

last time

dividing addresses into page number (PN) + page offset (PO)

storing page tables in memory

- represent page table entry (row) as integer

- array of those integers

- page table base register = start of address

(1-level) page table lookup

- access entry from memory at $(PTBR + \text{virtual PN} \times \text{entry size})$

 - array lookup

- check valid bit/etc. in entry

- use physical page number from entry combined with page offset

- access memory at that location

(started) multi-level page tables

- tree-like structure

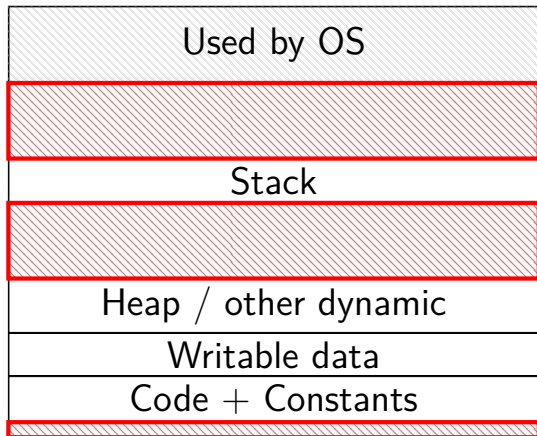
huge page tables

huge virtual address spaces!

impossible to store PTE for every page

how can we save space?

holes



most pages are **invalid**

saving space

basic idea: don't store (most) invalid page table entries

use a data structure other than a flat array

want a map — lookup key (virtual page number), get value (PTE)

options?

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actually used by some historical processors

but never common

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tree data structure

but not quite a search tree

search tree tradeoffs

lookup usually implemented in hardware

- lookup should be simple

- solution: lookup splits up address bits (no complex calculations)

lookup should not involve many memory accesses

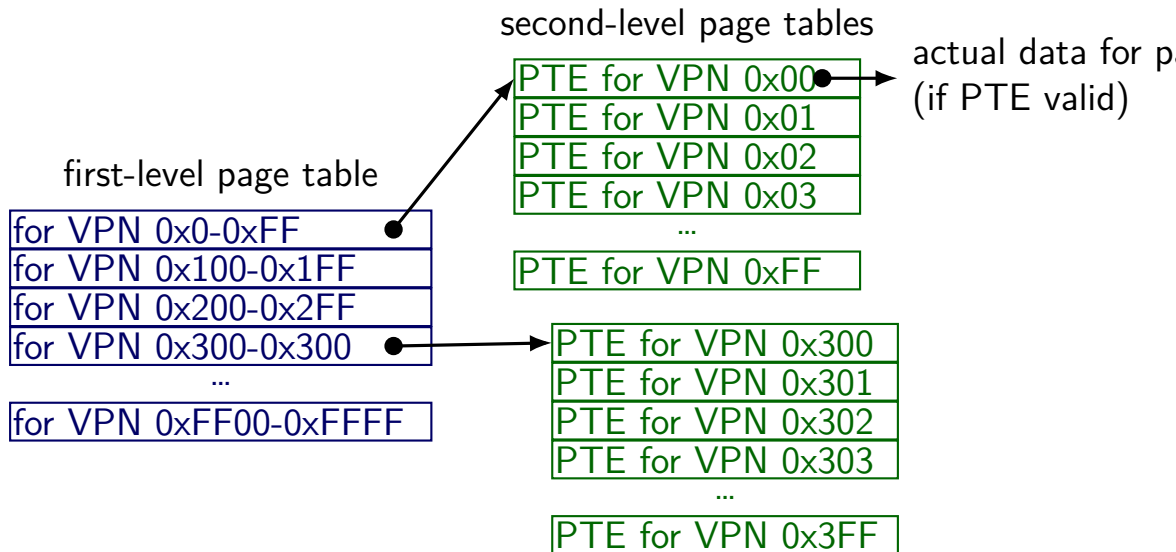
- doing two memory accesses is already very slow

- solution: tree with many children from each node

- (far from binary tree's left/right child)

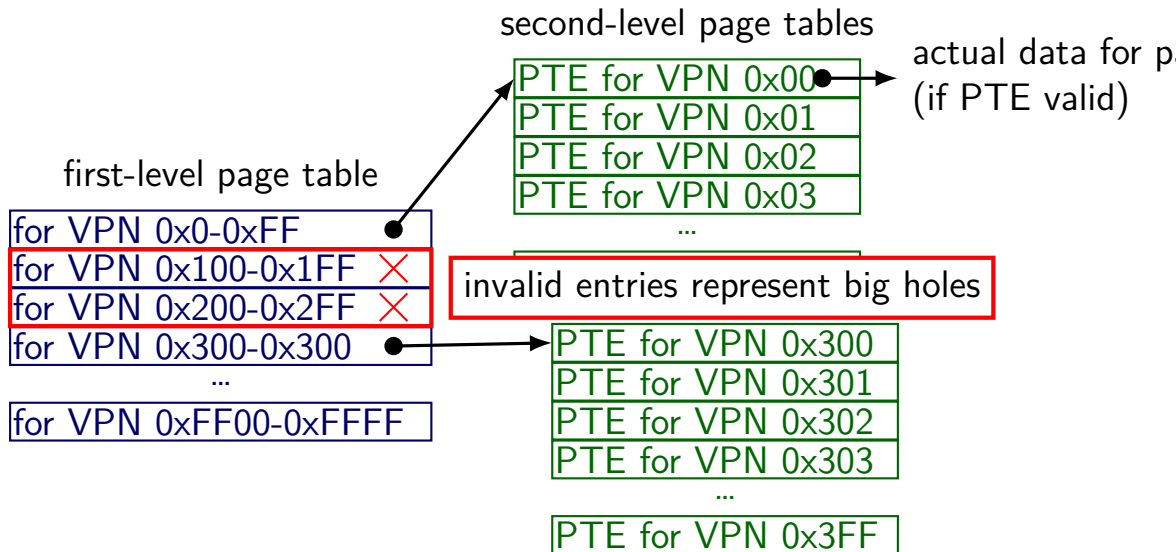
two-level page tables

two-level page tables for 65536 pages (16-bit VPN; 256 entries/table)



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first-level page table				for p d)
VPN range	valid	...	physical page # (of next page table)	
0x0000-0x00FF	1	...	0x22343	
0x0100-0x01FF	0	...	0x00000	
0x0200-0x02FF	0	...	0x00000	
0x0300-0x03FF	1	...	0x33454	
0x0400-0x04FF	1	...	0xFF043	
...	
0xFF00-0xFFFF	1	...	0xFF045	

first-level page table for VPN 0x000-0x00FF
for VPN 0x100-0x10FF
for VPN 0x200-0x20FF
for VPN 0x300-0x30FF
...
for VPN 0xFF00-0xFFFF

PTE for VPN 0x303
...
PTE for VPN 0x3FF

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first-level page table

for VPN 0x0-0xFF
for VPN 0x100-0x1FF ✗
for VPN 0x200-0x2FF ✗
for VPN 0x300-0x300
...
for VPN 0xFF00-0xFFFF

a second-level page table

VPN	valid	...	physical page # (of data)
0x300	0	1	0x42443
0x301	0	1	0x4A9DE
0x302	0	1	0x5C001
0x303	0	1	0x00000
0x304	0	1	0x6C223
...
0x3FF	...	1	0x00000

PTE for VPN 0x303

...

PTE for VPN 0x3FF

or p
l)

two-level page tables

two-level page tables for 65536 pages (16-bit VPN: 256 entries/table)

first-level page table

for VPN 0x0-0xFF	
for VPN 0x100-0x1FF	×
for VPN 0x200-0x2FF	×
for VPN 0x300-0x300	
...	
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PTE for VPN 0x303

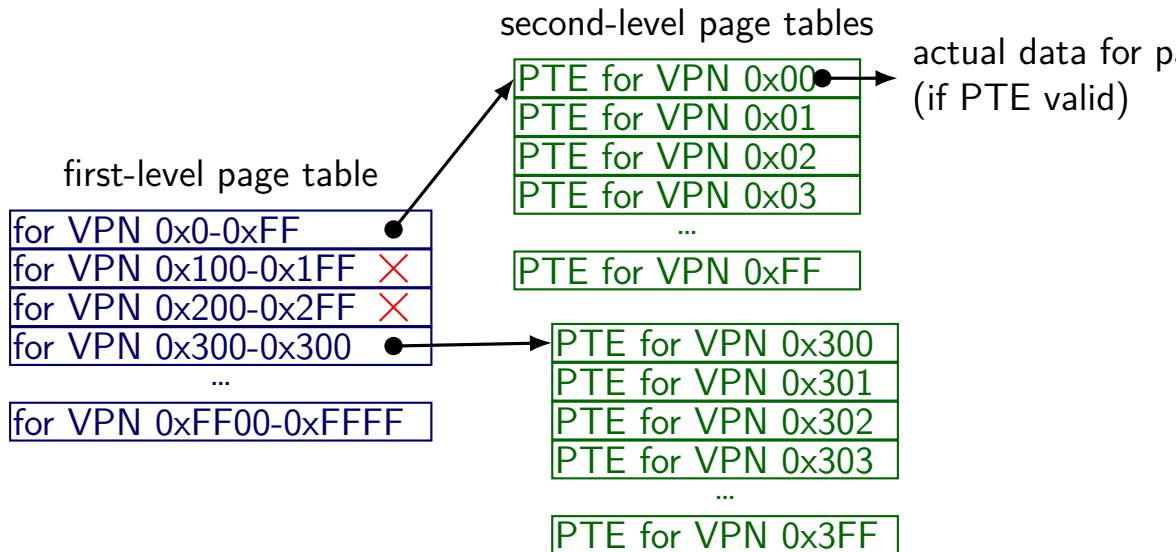
...

PTE for VPN 0x3FF

or p
l)

two-level page tables

two-level page tables for 65536 pages (16-bit VPN; 256 entries/table)



two-level page table lookup

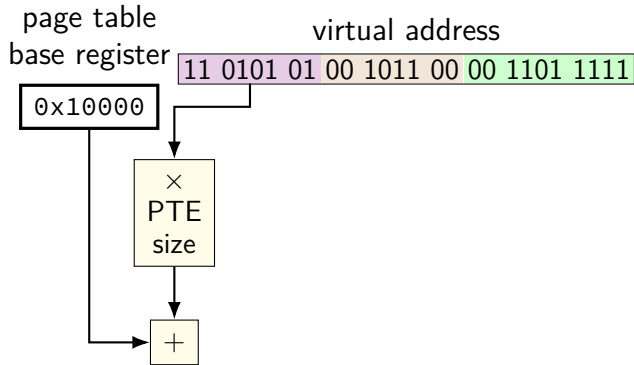
virtual address

11 0101 01 00 1011 00	00 1101 1111
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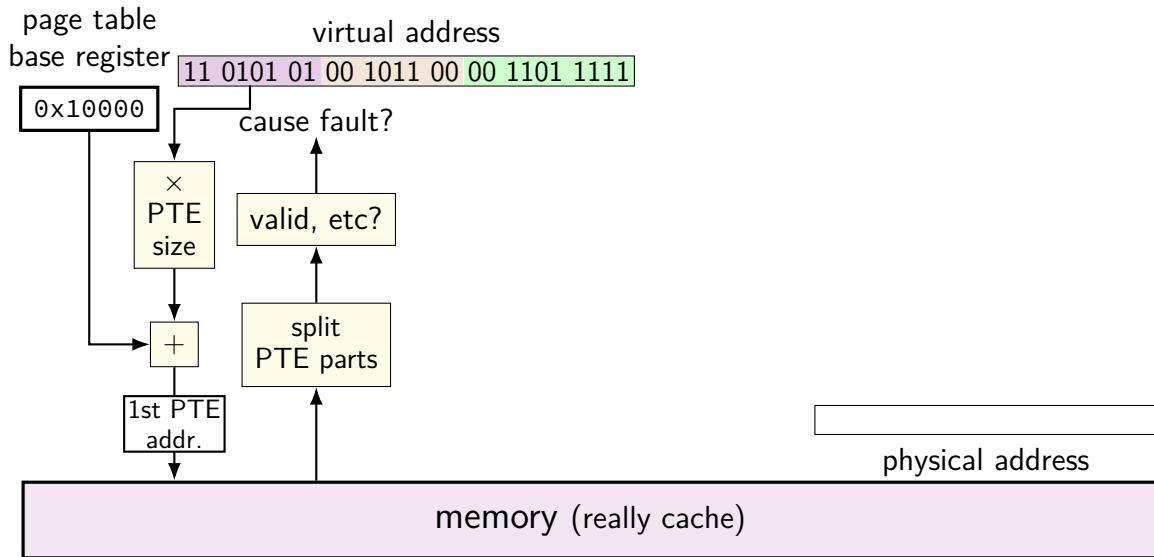
VPN — split into two parts (one per level)

