# 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

```
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

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

on directories, ‘execute’ means ‘search’ instead

# permissions encoding

permissions encoded as 9-bit number, can write as octal: XYZ

octal divides into three 3-bit parts:

user permissions (X), group permissions (Y), other permission (Z)

each 3-bit part has a bit for 'read' (4), 'write' (2), 'execute' (1)

`700` — user read+write+execute; group none; other none

`451` — user read; group read+execute; other none

# chmod — exact permissions

```
chmod 700 file
chmod u=rwx,og= file
```

user read write execute; group/others no accesss

---

```
chmod 451 file
chmod u=r,g=rx,o= file
```

user read; group read/execute; others no access

# chmod — adjusting permissions

`chmod u+rx foo`

add user read and execute permissions
leave other settings unchanged

---

`chmod o-rwx,u=rx foo`

remove other read/write/execute permissions
set user permissions to read/execute
leave group settings unchanged

# 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
```

# POSIX ACLs on command line

`getfacl file`

---

`setfacl -m 'user:tj1a:---' file`

add line to ACL

---

`setfacl -x 'user:tj1a' file`

REMOVE line from acl

---

`setfacl -M acl.txt file`

add to acl, but read what to add from a file

---

`setfacl -X acl.txt file`

remove from acl, but read what to remove from a file

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

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

C. making the user ID a system call argument rather than storing it persistently in the OS's memory

# 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?

# 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?

…

# other privileged escalation issues

sudo problem: trusted code that's supposed to enforce restriction can be fooled into not really enforcing it

also can occur in other contexts:

system call letting program access things it shouldn't?

browser letting web page javascript access things it shouldn't?

web application giving users access to files they shouldn't have?

mobile phone OS allowing location access without location permission?

