opening a file?

`open("/u/creiss/private.txt", O_RDONLY)`

say, private file on portal

on Linux: makes *system call*

kernel needs to decide if this should work or not

how does OS decide this?

argument: needs extra metadata

what would be wrong using...

system call arguments?

where the code calling open came from?

authorization v authentication

authentication — who is who

authorization v authentication

authentication — who is who

authorization — who can do what

probably need authentication first...

authentication

password

hardware token

...

user IDs

most common way OSes identify what *domain* process belongs to:

(unspecified for now) procedure sets user IDs

every process has a user ID

user ID used to decide what process is authorized to do

POSIX user IDs

```
uid_t geteuid(); // get current process's "effective" user ID
```

process's user identified with unique number

kernel typically only knows about number

effective user ID is used for all permission checks

also some other user IDs — we'll talk later

POSIX user IDs

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uid_t geteuid(); // get current process's "effective" user ID
```

process's user identified with unique number

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also some other user IDs — we'll talk later

standard programs/library maintain number to name mapping

- `/etc/passwd` on typical single-user systems
- network database on department machines

POSIX groups

```
gid_t getegid(void);
    // process's"effective" group ID

int getgroups(int size, gid_t list[]);
    // process's extra group IDs
```

POSIX also has *group IDs*

like user IDs: kernel only knows numbers

standard library+databases for mapping to names

also process has some other group IDs — we'll talk later

id

```
cr4bd@power4
: /net/zf14/cr4bd ; id
uid=858182(cr4bd) gid=21(csfaculty)
        groups=21(csfaculty),325(instructors),90027(cs4414)
```

id command displays uid, gid, group list

names looked up in database

- kernel doesn't know about this database
- code in the C standard library

groups that don't correspond to users

example: video group for access to monitor

put process in video group when logged in directly

don't do it when SSH'd in

groups that don't correspond to users

example: video group for access to monitor

put process in video group when logged in directly

don't do it when SSH'd in

...but: user can keep program running with video group in the background after logout?

POSIX file permissions

POSIX files have a very restricted access control list

one user ID + read/write/execute bits for user

"owner" — also can change permissions

one group ID + read/write/execute bits for group

default setting — read/write/execute

(see docs for chmod command)

POSIX/NTFS ACLs

more flexible access control lists

list of (user or group, read or write or execute or …)

supported by NTFS (Windows)

a version standardized by POSIX, but usually not supported

POSIX ACL syntax

```
# group students have read+execute permissions
group:students:r−x
# group faculty has read/write/execute permissions
group:faculty:rwx
# user mst3k has read/write/execute permissions
user:mst3k:rwx
# user tj1a has no permissions
user:tj1a:−−−

# POSIX acl rule:
    # user take precedence over group entries
```

authorization checking on Unix

checked on system call entry

- no relying on libraries, etc. to do checks

files (open, rename, …) — file/directory permissions

processes (kill, …) — process UID = user UID

…

keeping permissions?

which of the following would still be secure?

A. setting up a read-only page table entry that allows a process to directly access its user ID from its process control block in user mode

B. performing authorization checks in the standard library in addition to system call handlers

C. performing authorization checks in the standard library instead of system call handlers

D. making the user ID a system call argument rather than storing it in the process control block

superuser

user ID `0` is special

superuser or *root*

(non-Unix) or Administrator or SYSTEM or ...

some system calls: only work for uid `0`

shutdown, mount new file systems, etc.

automatically passes all (or almost all) permission checks

superuser v kernel mode

superuser : OS :: kernel mode : hardware

programs running as superuser still in user mode

- just change in how OS acts on system calls, etc.

how does login work?

```
somemachine login: jo
password: ********

jo@somemachine$ ls
...
```

this is a program which...

checks if the password is correct, and

changes user IDs, and

runs a shell

how does login work?

```
somemachine login: jo
password: ********

jo@somemachine$ ls
...
```

this is a program which...

checks if the password is correct, and

changes user IDs, and

runs a shell

Unix password storage

typical single-user system: `/etc/shadow`

- only readable by root/superuser

department machines: network service

- Kerberos / Active Directory:
- server takes (encrypted) passwords
- server gives tokens: “yes, really this user”
- can cryptographically verify tokens come from server

aside: beyond passwords

/bin/login entirely user-space code

only thing special about it: when it's run

could use any criteria to decide, not just passwords

- physical tokens
- biometrics
- ...

how does login work?

```
somemachine login: jo
password: ********

jo@somemachine$ ls
...
```

this is a program which...

checks if the password is correct, and

changes user IDs, and

runs a shell

changing user IDs

```
int setuid(uid_t uid);
```

if superuser: sets effective user ID to arbitrary value

- and a "real user ID" and a "saved set-user-ID" (we'll talk later)

system starts in/login programs run as superuser

- voluntarily restrict own access before running shell, etc.

sudo

```
tj1a@somemachine$ sudo restart
Password: *********
```

sudo: run command with superuser permissions

started by non-superuser

recall: inherits non-superuser UID

can't just call `setuid(0)`

set-user-ID sudo

extra metadata bit on *executables*: set-user-ID

if set: `exec()` syscall changes effective user ID to owner's ID

`sudo` program: owned by root, marked set-user-ID

marking setuid: `chmod u+s`

set-user ID gates

set-user ID program: gate to higher privilege

controlled access to extra functionality

make authorization/authentication decisions *outside the kernel*

way to allow normal users to do *one thing that needs privileges*

- write program that does that one thing — nothing else!
- make it owned by user that can do it (e.g. root)
- mark it set-user-ID

want to allow only some user to do the thing

- make program check which user ran it

uses for setuid programs

mount USB stick

- setuid program controls option to kernel mount syscall
- make sure user can't replace sensitive directories
- make sure user can't mess up filesystems on normal hard disks
- make sure user can't mount new setuid root files

control access to device — printer, monitor, etc.

- setuid program talks to device + decides who can

write to secure log file

- setuid program ensures that log is append-only for normal users

bind to a particular port number < 1024

- setuid program creates socket, then becomes not root

set-user-ID program v syscalls

hardware decision: some things only for kernel

system calls: *controlled* access to things kernel can do

decision about how can do it: in the kernel

kernel decision: some things only for root (or other user)

set-user-ID programs: controlled access to things root/... can do

decision about how can do it: made by root/...

privilege escalation

privilege escalation — vulnerabilities that allow more privileges

code execution/corruption in utilities that run with high privilege

- e.g. buffer overflow, command injection

- login, sudo, system services, …
- bugs in system call implementations

logic errors in checking delegated operations

a broken setuid program: setup

suppose I have a directory all-grades on shared server

in it I have a folder for each assignment

and within that a text file for each user's grade + other info

say I don't have flexible ACLs and want to give each user access

a broken setuid program: setup

suppose I have a directory all-grades on shared server

in it I have a folder for each assignment

and within that a text file for each user's grade + other info

say I don't have flexible ACLs and want to give each user access

one (bad?) idea: setuid program to read grade for assignment

`./print_grade assignment`

outputs grade from `all-grades/assignment/USER.txt`

a very broken setuid program

print_grade.c:

```
int main(int argc, char **argv) {
    char filename[500];
    sprintf(filename, "all-grades/%s/%s.txt",
            argv[1], getenv("USER"));
    int fd = open(filename, O_RDWR);
    char buffer[1024];
    read(fd, buffer, 1024);
    printf("%s: %s\n", argv[1], buffer);
}
```

HUGE amount of stuff can go wrong

examples?

another very broken setuid program (setup)

allow users to print files, but only if less than 1KB

another very broken setuid program

print_short_file.c:

```
int main(int argc, char **argv) {
    struct stat st;
    if (stat(argv[1], &st) == -1) abort();
    // make sure argv[1] is owned by user running this
    if (st.st_uid != getuid()) abort();
    // and that it's less than 1 KB
    if (st.st_size >= 1024) abort();
    char command[1024];
    sprintf(command, "print %1000s", argv[1]);
    system(command);
    return EXIT_SUCCESS;
}
```

set-user ID programs are very hard to write

what if stdin, stdout, stderr start closed?

what if signals setup weirldy?

what if the PATH env. var. set to directory of malicious programs?

what if `argc == 0`?

what if dynamic linker env. vars are set?

what if some bug allows memory corruption?

…

some security tasks (1)

helping students collaborate in ad-hoc small groups on shared server?

Q1: what to allow/prevent?

Q2: how to use POSIX mechanisms to do this?

some security tasks (2)

letting students assignment files to faculty on shared server?

Q1: what to allow/prevent?

Q2: how to use POSIX mechanisms to do this?

some security tasks (3)

running untrusted game program from Internet?

Q1: what to allow/prevent?

Q2: how to use POSIX mechanisms to do this?

backup slides

a delegation problem

consider printing program marked setuid to access printer

- decision: no accessing printer directly
- printing program enforces page limits, etc.

command line: file to print

can printing program just call open()?

a broken solution

