TCP/IP SECURITY

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TODAY'S PAPERS

Off-Path TCP Exploits: Global Rate Limit Considered Dangerous

Yue Cao, Zhiyun Qian, Zhongjie Wang, Tuan Dao, Srikanth V. Krishnamurthy, Lisa M. Marvel[†]
University of California, Riverside, [†]*US Army Research Laboratory*
{ycao009,zhiyunq,zwang048,tdao006,krish}@cs.ucr.edu, lisa.m.marvel.civ@mail.mil

Abstract

In this paper, we report a subtle yet serious side channel vulnerability (CVE-2016-5696) introduced in a recent TCP specification. The specification is faithfully implemented in Linux kernel version 3.6 (from 2012) and beyond, and affects a wide range of devices and hosts. In a nutshell, the vulnerability allows a blind off-path attacker to infer if any two arbitrary hosts on the Internet are communicating using a TCP connection. Further, if the connection is present, such an off-path attacker can also infer the TCP sequence numbers in use, from both sides of the connection; this in turn allows the attacker to cause connection termination and perform data injection attacks. We illustrate how the attack can be leveraged to disrupt or degrade the privacy guarantees of an anonymity network such as Tor, and perform web connection hijacking. Through extensive experiments, we show that the attack is fast and reliable. On average, it takes about 40 to 60 seconds to finish and the success rate is 88% to 97%. Finally, we propose changes to both the TCP specification and implementation to eliminate the root cause of the problem.

1 Introduction

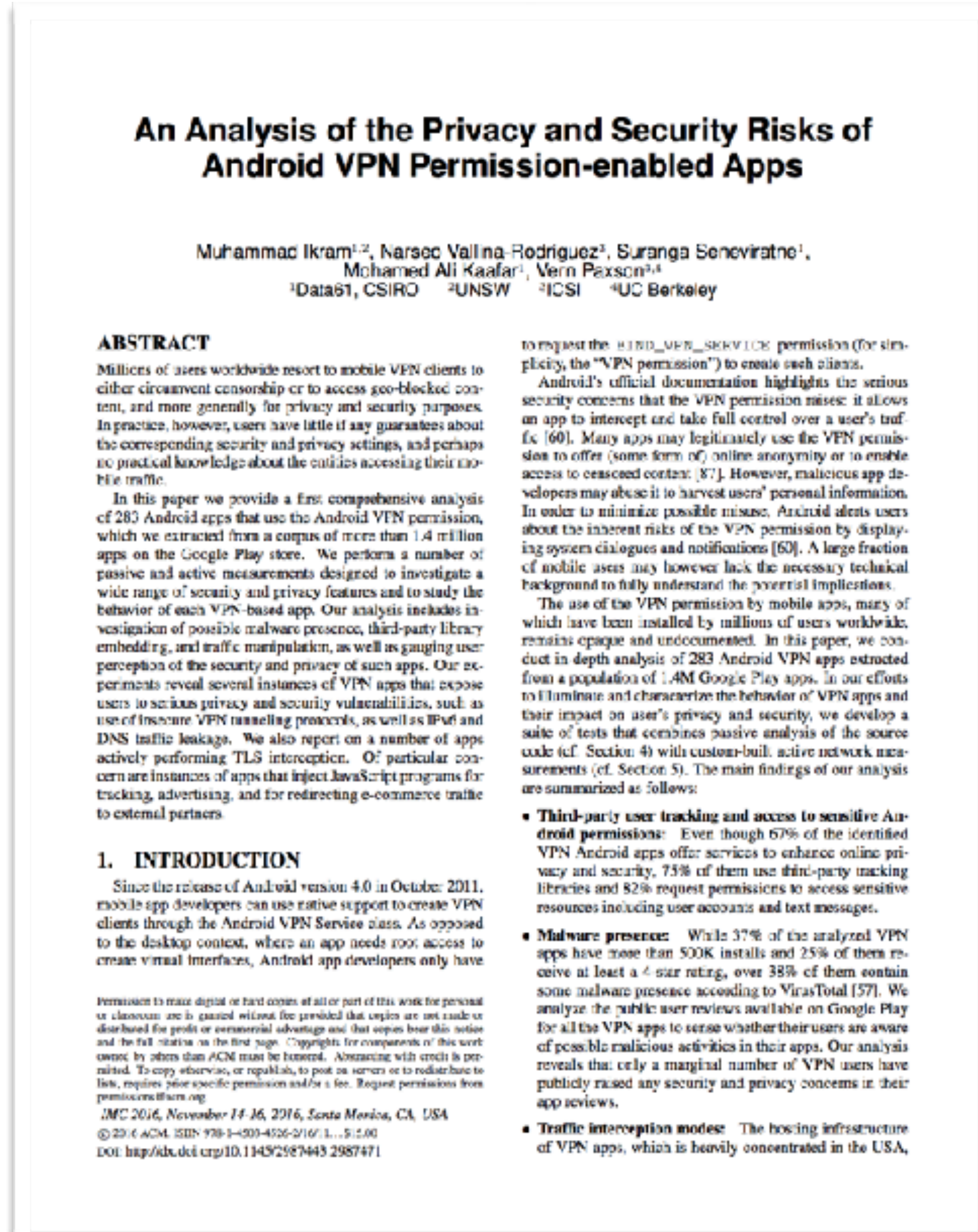
TCP and networking stacks have recently been shown to leak various types of information via side channels, to a blind off-path attacker [22, 14, 12, 21, 11, 29, 5]. However, it is generally believed that an adversary cannot easily know whether any two arbitrary hosts on the Internet are communicating using a TCP connection without being on the communication path. It is further believed that such an off-path attacker cannot tamper with or terminate a connection between such arbitrary hosts. In this work, we challenge this belief and demonstrate that it can be broken due to a subtle yet serious side channel vulnerability introduced in the latest TCP specification.

The two most relevant research efforts are the following: 1) In 2012, Qian *et al.*, framed the so called "TCP sequence number inference attack", which can be launched by an off-path attacker [22, 23]. However, the attack requires a piece of unprivileged malware to be running on the client to assist the off-path attacker; this greatly limits the scope of the attack. 2) In 2014, Knockel *et al.*, identified a side channel that allows an off-path attacker to count the packets sent between two arbitrary hosts [21]. The limitation is that the proposed attack requires on average, an hour of preparation time and works at the IP layer only (cannot count how many packets are sent over a specific TCP connection).

In this paper, we discover a much more powerful off-path attack that can quickly 1) test whether any two arbitrary hosts on the Internet are communicating using one or more TCP connections (and discover the port numbers associated with such connections); 2) perform TCP sequence number inference which allows the attacker to subsequently, forcibly terminate the connection or inject a malicious payload into the connection. We emphasize that the attack can be carried out by a purely off-path attacker without running malicious code on the communicating client or server. This can have serious implications on the security and privacy of the Internet at large.

The root cause of the vulnerability is the introduction of the *challenge ACK* responses [26] and the global rate limit imposed on certain TCP control packets. The feature is outlined in RFC 5961, which is implemented faithfully in Linux kernel version 3.6 from late 2012. At a very high level, the vulnerability allows an attacker to create contention on a shared resource, i.e., the global rate limit counter on the target system by sending spoofed packets. The attacker can then subsequently observe the effect on the counter changes, measurable through probing packets.

Through extensive experimentation, we demonstrate that the attack is extremely effective and reliable. Given any two arbitrary hosts, it takes only 10 seconds to successfully infer whether they are communicating. If there is a connection, subsequently, it takes also only tens of



An Analysis of the Privacy and Security Risks of Android VPN Permission-enabled Apps

Muhammad Ikram[1,2], Narseo Vallina-Rodriguez[3], Suranga Seneviratne[1], Mohamed Ali Kaafar[1], Vern Paxson[3,4]
[1]Data61, CSIRO [2]UNSW [3]ICSI [4]UC Berkeley

ABSTRACT

Millions of users worldwide resort to mobile VPN clients to either circumvent censorship or to access geo-blocked content, and more generally for privacy and security purposes. In practice, however, users have little if any guarantees about the corresponding security and privacy settings, and perhaps no practical knowledge about the entities accessing their mobile traffic.

In this paper we provide a first comprehensive analysis of 283 Android apps that use the Android VPN permission, which we extracted from a corpus of more than 1.4 million apps on the Google Play store. We perform a number of passive and active measurements designed to investigate a wide range of security and privacy features and to study the behavior of each VPN-based app. Our analysis includes investigation of possible malware presence, third-party library embedding, and traffic manipulation, as well as gauging user perception of the security and privacy of such apps. Our experiments reveal several instances of VPN apps that expose users to serious privacy and security vulnerabilities, such as use of insecure VPN tunneling protocols, as well as IPv6 and DNS traffic leakage. We also report on a number of apps actively performing TLS interception. Of particular concern are instances of apps that inject JavaScript programs for tracking, advertising, and for redirecting e-commerce traffic to external partners.

1. INTRODUCTION

Since the release of Android version 4.0 in October 2011, mobile app developers can use native support to create VPN clients through the Android VPN Service class. As opposed to the desktop context, where an app needs root access to create virtual interfaces, Android app developers only have to request the BIND_VPN_SERVICE permission (for simplicity, the "VPN permission") to create such clients.

Android's official documentation highlights the serious security concerns that the VPN permission raises: it allows an app to intercept and take full control over a user's traffic [60]. Many apps may legitimately use the VPN permission to offer (some form of) online anonymity or to enable access to censored content [87]. However, malicious app developers may abuse it to harvest users' personal information. In order to minimize possible misuse, Android alerts users about the inherent risks of the VPN permission by displaying system dialogues and notifications [60]. A large fraction of mobile users may however lack the necessary technical background to fully understand the potential implications.

The use of the VPN permission by mobile apps, many of which have been installed by millions of users worldwide, remains opaque and undocumented. In this paper, we conduct in depth analysis of 283 Android VPN apps extracted from a population of 1.4M Google Play apps. In our efforts to illuminate and characterize the behavior of VPN apps and their impact on user's privacy and security, we develop a suite of tests that combines passive analysis of the source code (cf. Section 4) with custom-built active network measurements (cf. Section 5). The main findings of our analysis are summarized as follows:

- **Third-party user tracking and access to sensitive Android permissions:** Even though 67% of the identified VPN Android apps offer services to enhance online privacy and security, 75% of them use third-party tracking libraries and 82% request permissions to access sensitive resources including user accounts and text messages.
- **Malware presence:** While 37% of the analyzed VPN apps have more than 500K installs and 25% of them receive at least a 4-star rating, over 38% of them contain some malware presence according to VirusTotal [57]. We analyze the public user reviews available on Google Play for all the VPN apps to sense whether their users are aware of possible malicious activities in their apps. Our analysis reveals that only a marginal number of VPN users have publicly raised any security and privacy concerns in their app reviews.
- **Traffic interception modes:** The hosting infrastructure of VPN apps, which is heavily concentrated in the USA,

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WHY DOES THE INTERNET WORK?

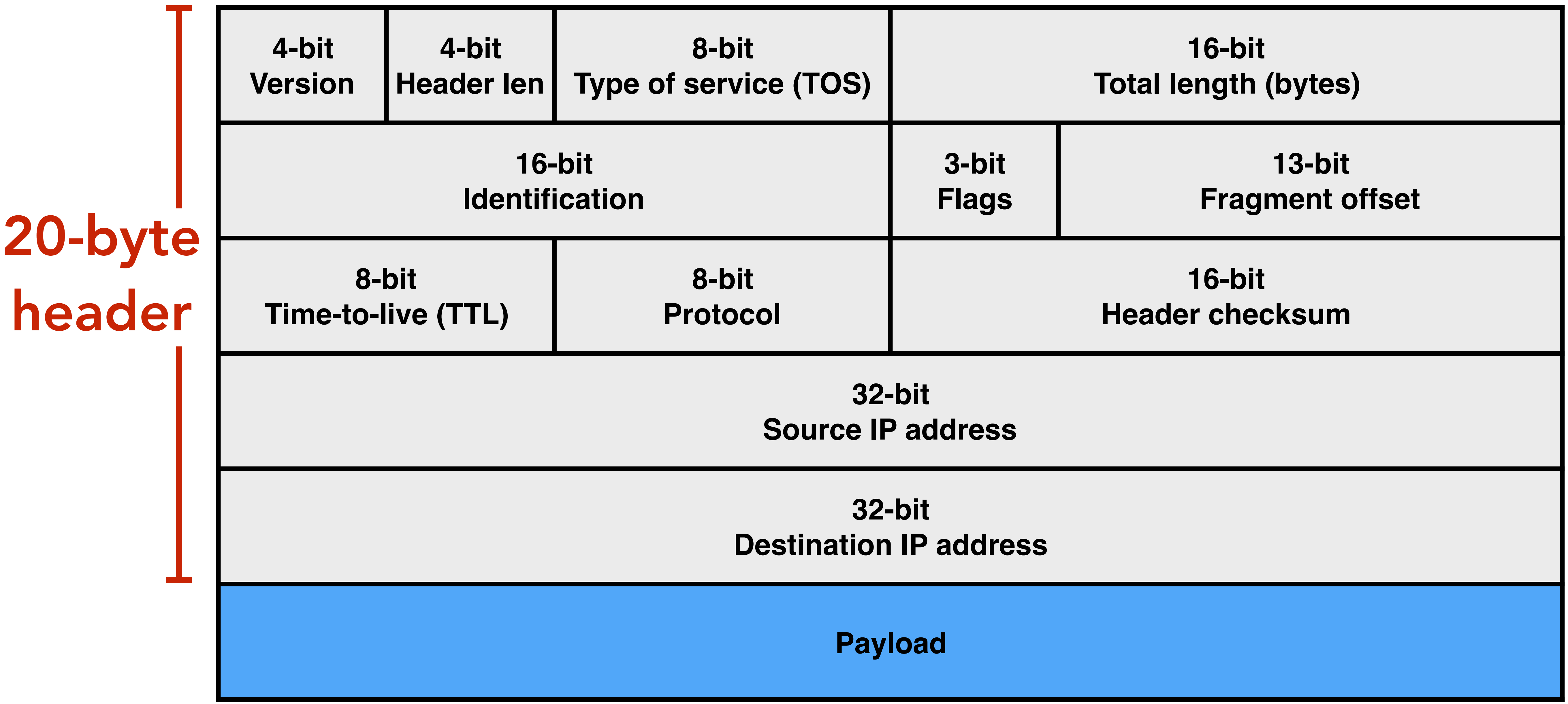
1. PROTOCOLS **Agreements on how to communicate**

Publicly standardized, esp. via Requests for Comments (RFCs)

RFC 826: ARP   RFC 103{4,5}: DNS   RFC 793: TCP

Code to the protocol and your product will work with other products

WHY DOES THE INTERNET WORK?



The payload is the "data" that IP is delivering:

May contain another protocol's header & payload, and so on

WHY DOES THE INTERNET WORK?

2. THE NETWORK IS DUMB

End-hosts are the periphery (users, devices)

Routers and **switches** are interior nodes that

- **Route** (figure out where to forward)
- **Forward** (actually send)

- Principle: the routers have no knowledge of ongoing connections through them
  - They do "destination-based" routing and forwarding
    - Given the destination in the packet, send it to the "next hop" that is best suited to help ultimately get the packet there

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Mental model: The postal system

WHY DOES THE INTERNET WORK?

3. LAYERS

- The design of the Internet is strongly partitioned into layers
  - Each layer relies on the services provided by the layer immediately below it…
  - … and provides service to the layer immediately above it

LAYERS OF THE INTERNET

PHYSICAL

Send / receive bit

Broadcasts on shared link

LAYERS OF THE INTERNET

LINK	Local send/recv	*Adds framing & destination; Still assumes shared link*
PHYSICAL	Send / receive bit	*Broadcasts on shared link*

LAYERS OF THE INTERNET

NETWORK (IP)	Global send/recv	*Adds global addresses; Requires routing*
LINK	Local send/recv	*Adds framing & destination; Still assumes shared link*
PHYSICAL	Send / receive bit	*Broadcasts on shared link*

LAYERS OF THE INTERNET

TRANSPORT (TCP,UDP)	Process send/recv	*E2E communication between processes; Adds ports/reliability*
NETWORK (IP)	Global send/recv	*Adds global addresses; Requires routing*
LINK	Local send/recv	*Adds framing & destination; Still assumes shared link*
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LAYERS OF THE INTERNET

APPLICATION	Arbitrary	*Application-specific semantics*
TRANSPORT (TCP,UDP)	Process send/recv	*E2E communication between processes; Adds ports/reliability*
NETWORK (IP)	Global send/recv	*Adds global addresses; Requires routing*
LINK	Local send/recv	*Adds framing & destination; Still assumes shared link*
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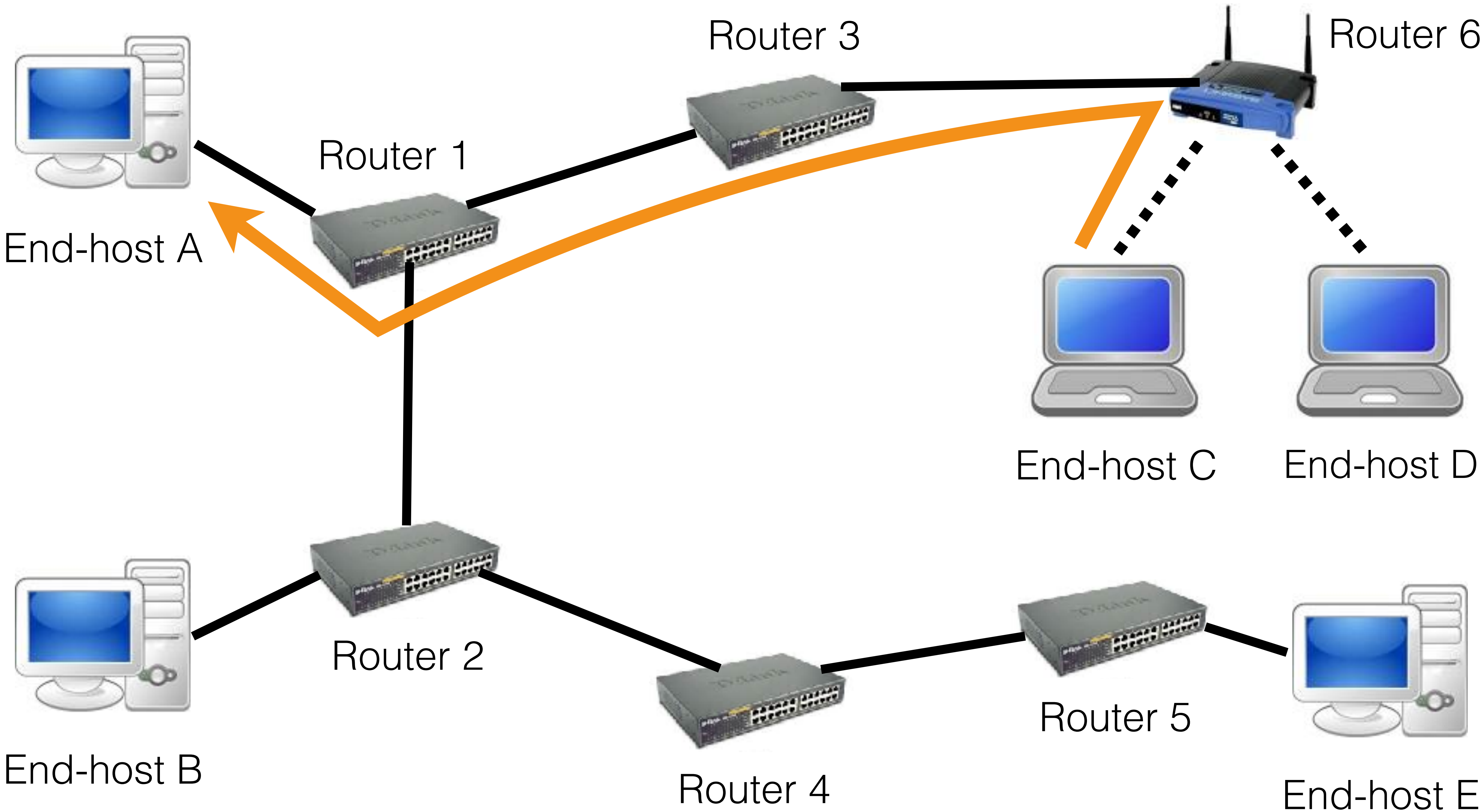
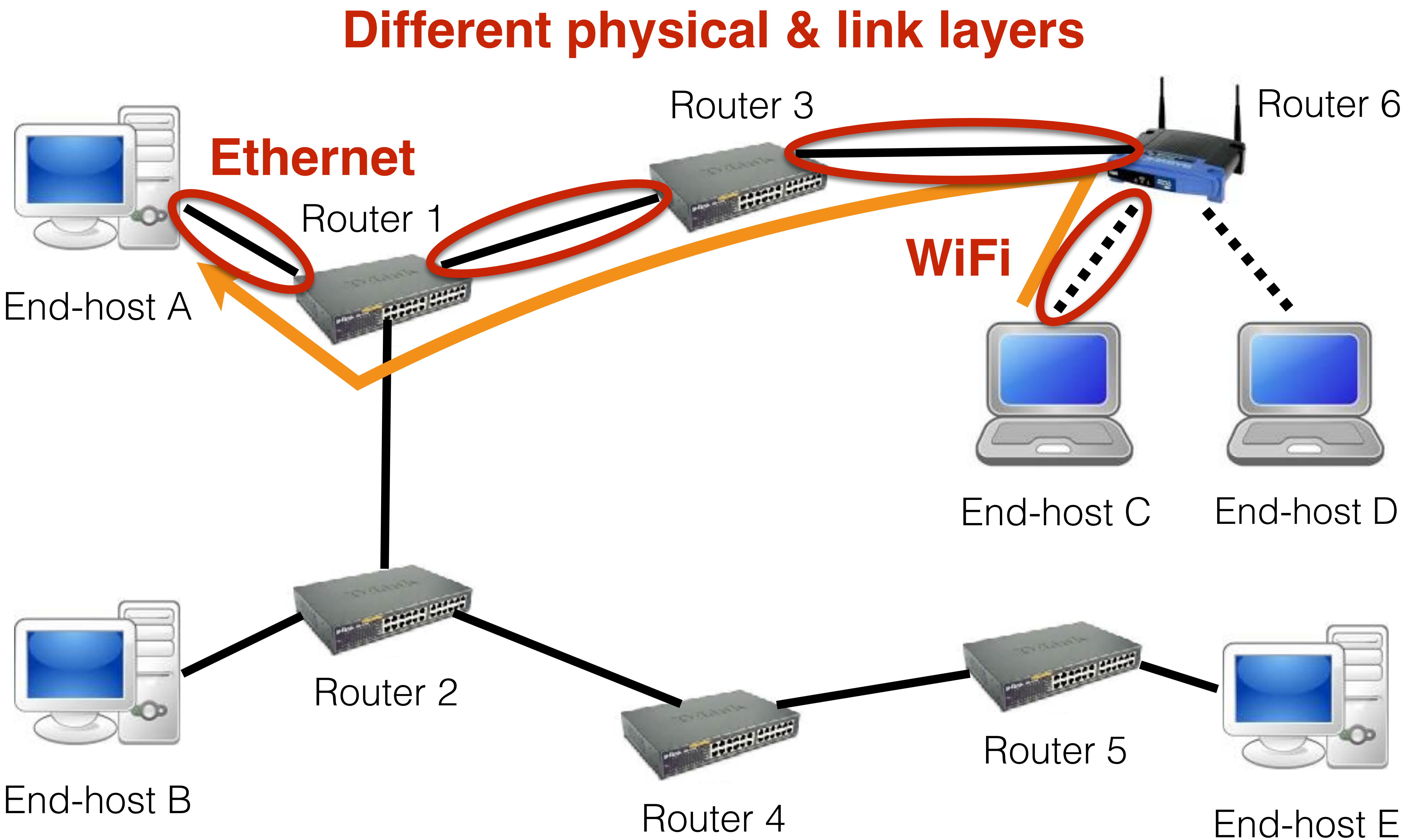
Hop-by-hop vs. end-to-end layers

Host C communicates with host A

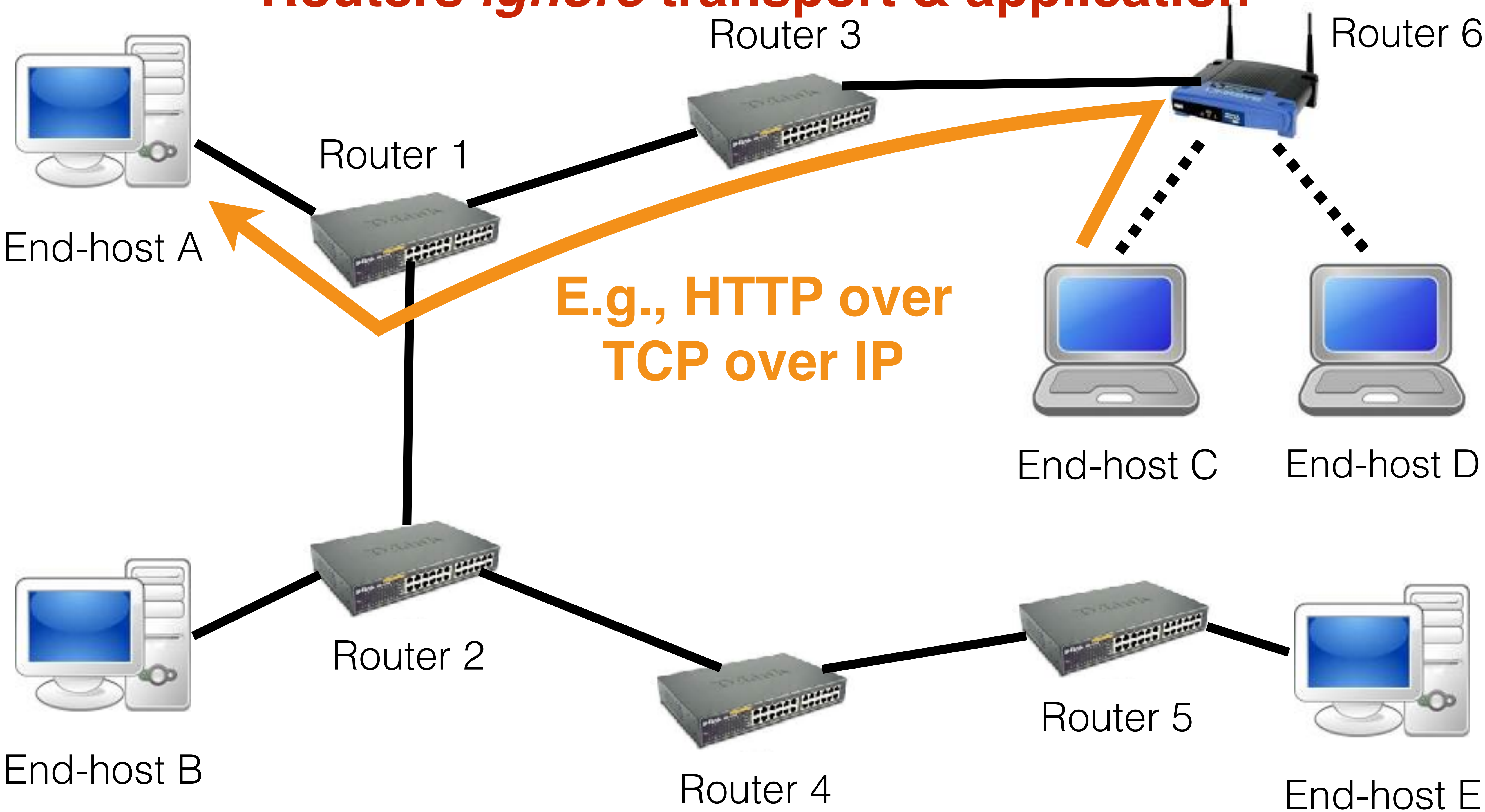


Hop-by-hop vs. end-to-end layers

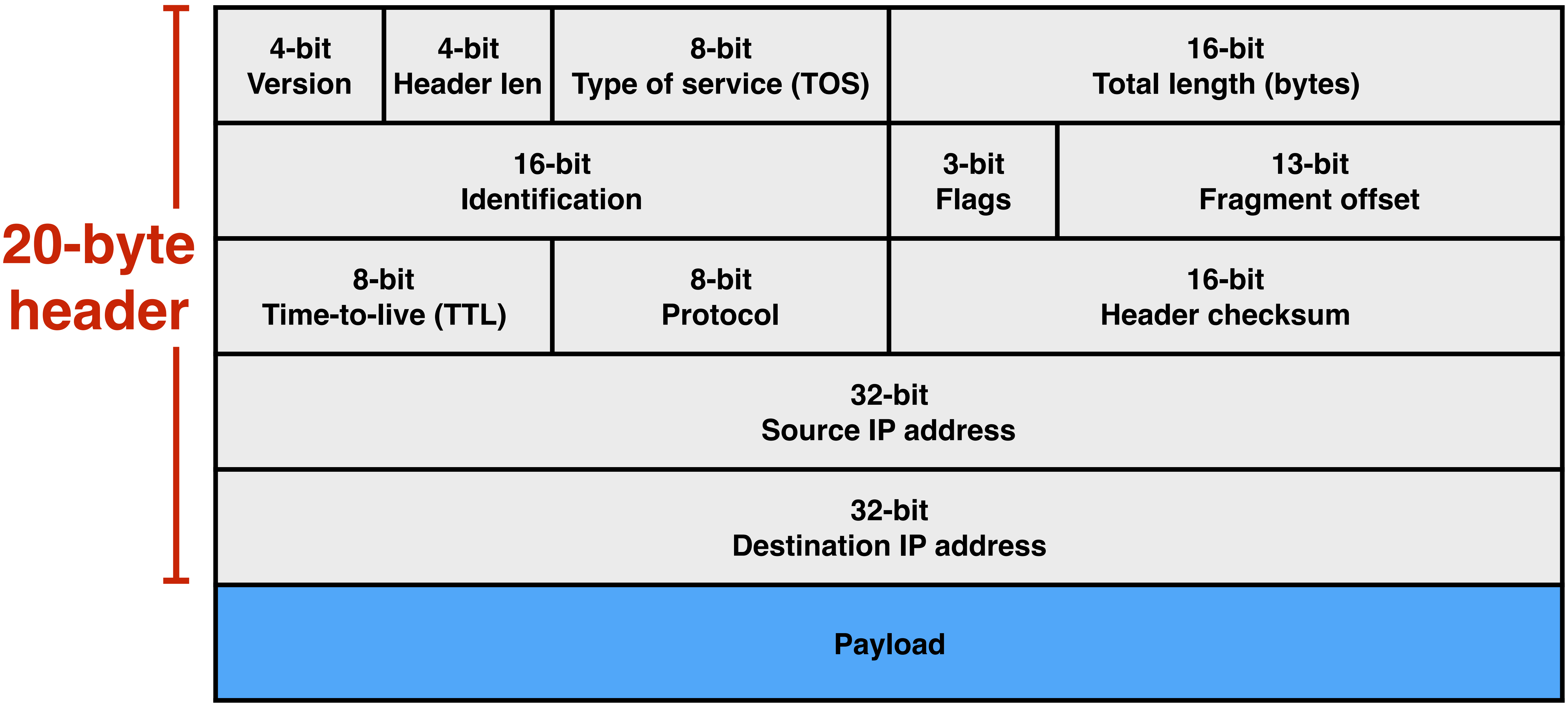


Hop-by-hop vs. end-to-end layers

Same network, transport, and application layers (3/4/7)
Routers *ignore* transport & application



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

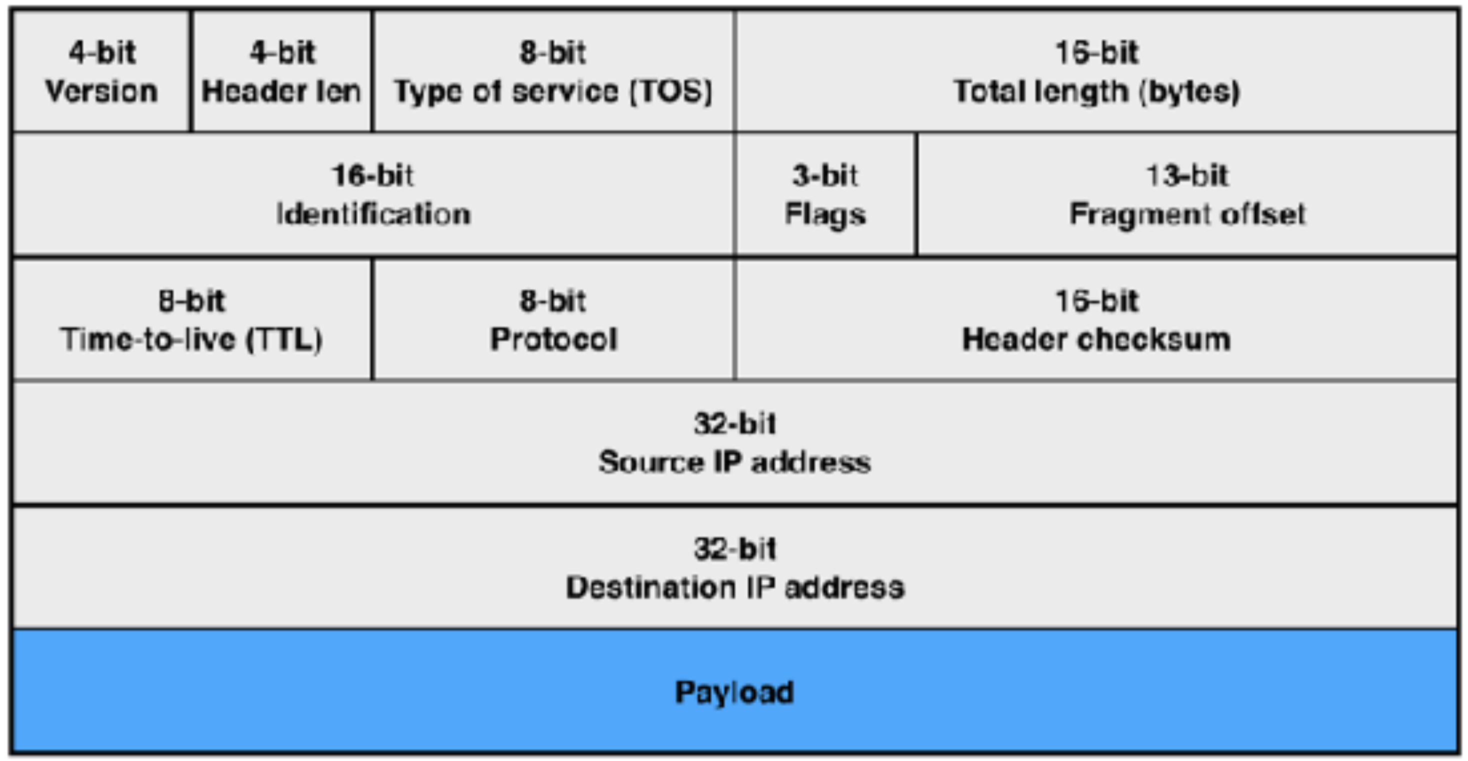
IP: “Best effort” packet delivery

- 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!

Attacks on IP



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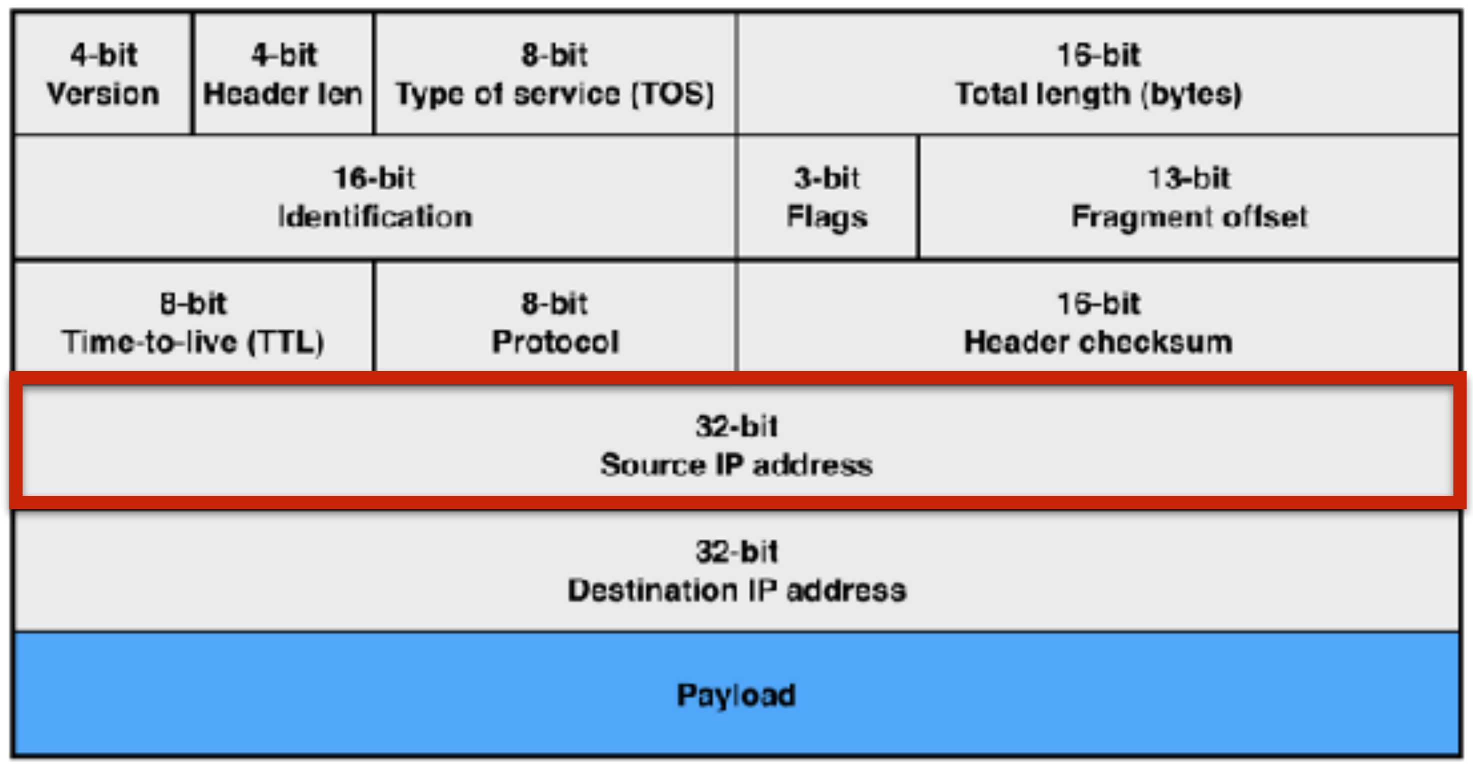
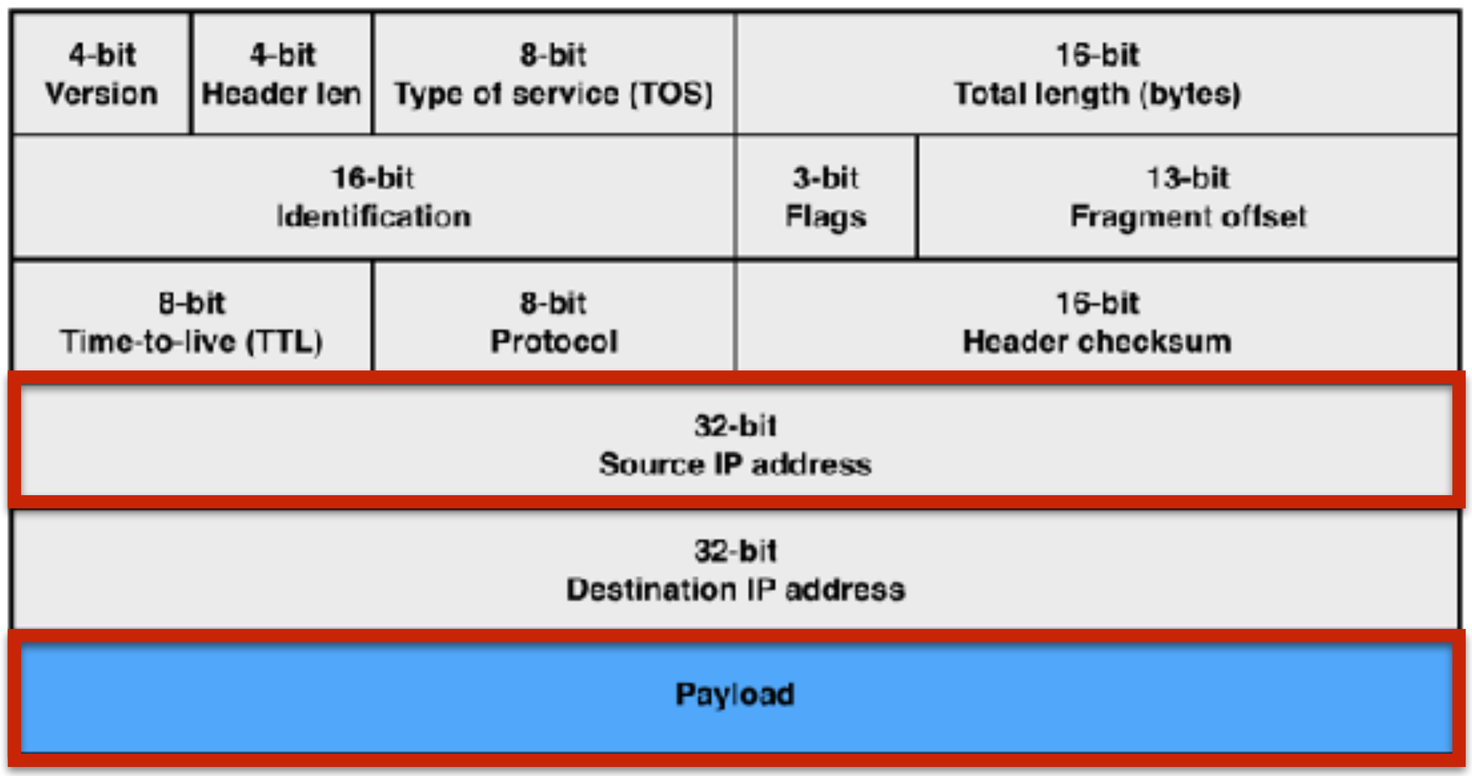


Source-spoof

There is nothing in IP that enforces that your source IP address is really "yours"

Attacks on IP



Source-spoof

There is nothing in IP that enforces that your source IP address is really "yours"

Eavesdrop / Tamper

IP provides no protection of the *payload* or *header*

Source-spoofing

- Why source-spoof?
    - Consider spam: send many emails from one computer
    - Easy defense: block many emails from a given (source) IP address
    - Easy countermeasure: spoof the source IP address
    - Counter-countermeasure?

- How do you know if a packet you receive has a spoofed source?

Salient network features

- Recall: The Internet operates via *destination-based routing*
- attacker: pkt (spoofed source) -> destination
  destination: pkt -> spoofed source
- In other words, the response goes to the spoofed source, *not* the attacker

Defending against source-spoofing

- How do you know if a packet you receive has a spoofed source?
  - Send a challenge packet to the (possibly spoofed) source (e.g., a difficult to guess, random nonce)
  - If the recipient can answer the challenge, then likely that the source was not spoofed

- So do you have to do this with every packet??
  - Every packet should have something that's difficult to guess
  - Recall the query ID in the DNS queries! Easy to predict => Kaminsky attack

Source spoofing

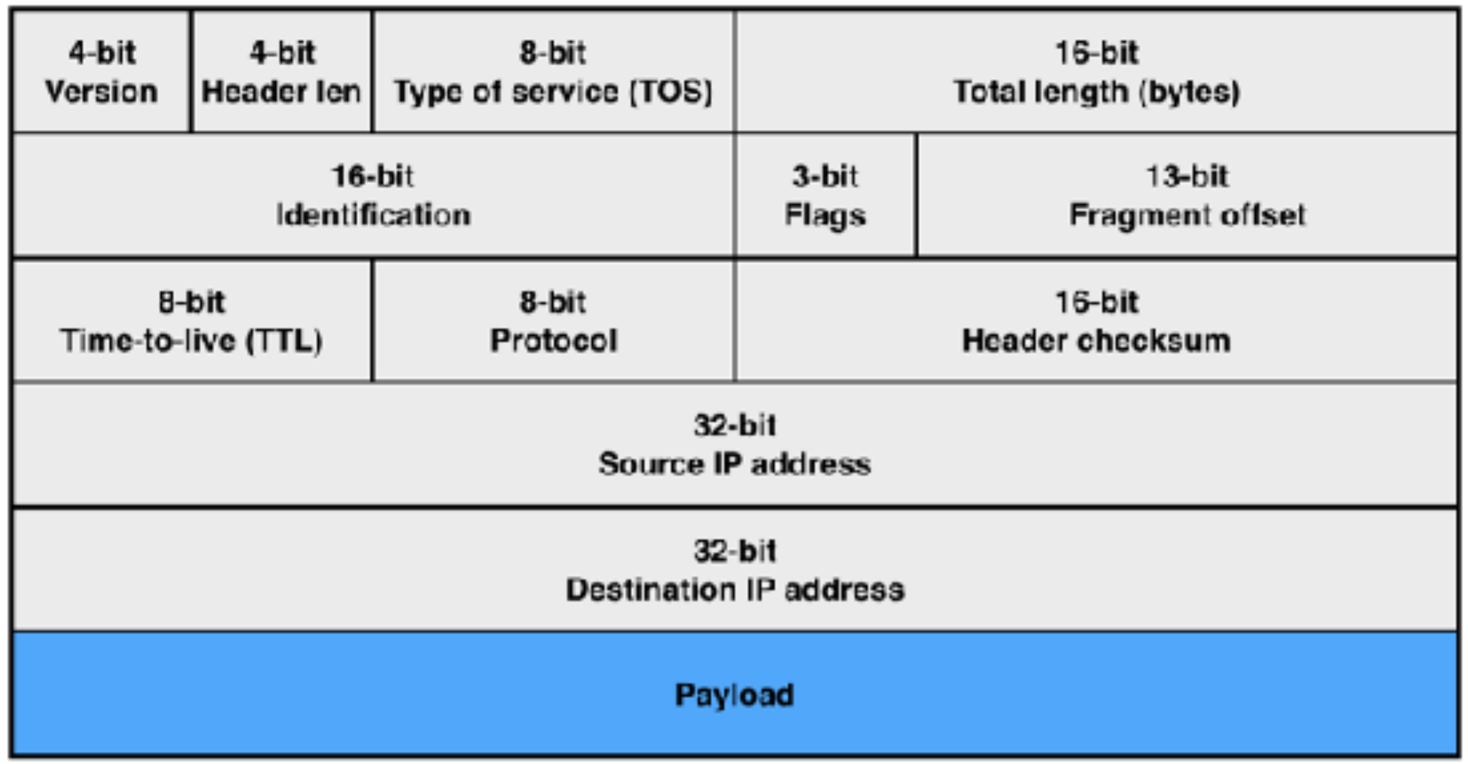
- Why source-spoof?
  - Consider DoS attacks: generate as much traffic as possible to congest the victim's network
  - Easy defense: block all traffic from a given source near the edge of your network
  - Easy countermeasure: spoof the source address
- Challenges won't help here; the damage has been done by the time the packets reach the core of our network
- Ideally, detect such spoofing *near the source*

Egress filtering

- The point (router/switch) at which traffic *enters* your network is the *ingress point*
- The point (router/switch) at which traffic *leaves* your network is the *egress point*
- You don't know who owns all IP addresses in the world, but you *do* know who in *your own network* gets what IP addresses
    - If you see a packet with a source IP address that doesn't belong to your network trying to cross your egress point, then *drop it*

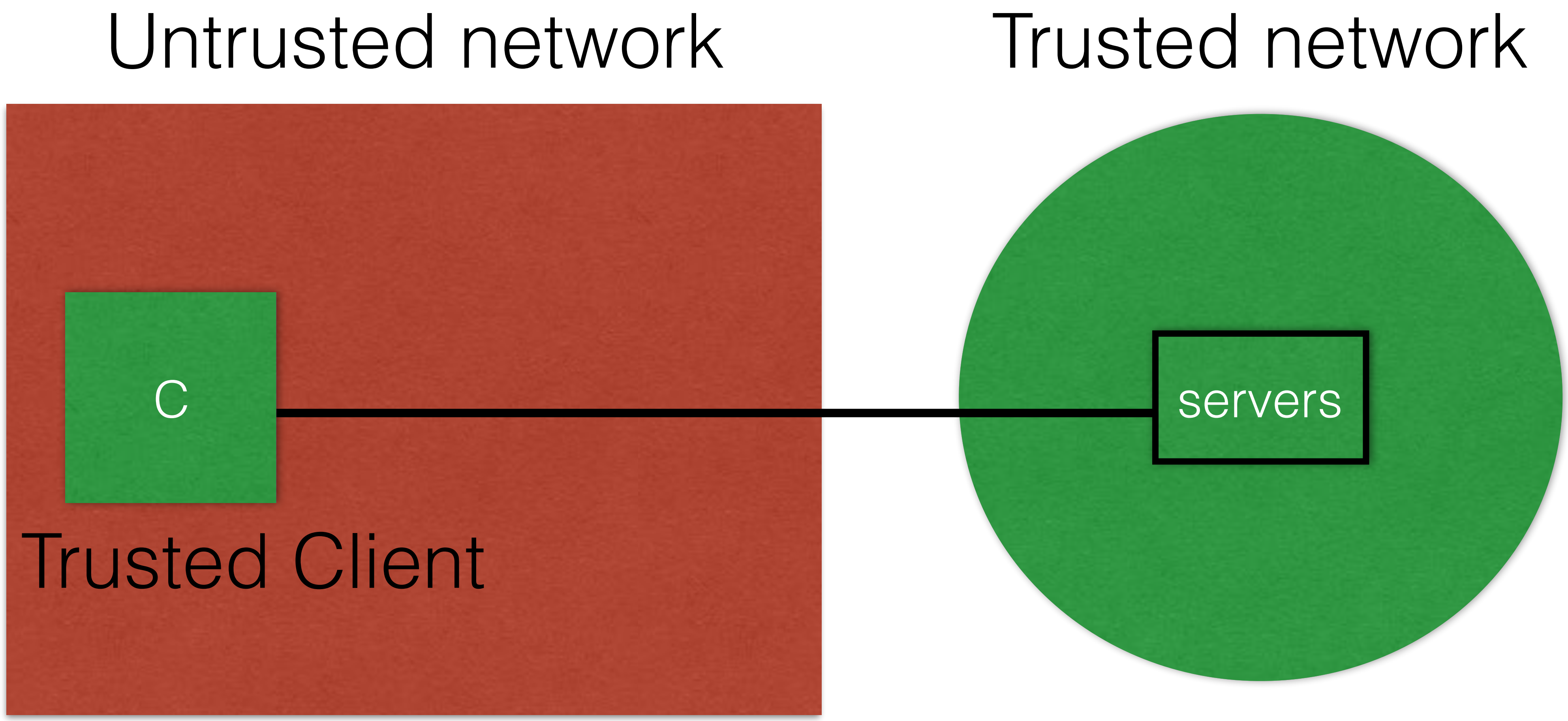
Egress filtering is not widely deployed

Eavesdropping / Tampering



- No security built into IP
- => Deploy secure IP *over IP*

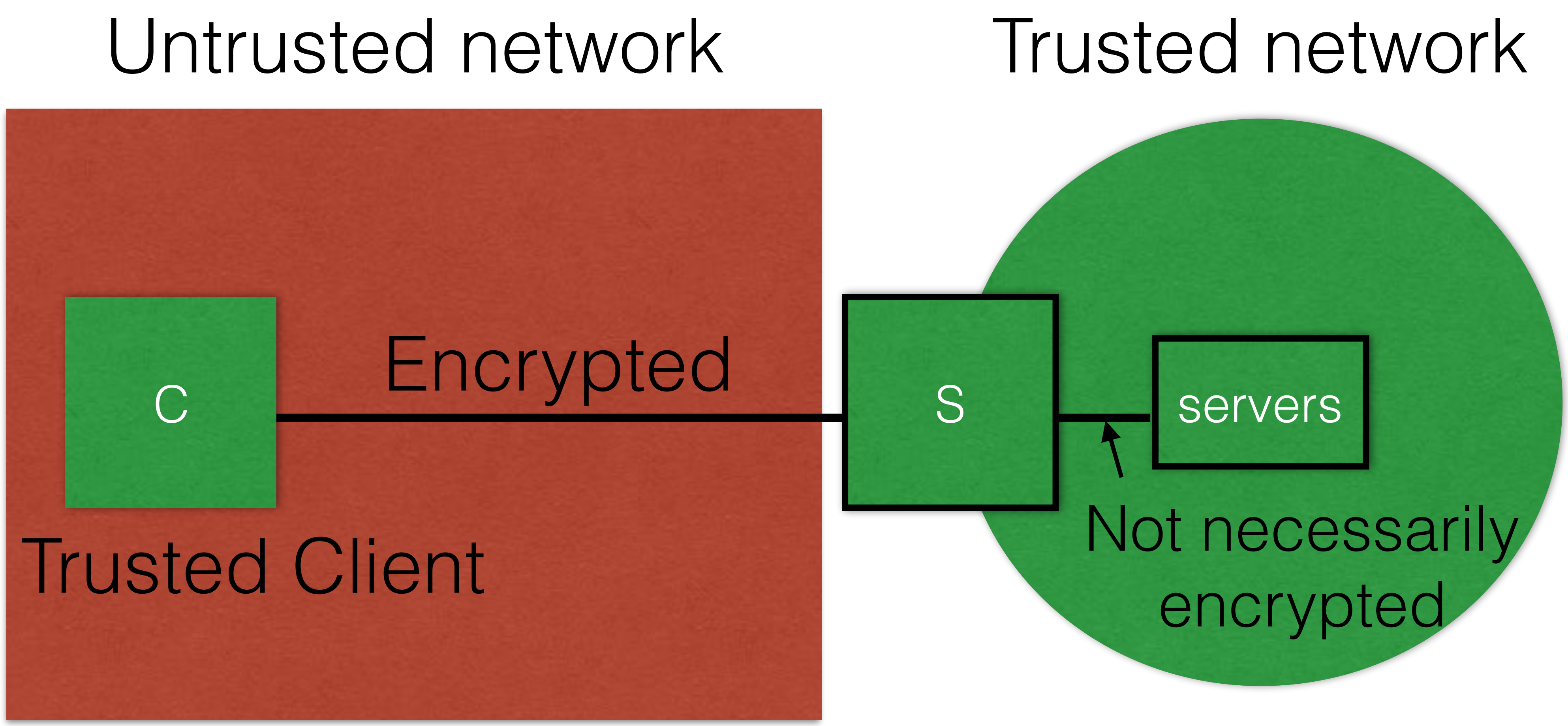
Virtual Private Networks (VPNs)



Goal: Allow the client to connect to the trusted network from within an untrusted network

Example: Connect to your company's network (for payroll, file access, etc.) while visiting a competitor's office

Virtual Private Networks (VPNs)



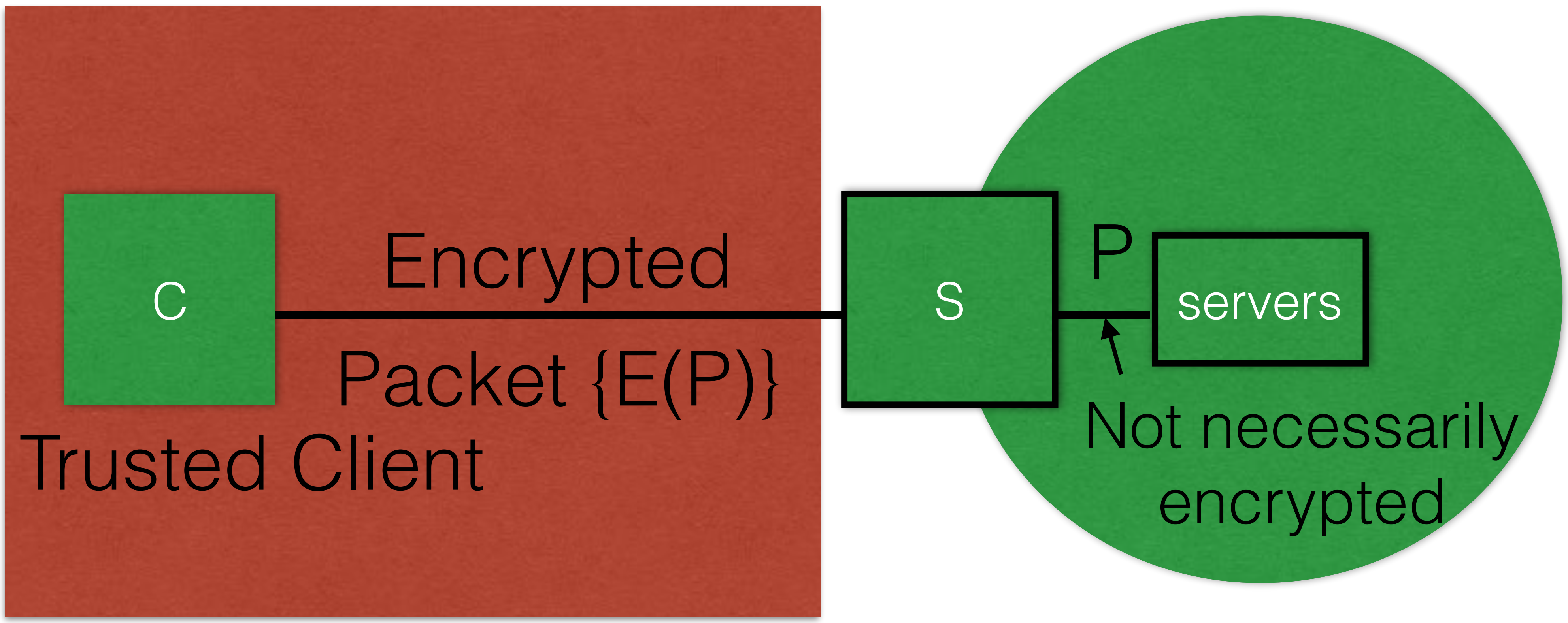
Idea: A VPN “client” and “server” together create end-to-end encryption/authentication

Predominate way of doing this: IPSec

IPSec

- Operates in a few different modes
  - Transport mode: Simply encrypt the payload but not the headers
  - Tunnel mode: Encrypt the payload *and* the headers
- But how do you encrypt the headers? How does routing work?
  - Encrypt the entire IP packet and make that the payload of another IP packet

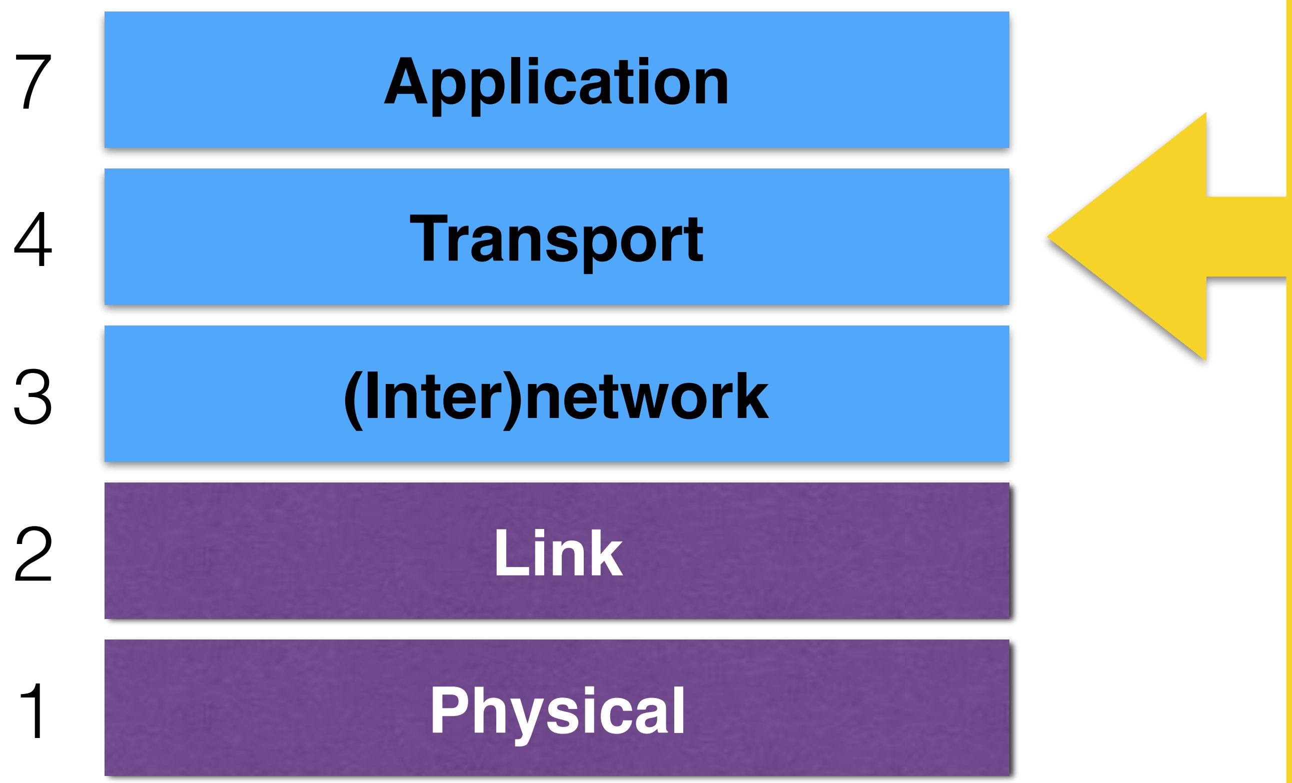
Tunnel mode



The VPN server decrypts and then sends the payload (itself a full IP packet) as if it had just received it from the network

From the client/servers' perspective:
Looks like the client is physically connected to the network!

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

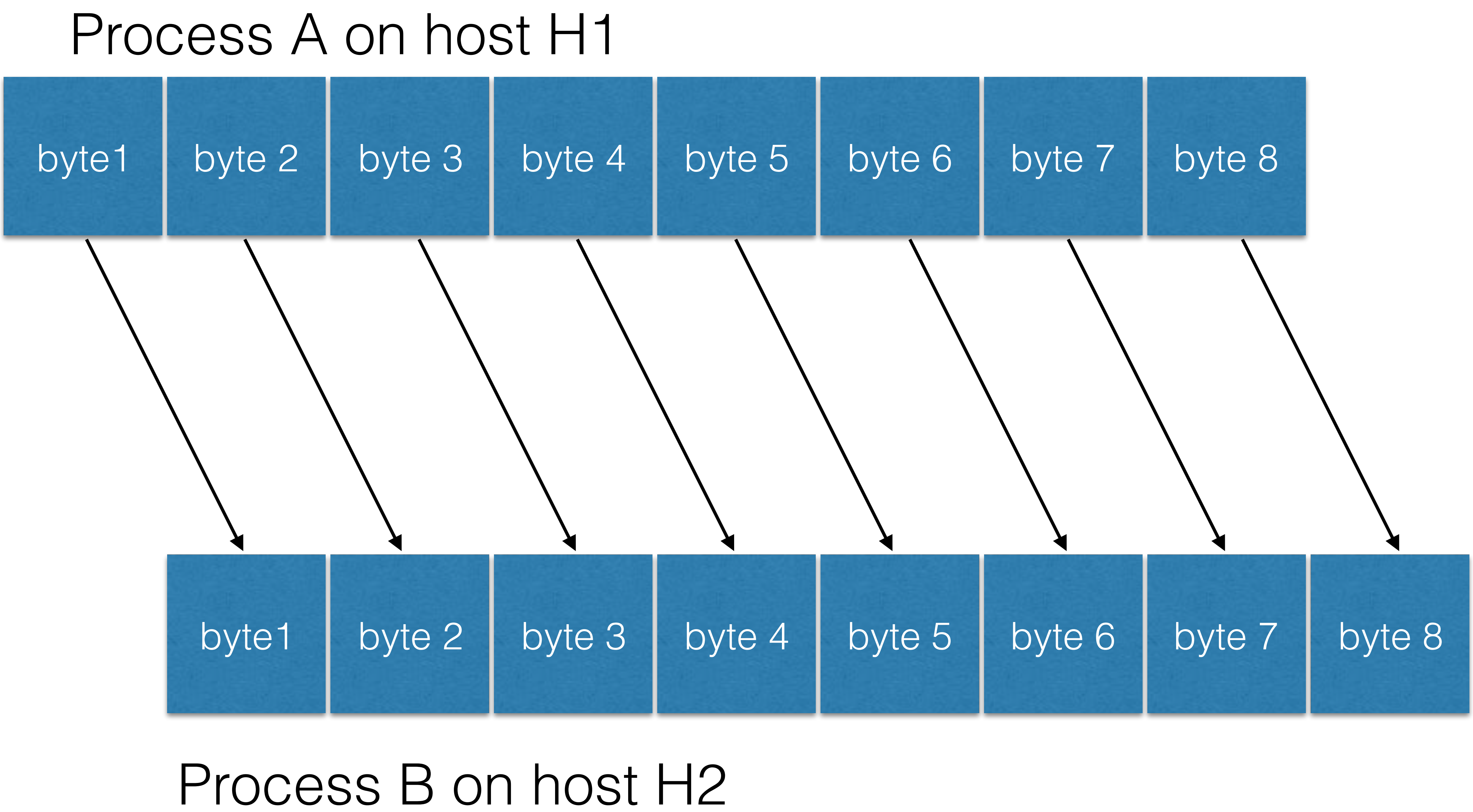
- Given best-effort deliver, the goal is to ensure *reliability*
    - All packets are delivered to applications
    - … in order
    - … unmodified (with reasonably high probability)
- Must robustly detect and retransmit lost data

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)

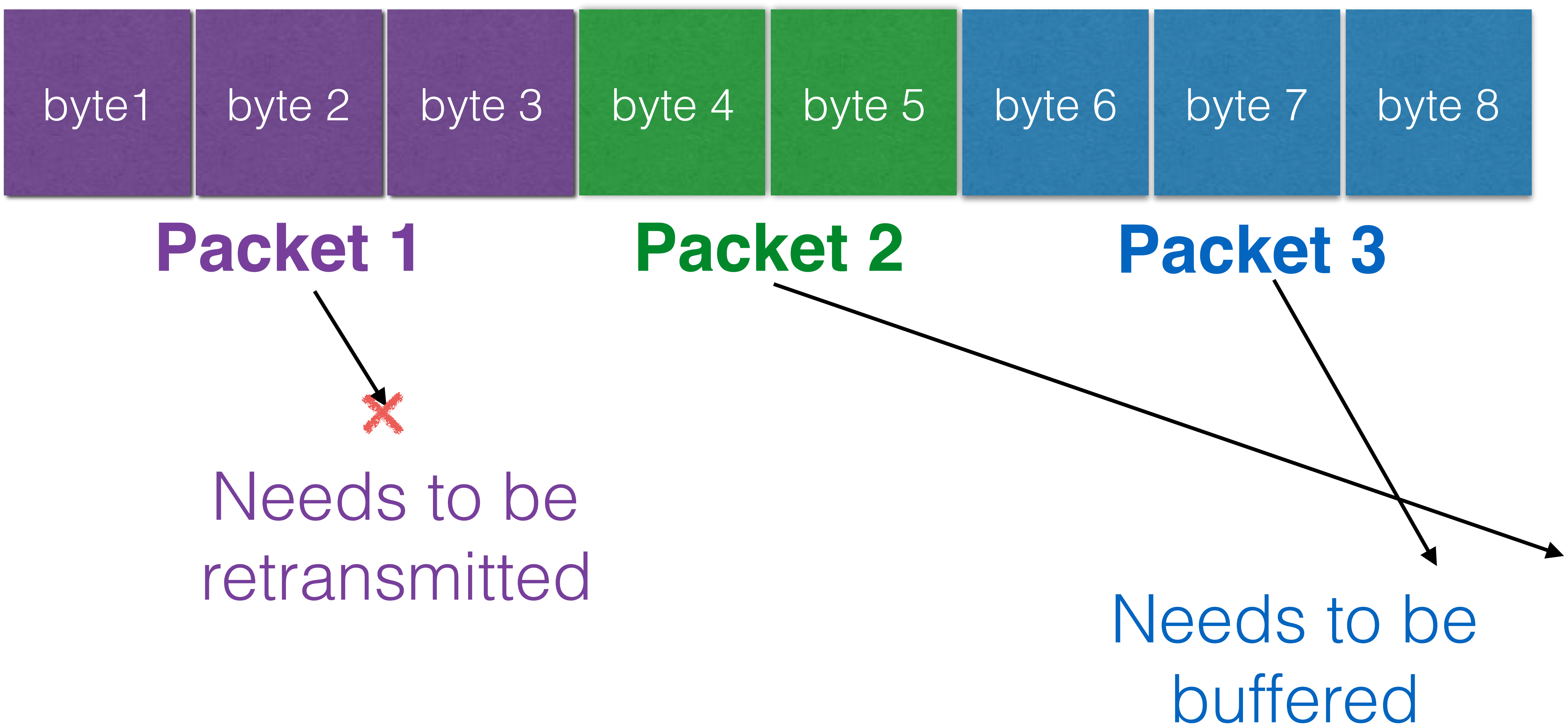
TCP bytestream service

Abstraction: Each *byte* reliably delivered in order



TCP bytestream service

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



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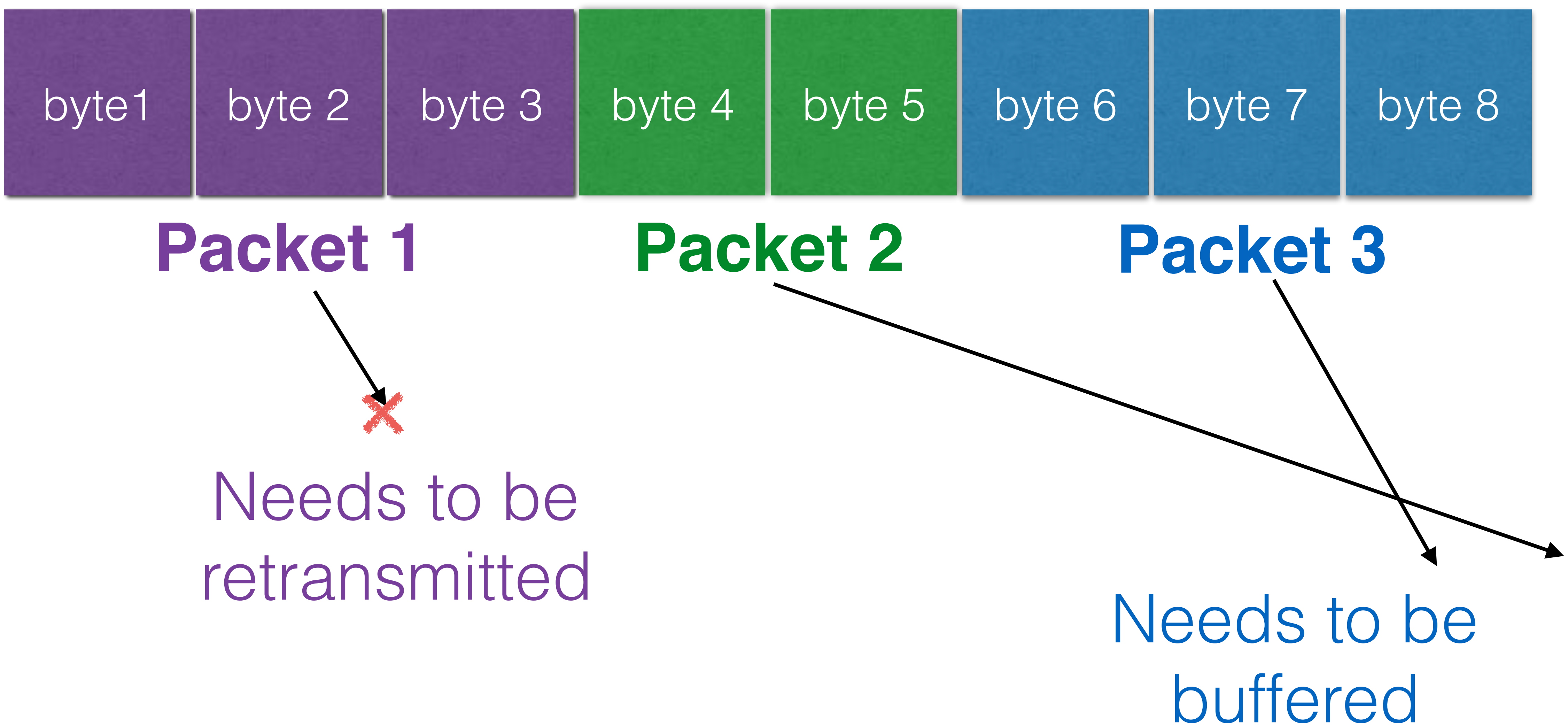
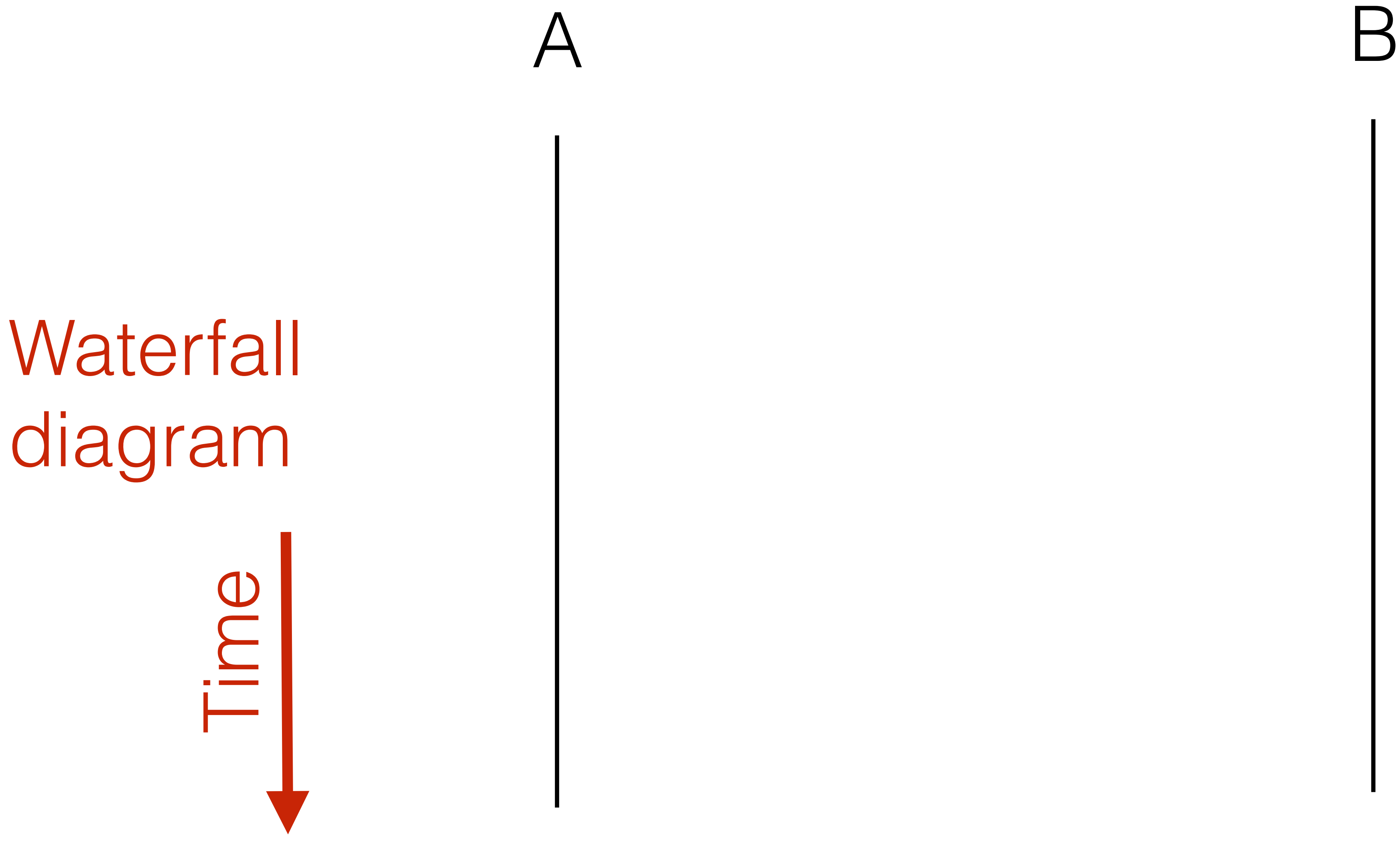


TCP's first job: achieve the abstraction while hiding the reality from the application

How does TCP achieve reliability?



