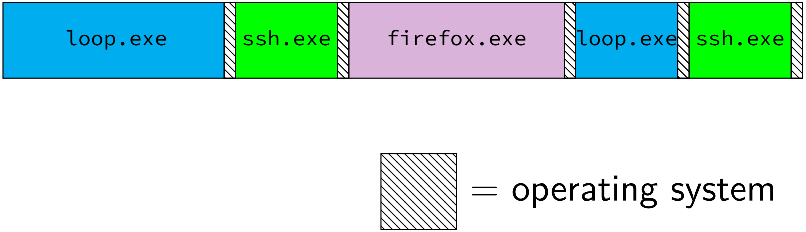
exceptions / virutal memory 1

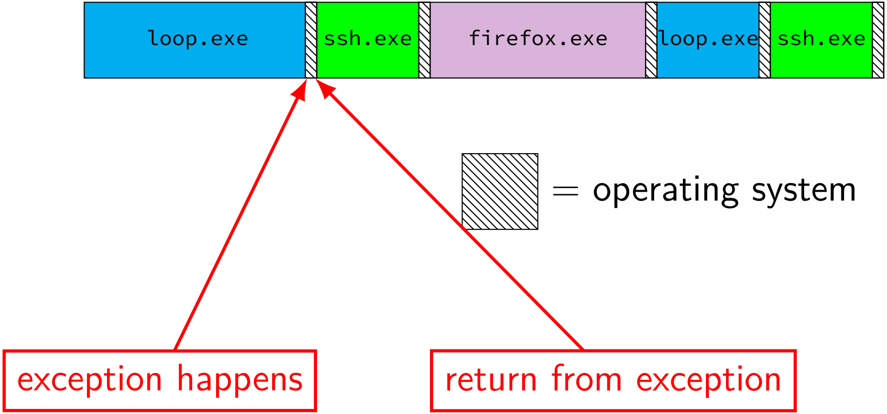
last time

- vector instructions
  - addt'l operations — set1, shuffle, …
  - vectorization examples
  - other vector instruction sets
- process idea
  - thread = illusion of own CPU
  - multiple threads on one CPU with time multiplexing
  - address space = illusion of own memory
  - address translation to create address spaces
- exceptions
  - hardware runs OS
  - asynchronous — external event (timer, I/O)
  - synchronous (program triggered) — system call (request), fault (error)

time multiplexing really



time multiplexing really



OS and time multiplexing

starts running instead of normal program

- mechanism for this: exceptions (later)

saves old program counter, registers somewhere

sets new registers, jumps to new program counter

called context switch

- saved information called context

context

all registers values

`%rax` `%rbx`, …, `%rsp`, …

condition codes

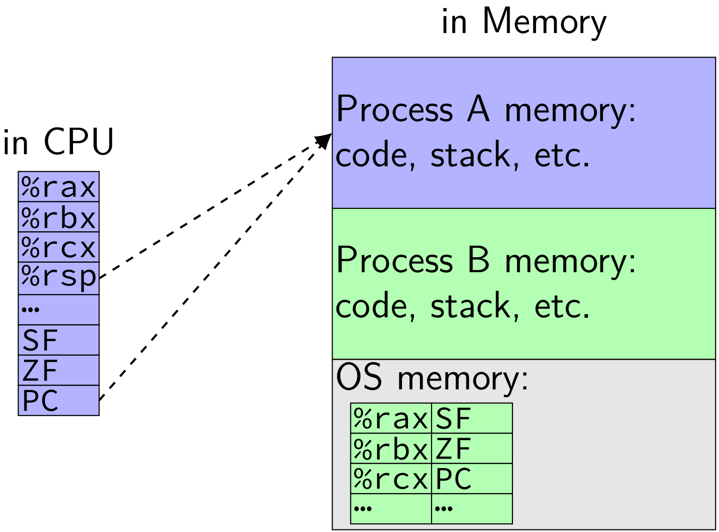
program counter

i.e. all visible state in your CPU except memory

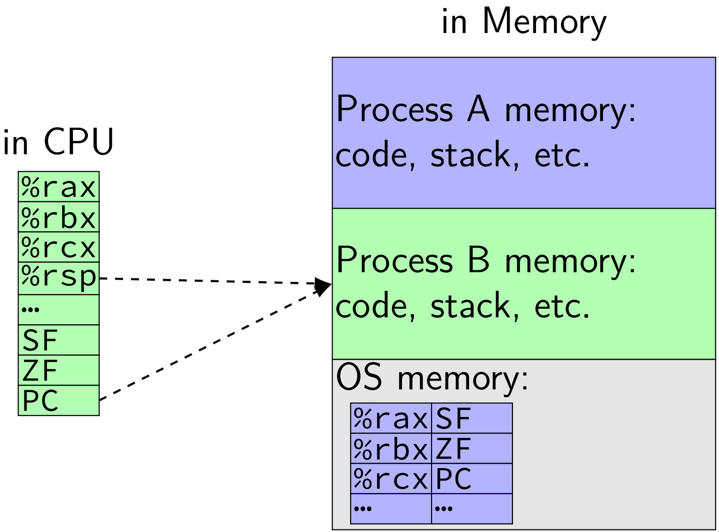
context switch pseudocode

```
context_switch(last, next):
  copy_preexception_pc last->pc
  mov rax,last->rax
  mov rcx, last->rcx
  mov rdx, last->rdx
  ...
  mov next->rdx, rdx
  mov next->rcx, rcx
  mov next->rax, rax
  jmp next->pc
```

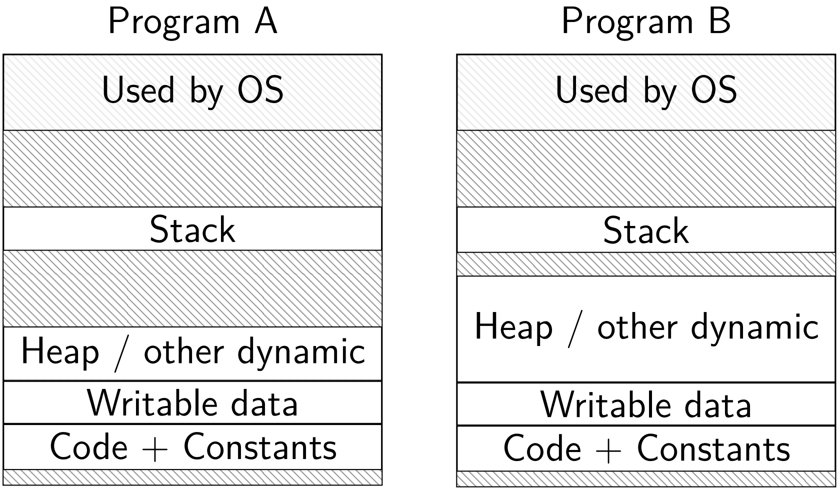
contexts (A running)



contexts (B running)



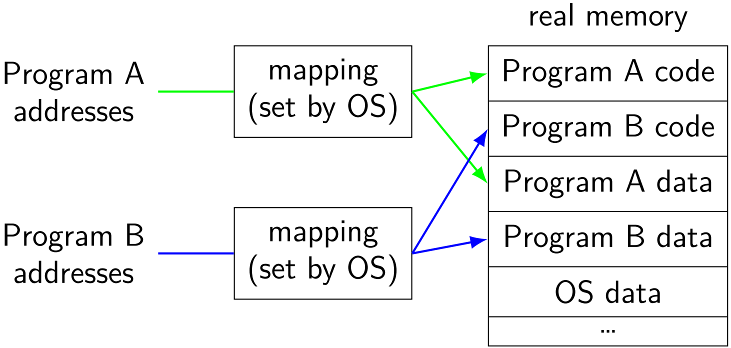
program memory (two programs)



address space

programs have illusion of own memory

called a program's address space



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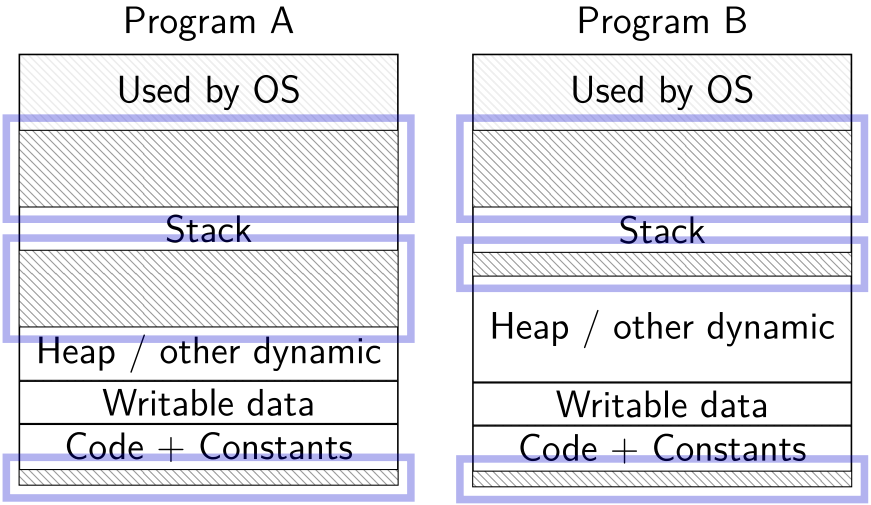

