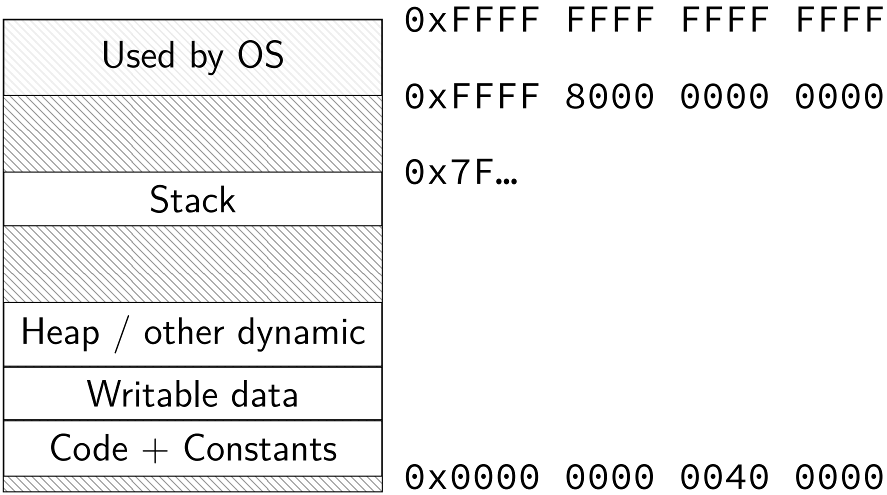
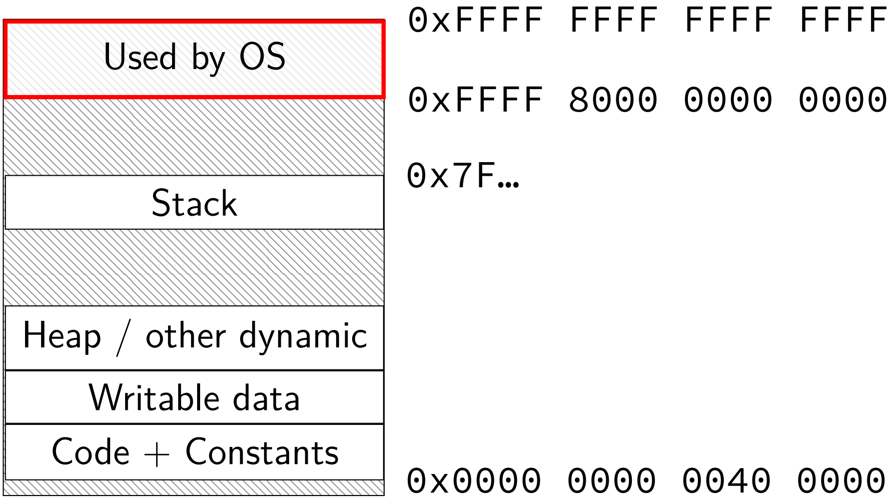
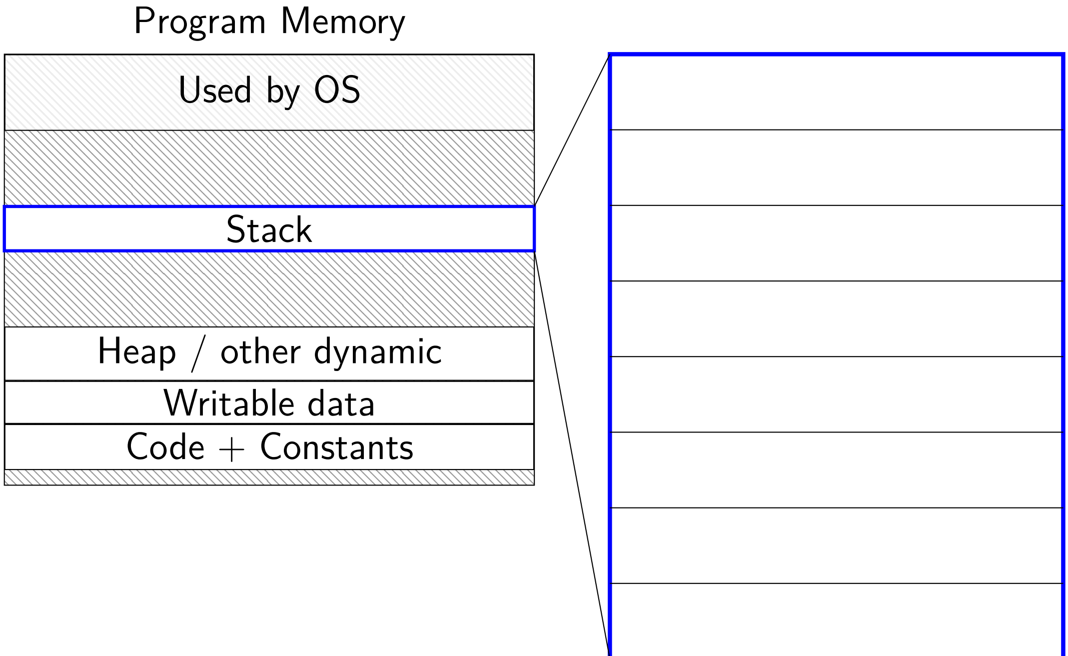
program memory



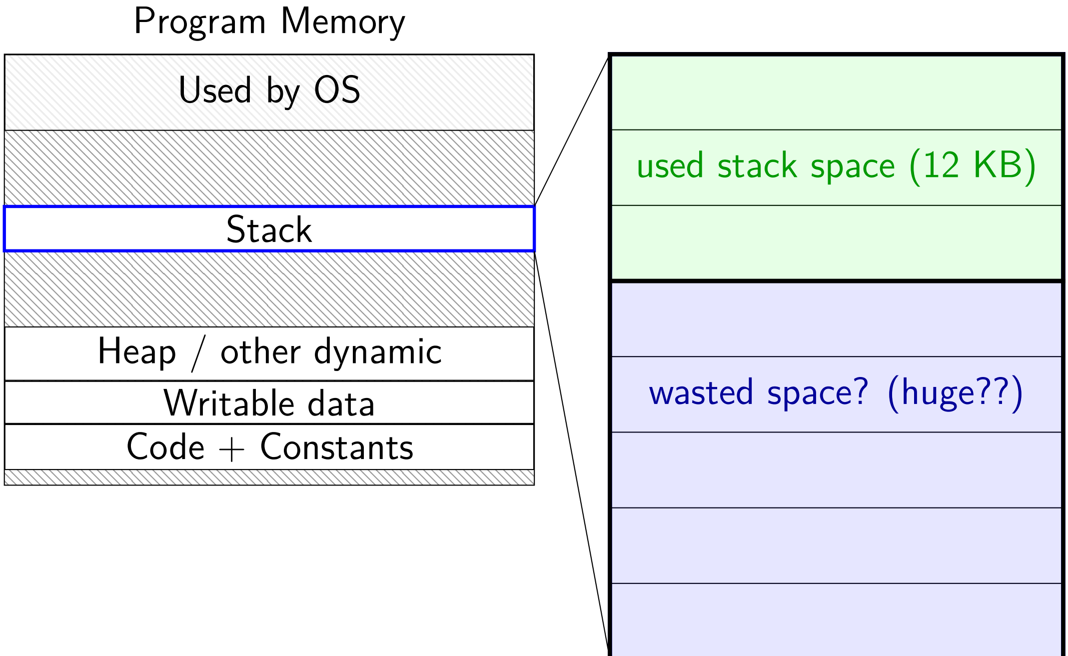
program memory



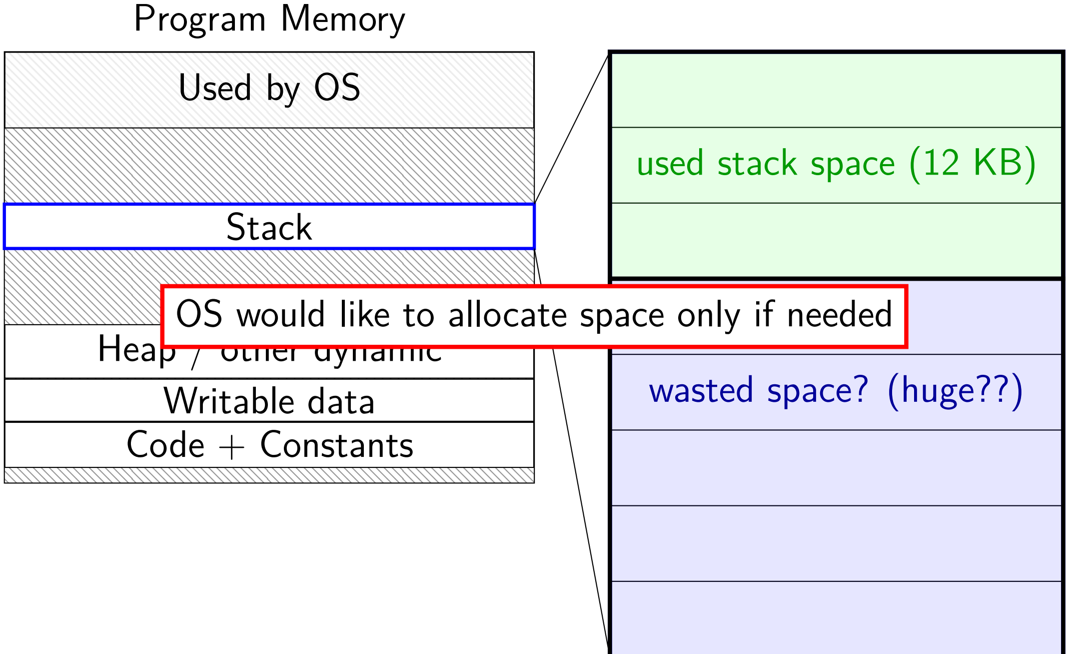
space on demand



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

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```
...
// 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

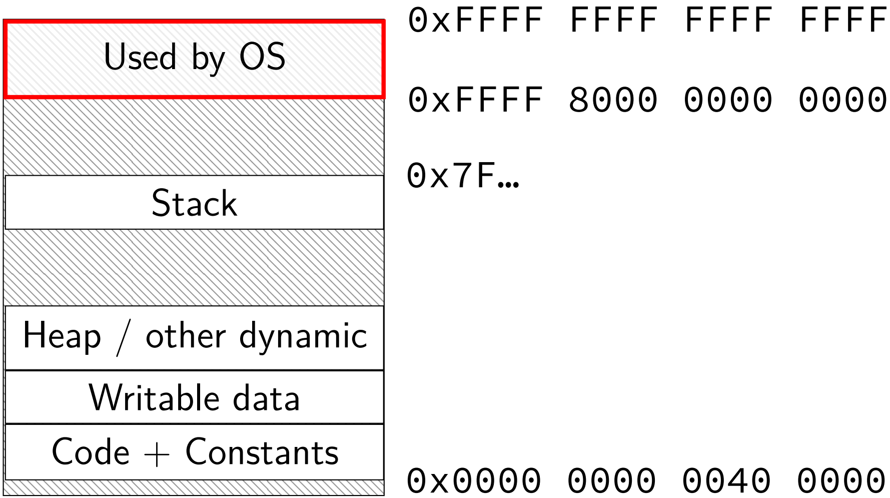
only change: load from file, etc. instead of allocating empty page

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

program memory



running OS code

system calls, I/O events, etc. run OS code in kernel mode

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where in memory is this OS code?

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- probably have a page table entry pointing to it
- marked not accessible in user mode

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where in memory is this OS code?

- probably have a page table entry pointing to it
- marked not accessible in user mode

code better not be modified by user program

- otherwise: uncontrolled way to “escape” user mode

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
```

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]
```

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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
7f60c7a7a
7f60c7a7b                                                 gnu/ld-2.19.s
7f60c7a7c                                                 gnu/ld-2.19.s
7f60c7a7d
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 ...

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
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0x28-B	89 9A AB BC
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phys. page 0

phys. page 1

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

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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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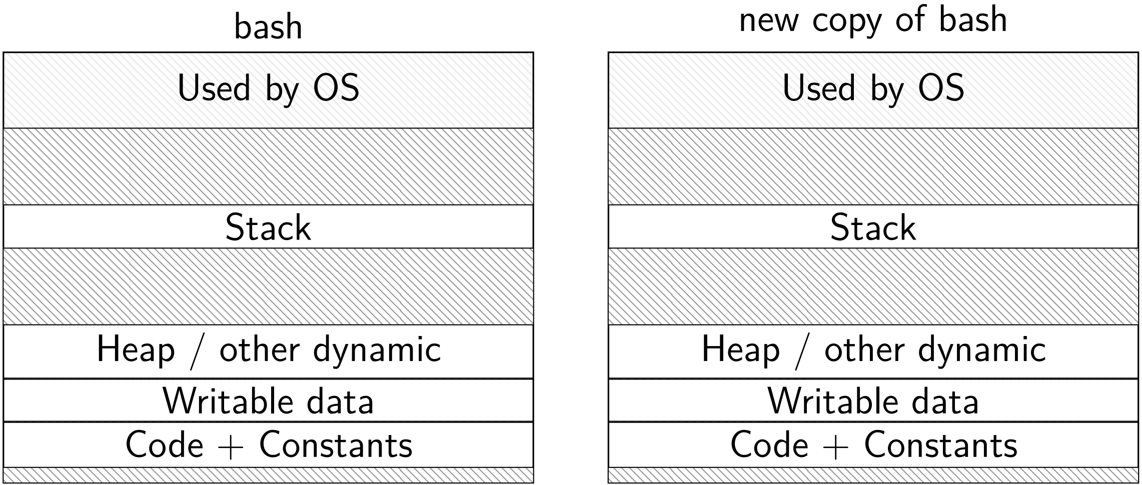
do we really need a complete copy?