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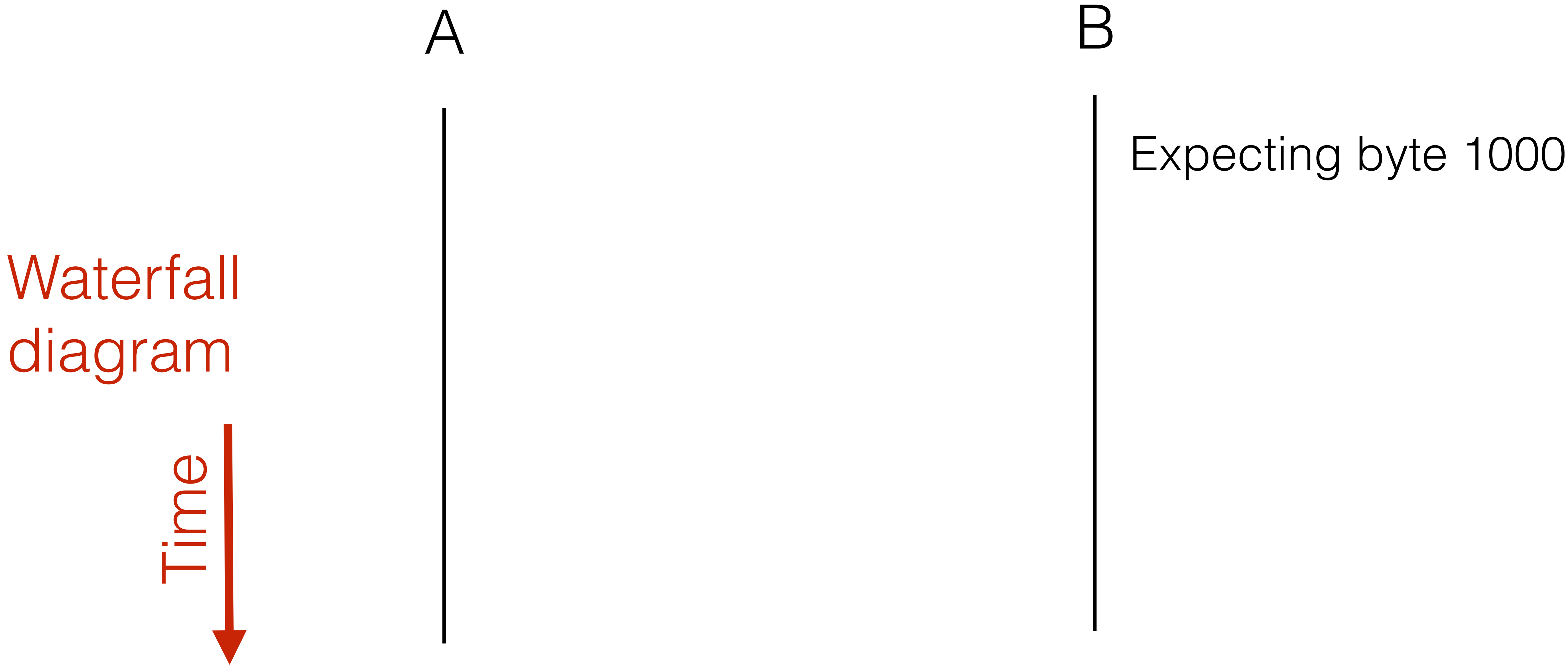

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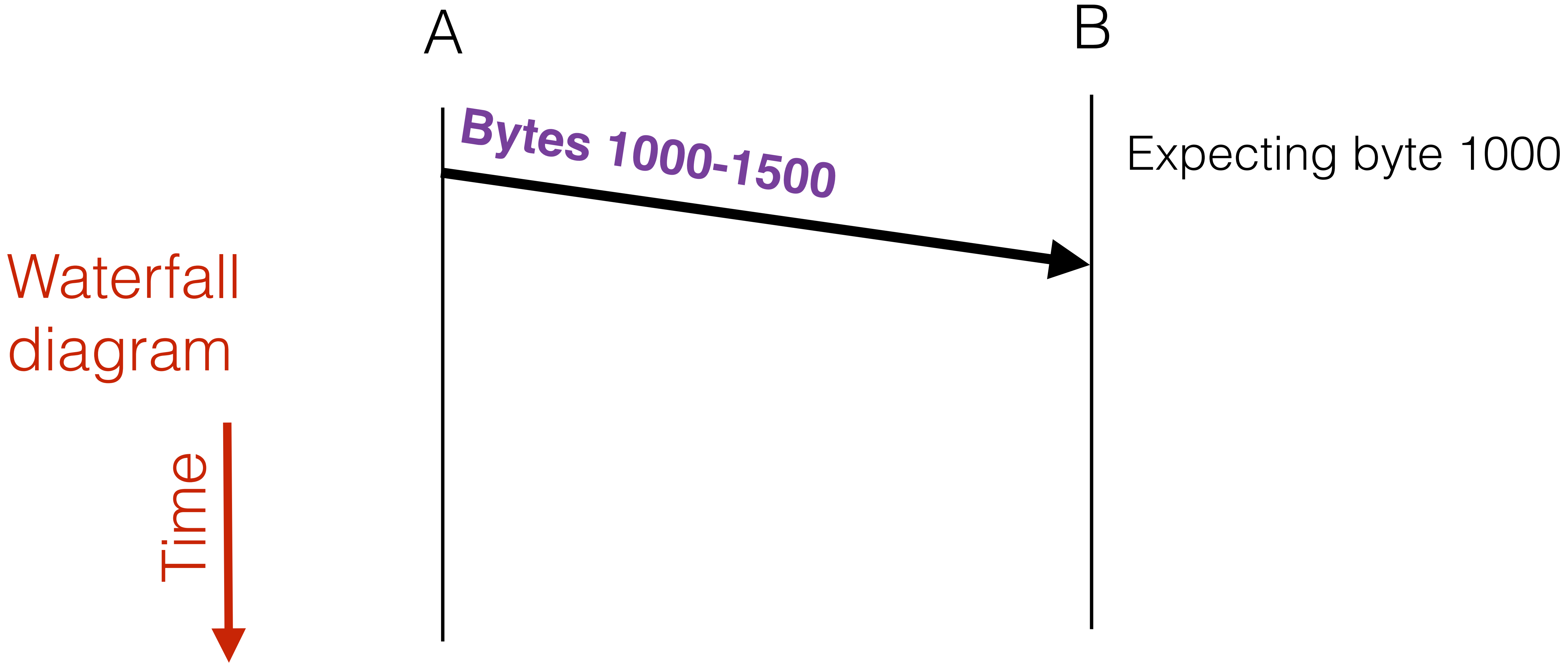

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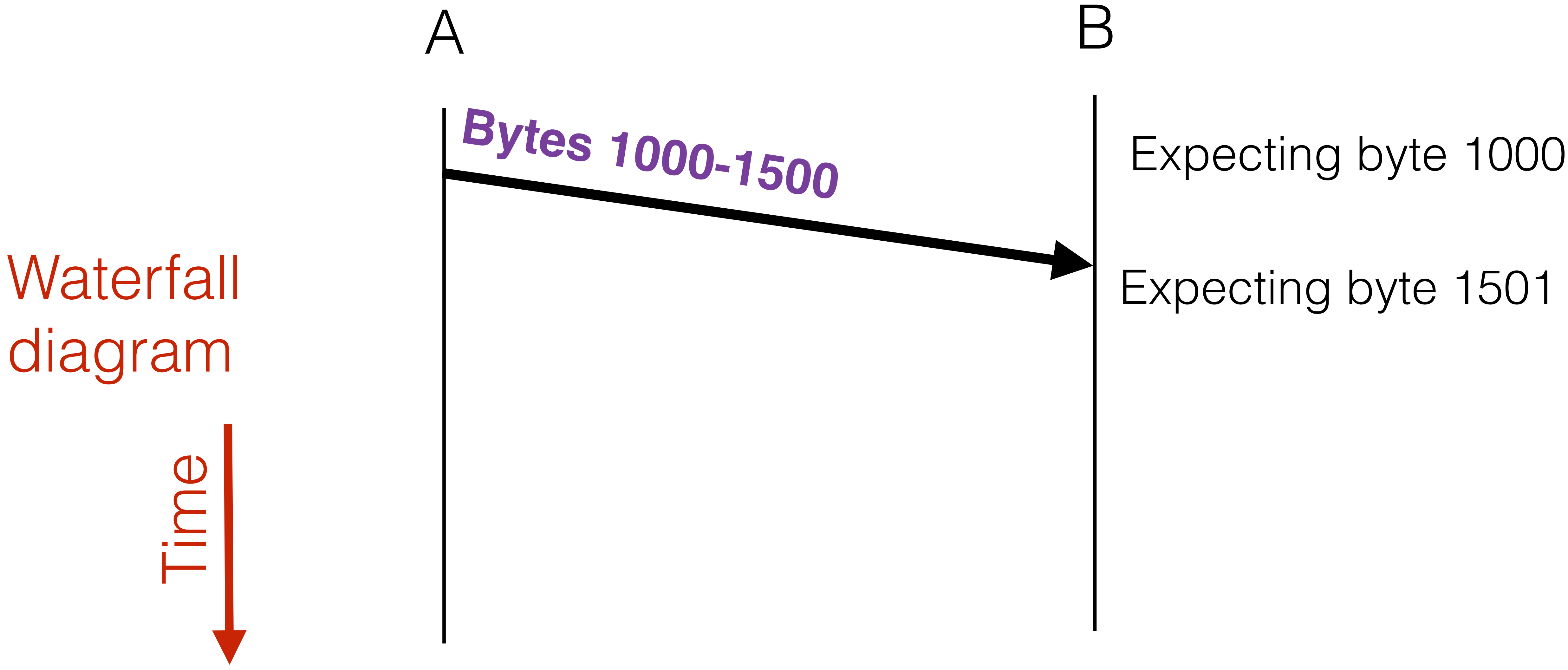

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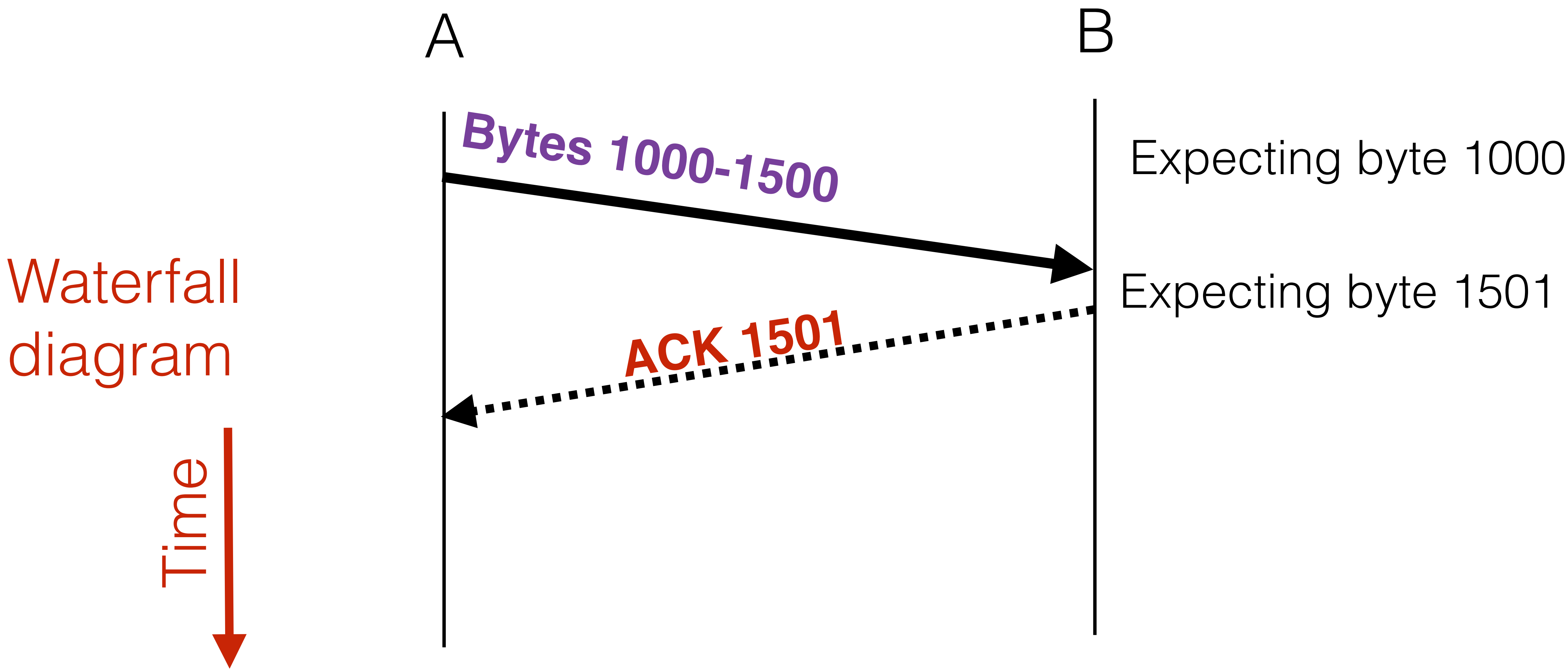

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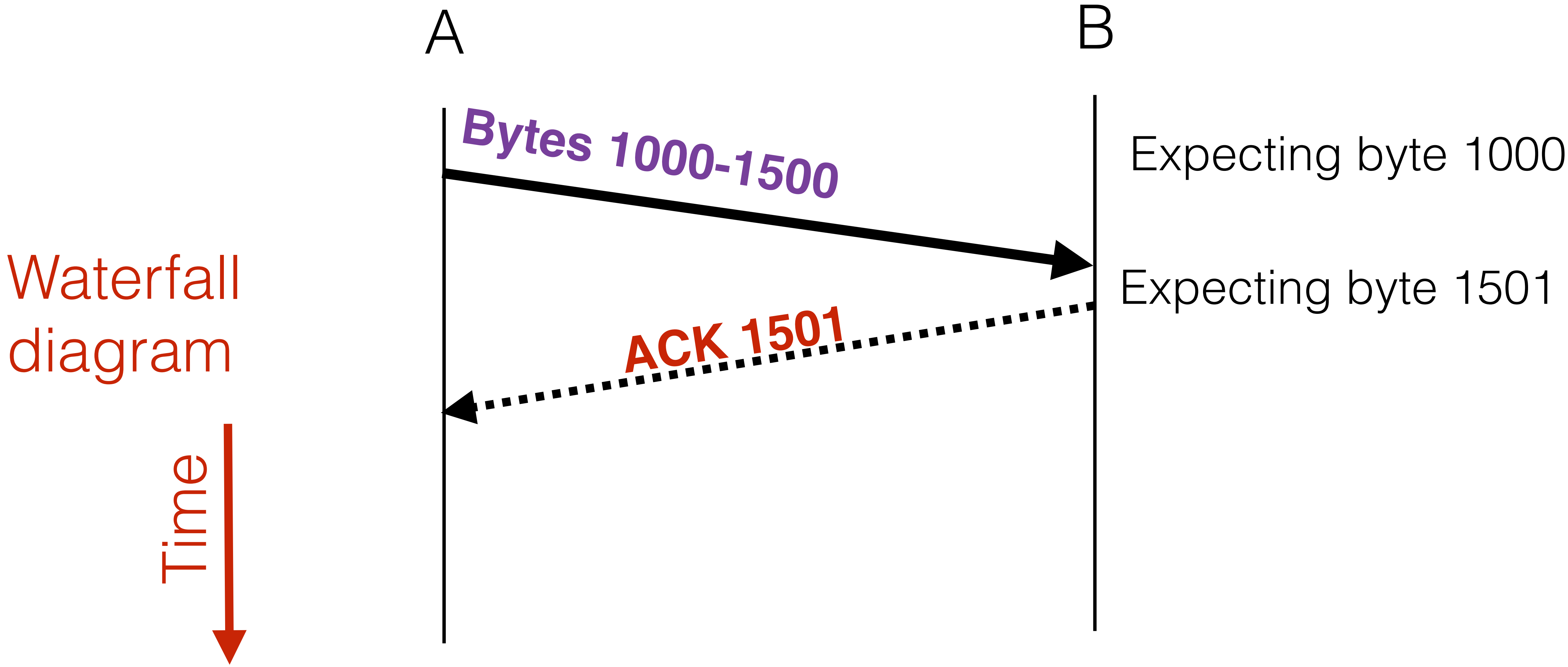
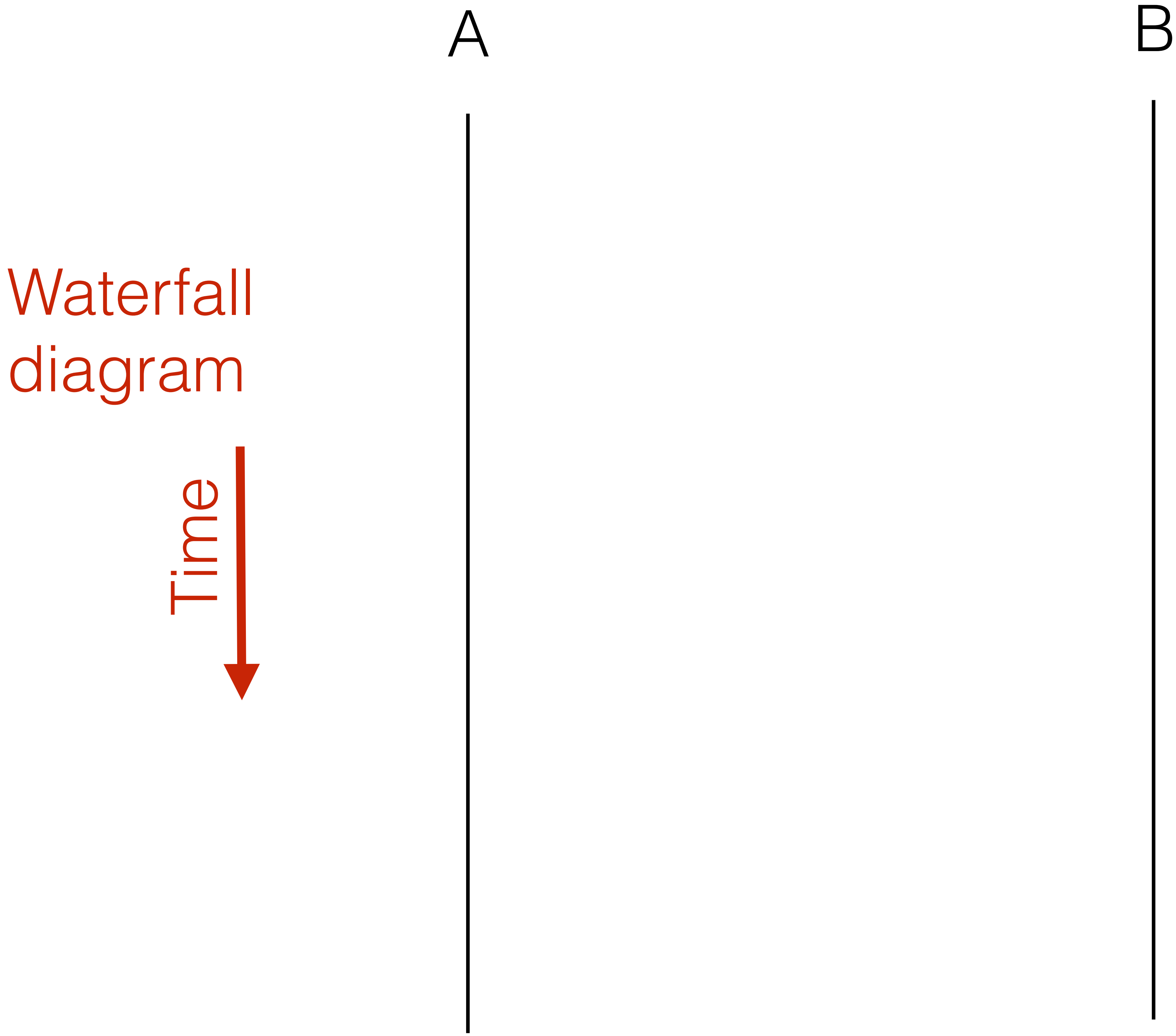


Reliability through acknowledgments
to determine whether something was received.

How does TCP achieve reliability?



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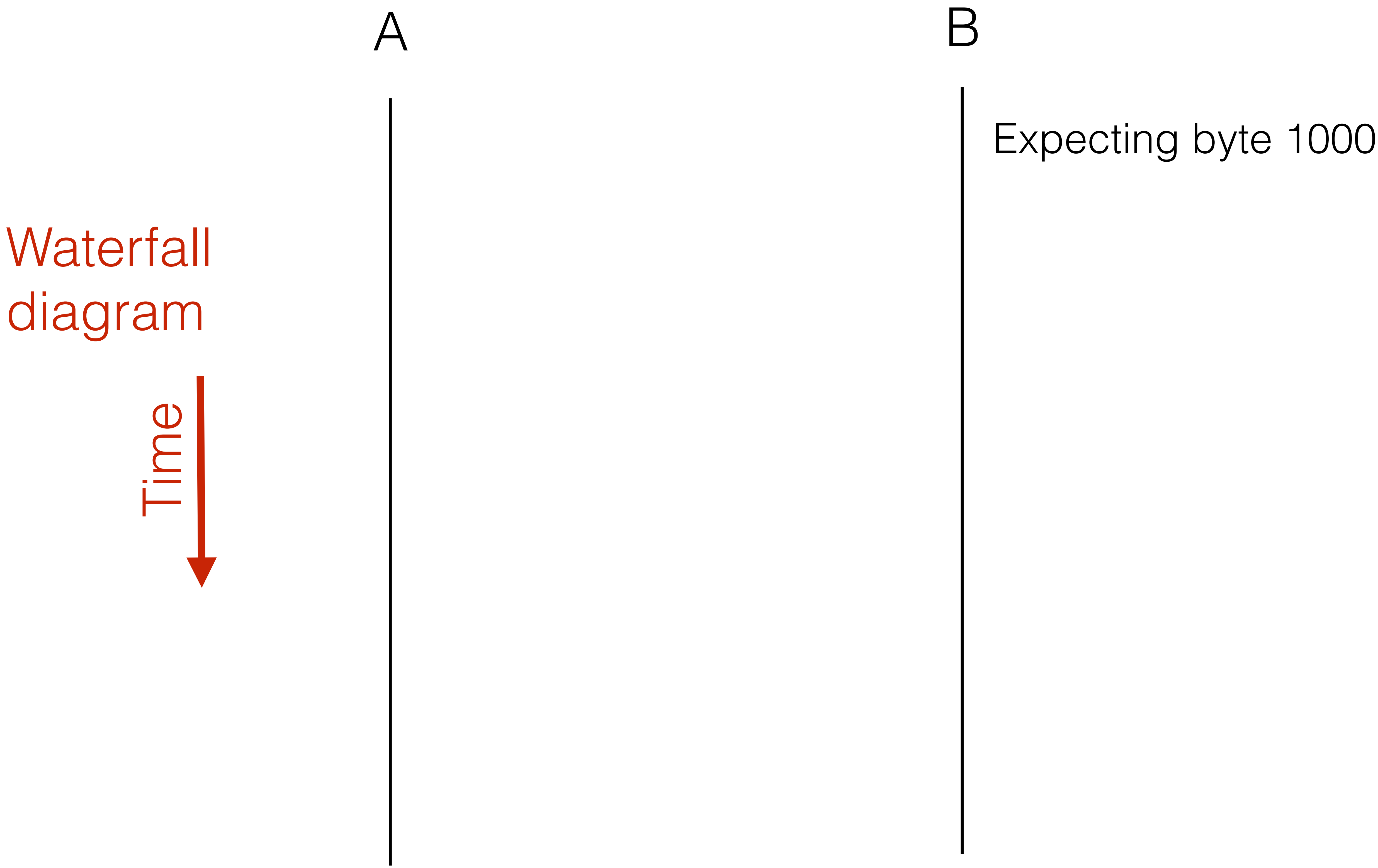

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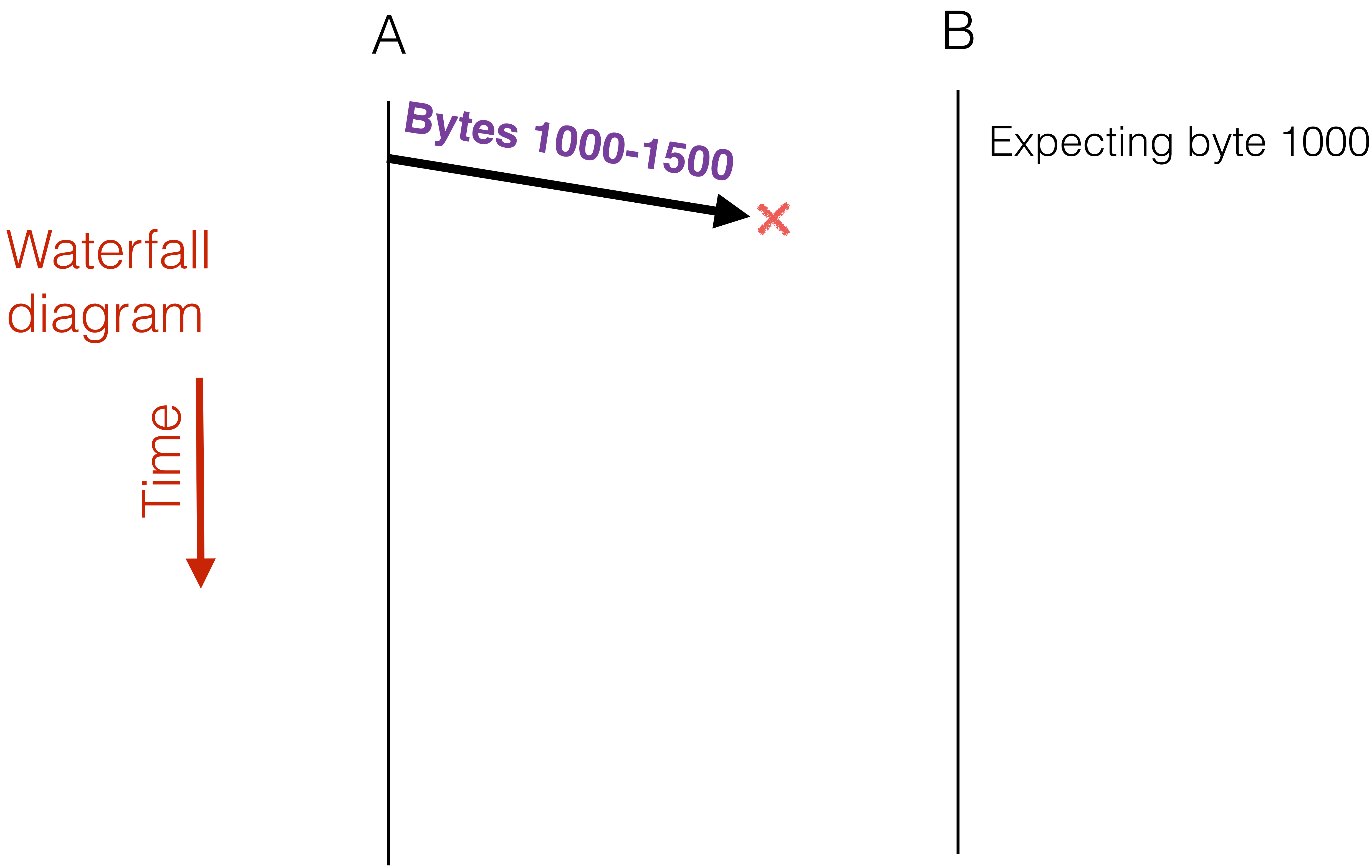

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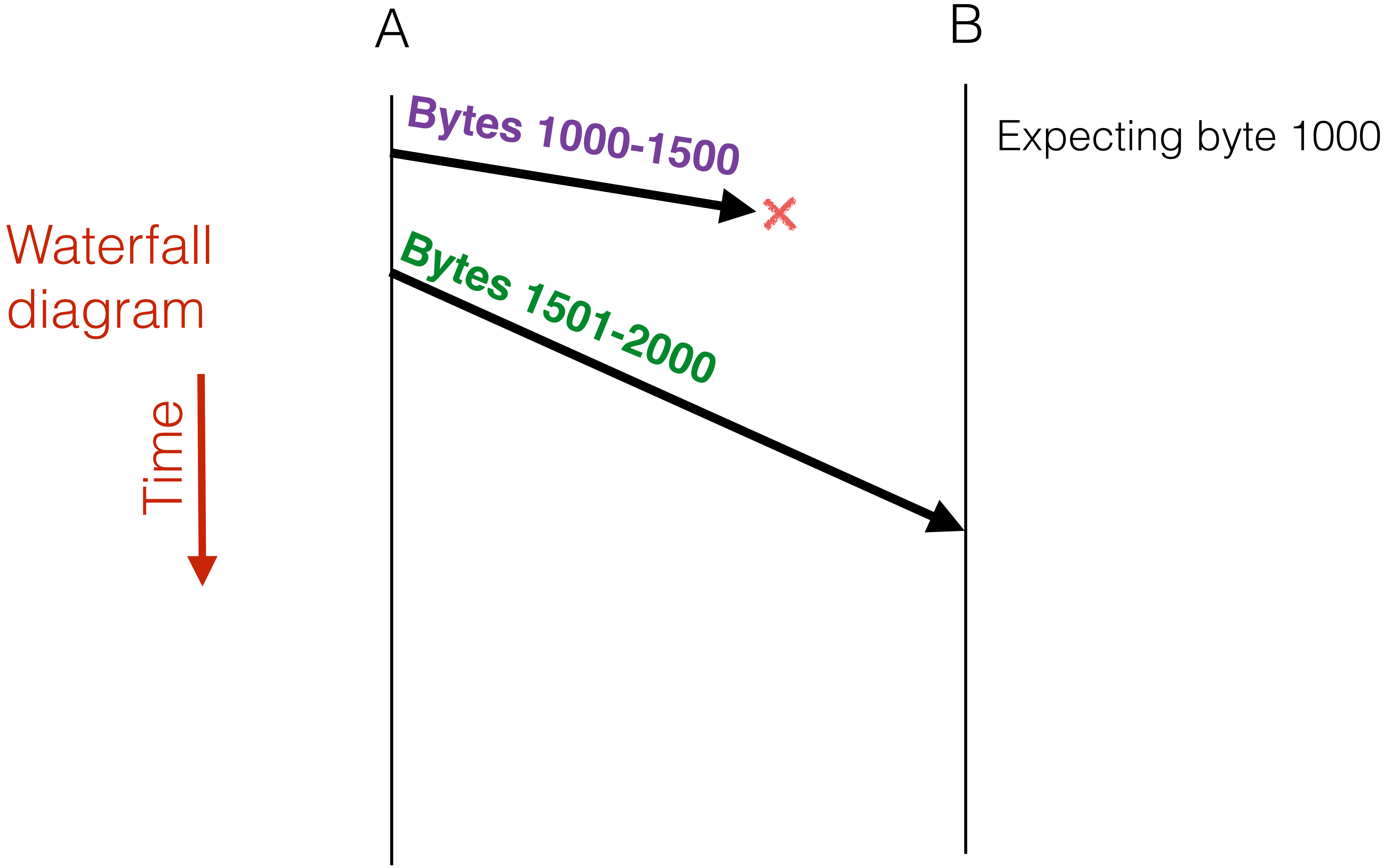

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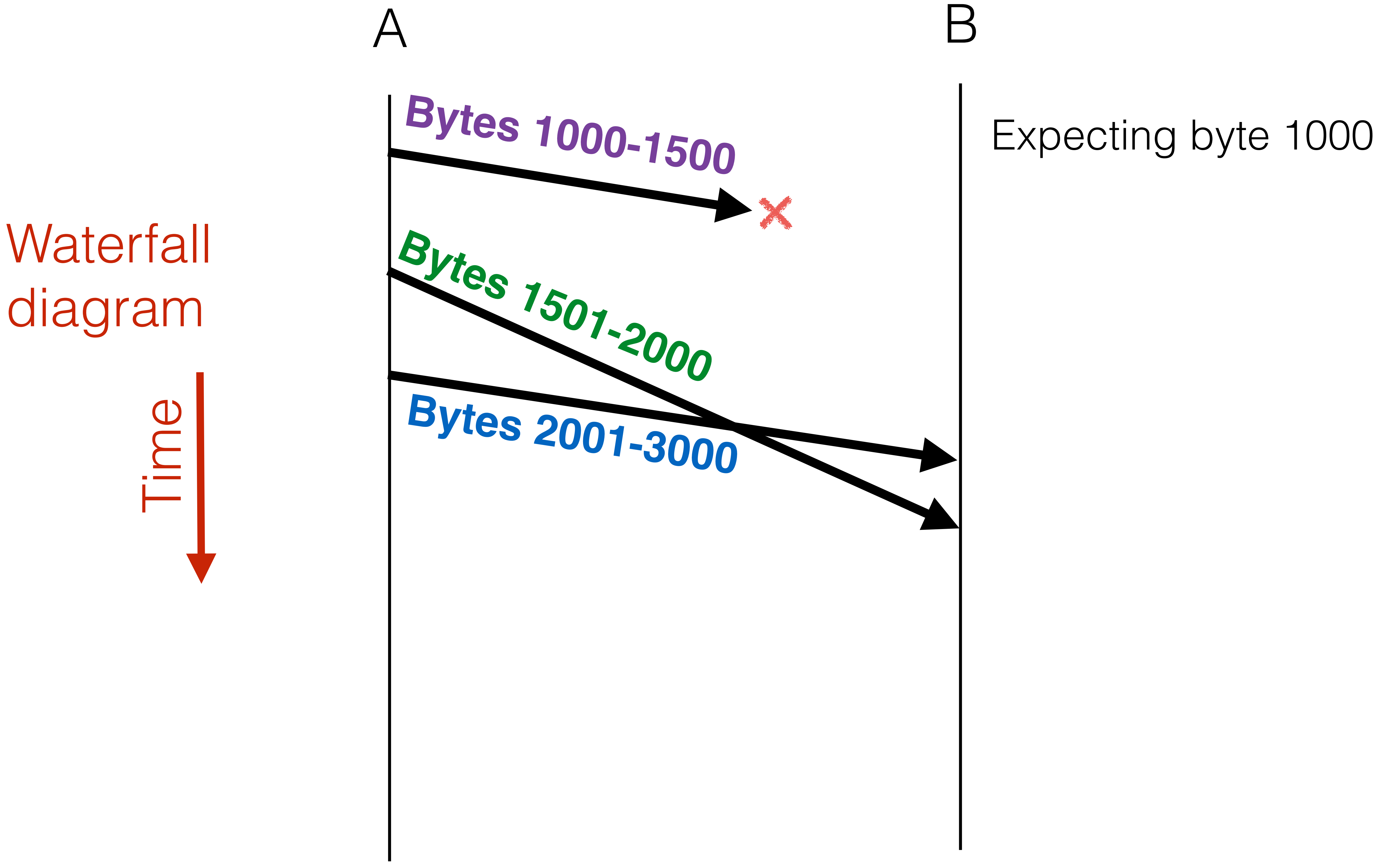

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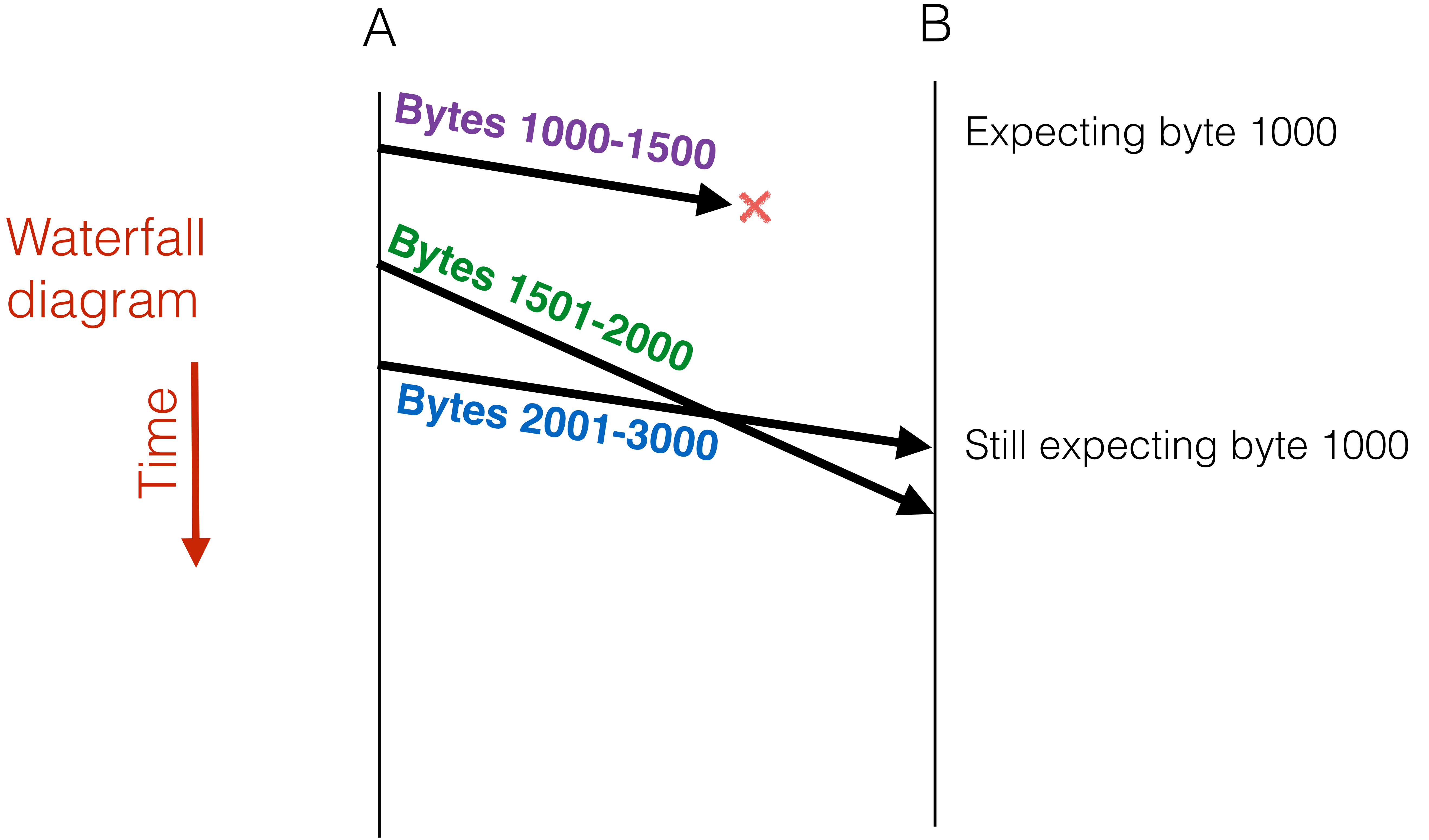

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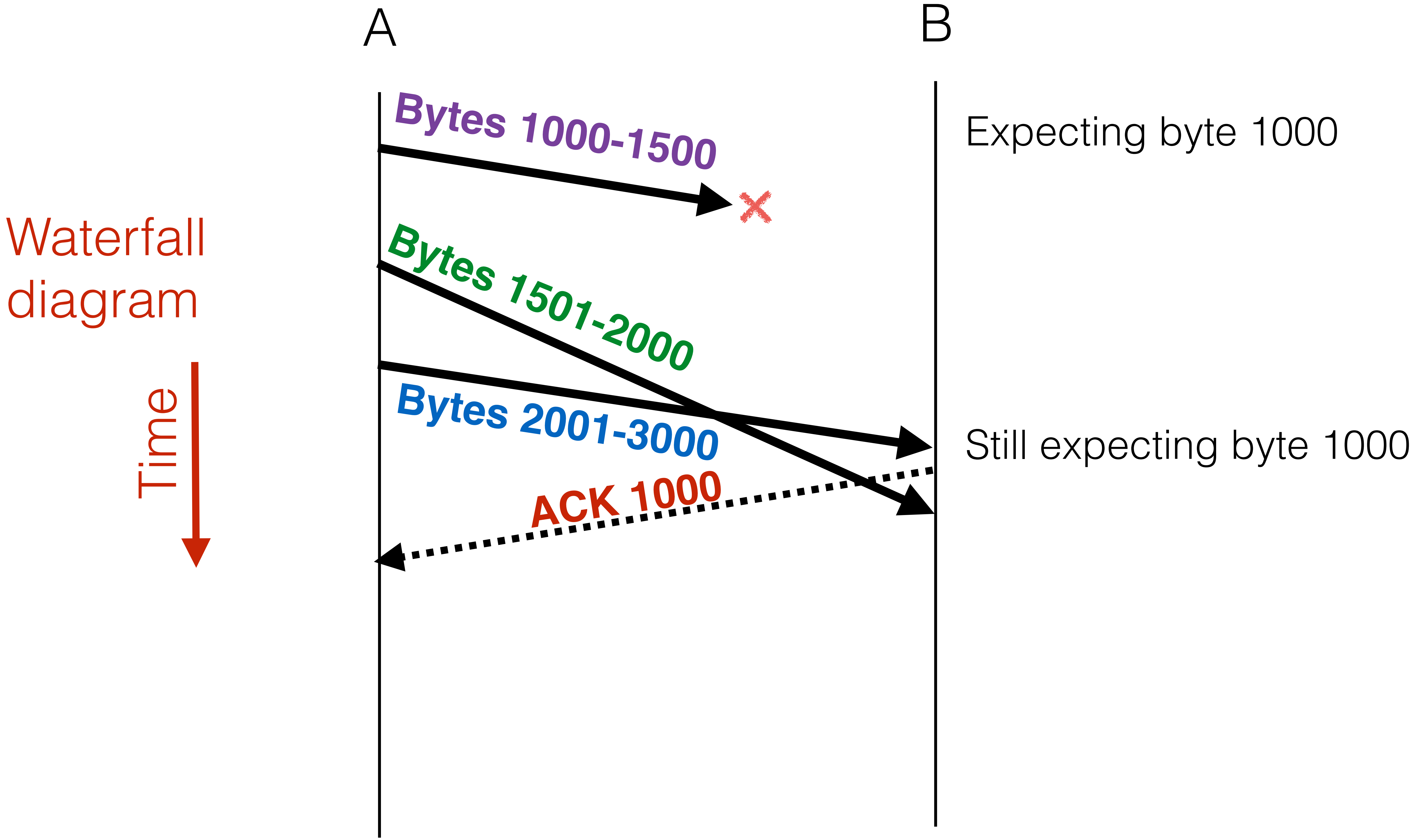

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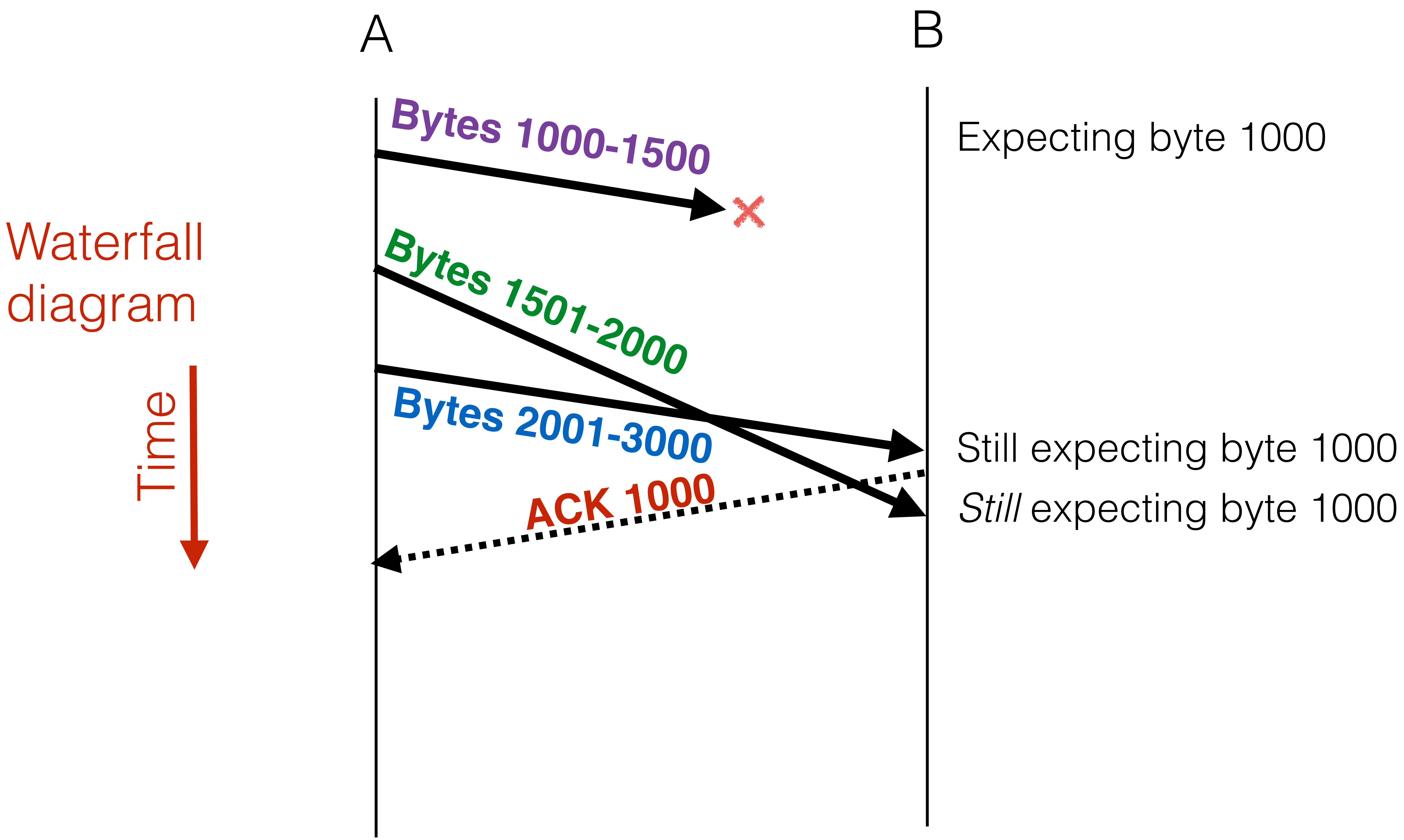

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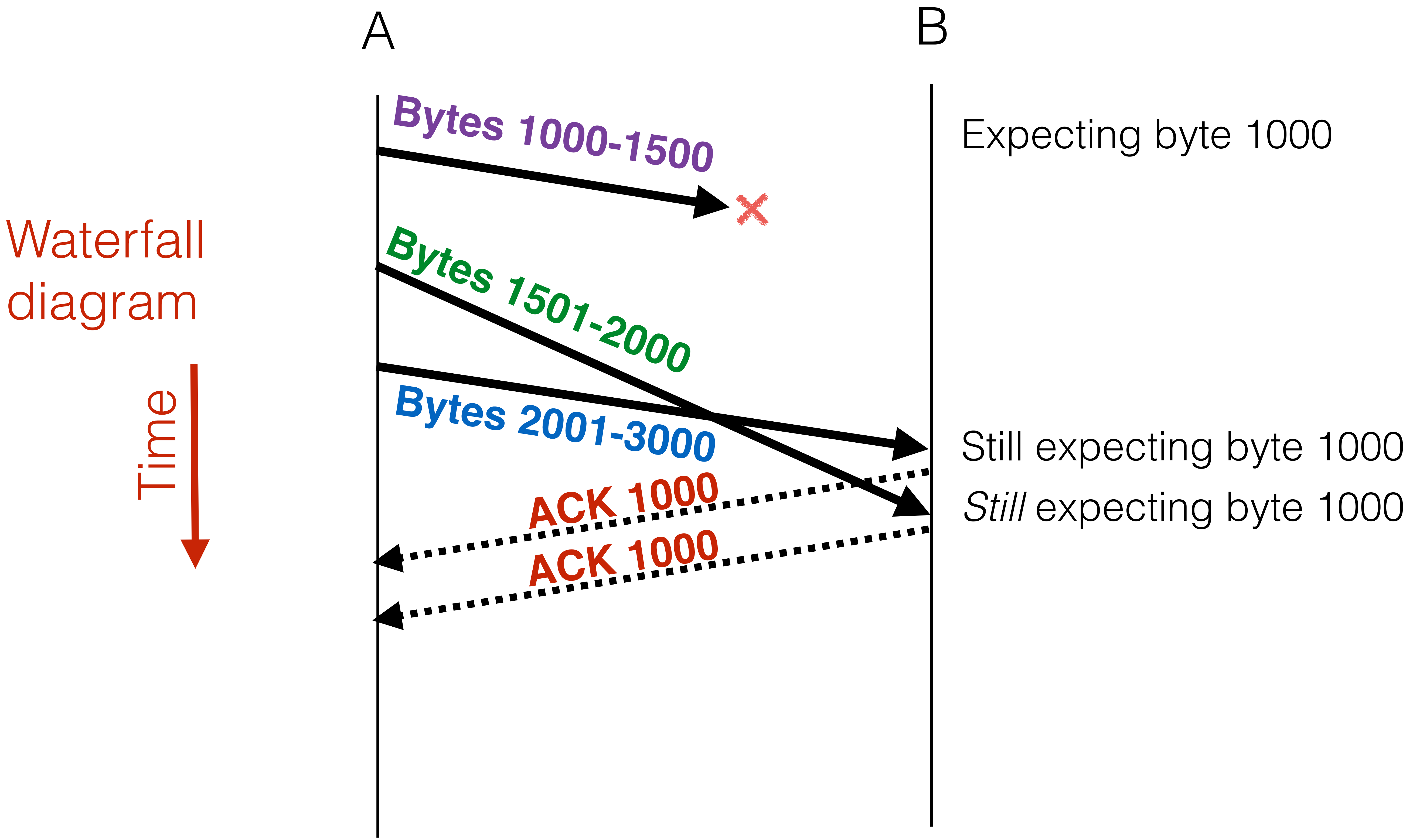

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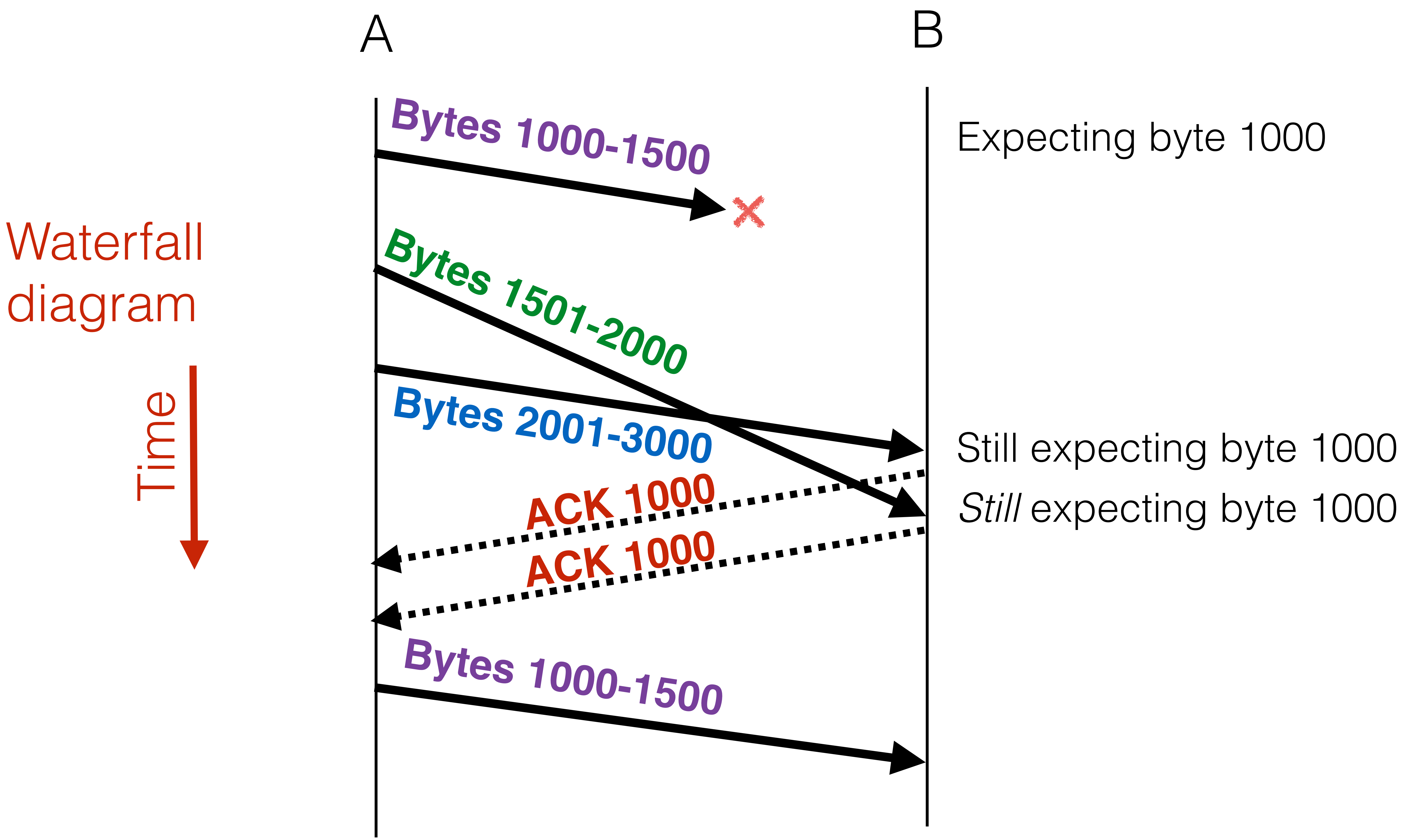

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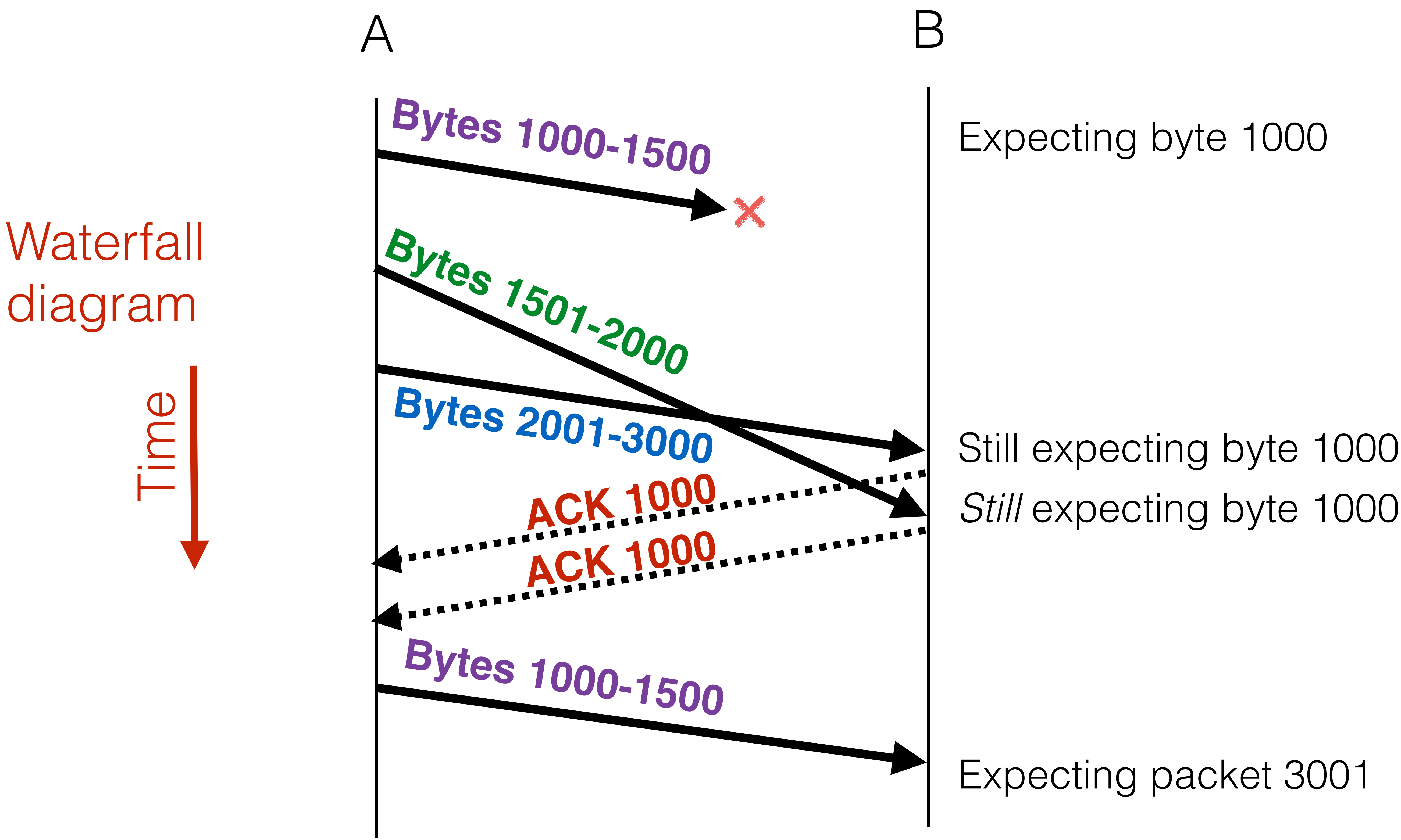
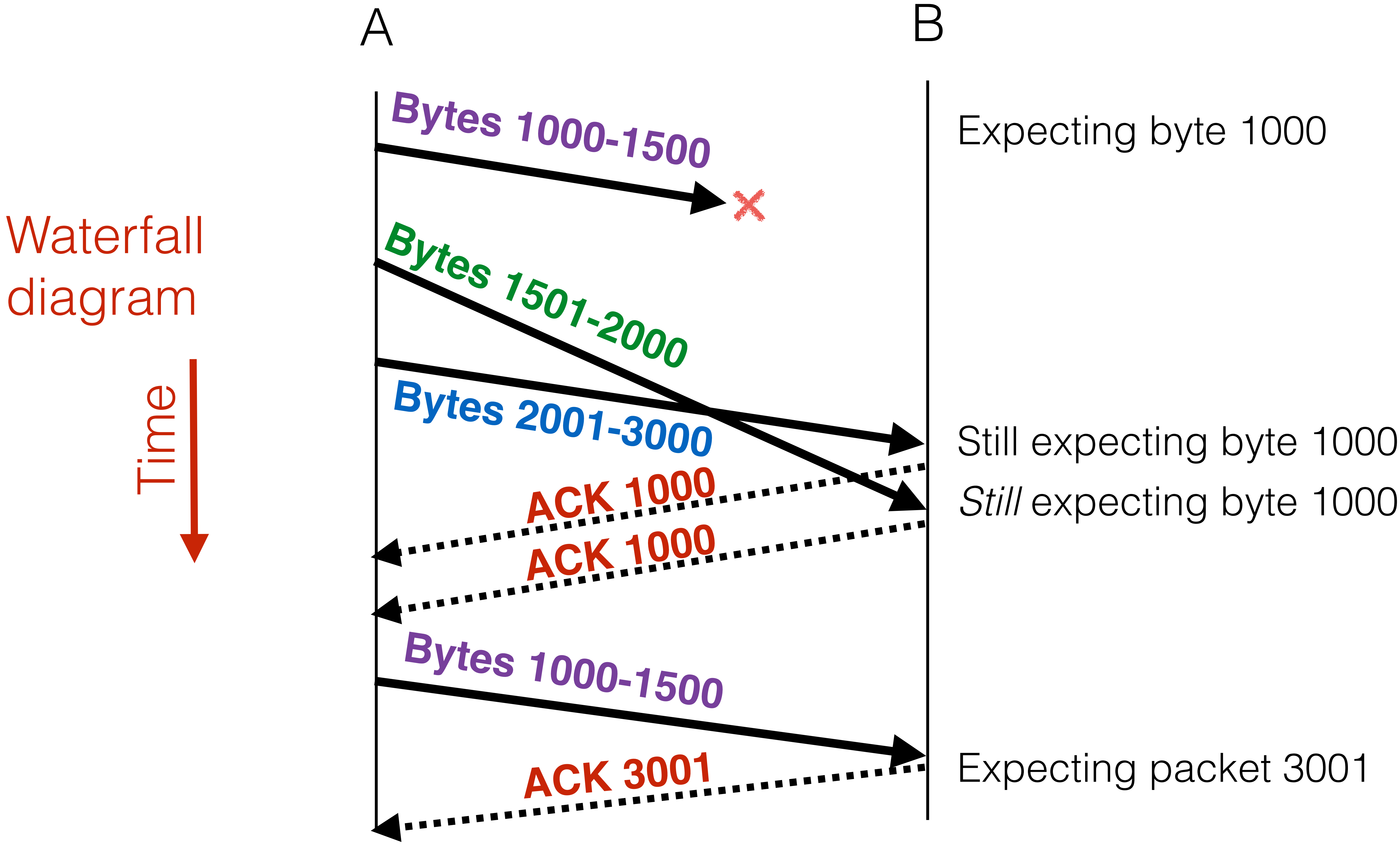


How does TCP achieve reliability?



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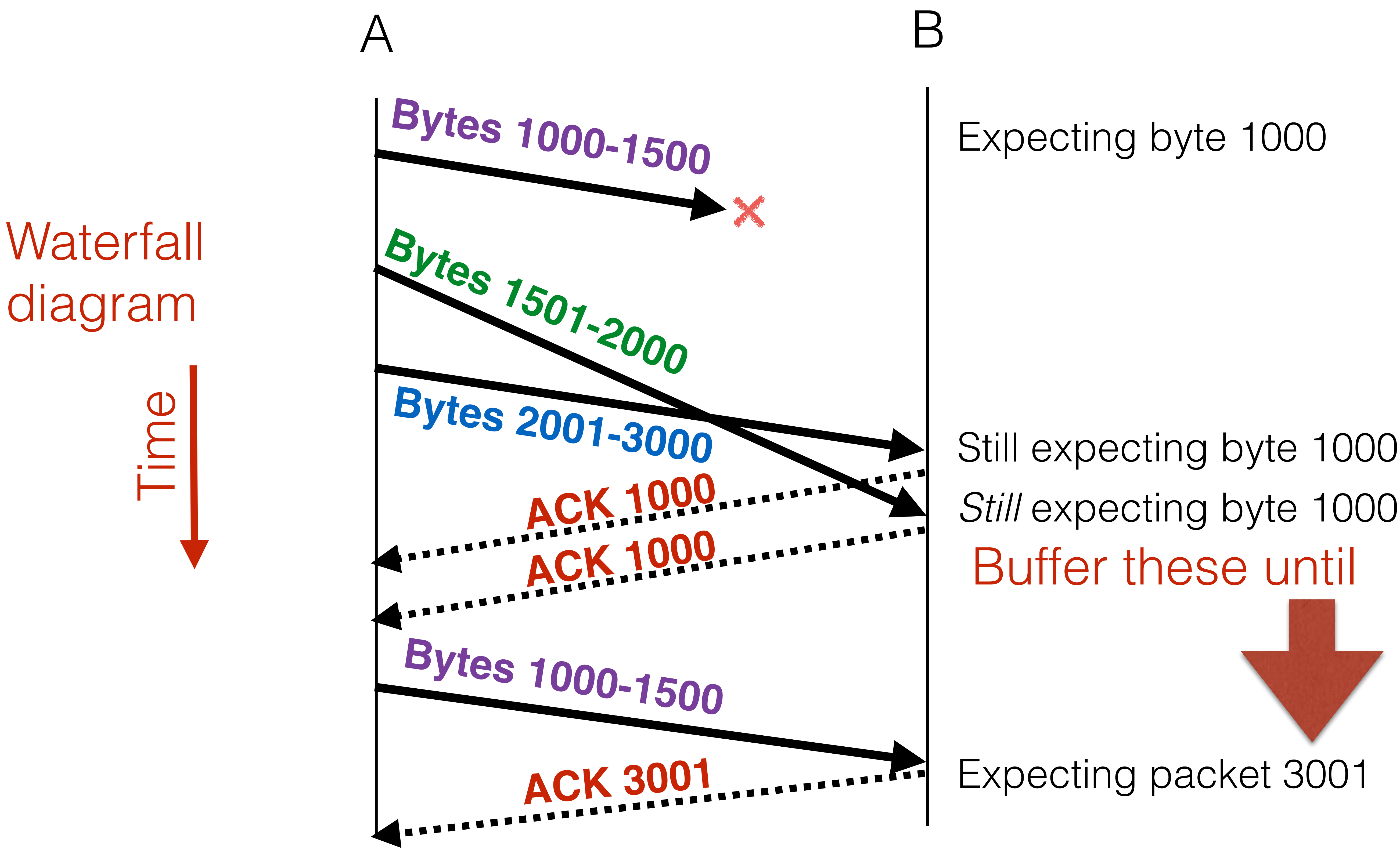
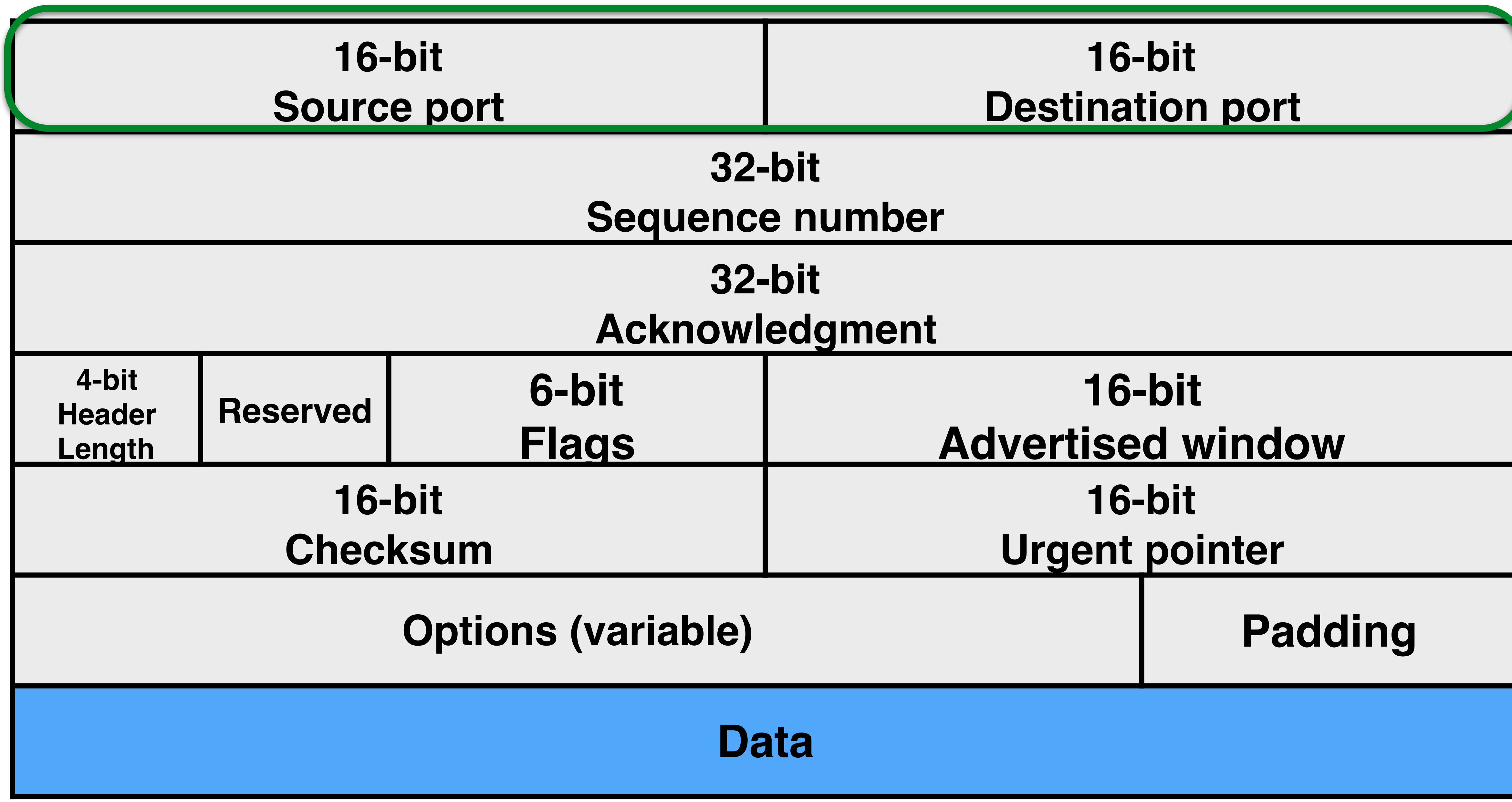


TCP congestion control

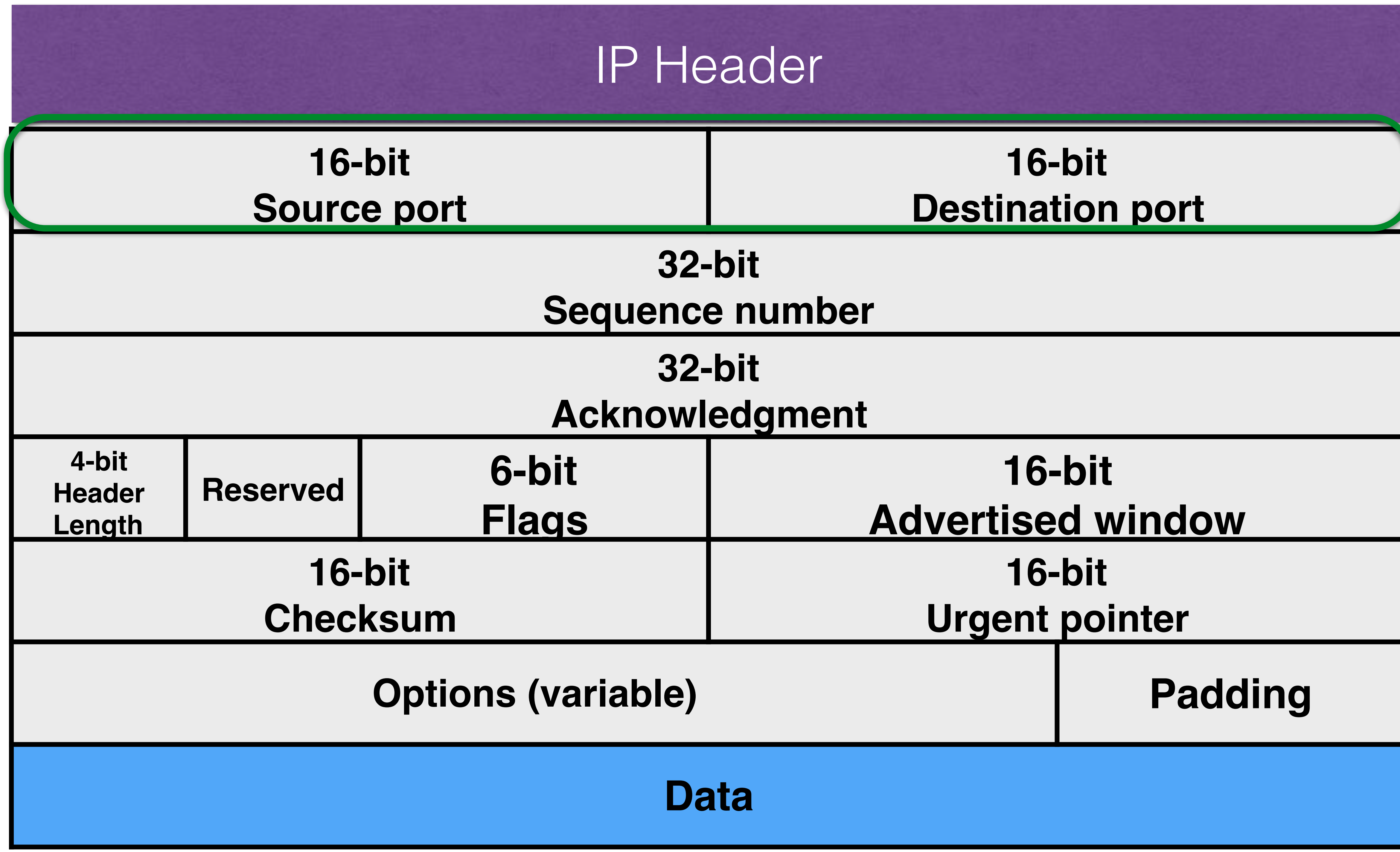
TCP's second job: don't break the network!

- 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


IP Header
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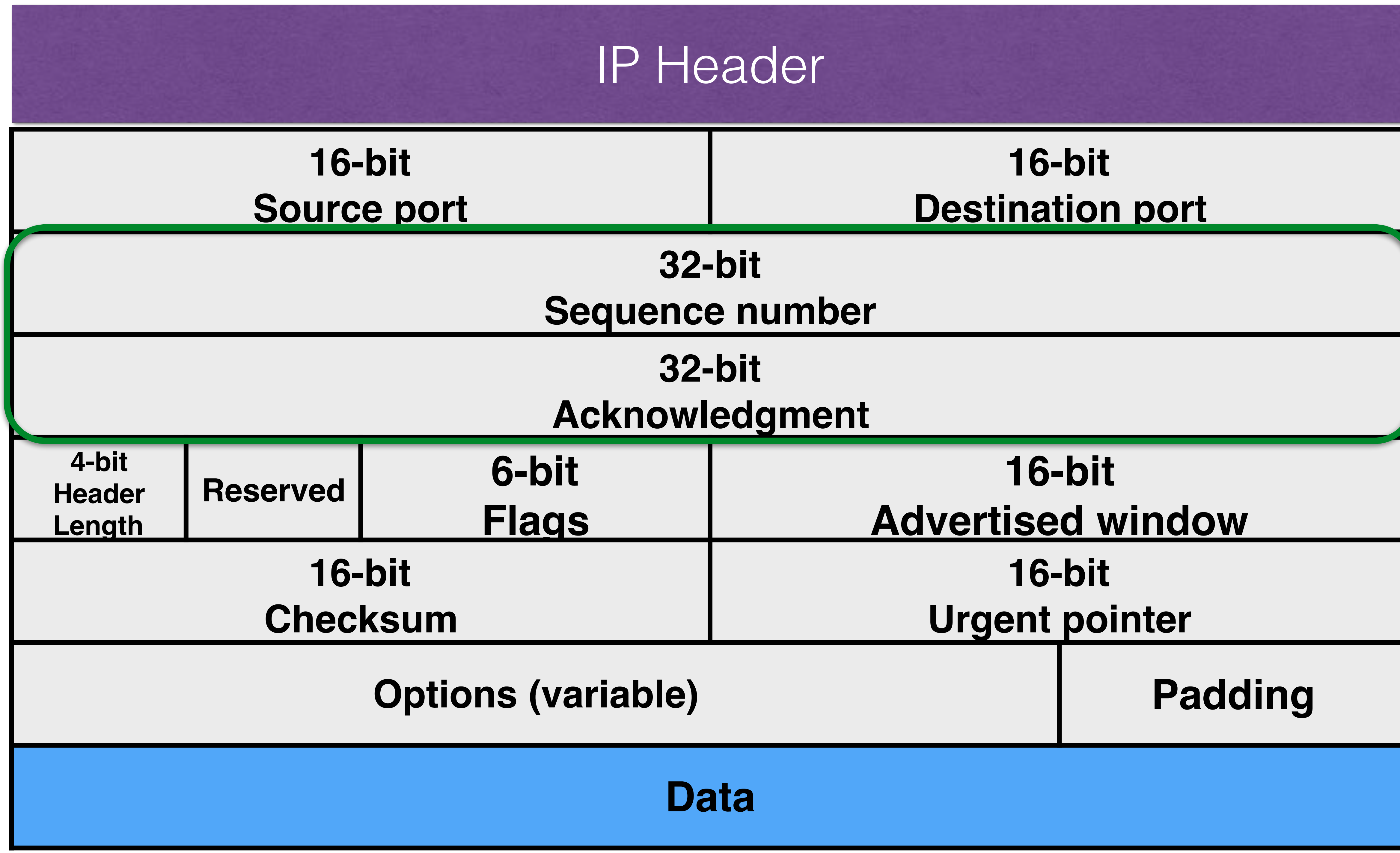
Acknowledgment
4-bit
Header
Length
Reserved
6-bit
Flags
16-bit
Advertised window
16-bit
Checksum
16-bit
Urgent pointer
Options (variable)
Padding
Data

TCP 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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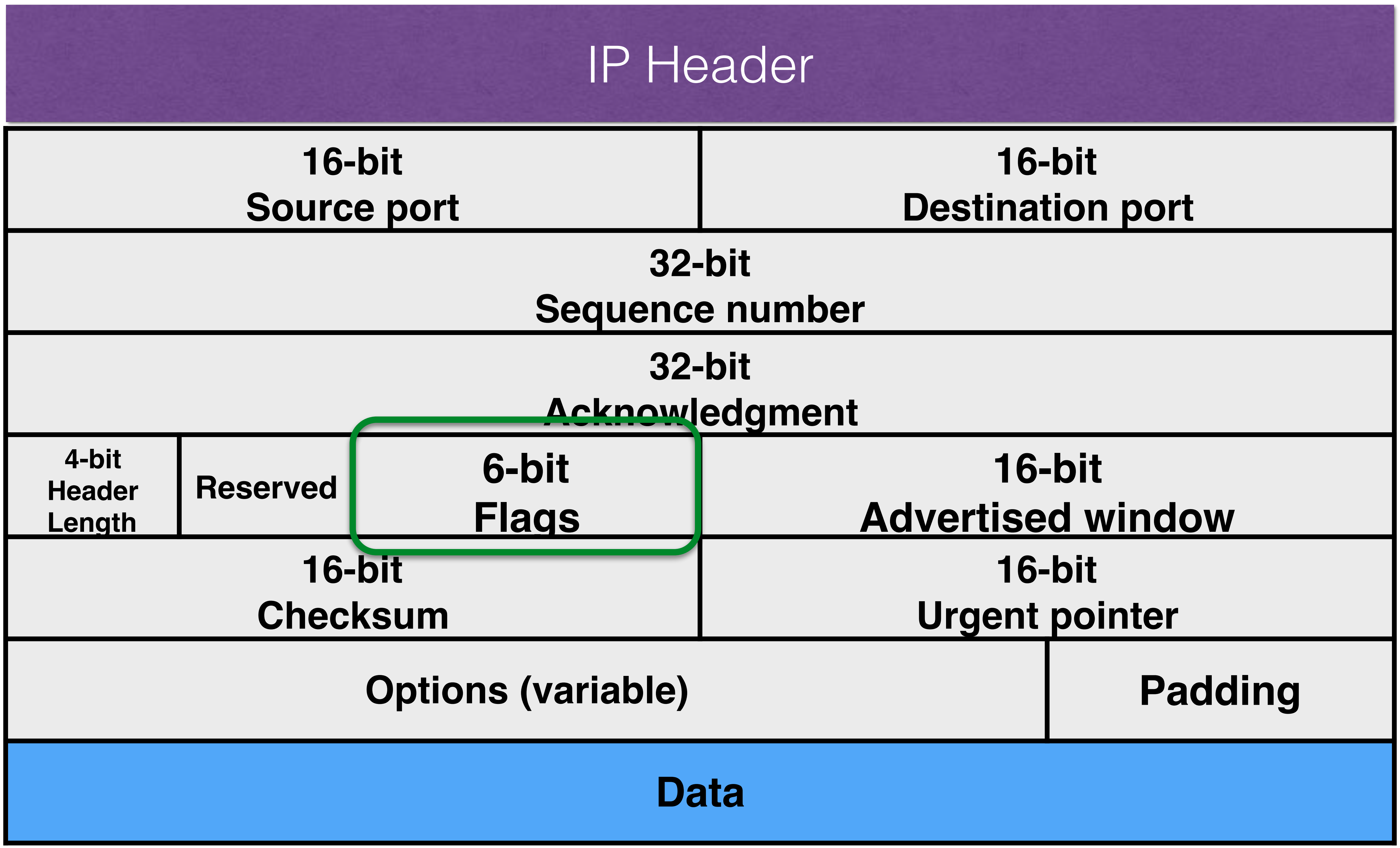
6-bit
Flags
16-bit
Advertised window
16-bit
Checksum
16-bit
Urgent pointer
Options (variable)
Padding
Data

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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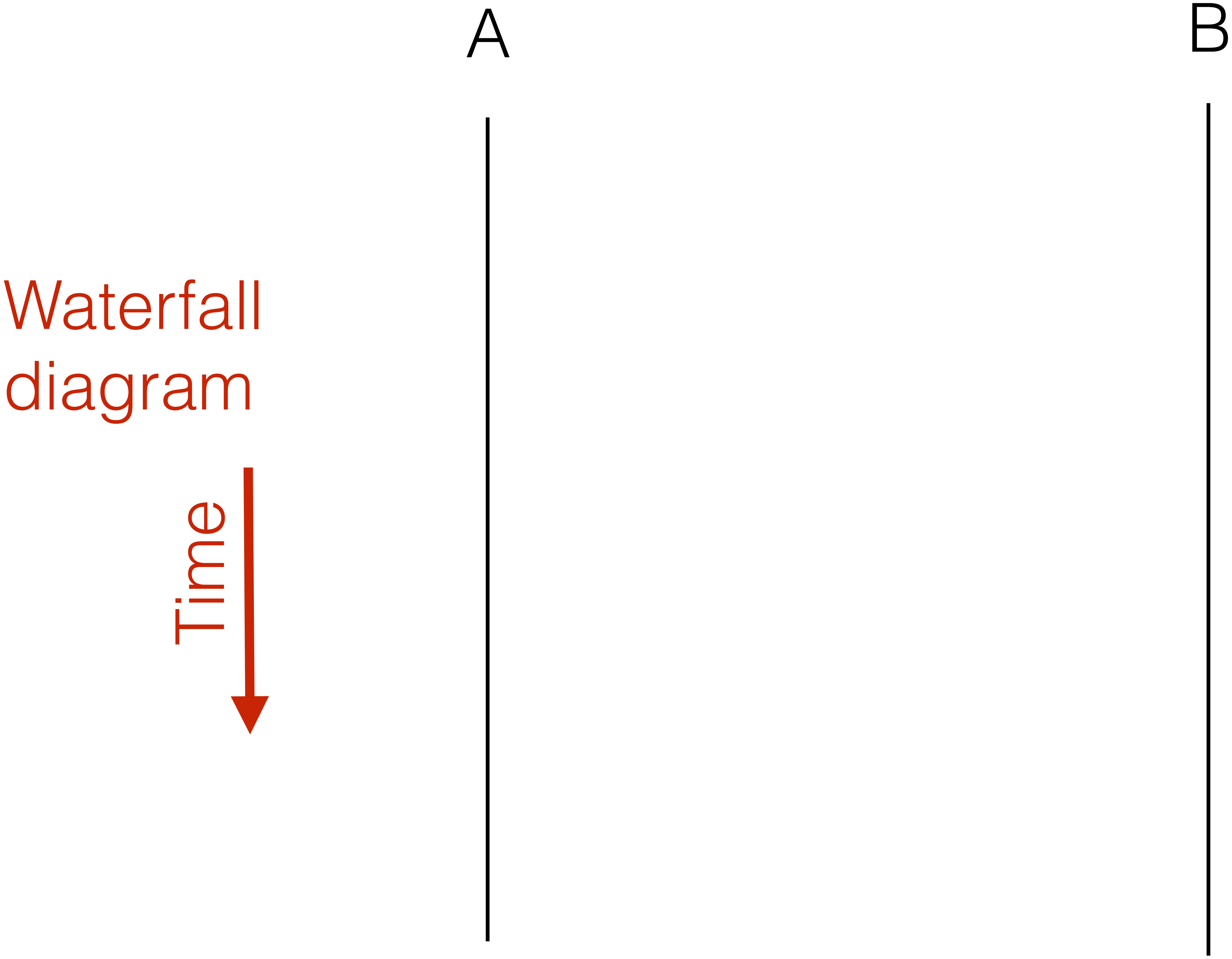
6-bit
Flags
16-bit
Advertised window
16-bit
Checksum
16-bit
Urgent pointer
Options (variable)
Padding
Data