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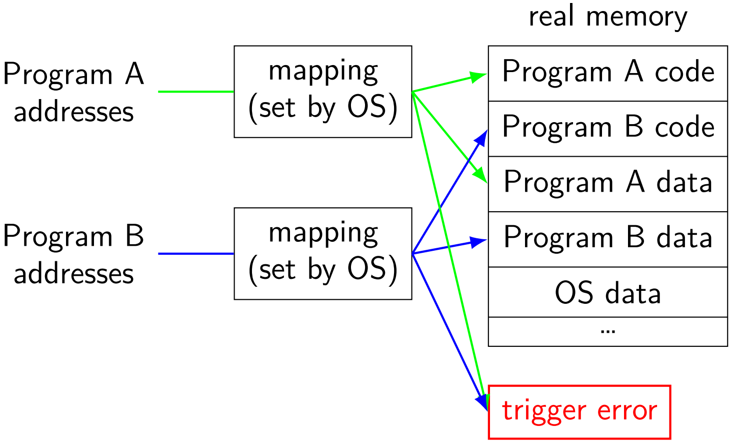


address space mechanisms

topic after exceptions

called virtual memory

mapping called page tables

mapping part of what is changed in context switch

exception implementation

detect condition (program error or external event)

save current value of PC somewhere

jump to exception handler (part of OS)

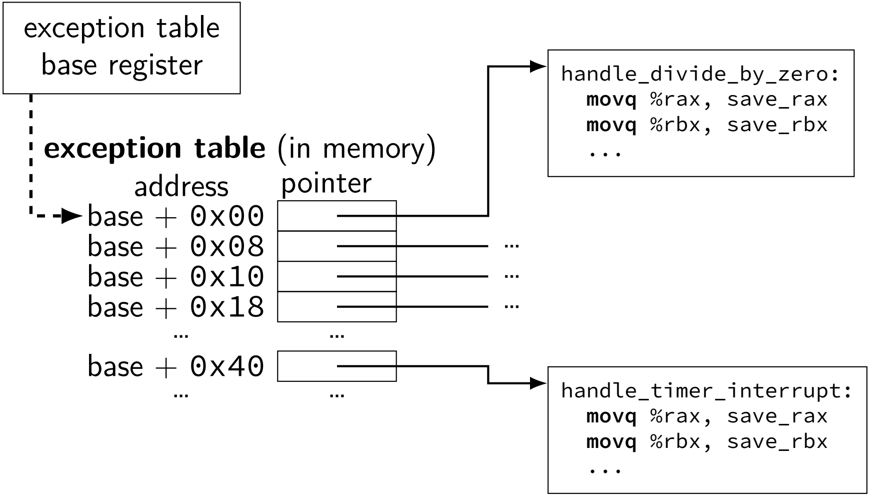
    jump done without program instruction to do so

exception implementation: notes

I/textbook describe a simplified version

real x86/x86-64 is a bit more complicated
(mostly for historical reasons)

locating exception handlers



running the exception handler

hardware saves the old program counter (and maybe more)

identifies location of exception handler via table

then jumps to that location

OS code can save anything else it wants to , etc.

added to CPU for exceptions

new instruction: set exception table base

new logic: jump based on exception table

- may need to cancel partially completed instructions before jumping

new logic: save the old PC (and maybe more)

- to special register or to memory

new instruction: return from exception

- i.e. jump to saved PC

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- i.e. jump to saved PC

exception handler structure

1. save process's state somewhere
2. do work to handle exception
3. restore a process's state (maybe a different one)
4. jump back to program

```
handle_timer_interrupt:
  mov_from_saved_pc save_pc_loc
  movq %rax, save_rax_loc
  ... // choose new process to run here
  movq new_rax_loc, %rax
  mov_to_saved_pc new_pc
  return_from_exception
```

exceptions and time slicing

timer interrupt

exception table lookup

```
handle_timer_interrupt:
    ...
    ...
    set_address_space ssh_address_space
    mov_to_saved_pc saved_ssh_pc
    return_from_exception
```

defeating time slices?

```
my_exception_table:
    ...
my_handle_timer_interrupt:
    // HA! Keep running me!
    return_from_exception

main:
    set_exception_table_base my_exception_table
loop:
    jmp loop
```

defeating time slices?

wrote a program that tries to set the exception table:

```
my_exception_table:
    ...

main:
    // "Load Interrupt
    //  Descriptor Table"
    // x86 instruction to set exception table
    lidt my_exception_table
    ret
```

result: `Segmentation fault` (exception!)

types of exceptions

interrupts — externally-triggered
- timer — keep program from hogging CPU
- I/O devices — key presses, hard drives, networks, …

aborts — hardware is broken

} **asynchronous** — not triggered by running program

traps — intentionally triggered exceptions
- system calls — ask OS to do something

faults — errors/events in programs
- memory not in address space ("Segmentation fault")
- privileged instruction
- divide by zero
- invalid instruction

} **synchronous** — triggered by current program

privileged instructions

can't let any program run some instructions

allows machines to be shared between users (e.g. lab servers)

examples:

- set exception table
- set address space
- talk to I/O device (hard drive, keyboard, display, …)
- …

processor has two modes:

- kernel mode — privileged instructions work
- user mode — privileged instructions cause exception instead

kernel mode

extra one-bit register: "are we in kernel mode"

exceptions enter kernel mode

return from exception instruction leaves kernel mode

types of exceptions

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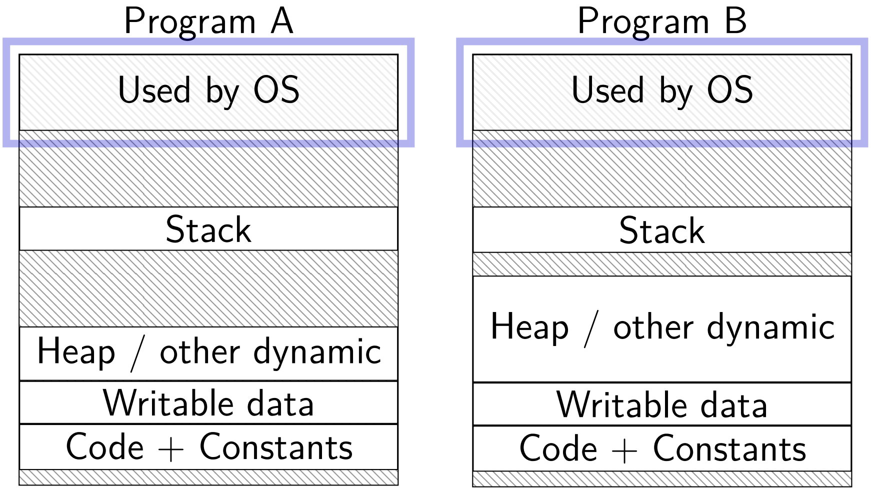
what about editing OS code/data?

backdoor way to run priviliged instructions?

ruins illusion of having own memory?

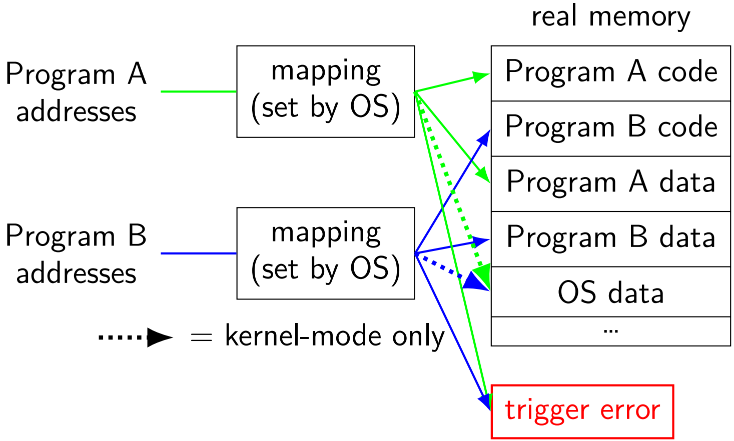
program memory (two programs)



address space

programs have illusion of own memory

called a program's address space



protection fault

when program tries to access memory it doesn't own

e.g. trying to write to OS address

when program tries to do other things that are not allowed

e.g. accessing I/O devices directly

e.g. changing exception table base register

OS gets control — can crash the program

or more interesting things

types of exceptions

interrupts — externally-triggered
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- I/O devices — key presses, hard drives, networks, …

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- invalid instruction

} **synchronous** — triggered by current program

which requires kernel mode?

which operations are likely to fail (trigger an exception to run the OS instead) if attempted in user mode?

