network

networking

networking: enable machine-to-machine communication

goal: enable *applications* that span multiple computers

- websites
- streaming video
- email
- chat
- …

challenge: realities of the real-world

- massive scale
- consequences of success
- security
- geopolitical and economic concerns

sockets is the de-facto API for networking

open *connection* then …

- read+write just like a terminal file

doesn't look like individual messages

"connection abstraction"

mailbox model

mailbox abstraction: send/receive messages

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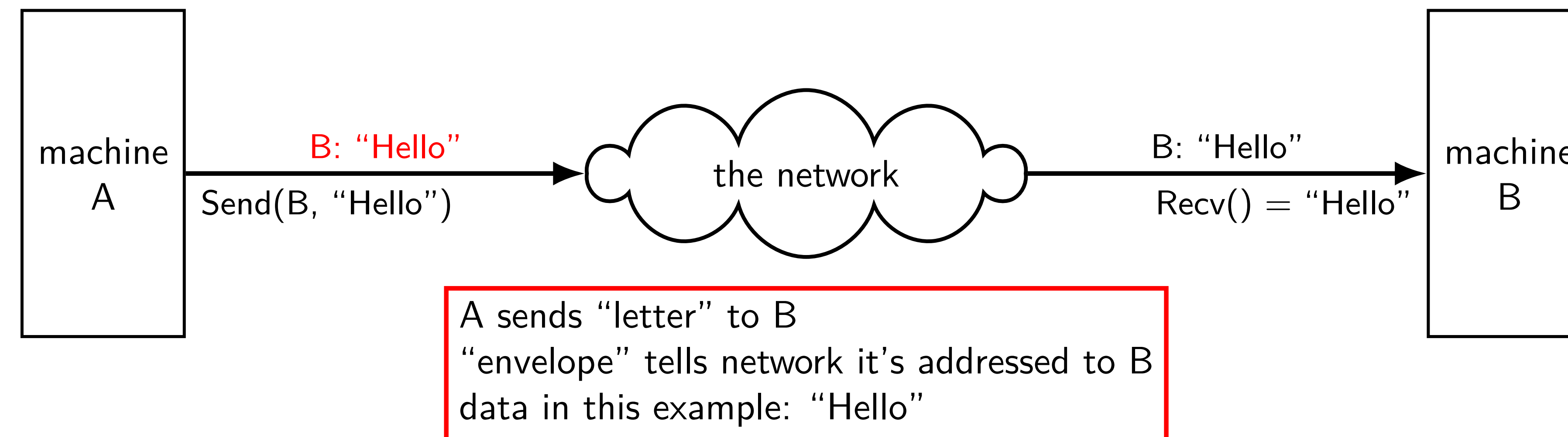
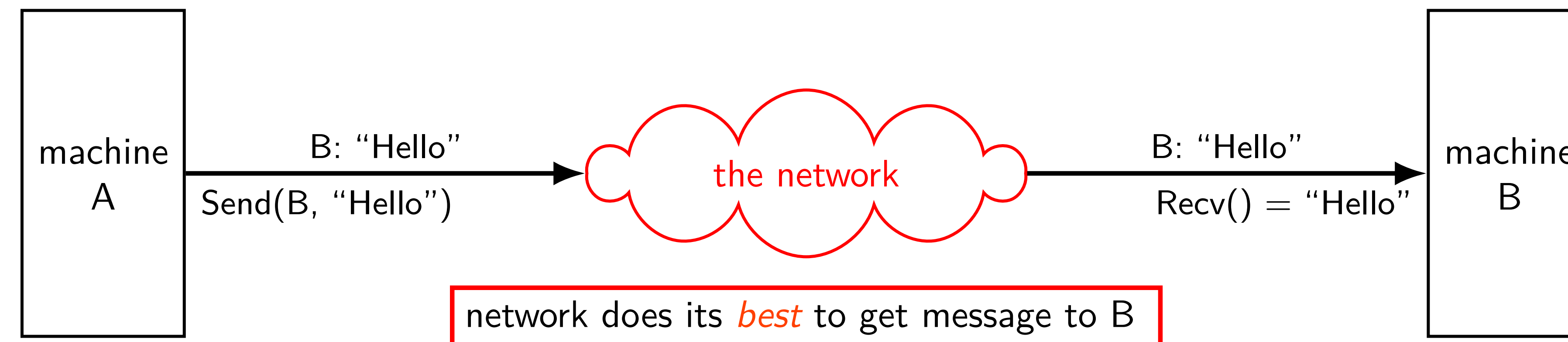
mailbox abstraction: send/receive messages



mailbox model

mailbox abstraction: send/receive messages



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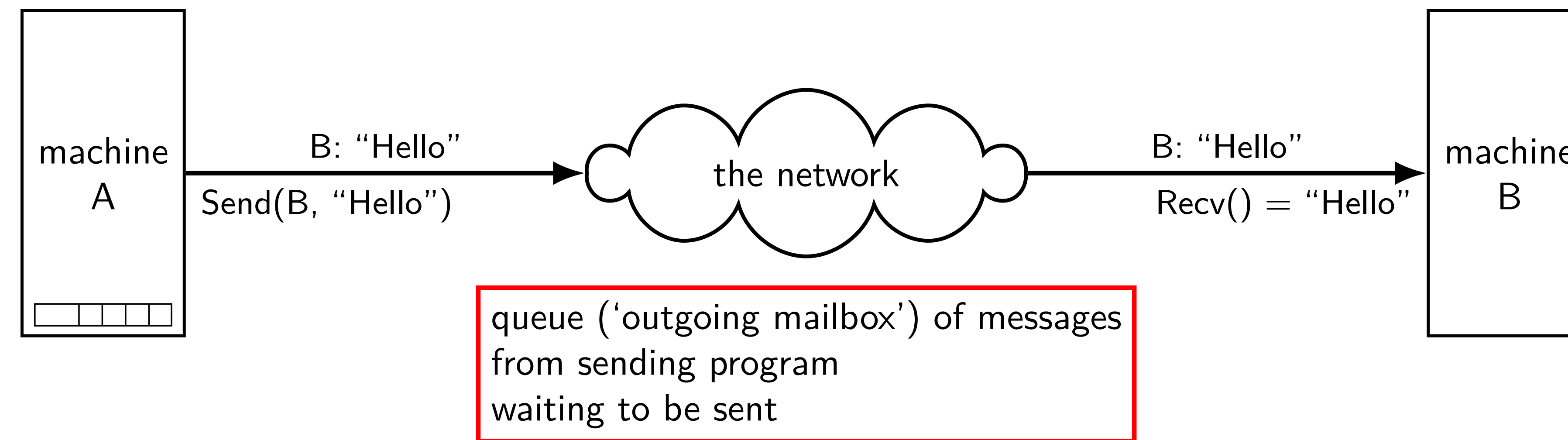

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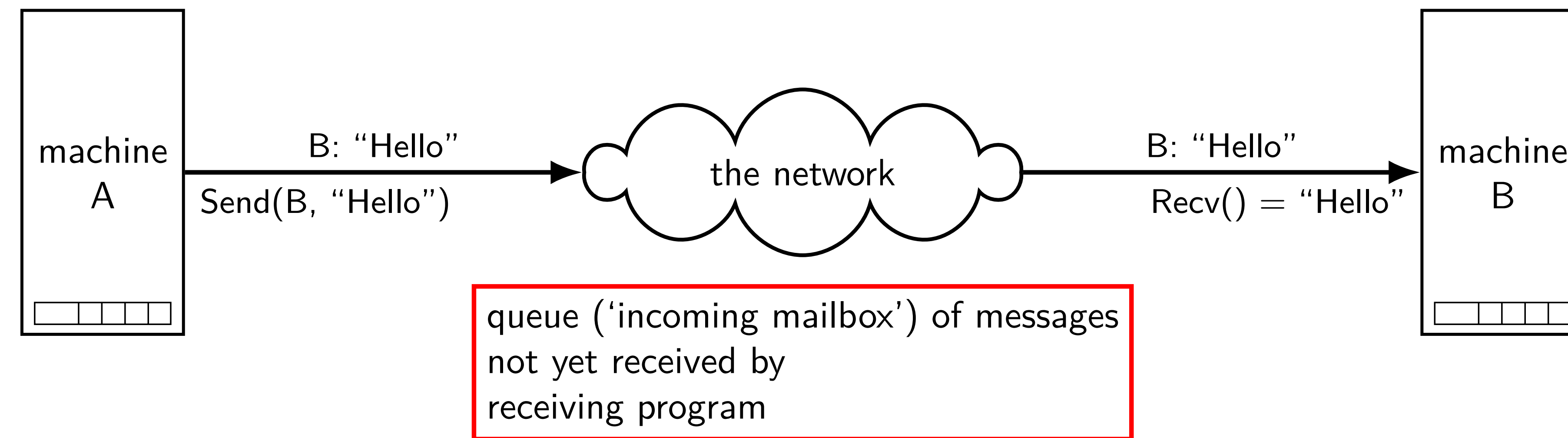


connections over mailboxes

real Internet: mailbox-style communication

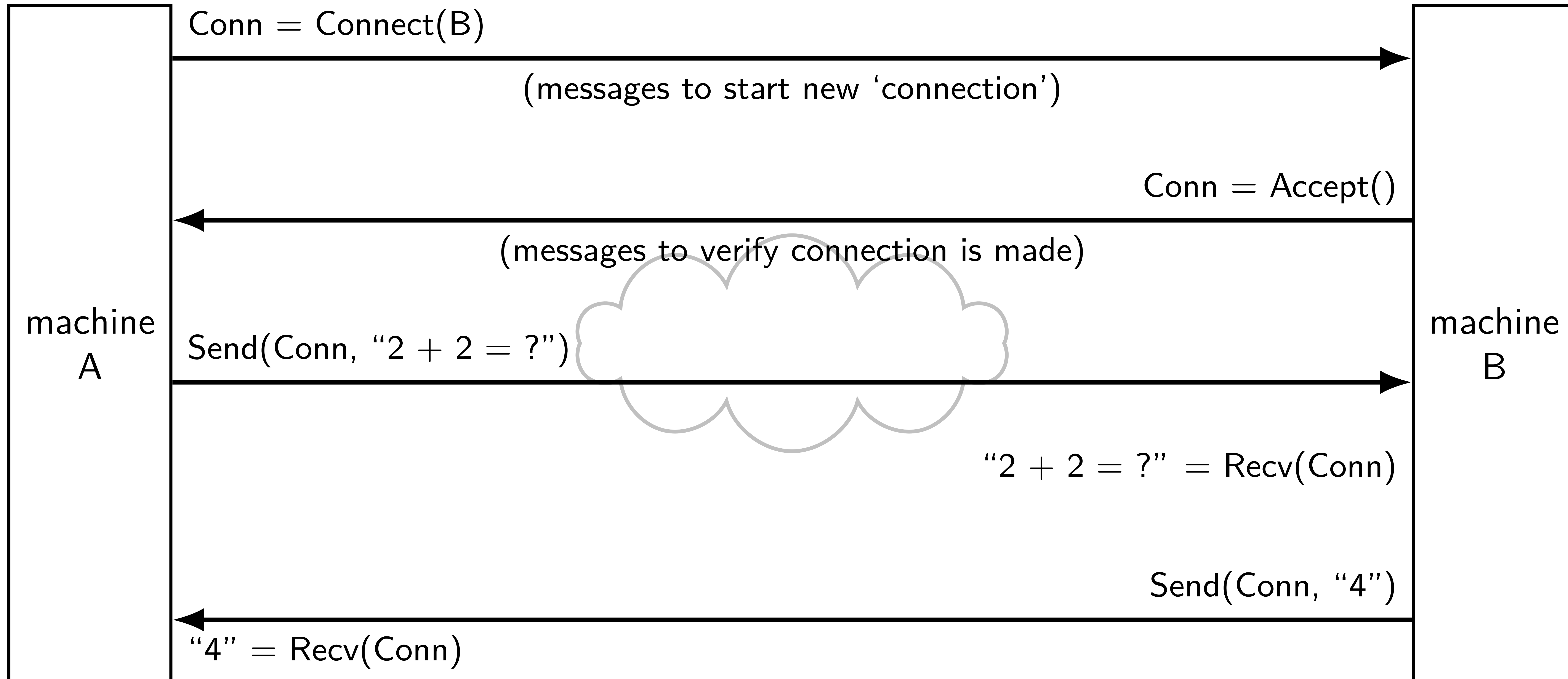
- send “letters” (packets) to particular mailboxes
- have “envelope” (header) saying where they go

“best-effort”

- no guarantee on order, when received
- no guarantee on *if* received

sockets implemented on top of this

connections



networking layers

application	HTTP, SSH, SMTP, …	application-defined meanings
transport	TCP, UDP, …	reach correct program reliability/streams
network	IPv4, IPv6	reach correct machine (across networks)
link	Ethernet, Wi-Fi, …	coordinate shared wire/radio
physical	Ethernet, Wi-Fi, …	encode bits for wire/radio

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layers terminology

application	application-defined meanings	
transport	reach correct program, reliablity/streams	segments/datagrams
network	reach correct machine (across networks)	packets
link	coordinate shared wire/radio	frames
physical	encode bits for wire/radio	

layer encapsulation

upper layers implemented using lower layers

example: implement reliable + large messages (transport layer)
by sending multiple unreliable messages across networks (network layer)

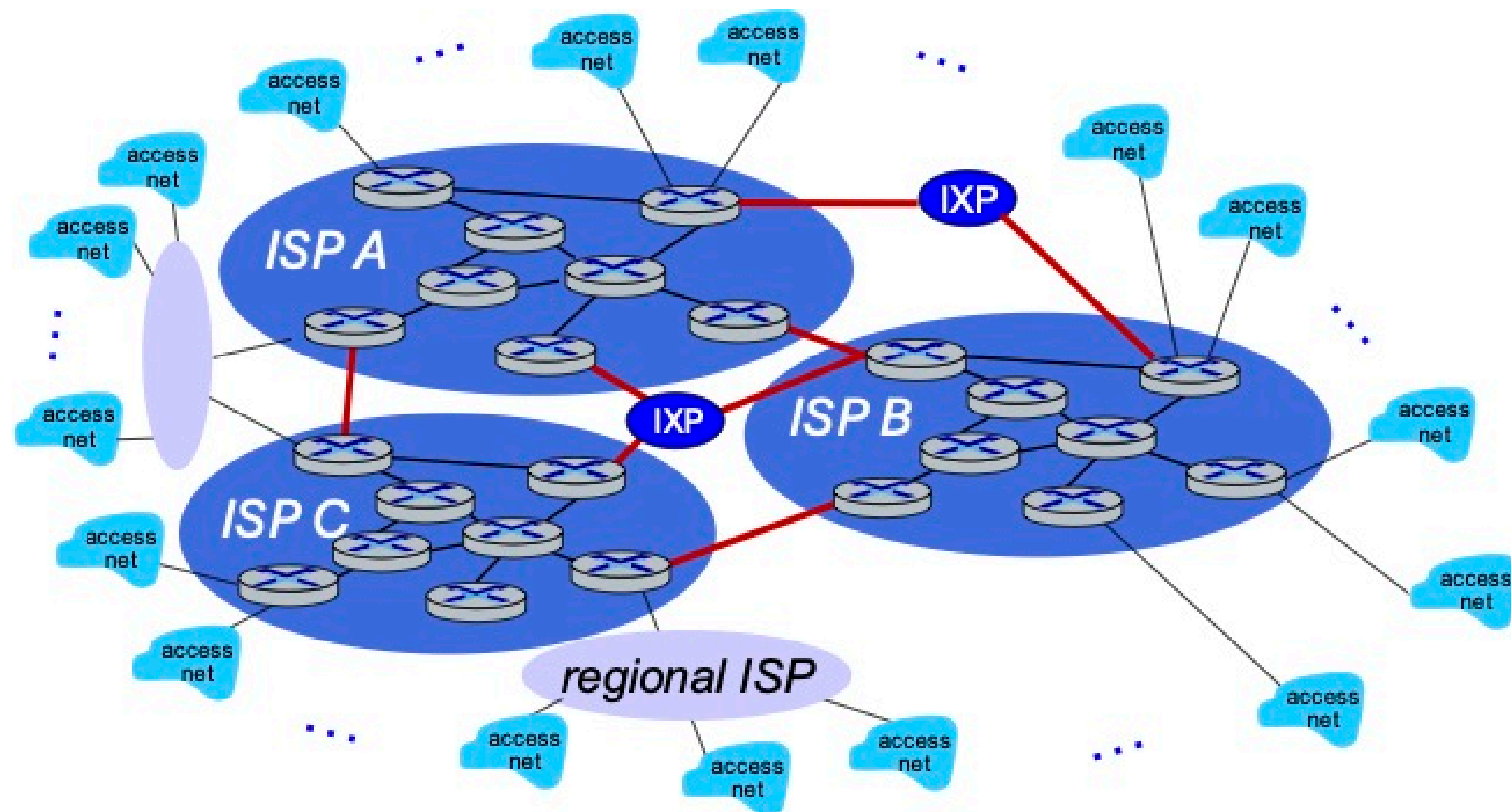
example: implement reaching machine across networks (network layer)
by sending multiple messages on local networks (link layer)

reality: you don't own the network!