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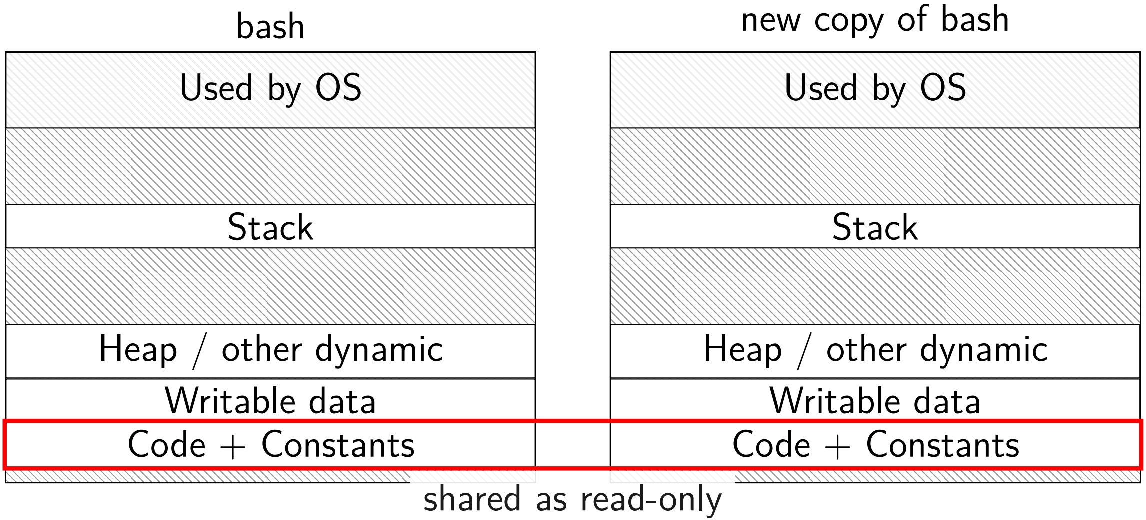

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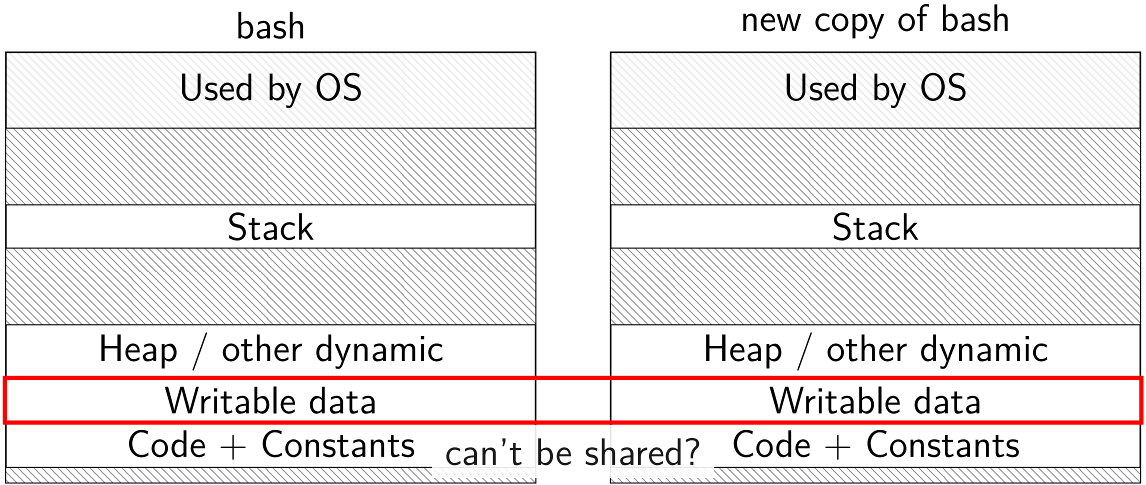

trick for extra sharing

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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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
…	…	…	…

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VPN	valid?	write?	physical page
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…	…	…	…

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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
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…	…	…	…

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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
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…	…	…	…

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0x00605	1	1	0x300FD
…	…	…	…

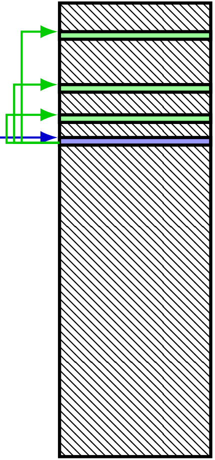
after allocating a copy, OS reruns the write instruction

fork (w/ copy-on-write, if parent writes first)

parent process info

user regs	`rax (return val.)=`~~42~~*child pid*`,` `rcx=133, …`
page tables	
open files	`fd 0: …` `fd 1: …`
…	…

memory



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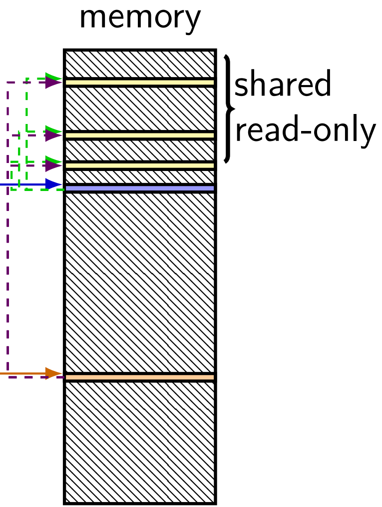
page tables	
open files	`fd 0: …` `fd 1: …`
…	…

copy

child process info

user regs	`rax (return val.)=`~~`42`~~`0,` `rcx=133, …`
page tables	
open files	`fd 0: …` `fd 1: …`
…	…



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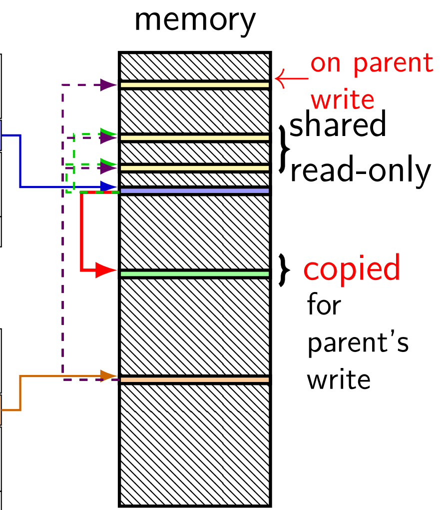

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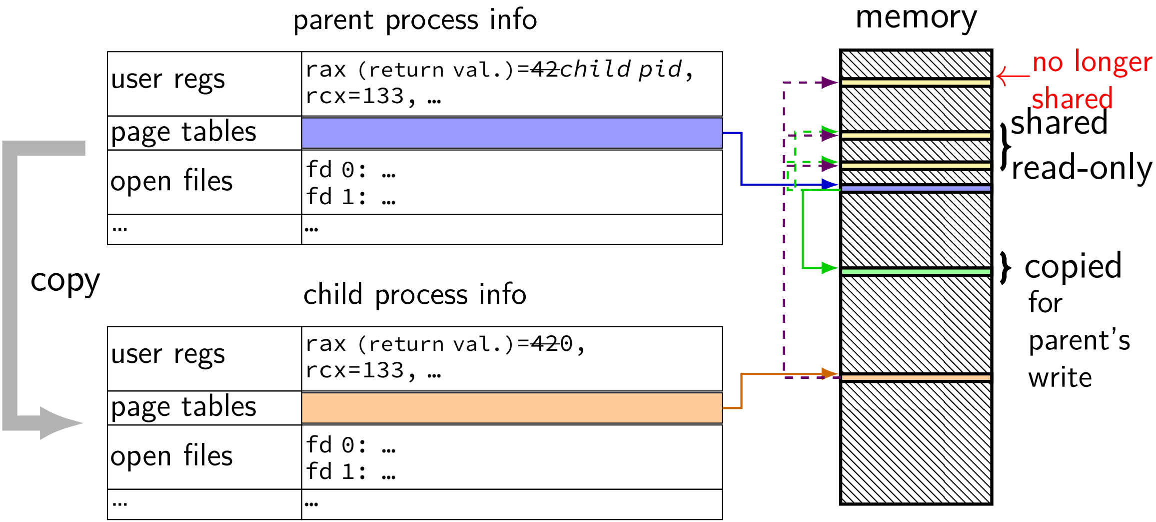

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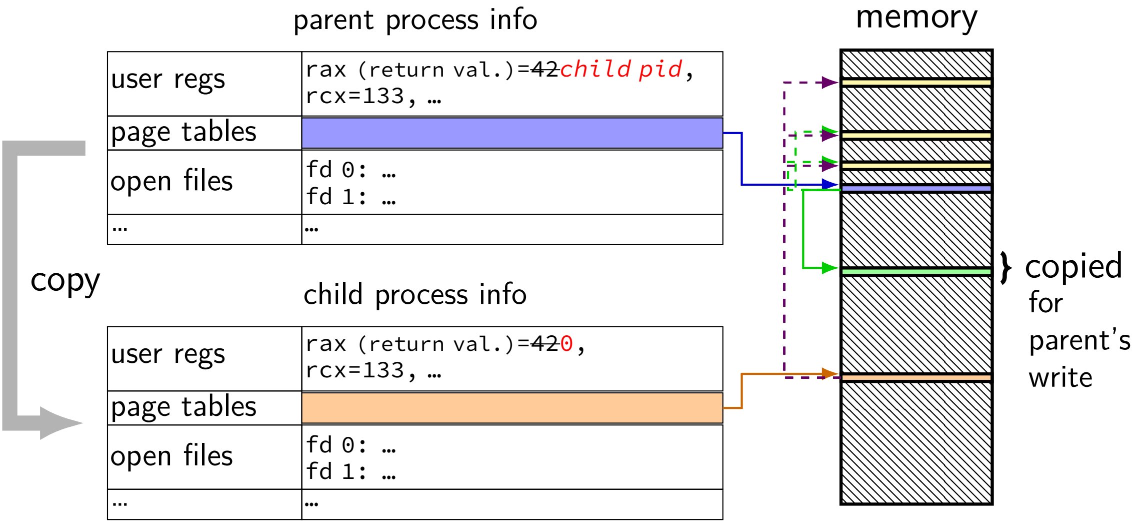

page tricks generally

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 `0x7FFFFFFFF` are the stack"

page table is for the hardware and not the OS

example page table tricks

allocating space on demand

loading code/data from files on disk on demand

saving data temporarily to disk, reloading to memory on demand

“swapping”

stopping in a debugger when a variable is modified

detecting whether memory was read/written recently

sharing memory between programs on two different machines

“copy-on-write” (later)

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

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)

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page table
base register

`0x00010000`

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page table
base register

`0x00010000`

physical memory

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

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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
…	
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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

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0x00000000-1	00000000 00000000
…	
0x00010000-1	00000000 00000000
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0x00010004-5	10000010 11000000
0x00010006-7	10110000 00110000
…	
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…			
1111 1111	1	…	00 1110 1000

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…	
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page tables in memory

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...			
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0000 0010	1	...	00 0000 1100
0000 0011	1	...	11 0000 0011
...			
1111 1111	1	...	00 1110 1000

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...	
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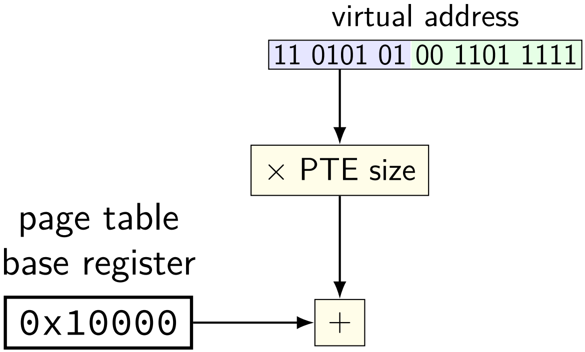
memory access with page table