A. reading data on disk by running special instructions that communicate with the hard disk device

B. changing a program's address space to allocate it more memory

C. returning from a standard library function

D. incrementing the stack pointer

kernel services

allocating memory? (change address space)

reading/writing to file? (communicate with hard drive)

read input? (communicate with keyborad)

all need privileged instructions!

need to run code in kernel mode

Linux x86-64 system calls

special instruction: `syscall`

triggers trap (deliberate exception)

Linux syscall calling convention

before `syscall`:

`%rax` — system call number

`%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9` — args

after `syscall`:

`%rax` — return value

on error: `%rax` contains -1 times “error number”

almost the same as normal function calls

Linux x86-64 hello world

```
.globl _start
.data
hello_str: .asciz "Hello, World!\n"
.text
_start:
  movq $1, %rax # 1 = "write"
  movq $1, %rdi # file descriptor 1 = stdout
  movq $hello_str, %rsi
  movq $15, %rdx # 15 = strlen("Hello, World!\n")
  syscall

  movq $60, %rax # 60 = exit
  movq $0, %rdi
  syscall
```

approx. system call handler

```
sys_call_table:
    .quad handle_read_syscall
    .quad handle_write_syscall
    // ...

handle_syscall:
    ... // save old PC, etc.
    pushq %rcx // save registers
    pushq %rdi
    ...
    call *sys_call_table(,%rax,8)
    ...
    popq %rdi
    popq %rcx
    return_from_exception
```

Linux system call examples

`mmap`, `brk` — allocate memory

`fork` — create new process

`execve` — run a program in the current process

`_exit` — terminate a process

`open`, `read`, `write` — access files

terminals, etc. count as files, too

which of these require exceptions? context switches?

A. program calls a function in the standard library

B. program writes a file to disk

C. program A goes to sleep, letting program B run

D. program exits

E. program returns from one function to another function

F. program pops a value from the stack

a note on terminology (1)

real world: inconsistent terms for exceptions

we will follow textbook's terms in this course

the real world won't

you might see:

- 'interrupt' meaning what we call 'exception' (x86)
- 'exception' meaning what we call 'fault'
- 'hard fault' meaning what we call 'abort'
- 'trap' meaning what we call 'fault'
- ... and more

a note on terminology (2)

we use the term “kernel mode”

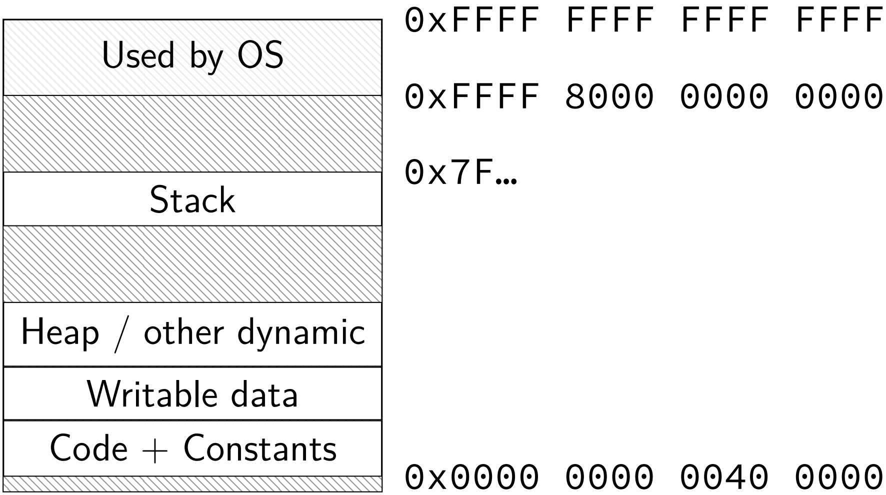
some additional terms:

- supervisor mode
- privileged mode
- ring `0`

some systems have multiple levels of privilege

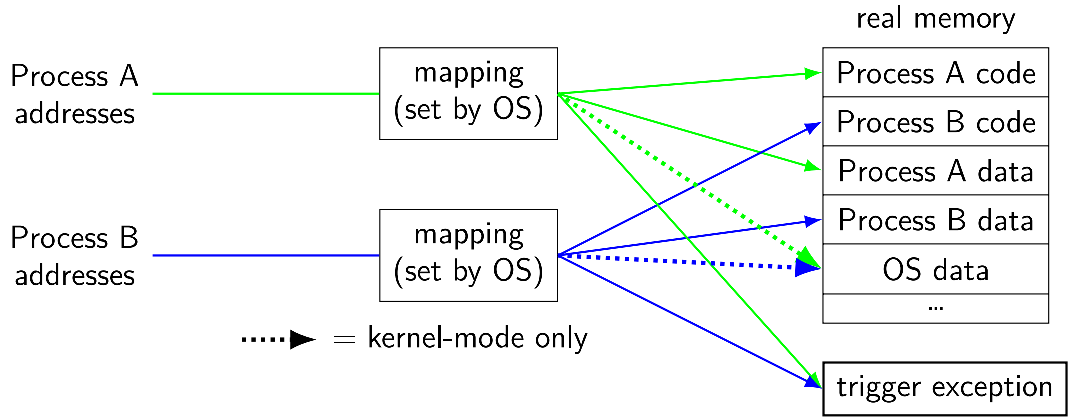
- different sets of priviliged operations work

program memory



address spaces

illuision of dedicated memory



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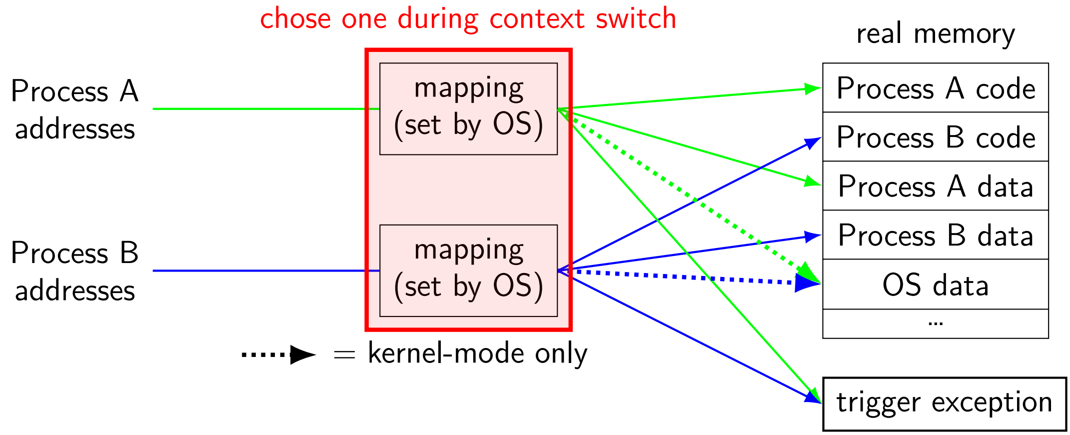
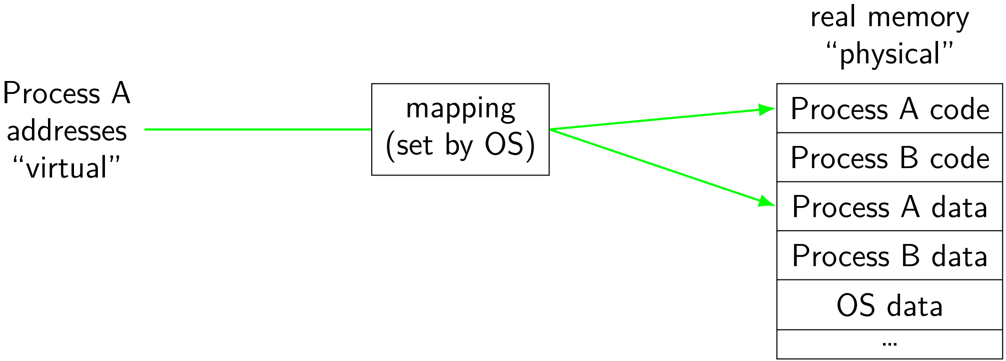