the internet is a series of connected networks

packets traverse routers within and between networks

those networks provide "best-effort" service



network limitations/failures

messages lost

messages delayed/reordered

messages limited in size

messages corrupted

network limitations/failures

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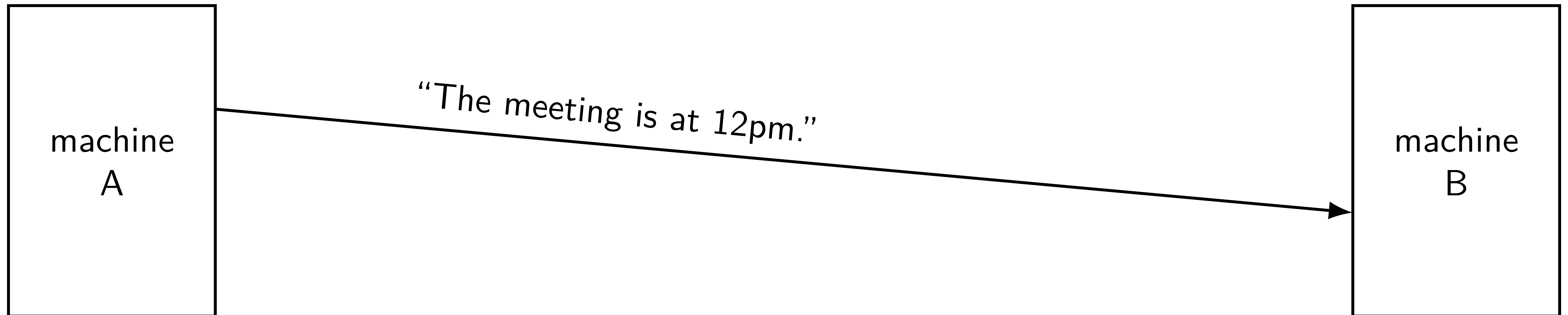
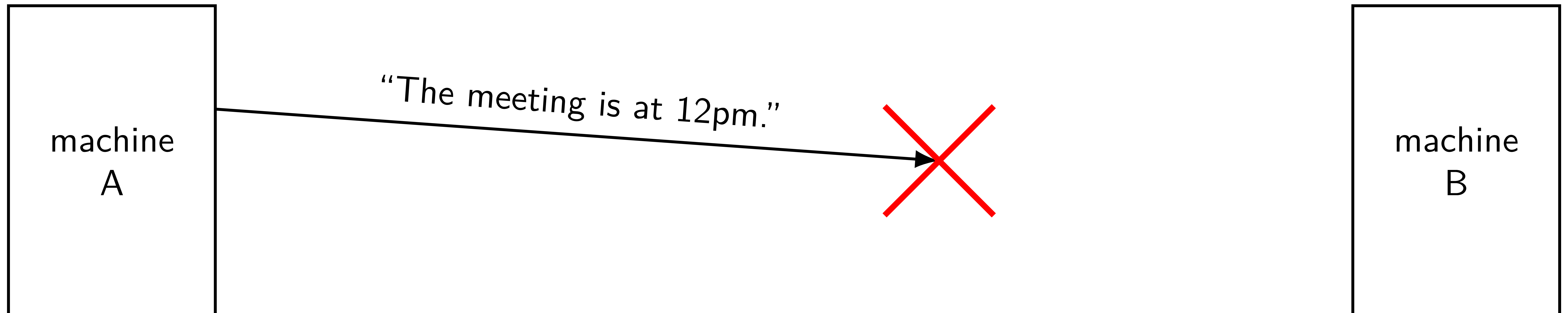
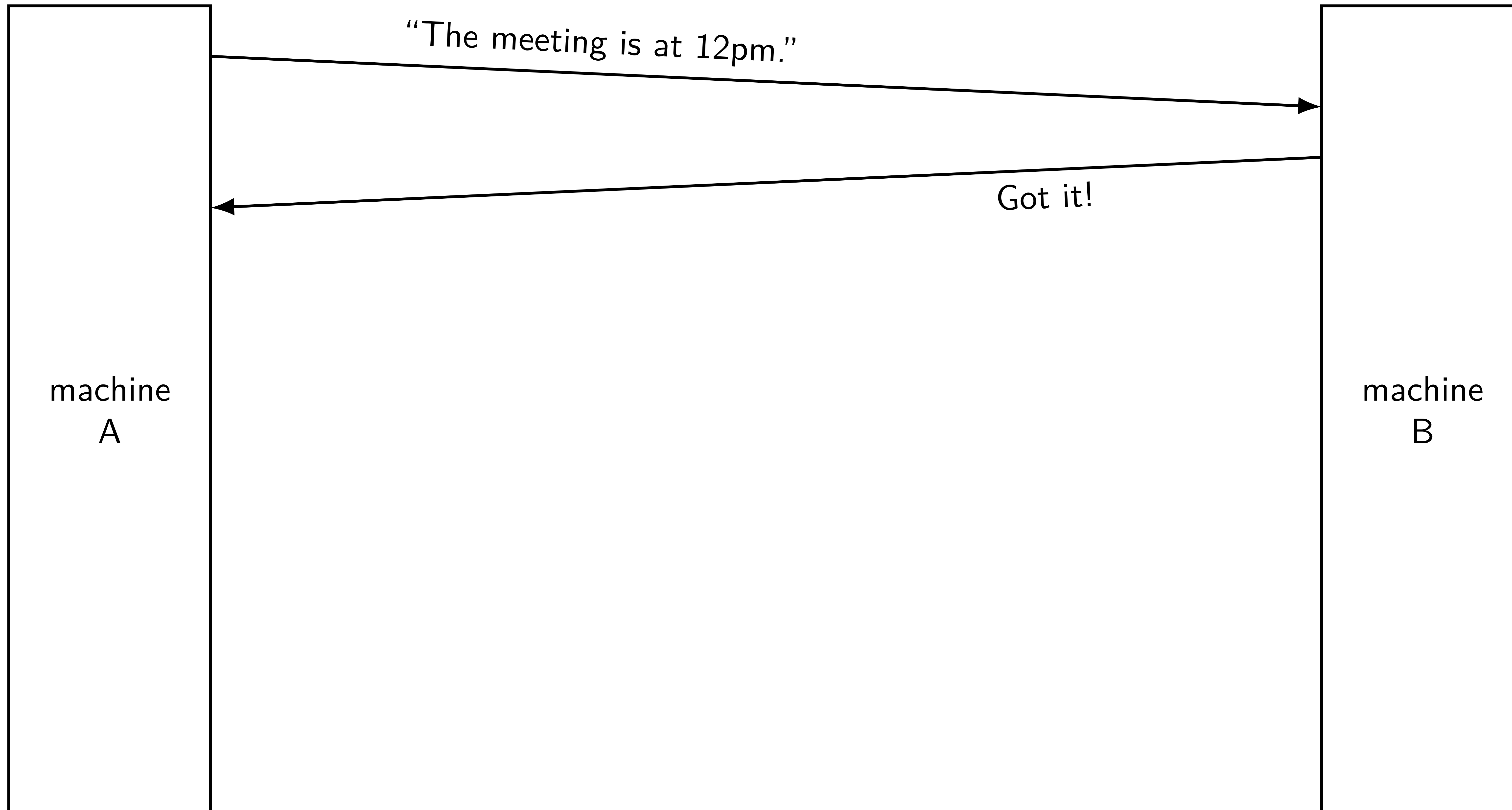
messages corrupted

dealing with network message lost





handling lost message: acknowledgements



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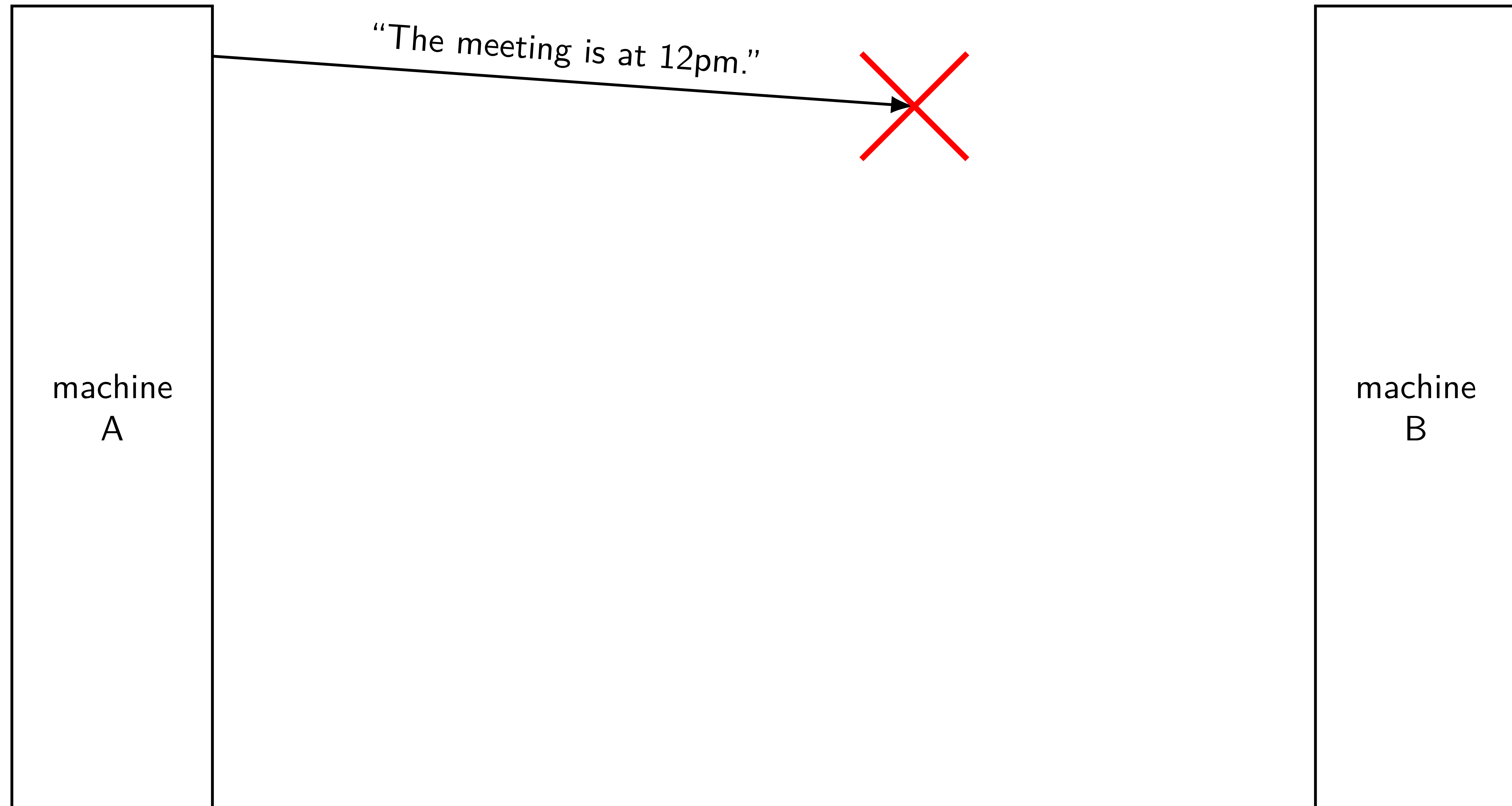

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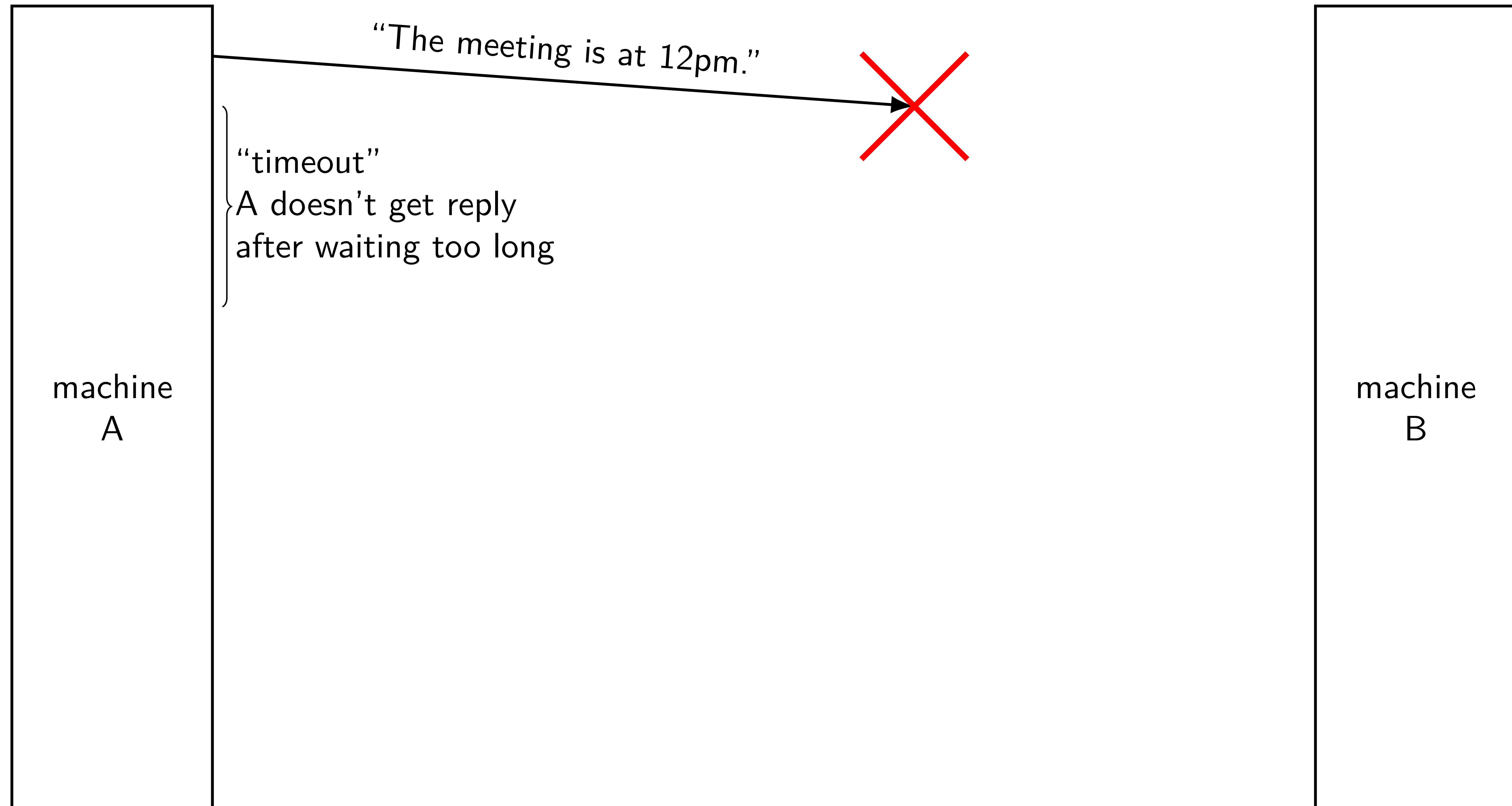
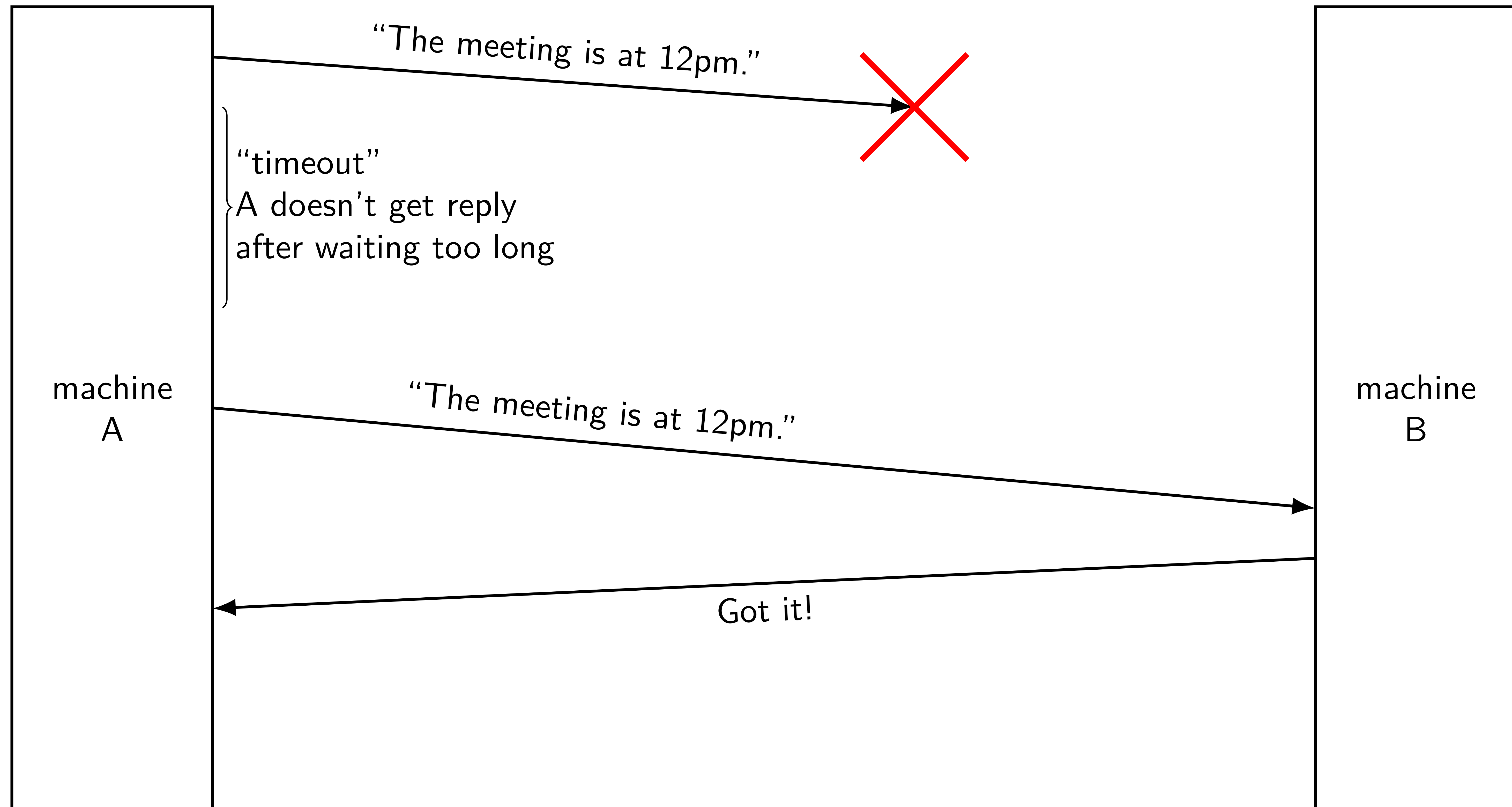
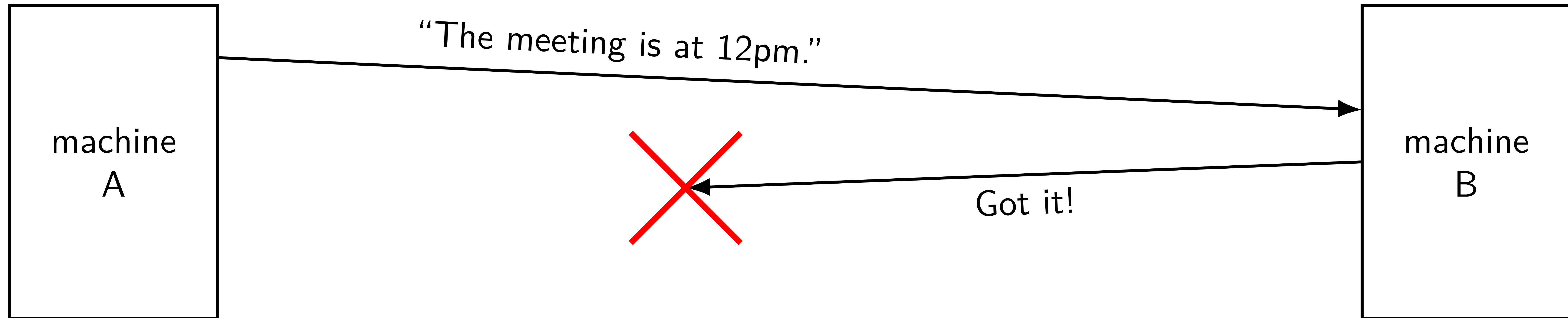


handling lost message



exercise: lost acknowledgement

exercise: how to fix this?



A. machine A needs to send "Got 'got it!' "
B. machine B should resend "Got it!" on its own
C. machine A should resend the original message on its own
D. none of these

answers

send “Got ‘got it!’ ”?

- same problem: Now send ‘Got Got Got it’?

resend “Got it!” own its own?