…

# 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

# 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;
}
```

# 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

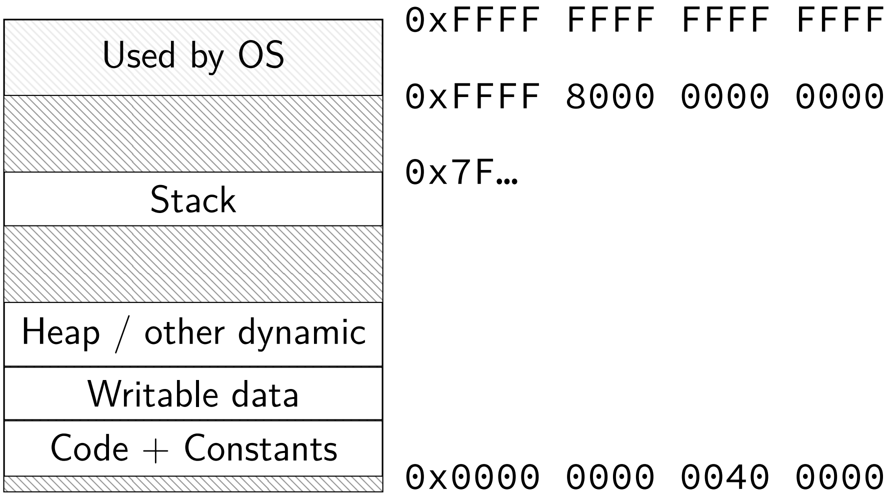
which (if any) of the following would fix for a TOCTTOU vulnerability in our setuid printing application? (assume the Unix-permissions without ACLs are in use)

[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

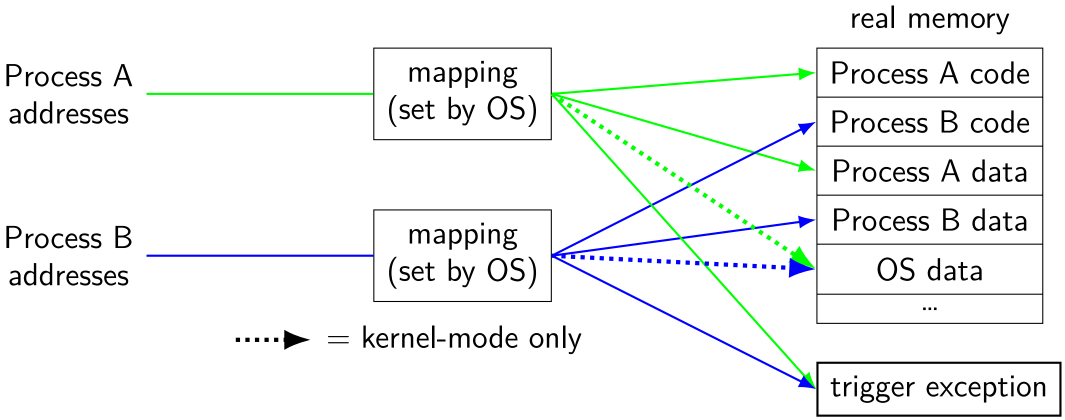
[C] before opening the path, verify that the user controls the file referred to by the path **and** the directory containing it

# program memory



# address spaces

illuision of dedicated memory



# address spaces

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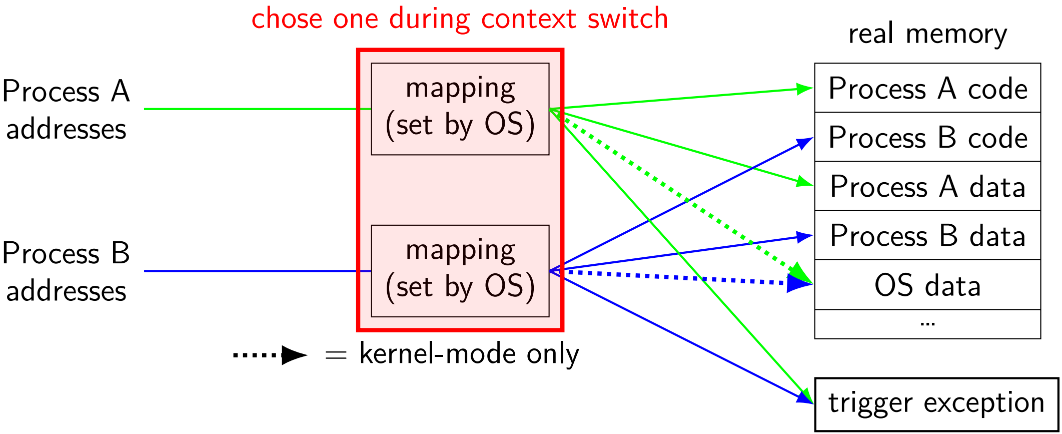
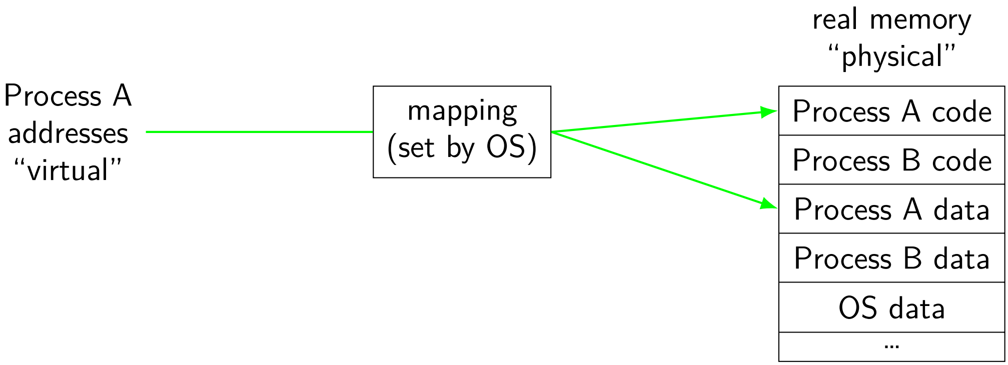
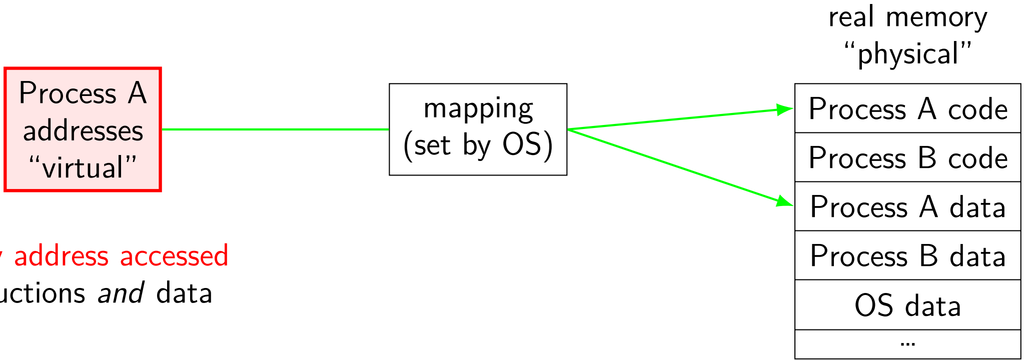


# address translation

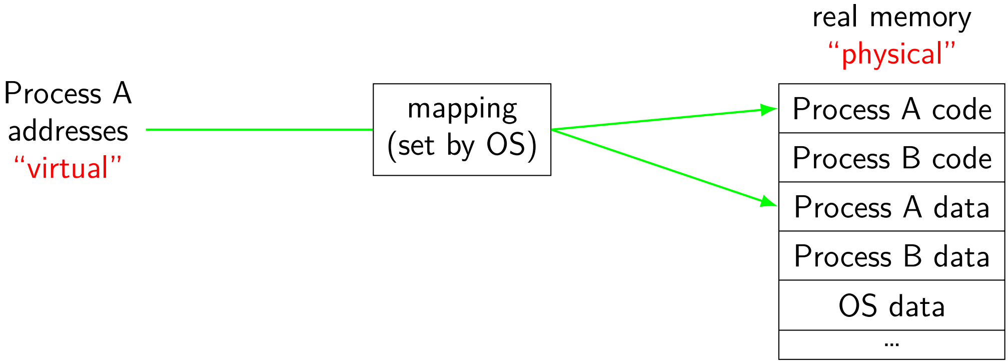


# address translation



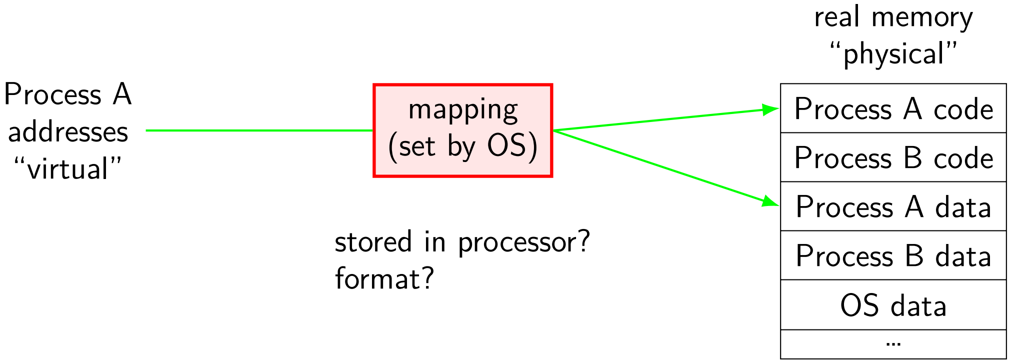

every address accessed
instructions *and* data

# address translation



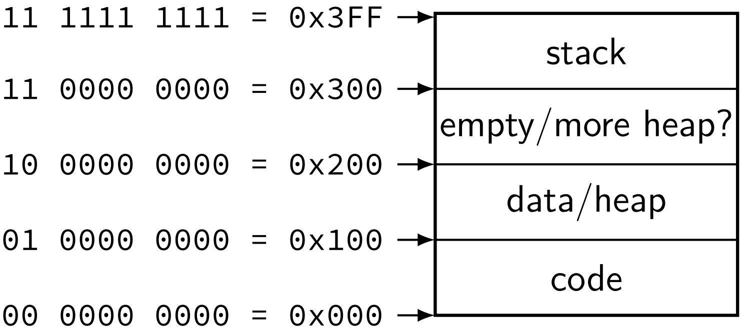

program addresses are ‘virtual’
real addresses are ‘physical’
can be different sizes!

# address translation

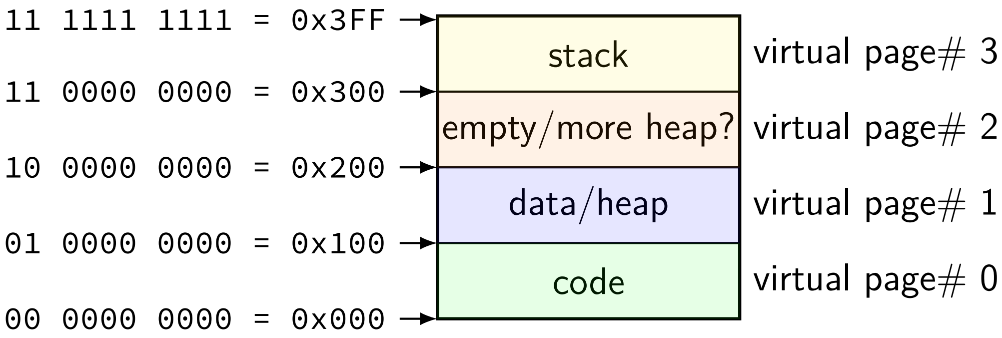



stored in processor?
format?

# toy program memory



# toy program memory



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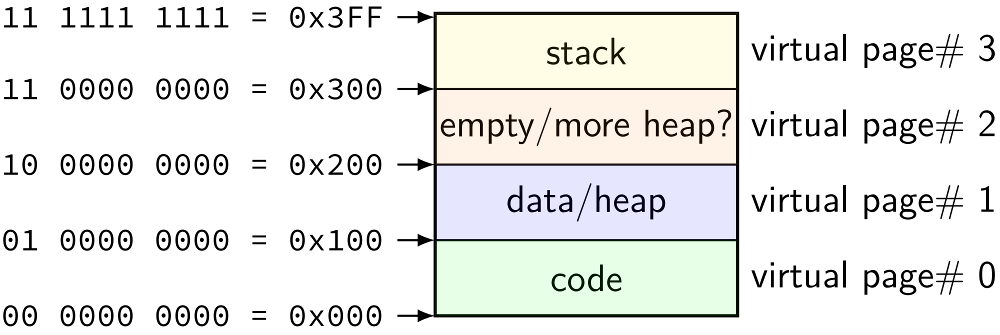
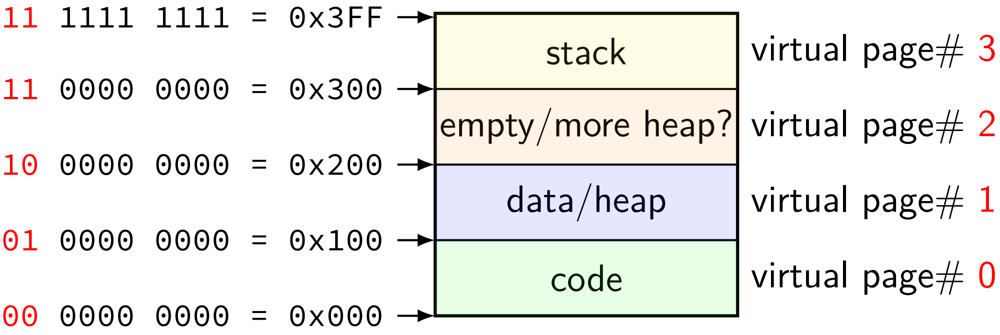


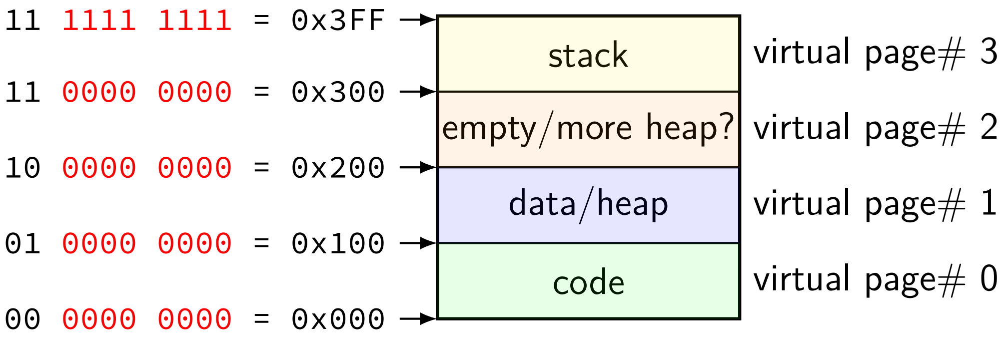

divide memory into pages ($2^8$ bytes in this case)
"virtual" = addresses the program sees

# 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

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` |

real memory
physical addresses

| |
|---|
| `111 0000 0000 to 111 1111 1111` |
| |
| |
| |
| |
| |
| `001 0000 0000 to 001 1111 1111` |
| `000 0000 0000 to 000 1111 1111` |

# toy physical memory

real memory

physical addresses

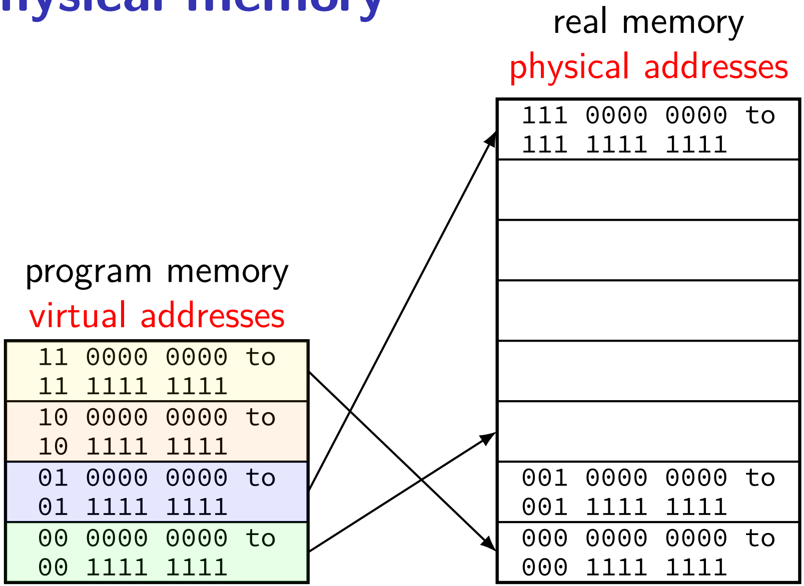
| | |
|---|---|
| 111 0000 0000 to 111 1111 1111 | physical page 7 |
| | |
| | |
| | |
| | |
| | |
| 001 0000 0000 to 001 1111 1111 | physical page 1 |
| 000 0000 0000 to 000 1111 1111 | physical page 0 |

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



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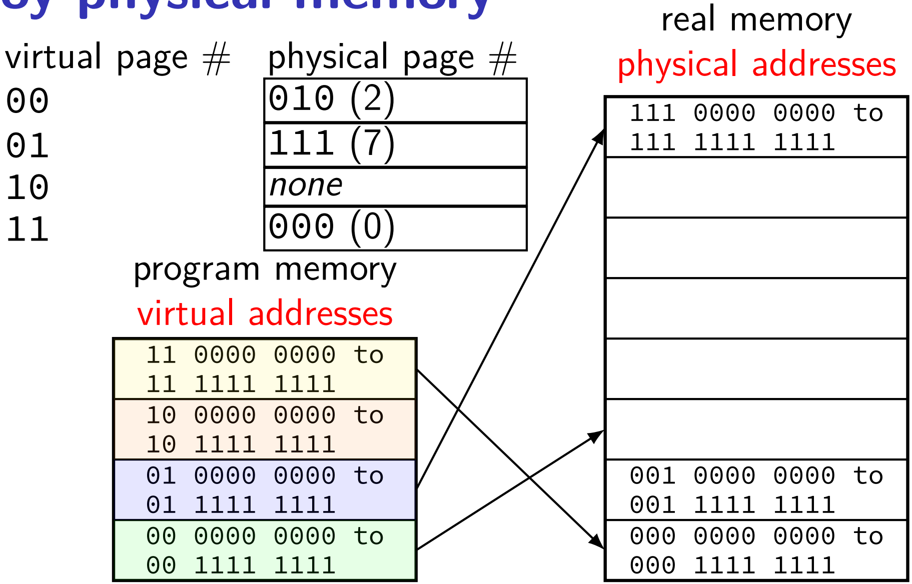


# toy physical memory

**page table!**

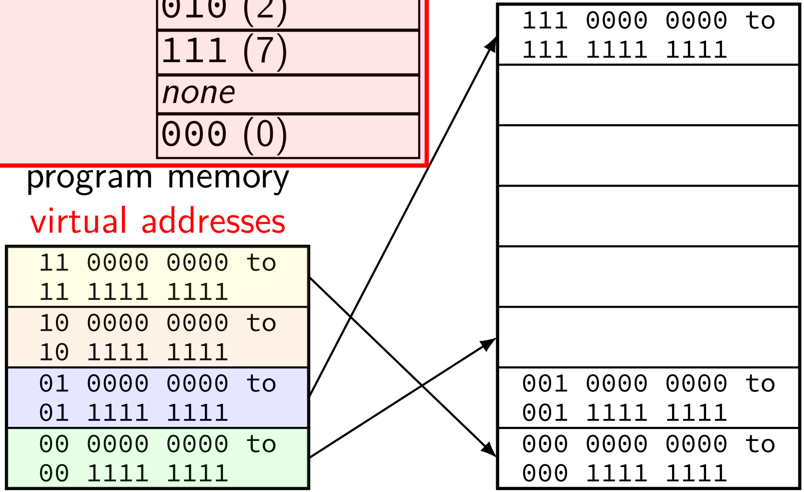
| virtual page # | physical page # |
|---|---|
| 00 | 010 (2) |
| 01 | 111 (7) |
| 10 | *none* |
| 11 | 000 (0) |

program memory

virtual addresses

real memory

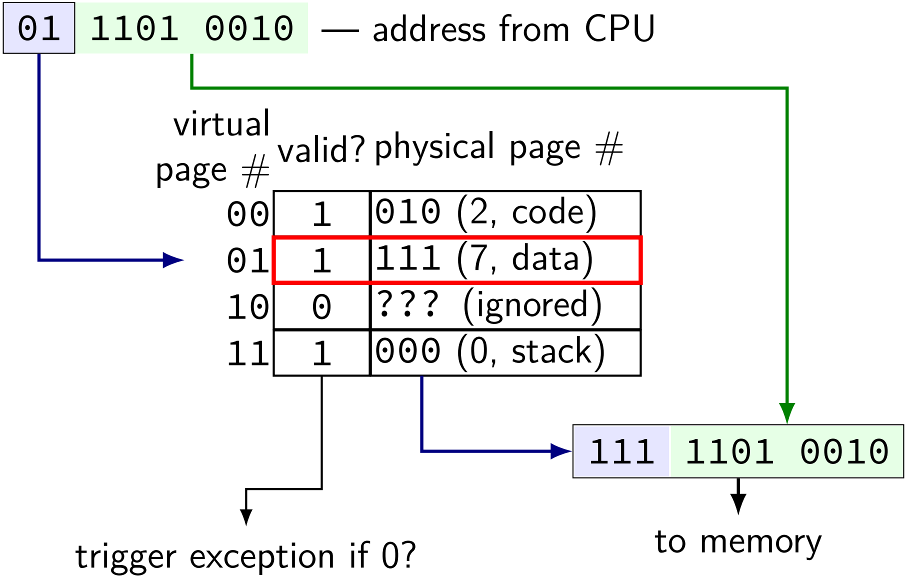
physical addresses



# 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



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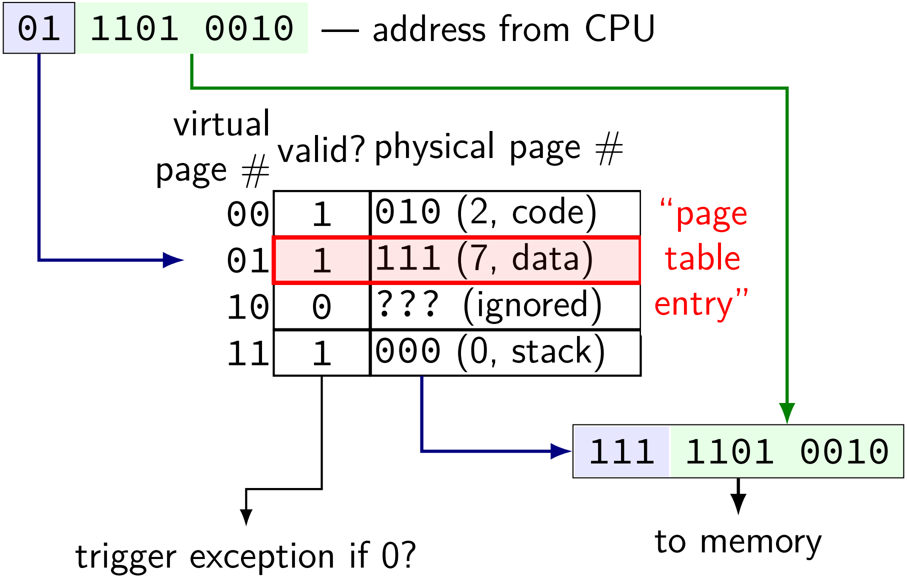
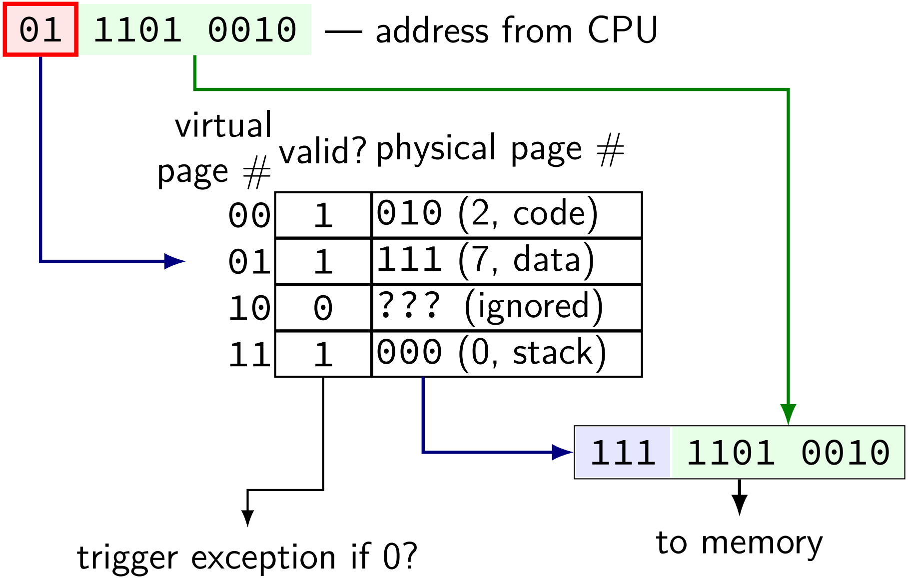
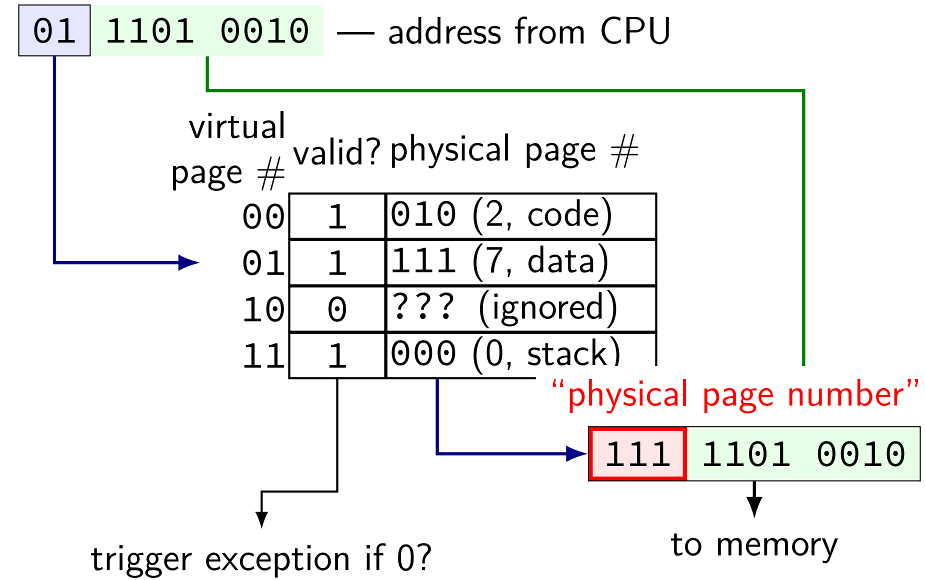


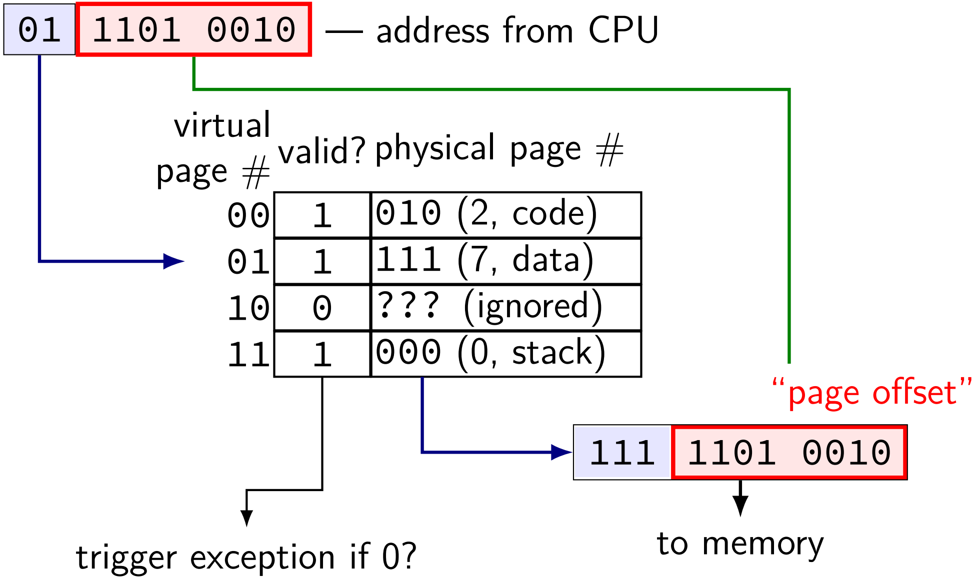
# t “virtual page number” lookup



# toy page table lookup



# toy pag “page offset” ookup



# switching page tables

part of context switch is changing the page table

extra privileged instructions

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where in memory is the code that does this switching?

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- 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