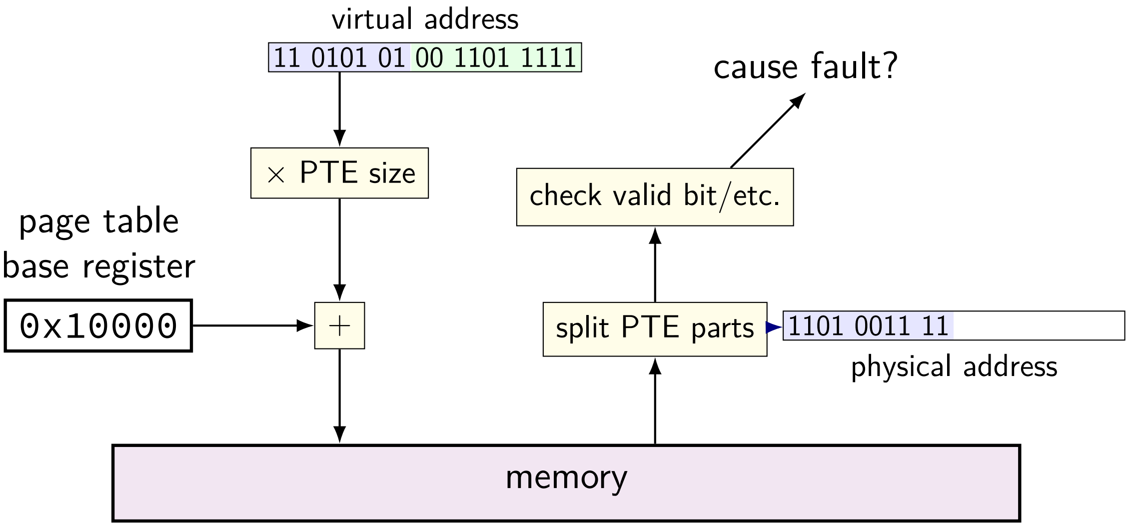
virtual address

11 0101 01	00 1101 1111

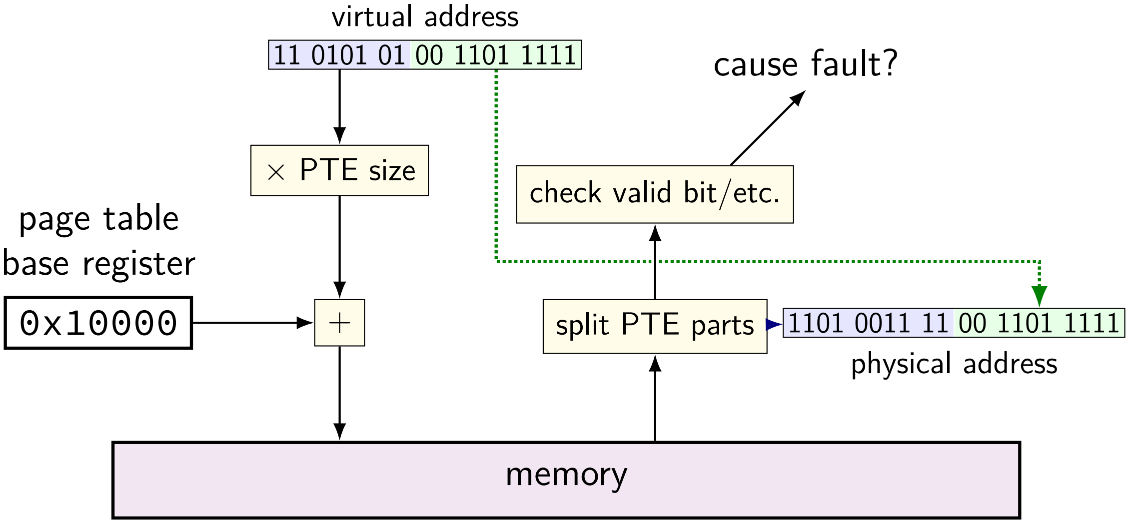
memory access with page table



memory access with page table



memory access with page table



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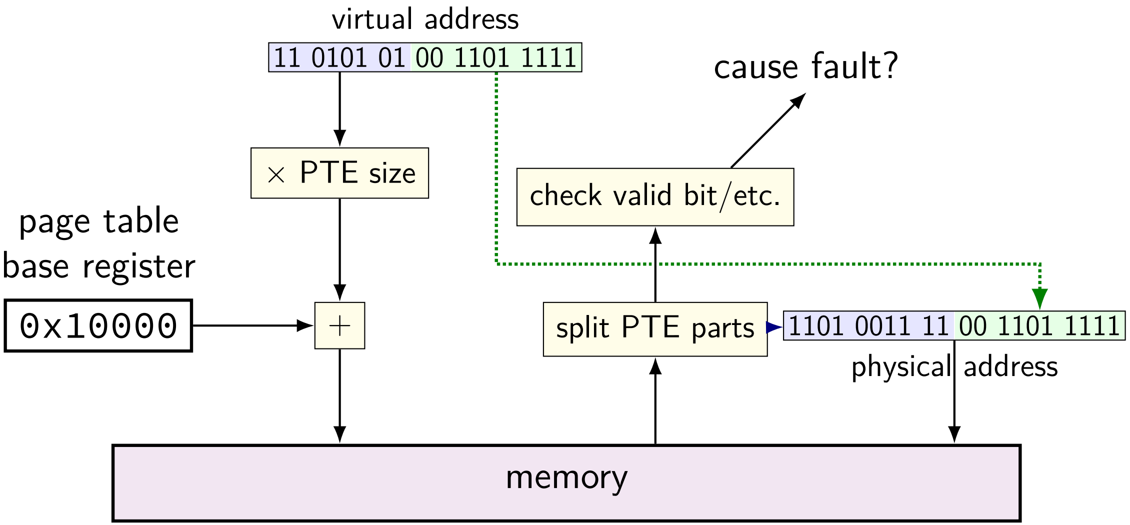

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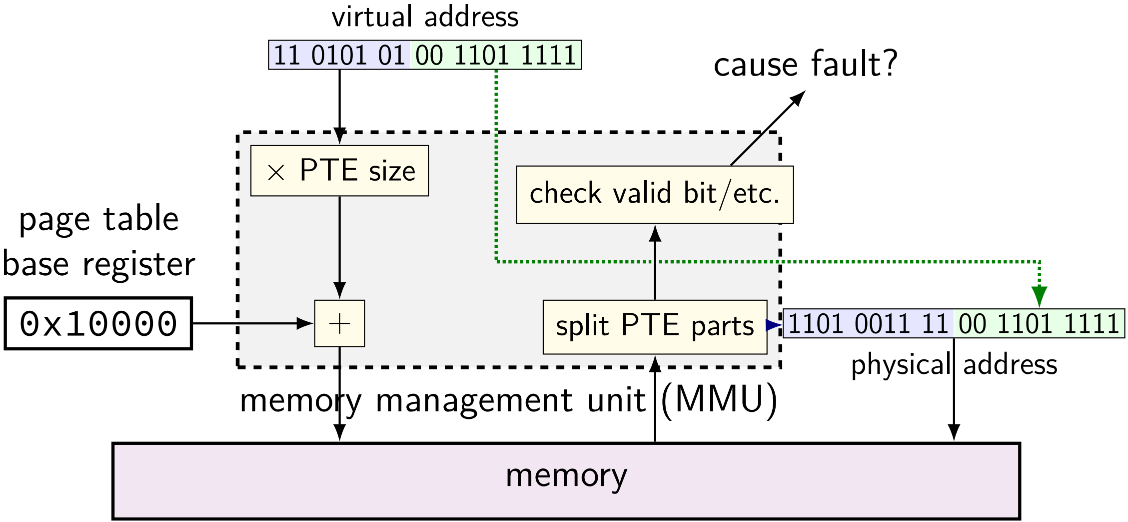

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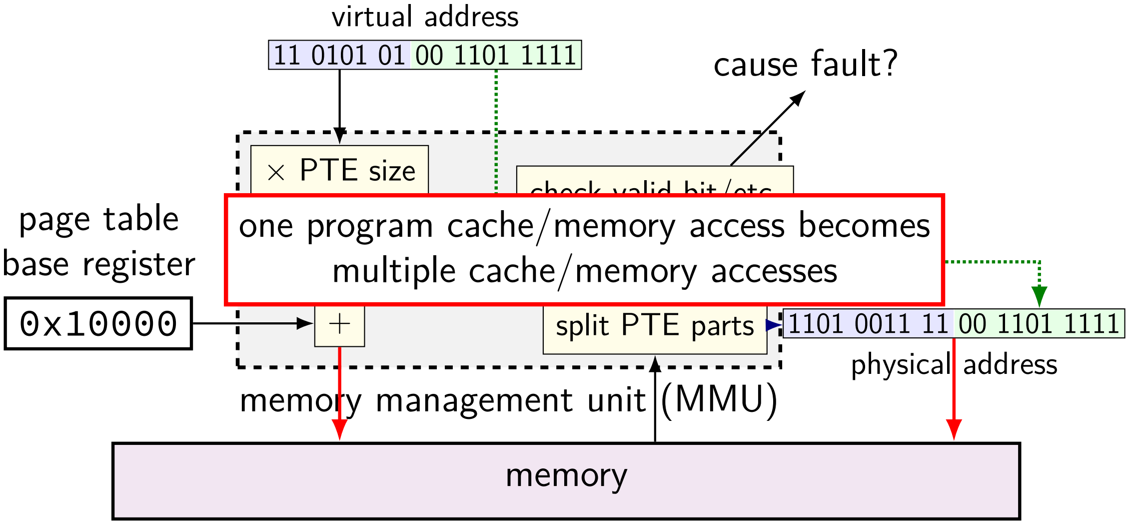
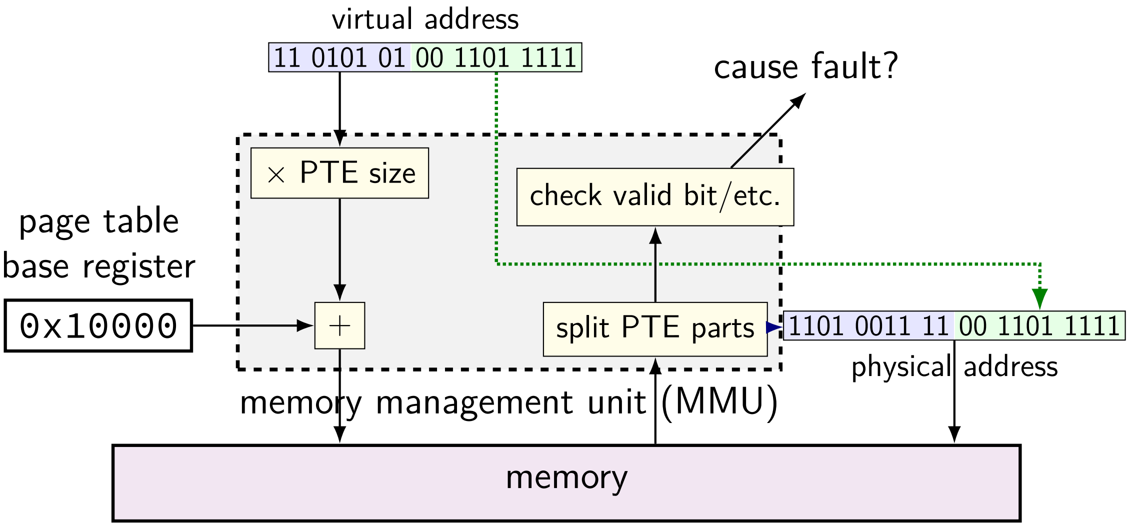


one program cache/memory access becomes multiple cache/memory accesses

memory access with page table



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
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0x28-B	89 9A AB BC
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`0x31` = `11 0001`

PTE addr:

`0x20` + `110` ×1 = `0x26`

PTE value:

`0xF6` = `1111 0110`

PPN `111`, valid 1

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

→ `0x0C`

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$\rightarrow$ `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	A0 E2 D1 F3
0x24-7	E4 E5 F6 07
0x28-B	89 9A AB BC
0x2C-F	CD DE EF F0
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0x18-B	1C 2C 3C 4C
0x1C-F	1C 2C 3C 4C

physical addresses	bytes
0x20-3	A0 E2 D1 F3
0x24-7	E4 E5 F6 07
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:

`0xD1` = `1101 0001`

PPN `110`, valid `1`

M[`110 001`] = **M[**`0x32`**]**

→ `0xBA`

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`0x12` $=$ `01 0010`

PTE addr:

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

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pagetable assignment

pagetable assignment

simulate page tables (on top of normal program memory)

- alternately: implement another layer of page tables on top of the existing system's

in assignment:

virtual address $\sim$ arguments to your functions

physical address $\sim$ your program addresses (normal pointers)

pagetable assignment API

```
/* configuration parameters */
#define POBITS ...
#define LEVELS /* later /
```

```
size_t ptbr; // page table base register
    // points to page table (array of page table entries)

// lookup "virtual" address 'va' in page table ptbr points to
// return (void*) (~0L) if invalid
void *translate(size_t va);

// make it so 'va' is valid, allocating one page for its data
// if it isn't already
void page_allocate(size_t va)
```

translate()

with POBITS=12, LEVELS=1:

ptbr = GetPointerToTable(

VPN	valid?	physical
0	0	—
1	1	0x9999
2	0	—
3	1	0x3333
...	...	...

)

```
translate(0x0FFF) == (void*) ~0L
translate(0x1000) == (void*) 0x9999000
translate(0x1001) == (void*) 0x9999001
translate(0x2000) == (void*) ~0L
translate(0x2001) == (void*) ~0L
translate(0x3000) == (void*) 0x3333000
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with POBITS=12, LEVELS=1:

ptbr = GetPointerToTable(

VPN	valid?	physical
0	0	—
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...	...	...

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translate(0x2001) == (void*) ~0L
translate(0x3000) == (void*) 0x3333000

page_allocate()

with POBITS=12, LEVELS=1:

ptbr == 0

page_allocate(0x1000) *or* page_allocate(0x1001) *or* ...

page_allocate()

with POBITS=12, LEVELS=1:

ptbr == 0

page_allocate(0x1000) *or* page_allocate(0x1001) *or* ...

ptbr *now* == GetPointerToTable(

VPN	valid?	physical
0	0	—
1	1	(new)
2	0	—
3	1	—
...	...	...

)

allocated with `posix_memalign`

page_allocate()

with POBITS=12, LEVELS=1:

ptbr == 0

page_allocate(0x1000) *or* page_allocate(0x1001) *or* ...

ptbr *now* == GetPointerToTable(

VPN	valid?	physical
0	0	—
1	1	(new)
2	0	—
3	1	—
...	...	...

)

allocated with `posix_memalign`

posix_memalign

