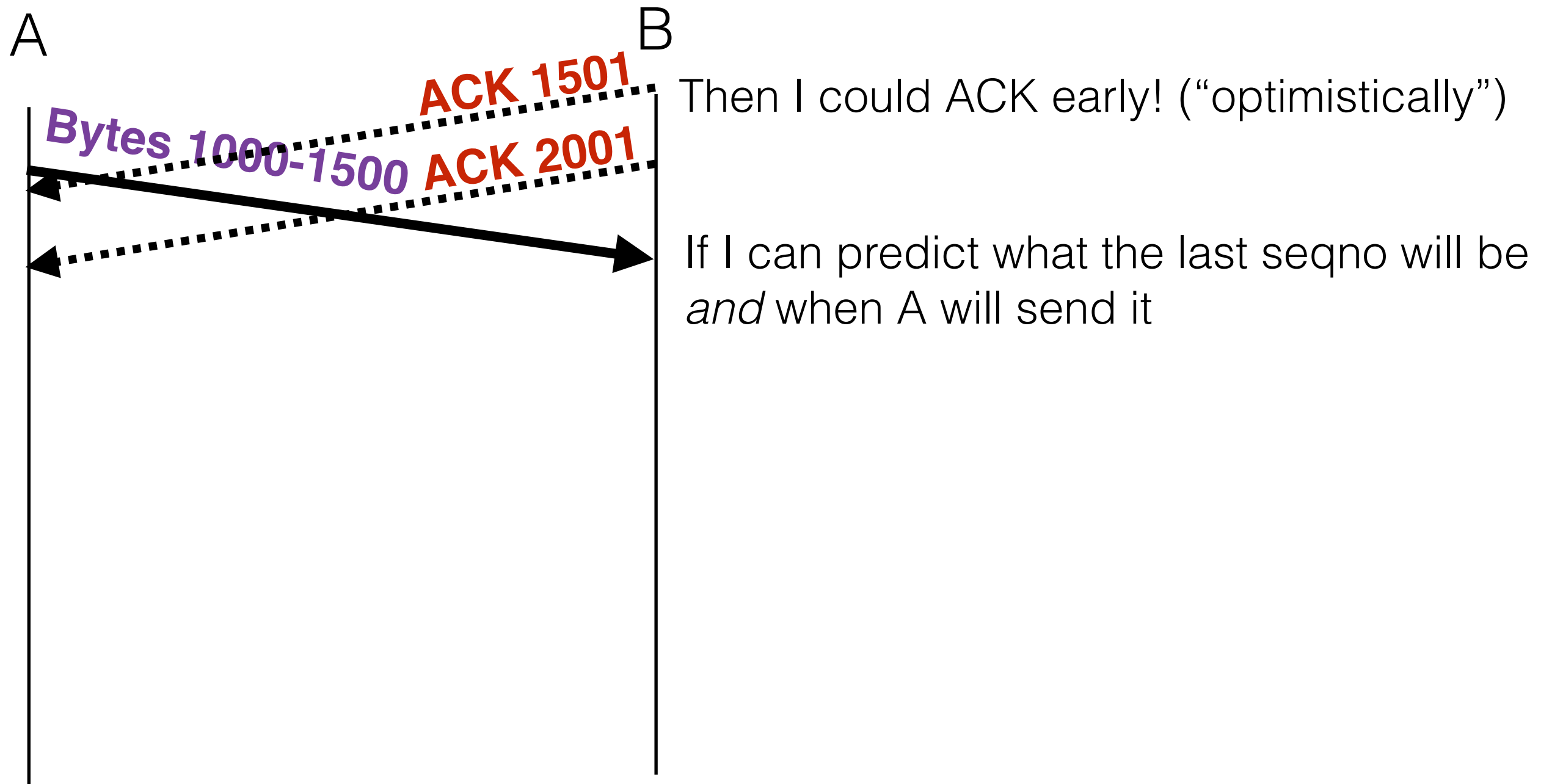
Opt-ack attack



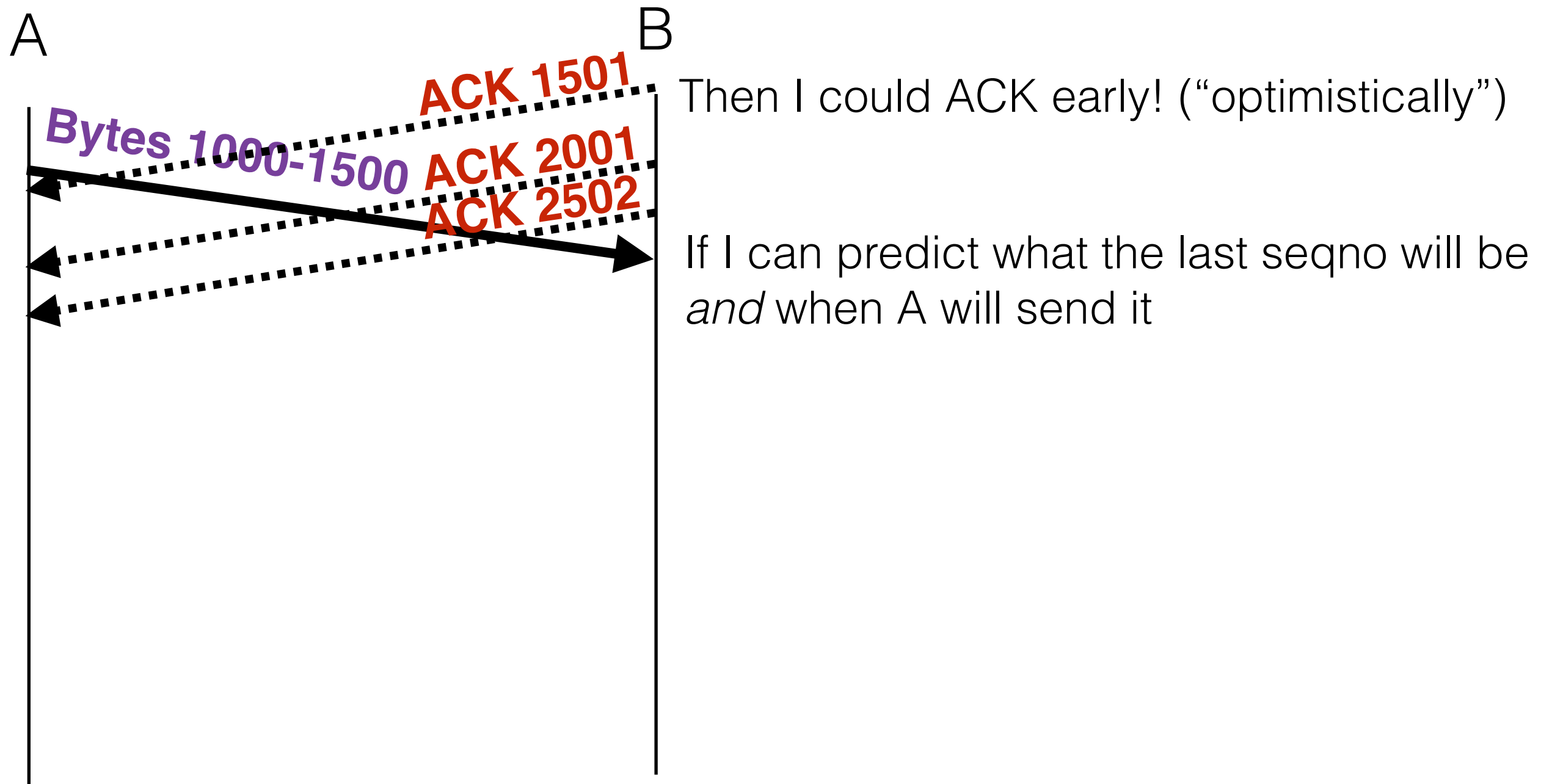
Opt-ack attack