```
if (original user can read file from argument) {
    open(file from argument);
    read contents of file;
    write contents of file to printer
    close(file from argument);
}
```

hope: this prevents users from printing files than can't read

problem: race condition!

a broken solution / why

setuid program	other user program
	create normal file `toprint.txt`
check: can user access? (yes)	—
	`unlink("toprint.txt")`
	`link("/secret", "toprint.txt"`
`open("toprint.txt")`	—
read ...	—

link: create new directory entry for file

- another option: rename, symlink ("symbolic link" — alias for file/directory)
- another possibility: run a program that creates secret file (e.g. temporary file used by password-changing program)

time-to-check-to-time-of-use vulnerability

TOCTTOU solution

temporarily ‘become’ original user

then open

then turn back into set-uid user

this is why POSIX processes have multiple user IDs

can swap out effective user ID temporarily

practical TOCTTOU races?

can use symlinks *maze* to make check slower

symlink `toprint.txt` → `a/b/c/d/e/f/g/normal.txt`
symlink `a/b` → `../a`
symlink `a/c` → `../a`
…

lots of time spent following symbolic links when program opening toprint.txt

gives more time to sneak in unlink/link or (more likely) rename

exercise

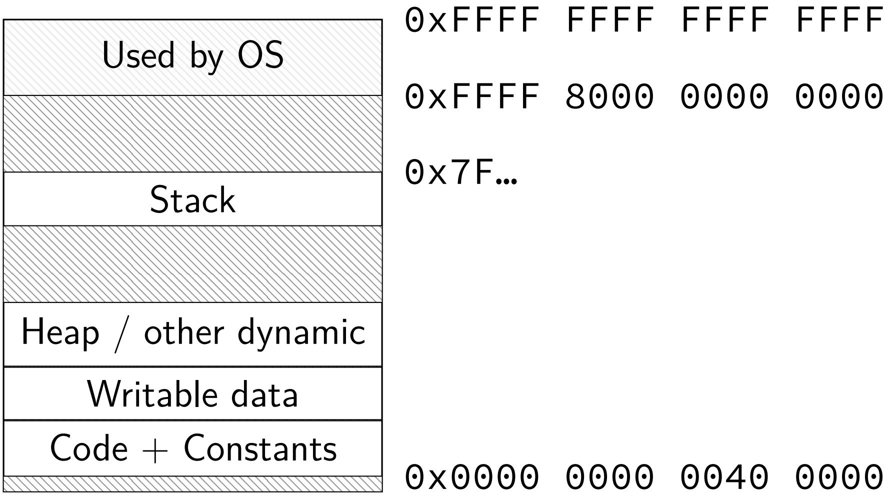
which (if any) of the following would fix for a TOCTTOU vulnerability in our setuid printing application? (assume the Unix-permissions without ACLs are in use)

[A] **both before and after** opening the path passed in for reading, check that the path is accessible to the user who ran our application

[B] after opening the path passed in for reading, using `fstat` with the file descriptor opened to check the permissions on the file

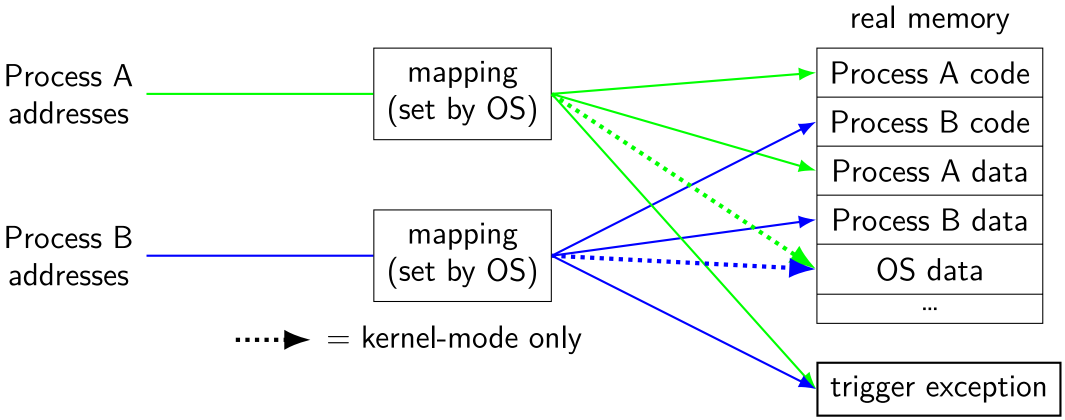
[C] before opening the path, verify that the user controls the file referred to by the path **and** the directory containing it

program memory



address spaces

illuision of dedicated memory



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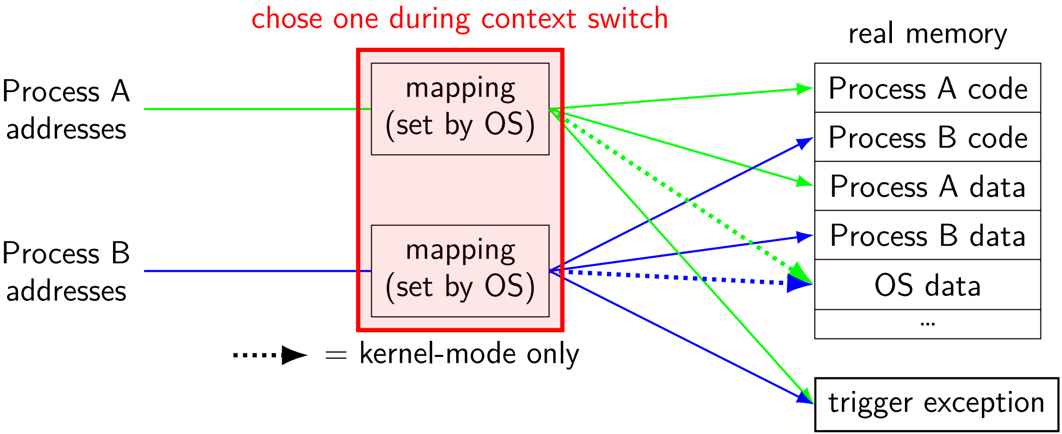
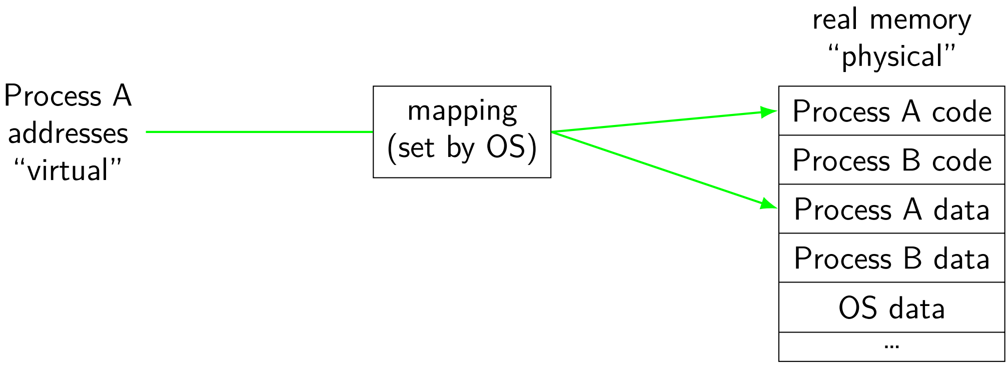
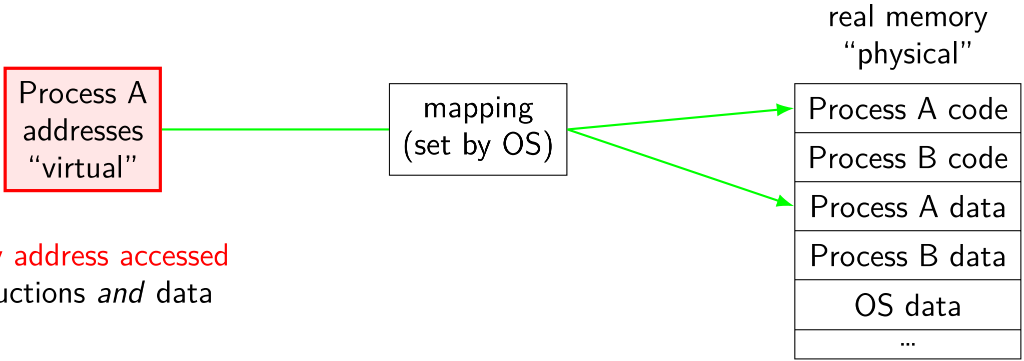


address translation

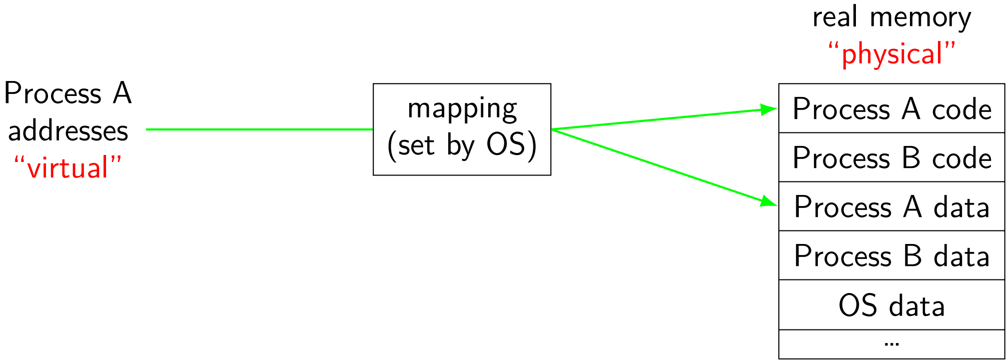


address translation



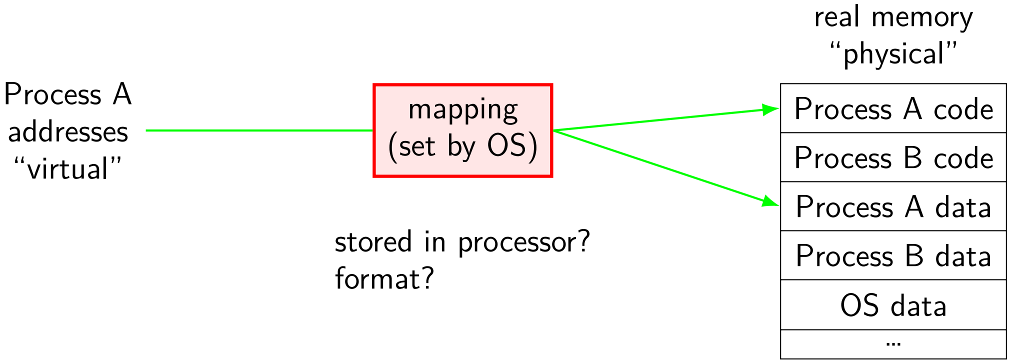
every address accessed
instructions *and* data

address translation



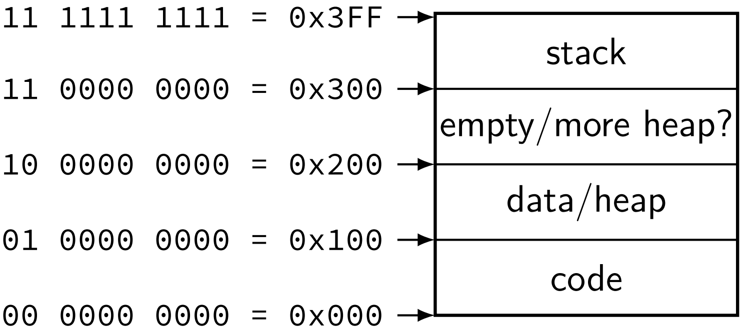
program addresses are 'virtual'
real addresses are 'physical'
can be different sizes!

address translation

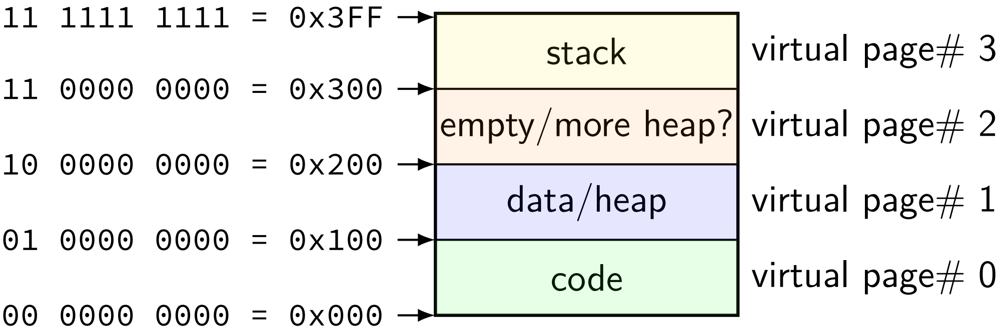


stored in processor?
format?

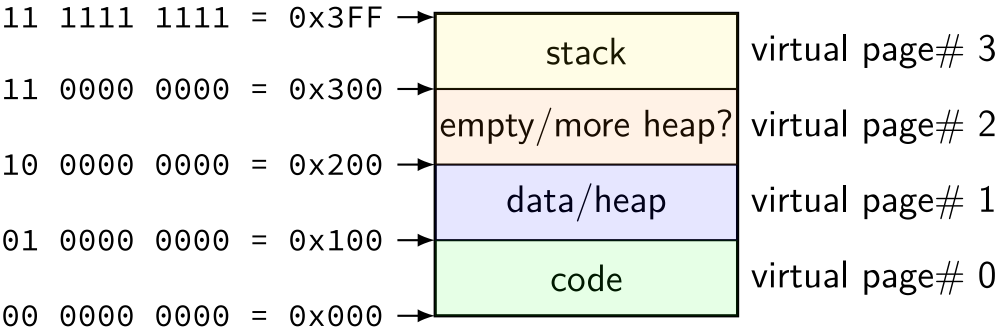
toy program memory



toy program memory

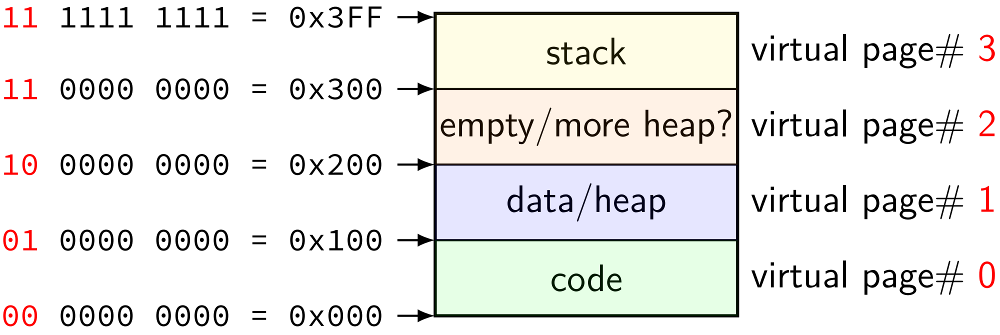


toy program memory



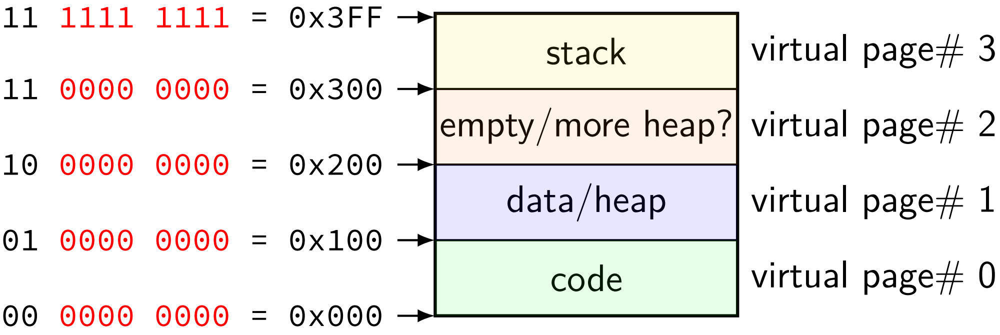
divide memory into pages (2^8 bytes in this case)
"virtual" = addresses the program sees

toy program memory



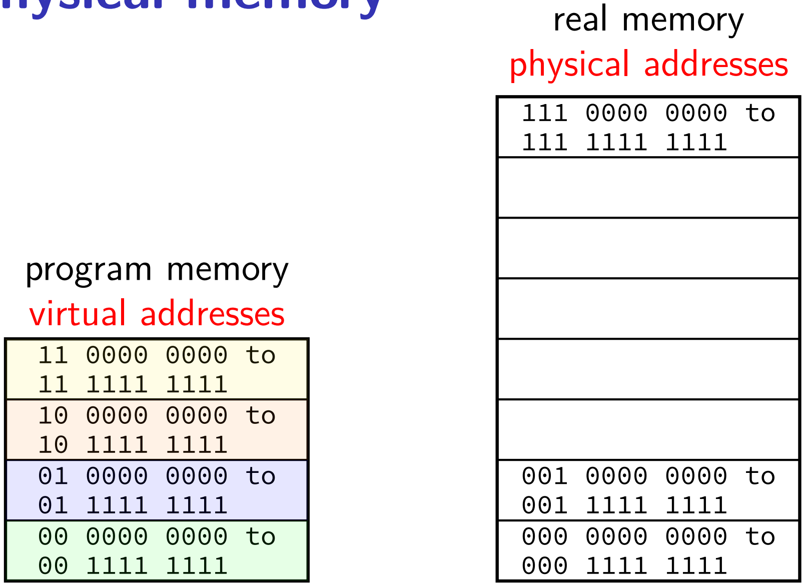
page number is upper bits of address
(because page size is power of two)

toy program memory



rest of address is called page offset

toy physical memory



toy physical memory

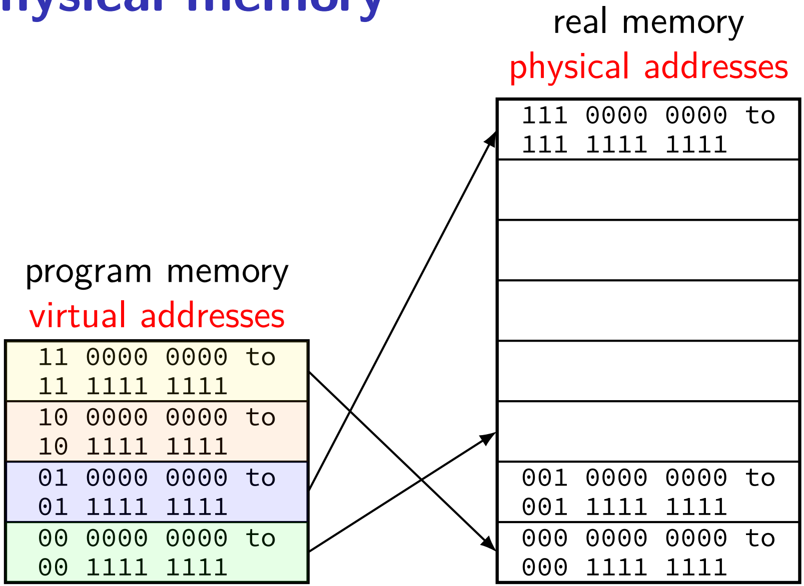
real memory
physical addresses

111 0000 0000 to 111 1111 1111	physical page 7
001 0000 0000 to 001 1111 1111	physical page 1
000 0000 0000 to 000 1111 1111	physical page 0

program memory
virtual addresses

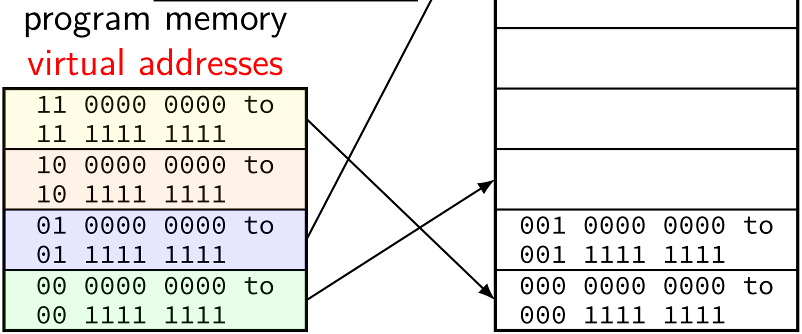
11 0000 0000 to 11 1111 1111
10 0000 0000 to 10 1111 1111
01 0000 0000 to 01 1111 1111
00 0000 0000 to 00 1111 1111

toy physical memory



toy physical memory

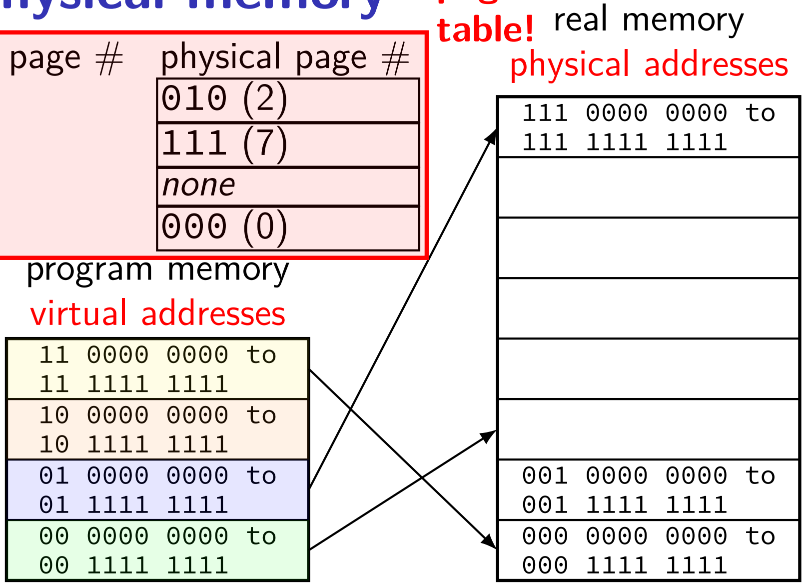
virtual page #	physical page #
00	010 (2)
01	111 (7)
10	*none*
11	000 (0)



toy physical memory

page table!

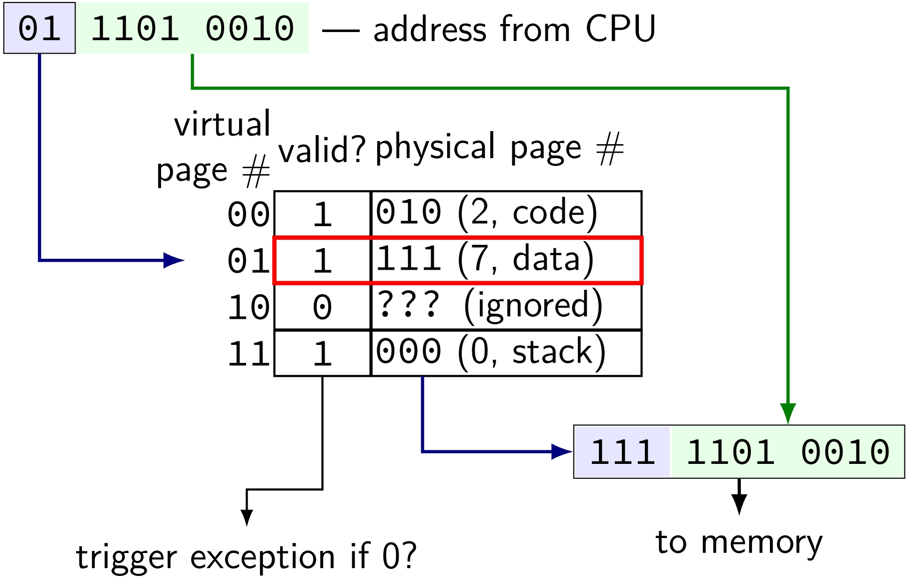
virtual page #	physical page #
00	010 (2)
01	111 (7)
10	*none*
11	000 (0)



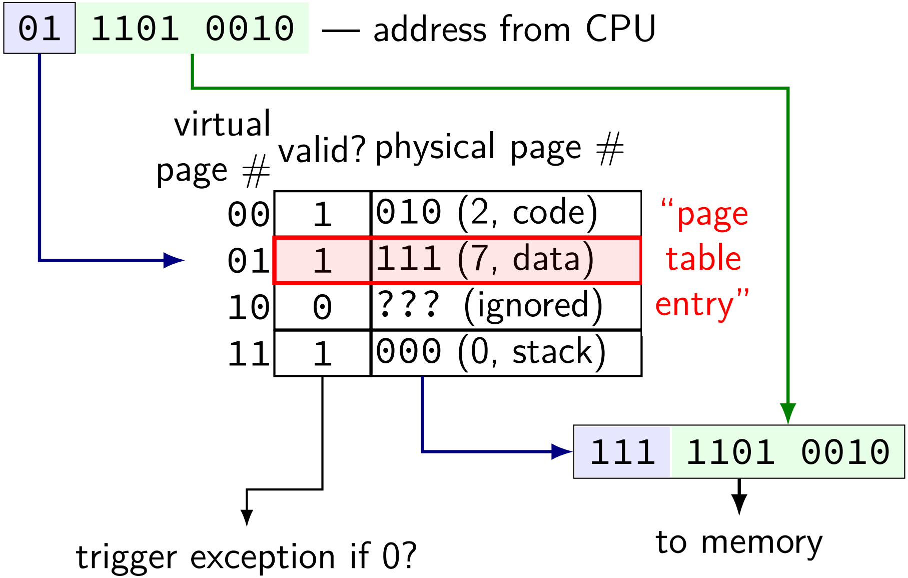
toy page table lookup

virtual page #	valid?	physical page #
`00`	`1`	`010` (2, code)
`01`	`1`	`111` (7, data)
`10`	`0`	`???` (ignored)
