Computer Organization and Networks

Chapter 9: Networking Ⅱ

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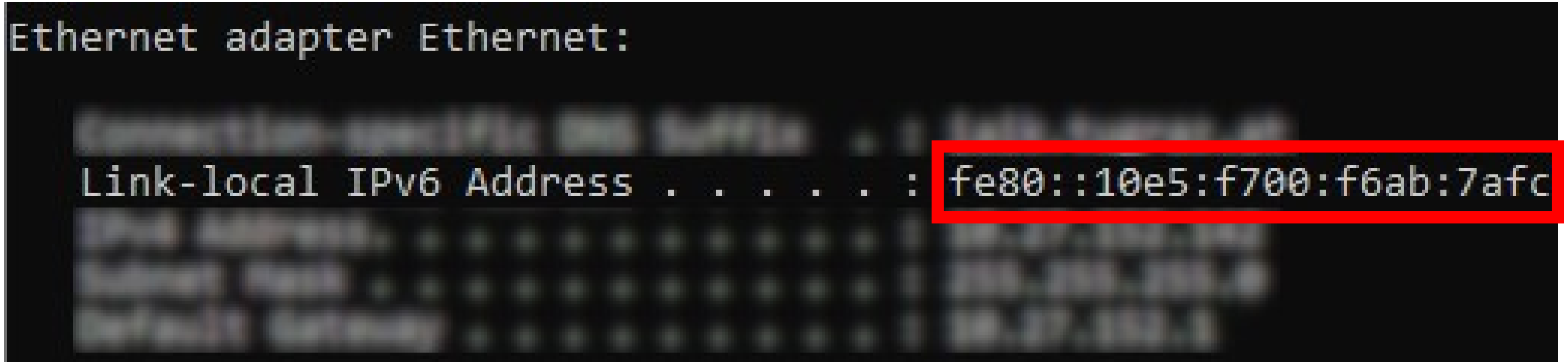
IPv6

- **I**nternet **P**rotocol, **v**ersion **6**
- Successor to IPv4

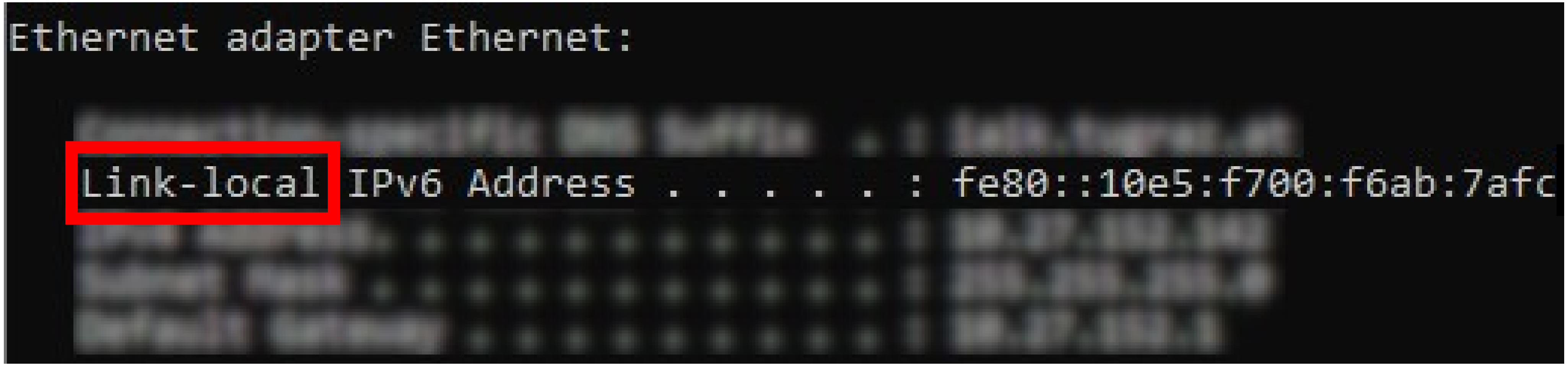
- Not natively interoperable with IPv4
  - IPv4-only devices cannot communicate with IPv6-only devices
  - Most modern devices implement *both* IPv4 and IPv6
  - Eventually, IPv4 will be phased out…

IPv6 addressing



- 128-bit address
  - Notation: 16-bit hexadecimal blocks separated by colons (`:`)
  - Zero blocks can be omitted using double colon (`::`)
  - **`fe80::10e5:f700:f6ab:7afc`** is the same as
    `fe 80 00 00 00 00 00 00 10 e5 f7 00 f6 ab 7a fc`

IPv6 addressing



- 64-bit *network prefix*, 64-bit *interface identifier*
- A single interface (e.g.: a network card) may have multiple addresses
  - Addresses share the *interface identifier*
- Addresses have a *scope* in which they are valid

IPv6 scoping

- Global addresses
  - Valid in any network connected to the internet
  - May be routed on the public internet
- Unique-local addresses (in **`fc00::/7`**)
  - Same idea as IPv4 private networks
    - No assignment/registration needed
    - Routed only in local networks, but *not* on the public internet
- Link-local addresses (in **`fe80::/64`**)
  - Only valid within the Link Layer network

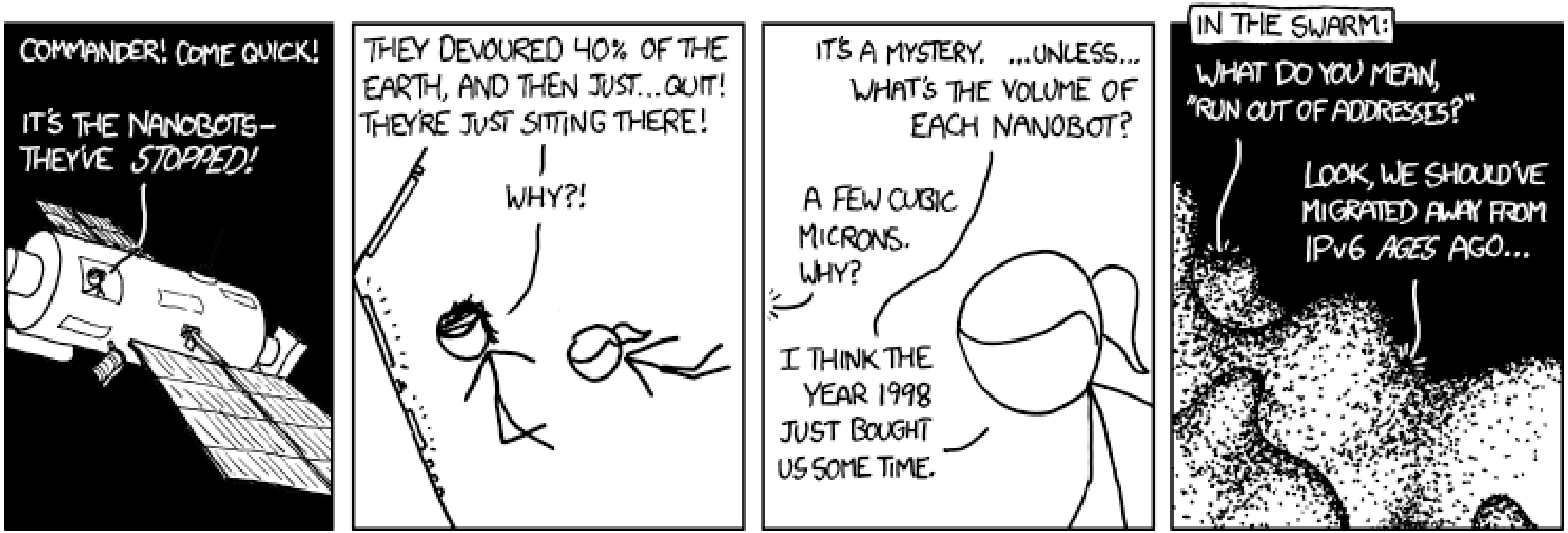
IPv6 packet overview

Offsets	Octet	0								1								2								3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	0	*Version*				*Traffic class*								*Flow label*																			
4	32	*Payload length*																*Next header*								*Hop limit*							
8	64	*Source address*																															
12	96																																
16	128																																
20	160																																
24	192	*Destination address*																															
28	224																																
32	256																																
36	288																																

- Similar fields to IPv4 packets
  - Version is always `0110` (version 6)
  - Length, Source and Destination fields
  - Optional extension header blocks
- Header checksum removed
  - Relies on Link Layer to provide error detection
- Fragmentation (mostly) removed
  - No fragmentation by routers
  - Fragmentation by hosts only as an extension
    - Transport Layer is expected to perform fragmentation

IPv6 recap

- Successor to IPv4
  - “Permanent” solution to IP address exhaustion
    - We’ll talk about IPv4 workarounds in a bit!
  - Some protocol-level improvements
  - Not interoperable with IPv4
- Supported by most modern end-user devices
  - Server-side support is… still lacking [https://ipv6.watch]
- 128-bit addresses (64-bit network part, 64-bit interface identifier)
  - 2^{64} networks, each consisting of 2^{64} hosts



xkcd #865 “Nanobots” | Randall Munroe | *https://xkcd.com/*

Image: own work, derived from Public Domain

The Transport Layer

The Transport Layer

- Computers A and B are capable of sending data to each other
- **Goal:** Allow multiple applications to communicate reliably

