Computer Organization and Networks

Chapter 6: Networking I

Winter 2023/2024

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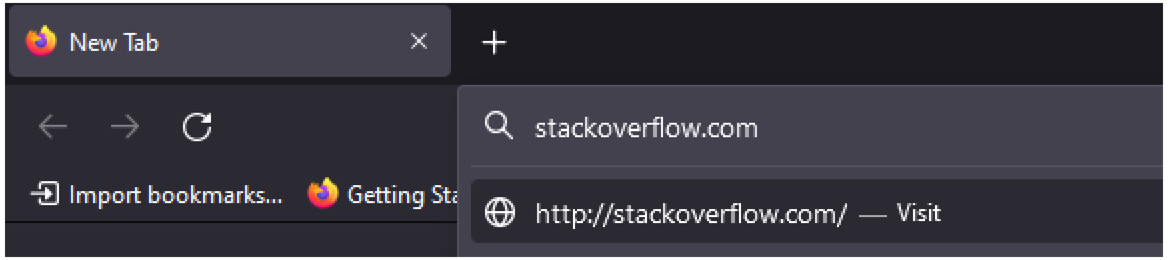
he/his

Motivation

- You’ve built a CPU
  - Now let’s make it talk to others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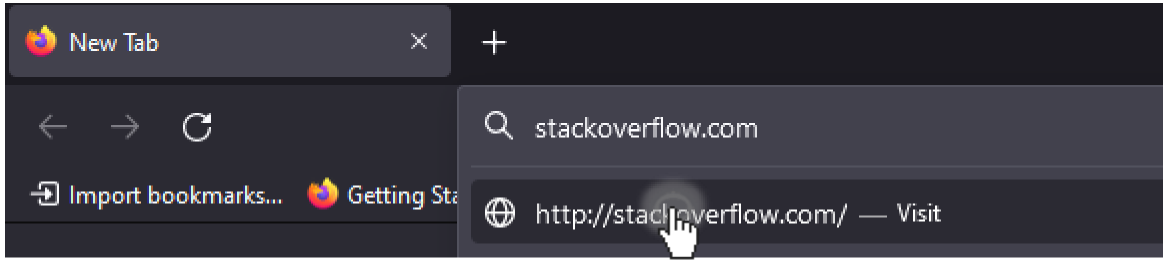
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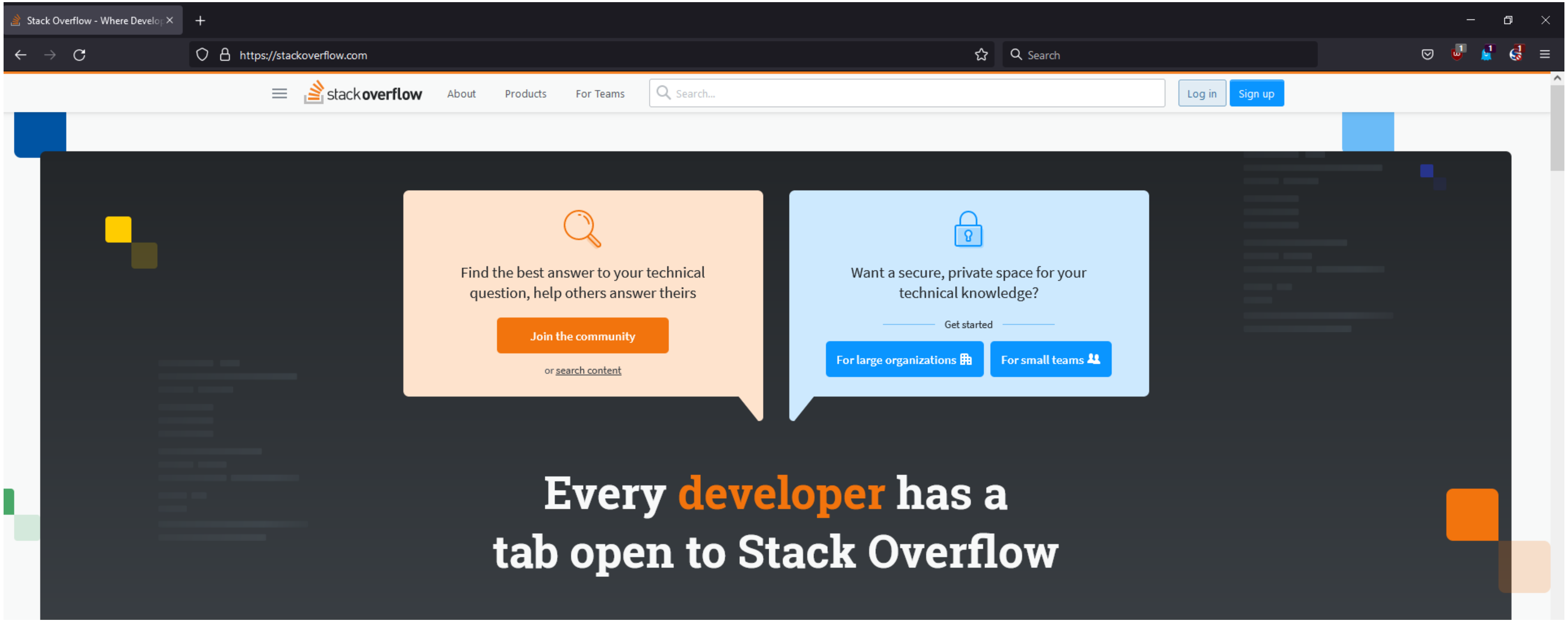
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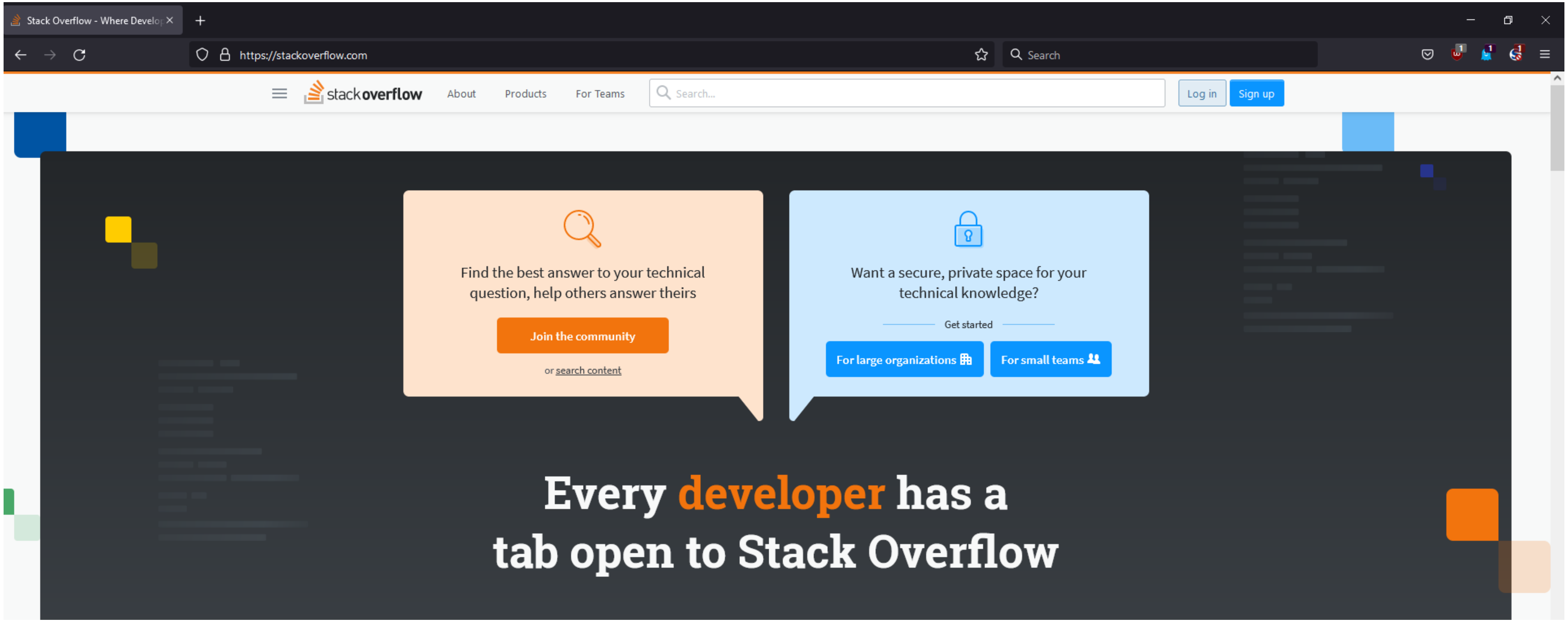
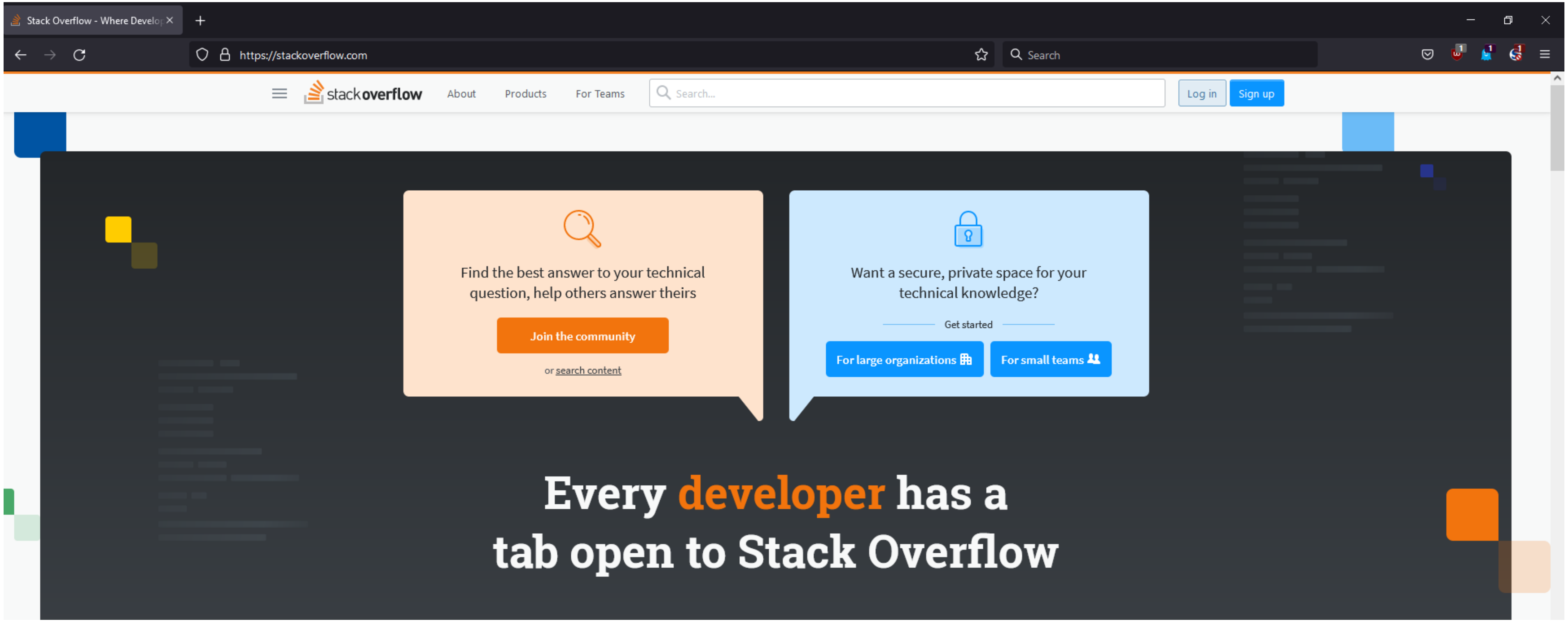
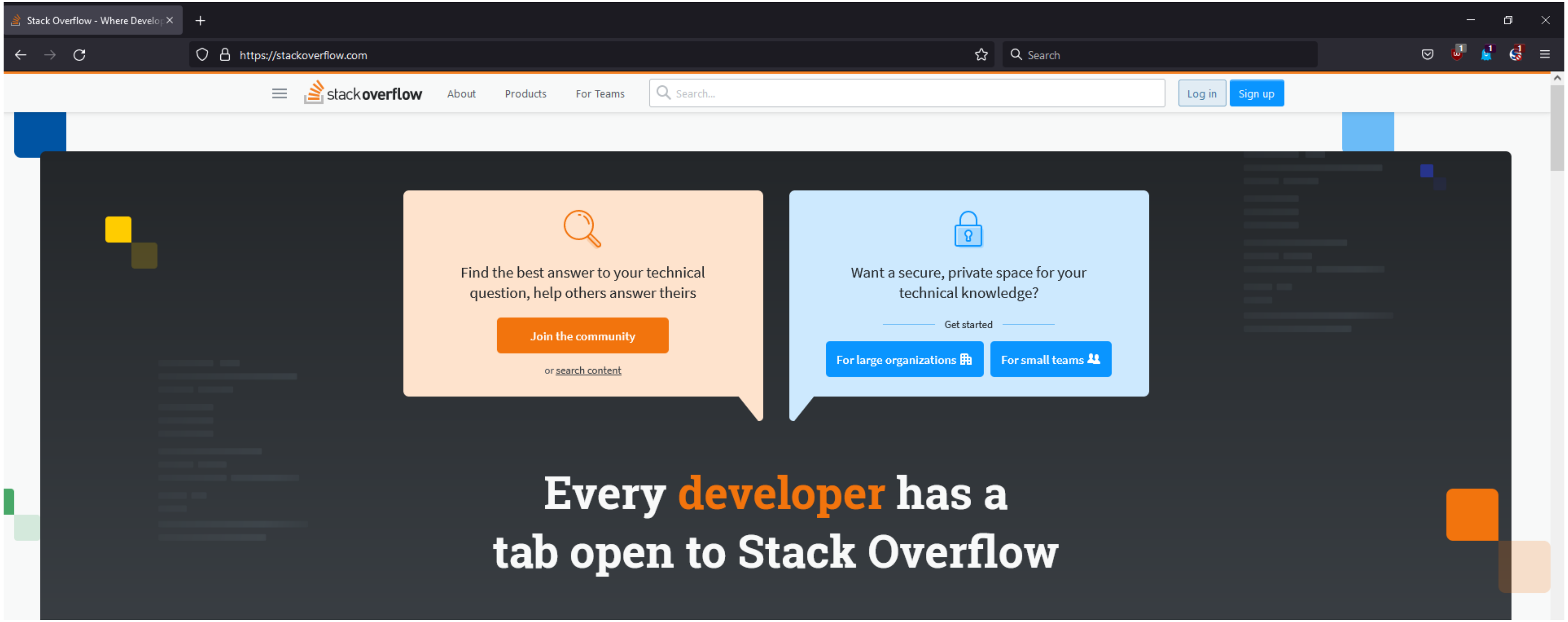


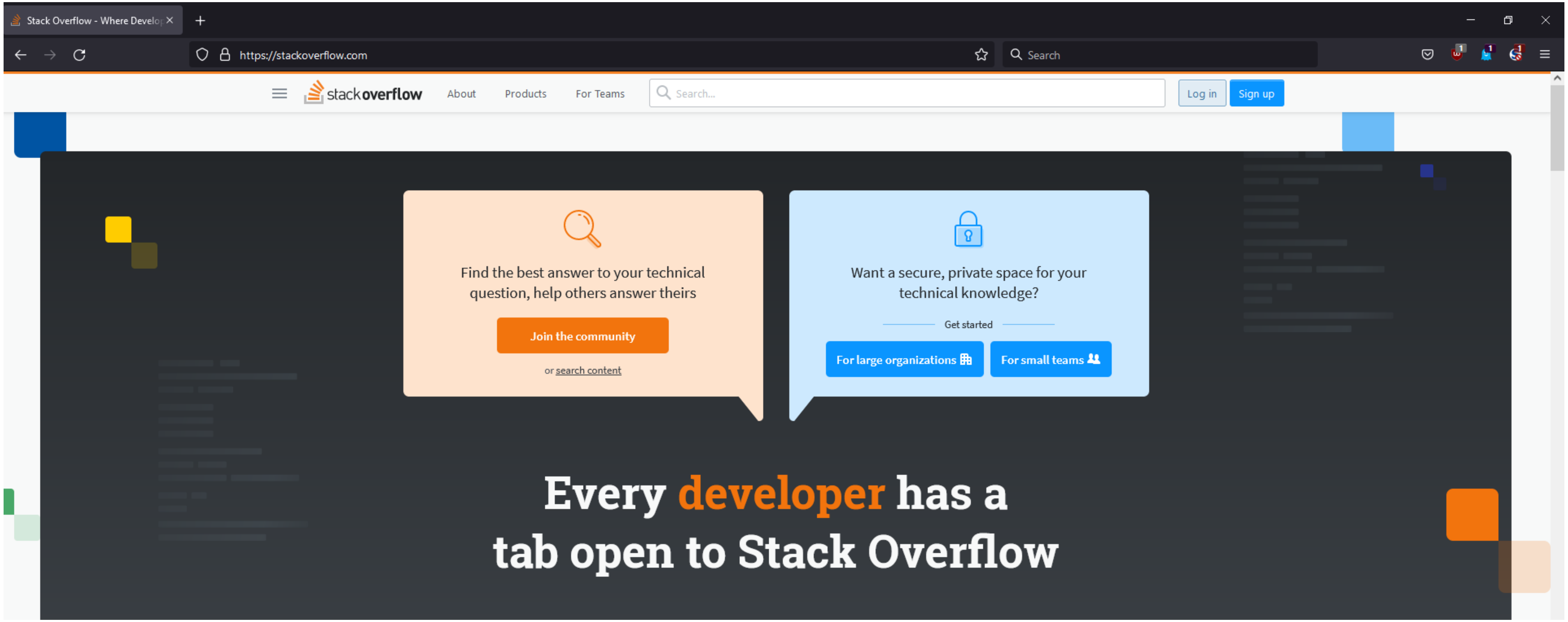
- OK, what did we just do?



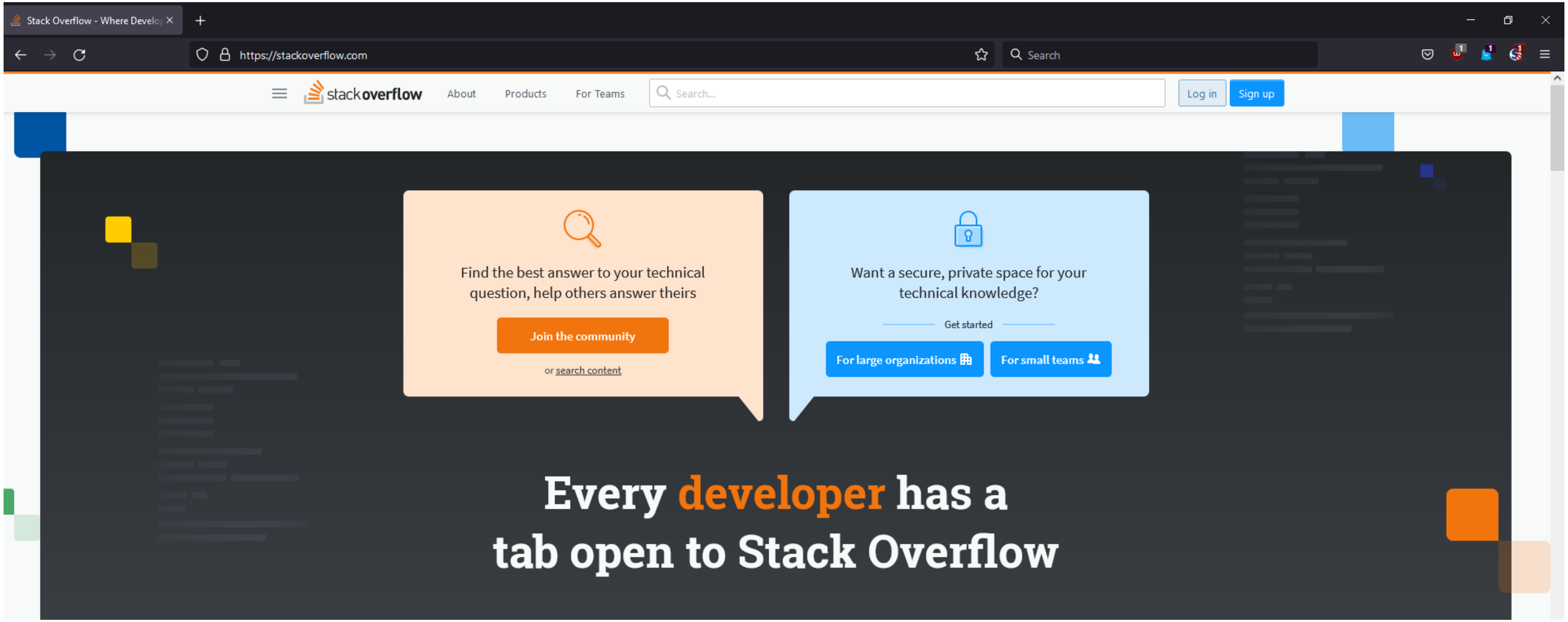
- OK, what did our browser just do?