`11`	`1`	`000` (0, stack)

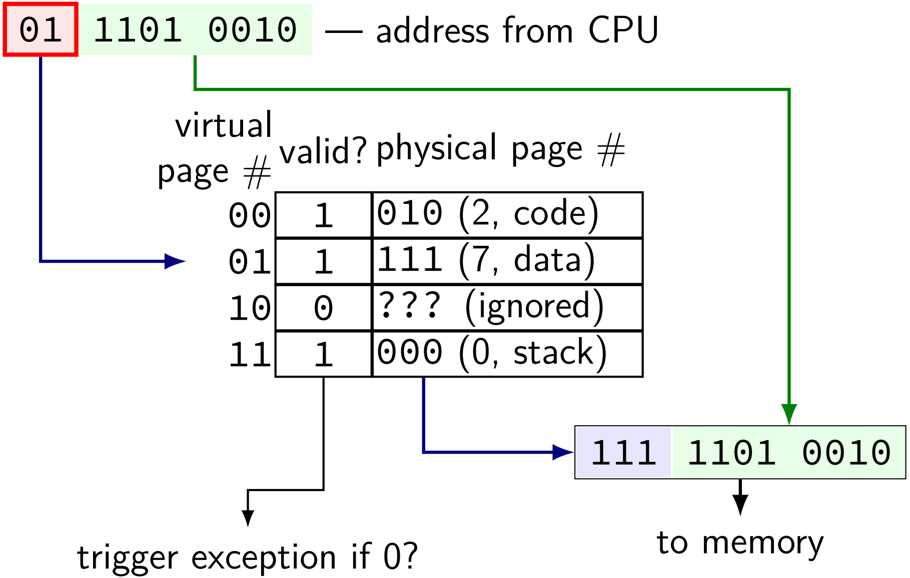
toy page table lookup



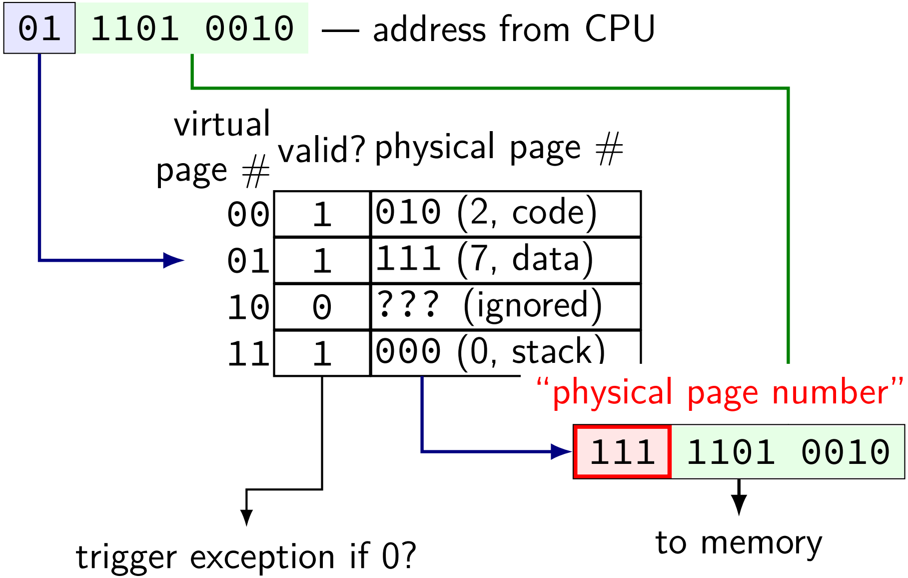
toy page table lookup



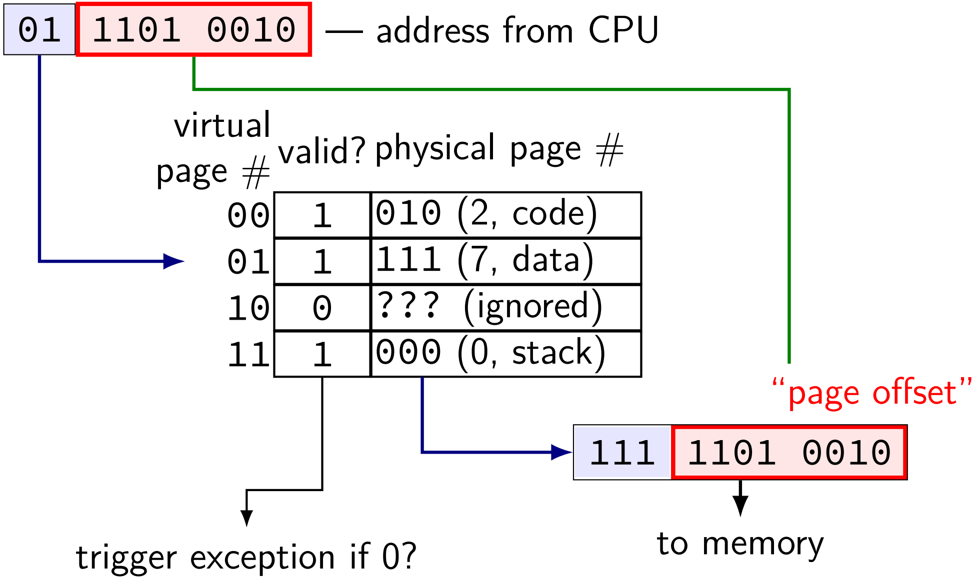
t “virtual page number” lookup



toy page table lookup



toy pag “page offset” ookup



switching page tables

part of context switch is changing the page table

extra privileged instructions

switching page tables

part of context switch is changing the page table

extra privileged instructions

where in memory is the code that does this switching?

switching page tables

part of context switch is changing the page table

extra privileged instructions

where in memory is the code that does this switching?

- probably have a page table entry pointing to it
- hopefully marked kernel-mode-only

switching page tables

part of context switch is changing the page table

extra privileged instructions

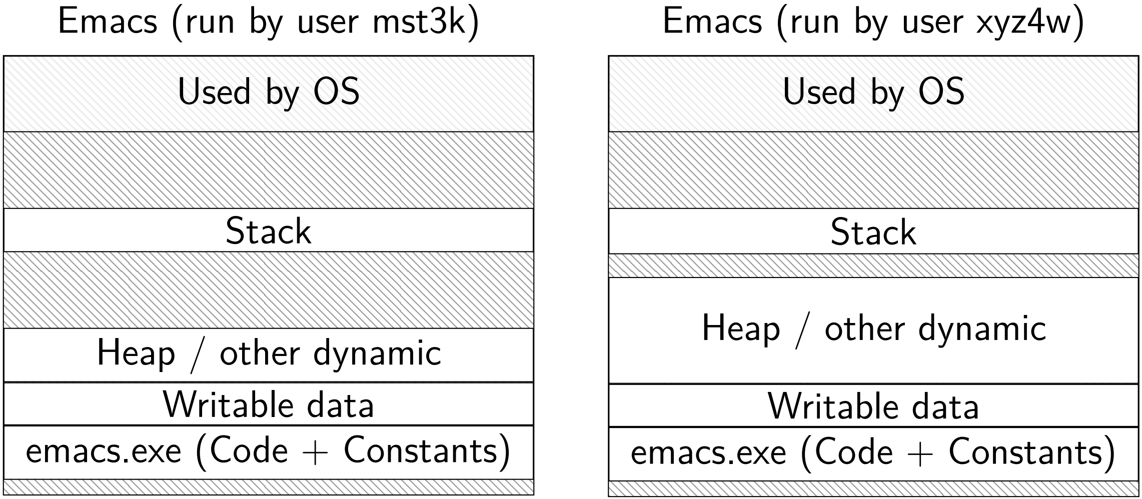
where in memory is the code that does this switching?

- probably have a page table entry pointing to it
- hopefully marked kernel-mode-only

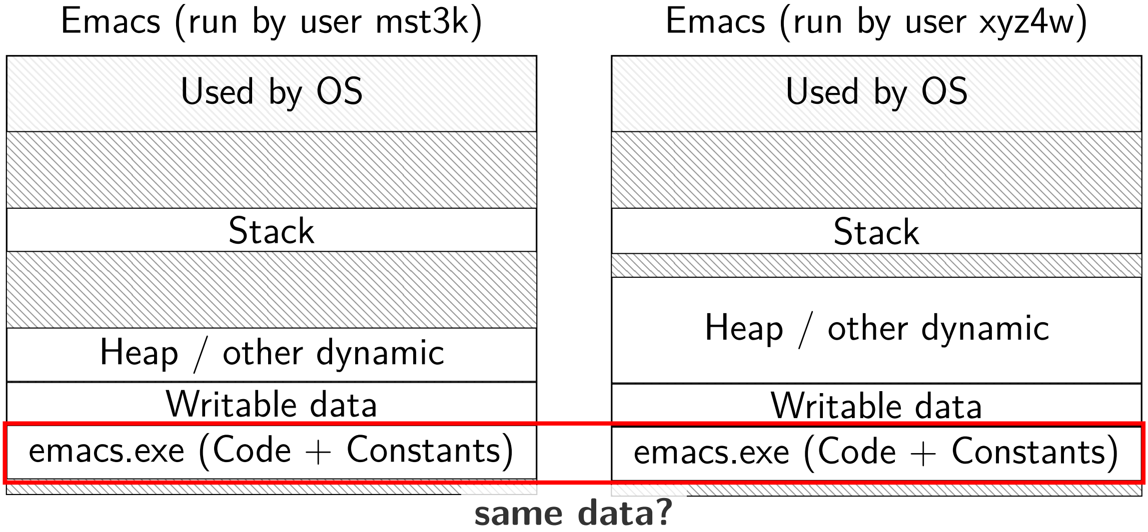
code better not be modified by user program

- otherwise: uncontrolled way to "escape" user mode

emacs (two copies)



emacs (two copies)



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"

typical page table entries

solution: same idea as kernel-only bit

page table entry will have more permissions bits

- can read?
- can write?
- can execute?

checked by MMU like valid/kernel bit

page table (logically)

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

on virtual address sizes

virtual address size = size of pointer?

often, but — sometimes part of pointer not used

example: typical x86-64 only use 48 bits

- rest of bits have fixed value

virtual address size is amount used for mapping

address space sizes

amount of stuff that can be addressed $=$ address space size

based on number of unique addresses

e.g. 32-bit virtual address $= 2^{32}$ byte virtual address space

e.g. 20-bit physical addresss $= 2^{20}$ byte physical address space

address space sizes

amount of stuff that can be addressed = address space size

- based on number of unique addresses

e.g. 32-bit virtual address = 2^{32} byte virtual address space

e.g. 20-bit physical addresss = 2^{20} byte physical address space

what if my machine has 3GB of memory (not power of two)?

- not all addresses in physical address space are useful
- most common situation (since CPUs support having a lot of memory)

exercise: page counting

suppose 32-bit virtual (program) addresses

and each page is 4096 bytes (2^{12} bytes)

how many virtual pages?

exercise: page counting

suppose 32-bit virtual (program) addresses

and each page is 4096 bytes (2^{12} bytes)

how many virtual pages?

exercise: page table size

suppose 32-bit virtual (program) addresses

suppose 30-bit physical (hardware) addresses

each page is 4096 bytes (2^{12} bytes)

pgae table entries have physical page $\#$, valid bit, kernel-mode bit

how big is the page table (if laid out like ones we've seen)?

exercise: page table size

suppose 32-bit virtual (program) addresses

suppose 30-bit physical (hardware) addresses

each page is 4096 bytes (2^{12} bytes)

pgae table entries have physical page #, valid bit, kernel-mode bit

how big is the page table (if laid out like ones we've seen)?

- issue: where can we store that?

exercise: address splitting

and each page is 4096 bytes (2^{12} bytes)

split the address `0x12345678` into page number and page offset:

exercise: address splitting

and each page is 4096 bytes (2^{12} bytes)

split the address `0x12345678` into page number and page offset:

page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout

valid (bit 15)	kernel (bit 14)	physical page # (bits 4–13)	unused (bit 0-3)

page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout

valid (bit 15)	kernel (bit 14)	physical page # (bits 4–13)	unused (bit 0-3)

page table base register

`0x00010000`