- Concerns:
  - How to distinguish which application data is meant for? (multiplexing)
  - What if data is lost on the lower layers? (reliability)
  - How much data can the network handle? (congestion control)
  - How much data can the receiver handle? (flow control)

The Transport Layer

- The internet has two widely-used protocols at the Transport Layer:
  - **T**ransmission **C**ontrol **P**rotocol
    - Focused on reliable delivery
    - Connection-based
  - **U**ser **D**atagram **P**rotocol
    - Focused on speed
    - Connectionless

The Transport Layer: Ports

- Concept used for both TCP and UDP
- Source and destination identified by *port number*
  - 16 bits (65536 available ports)
  - TCP and UDP ports are *separate*
    - The protocols implement the same idea, but each only cares about its own ports…
- Common notation: Port number after IP address
  - **`127.0.0.1:8000`** is port 8000 at host 127.0.0.1
  - **`[::1]:8000`** is port 8000 at host ::1

UDP

- Fire-and-forget transmission of single datagrams
  - Useful for real-time applications
- Data may never arrive, may arrive out of order, …
  - Data loss must be tolerable for the upper-layer application
- Extremely simple and straightforward

UDP datagram header

Offsets	Octet	0								1								2								3							
Octet	Bit	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
0	0	Source port																Destination port															
4	32	Length																Checksum															

TCP

- Highly reliable transmission of a byte stream
  - Acknowledgments and re-transmission
  - Guaranteed to maintain data ordering
- Non-trivial protocol overhead
  - Still better than re-inventing the wheel if you need it!

TCP

- TCP connections have two sides: *server* and *client*

- *Server* listens on a specific port
  - Server port is fixed for all connections
- *Client* connects to that port on the server
  - Client uses a “random” ephemeral port, different for each connection
  - See for yourself: **`netstat –onb`** (Win) or **`netstat –tnap`** (Linux, Mac)

- Connections are uniquely identified by *client IP* + *client port*

The Transport Layer: Ports 2

- Two applications can't use the same port number
- Client needs to know which port number to connect to

- Port numbers are standardized by IANA
  - 0–1023: *well-known* ports
    - Examples: 22 (SSH), 80 (HTTP), 123 (NTP), 194 (IRC), 443 (HTTPS), …
  - 1024–49151: *registered* ports
    - Most server applications will use this range (even unregistered ones…)
  - 49152–65535: *dynamic* ports
    - Most OS will use this range for ephemeral (client) ports

TCP packet overview

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<tr><th>8</th><th>64</th><td colspan="32">[illegible]</td></tr>
<tr><th>12</th><th>96</th><td colspan="16">[illegible]</td><td colspan="16">[illegible]</td></tr>
<tr><th>16</th><th>128</th><td colspan="16">Checksum</td><td colspan="16">[illegible]</td></tr>
</table>

- Source + destination ports allow identification of connection
- Checksum over entire header + data

TCP data ordering

Offsets	Octet	0								1								2								3							
Octet	Bit	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0
0	0	[illegible]																[illegible]															
4	32	Sequence number																															
8	64	Acknowledgment number (if ACK set)																															
12	96	[illegible]				[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	ACK	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]															
16	128	[illegible]																[illegible]															

- TCP maintains a *sequence number* across the entire connection
  - Separate number for each end’s packets
- Receipt of contiguous data confirmed via *acknowledgment number*
  - Acknowledgement number := next expected sequence number
- This allows ordering of data and re-sending of lost packets!

TCP data ordering

Offsets	Octet	0								1								2								3							
Octet	Bit	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0
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16	128	[illegible]																[illegible]															

- Connection establishment: Three-way handshake
  - Client -> Server: **`SYN`**
  - Server -> Client: **`SYN + ACK`**
  - Client -> Server: **`ACK`**

TCP data ordering

Offsets	Octet	0								1								2								3							
Octet	Bit	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0
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16	128	[illegible]																[illegible]															

- Client -> Server: **SYN**
  - Sequence number: **seq_c**, chosen randomly

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- Server -> Client: **`SYN + ACK`**
  - Sequence number: **`seq_s`**, chosen randomly
  - Acknowledgement: **`seq_c+1`**

TCP data ordering

Offsets	Octet	0								1								2								3							
Octet	Bit	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0	7	6	5	4	3	2	1	0
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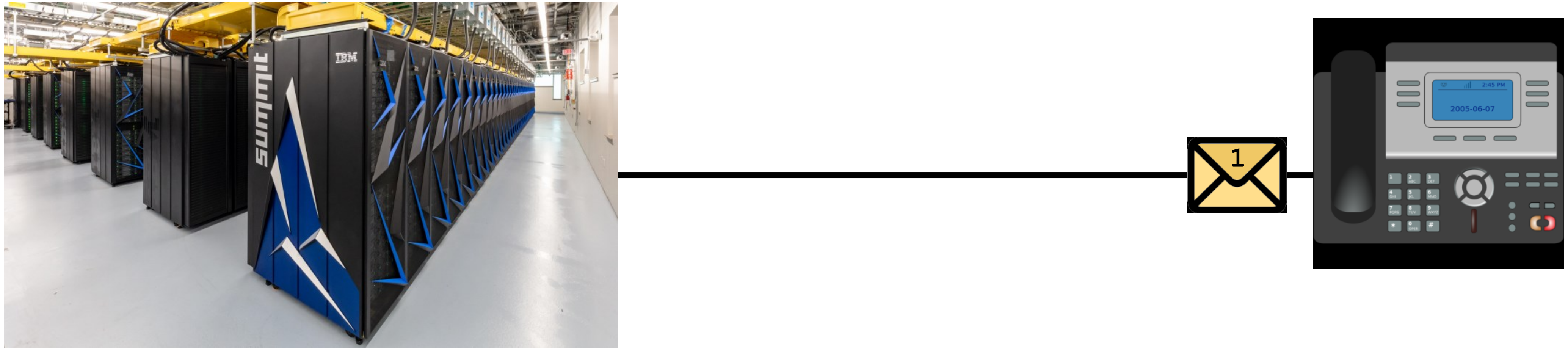
16	128	[illegible]																[illegible]															

- Client -> Server: **`ACK`**
  - Sequence number: **`seq_c+1`**
  - Acknowledgement: **`seq_s+1`**

- Now both sides know that the other side has their sequence number
  - Ready to communicate!

TCP flow control

- Imagine: a supercomputer talking to a desk phone via a 100Gbps link



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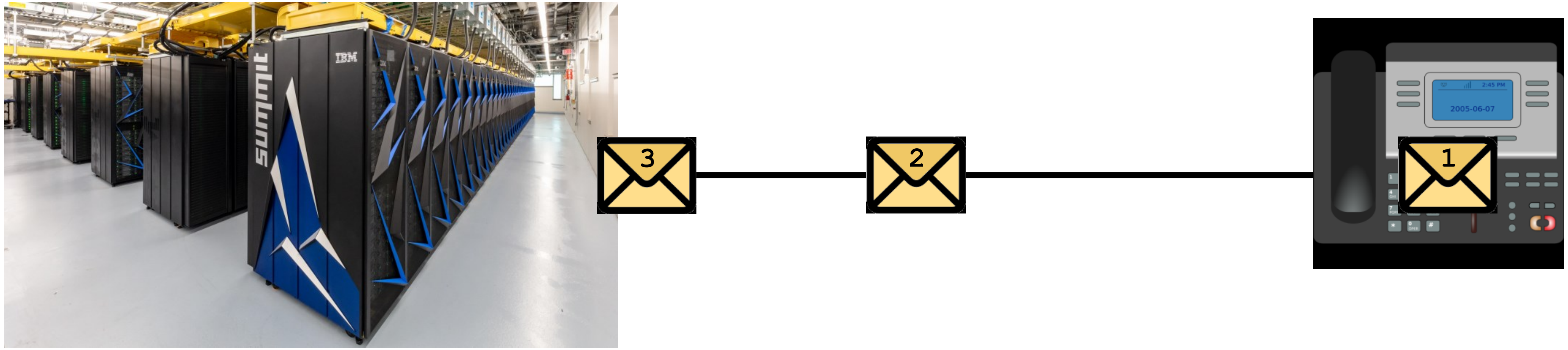

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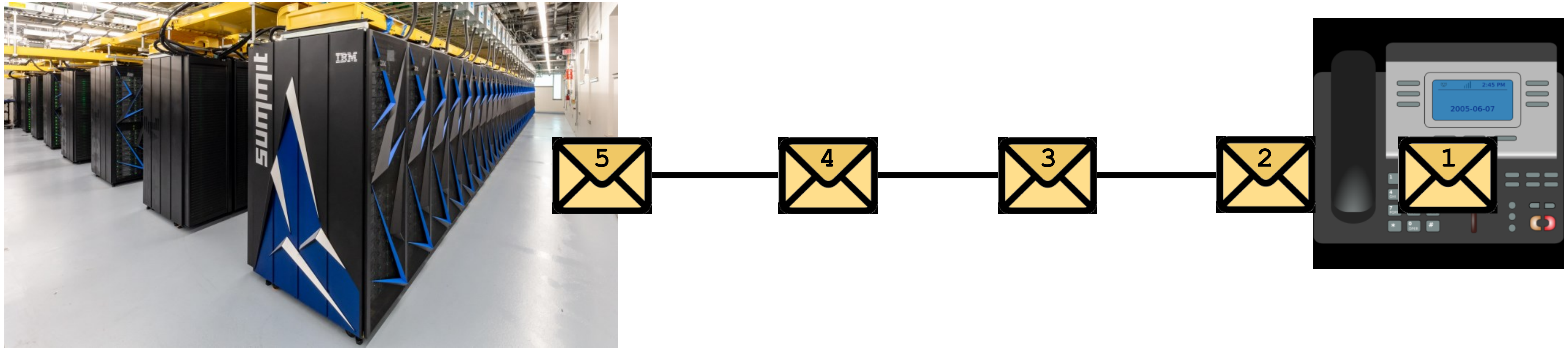