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



Setting up a connection

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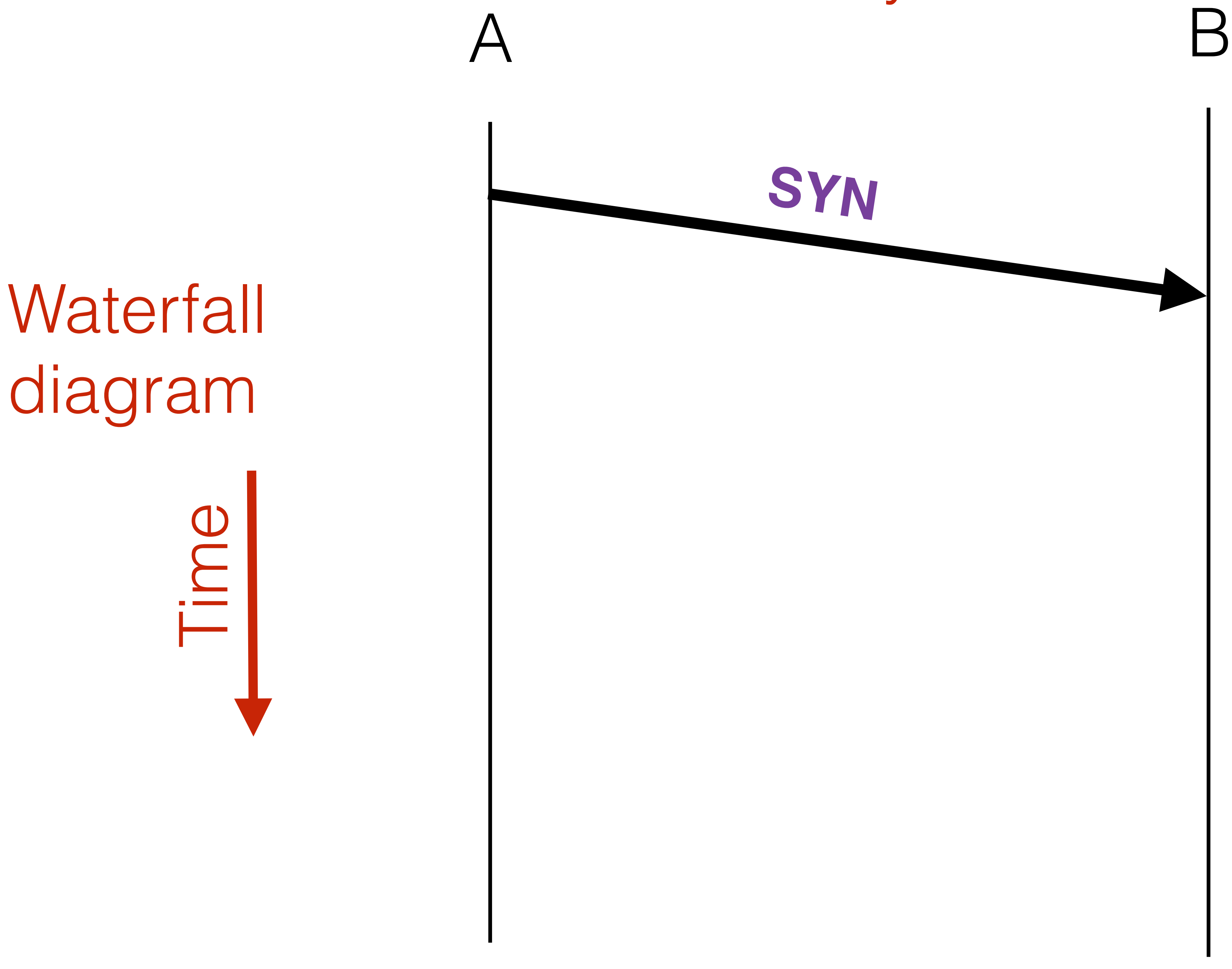
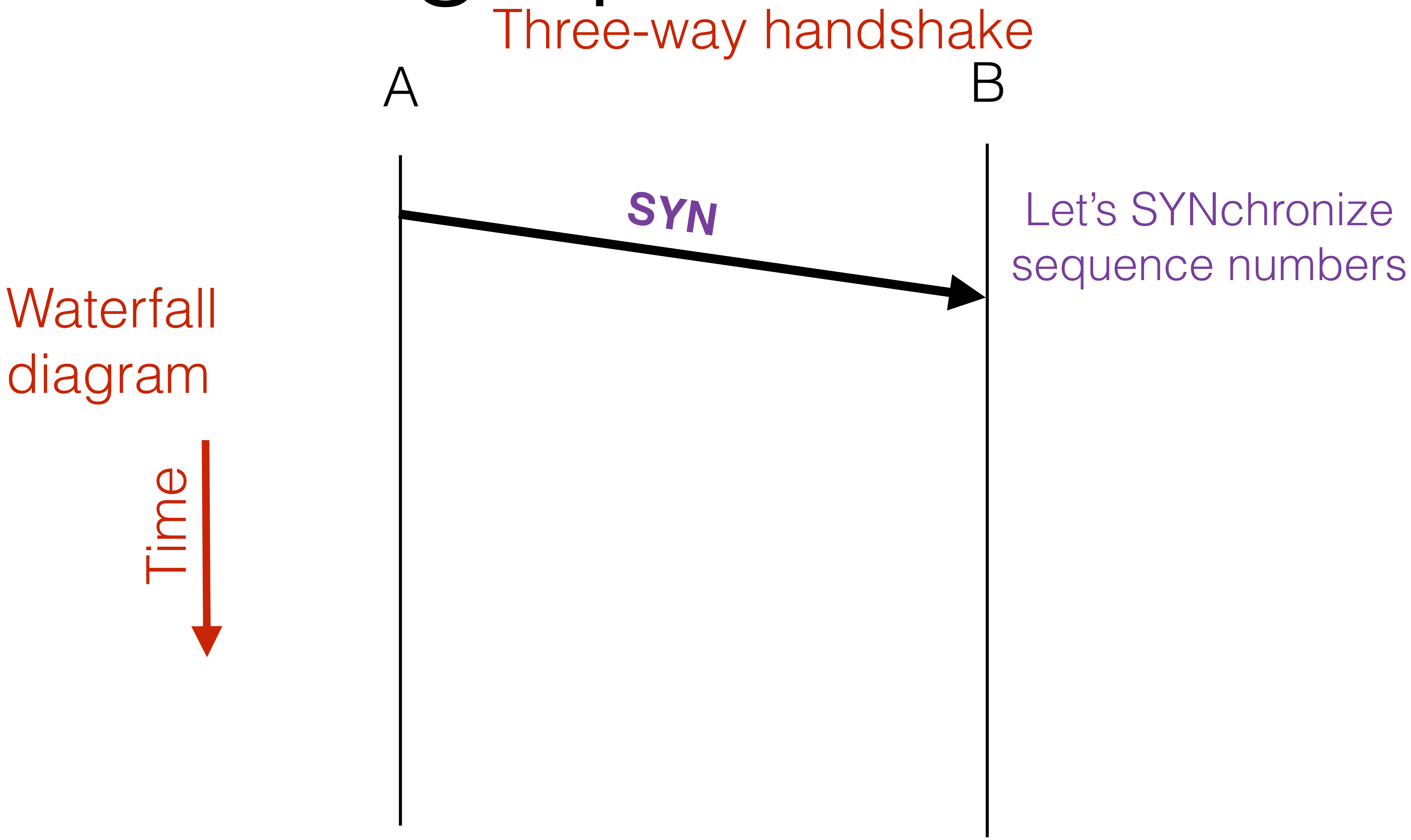
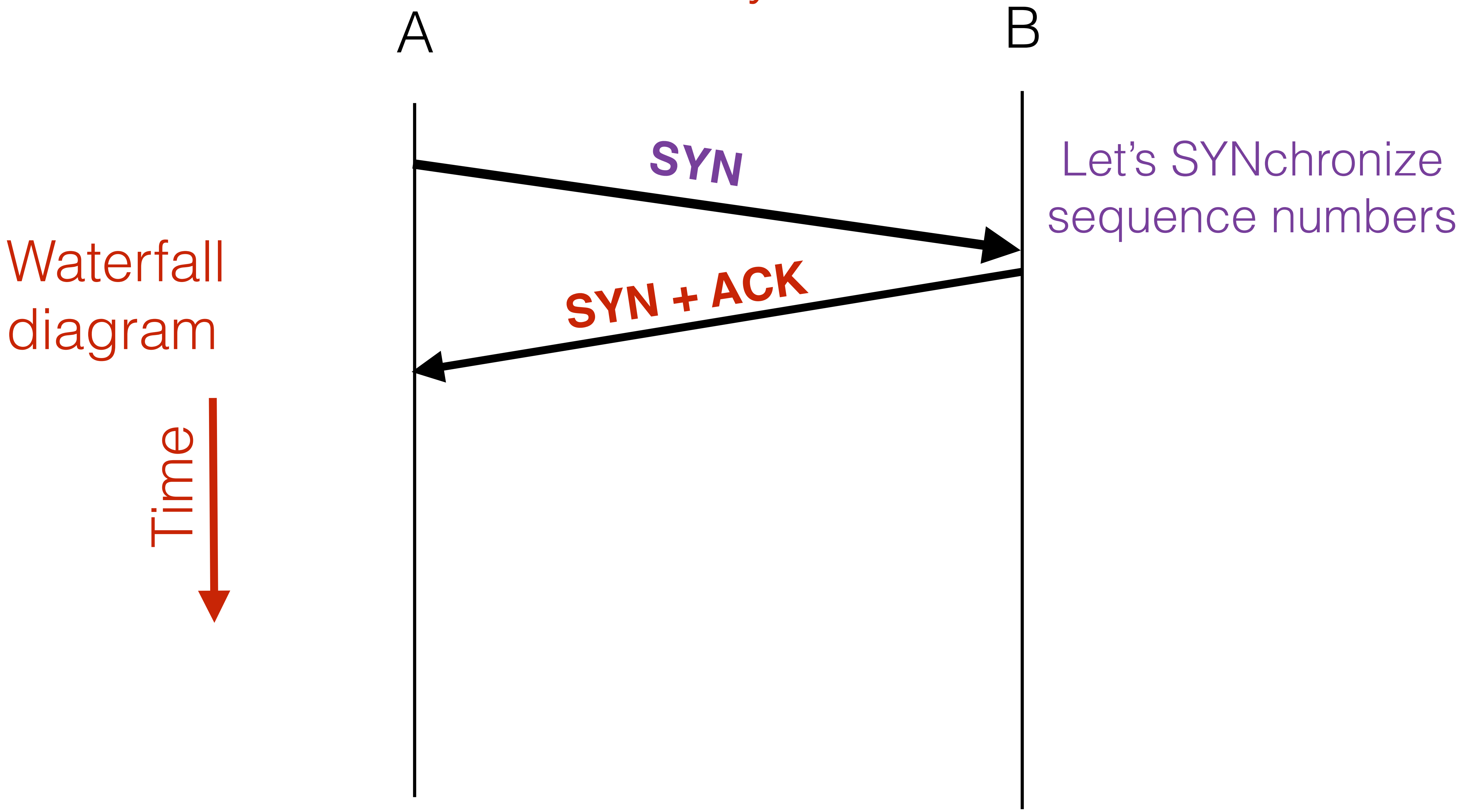


Setting up a connection



Setting up a connection

Three-way handshake



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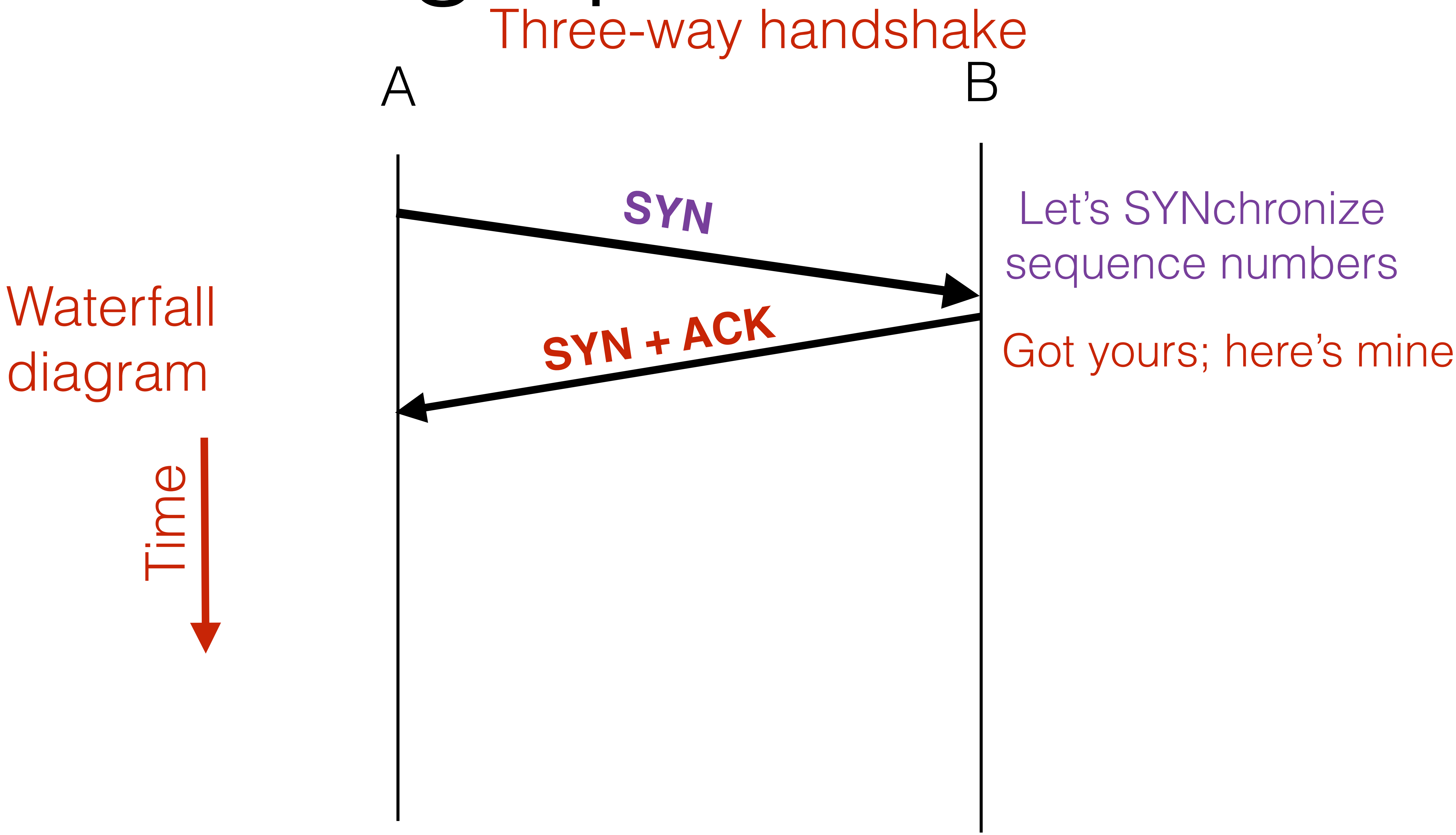

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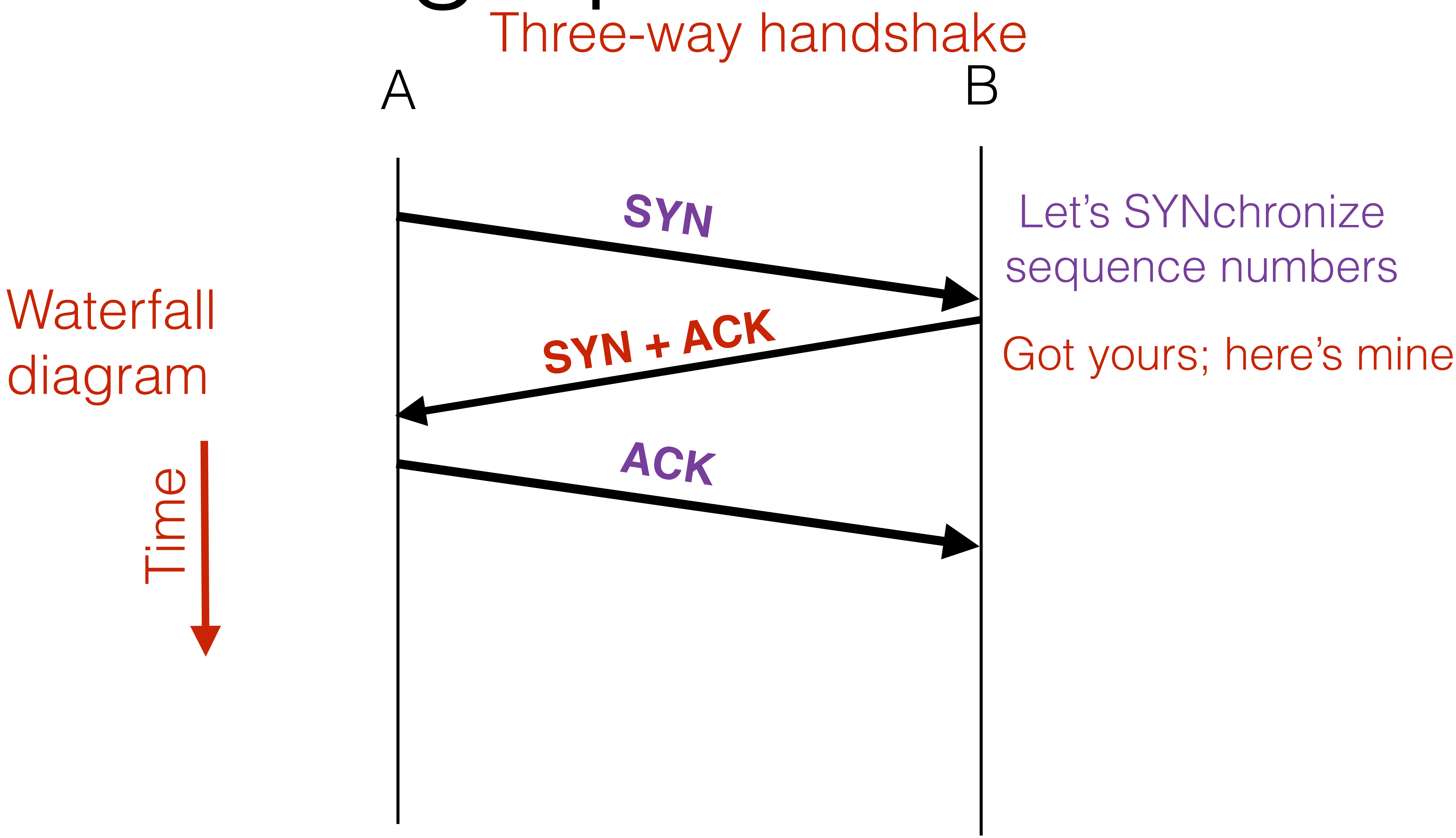
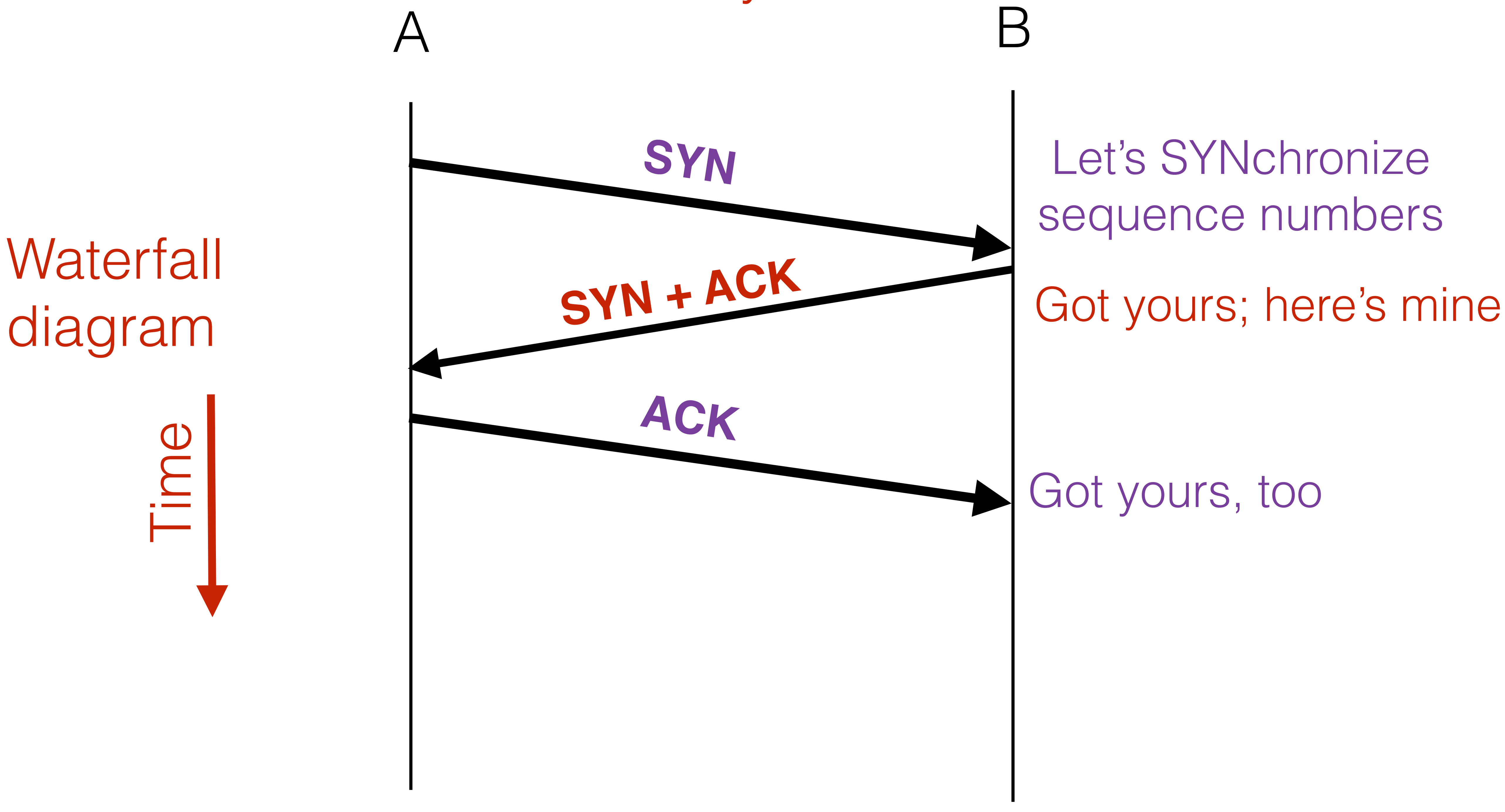
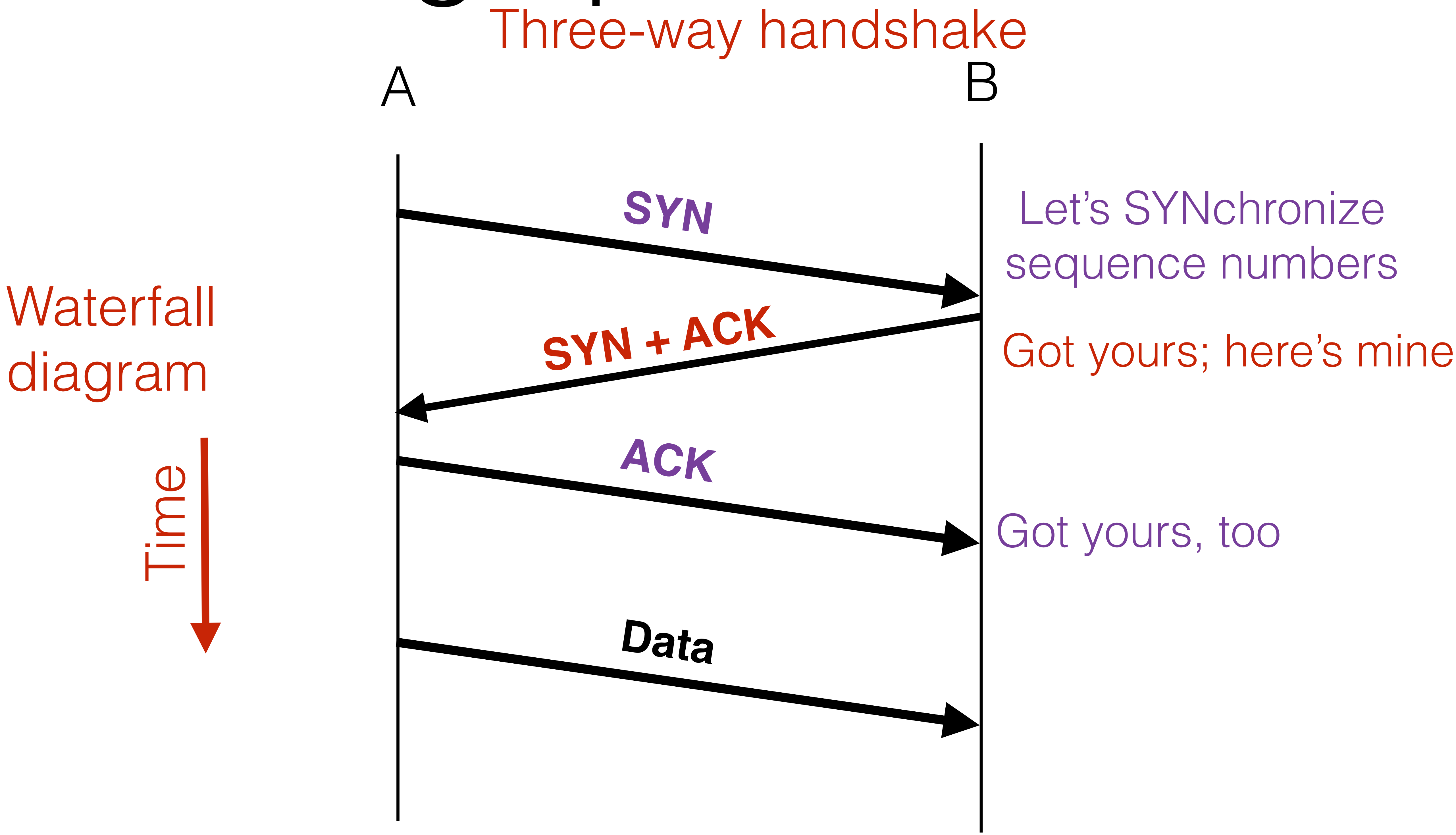


Setting up a connection

Three-way handshake

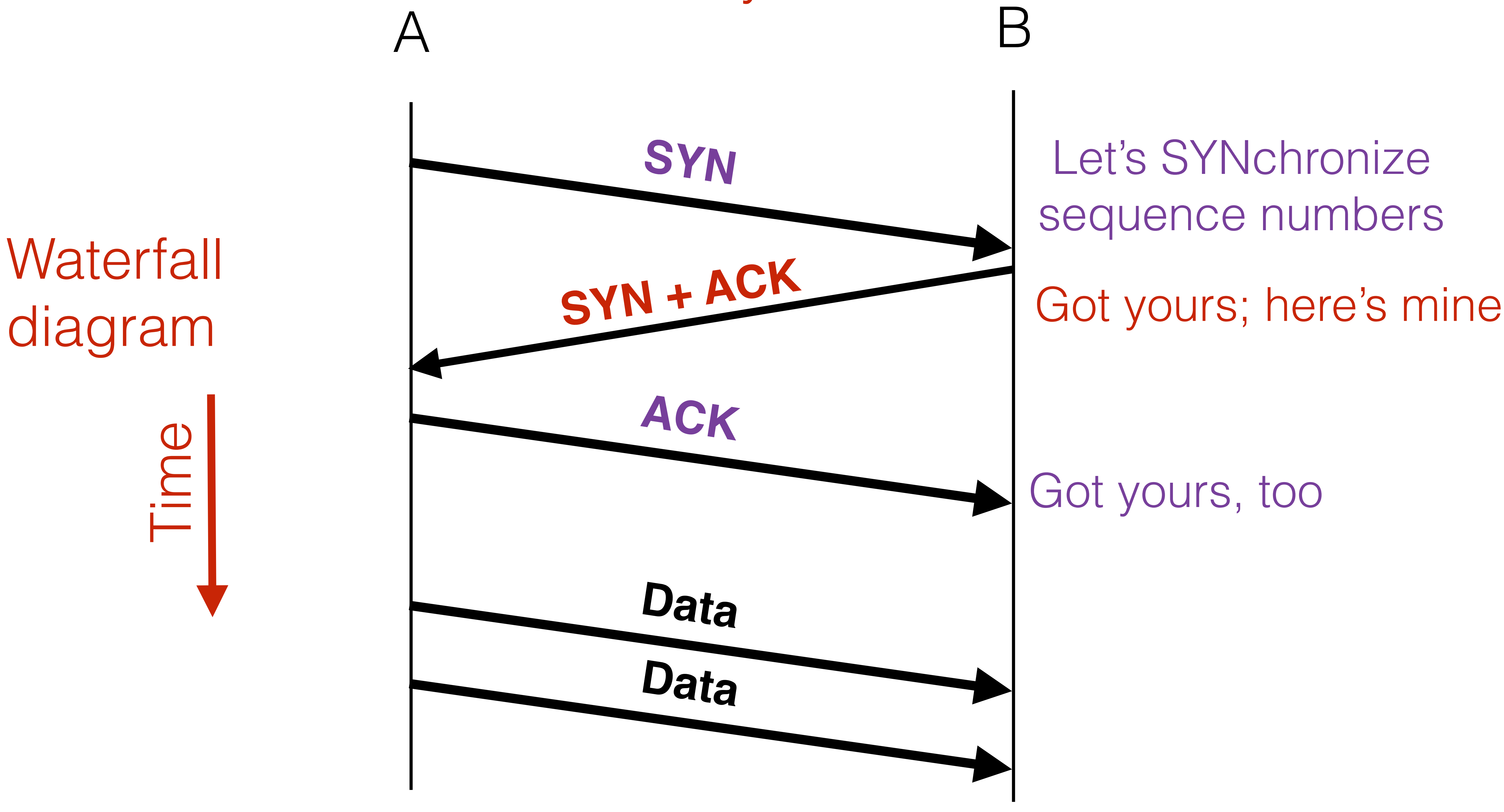


Setting up a connection



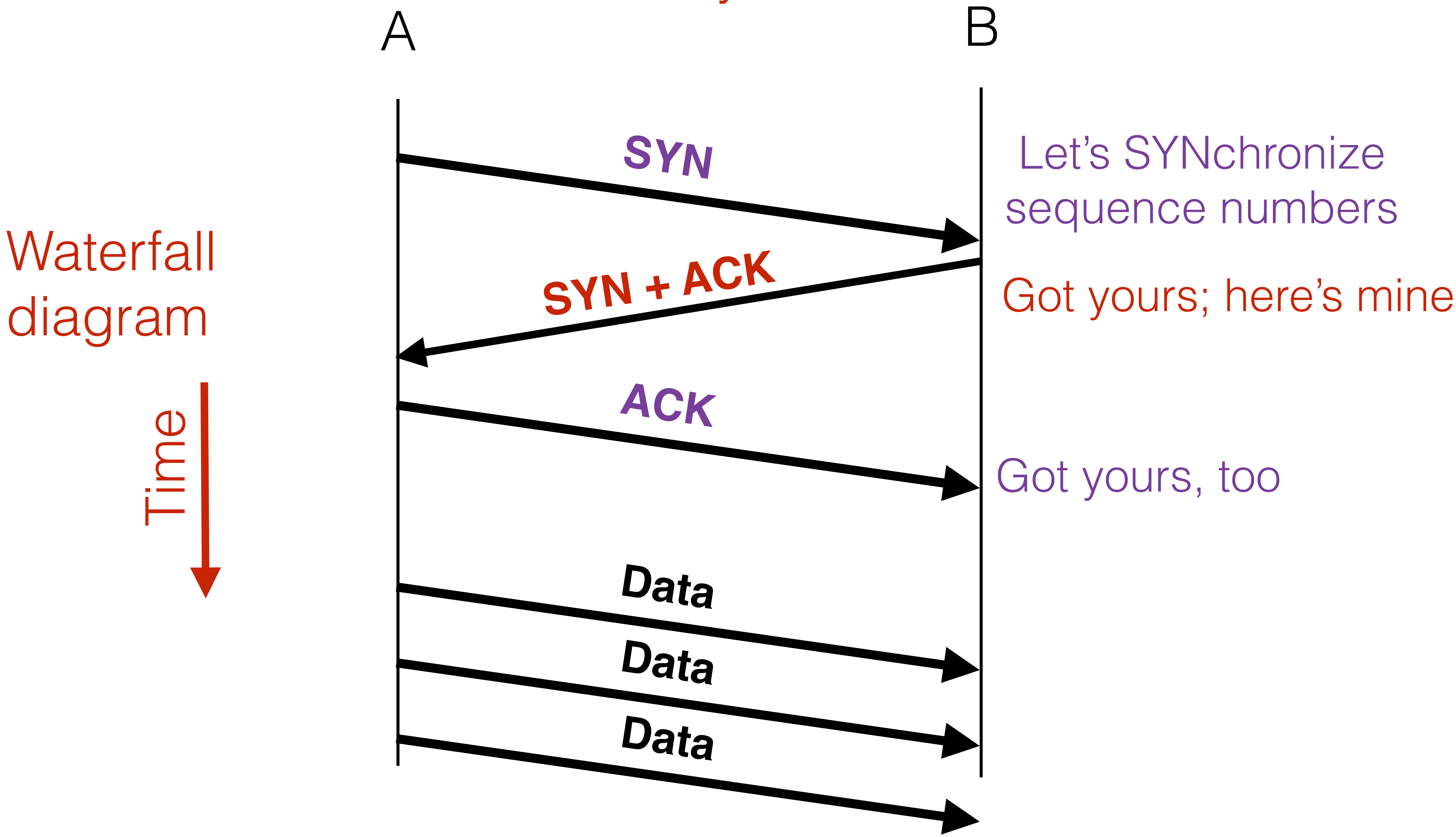
Setting up a connection

Three-way handshake



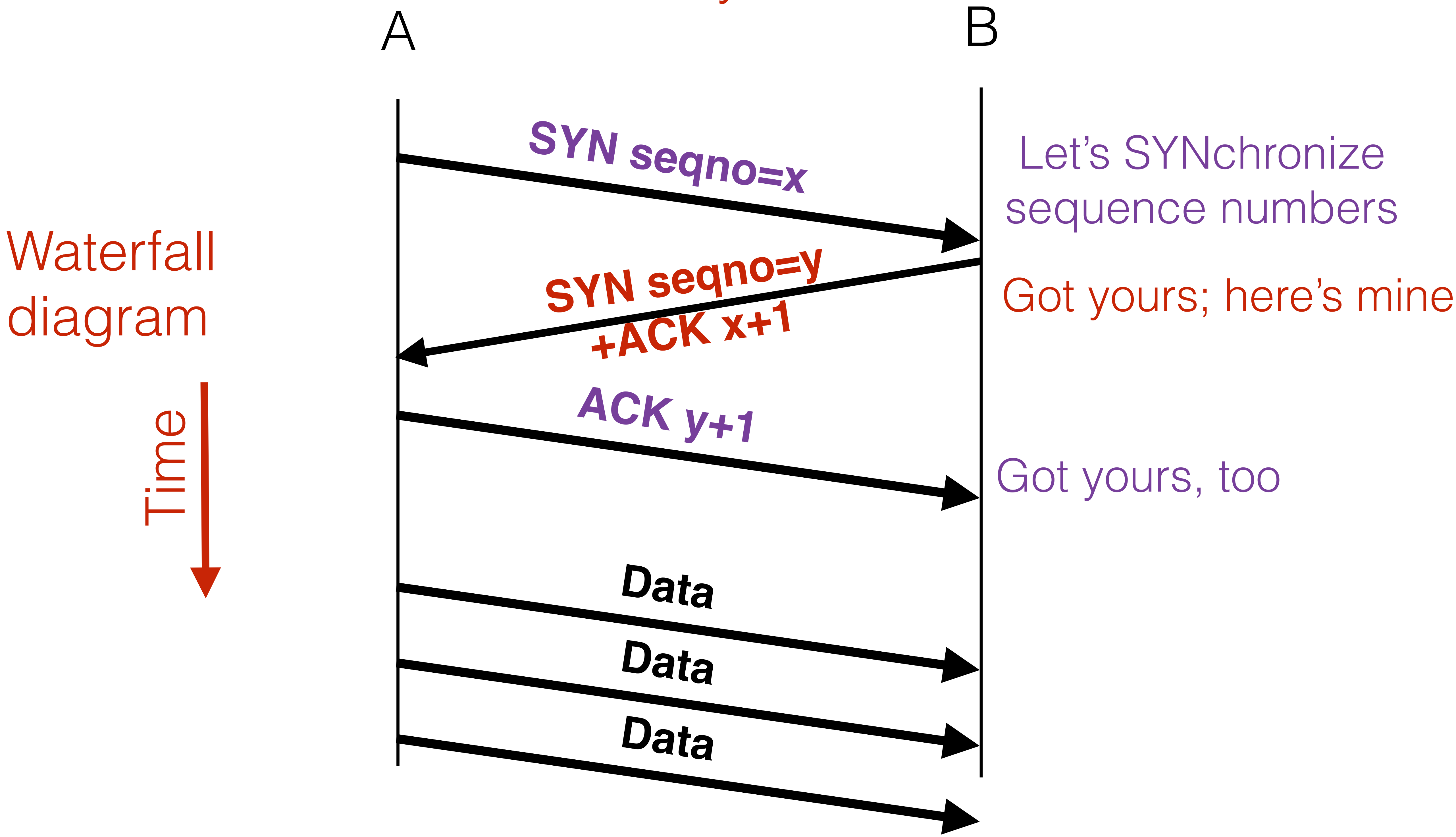
Setting up a connection

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

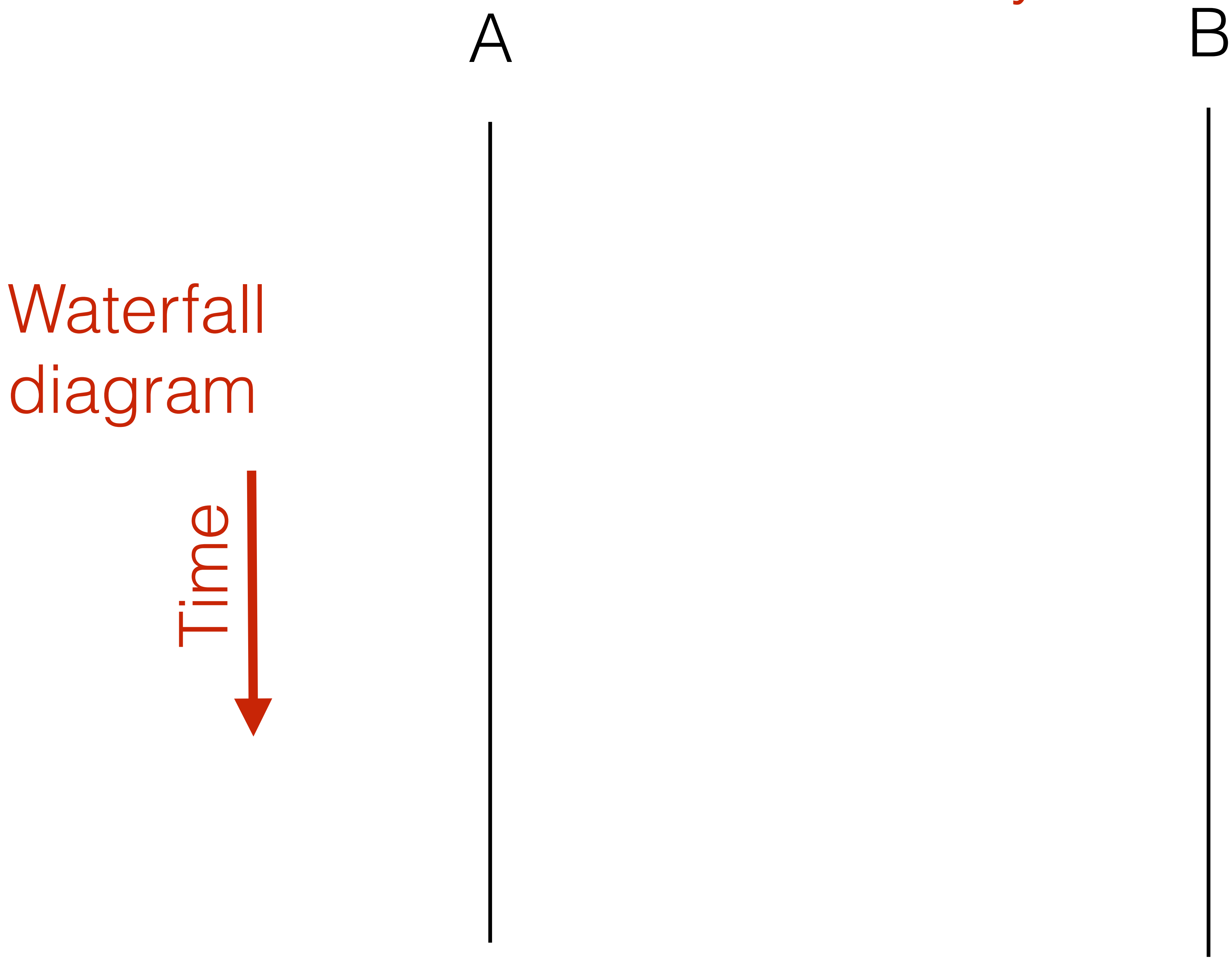
Attacks

- SYN flooding
- Injection attacks
- Opt-ack attack

SYN flooding

SYN flooding

Recall the three-way handshake:



SYN flooding

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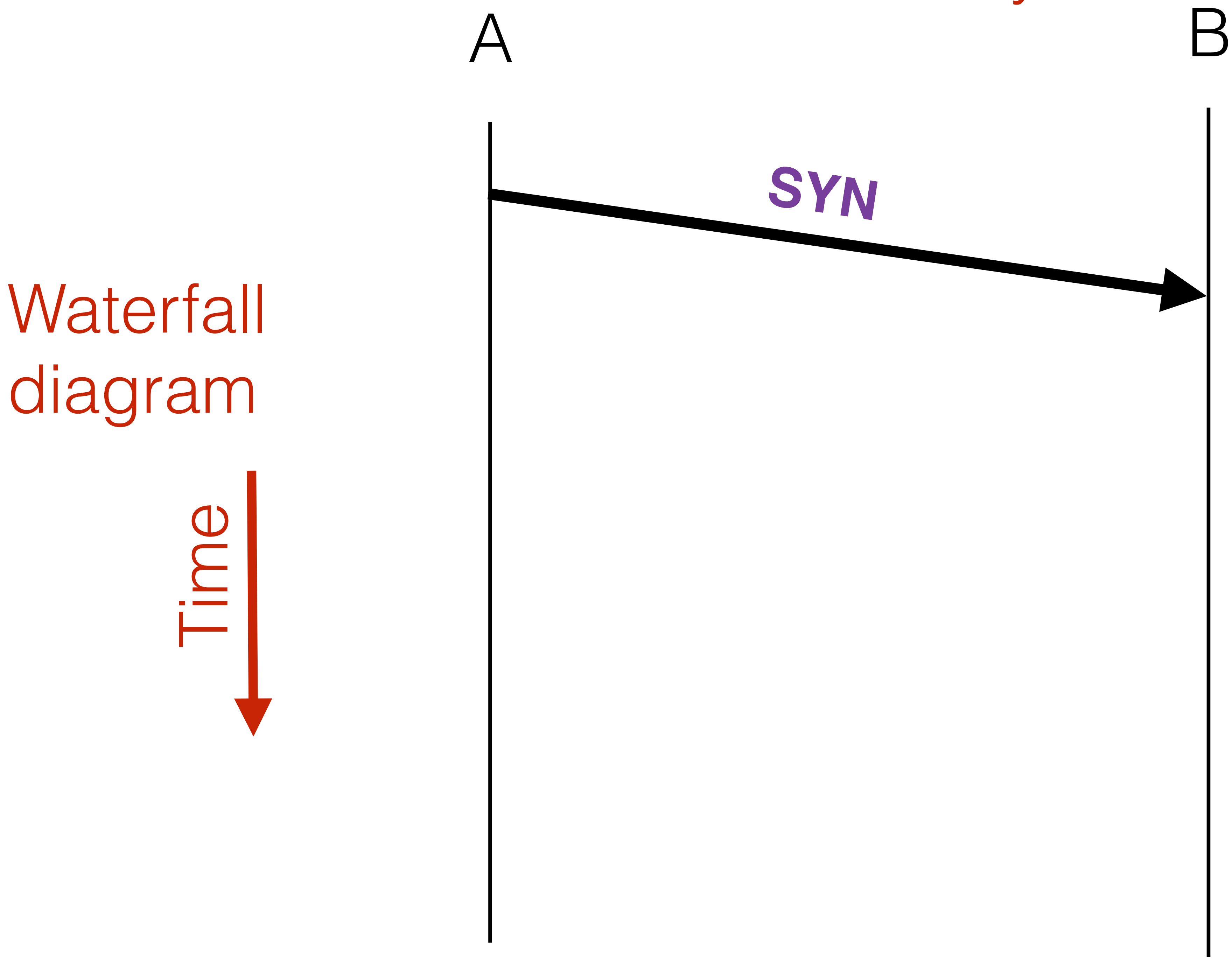

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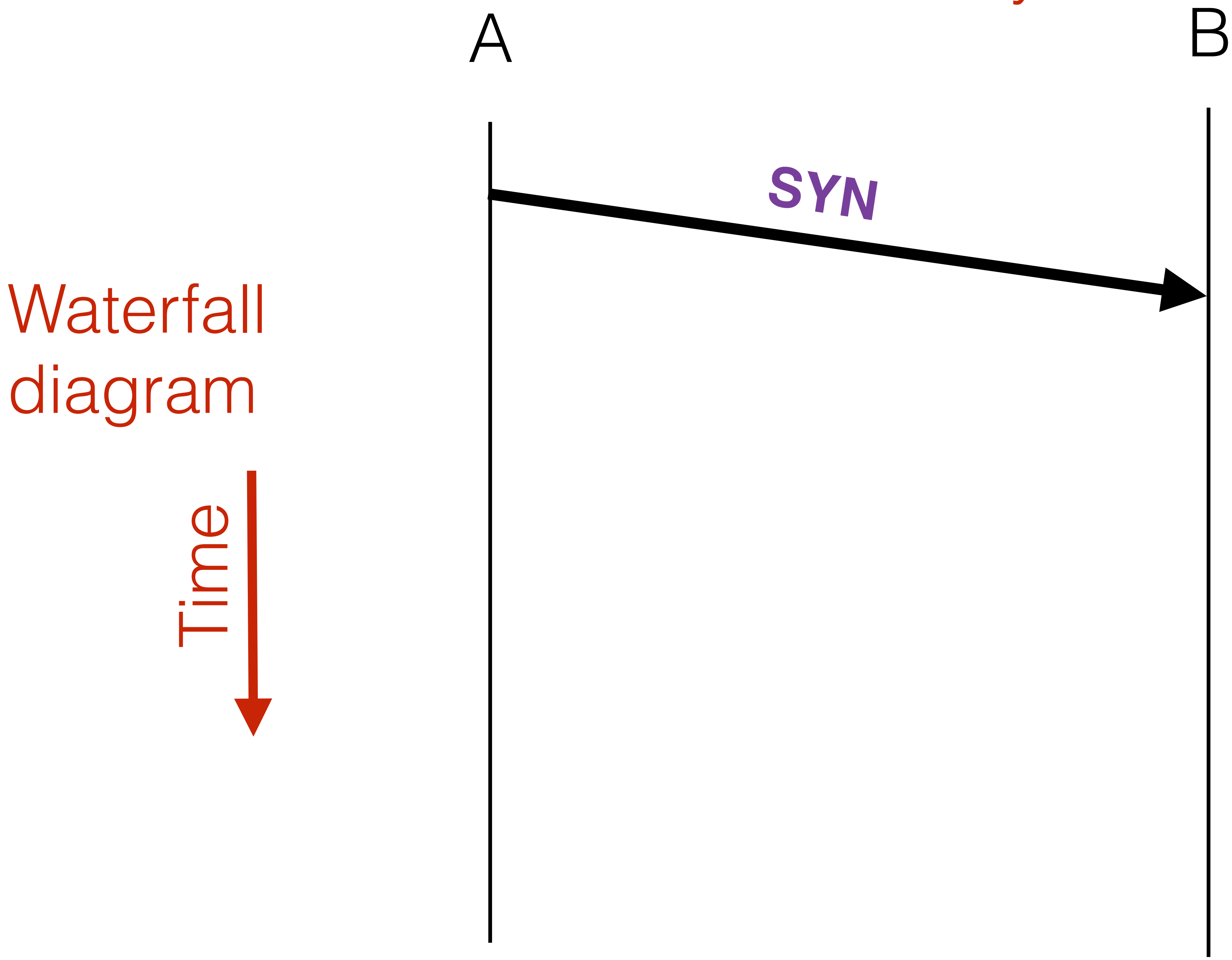

At this point, B allocates state for this new connection (incl. IP, port, maximum segment size)

SYN flooding

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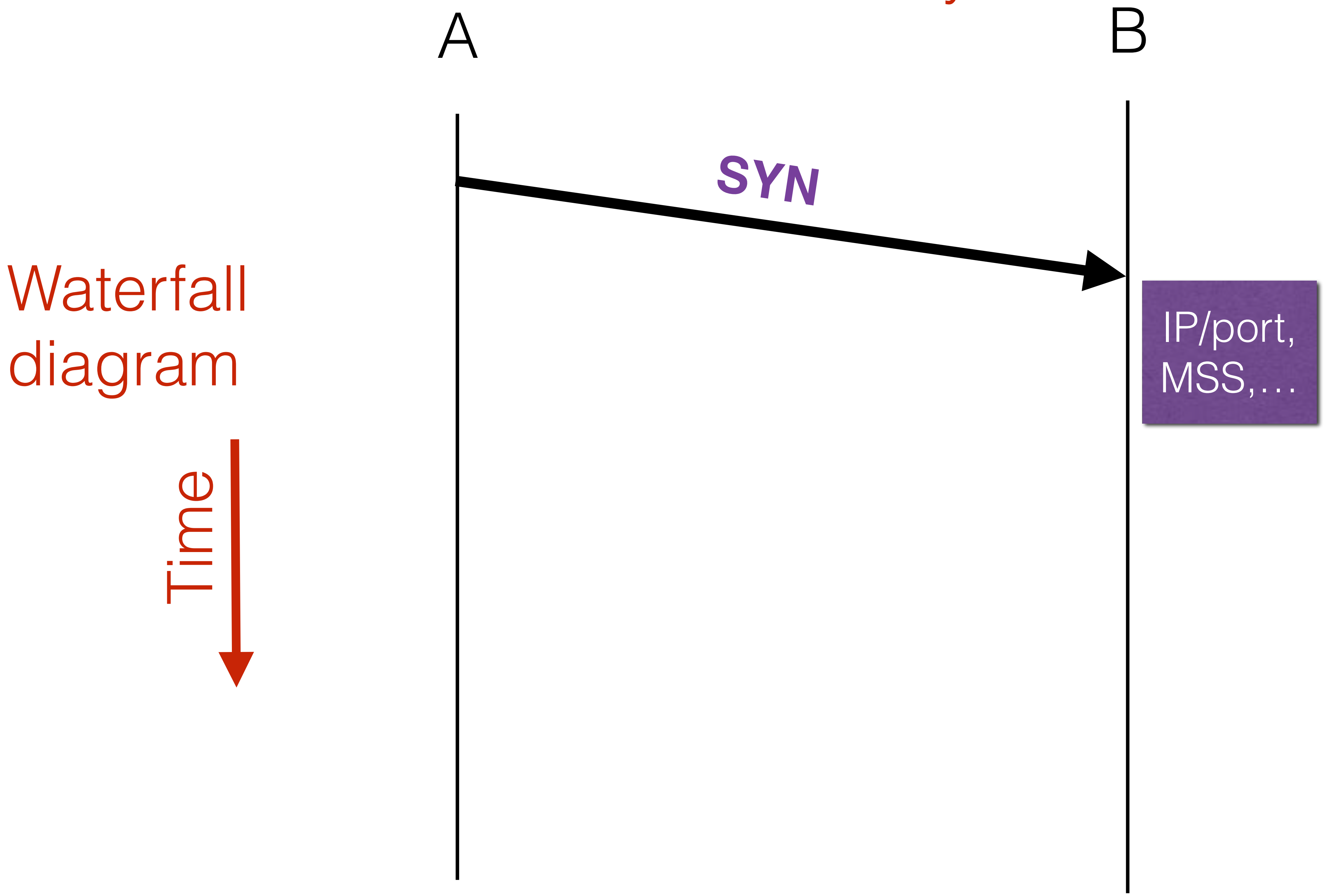

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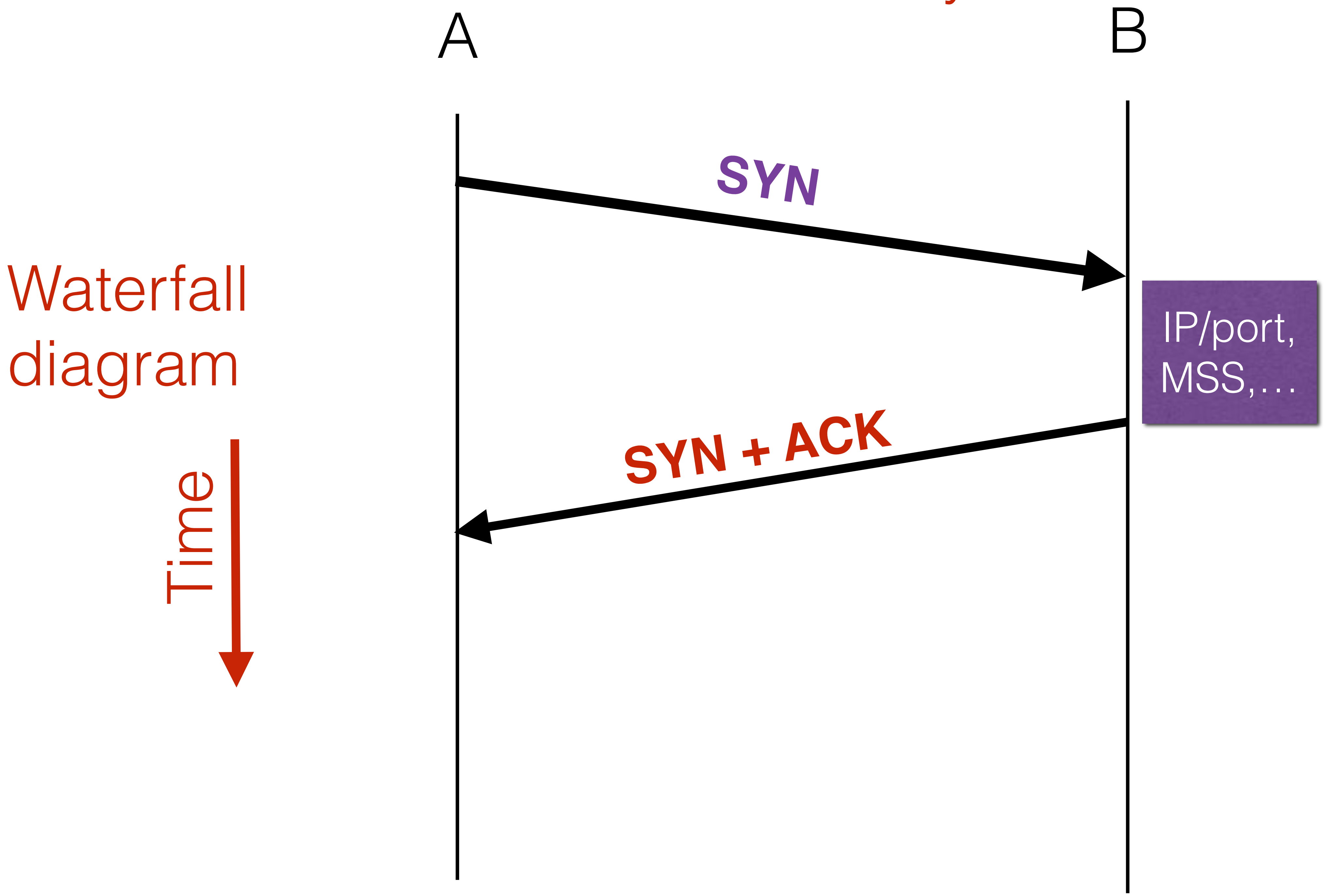

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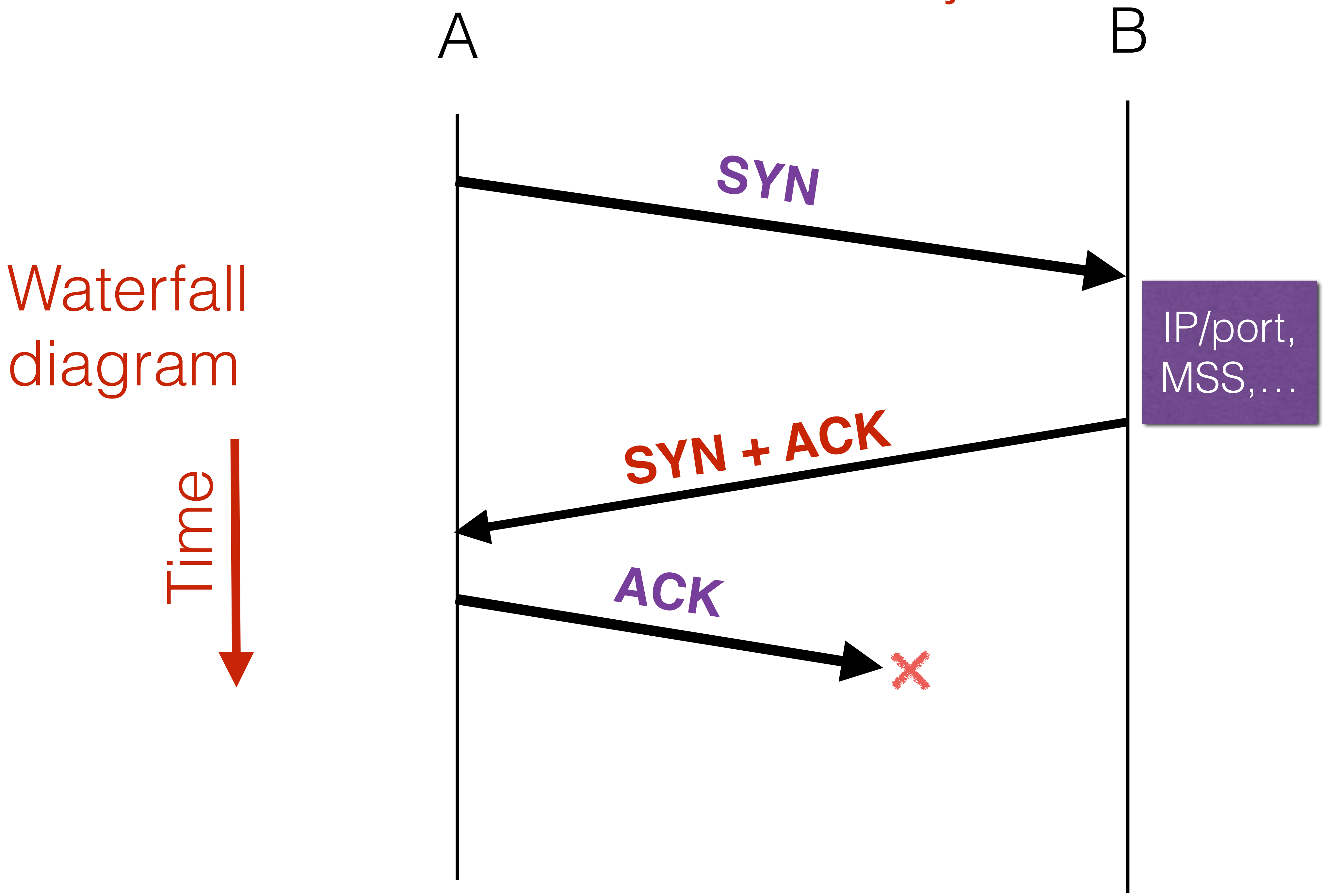

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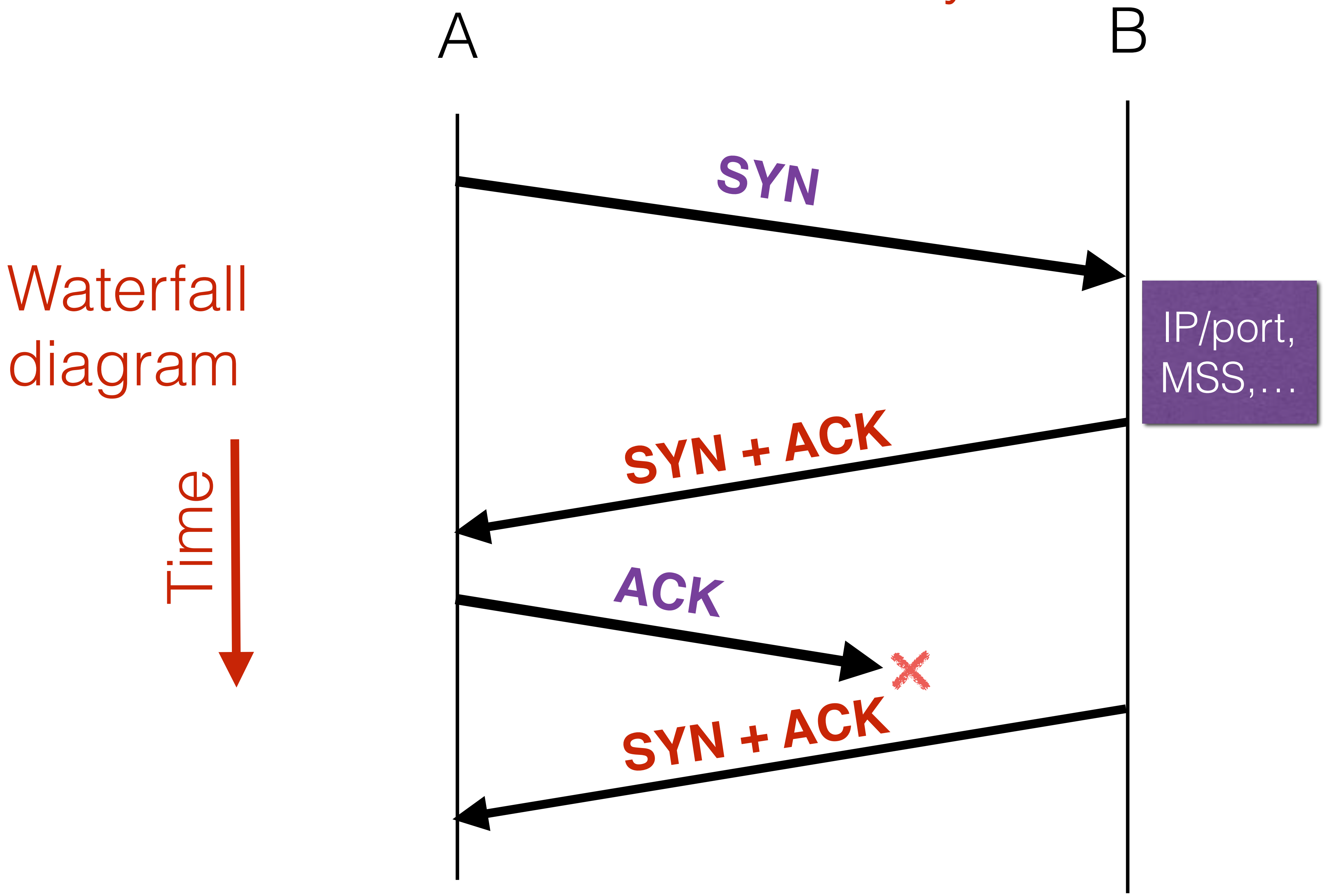

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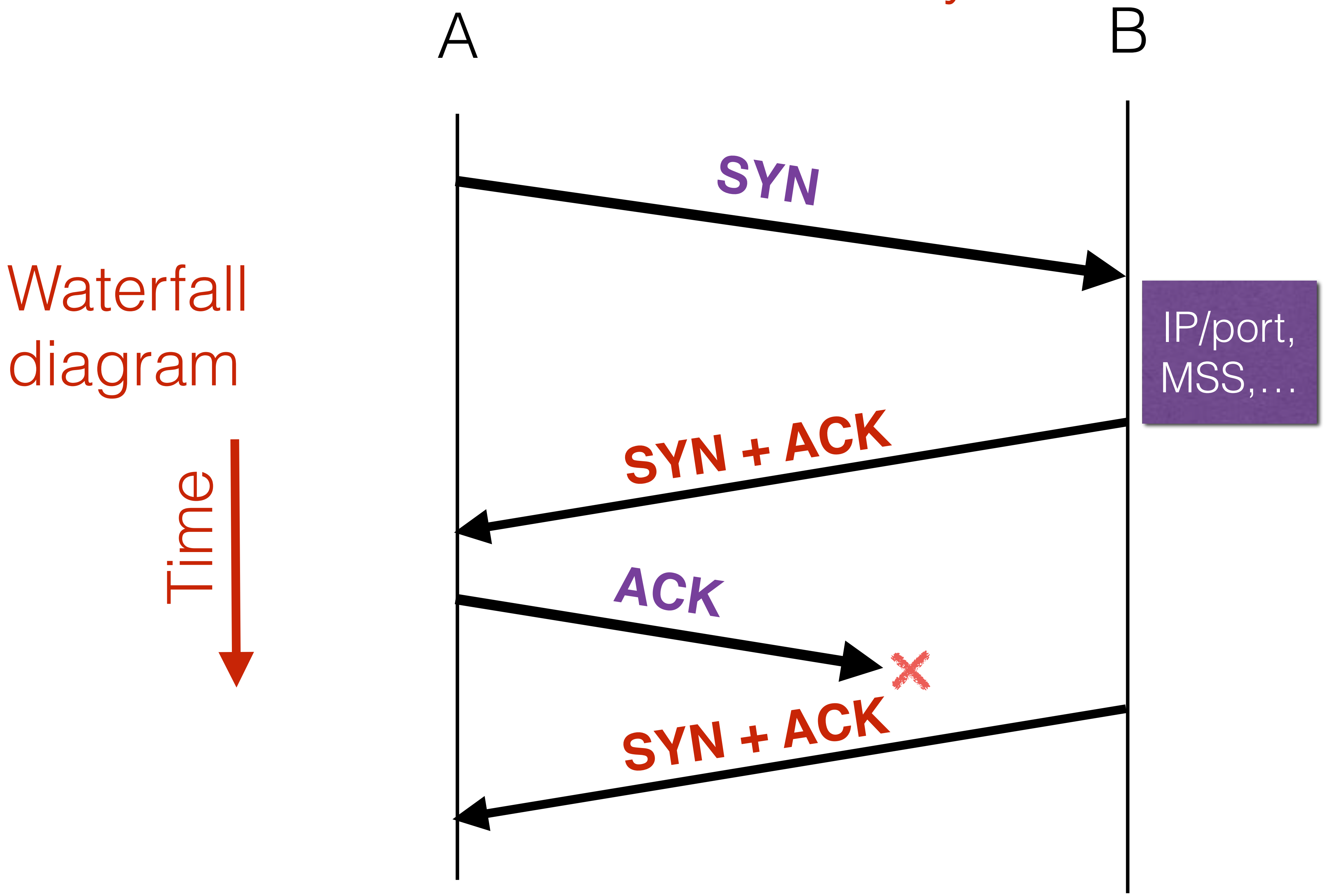
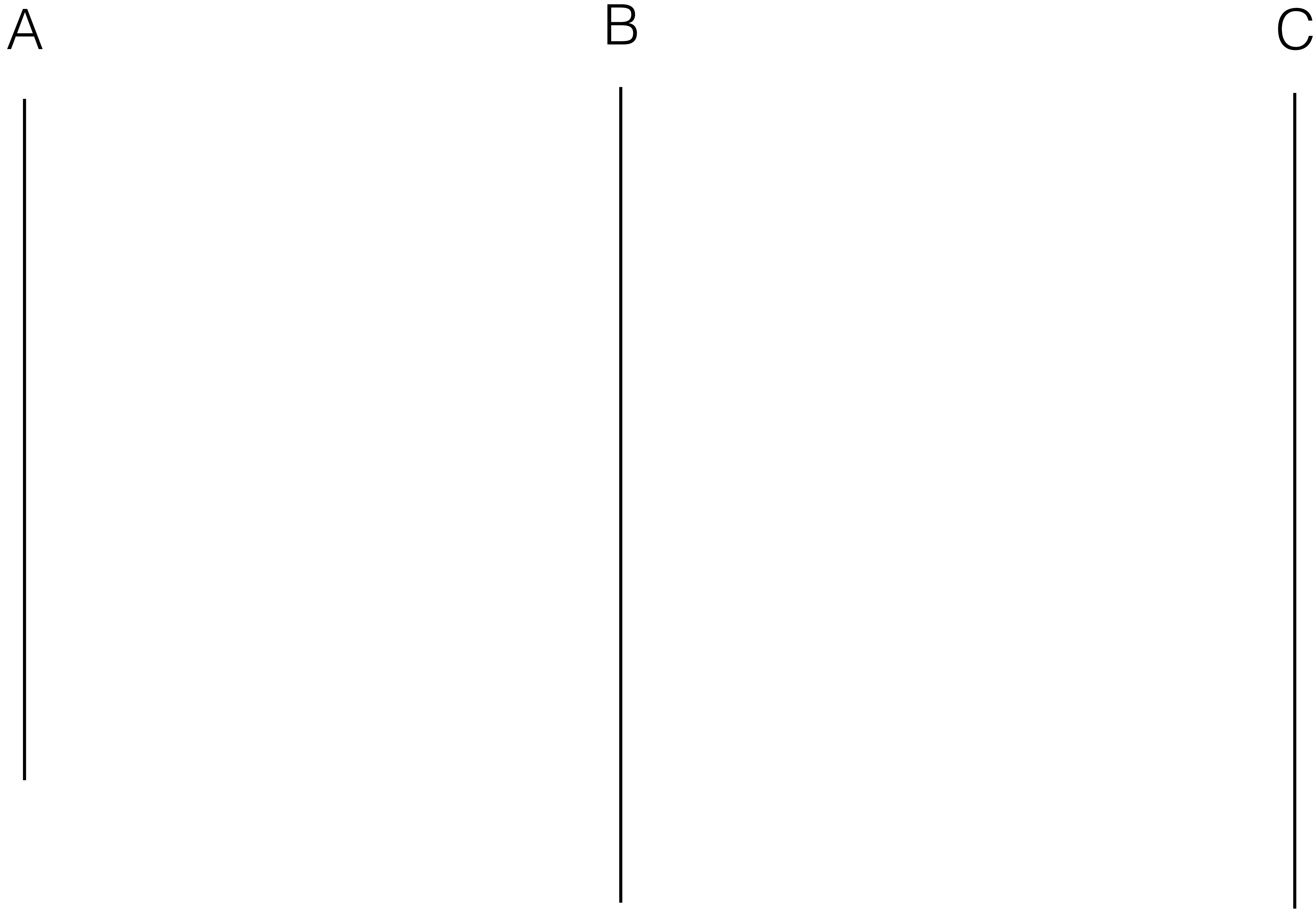


At this point, B allocates state for this new connection (incl. IP, port, maximum segment size)

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

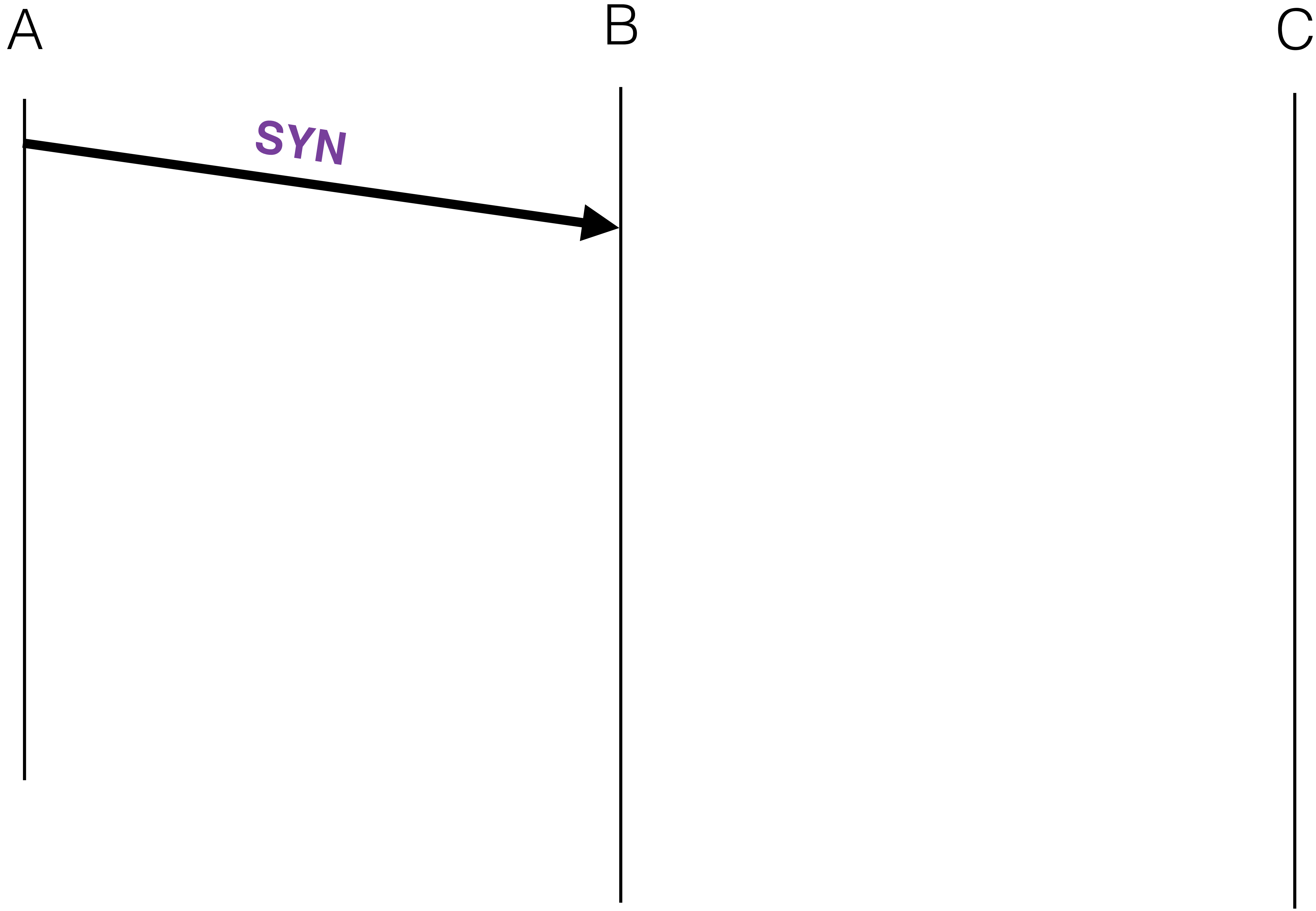
SYN flooding

The attack



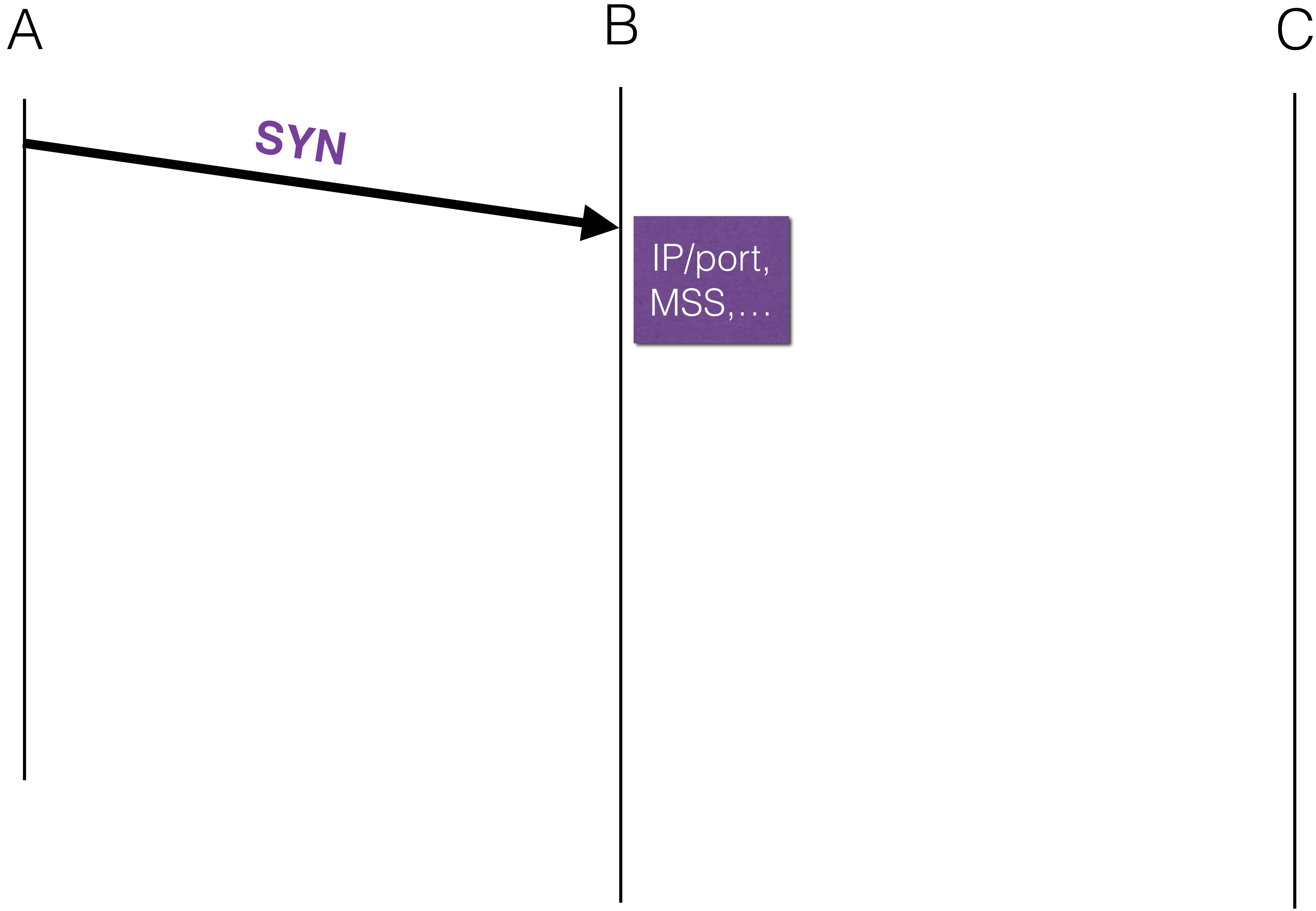
SYN flooding

The attack



SYN flooding

The attack



SYN flooding

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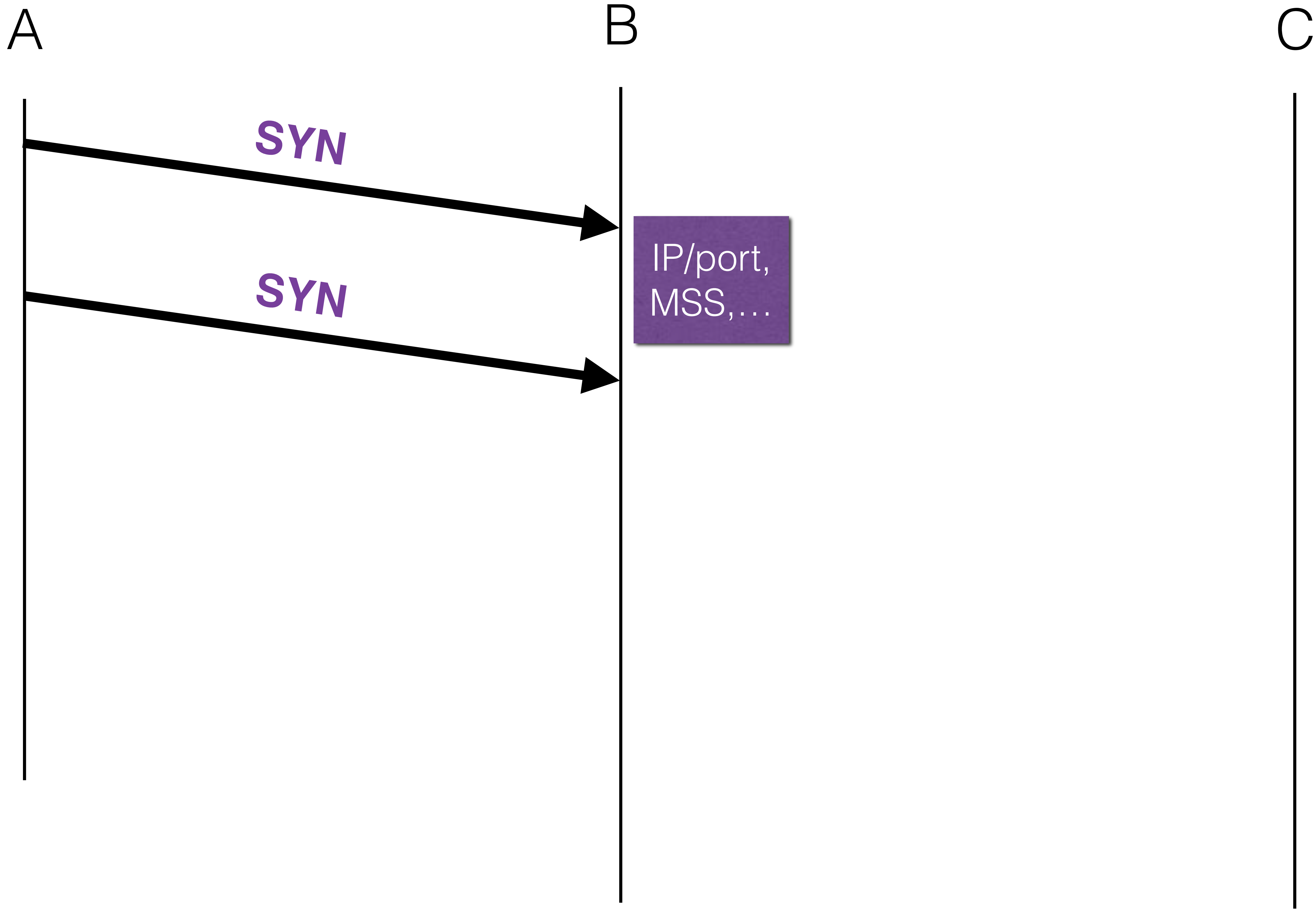
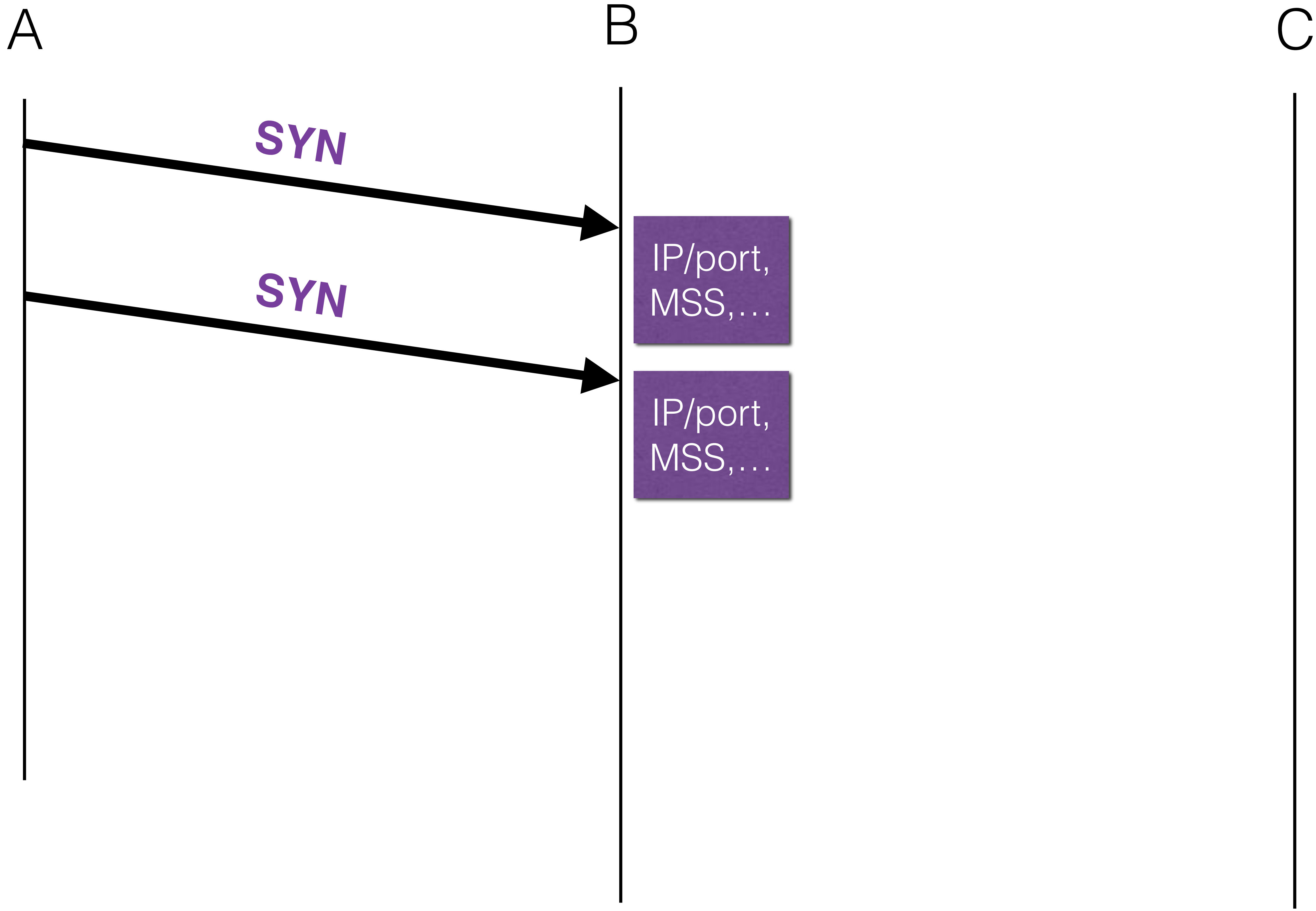