this example: parts equal sized — common, but not required

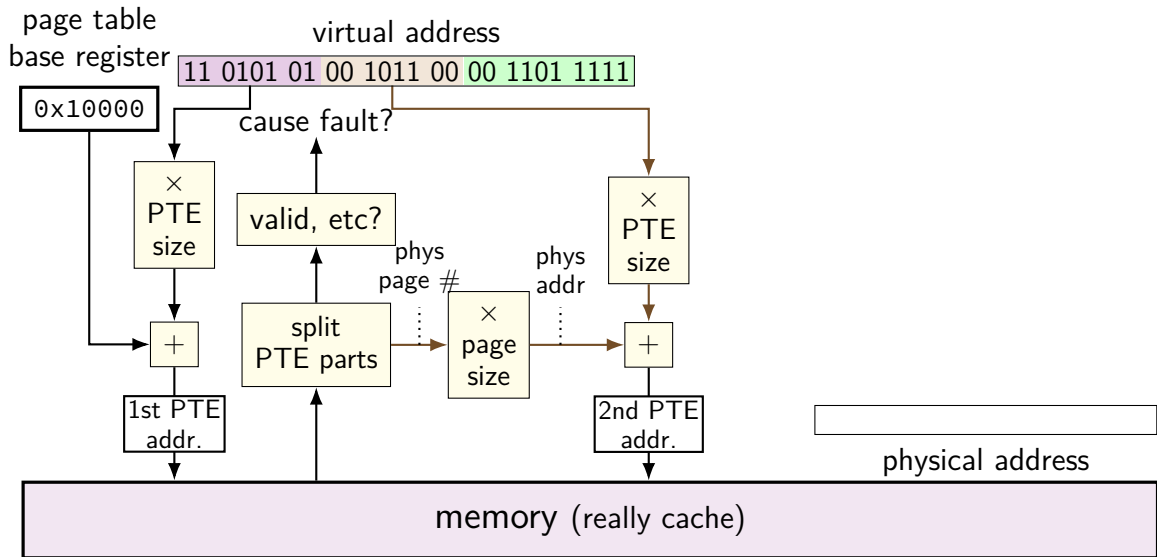
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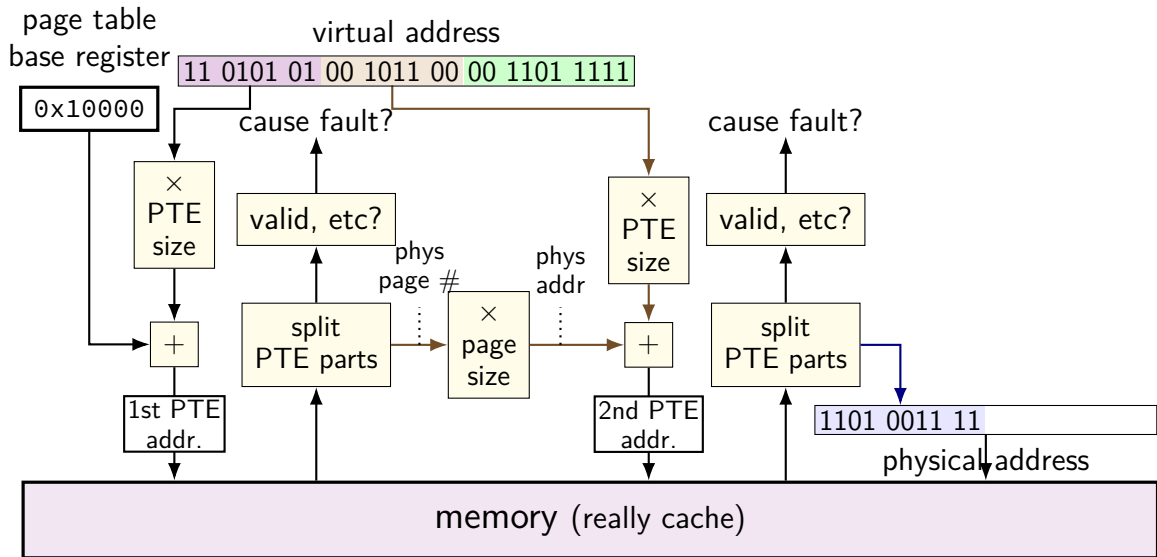
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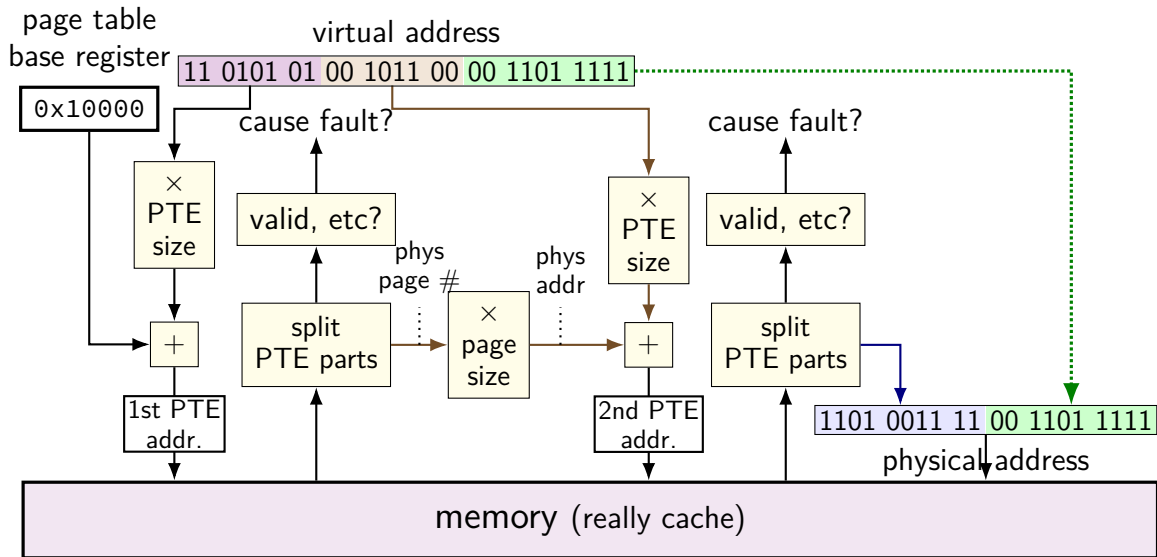
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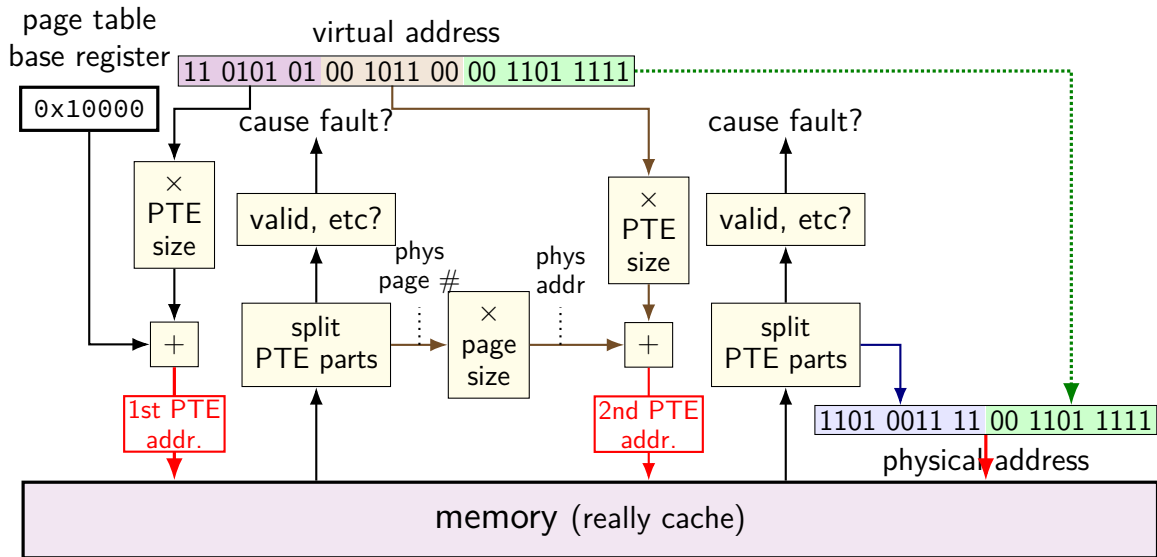
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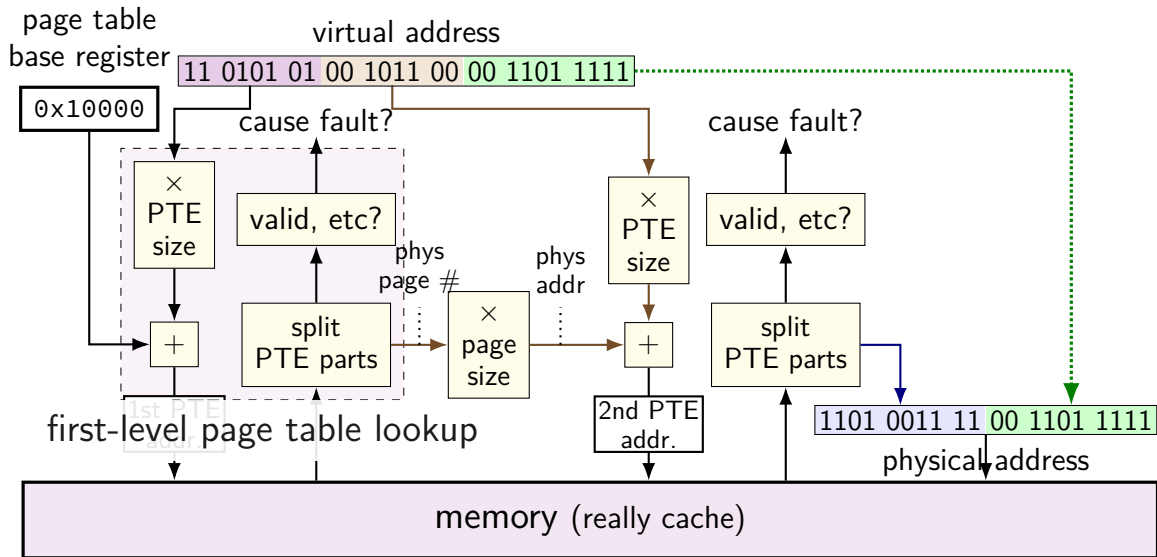
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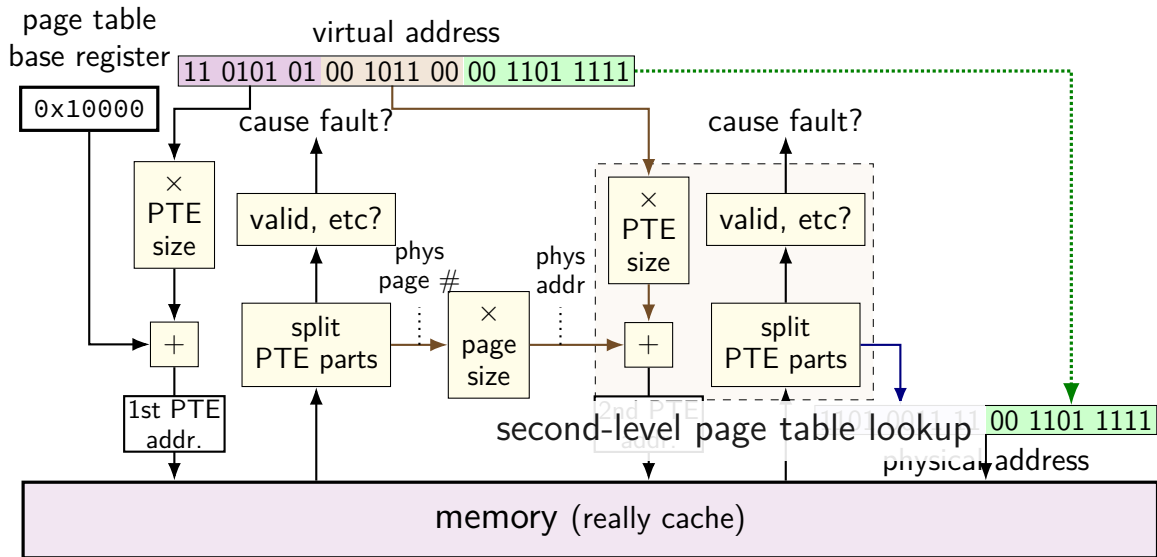
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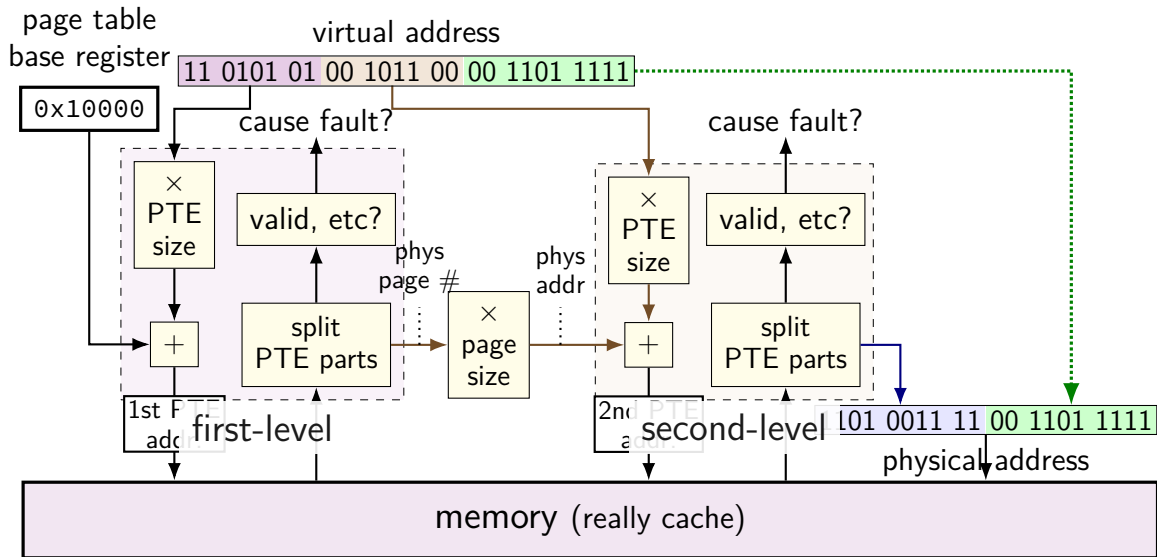
two-level page table lookup



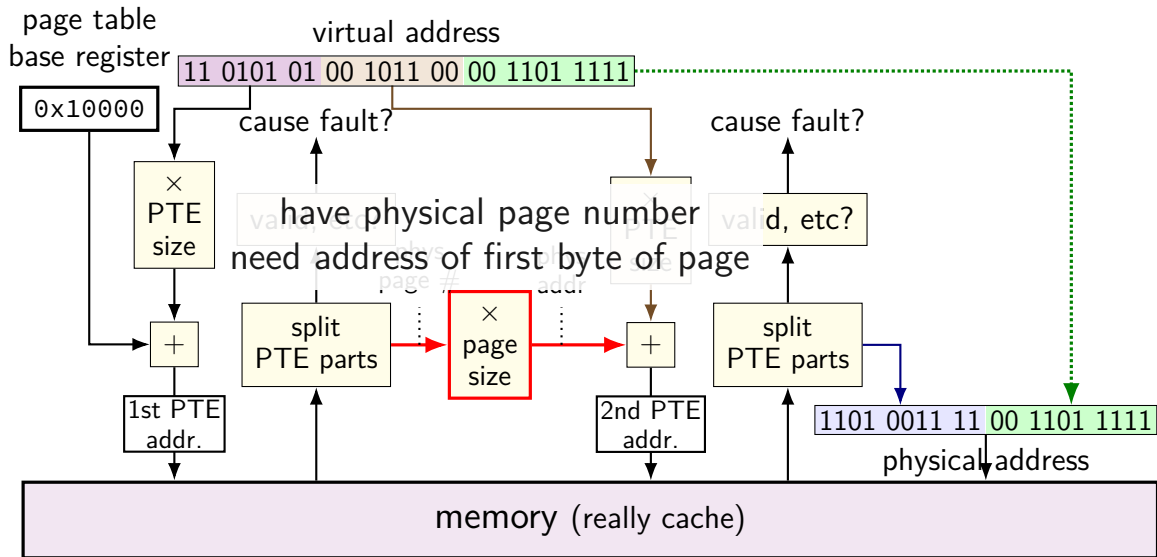
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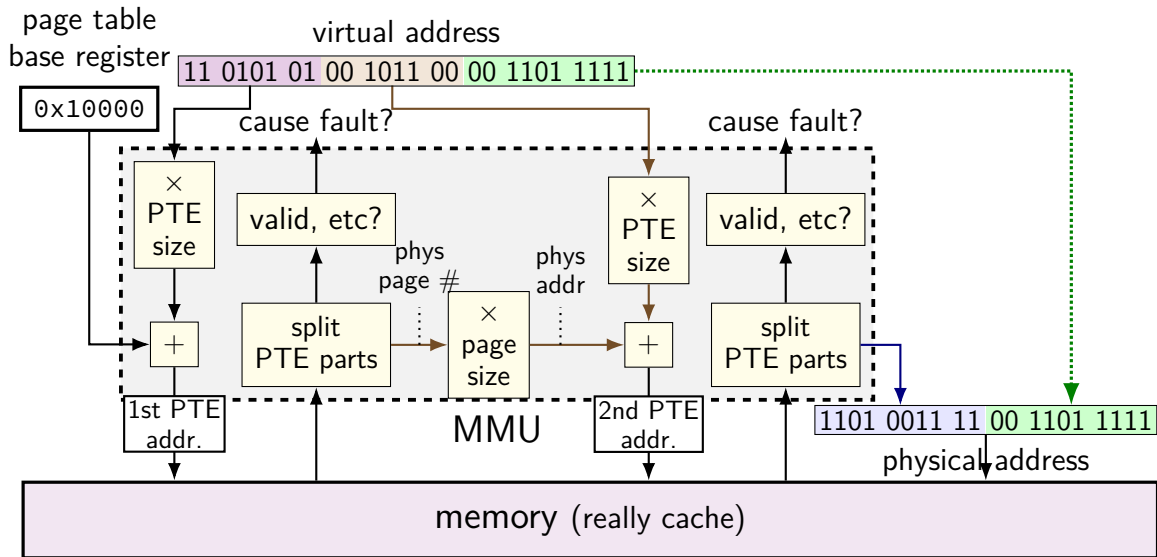
two-level page table lookup



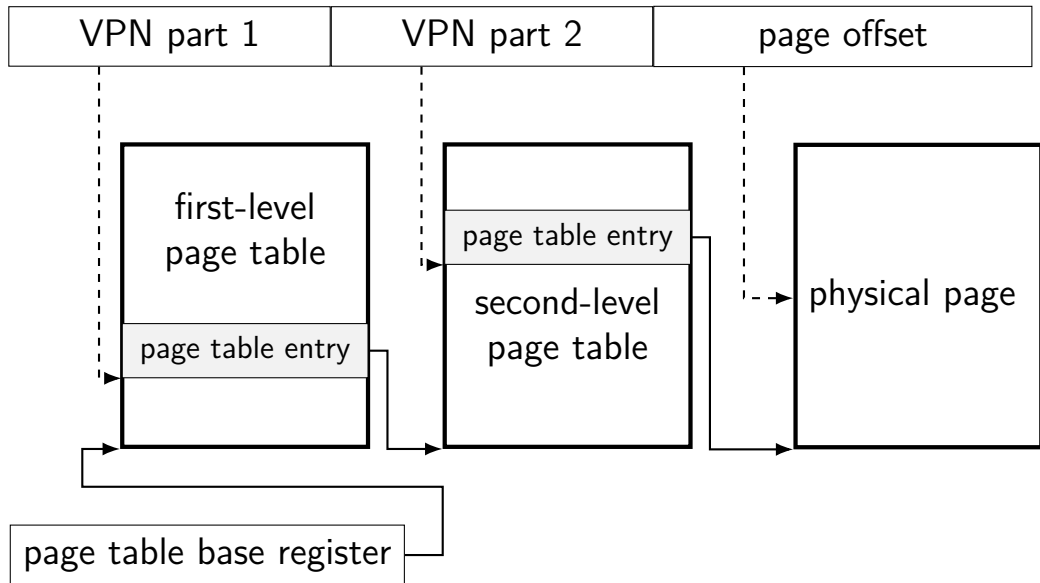
two-level page table lookup



two-level page table lookup



another view



multi-level page tables

VPN split into pieces for each level of page table

top levels: page table entries point to next page table

usually using physical page number of next page table

bottom level: page table entry points to destination page

validity checks at each level

x86-64 page table splitting

48-bit virtual address

12-bit page offset (4KB pages)

36-bit virtual page number, split into four 9-bit parts

page tables at each level: 2^9 entries, 8 bytes/entry
deliberate choice: each page table is one page

note on VPN splitting

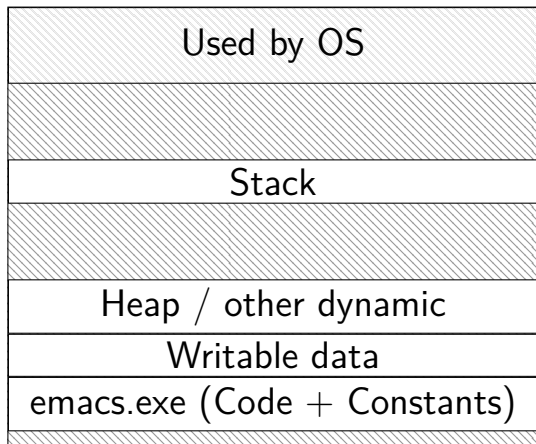
textbook labels it 'VPN 1' and 'VPN 2' and so on

these are parts of the virtual page number

(there are not multiple VPNs)

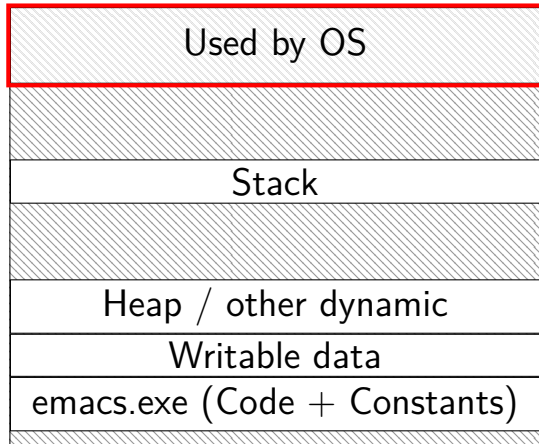
emacs (two copies)

Emacs (run by user mst3k)



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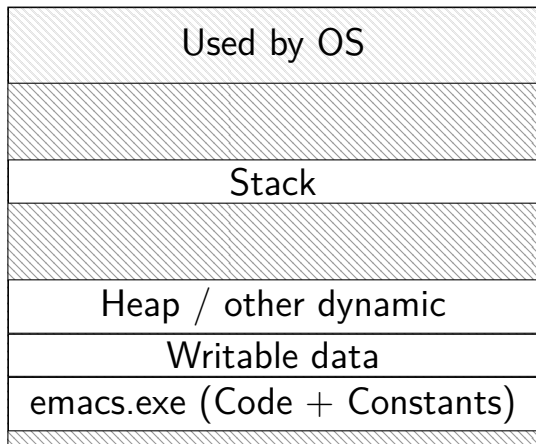
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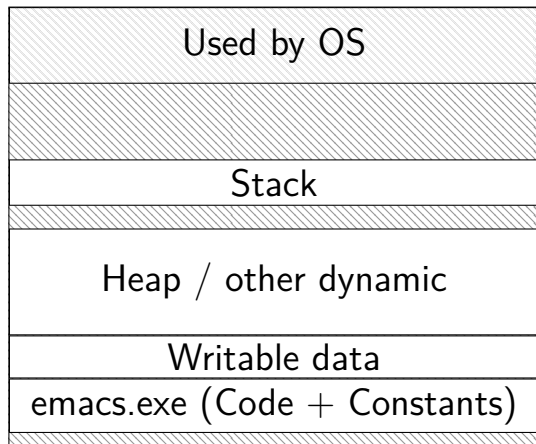
OS's memory