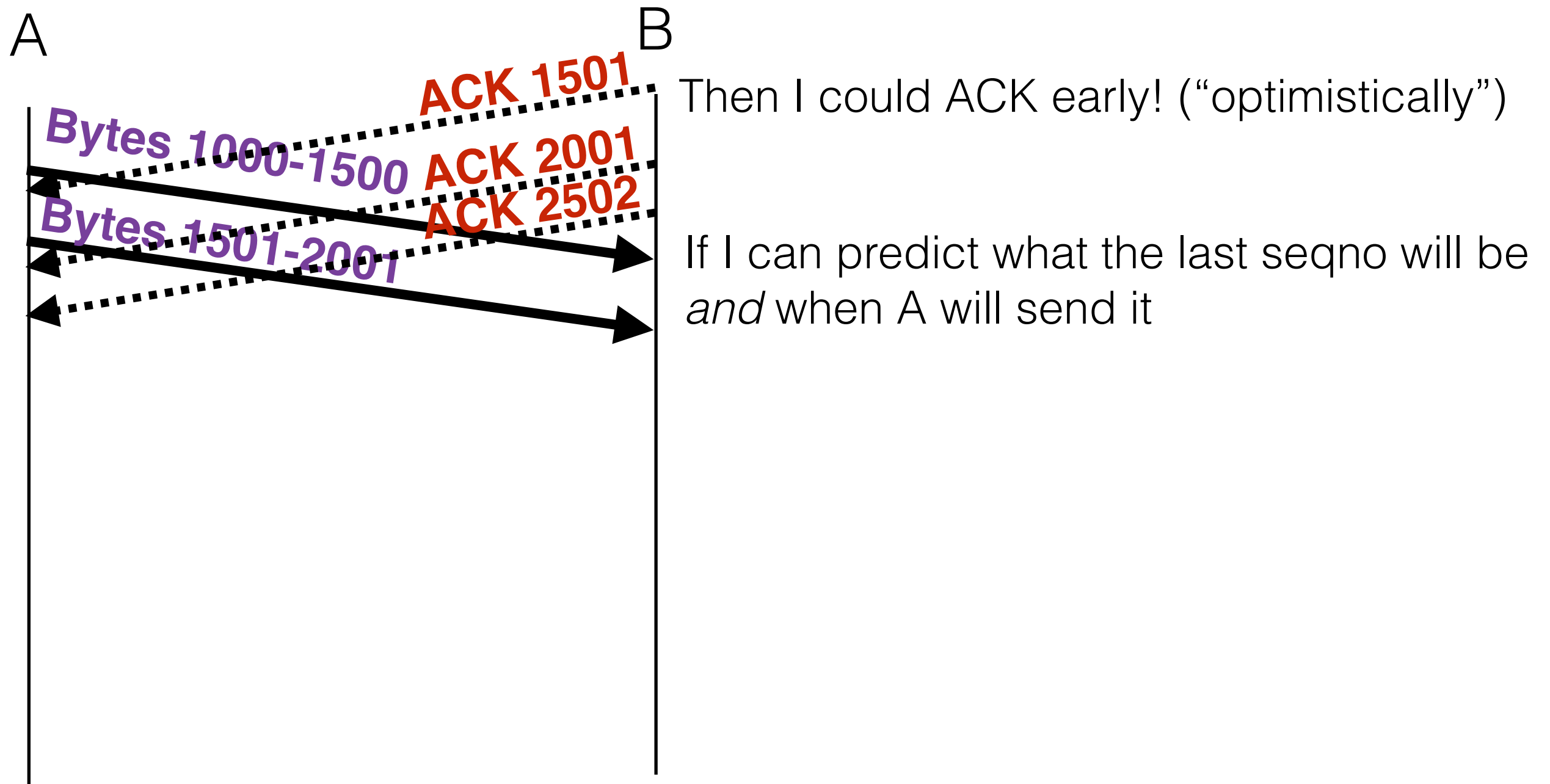
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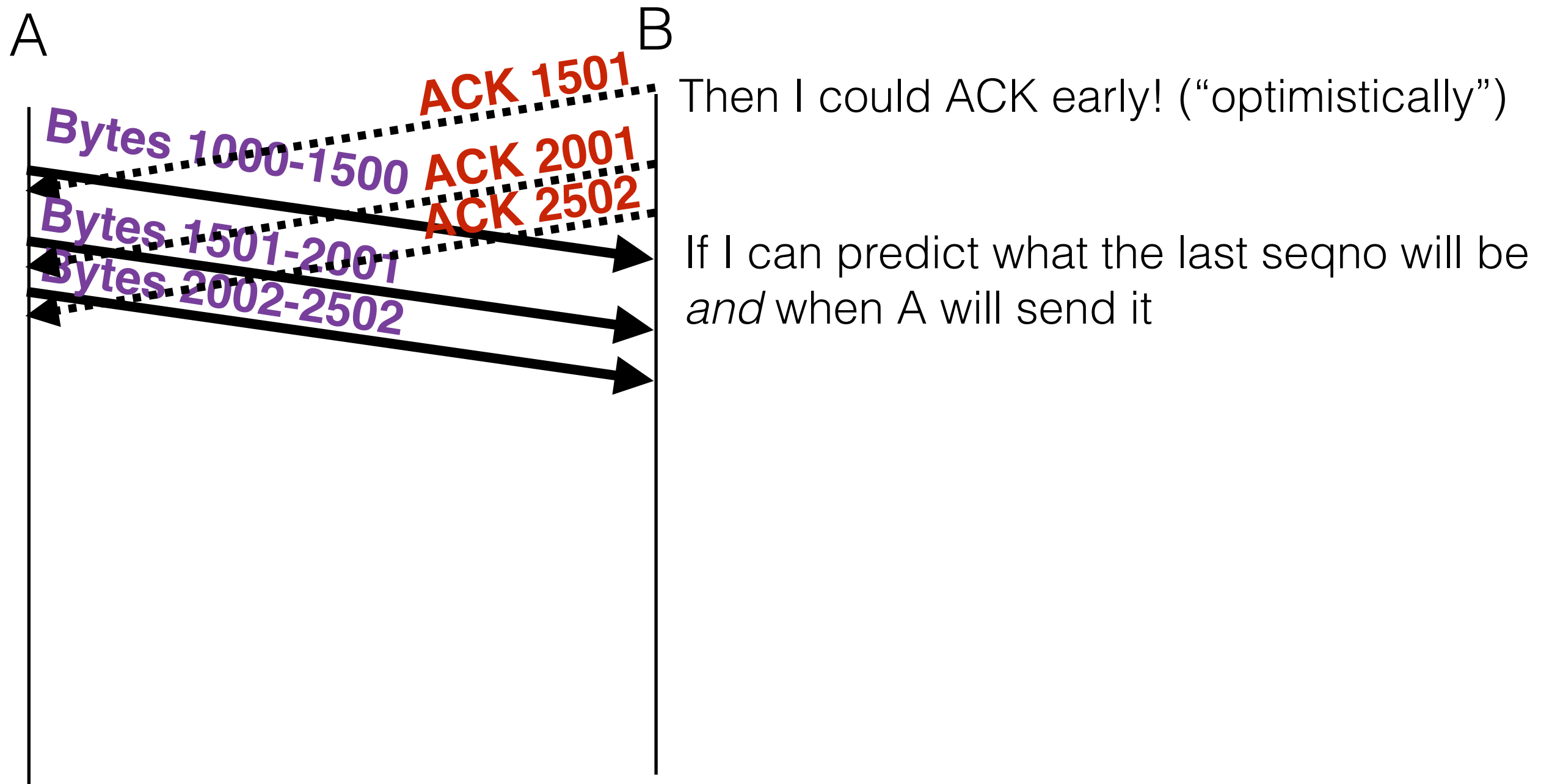