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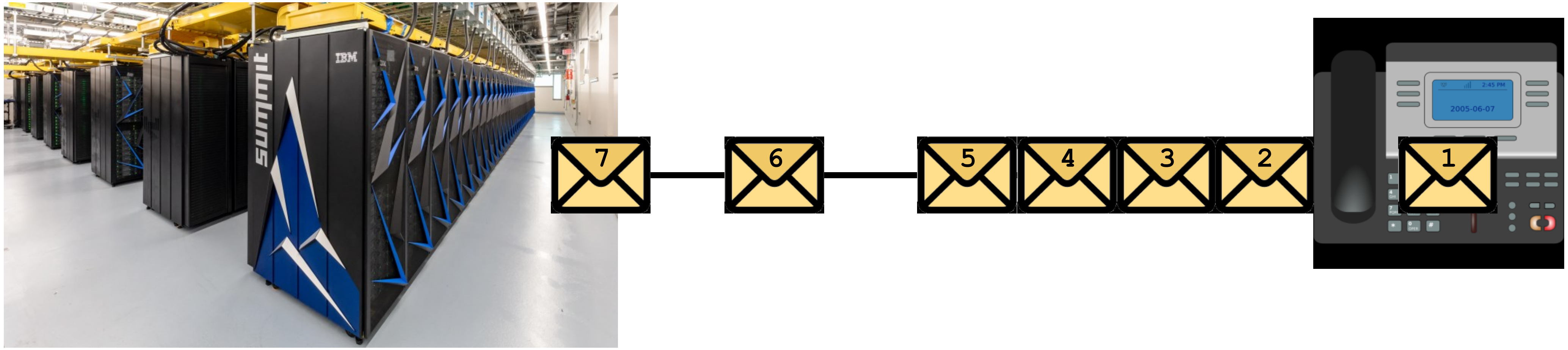

- The desk phone doesn’t stand a chance to keep up!

TCP flow control

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<tr><td>12</td><td>96</td><td colspan="4">Data offset</td><td colspan="3">Reserved
0 0 0</td><td>N S</td><td>C W R</td><td>E C E</td><td>U R G</td><td>A C K</td><td>P S H</td><td>R S T</td><td>S Y N</td><td>F I N</td><td colspan="16">Window Size</td></tr>
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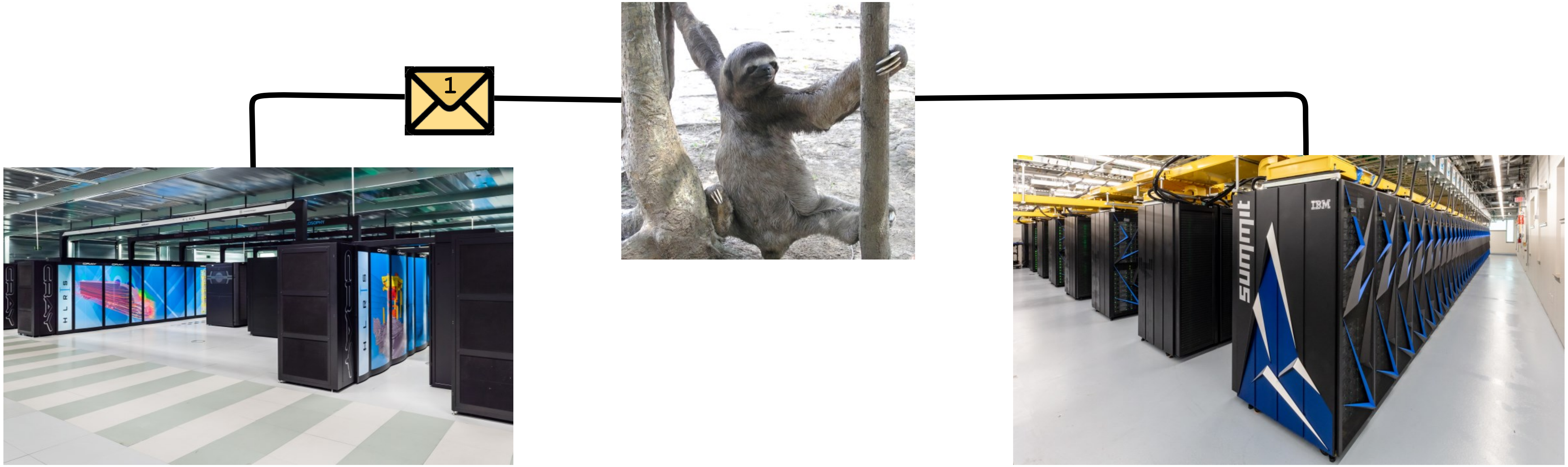
</table>

- Imagine: a supercomputer talking to a desk phone via a 100Gbps link

- *Window size* indicates how much more data the host can handle
- The other end must throttle its transmission rate to accommodate
  - Window size is relative to the last ACK'd packet

TCP congestion control

- Imagine: two supercomputers talking via a dial-up connection
  - Keep in mind: the “dial-up connection” could be some intermediate network



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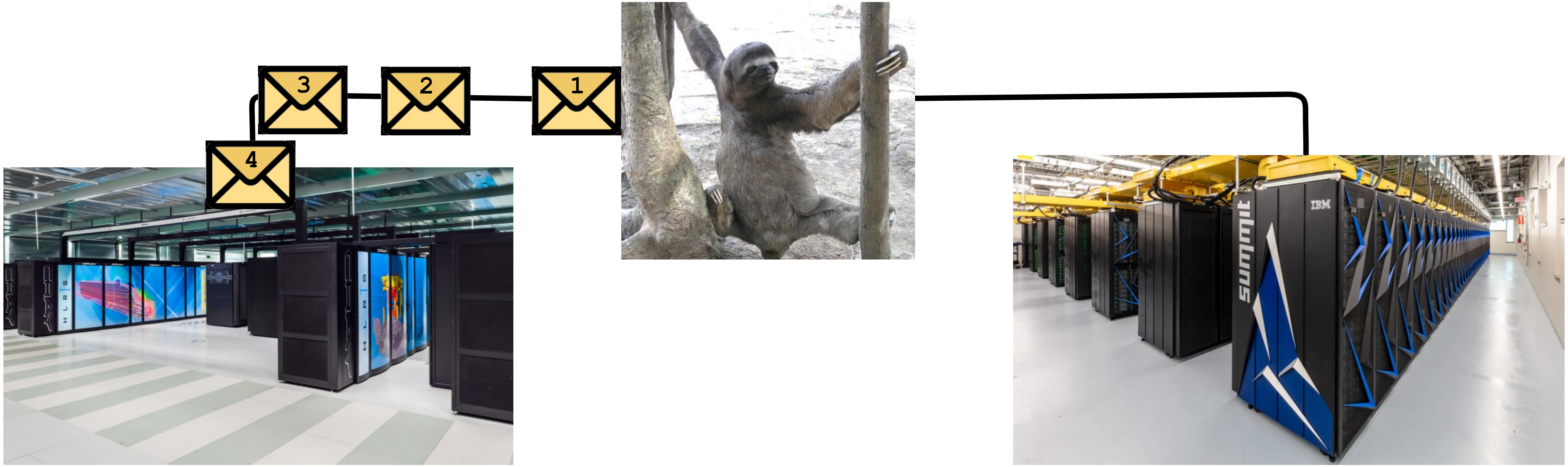

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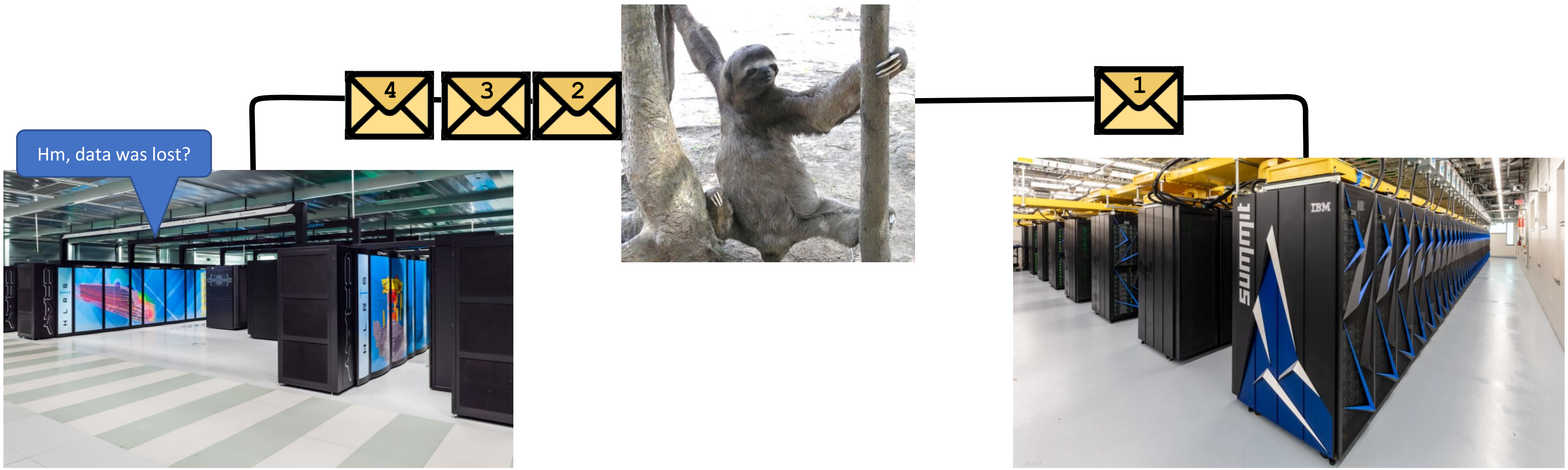