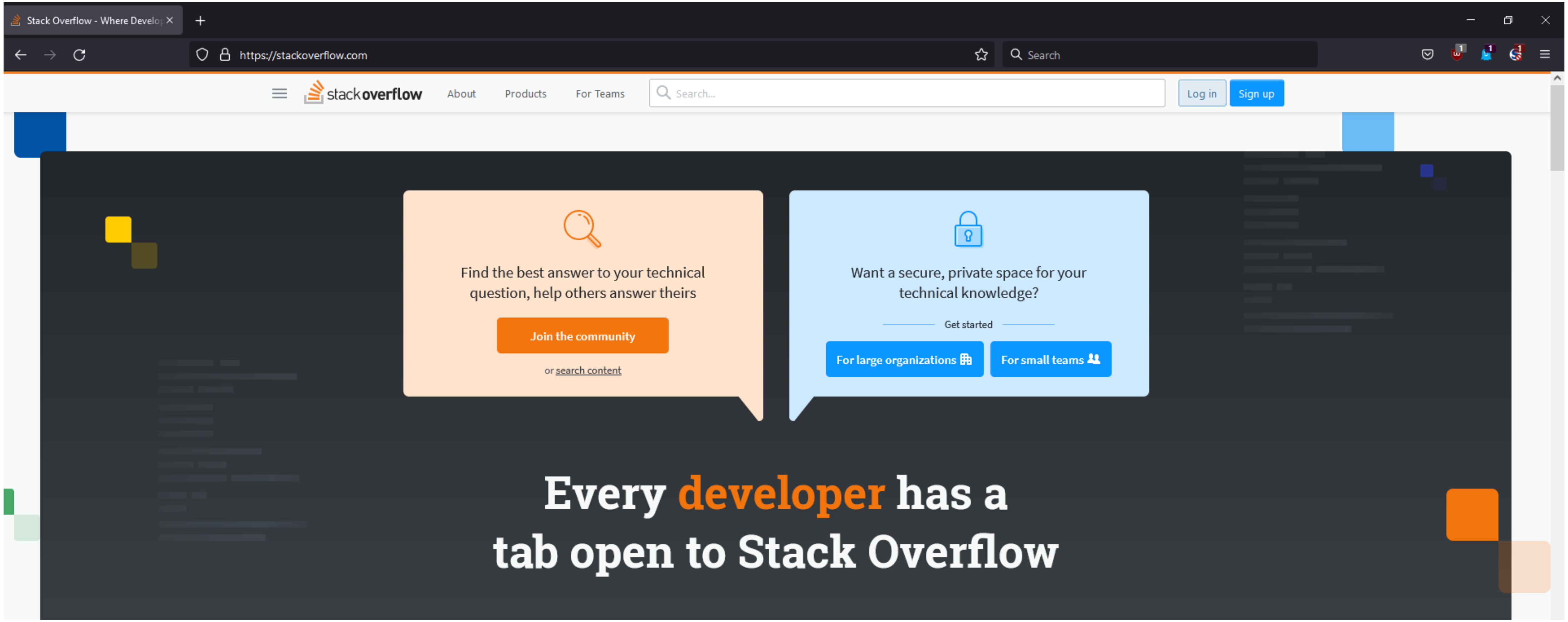
- OK, what did our OS just do?



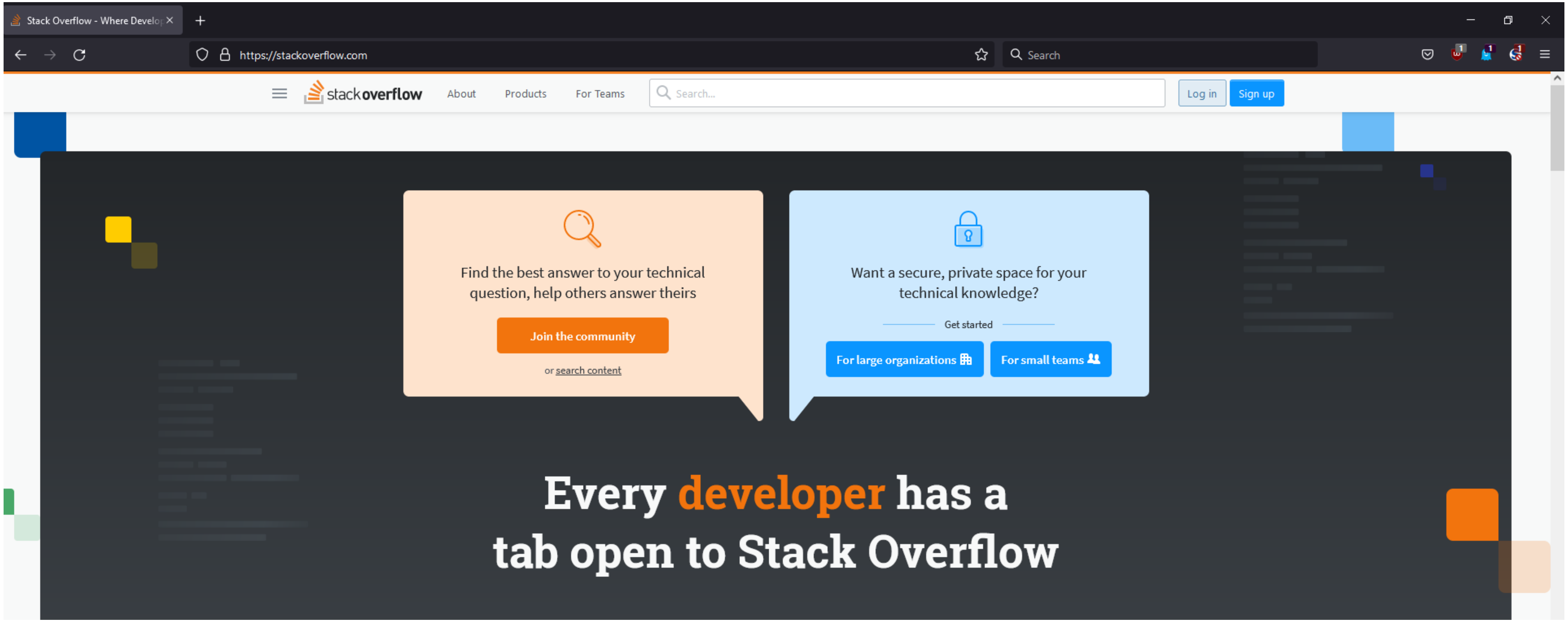
- OK, what did our network card just do?



- OK, what did our router just do?



- OK, what did the StackOverflow server just do?



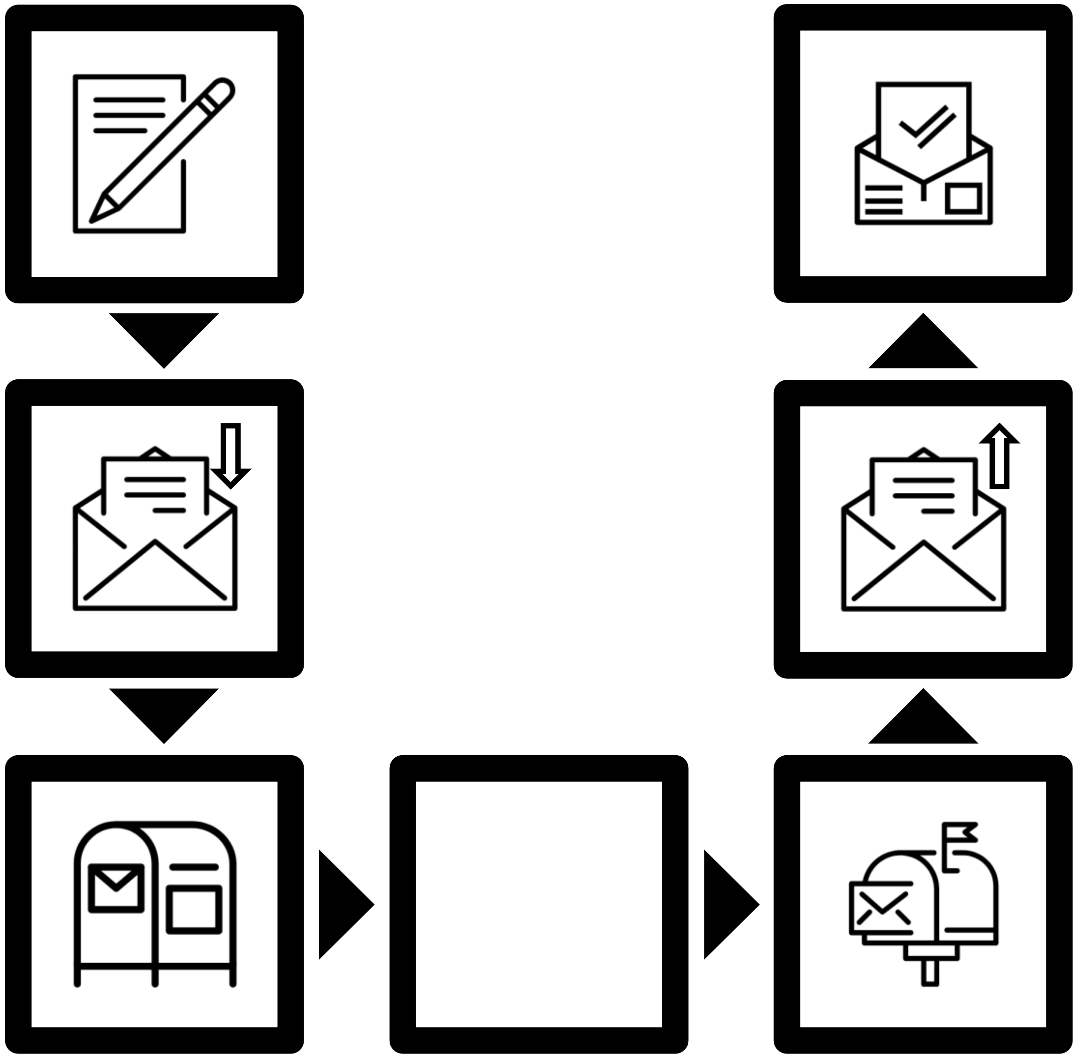
- By the time we’re done here, you’ll know!

Layers & Abstraction

- How do you send a postcard?

Layers & Abstraction

- How do you send a postcard?
  1. Write postcard
  2. Put postcard in envelope
  3. Mail envelope to recipient
  4. Recipient receives envelope
  5. Recipient opens envelope
  6. Recipient reads postcard



Layers & Abstraction

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  4. **<u>Recipient receives envelope</u>**
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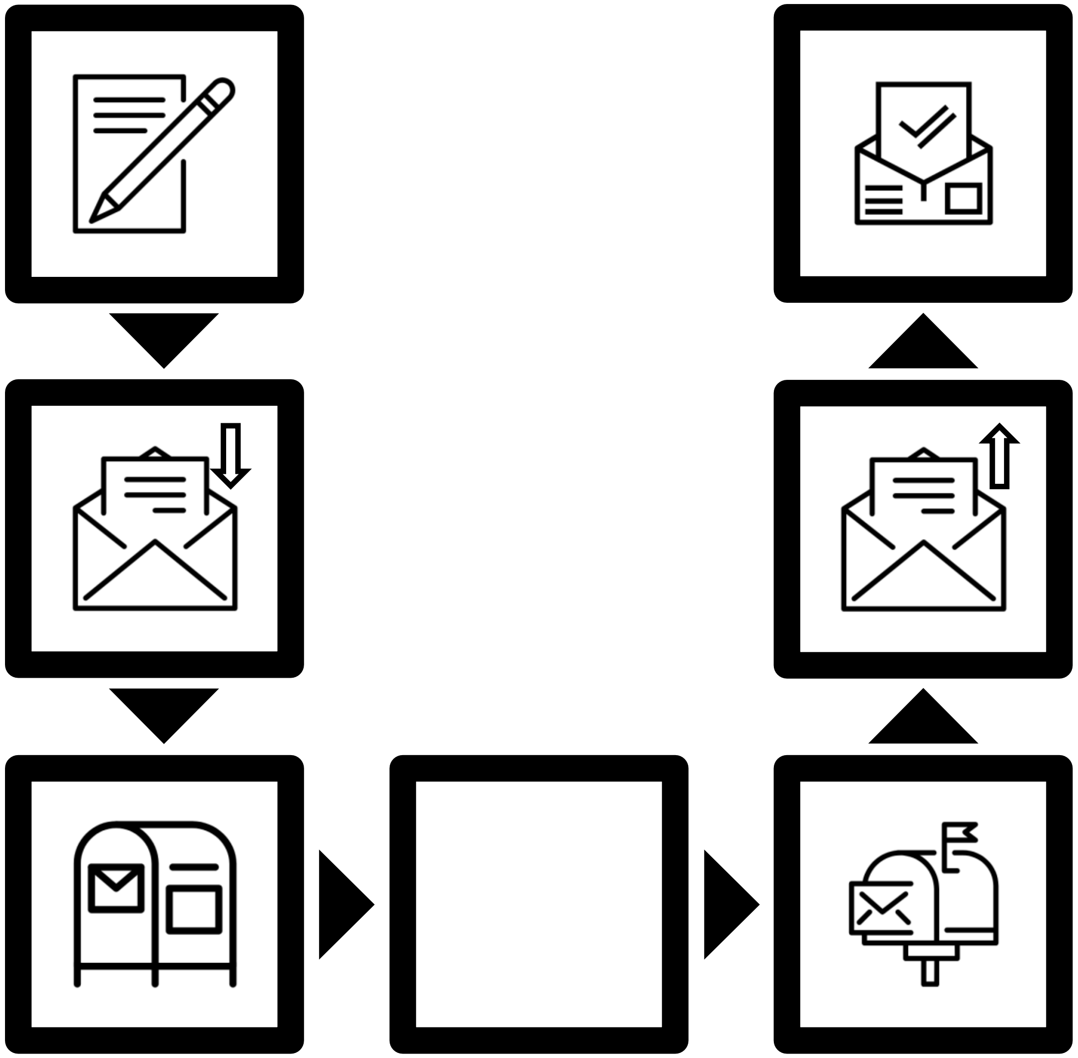
- How does the envelope get there?



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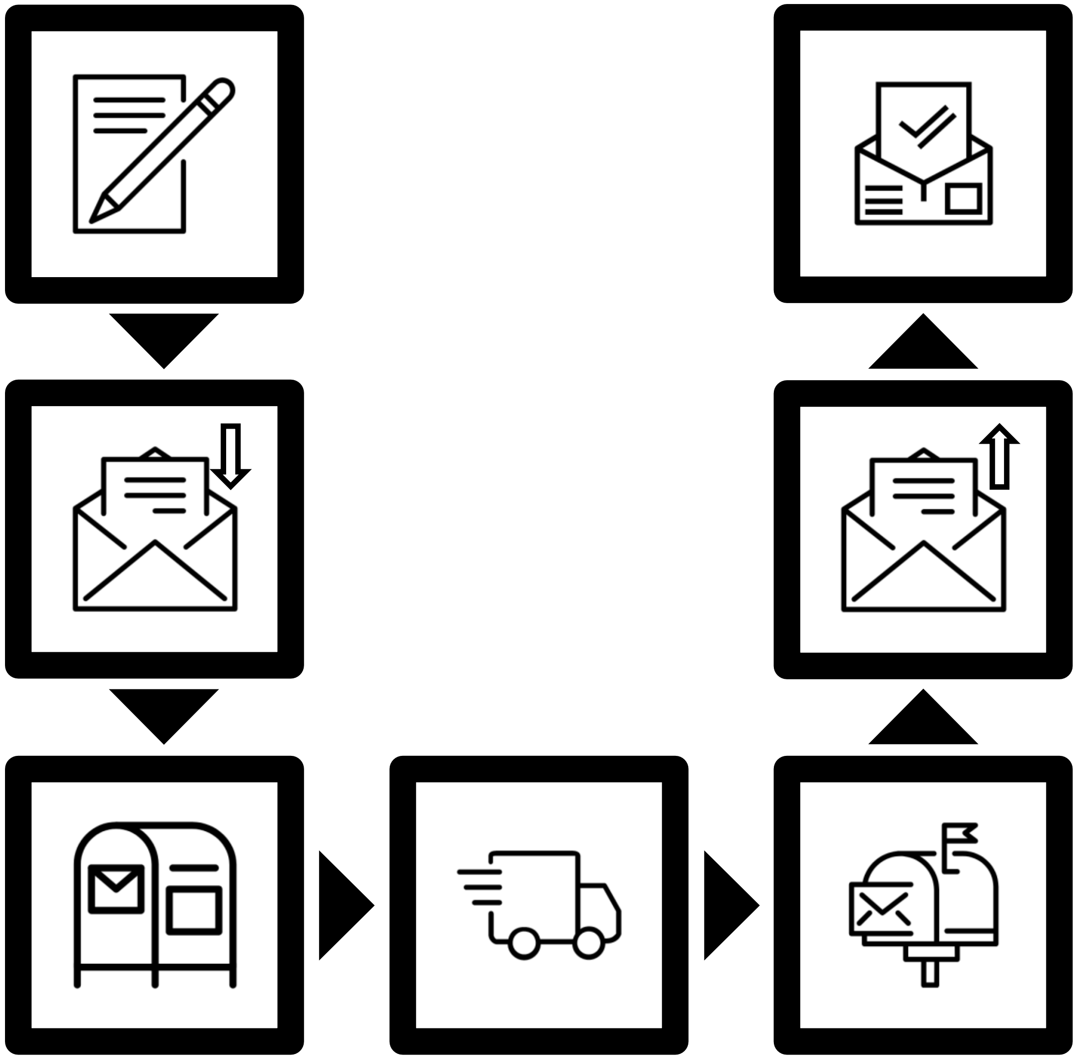

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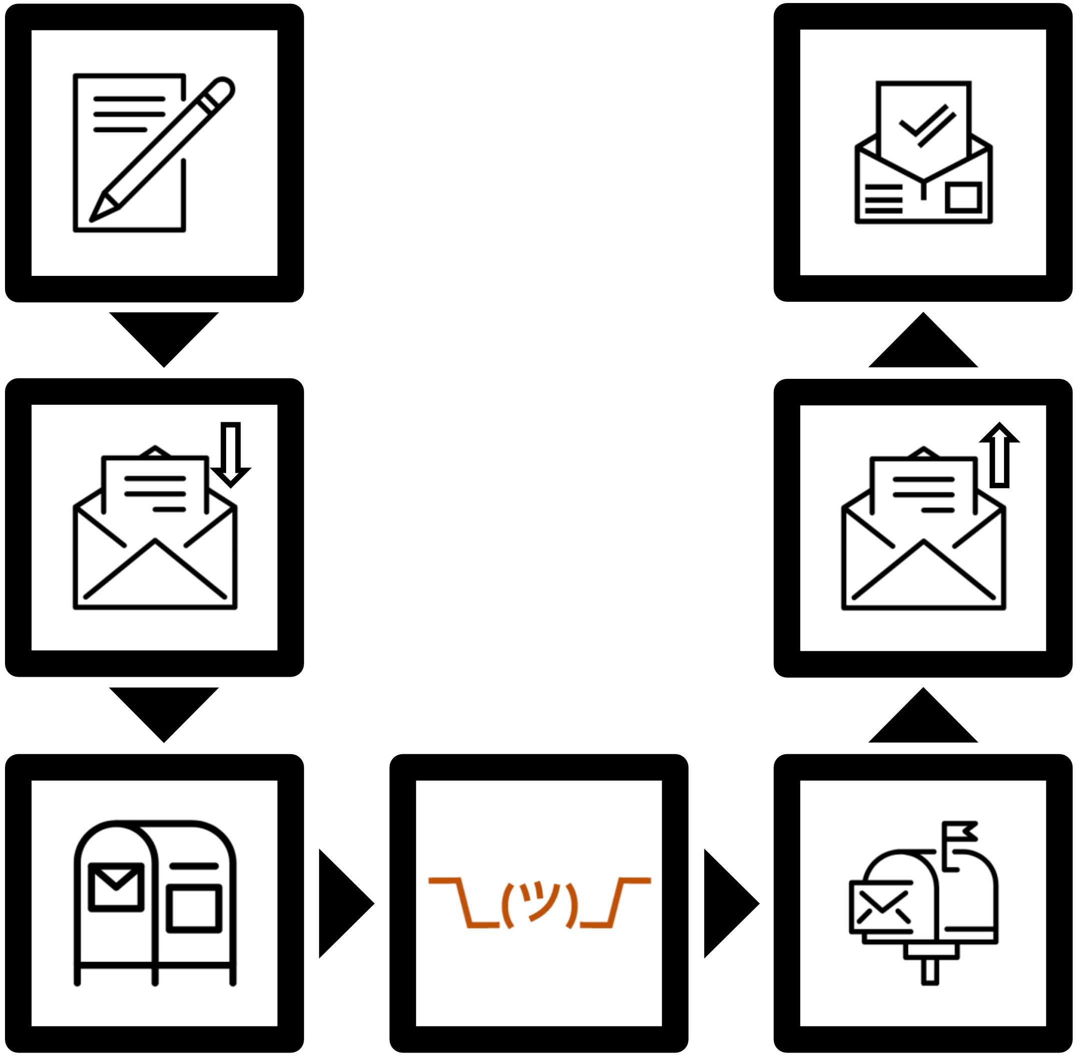
- How does the envelope get there?
  - We don’t care!