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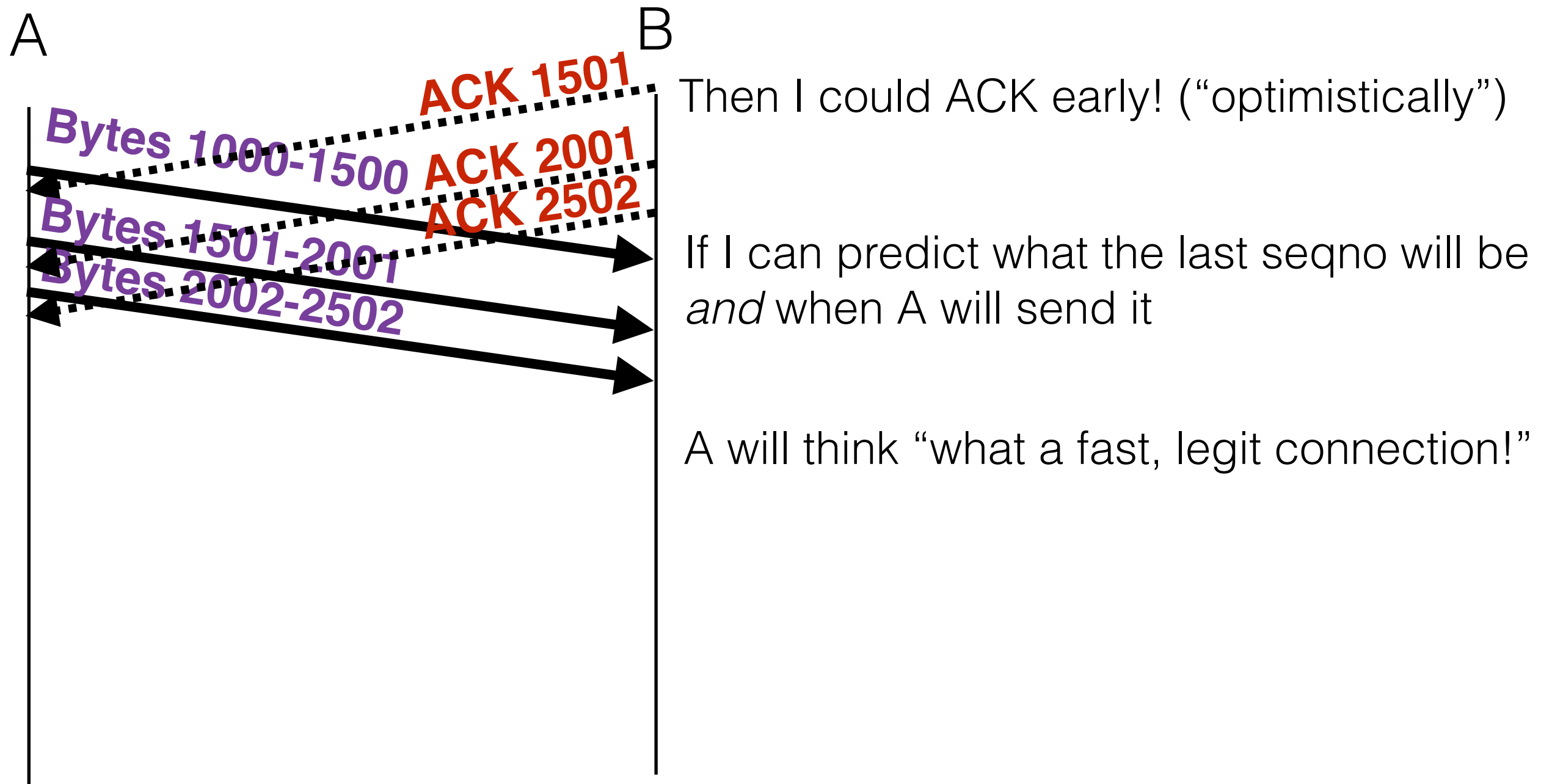
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