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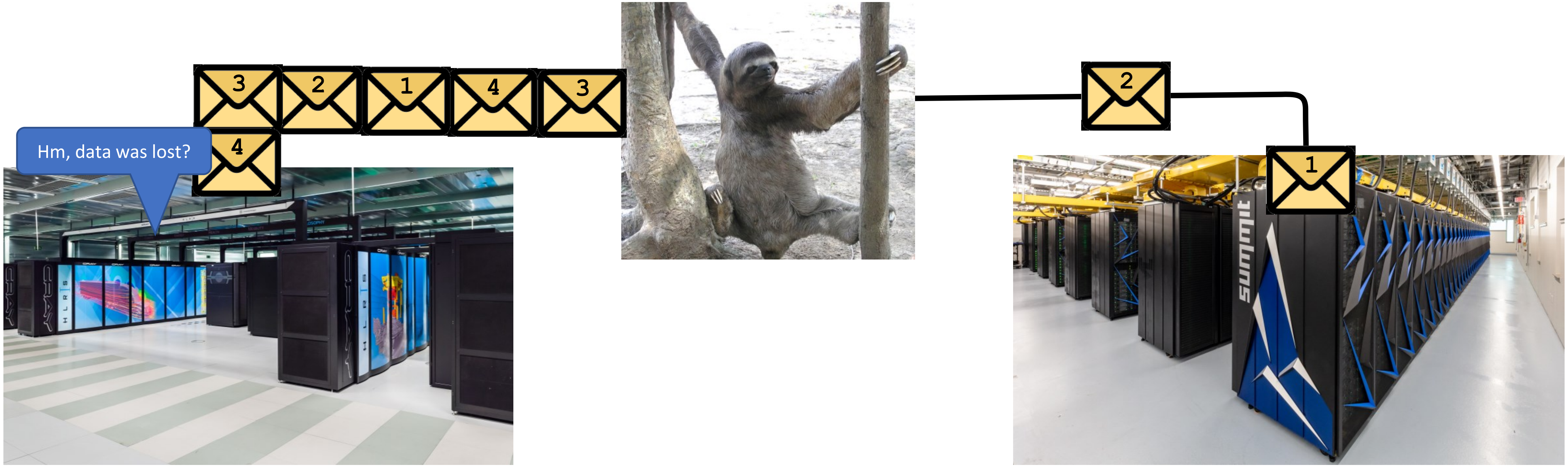

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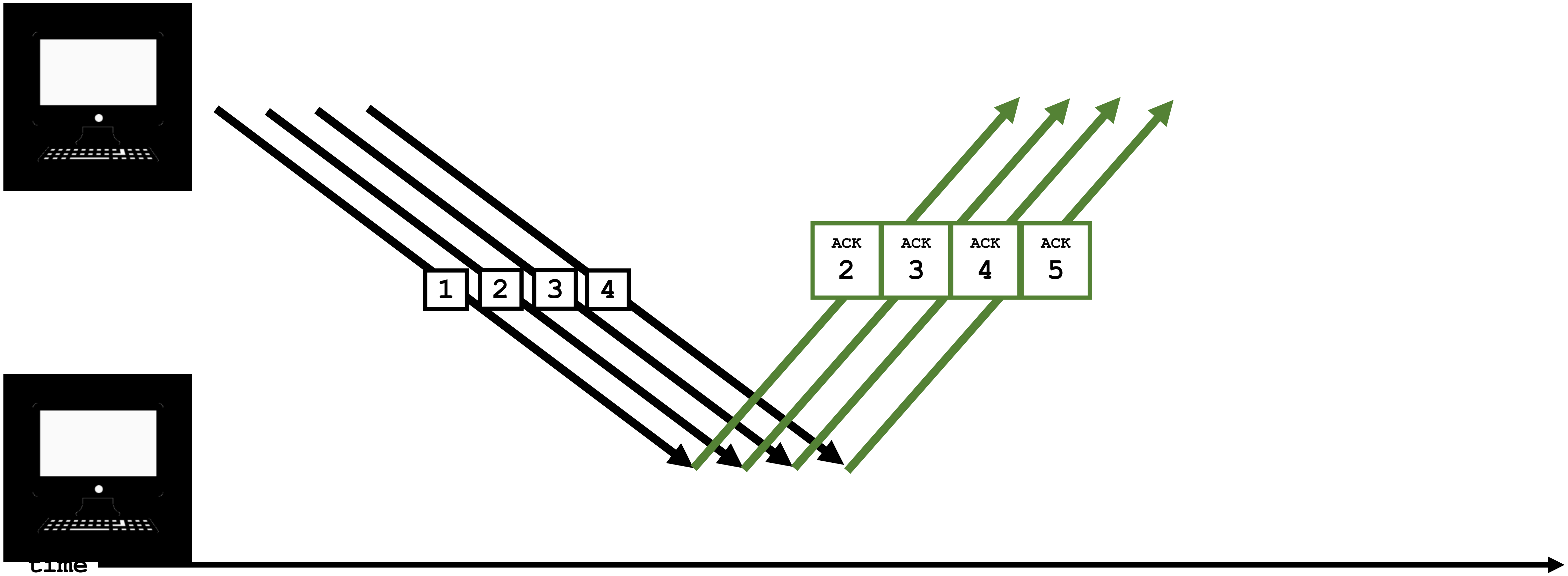
- If you just keep shoving data…
    - … it will get stuck in a queue somewhere …
        - ... so you think it was lost and send it again …
            - … now your queue is twice the size …
                - … and nothing useful gets done.

- How do we avoid that?

TCP congestion control

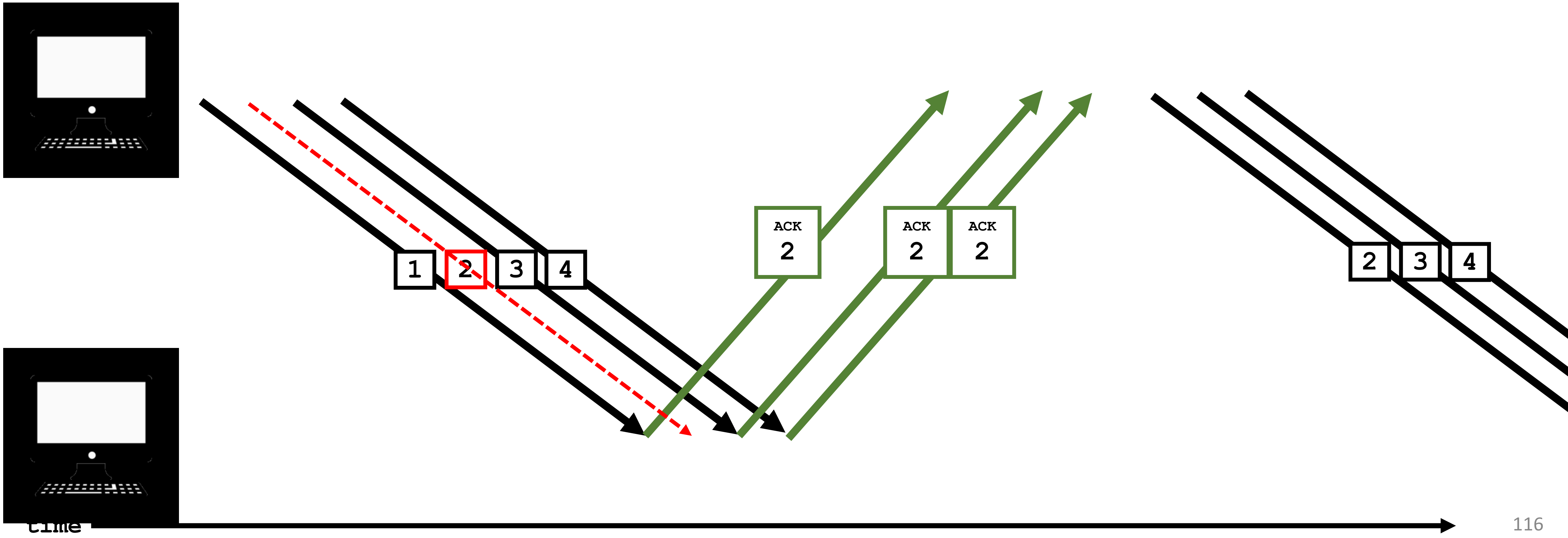
- Each side throttles its data transmission rate independently
  - No cooperation required
  - Different OS have different algorithms
- Basic concept:
  - Start at a relatively slow rate, then increase speed until data gets lost
  - Once data is lost, assume we overloaded the connection and slow down again
- Details differ from OS to OS