# 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, 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, 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 (chosen by processor)

| | | |
|---|---|---|
| valid (bit 15) | physical page # (bits 4–14) | other bits and/or unused (bit 0-3) |

# page tables in memory

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page table entry layout (chosen by processor)

| | | |
|---|---|---|
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page table
base register

`0x00010000`

# page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout (chosen by processor)

| | | |
|---|---|---|
| valid (bit 15) | physical page # (bits 4–14) | other bits and/or unused (bit 0-3) |

page table
base register

`0x00010000`

physical memory

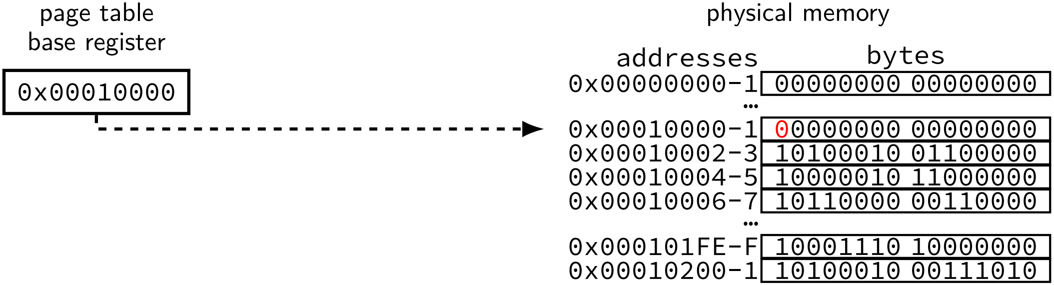
| addresses | bytes |
|---|---|
| 0x00000000-1 | 00000000 00000000 |
| ... | |
| 0x00010000-1 | 00000000 00000000 |
| 0x00010002-3 | 10100010 01100000 |
| 0x00010004-5 | 10000010 11000000 |
| 0x00010006-7 | 10110000 00110000 |
| ... | |
| 0x000101FE-F | 10001110 10000000 |
| 0x00010200-1 | 10100010 00111010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

# page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout (chosen by processor)

| valid (bit 15) | physical page # (bits 4–14) | other bits and/or unused (bit 0-3) |
|---|---|---|



# page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout (chosen by processor)

| valid (bit 15) | physical page # (bits 4–14) | other bits and/or 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 (chosen by processor)

| | | |
|---|---|---|
| valid (bit 15) | physical page # (bits 4–14) | other bits and/or 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 (chosen by processor)

| valid (bit 15) | physical page # (bits 4–14) | other bits and/or unused (bit 0-3) |
|---|---|---|

page table base register

`0x00010000`

page table (logically)

| virtual page # | valid? | … | physical page # |
|---|---|---|---|
| 0000 0000 | 0 | … | 00 0000 0000 |
| 0000 0001 | 1 | … | 10 0010 0110 |
| 0000 0010 | 1 | … | 00 0000 1100 |
| 0000 0011 | 1 | … | 11 0000 0011 |
| … | | | |
| 1111 1111 | 1 | … | 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 |
| 0x00010200-1 | 10100010 00111010 |

# page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout (chosen by processor)

| valid (bit 15) | physical page # (bits 4–14) | other bits and/or unused (bit 0-3) |
|---|---|---|

page table base register

`0x00010000`

page table (logically)

| virtual page # | valid? | … | physical page # |
|---|---|---|---|
| 0000 0000 | 0 | … | 00 0000 0000 |
| 0000 0001 | 1 | … | 10 0010 0110 |
| 0000 0010 | 1 | … | 00 0000 1100 |
| 0000 0011 | 1 | … | 11 0000 0011 |
| … | | | |
| 1111 1111 | 1 | … | 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 |
| 0x00010200-1 | 10100010 00111010 |

# page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout (chosen by processor)

| valid (bit 15) | physical page # (bits 4–14) | other bits and/or unused (bit 0-3) |
|---|---|---|

page table
base register

`0x00010000`

page table (logically)

| virtual page # | valid? | ... | physical page # |
|---|---|---|---|
| 0000 0000 | 0 | ... | 00 0000 0000 |
| 0000 0001 | 1 | ... | 10 0010 0110 |
| 0000 0010 | 1 | ... | 00 0000 1100 |
| 0000 0011 | 1 | ... | 11 0000 0011 |
| ... | | | |
| 1111 1111 | 1 | ... | 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 |