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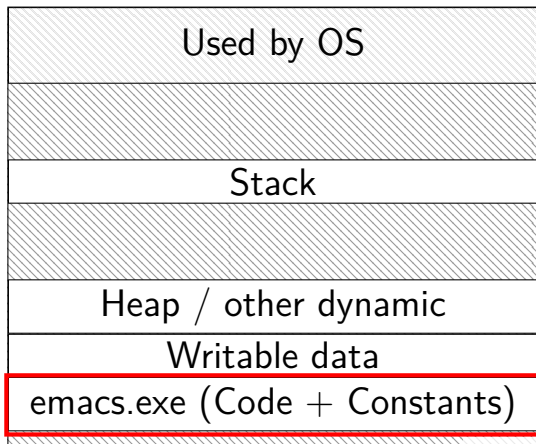


Emacs (run by user xyz4w)

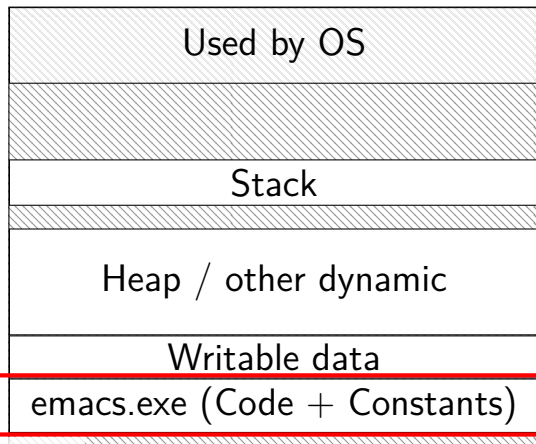


emacs (two copies)

Emacs (run by user mst3k)



Emacs (run by user xyz4w)



same data?

two copies of program

would like to only have one copy of program

what if mst3k's emacs tries to modify its code?

would break process abstraction:

“illusion of own memory”

permissions bits

page table entry will have more **permissions bits**

can access in user mode?

can read from?

can write to?

can execute from?

checked by MMU like valid bit

page table (logically)

virtual page #	valid?	user?	write?	exec?	physical page #
0000 0000	0	0	0	0	00 0000 0000
0000 0001	1	1	1	0	10 0010 0110
0000 0010	1	1	1	0	00 0000 1100
0000 0011	1	1	0	1	11 0000 0011
...					
1111 1111	1	0	1	0	00 1110 1000

assignment

2-level example

9-bit virtual addresses, 6-bit physical; 8 byte pages, 1 byte PTE

page tables 1 page; PTE: 3 bit PPN (MSB), 1 valid bit, 4 unused

page table base register 0x20; translate virtual address 0x131

physical addresses	bytes
0x00-3	00 11 22 33
0x04-7	44 55 66 77
0x08-B	88 99 AA BB
0x0C-F	CC DD EE FF
0x10-3	1A 2A 3A 4A
0x14-7	1B 2B 3B 4B
0x18-B	1C 2C 3C 4C
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2-level splitting

9-bit virtual address

6-bit physical address

8-byte pages \rightarrow 3-bit page offset (bottom bits)

9-bit VA: 6 bit VPN + 3 bit PO

6-bit PA: 3 bit PPN + 3 bit PO

8 entry page tables \rightarrow 3-bit VPN parts

9-bit VA: 3 bit VPN part 1; 3 bit VPN part 2

2-level exercise (1)

9-bit virtual addresses, 6-bit physical; 8 byte pages, 1 byte PTE
page tables 1 page; PTE: 3 bit PPN (MSB), 1 valid bit, 4 unused;
page table base register 0x08; translate virtual address 0x0FB

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2-level exercise (2)

9-bit virtual addresses, 6-bit physical; 8 byte pages, 1 byte PTE
page tables 1 page; PTE: 3 bit PPN (MSB), 1 valid bit, 4 unused;
page table base register 0x10; translate virtual address 0x109

physical addresses	bytes
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0x08-B	88 99 AA BB
0x0C-F	CC DD EE FF
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0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
0x34-7	DB 0B DB 0B
0x38-B	EC 0C EC 0C
0x3C-F	FC 0C FC 0C

2-level exercise (3)

9-bit virtual addresses, 6-bit physical; 8 byte pages, 1 byte PTE
page tables 1 page; PTE: 3 bit PPN (MSB), 1 valid bit, 4 unused
page table base register 0x08; translate virtual address 0x00B

physical addresses	bytes
0x00-3	00 11 22 33
0x04-7	44 55 66 77
0x08-B	88 99 AA BB
0x0C-F	CC DD EE FF
0x10-3	1A 2A 3A 4A
0x14-7	1B 2B 3B 4B
0x18-B	1C 2C 3C 4C
0x1C-F	1C 2C 3C 4C

physical addresses	bytes
0x20-3	D0 D1 D2 D3
0x24-7	D4 D5 D6 D7
0x28-B	89 9A AB BC
0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
0x34-7	DB 0B DB 0B
0x38-B	EC 0C EC 0C
0x3C-F	FC 0C FC 0C

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page tables 1 page; PTE: 3 bit PPN (MSB), 1 valid bit, 4 unused
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0x04-7	44 55 66 77
0x08-B	88 99 AA BB
0x0C-F	CC DD EE FF
0x10-3	1A 2A 3A 4A
0x14-7	1B 2B 3B 4B
0x18-B	1C 2C 3C 4C
0x1C-F	1C 2C 3C 4C

physical addresses	bytes
0x20-3	D0 D1 D2 D3
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0x00-3	00 11 22 33
0x04-7	44 55 66 77
0x08-B	88 99 AA BB
0x0C-F	CC DD EE FF
0x10-3	1A 2A 3A 4A
0x14-7	1B 2B 3B 4B
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0x30-3	BA 0A BA 0A
0x34-7	DB 0B DB 0B
0x38-B	EC 0C EC 0C
0x3C-F	FC 0C FC 0C

2-level exercise (4)

9-bit virtual addresses, 6-bit physical; 8 byte pages, 1 byte PTE
page tables 1 page; PTE: 3 bit PPN (MSB), 1 valid bit, 4 unused
page table base register 0x08; translate virtual address 0x1CB

physical addresses	bytes
0x00-3	00 11 22 33
0x04-7	44 55 66 77
0x08-B	88 99 AA BB
0x0C-F	CC DD EE FF
0x10-3	1A 2A 3A 4A
0x14-7	1B 2B 3B 4B
0x18-B	1C 2C 3C 4C
0x1C-F	1C 2C 3C 4C

physical addresses	bytes
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0x24-7	D4 D5 D6 D7
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0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
0x34-7	DB 0B DB 0B
0x38-B	EC 0C EC 0C
0x3C-F	FC 0C FC 0C

2-level exercise (5)

10-bit virtual addresses, 6-bit physical; 16 byte pages, 2 byte PTE

page tables 1 page; PTE: 2 bit PPN (MSB of first byte), 1 valid bit, rest unused

page table base register 0x10; translate virtual address 0x376

physical
addresses bytes

0x00-3	00 11 22 33
0x04-7	44 55 66 77
0x08-B	88 99 AA BB
0x0C-F	CC DD EE FF
0x10-3	1A 2A 3A 4A
0x14-7	1B 2B 3B 4B
0x18-B	1C 2C 3C 4C
0x1C-F	AC BC DC EC

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0x30-3	BA 0A BA 0A
0x34-7	DB 0B DB 0B
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physical
addresses bytes

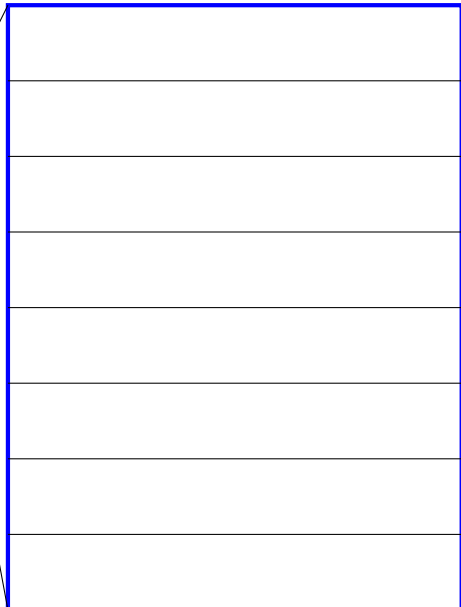
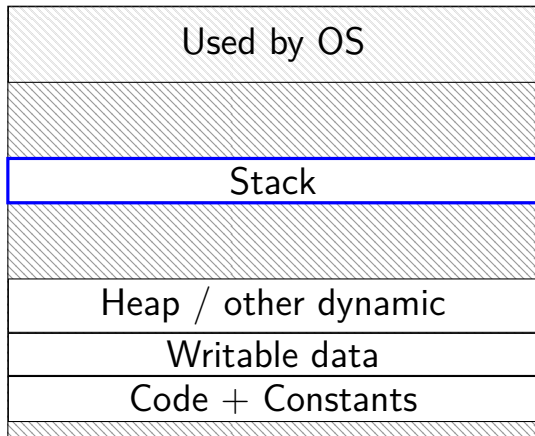
0x00-3	00 11 22 33
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0x08-B	88 99 AA BB
0x0C-F	CC DD EE FF
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0x34-7	DB 0B DB 0B
0x38-B	EC 0C EC 0C
0x3C-F	FC 0C FC 0C

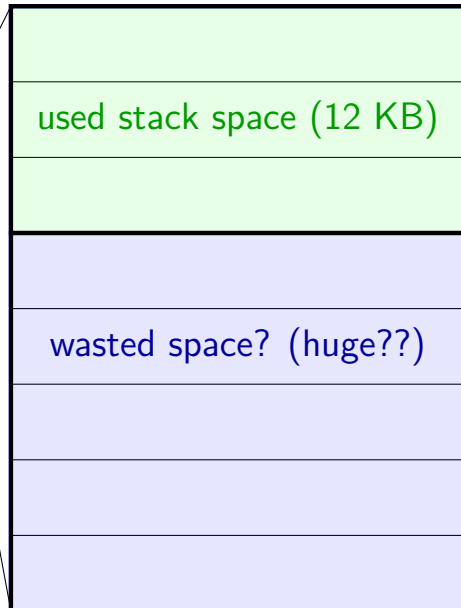
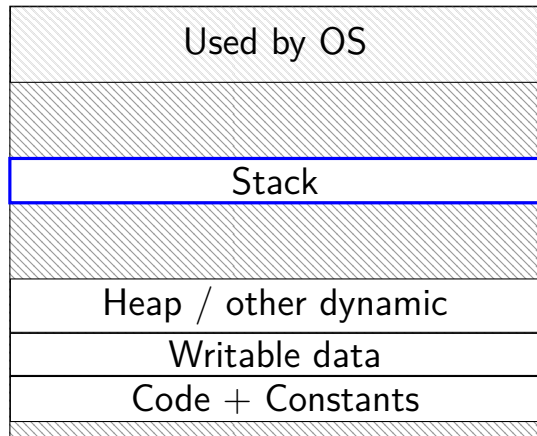
space on demand

Program Memory



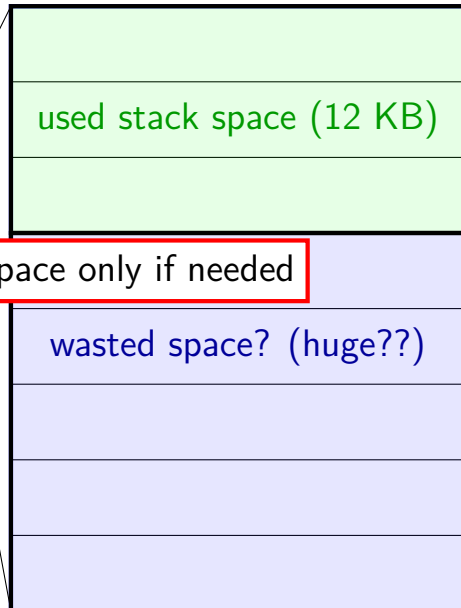
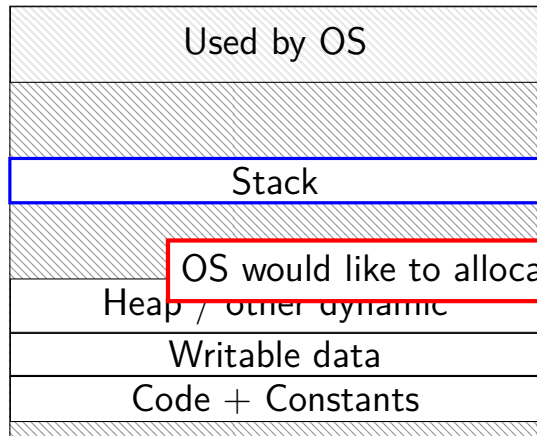
space on demand

Program Memory



space on demand

Program Memory



OS would like to allocate space only if needed

allocating space on demand

%rsp = 0x7FFFC000

```
...  
// requires more stack space  
A: pushq %rbx  
  
B: movq 8(%rcx), %rbx  
C: addq %rbx, %rax  
...
```

VPN

```
...  
0x7FFFB  
0x7FFFC  
0x7FFFD  
0x7FFFE  
0x7FFFF  
...
```

valid? physical
page

valid?	physical page
...	...
0	---
1	0x200DF
1	0x12340
1	0x12347
1	0x12345
...	...

allocating space on demand

%rsp = 0x7FFFC000

```
...  
// requires more stack space  
A: pushq %rbx  
   → page fault!  
B: movq 8(%rcx), %rbx  
C: addq %rbx, %rax  
...
```

VPN

```
...  
0x7FFFB  
0x7FFFC  
0x7FFFD  
0x7FFFE  
0x7FFFF  
...
```

valid? physical
page

valid?	physical page
...	...
0	---
1	0x200DF
1	0x12340
1	0x12347
1	0x12345
...	...

pushq triggers exception
hardware says “accessing address 0x7FFBFF8”
OS looks up what’s should be there — “stack”

allocating space on demand

%rsp = 0x7FFFC000

```
...  
// requires more stack space  
A: pushq %rbx restarted  
B: movq 8(%rcx), %rbx  
C: addq %rbx, %rax  
...
```

VPN	valid?	physical page
...
0x7FFFB	1	0x200D8
0x7FFFC	1	0x200DF
0x7FFFD	1	0x12340
0x7FFFE	1	0x12347
0x7FFFF	1	0x12345
...

in exception handler, OS allocates more stack space
OS updates the page table
then returns to retry the instruction

allocating space on demand

note: the space doesn't have to be initially empty

only change: load from file, etc. instead of allocating empty page

loading program can be merely creating empty page table

everything else can be handled in response to page faults

no time/space spent loading/allocating unneeded space

mmap

Linux/Unix has a function to “map” a file to memory

```
int file = open("somefile.dat", O_RDWR);
```

```
// data is region of memory that represents file  
char *data = mmap(..., file, 0);
```

```
// read byte 6 from somefile.dat  
char seventh_char = data[6];
```

```
// modifies byte 100 of somefile.dat  
data[100] = 'x';  
// can continue to use 'data' like an array
```


swapping almost mmap

access mapped file for first time, read from disk
(like swapping when memory was swapped out)

write “mapped” memory, write to disk eventually
(like writeback policy in swapping)
use “dirty” bit

extra detail: other processes should see changes
all accesses to file use **same physical memory**

Linux maps: list of maps

```
$ cat /proc/self/maps
```

```
00400000-0040b000 r-xp 00000000 08:01 48328831 /bin/cat
0060a000-0060b000 r--p 0000a000 08:01 48328831 /bin/cat
0060b000-0060c000 rw-p 0000b000 08:01 48328831 /bin/cat
01974000-01995000 rw-p 00000000 00:00 0 [heap]
```

```
7f60c718b000-7f60c7490000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7f60c7490000-7f60c7490000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7f60c764e000-7f60c764e000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7f60c784e000-7f60c784e000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7f60c7852000-7f60c7852000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7f60c7854000-7f60c7854000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7f60c7859000-7f60c7859000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7f60c7a39000-7f60c7a39000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7f60c7a7a000-7f60c7a7a000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
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```
7f60c7a7b000-7f60c7a7b000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
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7f60c7a7c000-7f60c7a7c000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7f60c7a7d000-7f60c7a7d000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7ffc5d2b2000-7ffc5d2b2000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7ffc5d3b0000-7ffc5d3b0000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
7ffc5d3b3000-7ffc5d3b3000 r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