TCP: Selective Acknowledgment



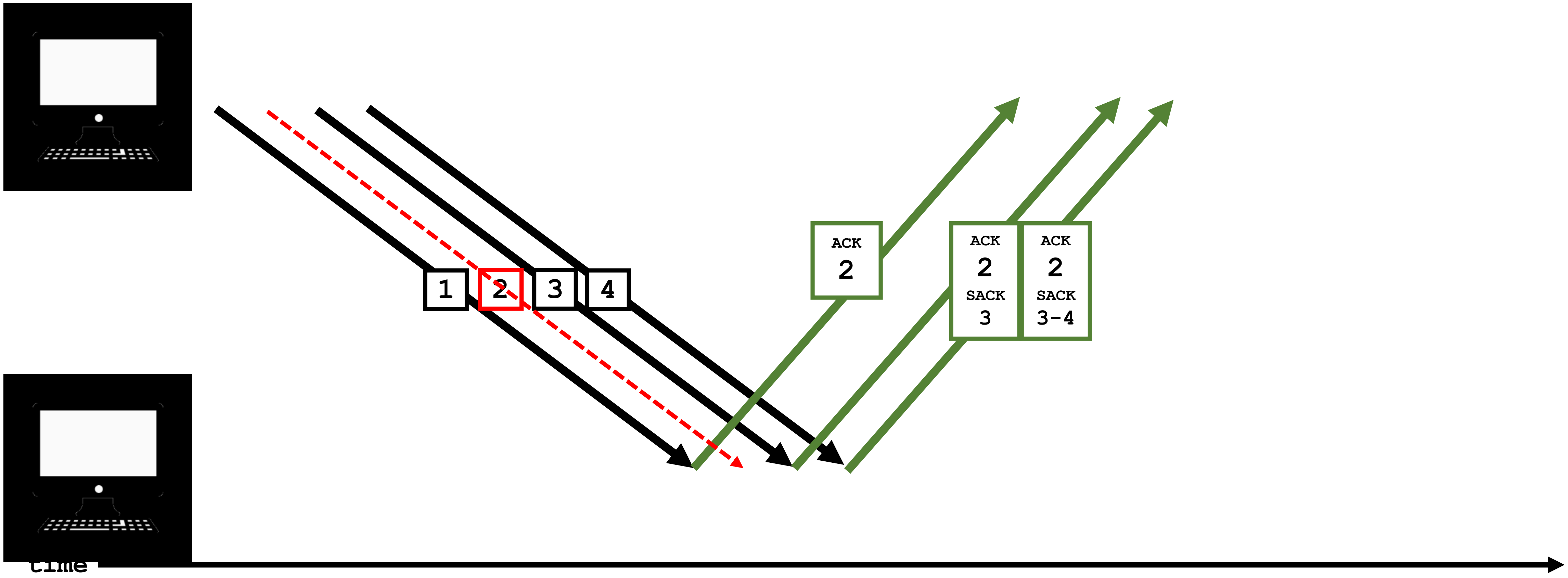
TCP: Selective Acknowledgment

- “Standard” TCP does not deal with packet loss efficiently
  - Superfluous data is re-sent, wasting time and bandwidth!



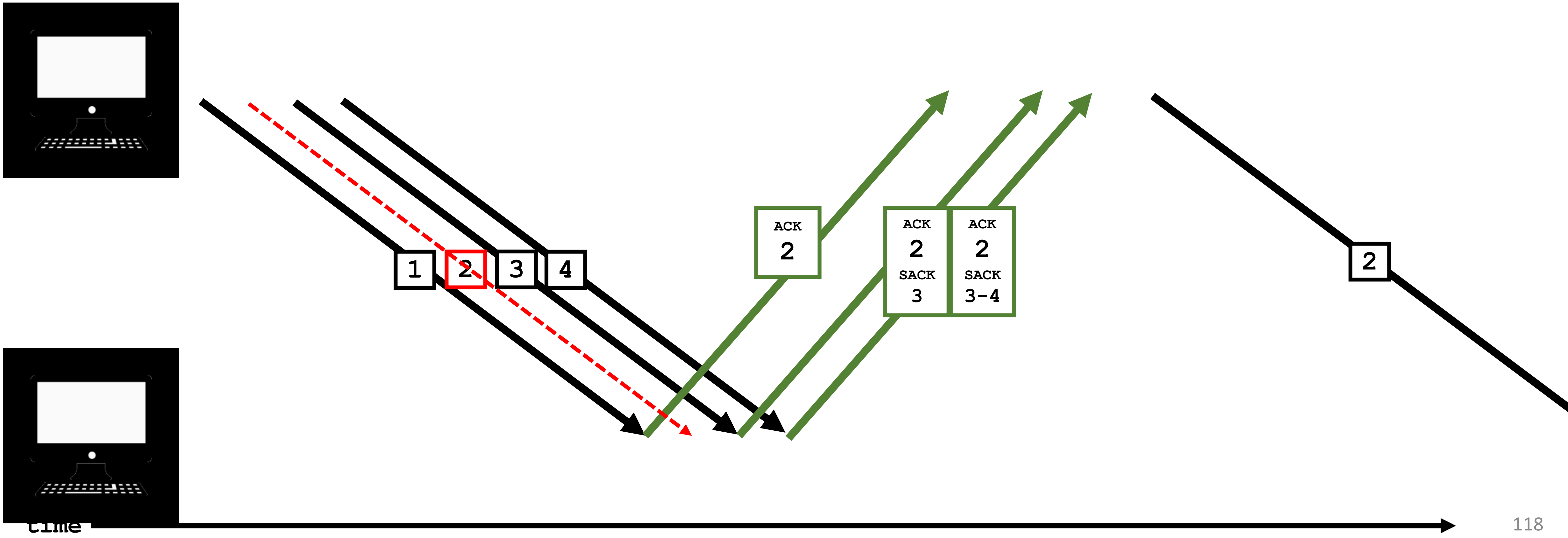
TCP: Selective Acknowledgment

- The SACK extension lets the recipient acknowledge further ranges



TCP: Selective Acknowledgment

- The SACK extension lets the recipient acknowledge further ranges
  - These ranges do not need to be re-sent!



Transport Layer recap

- Two main protocols: TCP and UDP
  - TCP: highly reliable, but comes with overhead
  - UDP: low overhead, but no reliability guarantees
- *Port numbers* identify target application
  - By convention, low port numbers (0–1023) are reserved for specific services
  - 1024–49151 are used by other servers
  - 49152–65535 are used for ephemeral ports

TCP recap

- *Client* establishes connection to *Server*
  - Server listens on a pre-agreed port
  - Client uses a “random” port (49152–65535)
- *Sequence numbers* and *acknowledgement numbers*
  - Client and server have separate counters
  - Acknowledgement of received data using the other side’s counter
  - Re-ordering and re-sending if necessary

TCP recap

- ***Flow Control*** protects the ***recipient***
  - Recipient advertises its capacity
  - Sender has to abide by it
- ***Congestion Control*** protects the ***network***
  - Transmission rate is gradually increased
    - Throttled back if packet loss is detected
  - Each side handles this independently
  - Details differ from OS to OS

The Network Layer

(again?)

Recap: IPv4 address exhaustion

- IPv4 addresses are 32 bits long
  - 2^{32} is about 4 billion
- Every Internet-enabled device needs an address to communicate
  - There are a lot of devices
- The internet is (mostly) out of IPv4 addresses!

Port Address Translation

- “Hide” an entire private network behind a single public IP
    - Rewrite IP packets at the boundary

- Also known as:
    - “PAT”
    - Network Address Translation (“NAT”)
    - Network Address and Port Translation (“NAPT”)
    - NAT overloading
    - IP masquerading