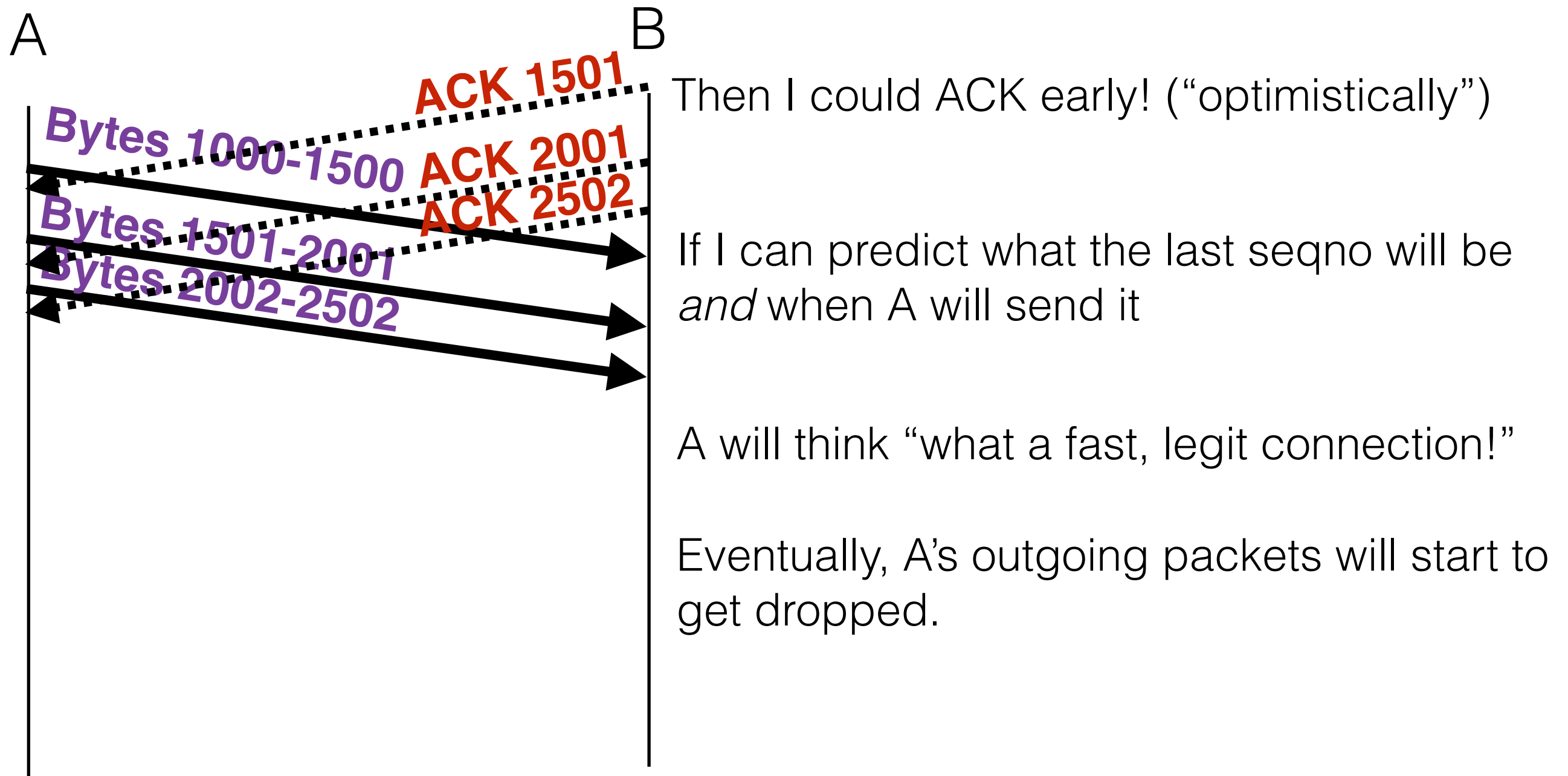
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