address translation



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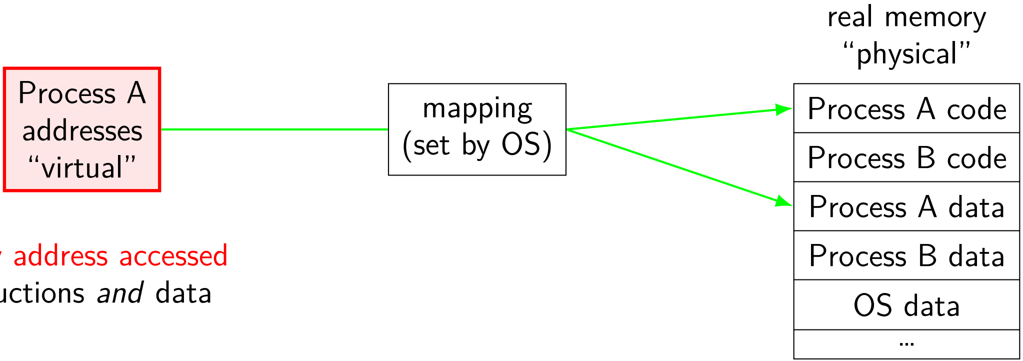
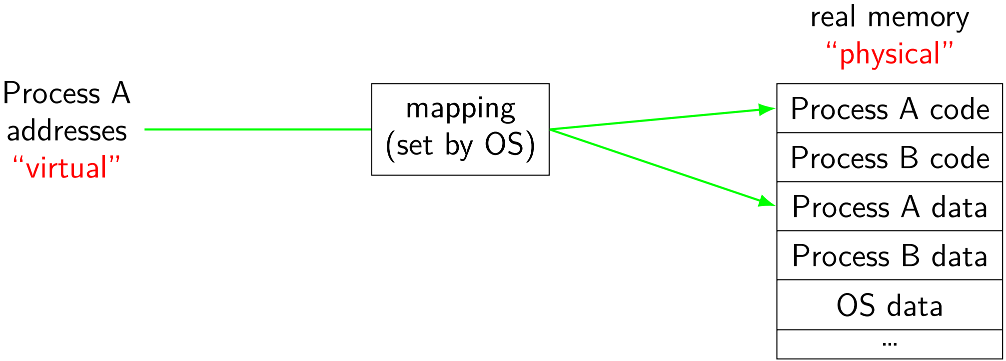


every address accessed

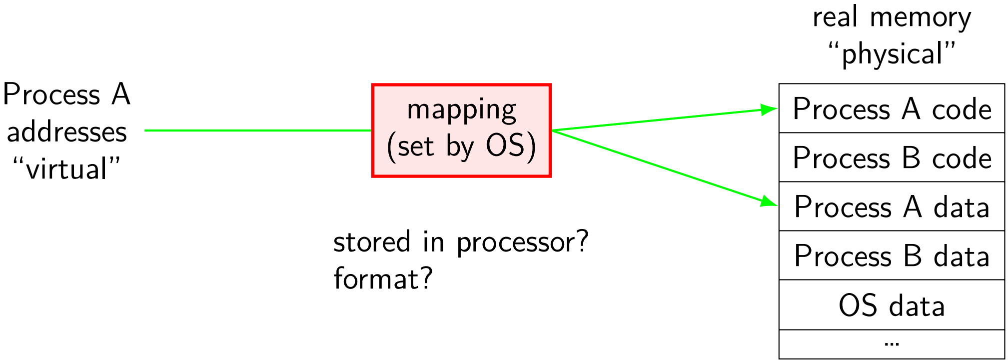
instructions *and* data

address translation



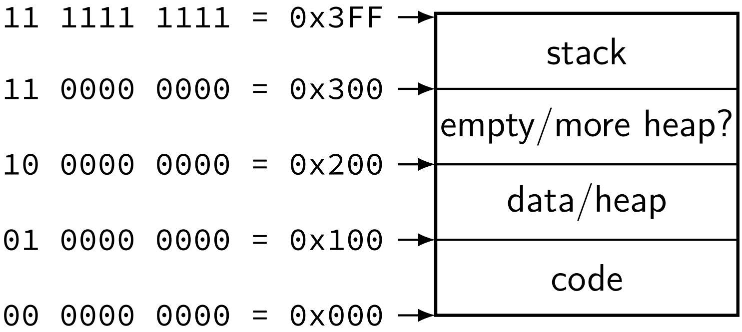
program addresses are 'virtual'
real addresses are 'physical'
can be different sizes!

address translation



stored in processor?
format?

toy program memory



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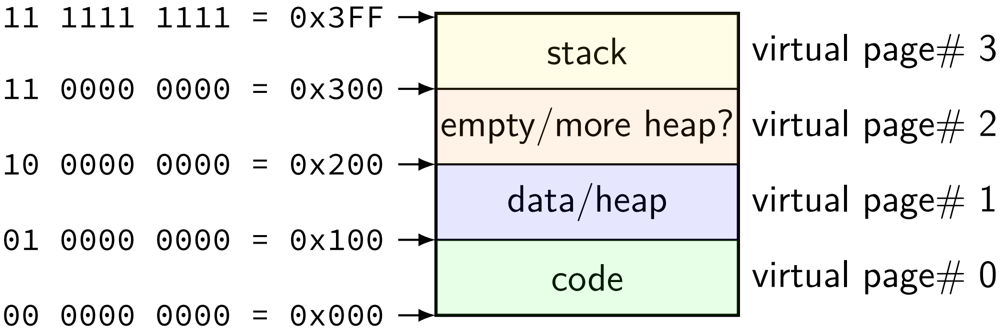
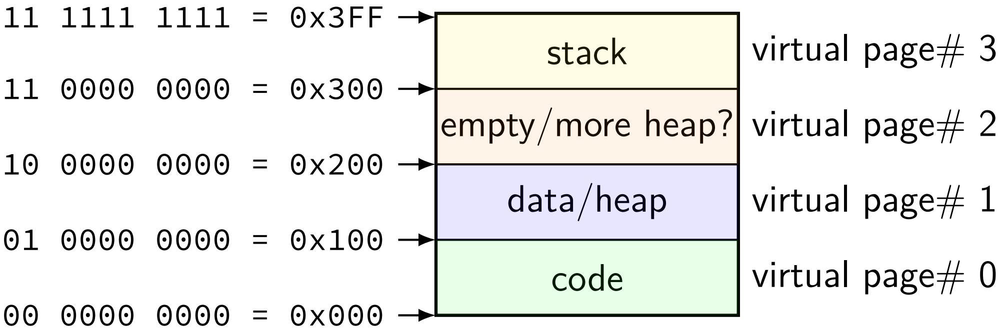
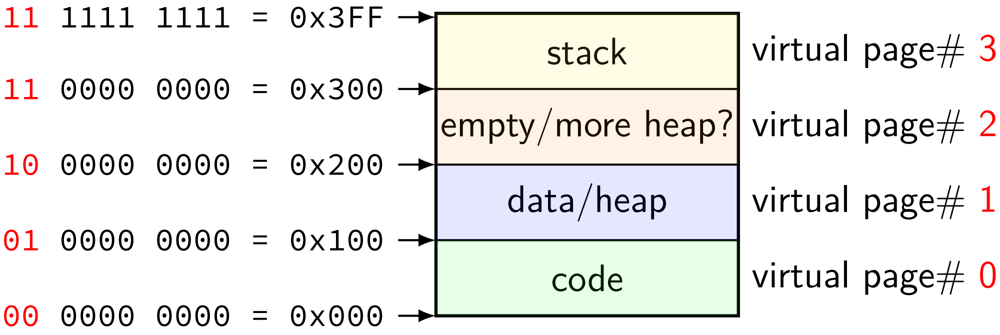


toy program memory



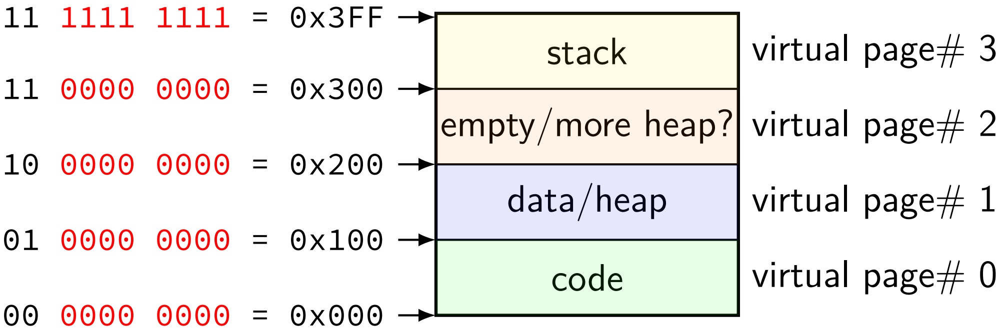
divide memory into pages (2^8 bytes in this case)
"virtual" = addresses the program sees