Port Address Translation

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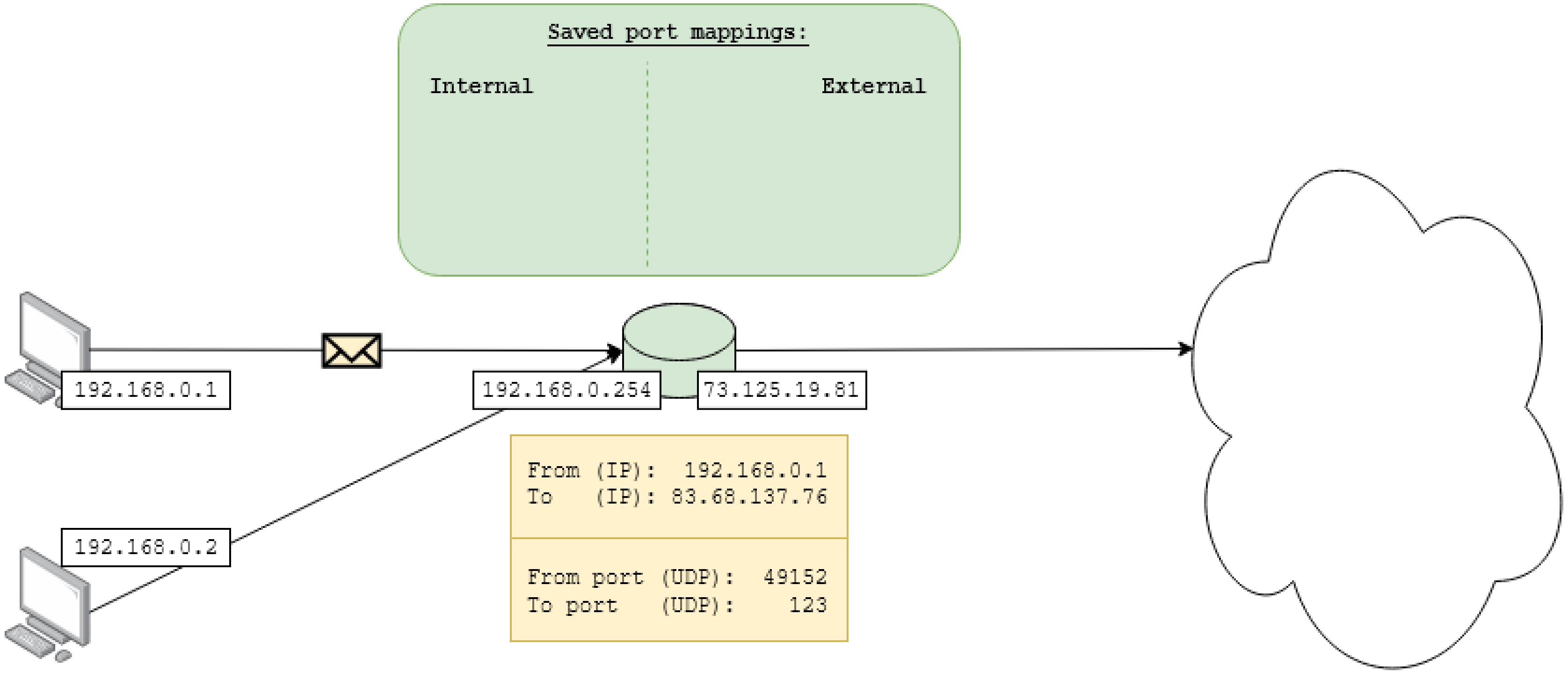

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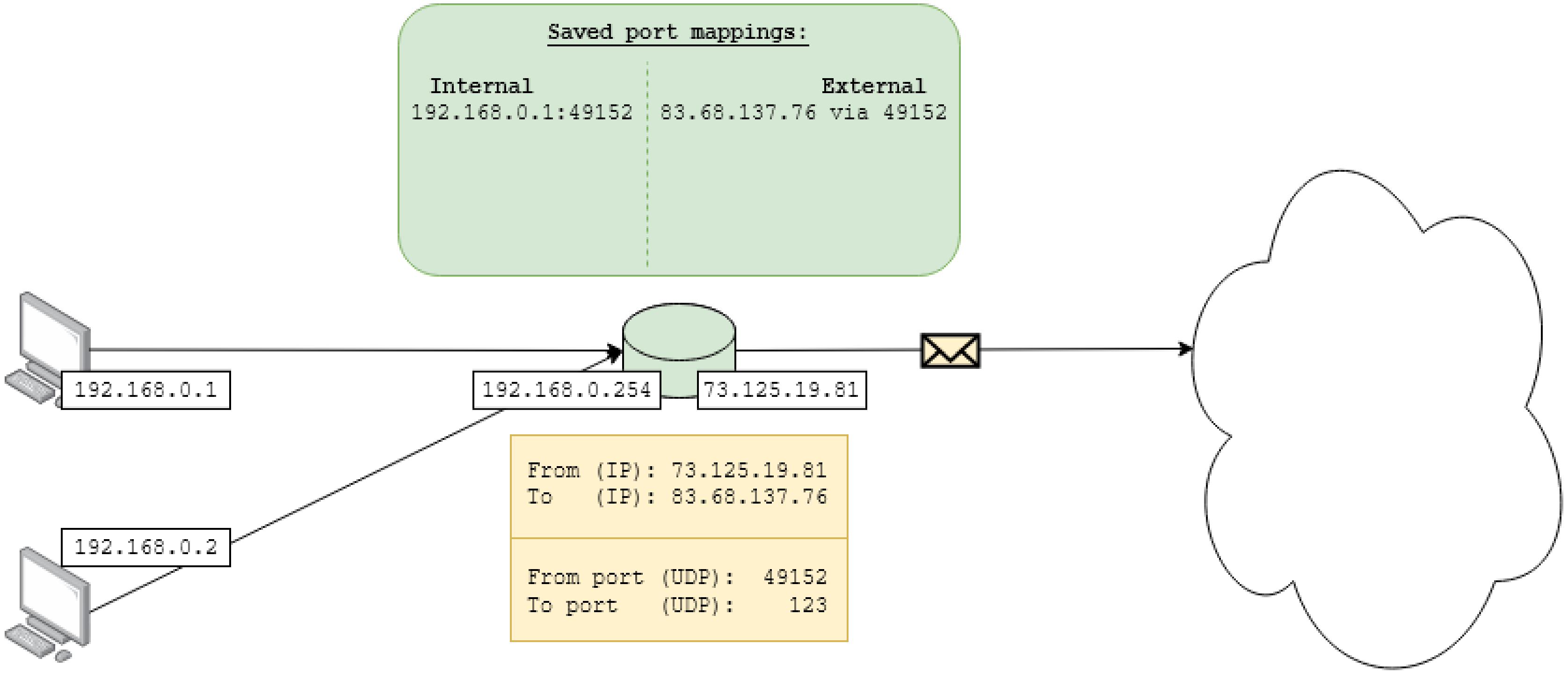

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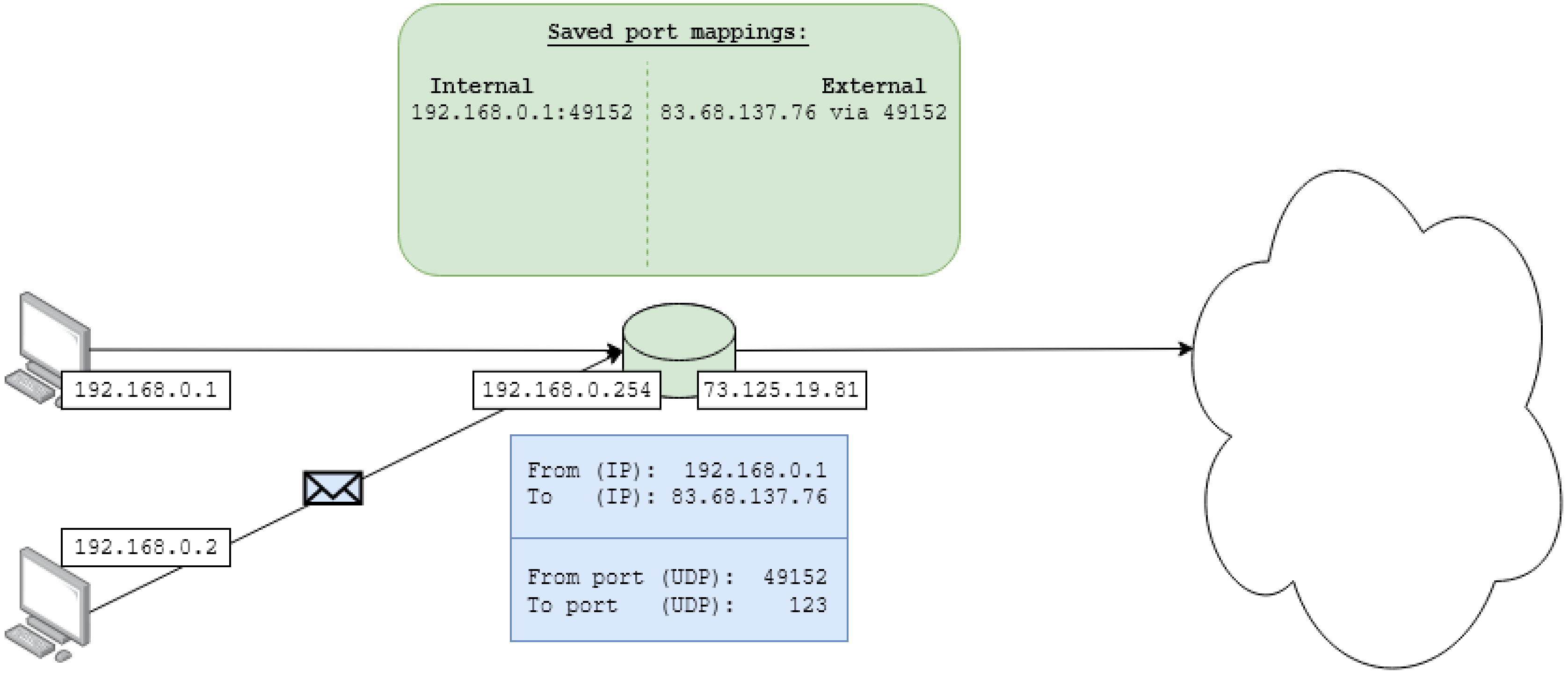