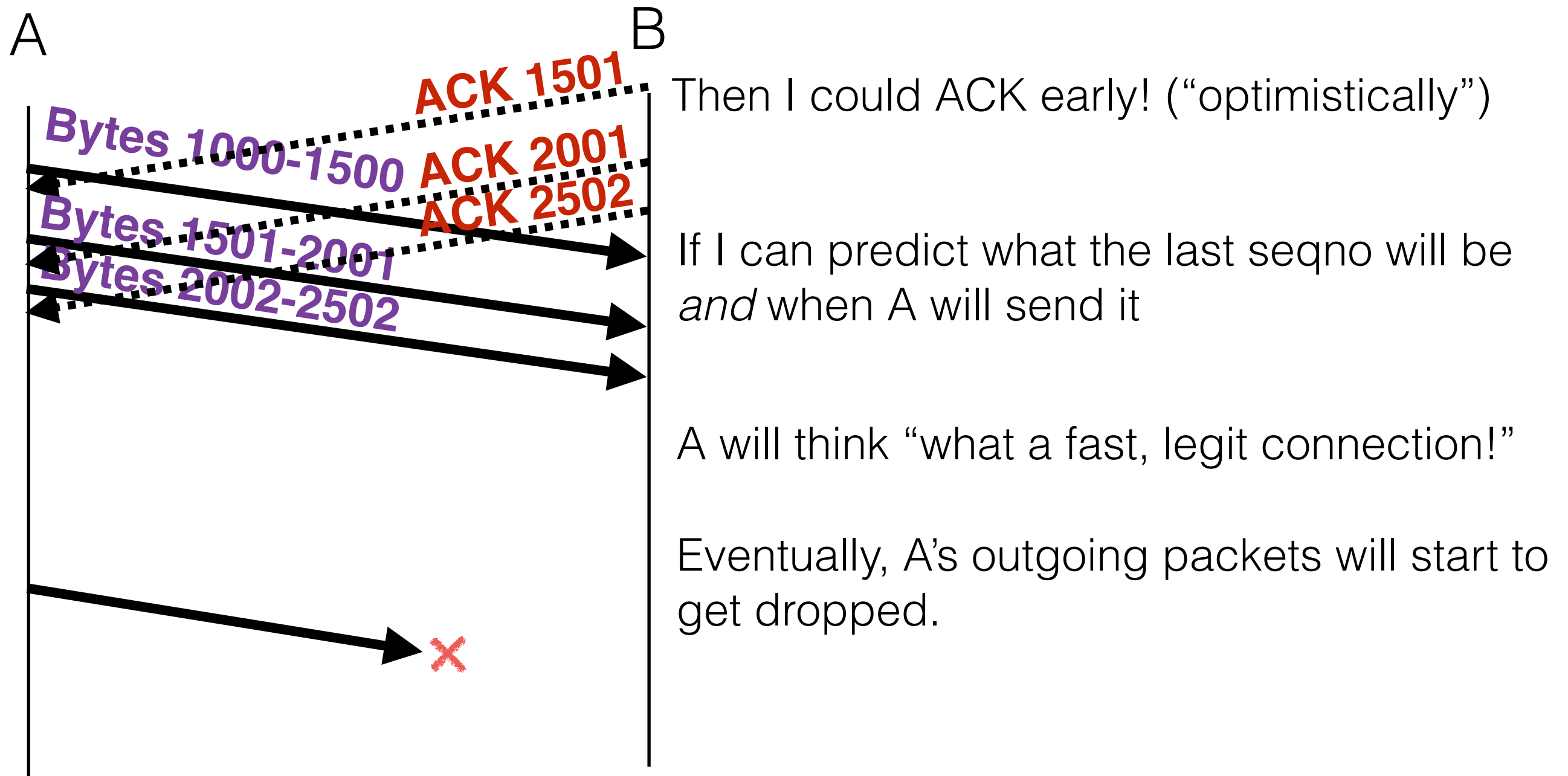
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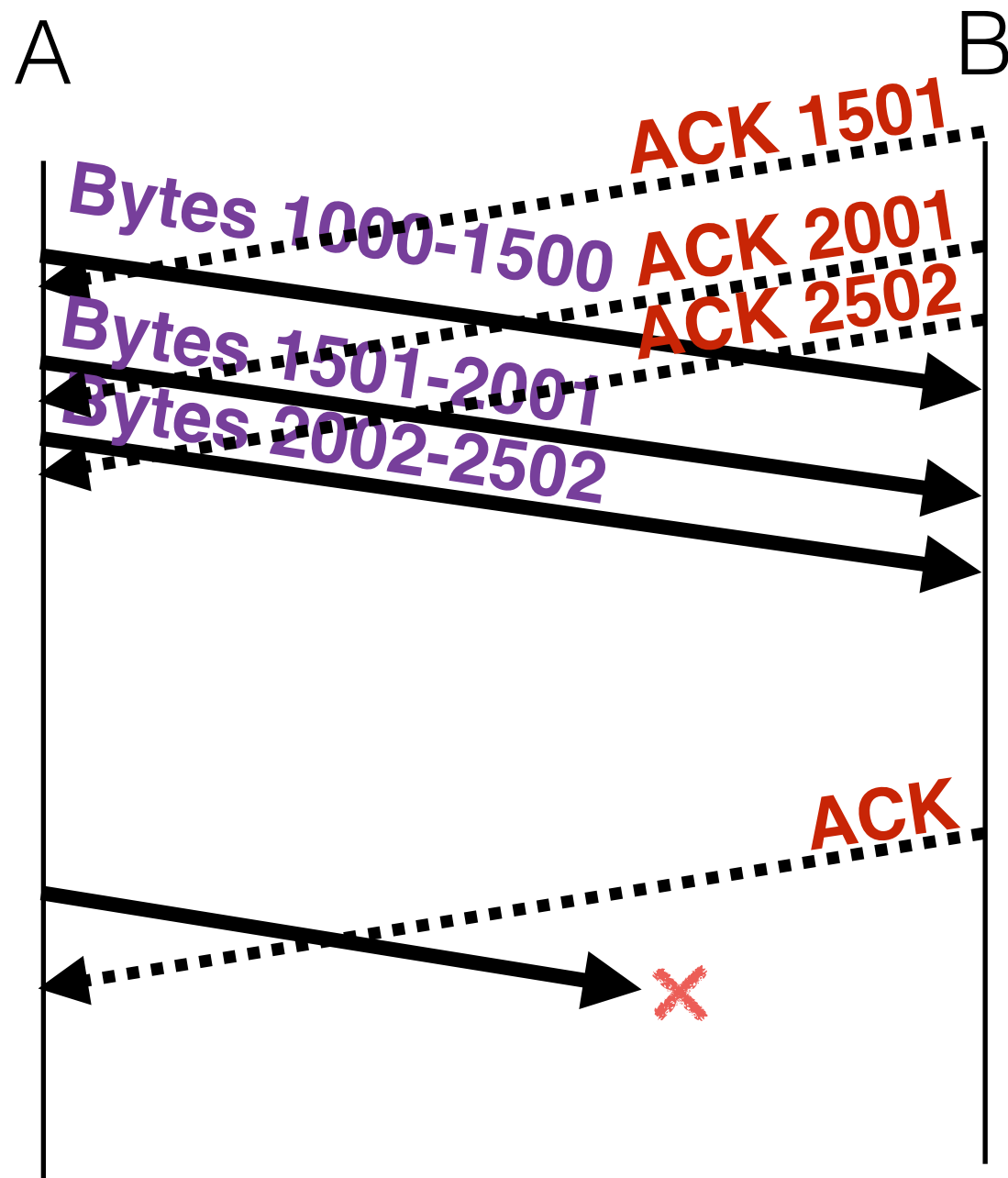