page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout

valid (bit 15)	kernel (bit 14)	physical page # (bits 4–13)	unused (bit 0-3)

page table base register

`0x00010000`

physical memory

addresses	bytes
0x00000000-1	00000000 00000000
...	
0x00010000-1	00000000 00000000
0x00010002-3	10100010 01100000
0x00010004-5	10000010 11000000
0x00010006-7	10110000 00110000
...	
0x000101FE-F	10001110 10000000
0x00010200-1	10100010 00111010

page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout

valid (bit 15)	kernel (bit 14)	physical page # (bits 4–13)	unused (bit 0-3)

page table base register

`0x00010000`

physical memory

addresses	bytes
0x00000000-1	00000000 00000000
...	
0x00010000-1	00000000 00000000
0x00010002-3	10100010 01100000
0x00010004-5	10000010 11000000
0x00010006-7	10110000 00110000
...	
0x000101FE-F	10001110 10000000
0x00010200-1	10100010 00111010

page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout

valid (bit 15)	kernel (bit 14)	physical page # (bits 4–13)	unused (bit 0-3)

page table base register

`0x00010000`

physical memory

addresses	bytes
0x00000000-1	00000000 00000000
…	
0x00010000-1	00000000 00000000
0x00010002-3	10100010 01100000
0x00010004-5	10000010 11000000
0x00010006-7	10110000 00110000
…	
0x000101FE-F	10001110 10000000
0x00010200-1	10100010 00111010

page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout

valid (bit 15)	kernel (bit 14)	physical page # (bits 4–13)	unused (bit 0-3)

page table base register

`0x00010000`

physical memory

addresses	bytes
0x00000000-1	00000000 00000000
...	
0x00010000-1	00000000 00000000
0x00010002-3	10100010 01100000
0x00010004-5	10000010 11000000
0x00010006-7	10110000 00110000
...	
0x000101FE-F	10001110 10000000
0x00010200-1	10100010 00111010

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valid (bit 15)	kernel (bit 14)	physical page # (bits 4–13)	unused (bit 0-3)

page table base register

`0x00010000`

page table (logically)

virtual page #	valid?	kernel?	physical page #
0000 0000	0	0	00 0000 0000
0000 0001	1	0	10 0010 0110
0000 0010	1	0	00 0000 1100
0000 0011	1	0	11 0000 0011
…			
1111 1111	1	0	00 1110 1000

physical memory

addresses	bytes
0x00000000-1	00000000 00000000
…	
0x00010000-1	00000000 00000000
0x00010002-3	10100010 01100000
0x00010004-5	10000010 11000000
0x00010006-7	10110000 00110000
…	
0x000101FE-F	10001110 10000000
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page tables in memory

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0000 0001	1	0	10 0010 0110
0000 0010	1	0	00 0000 1100
0000 0011	1	0	11 0000 0011
…			
1111 1111	1	0	00 1110 1000

physical memory

addresses	bytes
0x00000000-1	00000000 00000000
…	
0x00010000-1	00000000 00000000
0x00010002-3	10100010 01100000
0x00010004-5	10000010 11000000
0x00010006-7	10110000 00110000
…	
0x000101FE-F	10001110 10000000
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page tables in memory

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0000 0010	1	0	00 0000 1100
0000 0011	1	0	11 0000 0011
…			
1111 1111	1	0	00 1110 1000

physical memory

addresses	bytes
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…	
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0x00010002-3	10100010 01100000
0x00010004-5	10000010 11000000
0x00010006-7	10110000 00110000
…	
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page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout

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0000 0000	0	0	00 0000 0000
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0000 0010	1	0	00 0000 1100
0000 0011	1	0	11 0000 0011
…			
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physical memory

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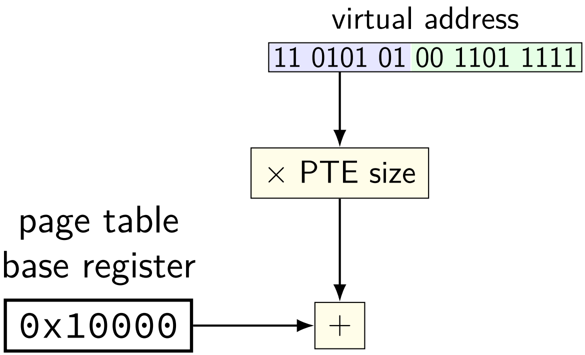
0x00000000-1	00000000 00000000
…	
0x00010000-1	00000000 00000000
0x00010002-3	10100010 01100000
0x00010004-5	10000010 11000000
0x00010006-7	10110000 00110000
…	
0x000101FE-F	10001110 10000000
0x00010200-1	10100010 00111010

memory access with page table