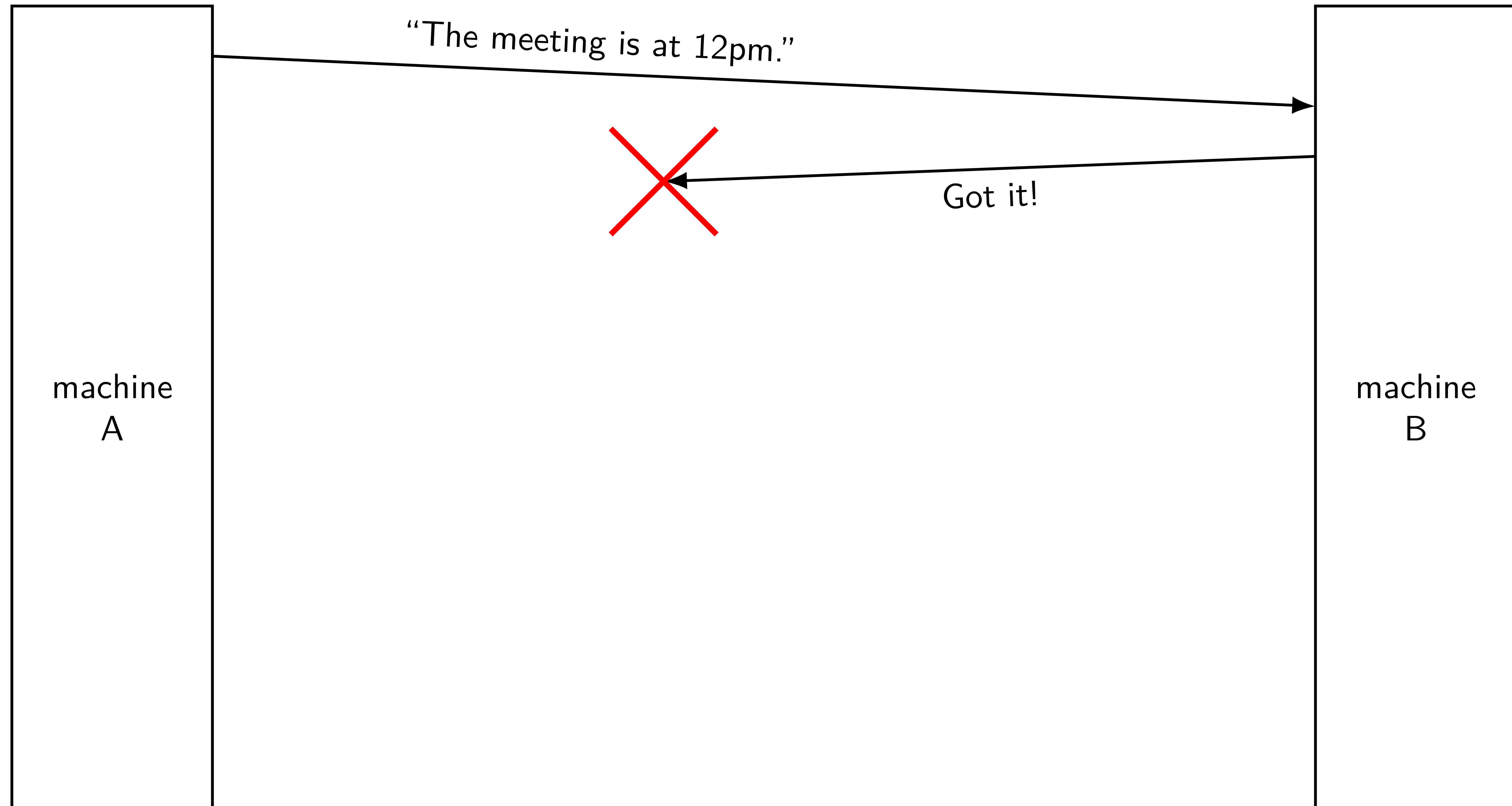
- how many times? — B doesn’t have that info

resend original message?

- yes!
- as far as machine A can see, *exact same situation* as losing original message

lost acknowledgements

lost acknowledgements



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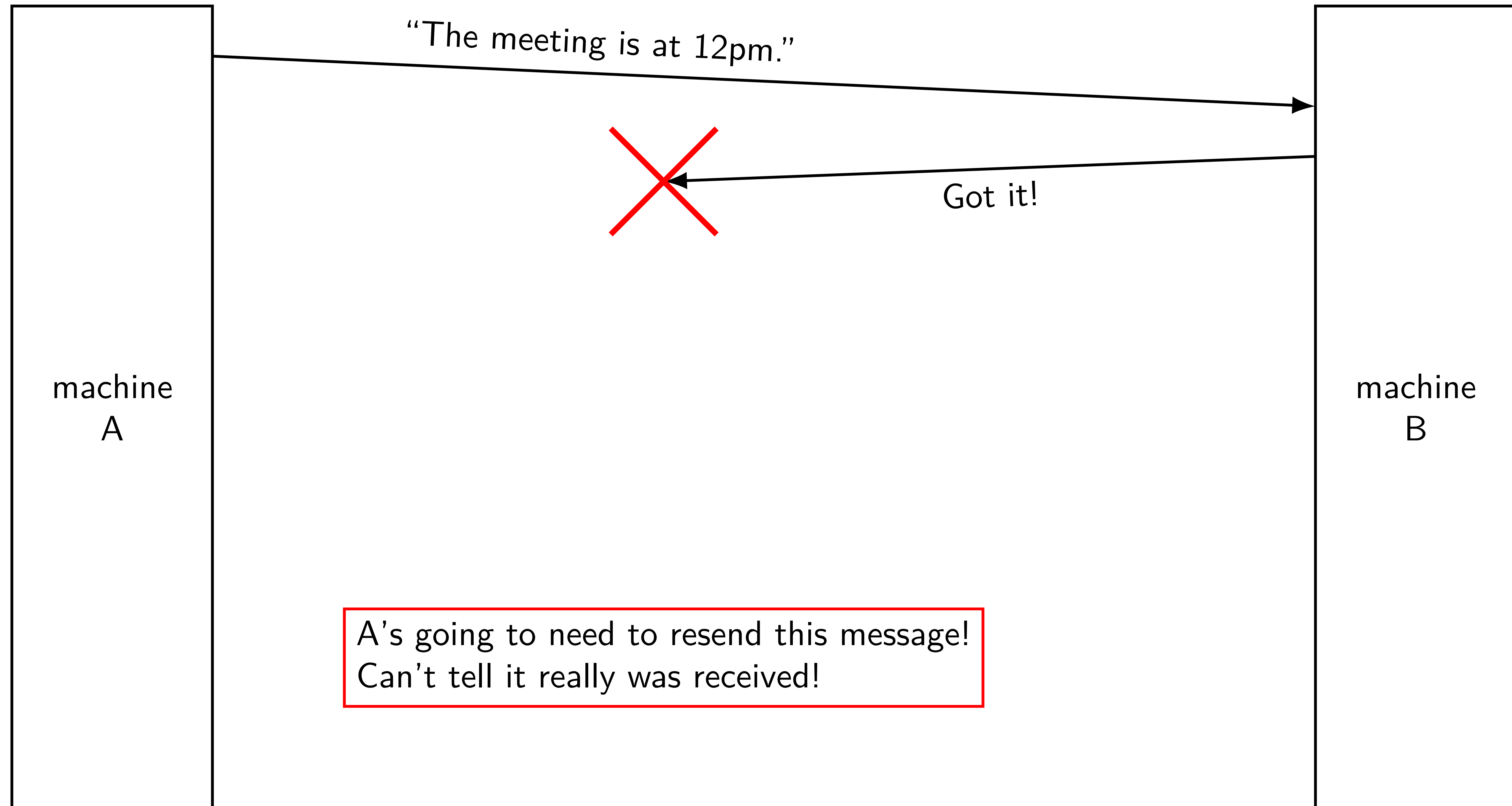

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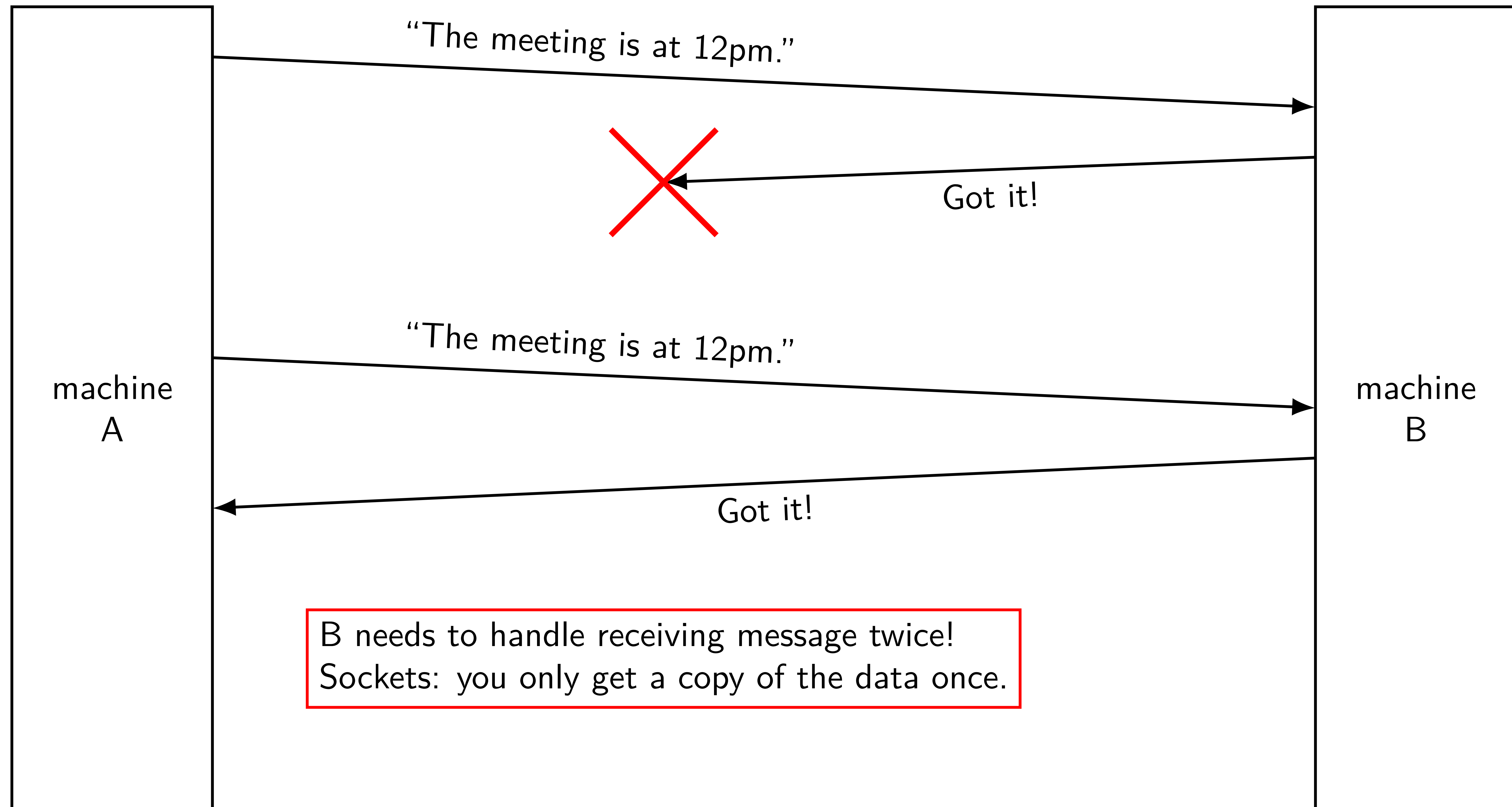
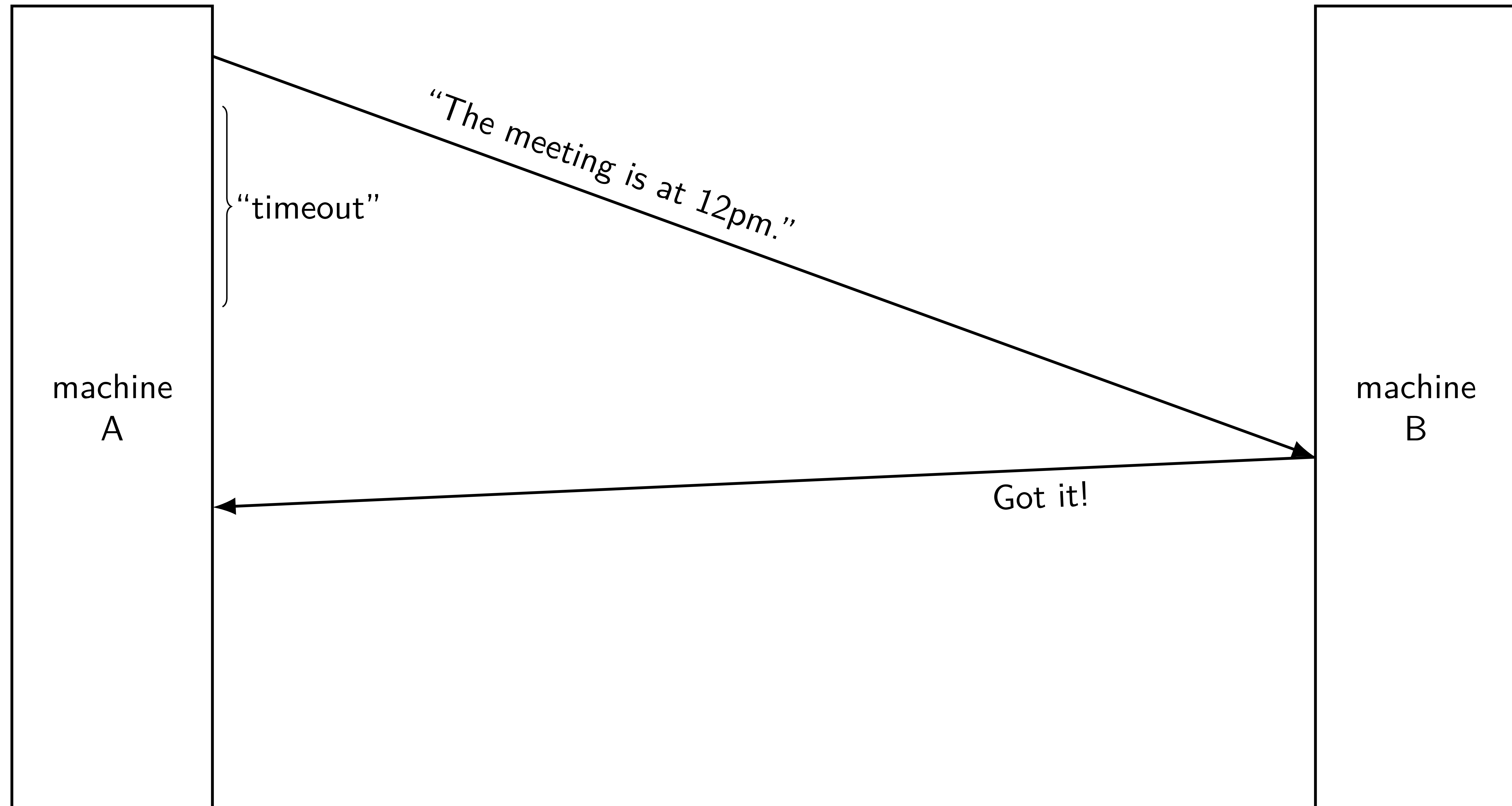


delayed message

delayed message



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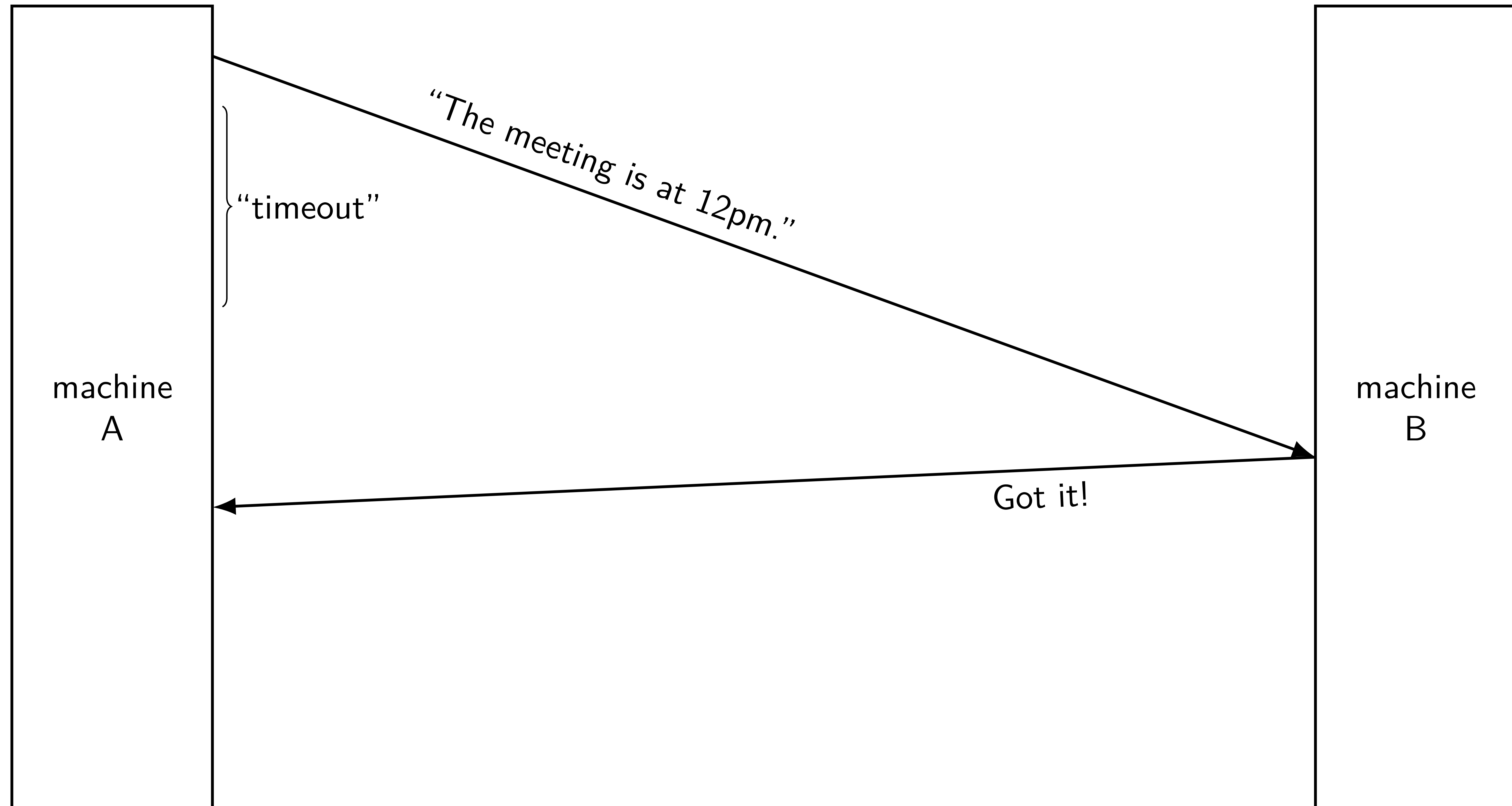

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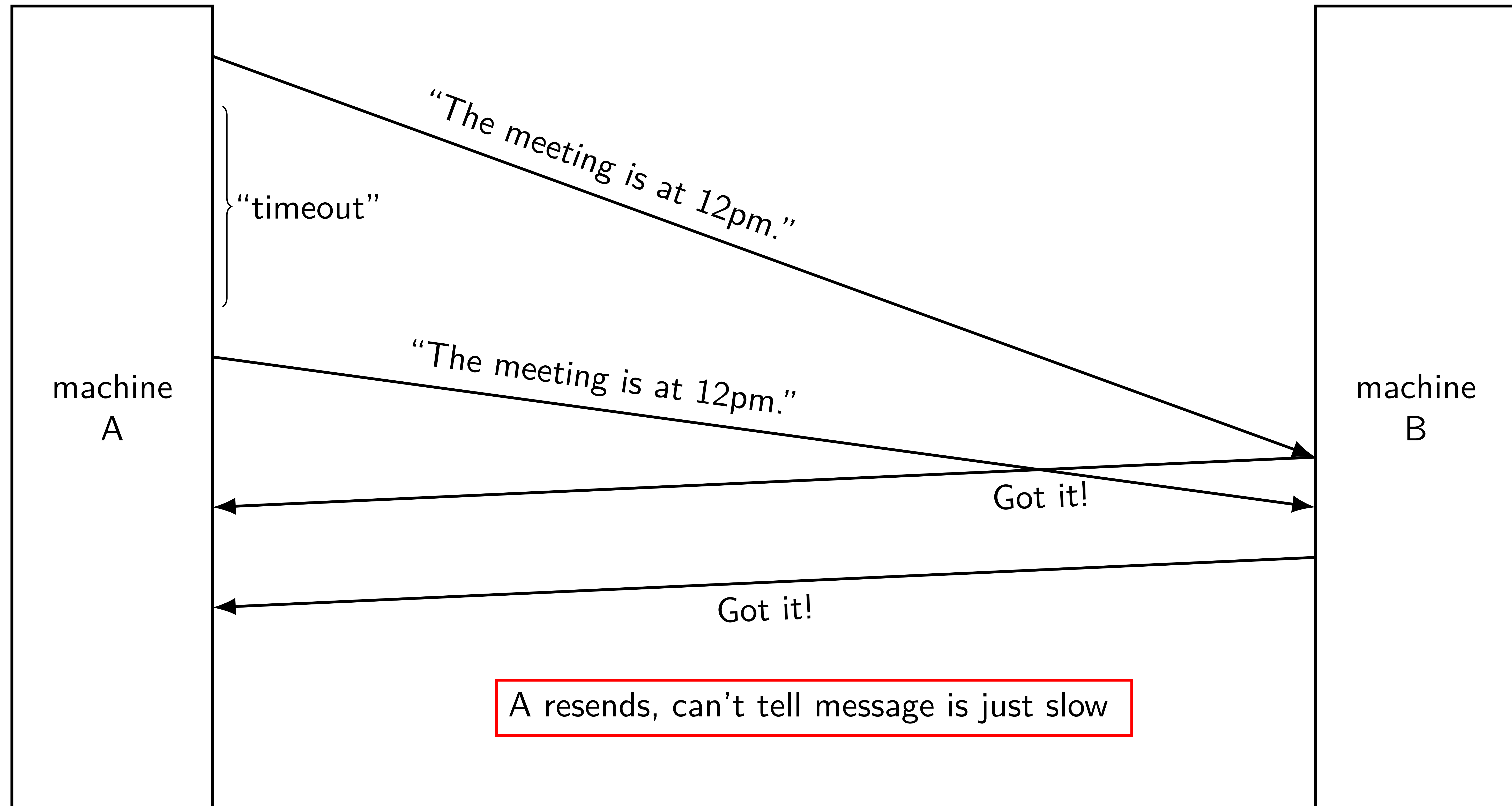