```
void *result;
error_code =
    posix_memalign(&result, alignment, size);
```

allocate `size` bytes

choosing address that is multiple of `alignment`

- can make sure allocation starts at beginning of page

`error_code` indicates if out-of-memory, etc.

fills in `result` (passed via pointer)

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parts

part 1 (next week): LEVELS=1, POBITS=12 and

- translate() OR
- page_allocate()

part 2: all LEVELS, both functions

- in preparation for code review
- originally scheduled for lab on the 27th
- will move to lab just after reading day
- (might mean I need to cancel lab one week)

part 3: final submission

- Friday after code review
- most of grade based on this
- will test previous parts again

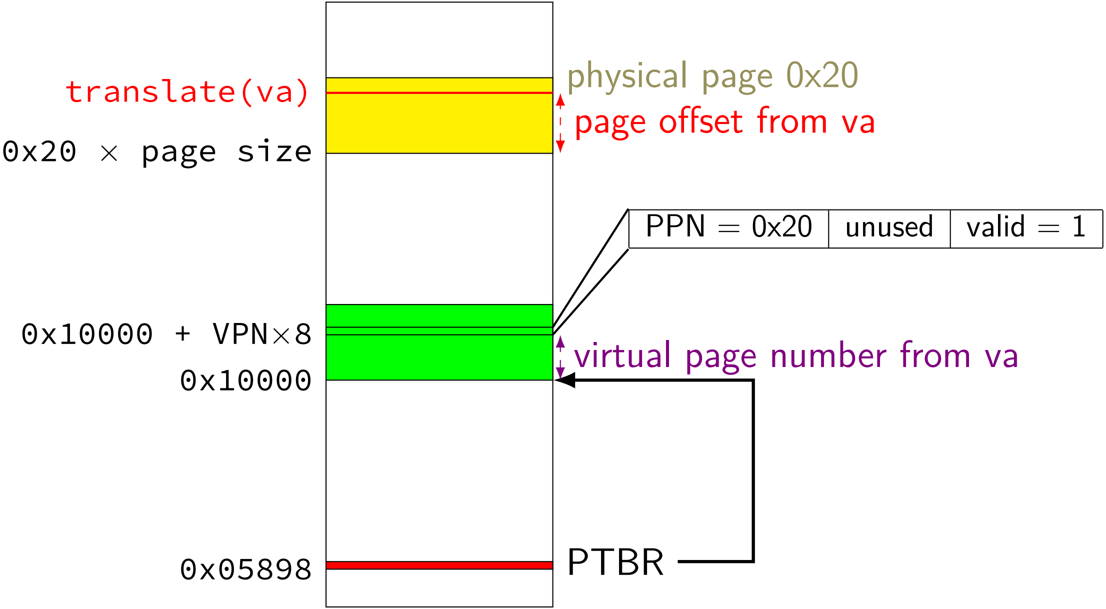
address/page table entry format

(with POBITS=12, LEVELS=1)

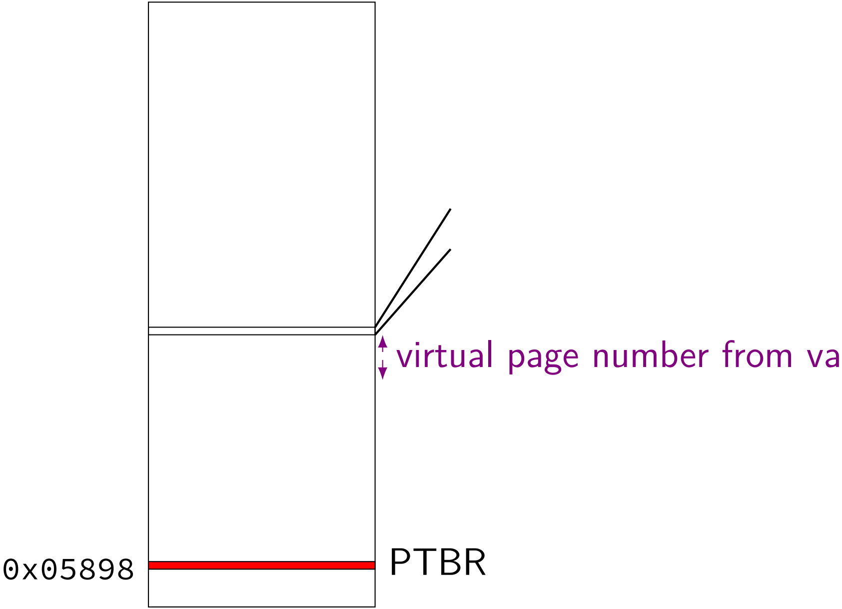
	bits 63–21	bits 20–12	bits 11–1	bit 0
page table entry	physical page number		unused	valid bit
virtual address	unused	virtual page number	page offset	
physical address	physical page number		page offset	

in assignment: value from posix_memalign = physical address

pa = translate(va) [LEVELS=1]



first page_allocate(va) [LEVELS=1]



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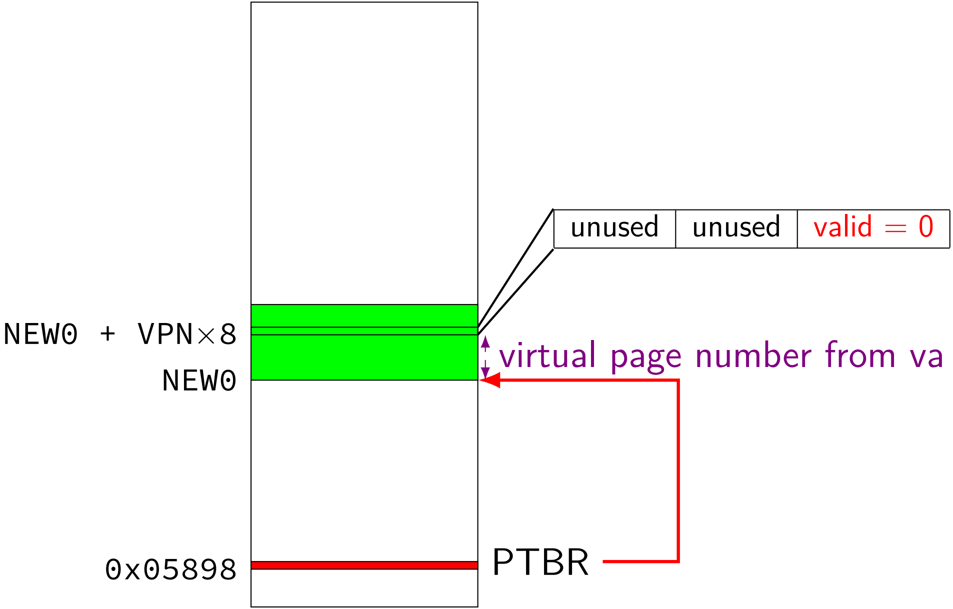
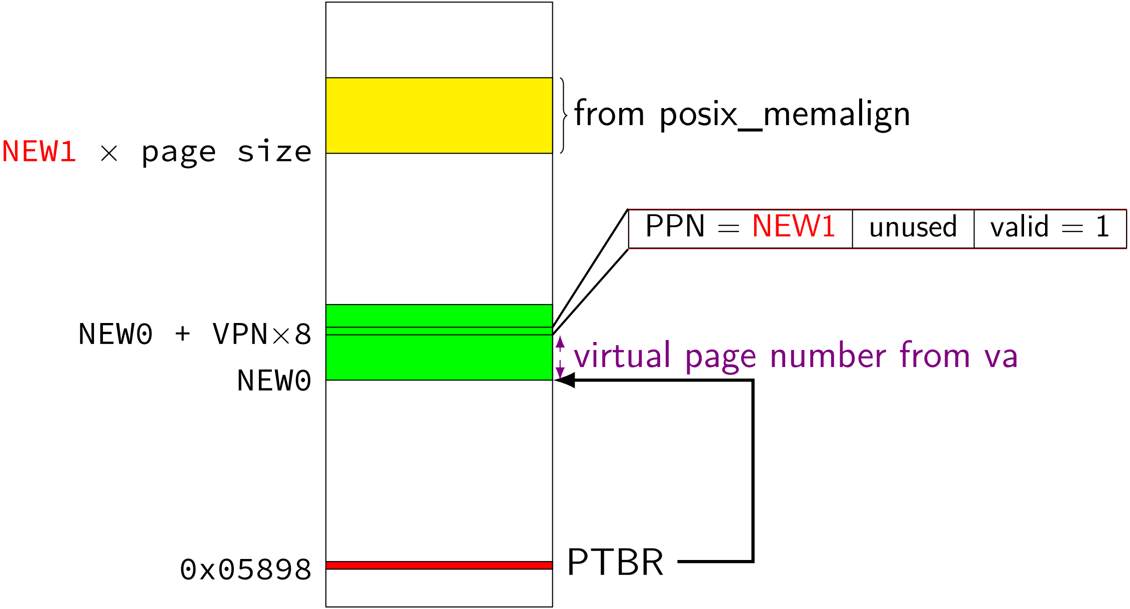
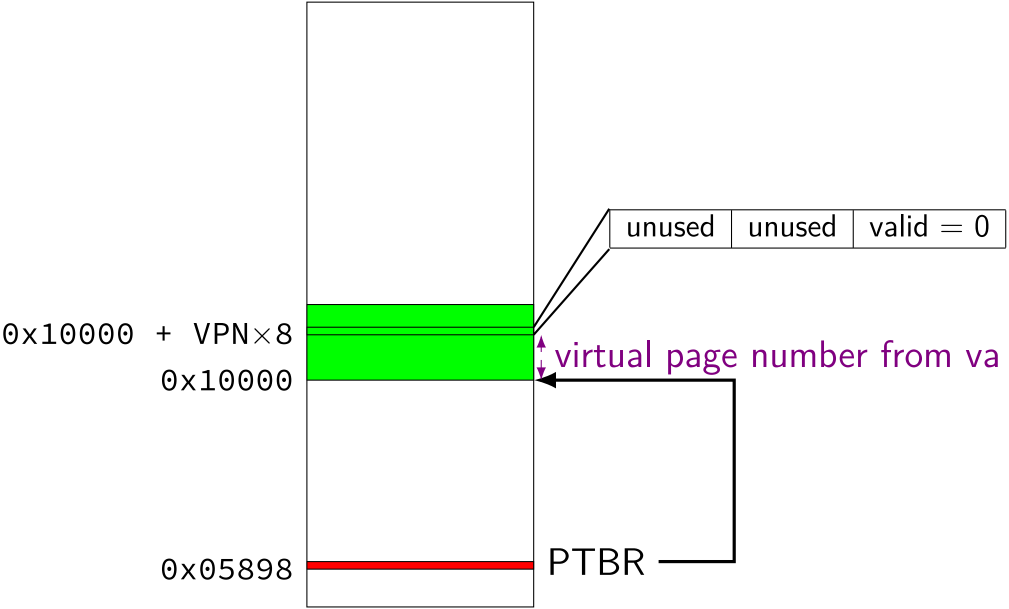


first page_allocate(va) [LEVELS=1]



page_allocate(va) [LEVELS=1]



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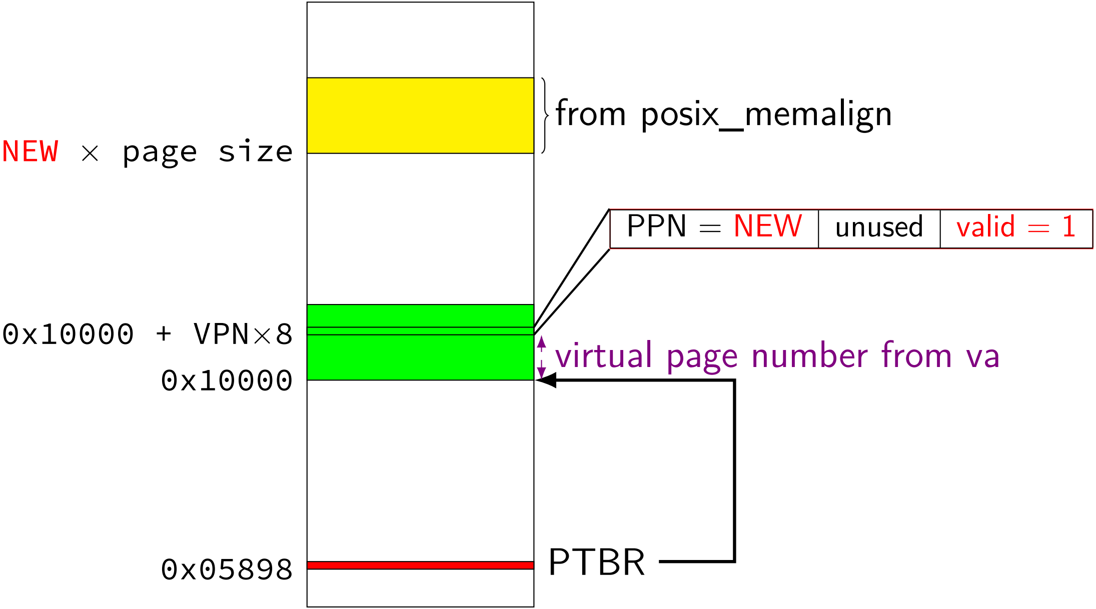
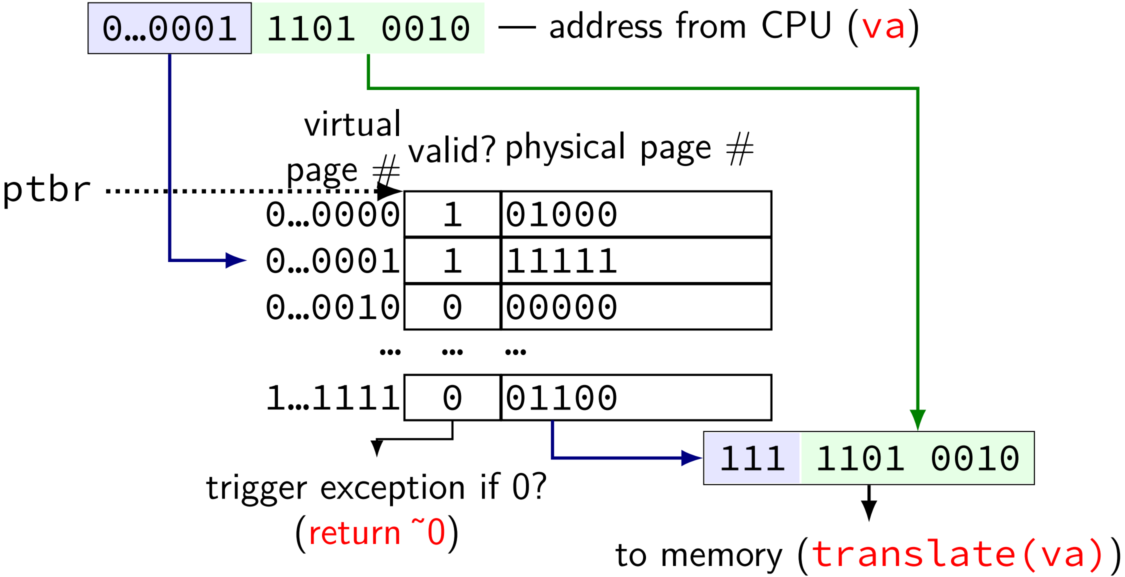


page table lookup (and translate())



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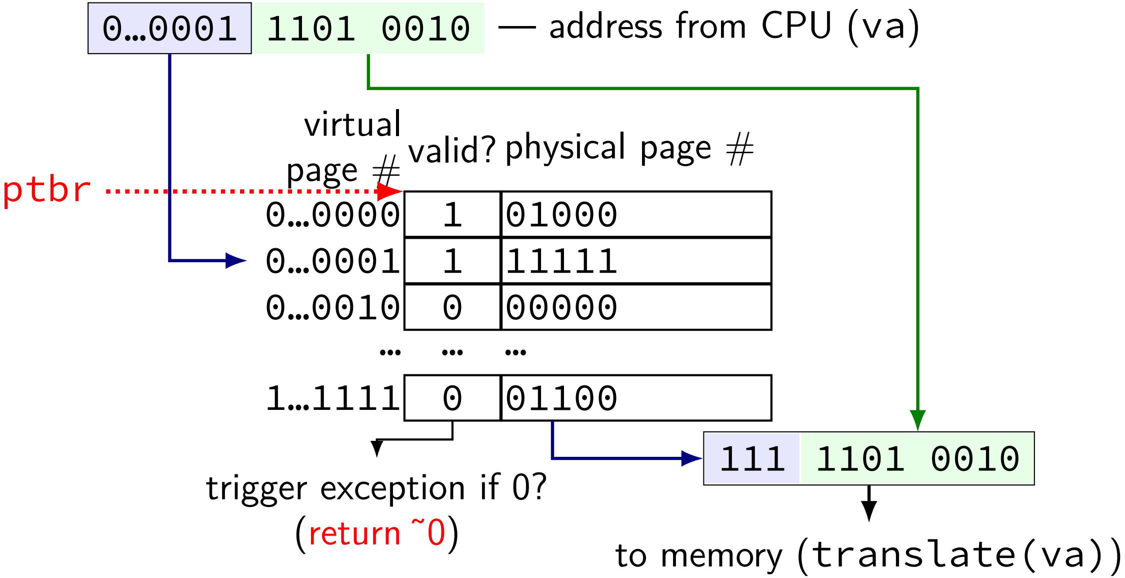

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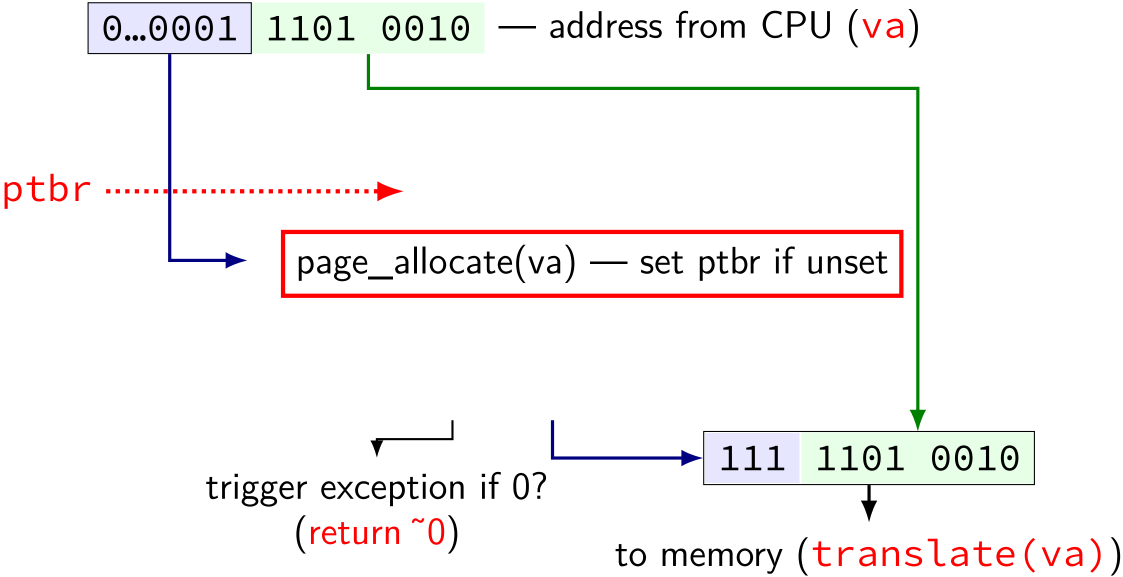

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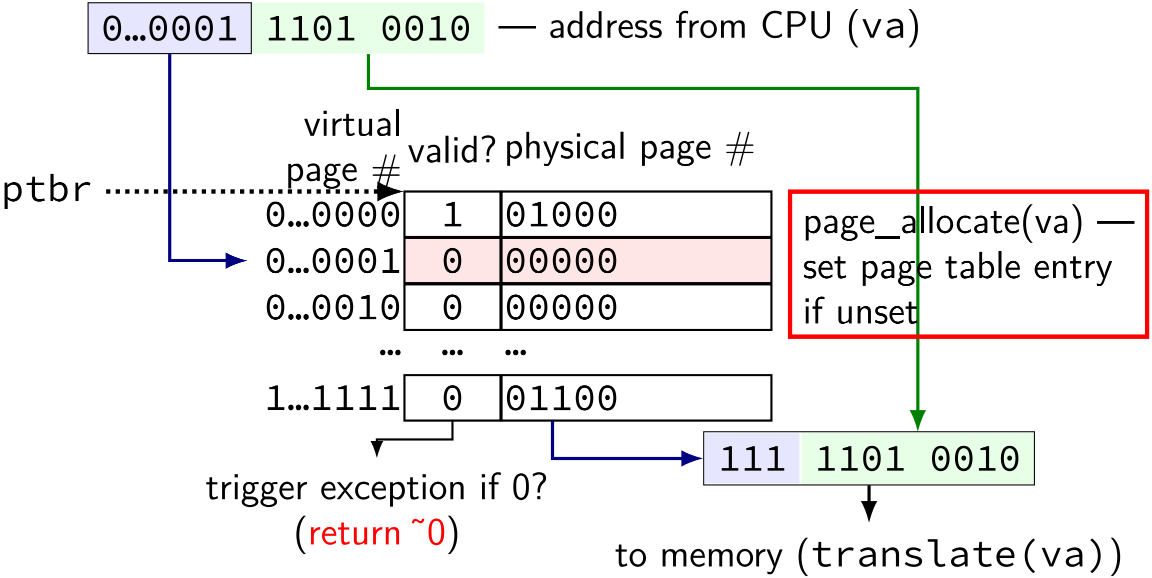

exercise: 64-bit system

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

4096 byte pages

exercise: 64-bit system

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4096 byte pages

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

exercise: 64-bit system

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