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

program memory

virtual addresses

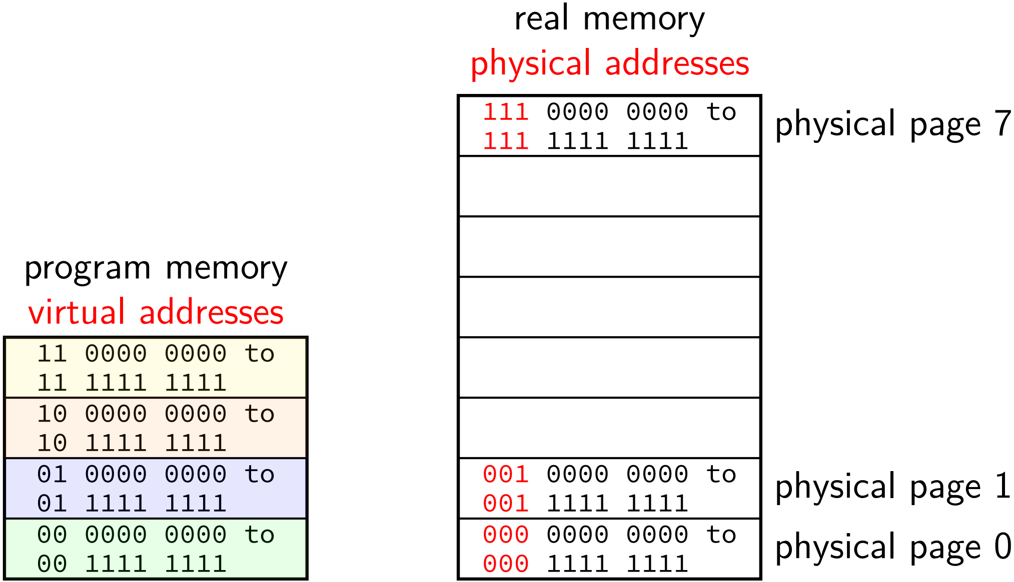
11 0000 0000 to 11 1111 1111
10 0000 0000 to 10 1111 1111
01 0000 0000 to 01 1111 1111
00 0000 0000 to 00 1111 1111

real memory

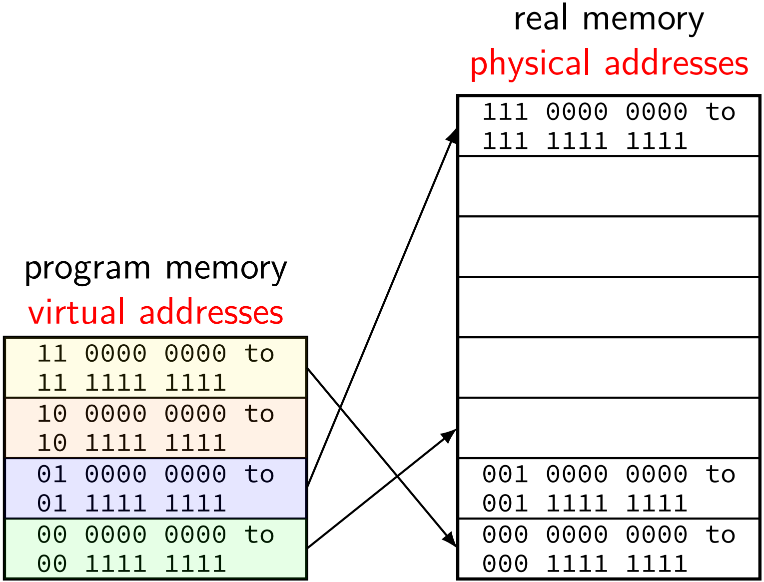
physical addresses

111 0000 0000 to 111 1111 1111
001 0000 0000 to 001 1111 1111
000 0000 0000 to 000 1111 1111

toy physical memory

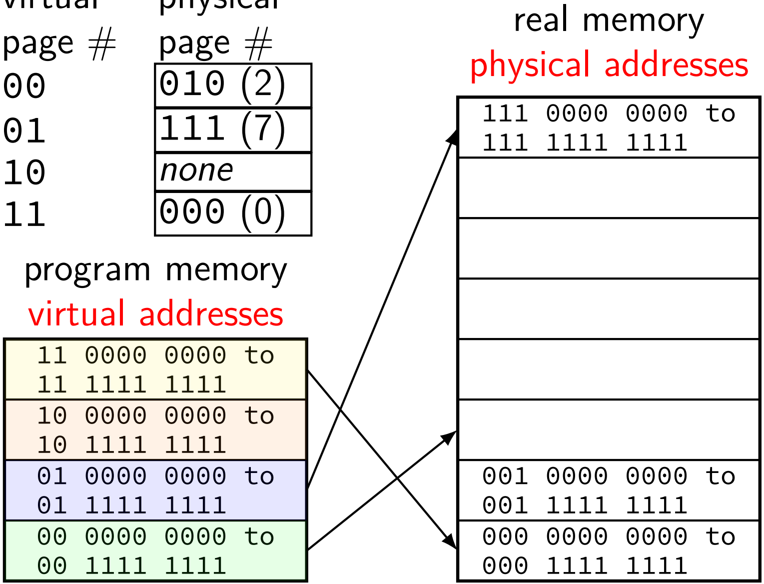


toy physical memory



toy physical memory

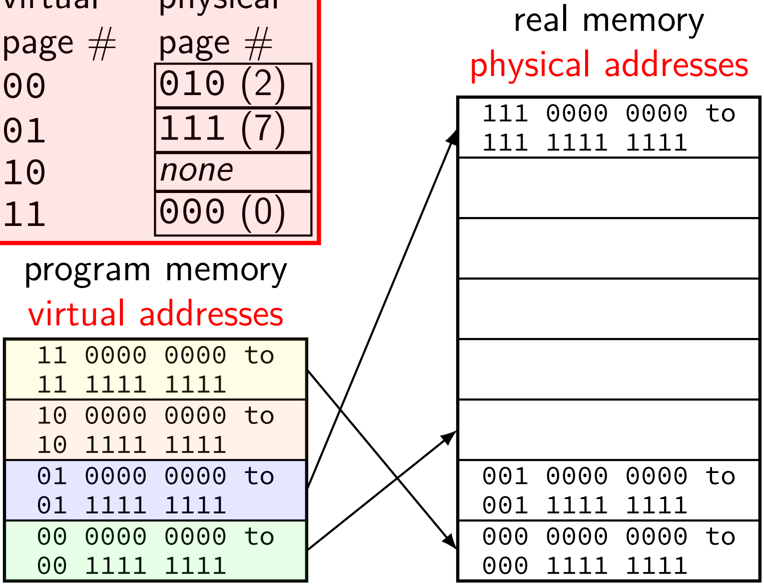
virtual page #	physical page #
00	010 (2)
01	111 (7)
10	*none*
11	000 (0)



toy physical memory

page table!

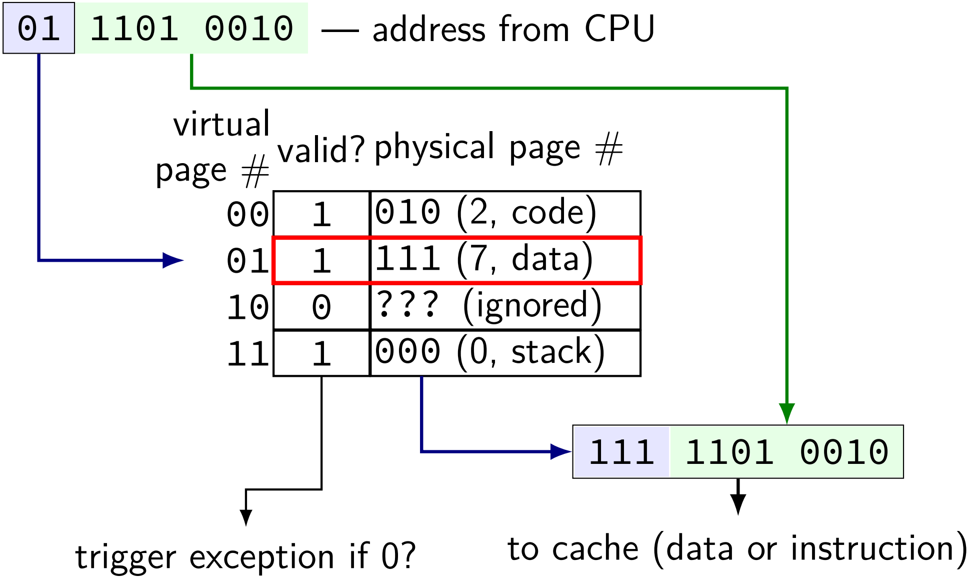
virtual page #	physical page #
00	010 (2)
01	111 (7)
10	*none*
11	000 (0)