| 0x00010200-1 | 10100010 00111010 |

# page tables in memory

where can processor store megabytes of page tables? in memory

page table entry layout (chosen by processor)

| valid (bit 15) | physical page # (bits 4–14) | other bits and/or unused (bit 0-3) |
|---|---|---|

page table
base register

0x00010000

page table (logically)

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

physical memory

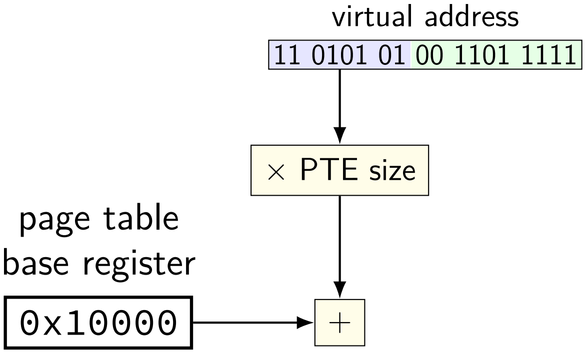
| addresses | bytes |
|---|---|
| 0x00000000-1 | 00000000 00000000 |
| ... | |
| 0x00010000-1 | 00000000 00000000 |
| 0x00010002-3 | 10100010 01100000 |
| 0x00010004-5 | 10000010 11000000 |
| 0x00010006-7 | 10110000 00110000 |
| ... | |
| 0x000101FE-F | 10001110 10000000 |
| 0x00010200-1 | 10100010 00111010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

# memory access with page table

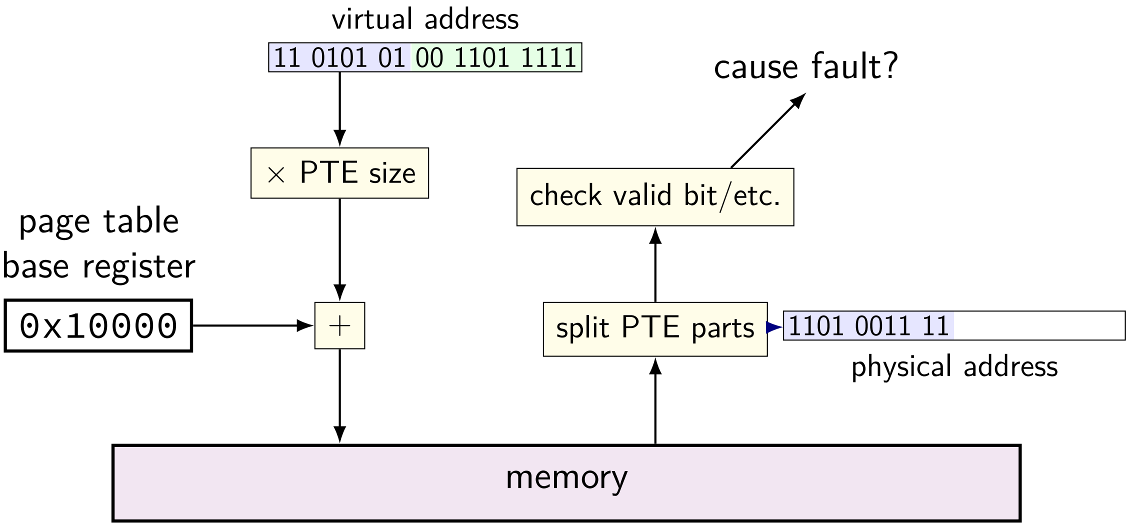
virtual address

| | |
|---|---|
| 11 0101 01 | 00 1101 1111 |

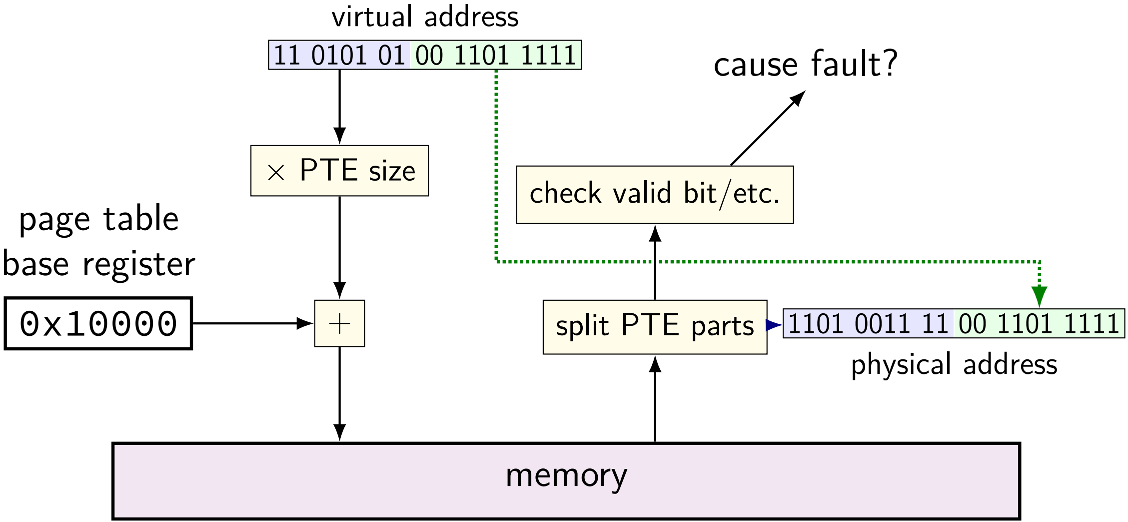
# memory access with page table



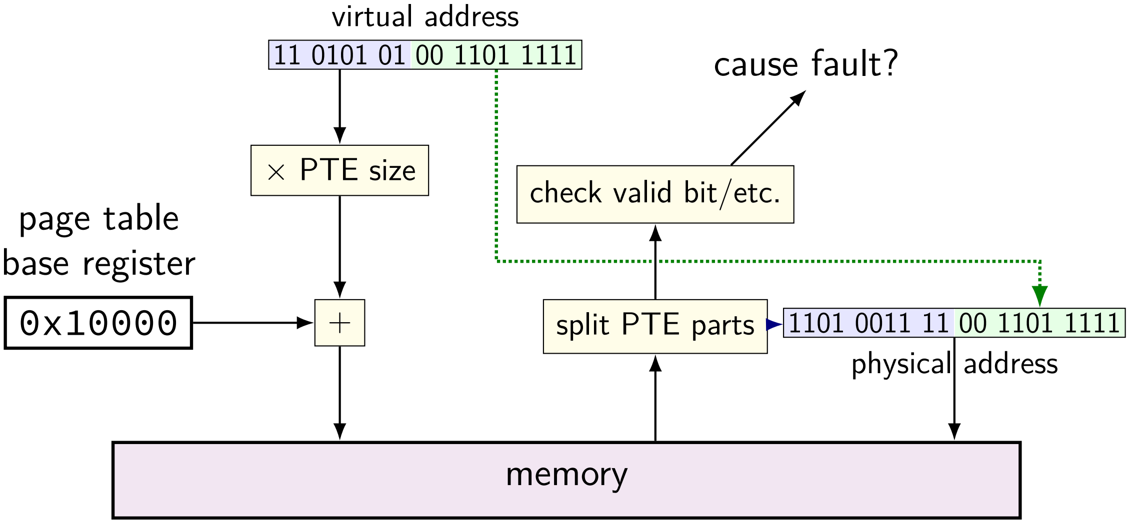
# memory access with page table



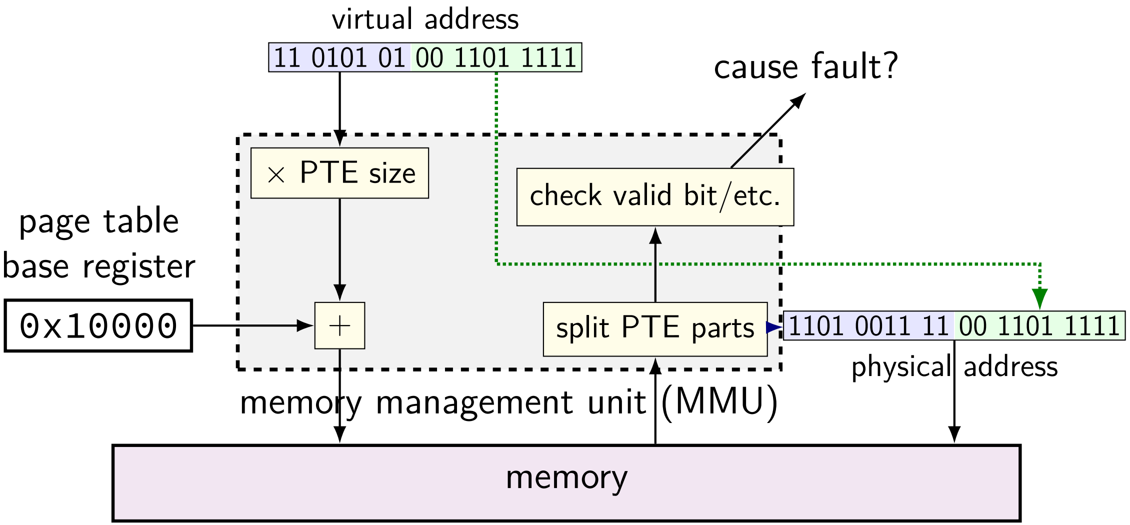
# memory access with page table



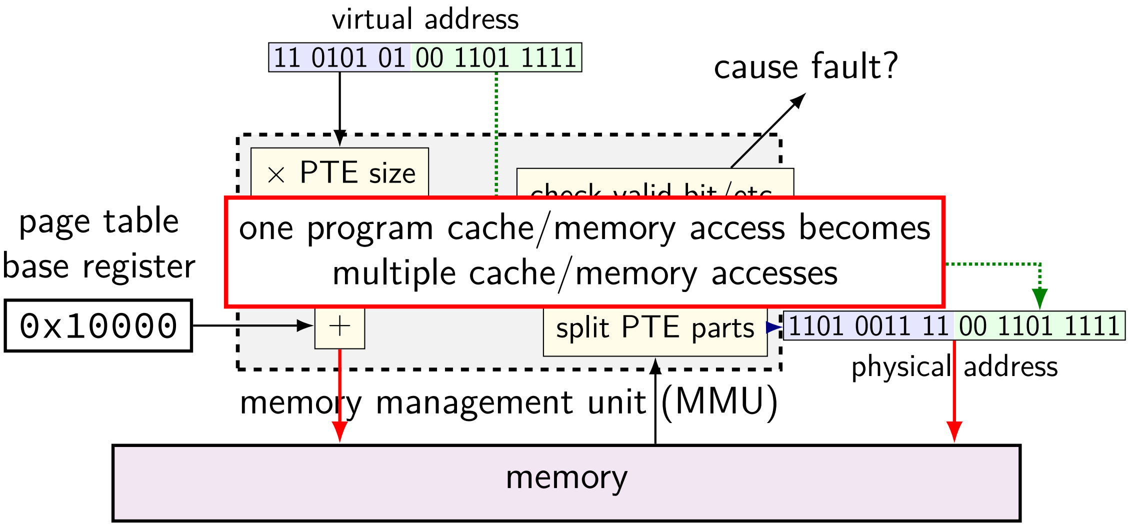
# memory access with page table



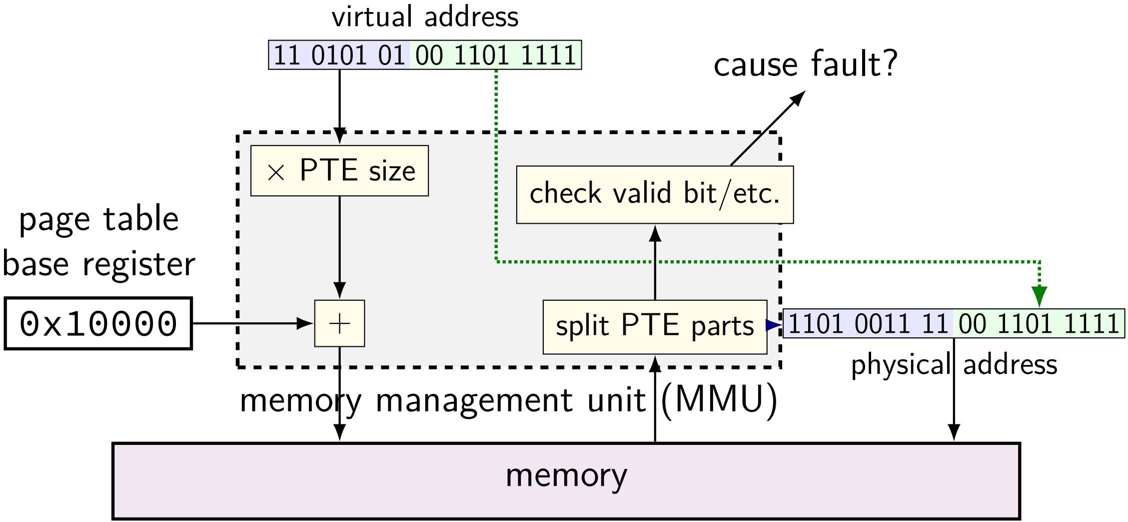
# memory access with page table



# memory access with page table



# 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 |
| 0x38−B | DC 0C DC 0C |
| 0x3C−F | EC 0C EC 0C |

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

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| 00 | 1 | 010 |
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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 |
| 0x1C-F | 1C 2C 3C 4C |

phys. page 0

phys. page 1

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

# 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 |
| 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 |
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| 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 |
| 0x38-B | DC 0C DC 0C |
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# exercise

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

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| virtual page # | valid? | physical page # |
|---|---|---|
| 00 | 1 | 010 |
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| 11 | 1 | 000 |

| physical addresses | bytes |
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| 0x00-3 | 00 11 22 33 |
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| 0x0C-F | CC DD EE FF |
| 0x10-3 | 1A 2A 3A 4A |
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| 0x18-B | 1C 2C 3C 4C |
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| 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 |
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|---|---|---|
| 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 |
| 0x38-B | DC 0C DC 0C |
| 0x3C-F | EC 0C EC 0C |

# 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 |
| 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 |
| 0x38-B | DC 0C DC 0C |
| 0x3C-F | EC 0C EC 0C |

# 1-level exercise (1)

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;

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 |
| 0x3C-F | EC 0C EC 0C |

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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 |