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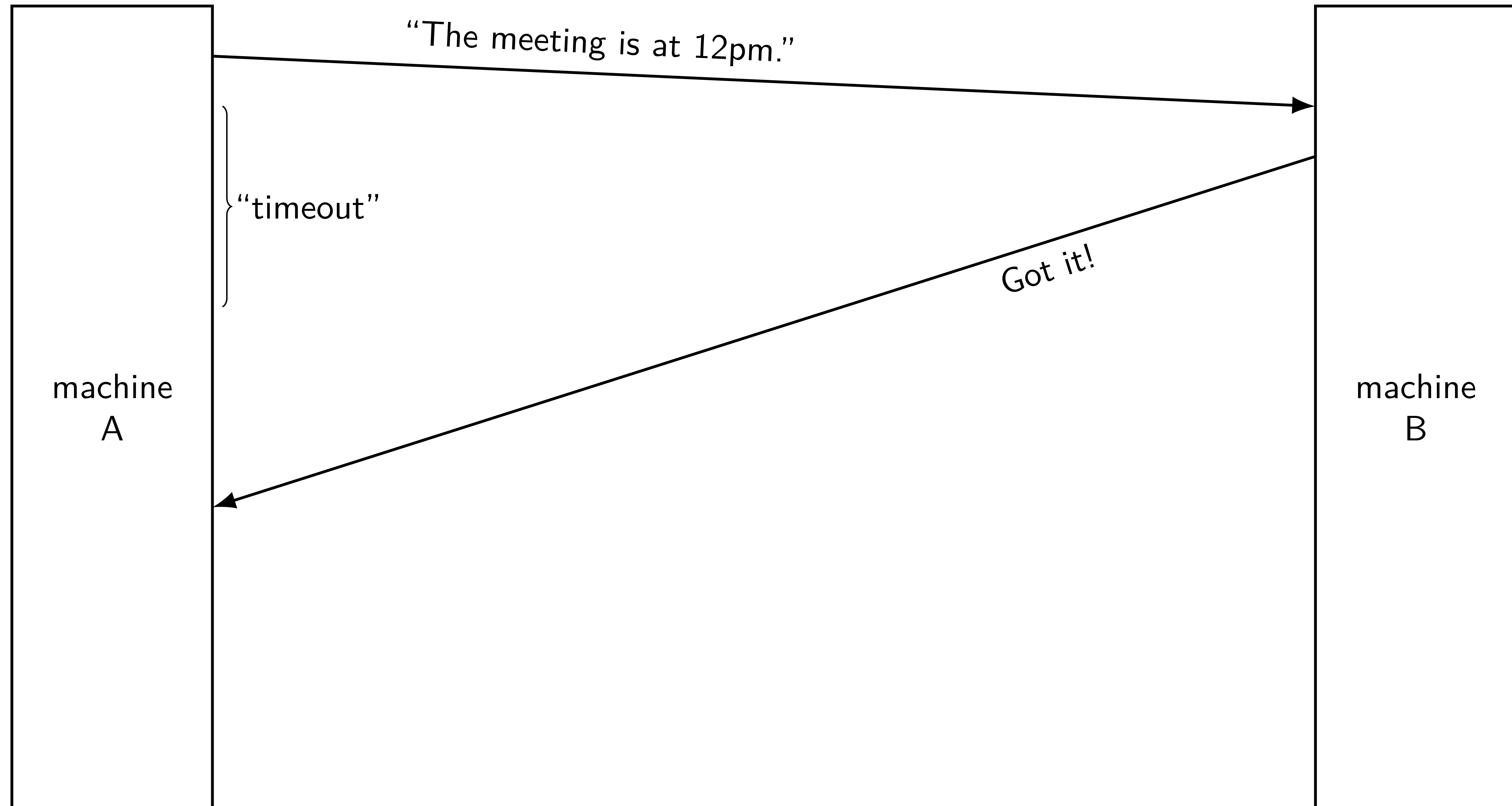

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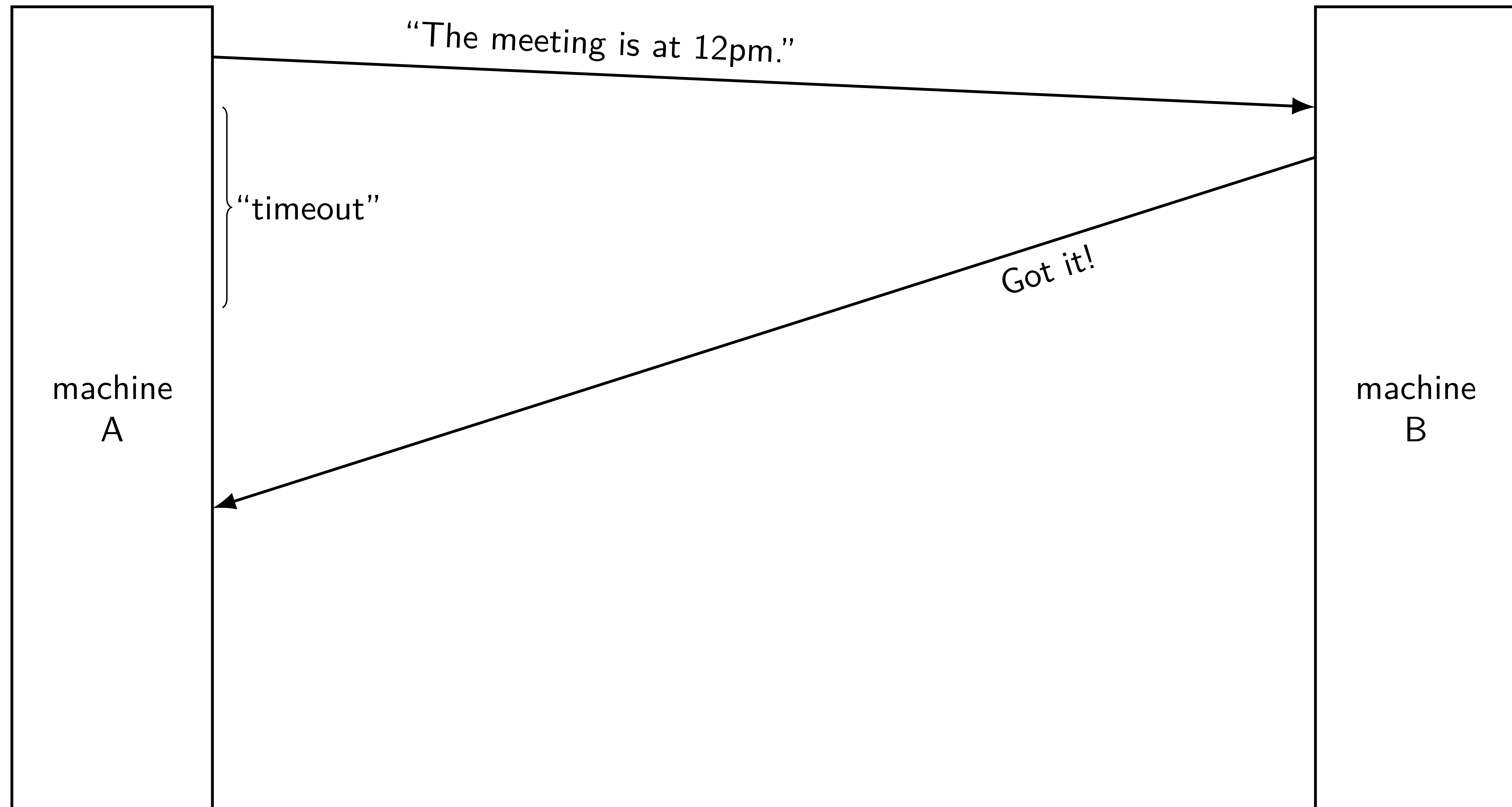

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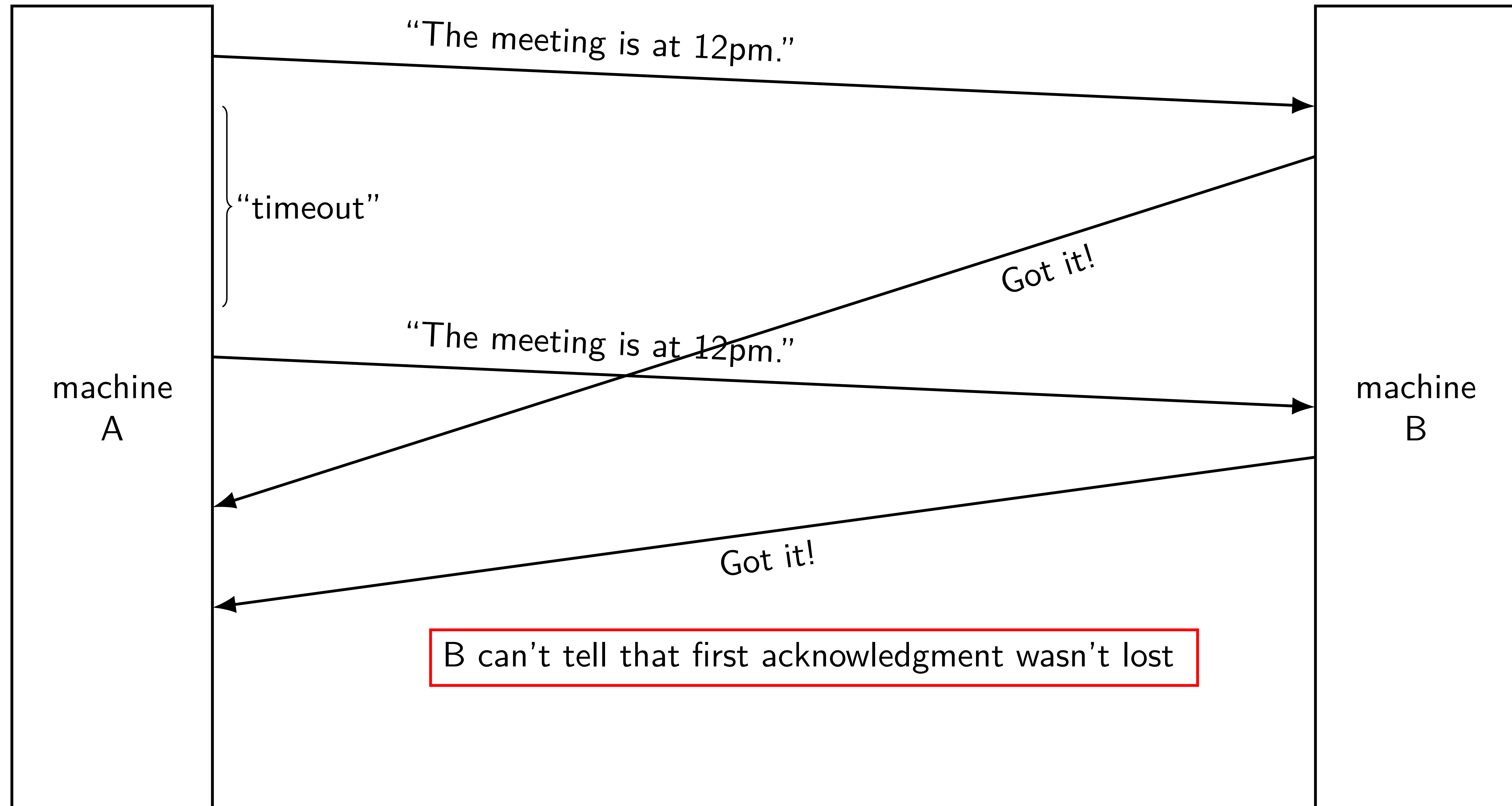
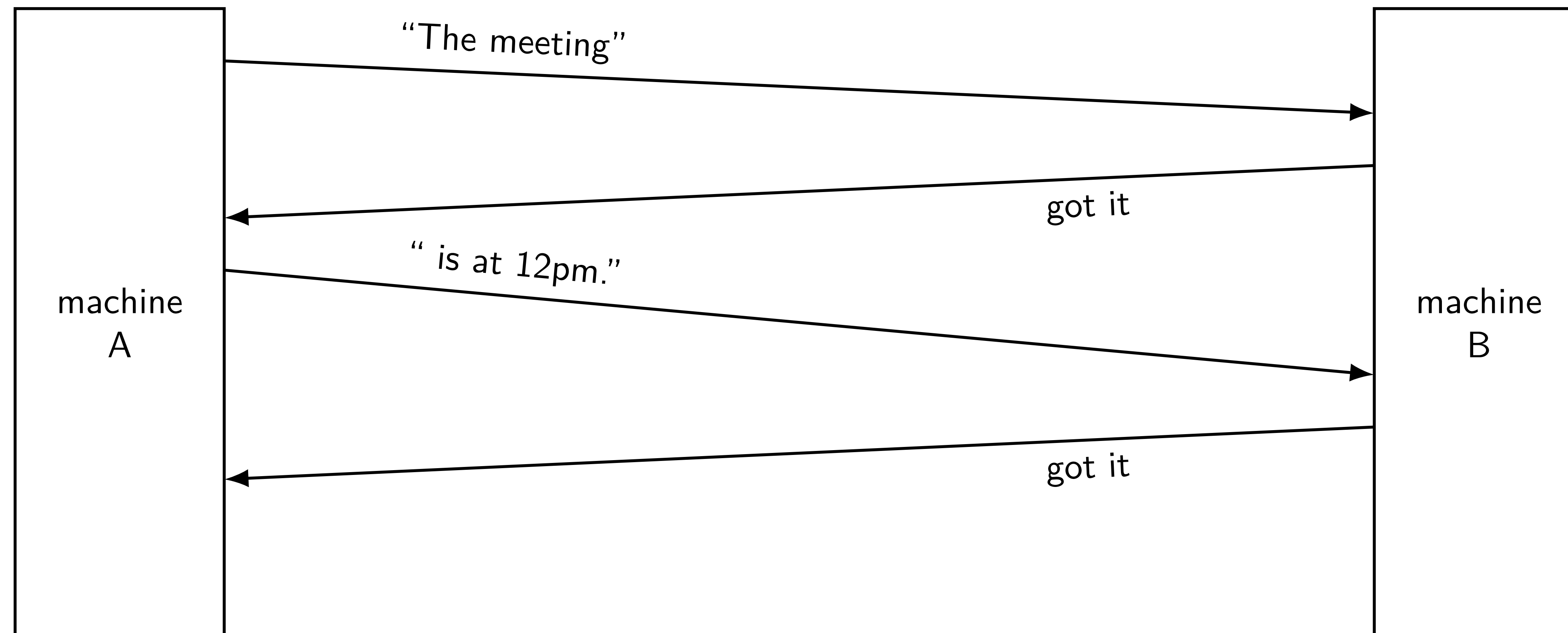
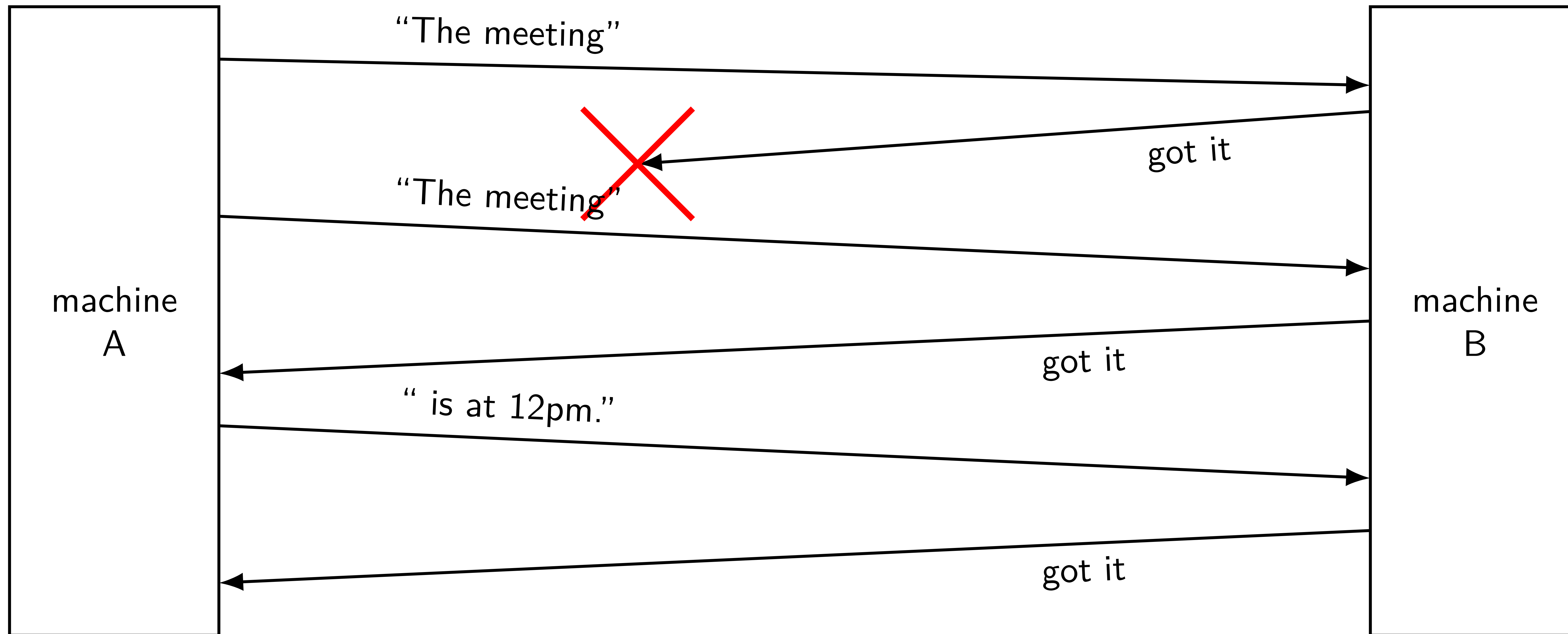


splitting messages: try 1

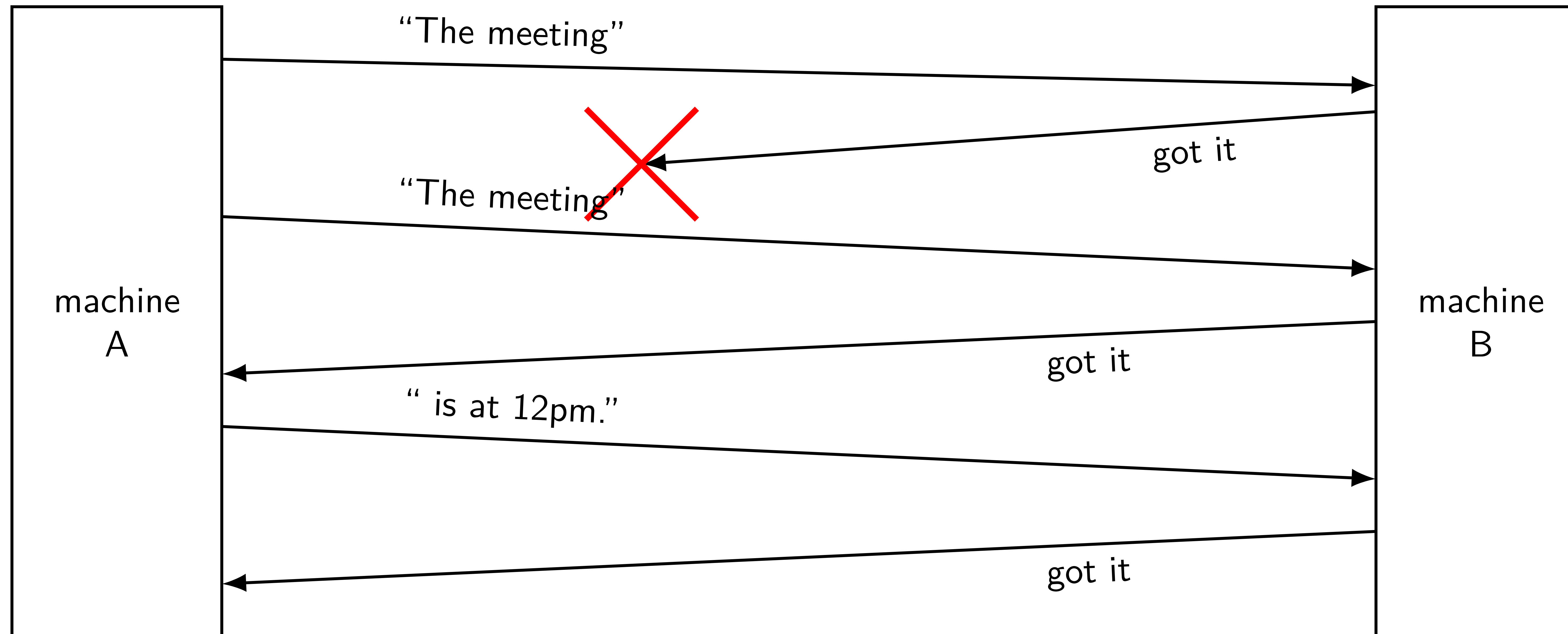


reconstructed message:
The meeting is at 12pm.