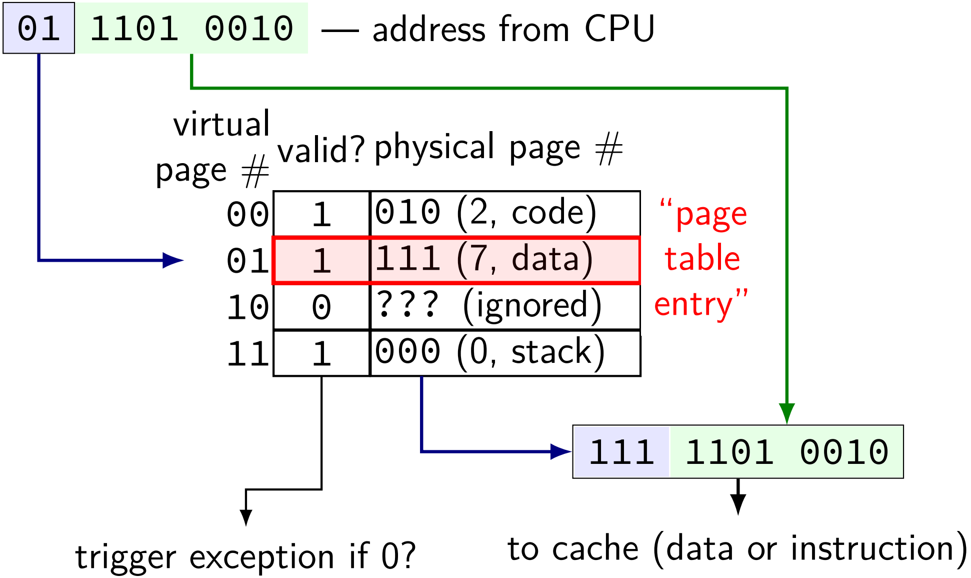
toy page table lookup

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

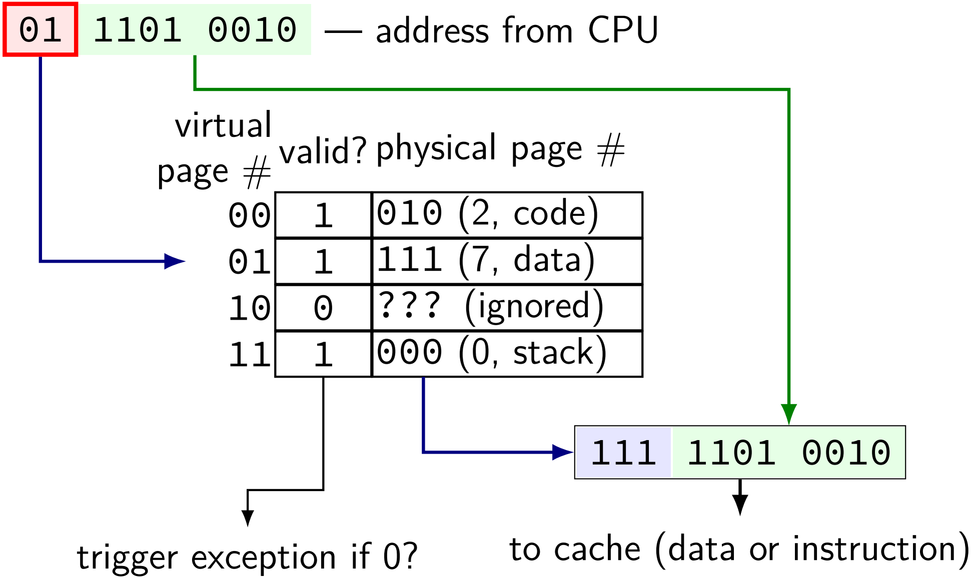
toy page table lookup



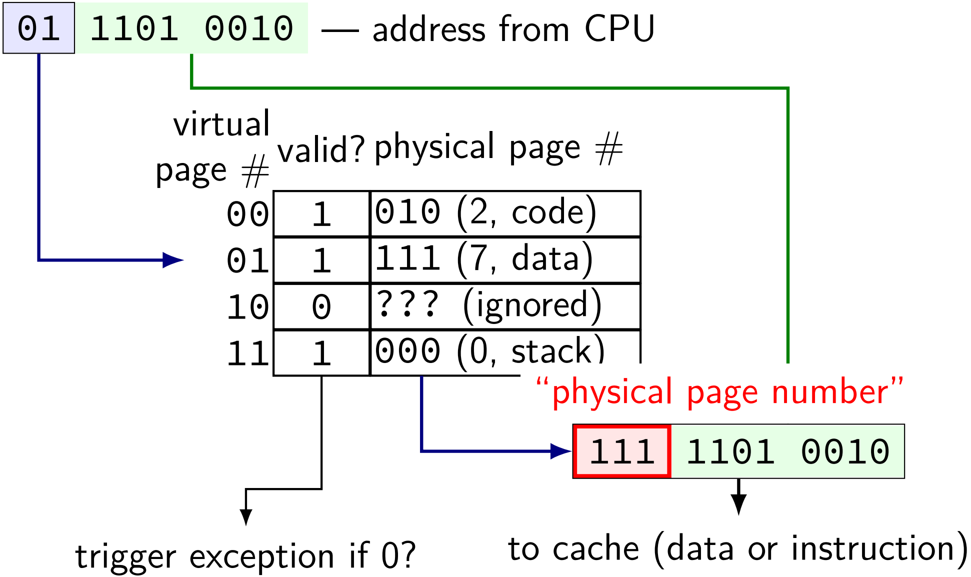
toy page table lookup



“virtual page number” lookup

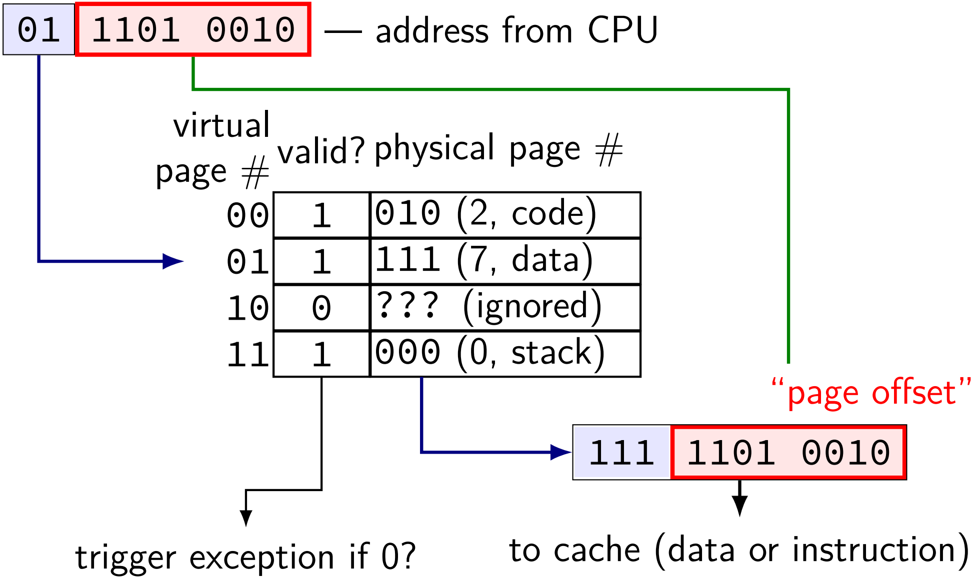


toy page table lookup



toy pa ookup

“page offset”



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

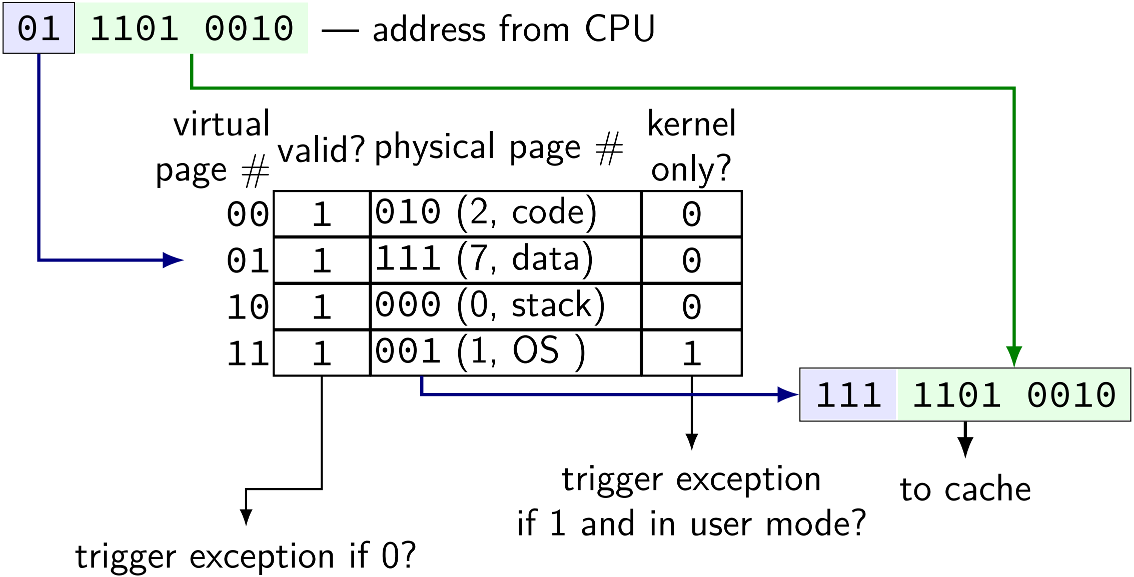
code better not be modified by user program