| 0x3C-F | EC 0C EC 0C |

`0x31` = `11 0001`

*PTE addr:*

`0x20` + 6 ×1 = `0x26`

*PTE value:*

`0xF6` = `1111 0110`

PPN `111`, valid 1

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

→ `0x0C`

# 1-level exercise (1)

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;

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 |
| 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 exercise (1)

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;

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 |
| 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 exercise (2)

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

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 exercise (2)

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

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 exercise (2)

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

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 |
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| physical addresses | bytes |
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| 0x20-3 | D0 D1 D2 D3 |
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| 0x2C-F | CD DE EF F0 |
| 0x30-3 | BA 0A BA 0A |
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| 0x38-B | DC 0C DC 0C |
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`0x12` $=$ `01 0010`

*PTE addr:*

`0x20` $+ 2 \times 1 =$ `0x22`

*PTE value:*

`0xD2` $=$ `1101 0010`

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# exercise: 64-bit system

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

4096 byte pages

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

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4096 byte pages

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

exercise: how large are physical page numbers?

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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??)

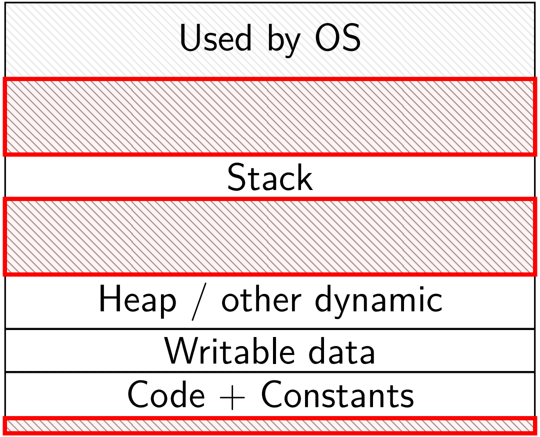
# huge page tables

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?

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hashtable

- actually used by some historical processors
- but never common

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- actually used by some historical processors
- but never common

tree data structure

- but not quite a search tree

# search tree tradeoffs

lookup usually implemented in hardware

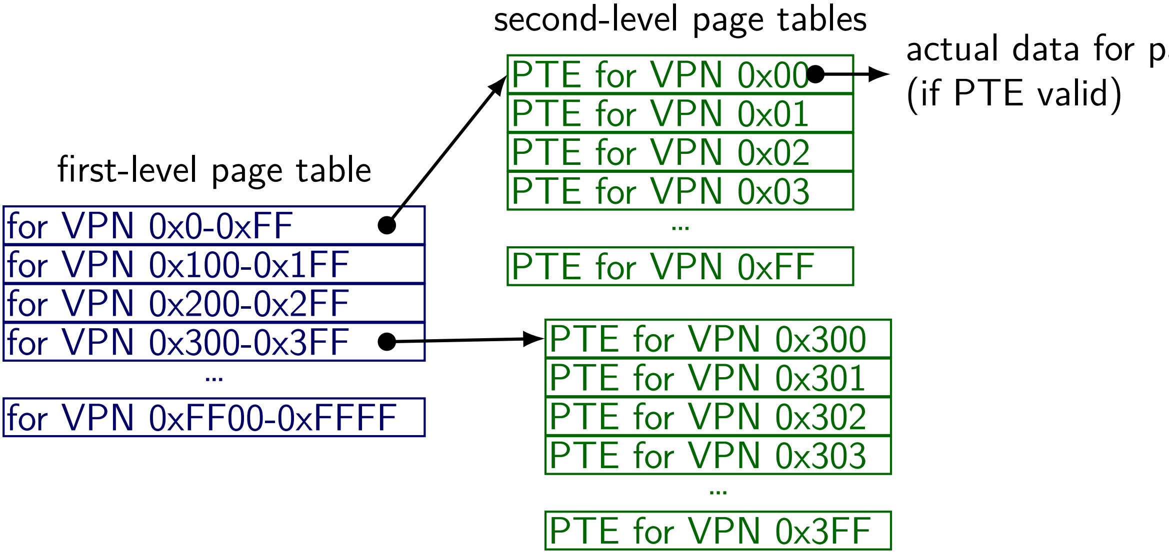
- lookup should be simple
- solution: lookup splits up address bits (no complex calculations)

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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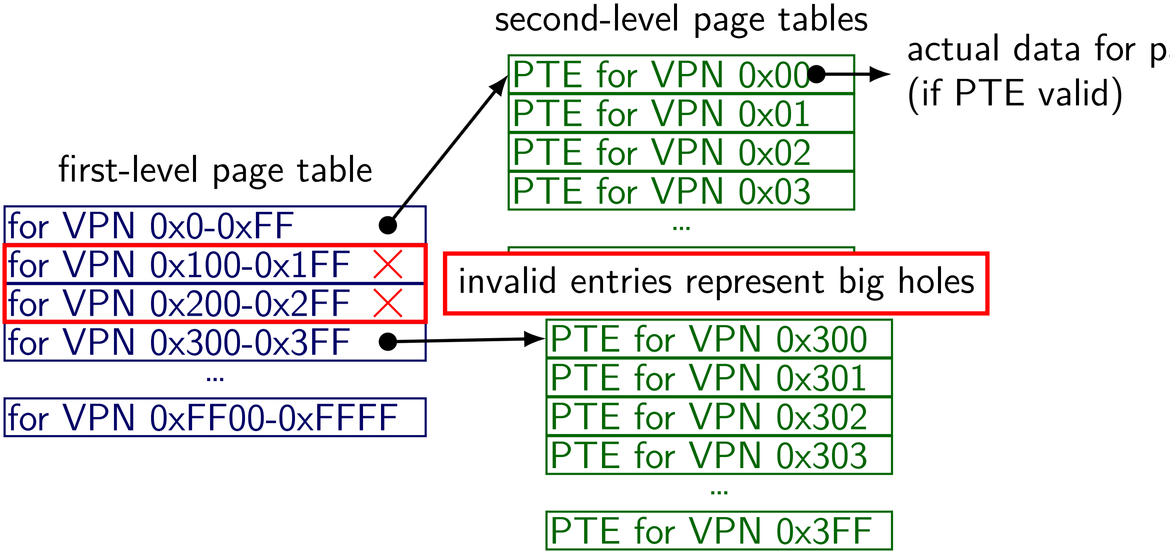

# two-level page tables

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

**first-level page table**

| VPN range | valid | … | 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 pag

for VPN 0x0-0xF

for VPN 0x100-0

for VPN 0x200-0

for VPN 0x300-0

…

for VPN 0xFF00

for p

d)

PTE for VPN 0x303

…

PTE for VPN 0x3FF

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

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

| |
|---|
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| … |
| 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

# 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 0x300-0x3FF

…