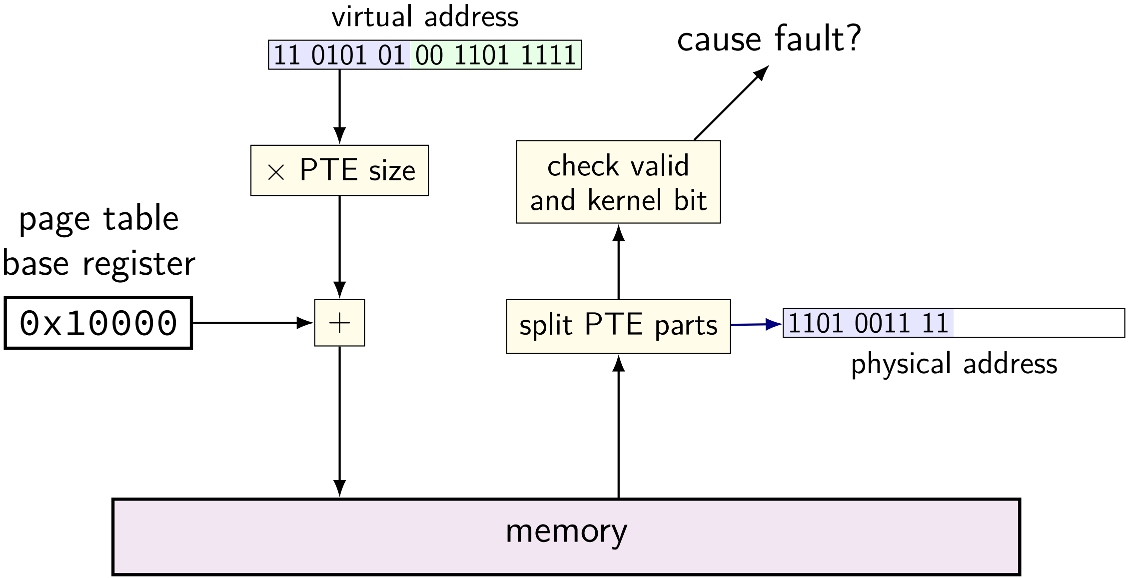
virtual address

11 0101 01	00 1101 1111

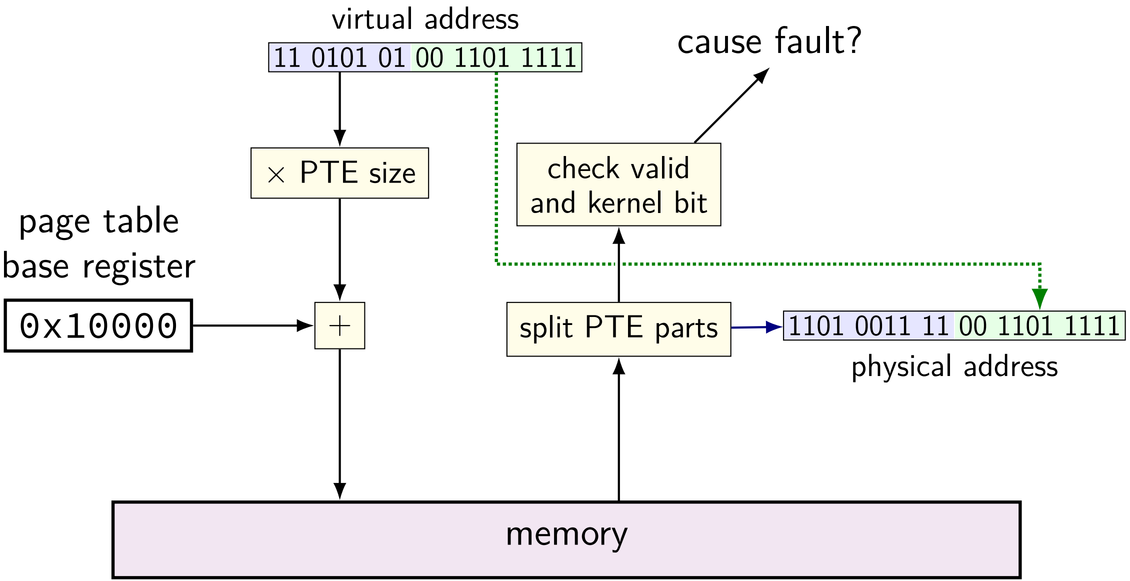
memory access with page table



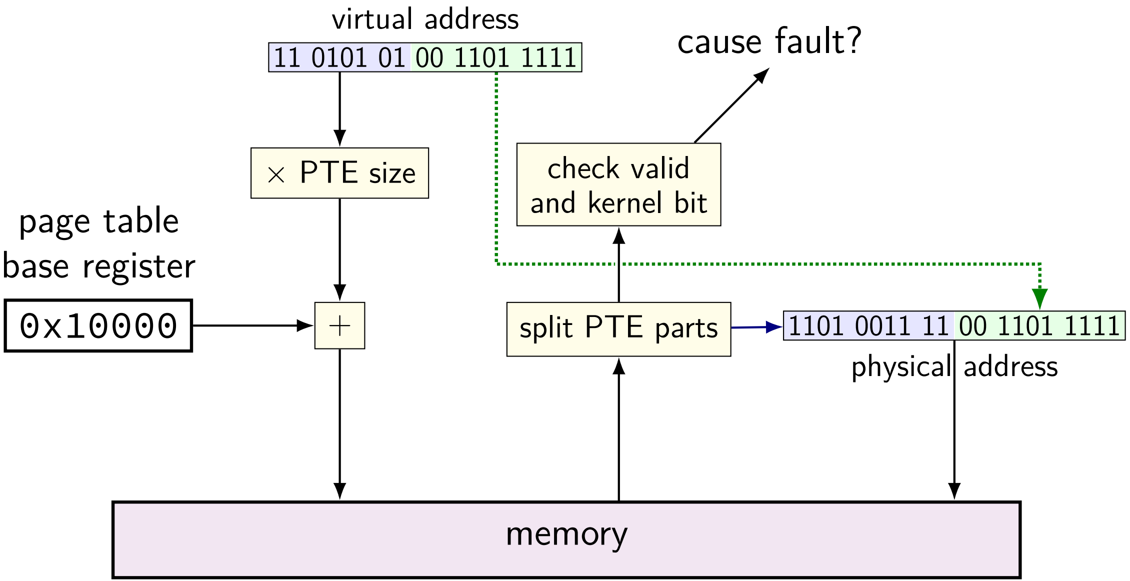
memory access with page table



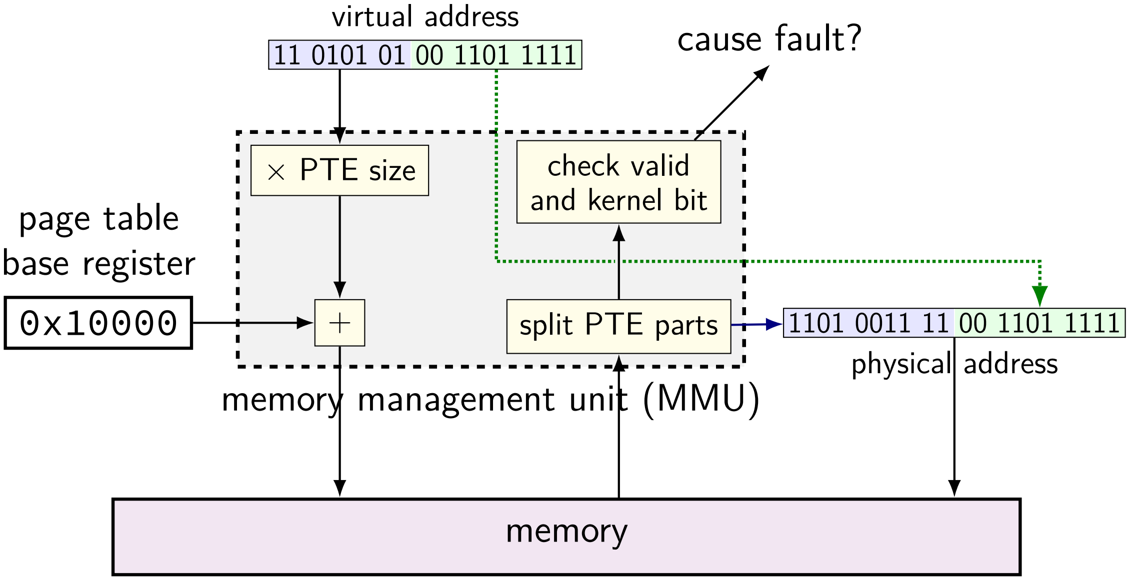
memory access with page table



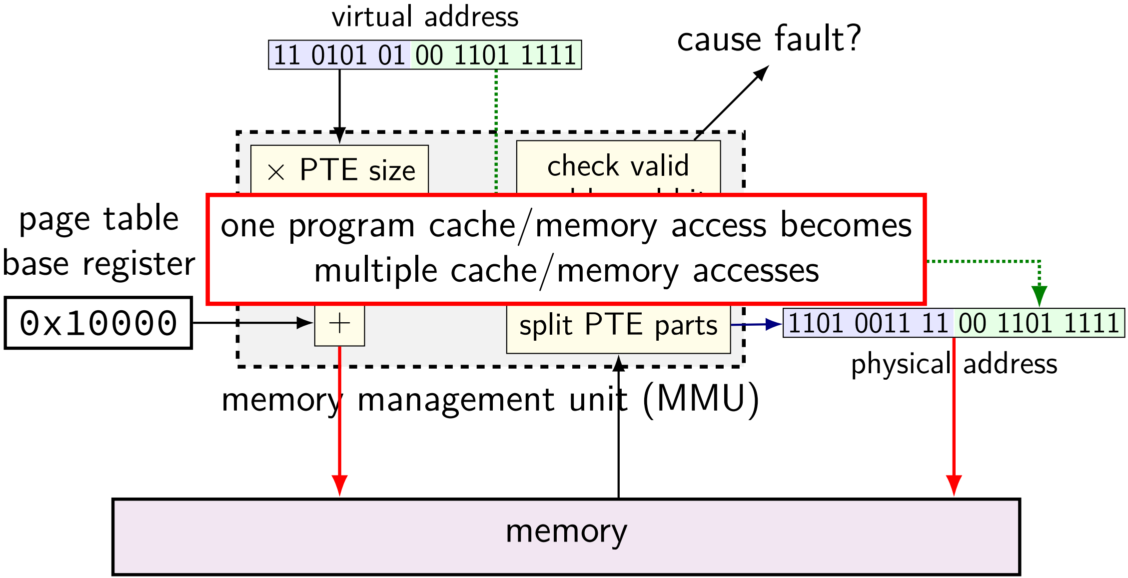
memory access with page table



memory access with page table

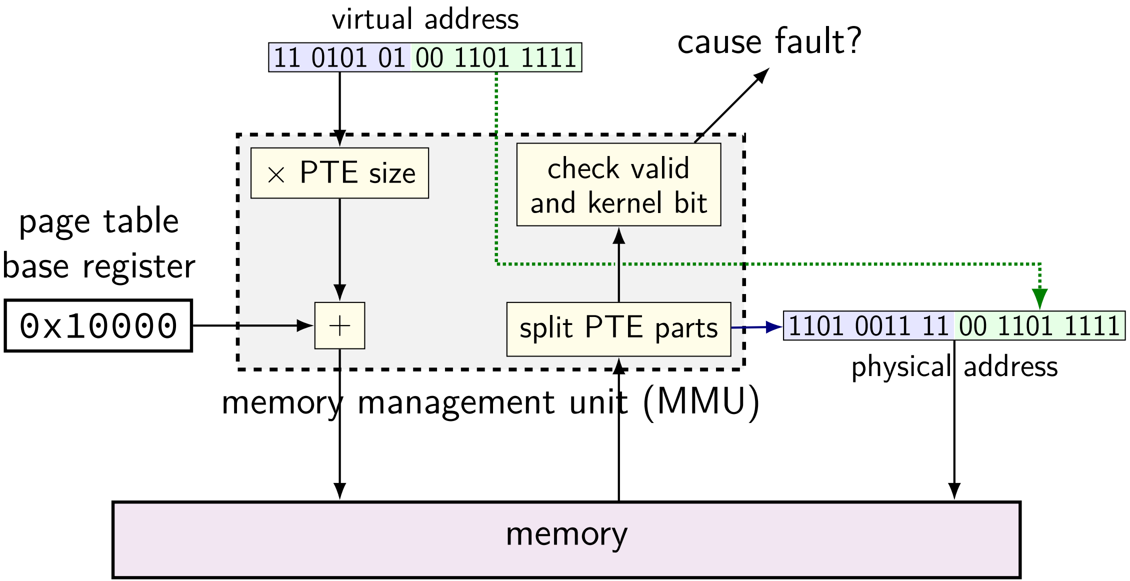


memory access with page table



one program cache/memory access becomes multiple cache/memory accesses

memory access with page table



exercise setup

5-bit virtual addresses, 6-bit physical addresses, 8-byte pages

page table

virtual page #	valid?	physical page #
00	1	010
01	1	111
10	0	000
11	1	000

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	CB 0B CB 0B
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0x04-7	44 55 66 77	0x24-7	D4 D5 D6 D7
0x08-B	88 99 AA BB	0x28-B	89 9A AB BC
0x0C-F	CC DD EE FF	0x2C-F	CD DE EF F0
0x10-3	1A 2A 3A 4A	0x30-3	BA 0A BA 0A
0x14-7	1B 2B 3B 4B	0x34-7	CB 0B CB 0B
0x18-B	1C 2C 3C 4C	0x38-B	DC 0C DC 0C
0x1C-F	1C 2C 3C 4C	0x3C-F	EC 0C EC 0C

phys. page 0

phys. page 1

exercise

5-bit virtual addresses, 6-bit physical addresses, 8-byte pages

(virtual addresses) `0x18` = ???; `0x03` = ???; `0x0A` = ???; `0x13` = ???

page table

virtual page #	valid?	physical page #
00	1	010
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10	0	000
11	1	000

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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
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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
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0x1C-F	1C 2C 3C 4C

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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	CB 0B CB 0B
0x38-B	DC 0C DC 0C
0x3C-F	EC 0C EC 0C

1-level example

6-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 other bits;

page table base register `0x20`; translate virtual address `0x31`

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	F4 F5 F6 F7
0x28-B	89 9A AB BC
0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
0x34-7	CB 0B CB 0B
0x38-B	DC 0C DC 0C
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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
0x24-7	F4 F5 F6 F7
0x28-B	89 9A AB BC
0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
0x34-7	CB 0B CB 0B
0x38-B	DC 0C DC 0C
0x3C-F	EC 0C EC 0C

`0x31` $=$ `11 0001`

PTE addr:

`0x20` $+ 6 \times 1 =$ `0x26`

PTE value:

`0xF6` $=$ `1111 0110`

PPN `111`, valid `1`

M[`111 001`] $=$ **M[**`0x39`]

$\rightarrow$ `0x0C`

1-level example

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

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0x2C-F	CD DE EF F0
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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
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0x24-7	F4 F5 F6 F7
0x28-B	89 9A AB BC
0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
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`0x31` = `11 0001`

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`0x20` + 6 × 1 = `0x26`

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M[`111 001`] = **M[**`0x39`]

→ `0x0C`

1-level example

6-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 other bits;

page table base register `0x20`; translate virtual address `0x12`

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	F4 F5 F6 F7
0x28-B	89 9A AB BC
0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
0x34-7	CB 0B CB 0B
0x38-B	DC 0C DC 0C
0x3C-F	EC 0C EC 0C

1-level example

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

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page table base register `0x20`; translate virtual address `0x12`

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	F4 F5 F6 F7
0x28-B	89 9A AB BC
0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
0x34-7	CB 0B CB 0B
0x38-B	DC 0C DC 0C
0x3C-F	EC 0C EC 0C