Layers & Abstraction

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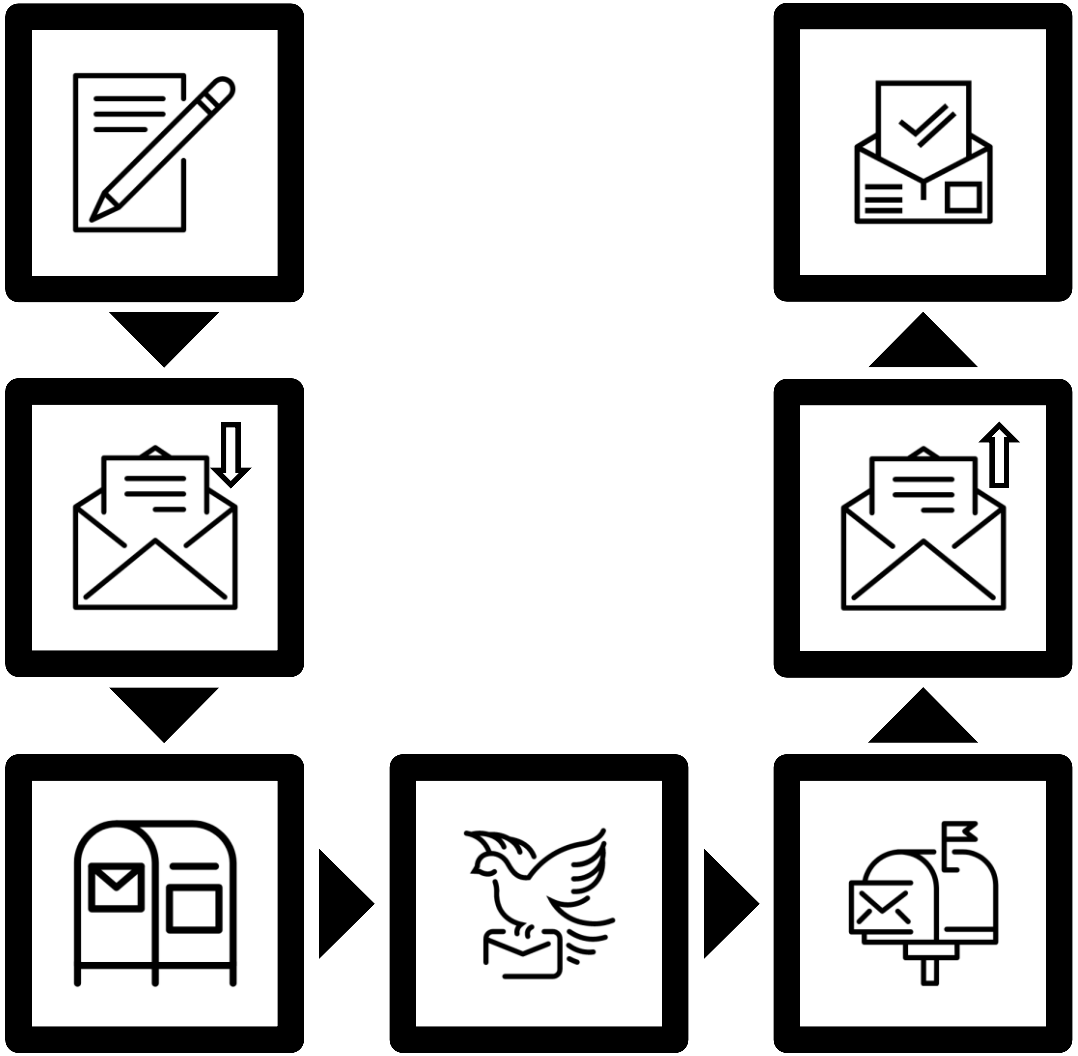
- Use a homing pigeon instead?



Layers & Abstraction

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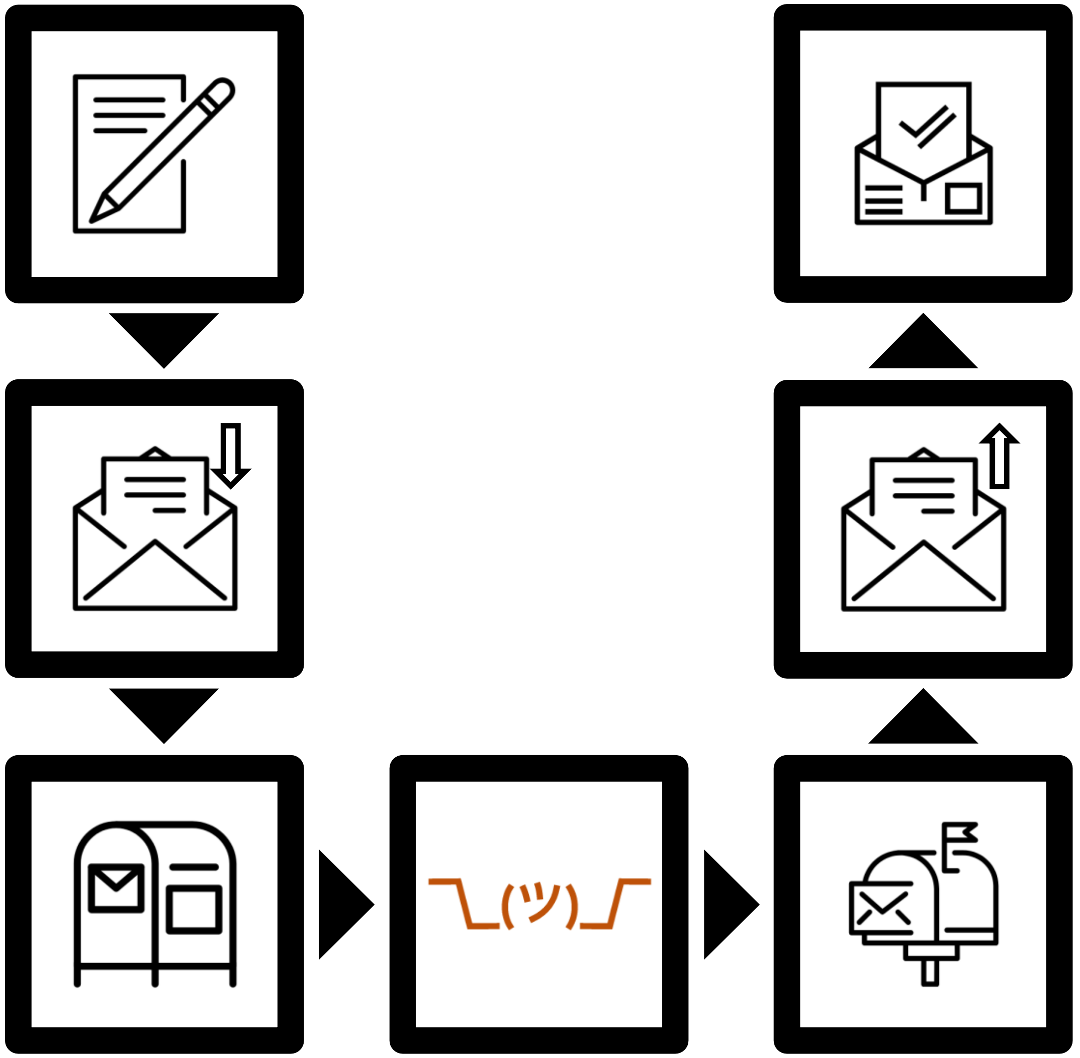
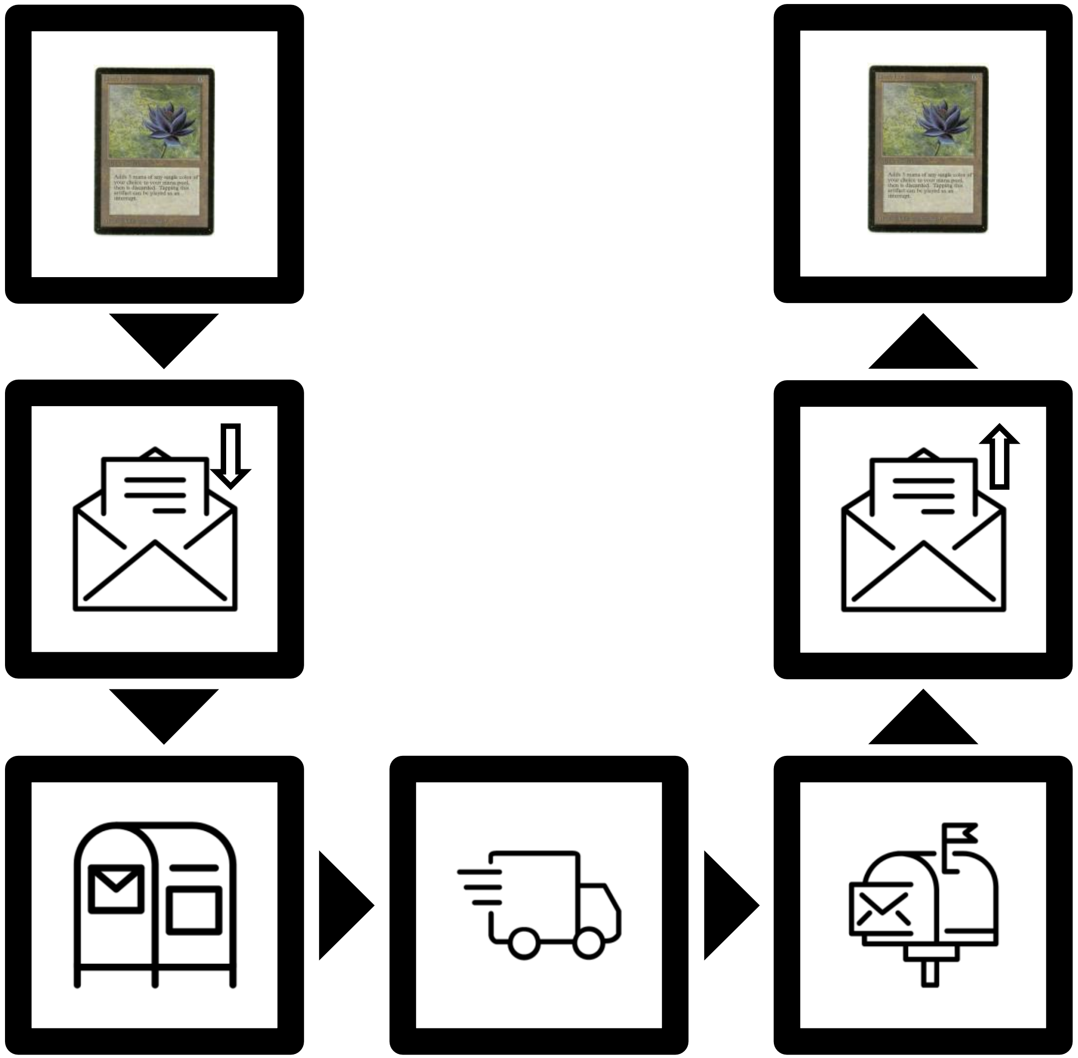
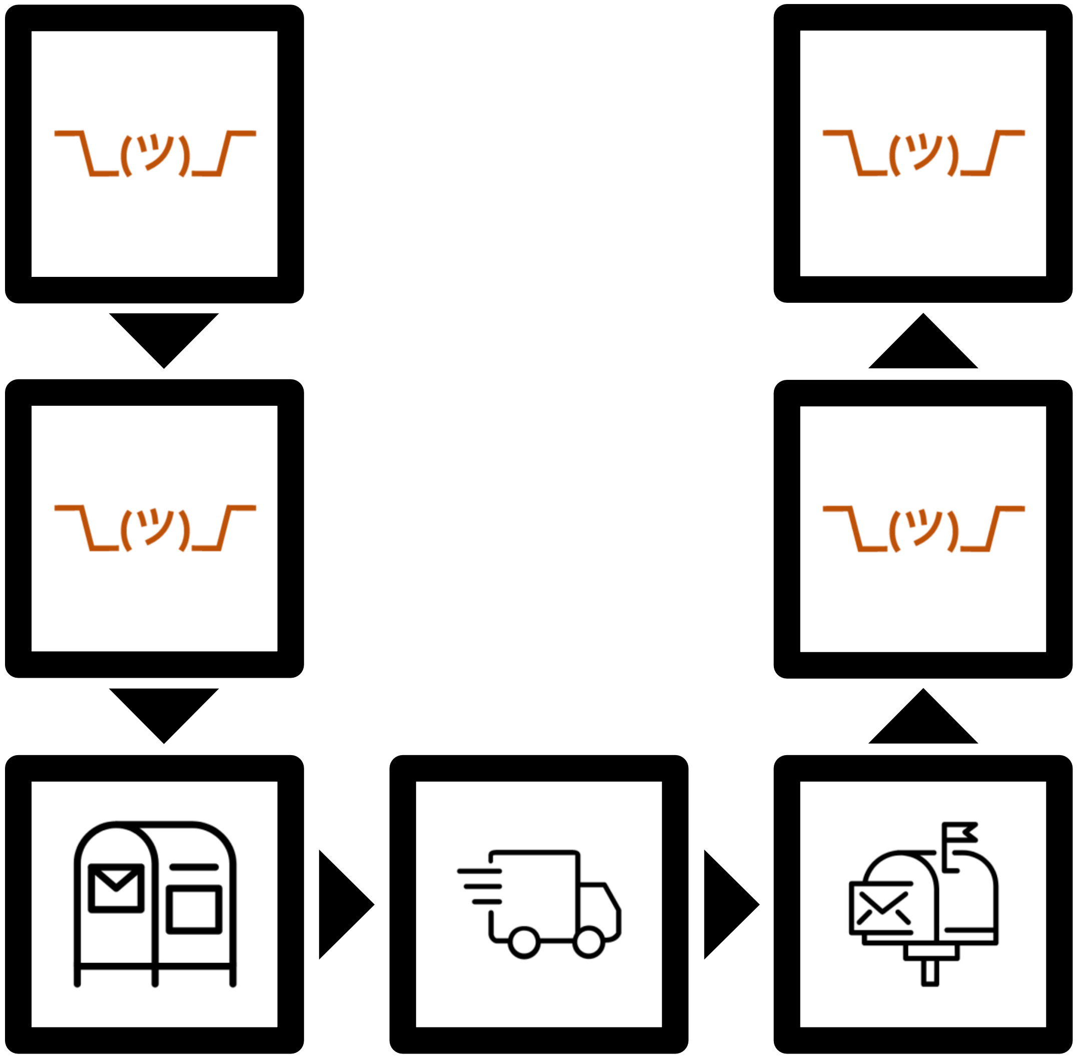


Layers & Abstraction



- Mail a trading card instead?

Layers & Abstraction



- Mail a trading card instead?
  - The post office doesn’t care!

Layers & Abstraction

- Division of responsibility
  - I don’t need to care how my envelope gets there
    - Transporting it is the post office’s job
  - The post office only needs to care about envelopes
    - Securing the something *inside* an envelope is my job

- No need to constantly re-invent the wheel!

Layers & Abstraction

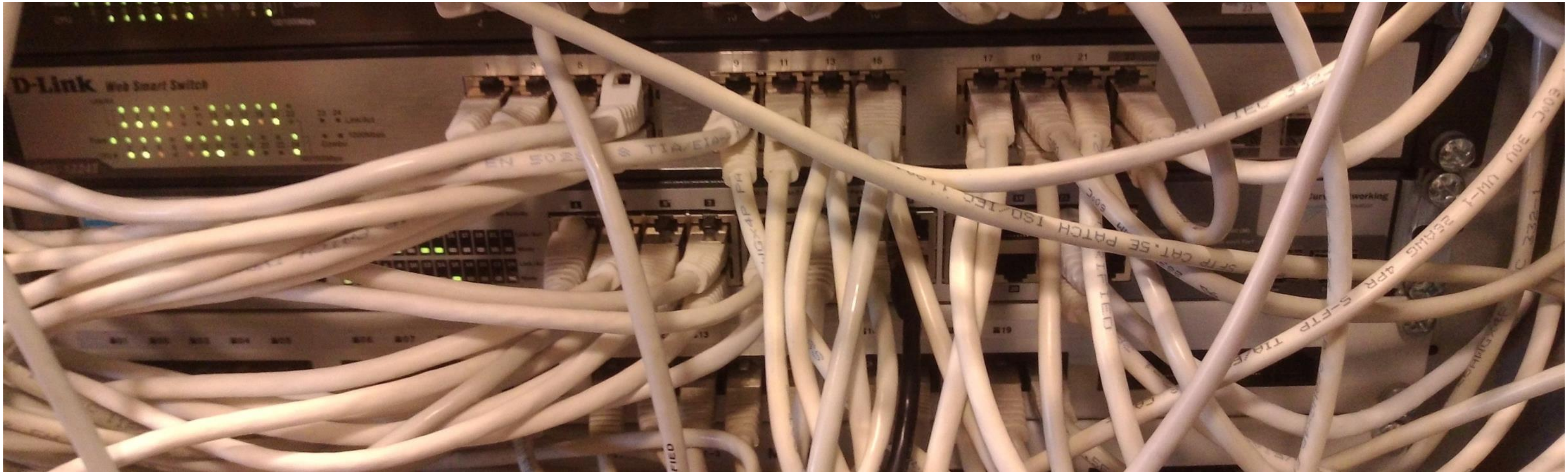
- Networking equivalent: **Layers**
- 1980/90s: competing models & protocol suites
  - TCP/IP, OSI, …
- Modern internet uses the TCP/IP model
  - So that's what we'll talk about!
  - Less powerful than OSI, but more flexible

The TCP/IP model

- Link layer
  - Send a chunk of data to a **directly connected** computer
- Internet layer
  - Route a chunk of data to a **remote** computer along a series of direct links
- Transport layer
  - Transmit a **structured** bit stream across the internet
- Application layer
  - **Offer services** without having to worry about details

Layers & Abstraction

- Abstraction:
  - Keeps complexity manageable
  - May introduce inefficiencies
  - Introduces rigidity
- Real-world protocols are not *fully* isolated from one another
  - Designers will consider properties of other layers’ common protocols



The Link Layer

The Link Layer

- Computers A, B, C, etc. are all “connected” to each other
- **Goal:** Send data from A to C

- Properties of the medium:
  - If you speak, can “everyone” hear you?