- otherwise: uncontrolled way to “escape” user mode

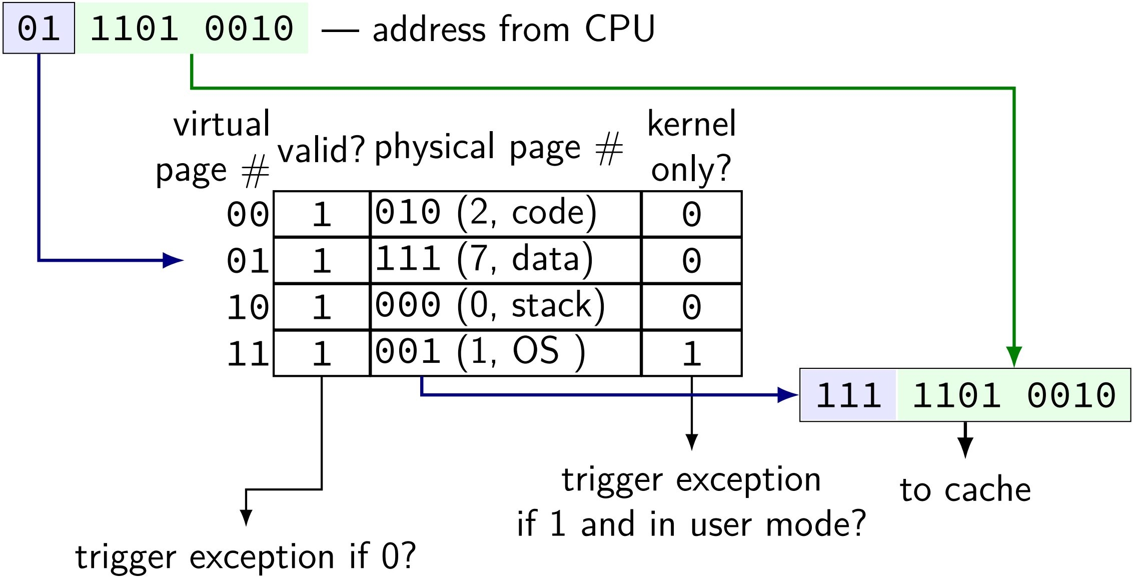
kernel-mode only

virtual page #	valid?	physical page #	kernel only?
00	1	010 (2, code)	0
01	1	111 (7, data)	0
10	1	000 (0, stack)	0
11	1	001 (1, OS)	1

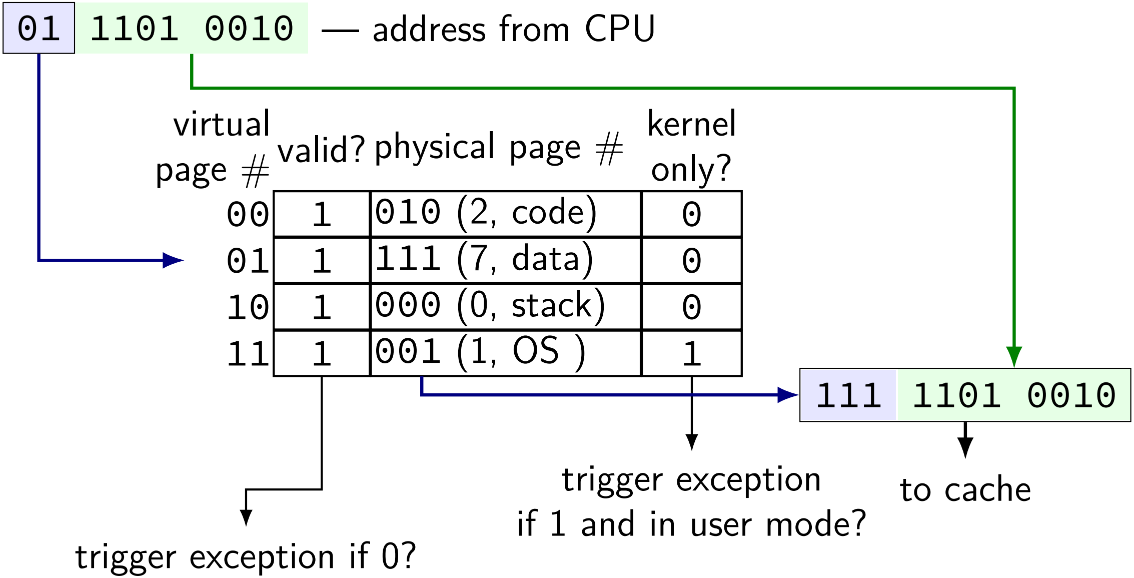
kernel-mode only



kernel-mode only



kernel-mode only



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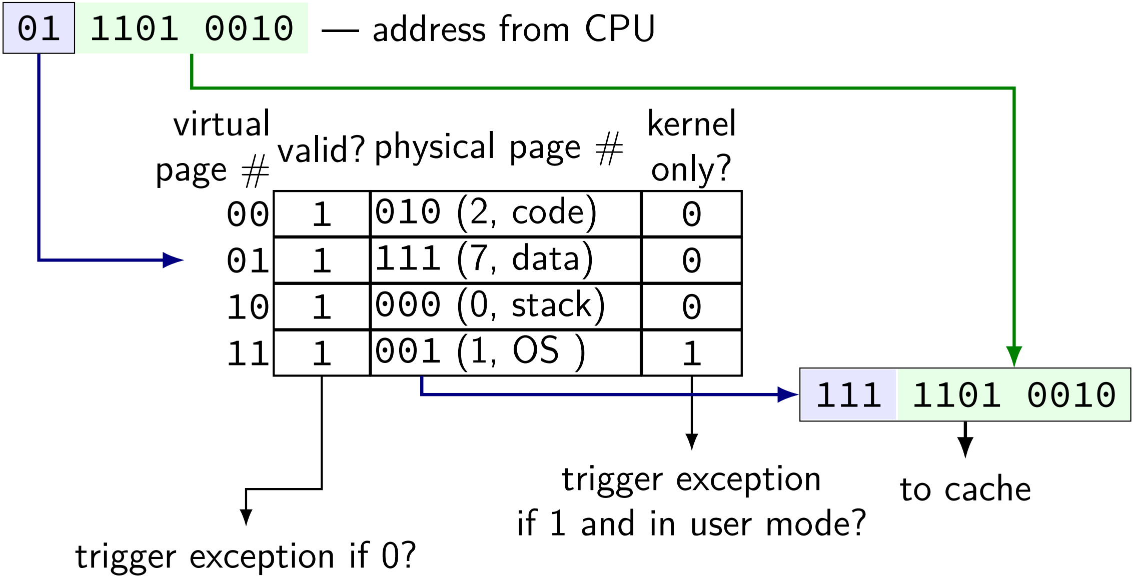

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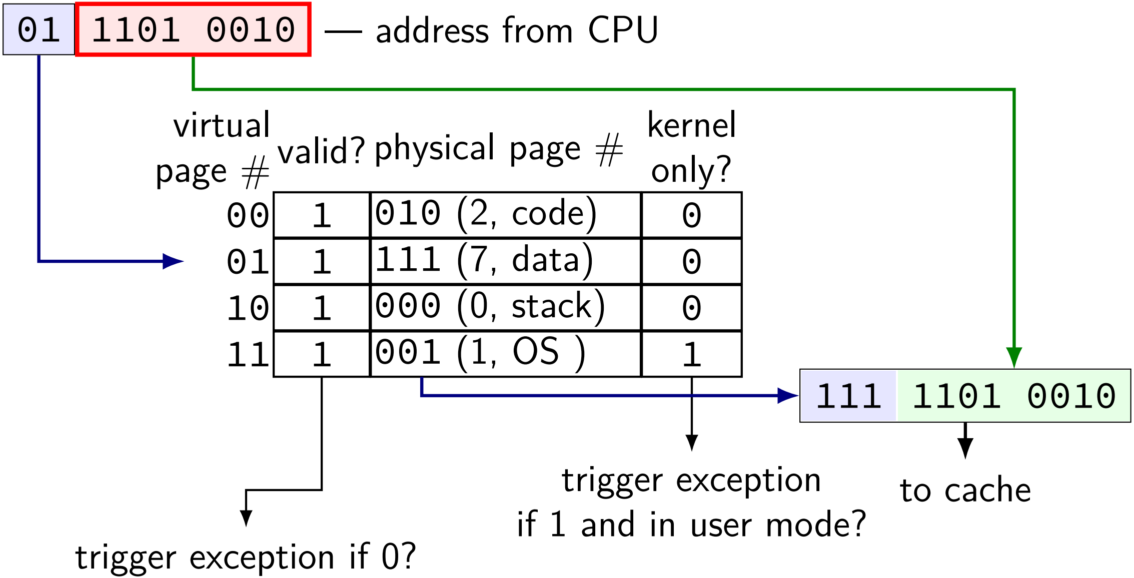


on virtual address sizes

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?