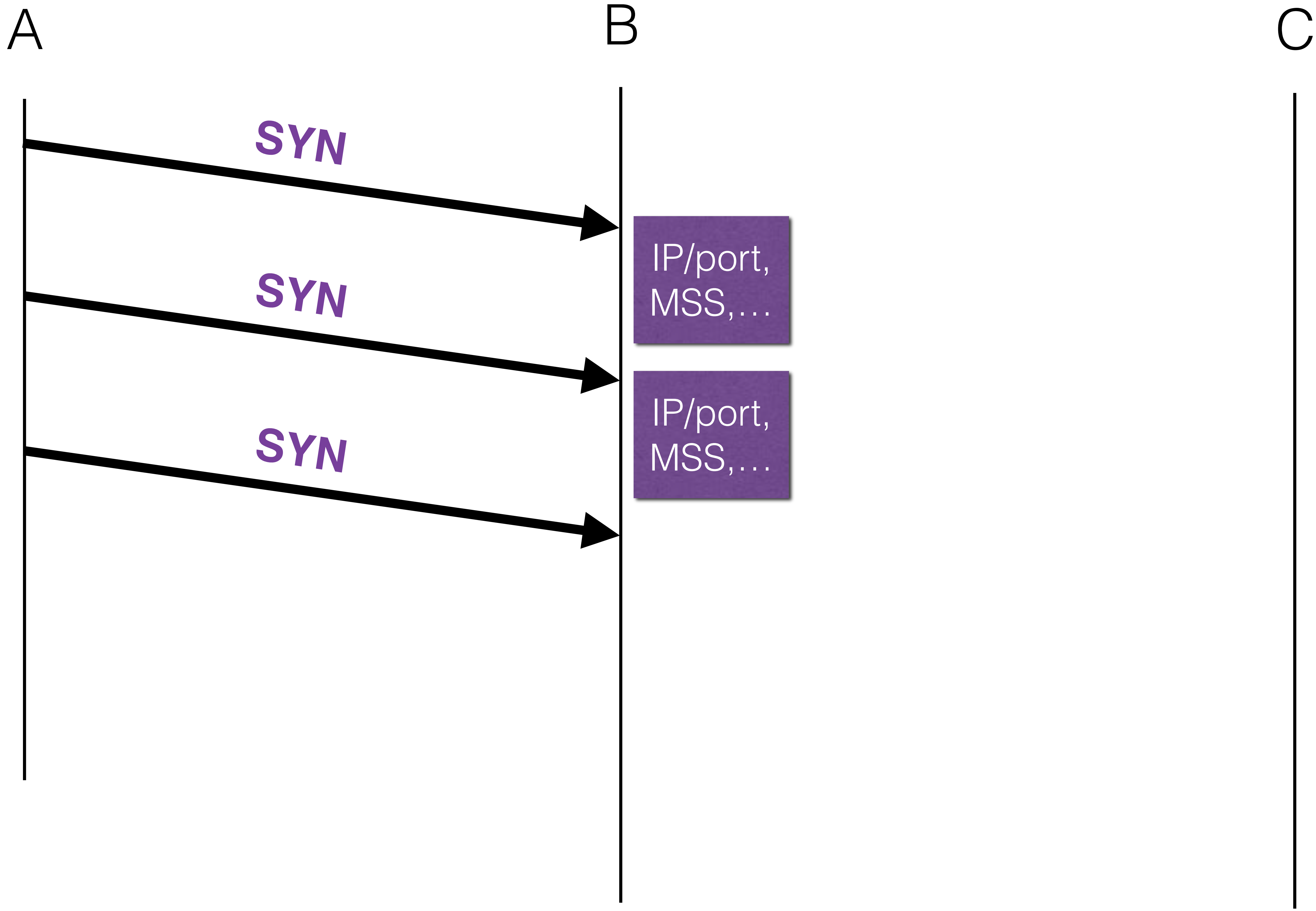
SYN flooding

The attack



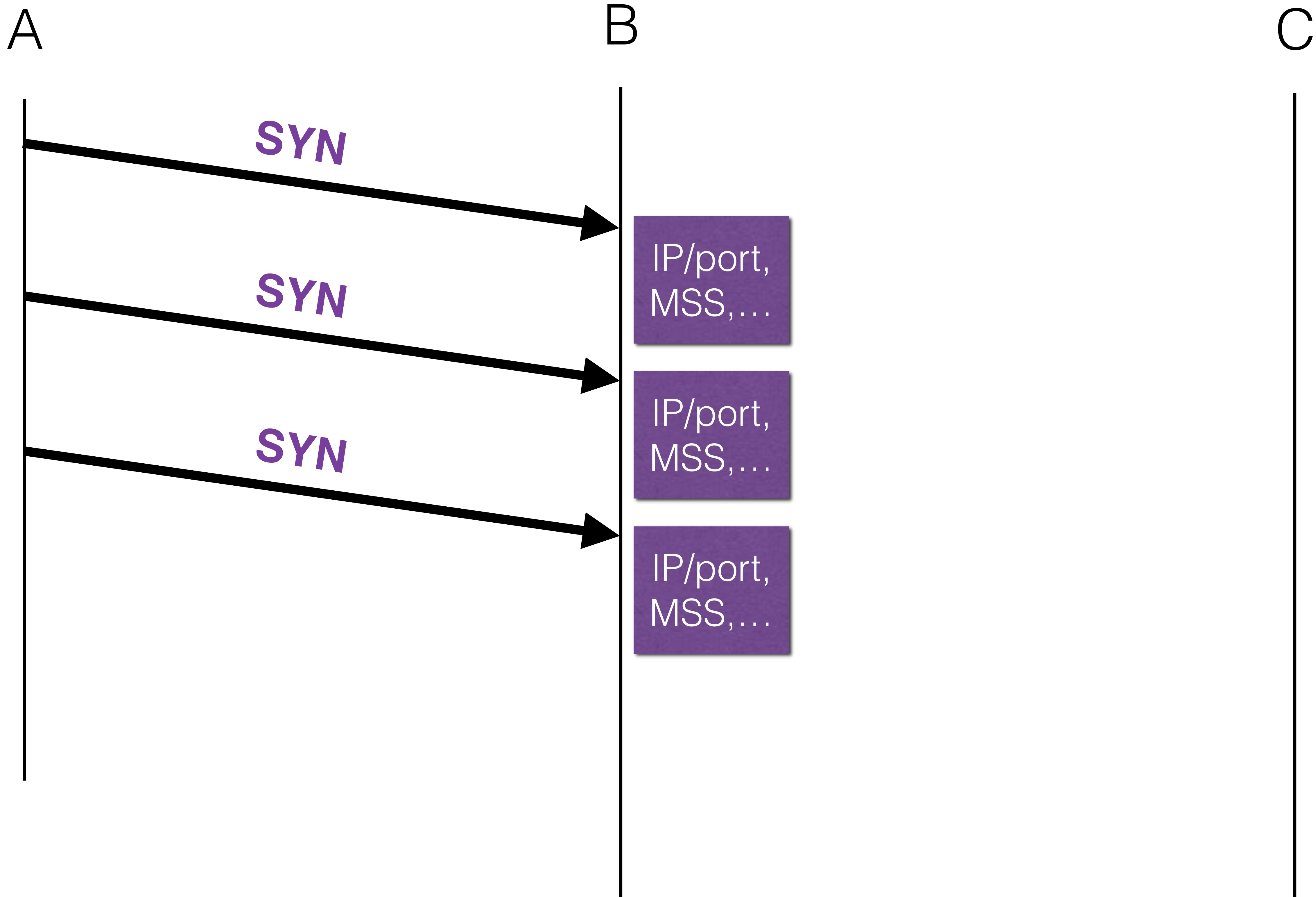
SYN flooding

The attack



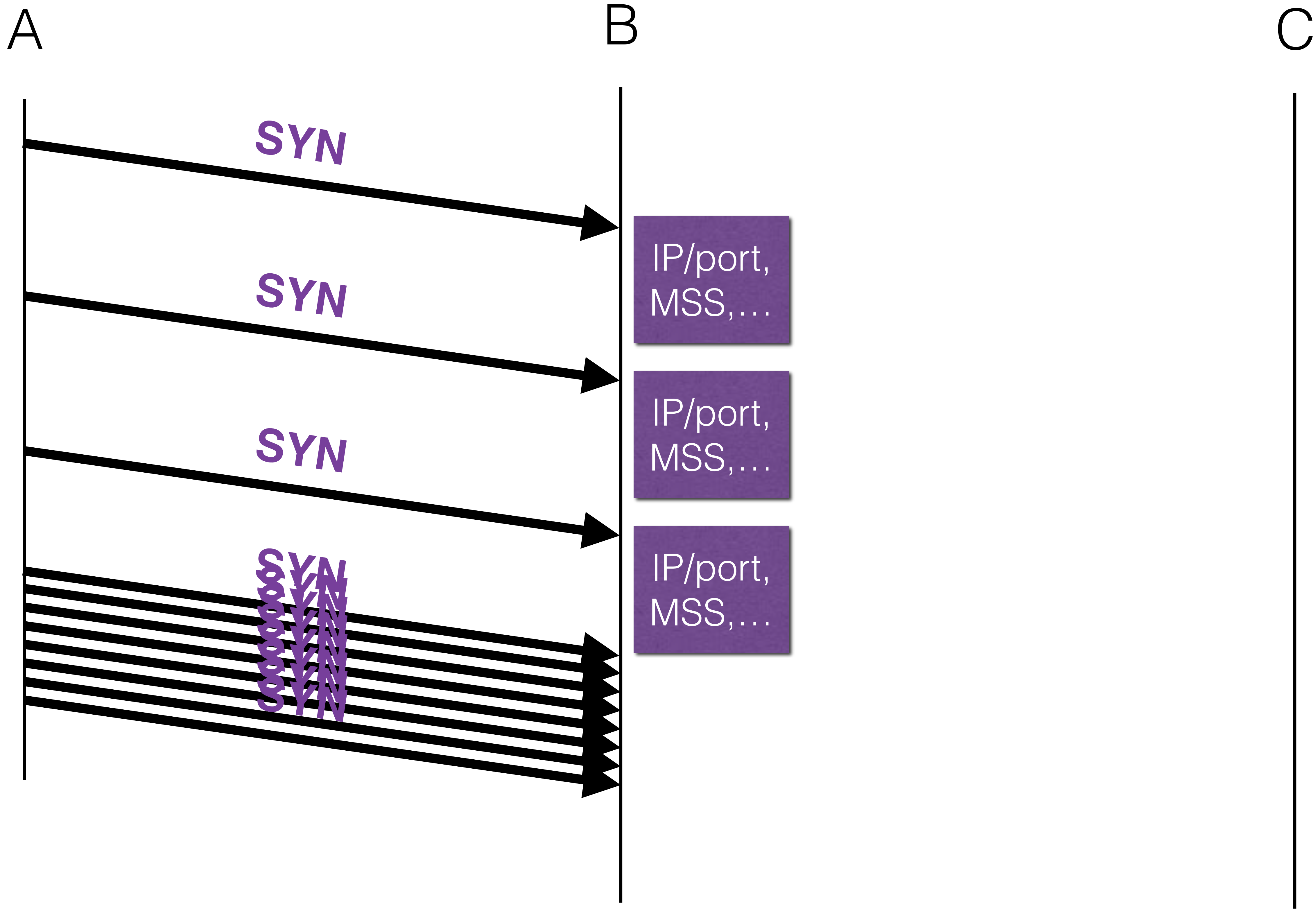
SYN flooding

The attack



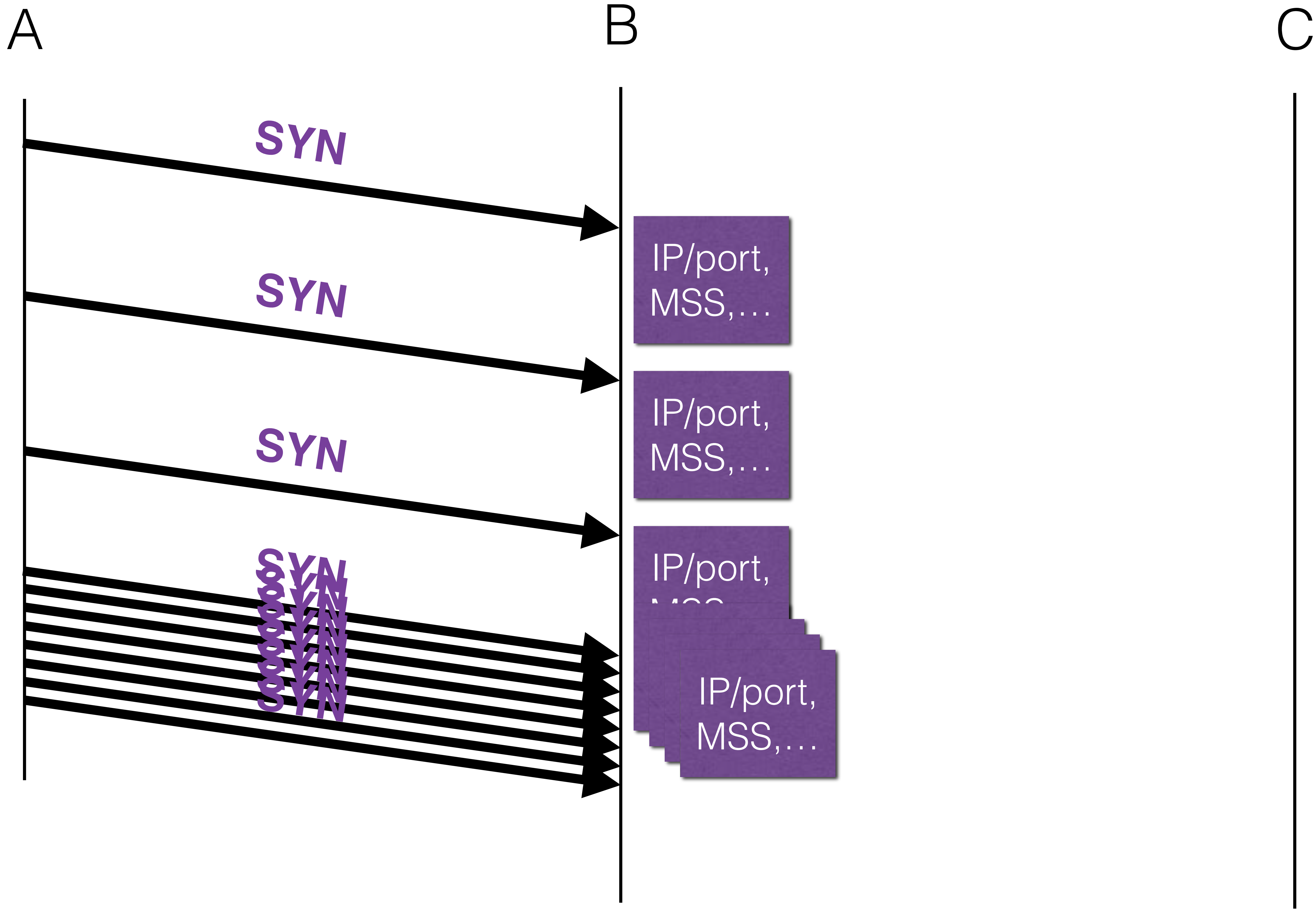
SYN flooding

The attack



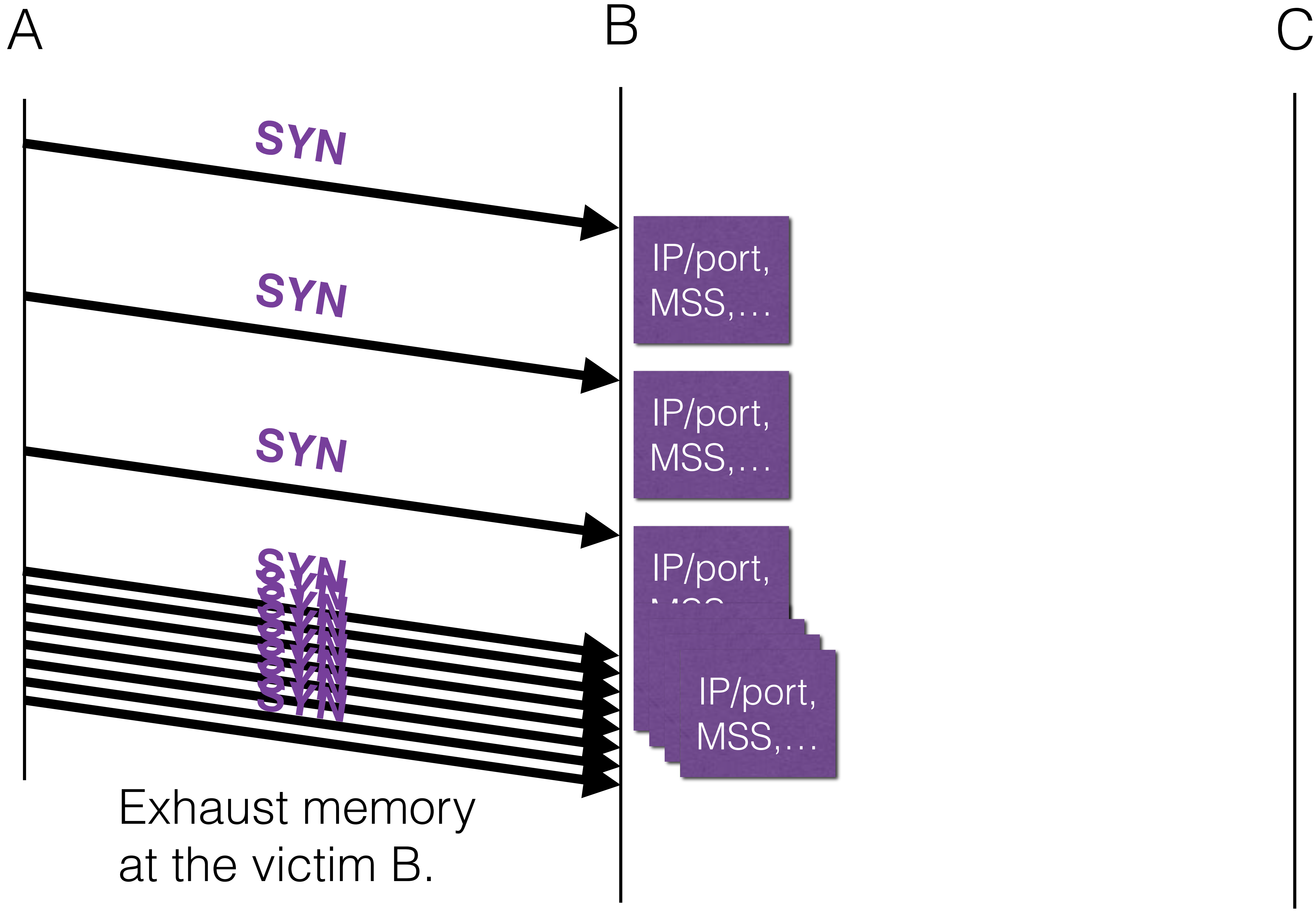
SYN flooding

The attack



SYN flooding

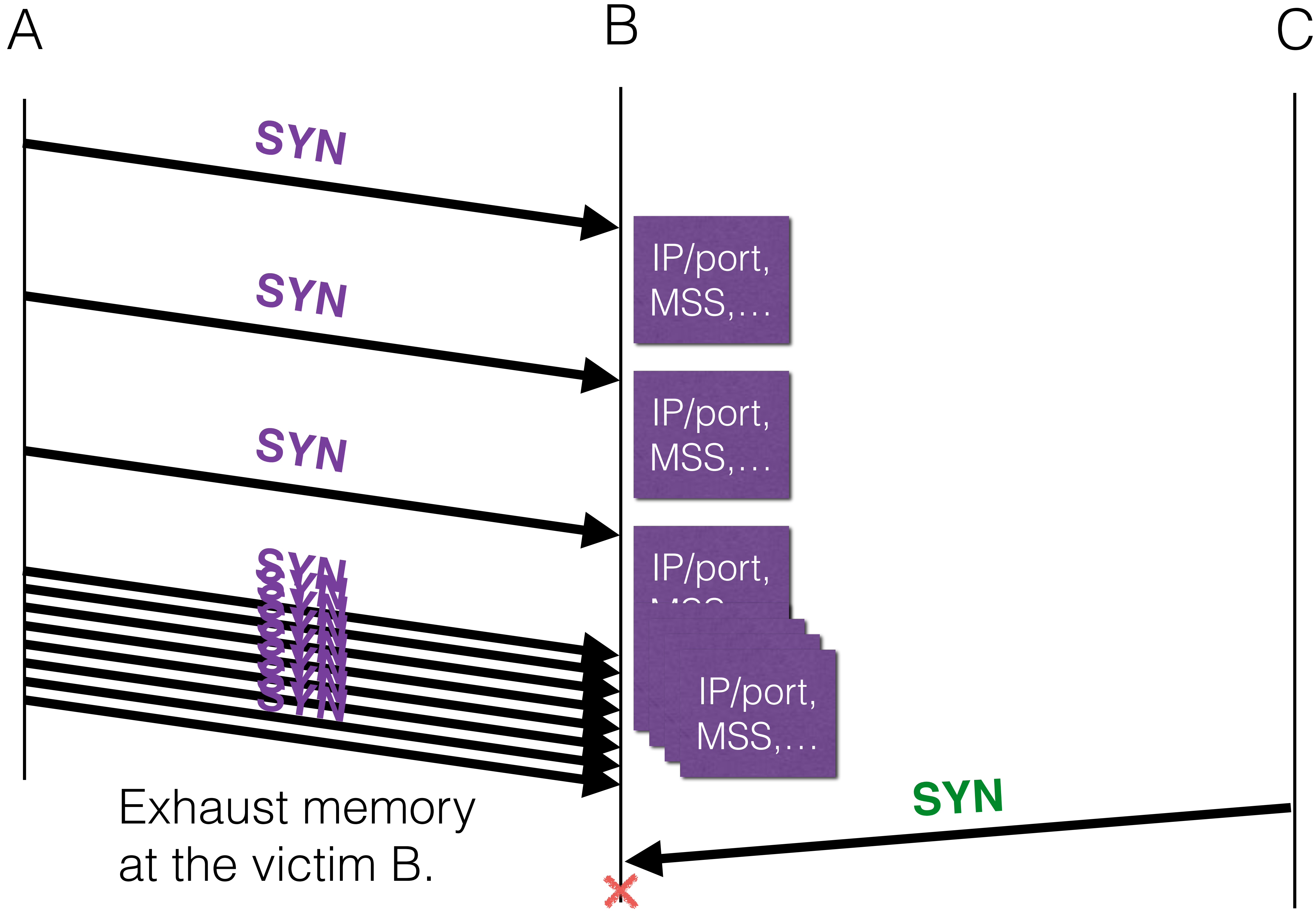
The attack



Exhaust memory
at the victim B.

SYN flooding

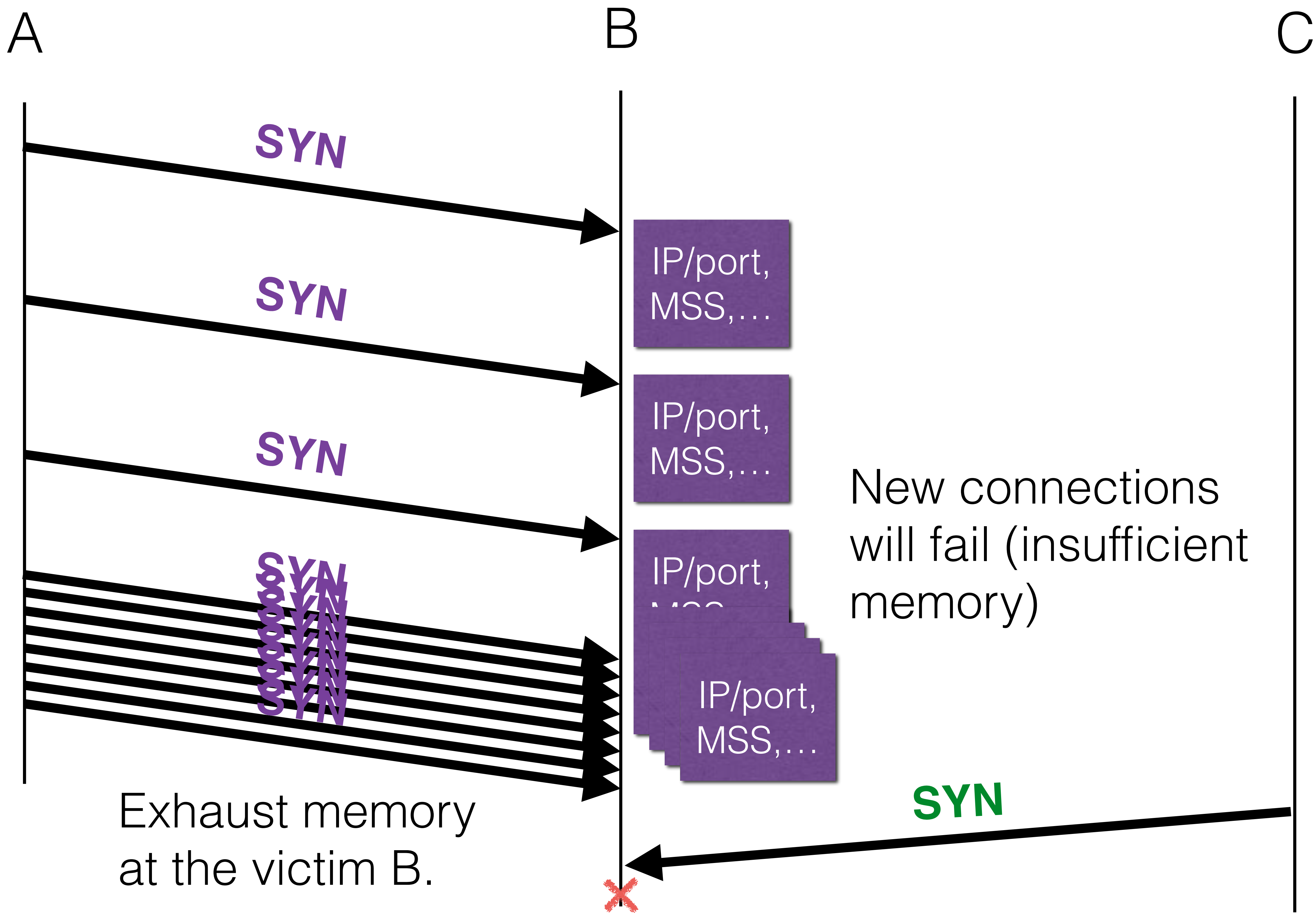
The attack



Exhaust memory at the victim B.

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

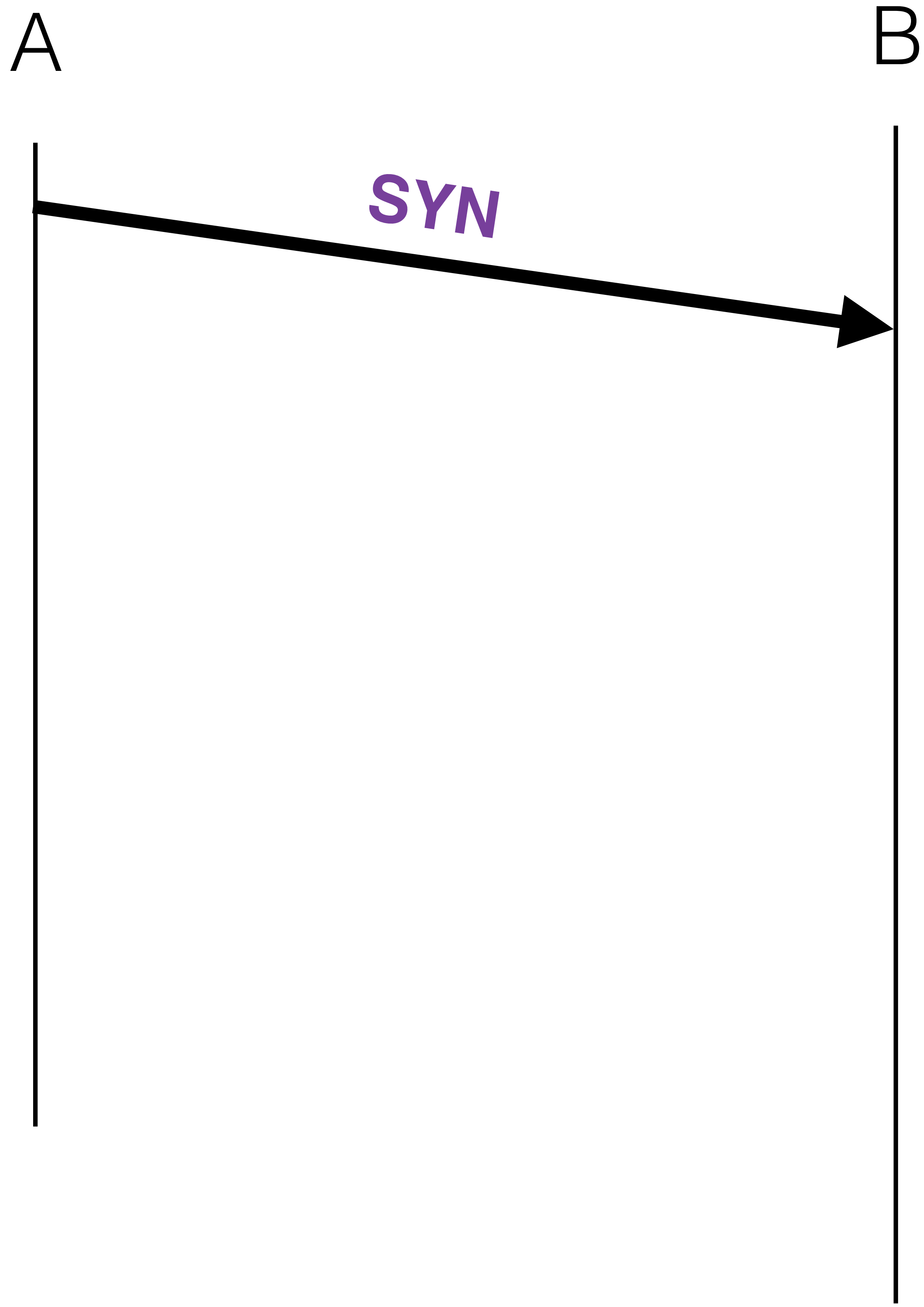
The defense

A

B

SYN cookies

The defense



SYN cookies

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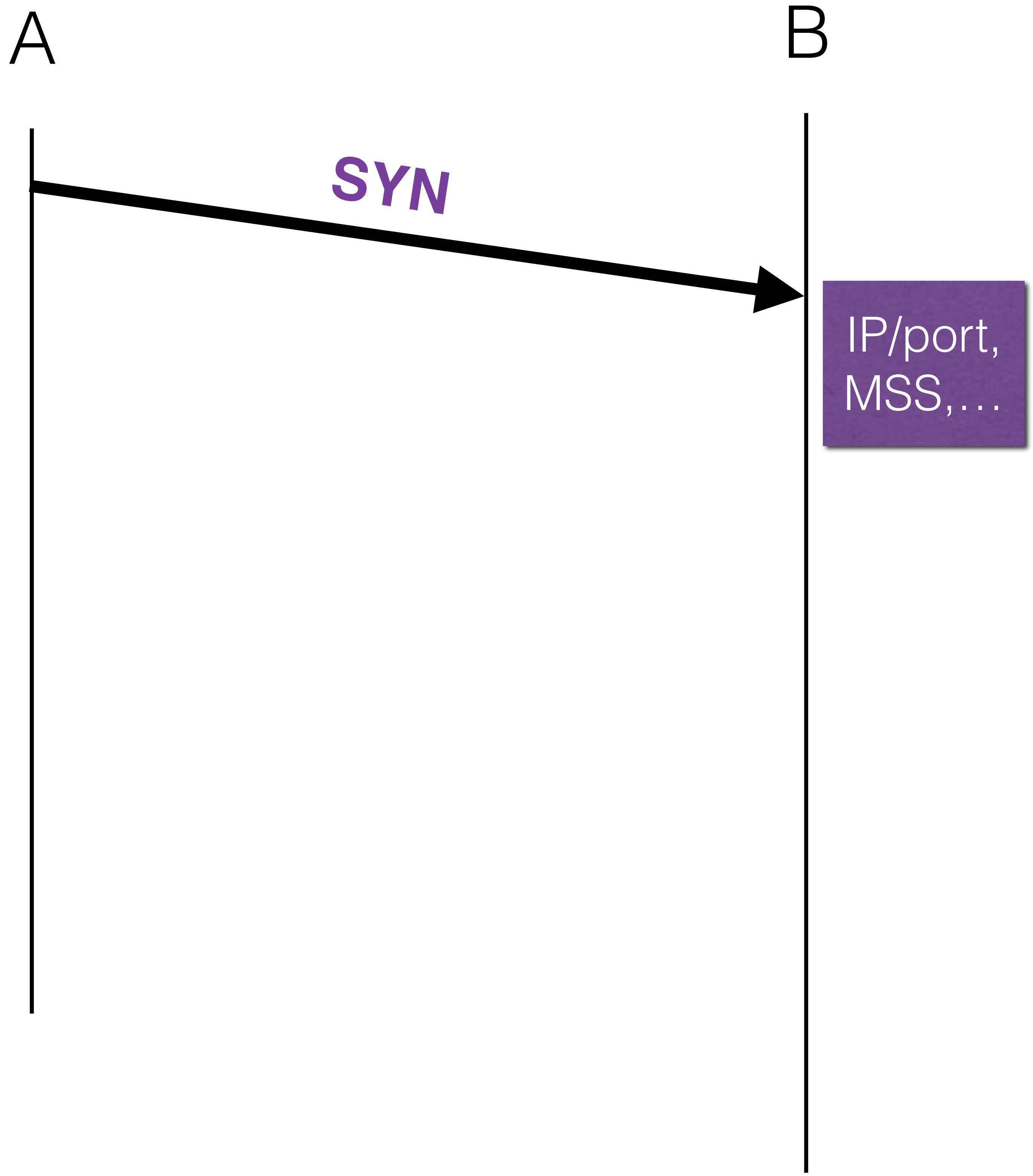

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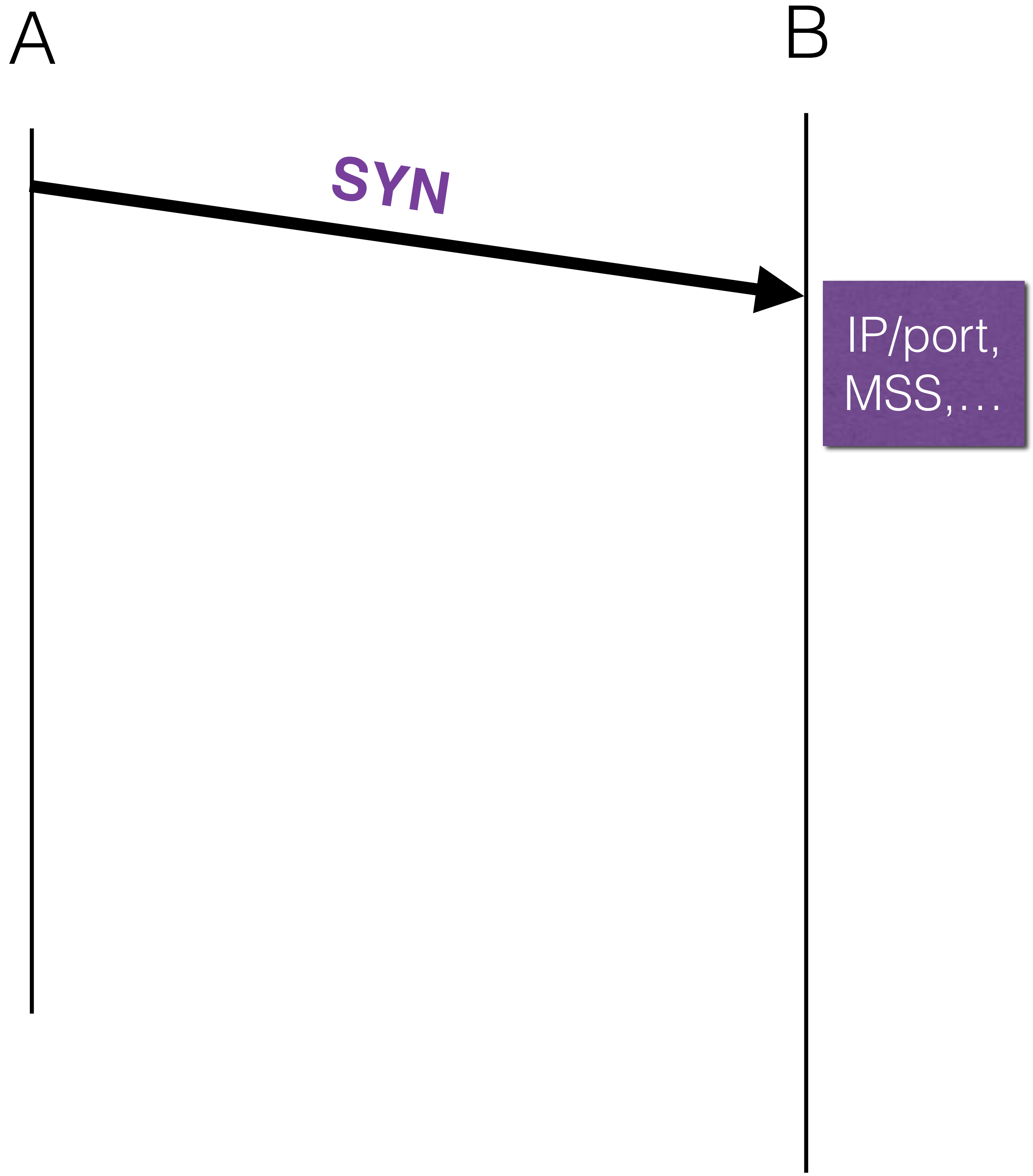
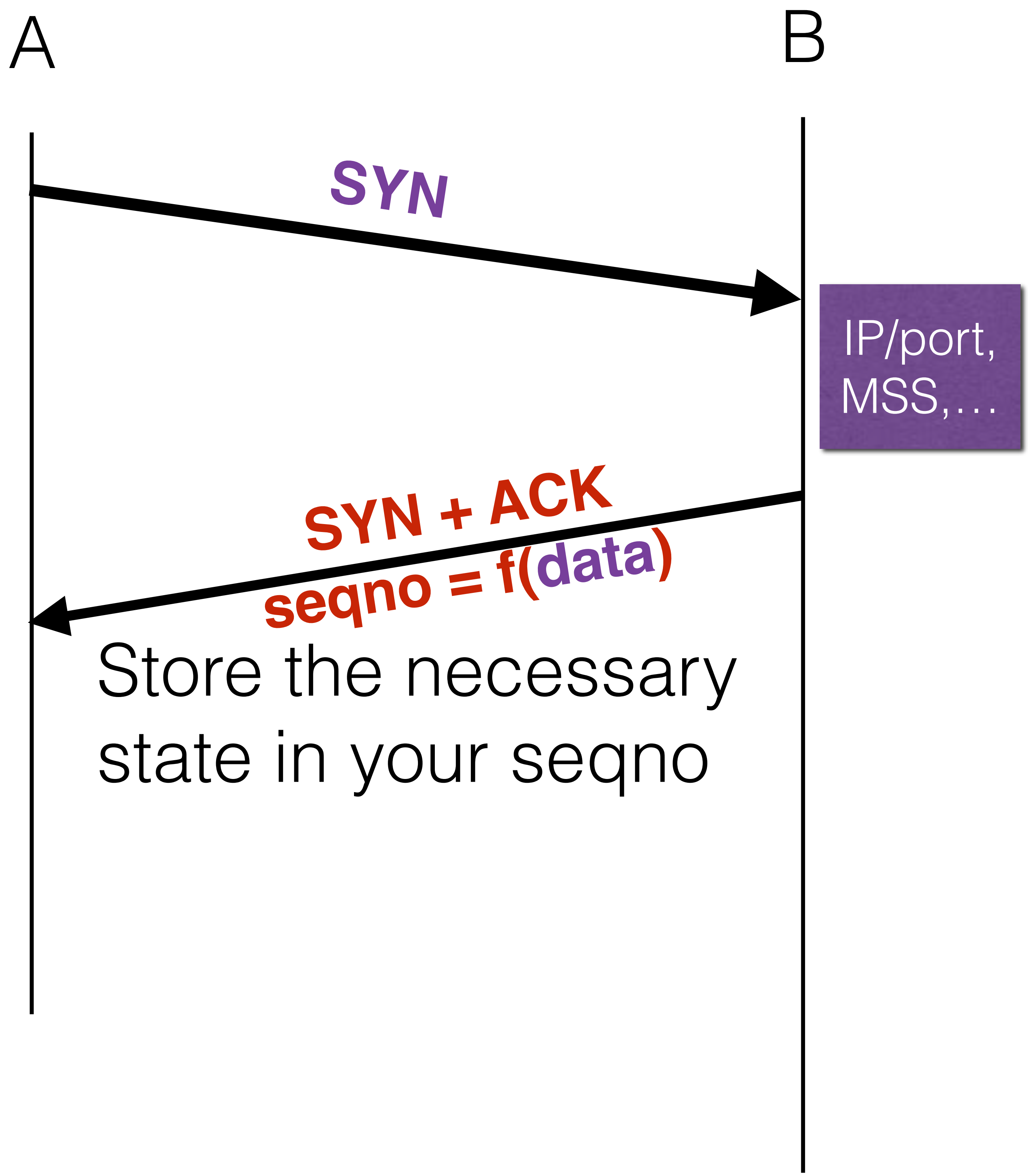


Rather than store this data, send it to the host who is initiating the connection and have him return it to you

SYN cookies

The defense



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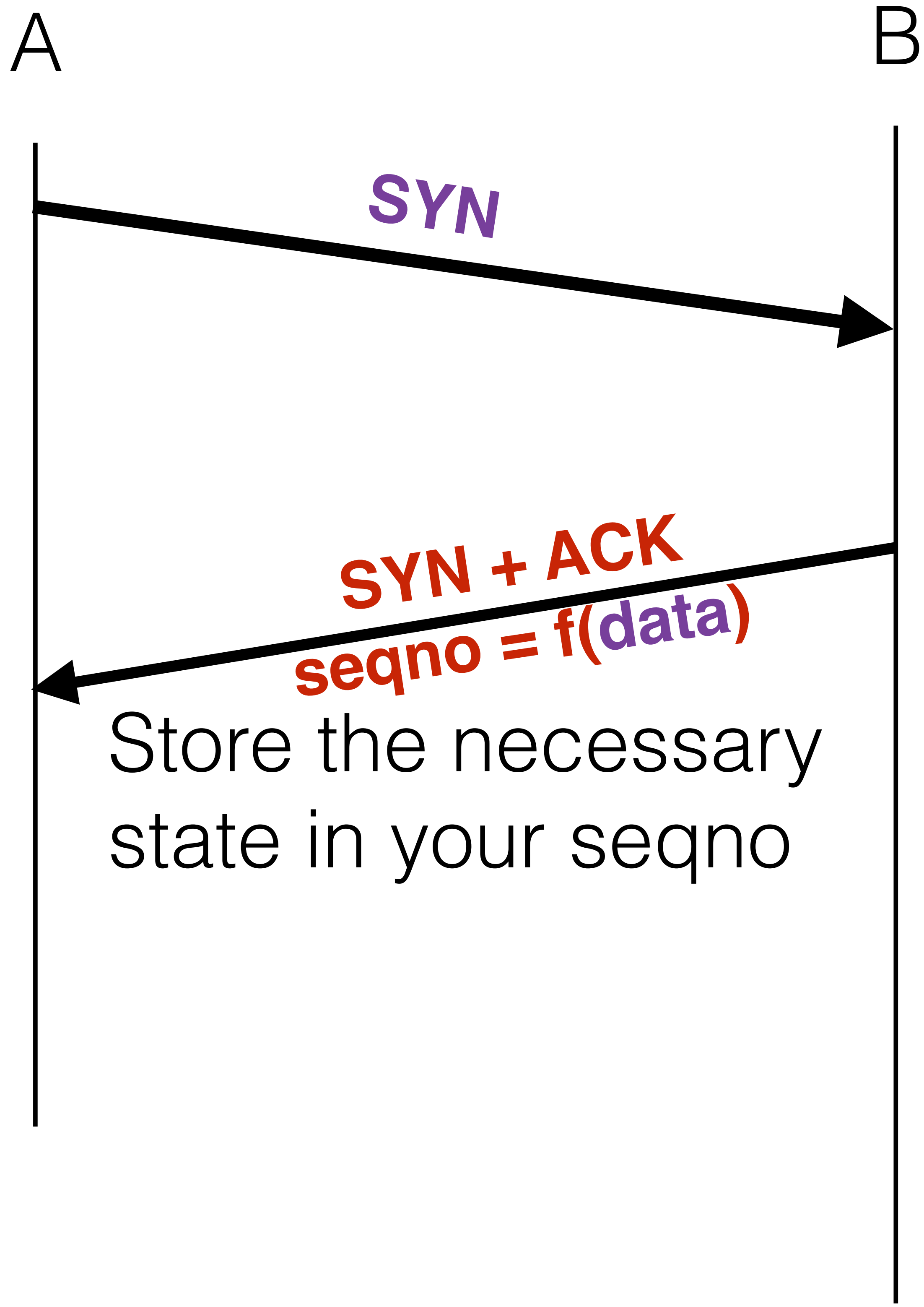
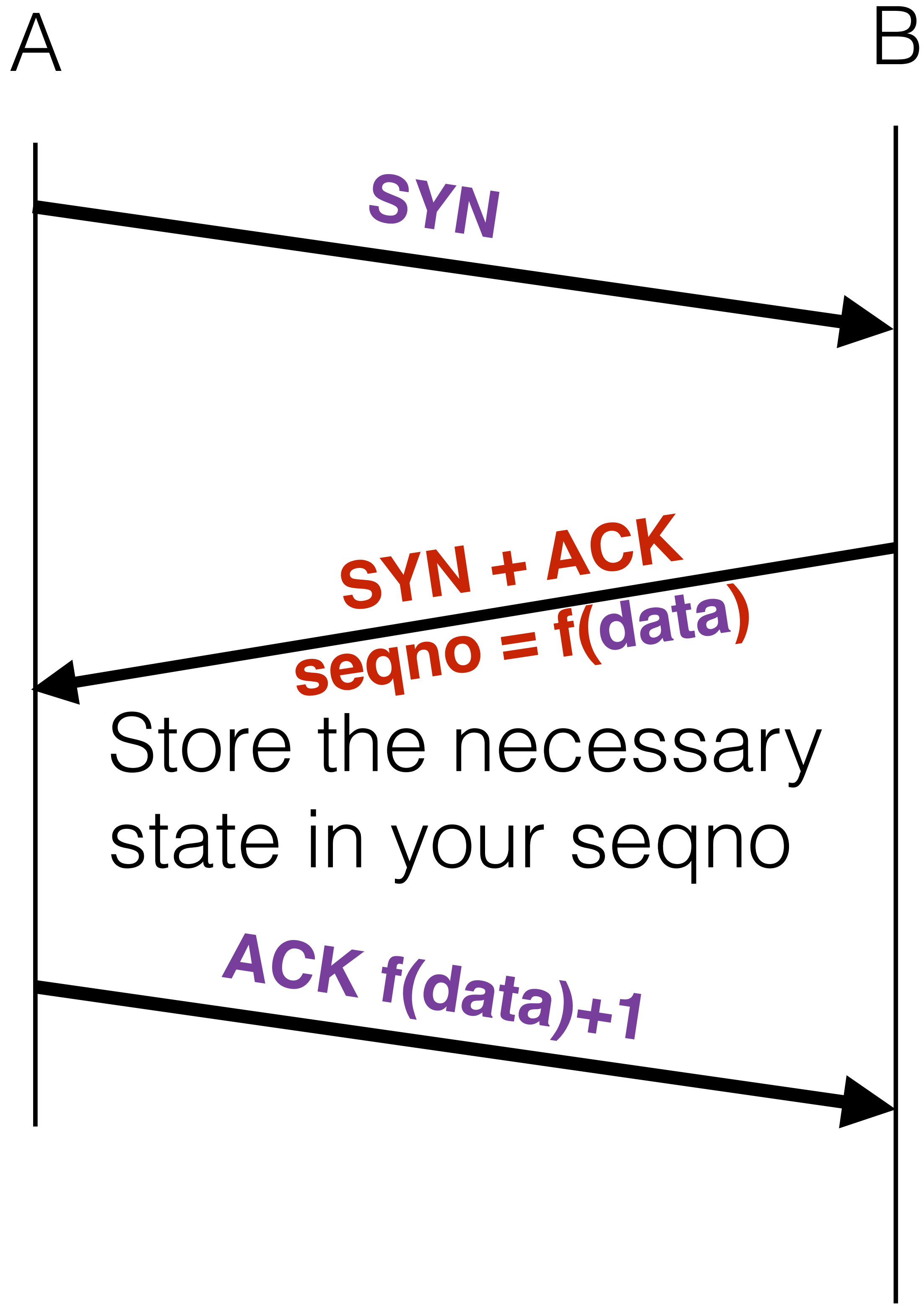


Store the necessary state in your seqno

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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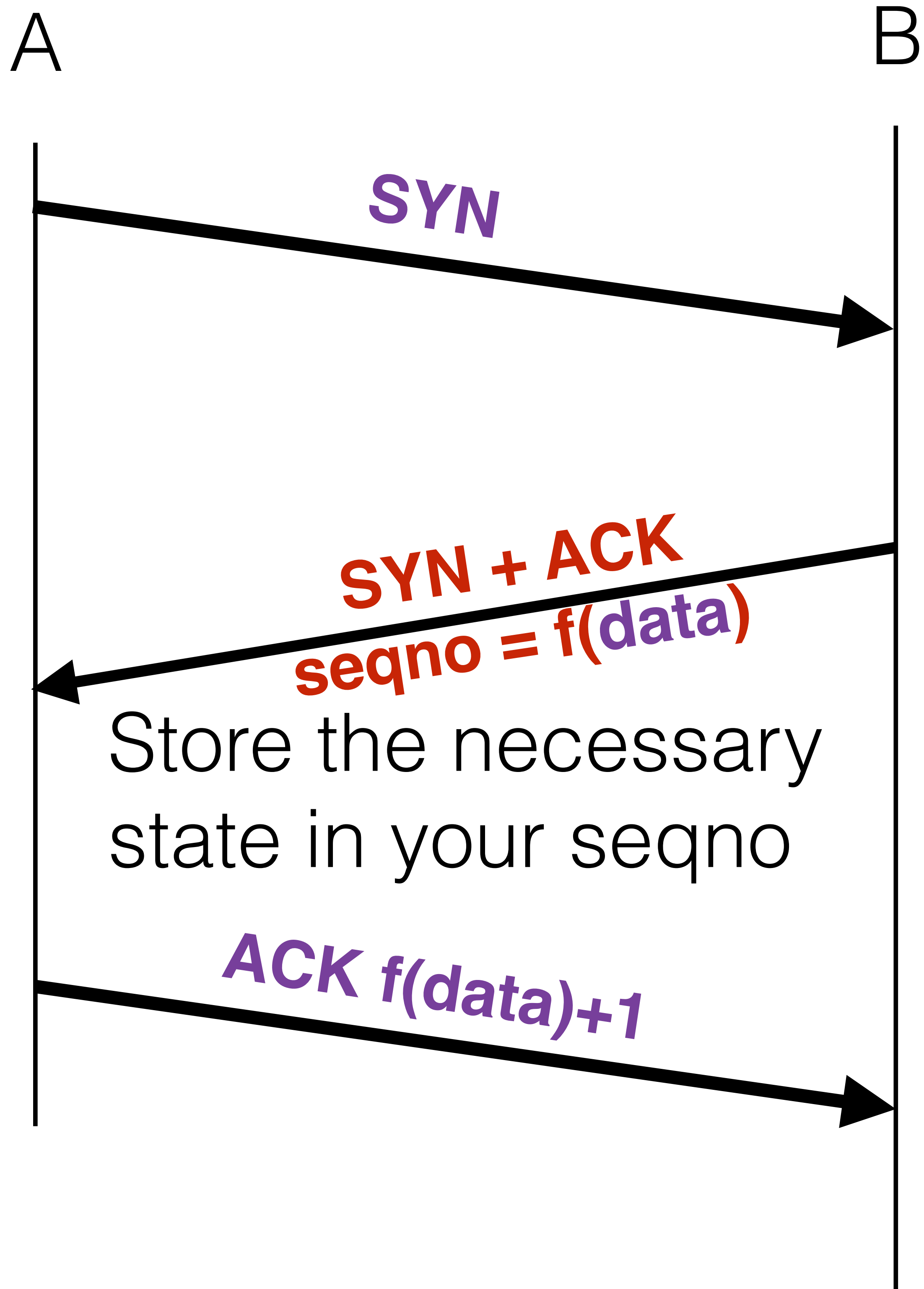
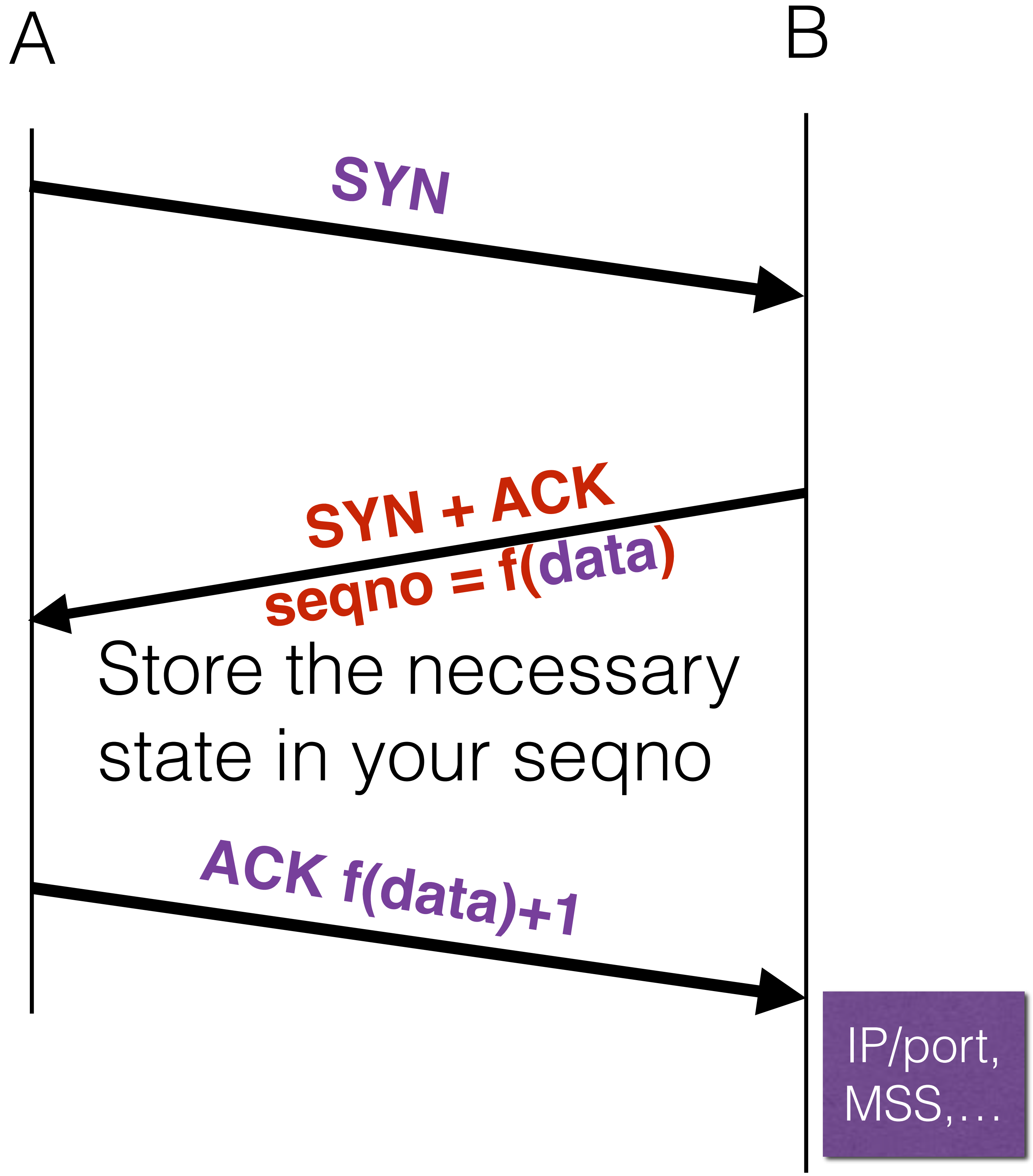


Rather than store this data, send it to the host who is initiating the connection and have him return it to you

Check that f(data) is valid for this connection. Only at that point do you allocate state.

SYN cookies

The defense



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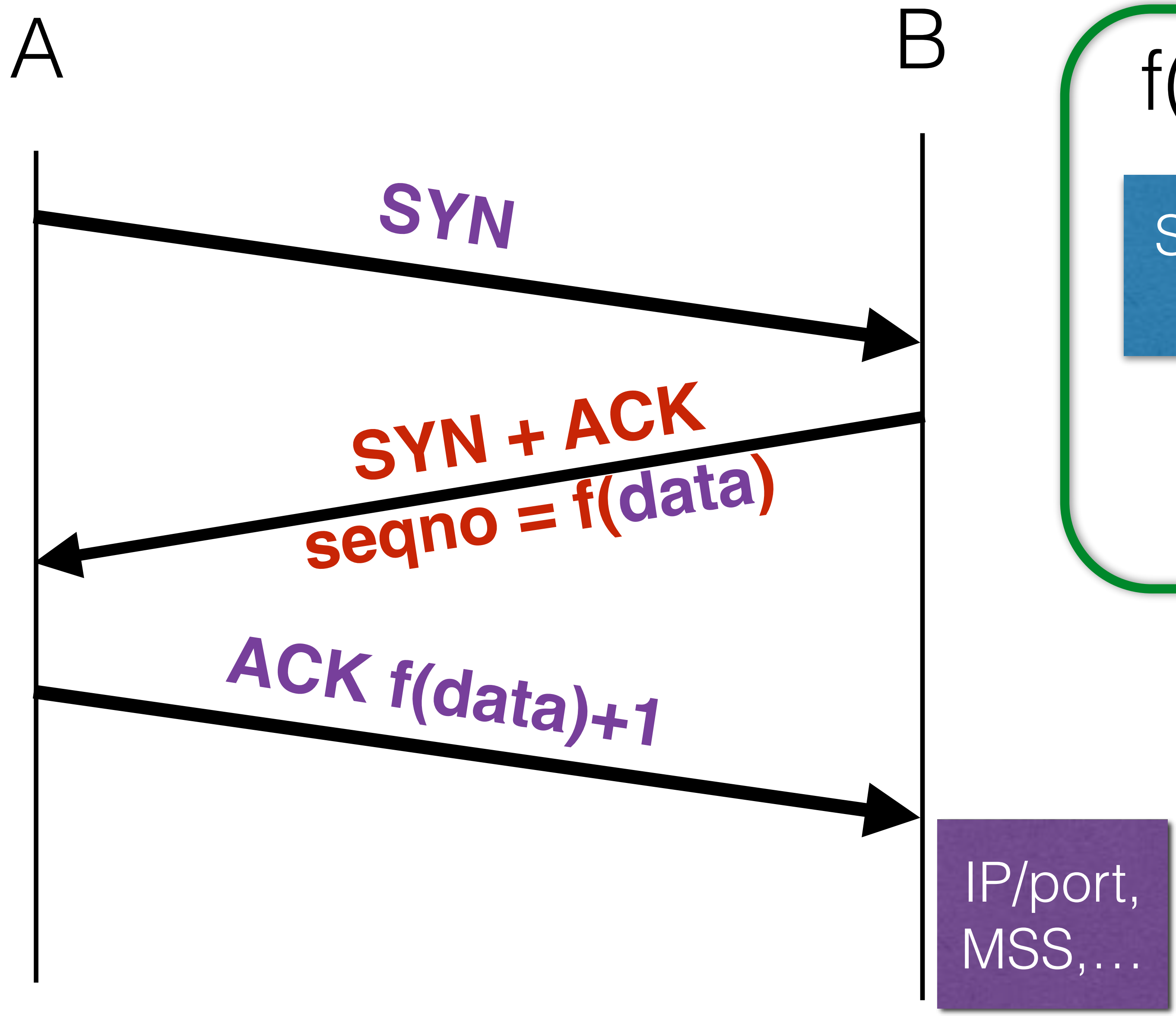
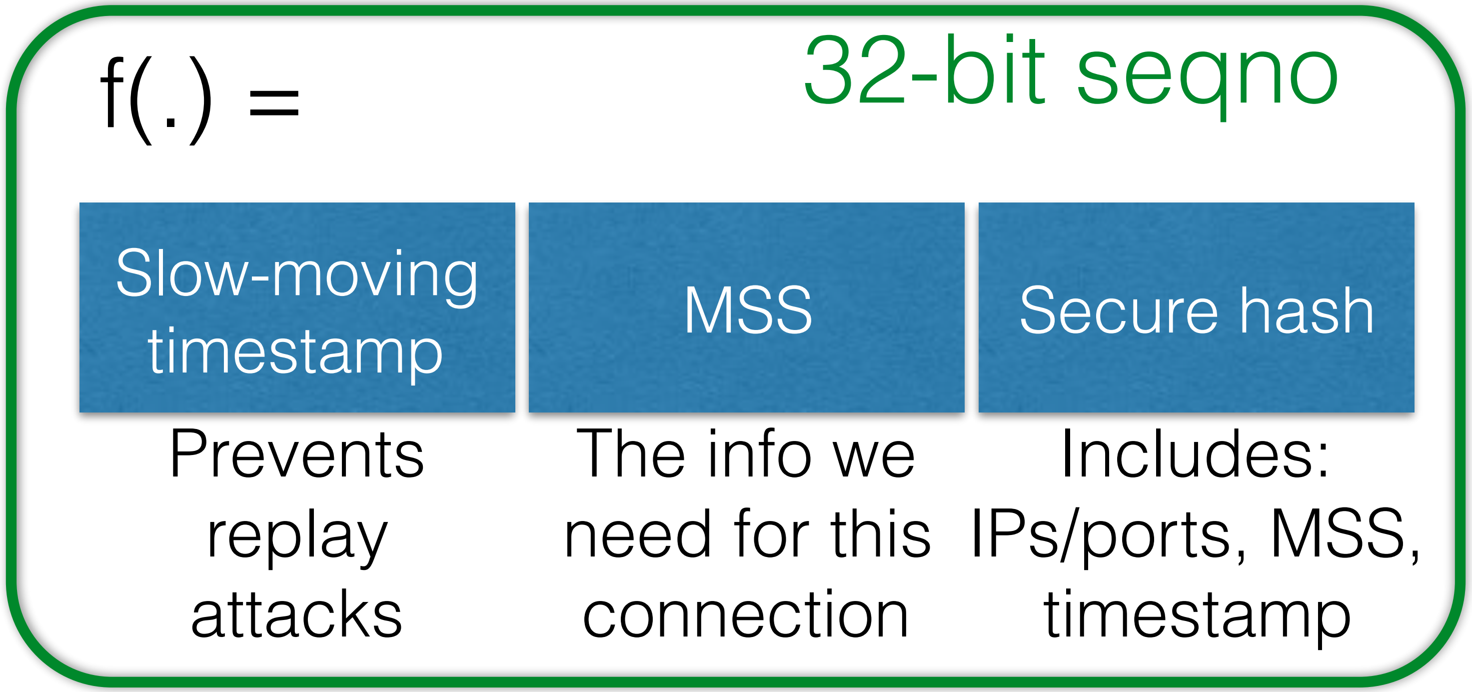
SYN cookie format





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

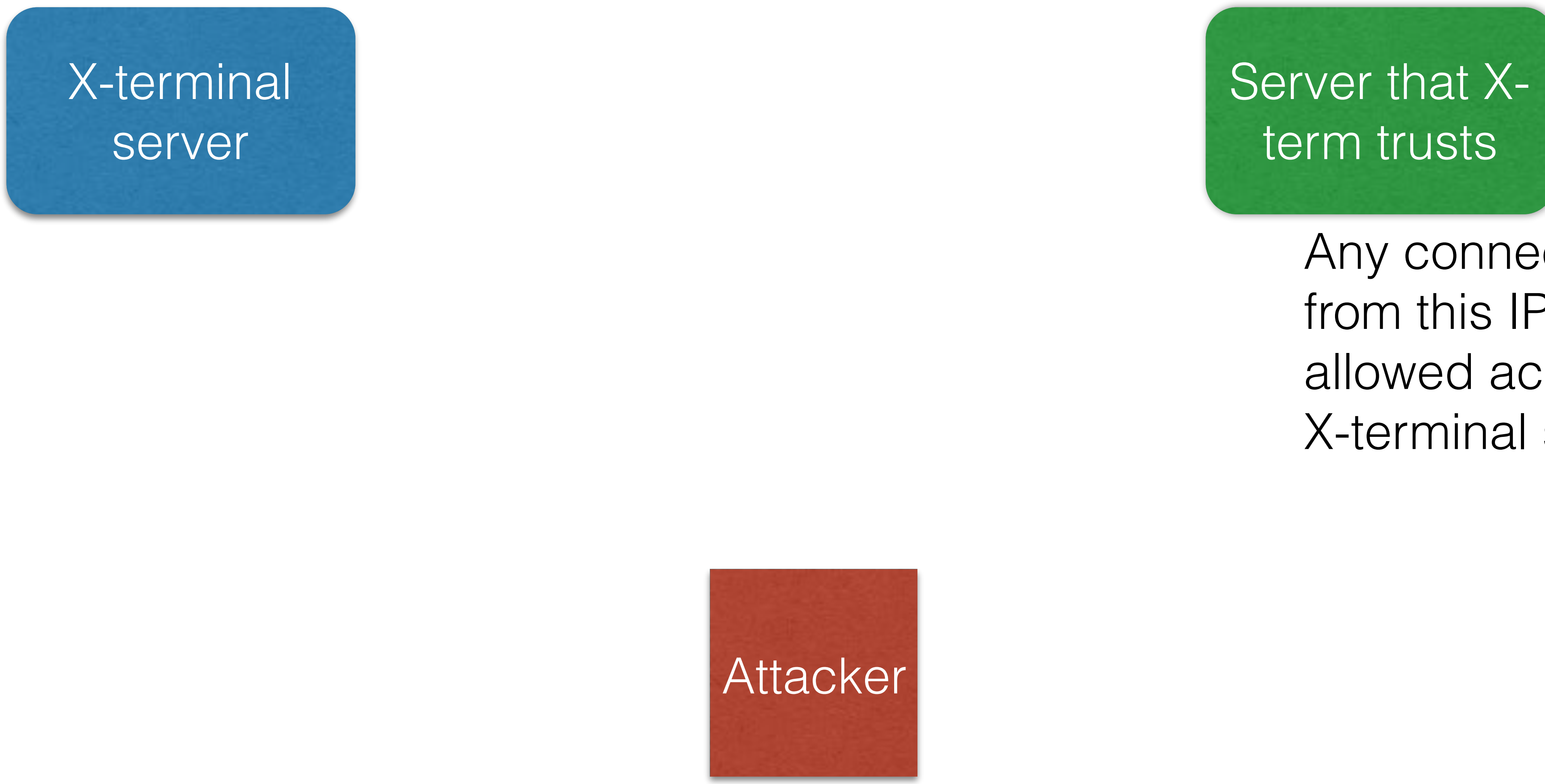
- Suppose you are on the path between src and dst; what can you do?
    - Trivial to inject packets with the correct sequence number

- What if you are not on the path?
    - Need to guess the sequence number
    - Is this difficult to do?

Initial sequence numbers

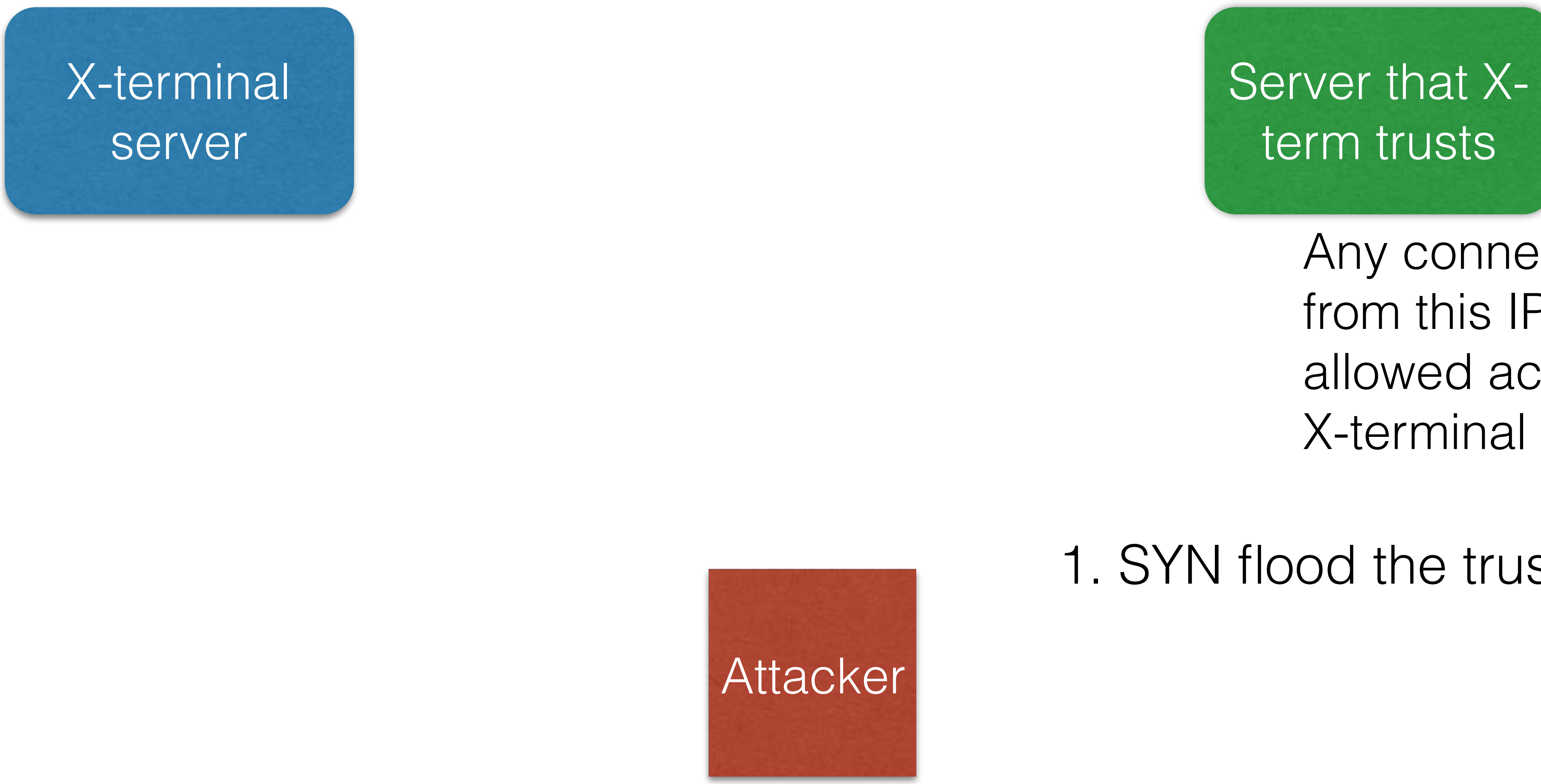
- Initial sequence numbers used to be deterministic
- What havoc can we wreak?
  - Send RSTs
  - Inject data packets into an existing connection (TCP veto attacks)
  - *Initiate and use an entire connection without ever hearing the other end*

Mitnick attack



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

Mitnick attack



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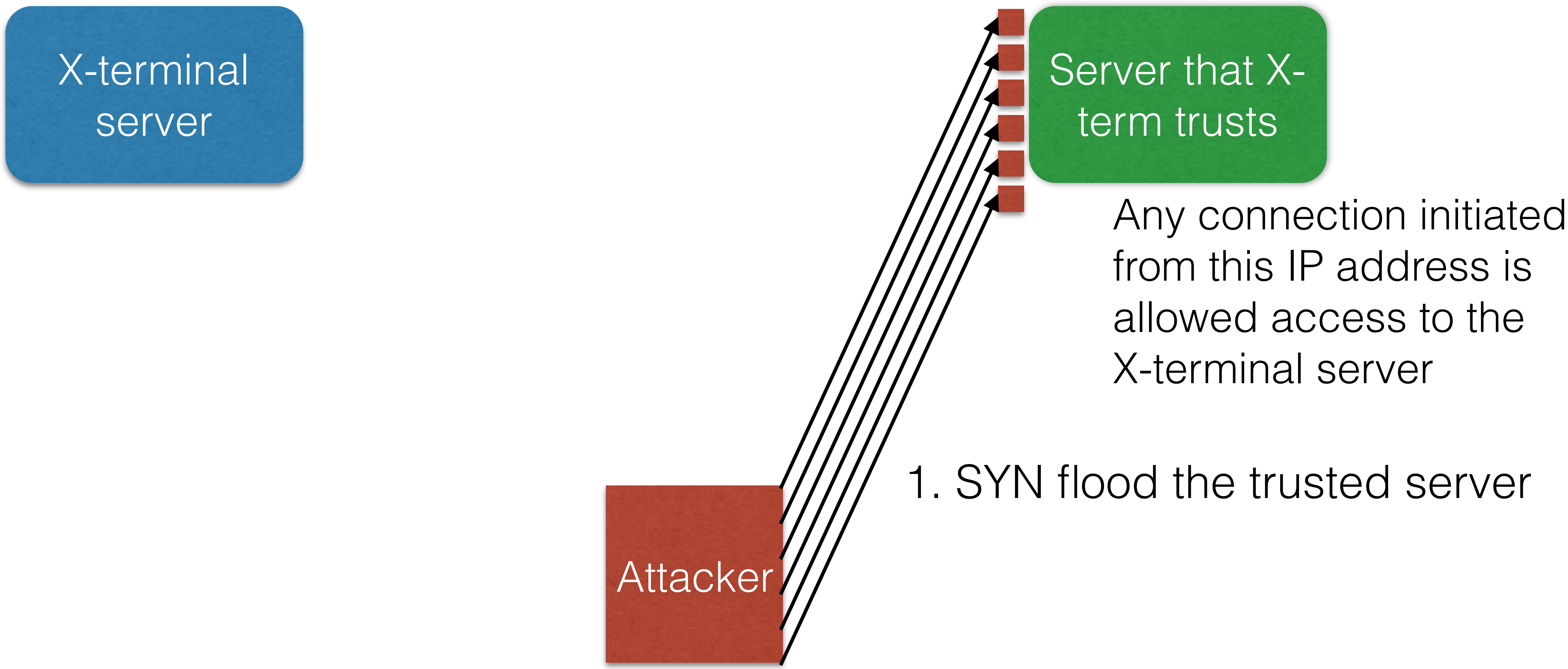
1. SYN flood the trusted server

Mitnick attack



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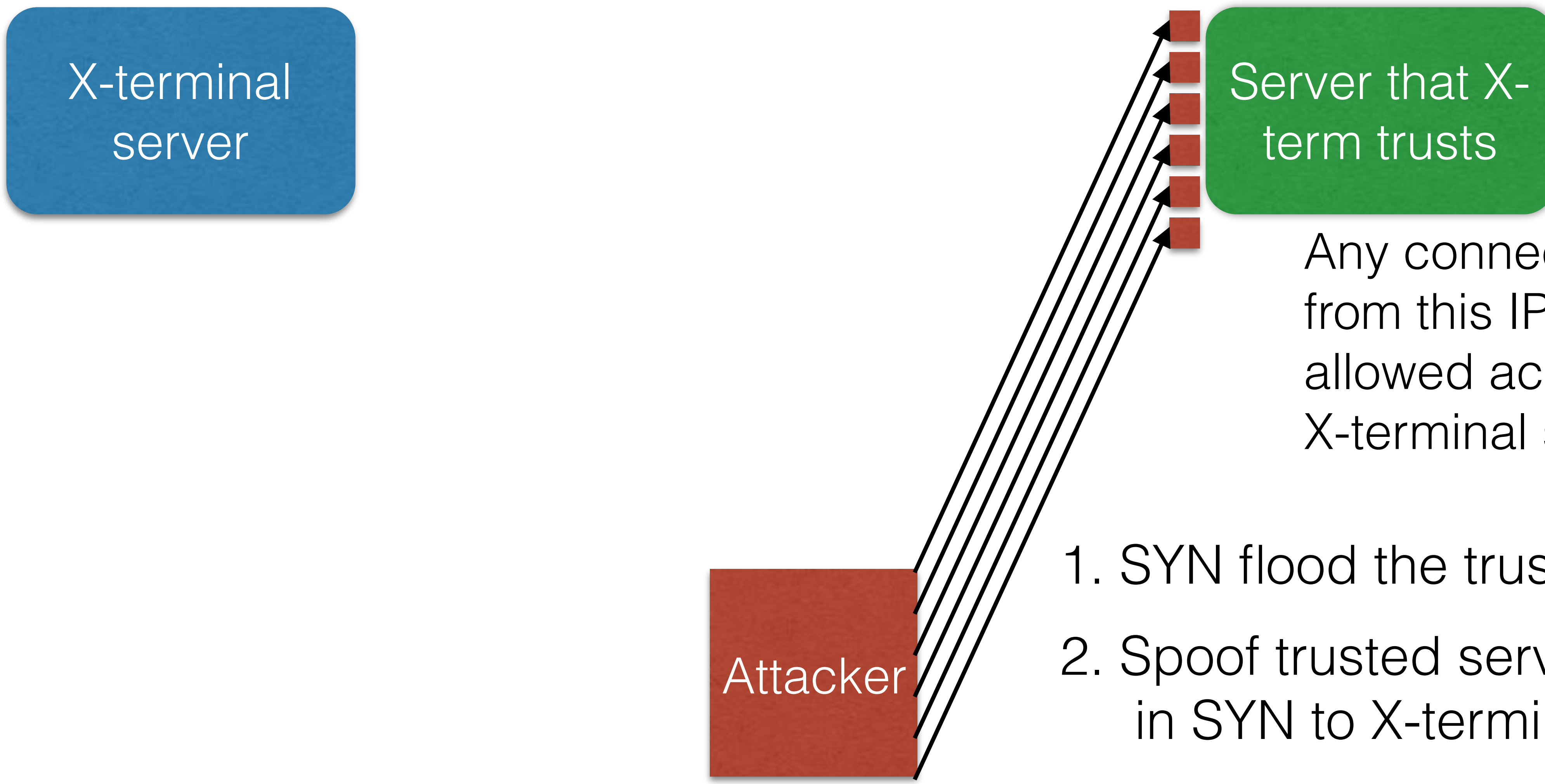
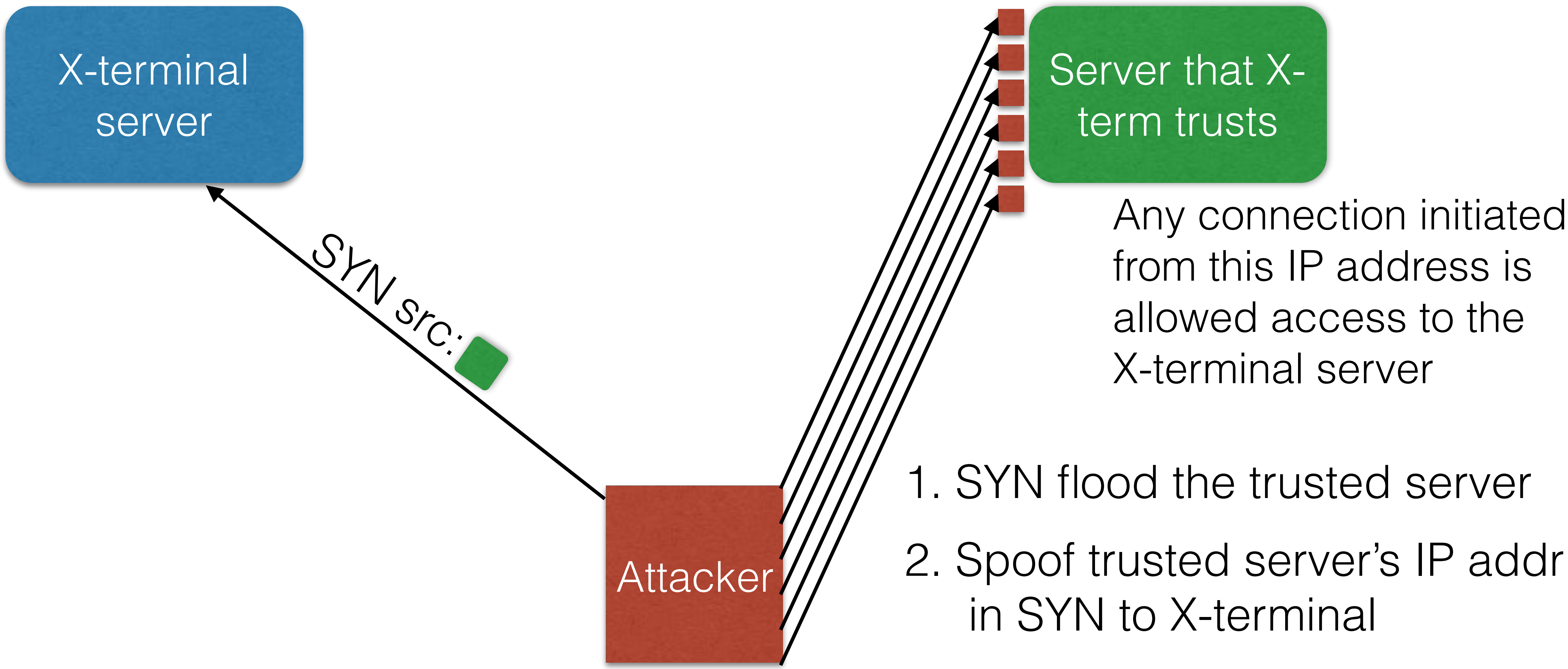


Any connection initiated from this IP address is allowed access to the X-terminal server