`0x12` = `01 0010`

PTE addr:

`0x20` + 2 × 1 = `0x22`

PTE value:

`0xD2` = `1101 0010`

PPN `110`, valid `1`

M[`110 010`] = **M[**`0x32`]

→ `0xBA`

1-level example

6-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 other bits;

page table base register `0x20`; translate virtual address `0x12`

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	F4 F5 F6 F7
0x28-B	89 9A AB BC
0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
0x34-7	CB 0B CB 0B
0x38-B	DC 0C DC 0C
0x3C-F	EC 0C EC 0C

`0x12` = `01 0010`

PTE addr:

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PTE value:

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PPN `110`, valid 1

M[`110 010`] = **M[**`0x32`]

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1-level example

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

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page table base register `0x20`; translate virtual address `0x12`

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
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0x30-3	BA 0A BA 0A
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exercise: 64-bit system

my desktop: 39-bit physical addresses; 48-bit virtual addresses

4096 byte pages

exercise: 64-bit system

my desktop: 39-bit physical addresses; 48-bit virtual addresses

top 16 bits of 64-bit addresses not used for translation

4096 byte pages

exercise: 64-bit system

my desktop: 39-bit physical addresses; 48-bit virtual addresses

4096 byte pages

exercise: how many page table entries? (assuming page table like shown before)

exercise: how large are physical page numbers?

exercise: 64-bit system

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4096 byte pages

exercise: how many page table entries? (assuming page table like shown before)

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my desktop: 39-bit physical addresses; 48-bit virtual addresses

4096 byte pages

exercise: how many page table entries? (assuming page table like shown before)

exercise: how large are physical page numbers?

page table entries are 8 bytes (room for expansion, metadata)

- trick: power of two size makes table lookup faster

would take up 2^{39} bytes?? (512GB??)

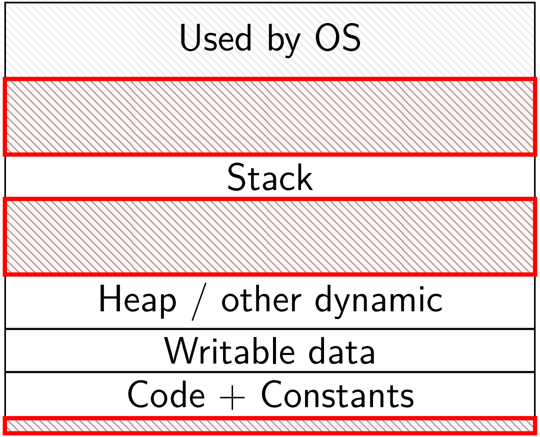
huge page tables

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?

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?

hashtable

- actually used by some historical processors
- but never common

saving space

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options?

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tree data structure

- but not quite a search tree

search tree tradeoffs

lookup usually implemented in hardware

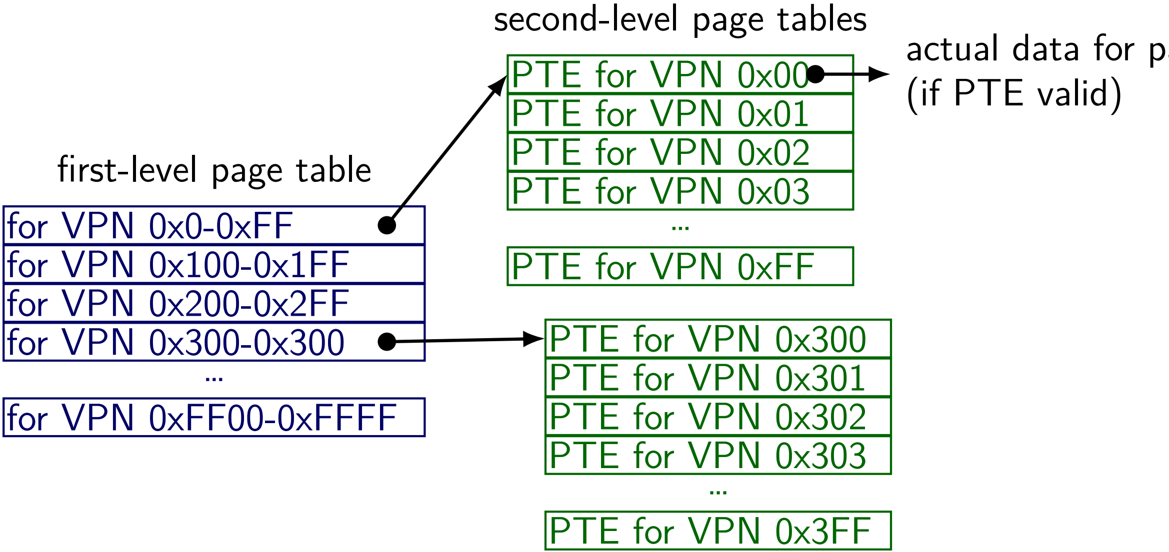
- lookup should be simple
- solution: lookup splits up address bits (no complex calculations)

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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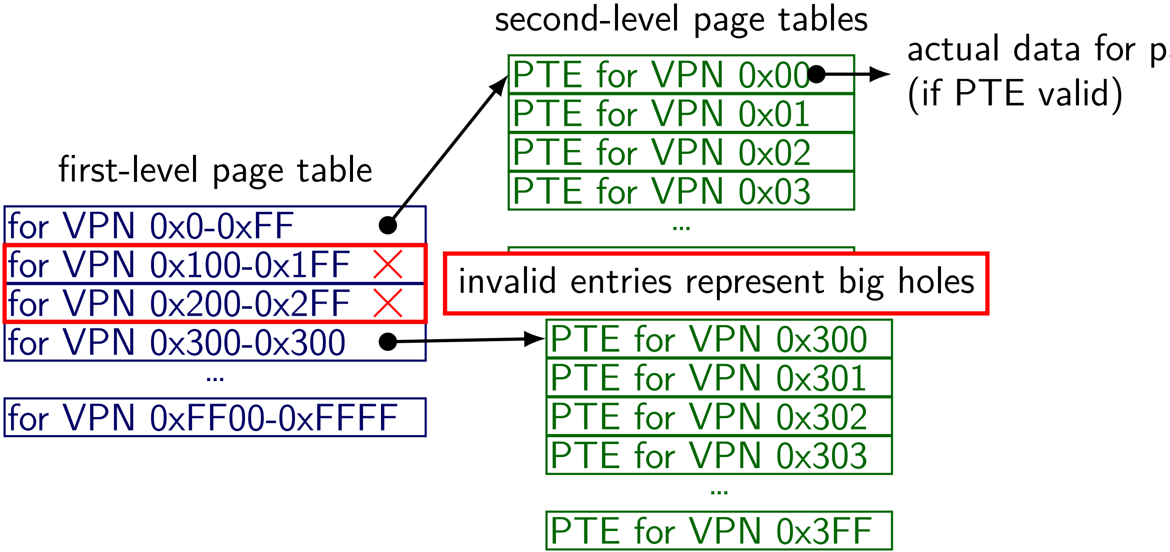

two-level page tables

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

first-level page table

VPN range	valid	kernel	write	physical page # (of next page table)
0x0000-0x00FF	1	0	1	0x22343
0x0100-0x01FF	0	0	1	0x00000
0x0200-0x02FF	0	0	0	0x00000
0x0300-0x03FF	1	1	0	0x33454
0x0400-0x04FF	1	1	0	0xFF043
…	…	…	…	…
0xFF00-0xFFFF	1	1	0	0xFF045

first-level pag

for VPN 0x0-0xF

for VPN 0x100-0

for VPN 0x200-0

for VPN 0x300-0

…

for VPN 0xFF00

PTE for VPN 0x303

…

PTE for VPN 0x3FF

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...
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0x0400–0x04FF	1	1	0	0xFF043
...	...	...	...	...
0xFF00–0xFFFF	1	1	0	0xFF045

PTE for VPN 0x303

...

PTE for VPN 0x3FF

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...

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

...

PTE for VPN 0x3FF

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 ●
...
for VPN 0xFF00-0xFFFF

a second-level page table

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