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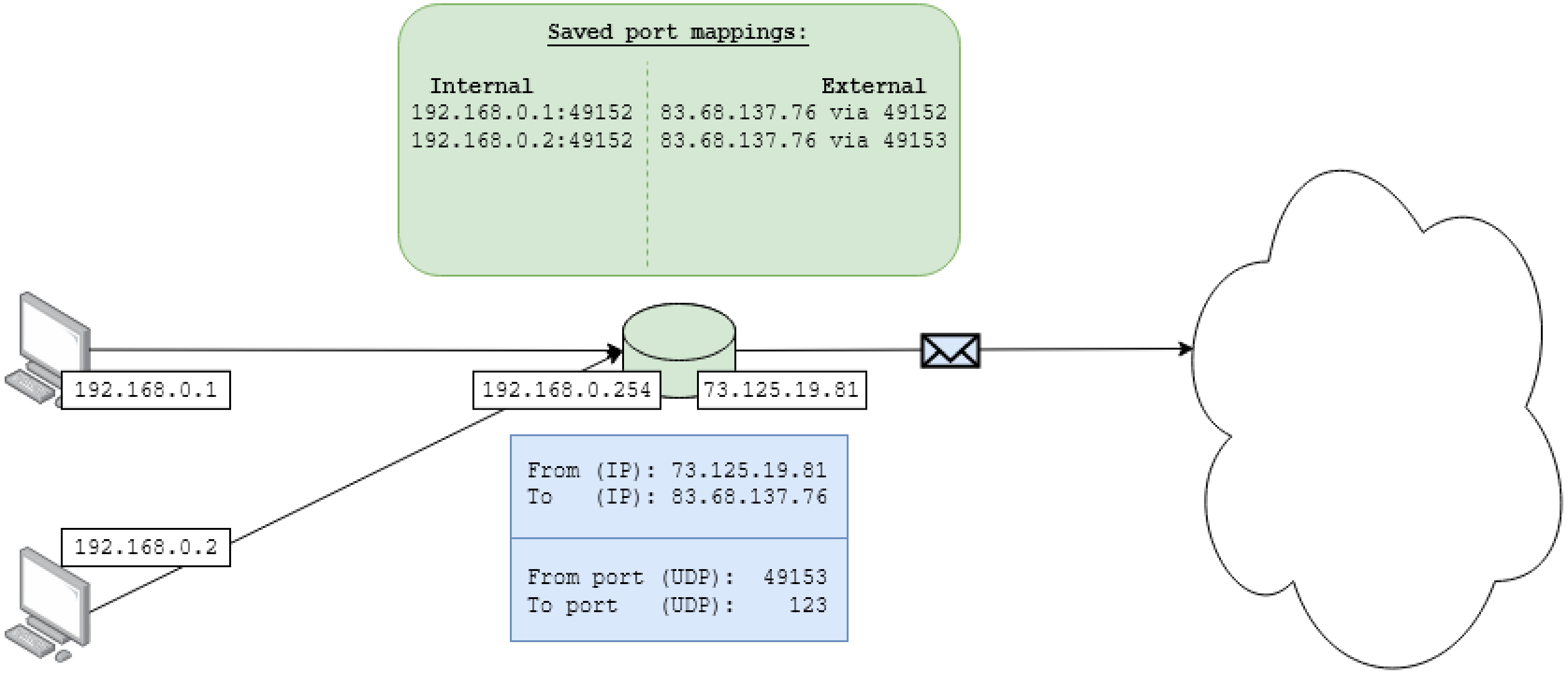

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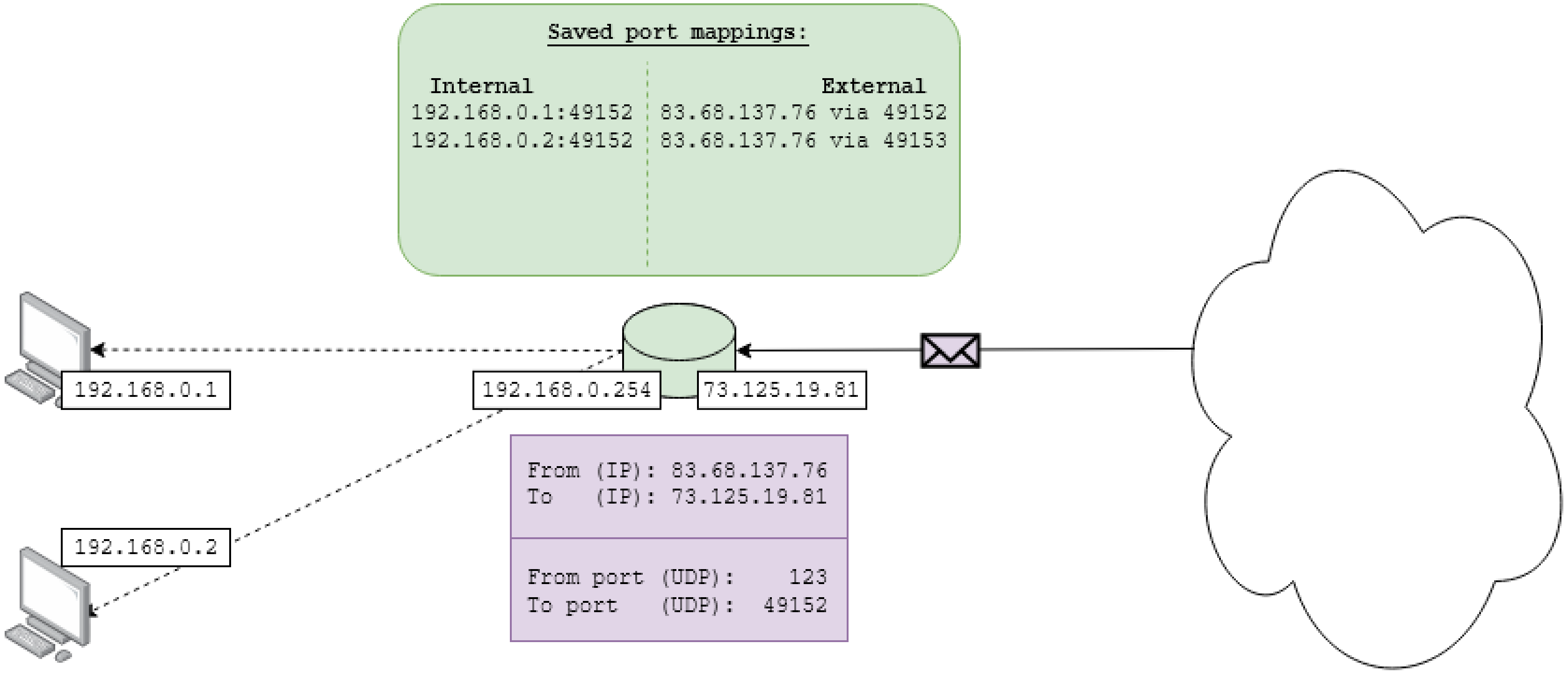