```
ffffffffffff-ffffffffffff r--p 00000000 08:01 77483660 /usr/lib/locale/locale-archive
```

OS tracks list of struct `vm_area_struct` with:
(shown in this output):

virtual address start, end

permissions

offset in backing file (if any)

pointer to backing file (if any)

(not shown):

info about sharing of non-file data ...

page tricks generally

deliberately make program trigger page/protection fault

but don't assume page/protection fault is an error

have separate data structures represent logically allocated memory

e.g. “addresses 0x7FFF8000 to 0x7FFFFFFF are the stack”

page table is for the hardware and not the OS

hardware help for page table tricks

information about the address causing the fault

- e.g. special register with memory address accessed

- harder alternative: OS disassembles instruction, look at registers

(by default) rerun faulting instruction when returning from exception

precise exceptions: no side effects from faulting instruction or after

- e.g. `pushq` that caused did not change `%rsp` before fault

- e.g. instructions reordered after faulting instruction not visible

swapping

early motivation for virtual memory: **swapping**

using disk (or SSD, ...) as the next level of the memory hierarchy
how our textbook and many other sources presents virtual memory

OS allocates **program space on disk**
own mapping of virtual addresses to location on disk

DRAM is a cache for disk

swapping

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DRAM is a cache for disk

swapping versus caching

“cache block” \approx physical page

fully associative

every virtual page can be stored in any physical page

replacement/cache misses managed by the OS

normal cache hits happen in hardware

hardware's page table lookup

common case that needs to be very fast

swapping components

“swap in” a page — exactly like allocating on demand!

- OS gets page fault — invalid in page table
- check where page actually is (from virtual address)
- read from disk
- eventually restart process

“swap out” a page

- OS marks as invalid in the page table(s)
- copy to disk (if modified)

HDD/SDDs are slow

HDD reads and writes: milliseconds to tens of milliseconds

- minimum size: 512 bytes

- writing tens of kilobytes basically as fast as writing 512 bytes

SSD reads and writes: hundreds of microseconds

- designed for reads/writes of kilobytes (not much smaller)

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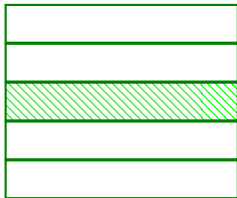
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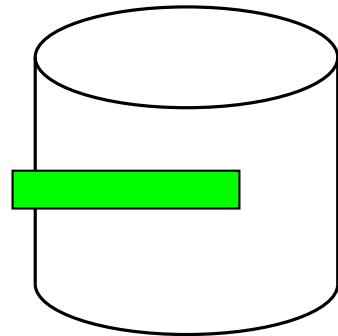
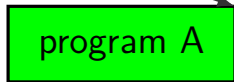
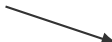
swapping timeline

program A pages



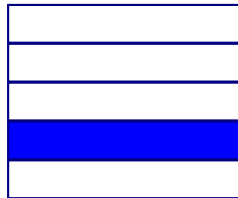
...

page fault



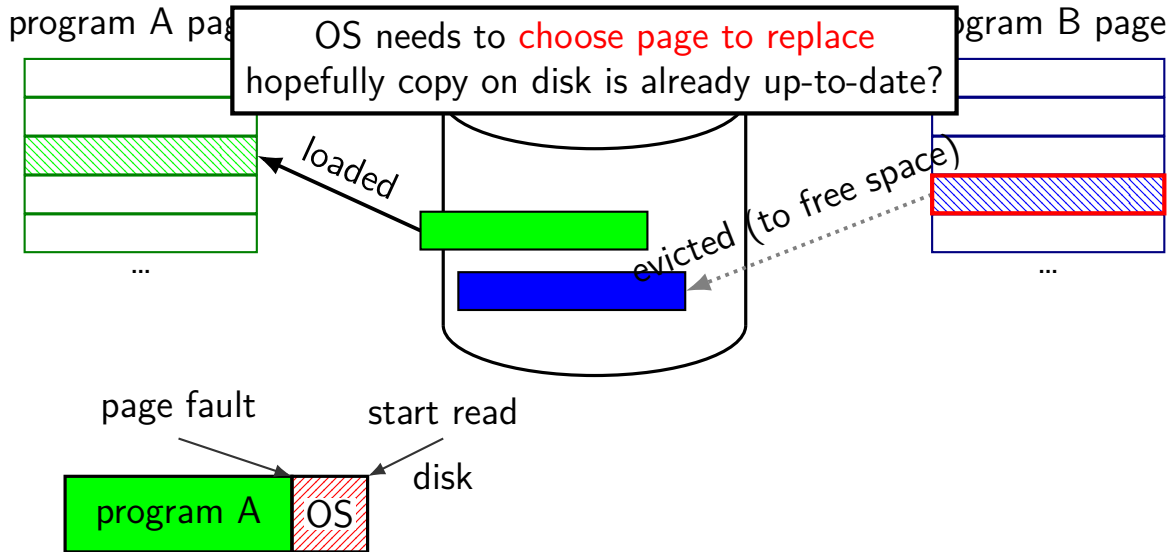
disk

program B page

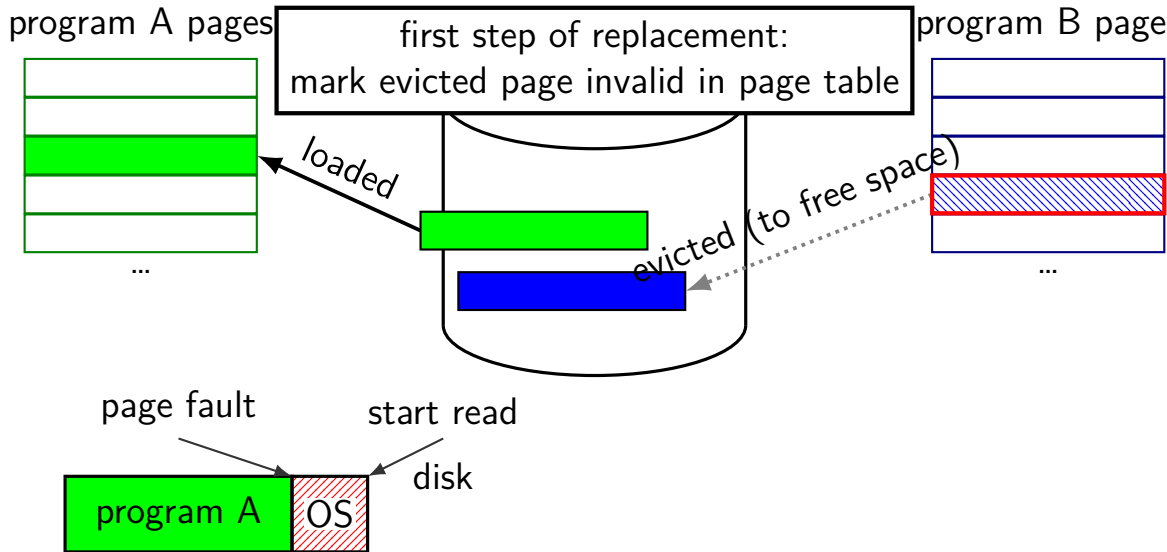


...

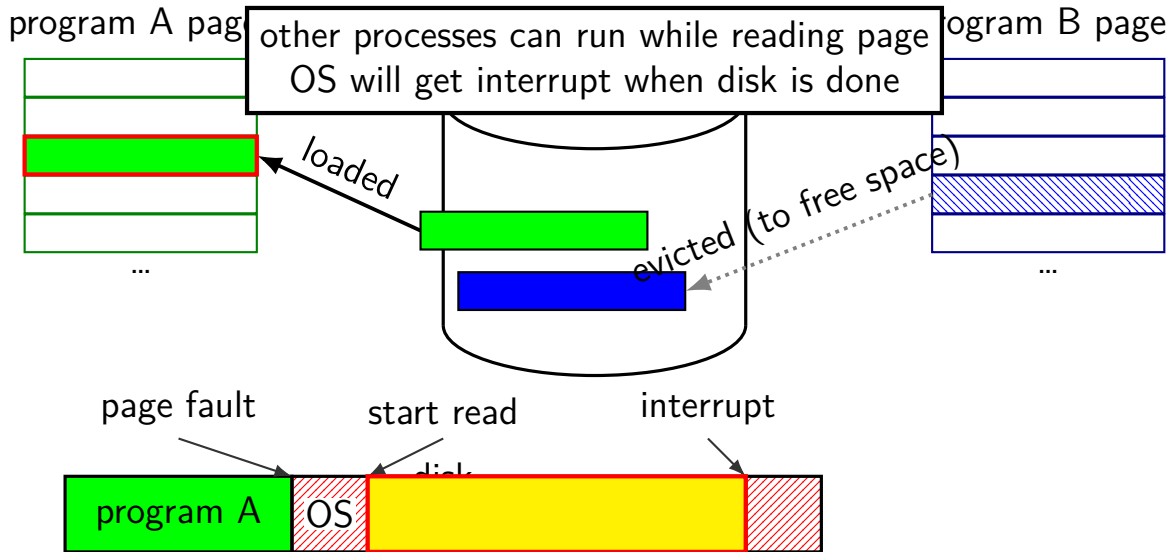
swapping timeline



swapping timeline

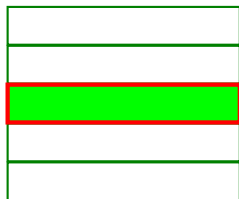


swapping timeline



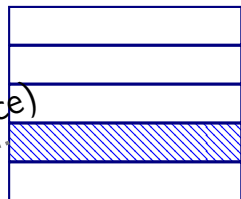
swapping timeline

program A pages



process A's page table updated
and restarted from point of fault

program B page



loaded

evicted (to free space)

page fault

start read

interrupt



fast copies

Unix mechanism for starting a new process: `fork()`

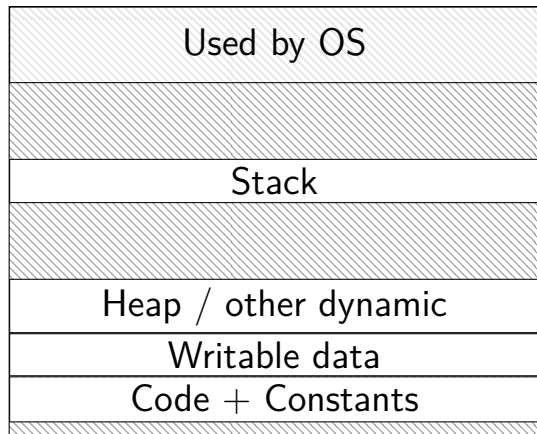
creates a **copy** of an entire program!