1. SYN flood the trusted server
2. Spoof trusted server's IP addr in SYN to X-terminal

Mitnick attack



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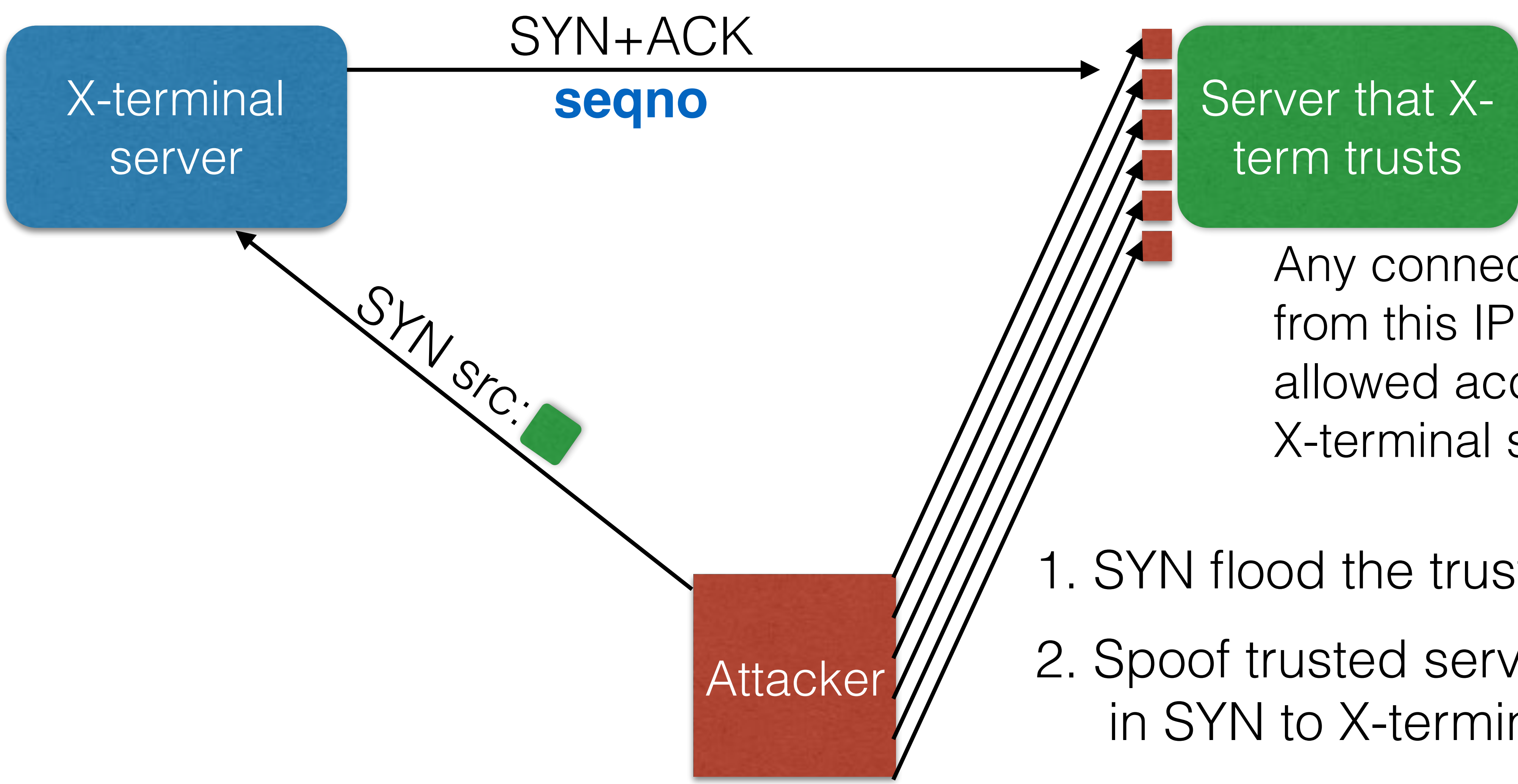

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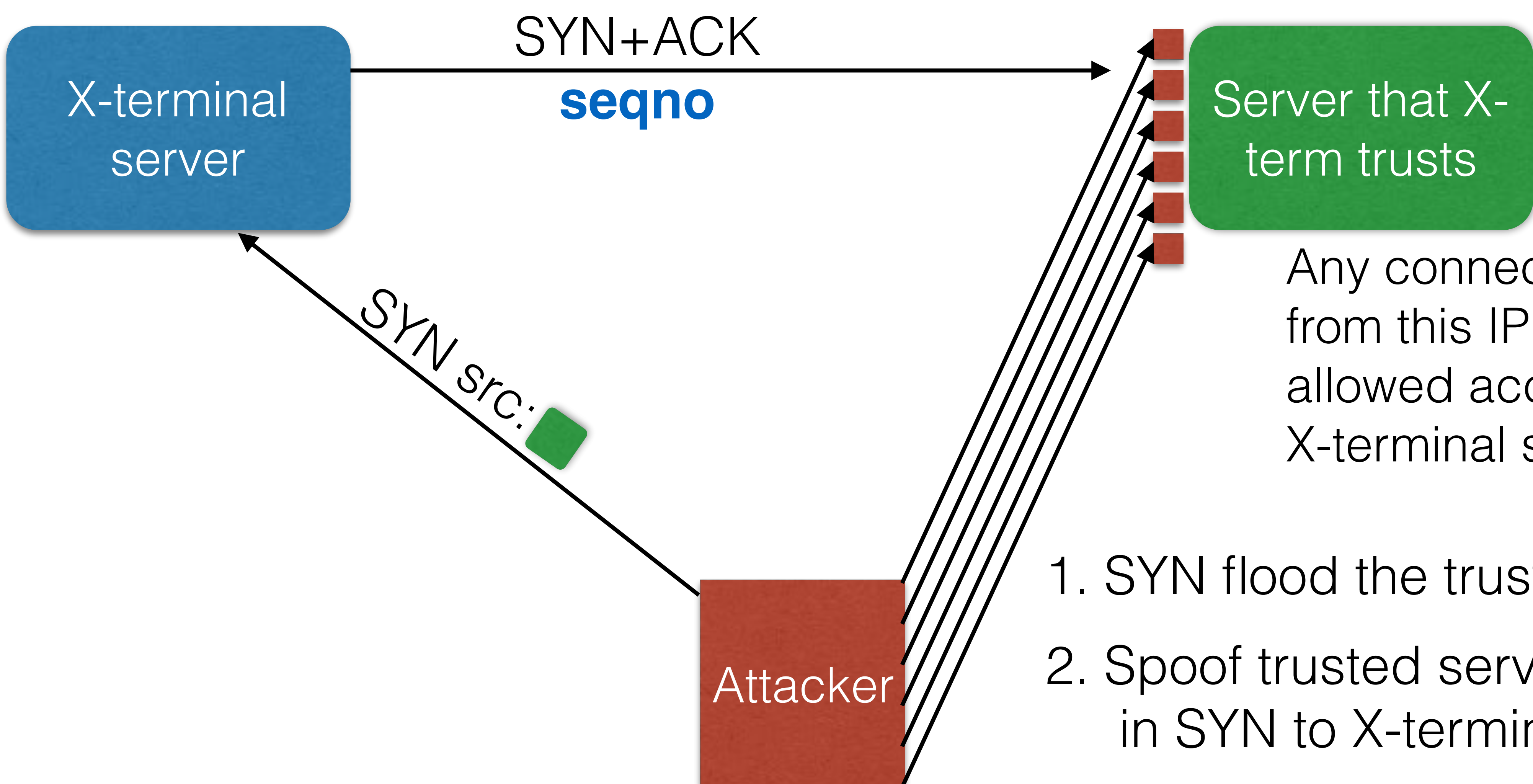
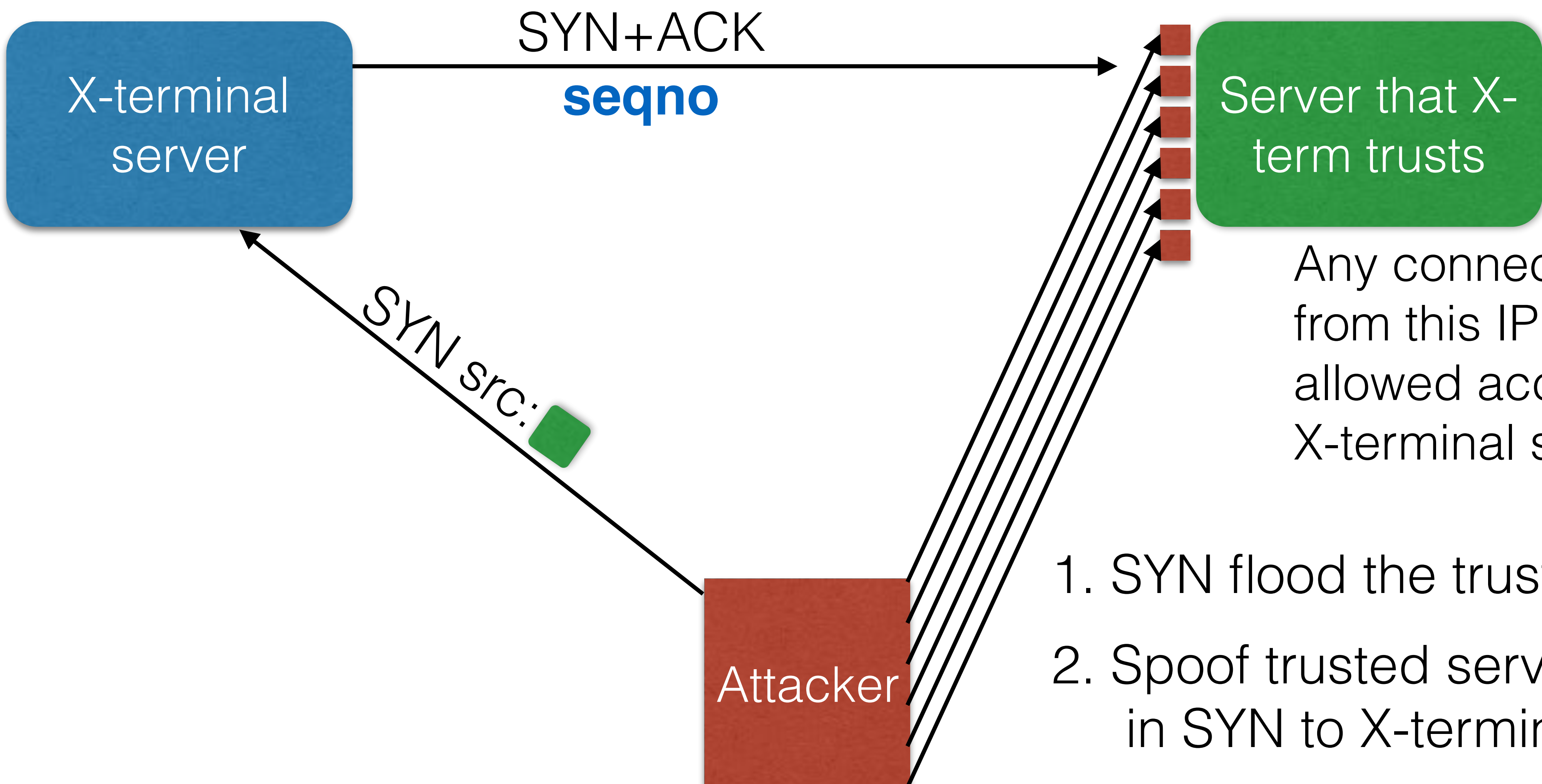


Any connection initiated from this IP address is allowed access to the X-terminal server

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

Mitnick attack



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

1. SYN flood the trusted server
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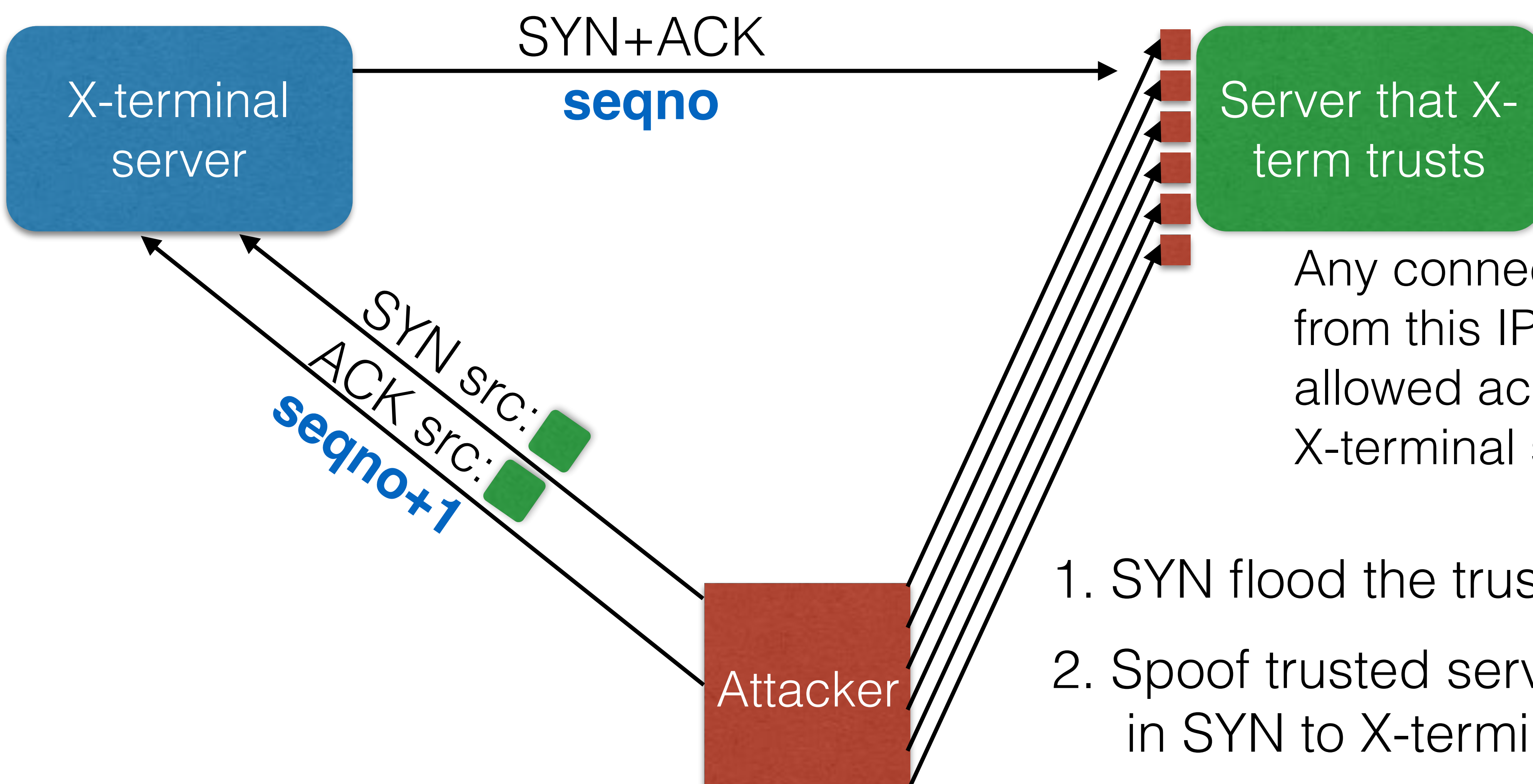
3. Trusted server too busy to RST
4. ACK with the guessed **seqno**

Mitnick attack



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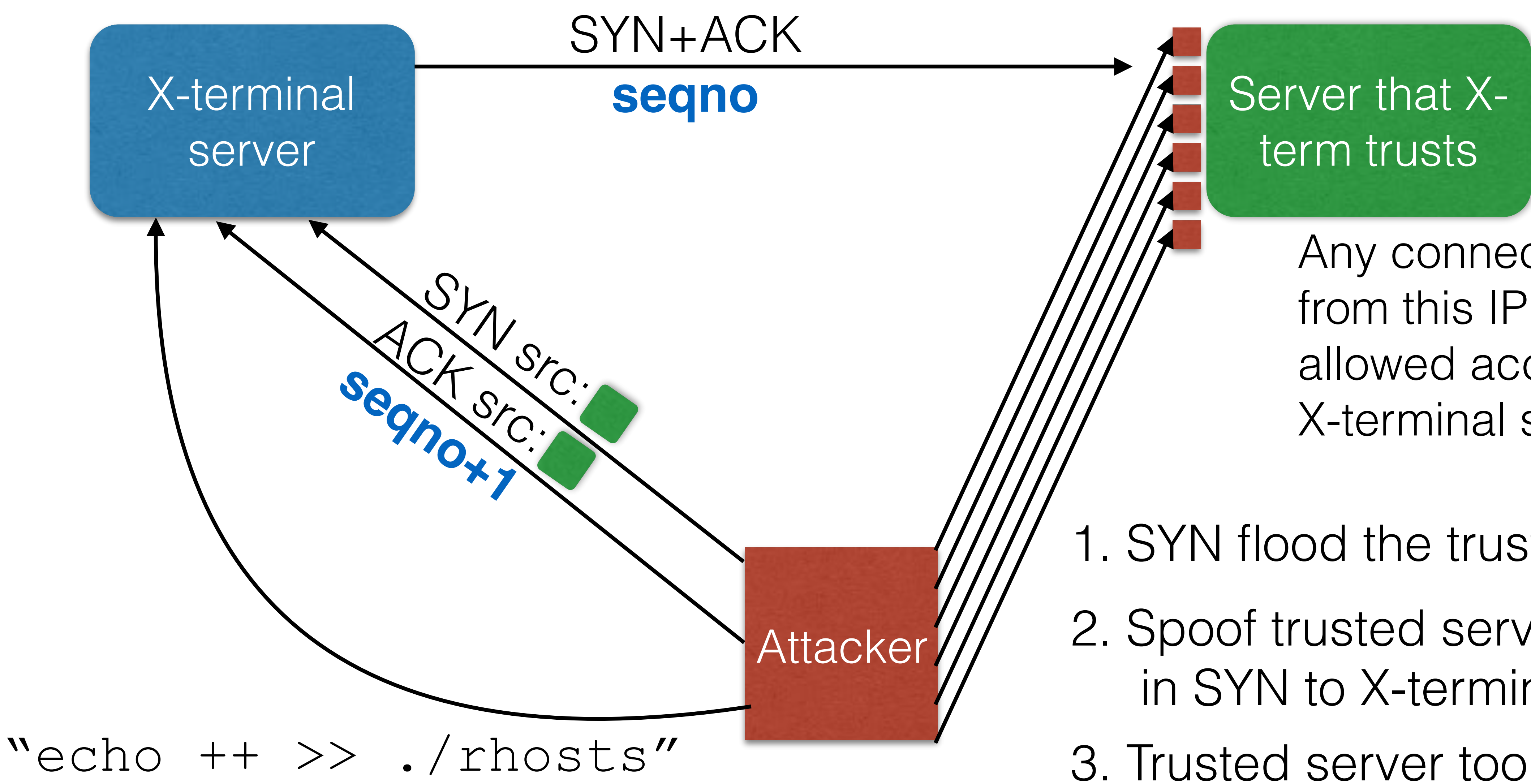

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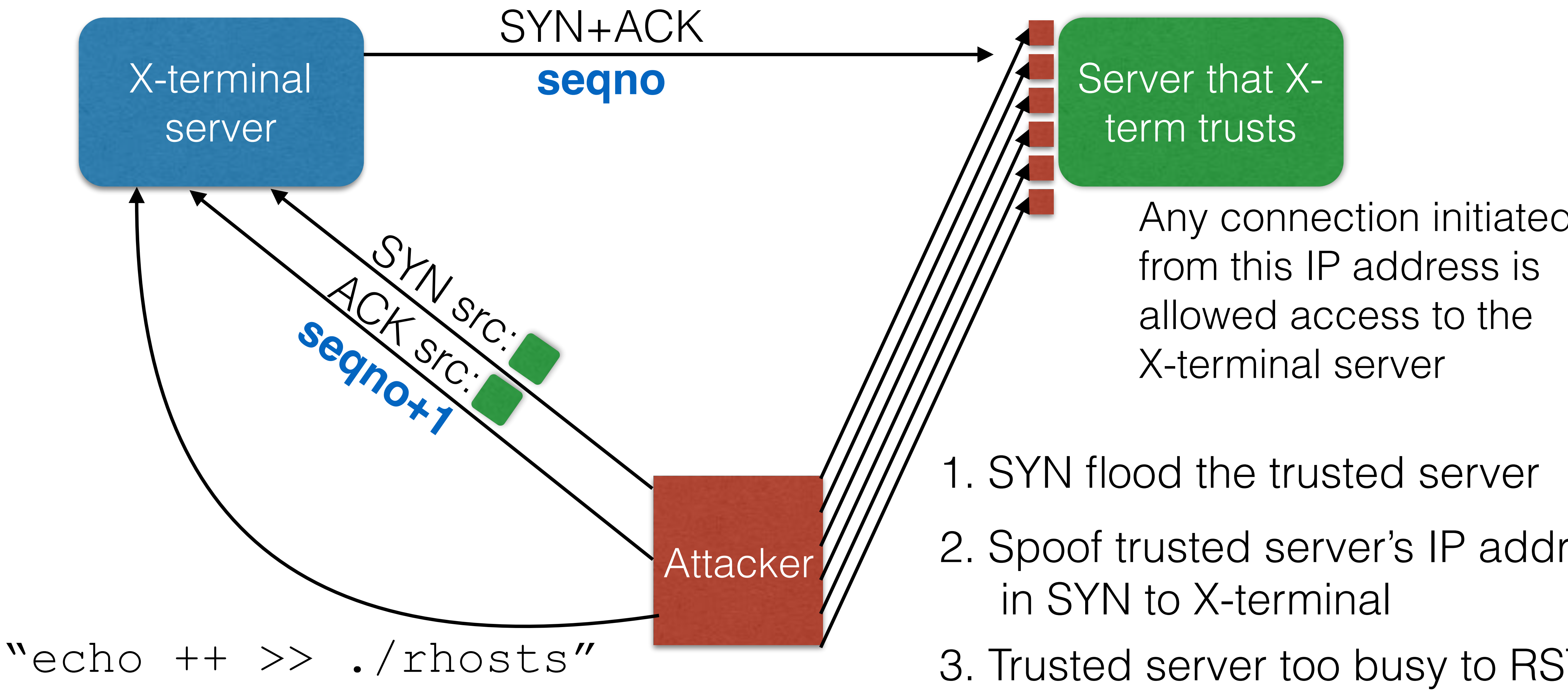

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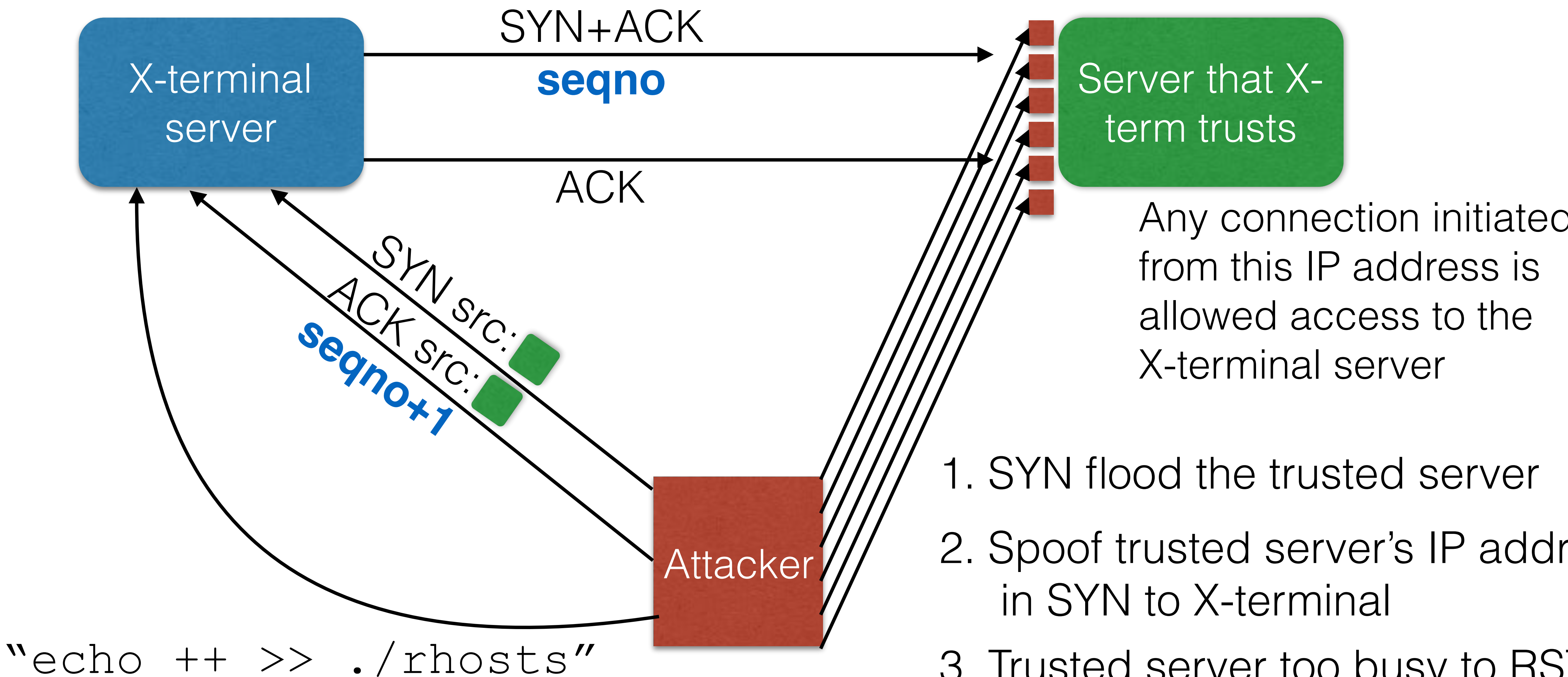

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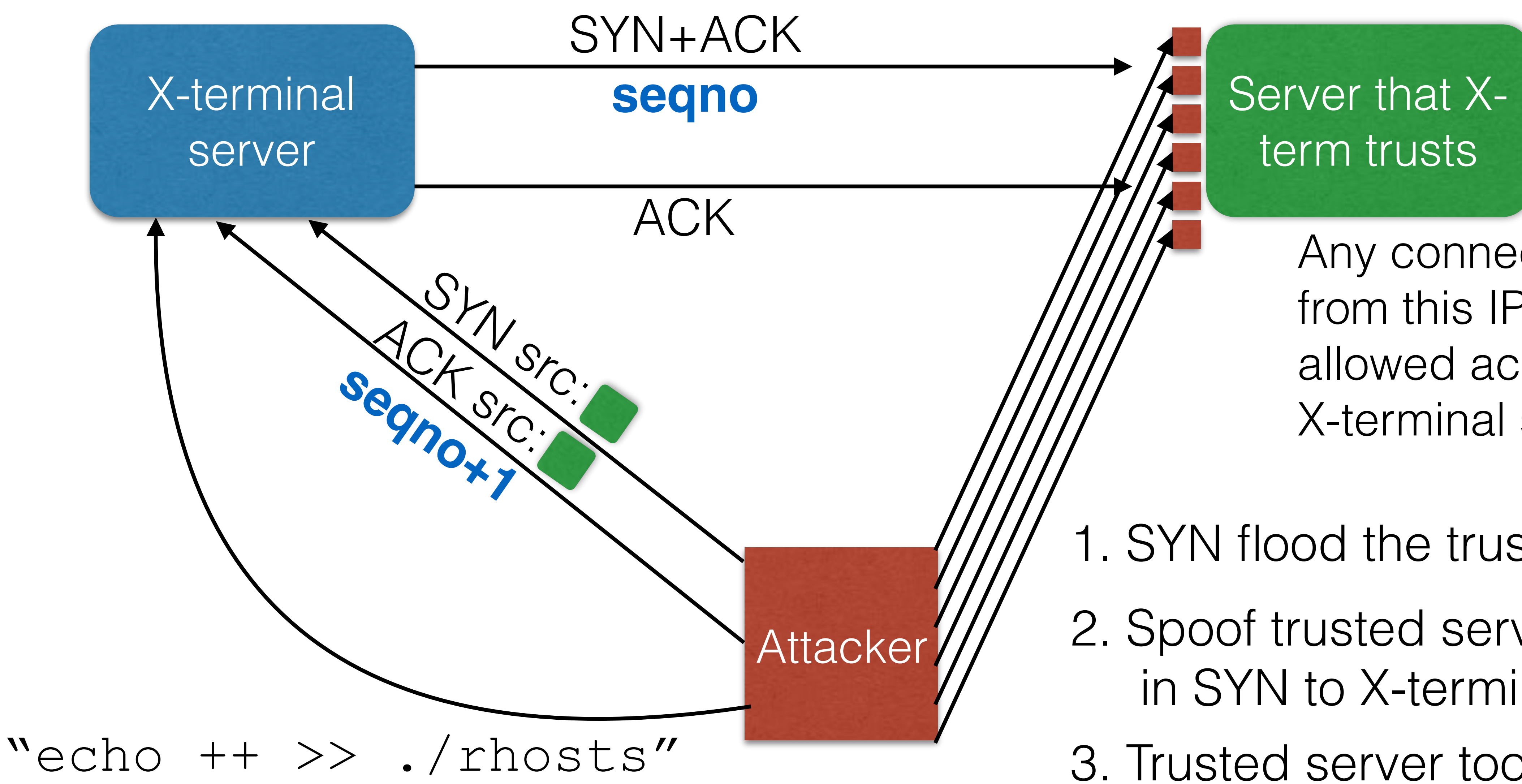

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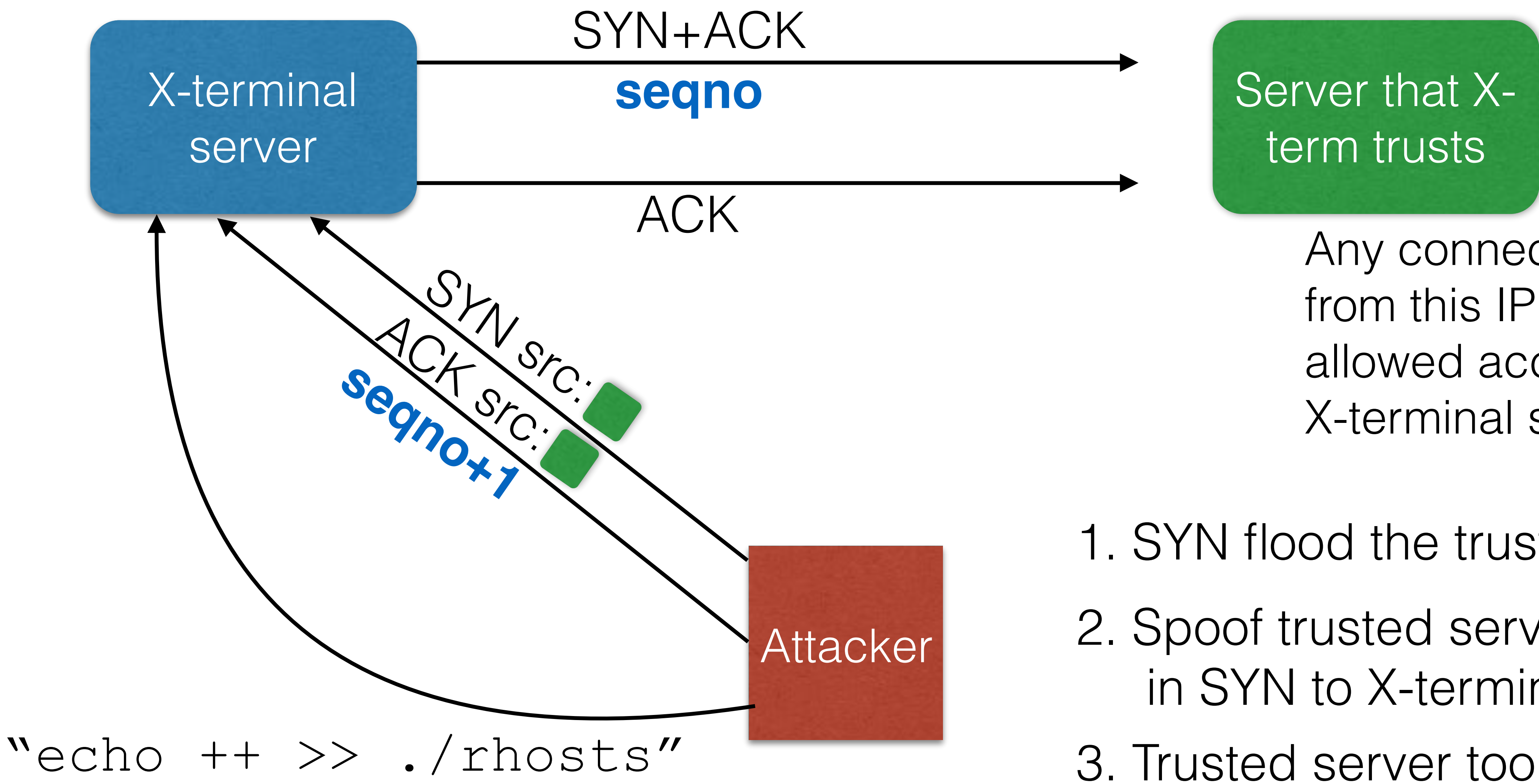

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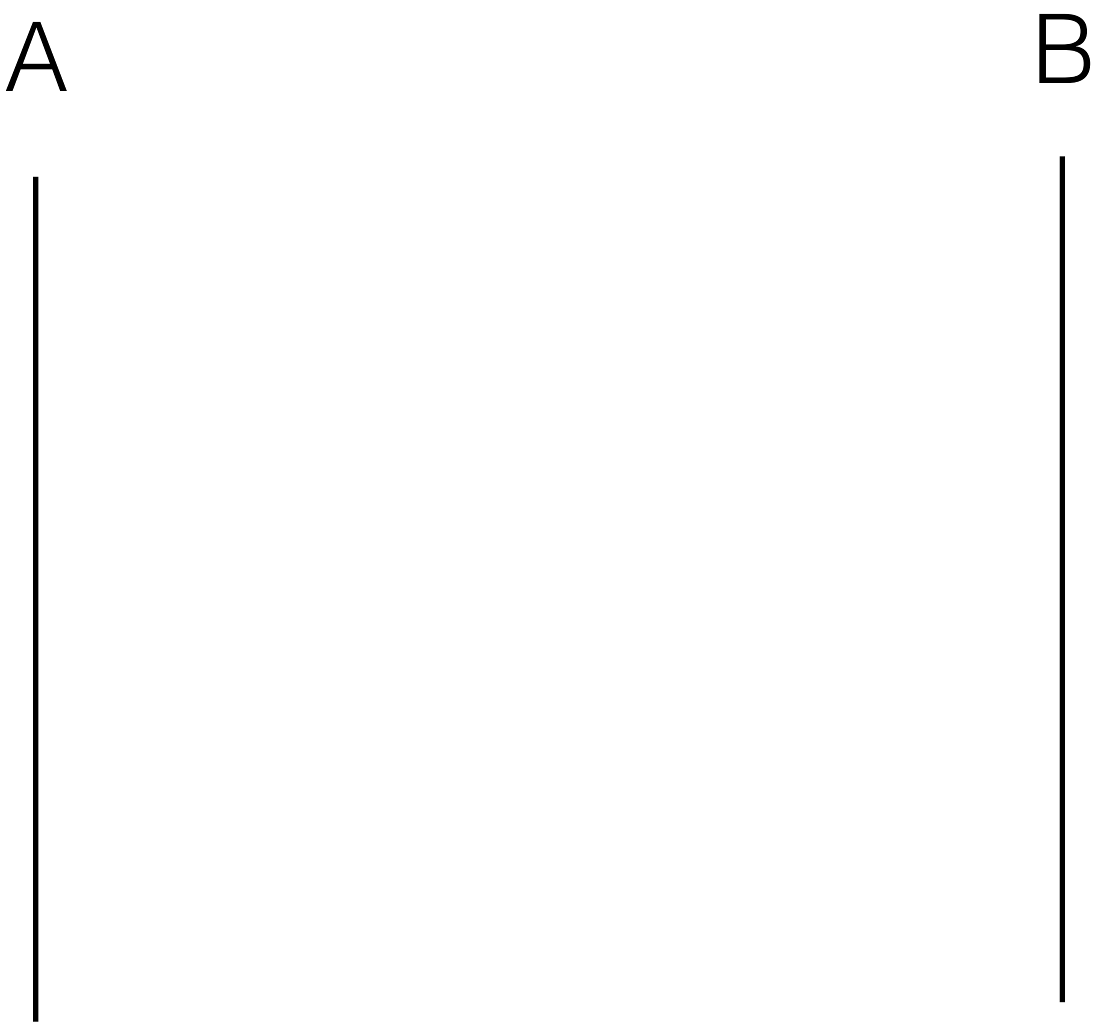
Defenses

- Initial sequence number must be difficult to predict!

Opt-ack attack



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

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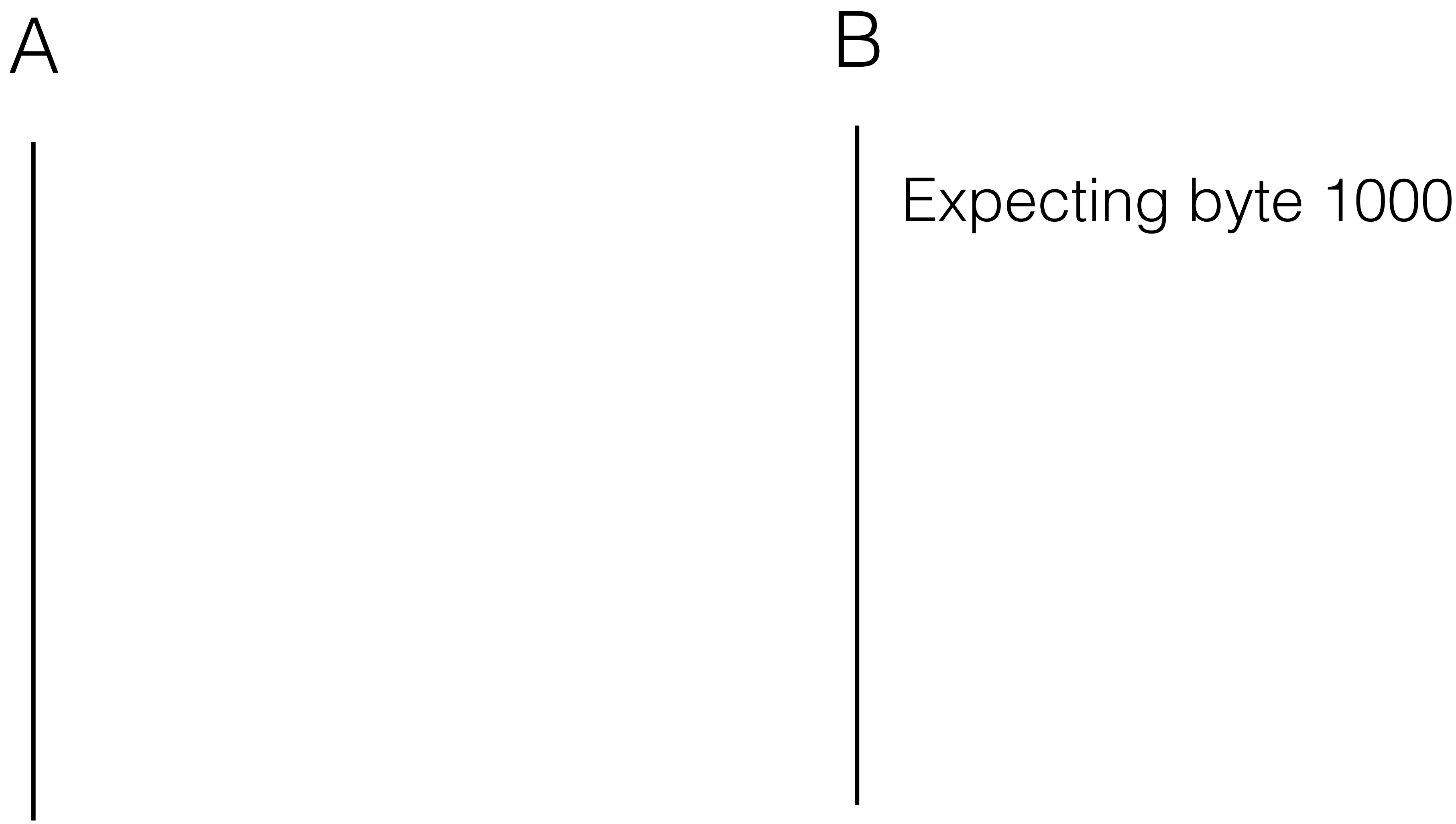

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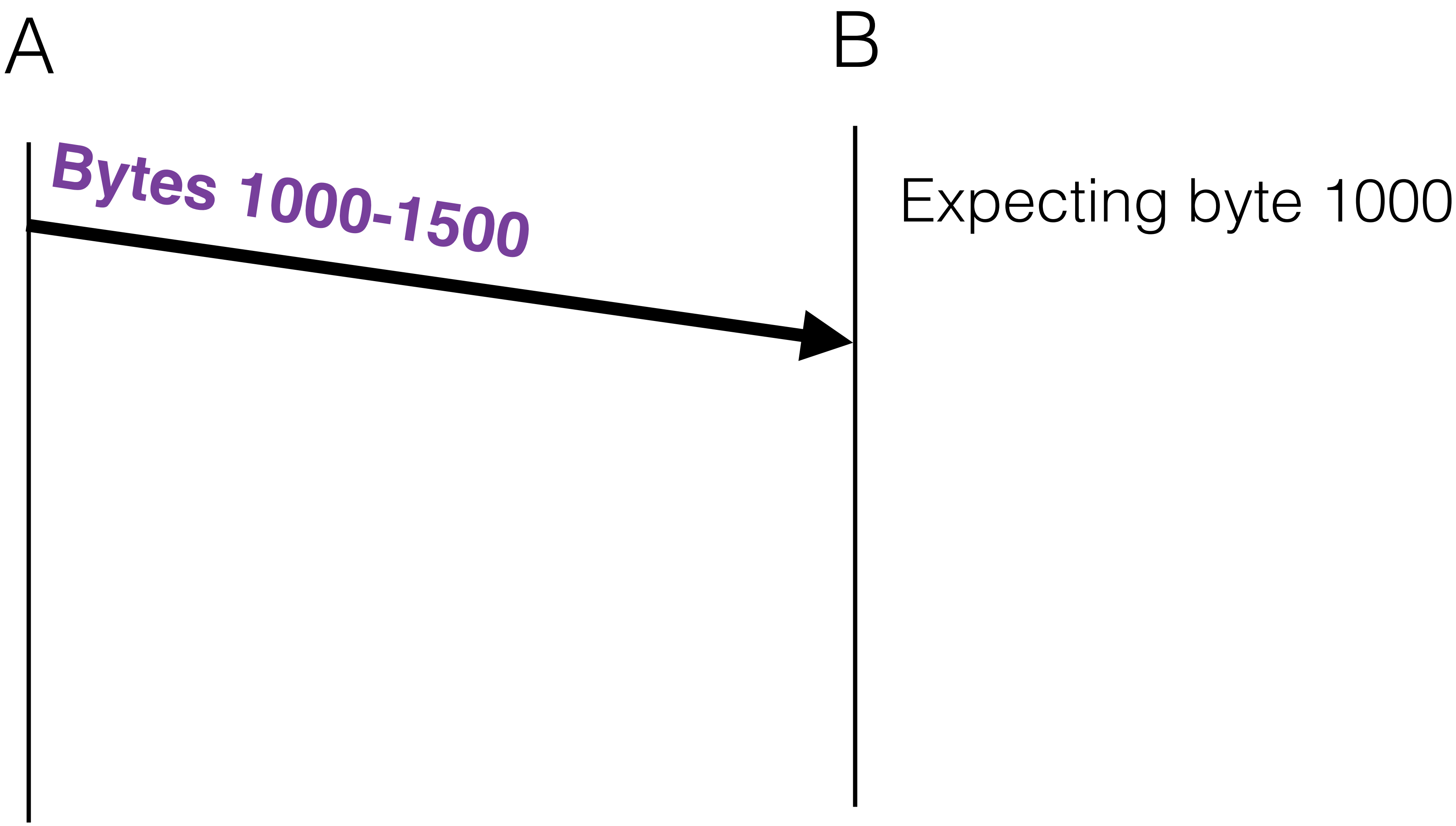

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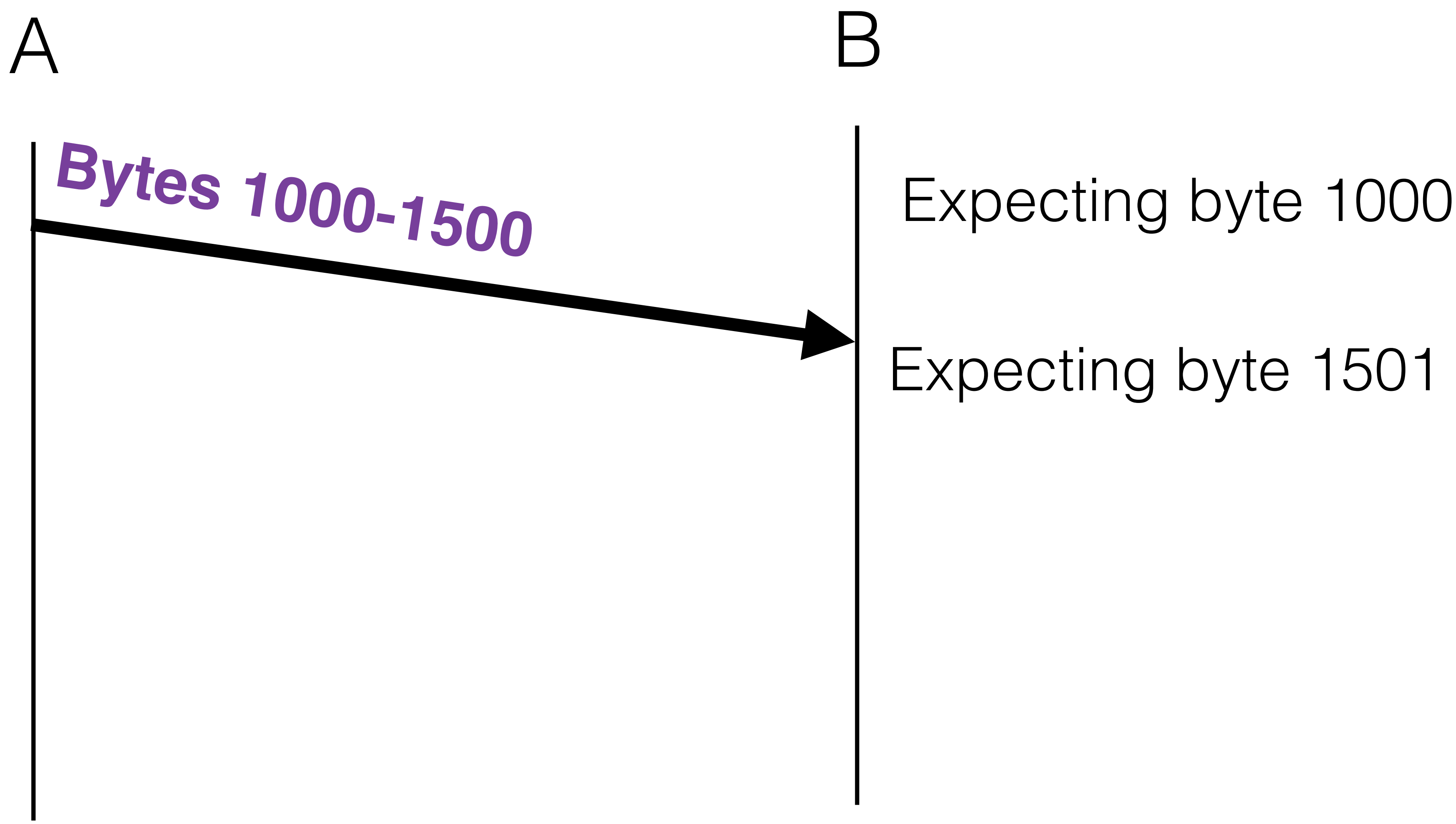

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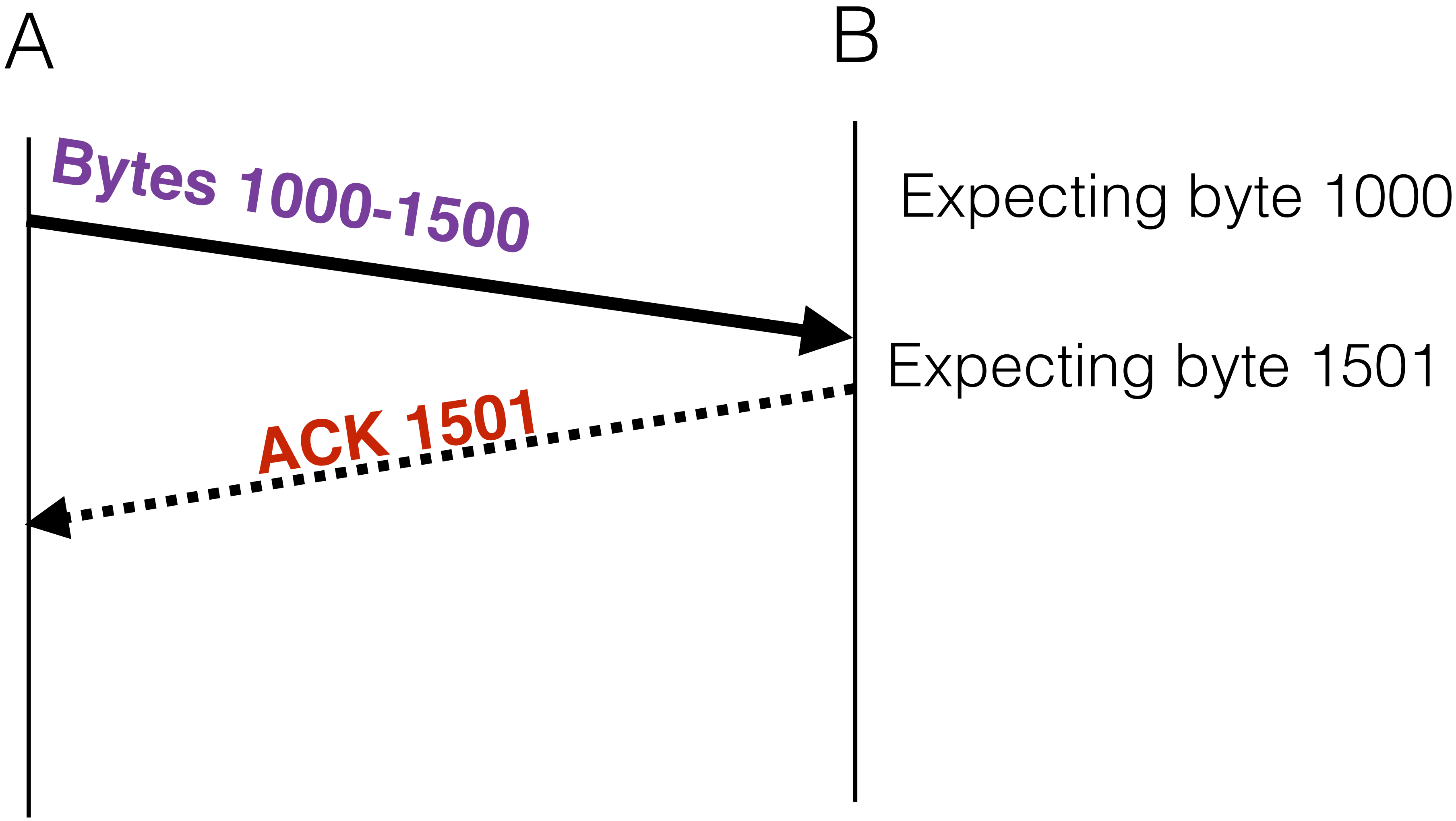

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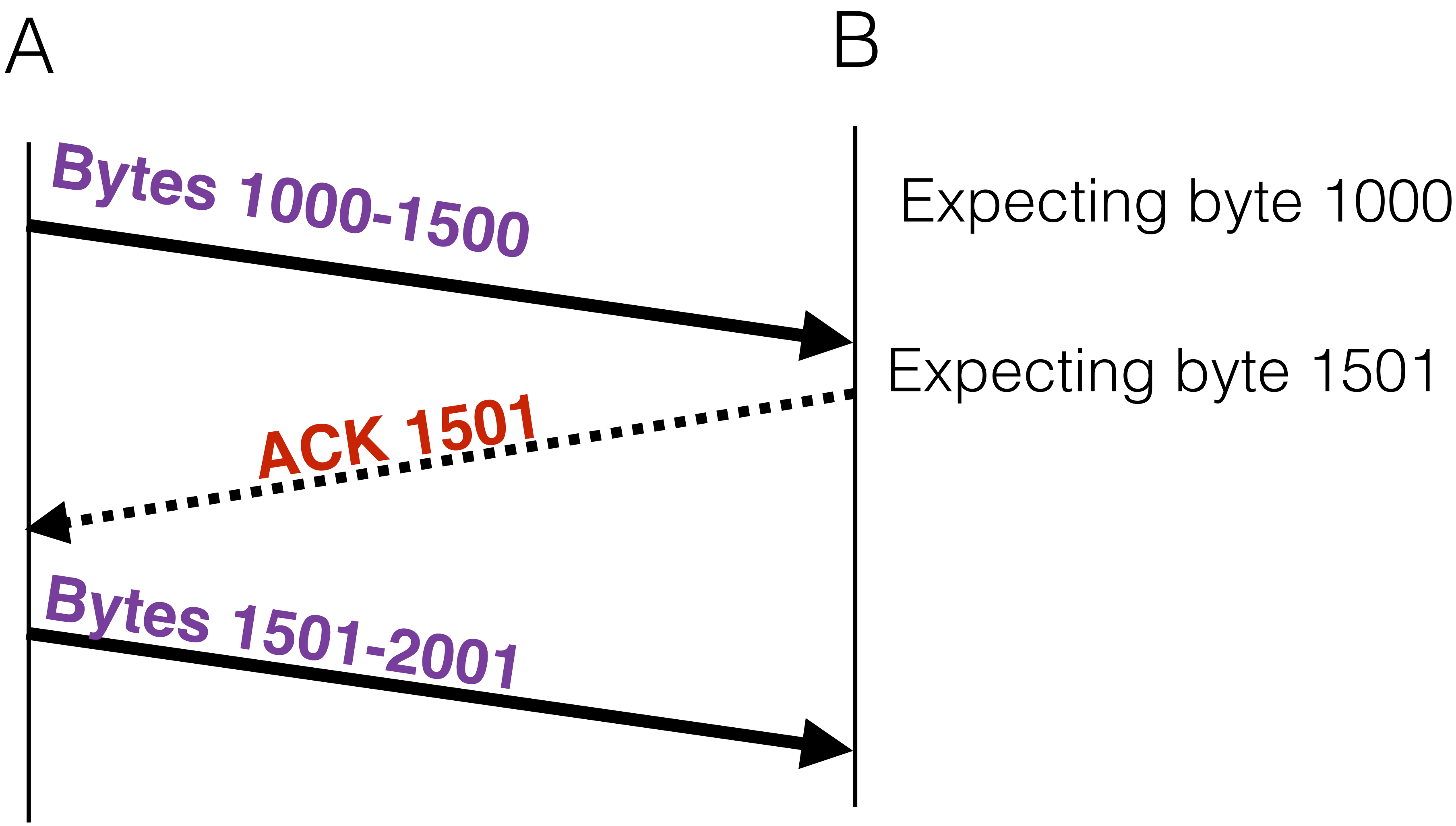

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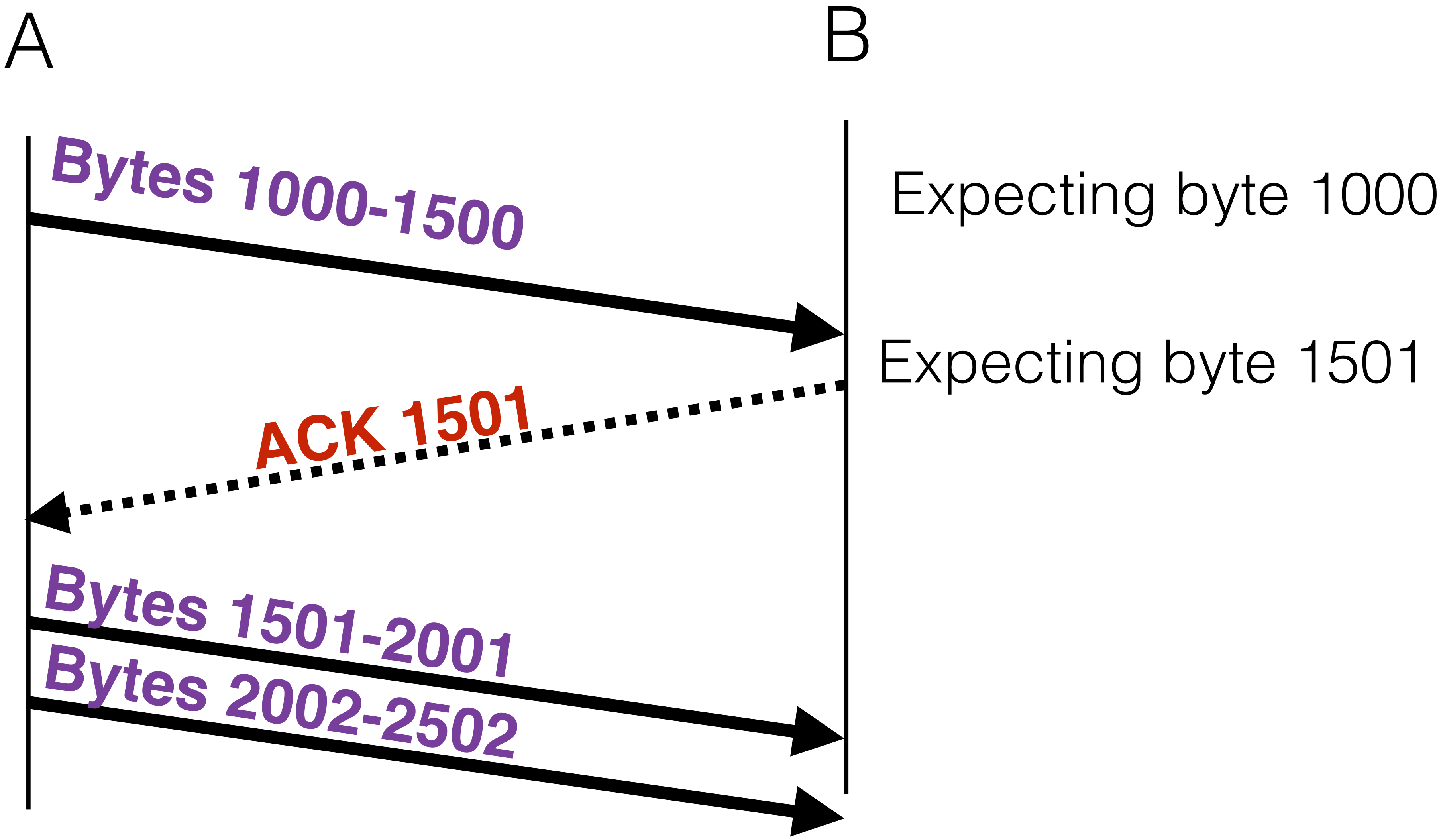

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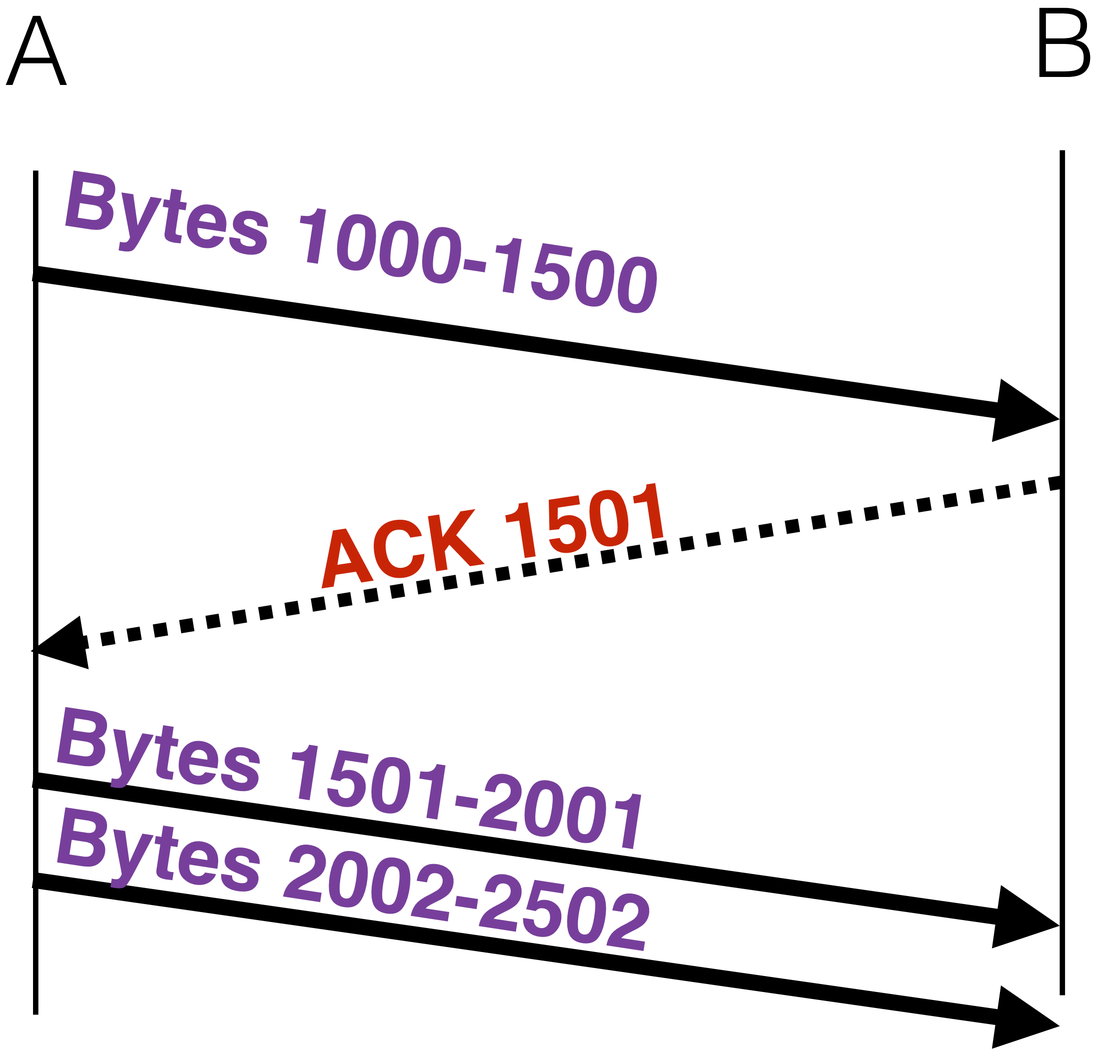

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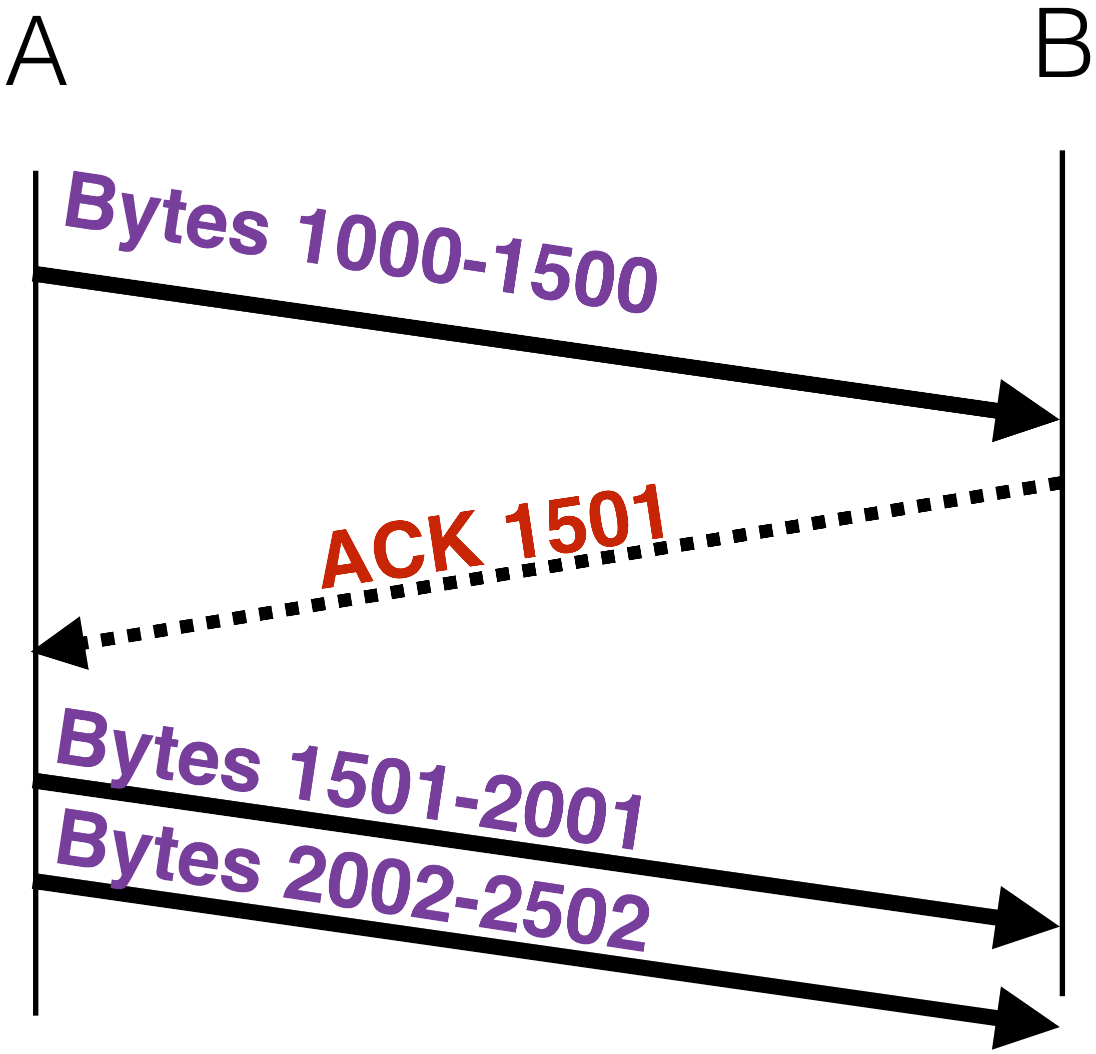
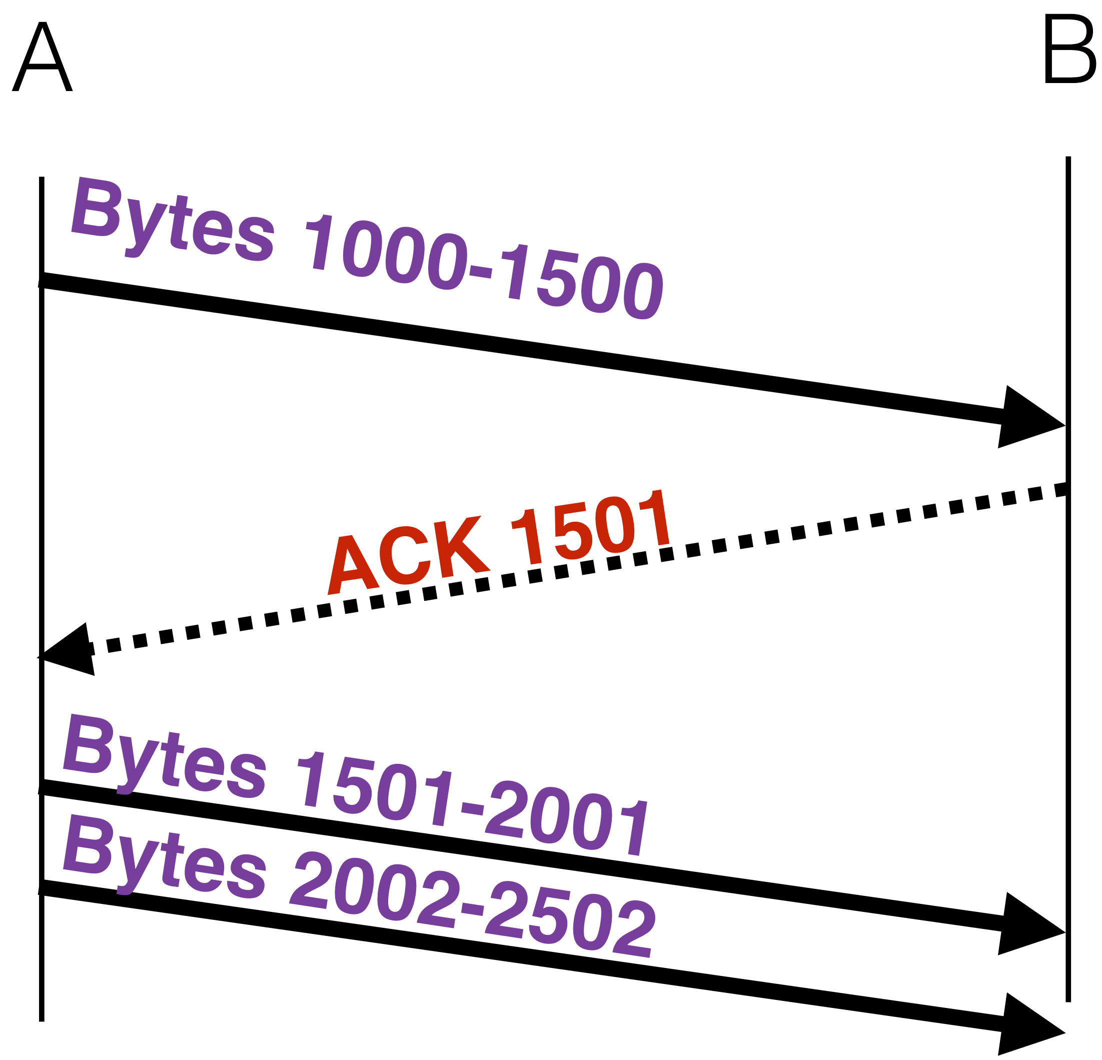


If I could convince you to send REALLY quickly, then you would effectively DoS your own network!

Opt-ack attack



But to get you to send faster, I need to get data in order to ACK, so I need to receive quickly

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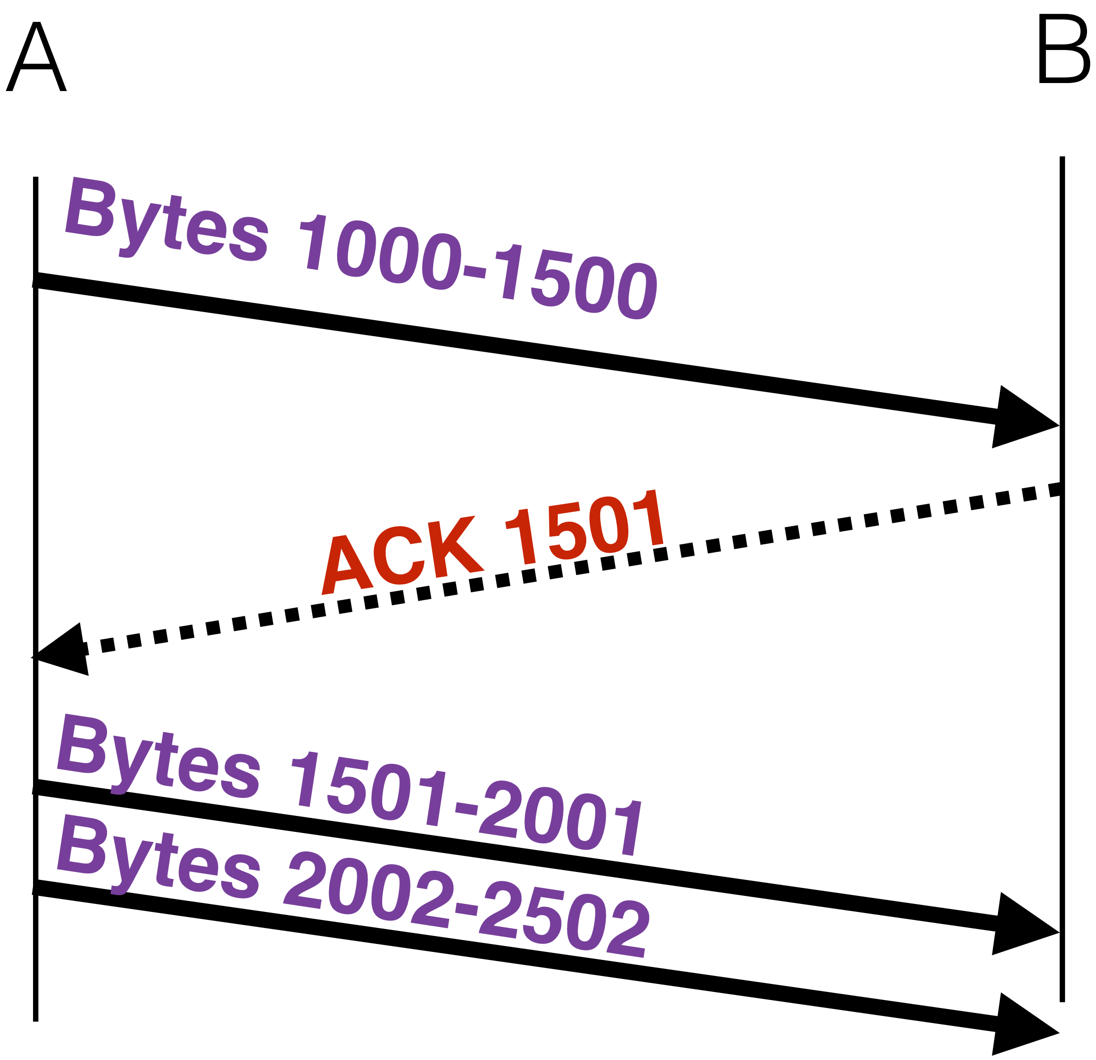

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...or do I?