splitting messages: try 1 — problem 1



splitting messages: try 1 — problem 1



reconstructed message:

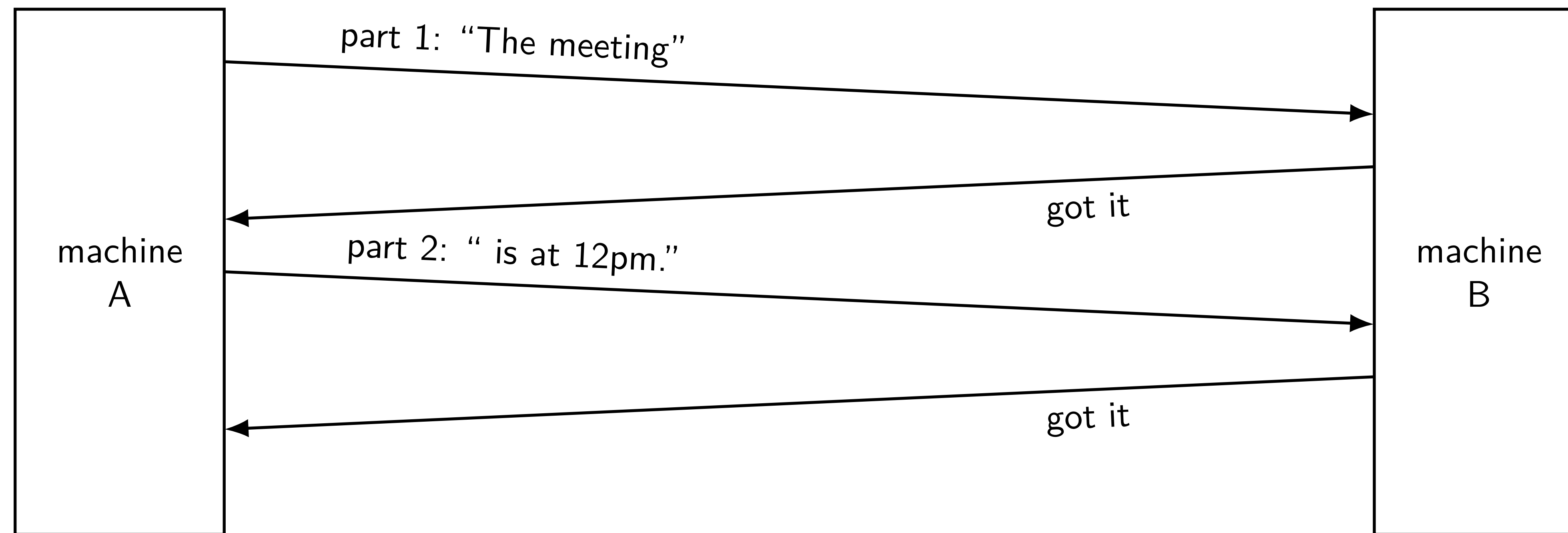
The meetingThe meeting is at 12pm.

exercise: other problems?

other scenarios where we'd also have problems?

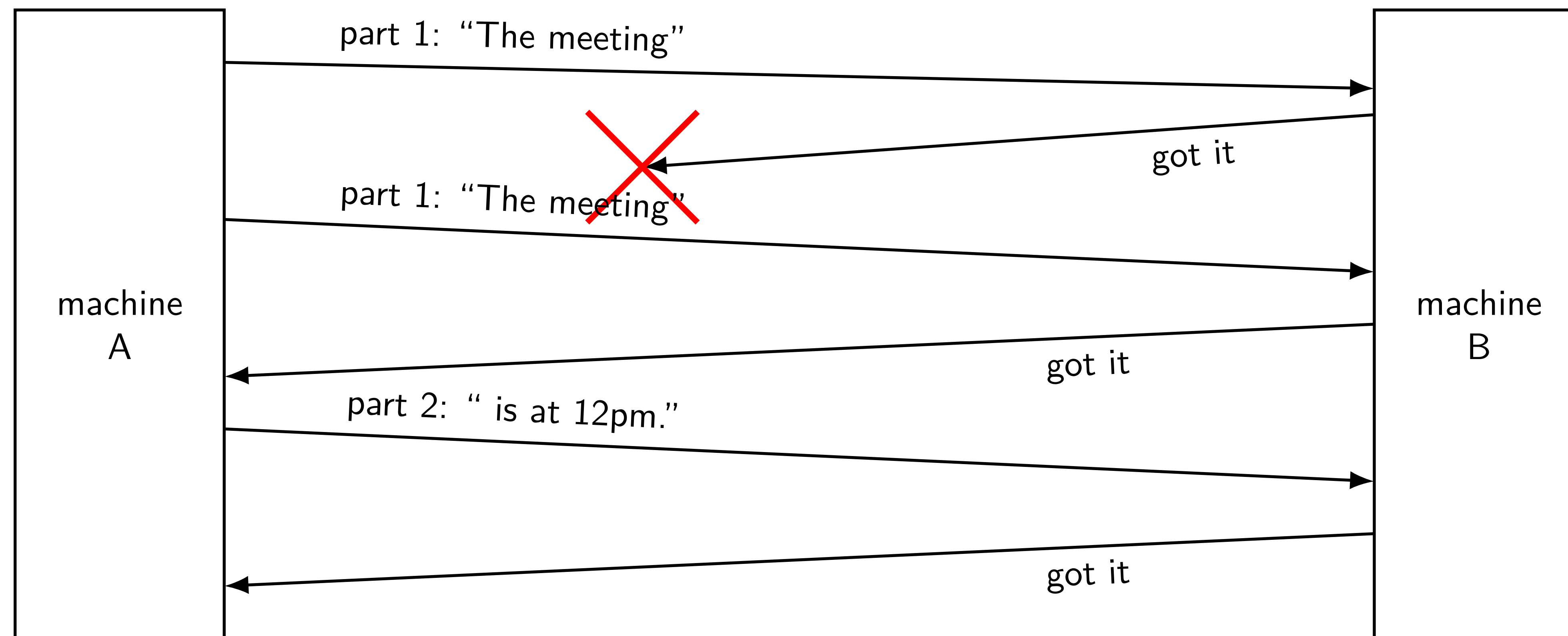
1. message (instead of acknowledgment) is lost
2. first message from machine A is delayed a long time by network
3. acknowledgment of second message lost instead of first

splitting messages: try 2



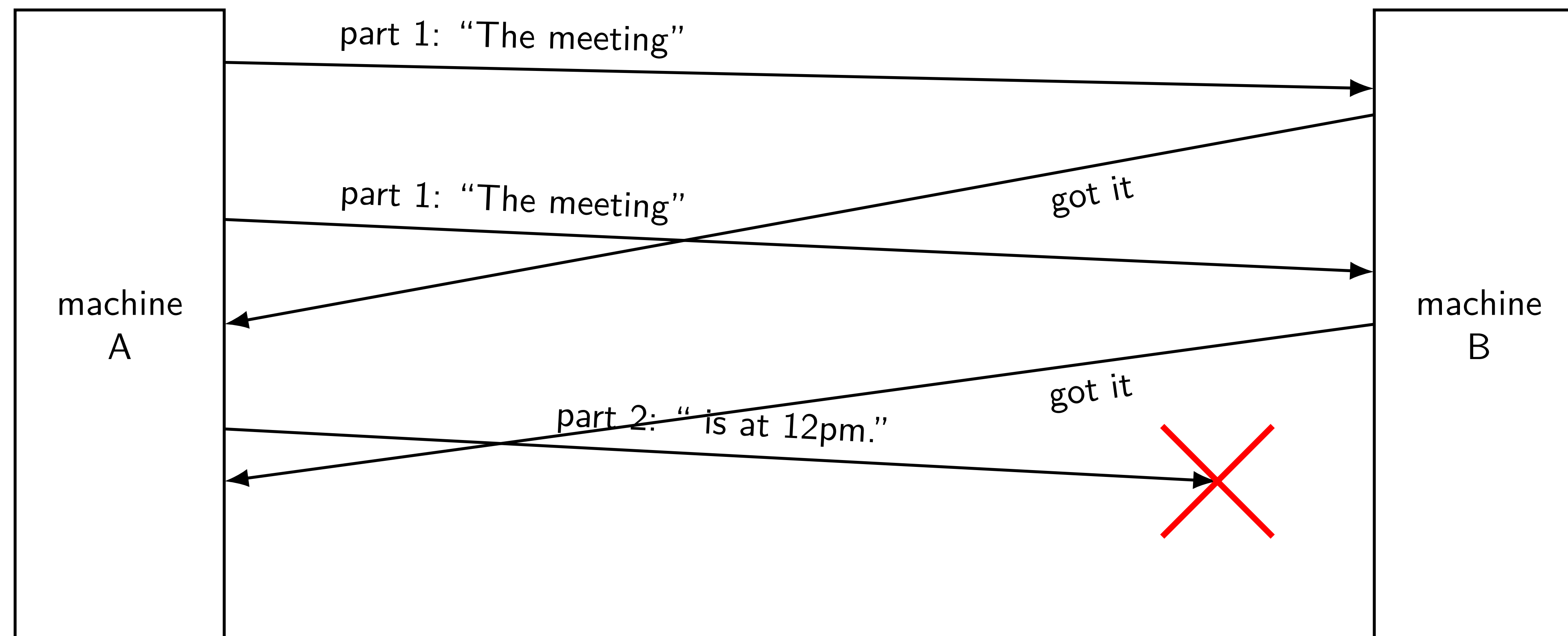
reconstructed message:
The meeting is at 12pm.

splitting messages: try 2 — missed ack



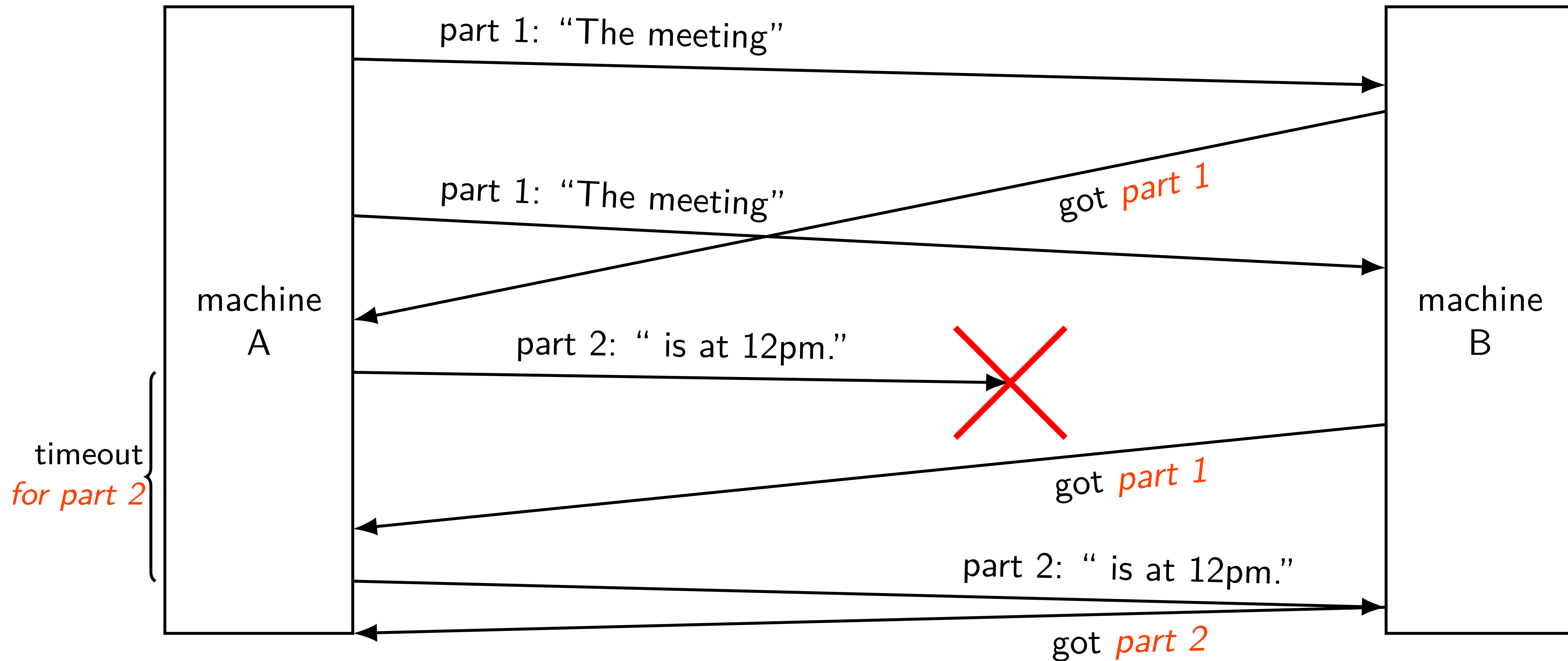
reconstructed message:
The meeting is at 12pm.

splitting messages: try 2 — problem



A thinks: part 1 + part 2 acknowleged!

splitting messages: version 3



message corrupted

corruption: e.g., a bit flip

- sent: `I LIKE CATS` (`49204C494B452043415453`)
- recv: `I LIKE BATS` (`49204C494B452042415453`)

instead of sending "message", send "message" + checksum

- checksum is some calculation using the original message
- ex: checksum(`I LIKE CATS`) = 0xD9
- send `49204C494B452043415453D9`

receiver then also computes the checksum with the same data

- if matches: keep the message
- if does not match: pretend like the message was lost (i.e., drop the message)

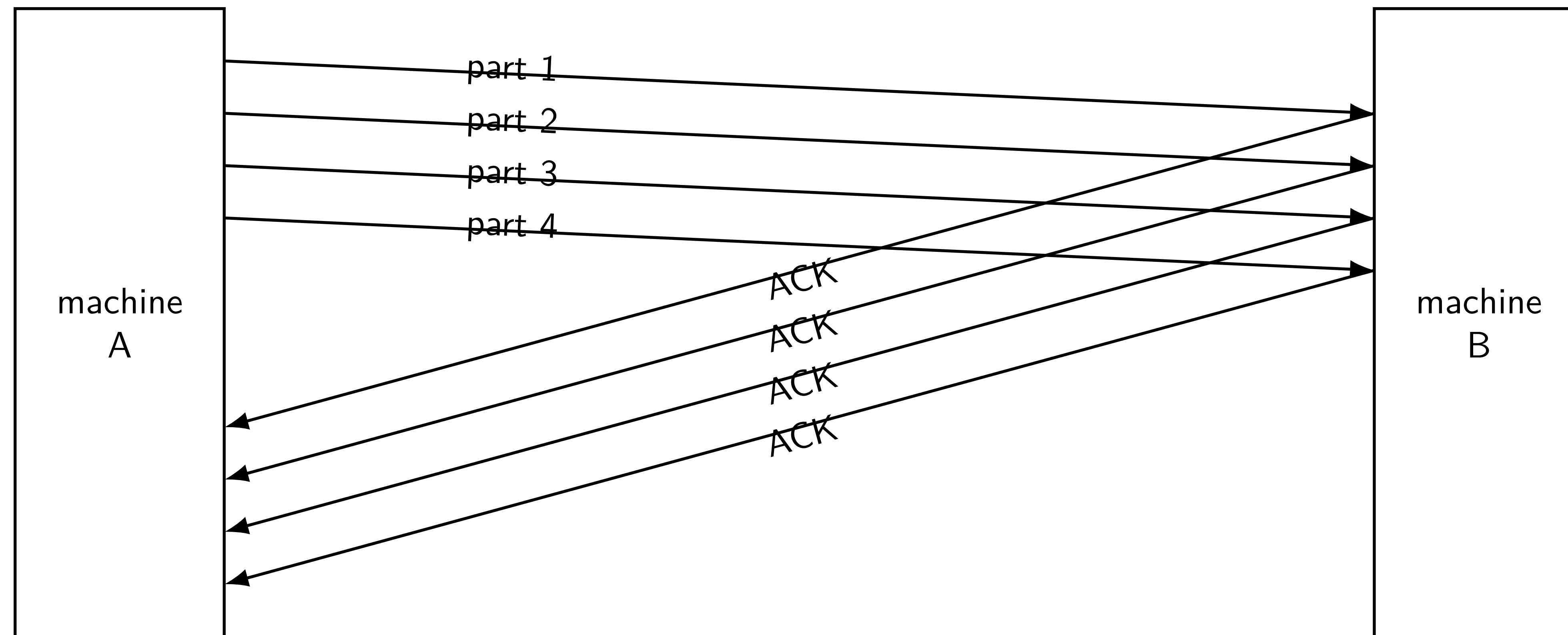
going faster

so far: send one message, wait for acknowledgment

very slow!

instead, can send a bunch of parts and get them acknowledged together

transmission window (ex: size 4)



Send a *window* of parts speculatively, then wait for ACKs.