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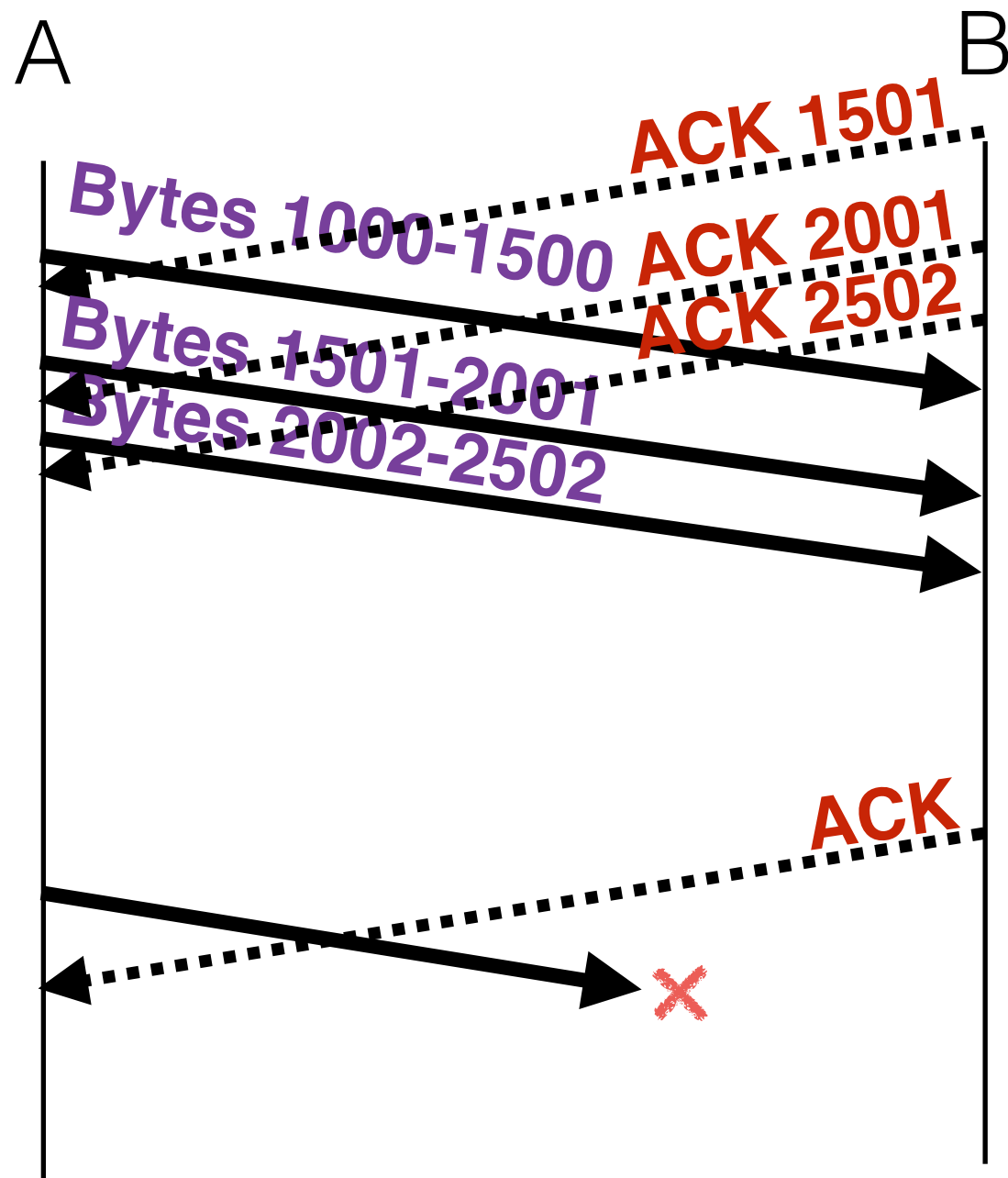
Then I could ACK early! (“optimistically”)