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

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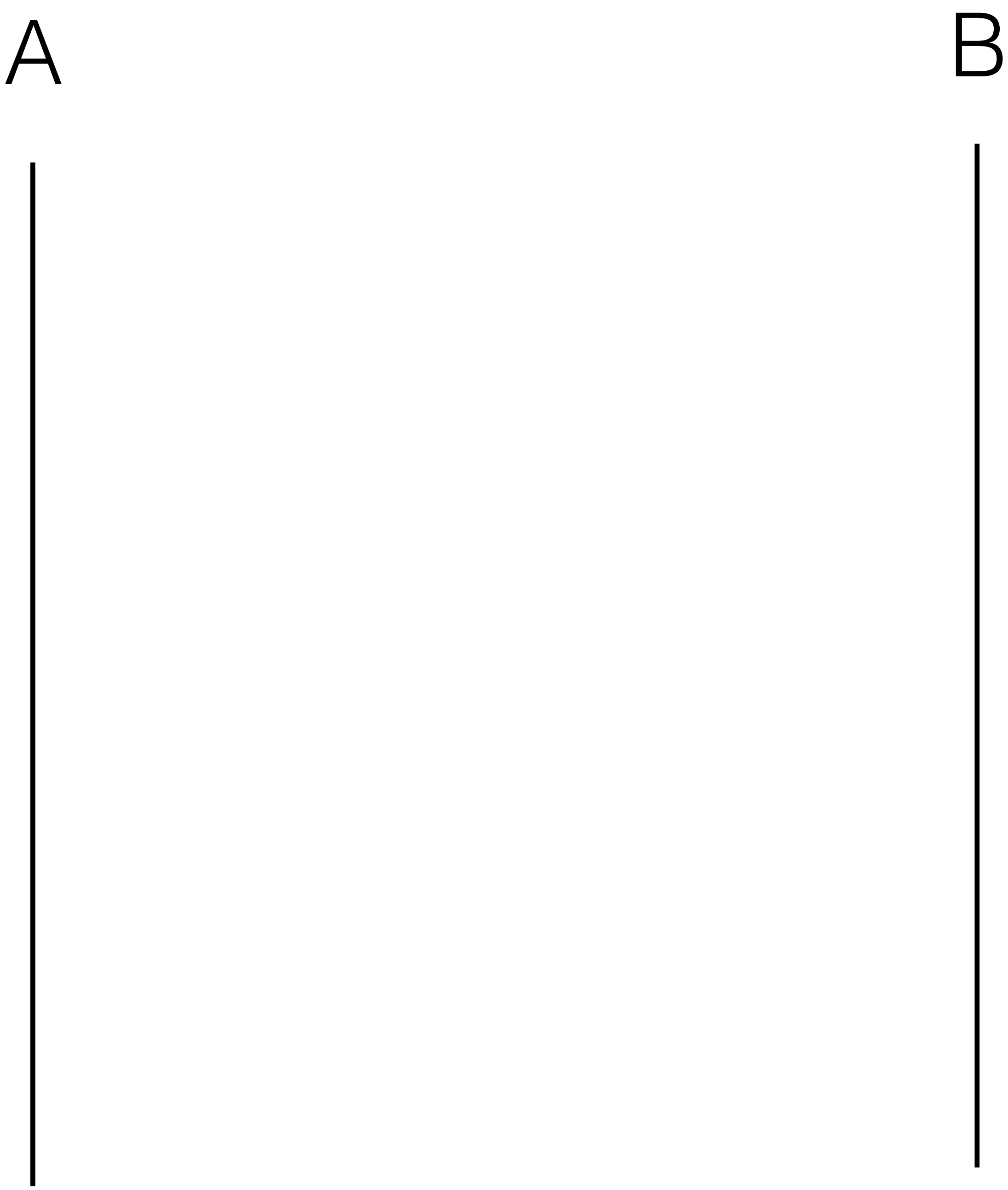

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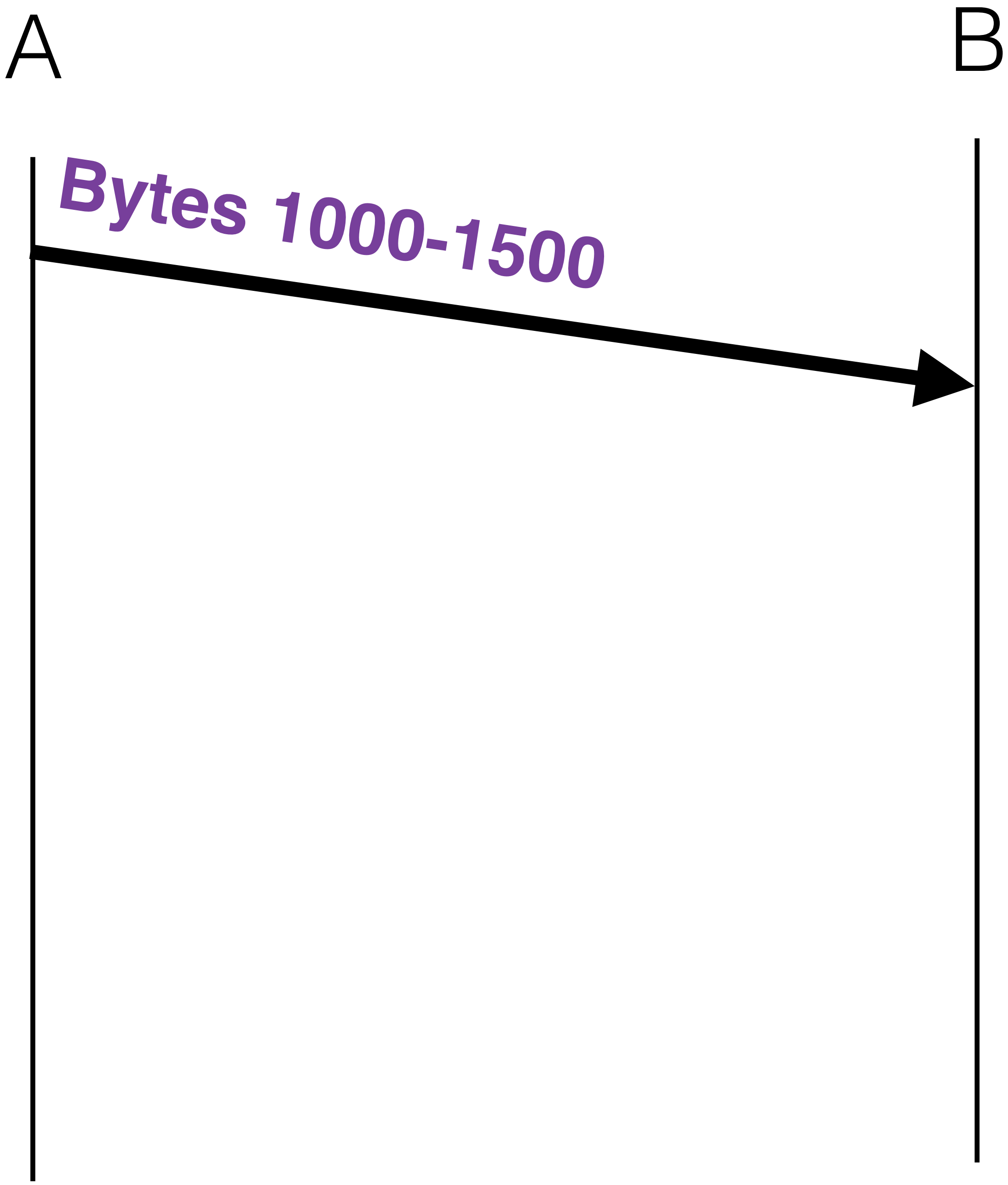

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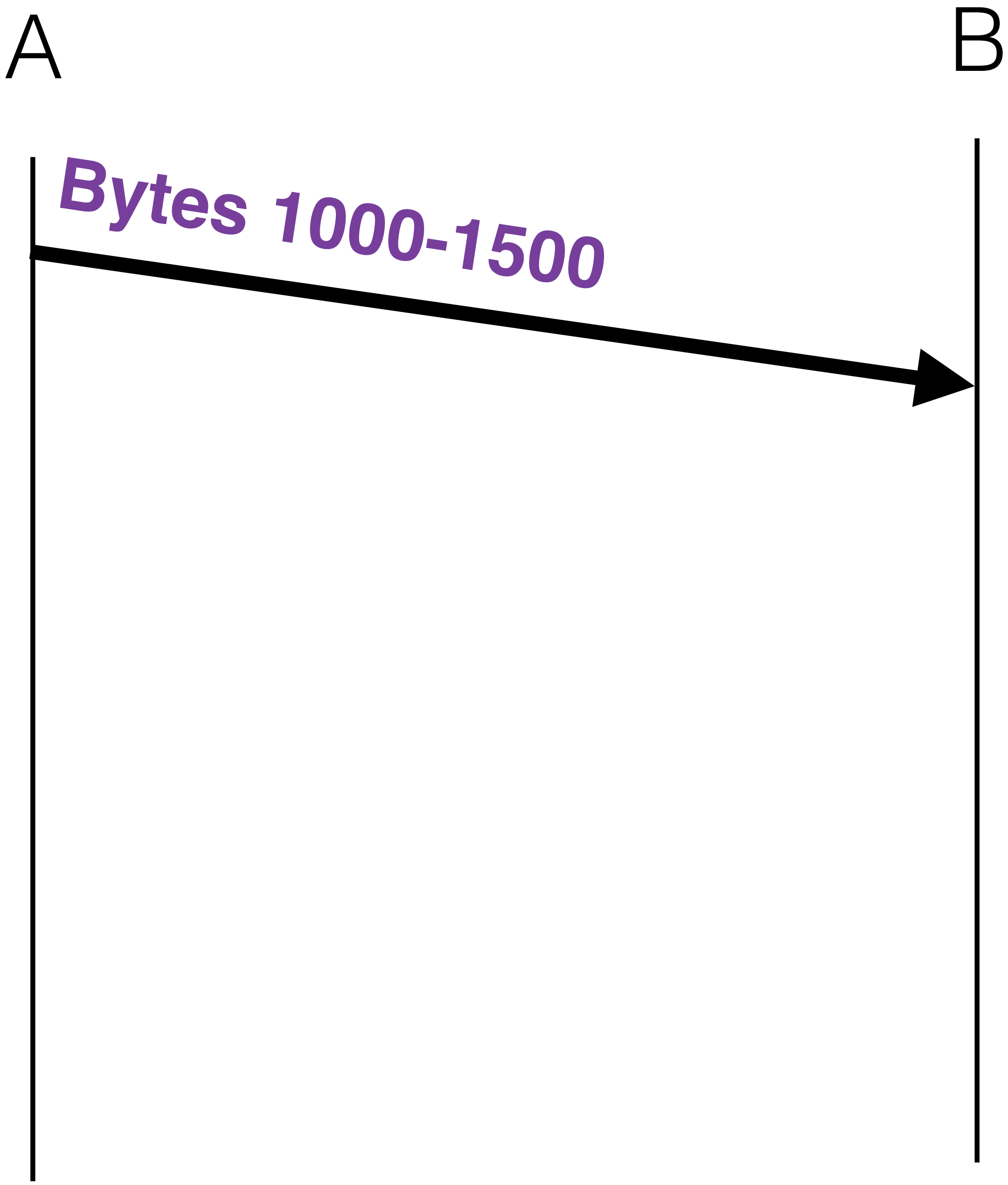

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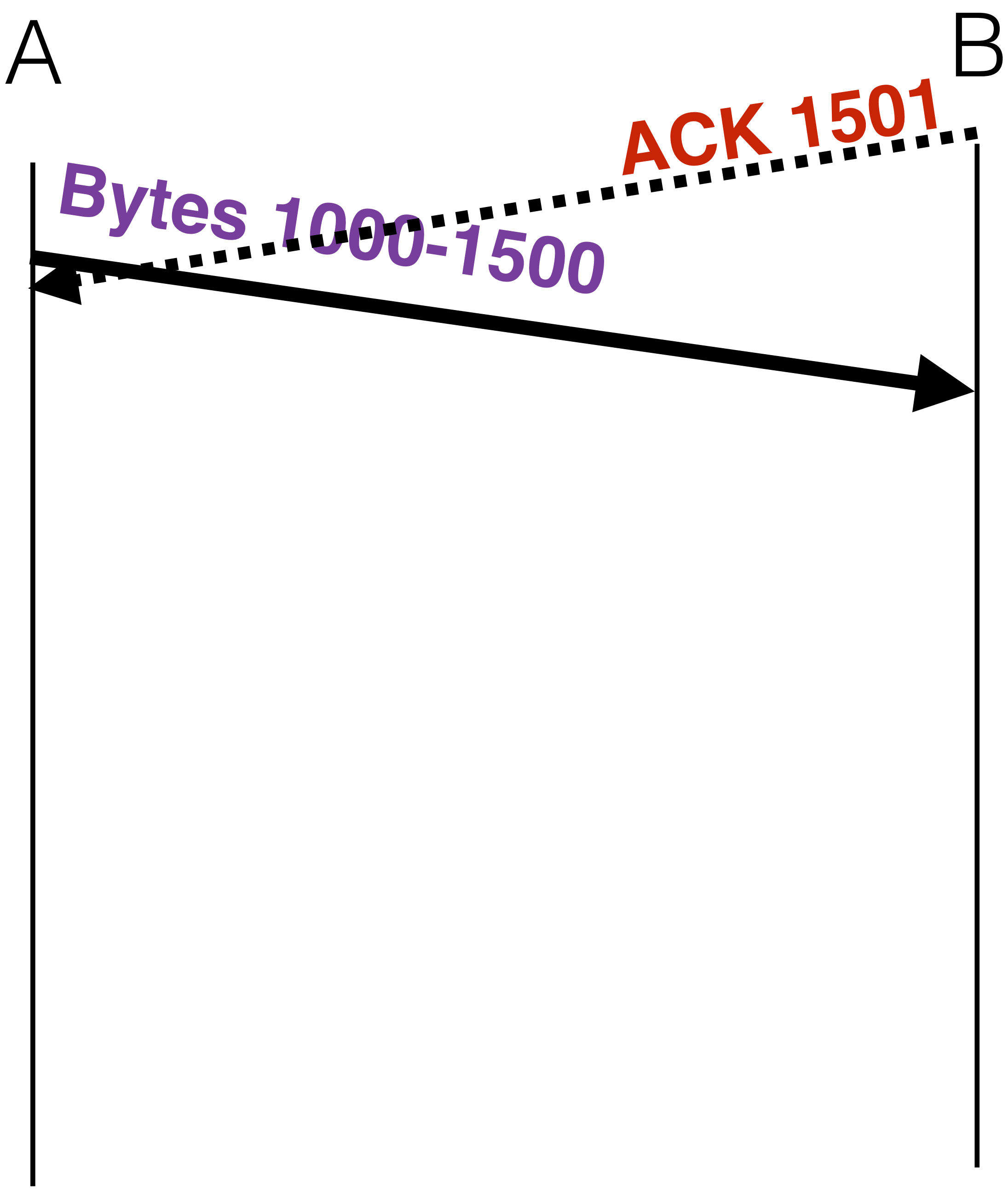

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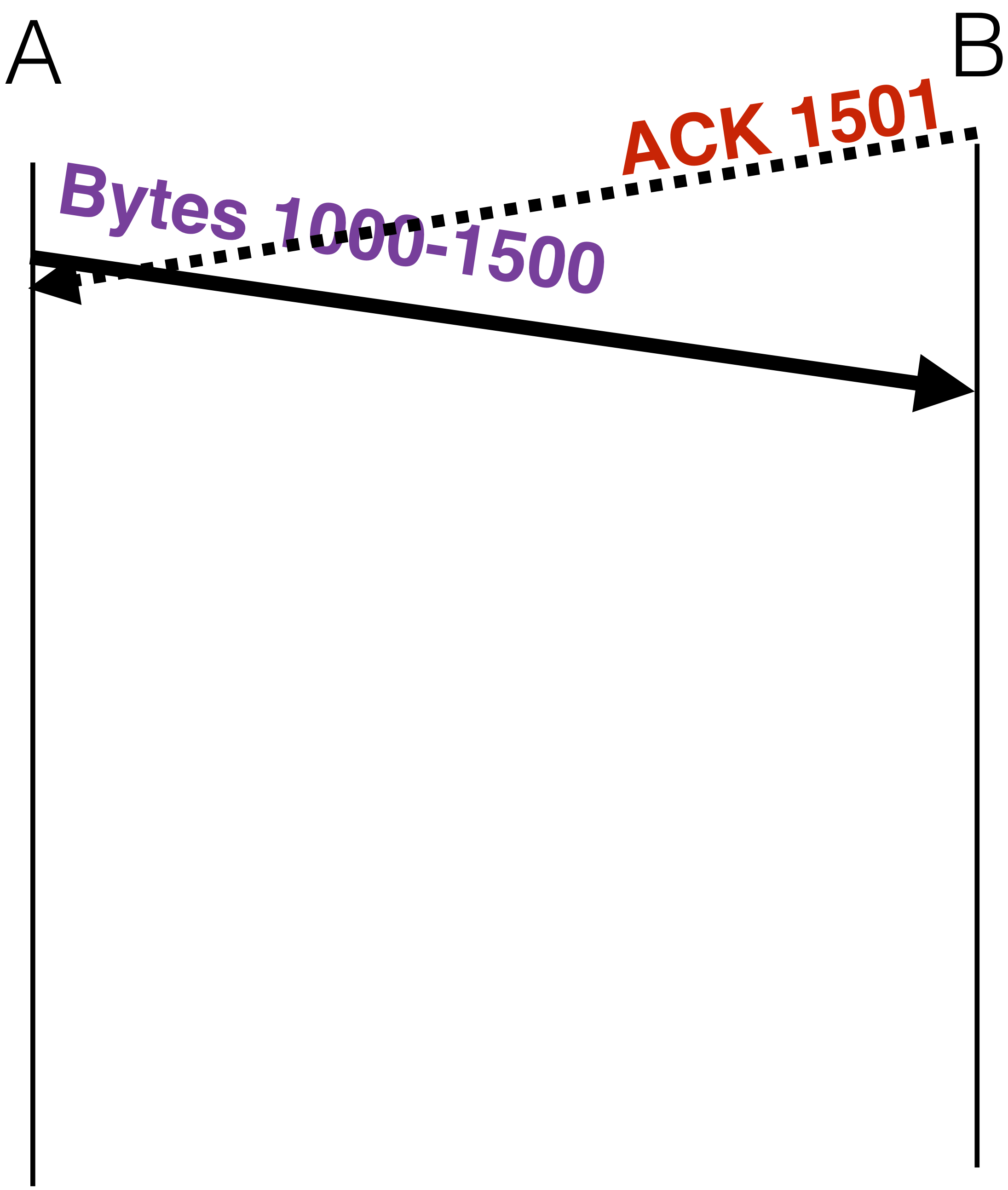

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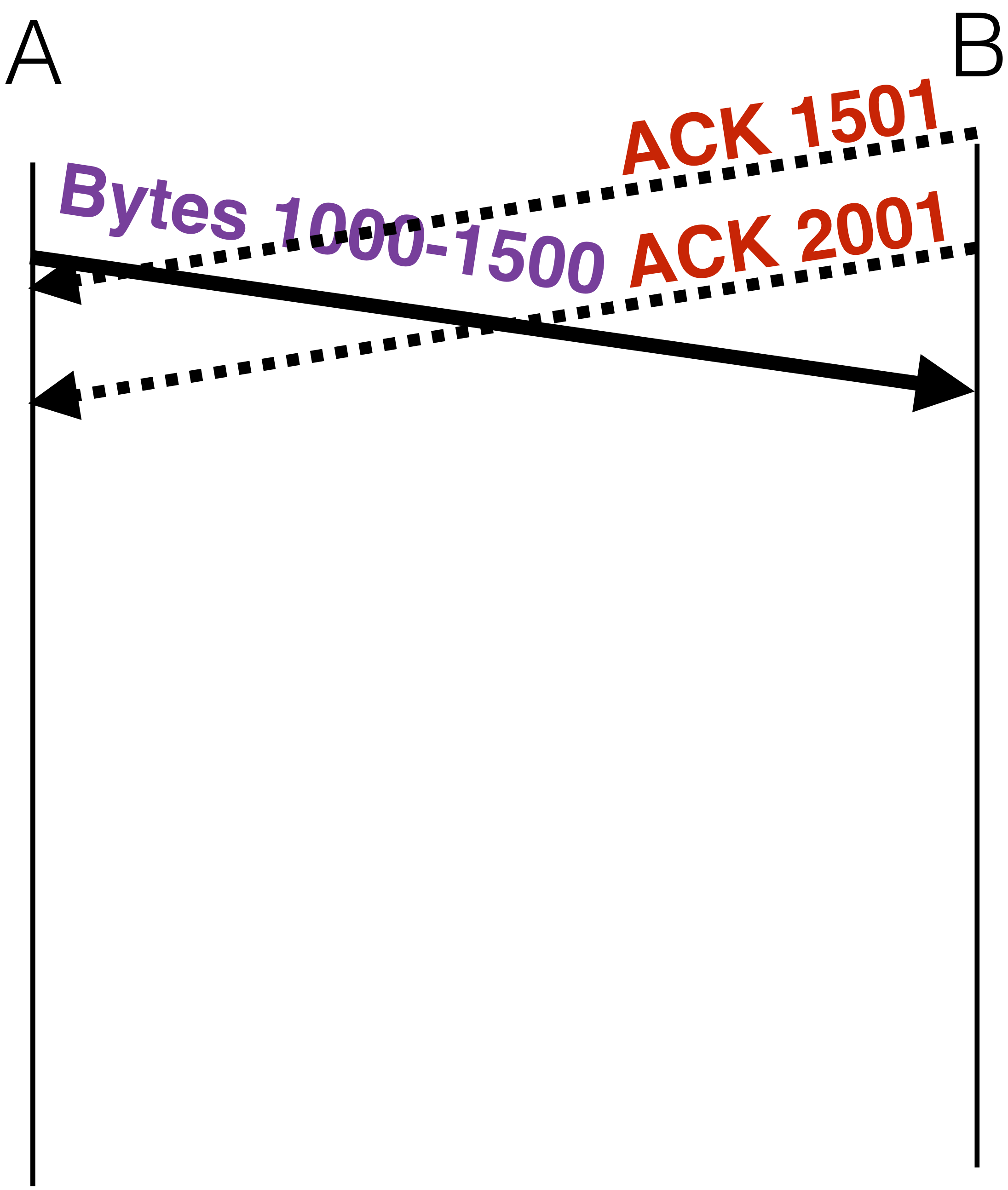

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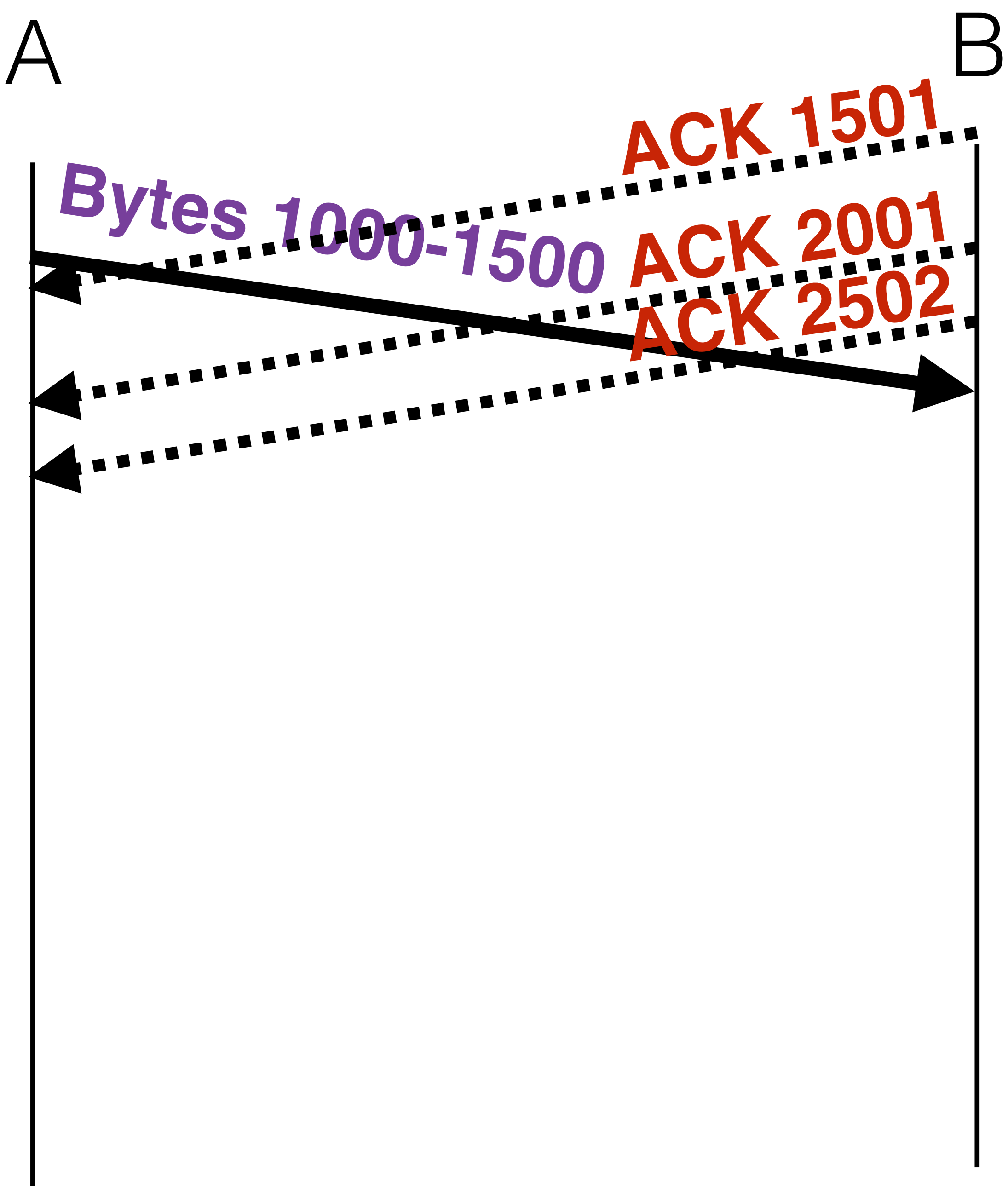

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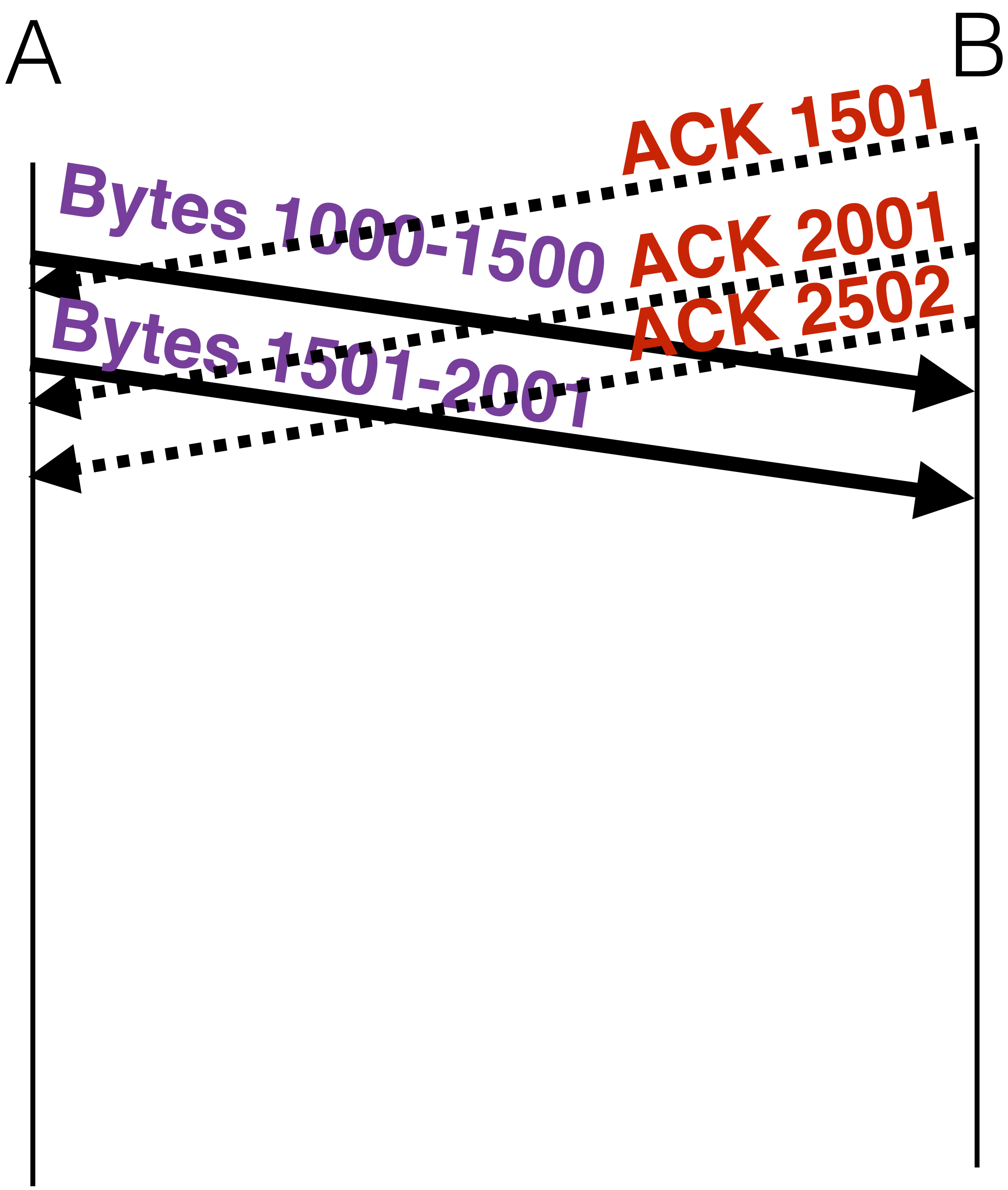

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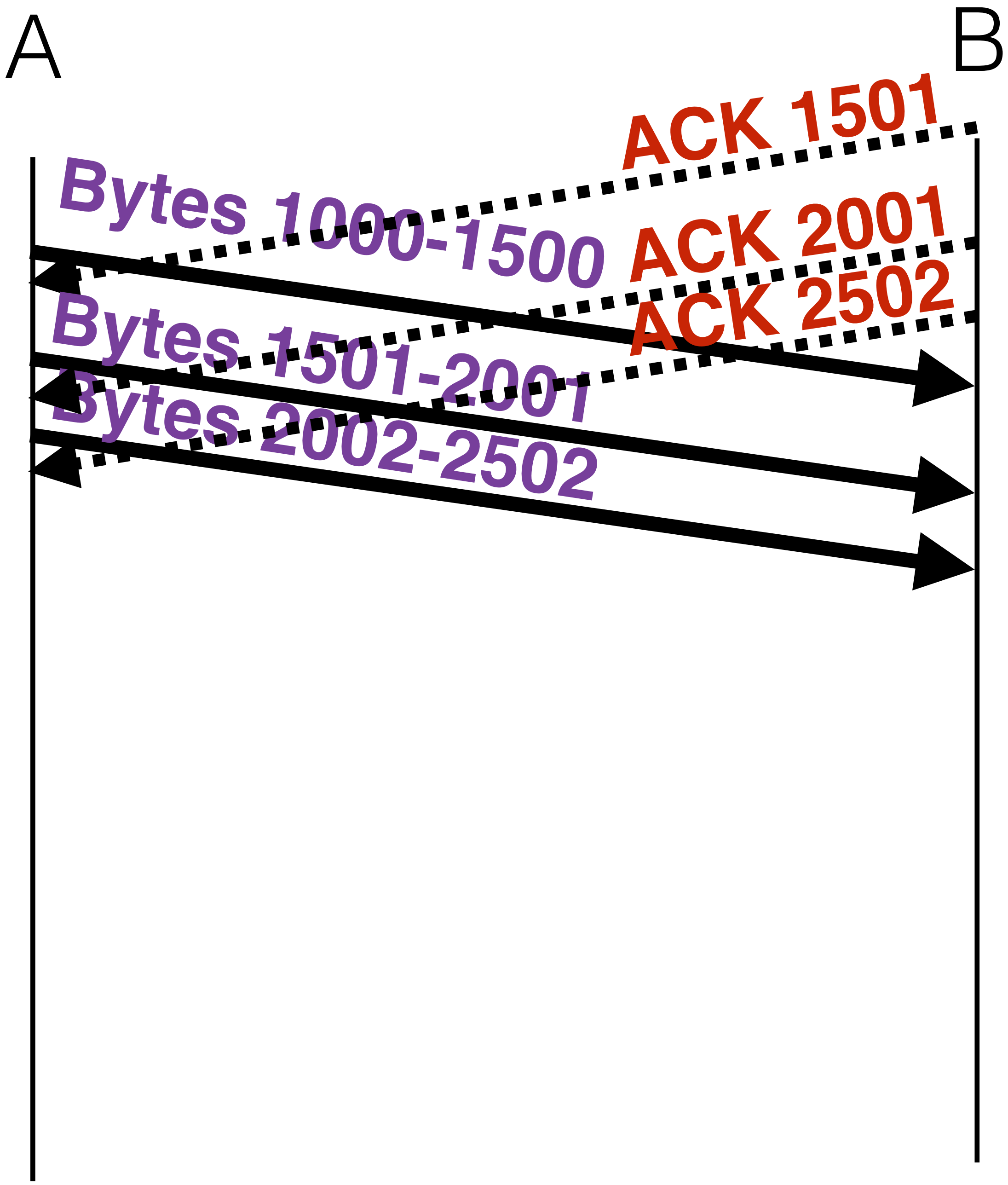

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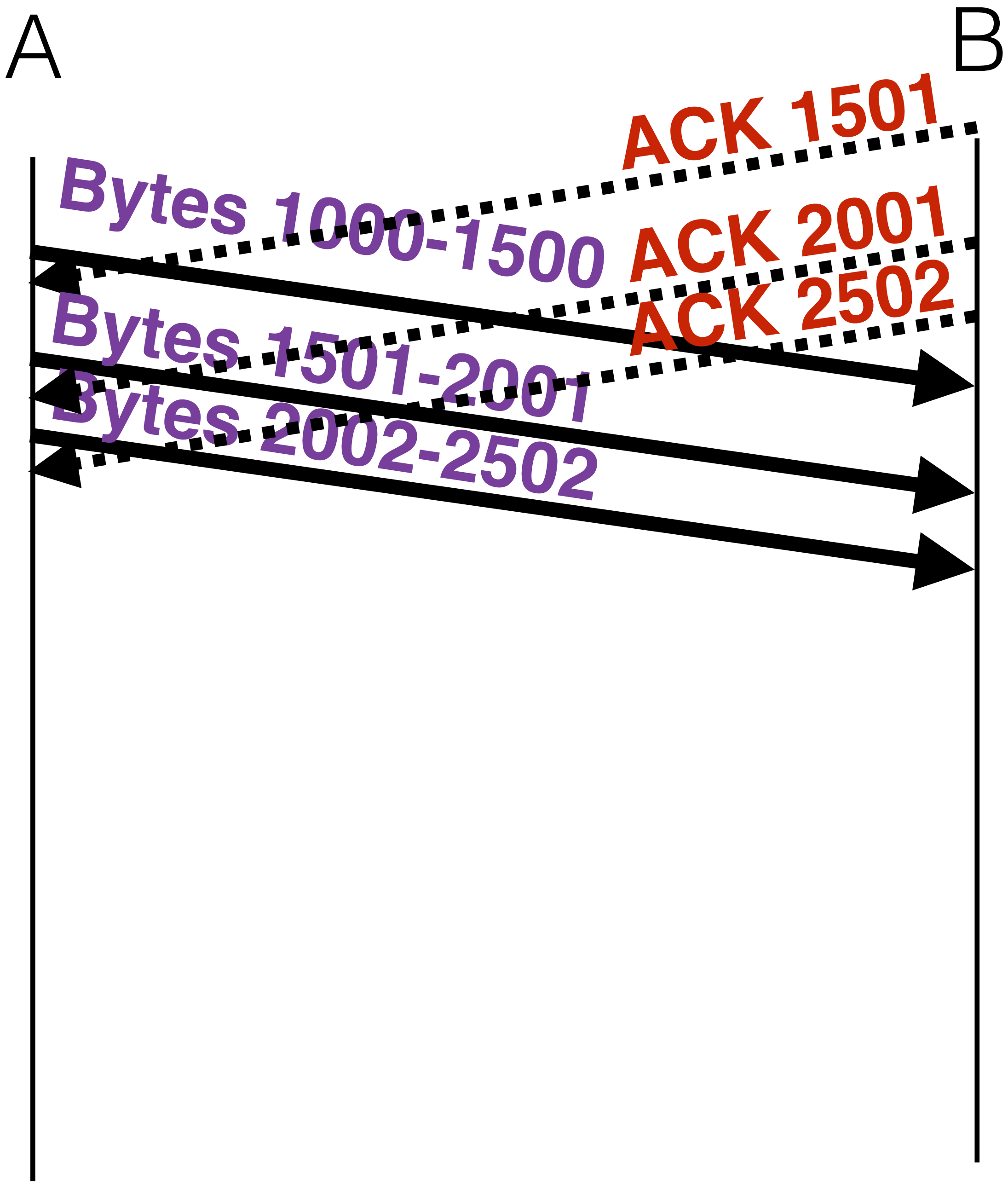

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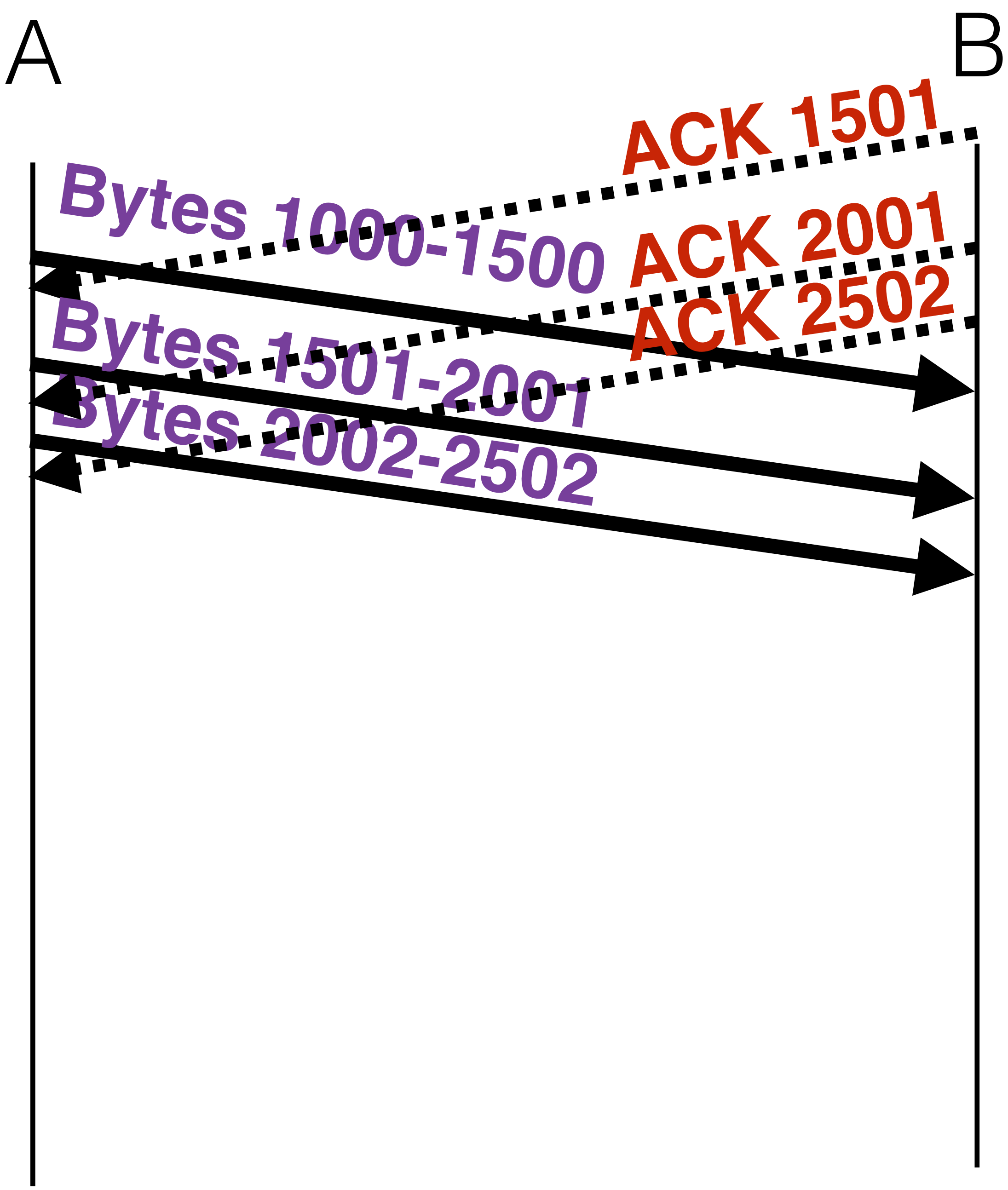

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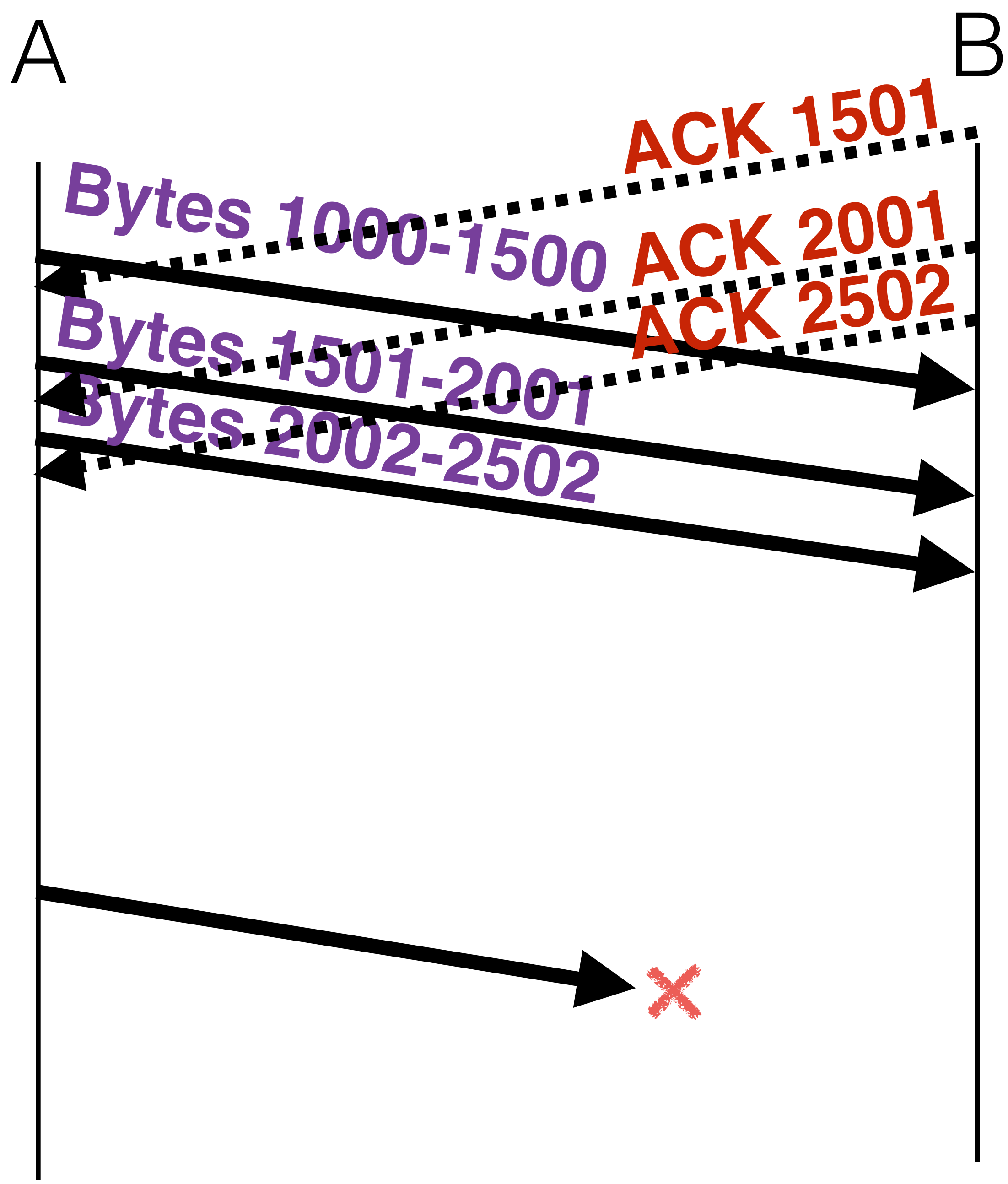

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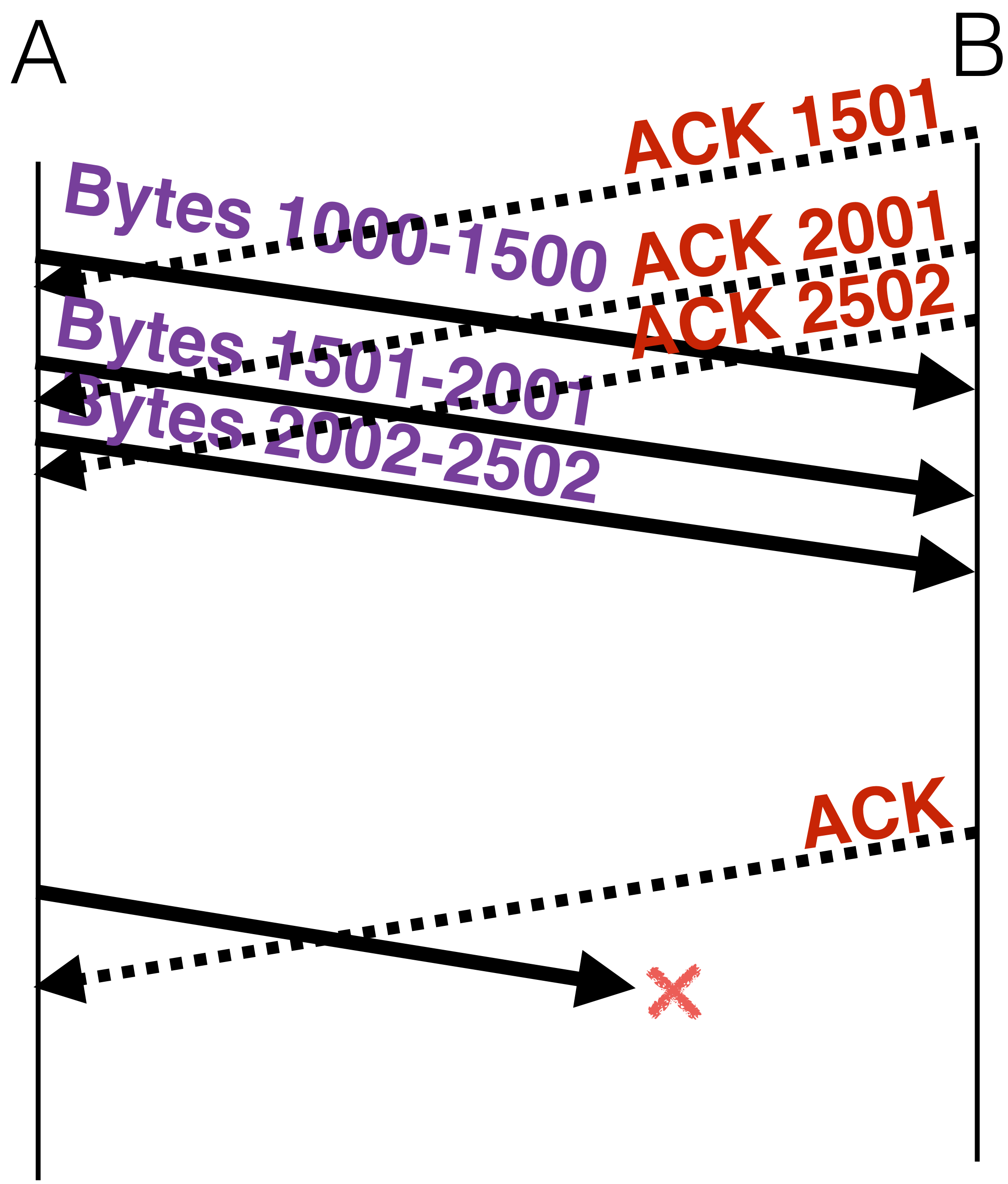

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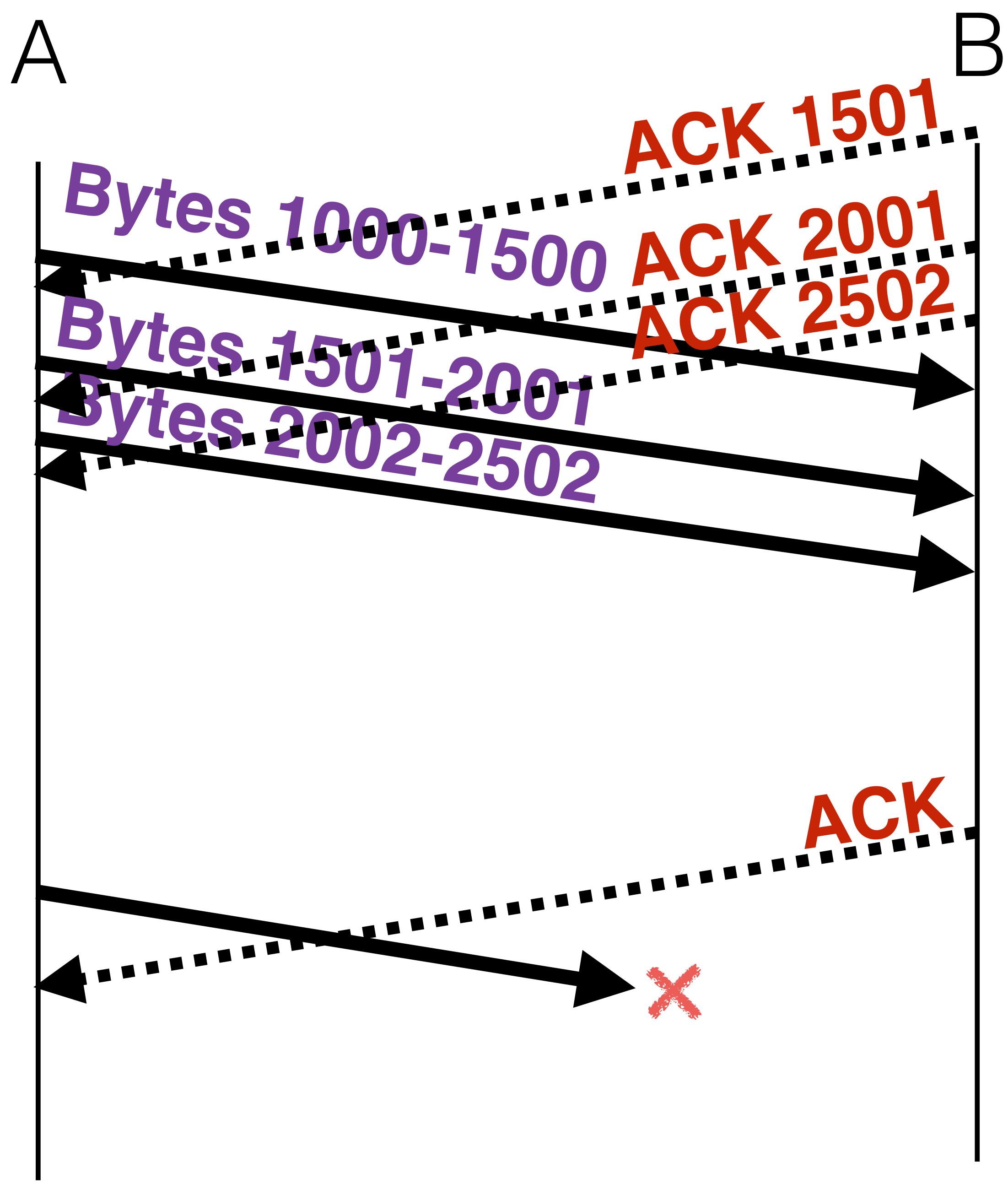

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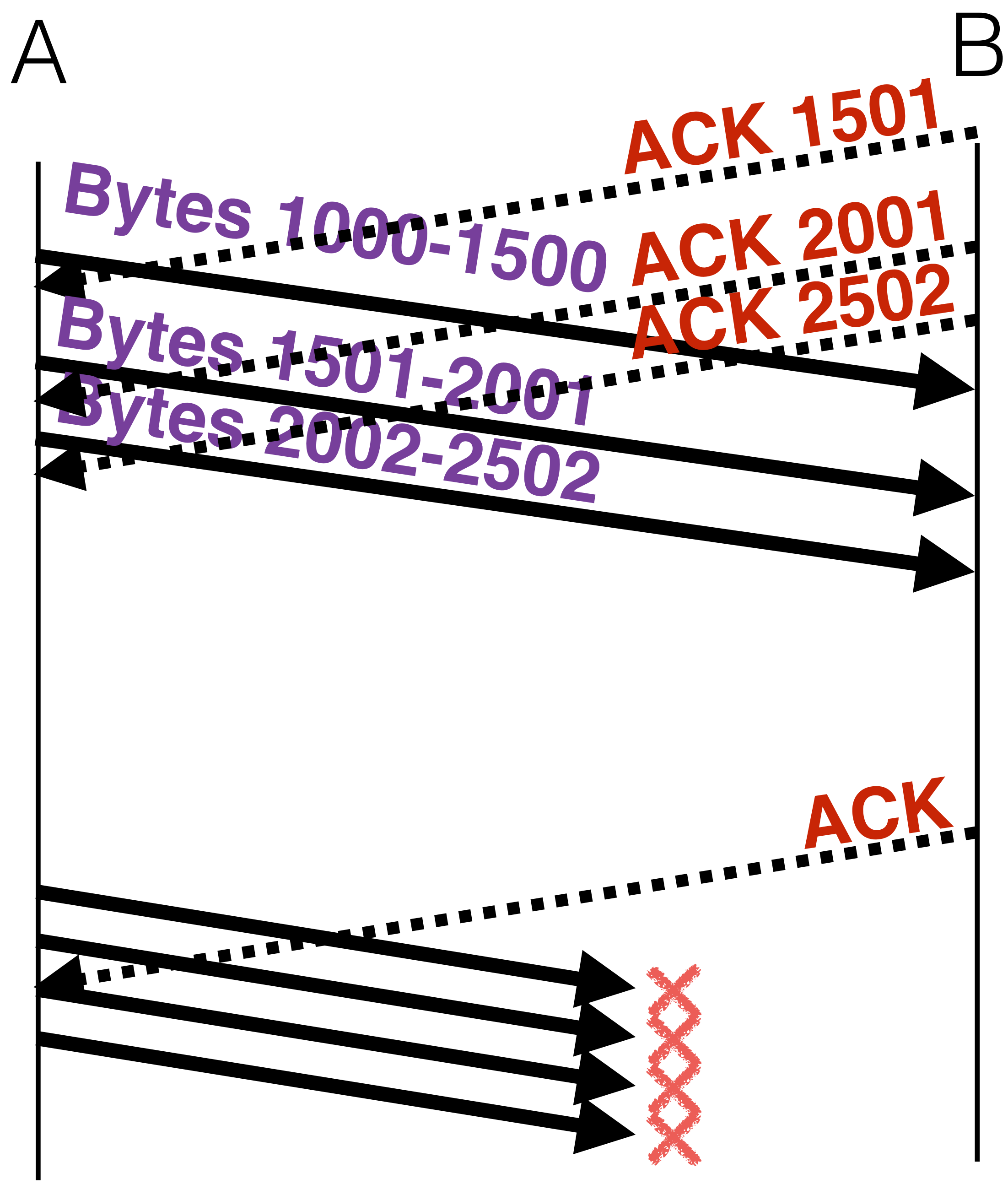

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Amplification

- 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:

Packets sent per ACK × Bytes per packet

$$\frac{\text{Max window size}}{\text{MSS}} \times (14 + 40 + \text{MSS})$$

Ethernet, TCP/IP, Payload

- Max ACKs attacker can send per second:

Opt-ack's amplification factor

- Max bytes sent by victim per ACK:

Packets sent per ACK — Bytes per packet

$$\frac{\text{Max window size}}{\text{MSS}} \times (14 + 40 + \text{MSS})$$

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) ~ **1336x**
- Window scaling lets you increase this by a factor of 2^14
- Window scaling amp factor: ~1336 * 2^14 ~ **22M**
- Using minimum MSS of 88: ~ **32M**

Opt-ack defenses

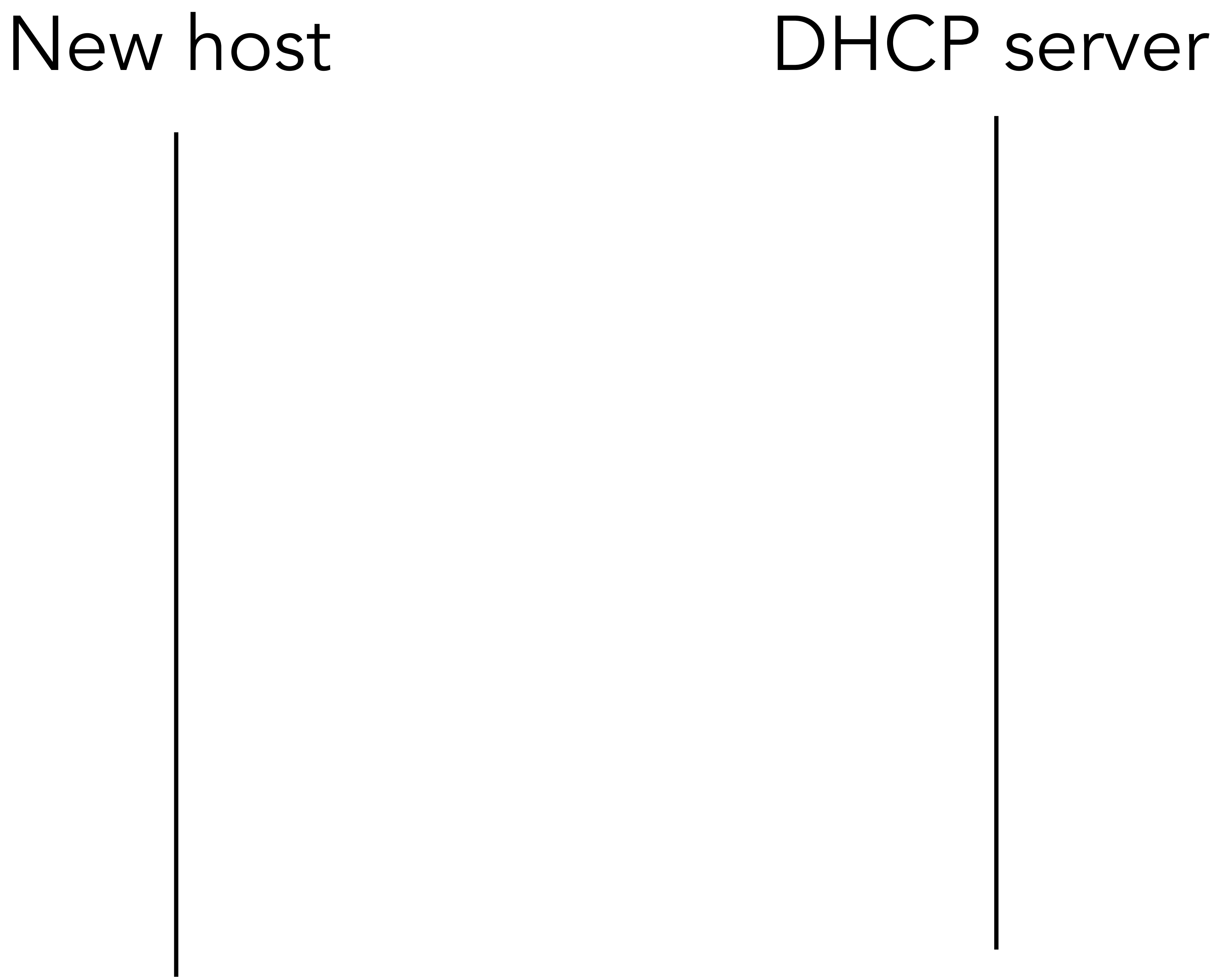
- Is there a way we could defend against opt-ack in a way that is still compatible with existing implementations of TCP?
- An important goal in networking is *incremental deployment*: ideally, we should be able to benefit from a system/modification when even a subset of hosts deploy it.

NAMING

- IP addresses allow global connectivity
- But they're pretty useless for humans!
  - Can't be expected to pick their own IP address
  - Can't be expected to remember another's IP address
- **DHCP** : Setting IP addresses
- **DNS** : Mapping a memorable name to a routable IP address

DHCP

DYNAMIC HOST CONFIGURATION PROTOCOL



DHCP

DYNAMIC HOST CONFIGURATION PROTOCOL

New host

DHCP server

Doesn't have an
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Solution: Discover one on the local subnet

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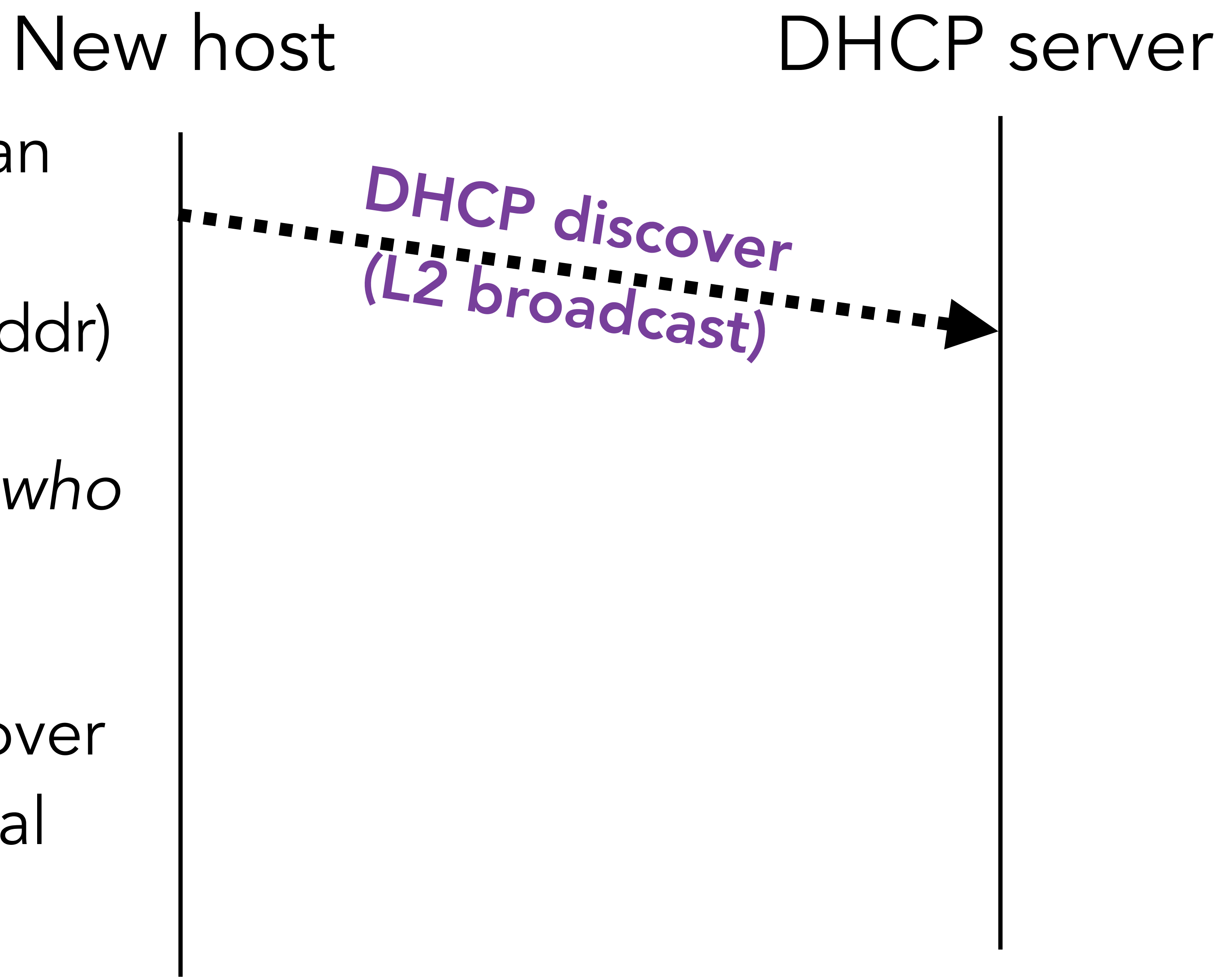

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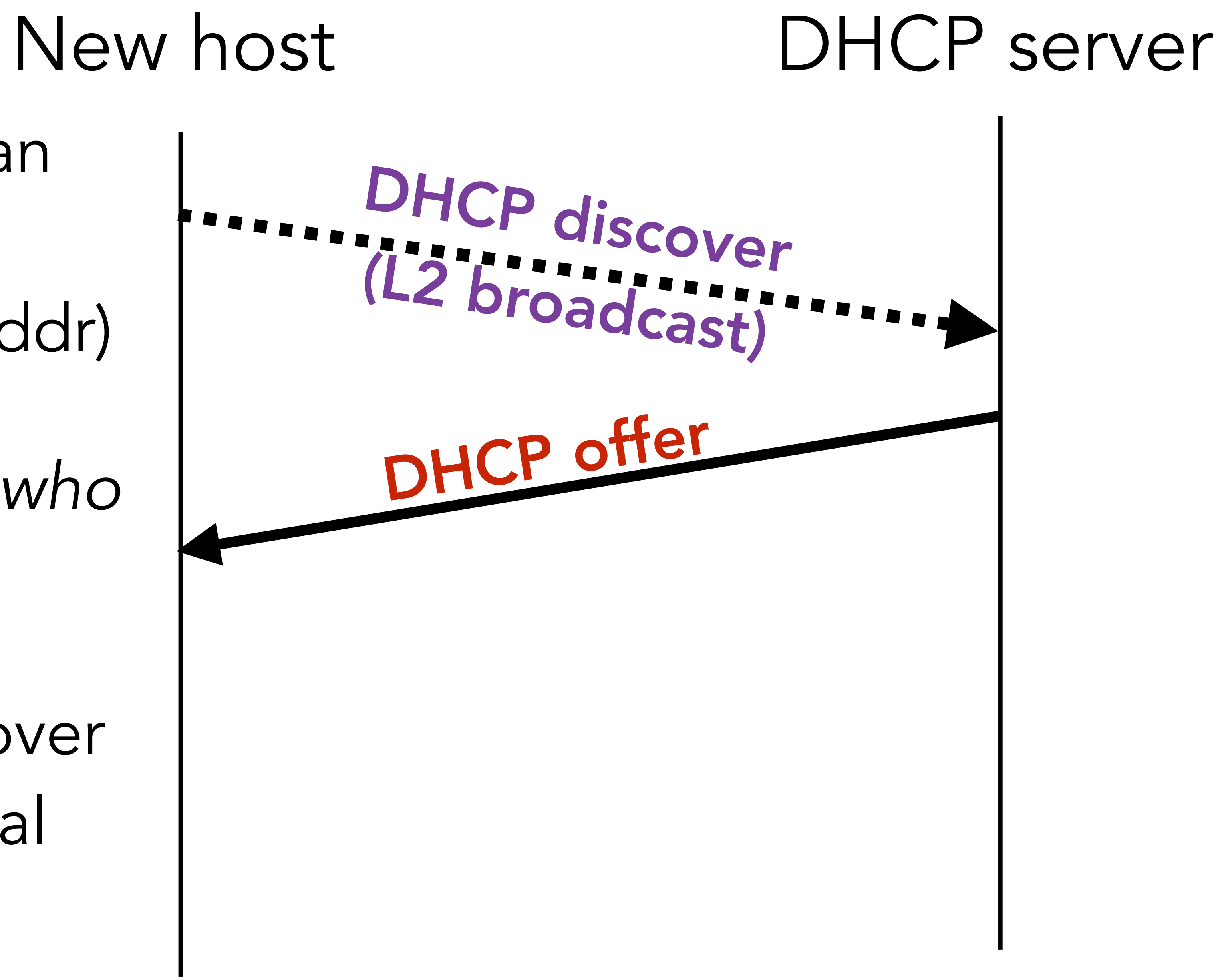

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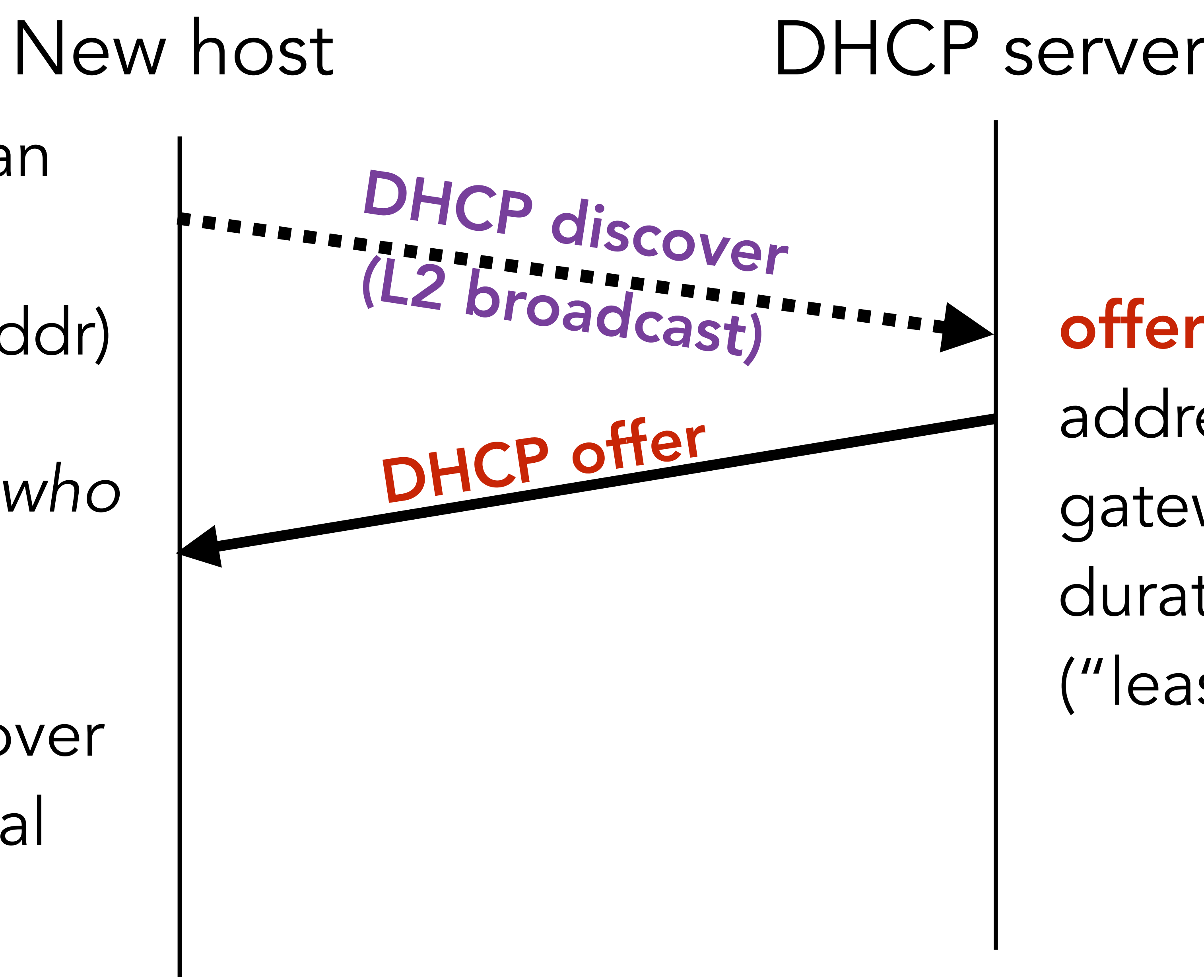

offer includes: IP address, DNS server, gateway router, and duration of this offer (“lease” time)

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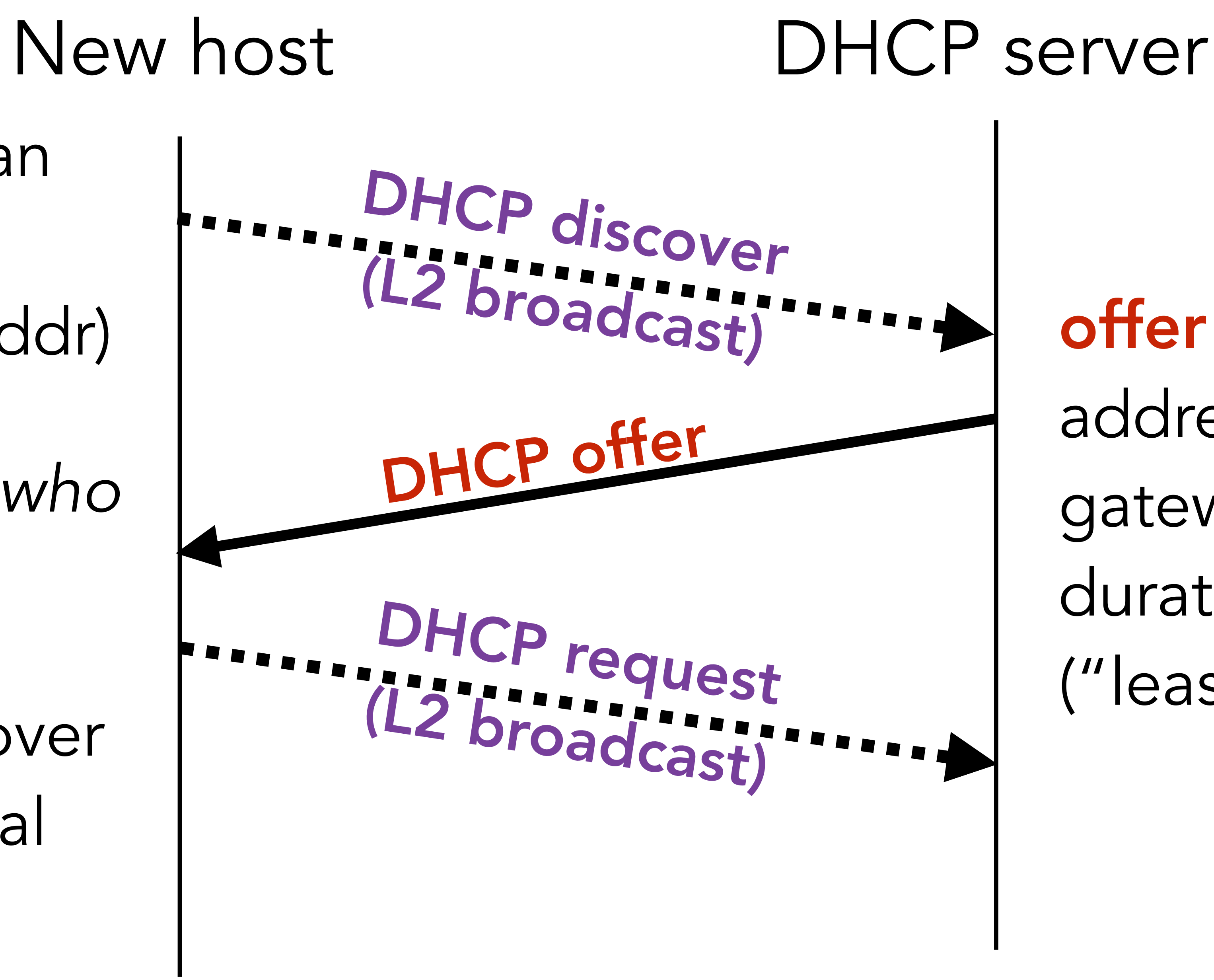

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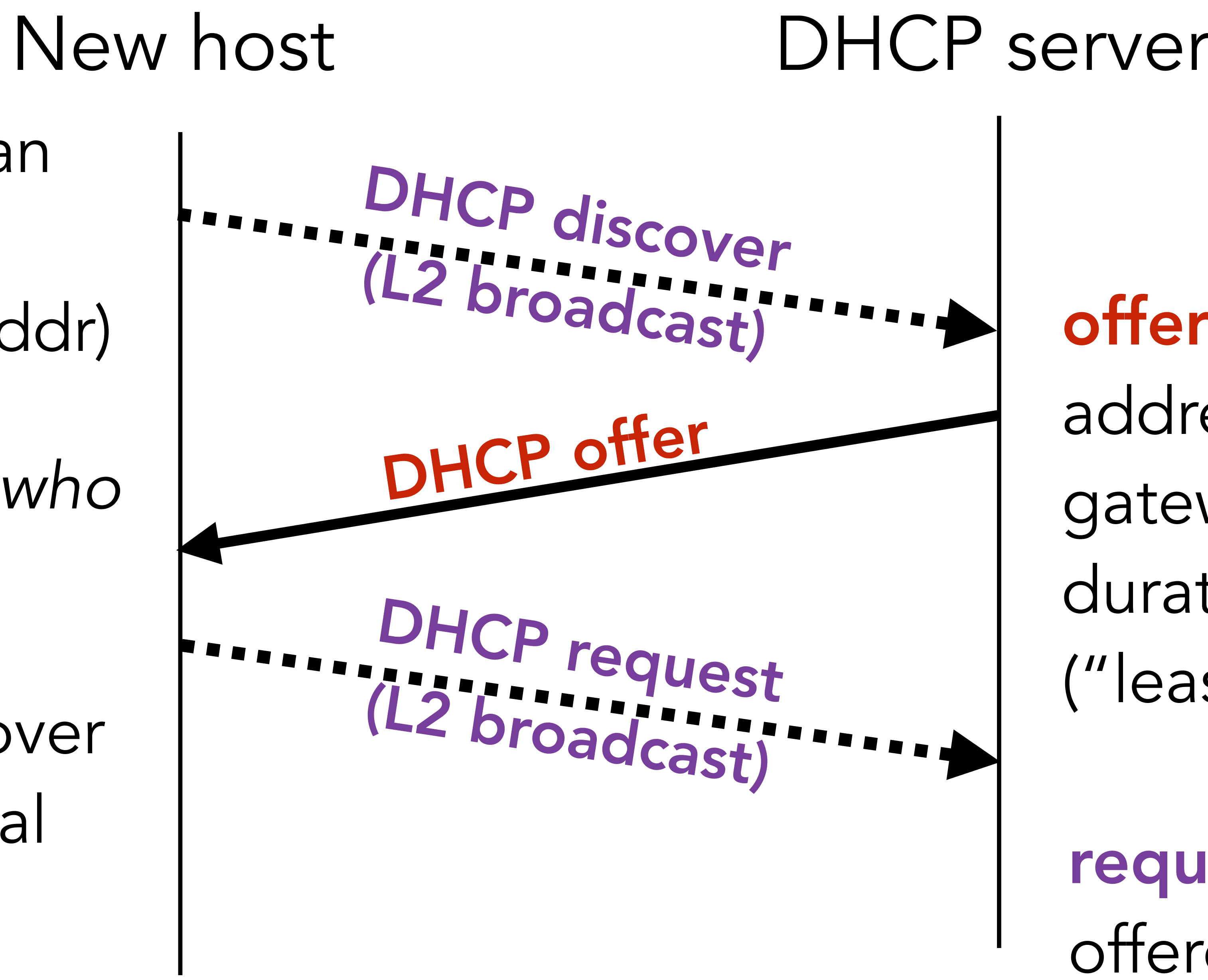

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request asks for the offered IP address

DHCP

DYNAMIC HOST CONFIGURATION PROTOCOL

New host DHCP server

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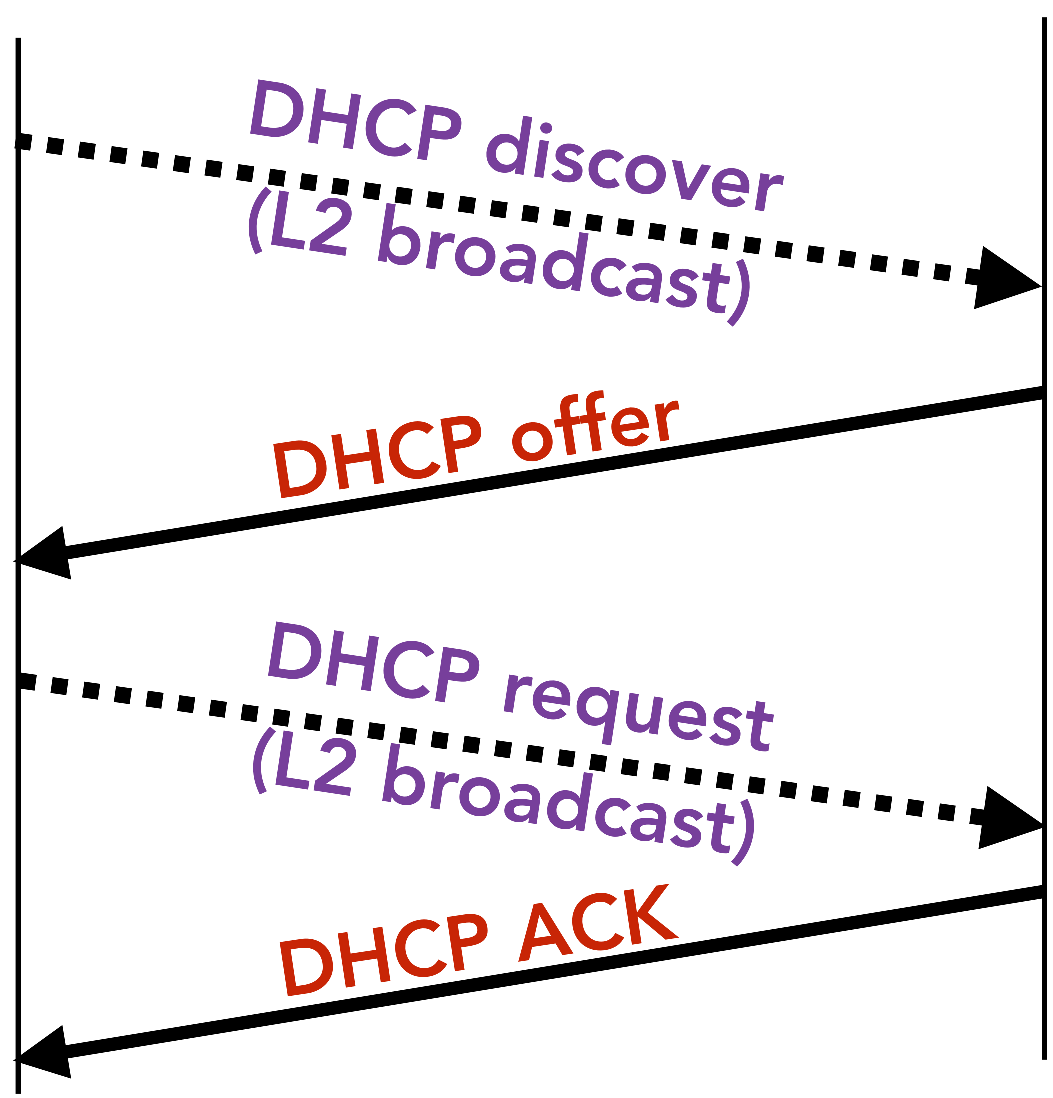
Doesn't know *who* to ask for one

Solution: Discover one on the local subnet



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request asks for the offered IP address

DHCP ATTACKS

- Requests are broadcast: attackers on the same subnet can hear new host's request

- Race the *actual* DHCP server to replace:
  - DNS server
    - Redirect any of a host's lookups ("what IP address should I use when trying to connect to google.com?") to a machine of the attacker's choice
  - Gateway
    - The gateway is where the host sends all of its outgoing traffic (so that the host doesn't have to figure out routes himself)
    - Modify the gateway to intercept all of a user's traffic
    - Then relay it to the gateway (MITM)
    - How could the user detect this?