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transport layer protocols: UDP vs. TCP

TCP: stream to other program

- reliable transmission of as much data as you want
- "connecting" fails if server not responding
- write(fd, "a", 1); write(fd, "b", 1) = write(fd, "ab", 2)
- (at least) one socket per remote program being talked to

UDP: messages sent to program, but no reliablity/streams

- unreliable transmission of short messages
- write(fd, "a", 1); write(fd, "b", 1) $\neq$ write(fd, "ab", 2)
- "connecting" just sets default destination
- can sendto()/recvfrom() multiple other programs with one socket
  - (but don't have to)

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upcoming lab

request + receive message split into pieces

you are responsible for:

- requesting parts in order
- resending requests if messages lost/corrupted

“acknowledge” receiving part X to request part X+1

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protocol

`GET(x)` — retrieve message x (x = 0, 1, 2, or 3)

- other end acknowledges by giving data
- if they don't reply, you need to send again
- higher numbered messages have errors/etc. that are harder to handle

`ACK(n)`

- request message part $n + 1$ by acknowledging message part n
- not quite same purpose as acknowledgments in prior examples
- (in lab, the response is your 'acknowledgment' of your request;
- you retry if you don't get it)

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callback-based programming (1)

```
/* library code you don't write */
/* lab: part of waitForAllTimeoutsAndMessagesThenExit() */
void mainLoop() {
    while (notExiting) {
        Event event = waitForAndGetNextEvent();
        if (event.type == RECIEVED) {
            recvd(...);
        } else if (event.type == TIMEOUT) {
            (event.timeout_function)(...);
        }
        ...
    }
}
```

callback-based programming (2)

```
/* your code, called by library */
void recvd(...) {
    ...
    setTimeout(..., timerCallback, ...);
}

void timerCallback(...) {
    ...
}

int main() {
    send(.../* first message */);
    ... /* other initial setup */
    waitForAllTimeoutsAndMessagesThenExit(); // runs mainLoop()
}
```

callback-based programing (3)

```
packet = getNextPacket()
doSomething(packet);
sleep(10);
doAnotherThing();
packet = getNextPacket();
doYetAnotherThing(packet);
```

turns into code like:

```
afterTimeout() {
    doAnotherThing(); mode = 2;
}
recvdPacket(packet) {
    if (mode == 1) {
        doSomething(packet);
        setTimeout(10, afterTimeout);
    } else if (mode == 2)
        doYetAnotherThing(packet);
    } else ...
}
```

callback-based programming uses

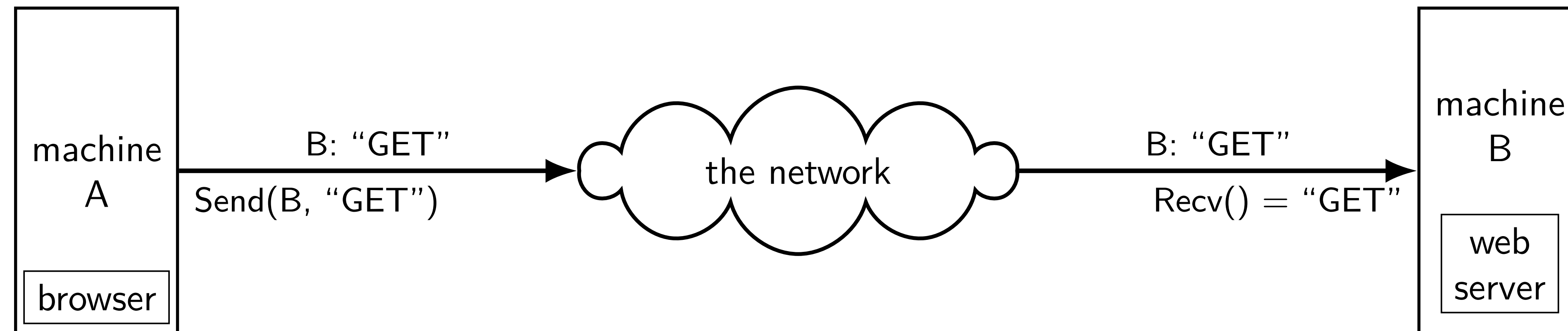
writing scripts in a webpage

many graphical user interface libraries

sometimes servers that handle lots of connections

mailbox model: importance of naming

mailbox abstraction: send/receive messages



how does the network know what “B” is?
how does B know the message is for the web server?
how does the response get to “A”?

names and addresses

name *logical identifier*	*address* *location/how to locate*
variable `counter`	memory address `0x7FFF9430`
DNS name `www.virginia.edu`	IPv4 address `128.143.22.36`
DNS name `mail.google.com`	IPv4 address `216.58.217.69`
DNS name `mail.google.com`	IPv6 address `2607:f8b0:4004:80b::2005`
DNS name `cso2.cs.virginia.edu`	IPv4 address `128.143.67.91`
DNS name `cso2.cs.virginia.edu`	MAC address `18:66:da:2e:7f:da`
service name `https`	port number `443`
service name `ssh`	port number `22`

the network layer

the Internet Protocol (IP) version 4 or version 6

- there are also others, but quite uncommon today

allows send messages to/recv messages from other networks

- “internetwork”

messages called “packets”

IPv4 addresses

32-bit numbers

typically written like 128.143.67.11

- four 8-bit decimal values separated by dots
- first part is most significant
- same as $128 \cdot 256^3 + 143 \cdot 256^2 + 67 \cdot 256 + 11 = 2\,156\,782\,459$

organizations get blocks of IPs

- e.g. UVa has 128.143.0.0–128.143.255.255
- e.g. Google has 216.58.192.0–216.58.223.255 and 74.125.0.0–74.125.255.255 and 35.192.0.0–35.207.255.255

some IPs reserved for non-Internet use (127.x.x.x, 10.x.x.x, 192.168.x.x, …)

IPv6 addresses

IPv6 like IPv4, but with 128-bit numbers

written in hex, 16-bit parts, seperated by colons (`:`)

strings of 0s represented by double-colons (`::`)

typically given to users in blocks of 2^{80} or 2^{64} addresses

- no need for address translation?

`2607:f8b0:400d:c00::6a` =

`2607:f8b0:400d:0c00:0000:0000:0000:006a`

- `2607f8b0400d0c00000000000000006a`$_{\text{SIXTEEN}}$

global routing

IP addresses identify machines on the global internet

address grouped geographically

- for example, 100.128.0.0-100.255.255.255 all used in the US

routing: finding a path for packets from source to destination across internet

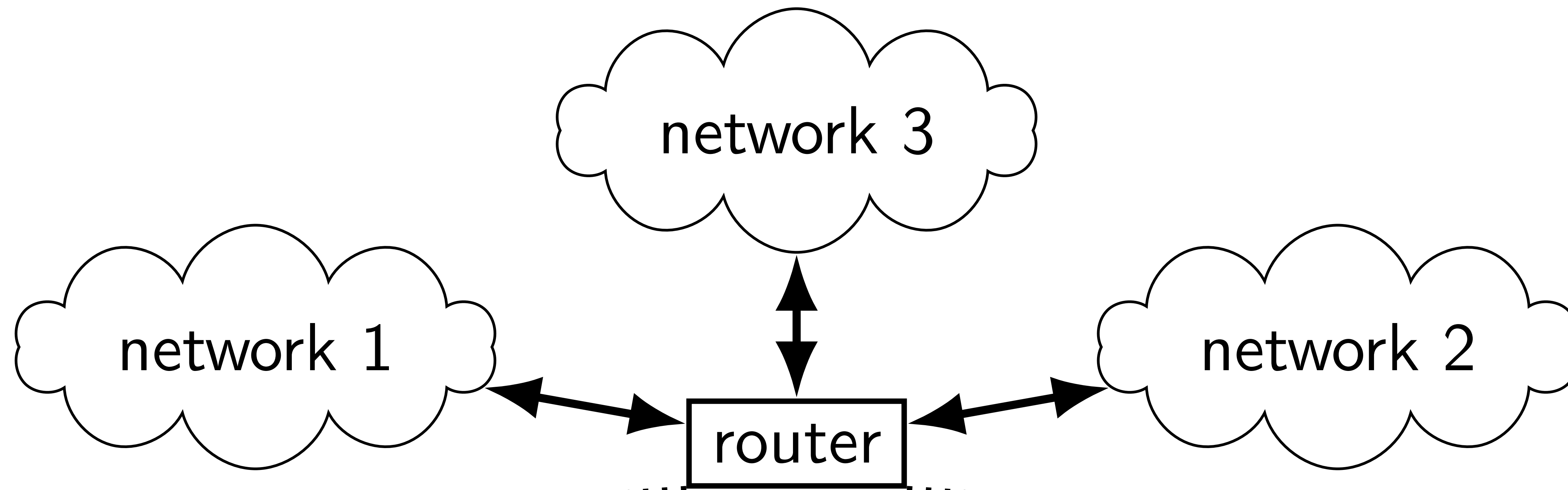
- *routers* are network equipment that send packets to other routers
- routers advertise what IP address ranges they can route to
- intuition: get packets closer with each hop

analogy: airplane routing

- want to fly CHO to LAX
- route: CHO-ATL-LAX

routing protocols determine routes from all sources to all destinations

IPv4 addresses and forwarding



if I receive data for...	send it to...
128.143.0.0—128.143.255.255	network 1, 11.4.3.2
192.107.102.0–192.107.102.255	network 1, 11.4.3.2
...	...
4.0.0.0–7.255.255.255	network 2, 12.4.6.4
64.8.0.0–64.15.255.255	network 2, 45.4.0.1
...	...
anything else	network 3, 199.44.33.1

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connections in TCP/IP

connection identified by *4-tuple*

used by OS to lookup "where is the socket?"

(local IP address, local port, remote IP address, remote port)

local IP address, port number can be set with `bind()` function

typically always done for servers, not done for clients

system will choose default if you don't

port numbers

we run multiple programs on a machine

- IP addresses identifying machine — not enough

so, add 16-bit *port numbers*

- think: multiple PO boxes at address

0–49151: typically assigned for particular services

- 80 = http, 443 = https, 22 = ssh, …

49152–65535: allocated on demand

- default “return address” for client connecting to server

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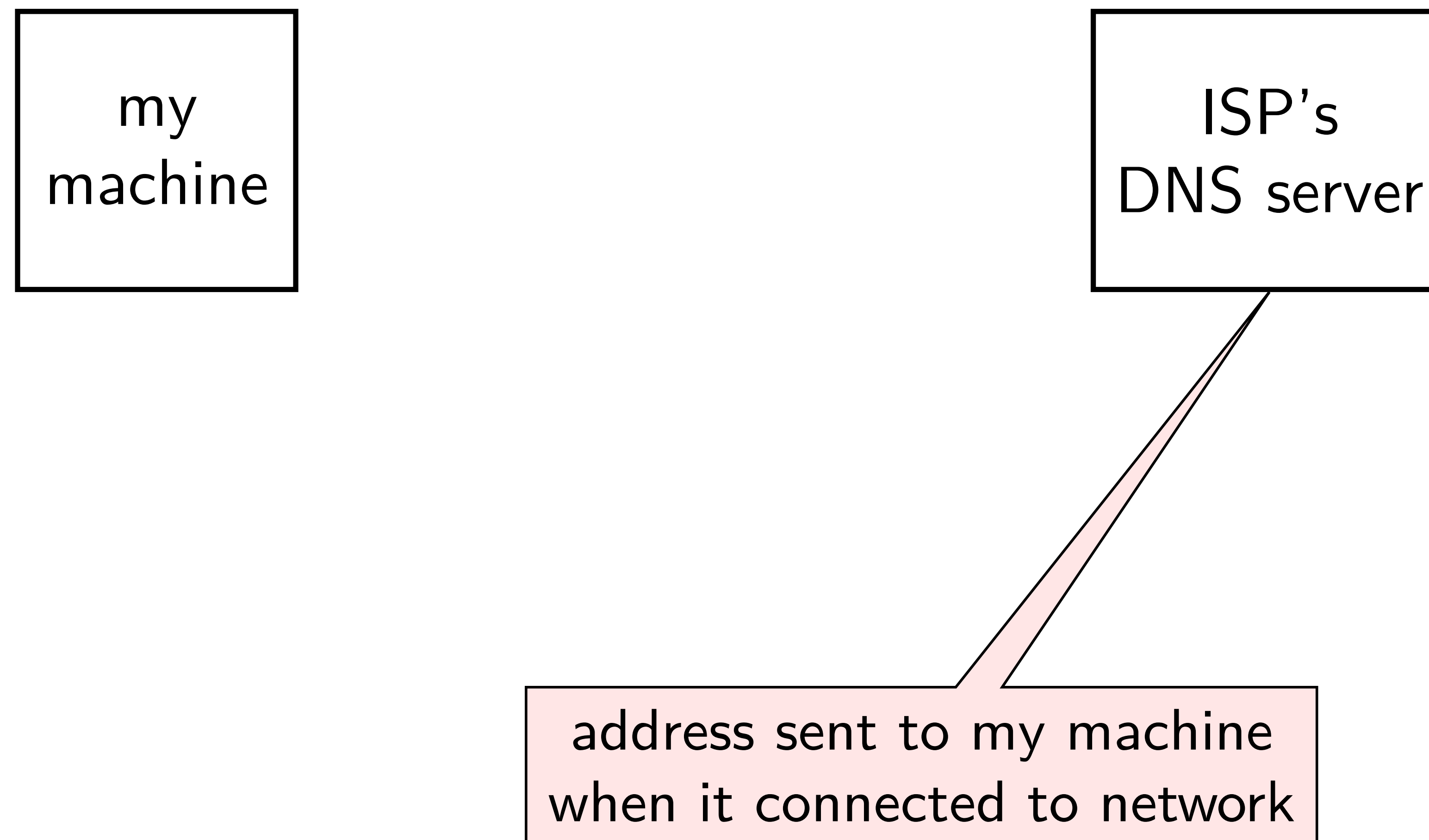
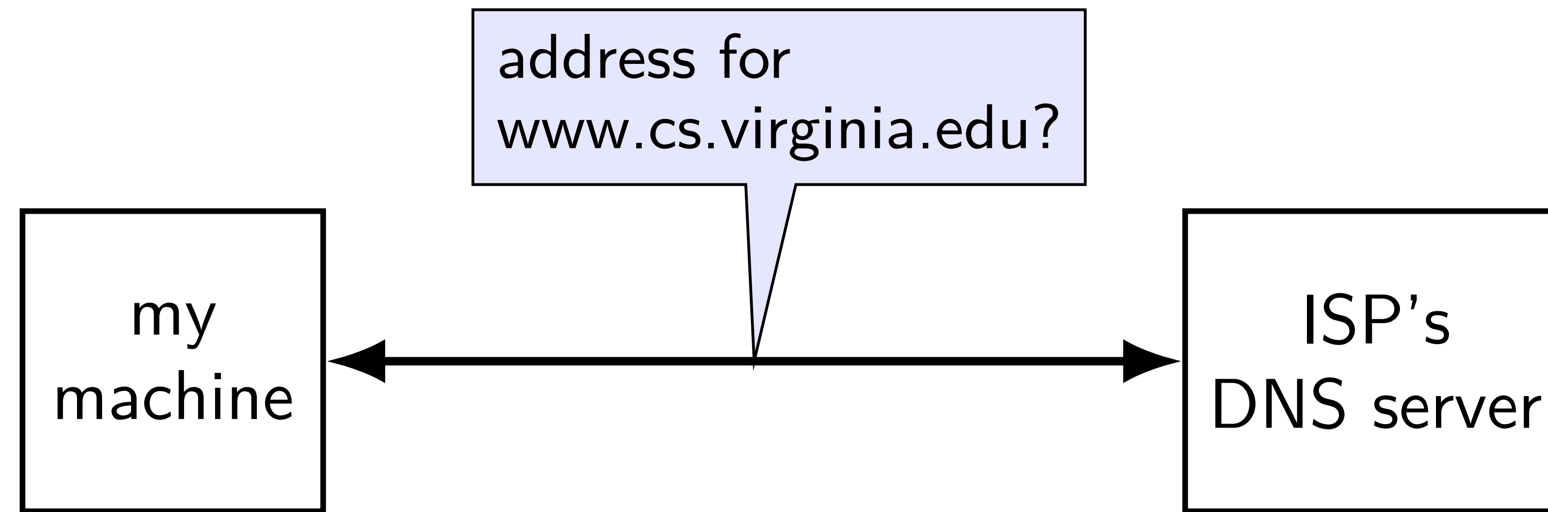
DNS name `www.virginia.edu`	IPv4 address `128.143.22.36`
DNS name `mail.google.com`	IPv4 address `216.58.217.69`
DNS name `mail.google.com`	IPv6 address `2607:f8b0:4004:80b::2005`
DNS name `cso2.cs.virginia.edu`	IPv4 address `128.143.67.91`
DNS name `cso2.cs.virginia.edu`	MAC address `18:66:da:2e:7f:da`
service name `https`	port number `443`
service name `ssh`	port number `22`