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…

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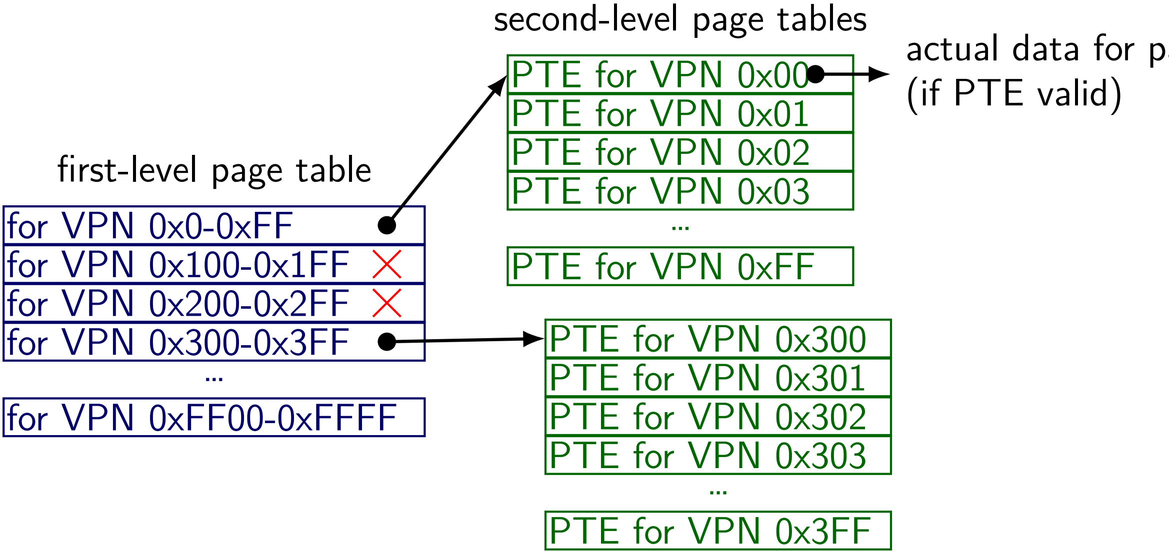
# two-level page tables

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



# two-level page table lookup

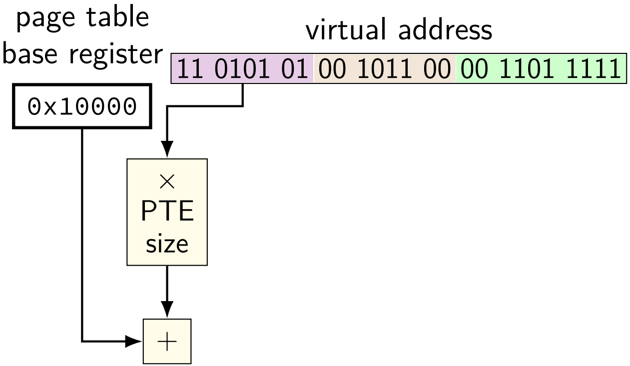
virtual address

| | | |
|---|---|---|
| 11 0101 01 | 00 1011 00 | 00 1101 1111 |

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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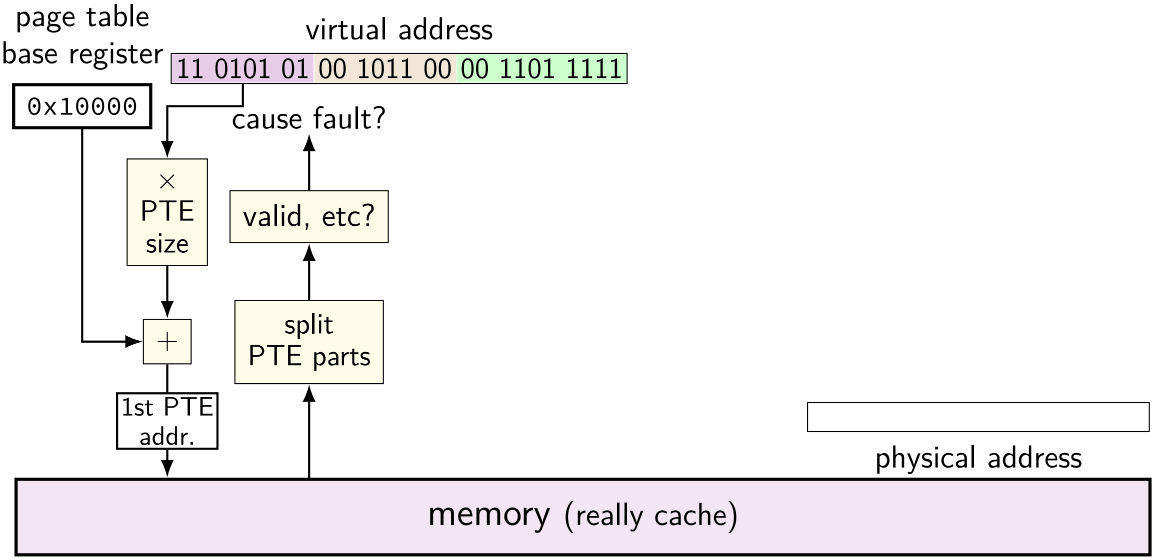

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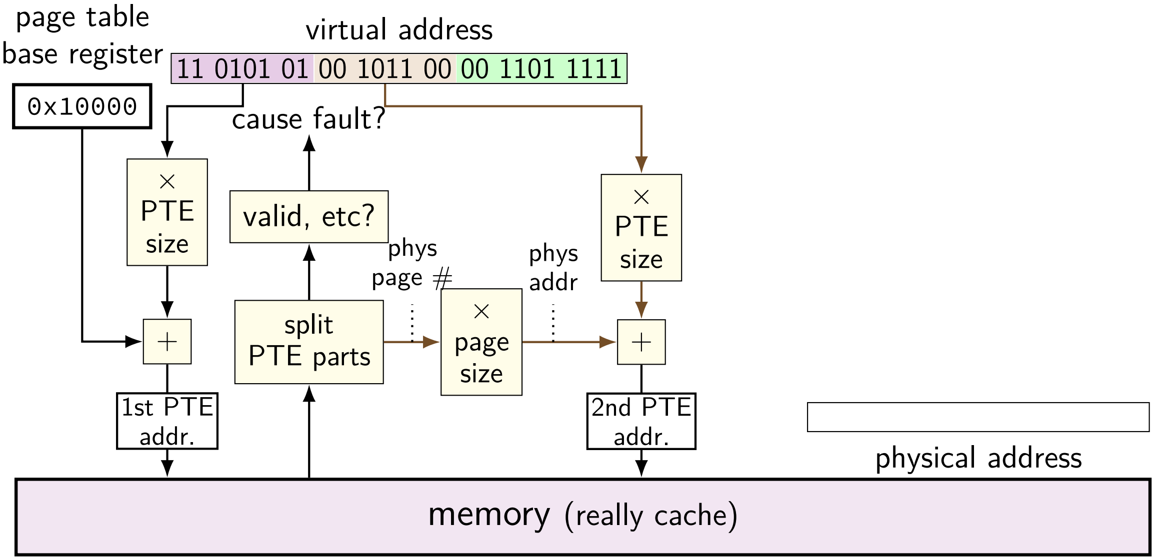

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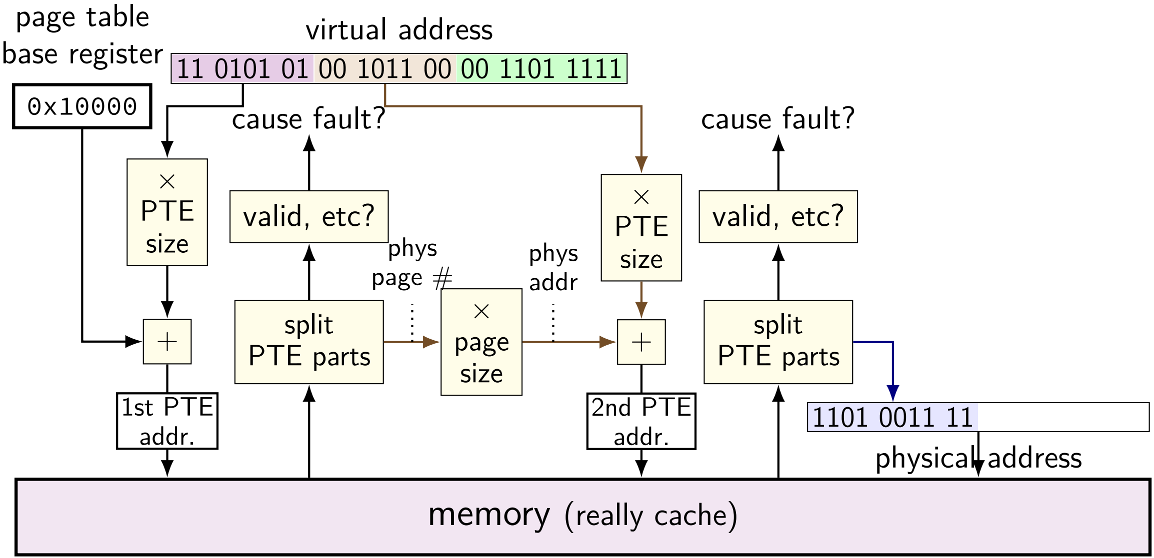

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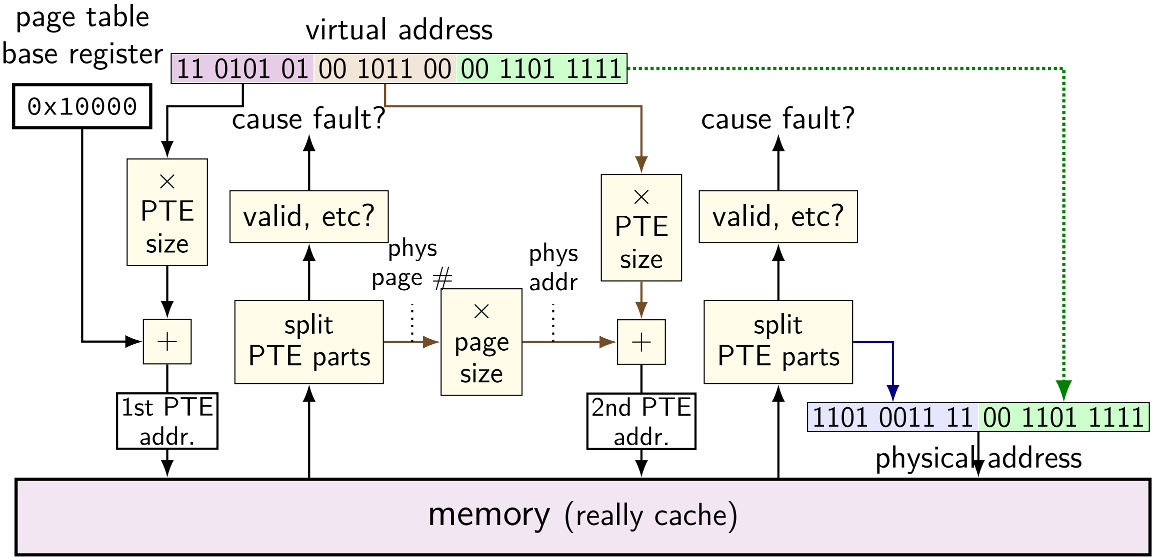

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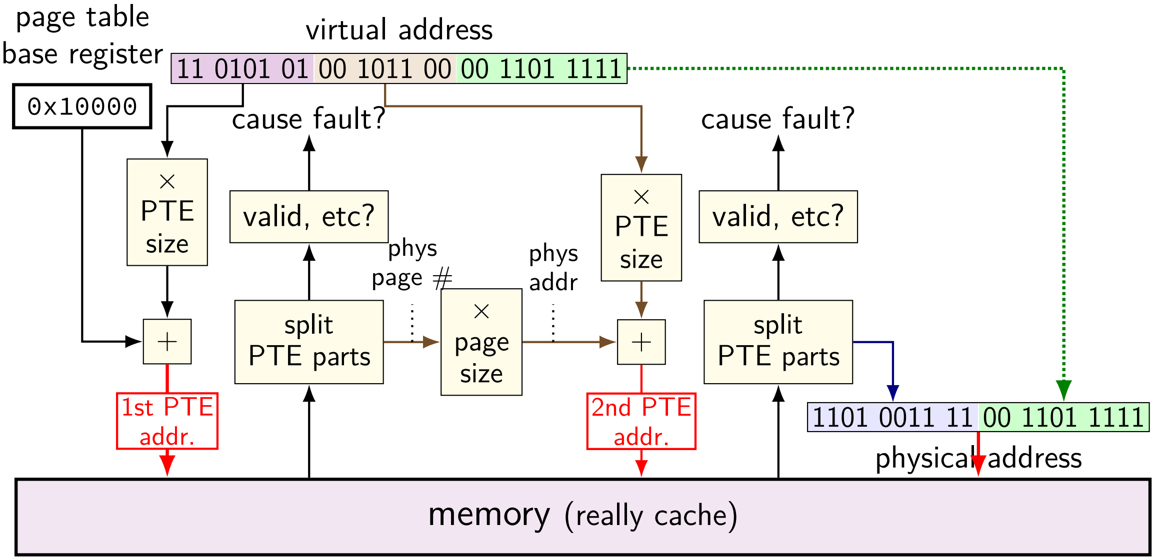

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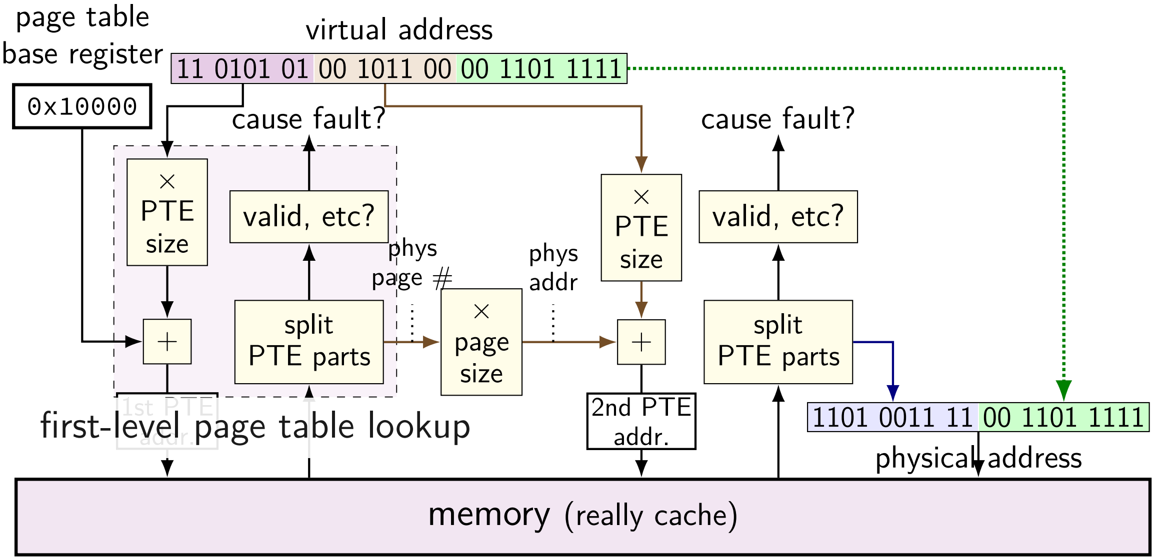

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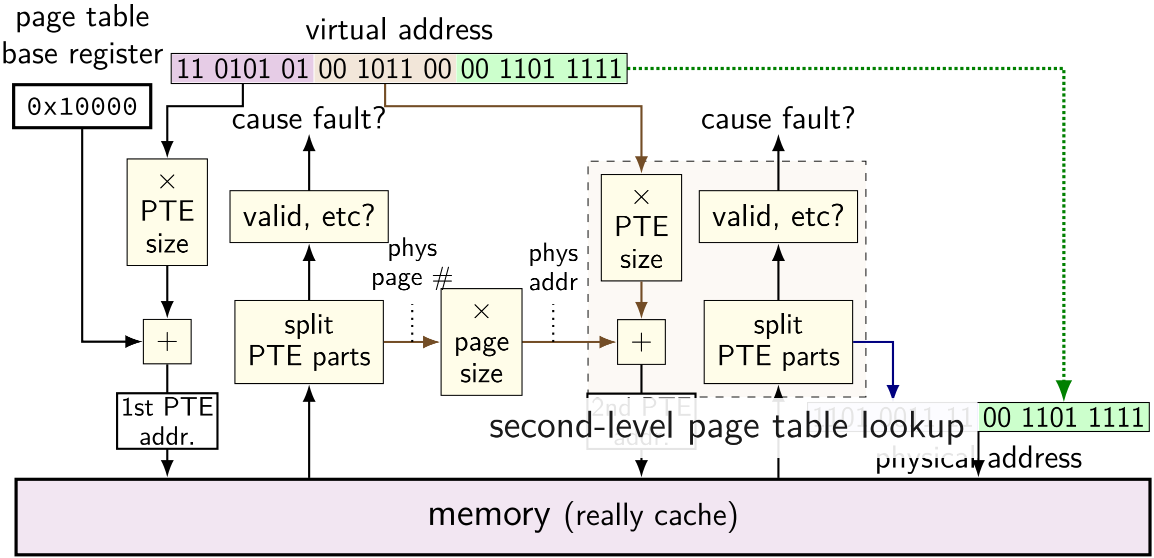

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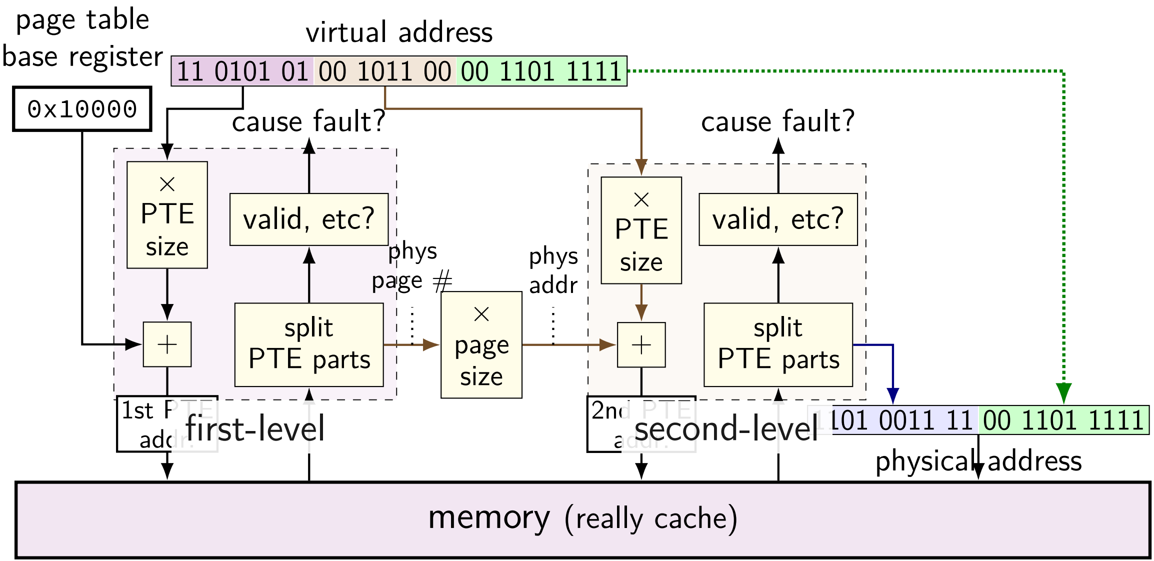

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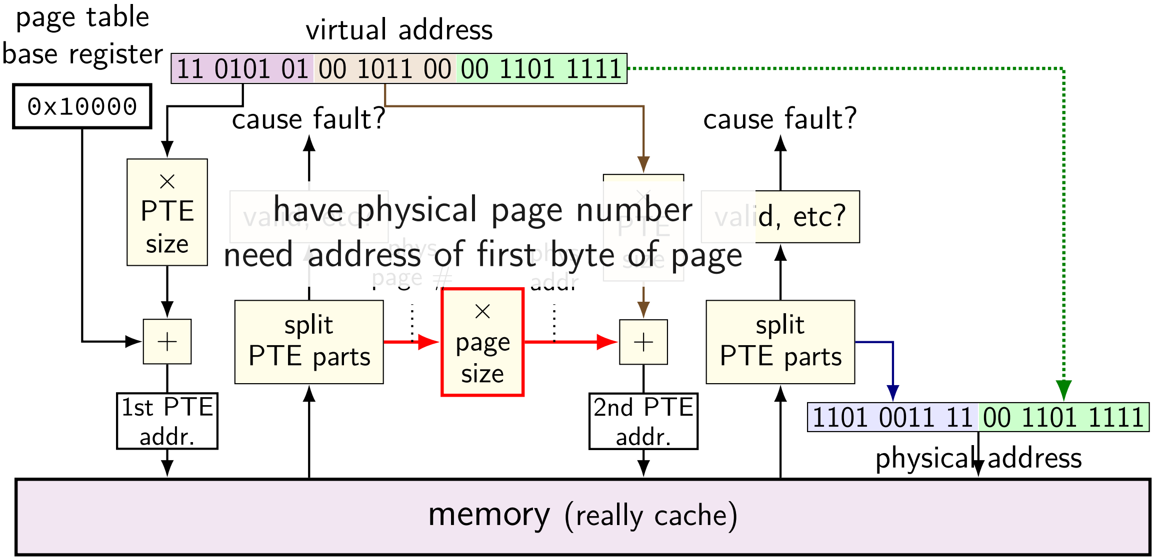

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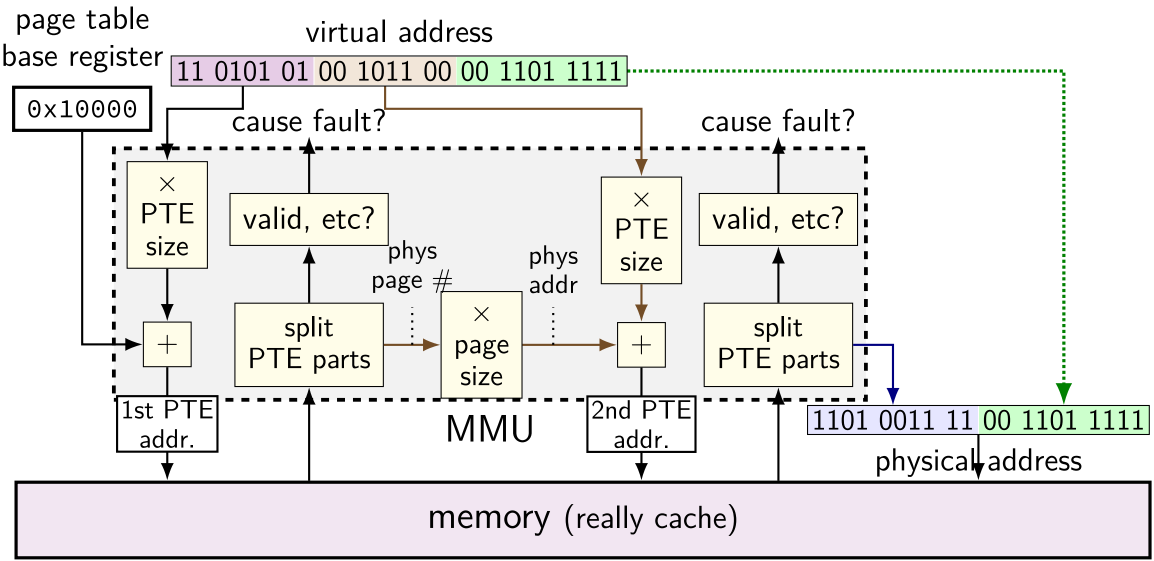
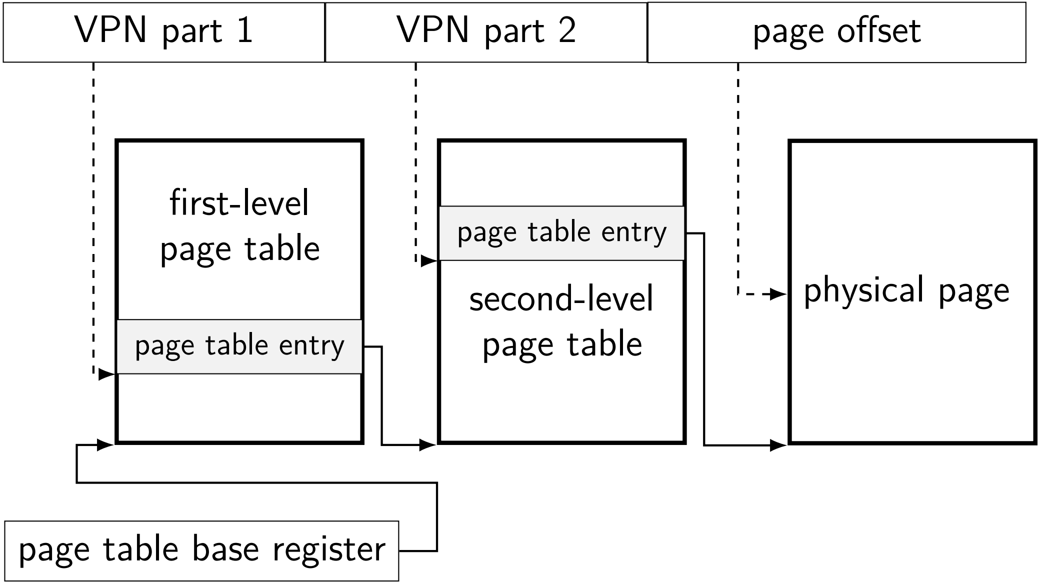


# another view



# 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 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

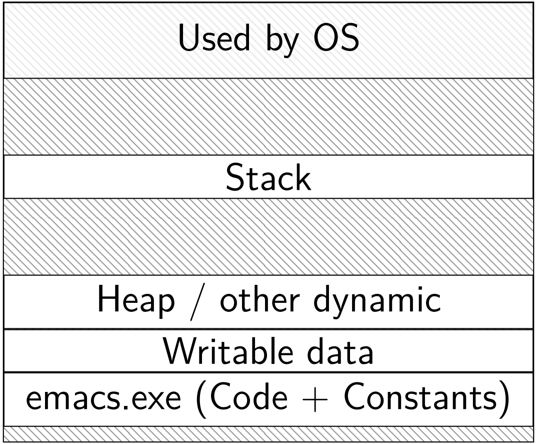
# note on VPN splitting

indexes used for lookup parts of the virtual page number

(there are not multiple VPNs)

# emacs.exe

Emacs (run by user mst3k)



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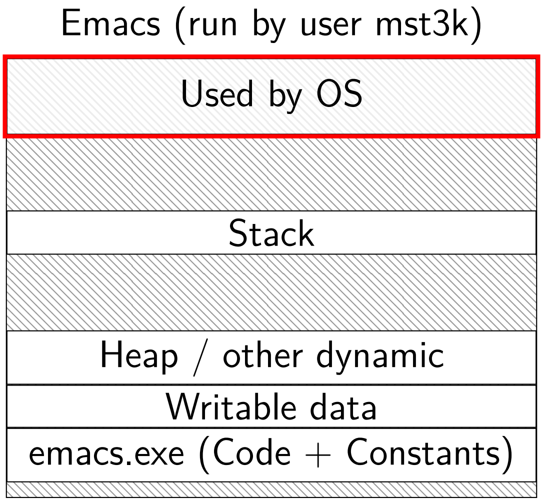
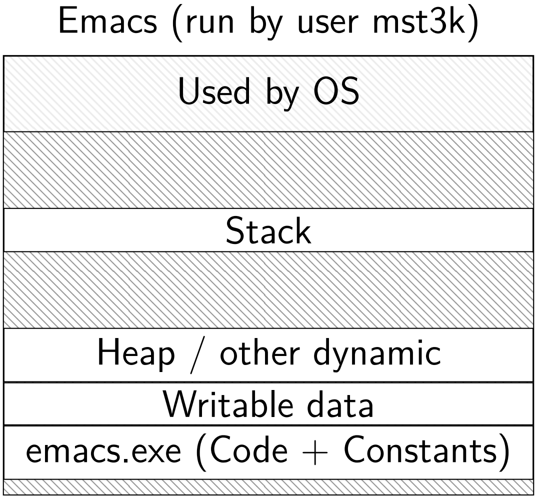
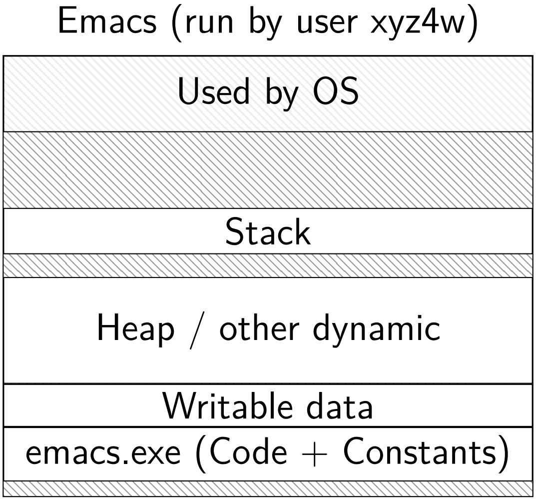



**OS's memory**

# emacs (two copies)



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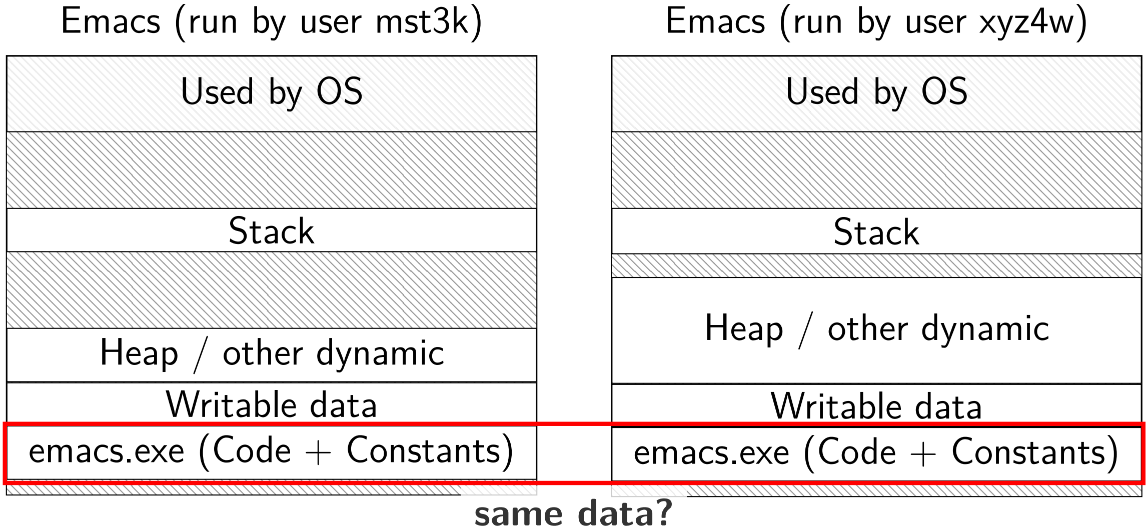

# two copies of program

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 |
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| 0x00-3 | 00 11 22 33 |
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| 0x30-3 | BA 0A BA 0A |
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| 0x3C-F | FC 0C FC 0C |

# 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 |
| 0x34-7 | DB 0B DB 0B |
| 0x38-B | EC 0C EC 0C |
| 0x3C-F | FC 0C FC 0C |

# 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 |
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| physical addresses | bytes |
|---|---|
| 0x20-3 | D0 D1 D2 D3 |
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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 (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 |
| 0x34-7 | DB 0B DB 0B |
| 0x38-B | EC 0C EC 0C |
| 0x3C-F | FC 0C FC 0C |

# 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 |
| 0x34-7 | DB 0B DB 0B |
| 0x38-B | EC 0C EC 0C |
| 0x3C-F | FC 0C FC 0C |

# 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 |
| 0x34-7 | DB 0B DB 0B |
| 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 |
| 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 |
| 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 |
| 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 (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 |