HOSTNAMES AND IP ADDRESSES

```
gold:~ dml$ ping google.com
PING google.com (74.125.228.65): 56 data bytes
64 bytes from 74.125.228.65: icmp_seq=0 ttl=52 time=22.330 ms
64 bytes from 74.125.228.65: icmp_seq=1 ttl=52 time=6.304 ms
64 bytes from 74.125.228.65: icmp_seq=2 ttl=52 time=5.186 ms
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```

google.com is easy to remember, but not routable

74.125.228.65 is routable

Name resolution:

The process of mapping from one to the other

TERMINOLOGY

- www.cs.umd.edu = "**domain name**"
  - www.cs.umd.edu is a "subdomain" of cs.umd.edu

- Domain names can map to a set of IP addresses

```
gold:~ dml$ dig google.com

; <<>> DiG 9.8.3-P1 <<>> google.com
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 35815
;; flags: qr rd ra; QUERY: 1, ANSWER: 11, AUTHORITY: 0, ADDITIONAL: 0

;; QUESTION SECTION:
;google.com.            IN   A

;; ANSWER SECTION:
google.com.       105  IN   A    74.125.228.70
google.com.       105  IN   A    74.125.228.66
google.com.       105  IN   A    74.125.228.64
google.com.       105  IN   A    74.125.228.69
google.com.       105  IN   A    74.125.228.78
google.com.       105  IN   A    74.125.228.73
google.com.       105  IN   A    74.125.228.68
google.com.       105  IN   A    74.125.228.65
google.com.       105  IN   A    74.125.228.72
```

We'll understand this more in a bit; for now, note that google.com is mapped to many IP addresses

TERMINOLOGY

- www.cs.umd.edu = "**domain name**"
  - www.cs.umd.edu is a "subdomain" of cs.umd.edu

- Domain names can map to a set of IP addresses

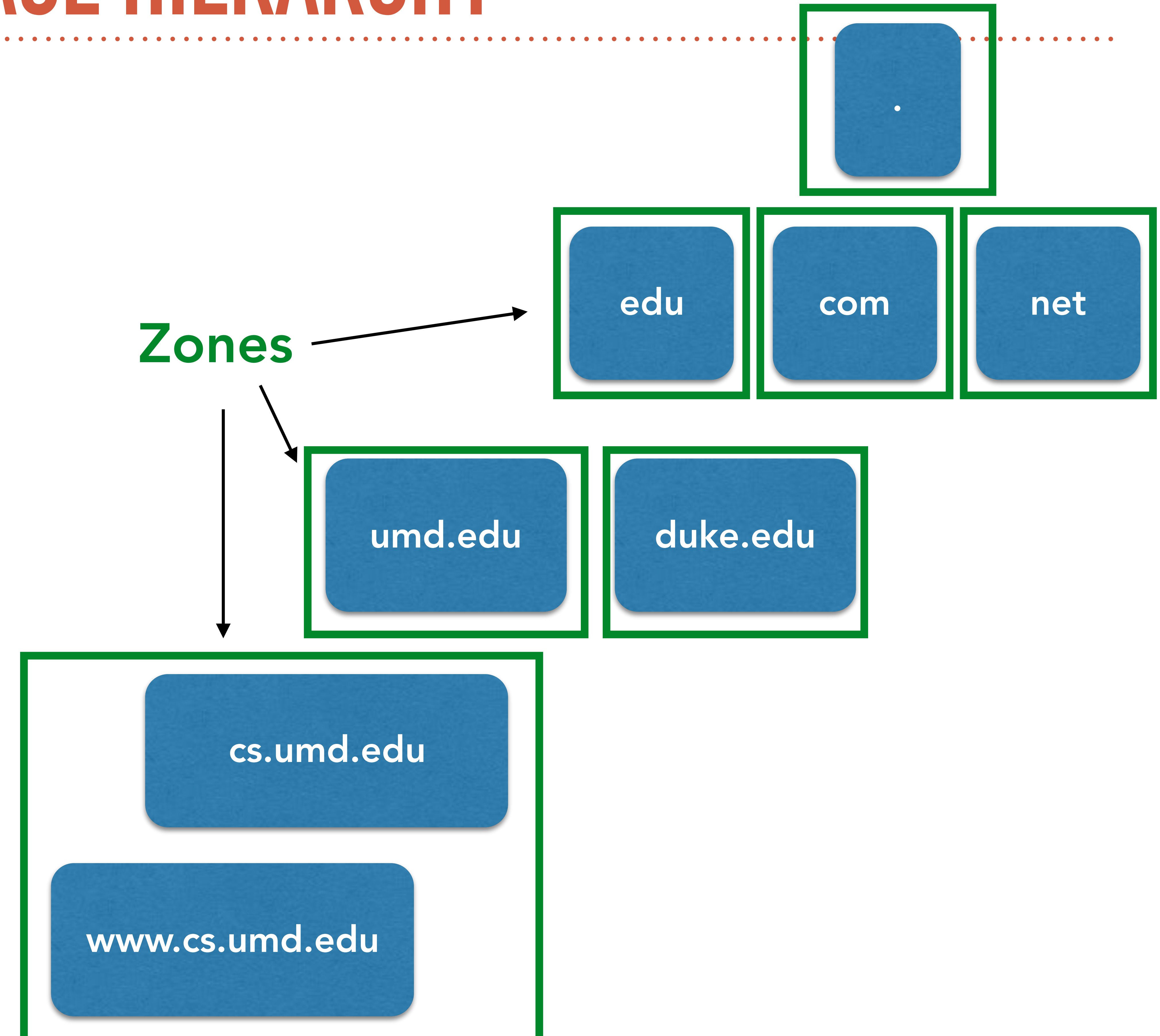
```
gold:~ dml$ dig google.com

; <<>> DiG 9.8.3-P1 <<>> google.com
;; global options: +cmd
;; Got answer:
;; ->>HEADER<<- opcode: QUERY, status: NOERROR, id: 35815
;; flags: qr rd ra; QUERY: 1, ANSWER: 11, AUTHORITY: 0, ADDITIONAL: 0