DNS: Domain Name System

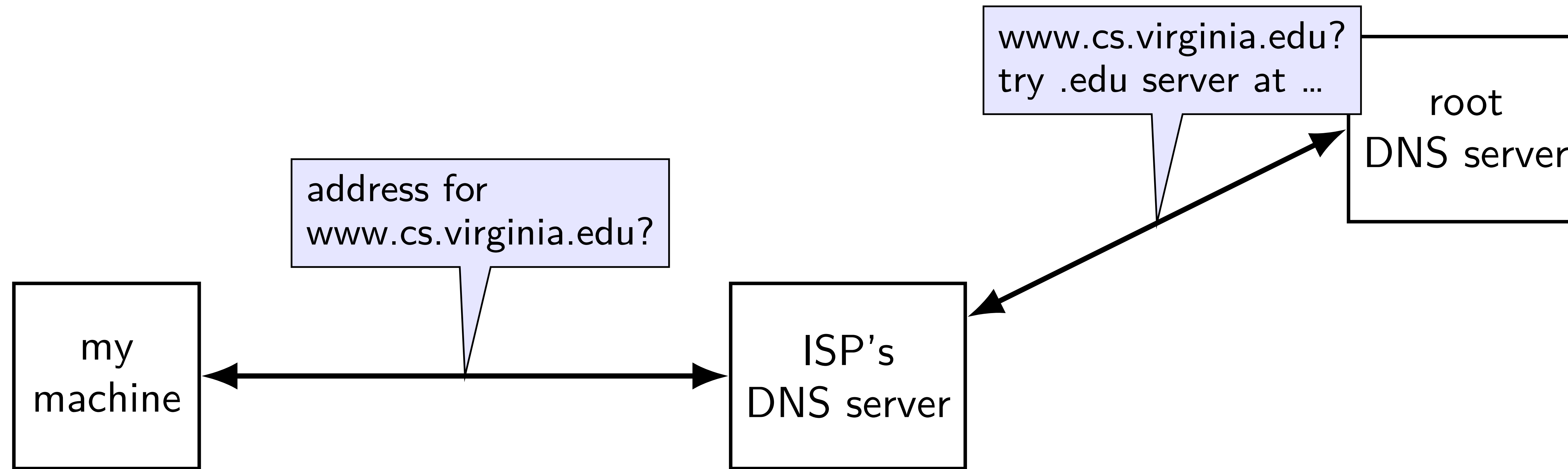
DNS: Domain Name System



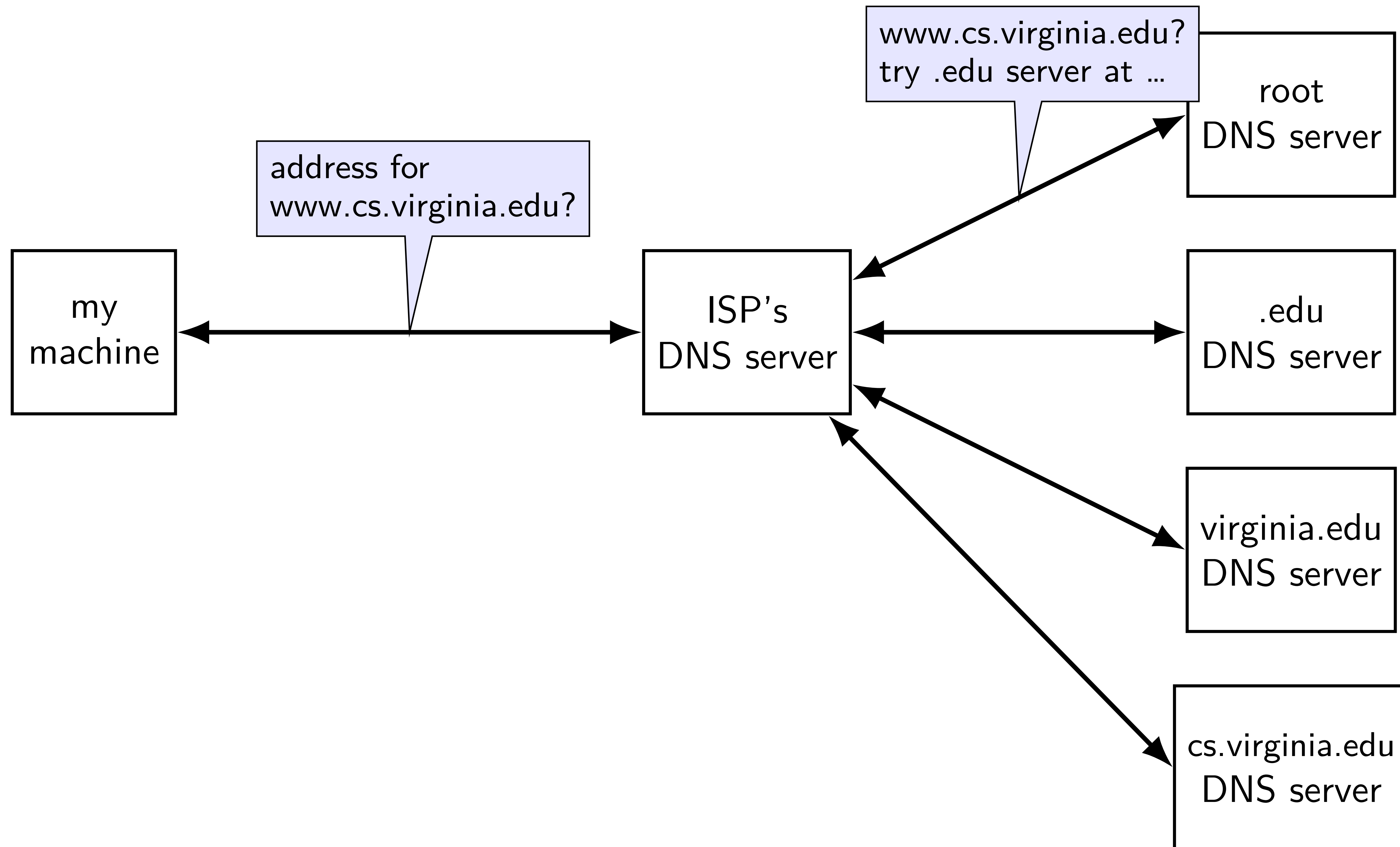
DNS: Domain Name System



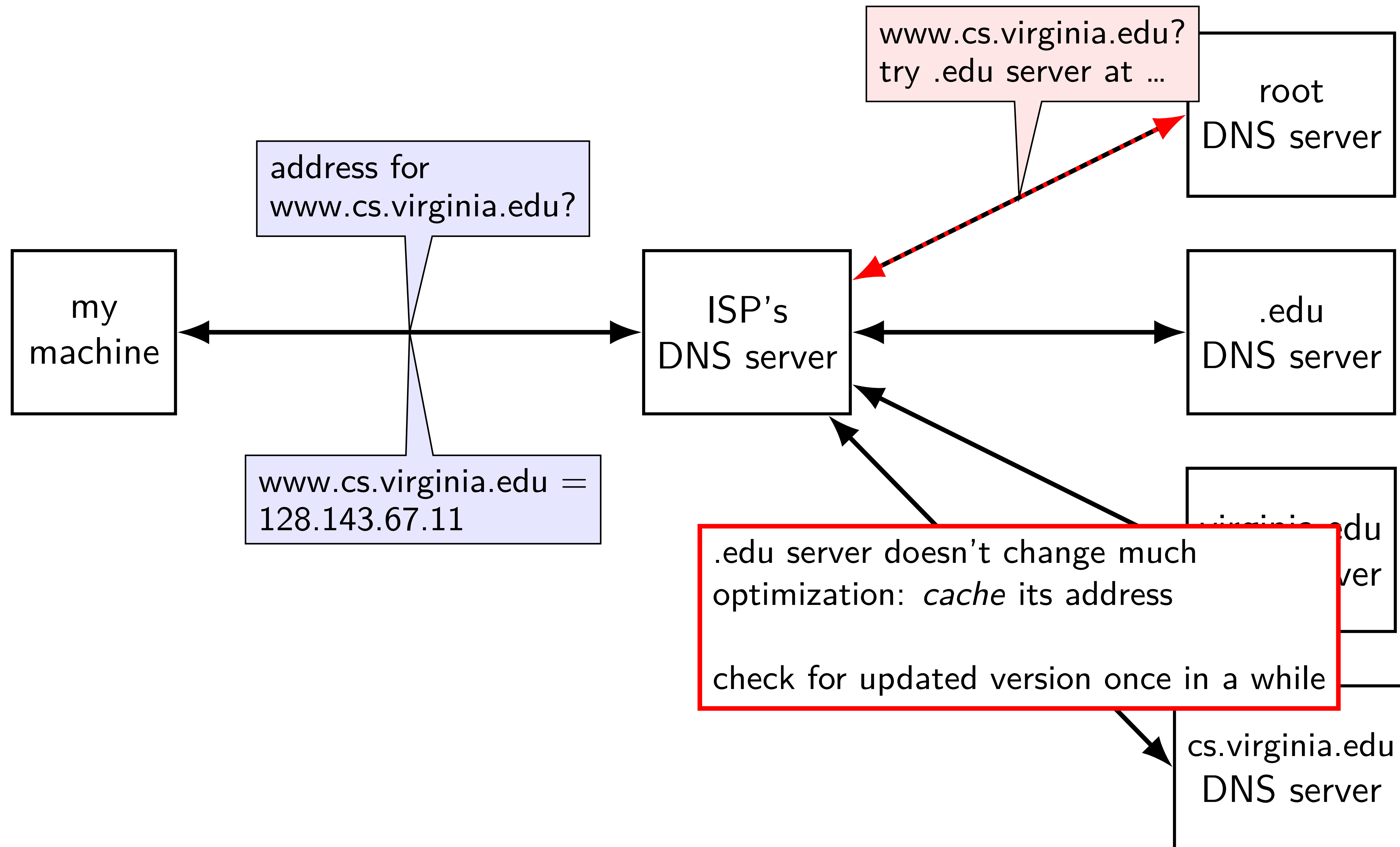
DNS: Domain Name System



DNS: Domain Name System



DNS: Domain Name System



URL / URIs

Uniform Resource Locators (URL)

- tells how to find “resource” on network
- uniform — one syntax for multiple protocols (types of servers, etc.)

Unifrom Resources Identifiers

- superset of URLs

URI examples

```
https://kytos02.cs.virginia.edu:443/cs3130-spring2023/quizzes/quiz.php?qid=02#q2

https://kytos02.cs.virginia.edu/cs3130-spring2023/quizzes/quiz.php?qid=02

https://www.cs.virginia.edu/

sftp://cr4bd@portal.cs.virginia.edu/u/cr4bd/file.txt

tel:+1-434-982-2200

//www.cs.virginia.edu/~cr4bd/3130/S2023/

/~cr4bd/3130/S2023
```

URI generally

```
scheme://authority/path?query#fragment
```

scheme: — what protocol

//authority/

- authority = user@host:port OR host:port OR user@host OR host

path

- which resource

?query — usually key/value pairs

#fragment — place in resource

most components (sometimes) optional

HTTP: HyperText Transfer Protocol

primary application-layer protocol for the Web
- introduced in 1991
- version 1.1 in 1997, version 2 in 2015, version 3 in 2022

text-based protocol

standard port: 80 (non-encrypted), 443 (encrypted)

uses TCP (or TCP + TLS for encrypted version)

client-server protocol
- server = always on machine, never initiaites contact
- client = sometimes on machine, initiates contact

ex. URL: `http://www.foo.com/bar`

HTTP: HyperText Transfer Protocol

`http://www.foo.com/bar`

HTTP client (example: web browser):

- does a DNS lookup for www.foo.com (gets 123.156.189.12)
- connects via TCP to 123.156.189.12 port 80
- sends something like:

```
GET /bar HTTP/1.1
Host: www.foo.com
...
```

server replies with status code + (usually) some data

- 200 OK, 403 Unauthorized, 404 Not Found, 500 Internal Server Error, …

HTTP

GET — get resource

POST — sending forms

HEAD — get metadata about file (without getting its data)

PUT, DELETE, …

all requests/replies have many possible headers

- filetype inforation
- login-related information (usually)
- metadata used for caching webpages
- …

networking layers

application	HTTP, SSH, SMTP, …	application-defined meanings
transport	TCP, UDP, …	reach correct program reliability/streams
network	IPv4, IPv6	reach correct machine (across networks)
link	Ethernet, Wi-Fi, …	coordinate shared wire/radio
physical	Ethernet, Wi-Fi, …	encode bits for wire/radio

why IPv4 and IPv6?

ran out of IPv4 addresses

- 2^{32} *seemed* like a lot of addresses
- now there are more internet *users* than addresses

possible solutions:

- IPv6: use more bits for addresses, enough to never run out
  - pro: clean, scalable solution that will always work
  - con: every thing on the network needs to be updated
- NAT: user one IPv4 address for an entire network of devices
  - pro: can be implemented by any network
  - con: essentially a hack

NAT: network address translation

convert many private addresses to one public address

- within the local network: use private IP addresses for local addresses
- outside the local network: private IP addresses become a single public one
  - public address: address that can be routed on the internet

commonly how home networks work (and some ISPs)

certain IPv4 address blocks reserved for private/internal use

- `192.168.X.X`
- `172.16.X.X–172.31.X.X`
- `10.X.X.X`
- …

you can see this yourself!

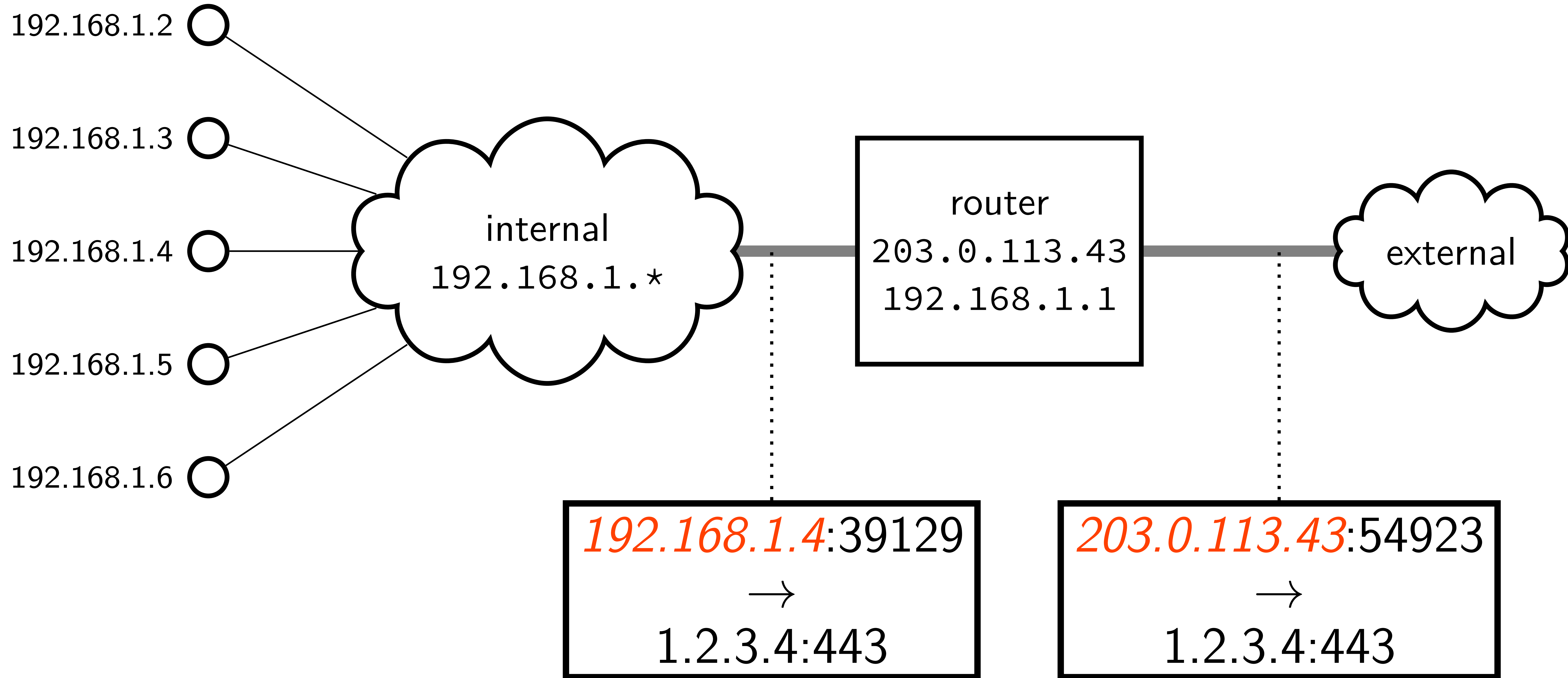
on your computer:

- go to https://whatismyipaddress.com/
- go to your computer’s network settings and look at the IP address

they don’t match!

- difference between the public and private address
- public address might match your colleagues’

NAT idea



NAT illusion

NAT illusion:

private IP address communicating directly with public IP

inside network, talking to outside:

- use private local address
- use public remote address
- never see router's address

outside network, talking to inside

- use public local address
- use router's public address

implementing NAT

remote host + port	outside local port number	inside IP	inside port number
128.148.17.3:443	54033	192.168.1.5	43222
11.7.17.3:443	53037	192.168.1.5	33212
128.148.31.2:22	54032	192.168.1.37	43010
128.148.17.3:443	63039	192.168.1.37	32132

table of the translations

need to update as new connections made

networking layers

application	HTTP, SSH, SMTP, …	application-defined meanings
transport	TCP, UDP, …	reach correct program reliability/streams
network	IPv4, IPv6	reach correct machine (across networks)
link	Ethernet, Wi-Fi, …	coordinate shared wire/radio
physical	Ethernet, Wi-Fi, …	encode bits for wire/radio

Backup slides

The Internet

Perhaps the most successful computer application ever

Can you name a computer program that doesn't use the internet?

```
\begin{center}

![](/network/internet_users.png){}

\end{center}
```

```
\begin{center}

![](/network/internet_reasons.png){}

\end{center}
```

```
\begin{center}

![](/network/internet_data.png){}

\end{center}
```

the link layer

Ethernet, Wi-Fi, Bluetooth, DOCSIS (cable modems), …

allows send/recv messages to machines on "same" network segment
- typically: wireless range+channel or connected to a single switch/router
- could be larger (if *bridging* multiple network segments)
- could be smaller (switch/router uses "virtual LANs")

typically: source+destination specified with MAC addresses
- MAC = media access control
- usually manufacturer assigned / hard-coded into device
- unique address per port/wifi transmitter/etc.

can specify destination of "anyone" (called *broadcast*)

messages usually called "frames"

the link layer

Ethernet, Wi-Fi, Bluetooth, DOCSIS (cable modems), …

allows send/recv messages to machines on *“same” network segment*

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can specify destination of “anyone” (called *broadcast*)

messages usually called “frames”

link layer jobs

divide raw bits into messages

identify who message is for on shared radio/wire

handle if two+ machines use radio/wire at same time

drop/resend messages if corruption detected

- resending more common in radio schemes (wifi, etc.)

link layer reliablity?

Ethernet + Wifi have checksums

Q1: Why doesn’t this give us uncorrupted messages?

  Why do we still have checksums at the higher layers?

Q2: What’s a benefit of doing this if we’re also doing it in the higher layer?

link layer quality of service

if frame gets…

event	on Ethernet	on WiFi
collides with another	detected + may resend	resend
not received	lose silently	resent
header corrupted	usually discard silently	usually resend
data corrupted	usually discard silently	usually resend
too long	not allowed to send	not allowed to send
reordered (v. other messages)	received out of order	received out of order
destination unknown	lose silently	usually resend??
too much being sent	discard excess?	discard excess?

network layer quality of service

if packet …

event	on IPv4/v6
collides with another	out of scope — handled by link layer
not received\tikzmark{not recv}	lost silently
header corrupted	usually discarded silently
data corrupted	received corrupted
too long	dropped with notice or “fragmented” + recombined
reordered (v. other messages)	received out of order
destination unknown	usually dropped with notice
too much being sent	discard excess

network layer quality of service

if packet …

event	on IPv4/v6
collides with another	out of scope — handled by link layer
not received\tikzmark{not recv}	lost silently
header corrupted	usually discarded silently
data corrupted	received corrupted
too long	dropped with notice or “fragmented” + recombined
reordered (v. other messages)	received out of order
destination unknown	usually dropped with notice
too much being sent	discard excess

firewalls

don’t want to expose network service to everyone?

solutions:

- service picky about who it accepts connections from
- filters in OS on machine with services
- filters on router

later two called “firewalls”

firewall rules examples?

ALLOW tcp port 443 (https) FROM everyone

ALLOW tcp port 22 (ssh) FROM *my desktop's IP address*

BLOCK tcp port 22 (ssh) FROM everyone else

ALLOW from address X to address Y

…

TCP state machine

TIME_WAIT, ESTABLISHED, …?