Shared Medium

Switched Medium

Addressing

An Ethernet frame, common on the modern Internet

- An *address* identifies a destination
  - Shared Medium: recipients can recognize messages
  - Switched Medium: we know where to send messages

- **MAC address**: 48-bit identifier
  - Used in: Ethernet, Wi-Fi, Bluetooth, …
  - Should be locally unique

- **Broadcast address**: `FF:FF:FF:FF:FF:FF`
  - Will be sent to all connected hosts

Image: Public Domain

The Link Layer

- Computers A, B, C, etc. are all “connected” to each other
- **Goal:** Send data from A to C

- Properties of the medium:
  - If you speak, can “everyone” hear you? (shared or switched medium)
  - Can you send and receive at the same time? (“half-duplex” vs “full-duplex”)
  - Can you send and listen at the same time? (collision detection)

- Concerns:
  - Was the data distorted over the “wire”? (integrity)

Checksums

An Ethernet frame, common on the modern Internet

- A *checksum* is…
  - … a fixed-size value
  - … calculated based on arbitrary data

- It allows us to detect errors!
  - Each message is sent with its correct checksum
  - If random bits get flipped, the checksum is no longer correct!

- This doesn’t help against an intelligent attacker!

Image: Public Domain

Example: Wi-Fi (IEEE 802.11)

Image: Public Domain

- Shared medium: Wireless radio
- Central access point
  - Nodes communicate via the AP
- Not full-duplex
  - If two nodes send at the same time, the signals are garbled
- No direct collision detection
  - If a node is sending, it cannot listen for transmissions at the same time
- Data is acknowledged
  - Collision -> no acknowledgment -> Data re-sent

Example: Wi-Fi (IEEE 802.11)

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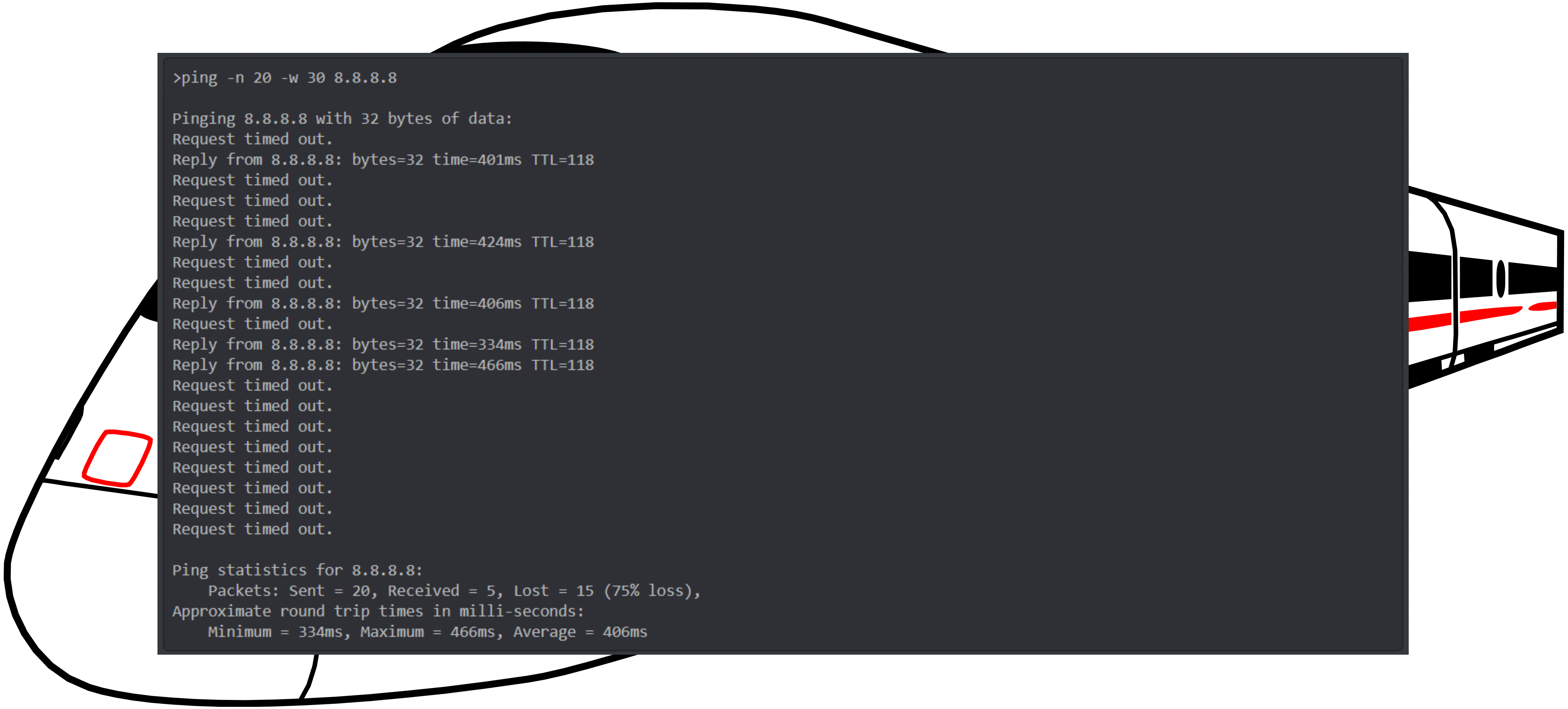
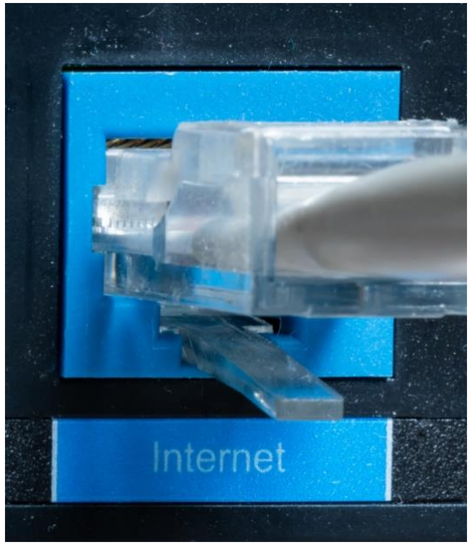


```
>ping -n 20 -w 30 8.8.8.8

Pinging 8.8.8.8 with 32 bytes of data:
Request timed out.
Reply from 8.8.8.8: bytes=32 time=401ms TTL=118
Request timed out.
Request timed out.
Request timed out.
Reply from 8.8.8.8: bytes=32 time=424ms TTL=118
Request timed out.
Request timed out.
Reply from 8.8.8.8: bytes=32 time=406ms TTL=118
Request timed out.
Reply from 8.8.8.8: bytes=32 time=334ms TTL=118
Reply from 8.8.8.8: bytes=32 time=466ms TTL=118
Request timed out.
Request timed out.
Request timed out.
Request timed out.
Request timed out.
Request timed out.
Request timed out.
Request timed out.

Ping statistics for 8.8.8.8:
    Packets: Sent = 20, Received = 5, Lost = 15 (75% loss),
Approximate round trip times in milli-seconds:
    Minimum = 334ms, Maximum = 466ms, Average = 406ms
```

Example: Ethernet (IEEE 802.3)



- Star-shaped structure
  - Clients directly connected to one or more *switches*
  - Hardware failure only disconnects that client
- Full-duplex (in modern networks)
  - No collisions possible
- Switched medium (mostly, in modern networks)
  - We'll talk details in a bit

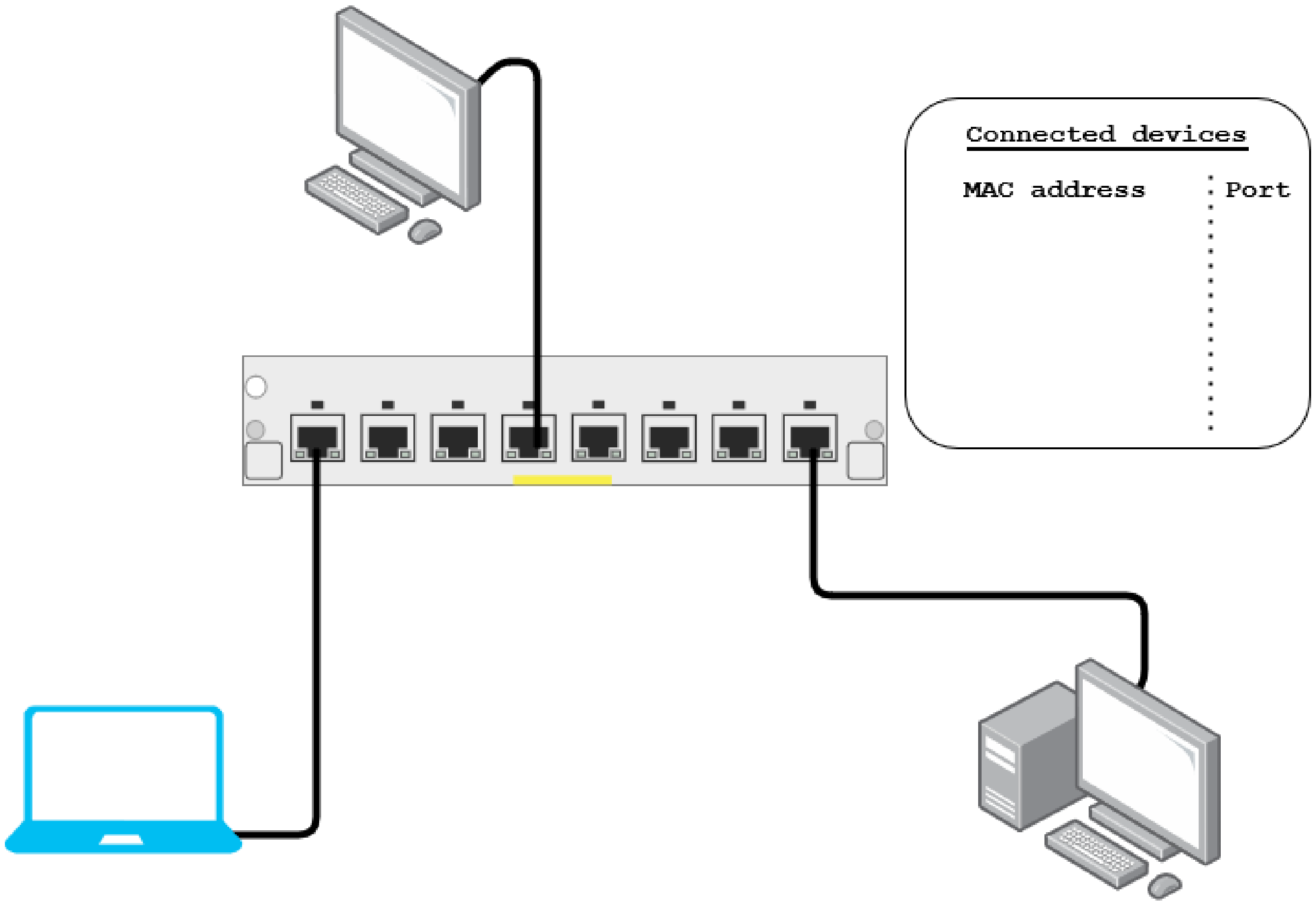
Ye Olde Ethernette

- Once upon a time, Ethernet was a shared medium…
  - At first, it used a single coaxial cable…
    - Physically connecting all the hosts!
  - Later, it used *Ethernet hubs* that emulated this…
    - Simply re-broadcast any received signal to all ports
- We interconnect hundreds of computers
  - Only one can talk at a time?

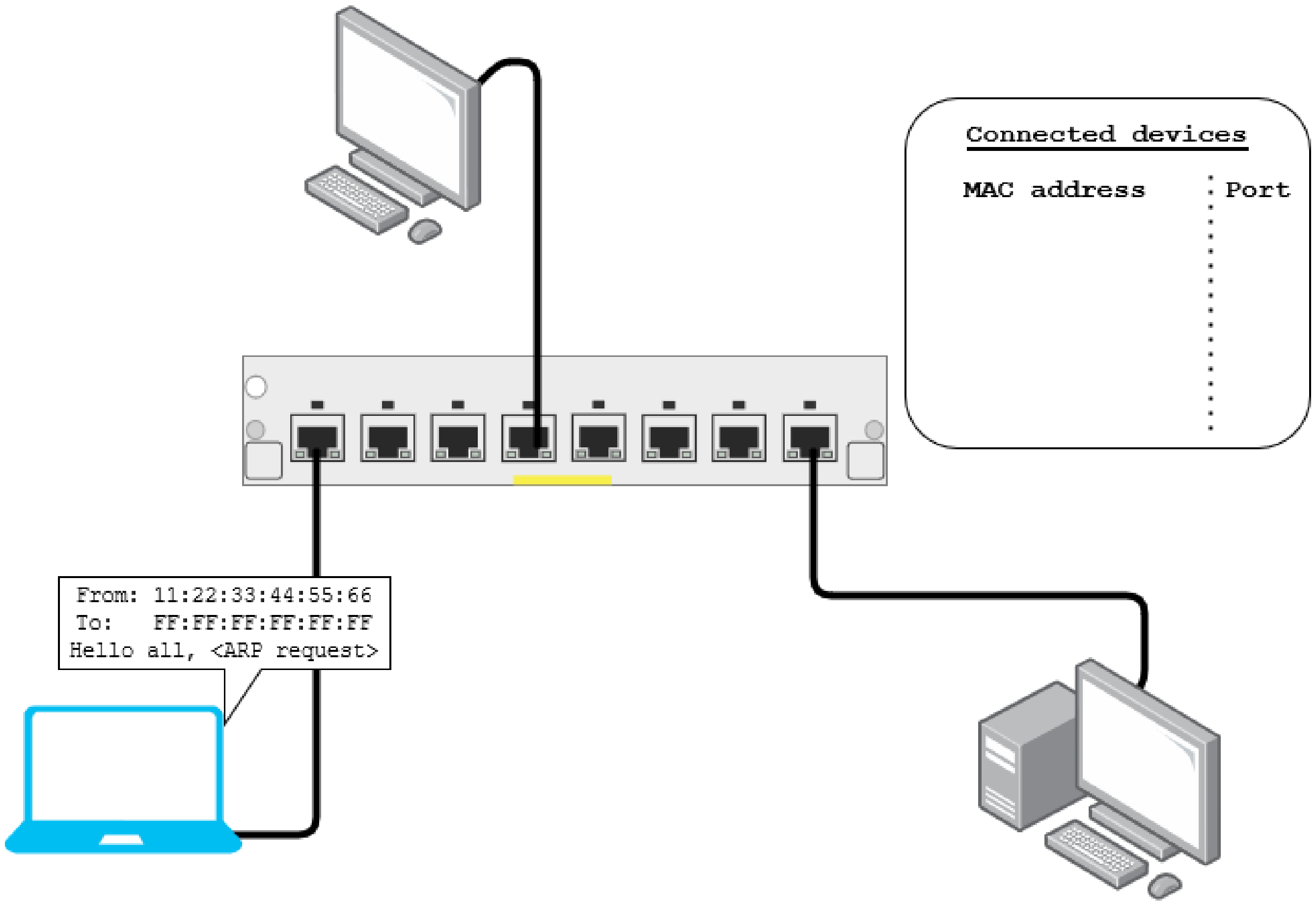
Ethernet: Switching

- Ethernet *switches* understand Link Layer data
    - Read source/destination MAC addresses
- Record source addresses to build map address <-> port
- Only forward packets to the appropriate port
    - Minimize wasted bandwidth
    - No collisions possible!