PTE for VPN 0x303

...

PTE for VPN 0x3FF

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
...
for VPN 0xFF00-0xFFFF

a second-level page table

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

PTE for VPN 0x303

...

PTE for VPN 0x3FF

two-level page tables

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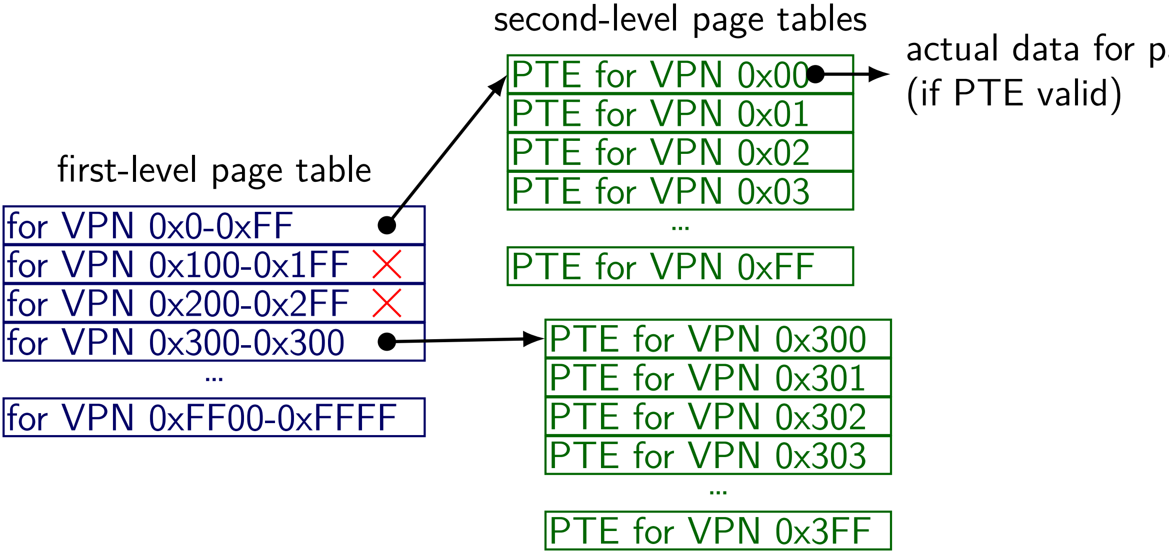


two-level page table lookup

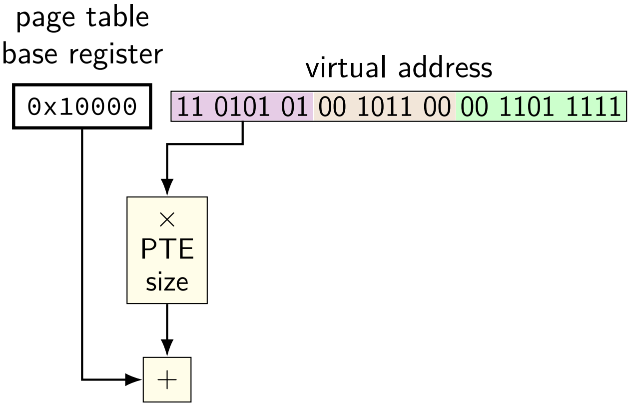
virtual address

11 0101 01	00 1011 00	00 1101 1111

VPN — split into two parts (one per level)

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

two-level page table lookup



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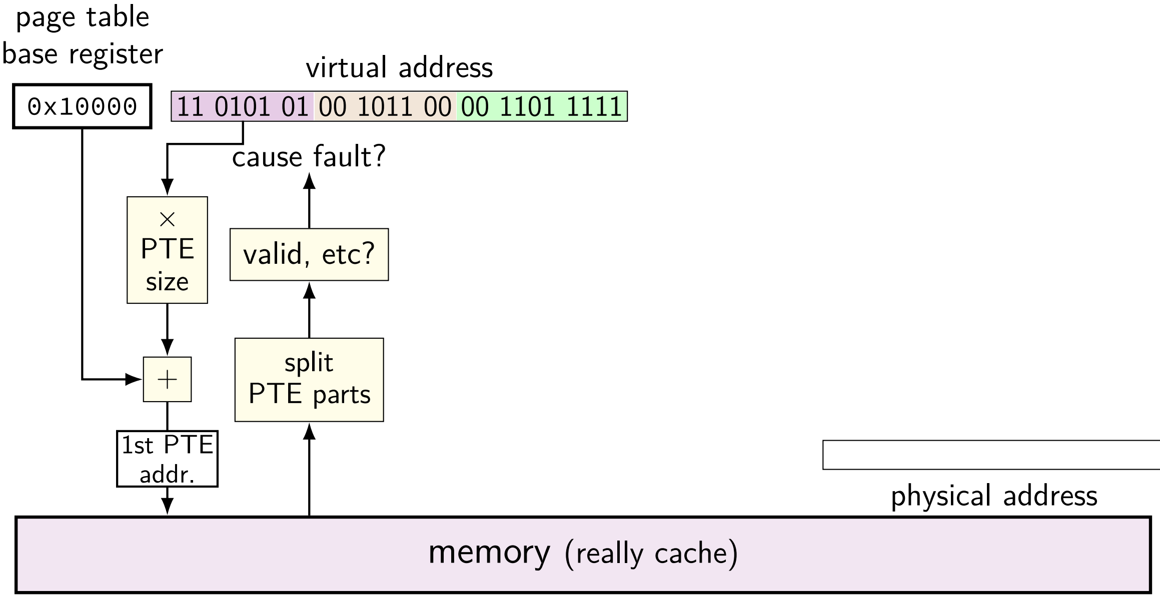

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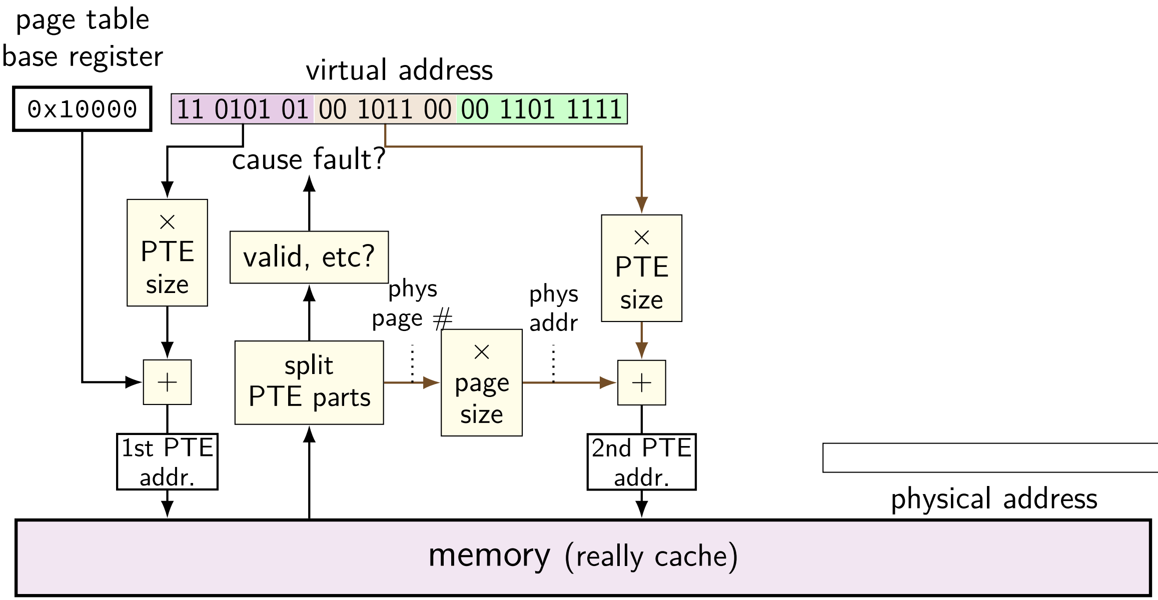

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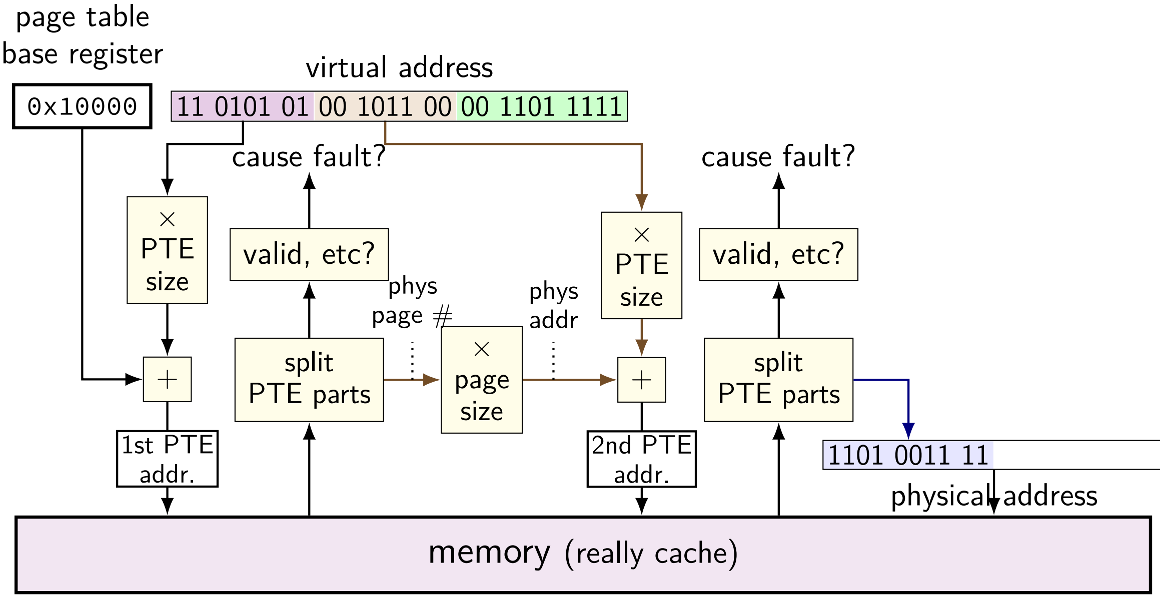

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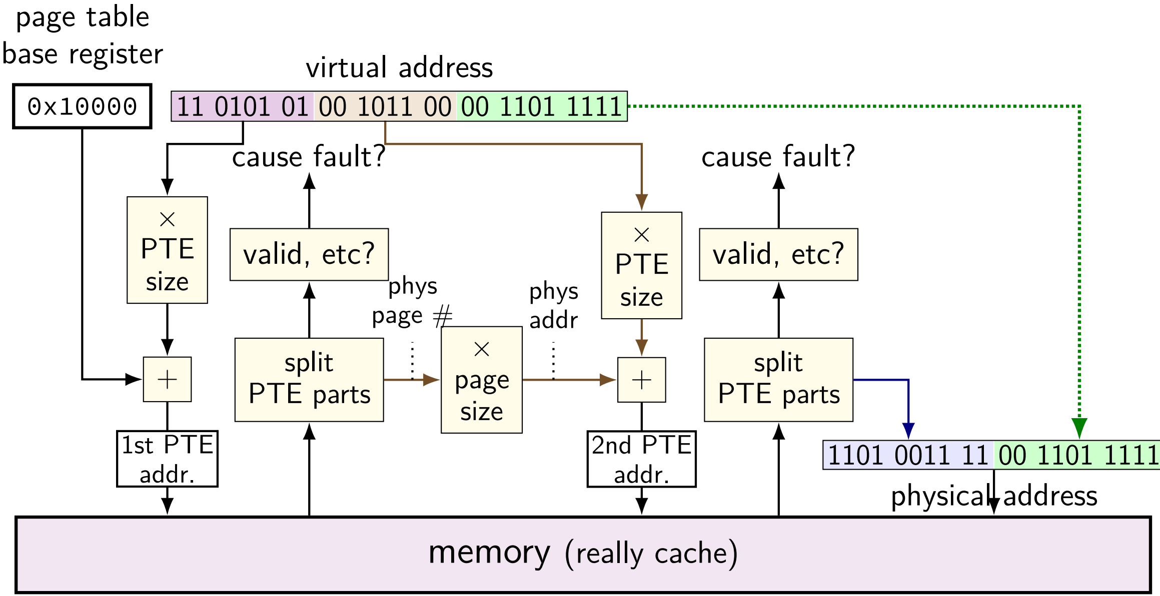

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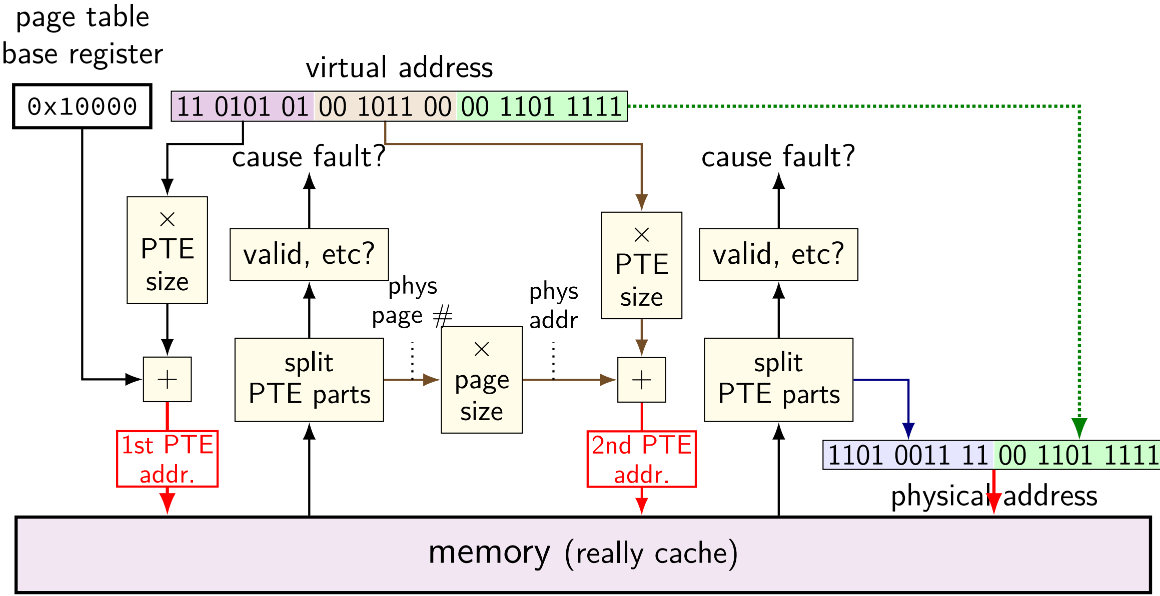

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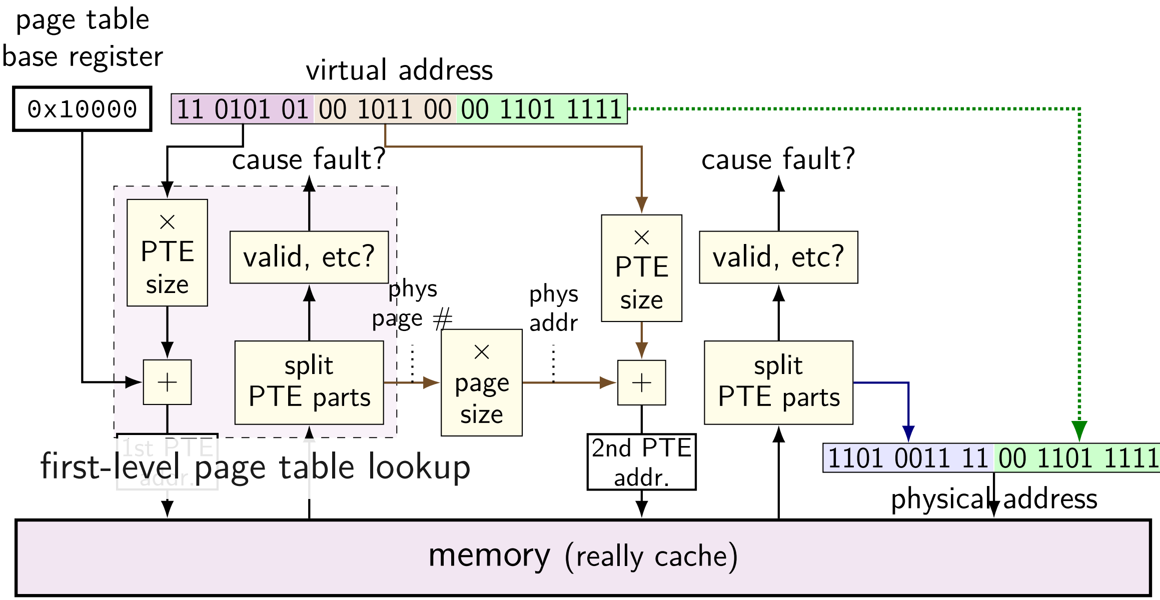

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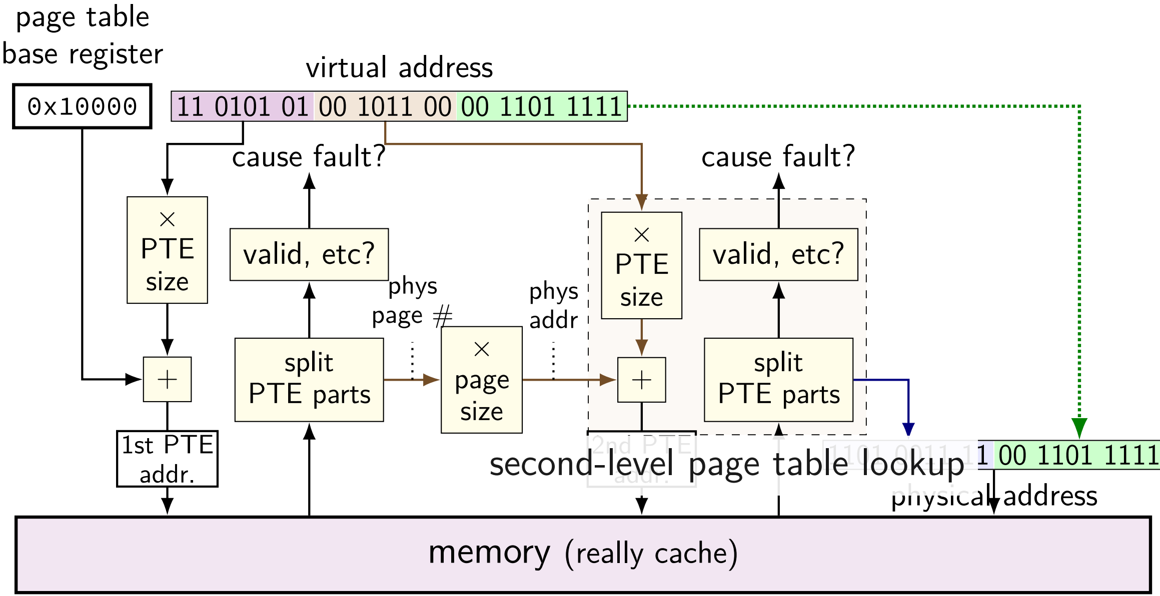

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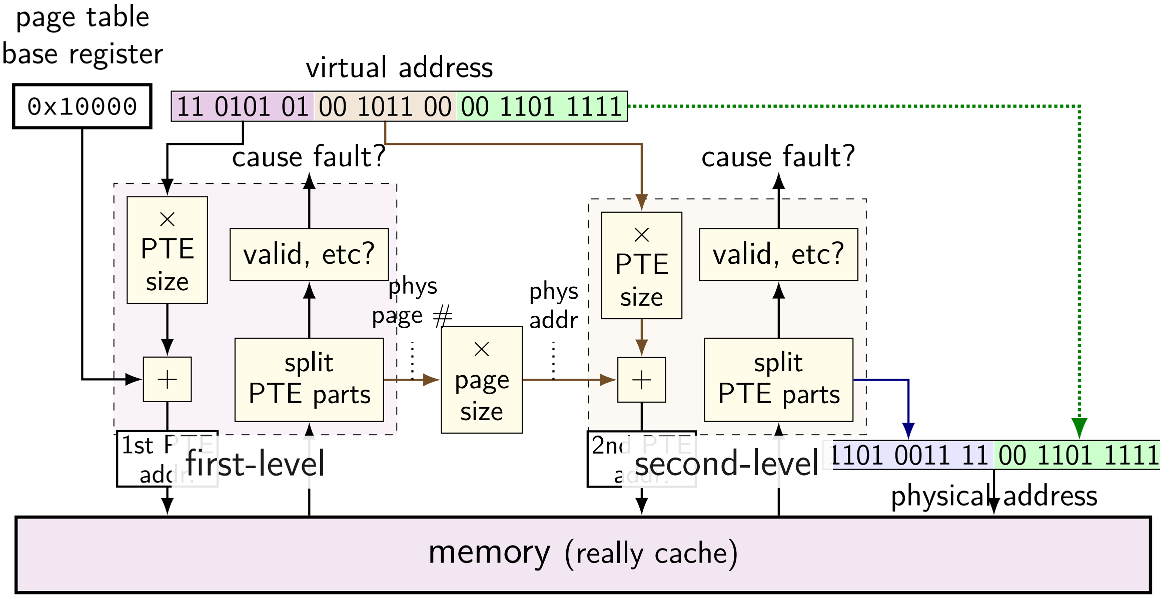

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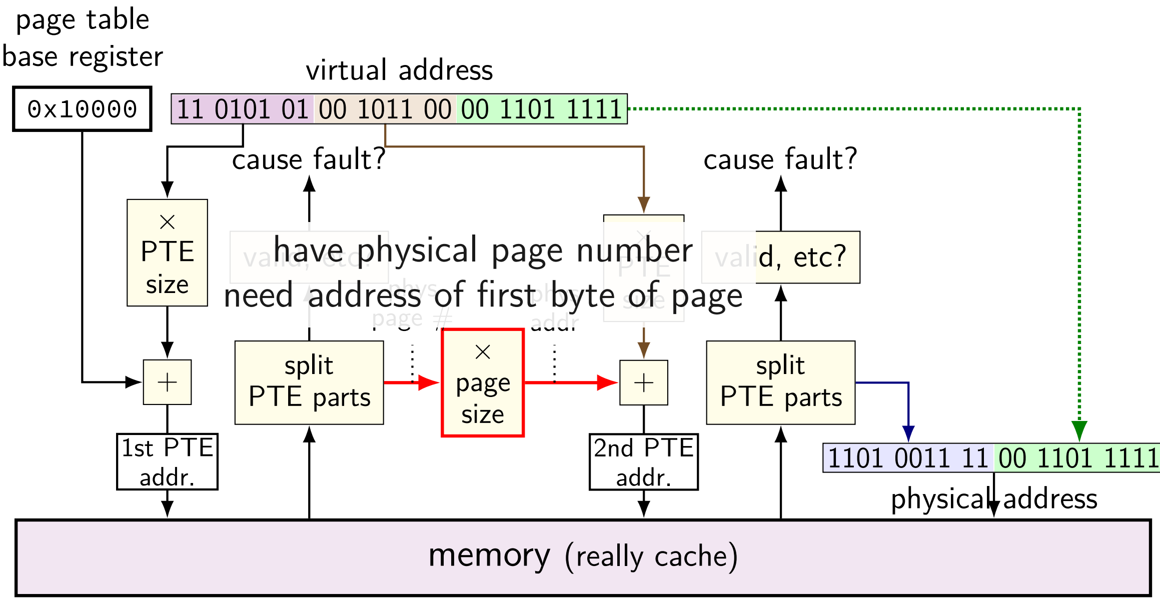

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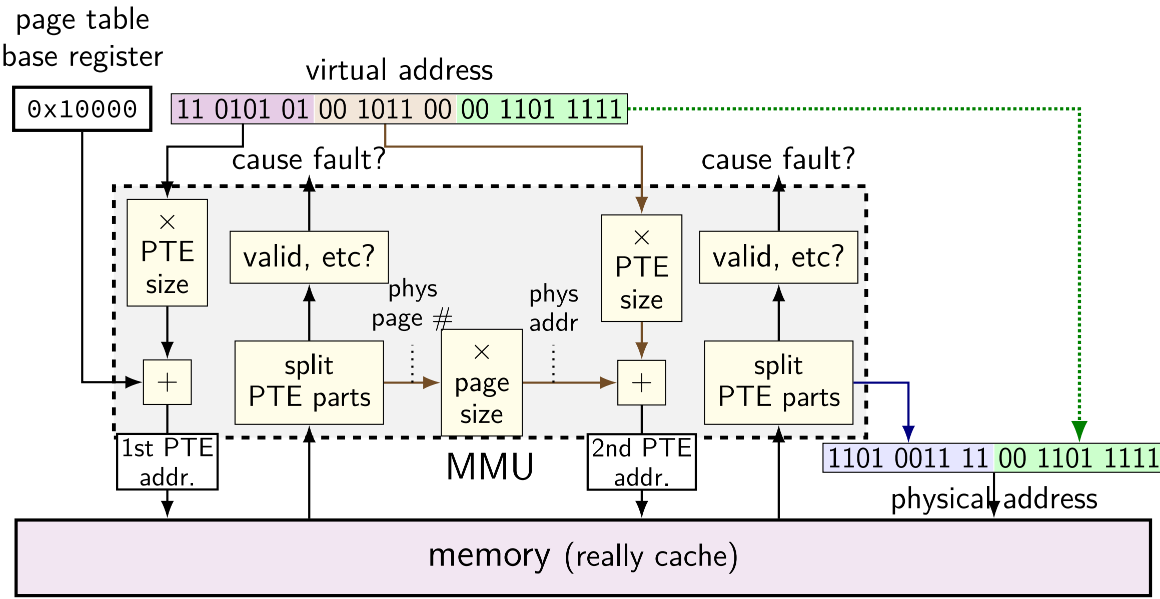
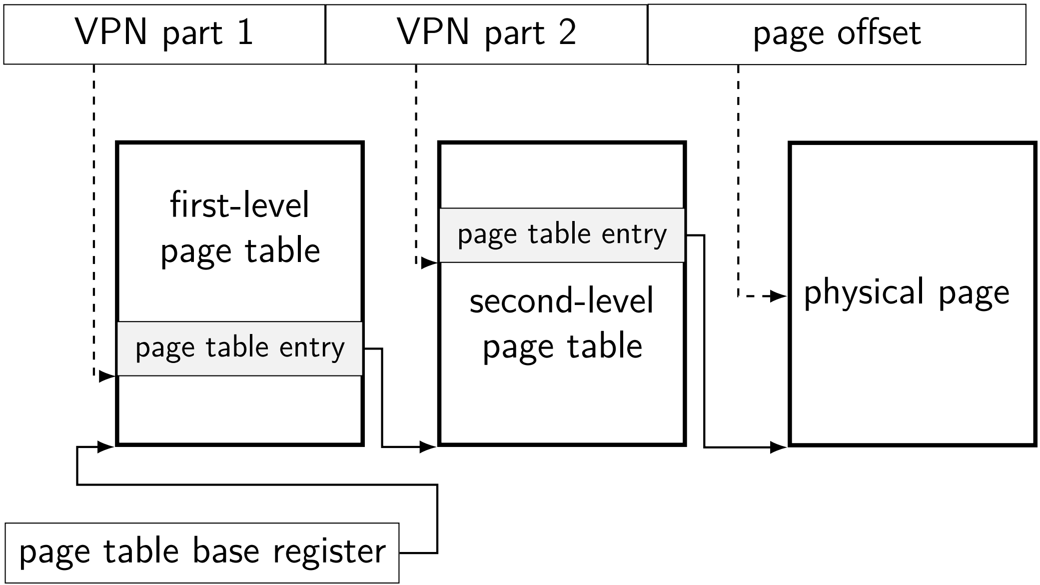


another view



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 and permission 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)

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
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
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0x34-7	DB 0B DB 0B
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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`

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
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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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0x2C-F	CD DE EF F0
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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`

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
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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`

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
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0x38-B	EC 0C EC 0C
0x3C-F	FC 0C FC 0C

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
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 5A 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

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
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0x1C-F	1C 2C 3C 4C

physical addresses	bytes
0x20-3	D0 D1 D2 D3
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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

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
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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
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

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
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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
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physical addresses	bytes
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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`

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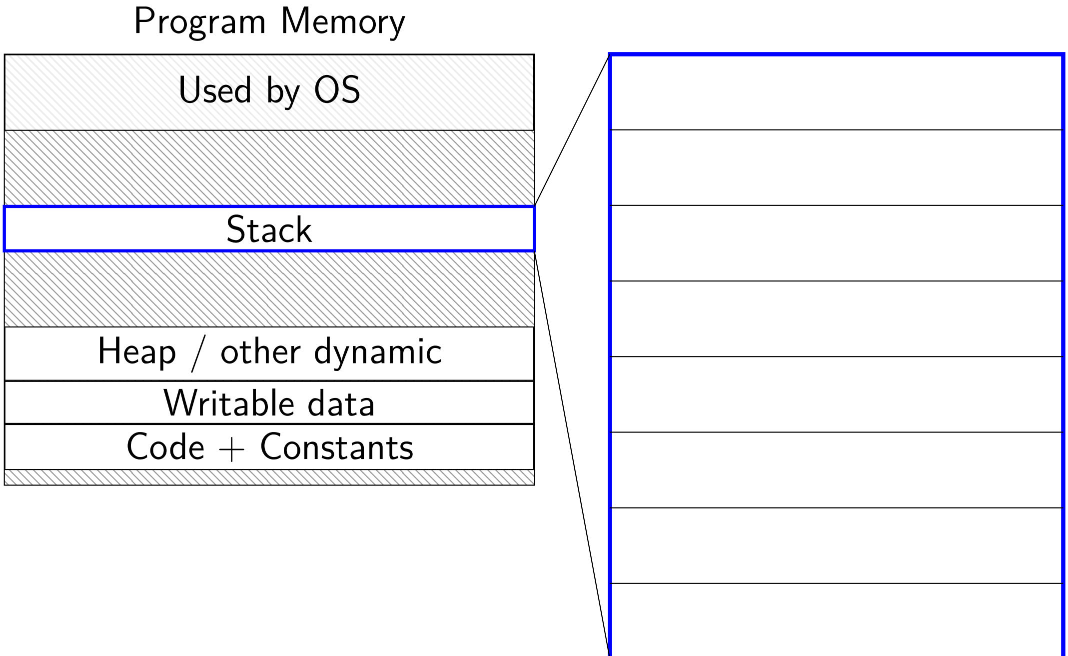
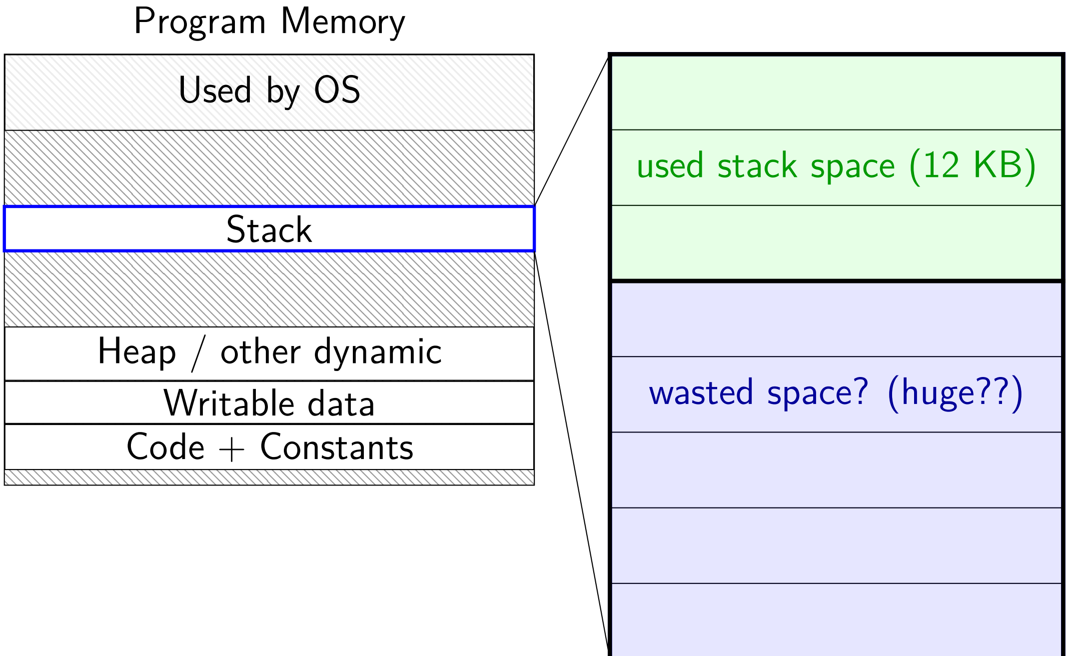
0x38-B	EC 0C EC 0C
0x3C-F	FC 0C FC 0C

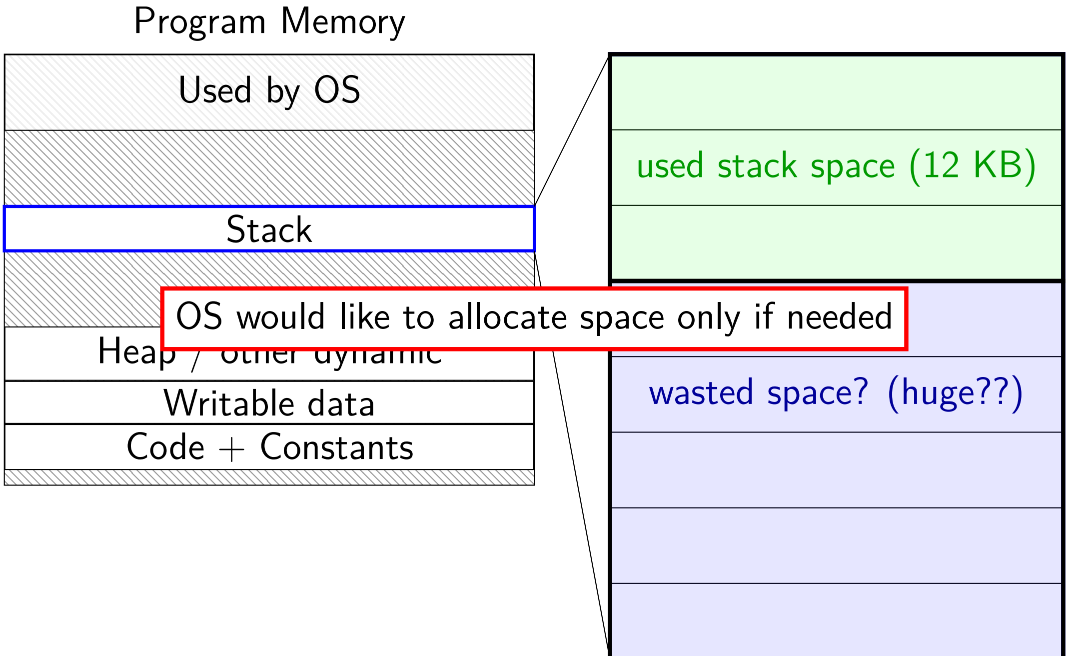
space on demand



space on demand



space on demand



allocating space on demand

`%rsp = 0x7FFFC000`