If I can predict what the last seqno will be
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A will think “what a fast, legit connection!”

Eventually, A’s outgoing packets will start to
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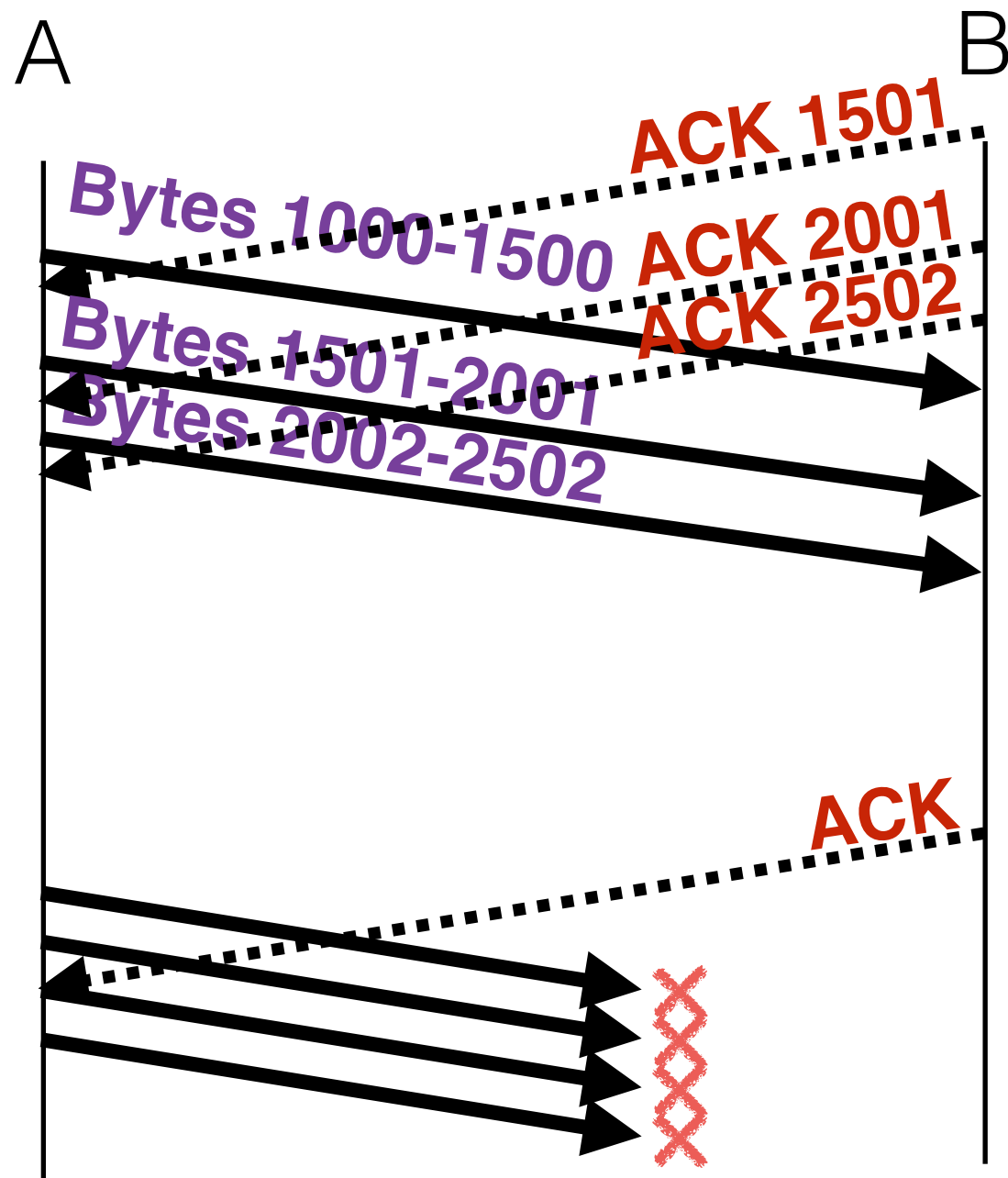
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Amplification