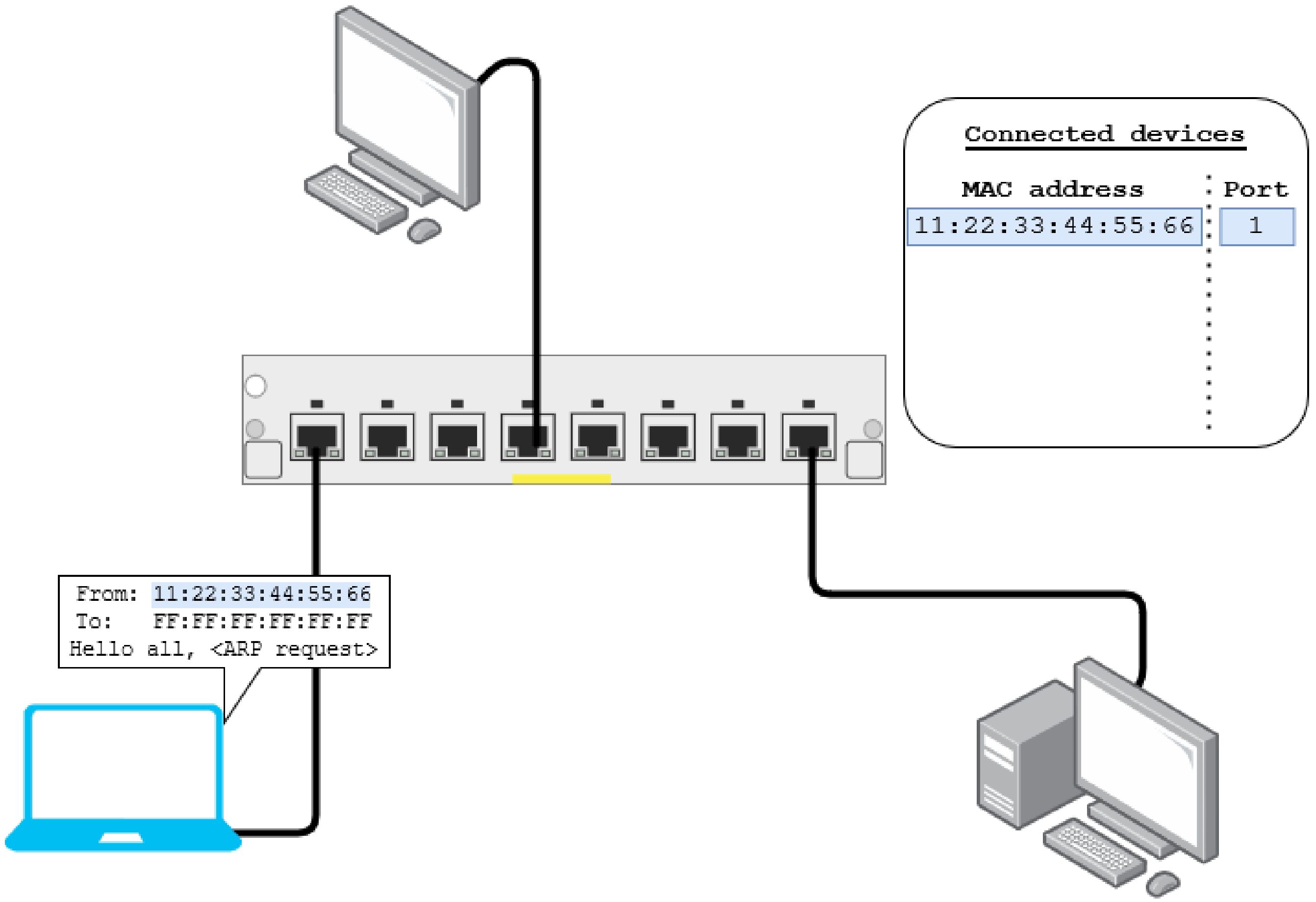
Ethernet: Switching



Ethernet: Switching



Ethernet: Switching



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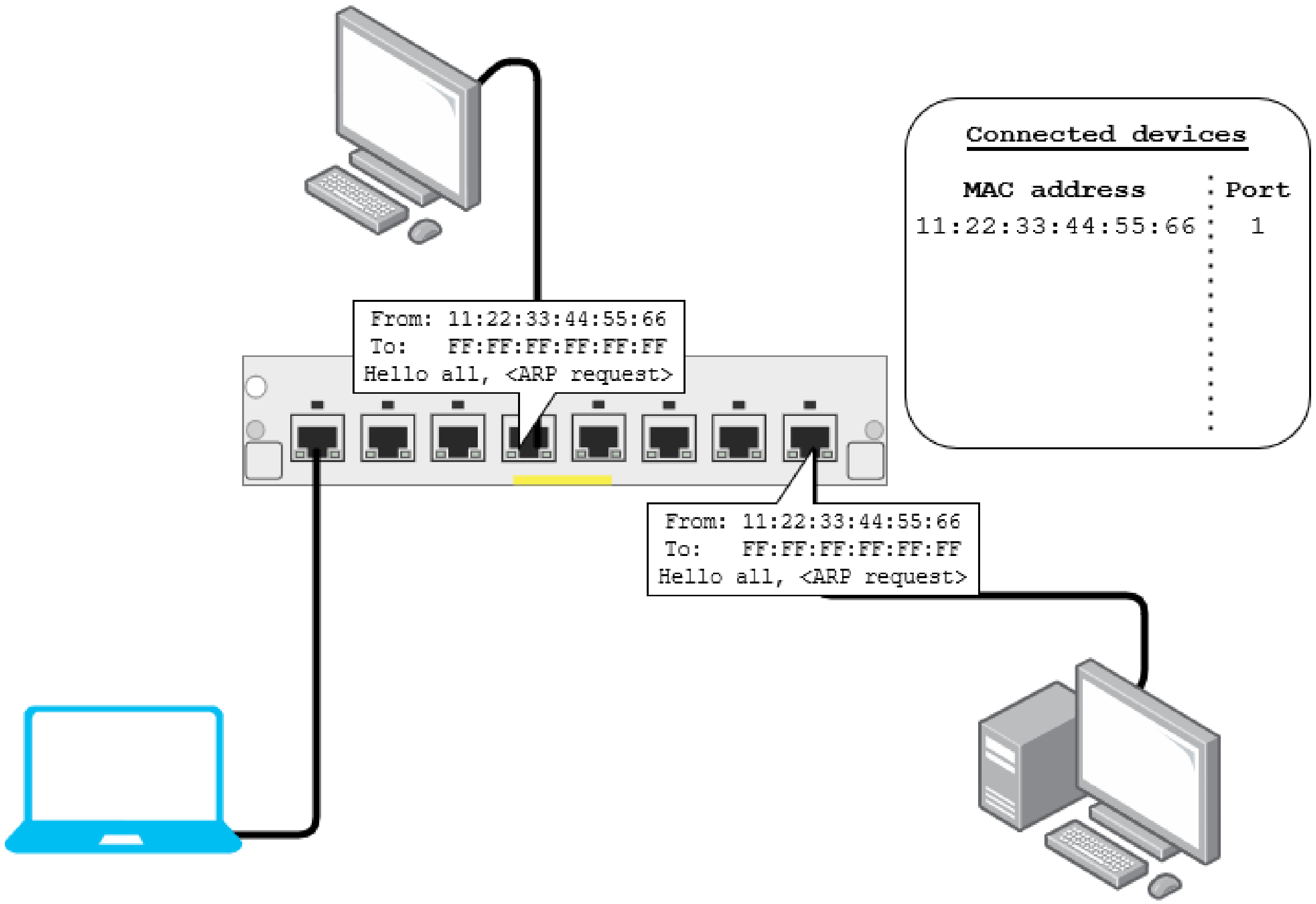
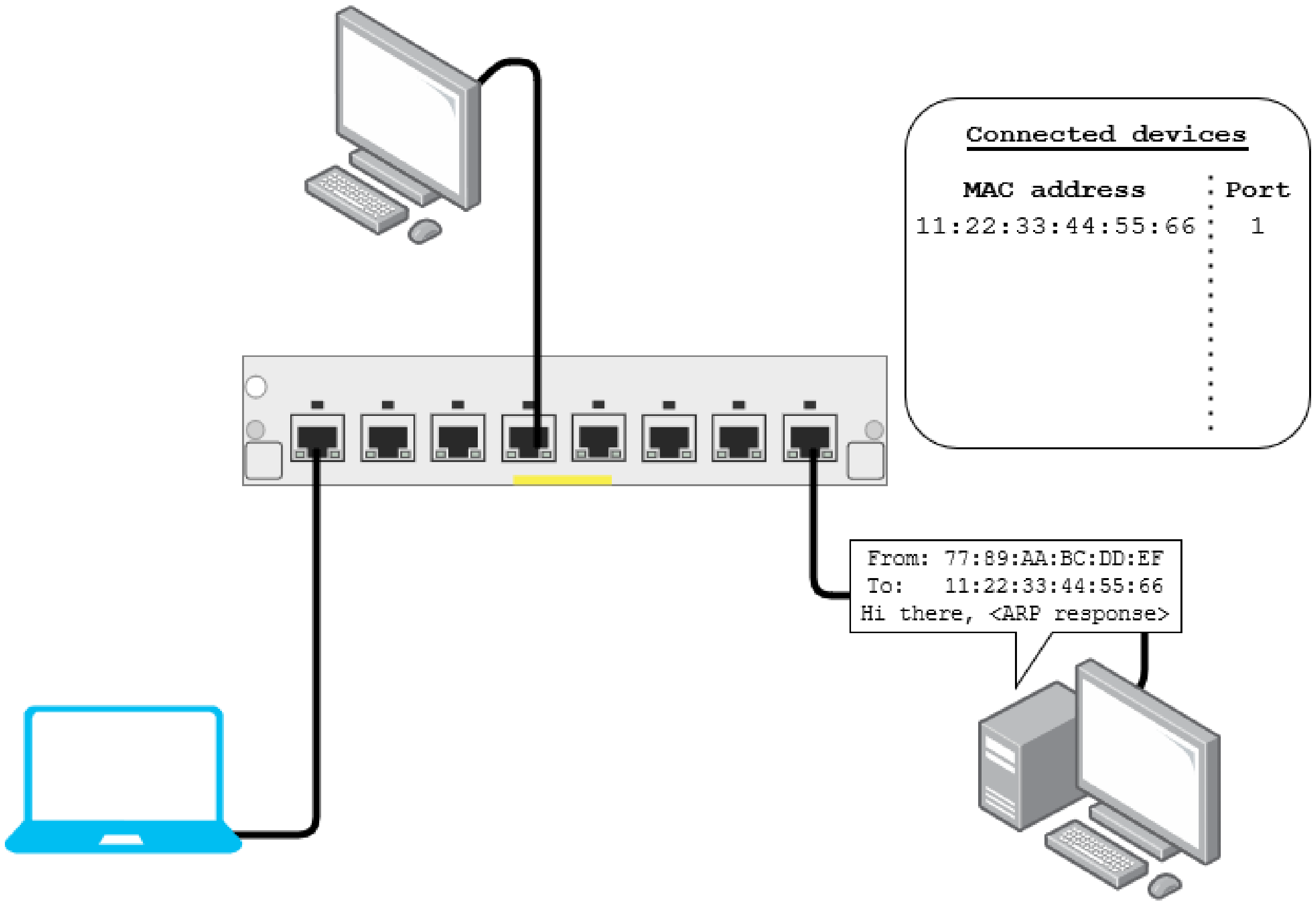


Ethernet: Switching



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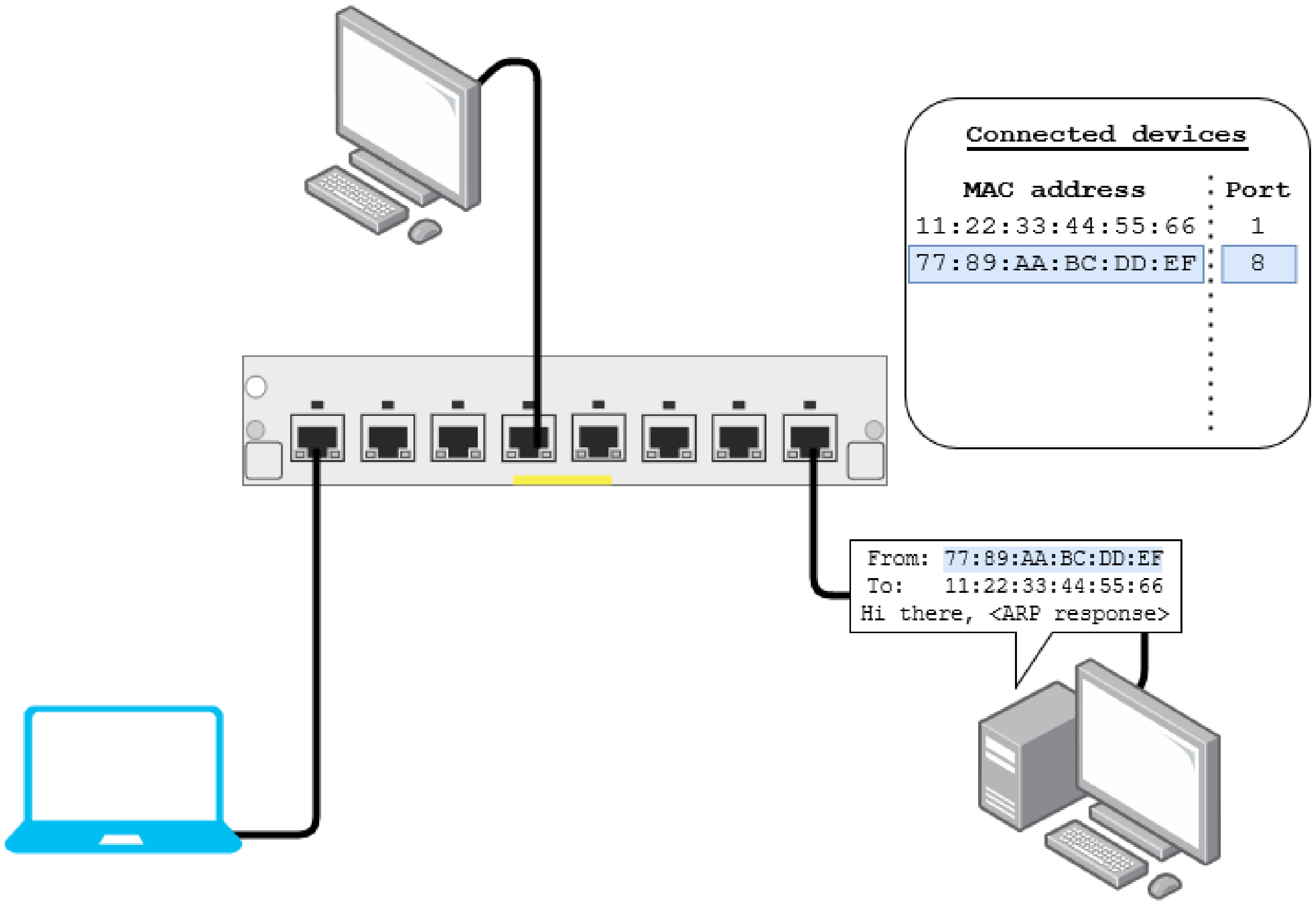

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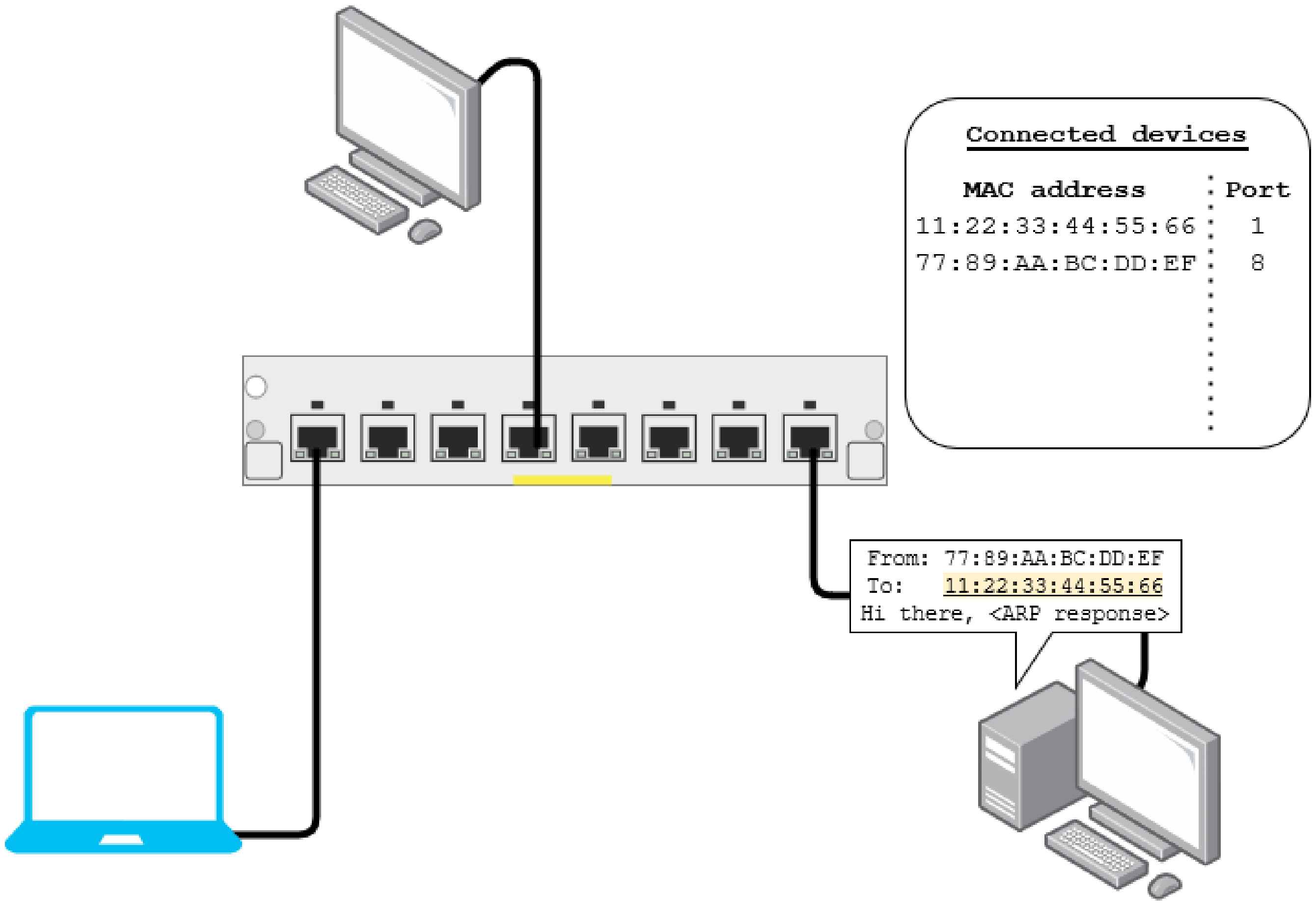

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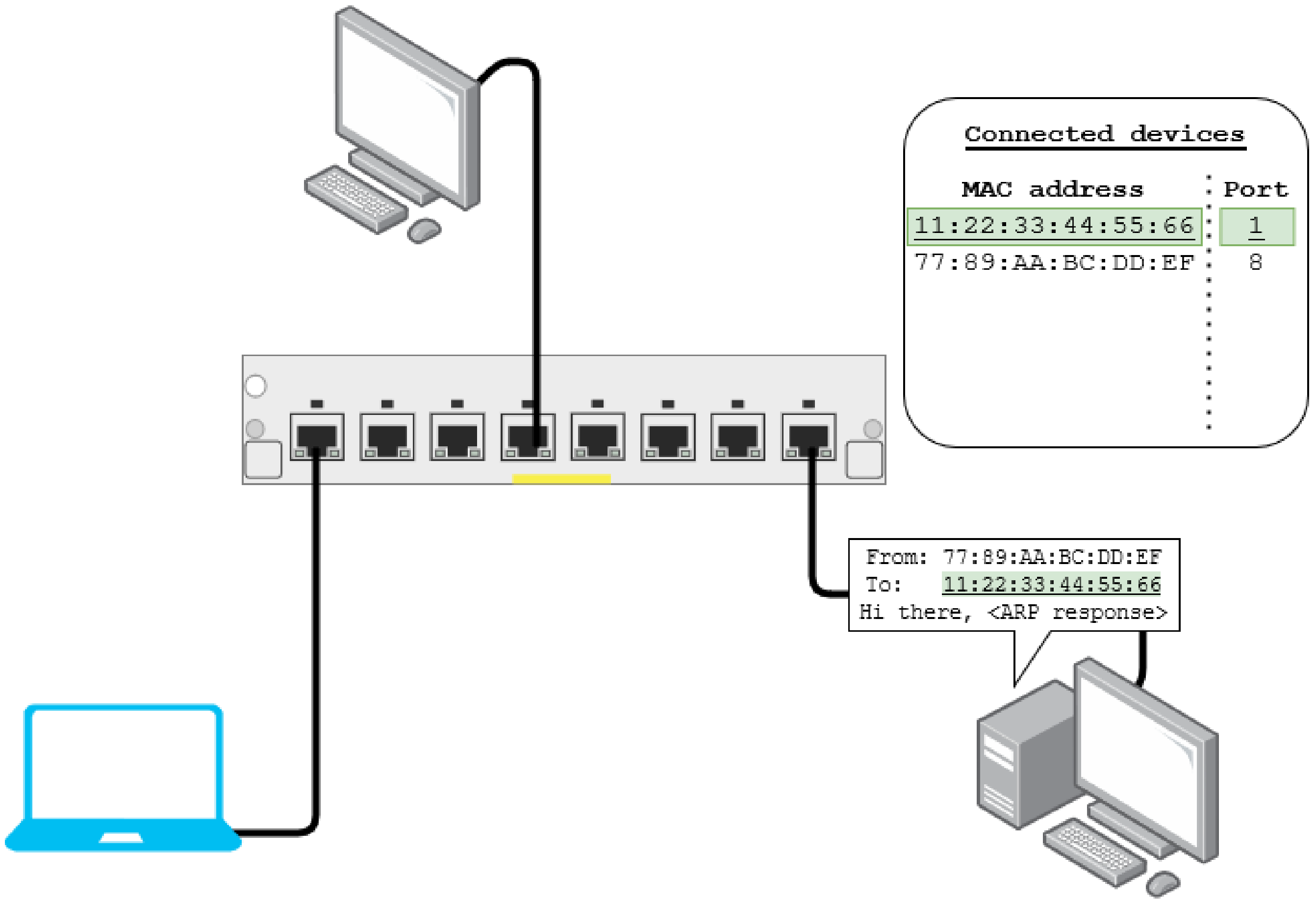
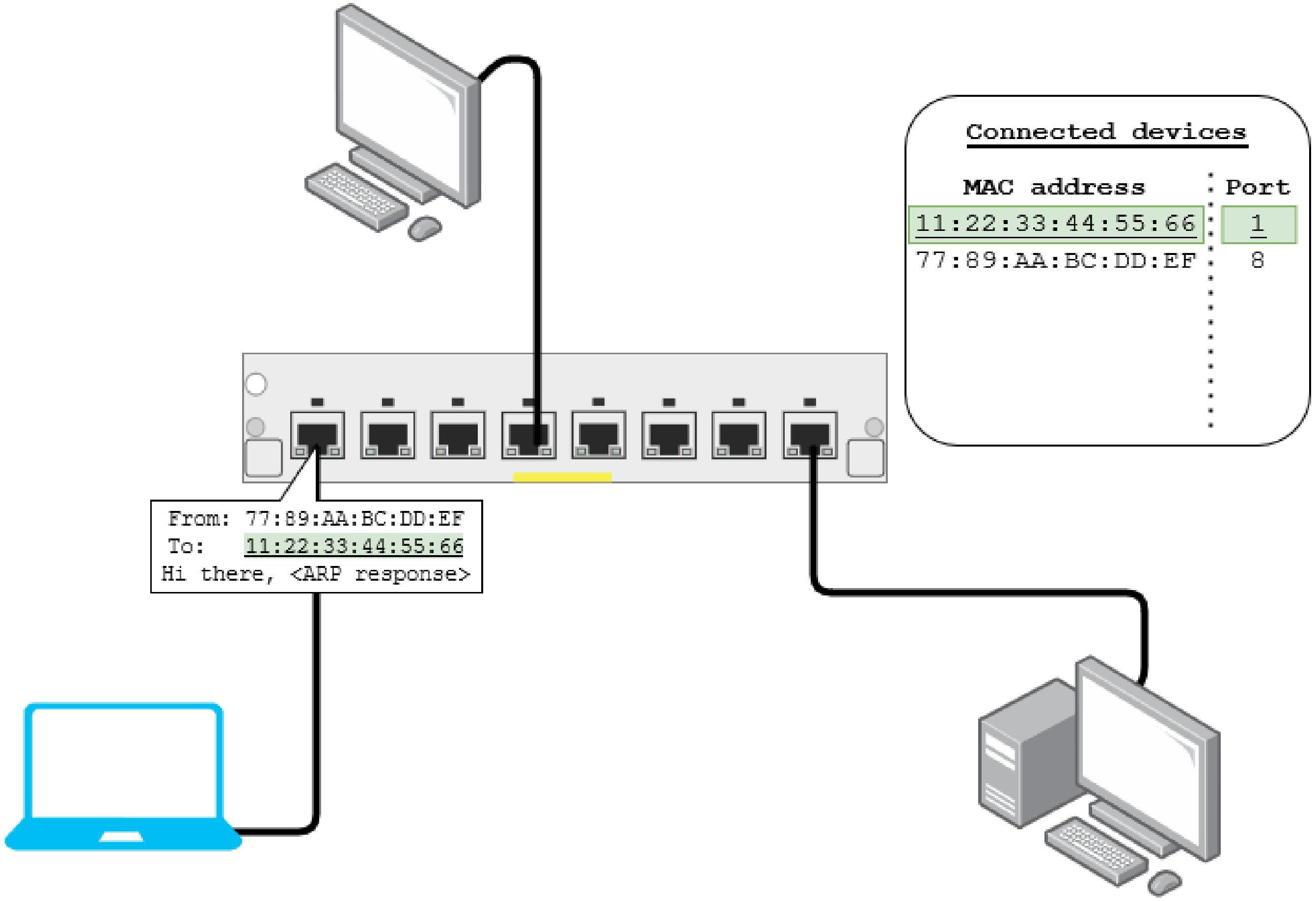
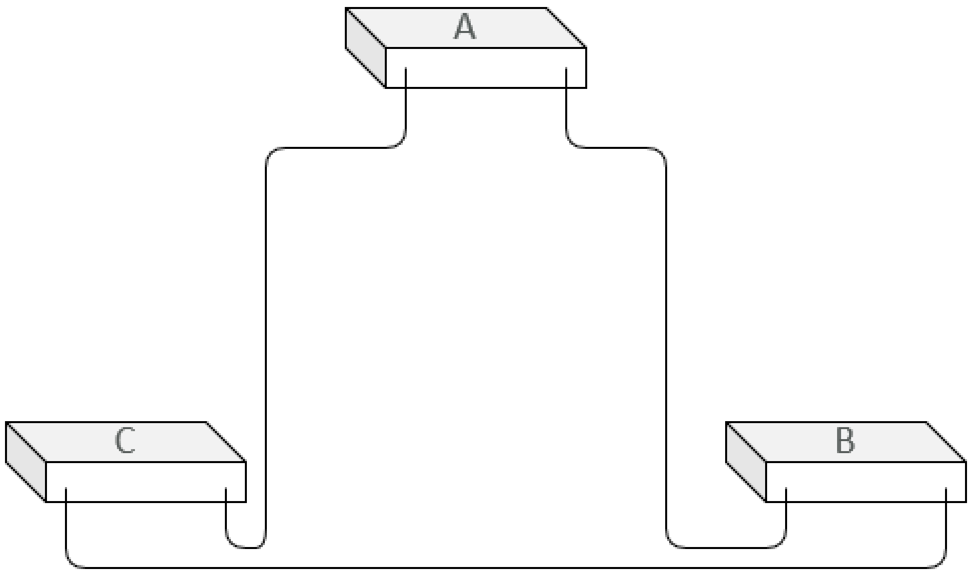