OS tracks “state” of TCP connection

- am I just starting the connection?
- is other end ready to get data?
- am I trying to close the connection?
- do I need to resend something?

standardized set of state names

TIME_WAIT

remember delayed messages?

problem for TCP ports

if I reuse port number, I can get message from old connection

solution: TIME_WAIT to make sure connection really done

- done after sending last message in connection

TCP state machine picture

querying the root

```
$ dig +trace +all www.cs.virginia.edu
...
edu.                172800  IN  NS  b.edu-servers.net.
edu.                172800  IN  NS  f.edu-servers.net.
edu.                172800  IN  NS  i.edu-servers.net.
edu.                172800  IN  NS  a.edu-servers.net.
...
b.edu-servers.net.  172800  IN  A   191.33.14.30
b.edu-servers.net.  172800  IN  AAAA    2001:503:231d::2:30
f.edu-servers.net.  172800  IN  A   192.35.51.30
f.edu-servers.net.  172800  IN  AAAA    2001:503:d414::30
...
;; Received 843 bytes from 198.97.190.53#53(h.root-servers.net) in 8 ms
...
```

querying the edu

```
$ dig +trace +all www.cs.virginia.edu
...
virginia.edu.        172800  IN  NS  nom.virginia.edu.
virginia.edu.        172800  IN  NS  uvaarpa.virginia.edu.
virginia.edu.        172800  IN  NS  eip-01-aws.net.virginia.edu.
nom.virginia.edu.    172800  IN  A   128.143.107.101
uvaarpa.virginia.edu.    172800  IN  A   128.143.107.117
eip-01-aws.net.virginia.edu. 172800 IN  A   44.234.207.10
;; Received 165 bytes from 192.26.92.30#53(c.edu-servers.net) in 40 ms
...
```

querying virginia.edu+cs.virginia.edu

```
$ dig +trace +all www.cs.virginia.edu
...
cs.virginia.edu.    3600    IN  NS  coresrv01.cs.virginia.edu.
coresrv01.cs.virginia.edu. 3600 IN  A   128.143.67.11
;; Received 116 bytes from 44.234.207.10#53(eip-01-aws.net.virginia.edu) in 72 ms

www.cs.Virginia.EDU.    172800  IN  A   128.143.67.11
cs.Virginia.EDU.    172800  IN  NS  coresrv01.cs.Virginia.EDU.
coresrv01.cs.Virginia.EDU. 172800 IN    A   128.143.67.11
;; Received 151 bytes from 128.143.67.11#53(coresrv01.cs.virginia.edu) in 4 ms
```

querying typical ISP's resolver

```
$ dig www.cs.virginia.edu
...
;; ANSWER SECTION:
www.cs.Virginia.EDU.      7183   IN   A   128.143.67.11
..
```

cached response

valid for 7183 more seconds

after that everyone needs to check again

‘connected’ UDP sockets

```
int fd = socket(AF_INET, SOCK_DGRAM, 0);
struct sockaddr_in my_addr= ...;
/* set local IP address + port */
bind(fd, &my_addr, sizeof(my_addr))
struct sockaddr_in to_addr = ...;
connect(fd, &to_addr); /* set remote IP address + port */
    /* doesn't actually communicate with remote address yet */
...
int count = write(fd, data, data_size);
// OR
int count = send(fd, data, data_size, 0 /* flags */);
    /* single message -- sent ALL AT ONCE */

int count = read(fd, buffer, buffer_size);
// OR
int count = recv(fd, buffer, buffer_size, 0 /* flags */);
    /* receives whole single message ALL AT ONCE */
```

UDP sockets on IPv4

```
int fd = socket(AF_INET, SOCK_DGRAM, 0);
struct sockaddr_in my_addr= ...;
/* set local IP address + port */
if (0 != bind(fd, &my_addr, sizeof(my_addr)))
    handle_error();
...
struct sockaddr_in to_addr = ...;
    /* send a message to specific address */
int bytes_sent = sendto(fd, data, data_size, 0 /* flags */,
    &to_addr, sizeof(to_addr));

struct sockaddr_in from_addr = ...;
    /* receive a message + learn where it came from */
int bytes_recvd = recvfrom(fd, &buffer[0], buffer_size, 0,
    &from_addr, sizeof(from_addr));
...
```

what about non-local machines?

when configuring network specify:

range of addresses to expect on local network

- 128.148.67.0-128.148.67.255 on my desktop
- “netmask”

gateway machine to send to for things outside my local network

- 128.143.67.1 on my desktop
- my desktop looks up the corresponding MAC address

routes on my desktop

```
$ /sbin/route -n
Kernel IP routing table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
0.0.0.0         128.143.67.1    0.0.0.0         UG    100    0        0 enp0s31f6
128.143.67.0    0.0.0.0         255.255.255.0   U     100    0        0 enp0s31f6
169.254.0.0     0.0.0.0         255.255.0.0     U     1000   0        0 enp0s31f6
```

network configuration says:

(line 2) to get to 128.143.67.0–128.143.67.255, send directly on local network

- “genmask” is mask (for bitwise operations) to specify how big range is

(line 3) to get to 169.254.0.0–169.254.255.255, send directly on local network

(line 1) to get anywhere else, use “gateway” 128.143.67.1

two types of addresses?

MAC addreses: on link layer

IP addresses: on network layer

how do we know which MAC address to use?

a table on my desktop

my desktop:

```
$ arp -an
? (128.143.67.140) at 3c:e1:a1:18:bd:5f [ether] on enp0s31f6
? (128.143.67.236) at <incomplete> on enp0s31f6
? (128.143.67.11) at 30:e1:71:5f:39:10 [ether] on enp0s31f6
? (128.143.67.92) at <incomplete> on enp0s31f6
? (128.143.67.5) at d4:be:d9:b0:99:d1 [ether] on enp0s31f6
```

…

network address to link-layer address + interface

only tracks things directly connected to my local network

- non-local traffic sent to local router

how is that table made?

ask all machines on local network (same switch)

“Who has 128.148.67.140”

the correct one replies

URLs and HTTP (1)

`http://www.foo.com:80/foo/bar?quux#q1`

lookup IP address of www.foo.com

connect via TCP to port 80:

```
GET /foo/bar?quux HTTP/1.1
Host: \\emphThree{www.foo.com:80}
```

exercise: why include the Host there?

URLs and HTTP (1)

`http://www.foo.com:80/foo/bar?quux#q1`

lookup IP address of www.foo.com

connect via TCP to port 80:

```
GET /foo/bar?quux HTTP/1.1
Host: \\emphThree{www.foo.com:80}
```

exercise: why include the Host there?

spoofing

if I only allow connections from my desktop's IP addresses, how would you attack this?

hint: how do we know what address messages come from?

connection setup: server, manual

```
int server_socket_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = INADDR_ANY; /* "any address I can use" */
    /* or: addr.s_addr.in_addr = INADDR_LOOPBACK (127.0.0.1) */
    /* or: addr.s_addr.in_addr = htonl(...); */
addr.sin_port = htons(9999); /* port number 9999 */

if (bind(server_socket_fd, &addr, sizeof(addr)) < 0) {
    /* handle error */
}
listen(server_socket_fd, MAX_NUM_WAITING);
...
int socket_fd = accept(server_socket_fd, NULL);
```

connection setup: server, manual

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int server_socket_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
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addr.sin_port = htons(9999); /* port number 9999 */

if (bind(server_socket_fd, &addr, sizeof(addr)) < 0) {
    /* handle error */
}
listen(server_socket_fd, MAX_NUM_WAITING);
...
int socket_fd = accept(server_socket_fd, NULL);
```

INADDR_ANY: accept connections for any address I can!
alternative: specify specific address

connection setup: server, manual

```
int server_socket_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = INADDR_ANY; /* "any address I can use" */
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if (bind(server_socket_fd, &addr, sizeof(addr)) < 0) {
    /* handle error */
}
listen(server_socket_fd, MAX_NUM_WAITING);
...
int socket_fd = accept(server_socket_fd, NULL);
```

bind to 127.0.0.1? only accept connections *from same machine*
what we recommend for FTP server assignment

connection setup: server, manual

```
int server_socket_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = INADDR_ANY; /* "any address I can use" */
    /* or: addr.s_addr.in_addr = INADDR_LOOPBACK (127.0.0.1) */
    /* or: addr.s_addr.in_addr = htonl(...); */
addr.sin_port = htons(9999); /* port number 9999 */

if (bind(server_socket_fd, &addr, sizeof(addr)) < 0) {
    /* handle error */
}
listen(server_socket_fd, MAX_NUM_WAITING);
...
int socket_fd = accept(server_socket_fd, NULL);
```

choose the number of unaccepted connections

connection setup: client — manual addresses

```
int sock_fd;

server = /* code on later slide */;
sock_fd = socket(
    AF_INET, /* IPv4 */
    SOCK_STREAM, /* byte-oriented */
    IPPROTO_TCP
);
if (sock_fd < 0) { /* handle error */ }

struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_addr = htonl(2156872459); /* 128.143.67.11 */
addr.sin_port = htons(80); /* port 80 */
if (connect(sock_fd, (struct sockaddr*) &addr, sizeof(addr)) {
    /* handle error */
}
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

connection setup: client — manual addresses

```
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    AF_INET, /* IPv4 */
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connection setup: client — manual addresses

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    AF_INET, /* IPv4 */
    SOCK_STREAM, /* byte-oriented */
    IPPROTO_TCP
);
if (sock_fd < 0) { /* handle error */ }

struct sockaddr_in addr;
addr.sin_family = AF_INET;
addr.sin_addr.s_add
addr.sin_port = hto
if (connect(sock_fd
    /* handle error
}
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

specify IPv4 instead of IPv6 or local-only sockets
specify TCP (byte-oriented) instead of UDP (‘datagram’ oriented)

connection setup: client — manual addresses

```
int sock_fd;

server = /* code on later slide */;
sock_fd = socket(
    AF_INET, /* IPv4 */
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if (connect(sock_fd, (struct sockaddr*) &addr, sizeof(addr)) {
    /* handle error */
}
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

htonl/s = host-to-network long/short
network byte order = big endian

connection setup: client — manual addresses

```
int sock_fd;

server = /* code on later slide */;
sock_fd = socket(
    AF_INET, /* IPv4 */
    SOCK_STREAM, /* byte-orie
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);
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addr.sin_port = htons(80); /* port 80 */
if (connect(sock_fd, (struct sockaddr*) &addr, sizeof(addr)) {
    /* handle error */
}
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

struct representing IPv4 address + port number
declared in <netinet/in.h>
see man 7 ip on Linux for docs

echo client/server

```
void client_for_connection(int socket_fd) {
    int n; char send_buf\[MAX_SIZE]; char recv_buf\[MAX_SIZE];
    while (prompt_for_input(send_buf, MAX_SIZE)) {
        n = write(socket_fd, send_buf, strlen(send_buf));
        if (n != strlen(send_buf)) {...error?...}
        n = read(socket_fd, recv_buf, MAX_SIZE);
        if (n <= 0) return; // error or EOF
        write(STDOUT_FILENO, recv_buf, n);
    }
}
```

```
void server_for_connection(int socket_fd) {
    int read_count, write_count; char request_buf\[MAX_SIZE];
    while (1) {
        read_count = read(socket_fd, request_buf, MAX_SIZE);
        if (read_count <= 0) return; // error or EOF
        write_count = write(socket_fd, request_buf, read_count);
        if (read_count != write_count) {...error?...}
    }
}
```

echo client/server

```
void client_for_connection(int socket_fd) {
    int n; char send_buf\[MAX_SIZE]; char recv_buf\[MAX_SIZE];
    while (prompt_for_input(send_buf, MAX_SIZE)) {
        n = write(socket_fd, send_buf, strlen(send_buf));
        if (n != strlen(send_buf)) {...error?...}
        n = read(socket_fd, recv_buf, MAX_SIZE);
        if (n <= 0) return; // error or EOF
        write(STDOUT_FILENO, recv_buf, n);
    }
}
```

```
void server_for_connection(int socket_fd) {
    int read_count, write_count; char request_buf\[MAX_SIZE];
    while (1) {
        read_count = read(socket_fd, request_buf, MAX_SIZE);
        if (read_count <= 0) return; // error or EOF
        write_count = write(socket_fd, request_buf, read_count);
        if (read_count != write_count) {...error?...}
    }
}
```

echo client/server

```
void client_for_connection(int socket_fd) {
    int n; char send_buf\[MAX_SIZE]; char recv_buf\[MAX_SIZE];
    while (prompt_for_input(send_buf, MAX_SIZE)) {
        n = write(socket_fd, send_buf, strlen(send_buf));
        if (n != strlen(send_buf)) {...error?...}
        n = read(socket_fd, recv_buf, MAX_SIZE);
        if (n <= 0) return; // error or EOF
        write(STDOUT_FILENO, recv_buf, n);
    }
}
```

```
void server_for_connection(int socket_fd) {
    int read_count, write_count; char request_buf\[MAX_SIZE];
    while (1) {
        read_count = read(socket_fd, request_buf, MAX_SIZE);
        if (read_count <= 0) return; // error or EOF
        write_count = write(socket_fd, request_buf, read_count);
        if (read_count != write_count) {...error?...}
    }
}
```

connection setup: server, address setup

```
/* example (hostname, portname) = ("127.0.0.1", "443") */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;

memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_INET; /* for IPv4 */
/* or: */ hints.ai_family = AF_INET6; /* for IPv6 */
/* or: */ hints.ai_family = AF_UNSPEC; /* I don't care */
hints.ai_flags = AI_PASSIVE;

rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }
```

connection setup: server, address setup

```
/* example (hostname, portname) = ("127.0.0.1", "443") */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
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memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_INET; /* for IPv4 */
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rv = getaddrinfo(hostname, portname, &hints, &server);
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connection setup: server, address setup

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hints.ai_family = AF_INET; /* for IPv4 */
/* or: */ hints.ai_family = AF_INET6; /* for IPv6 */
/* or: */ hints.ai_family = AF_UNSPEC; /* I don't care */
hints.ai_flags = AI_PASSIVE;

rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }
```

hostname could also be NULL
means "use all possible addresses"
only makes sense for servers

connection setup: server, address setup

```
/* example (hostname, portname) = ("127.0.0.1", "443") */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;

memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_INET; /* for IPv4 */
/* or: */ hints.ai_family = AF_INET6; /* for IPv6 */
/* or: */ hints.ai_family = AF_UNSPEC; /* I don't care */
hints.ai_flags = AI_PASSIVE;

rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }
```

`portname` could also be NULL
means "choose a port number for me"
only makes sense for servers

connection setup: server, address setup

```
/* example (hostname, portname) = ("127.0.0.1", "443") */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;

memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_INET; /* for IPv4 */
/* or: */ hints.ai_family = AF_INET6; /* for IPv6 */
/* or: */ hints.ai_family = AF_UNSPEC; /* I don't care */
hints.ai_flags = AI_PASSIVE;

rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }
```

AI_PASSIVE: "I'm going to use bind"

connection setup: server, addrinfo

```
struct addrinfo *server;
... getaddrinfo(...) ...

int server_socket_fd = socket(
    server->ai_family,
    server->ai_sockttype,
    server->ai_protocol
);

if (bind(server_socket_fd, ai->ai_addr, ai->ai_addr_len)) < 0) {
    /* handle error */
}
listen(server_socket_fd, MAX_NUM_WAITING);
...
int socket_fd = accept(server_socket_fd, NULL);
```

connection setup: client, using addrinfo

```
int sock_fd;
struct addrinfo *server = /* code on next slide */;

sock_fd = socket(
    server->ai_family,
     // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, server->ai_addr, server->ai_addrlen) < 0) {
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

connection setup: client, using addrinfo

```
int sock_fd;
struct addrinfo *server = /* code on next slide */;

sock_fd = socket(
    server->ai_family,
     // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, server->ai_addr, server->ai_addrlen) < 0) {
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

connection setup: client, using addrinfo

```
int sock_fd;
struct addrinfo *server = /* code on next slide */;

sock_fd = socket(
    server->ai_family,
     // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, ser
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd);
close(sock_fd);
```

addrinfo contains all information needed to setup socket
set by `getaddrinfo` function (next slide)
handles IPv4 and IPv6
handles DNS names, service names

connection setup: client, using addrinfo

```
int sock_fd;
struct addrinfo *server = /* code on next slide */;

sock_fd = socket(
    server->ai_family,
     // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, server->ai_addr, server->ai_addrlen) < 0) {
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

connection setup: client, using addrinfo

```
int sock_fd;
struct addrinfo *server = /* code on next slide */;

sock_fd = socket(
    server->ai_family,
     // ai_family = AF_INET (I
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, server->ai_addr, server->ai_addrlen) < 0) {
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

ai_addr points to struct representing address
type of struct depends whether IPv6 or IPv4

connection setup: client, using addrinfo

```
int sock_fd;
struct addrinfo *server = /* code on next slide */;

sock_fd = socket(
    server->ai_fami
     // ai_family =
    server->ai_socktype,
     // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_prototcol
     // ai_protocol = IPPROTO_TCP or ...
);
if (sock_fd < 0) { /* handle error */ }
if (connect(sock_fd, server->ai_addr, server->ai_addrlen) < 0) {
    /* handle error */
}
freeaddrinfo(server);
DoClientStuff(sock_fd); /* read and write from sock_fd */
close(sock_fd);
```

since addrinfo contains pointers to dynamically allocated memory, call this function to free everything

connection setup: lookup address

```
/* example hostname, portname = "www.cs.virginia.edu", "443" */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC; /* for IPv4 OR IPv6 */
// hints.ai_family = AF_INET4; /* for IPv4 only */

hints.ai_socktype = SOCK_STREAM; /* byte-oriented --- TCP */
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

/* eventually freeaddrinfo(result) */
```

connection setup: lookup address

```
/* example hostname, portname = "www.cs.virginia.edu", "443" */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC; /* for IPv4 OR IPv6 */
// hints.ai_family = AF_INET4; /* for IPv4 only */

hints.ai_socktype = SOCK_STREAM; /* byte-oriented --- TCP */
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

/* eventually freeaddrinfo(result) */
```

connection setup: lookup address

```
/* example hostname, portname = "www.cs.virginia.edu", "443" */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC; /* for IPv4 OR IPv6 */
// hints.ai_family = AF_INET4; /* for IPv4 only */

hints.ai_socktype = SOCK_STREAM; /* byte-oriented --- TCP */
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

/* eventually freeaddrinfo(result) */
```

NB: pass pointer *to pointer* to addrinfo to fill in

connection setup: lookup address

```
/* example hostname, portname = "www.cs.virginia.edu", "443" */
const char *hostname; const char *portname;
...
struct addrinfo *server;
struct addrinfo hints;
int rv;
memset(&hints, 0, sizeof(hints));
hints.ai_family = AF_UNSPEC; /* for IPv4 OR IPv6 */
// hints.ai_family = AF_INET4; /* for IPv4 only */

hints.ai_socktype = SOCK_STREAM; /* byte-oriented --- TCP */
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

/* eventually freeaddrinfo(result) */
```

AF_UNSPEC: choose between IPv4 and IPv6 for me
AF_INET, AF_INET6: choose IPv4 or IPV6 respectively

connection setup: multiple server addresses

```
struct addrinfo *server;
...
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

for (struct addrinfo *current = server; current != NULL;
      current = current->ai_next) {
    sock_fd = socket(current->ai_family, current->ai_socktype, current->ai_protocol);
    if (sock_fd < 0) continue;
    if (connect(sock_fd, current->ai_addr, current->ai_addrlen) == 0) {
        break;
    }
    close(sock_fd); // connect failed
}
freeaddrinfo(server);
DoClientStuff(sock_fd);
close(sock_fd);
```

connection setup: multiple server addresses

```
struct addrinfo *server;
...
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

for (struct addrinfo *current = server; current != NULL;
      current = current->ai_next) {
    sock_fd = socket(current->ai_family, current->ai_socktype, current->ai_protocol);
    if (sock_fd < 0) continue;
    if (connect(sock_fd, current->ai_addr, current->ai_addrlen) == 0) {
        break;
    }
    close(sock_fd); // connect failed
}
freeaddrinfo(server);
DoClientStuff(sock_fd);
close(sock_fd);
```

connection setup: multiple server addresses

```
struct addrinfo *server;
...
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) { /* handle error */ }

for (struct addrinfo *current = server; current != NULL;
      current = current->ai_next) {
    sock_fd = socket(current->ai_family, current->ai_socktype, current->ai_protocol);
    if (sock_fd < 0) continue;
    if (connect(sock_fd, current->ai_addr, current->ai_addrlen) == 0) {
        break;
    }
    close(sock_fd); // connect failed
}
freeaddrinfo(server);
DoClientStuff(sock_fd);
close(sock_fd);
```

addrinfo is a linked list
name can correspond to multiple addresses
example: redundant copies of web server
example: an IPv4 address and IPv6 address
example: wired + wireless connection on one machine

connection setup: old lookup function

```
/* example hostname, portnum= "www.cs.virginia.edu", 443*/
const char *hostname; int portnum;
...
struct hostent *server_ip;
server_ip = gethostbyname(hostname);

if (server_ip == NULL) { /* handle error */ }

struct sockaddr_in addr;
addr.s_addr = *(struct in_addr*) server_ip->h_addr_list[0];
addr.sin_port = htons(portnum);
sock_fd = socket(AF_INET, SOCK_STREAM, IPPROTO_TCP);
connect(sock_fd, &addr, sizeof(addr));
...
```

aside: on server port numbers

Unix convention: must be `root` to use ports 0–1023

root = superuser = ‘adminstrator user’ = what sudo does

so, for testing: probably ports > 1023