(usually, the copy then calls `execve` — replaces itself with another program)

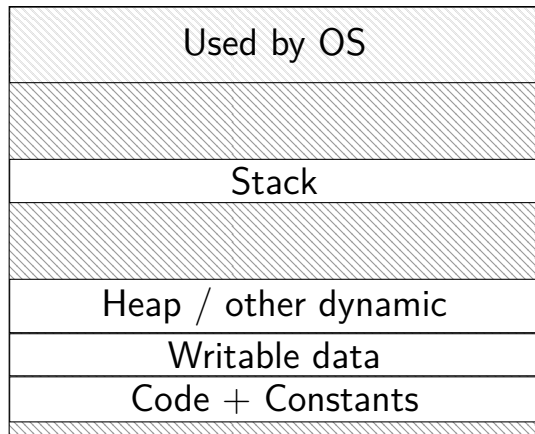
how isn't this really slow?

do we really need a complete copy?

bash

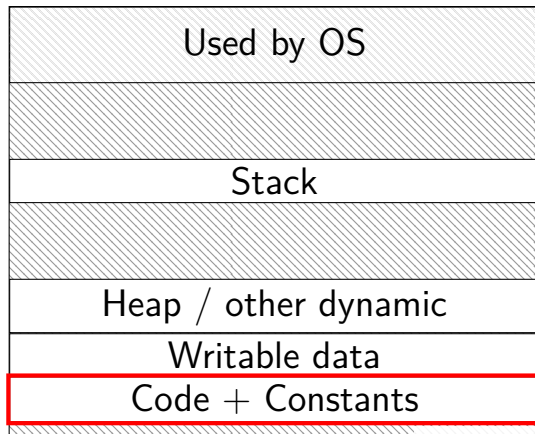


new copy of bash

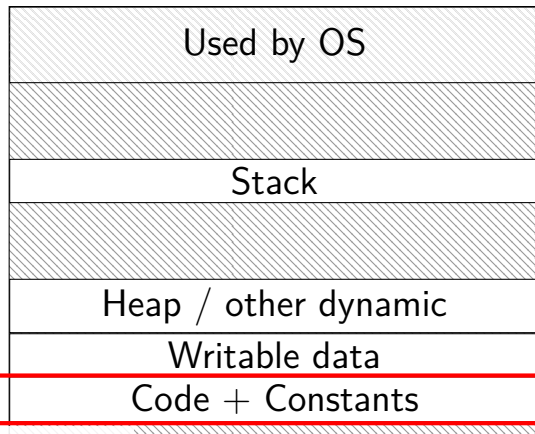


do we really need a complete copy?

bash



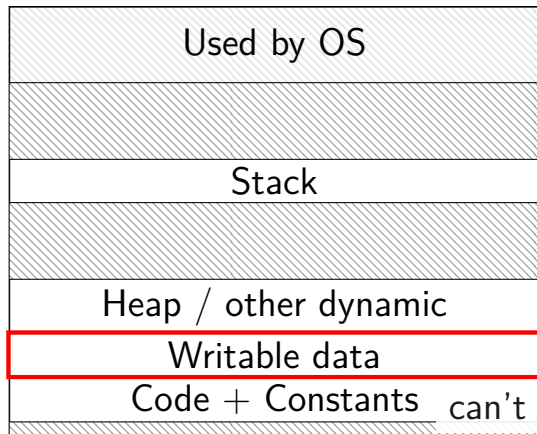
new copy of bash



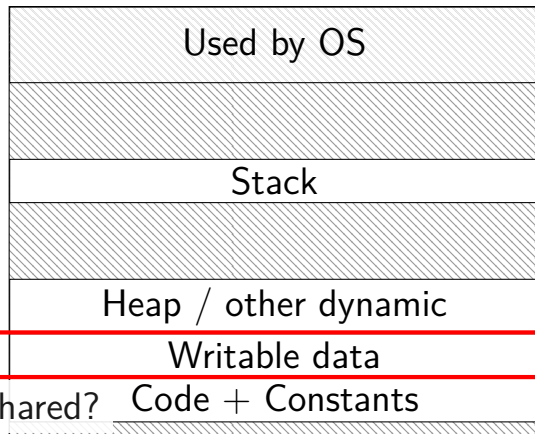
shared as read-only

do we really need a complete copy?

bash



new copy of bash



can't be shared?

trick for extra sharing

sharing writeable data is fine — until either process modifies the copy

can we detect modifications?

trick: tell CPU (via page table) shared part is read-only

processor will trigger a fault when it's written

copy-on-write and page tables

VPN	valid?	write?	physical page
...
0x00601	1	1	0x12345
0x00602	1	1	0x12347
0x00603	1	1	0x12340
0x00604	1	1	0x200DF
0x00605	1	1	0x200AF
...

copy-on-write and page tables

VPN	valid?	write?	physical page
...
0x00601	1	0	0x12345
0x00602	1	0	0x12347
0x00603	1	0	0x12340
0x00604	1	0	0x200DF
0x00605	1	0	0x200AF
...

VPN	valid?	write?	physical page
...
0x00601	1	0	0x12345
0x00602	1	0	0x12347
0x00603	1	0	0x12340
0x00604	1	0	0x200DF
0x00605	1	0	0x200AF
...

copy operation actually duplicates page table
both processes **share all physical pages**
but marks pages in **both copies as read-only**

copy-on-write and page tables

VPN	valid?	write?	physical page
...
0x00601	1	0	0x12345
0x00602	1	0	0x12347
0x00603	1	0	0x12340
0x00604	1	0	0x200DF
0x00605	1	0	0x200AF
...

VPN	valid?	write?	physical page
...
0x00601	1	0	0x12345
0x00602	1	0	0x12347
0x00603	1	0	0x12340
0x00604	1	0	0x200DF
0x00605	1	0	0x200AF
...

when either process tries to write read-only page
triggers a fault — OS actually copies the page

copy-on-write and page tables

VPN	valid?	write?	physical page
...
0x00601	1	0	0x12345
0x00602	1	0	0x12347
0x00603	1	0	0x12340
0x00604	1	0	0x200DF
0x00605	1	0	0x200AF
...

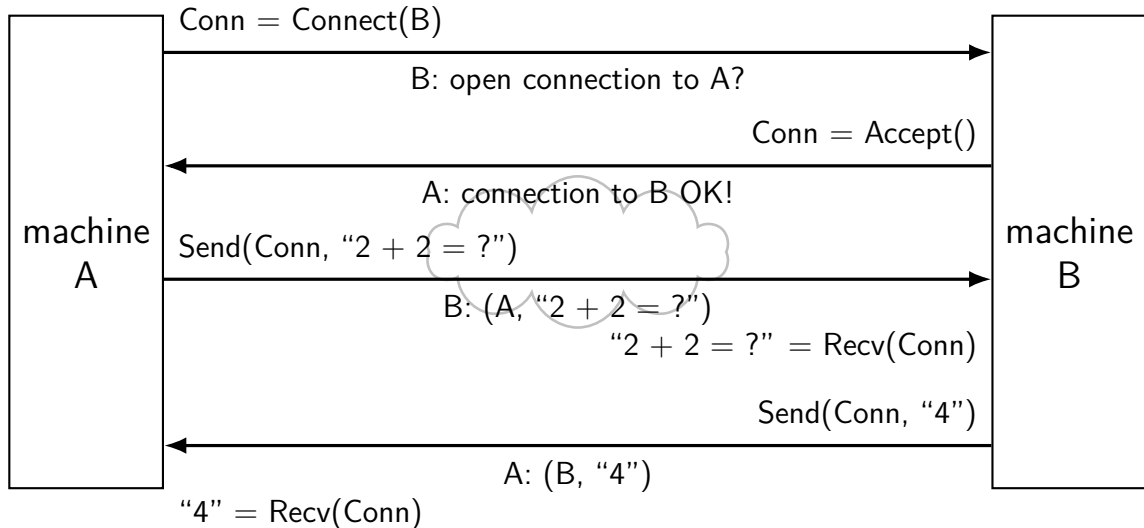
VPN	valid?	write?	physical page
...
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0x00602	1	0	0x12347
0x00603	1	0	0x12340
0x00604	1	0	0x200DF
0x00605	1	1	0x300FD
...

after allocating a copy, OS reruns the write instruction

connections

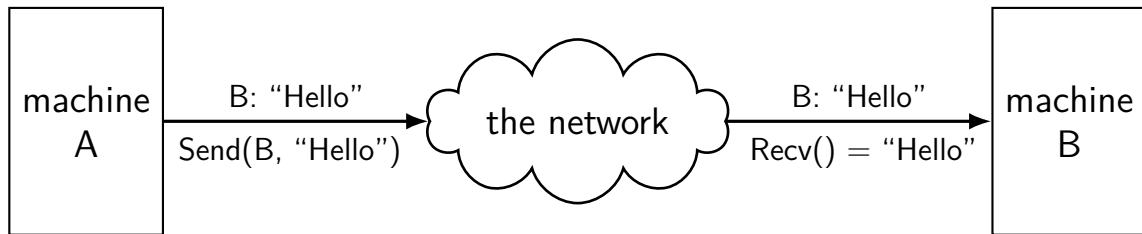
connections: two-way channel for messages

extra operations: connect, accept



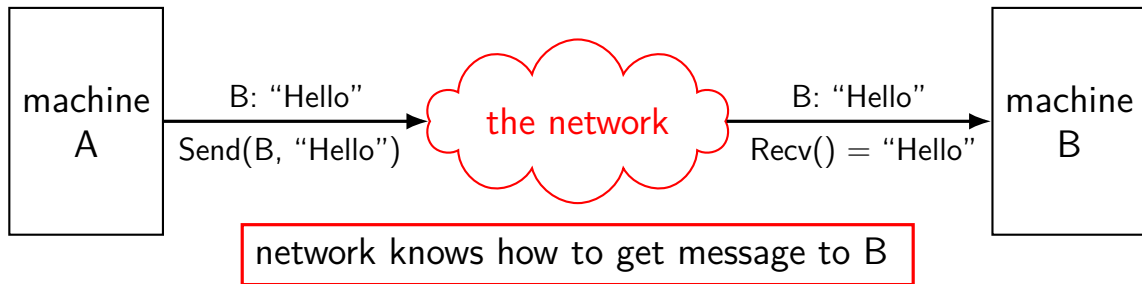
mailbox model

mailbox abstraction: send/receive messages



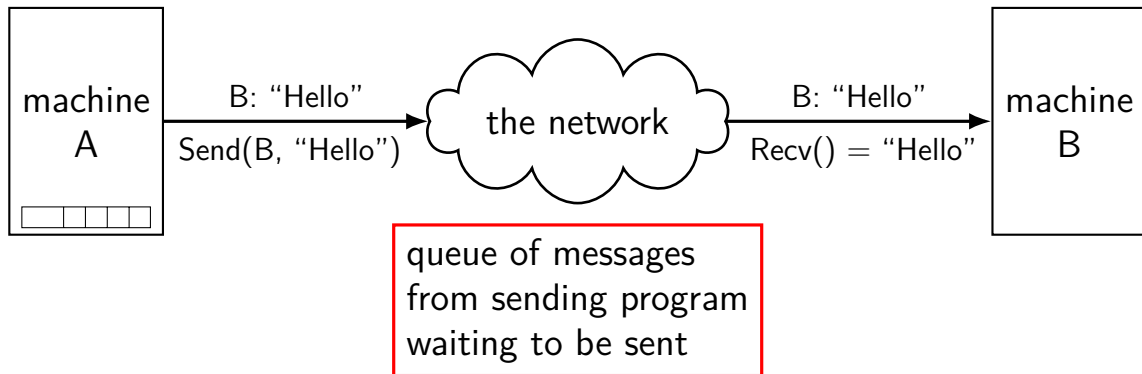
mailbox model

mailbox abstraction: send/receive messages



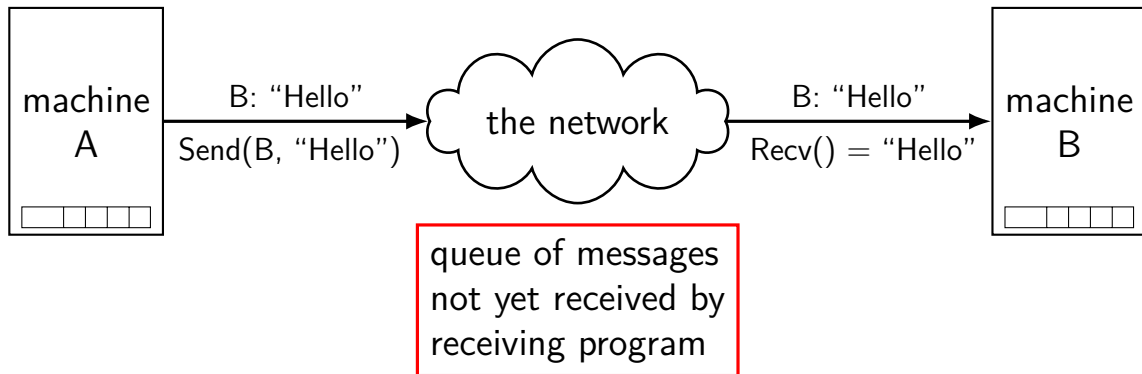
mailbox model

mailbox abstraction: send/receive messages



mailbox model

mailbox abstraction: send/receive messages



connections over mailboxes

real Internet: mailbox-style communication

- send packets to particular mailboxes

- no guarantee on order, when received

sockets implemented on top of this

recall: sockets

open connection then ...

read+write just like a terminal file

doesn't look like individual messages

“connection abstraction”

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	...	encode bits for wire/radio

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physical	...	encode bits for wire/radio

network limitations/failures

messages lost

messages delayed/reordered

messages limited in size