```
...
// requires more stack space
A: pushq %rbx

B: movq 8(%rcx), %rbx
C: addq %rbx, %rax
...
```

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

allocating space on demand

`%rsp = 0x7FFFC000`

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

page fault!

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

pushq triggers exception
hardware says "accessing address `0x7FFFBFF8`"
OS looks up what's should be there — "stack"

allocating space on demand

`%rsp = 0x7FFFC000`

```
...
// requires more stack space
A: pushq %rbx

B: movq 8(%rcx), %rbx
C: addq %rbx, %rax
...
```

restarted

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
7f60c749                                                u/libc-2.1
7f60c764                                                u/libc-2.1
7f60c784                                                u/libc-2.1
7f60c785                                                u/libc-2.1
7f60c785
7f60c785                                                u/ld-2.19.s
7f60c7a3
7f60c7a7
7f60c7a7                                                u/ld-2.19.s
7f60c7a7                                                u/ld-2.19.s
7f60c7a7
7ffc5d2b
7ffc5d3b
7ffc5d3b
fffffff
```

PCB contains 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 ...

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

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 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 writes and writes: hundreds of microseconds

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

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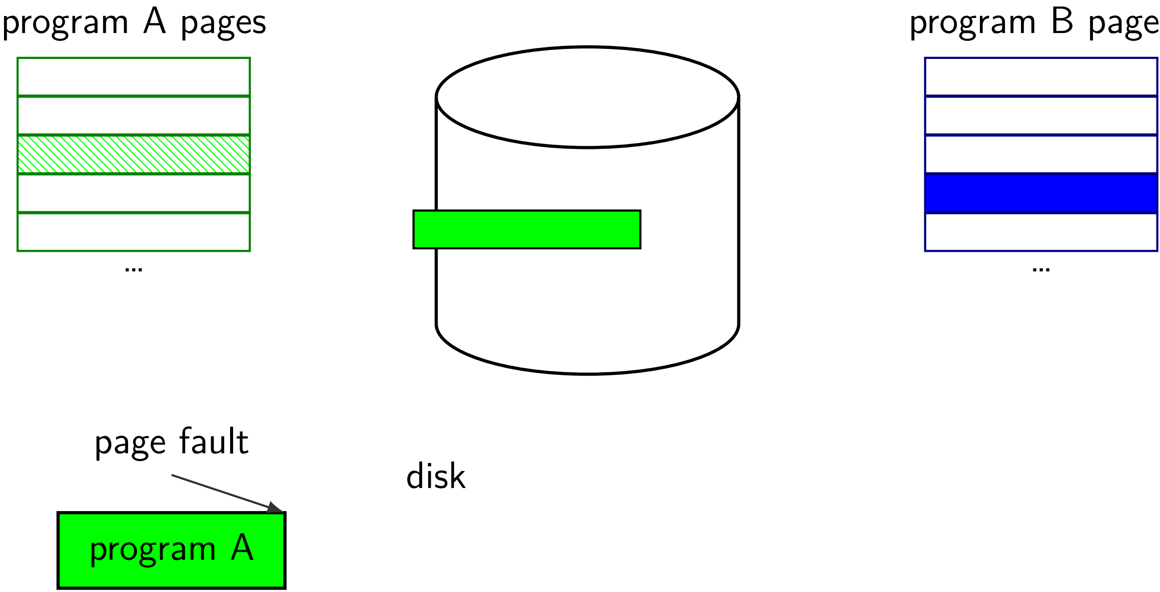
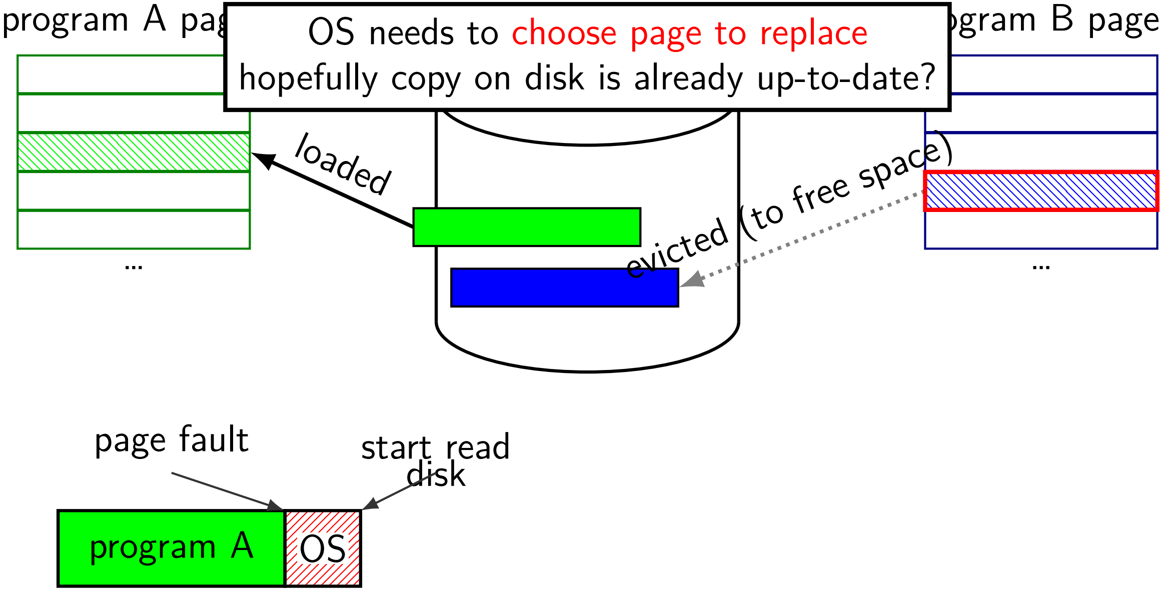
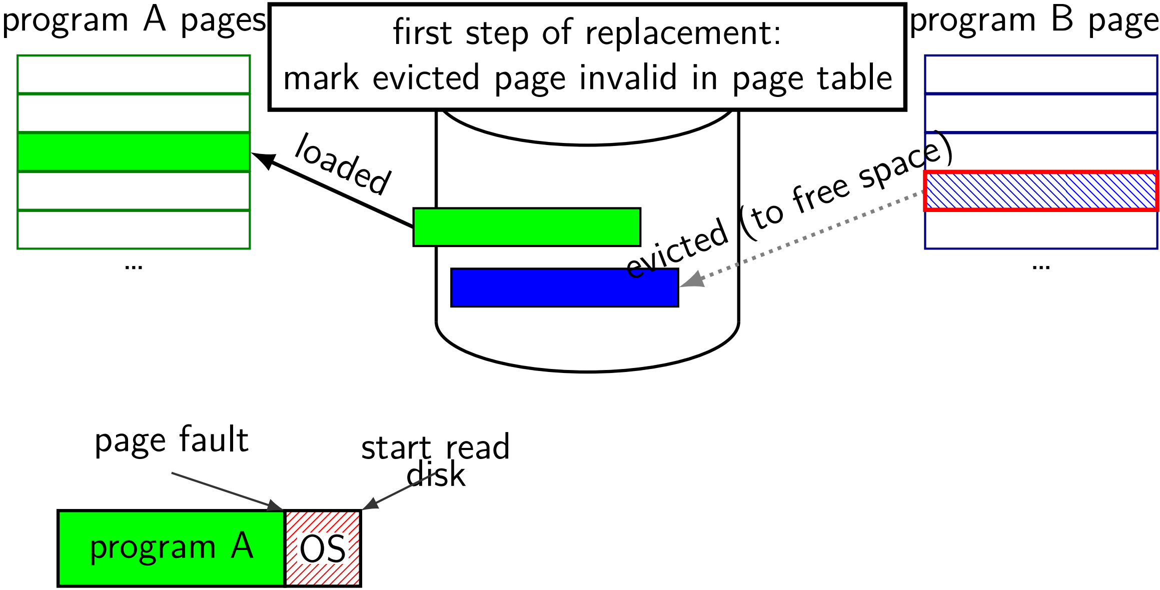
swapping timeline



swapping timeline

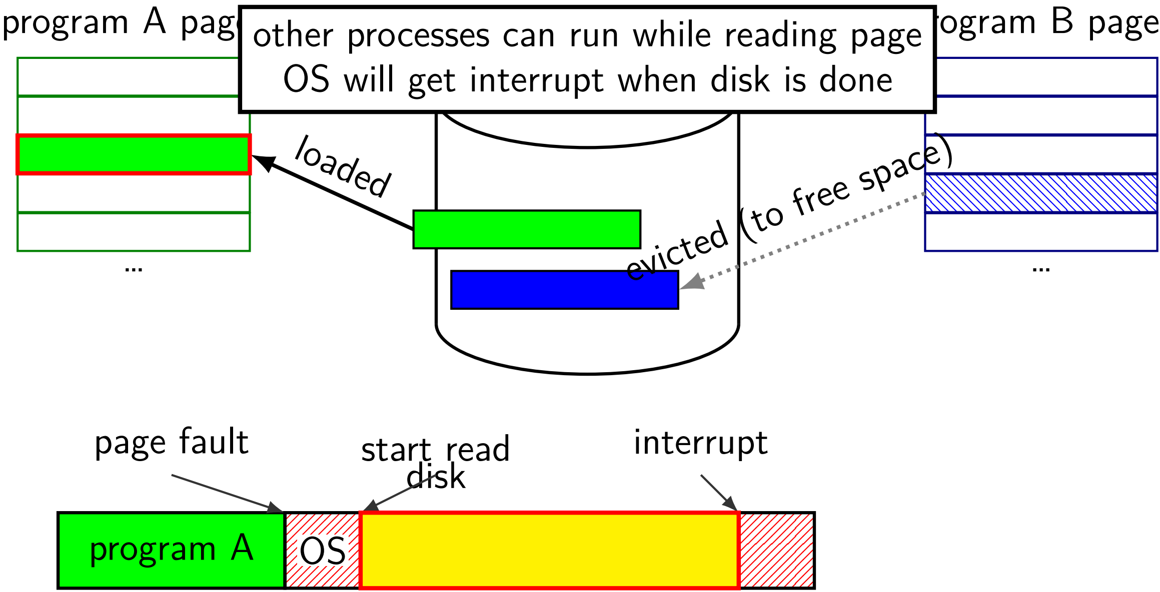


swapping timeline

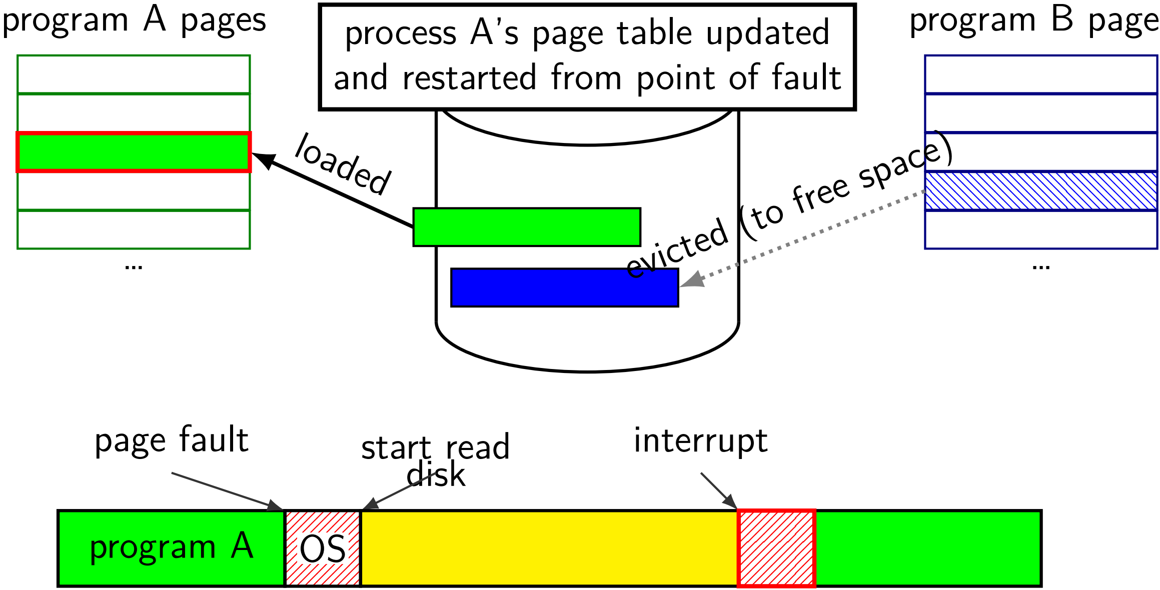


swapping timeline

other processes can run while reading page
OS will get interrupt when disk is done



swapping timeline



page tricks generally

deliberately make program trigger page/protection fault

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

have seperate data structures represent logically allocated memory

- e.g. "addresses `0x7FFF8000` to `0x7FFFFFFF` are the stack"
- might talk about Linux data structures later (book section 9.7)

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

backup slides