Ethernet: Switching



Ethernet: Switching Loops

- Multiple switches can be interconnected to form one big network
- **Problem:** switching loops
  - Why is it a problem? Broadcasts!
  - If a broadcast frame reaches this topology, it will multiply endlessly
- **Solution:** don't build switching loops!
  - However, they are useful for redundancy
- **S**panning **T**ree **P**rotocol
  - Supported by professional switches
  - Automatically disables redundant links until needed



Ethernet: V-LAN

- **V**irtual **LAN**s
  - Partition switch ports into different logical networks
  - Devices on different networks cannot send packets to each other
  - Broadcast packets are only broadcast to the device's VLAN
- Benefits
  - Partitioned networks
  - No re-wiring required
  - Configured in software
- Downsides
  - Configured in software

The Network Layer

The Network Layer

- Computers A and B are connected to different physical networks
- There is some way to get from A’s network to B’s network
- **Goal:** Send data from A to B

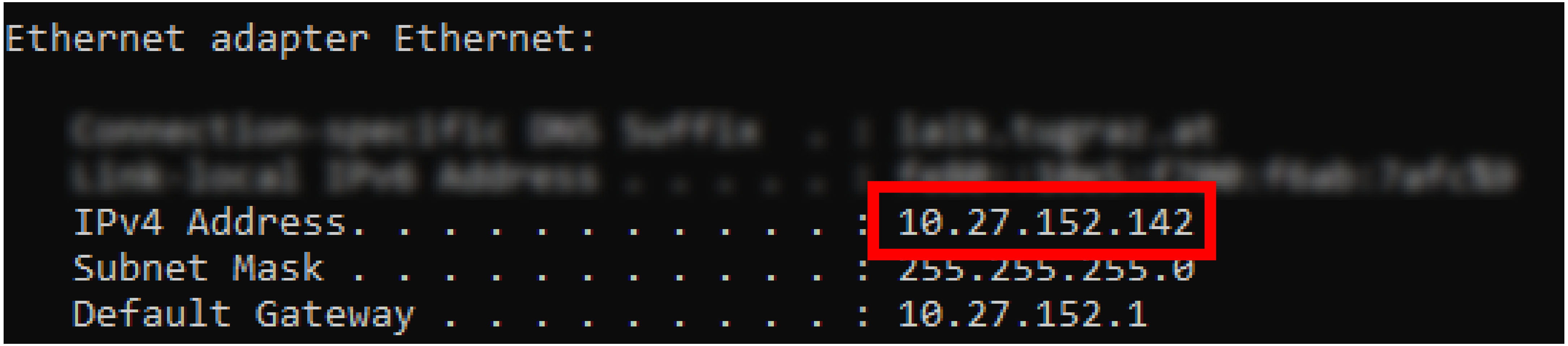
- Concerns:
  - How does the data get from A to B? (routing)
  - What if the data is too large for a certain path? (fragmentation)

IPv4

- **I**nternet **P**rotocol, **v**ersion **4**
- Foundation of today's internet

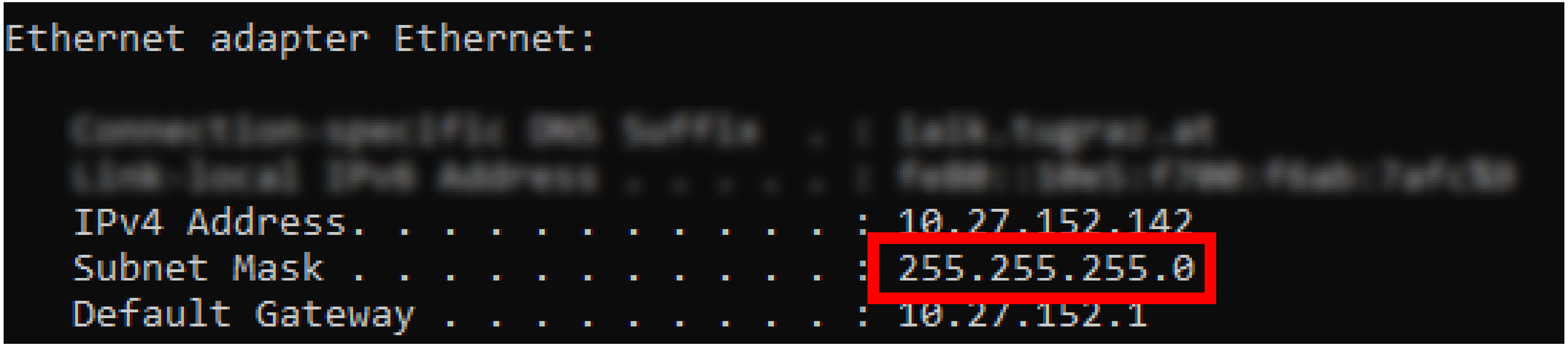
- Used in almost every network-enabled device

IPv4 addressing



- 32-bit address
  - Notation: bytes’ decimal value (0-255)
  - **`10.27.152.142`** is the same as **`0a 1b 98 8e`**
- Each participating network card has a single IPv4 address

IPv4 addressing



- 32-bit subnet mask
  - All ones, followed by all zeros
  - Splits address into *network prefix* and *host number*
  - Alternate notation: just specify number of ones
    - **`255.255.255.0`** is the same as **`/24`**

IPv4 addressing

Network prefix				Host number
10	. 27	. 152	.	142
00001010	.00011011	.10011000	.	10001110
11111111	**.11111111**	**.11111111**	.	00000000
255	. 255	. 255	.	0

IPv4 addressing

- All hosts with the same network prefix form a *subnet*
- Hosts within the same subnet can communicate directly
  - They're in the same Link Layer network!

- Two addresses per subnet have special meaning
  - Host number all zeros ≙ network identifier
    - `10.27.152.142/24` is part of the `10.27.152.0/24` network
  - Host number all ones ≙ broadcast address
    - `10.27.152.255/24` is the broadcast address for the `10.27.152.0/24` network

IPv4 addressing

- Subnet masks do not need to be full bytes
  - **`255.255.255.240`** (28 bits network prefix, 4 bits host number ≙ **`/28`**)
  - **`192.168.13.80/28`** can have up to 14 host addresses
    - Network address: **`192.168.13.80`** (**`80 ≙ 01010000`**)
    - First host address: **`192.168.13.81`** (**`81 ≙ 01010001`**)
    - Last host address: **`192.168.13.94`** (**`94 ≙ 01011110`**)
- Not every broadcast address ends with **`.255`**!
  - What is the broadcast address for **`192.168.195.0/28`**?
- Not every address that ends with **`.255`** is a broadcast address!
  - **`10.5.0.255/16`** is the 255th host in the **`10.5.0.0/16`** subnet

IPv4 addressing

- Need addresses for your home?
  - Private address space that anyone can use:
    - `10.0.0.0/8` (i.e., `10.0.0.0` to `10.255.255.255`)
    - `172.16.0.0/12` (i.e., `172.16.0.0` to `172.31.255.255`)
    - `192.168.0.0/16` (i.e., `192.168.0.0` to `192.168.255.255`)
  - Not globally unique
    - Won't work over the internet!
- Never configured an IP address before?
  - Your ISP modem likely does this for you!
  - **D**ynamic **H**ost **C**onfiguration **P**rotocol
  - Enabled by default on modern devices

IPv4 addressing

- Destination address in my subnet?
  - Talk to it using Data Link Layer

- …talk to it using Data Link Layer?
  - We only have an IP address
  - At the Data Link Layer, we need a MAC address

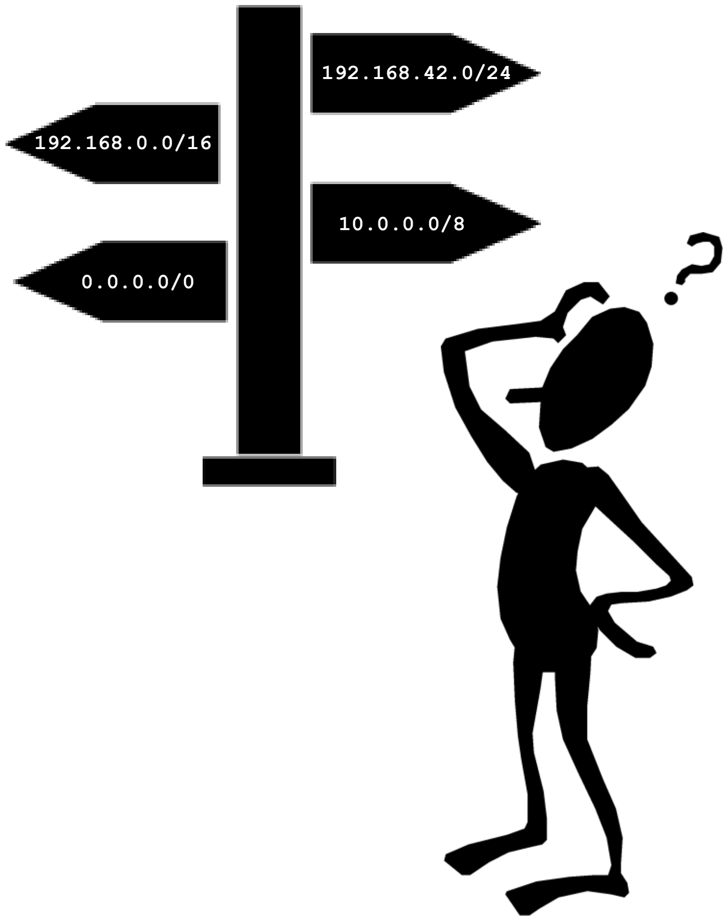
IPv4 addressing

- Destination address in my subnet?
    - Talk to it using Data Link Layer

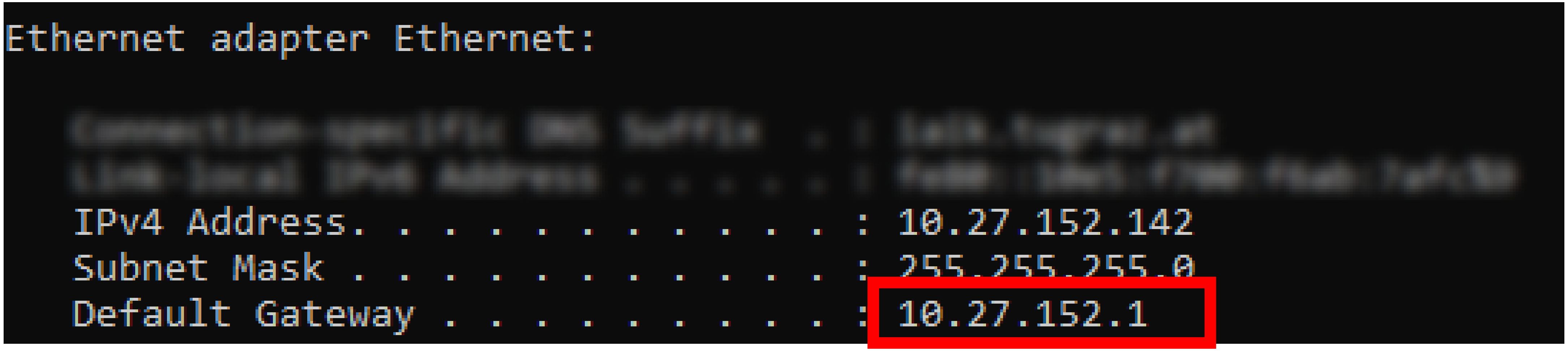
- **A**ddress **R**esolution **P**rotocol
    - Ethernet frames with type `0x0806`
    - Very simple stateless protocol
        - Request MAC for given IP (Ethernet broadcast)
        - Target responds (Ethernet unicast), now we know its MAC address
    - Heavily cached to avoid lots of broadcasting

IPv4 routing

- Destination address in my subnet?
  - Talk to it using Data Link Layer
- Destination address *not* in my subnet?
  - Check *routing table*
  - Maps destination address to *next hop*
    - Move packet in “the right direction”
  - Send packet to next hop using Data Link Layer
  - Eventually it gets there

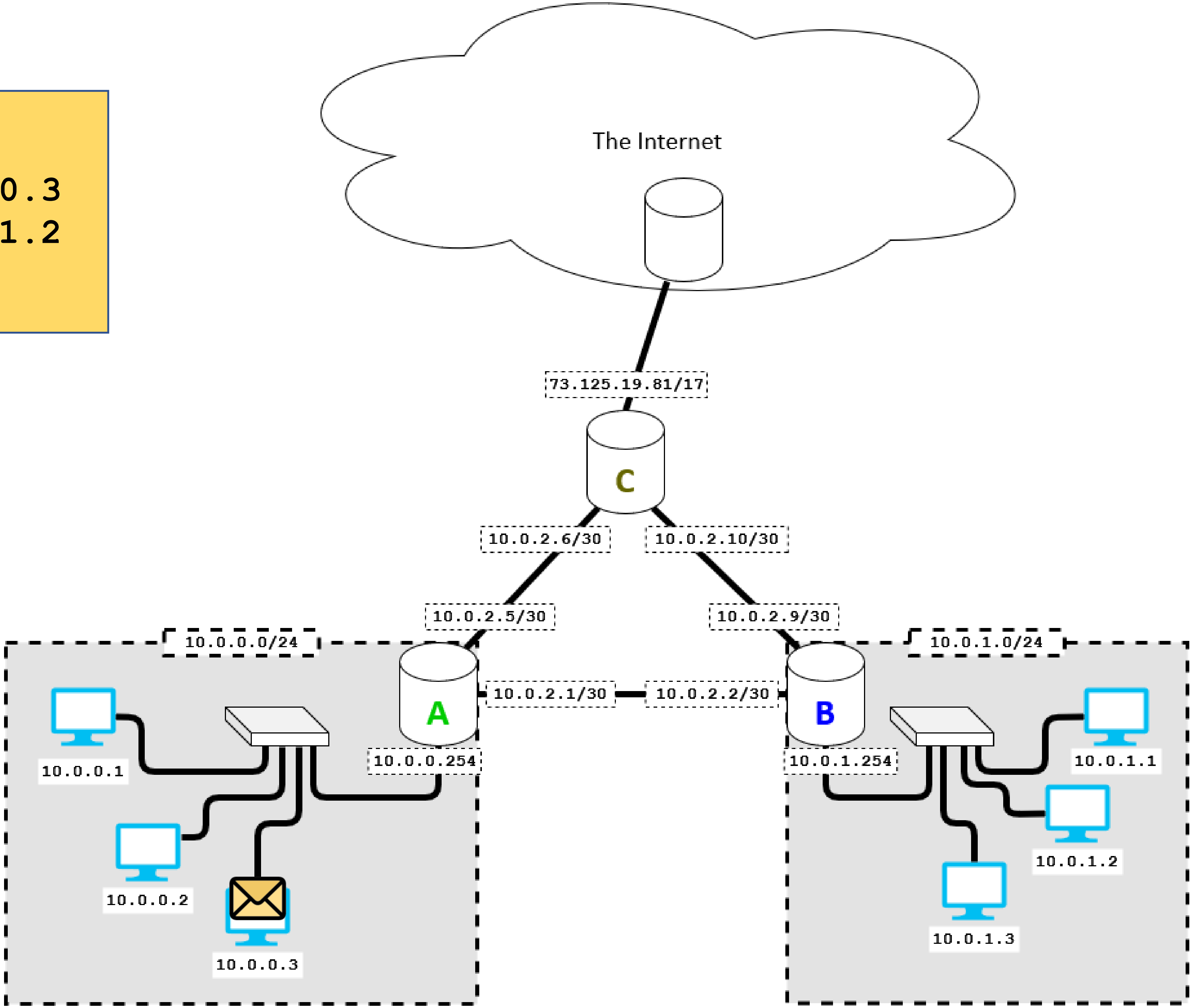


IPv4 routing



- Most host computers only have one entry in their routing table
  - Send any non-subnet data to this *router*
    - At home, this is usually your ISP modem!
  - The router will figure out where to pass the packet to