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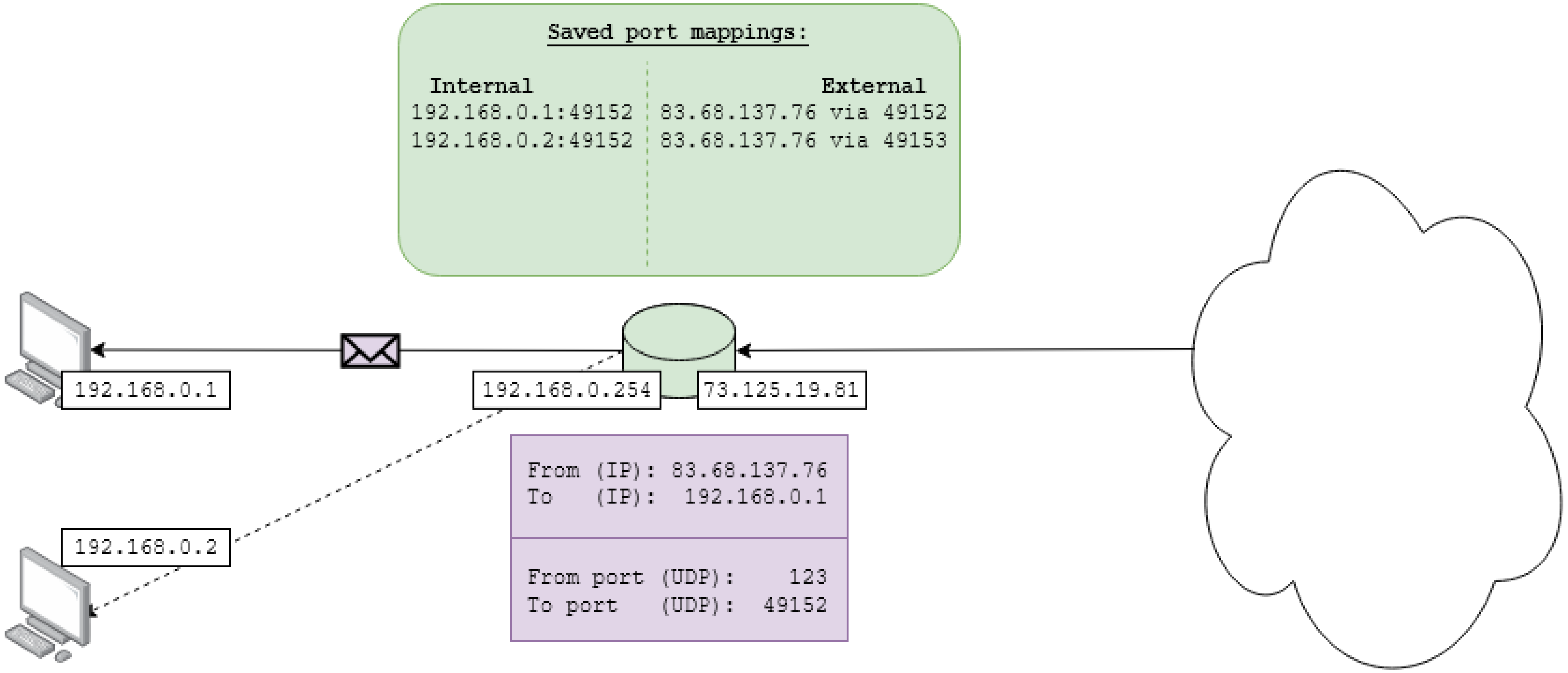
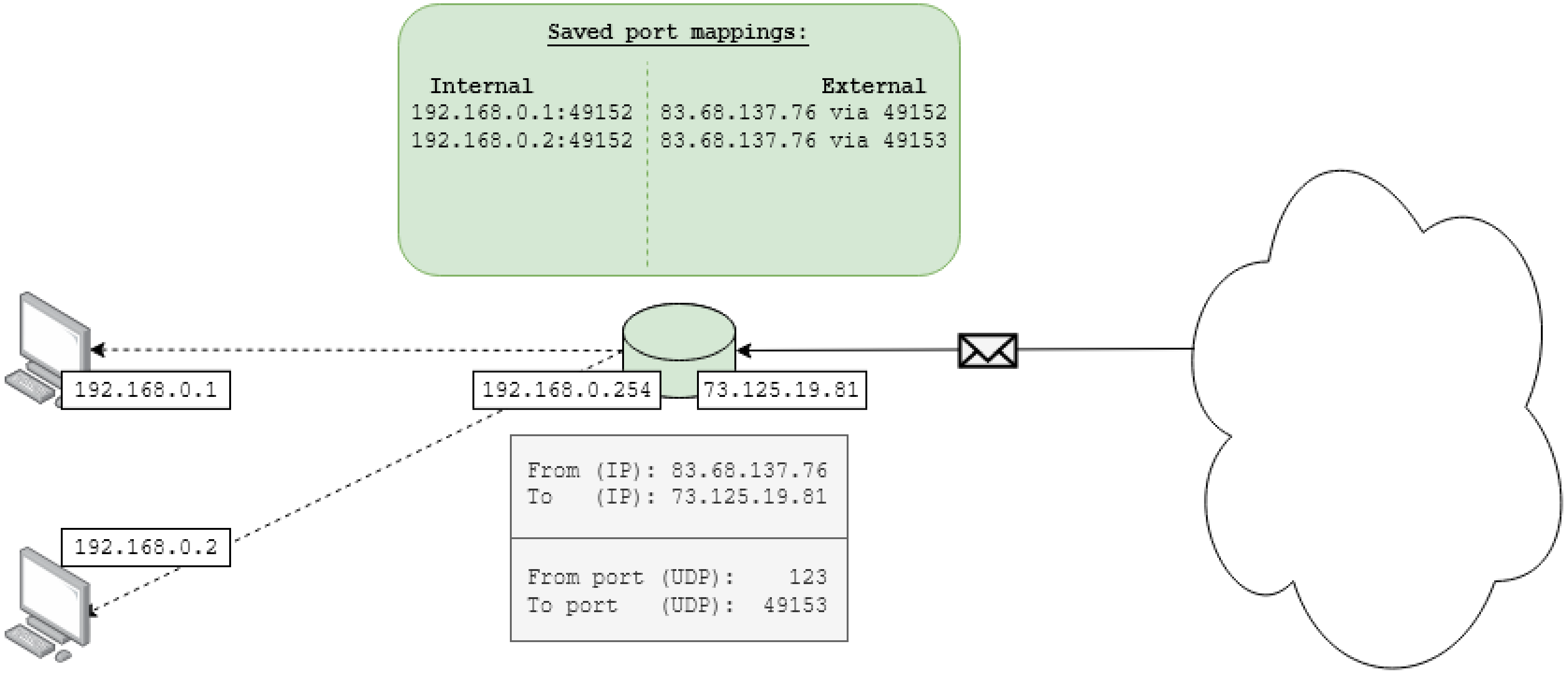


Port Address Translation

- “Hide” an entire private network behind a single public IP
  - Rewrite IP packets at the boundary
  - Rewrite TCP/UDP ports to disambiguate



Port Address Translation

- “Hide” an entire private network behind a single public IP
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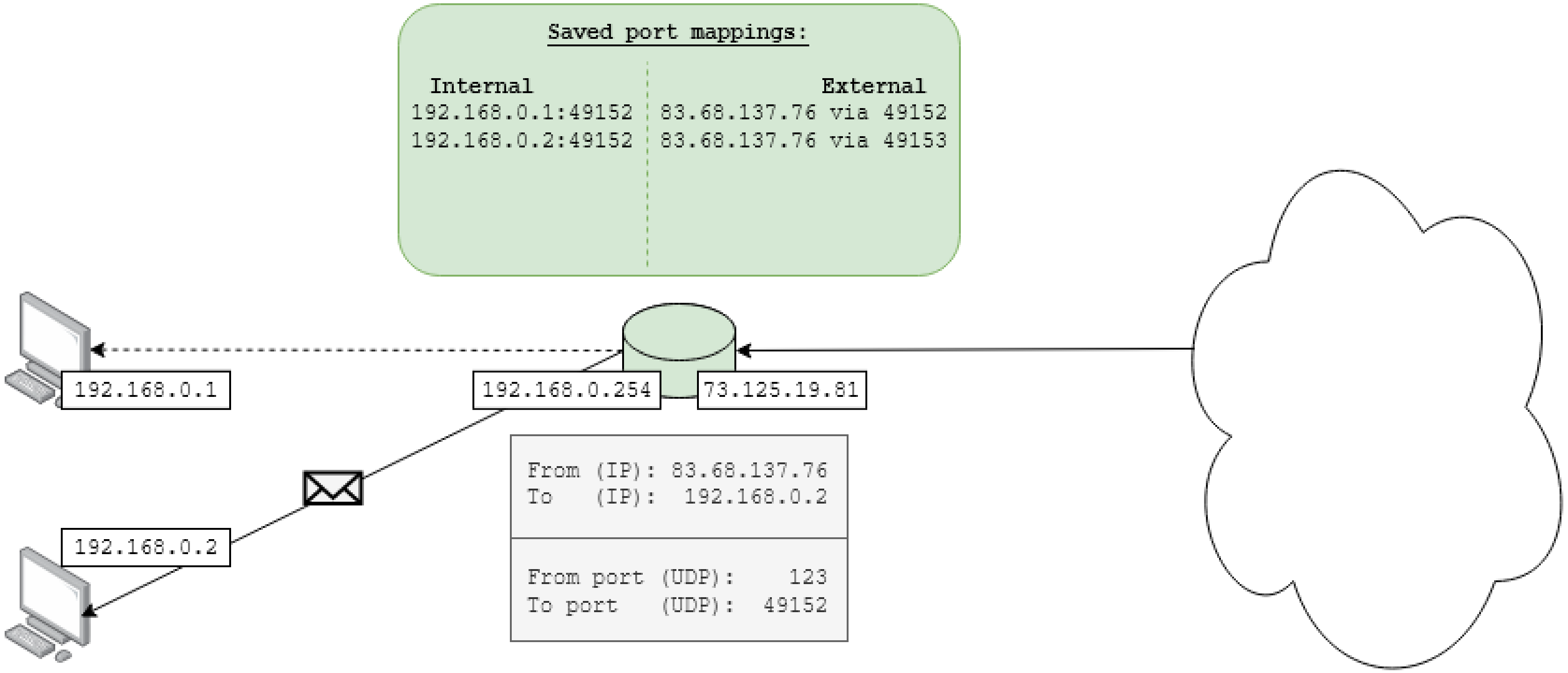

Port Address Translation

- "Hide" an entire private network behind a single public IP
  - Rewrite IP packets at the boundary
  - Rewrite TCP/UDP ports to disambiguate
- Transparent if a client "inside" connects to a server "outside"
  - The reverse will not work (by default)
- You can have PAT networks nested within PAT networks
  - Entire ISPs can connect all their clients using one publicly-routable IP address!

- Your home ISP router almost definitely does this!
  - Compare your **`ipconfig`**/**`ifconfig`** address with "what's my ip" (google)

IPv4 fragmentation – Issues

- 16-bit packet ID is insufficient for high transmission rates
  - 16 bit packet ID ≙ 65536 packets “in flight”
  - No acknowledgments ⇒ ID can’t be reused until TTL expires
  - 65536 packets ÷ 128 seconds = 512 packets per second

- Also: other issues

Further reading: https://datatracker.ietf.org/doc/html/rfc8900

IPv4 fragmentation – Issues

- Fragmentation splits TCP/UDP transmission units across IP packets
  - Only the first fragment has the transport layer header!
    - If it even does…? There's no minimum fragment size…
  - Which host should a PAT firewall forward the data to?
  - Firewalls can't effectively filter these packets either…

- Reassembly is very fragile
  - How long should fragments be kept around for?
    - Denial-of-service attacks!
  - How do you handle overlapping fragments?
    - They are valid as per the protocol spec…

Further reading: https://datatracker.ietf.org/doc/html/rfc8900