messages corrupted

network limitations/failures

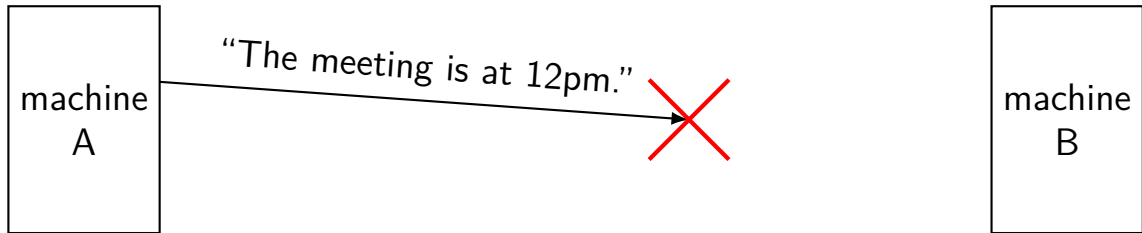
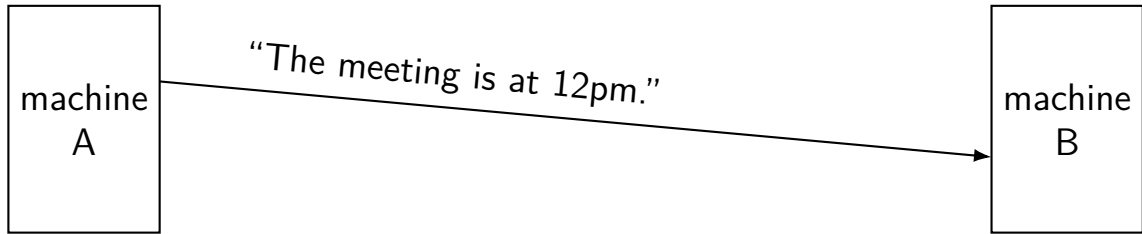
messages lost

messages delayed/reordered

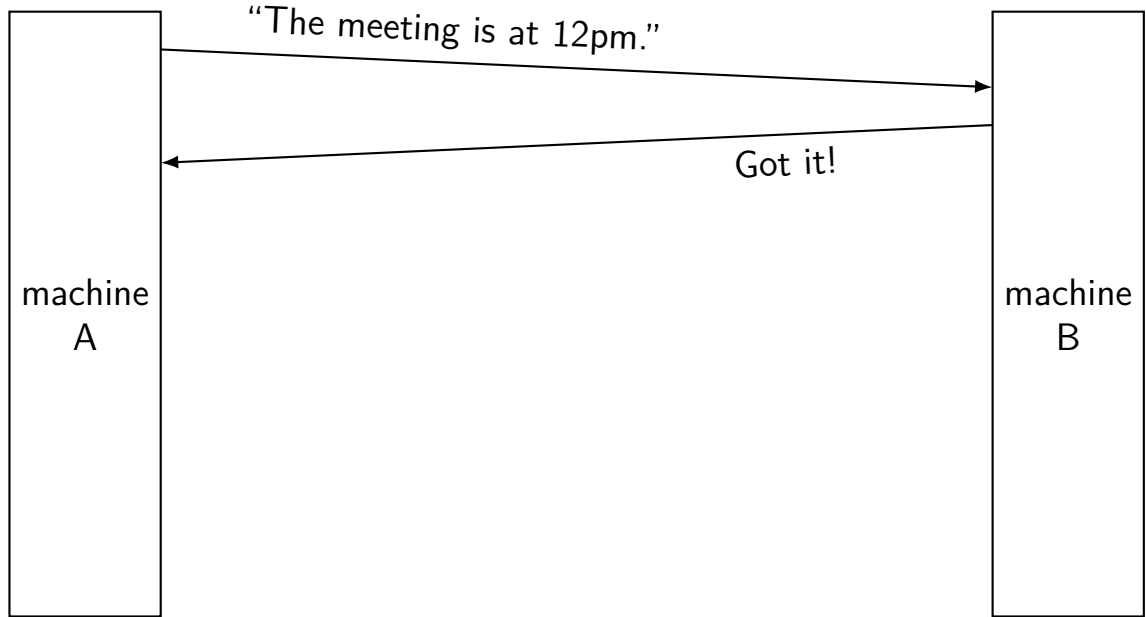
messages limited in size

messages corrupted

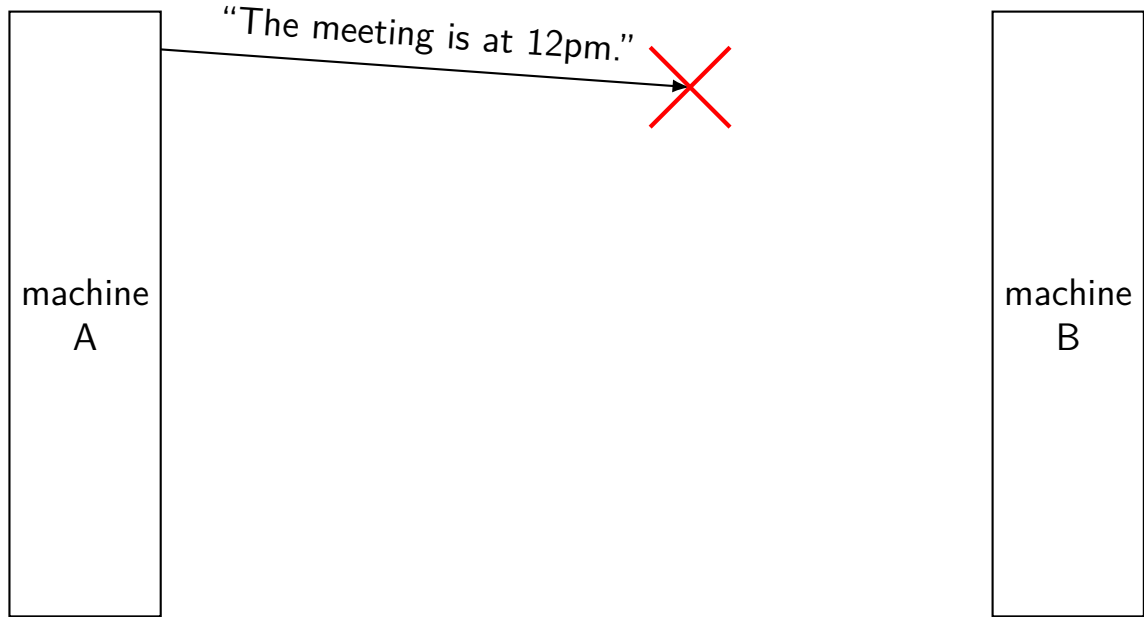
dealing with network message lost



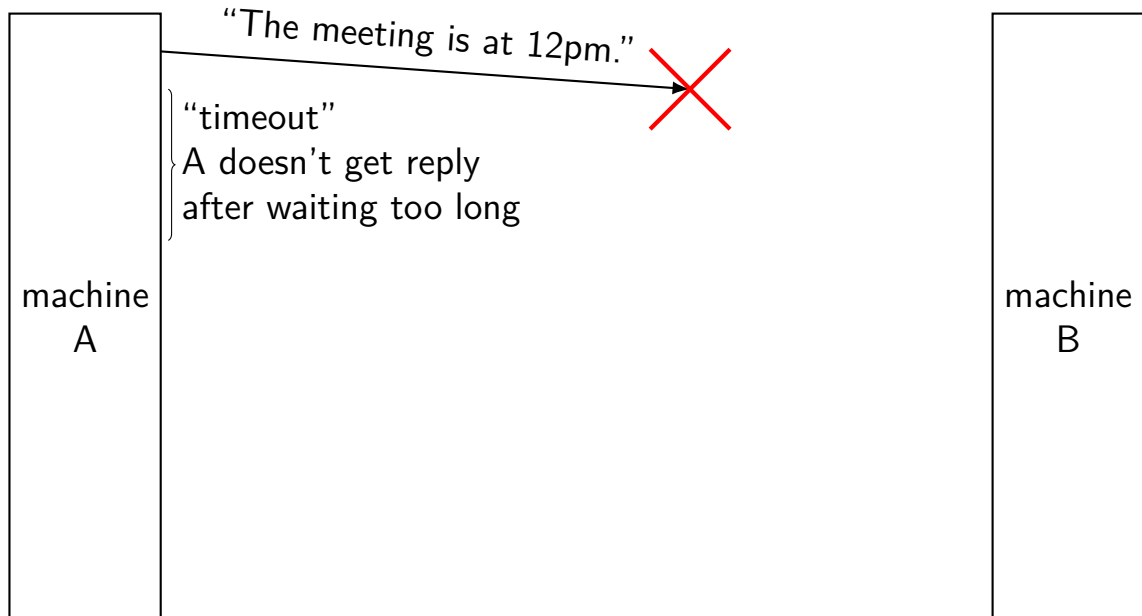
handling lost message: acknowledgements



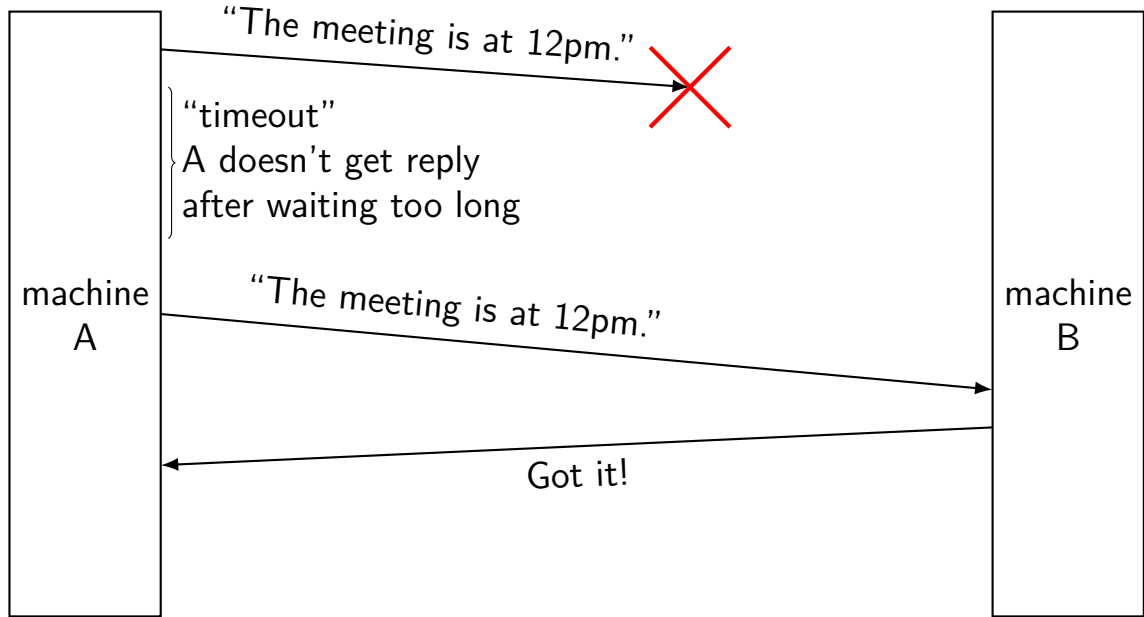
handling lost message



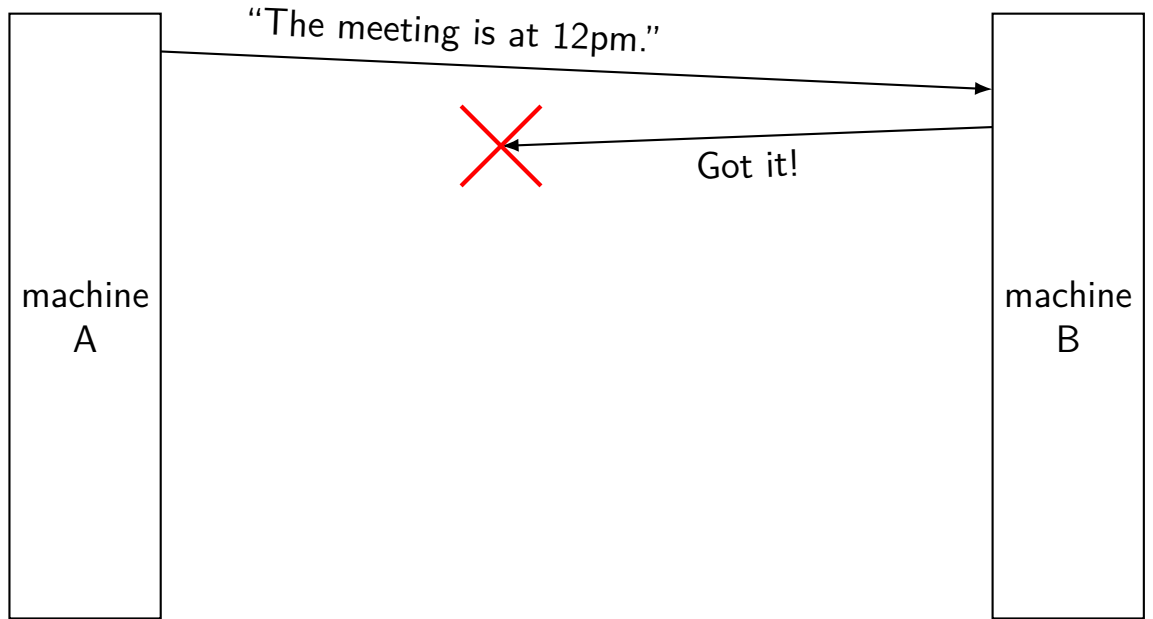
handling lost message



handling lost message

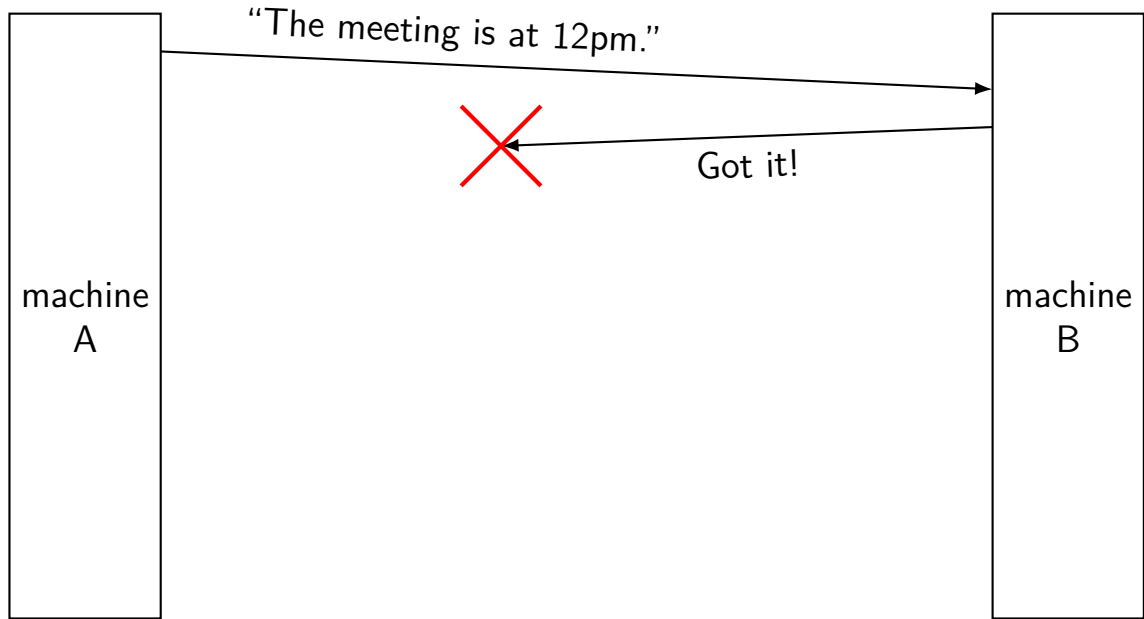


exercise: lost acknowledgement

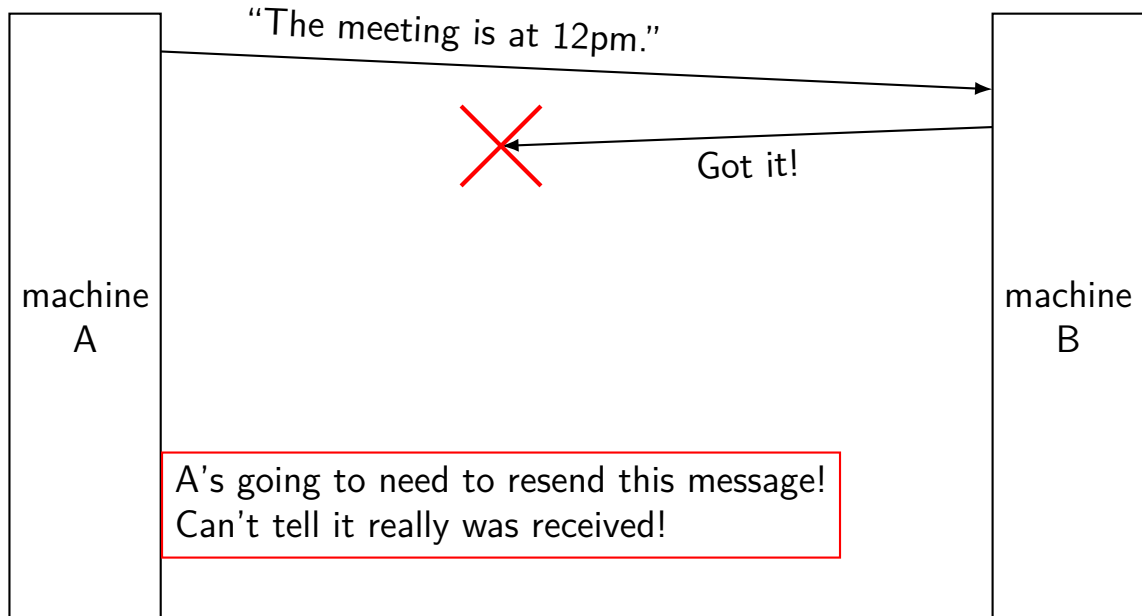


exercise: how to fix this?

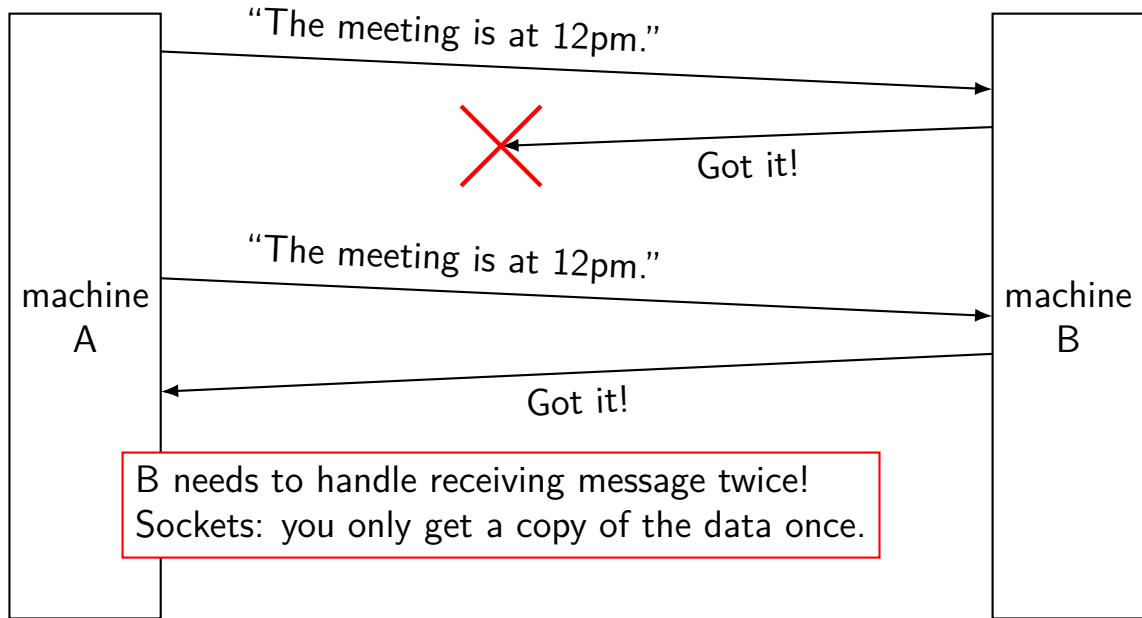
lost acknowledgements



lost acknowledgements



lost acknowledgements



network limitations/failures

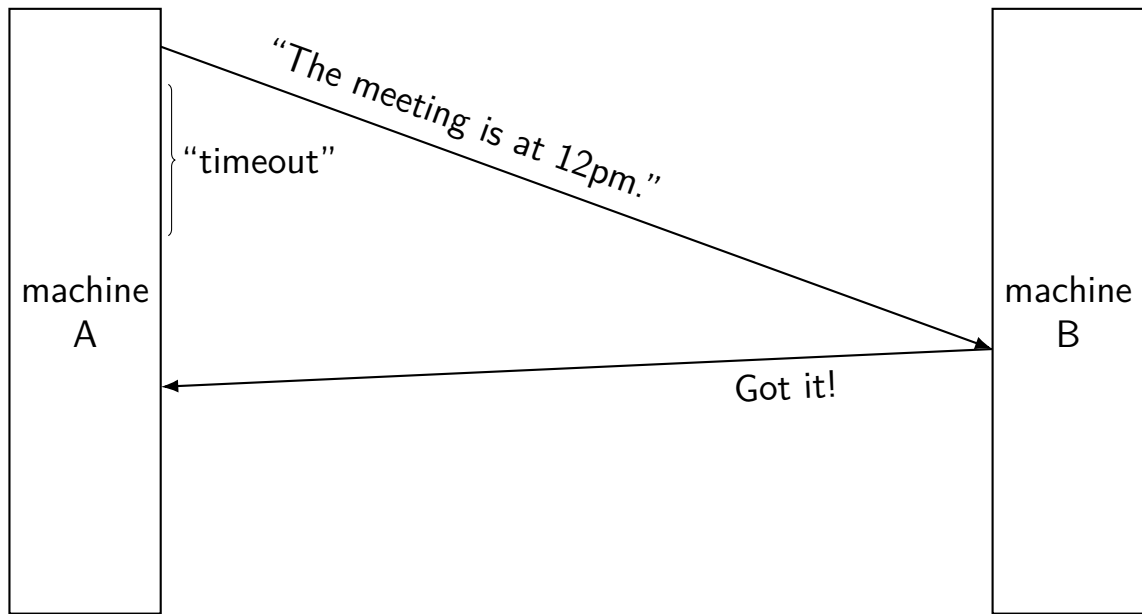
messages lost

messages delayed/reordered

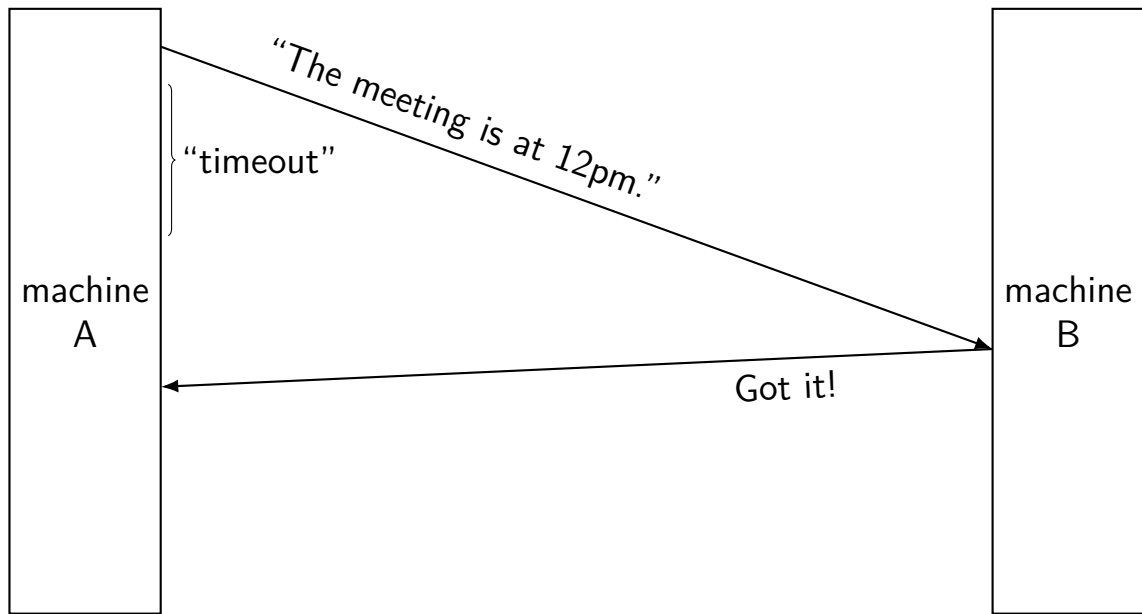
messages limited in size

messages corrupted

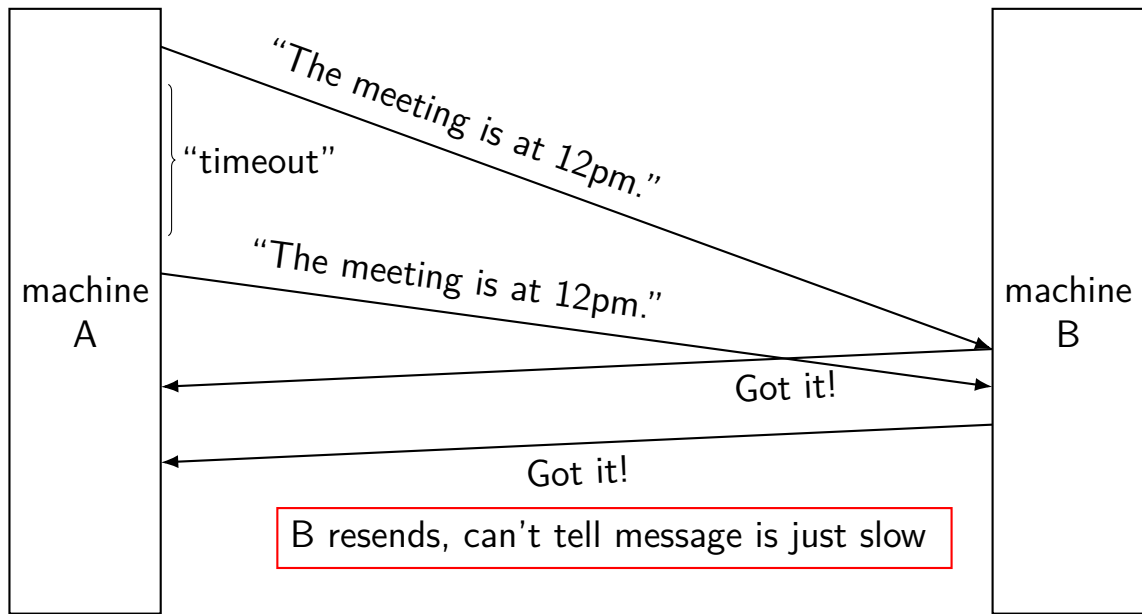
delayed message



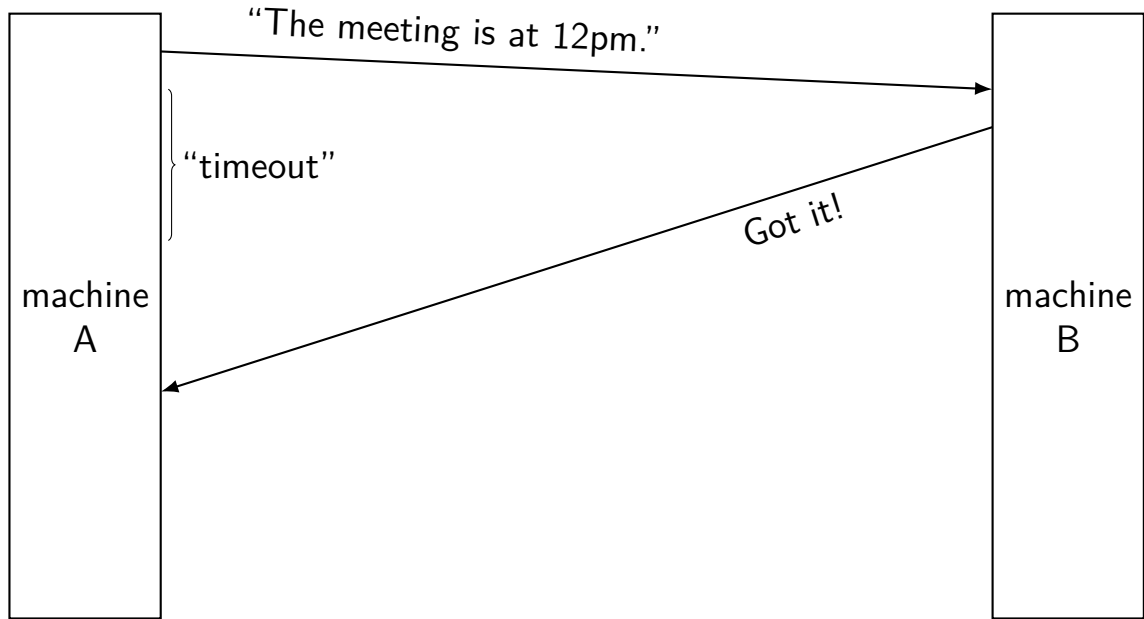
delayed message



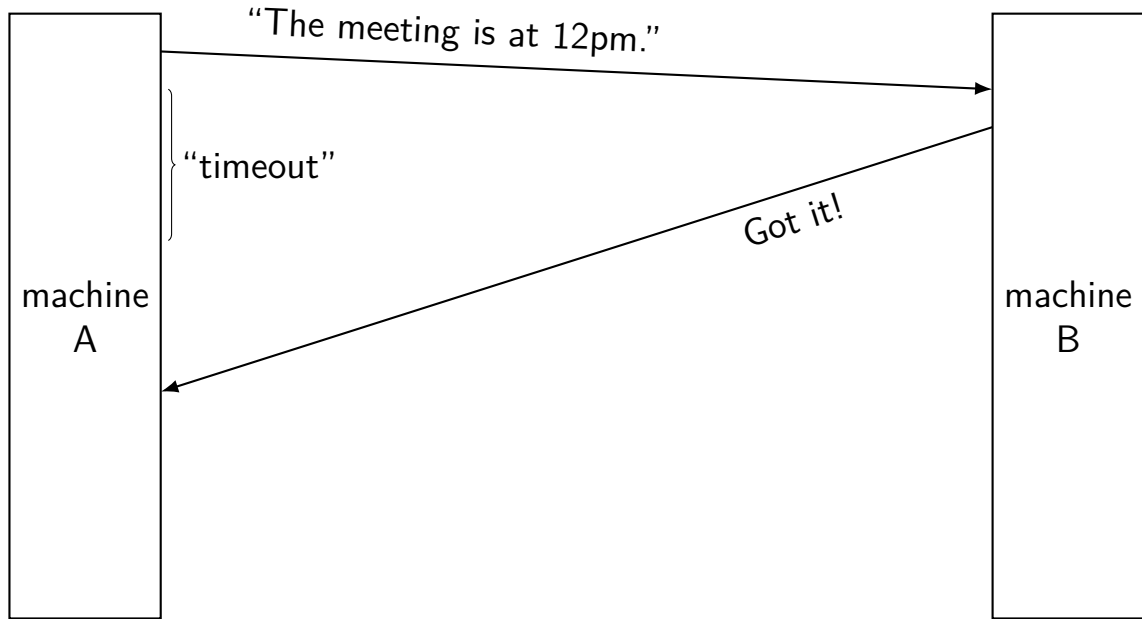
delayed message



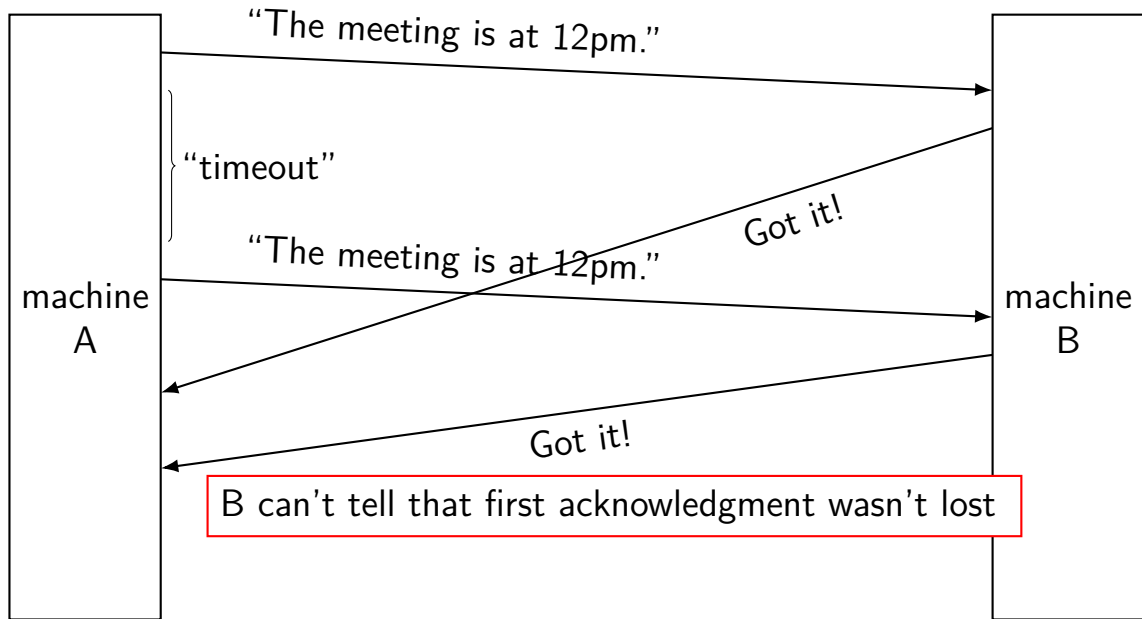
delayed acknowledgements



delayed acknowledgements



delayed acknowledgements



network limitations/failures

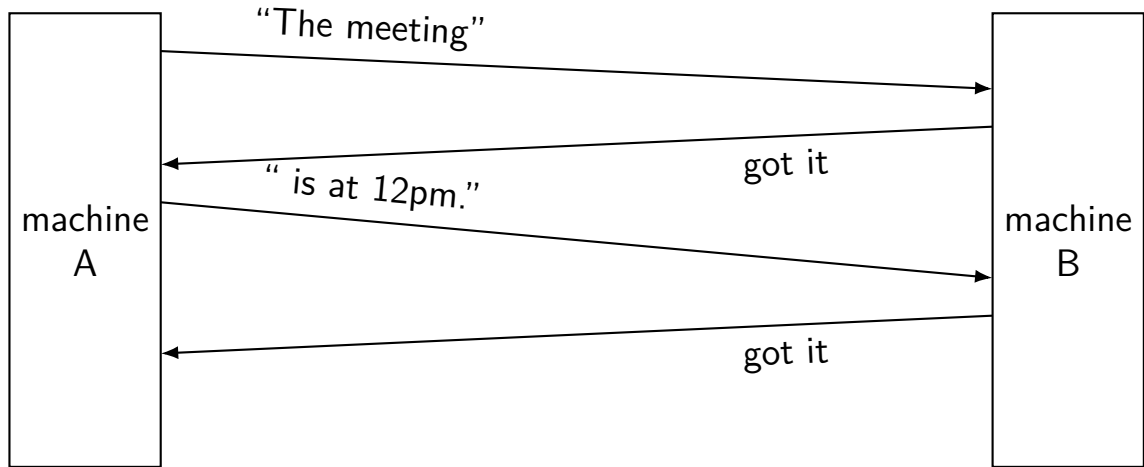
messages lost

messages delayed/reordered

messages limited in size

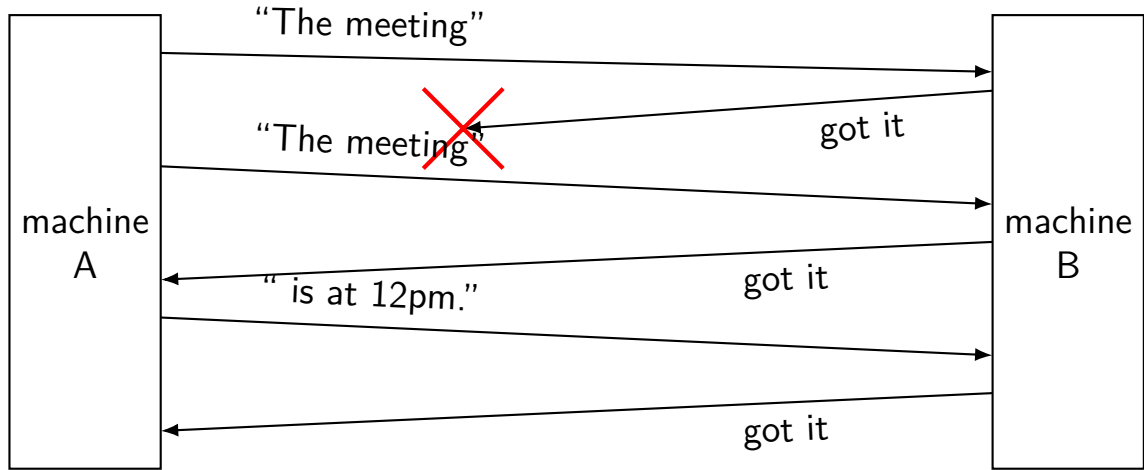
messages corrupted

splitting messages: try 1

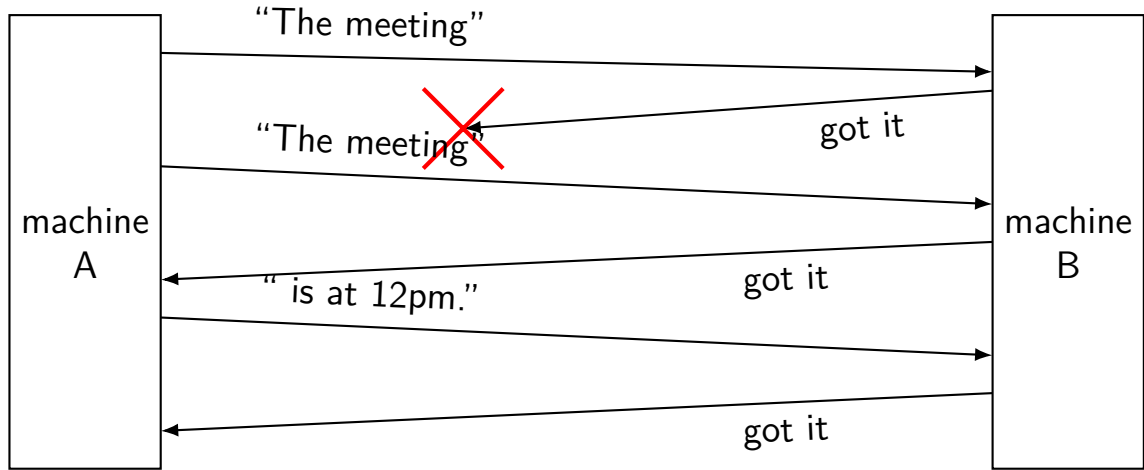


reconstructed message:
The meeting is at 12pm.

splitting messages: try 1 — problem 1



splitting messages: try 1 — problem 1



reconstructed message:

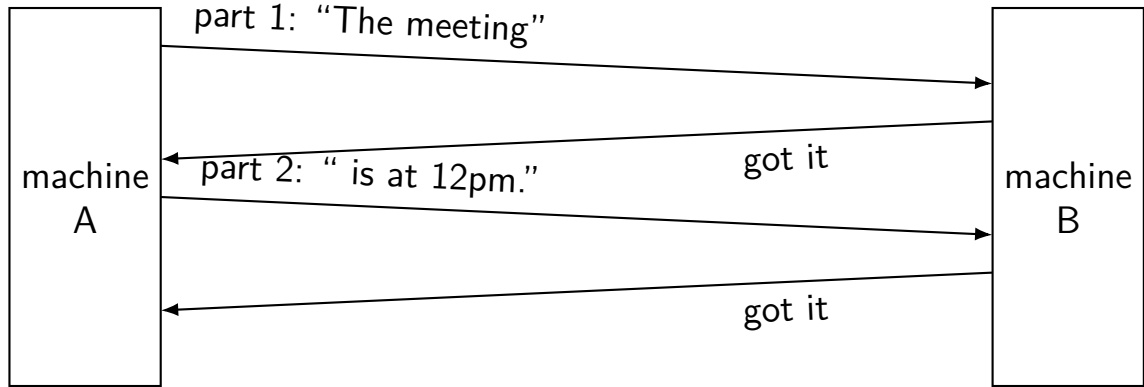
The meetingThe meeting is at 12pm.

exercise: other problems?

other scenarios where we'd also have problems?

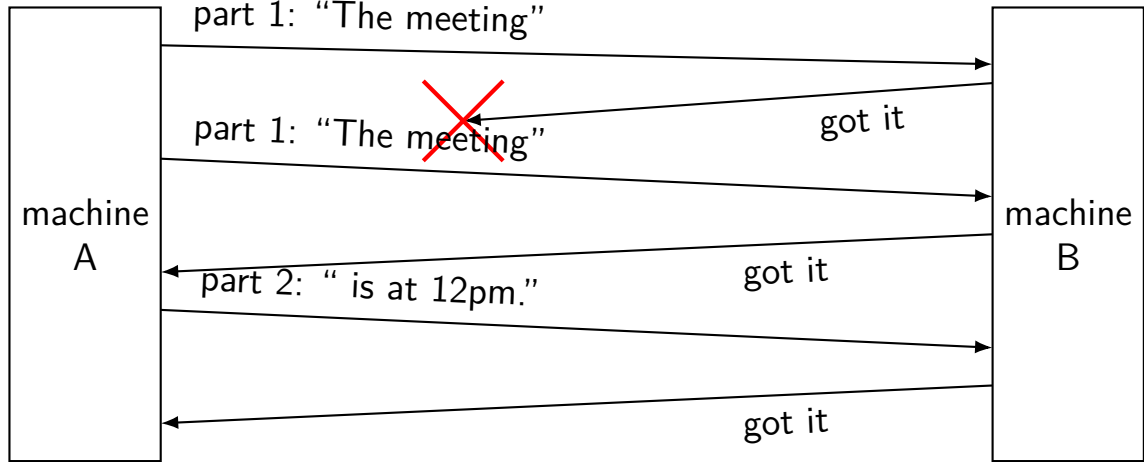
- A. message (instead of acknowledgment) is lost
- B. first message from A is delayed a long time by network
- C. acknowledgment of second message lost instead of first

splitting messages: try 2



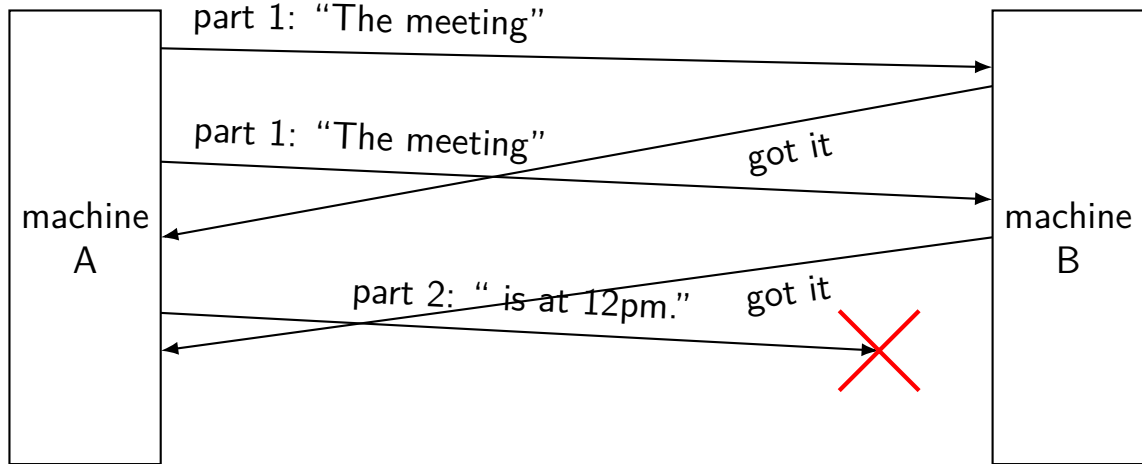
reconstructed message:
The meeting is at 12pm.

splitting messages: try 2 — missed ack



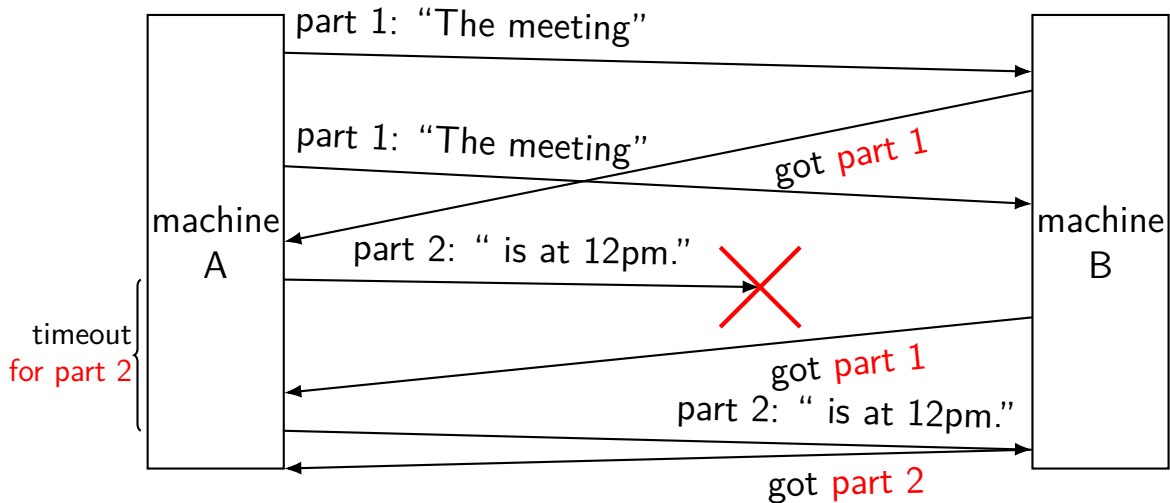
reconstructed message:
The meeting is at 12pm.

splitting messages: try 2 — problem



A thinks: part 1 + part 2 acknowledged!

splitting messages: version 3



network limitations/failures

messages lost

messages delayed/reordered

messages limited in size

messages corrupted

message corrupted

instead of sending “message”

say $\text{Hash}(\text{“message”}) = 0x\text{ABCDEF12}$

then send “0xABCDEF12,message”

when receiving, recompute hash

pretend message lost if does not match

“checksum”

these hashes commonly called “checksums”

in UDP/TCP, produced by adding message parts together (with wraparound)

going faster

so far: send one message, get acknowledgments

pretty slow

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

need to do *congestion control* to avoid overloading network

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	...	encode bits for wire/radio

more than four layers?

sometimes more layers above 'application'

e.g. HTTPS:

HTTP (app layer) on TLS (another app layer) on TCP (network) on ...

e.g. DNS over HTTPS:

DNS (app layer) on HTTP on on TLS on TCP on ...

e.g. SFTP:

SFTP (app layer??) on SSH (another app layer) on TCP on ...

e.g. HTTP over OpenVPN:

HTTP on TCP on IP on OpenVPN on UDP on different IP on ...

names and addresses

name	address
logical identifier	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
DNS name reiss-t3620.cs.virginia.edu	IPv4 address 128.143.67.91
DNS name reiss-t3620.cs.virginia.edu	MAC address 18:66:da:2e:7f
service name https	port number 443
service name ssh	port number 22

layers

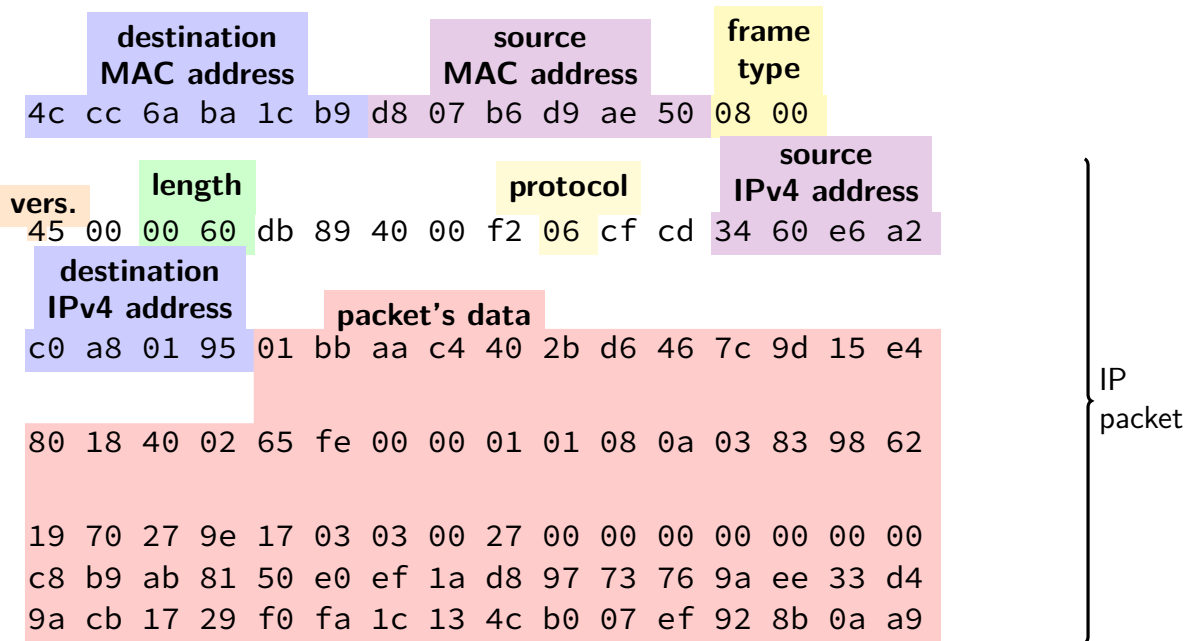
application	HTTP, SSH, SMTP, ...	application-defined meanings
transport	TCP, UDP, ...	reach correct program, reliability/streams
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link	Ethernet, Wi-Fi, ...	coordinate shared wire/radio
physical	...	encode bits for wire/radio

an Ethernet frame

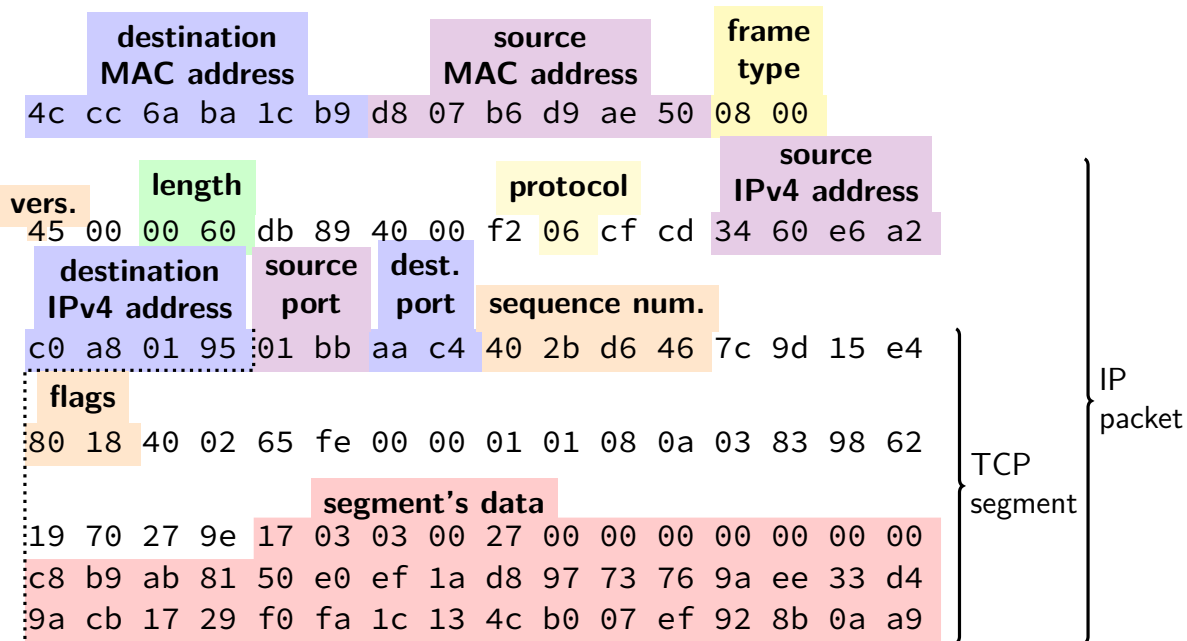
destination MAC address						source MAC address						frame type	
4c	cc	6a	ba	1c	b9	d8	07	b6	d9	ae	50	08	00

frame's data															
45	00	00	60	db	89	40	00	f2	06	cf	cd	34	60	e6	a2
c0	a8	01	95	01	bb	aa	c4	40	2b	d6	46	7c	9d	15	e4
80	18	40	02	65	fe	00	00	01	01	08	0a	03	83	98	62
19	70	27	9e	17	03	03	00	27	00	00	00	00	00	00	00
c8	b9	ab	81	50	e0	ef	1a	d8	97	73	76	9a	ee	33	d4
9a	cb	17	29	f0	fa	1c	13	4c	b0	07	ef	92	8b	0a	a9

an Ethernet frame



an Ethernet frame



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”

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?

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	...	encode bits for wire/radio

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 usually called “packets”

network layer quality of service

if packet ...

event

on IPv4/v6

collides with another

out of scope — handled by link layer

not received

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

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

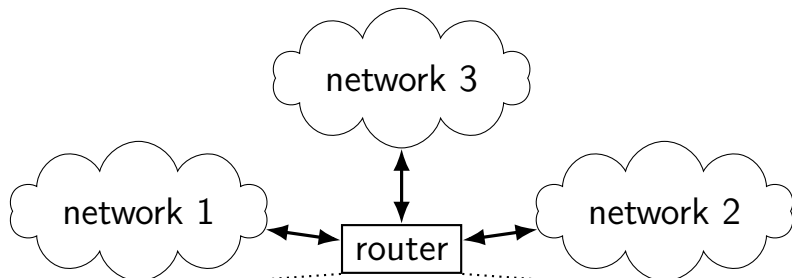
usually dropped with notice

too much being sent

discard excess

includes dropped by link layer
(e.g. if detected corrupted there)

IPv4 addresses and routing tables



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

layers

application	HTTP, SSH, SMTP, ...	application-defined meanings
transport	TCP, UDP, ...	reach correct program, reliability/streams
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physical	...	encode bits for wire/radio

port numbers

we run multiple programs on a machine

IP addresses identifying machine — not enough

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

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

UDP v TCP

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

- get assigned port number

- SOCK_DGRAM with `socket()` instead of `SOCK_STREAM`

- can `sendto()`/`recvfrom()` multiple other programs with one socket

 - (but don't have to)

- send messages which are limited in size, unreliable

TCP: stream to other program

- need to `bind()` + `listen()` + `accept()` or `connect()` to setup connection

- one socket per connection

- read/write bytes — divided into messages automatically

- reliable — acknowledgments/resending handled for you

connections in TCP/IP

connection identified by *5-tuple*

used by OS to lookup “where is the socket?”

(protocol=TCP/UDP, local IP addr., local port, remote IP addr., 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

connections on my desktop