From: **10.0.0.3**
To: **10.0.1.2**



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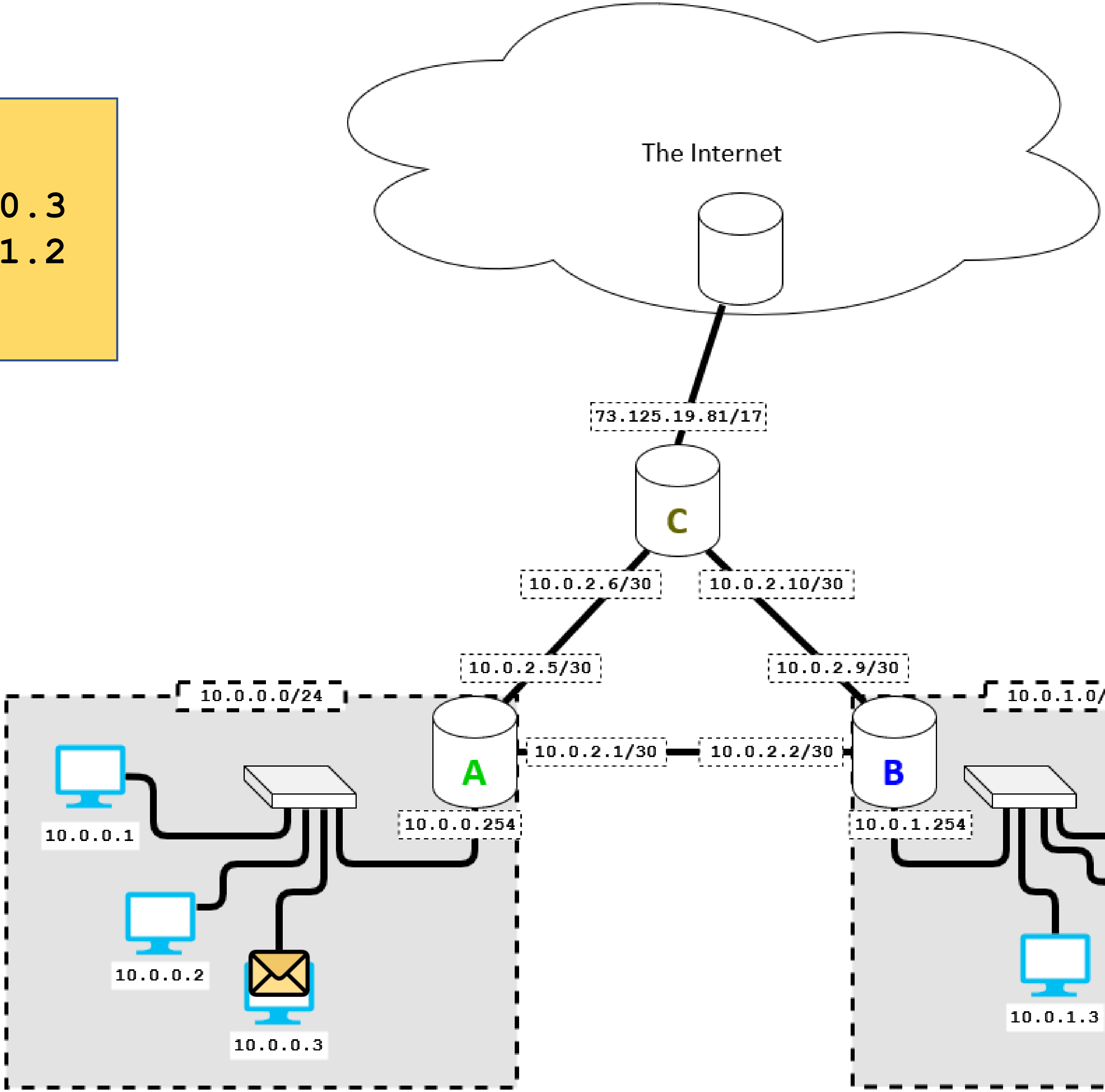
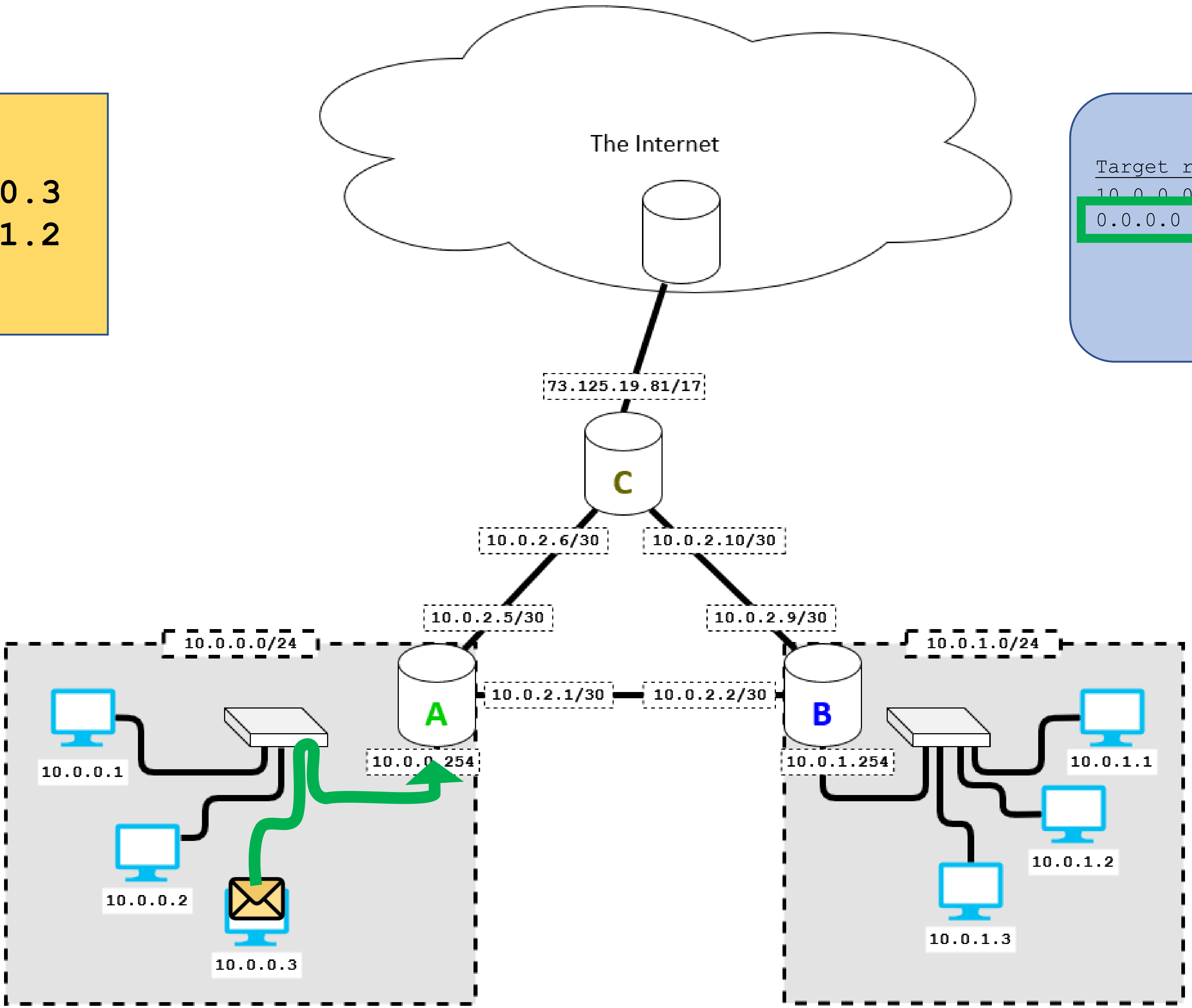


Routing Table

Target range		Next hop
10.0.0.0	/24	n/a
0.0.0.0	/ 0	10.0.0.254

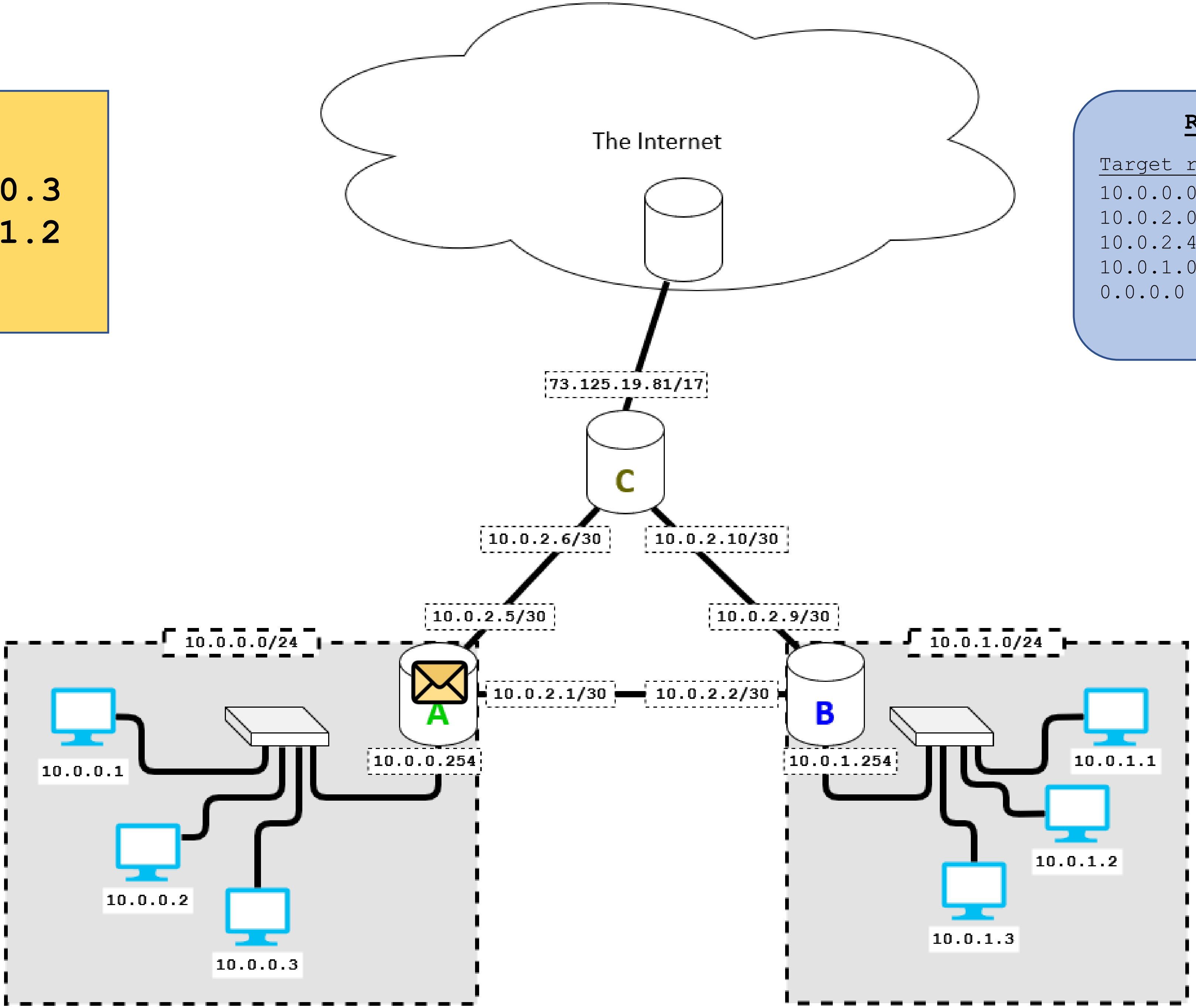
From: **10.0.0.3**
To: **10.0.1.2**



Routing Table

Target range		Next hop
10.0.0.0	/24	n/a
0.0.0.0	/ 0	10.0.0.254

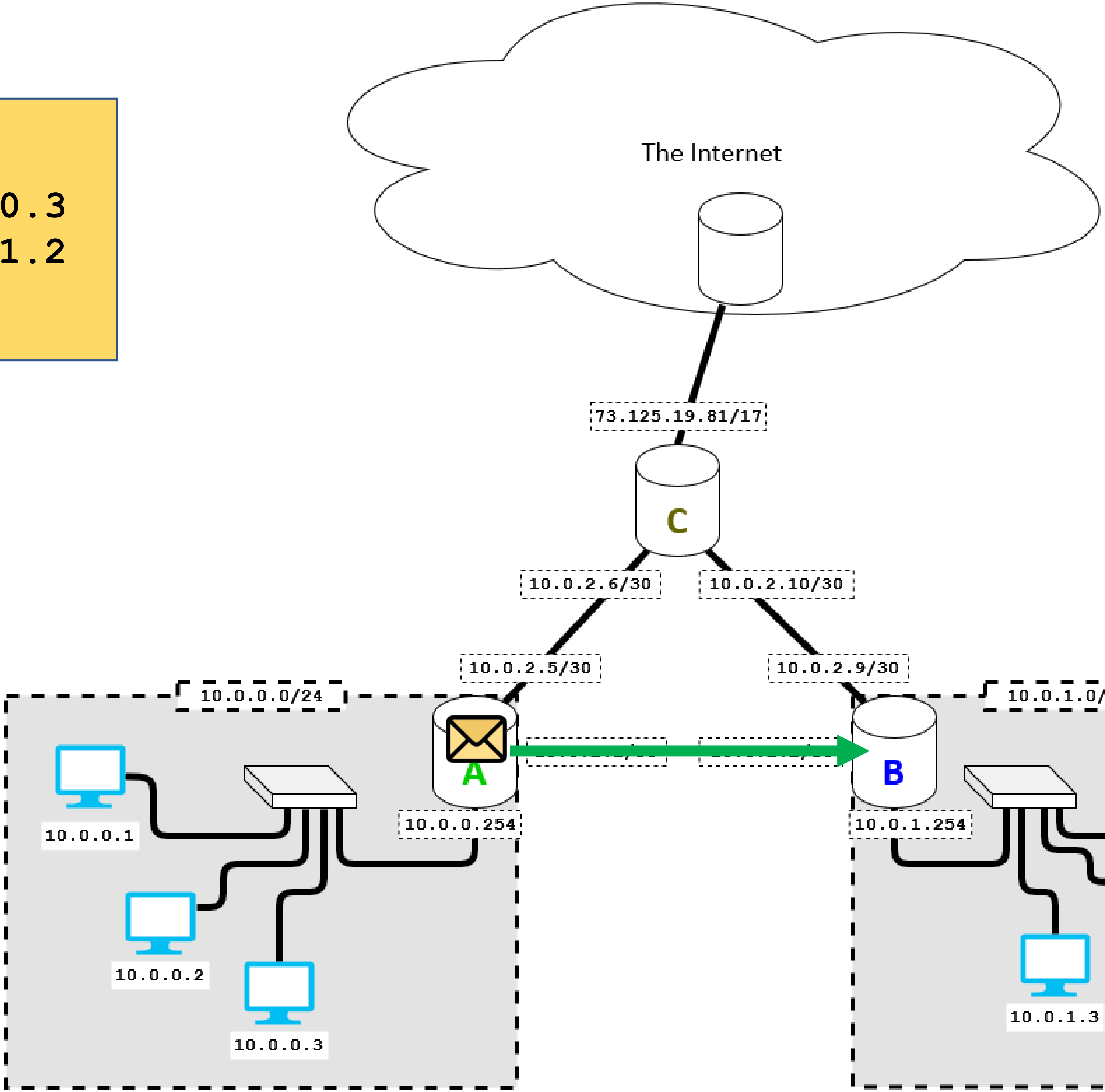
From: **10.0.0.3**
To: **10.0.1.2**



Routing Table on A

Target range		Next hop
10.0.0.0	/24	n/a
10.0.2.0	/30	n/a
10.0.2.4	/30	n/a
10.0.1.0	/24	10.0.2.2
0.0.0.0	/ 0	10.0.2.6

From: **10.0.0.3**
To: **10.0.1.2**



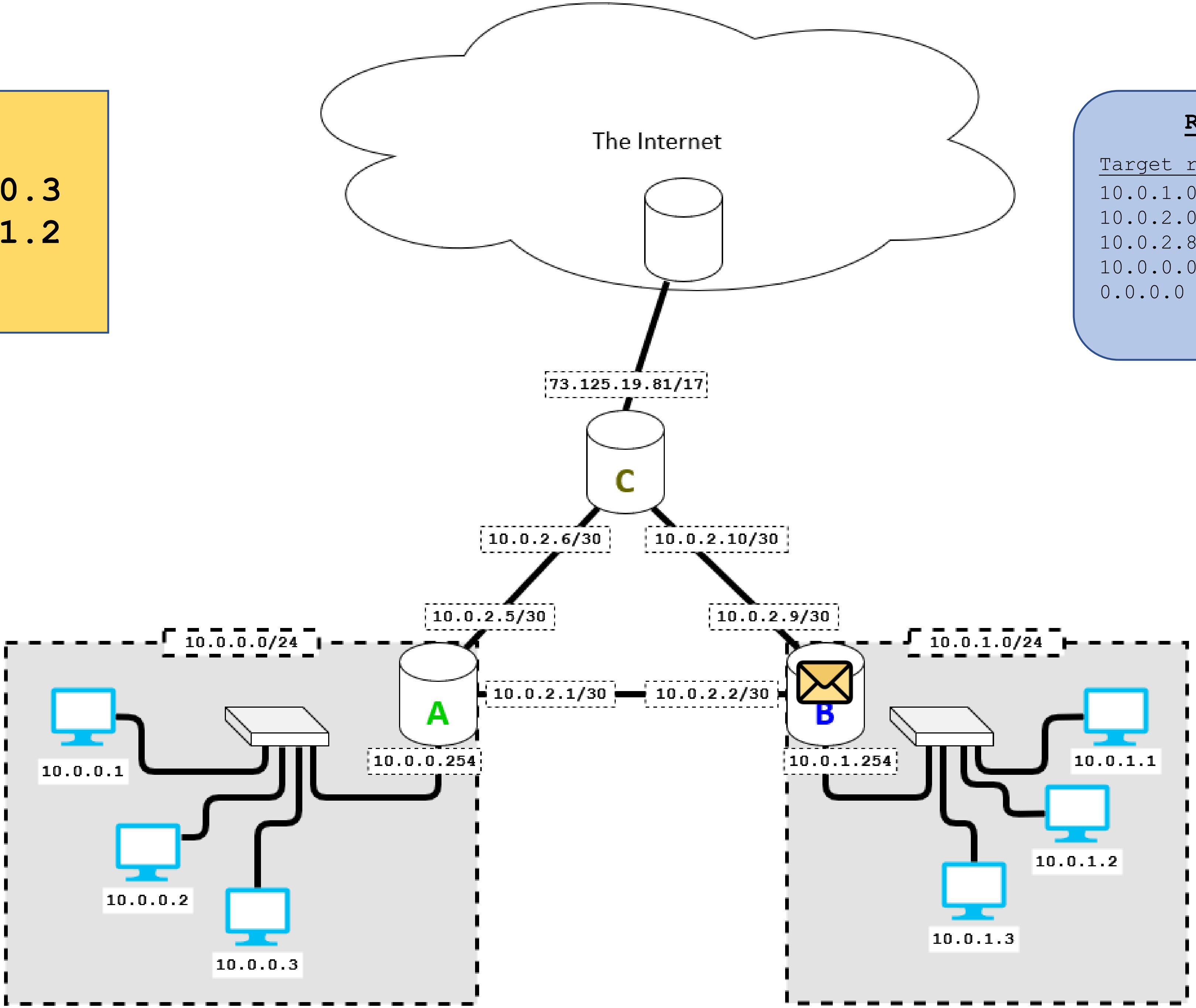
Routing Table on A

Target range		Next hop
10.0.0.0	/24	n/a
10.0.2.0	/30	n/a
10.0.2.4	/30	n/a
10.0.1.0	/24	10.0.2.2
0.0.0.0	/ 0	10.0.2.6