|---|---|
| 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 (5)

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

page tables 1 page; PTE 1st byte: (MSB) 2-bit PPN, 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 |

| physical addresses | bytes |
|---|---|
| 0x20-3 | D0 E1 D2 D3 |
| 0x24-7 | D4 E5 D6 E7 |
| 0x28-B | 89 9A AB BC |
| 0x2C-F | CD DE EF F0 |
| 0x30-3 | BA 0A BA 0A |
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page tables 1 page; PTE 1st byte: (MSB) 2-bit PPN, valid bit; rest unused

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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 |
| 0x1C-F | AC BC DC EC |

| physical addresses | bytes |
|---|---|
| 0x20-3 | D0 E1 D2 D3 |
| 0x24-7 | D4 E5 D6 E7 |
| 0x28-B | 89 9A AB BC |
| 0x2C-F | CD DE EF F0 |
| 0x30-3 | BA 0A BA 0A |
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| 0x10-3 | 1A 2A 3A 4A |
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|---|---|
| 0x00-3 | 00 11 22 33 |
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| 0x10-3 | 1A 2A 3A 4A |
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| 0x1C-F | AC BC DC EC |

| physical addresses | bytes |
|---|---|
| 0x20-3 | D0 E1 D2 D3 |
| 0x24-7 | D4 E5 D6 E7 |
| 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 |
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page tables 1 page; PTE 1st byte: (MSB) 2-bit PPN, 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 |
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| 0x20-3 | D0 E1 D2 D3 |
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page tables 1 page; PTE 1st byte: (MSB) 2-bit PPN, valid bit; rest unused

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

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|---|---|
| 0x00-3 | 00 11 22 33 |
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| 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 |

| physical addresses | bytes |
|---|---|
| 0x20-3 | D0 E1 D2 D3 |
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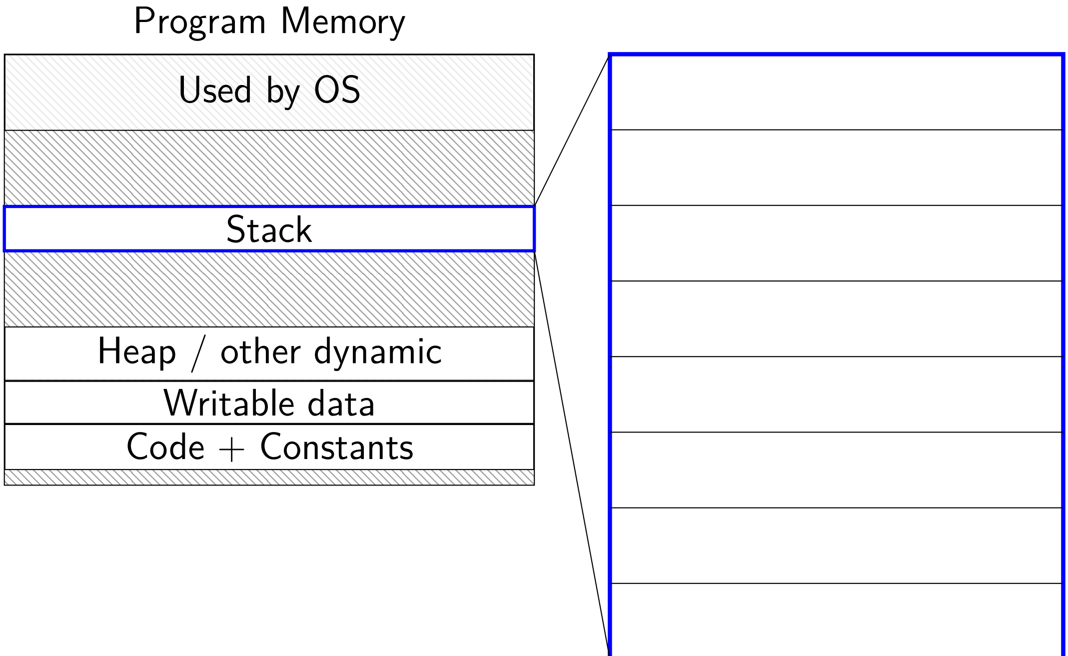
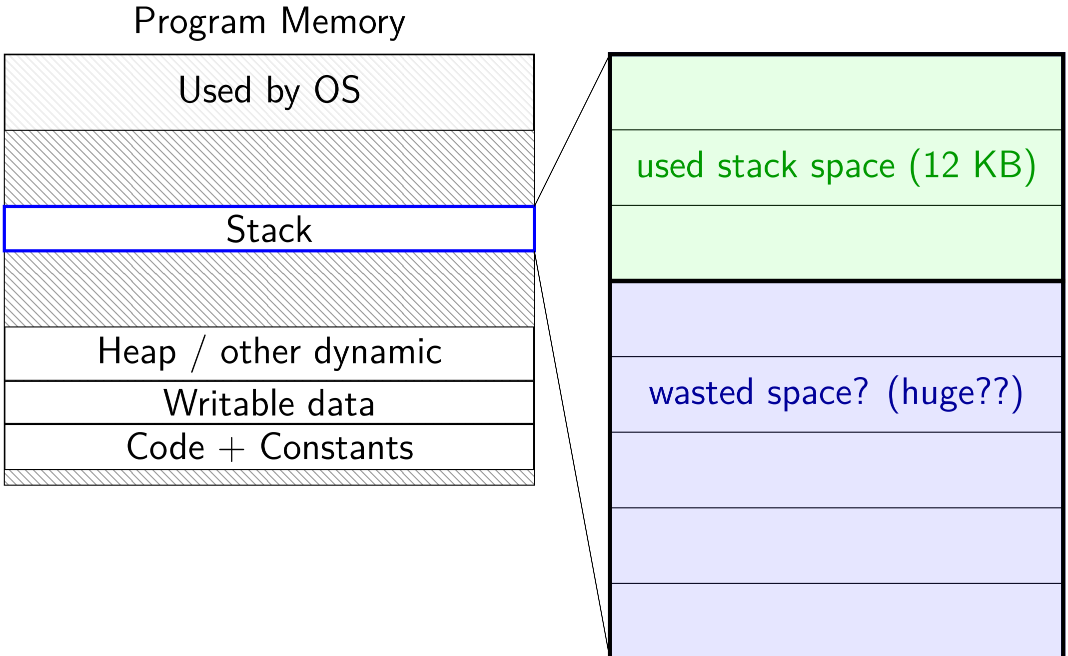
| 0x34-7 | DB 0B DB 0B |
| 0x38-B | EC 0C EC 0C |
| 0x3C-F | FC 0C FC 0C |

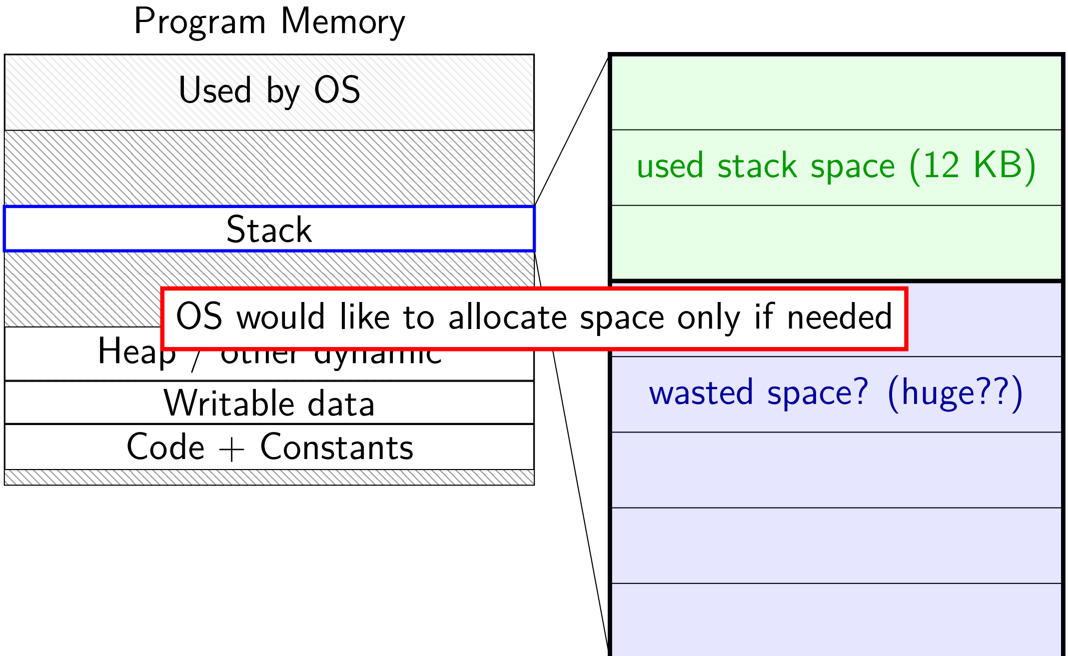
# space on demand



# 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
7f60c7490000-7f60c764e000 r-xp 00000000 08:01 96659129   /lib/x86_64-linux-gnu/libc-2.1
7f60c764e000-7f60c784e000 ---p 001be000 08:01 96659129   /lib/x86_64-linux-gnu/libc-2.1
7f60c784e000-7f60c7852000 r--p 001be000 08:01 96659129   /lib/x86_64-linux-gnu/libc-2.1
7f60c7852000-7f60c7854000 rw-p 001c2000 08:01 96659129   /lib/x86_64-linux-gnu/libc-2.1
7f60c7854000-7f60c7859000 rw-p 00000000 00:00 0
7f60c7859000-7f60c787c000 r-xp 00000000 08:01 96659109   /lib/x86_64-linux-gnu/ld-2.19.s
7f60c7a39000-7f60c7a3b000 rw-p 00000000 00:00 0
7f60c7a7a000-7f60c7a7b000 rw-p 00000000 00:00 0
7f60c7a7b000-7f60c7a7c000 r--p 00022000 08:01 96659109   /lib/x86_64-linux-gnu/ld-2.19.s
7f60c7a7c000-7f60c7a7d000 rw-p 00023000 08:01 96659109   /lib/x86_64-linux-gnu/ld-2.19.s
7f60c7a7d000-7f60c7a7e000 rw-p 00000000 00:00 0
7ffc5d2b2000-7ffc5d2d3000 rw-p 00000000 00:00 0          [stack]
7ffc5d3b0000-7ffc5d3b3000 r--p 00000000 00:00 0          [vvar]
7ffc5d3b3000-7ffc5d3b5000 r-xp 00000000 00:00 0          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0  [vsyscall]
```