```
cr4bd@reiss-t3620>/u/cr4bd
```

```
$ netstat --inet --inet6 --numeric
```

```
Active Internet connections (w/o servers)
```

Proto	Recv-Q	Send-Q	Local Address	Foreign Address	State
tcp	0	0	128.143.67.91:49202	128.143.63.34:22	ESTABLISHED
tcp	0	0	128.143.67.91:803	128.143.67.236:2049	ESTABLISHED
tcp	0	0	128.143.67.91:50292	128.143.67.226:22	TIME_WAIT
tcp	0	0	128.143.67.91:54722	128.143.67.236:2049	TIME_WAIT
tcp	0	0	128.143.67.91:52002	128.143.67.236:111	TIME_WAIT
tcp	0	0	128.143.67.91:732	128.143.67.236:63439	TIME_WAIT
tcp	0	0	128.143.67.91:40664	128.143.67.236:2049	TIME_WAIT
tcp	0	0	128.143.67.91:54098	128.143.67.236:111	TIME_WAIT
tcp	0	0	128.143.67.91:49302	128.143.67.236:63439	TIME_WAIT
tcp	0	0	128.143.67.91:50236	128.143.67.236:111	TIME_WAIT
tcp	0	0	128.143.67.91:22	172.27.98.20:49566	ESTABLISHED
tcp	0	0	128.143.67.91:51000	128.143.67.236:111	TIME_WAIT
tcp	0	0	127.0.0.1:50438	127.0.0.1:631	ESTABLISHED
tcp	0	0	127.0.0.1:631	127.0.0.1:50438	ESTABLISHED

non-connection sockets

TCP servers waiting for connections +
UDP sockets with no particular remote host

Linux: OS keeps 5-tuple with “wildcard” remote address

“listening” sockets on my desktop

```
cr4bd@reiss-t3620>/u/cr4bd
```

```
$ netstat --inet --inet6 --numeric --listen
```

```
Active Internet connections (only servers)
```

Proto	Recv-Q	Send-Q	Local Address	Foreign Address	State
tcp	0	0	127.0.0.1:38537	0.0.0.0:*	LISTEN
tcp	0	0	127.0.0.1:36777	0.0.0.0:*	LISTEN
tcp	0	0	0.0.0.0:41099	0.0.0.0:*	LISTEN
tcp	0	0	0.0.0.0:45291	0.0.0.0:*	LISTEN
tcp	0	0	127.0.0.1:51949	0.0.0.0:*	LISTEN
tcp	0	0	127.0.0.1:41071	0.0.0.0:*	LISTEN
tcp	0	0	0.0.0.0:111	0.0.0.0:*	LISTEN
tcp	0	0	127.0.0.1:32881	0.0.0.0:*	LISTEN
tcp	0	0	127.0.0.1:38673	0.0.0.0:*	LISTEN
....					
tcp6	0	0	:::42689	:::*	LISTEN
udp	0	0	128.143.67.91:60001	0.0.0.0:*	
udp	0	0	128.143.67.91:60002	0.0.0.0:*	
...					
udp6	0	0	:::59938	:::*	

URL / URIs

Uniform Resource Locators (URL)

tells how to find “resource” on network

Uniform Resource 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`

URI generally

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

`scheme`: — what protocol

`//authority/`

`authorirty` = `user@host:port` OR `host:port` OR `user@host` OR `host`

`path`

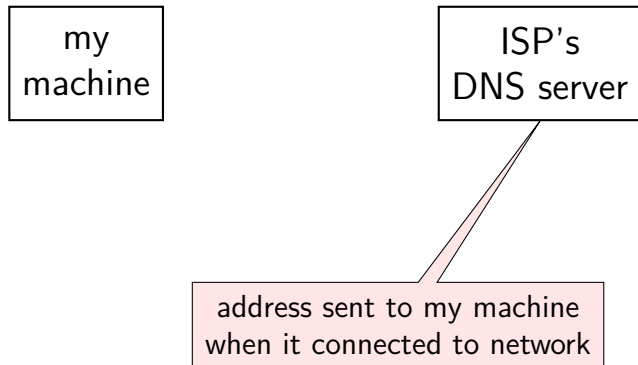
which resource

`?query` — usually key/value pairs

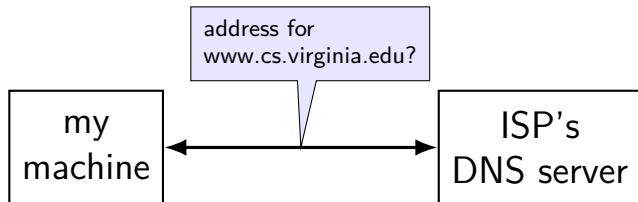
`#fragment` — place in resource

most components (sometimes) optional

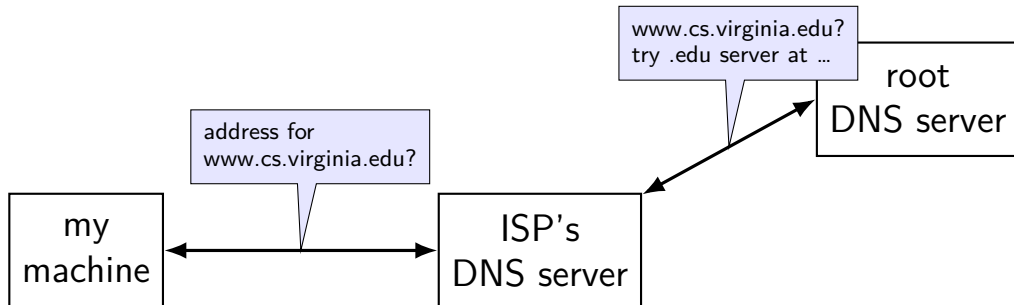
DNS: distributed database



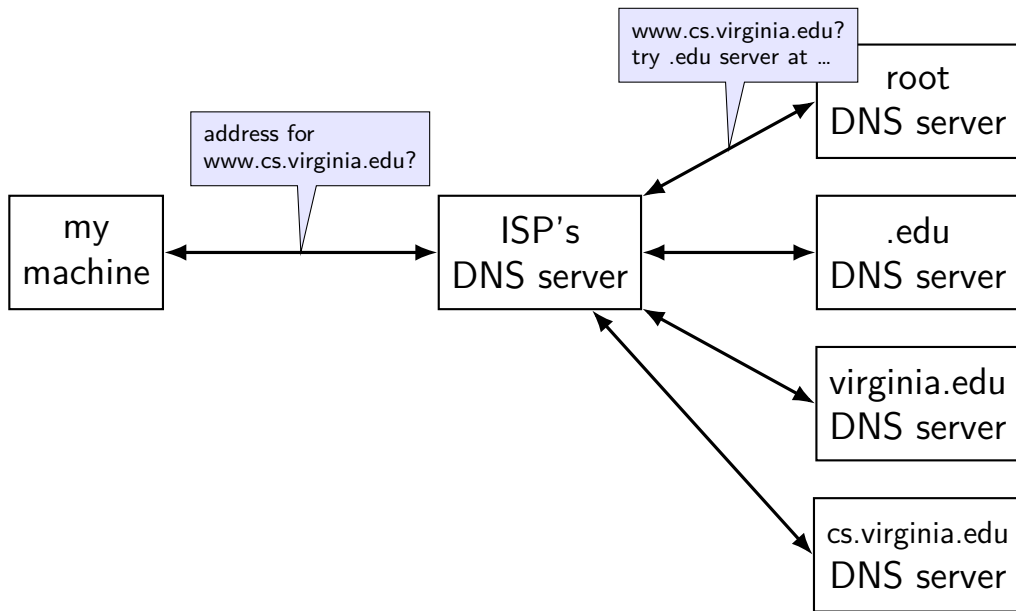
DNS: distributed database



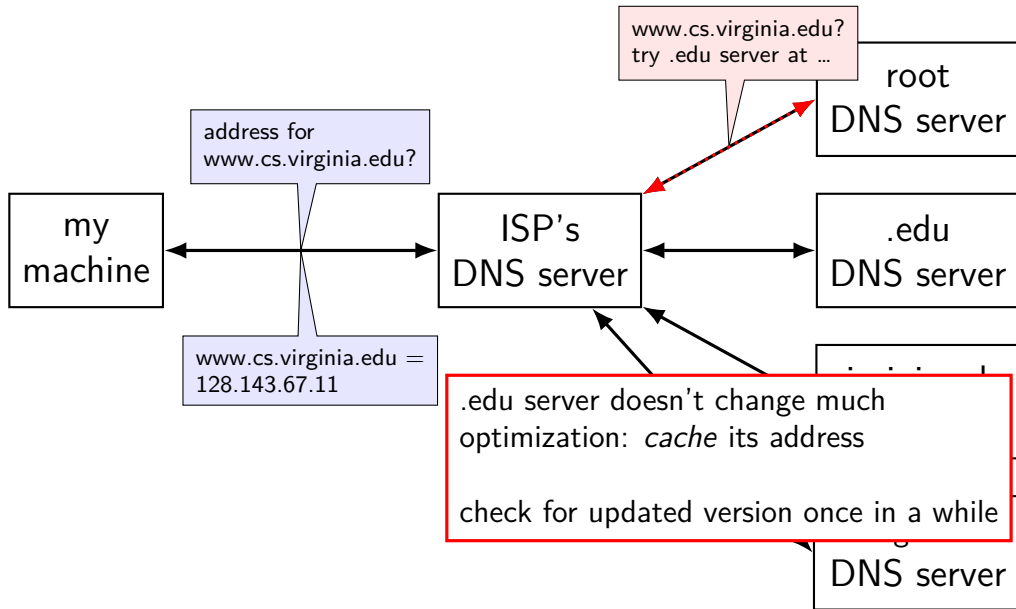
DNS: distributed database



DNS: distributed database



DNS: distributed database



autoconfiguration

problem: how does my machine get IP address

otherwise:

- have sysadmin type one in?

- just choose one?

- ask someone on local network to assign it

autoconfiguration

problem: how does my machine get IP address

otherwise:

- have sysadmin type one in?

- just choose one?

- ask someone on local network to assign it

DHCP high-level

protocol done over UDP

but since we don't have IP address yet, use 0.0.0.0

and since we don't know server address, use 255.255.255.255
= “everyone on the local network”

local server replies to request with address + time limit

backup slides

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

```
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, 10);
```

INADDR_ANY: accept connections for any address I can!

alternative: specify specific address

```
int server_socket_fd =
```

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, 10);
int
```

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, 10); /* choose the number of unaccepted connections */
...
int socket_fd = accept(server_socket_fd, NULL);
```

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

```
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 */
    // ...
}
// specify IPv4 instead of IPv6 or local-only sockets
// specify TCP (byte-oriented) instead of UDP ('datagram' oriented)
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

```
int sock_fd;

server = /* code */
sock_fd = socket(
    AF_INET, /*
    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

```
int sock_fd;
```

```
server = / struct representing IPv4 address + port number  
sock_fd = declared in <netinet/in.h>  
          AF_INET see man 7 ip on Linux for docs  
          SOCK_STREAM  
          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);
```

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;
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; /* hostname could also be NULL
                               means "use all possible addresses"
                               only makes sense for servers */
rv = getaddrinfo(hostname, portname, &hints, &server);
if (rv != 0) {
```

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 = 0;

rv = getaddrinfo(hostname, portname, &hints, NULL);
if (rv != 0) {
```

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 = "127.0.0.1";
...
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, addrinfo

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

```
int server_socket_fd = socket(  
    server->ai_family,  
    server->ai_socktype,  
    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_protocol,
    // 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_protocol,  
    // addrinfo contains all information needed to setup socket  
    // set by getaddrinfo function (next slide)  
);  
if (sock_fd < 0) {  
    if (errno == EAI_ADDRFAMILY) {  
        /* handles IPv4 and IPv6 */  
    }  
    /* handles DNS names, service names */  
}  
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_protocol,  
    // 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;  
  
sock_fd = socket(server->ai_family, server->ai_socktype,  
server->ai_protocol);  
// ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...  
server->ai_socktype,  
// ai_socktype = SOCK_STREAM (bytes) or ...  
server->ai_protocol  
// 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;
```

```
st
```

```
so
```

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

```
    // ai_family = AF_INET (IPv4) or AF_INET6 (IPv6) or ...
    server->ai_socktype,
    // ai_socktype = SOCK_STREAM (bytes) or ...
    server->ai_protocol
    // 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: 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_socktype = AF_INET; /* for TCP or UDP */
NB: pass pointer to pointer to addrinfo to fill in
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
...
struct
struct
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: 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);  
}  
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 = 'administrator user' = what sudo does

so, for testing: probably ports > 1023