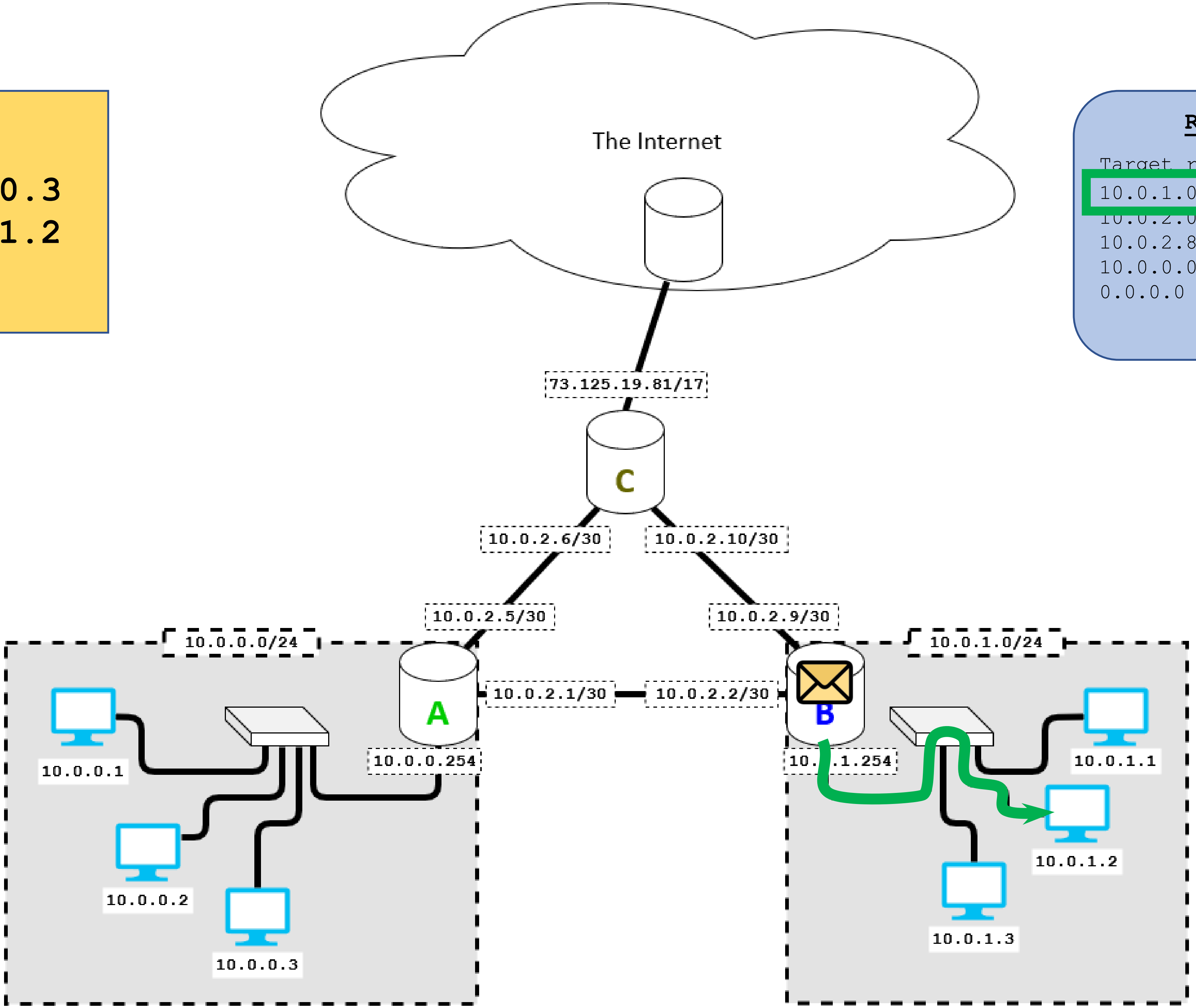
From: **10.0.0.3**
To: **10.0.1.2**

Routing Table on B

Target range		Next hop
10.0.1.0	/24	n/a
10.0.2.0	/30	n/a
10.0.2.8	/30	n/a
10.0.0.0	/24	10.0.2.1
0.0.0.0	/ 0	10.0.2.10



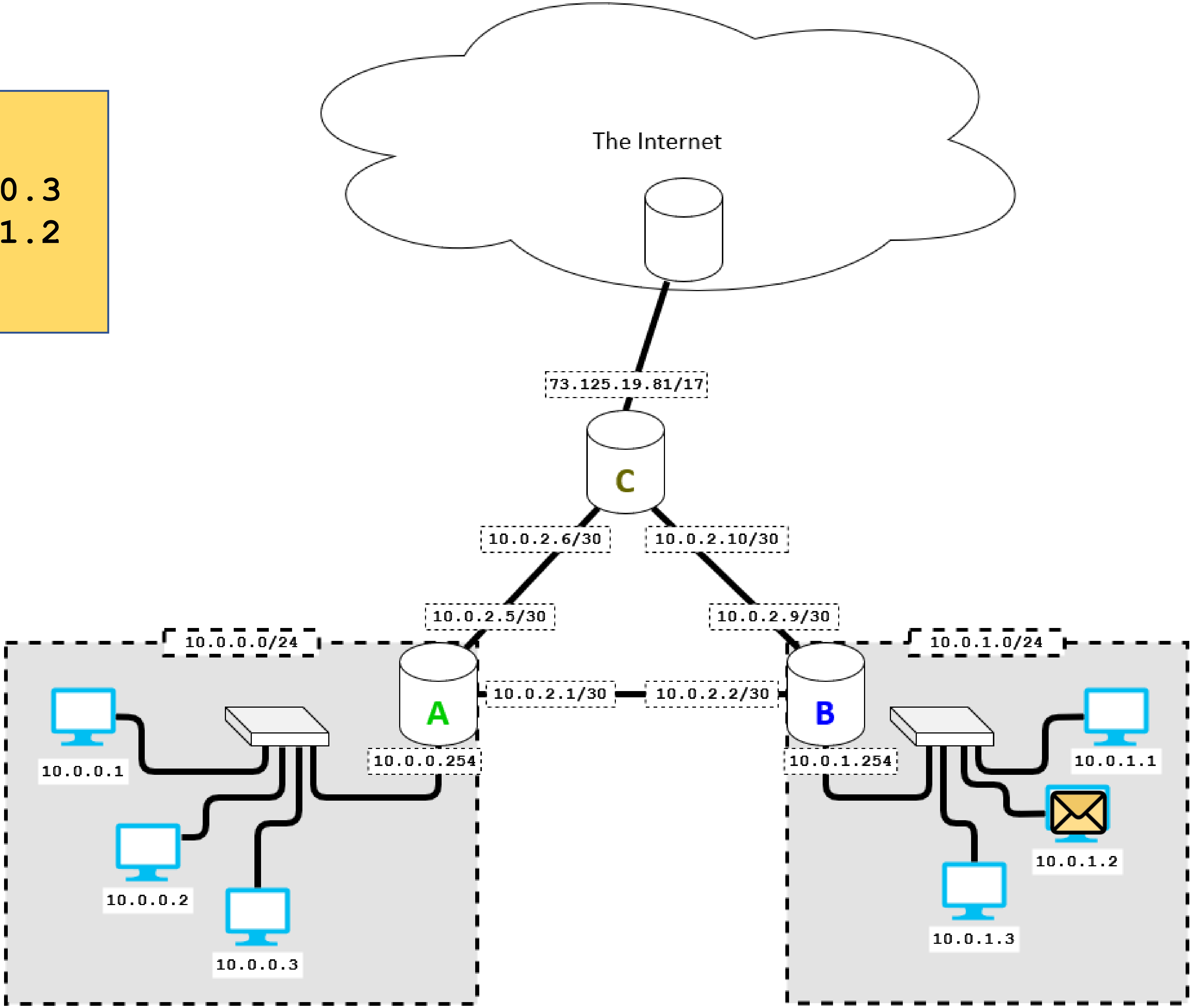
From: **10.0.0.3**
To: **10.0.1.2**



Routing Table on B

Target range		Next hop
10.0.1.0	/24	n/a
10.0.2.0	/30	n/a
10.0.2.8	/30	n/a
10.0.0.0	/24	10.0.2.1
0.0.0.0	/ 0	10.0.2.10

```
From: 10.0.0.3
To:   10.0.1.2
```



IPv4

- You can try this at home!
  - See your IP addresses:
    - **`ip addr`** or **`ifconfig`** (Linux, Mac), **`ipconfig`** (Windows)
  - See your routing table:
    - **`ip route`** or **`netstat –rn`** (Linux , Mac), **`route print`** (Windows)
  - Watch a packet over the internet:
    - **`traceroute`** (Linux , Mac), **`tracert`** (Windows)

```
Tracing route to stackoverflow.com [151.101.193.69]
over a maximum of 30 hops:

  1    <1 ms    <1 ms    <1 ms  10.27.152.1
  2    <1 ms    <1 ms    <1 ms  129.27.200.161
  3     *        *        *     Request timed out.
  4     1 ms     1 ms     1 ms  graz1.aco.net [193.171.21.41]
  5     5 ms     5 ms     5 ms  aconet-ias-aconet-gw.vie.at.geant.net [83.97.88.2]
  6     6 ms    11 ms     8 ms  aconet-ias-geant-gw.vie.at.geant.net [83.97.88.1]
  7     5 ms     5 ms     5 ms  193.203.0.65
  8     5 ms     5 ms     4 ms  151.101.193.69
```

IPv4 packet overview

<table>
<tr><th>Offsets</th><th>Octet</th><th colspan="8">0</th><th colspan="8">1</th><th colspan="8">2</th><th colspan="8">3</th></tr>
<tr><th>Octet</th><th>Bit</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th>31</th></tr>
<tr><td>0</td><td>0</td><td colspan="4">Version</td><td colspan="4">Header Length</td><td colspan="6">DSCP</td><td colspan="2">ECN</td><td colspan="16">Total Length</td></tr>
<tr><td>4</td><td>32</td><td colspan="16">Identification</td><td colspan="3">Flags</td><td colspan="13">Fragment Offset</td></tr>
<tr><td>8</td><td>64</td><td colspan="8">Time To Live</td><td colspan="8">Protocol</td><td colspan="16">Header Checksum</td></tr>
<tr><td>12</td><td>96</td><td colspan="32">Source IP Address</td></tr>
<tr><td>16</td><td>128</td><td colspan="32">Destination IP Address</td></tr>
</table>

- Version: always **`0100`** (version 4)
- Twin “Length” fields
  - Length of just the header
    - Optional header extensions may make it longer!
  - Length of this packet

IPv4 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																																
4	32																																
8	64	Time To Live																Header Checksum															
12	96																																
16	128																																

- Safeguards
  - *Header Checksum* protects header integrity
    - guards against header corruption on lower layer
  - *Time To Live* limits how far a packet can travel
    - after 256 hops, the packet is dropped
    - guards against routing issues (loops etc.)

IPv4 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				Header Length				DSCP						ECN		Total Length															
4	32	Identification																Flags			Fragment Offset												
8	64	Time To Live								Protocol								Header Checksum															
12	96	Source IP Address																															
16	128	Destination IP Address																															

- *Fragmentation* happens if a packet is too large for a given connection
  - Packet is split into two or more packets
  - Recipient re-assembles the fragments
- Fragments are routed as separate packets
  - Might take different routes, arrive out-of-order, etc.

IPv4 packet overview

<table>
<tr><th>Offsets</th><th>Octet</th><th colspan="8">0</th><th colspan="8">1</th><th colspan="8">2</th><th colspan="8">3</th></tr>
<tr><th>Octet</th><th>Bit</th><th>0</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th><th>31</th></tr>
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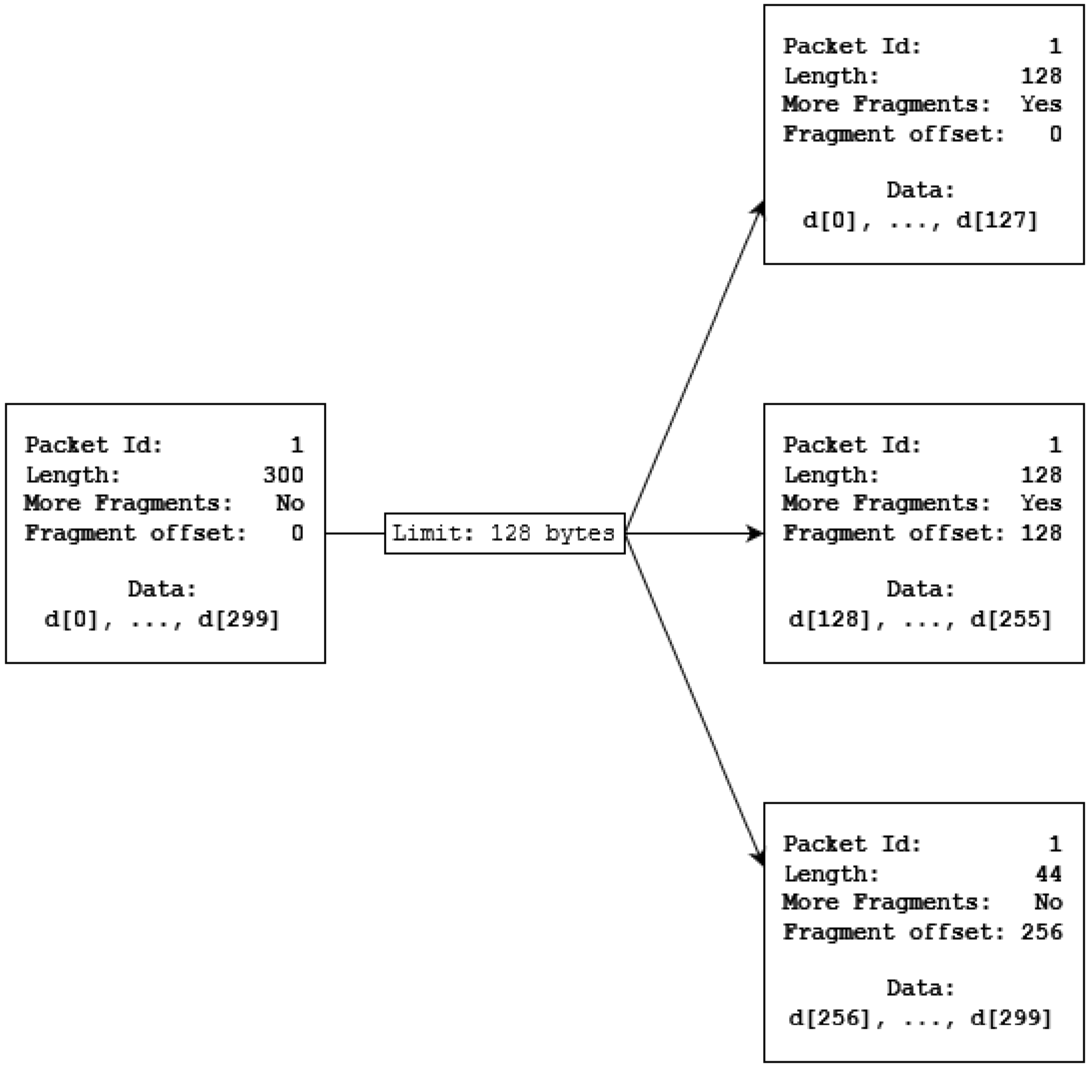
<tr><td>12</td><td>96</td><td colspan="32">Source IP Address</td></tr>
<tr><td>16</td><td>128</td><td colspan="32">Destination IP Address</td></tr>
</table>

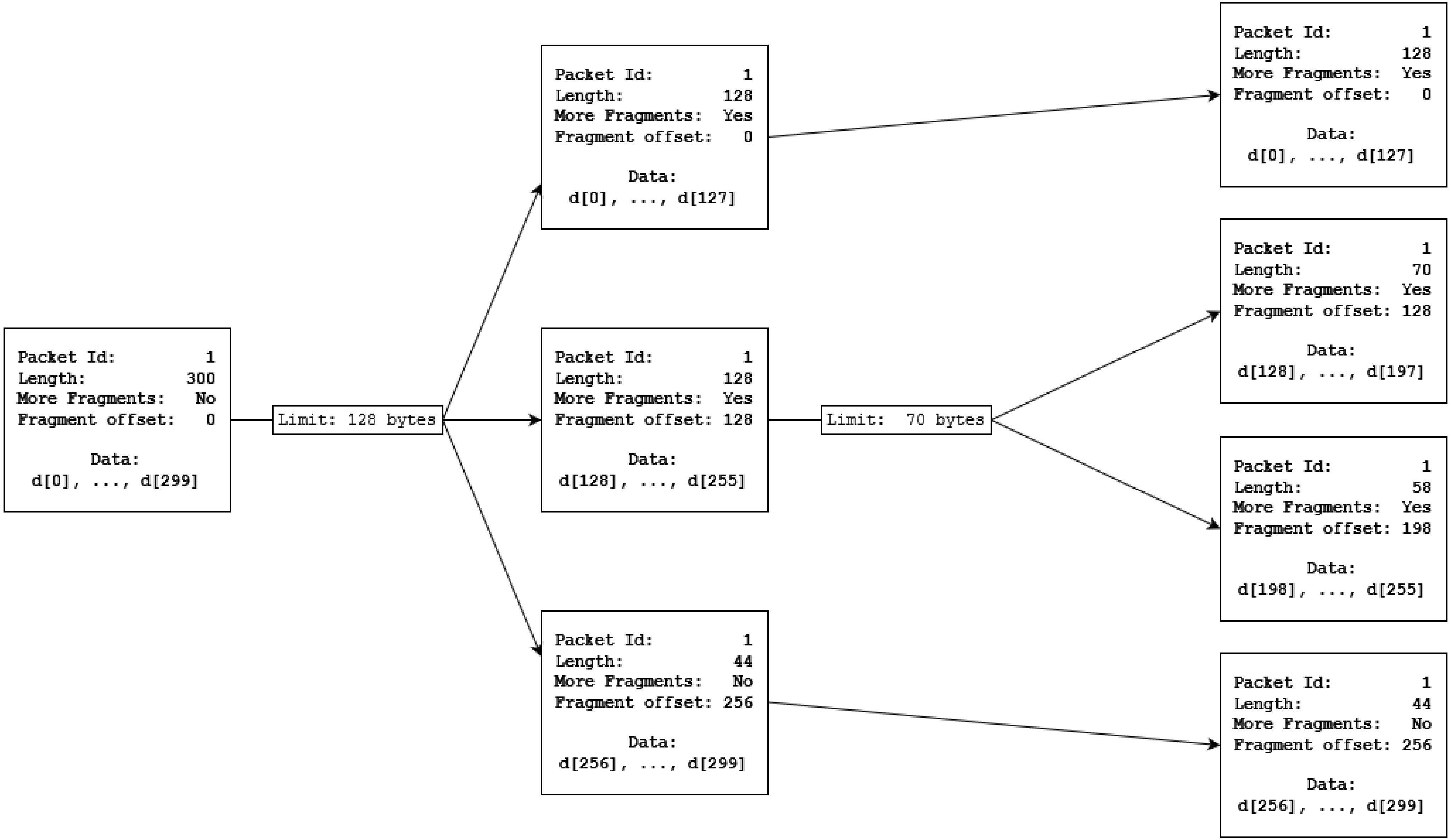
- *Identification* is the same across all fragments
- *Flags*: whether this is *not* the last packet (***M**ore **F**ragments* flag)
- *Fragment offset*: this fragment's position within the original message

IPv4 fragmentation

```
Packet Id:           1
Length:            300
More Fragments:     No
Fragment offset:     0

       Data:
 d[0], ..., d[299]
```


Packet Id: 1
Length: 300
More Fragments: No
Fragment offset: 0
Data:
d[0], ..., d[299]
Limit: 128 bytes
Packet Id: 1
Length: 128
More Fragments: Yes
Fragment offset: 0
Data:
d[0], ..., d[127]
Packet Id: 1
Length: 128
More Fragments: Yes
Fragment offset: 128
Data:
d[128], ..., d[255]
Packet Id: 1
Length: 44
More Fragments: No
Fragment offset: 256
Data:
d[256], ..., d[299]


Packet Id: 1
Length: 300
More Fragments: No
Fragment offset: 0
Data:
d[0], ..., d[299]
Limit: 128 bytes
Packet Id: 1
Length: 128
More Fragments: Yes
Fragment offset: 0
Data:
d[0], ..., d[127]
Packet Id: 1
Length: 128
More Fragments: Yes
Fragment offset: 128
Data:
d[128], ..., d[255]
Packet Id: 1
Length: 44
More Fragments: No
Fragment offset: 256
Data:
d[256], ..., d[299]
Limit: 70 bytes
Packet Id: 1
Length: 128
More Fragments: Yes
Fragment offset: 0
Data:
d[0], ..., d[127]
Packet Id: 1
Length: 70
More Fragments: Yes
Fragment offset: 128
Data:
d[128], ..., d[197]
Packet Id: 1
Length: 58
More Fragments: Yes
Fragment offset: 198
Data:
d[198], ..., d[255]
Packet Id: 1
Length: 44
More Fragments: No
Fragment offset: 256
Data:
d[256], ..., d[299]

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
  - We’ll talk details later
  - (We need to understand transport layer concepts first 😉)

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

IPv4 fragmentation – Alternatives

- Path MTU discovery
  - Detect the largest packet size that can be sent unfragmented

- How: it’s complicated
  - **D**on’t **F**ragment flag in IP header + trial & error
    - Problem: failure notifications might not arrive
  - More sophisticated trial & error at higher layers
    - Problem: need to re-invent this wheel for every transport layer protocol
    - Not every transport layer protocol is able to fragment data!

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