- The big deal with this attack is its *Amplification Factor*
 - Attacker sends x bytes of data, causing the victim to send many more bytes of data in response
 - Recent examples: NTP, DNSSEC
- Amplified in TCP due to cumulative ACKs
 - “ACK x ” says “I’ve seen all bytes up to but not including x ”

Opt-ack's amplification factor

- Max bytes sent by victim per ACK:
- Max ACKs attacker can send per second:

Opt-ack's amplification factor

- Max bytes sent by victim per ACK:

$$\begin{array}{c} \text{Packets sent per ACK} \\ \hline \frac{\text{Max window size}}{\text{MSS}} \end{array} \times \begin{array}{c} \text{Bytes per packet} \\ (14 + 40 + \text{MSS}) \end{array}$$

Ethernet TCP/IP Payload

- Max ACKs attacker can send per second:

Opt-ack's amplification factor

- Max bytes sent by victim per ACK:

$$\begin{array}{c} \text{Packets sent per ACK} \\ \hline \frac{\text{Max window size}}{\text{MSS}} \end{array} \times \begin{array}{c} \text{Bytes per packet} \\ (14 + 40 + \text{MSS}) \end{array}$$

Ethernet TCP/IP Payload

- Max ACKs attacker can send per second:

$$\frac{\text{Attacker bandwidth (bytes/sec)}}{(14 + 40)}$$

Size of ACK packet

Opt-ack's amplification factor

- Boils down to max window size and MSS
 - Default max window size: 65,536
 - Default MSS: 536
- Default amp factor: $65536 * (1/536 + 1/54) \sim \mathbf{1336x}$
- Window scaling lets you increase this by a factor of 2^{14}
- Window scaling amp factor: $\sim 1336 * 2^{14} \sim \mathbf{22M}$
- Using minimum MSS of 88: $\sim \mathbf{32M}$

Opt-ack defenses

- Is there a way we could defend against opt-ack in a way that is still compatible with existing implementations of TCP?
- An important goal in networking is *incremental deployment*: ideally, we should be able to benefit from a system/modification when even a subset of hosts deploy it.

Next time

- We now know how to communicate *reliably* and *securely* with a given destination IP address
- Next up: **Naming**
- How do we *get* an IP address, and can we attack that process?
 - DHCP
- Given bank.com, how do we get its IP address?
 - DNS
 - Kaminsky attack