4096 byte pages

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

exercise: how large are physical page numbers?

exercise: 64-bit system

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exercise: 64-bit system

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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??)

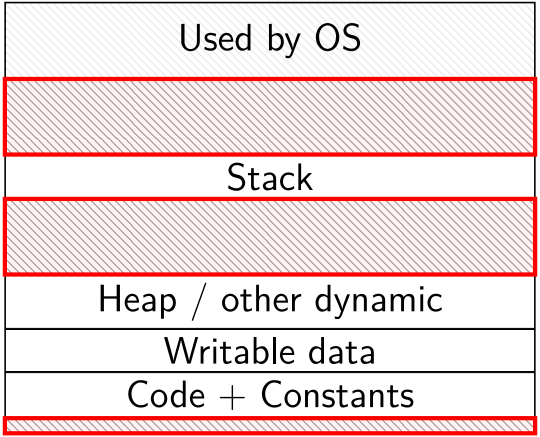
huge page tables

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?

saving space

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hashtable

- actually used by some historical processors
- but never common

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use a data structure other than a flat array

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options?

hashtable

- 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

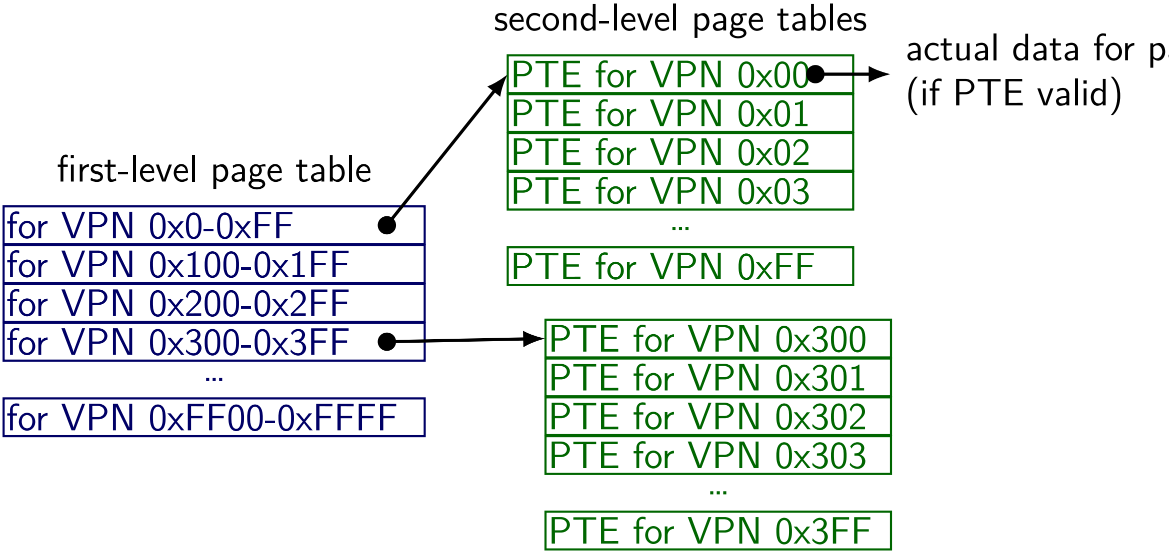
- lookup should be simple
- solution: lookup splits up address bits (no complex calculations)

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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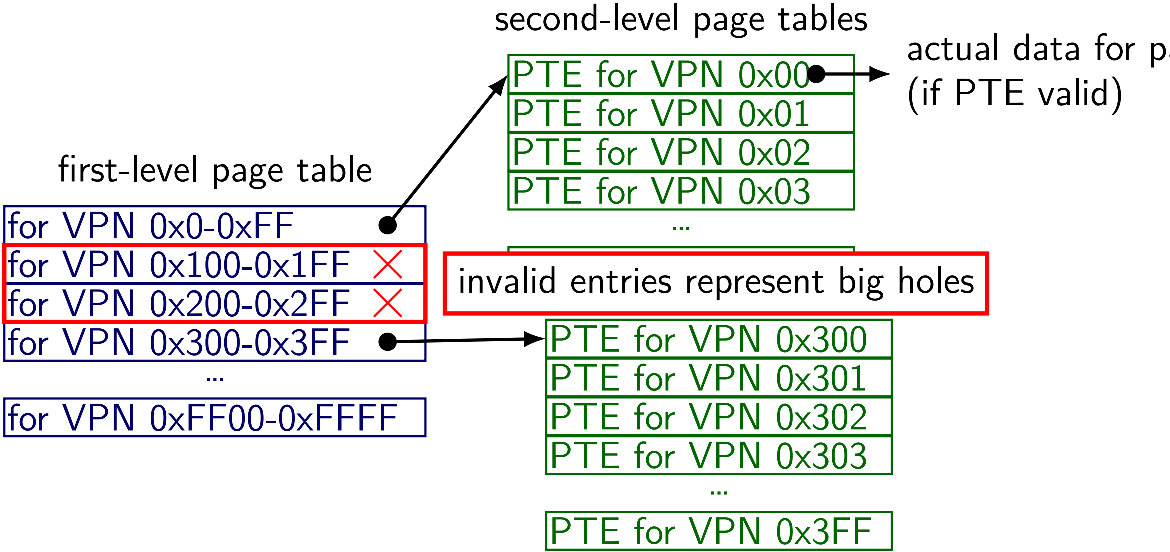

two-level page tables

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

first-level 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

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

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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

- for VPN 0x0-0xFF
- for VPN 0x100-0x1FF ✗
- for VPN 0x200-0x2FF ✗
- for VPN 0x300-0x3FF
- ...
- 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)

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for VPN 0x0-0xFF
for VPN 0x100-0x1FF ✗
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two-level page tables

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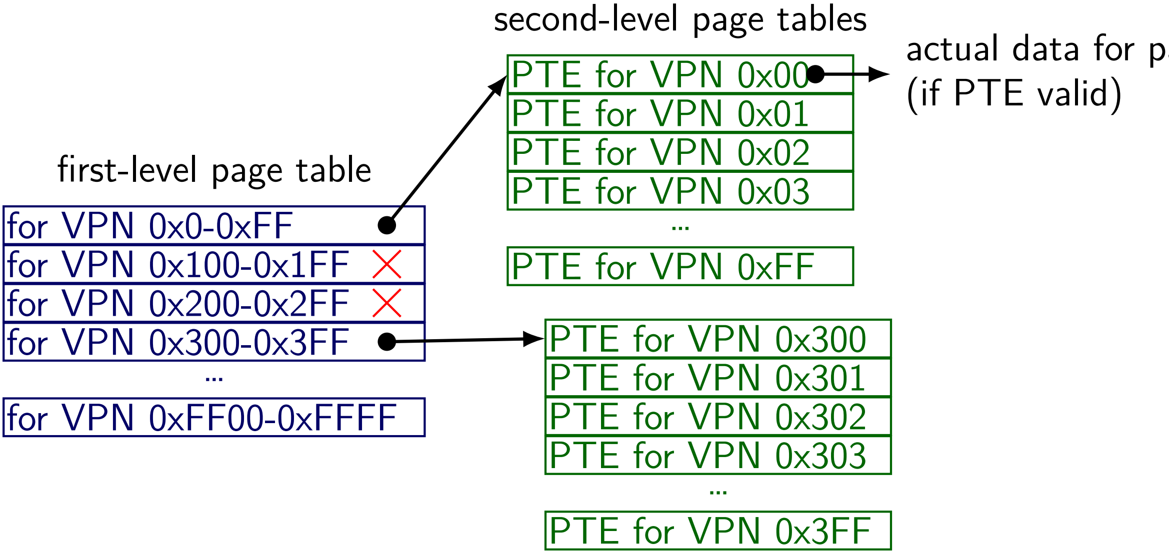


two-level page table lookup

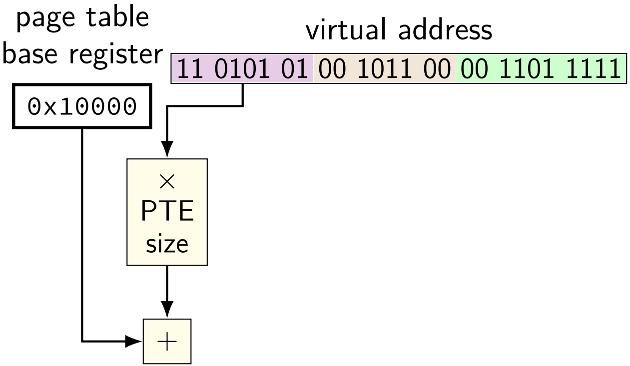
virtual address

11 0101 01	00 1011 00	00 1101 1111

VPN — split into two parts (one per level)

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

two-level page table lookup



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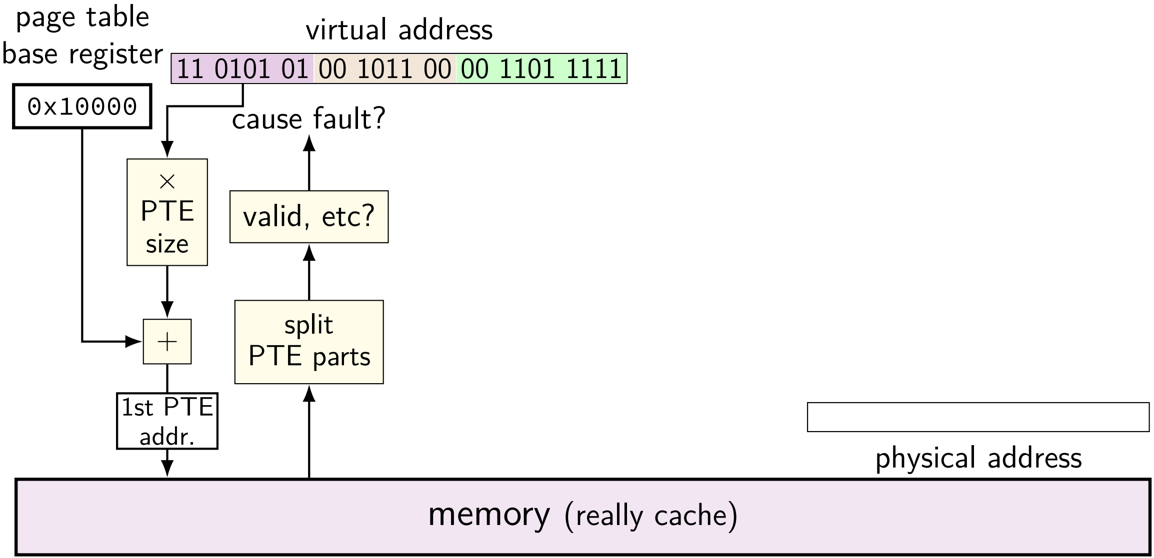

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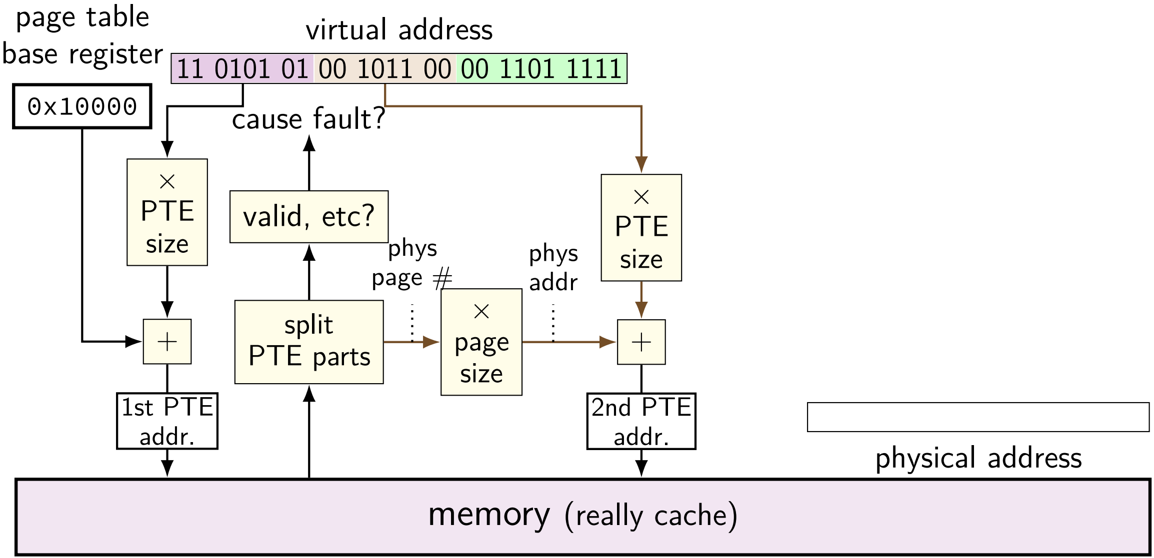