# 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
7f60c7490                                                gnu/libc-2.1
7f60c764e0                                               gnu/libc-2.1
7f60c784e0                                               gnu/libc-2.1
7f60c7852                                                gnu/libc-2.1
7f60c7854
7f60c7859                                                gnu/ld-2.19.s
7f60c7a39
7f60c7a7a0
7f60c7a7b0                                               gnu/ld-2.19.s
7f60c7a7c0                                               gnu/ld-2.19.s
7f60c7a7d0
7ffc5d2b2
7ffc5d3b0
7ffc5d3b3
ffffffff
```

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 seperate 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. can't notice if instructions were executed in parallel

# 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

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# 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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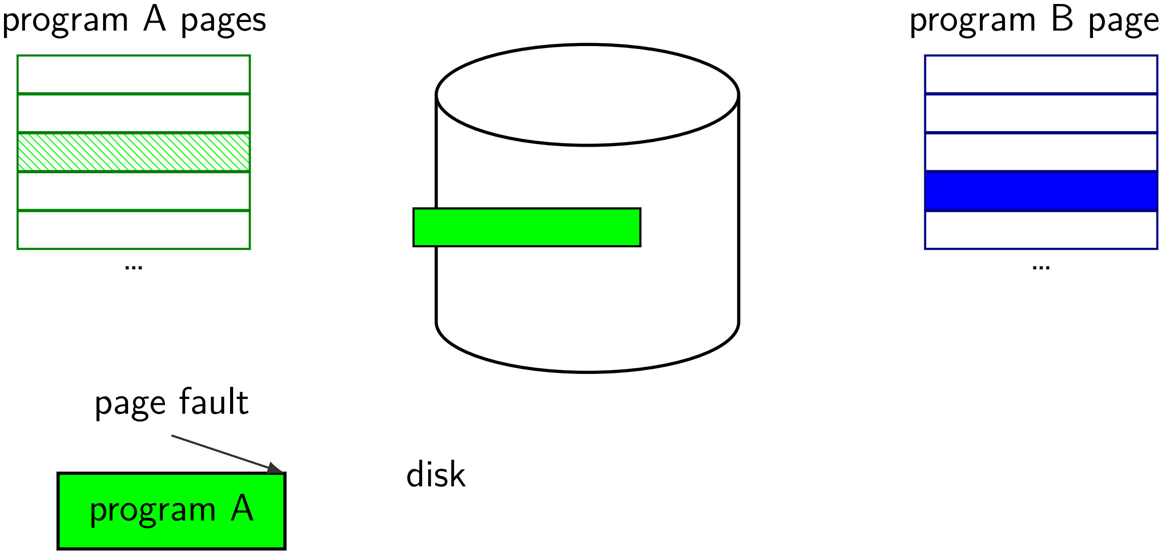
# swapping timeline



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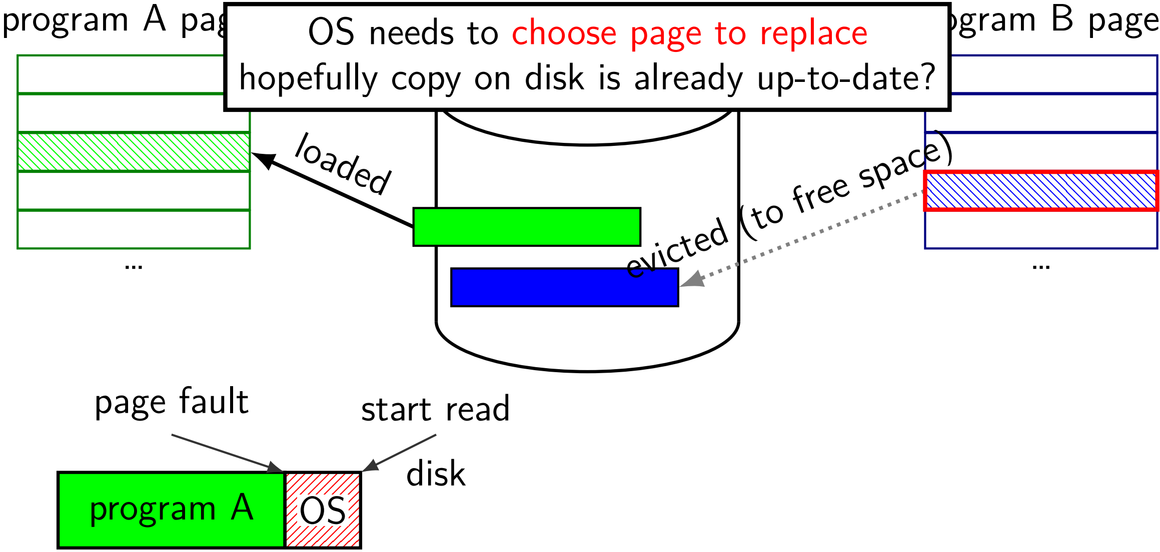

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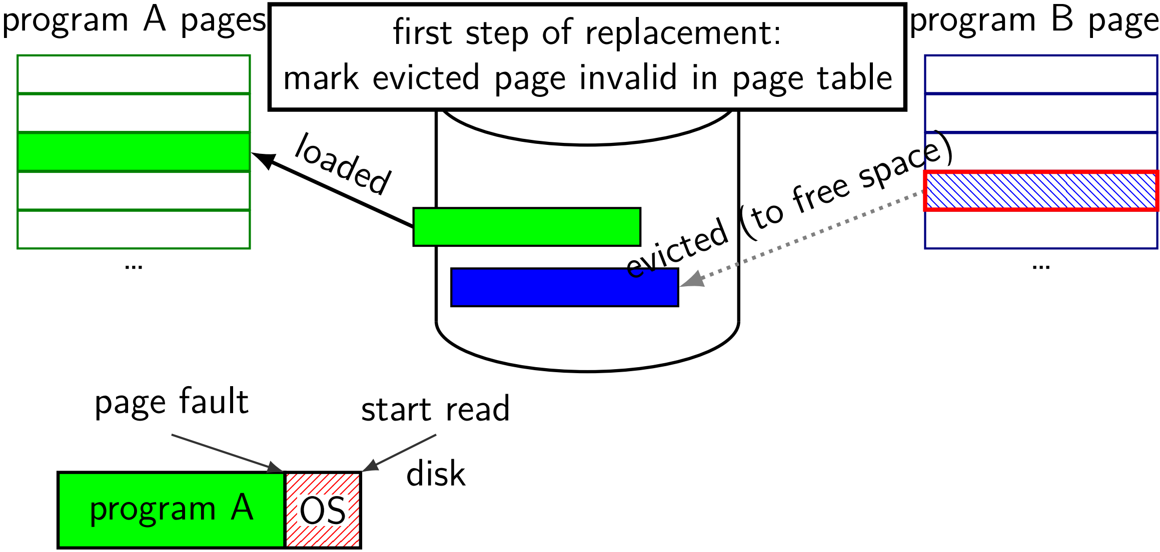

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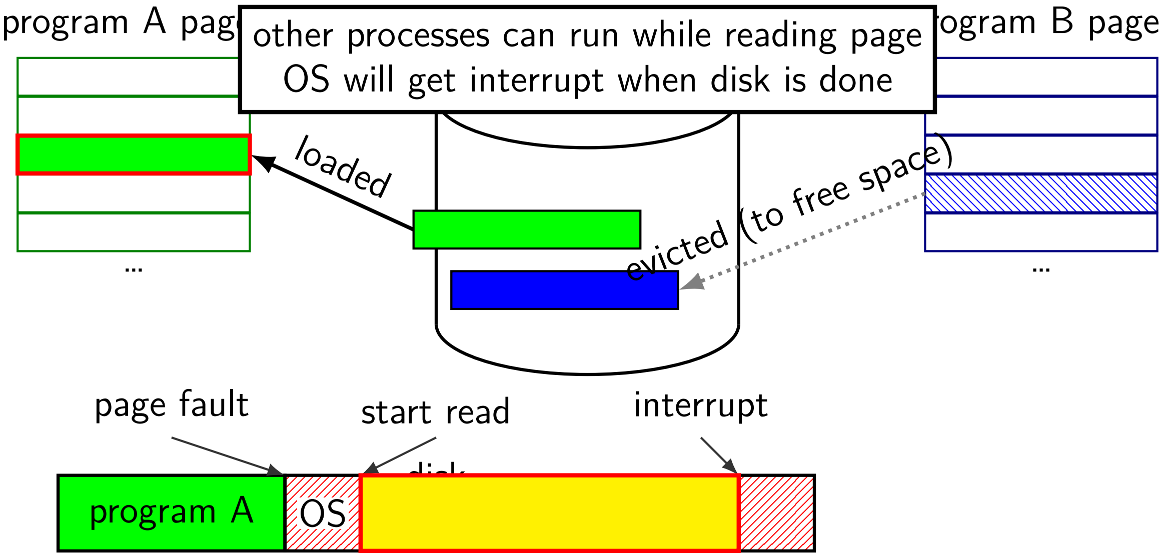

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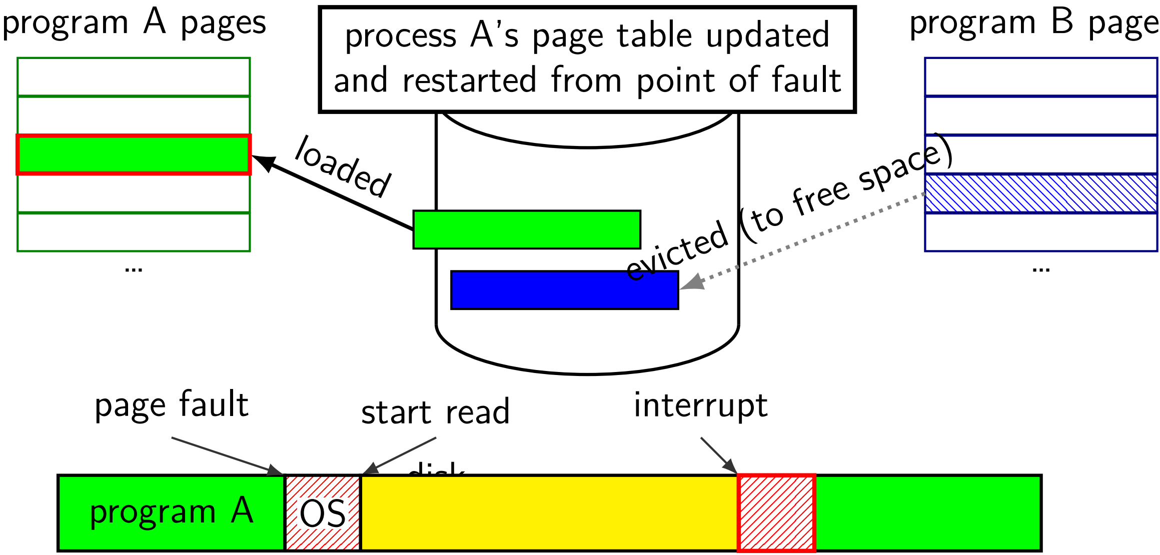

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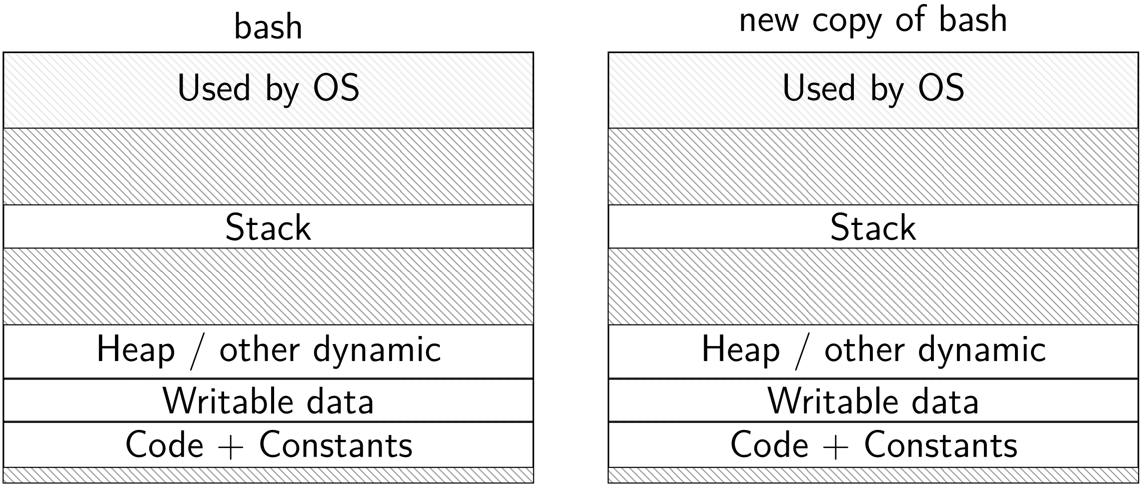

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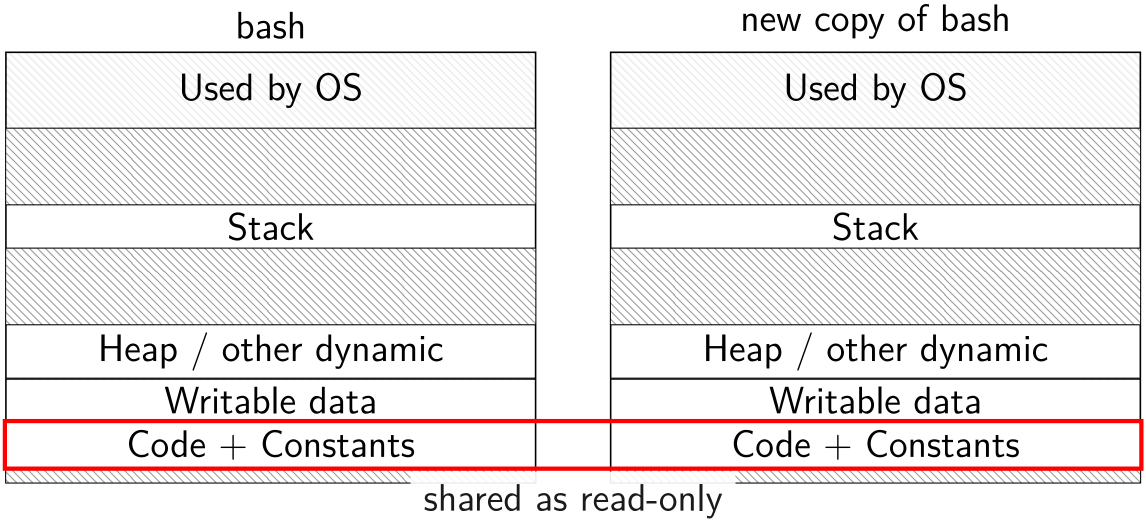

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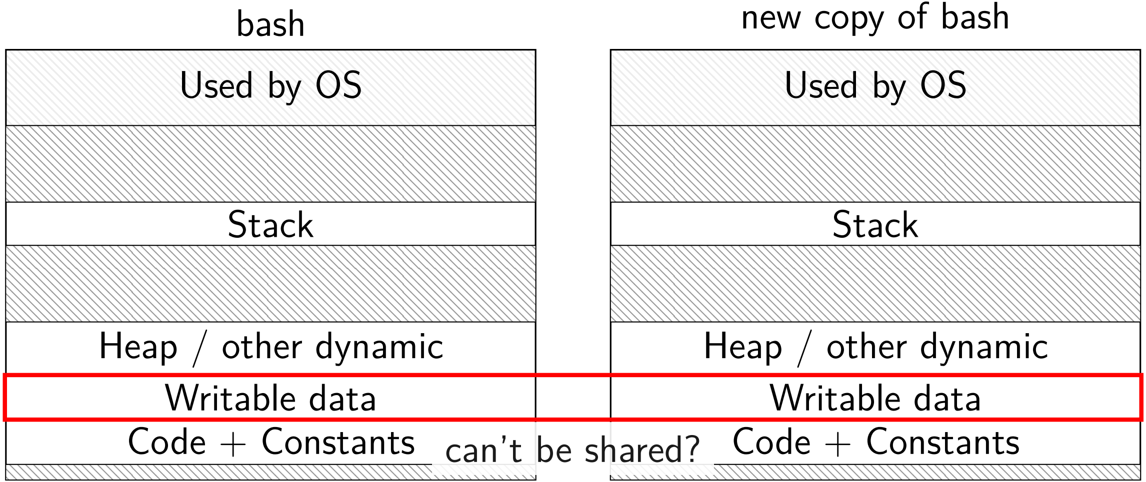

# trick for extra sharing

sharing writeable data is fine — until either process modifies it

- example: default value of global variables
- might typically not change
- (or OS might have preloaded executable's data anyways)

can we detect modifications?

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processor will trigger a fault when it's written

# copy-on-write and page tables

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| … | … | … | … |
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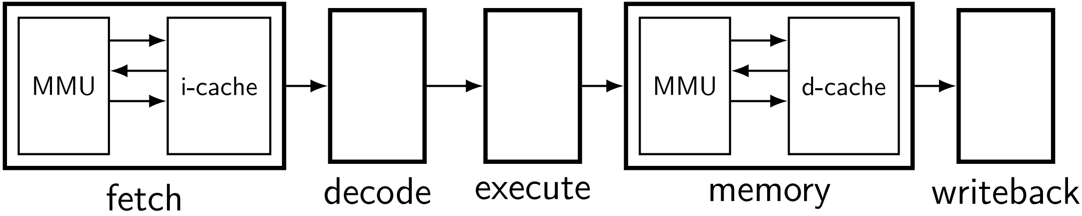
after allocating a copy, OS reruns the write instruction

# backup slides

# MMUs in the pipeline

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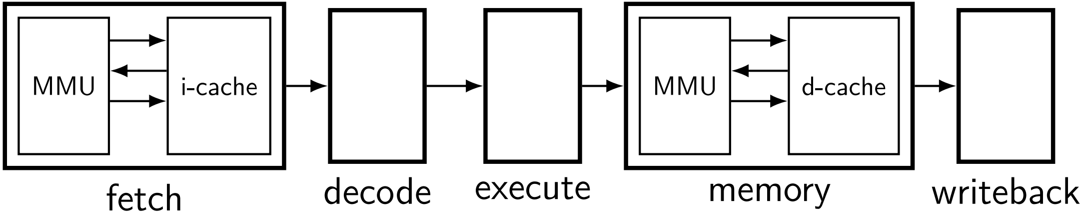


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challenging to make this fast (topic for a future date)

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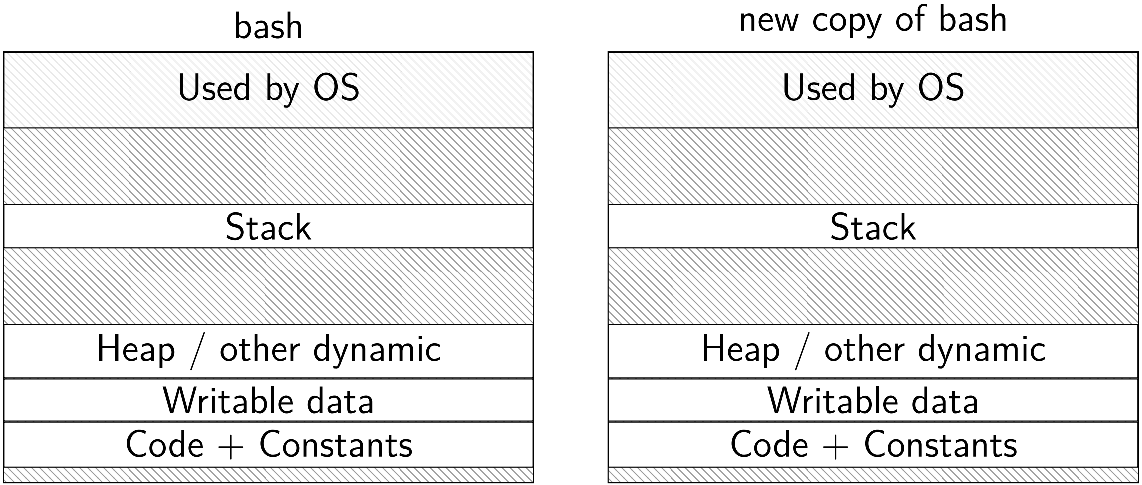

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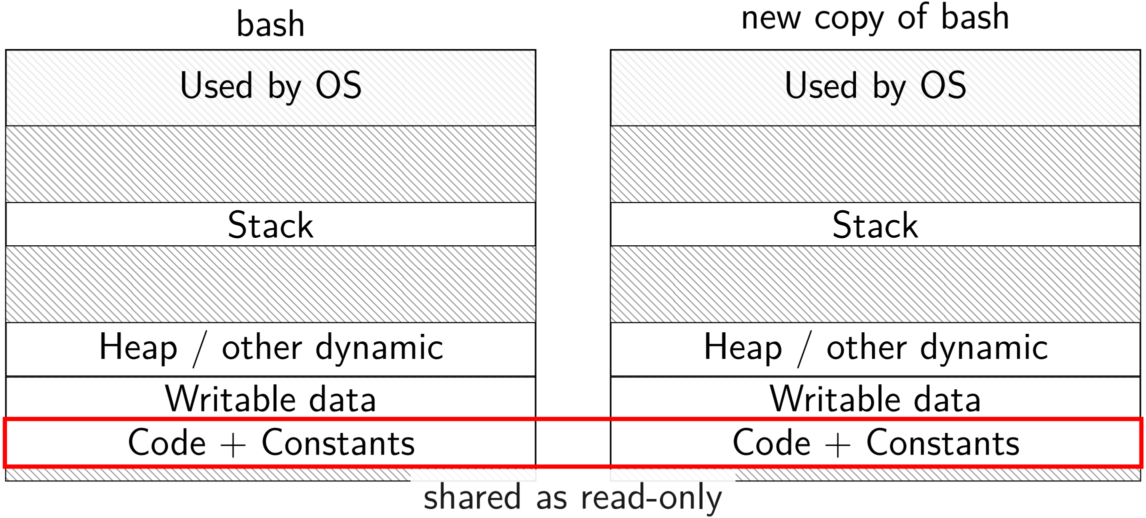

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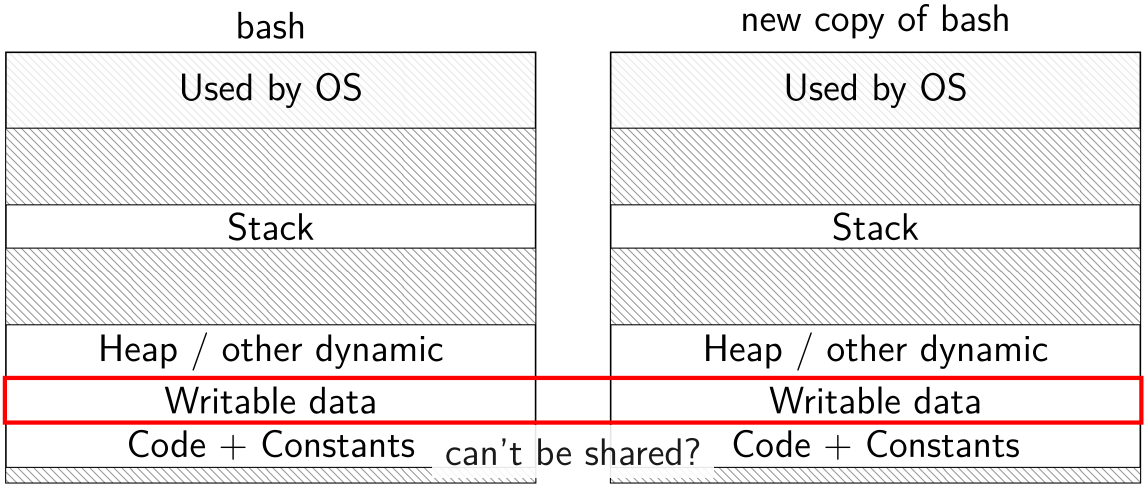

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