$2^{32}/2^{12} = 2^{20}$

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)?

2^{20} entries $\times(18+2)$ bits per entry

- 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 #: `0x12345`; offset: `0x678`

backup slides

fast copies

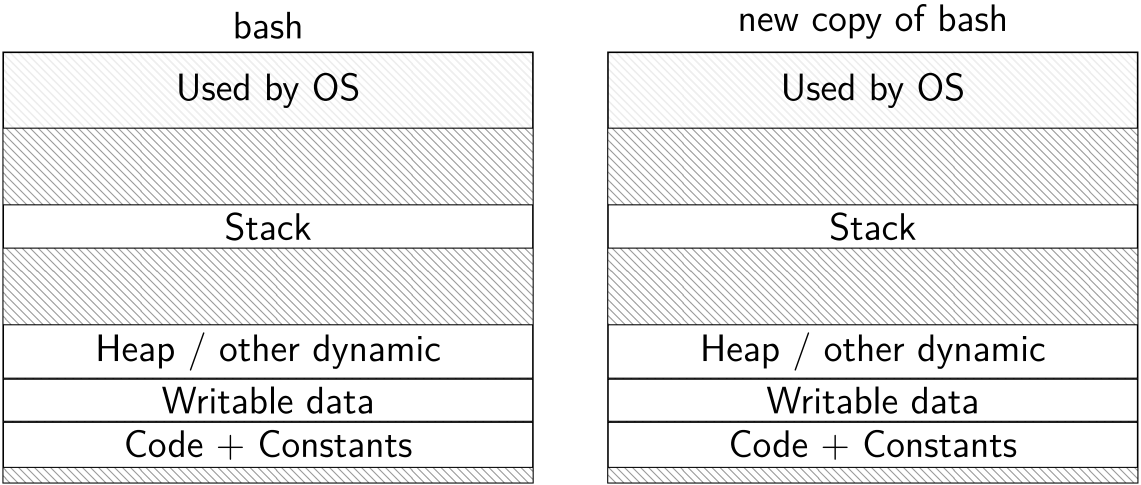
Unix mechanism for starting a new process: `fork()`

creates a copy of an entire program!

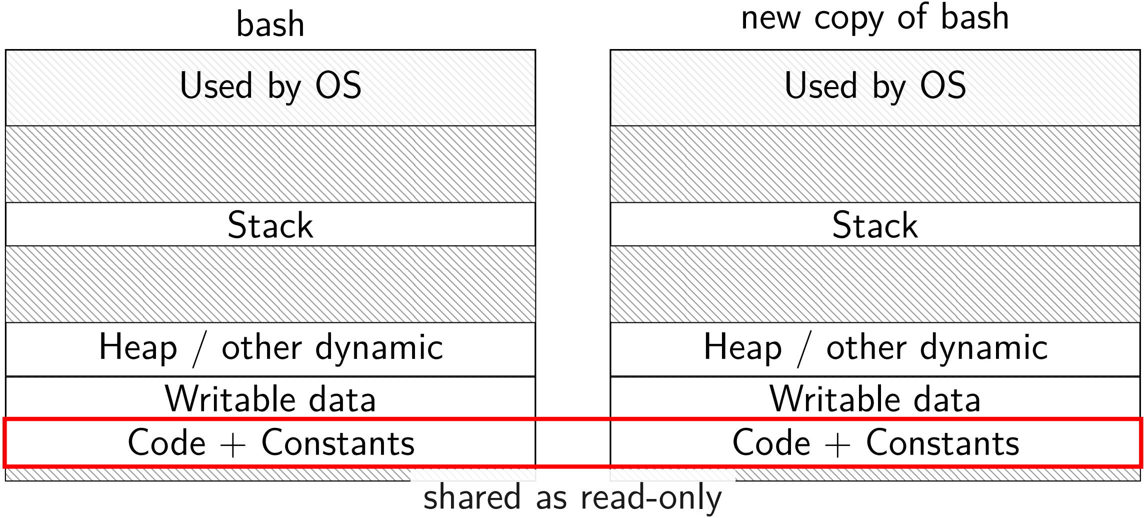
(usually, the copy then calls `execve` — replaces itself with another program)

how isn't this really slow?

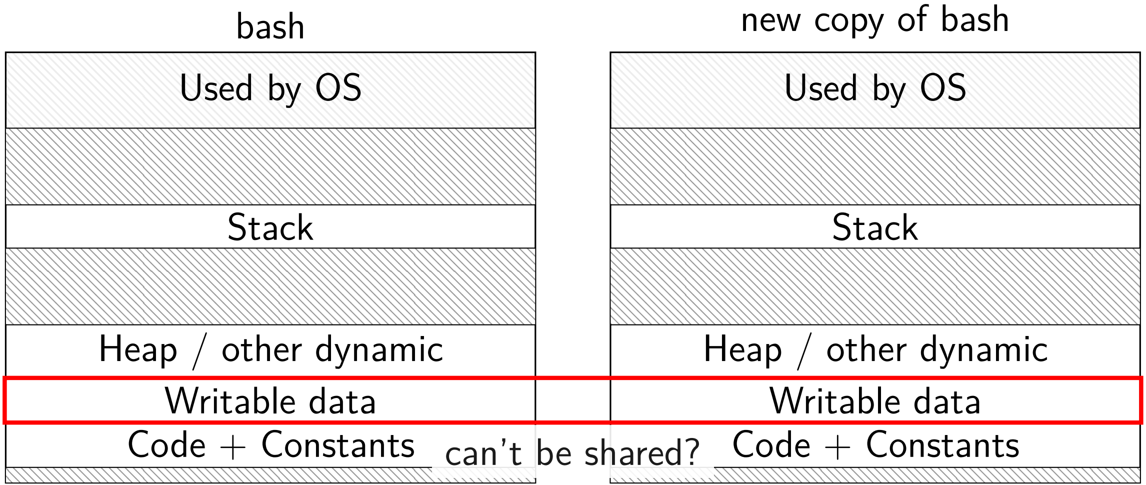
do we really need a complete copy?



do we really need a complete copy?



do we really need a complete copy?



trick for extra sharing

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

can we detect modifications?

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

processor will trigger a fault when it's written

copy-on-write and page tables

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

copy-on-write and page tables

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

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

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

copy-on-write and page tables

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

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

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

copy-on-write and page tables

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

VPN	valid?	write?	physical page
...	...	...	...
0x00601	1	0	0x12345
0x00602	1	0	0x12347
0x00603	1	0	0x12340
0x00604	1	0	0x200DF
0x00605	1	1	0x300FD
...	...	...	...

after allocating a copy, OS reruns the write instruction

replacement policy

since disks are so slow, replacement policy really matters

will be implemented in software

like with caches: something like least-recently-used usually good
- but exceptions: some access patterns won't work well

LRU replacement?

problem: need to identify when pages are used

- ideally every single time

not practical to do this exactly

- HW would need to keep a list of when each page was accessed, or
- SW would need to force every access to trigger a fault

trick: any page which hasn't been used in a while is probably fine

- not likely to make a difference whether it was last used 120 seconds ago or 300 seconds ago

LRU approximation intuition

one idea: detect accesses by marking page table entry invalid temporarily

e.g. every N seconds

on page fault:

if marked as invalid: make valid again

choose page which has stayed invalid for a long time

hardware support for access tracking

often hardware implements *accessed* bit in page table entries

set to 1 when page table entry is used by program

avoids requiring page fault

Linux x86-64 system calls

special instruction: `syscall`

triggers trap (deliberate exception)

Linux syscall calling convention

before `syscall`:

`%rax` — system call number

`%rdi`, `%rsi`, `%rdx`, `%r10`, `%r8`, `%r9` — args

after `syscall`:

`%rax` — return value

on error: `%rax` contains -1 times “error number”

almost the same as normal function calls

Linux x86-64 hello world

```
.globl _start
.data
hello_str: .asciz "Hello, World!\n"
.text
_start:
  movq $1, %rax # 1 = "write"
  movq $1, %rdi # file descriptor 1 = stdout
  movq $hello_str, %rsi
  movq $15, %rdx # 15 = strlen("Hello, World!\n")
  syscall

  movq $60, %rax # 60 = exit
  movq $0, %rdi
  syscall
```

approx. system call handler

```
sys_call_table:
    .quad handle_read_syscall
    .quad handle_write_syscall
    // ...

handle_syscall:
    ... // save old PC, etc.
    pushq %rcx // save registers
    pushq %rdi
    ...
    call *sys_call_table(,%rax,8)
    ...
    popq %rdi
    popq %rcx
    return_from_exception
```

Linux system call examples

`mmap`, `brk` — allocate memory

`fork` — create new process

`execve` — run a program in the current process

`_exit` — terminate a process

`open`, `read`, `write` — access files

- terminals, etc. count as files, too

system call wrappers

can't write C code to generate syscall instruction

solution: call "wrapper" function written in assembly

keyboard input timeline