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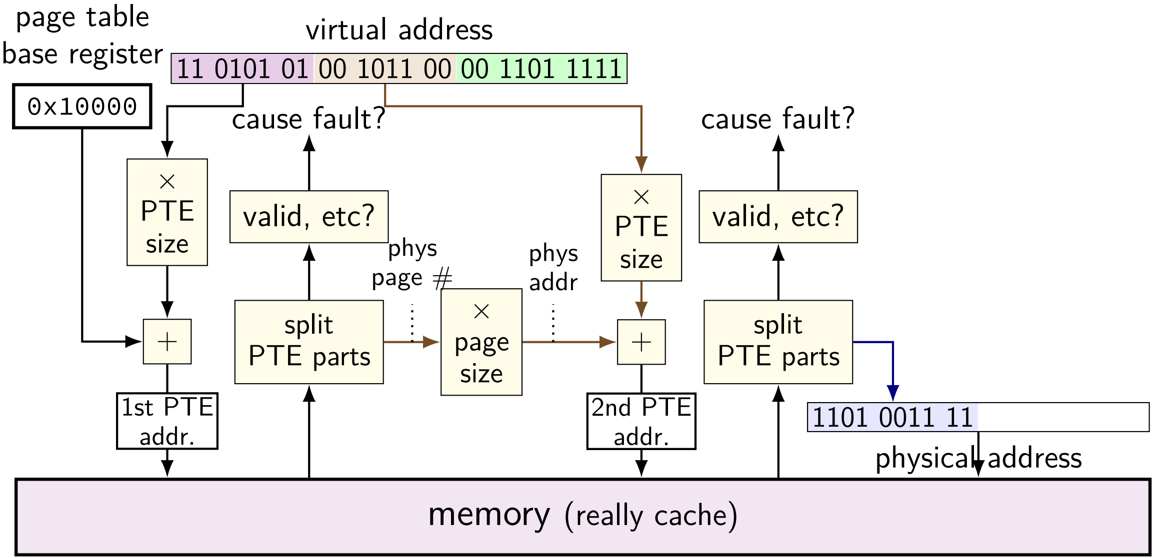

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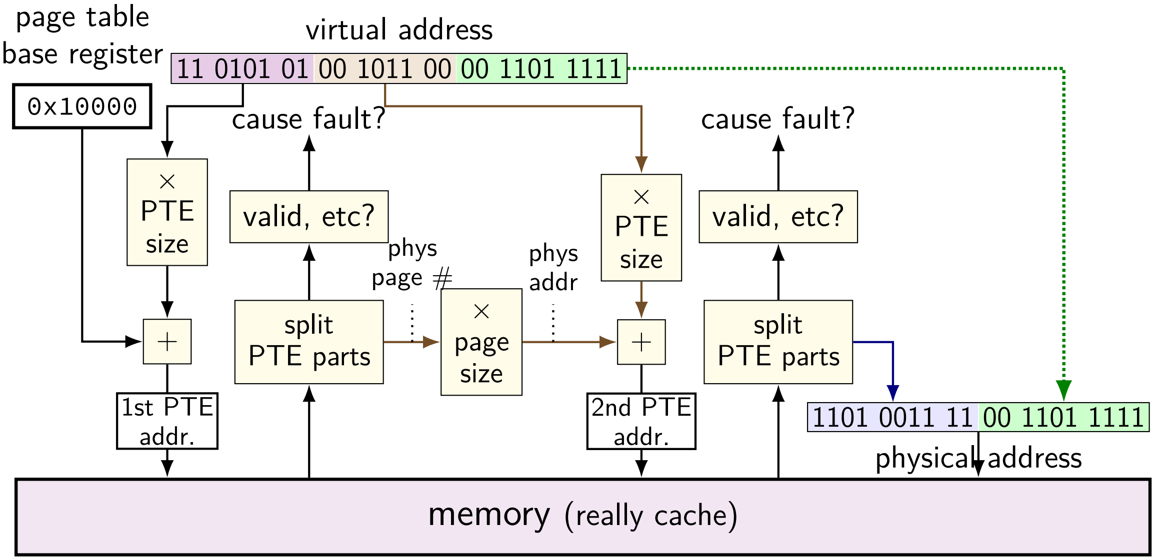

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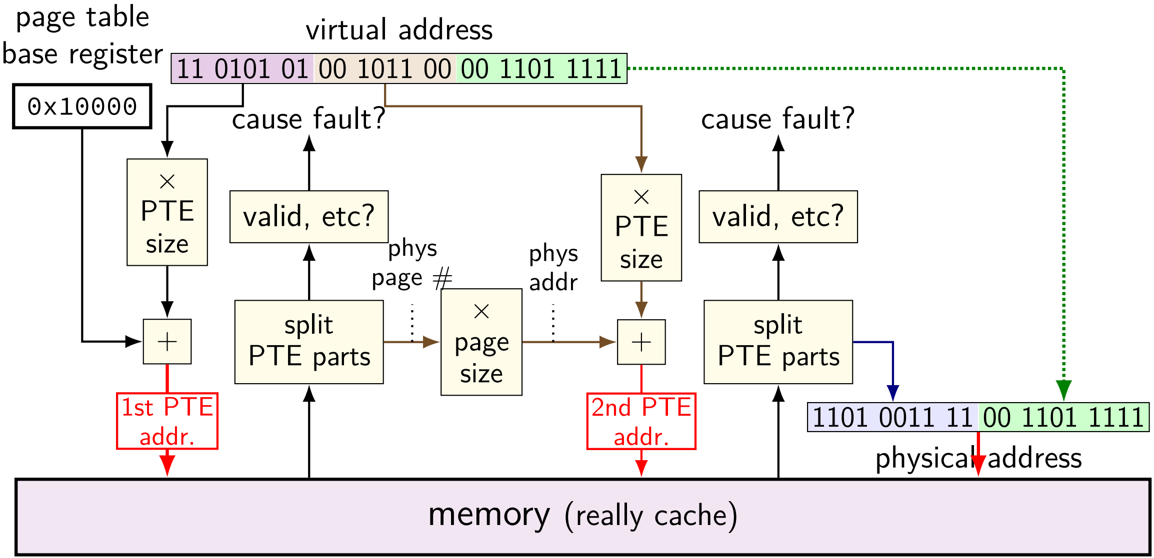

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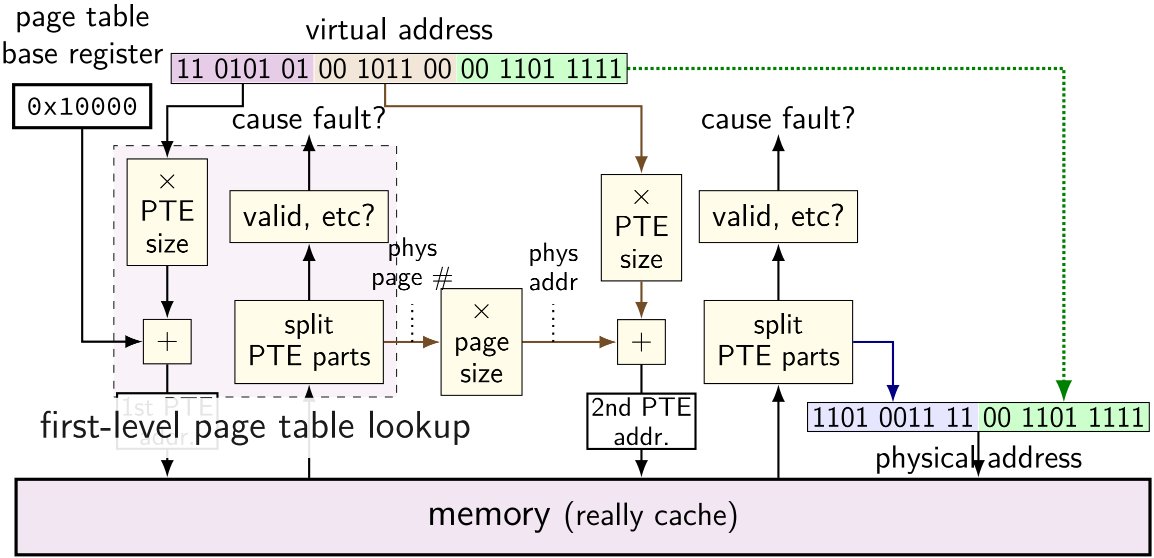

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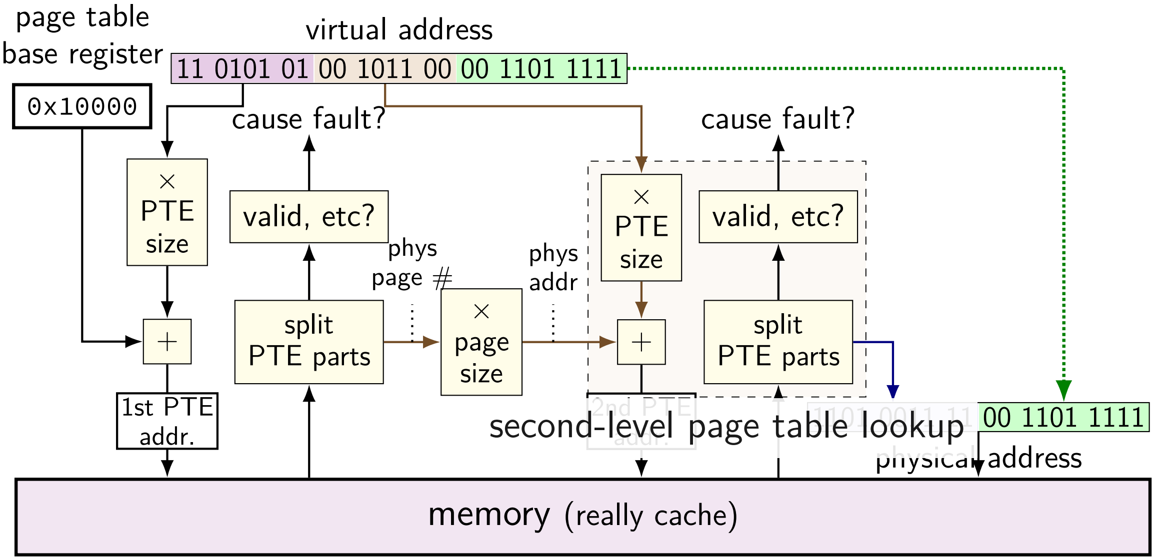

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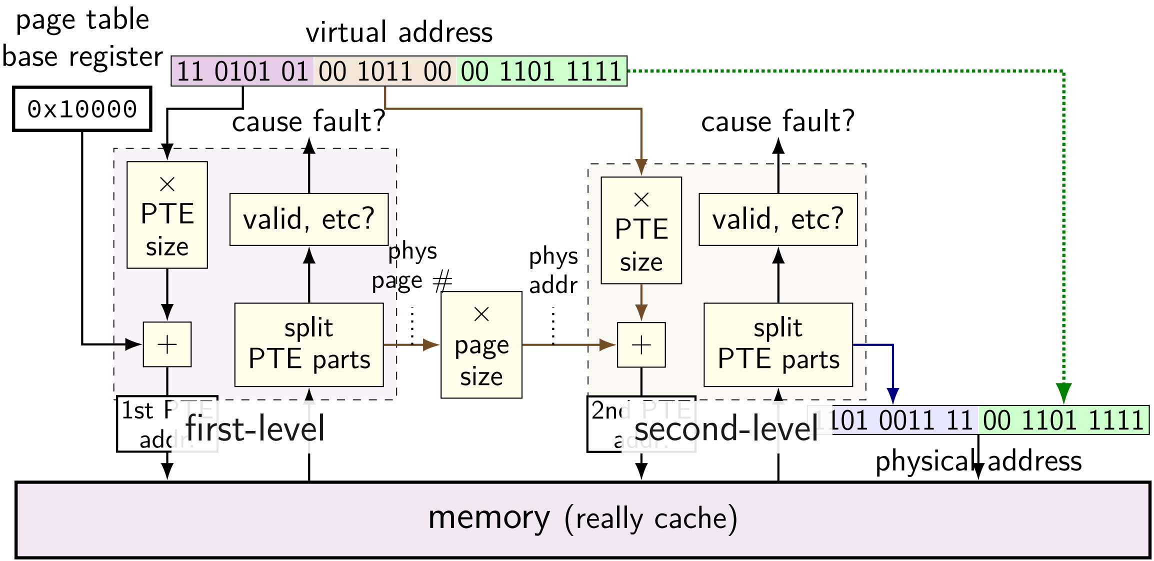

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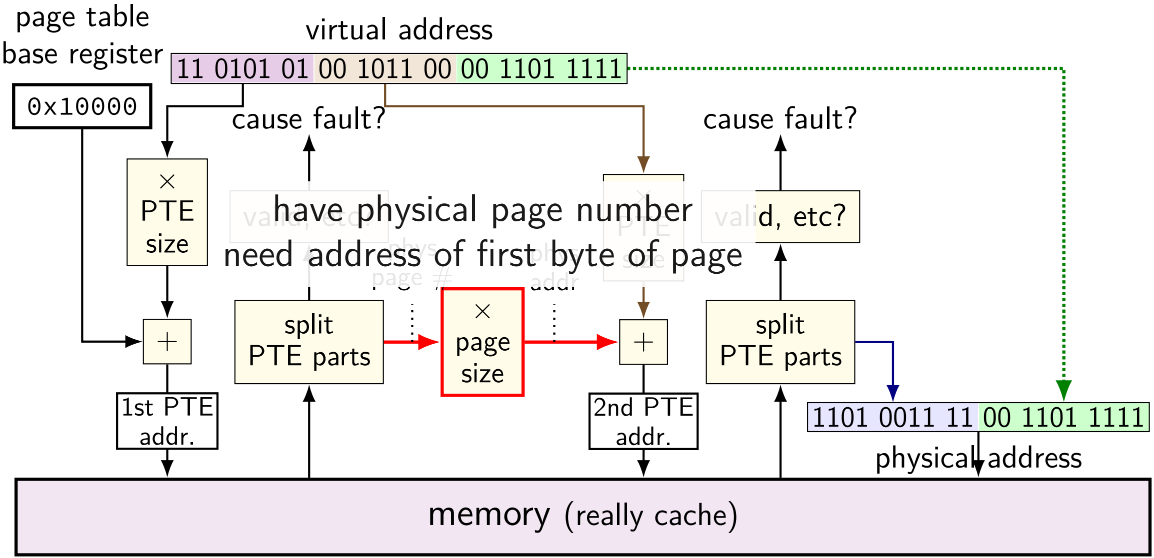

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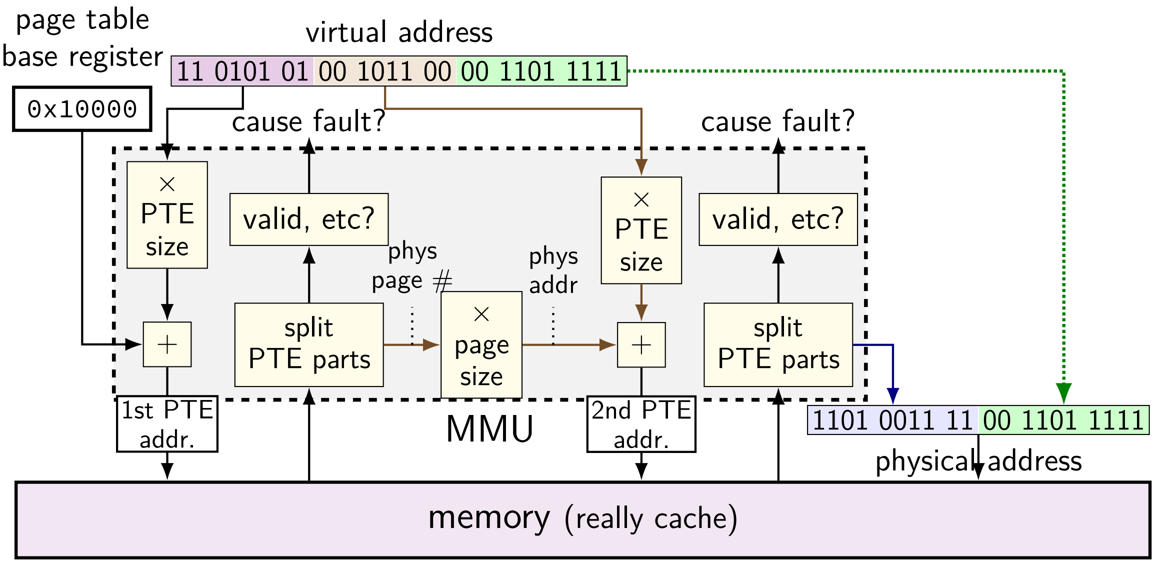
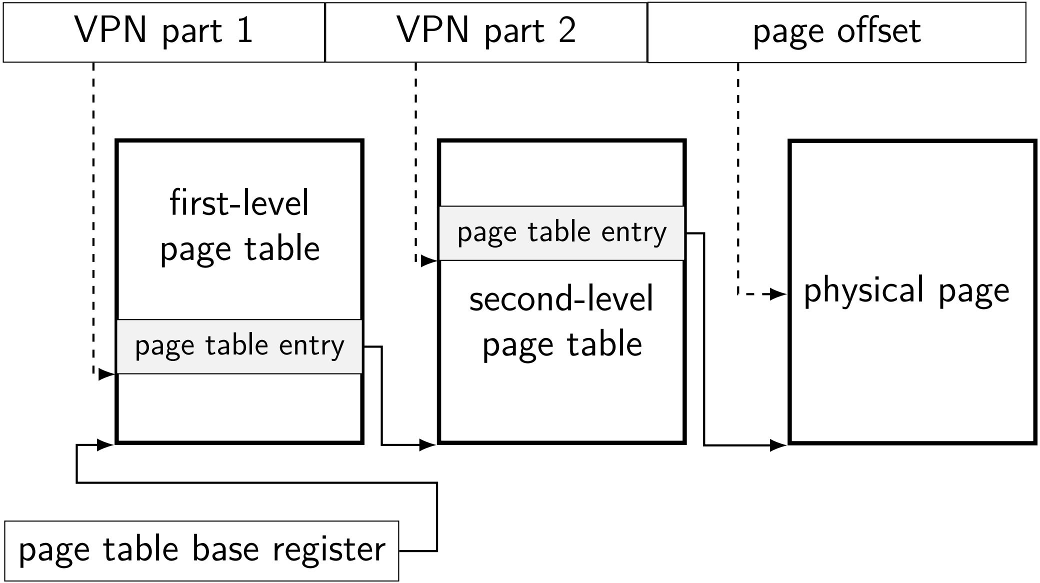


another view



multi-level page tables

VPN split into pieces for each level of page table

top levels: page table entries point to next page table
- usually using physical page number of next page table

bottom level: page table entry points to destination page

validity checks at each level

note on VPN splitting

indexes used for lookup parts of the virtual page number

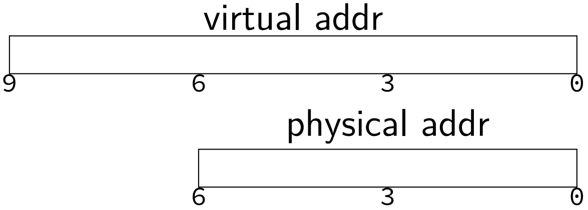
(there are not multiple VPNs)

assignment

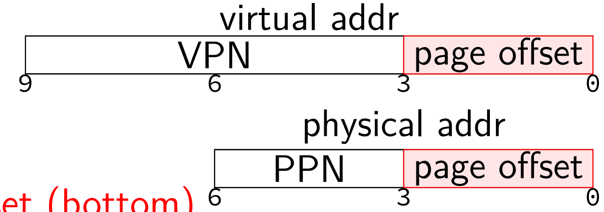
2-level splitting

9-bit virtual address

6-bit physical address



2-level splitting



9-bit virtual address

6-bit physical address

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

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

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

2-level splitting

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6-bit physical address

8-byte pages → 3-bit page offset (bottom)

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

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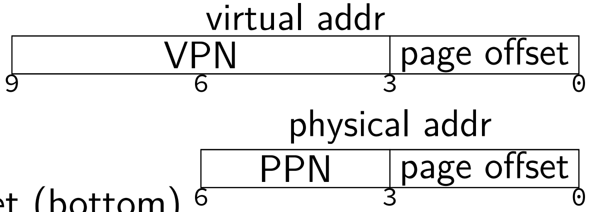
1 page page tables w/ 1 byte entry → 8 entry PTs

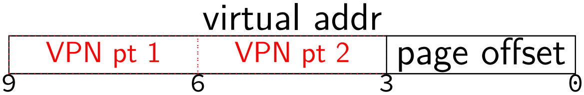


page table (either level)

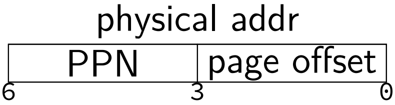
	valid?	PPN
0		
1		
2		
...	...	...
7		

2-level splitting

9-bit virtual address



6-bit physical address

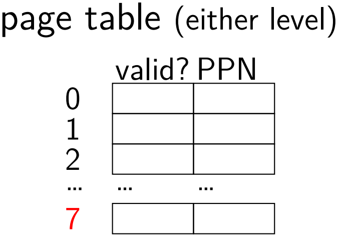


8-byte pages → 3-bit page offset (bottom)