;; QUESTION SECTION:
;google.com.            IN   A

;; ANSWER SECTION:
google.com.        105  IN   A    74.125.228.70
google.com.        105  IN   A    74.125.228.66
google.com.        105  IN   A    74.125.228.64
google.com.        105  IN   A    74.125.228.69
google.com.        105  IN   A    74.125.228.78
google.com.        105  IN   A    74.125.228.73
google.com.        105  IN   A    74.125.228.68
google.com.        105  IN   A    74.125.228.65
google.com.        105  IN   A    74.125.228.72
```

We'll understand this more in a bit; for now, note that google.com is mapped to many IP addresses

TERMINOLOGY

- “**zone**” = a portion of the DNS namespace, divided up for administrative reasons
  - Think of it like a collection of hostname/IP address pairs that happen to be lumped together
    - www.google.com, mail.google.com, dev.google.com, …
- Subdomains do not need to be in the same zone
  - Allows the owner of one zone (umd.edu) to delegate responsibility to another (cs.umd.edu)

NAMESPACE HIERARCHY



TERMINOLOGY

- "**Nameserver**" = A piece of code that answers queries of the form "What is the IP address for foo.bar.com?"
  - Every zone must run ≥2 nameservers
  - Several very common nameserver implementations: BIND, PowerDNS (more popular in Europe)
- "**Authoritative nameserver**":
  - Every zone has to maintain a file that maps IP addresses and hostnames ("www.cs.umd.edu is 128.8.127.3")
  - One of the name servers in the zone has the *master* copy of this file. It is the authority on the mapping.

TERMINOLOGY

- “**Resolver**” - while name servers *answer* queries, resolvers *ask* queries.
- Every OS has a resolver. Typically small and pretty dumb. All it typically does it forward the query to a local…
- “**Recursive nameserver**” - a nameserver which will do the heavy lifting, issuing queries on behalf of the client resolver until an authoritative answer returns.
- Prevalence
  - There is almost always a *local* (private) recursive name server
  - But very rare for name servers to support recursive queries otherwise

TERMINOLOGY

- “**Record**” (or “resource record”) = usually think of it as a mapping between hostname and IP address
- But more generally, it can map virtually anything to virtually anything
- Many record types:
  - (**A**)ddress records (IP <-> hostname)
  - Mail server (**MX**, mail exchanger)
  - SOA (start of authority, to delineate different zones)
  - Others for DNSSEC to be able to share keys
- Records are the unit of information

TERMINOLOGY

Nameservers within a zone must be able to give:

- **Authoritative answers (A)** for hostnames in that zone
  - The umd.edu zone's nameservers must be able to tell us what the IP address for umd.edu is

"A" record: umd.edu = 54.84.241.99

54.84.241.99 is a valid IP address for umd.edu

TERMINOLOGY

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"A" record: umd.edu = 54.84.241.99

54.84.241.99 is a valid IP address for umd.edu

- Pointers to **name servers (NS)** who host zones in its subdomains
  - The umd.edu zone's nameservers must be able to tell us what the name and IP address of the cs.umd.edu zone's nameservers

"NS" record: umd.edu = ipa01.cs.umd.edu.

Ask ipa01.cs.umd.edu for all cs.umd.edu subdomains

DNS

Domain Name Service at a very high level

Requesting host

What is an IP address for cs.umd.edu?

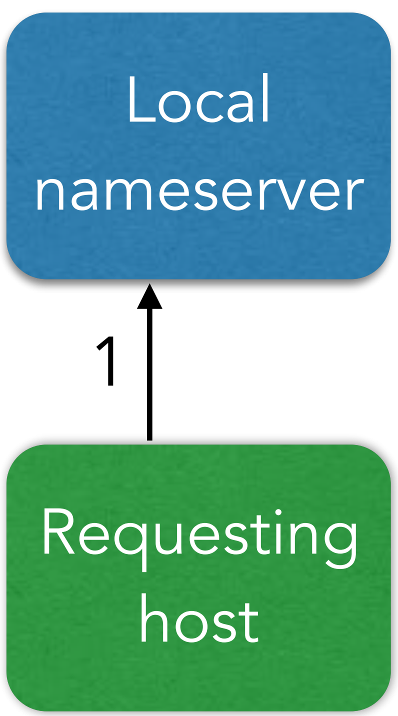
DNS

Domain Name Service at a very high level

What is an IP address for cs.umd.edu?

DNS

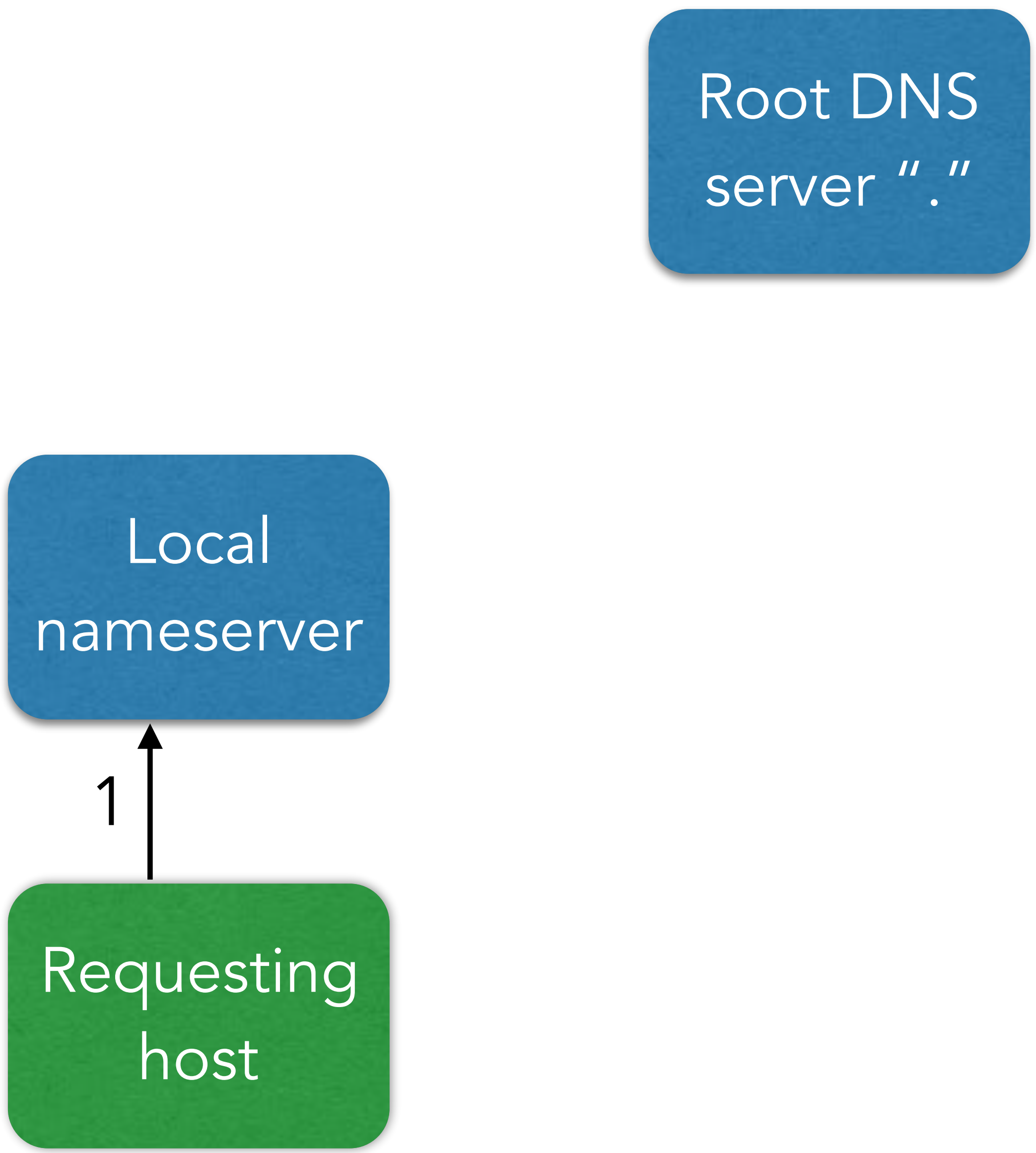
Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

DNS

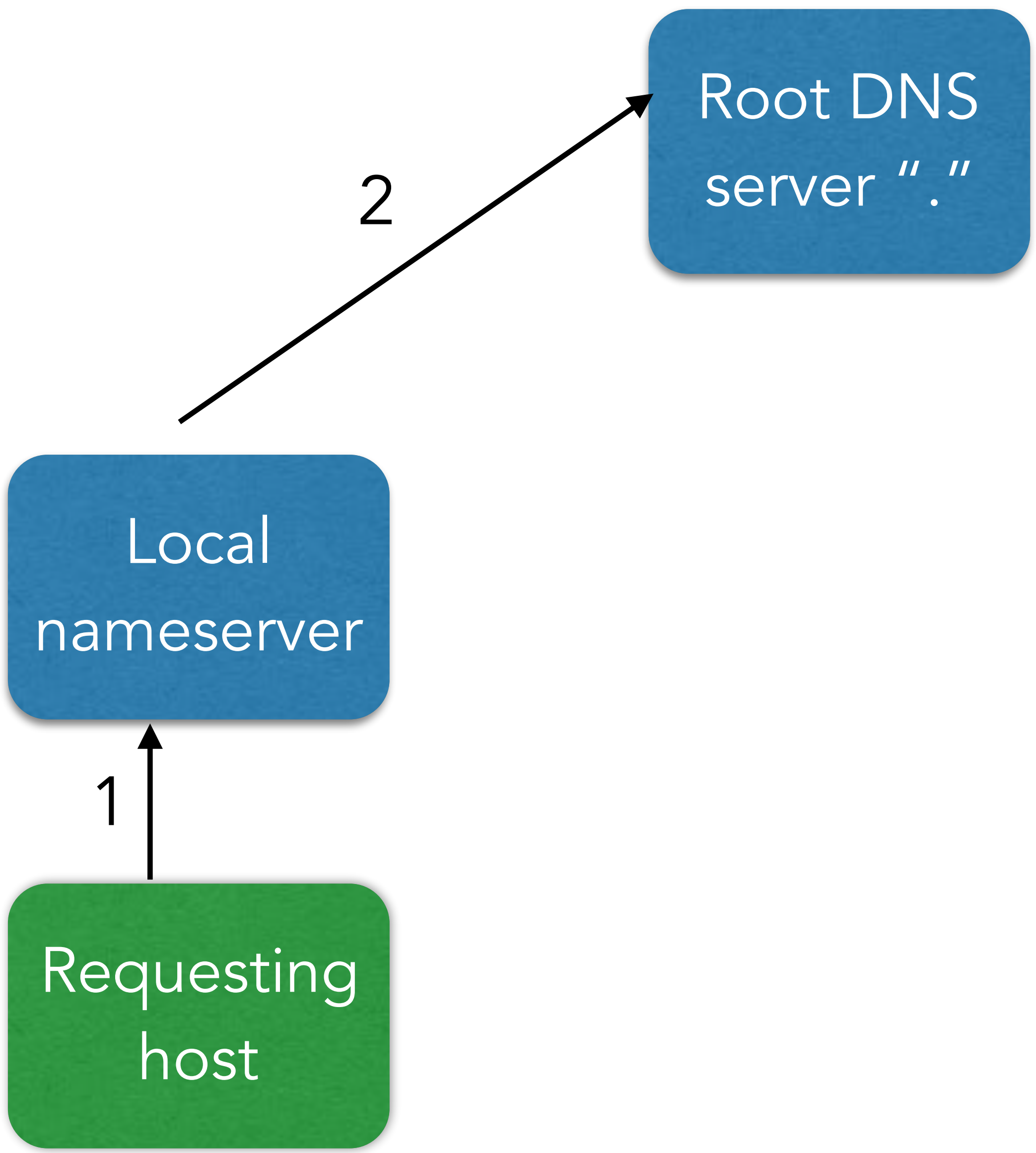
Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

DNS

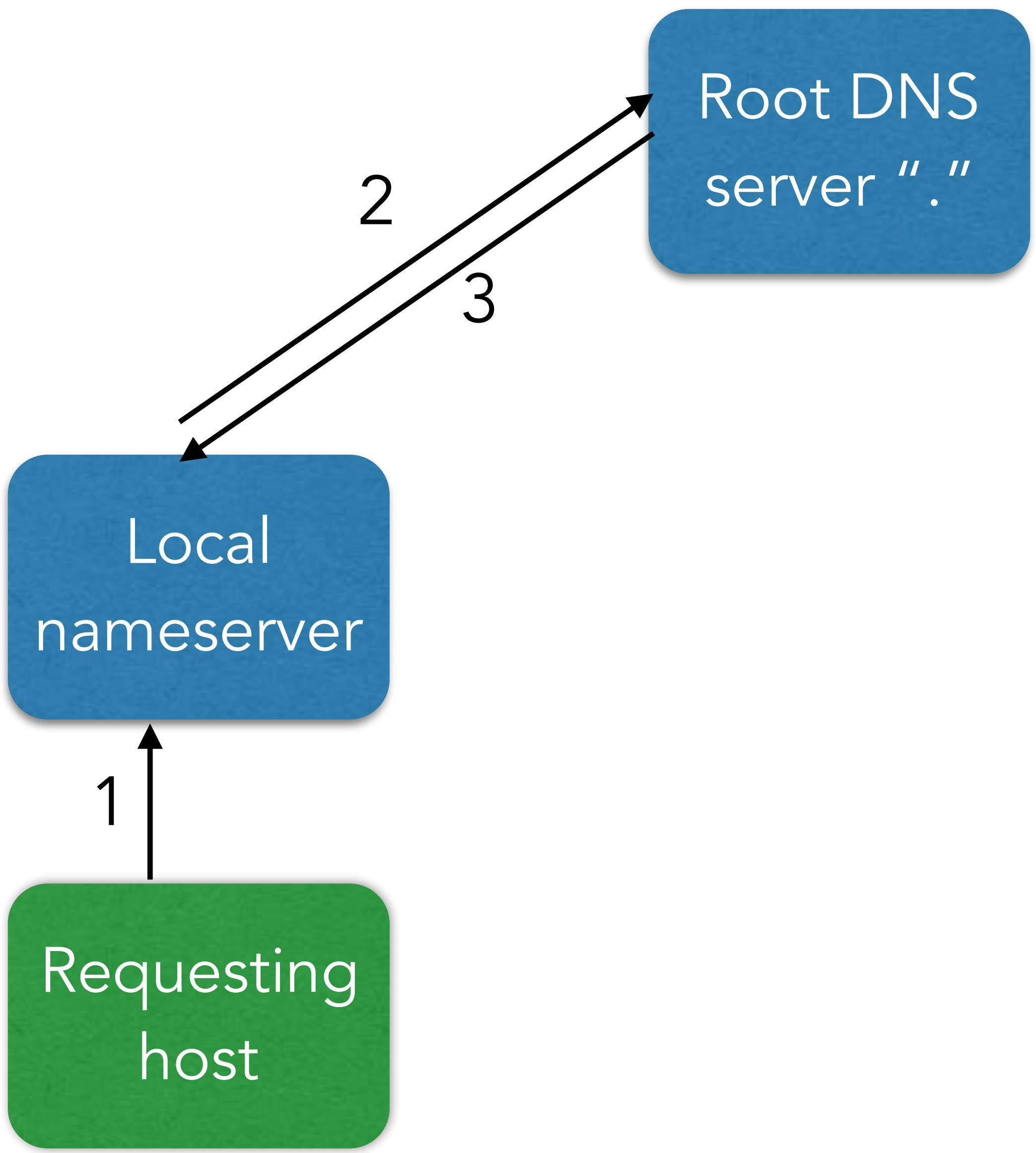
Domain Name Service at a very high level



What is an IP address
for cs.umd.edu?

DNS

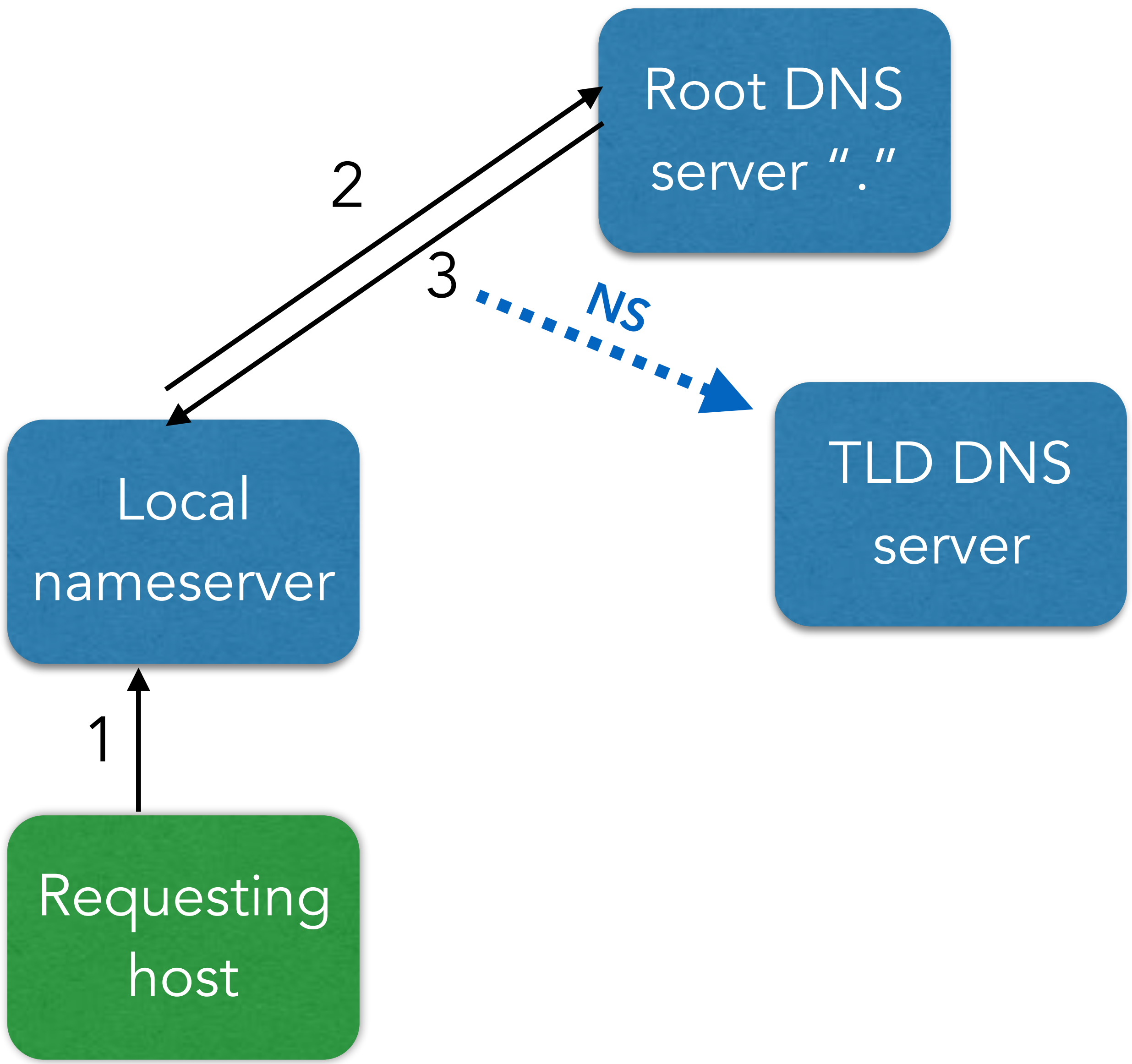
Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

DNS

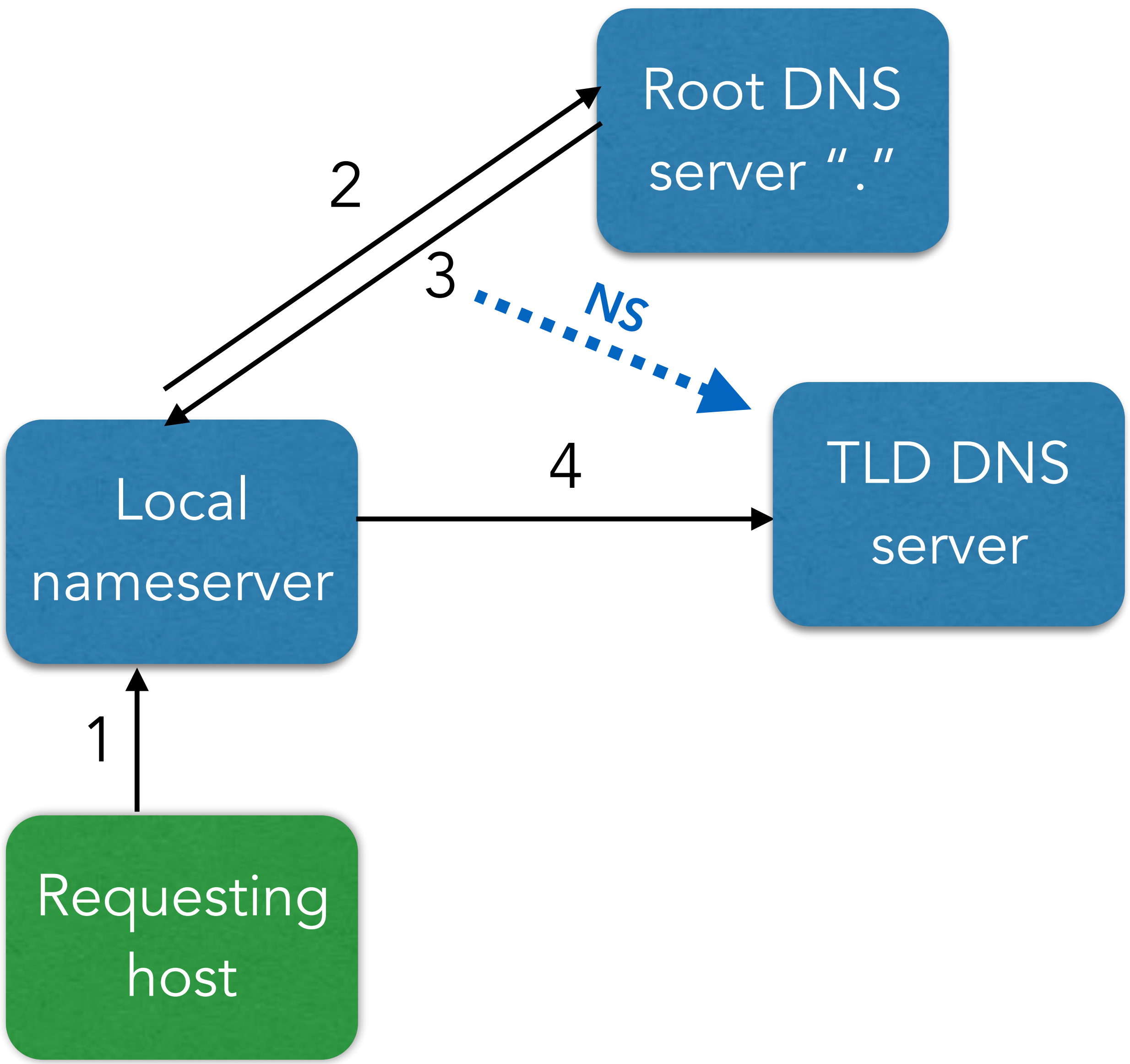
Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

DNS

Domain Name Service at a very high level



What is an IP address
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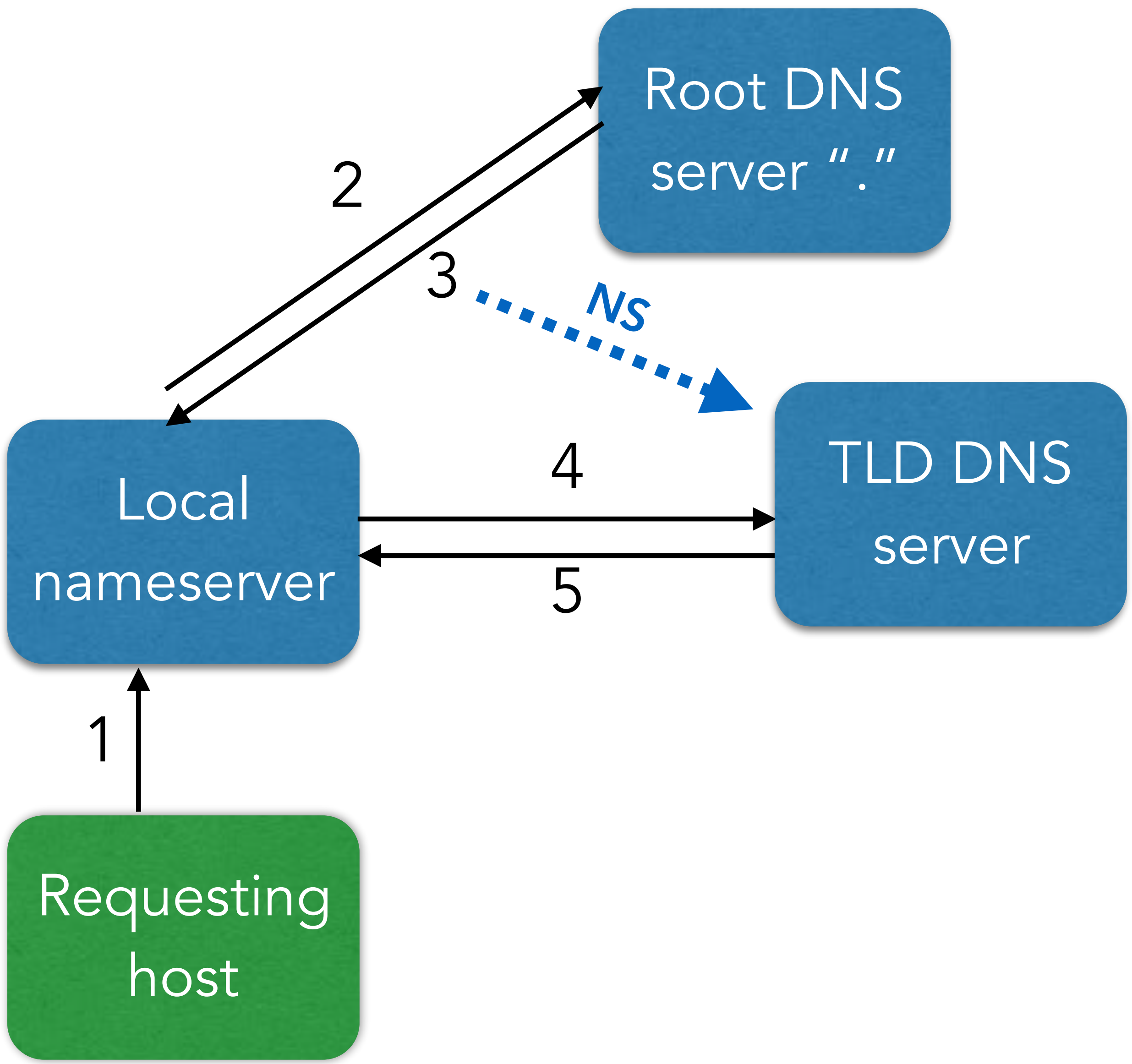
DNS

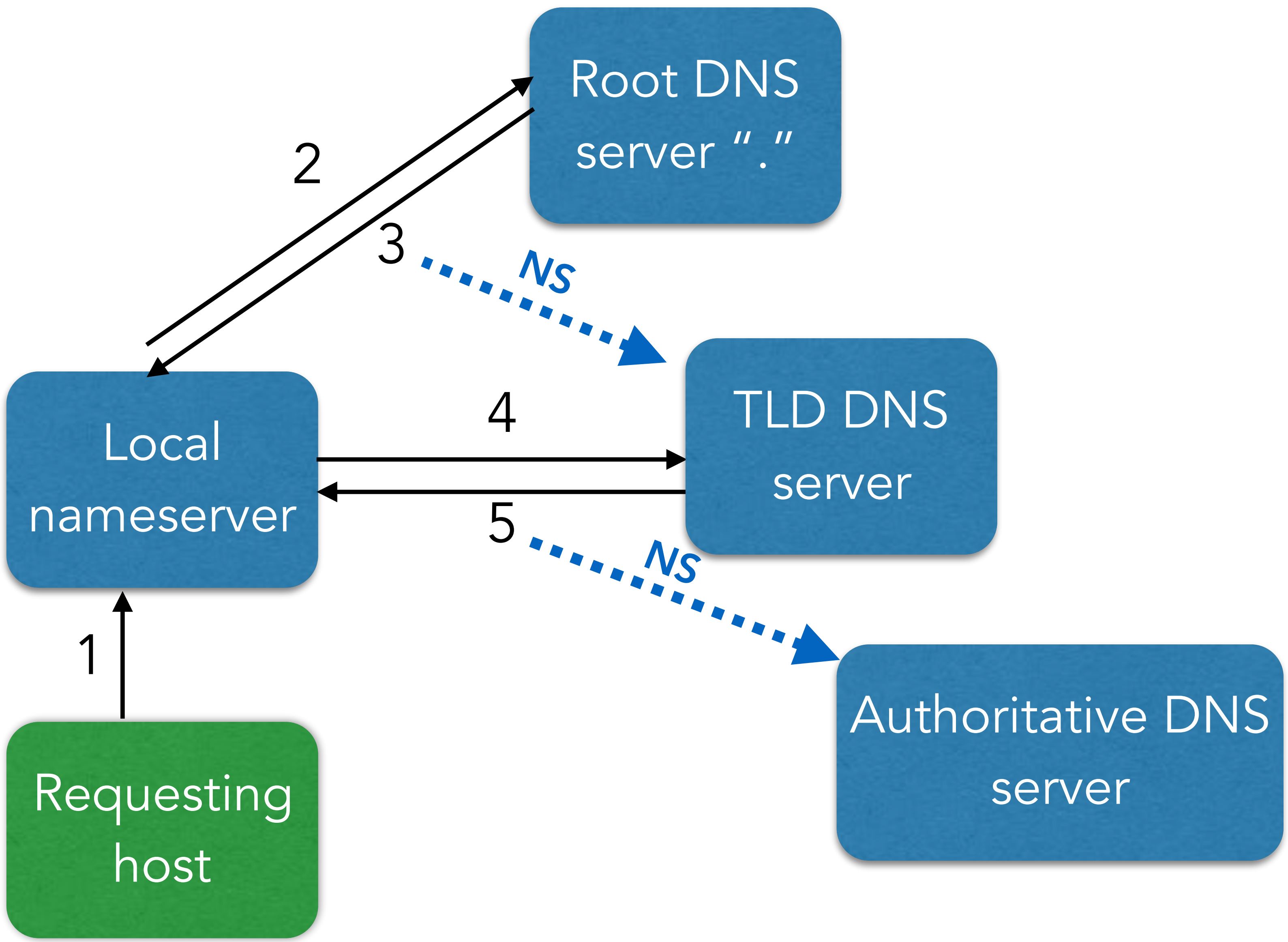
Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

DNS

Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

DNS

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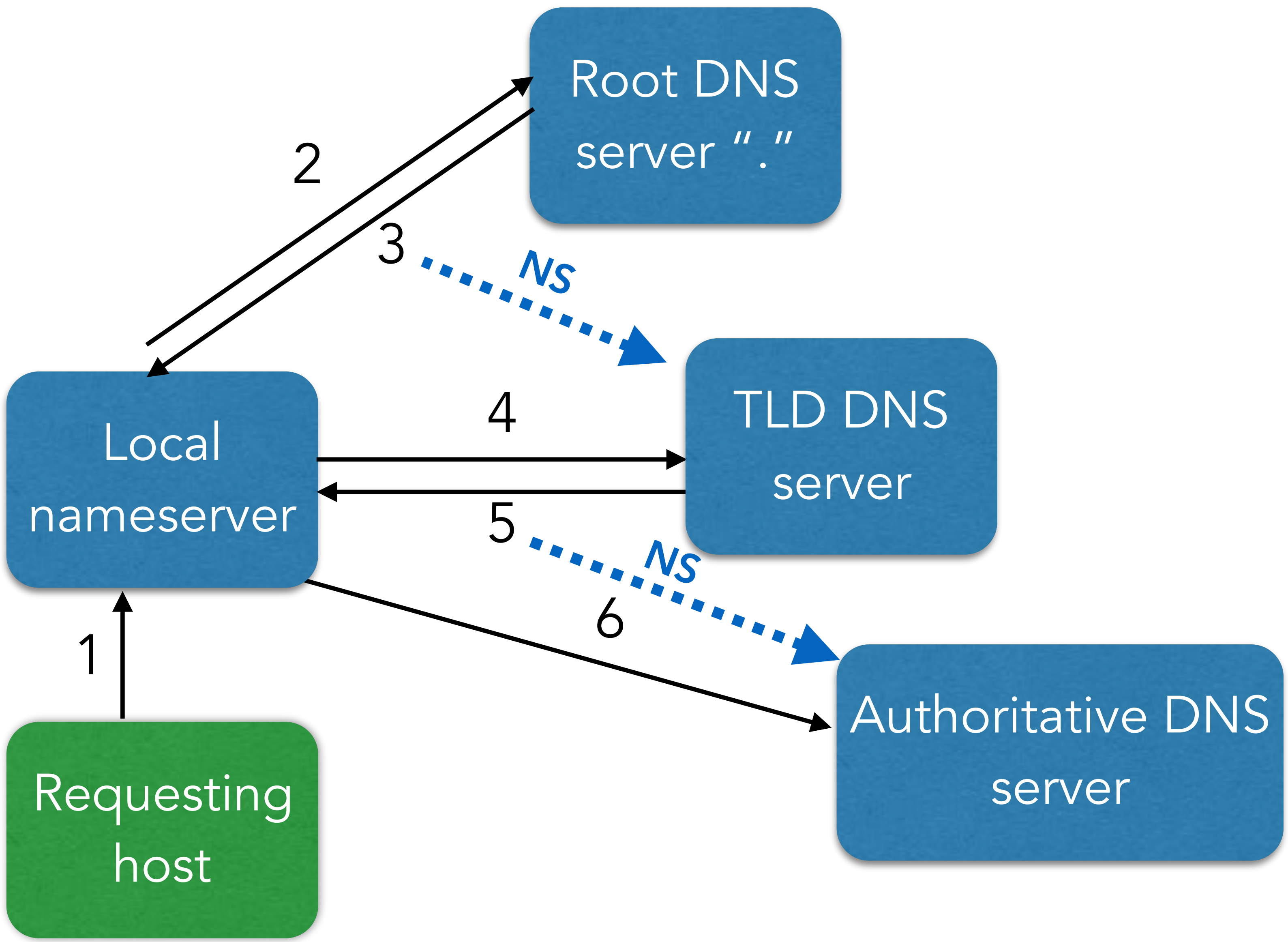

What is an IP address for cs.umd.edu?

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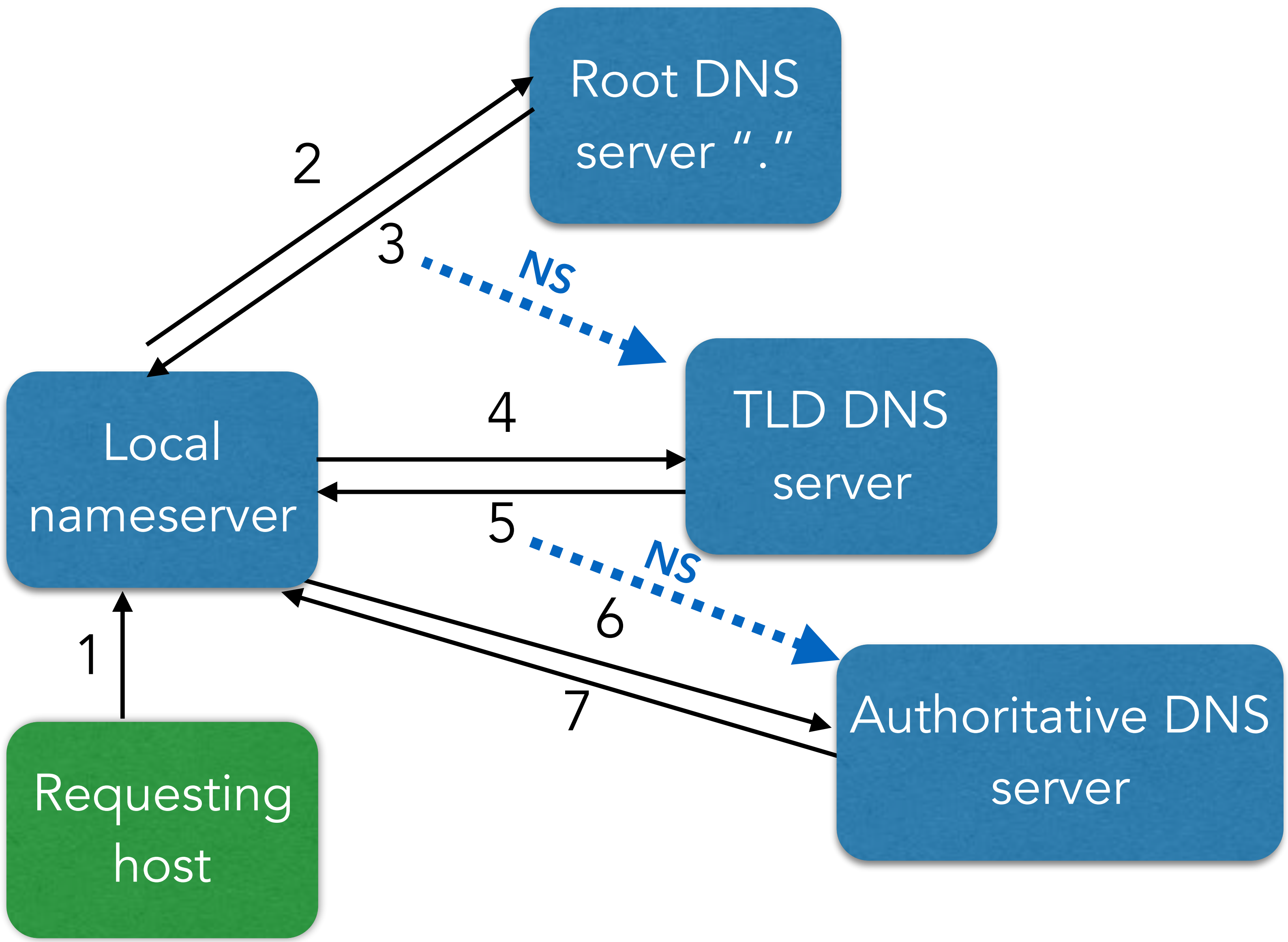
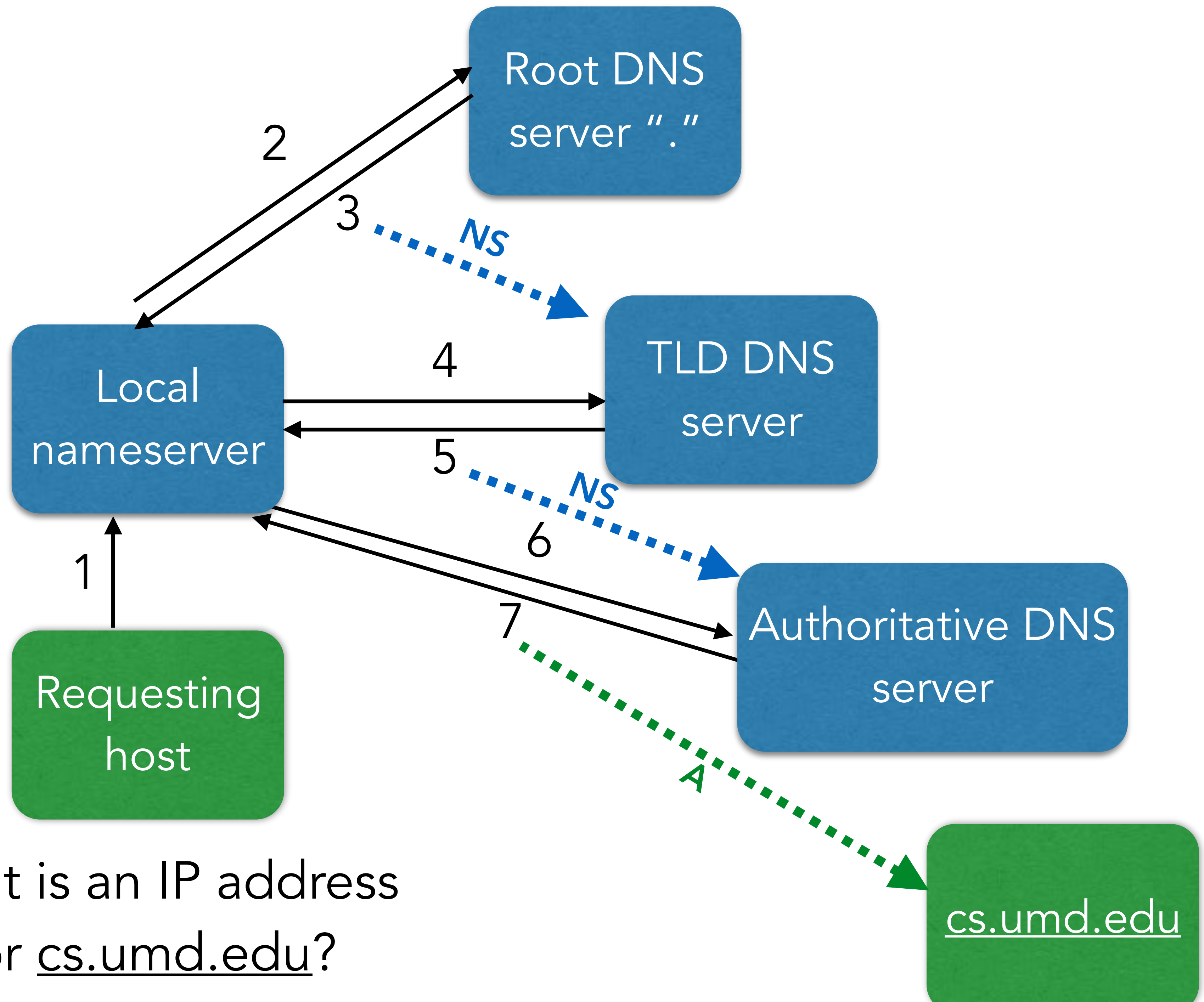
Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

DNS

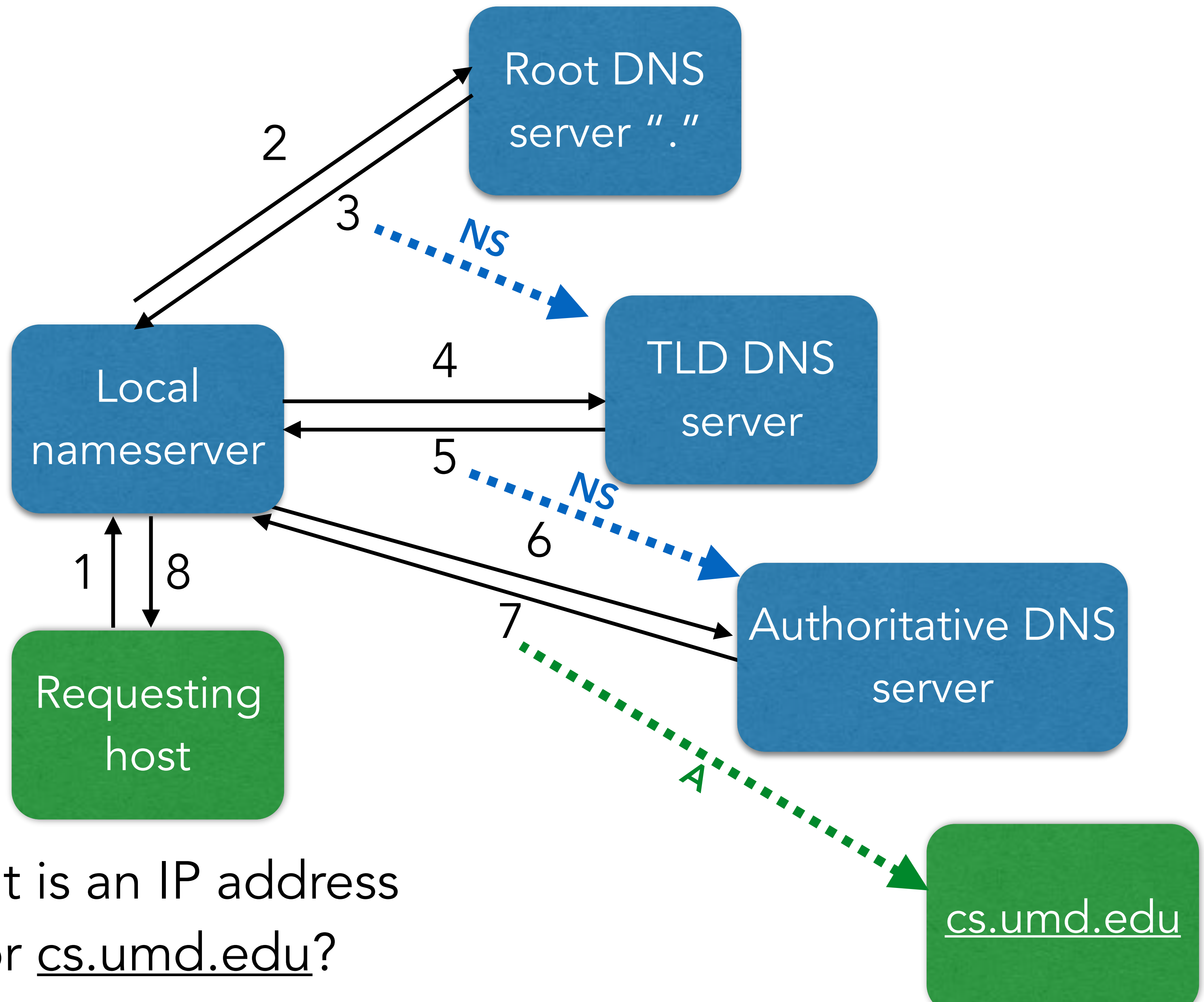
Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

DNS

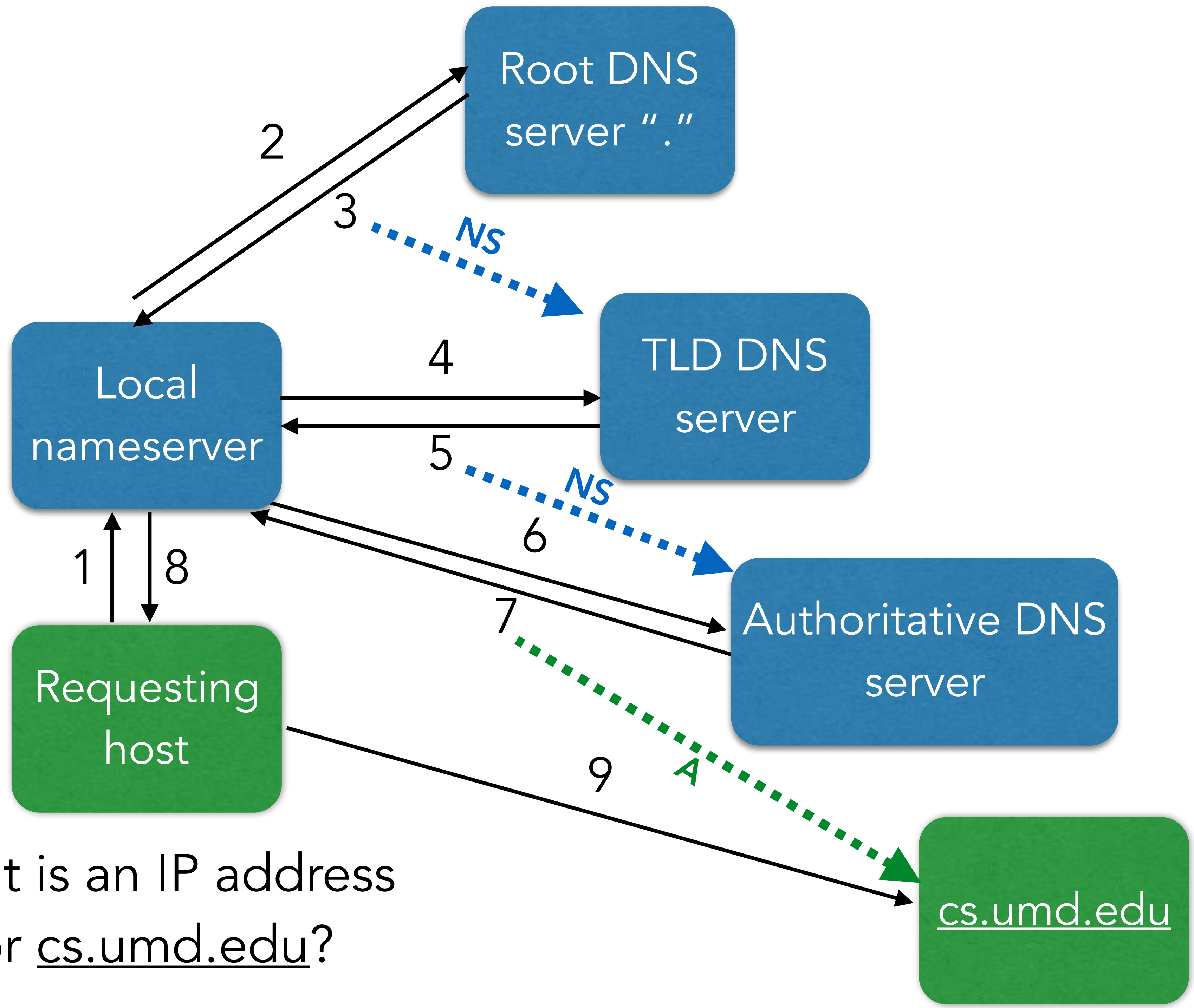
Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

DNS

Domain Name Service at a very high level



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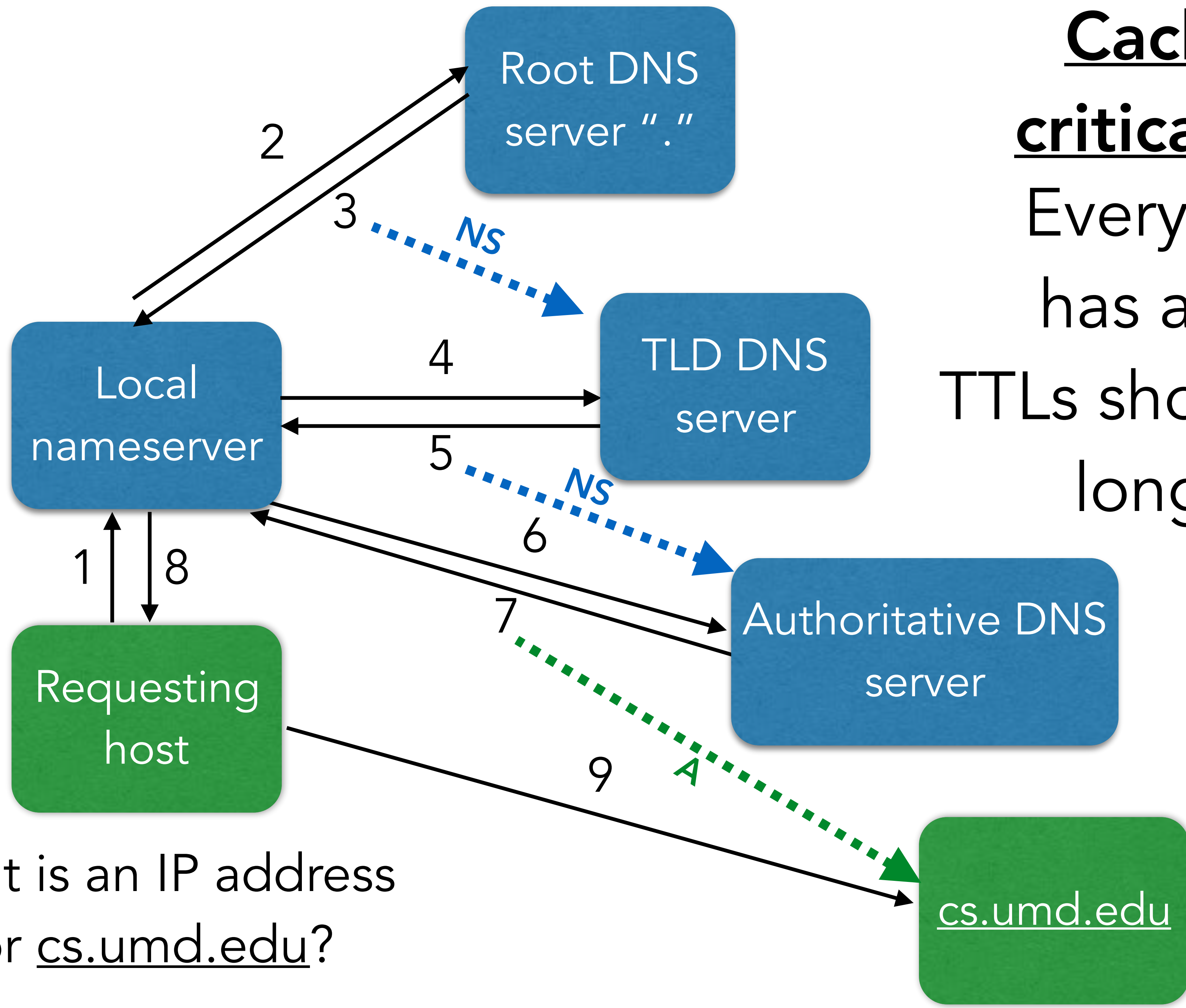
DNS

Domain Name Service at a very high level



What is an IP address for cs.umd.edu?

<u>Caching responses is critical to DNS's success</u>

Every response (3,5,7,8) has a time-to-live (TTL). TTLs should be reasonably long (days), but some are minutes.

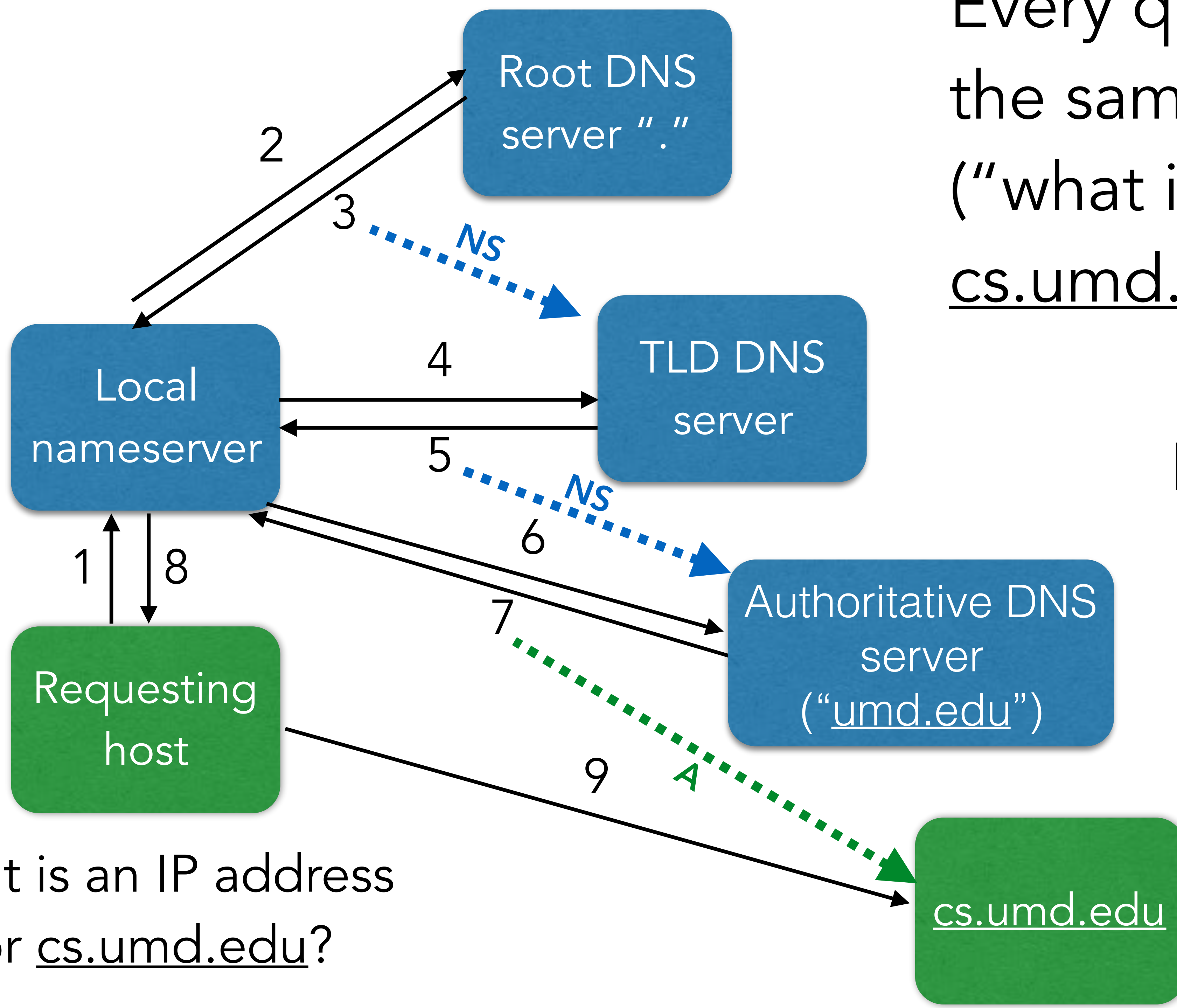
HOW DO THEY KNOW THESE IP ADDRESSES?

- Local DNS server: host learned this via DHCP
- A parent knows its children: part of the registration process
- Root nameserver: *hardcoded* into the local DNS server (and every DNS server)
  - 13 root servers (logically): A-root, B-root, …, M-root
  - These IP addresses change *very* infrequently
  - **UMD runs D-root.**
    - IP address changed beginning of 2013!!
    - For the most part, the change-over went alright, but Lots of weird things happened — ask me some time.

CACHING

- Central to DNS's success
- Also central to attacks
- "Cache poisoning": filling a victim's cache with false information

QUERIES



What is an IP address for cs.umd.edu?

Every query (2,4,6) has the same request in it ("what is the IP address for cs.umd.edu?")

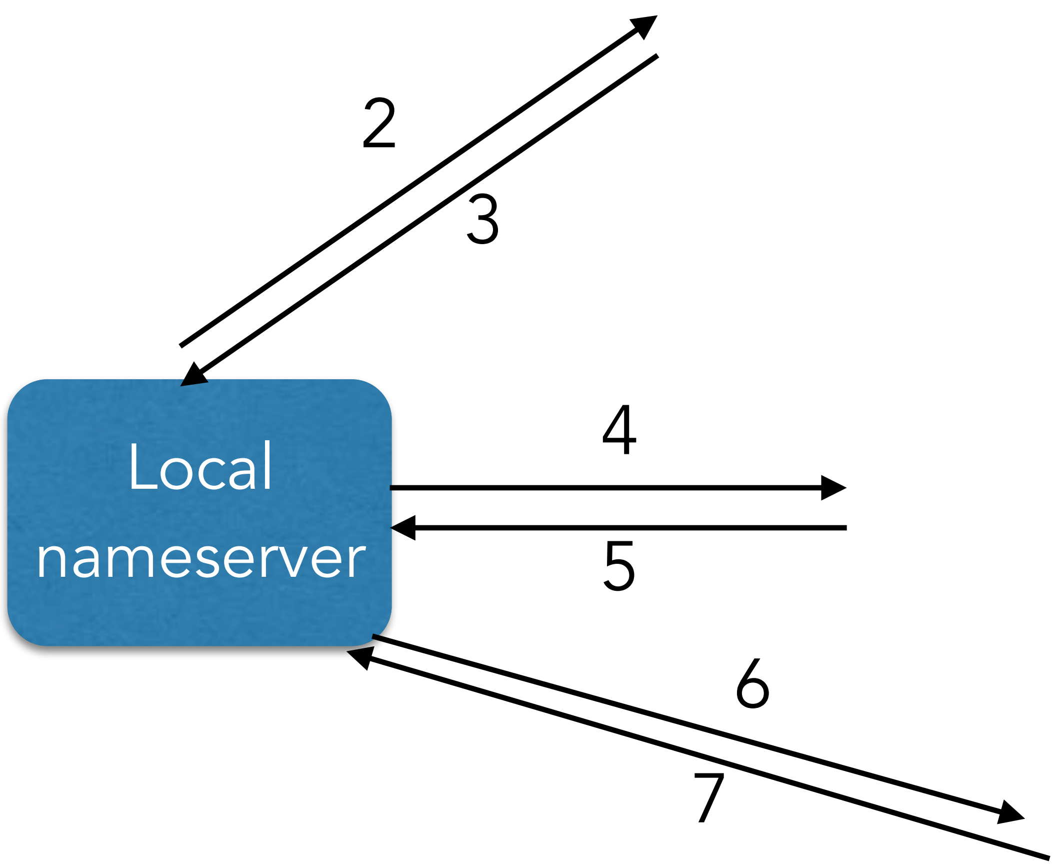
But **different**:

- dst IP (port = 53)
- query ID

WHAT'S IN A RESPONSE?

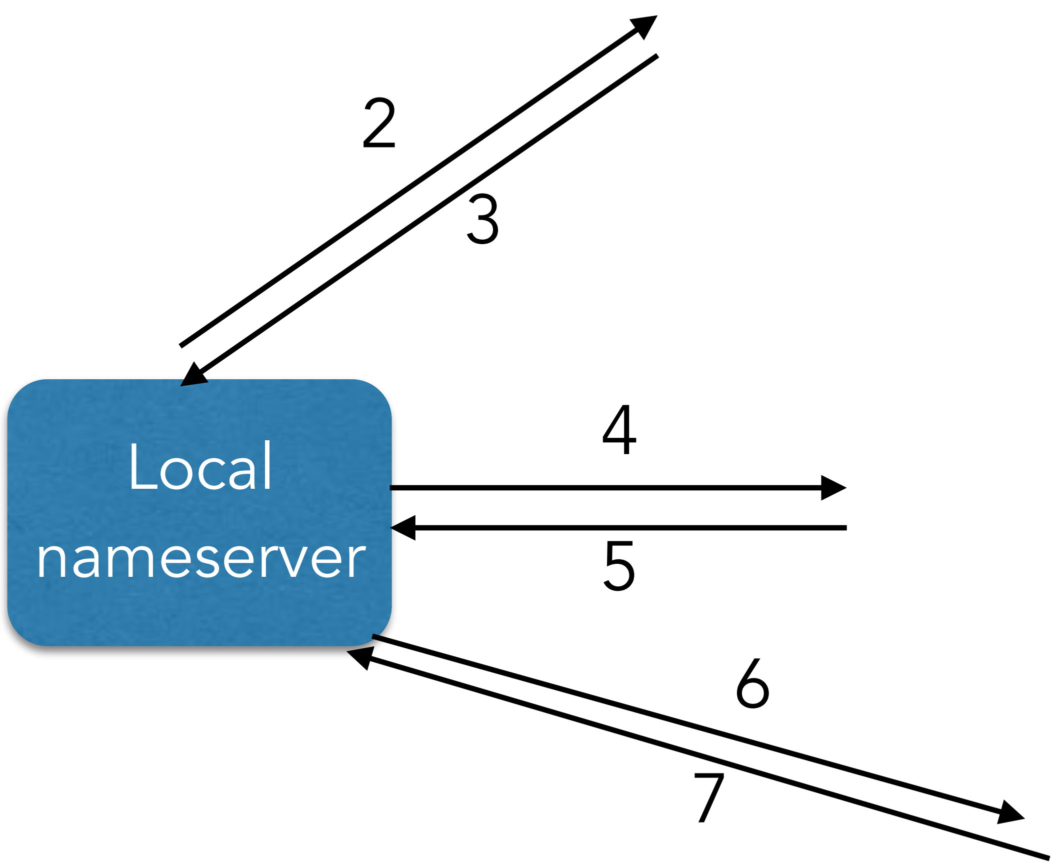
- Many things, but for the attacks we're concerned with…
- A record: gives "the authoritative response for the IP address of this hostname"
- NS record: describes "this is the name of the nameserver who should know more about how to answer this query than I do"
  - Often also contains "glue" records (IP addresses of those name servers to avoid chicken and egg problems)
  - Resolver will generally cache all of this information

QUERY IDS



- The local resolver has a lot of incoming/outgoing queries at any point in time.
- To determine which response maps to which queries, it uses a *query ID*
- Query ID: 16-bit field in the DNS header
  - Requester sets it to whatever it wants
  - Responder must provide the same value in its response

QUERY IDS



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- Query ID: 16-bit field in the DNS header
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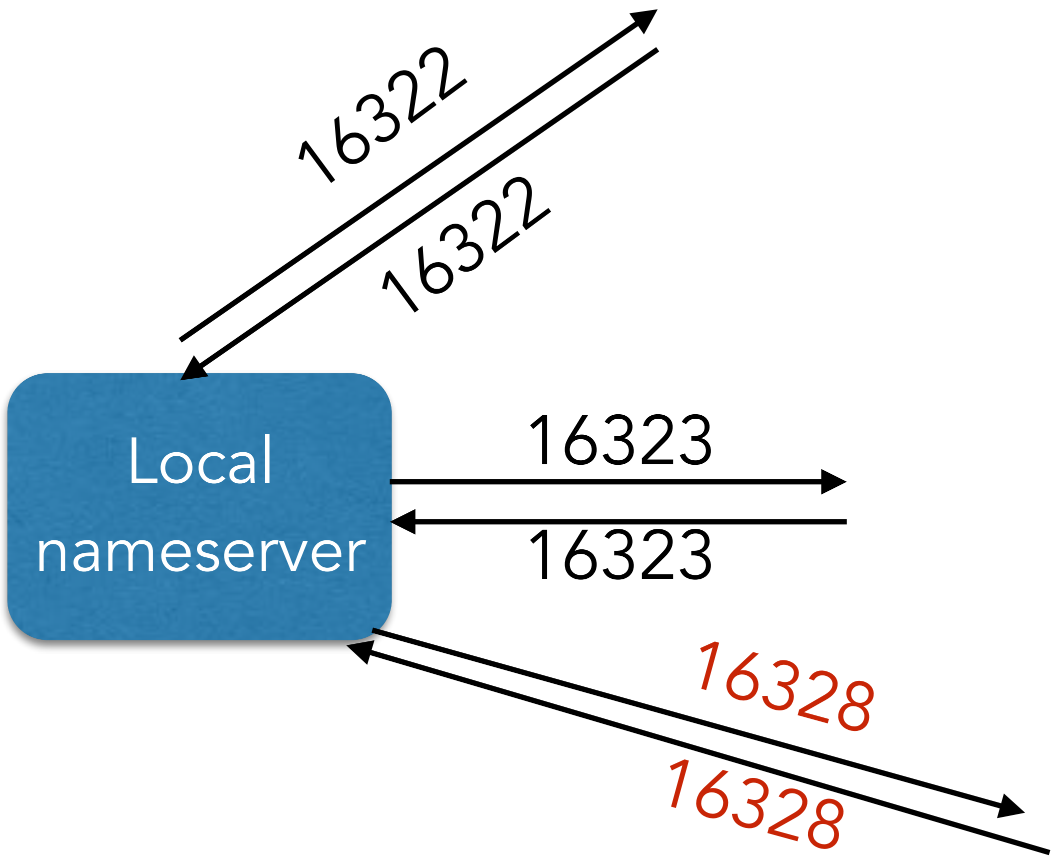
  - Responder must provide the same value in its response

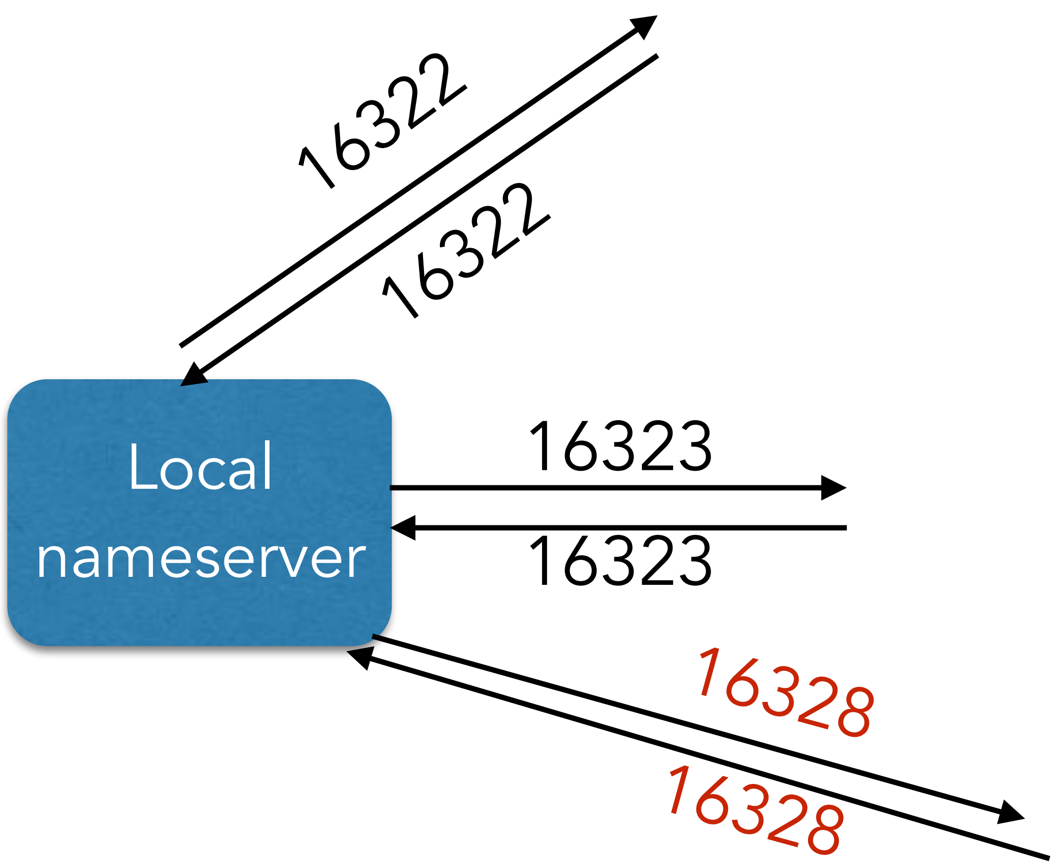
How would you implement query IDs at a resolver?

QUERY IDS USED TO INCREMENT



- Global query ID value
- Map outstanding query ID to local state of who to respond to (the client)
- Basically:
  new Packet(queryID++)

QUERY IDS USED TO INCREMENT

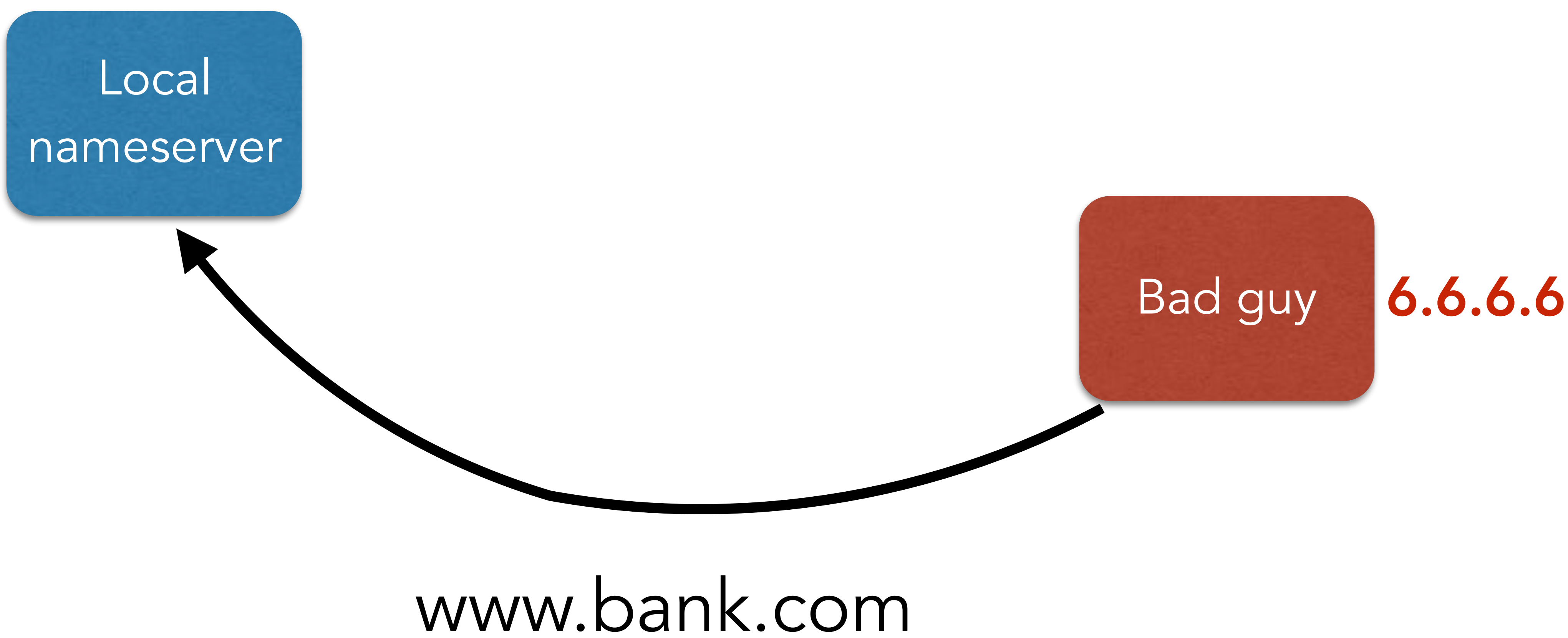


- Global query ID value
- Map outstanding query ID to local state of who to respond to (the client)
- Basically:
  new Packet(queryID++)

How would you attack this?

CACHE POISONING

CACHE POISONING



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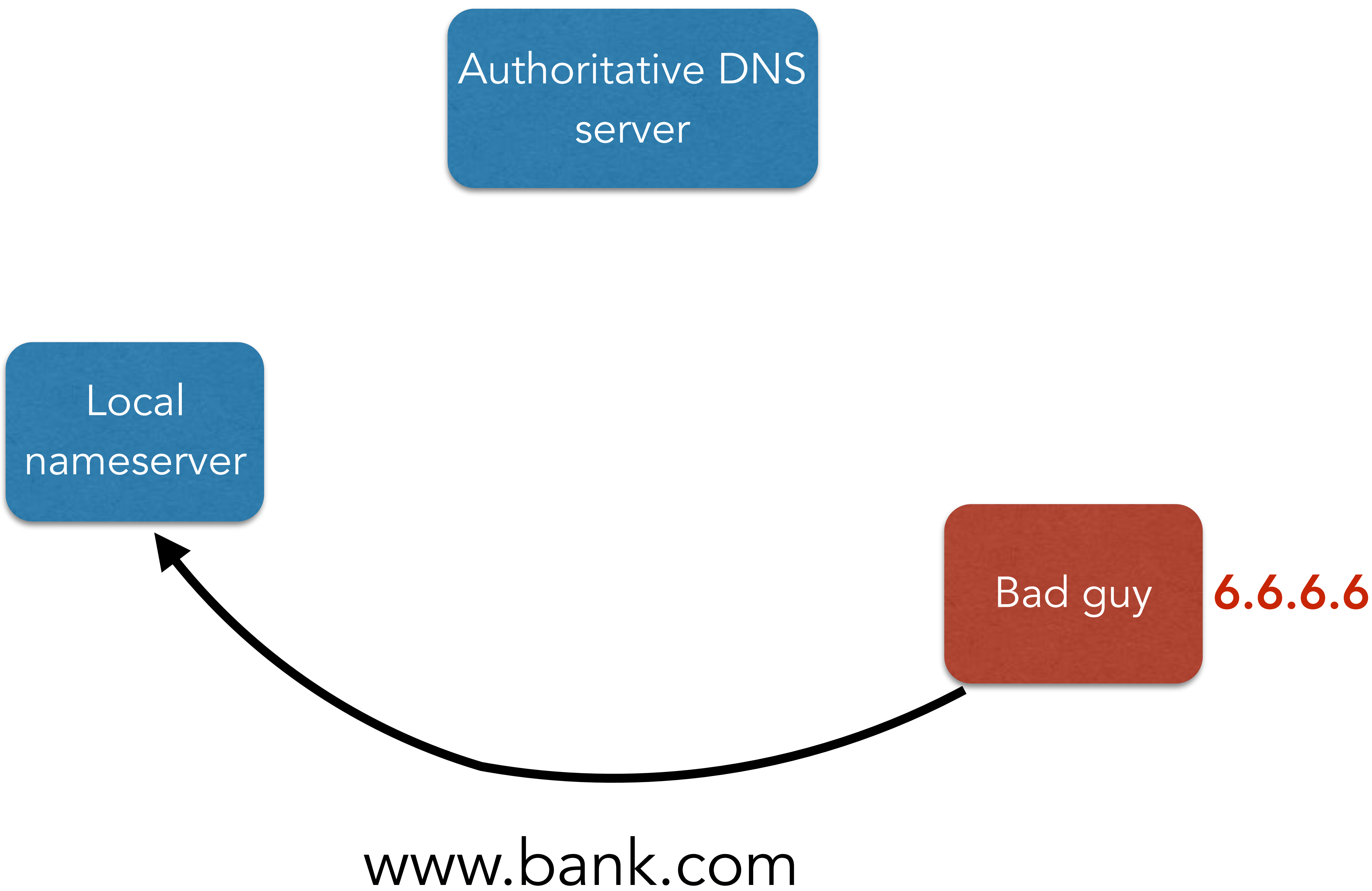

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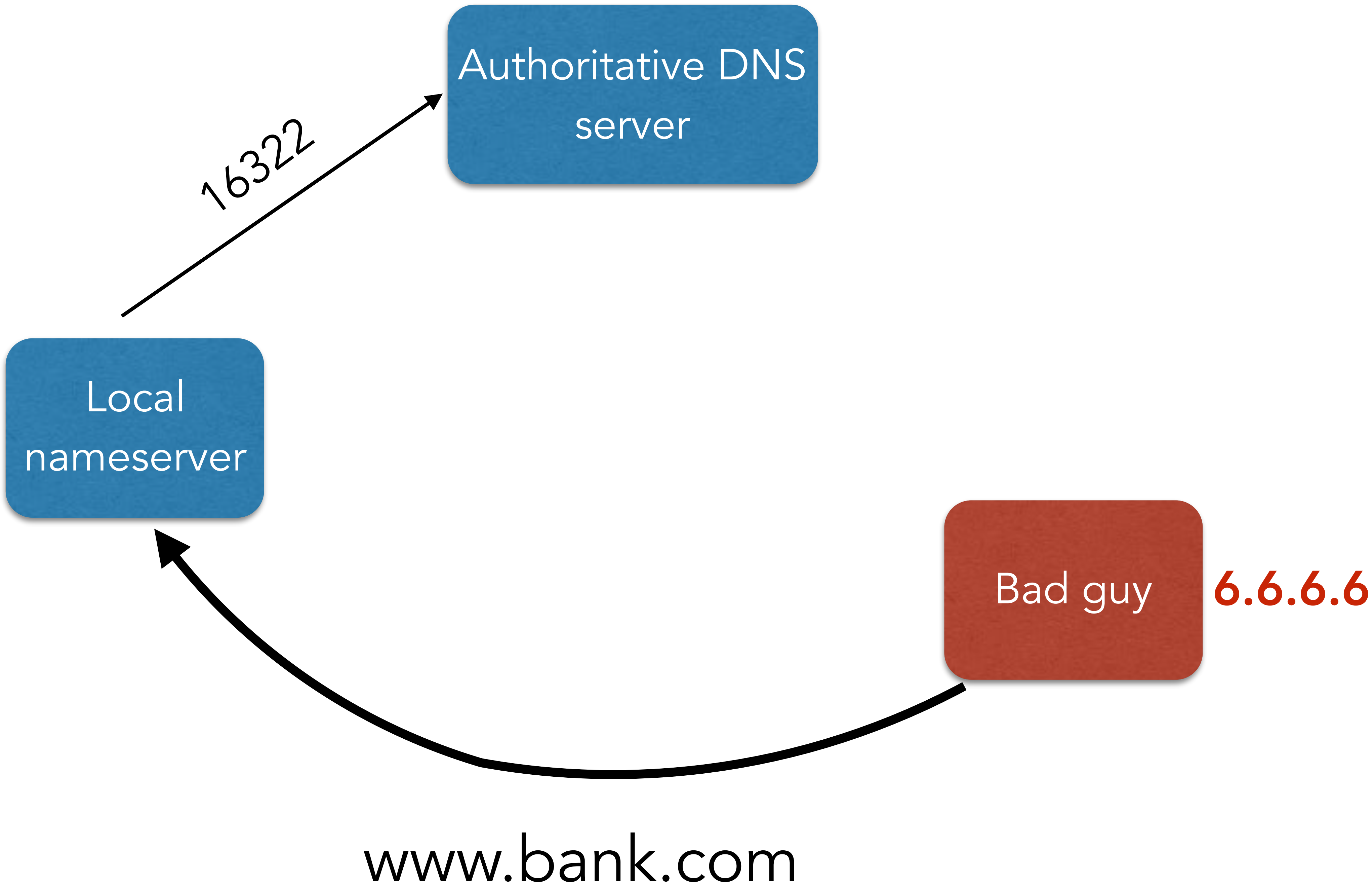

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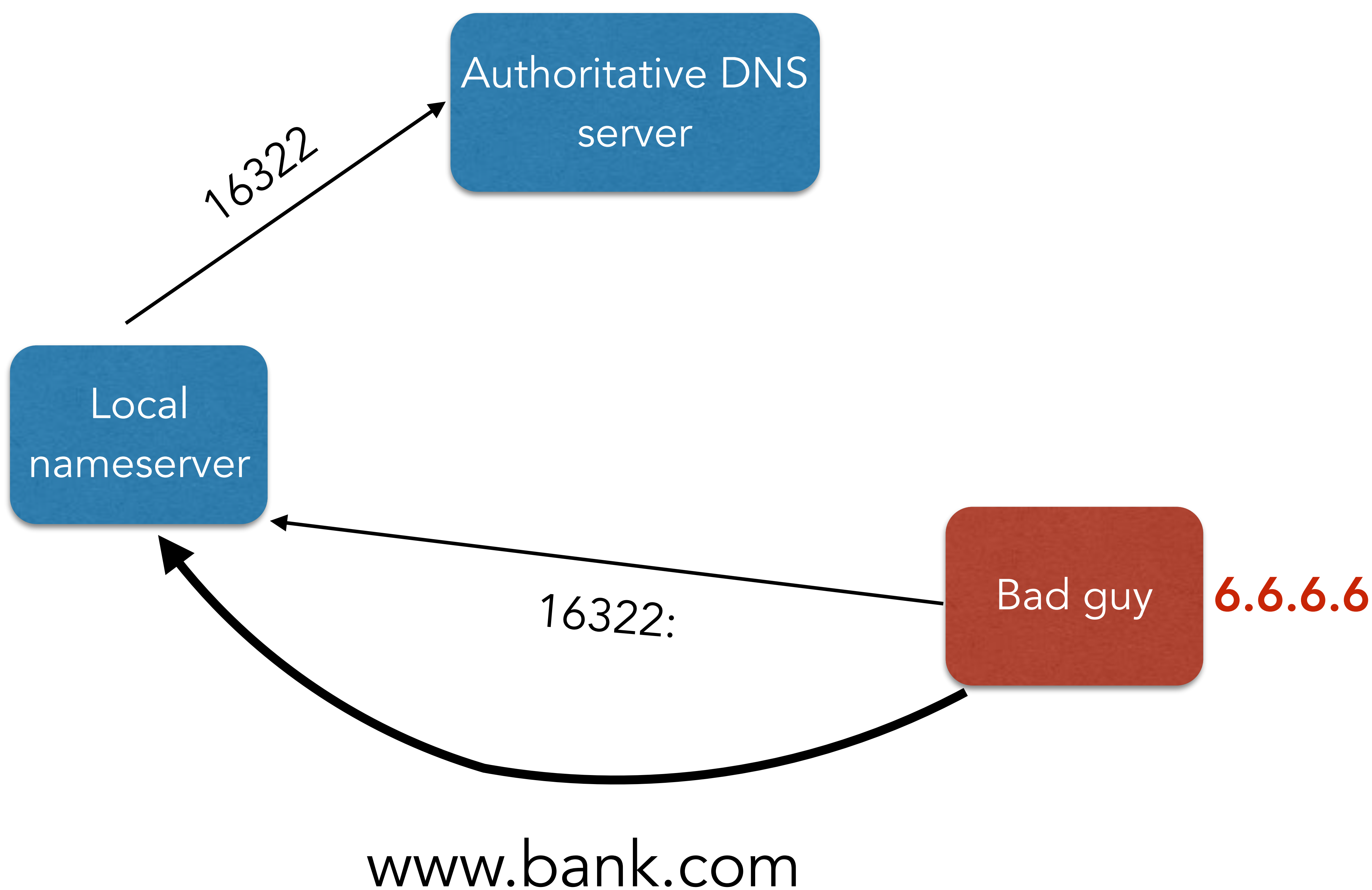
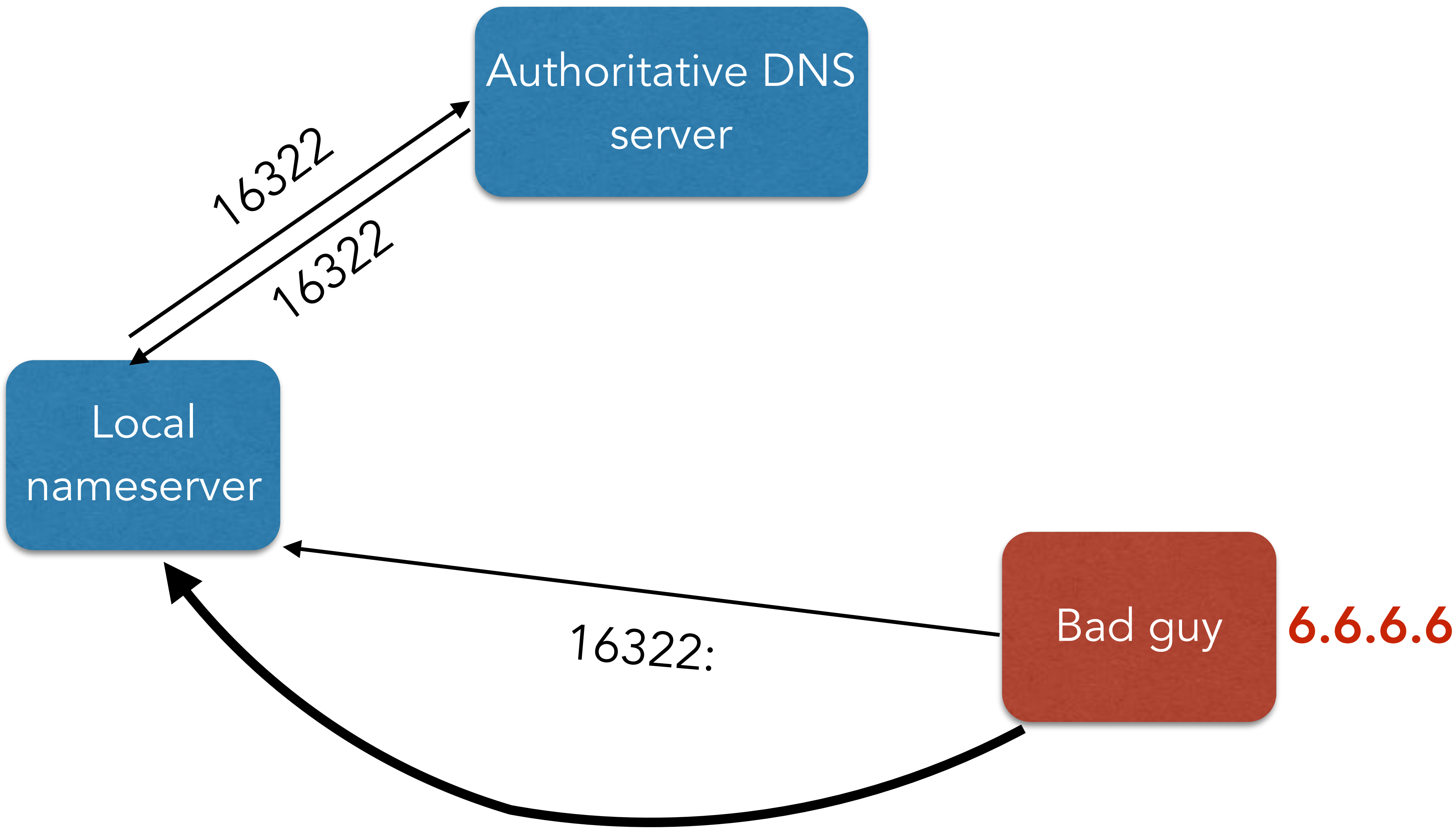
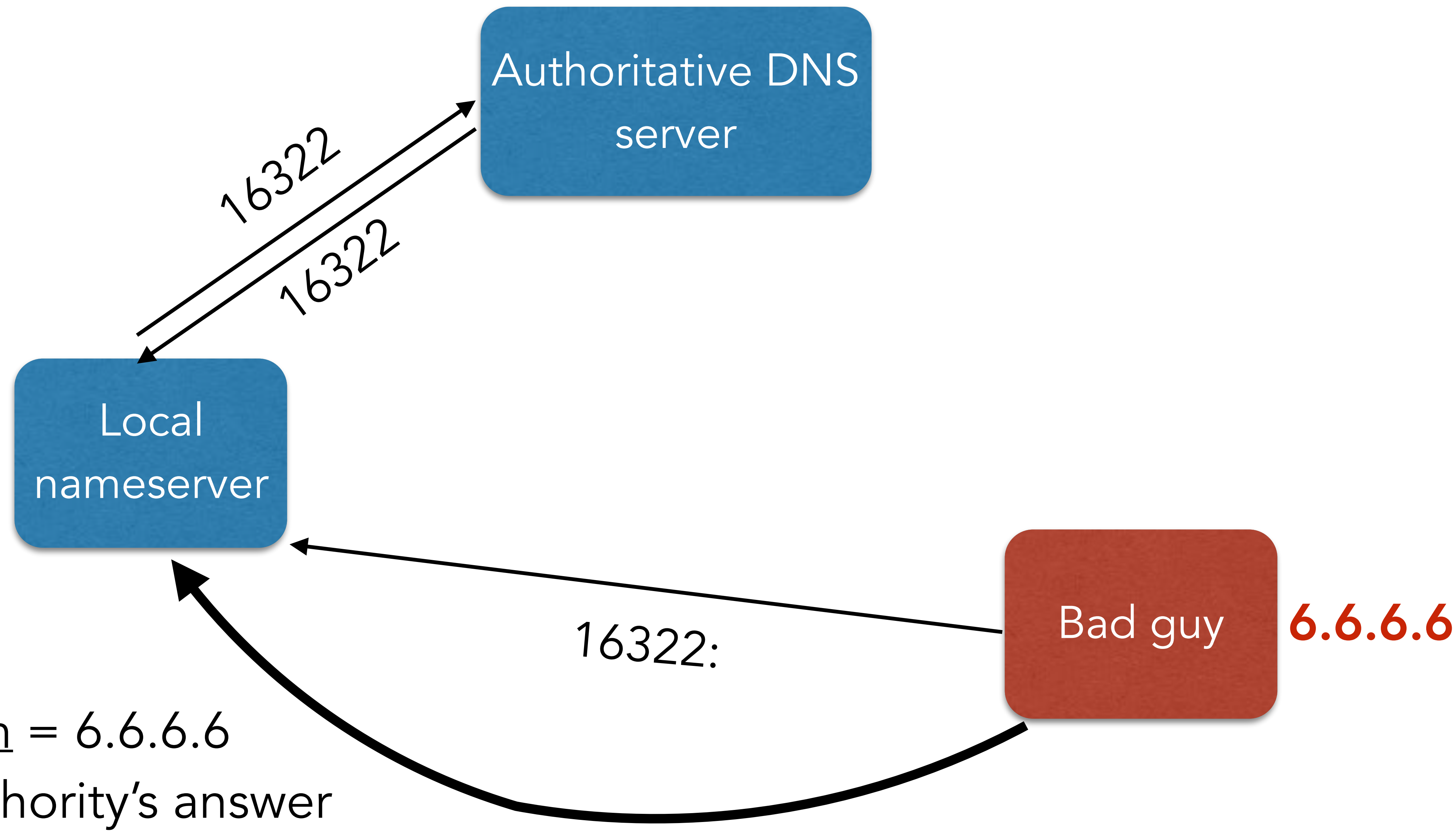


CACHE POISONING



www.bank.com

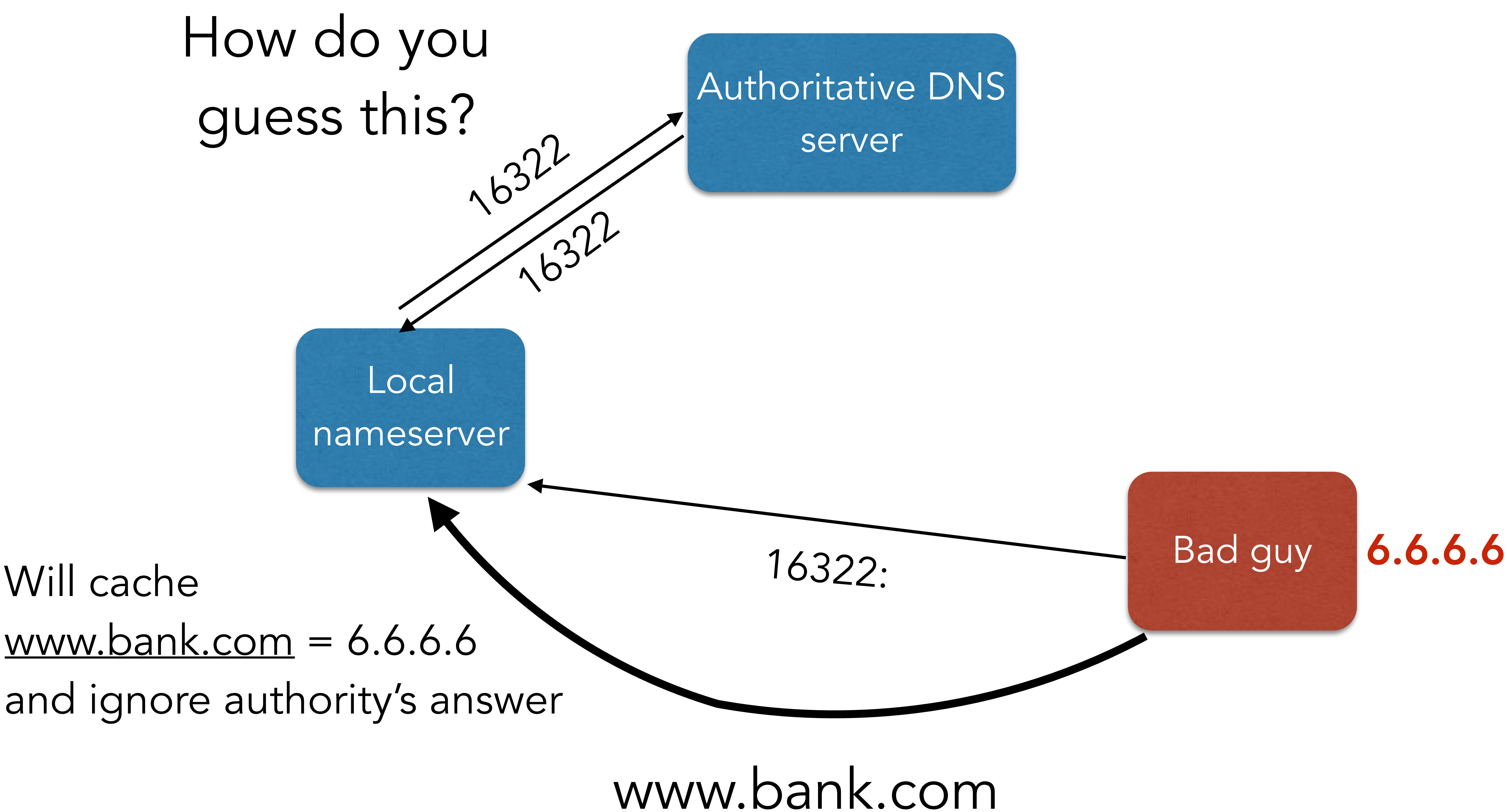
CACHE POISONING



Will cache
www.bank.com = 6.6.6.6
and ignore authority's answer

www.bank.com

CACHE POISONING



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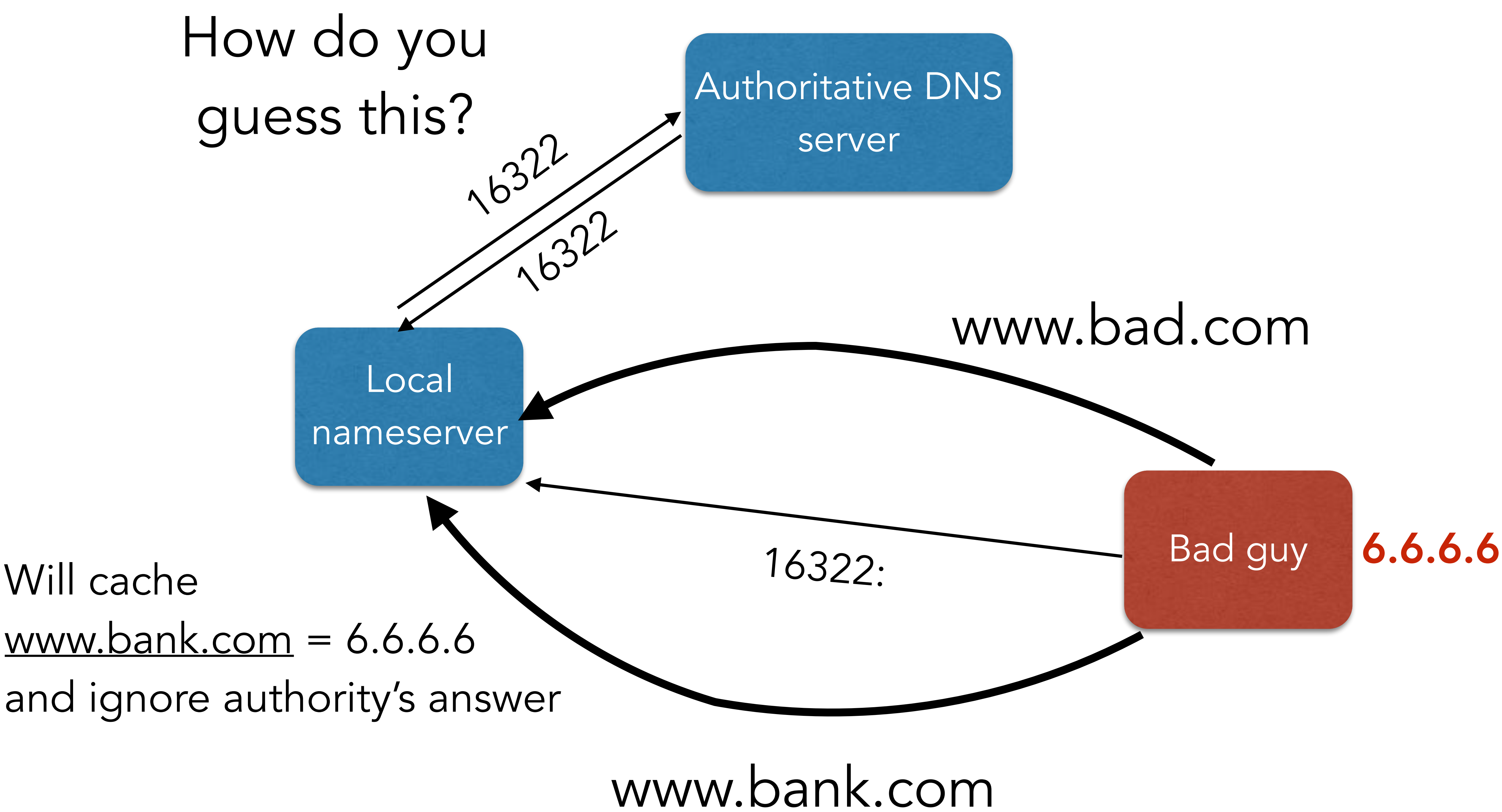

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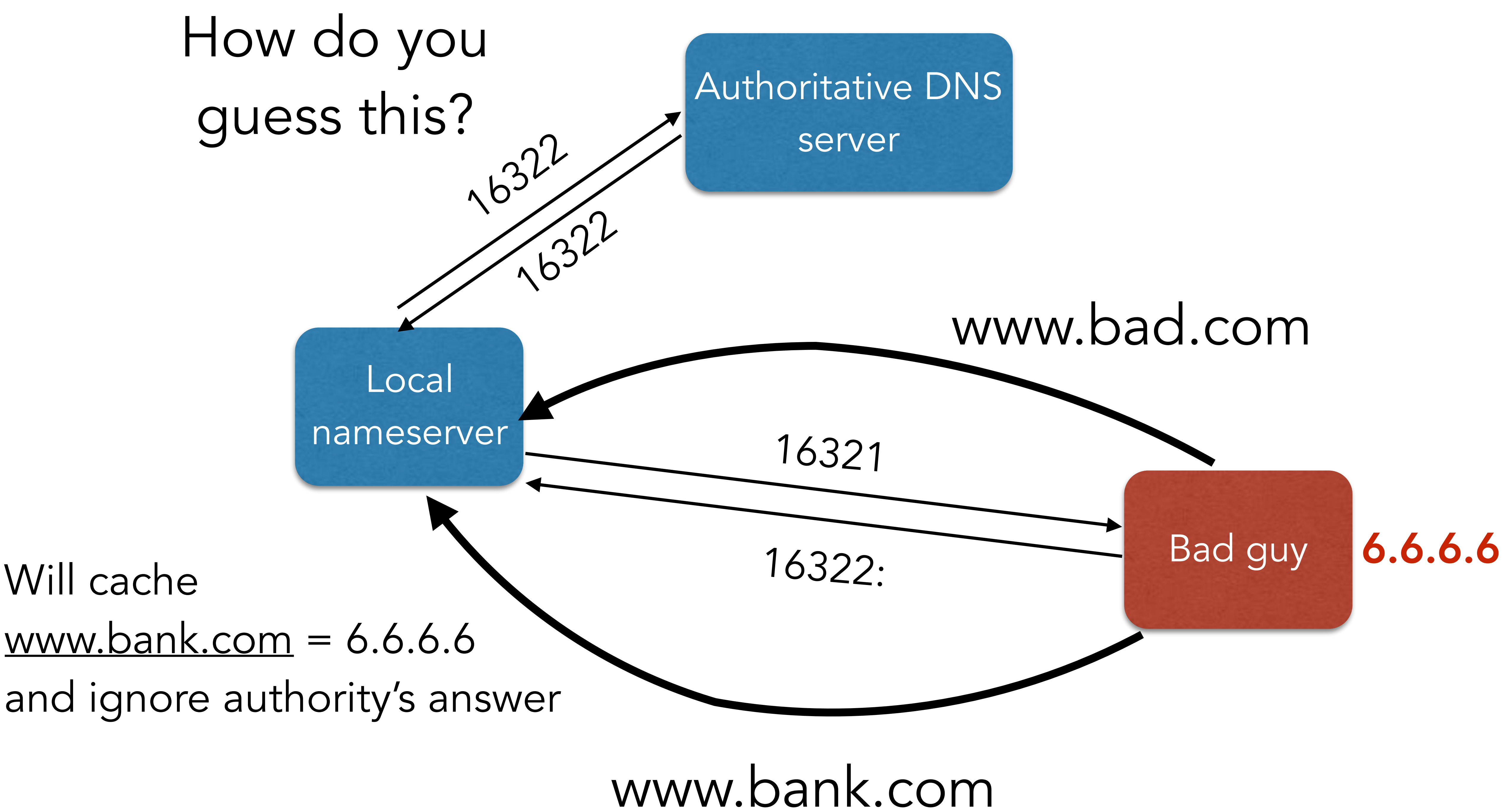

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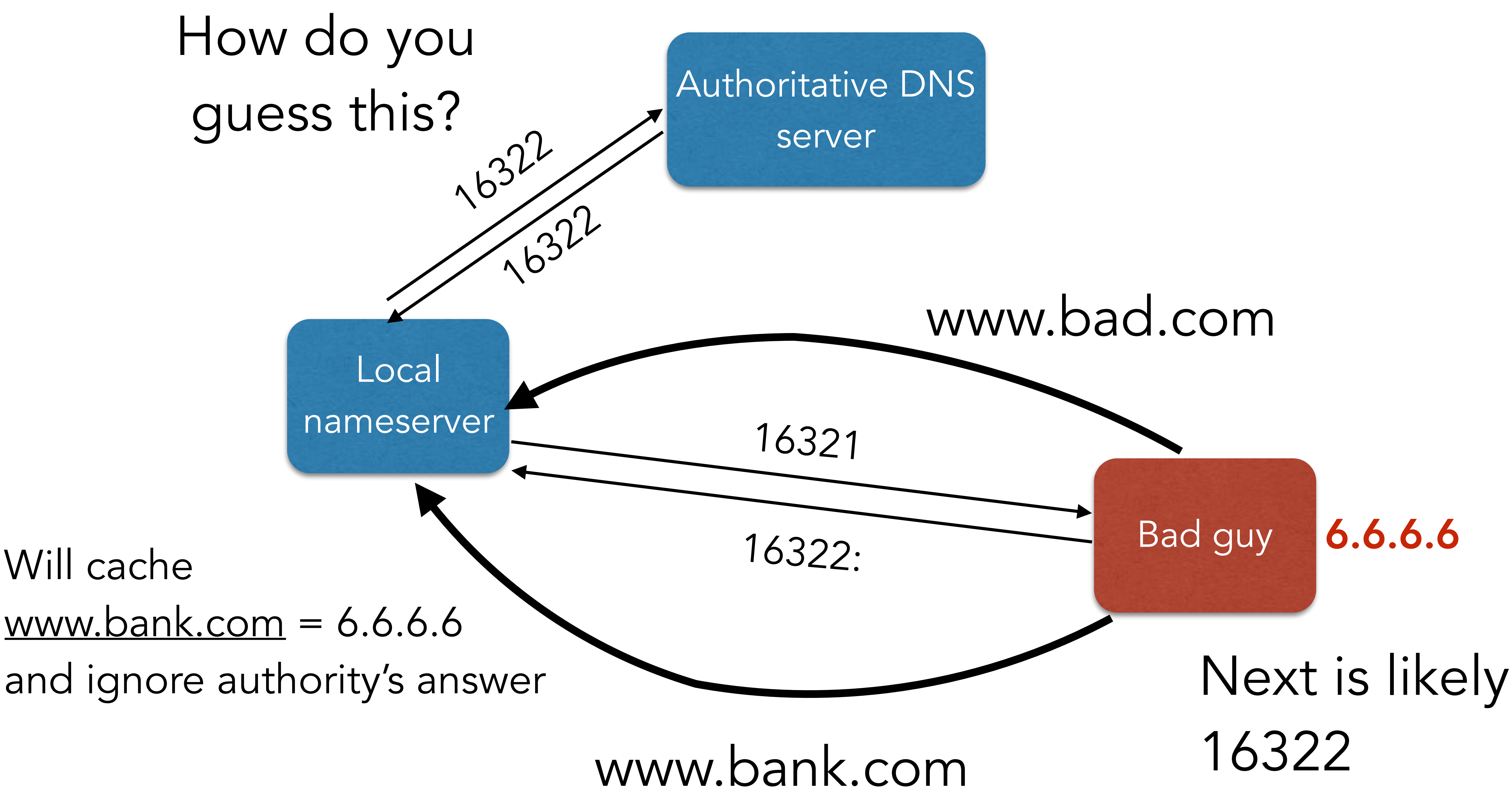
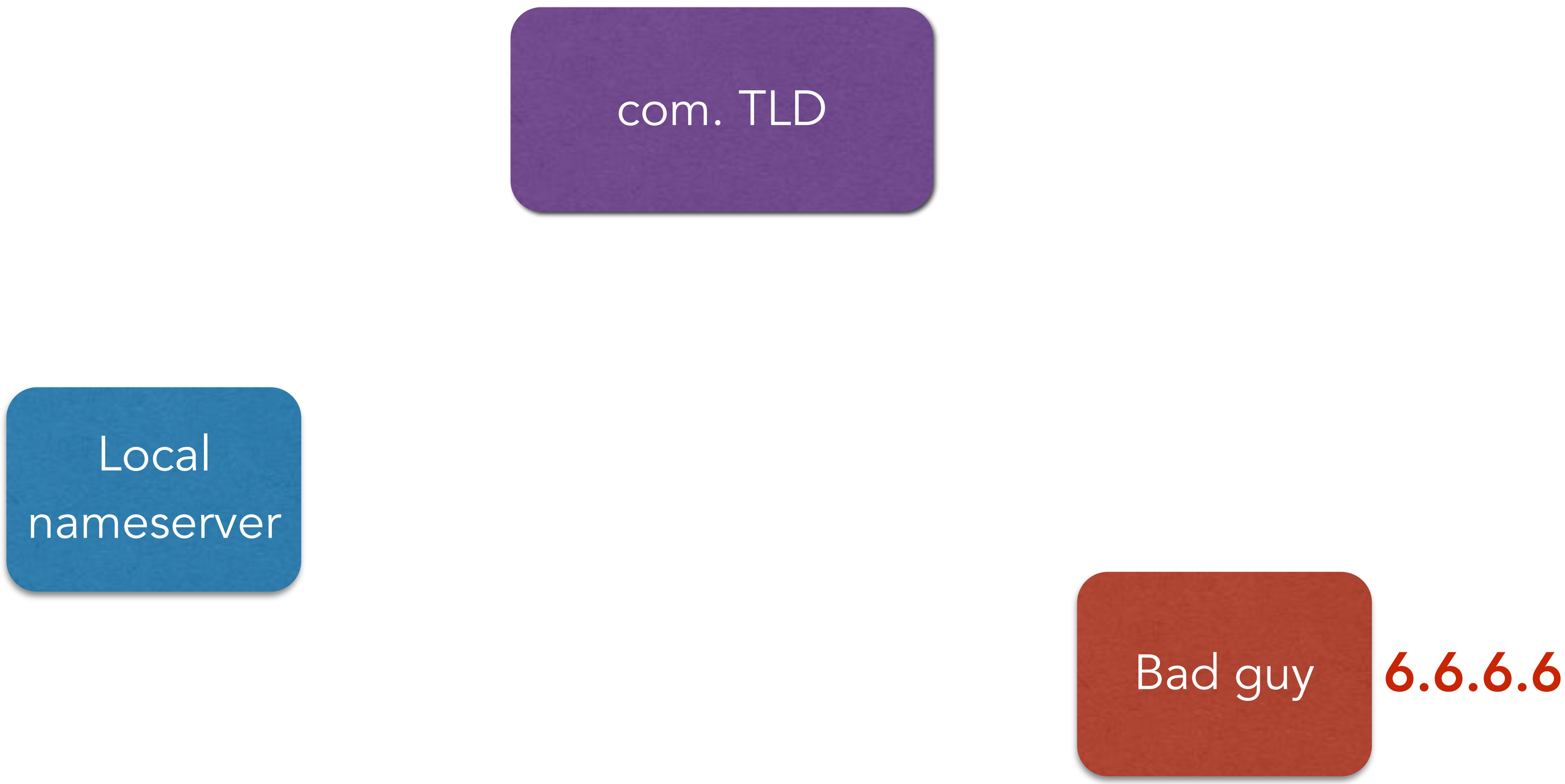


DETAILS OF GETTING THE ATTACK TO WORK

- Must guess query ID: ask for it, and go from there
  - Partial fix: randomize query IDs
  - Problem: small space
  - Attack: issue a Lot of query IDs
- Must guess source port number
  - Typically constant for a given server (often always 53)
- The answer must not already be in the cache
  - It will avoid issuing a query in the first place

CACHE POISONING

Can we do more harm than a single record?



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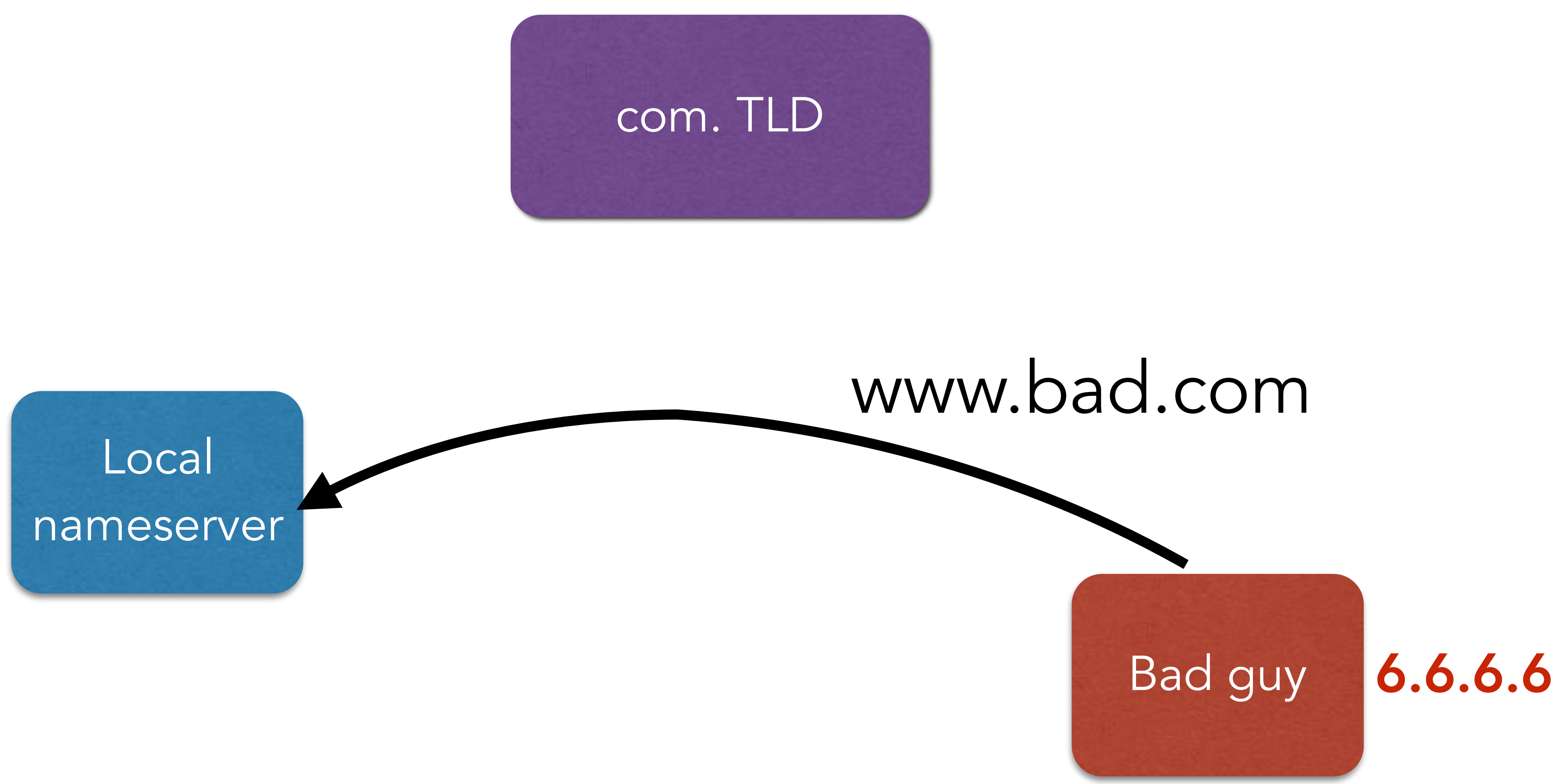

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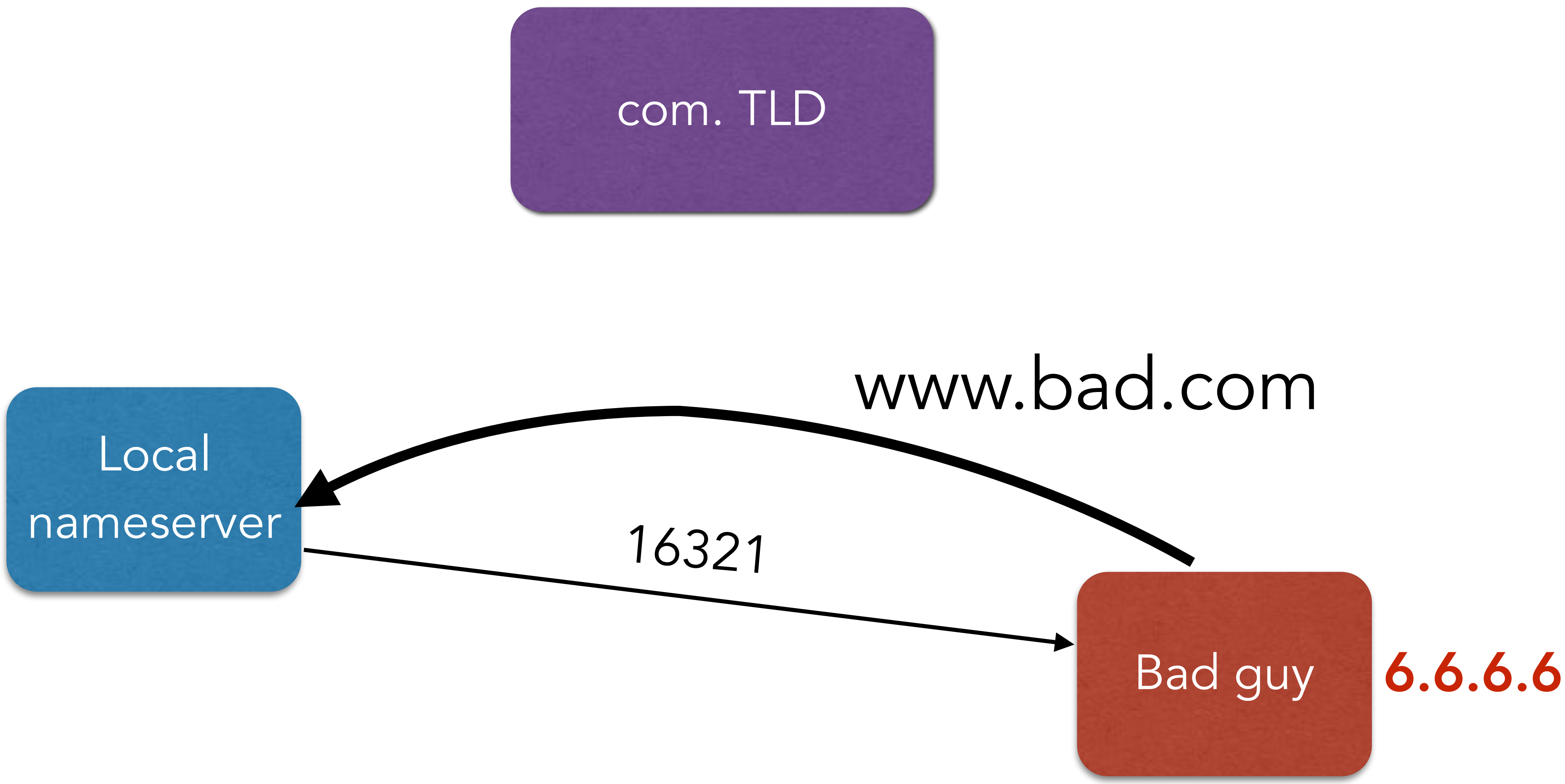

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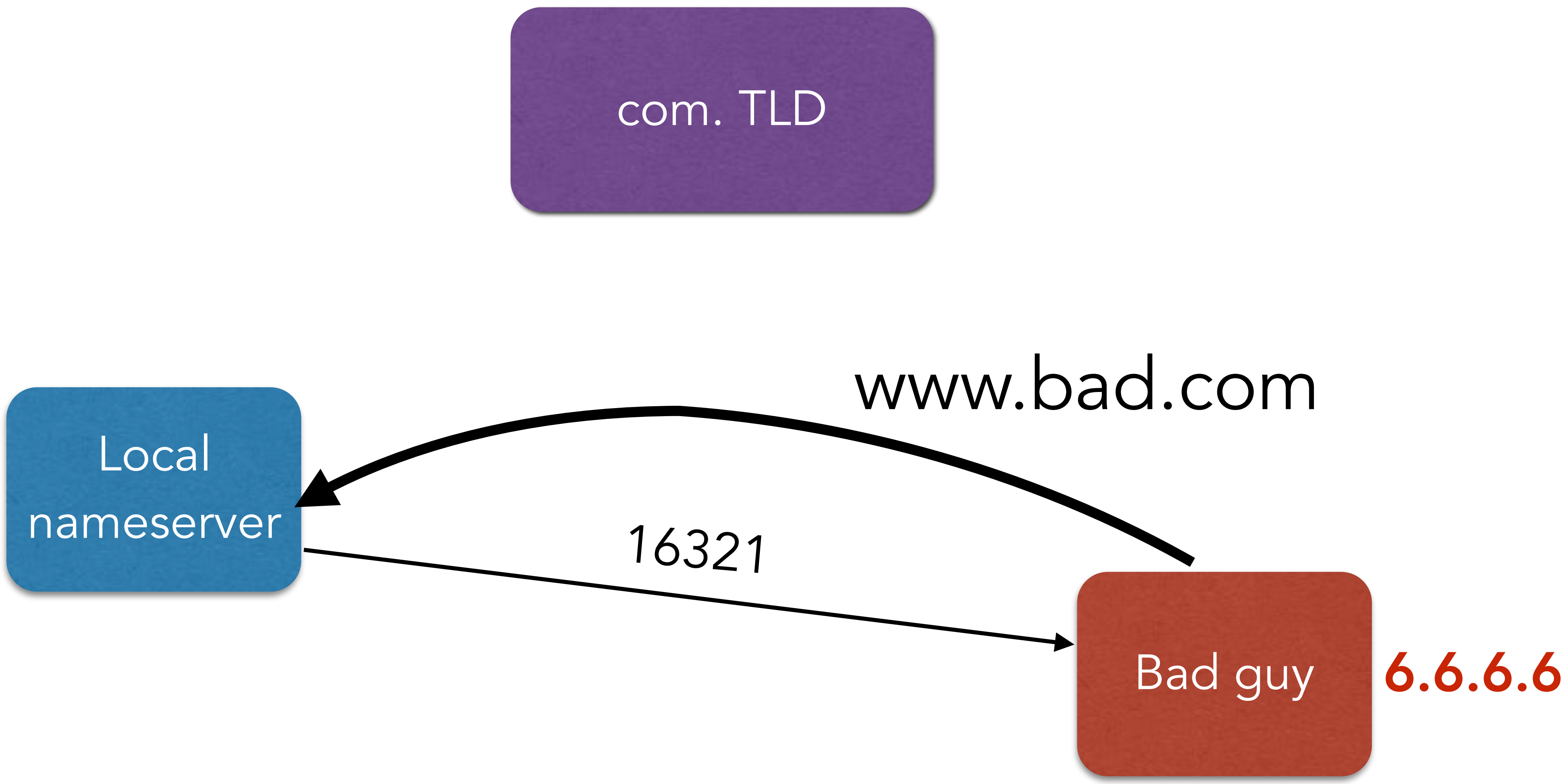

Next is likely 16322

CACHE POISONING

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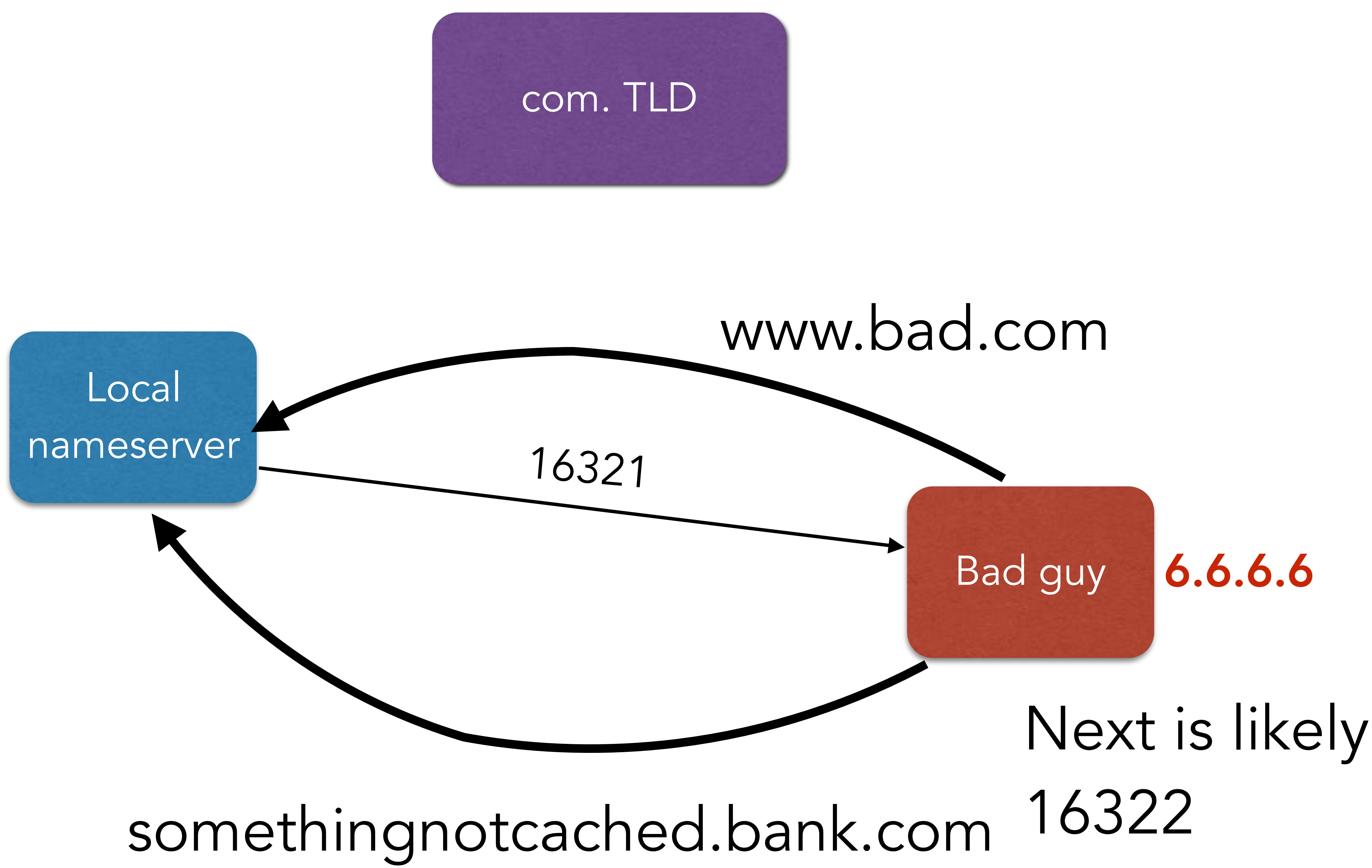

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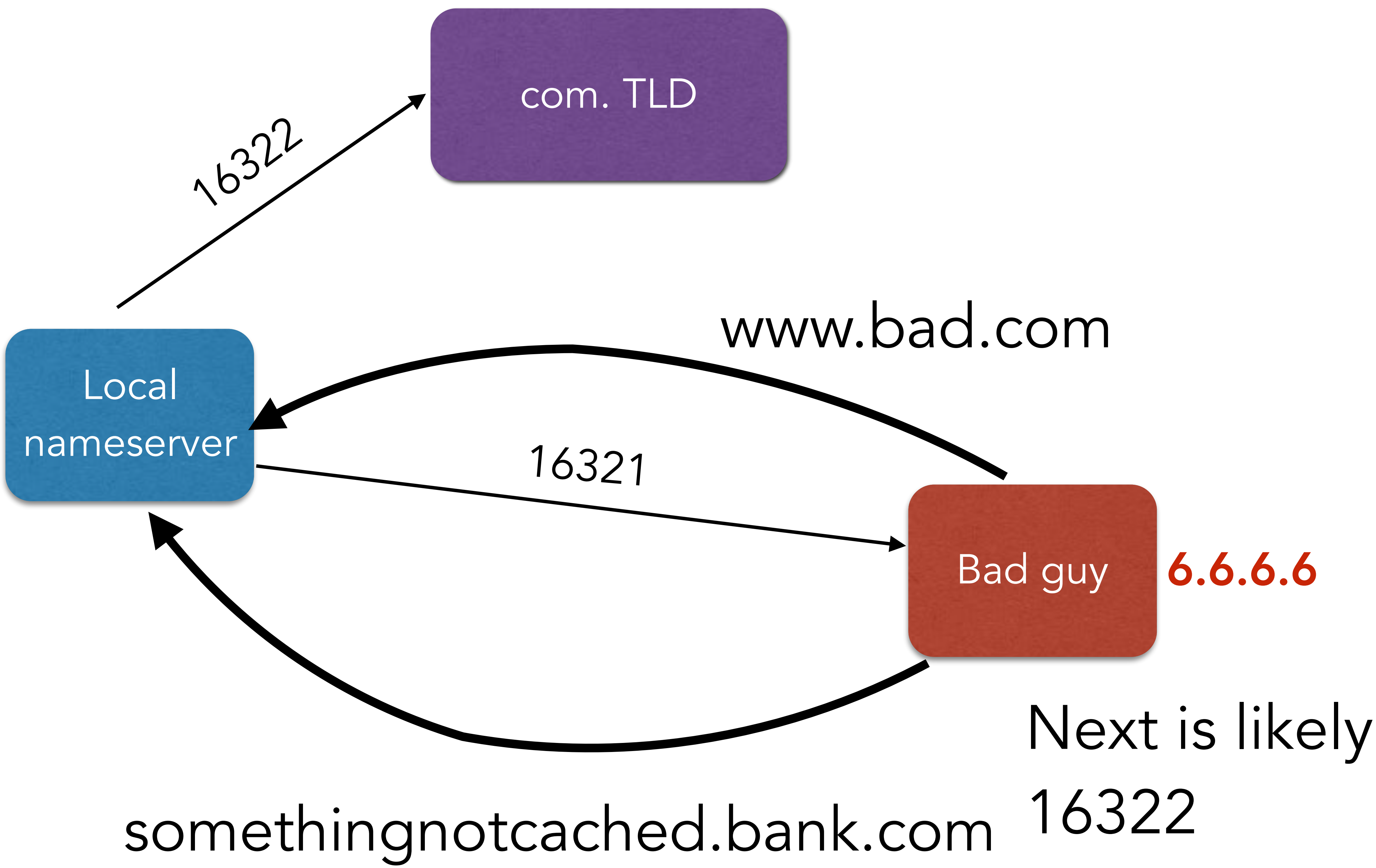

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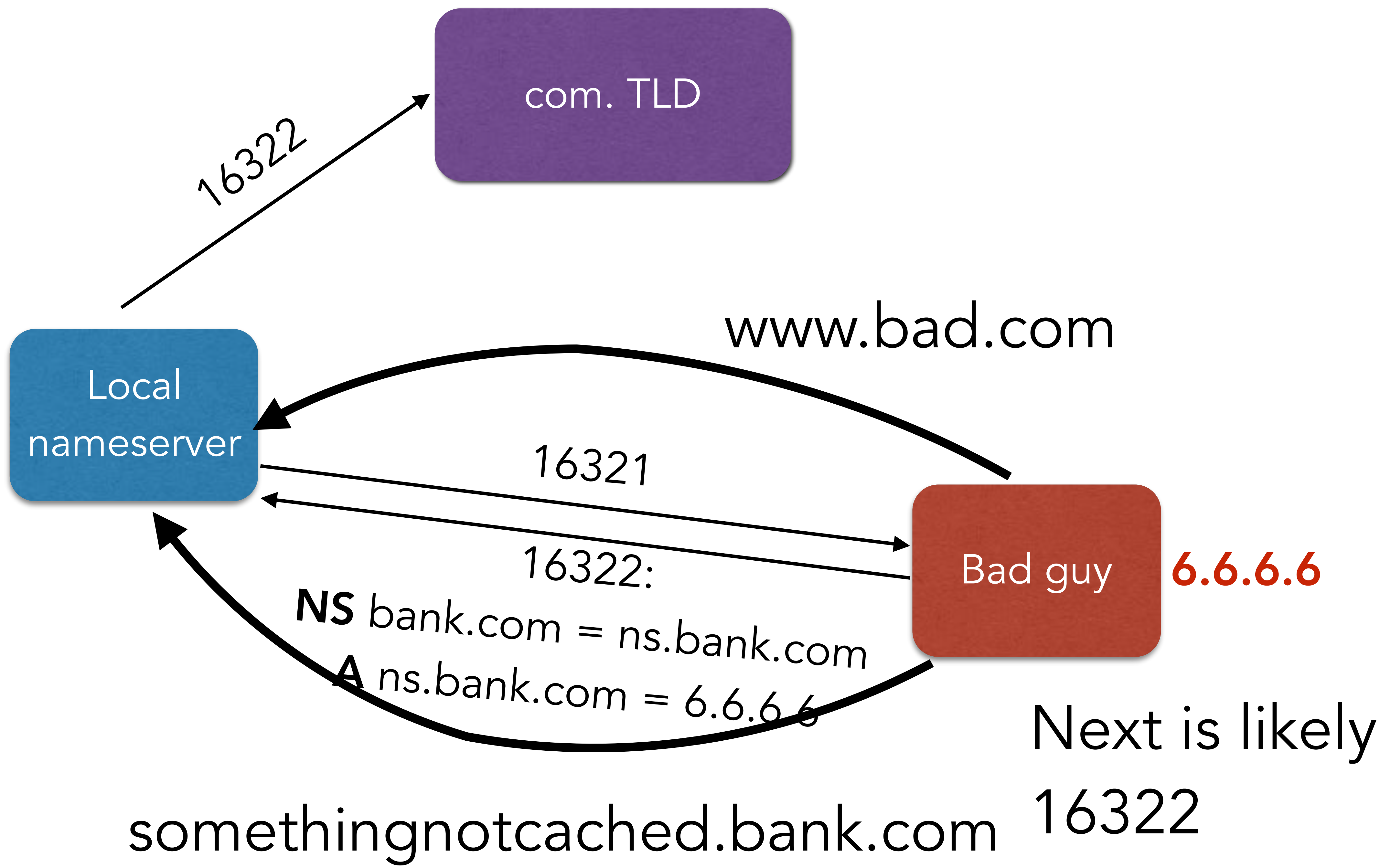

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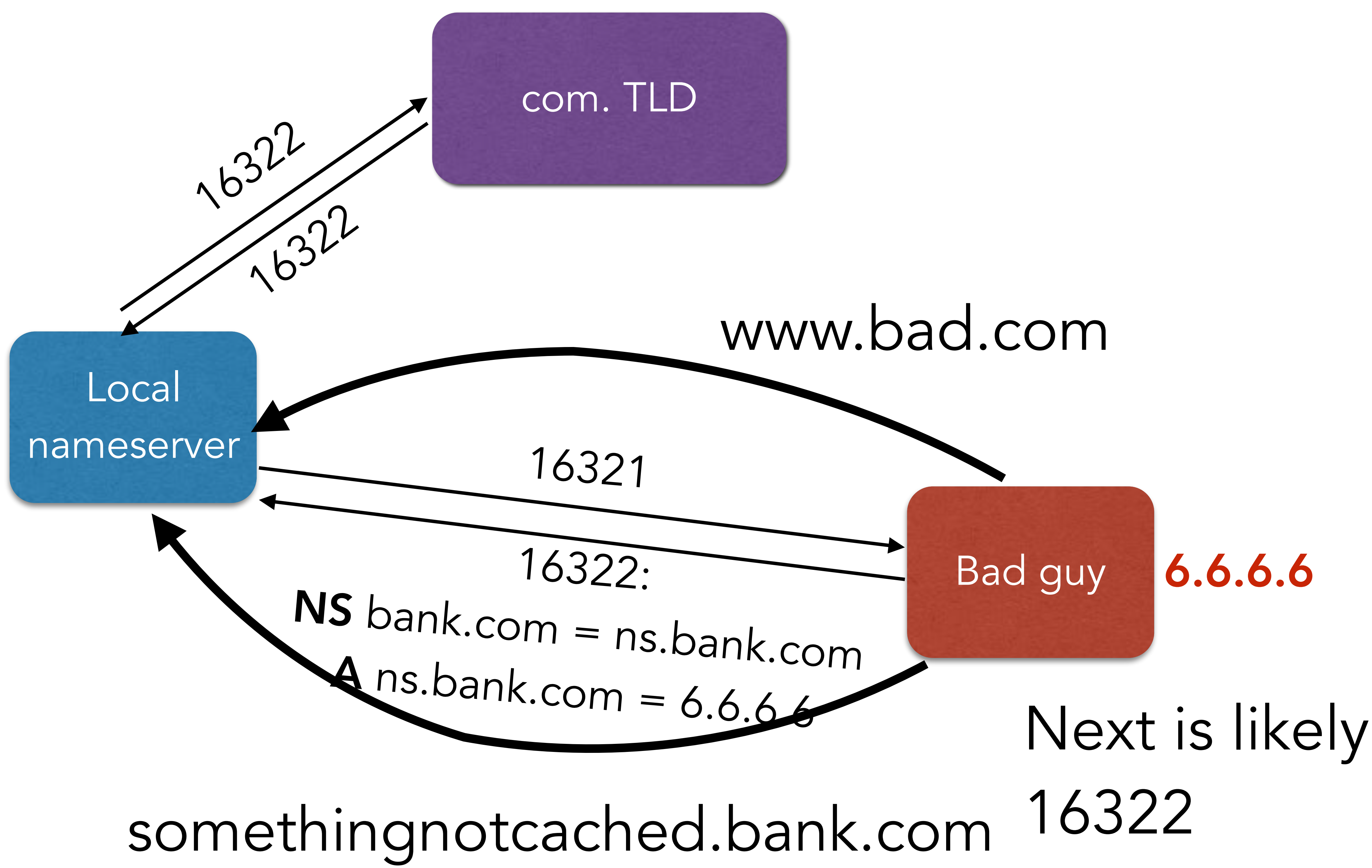

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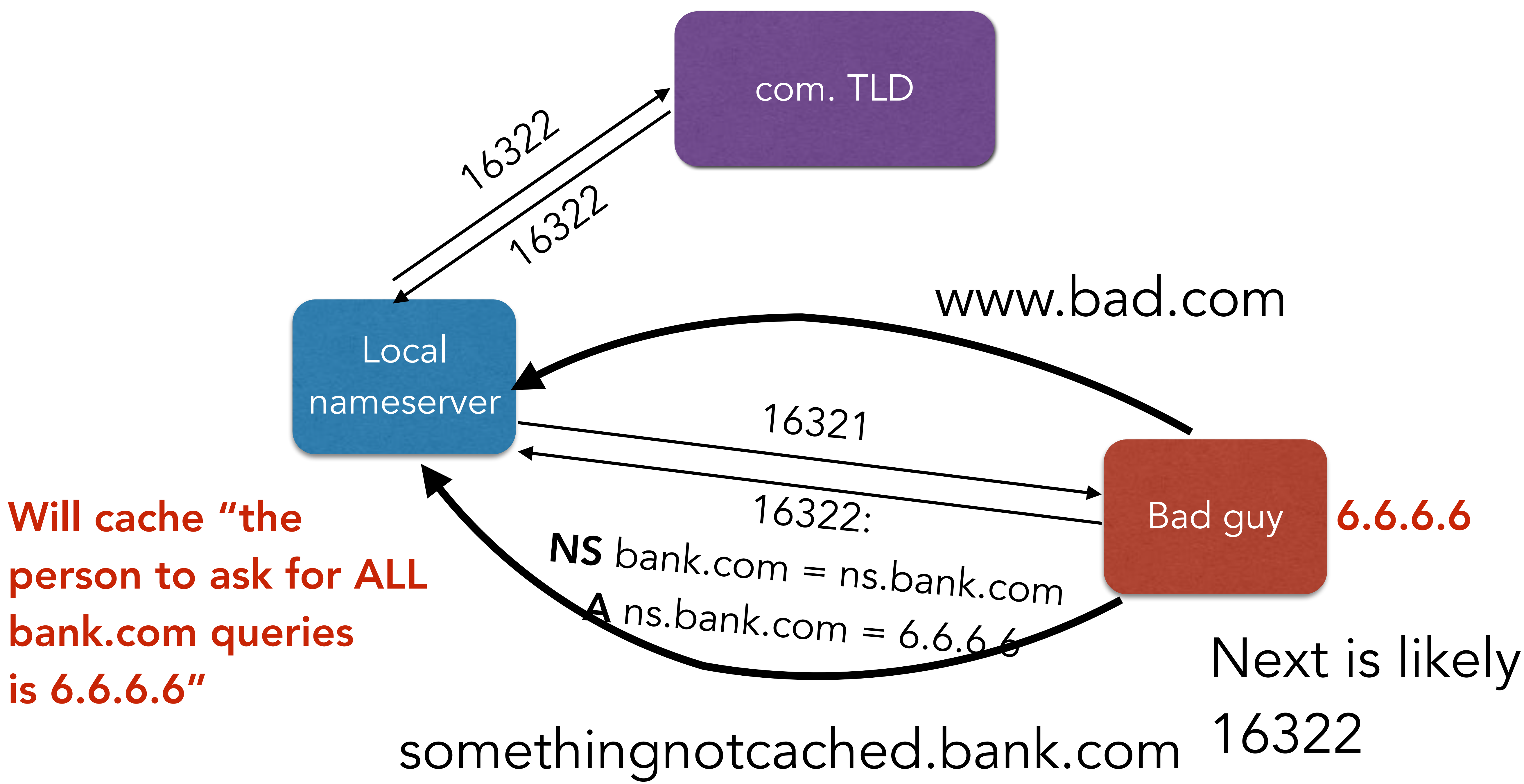
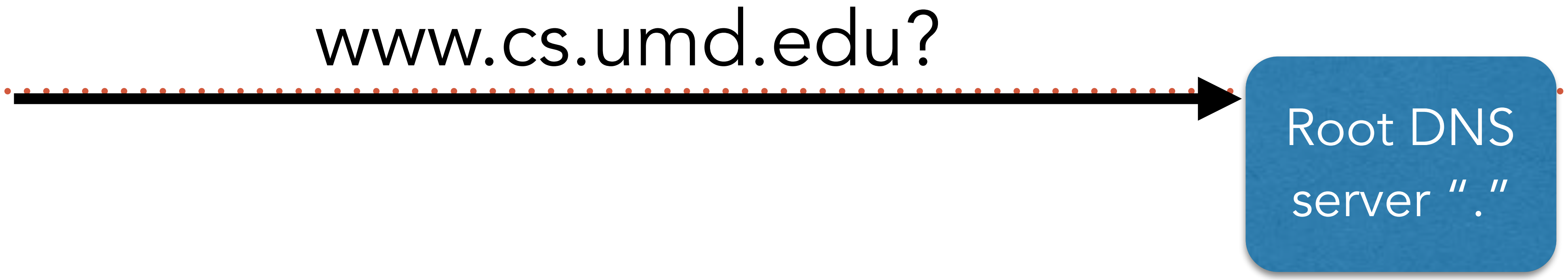


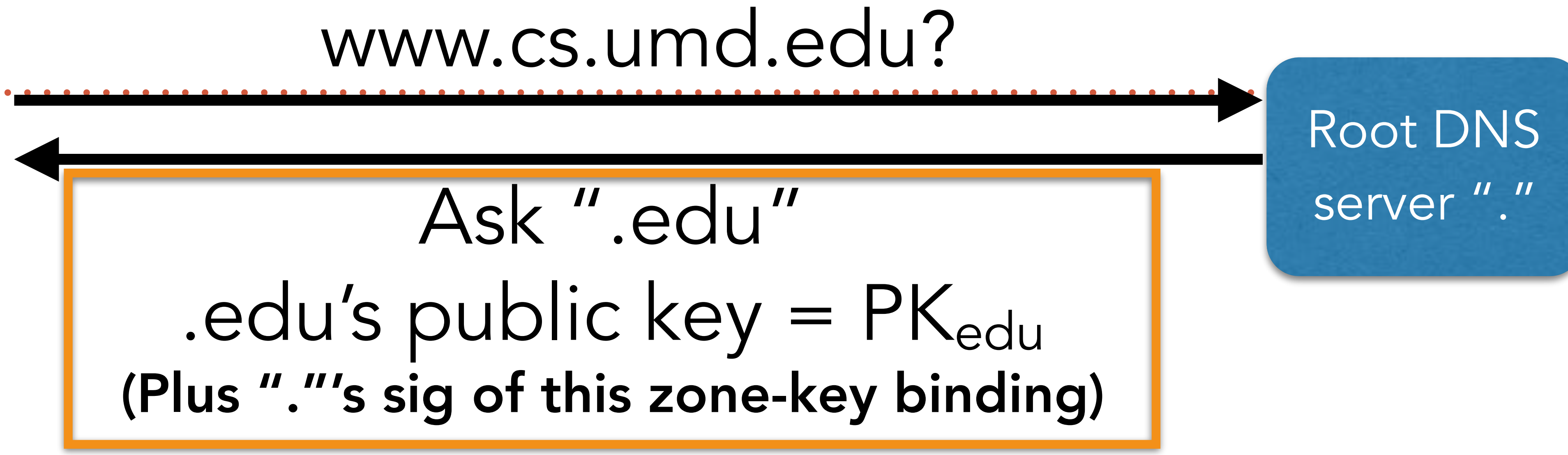
SOLUTIONS?

- Randomizing query ID?
  - Not sufficient alone: only 16 bits of entropy
- Randomize source port, as well
  - There’s no reason for it stay constant
  - Gets us another 16 bits of entropy
- DNSSEC?

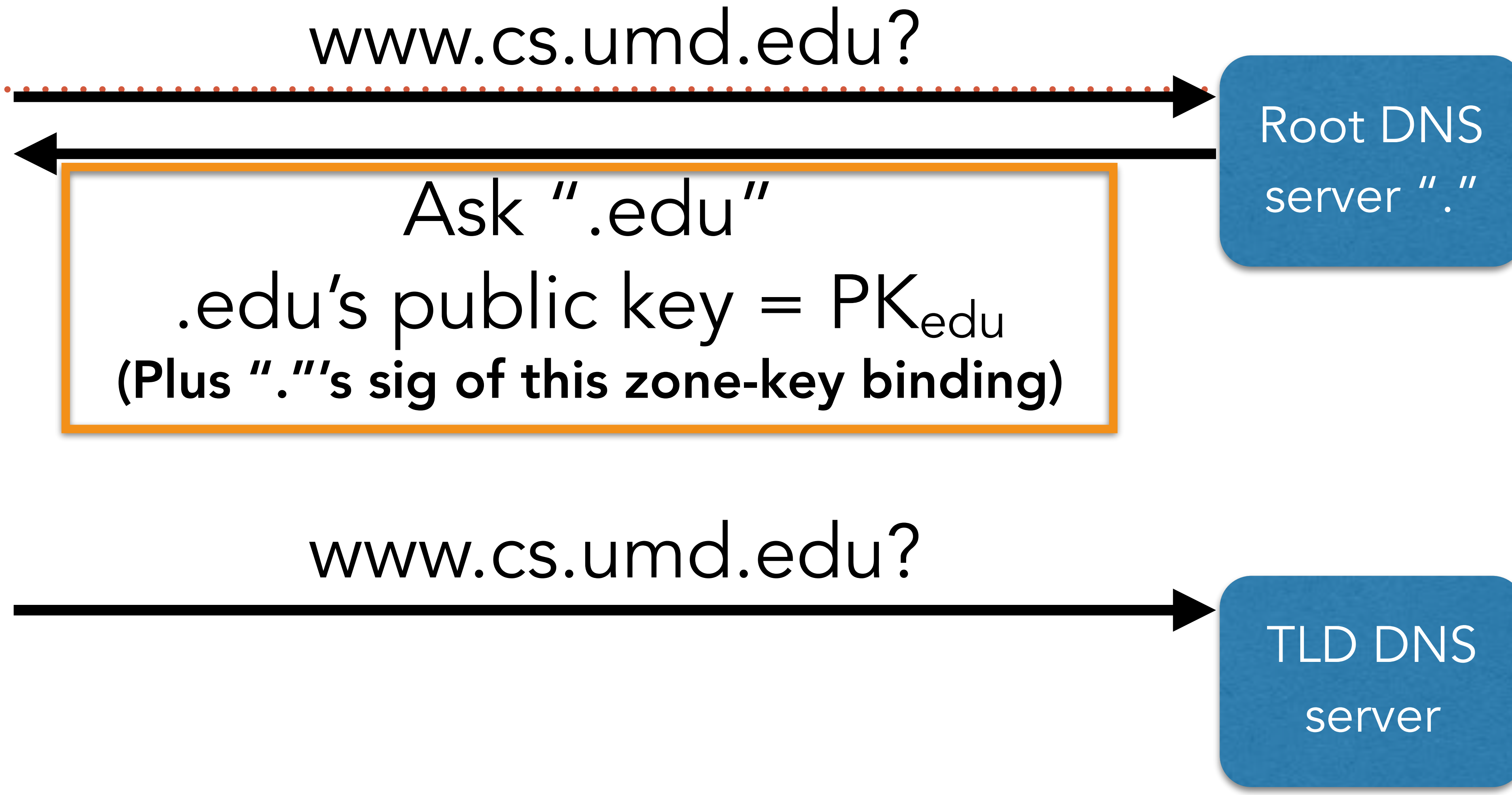
DNSSEC



DNSSEC

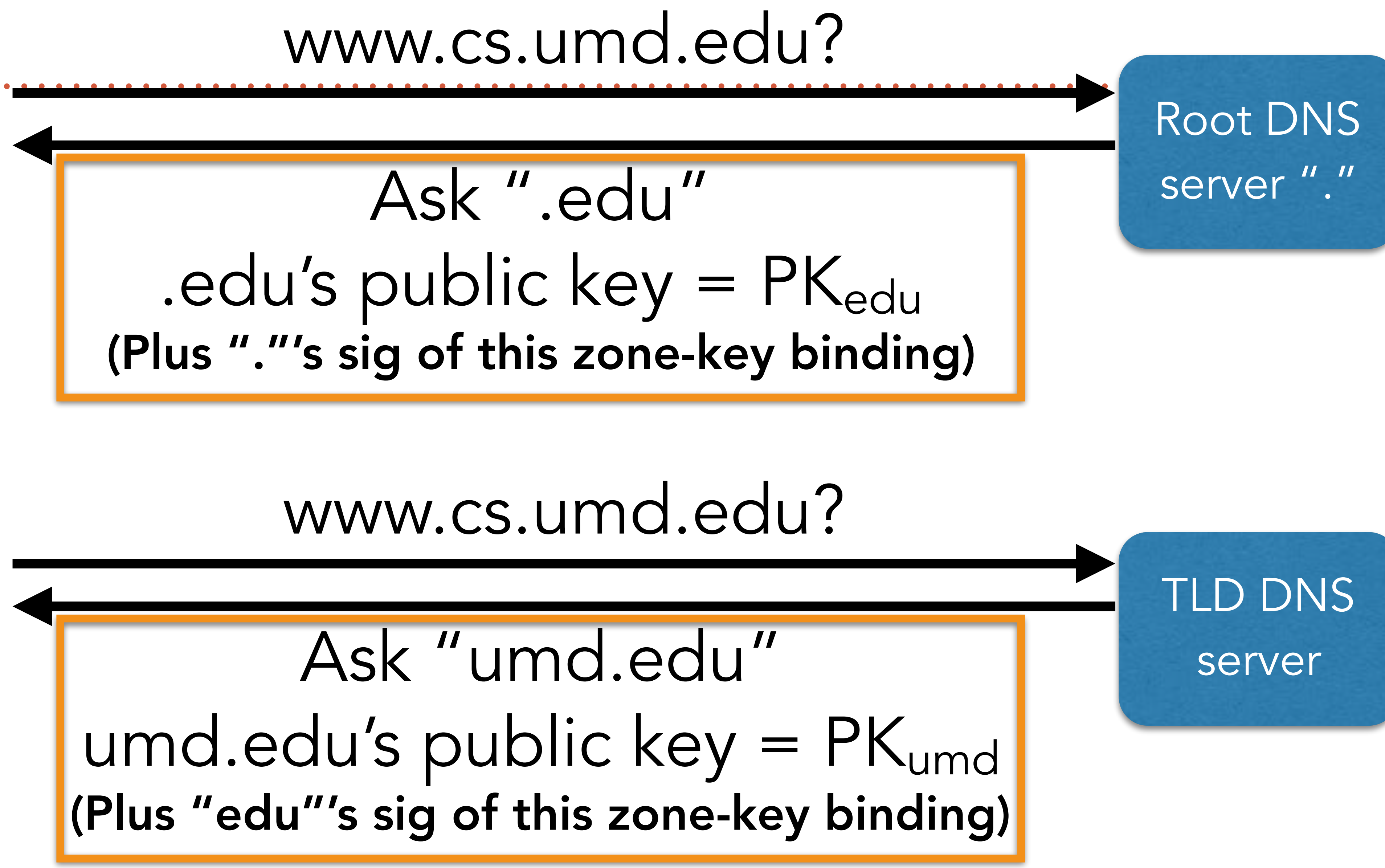

www.cs.umd.edu?
Root DNS server "."
Ask ".edu"
.edu's public key = PK_{edu}
(Plus "."'s sig of this zone-key binding)

DNSSEC



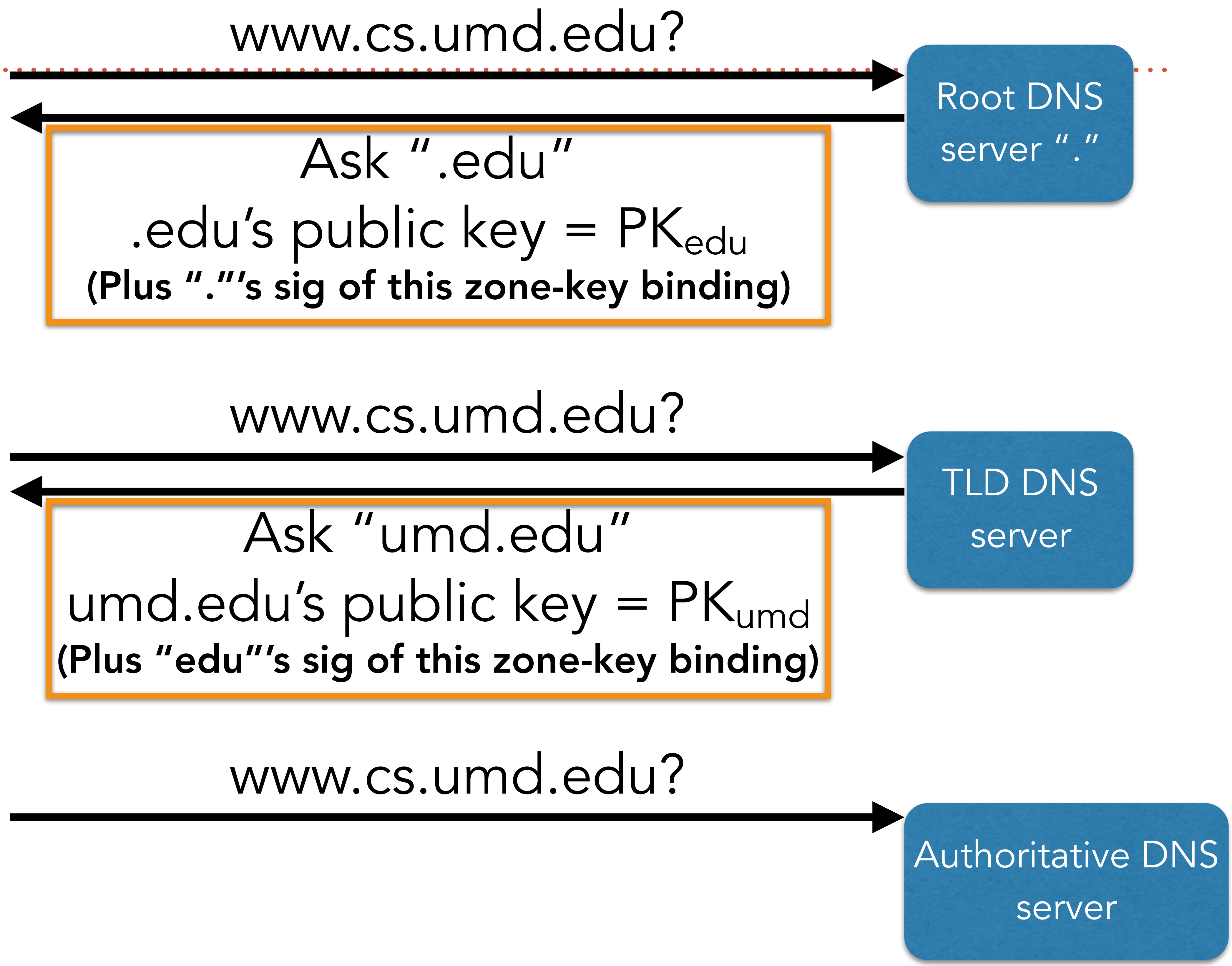
www.cs.umd.edu?
Root DNS server "."
Ask ".edu"
.edu's public key = PK$_{edu}$
(Plus "."'s sig of this zone-key binding)
www.cs.umd.edu?
TLD DNS server

DNSSEC



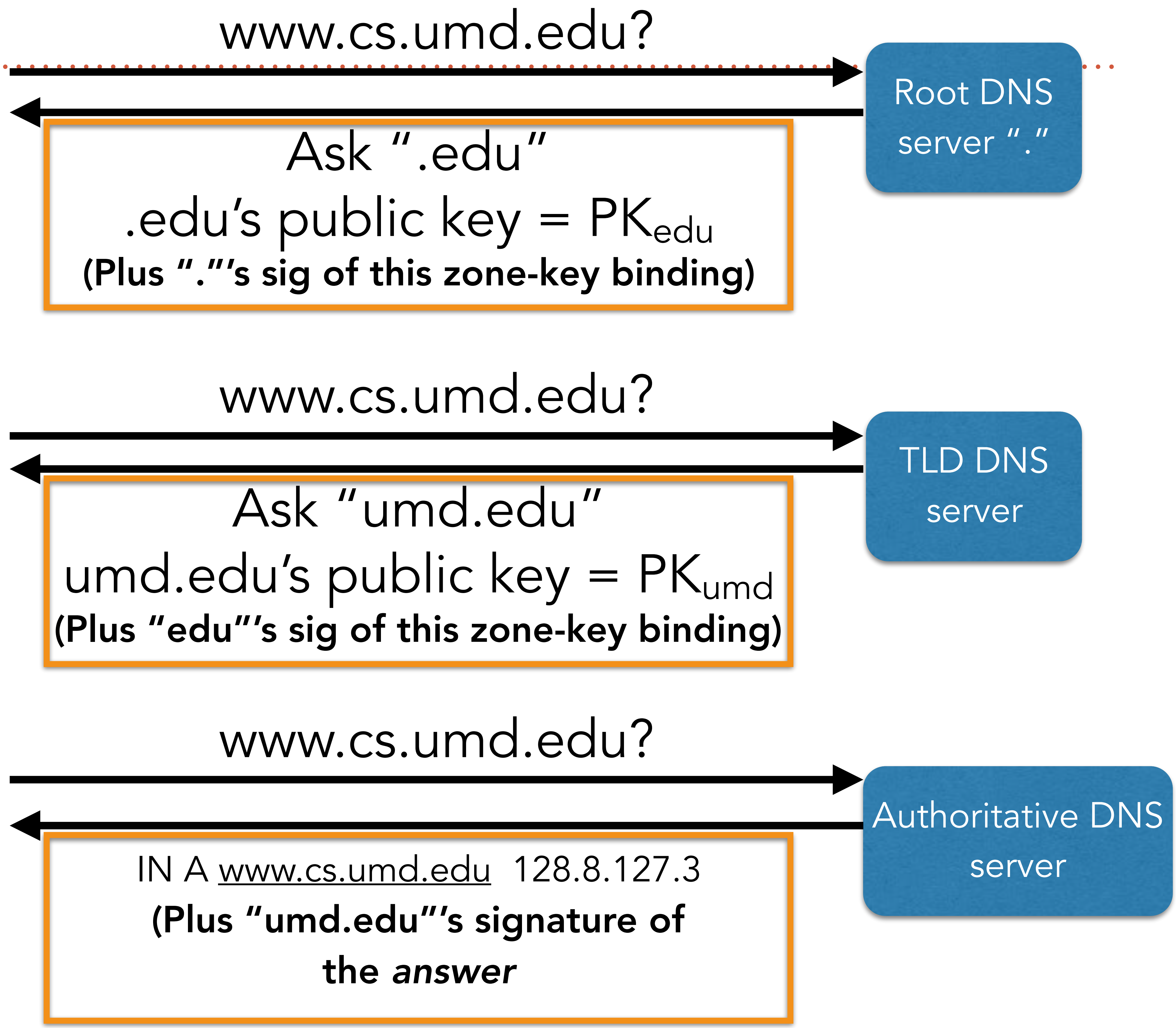
www.cs.umd.edu?
Root DNS server "."
Ask ".edu"
.edu's public key = PKedu
(Plus "."'s sig of this zone-key binding)
www.cs.umd.edu?
TLD DNS server
Ask "umd.edu"
umd.edu's public key = PKumd
(Plus "edu"'s sig of this zone-key binding)

DNSSEC

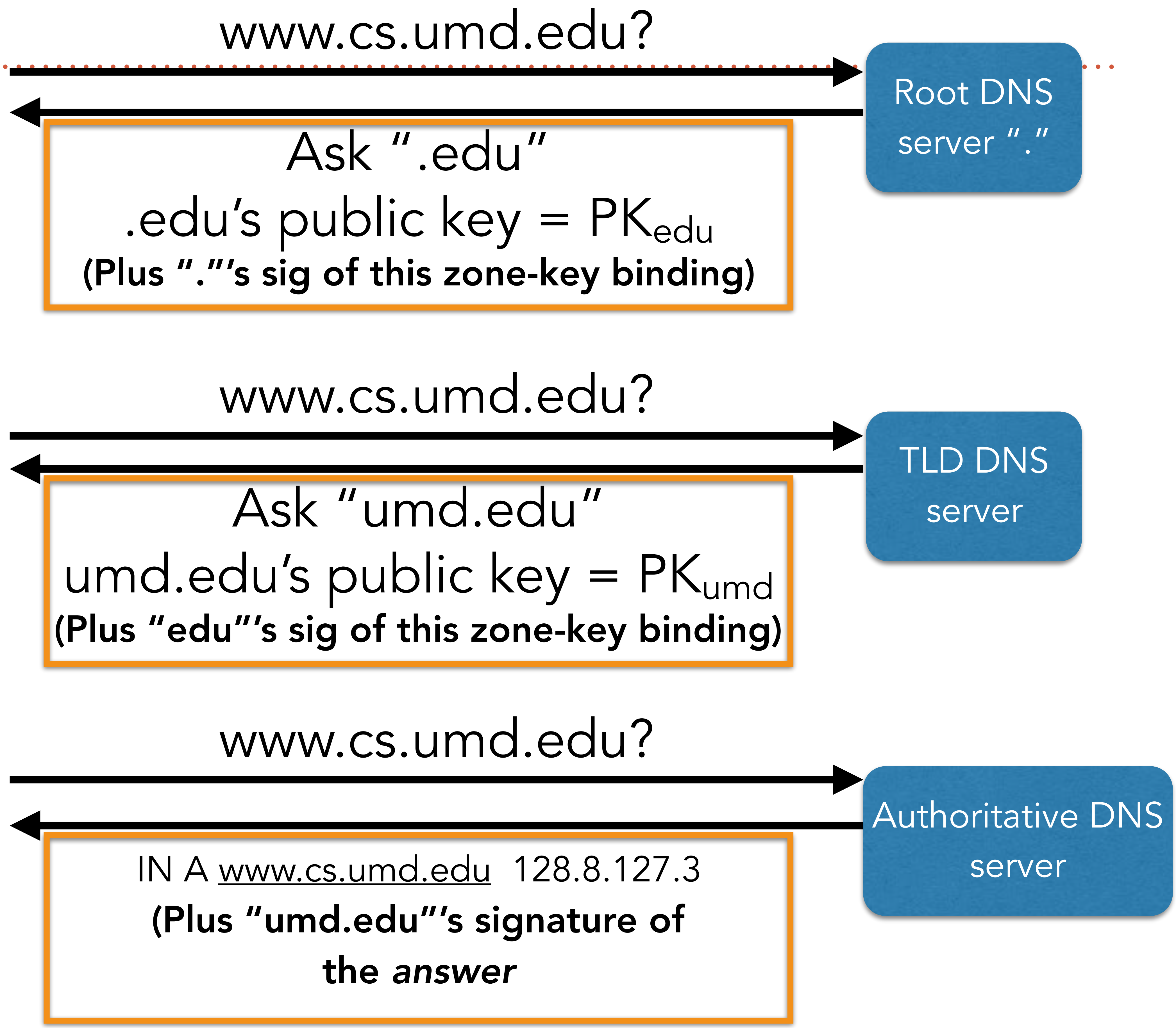


www.cs.umd.edu?
Root DNS server "."
Ask ".edu"
.edu's public key = PK_edu
(Plus "."'s sig of this zone-key binding)
www.cs.umd.edu?
TLD DNS server
Ask "umd.edu"
umd.edu's public key = PK_umd
(Plus "edu"'s sig of this zone-key binding)
www.cs.umd.edu?
Authoritative DNS server

DNSSEC


www.cs.umd.edu?
Root DNS server "."
Ask ".edu"
.edu's public key = PK$_{edu}$
(Plus "."'s sig of this zone-key binding)
www.cs.umd.edu?
TLD DNS server
Ask "umd.edu"
umd.edu's public key = PK$_{umd}$
(Plus "edu"'s sig of this zone-key binding)
www.cs.umd.edu?
Authoritative DNS server
IN A www.cs.umd.edu 128.8.127.3
(Plus "umd.edu"'s signature of the *answer*

DNSSEC



Only the authoritative answer is signed

PROPERTIES OF DNSSEC

- If everyone has deployed it, and if you know the root's keys, then prevents spoofed responses
  - Very similar to PKIs in this sense
- But unlike PKIs, we still want authenticity despite the fact that not everyone has deployed DNSSEC
  - What if someone replies back without DNSSEC?
  - Ignore = secure but you can't connect to a lot of hosts
  - Accept = can connect but insecure
- Back to our notion of incremental deployment
  - DNSSEC is not all that useful incrementally