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

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

1 page page tables w/ 1 byte entry → 8 entry PTs



8 entry page tables → 3-bit VPN parts

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

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 `0x129`

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	00 91 72 13
0x24-7	F4 A5 36 07
0x28-B	89 9A AB BC
0x2C-F	CD DE EF F0
0x30-3	BA 0A BA 0A
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2-level exercise (1)

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

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

page table base register `0x08`; translate virtual address `0x0FB`

physical addresses	bytes	physical addresses	bytes
0x00-3	00 11 22 33	0x20-3	D0 D1 D2 D3
0x04-7	44 55 66 77	0x24-7	D4 D5 D6 D7
0x08-B	88 99 AA BB	0x28-B	89 9A AB BC
0x0C-F	CC DD EE FF	0x2C-F	CD DE EF F0
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0x0C-F	CC DD EE FF	0x2C-F	CD DE EF F0
0x10-3	1A 2A 3A 4A	0x30-3	BA 0A BA 0A
0x14-7	1B 2B 3B 4B	0x34-7	DB 0B DB 0B
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0x1C-F	1C 2C 3C 4C	0x3C-F	FC 0C FC 0C

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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
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0x04-7	44 55 66 77
0x08-B	88 99 AA BB
0x0C-F	CC DD EE FF
0x10-3	1A 2A 3A 4A
0x14-7	1B 2B 3B 4B
0x18-B	1C 2C 3C 4C
0x1C-F	1C 2C 3C 4C

physical addresses	bytes
0x20-3	D0 D1 D2 D3
0x24-7	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	physical addresses	bytes
0x00-3	00 11 22 33	0x20-3	D0 D1 D2 D3
0x04-7	44 55 66 77	0x24-7	D4 D5 D6 D7
0x08-B	88 99 AA BB	0x28-B	89 9A AB BC
0x0C-F	CC DD EE FF	0x2C-F	CD DE EF F0
0x10-3	1A 2A 3A 4A	0x30-3	BA 0A BA 0A
0x14-7	1B 2B 3B 4B	0x34-7	DB 0B DB 0B
0x18-B	1C 2C 3C 4C	0x38-B	EC 0C EC 0C
0x1C-F	1C 2C 3C 4C	0x3C-F	FC 0C FC 0C

2-level exercise (3)

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

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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
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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
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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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0x30-3	BA 0A BA 0A
0x34-7	DB 0B DB 0B
0x38-B	EC 0C EC 0C
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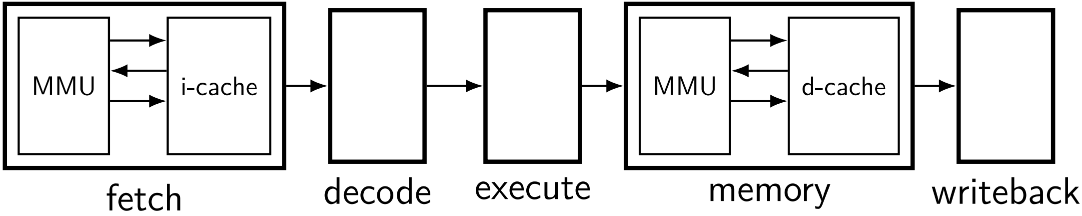
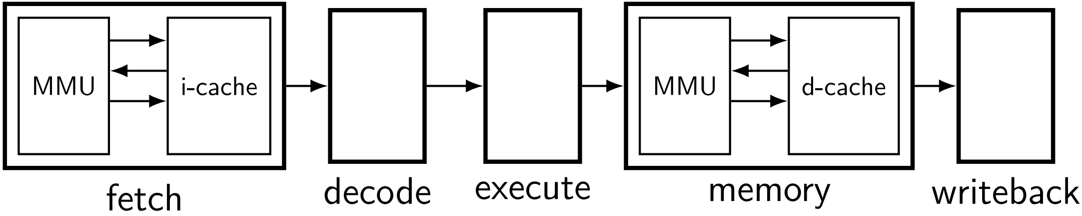
backup slides

MMUs in the pipeline



up to four memory accesses per instruction

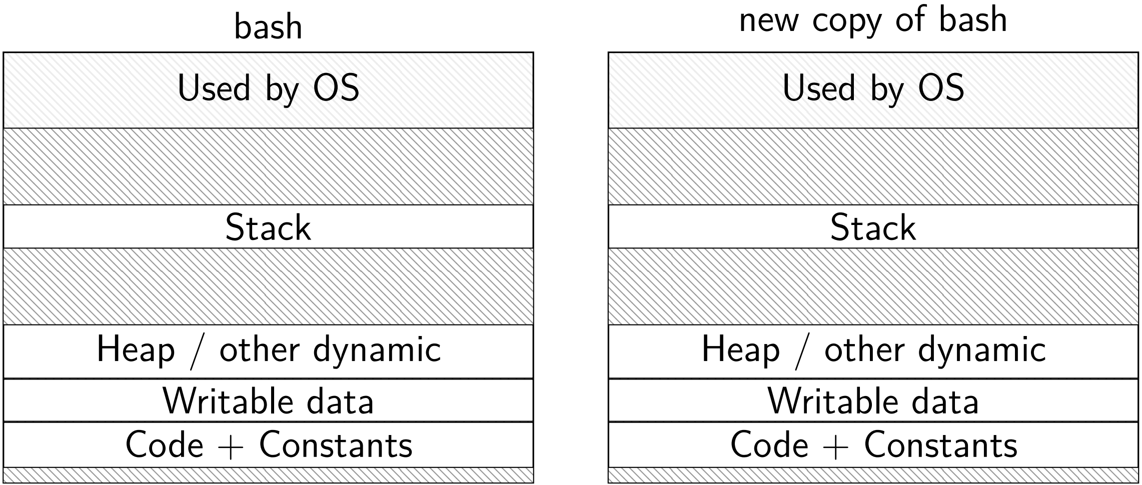
MMUs in the pipeline



up to four memory accesses per instruction

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

do we really need a complete copy?



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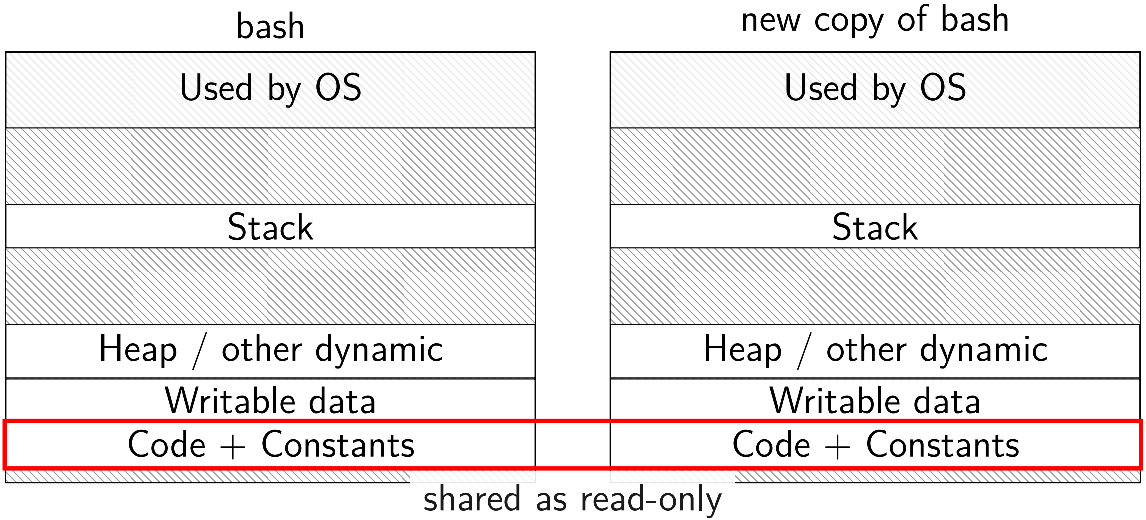

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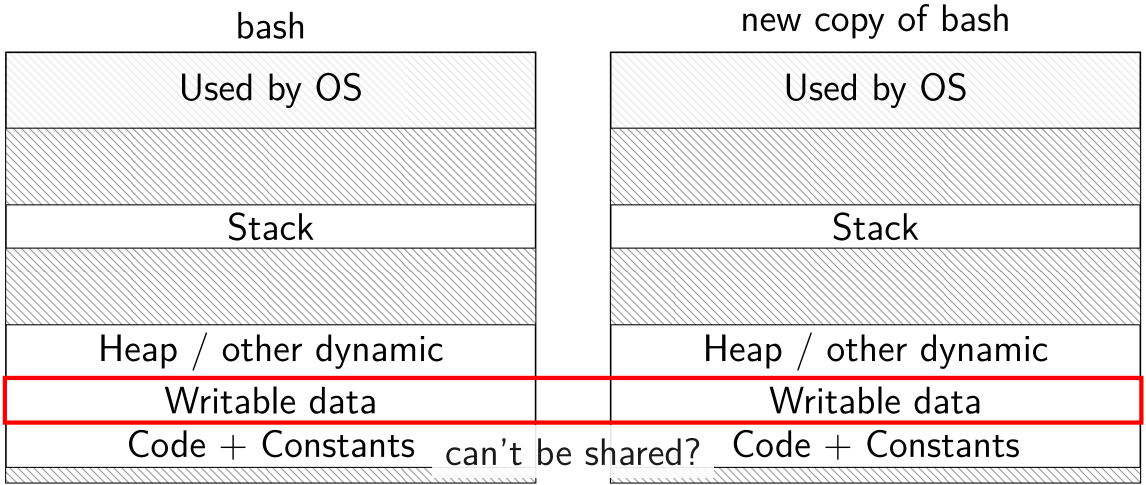

trick for extra sharing

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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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
...	...	...	...

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VPN	valid?	write?	physical page
…	…	…	…
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…	…	…	…

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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
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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
…	…	…	…

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0x00601	1	0	0x12345
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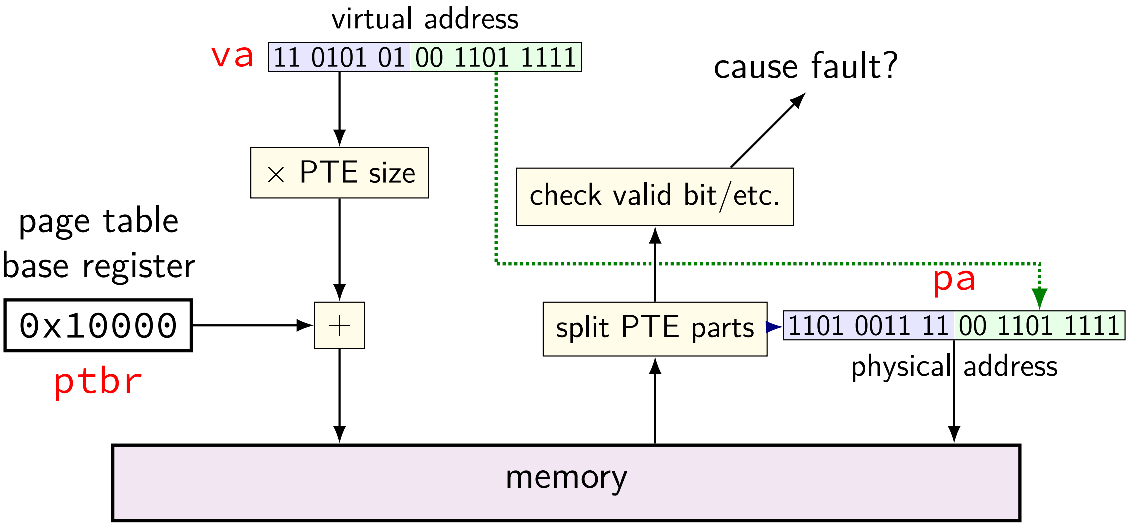
0x00603	1	0	0x12340
0x00604	1	0	0x200DF
0x00605	1	1	0x300FD
…	…	…	…

after allocating a copy, OS reruns the write instruction

pa=translate(va)



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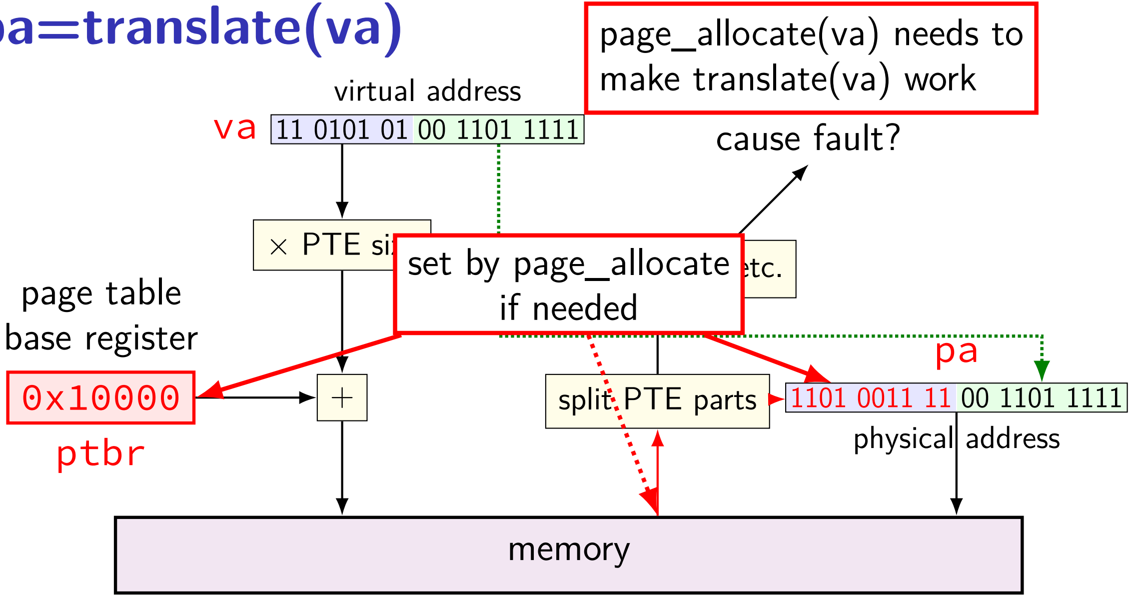

swapping

early motivation for virtual memory: swapping

using disk (or SSD, ...) as the next level of the memory hierarchy

how our textbook and many other sources presents virtual memory

OS allocates program space on disk

own mapping of virtual addresses to location on disk

DRAM is a cache for disk

swapping

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OS allocates program space on 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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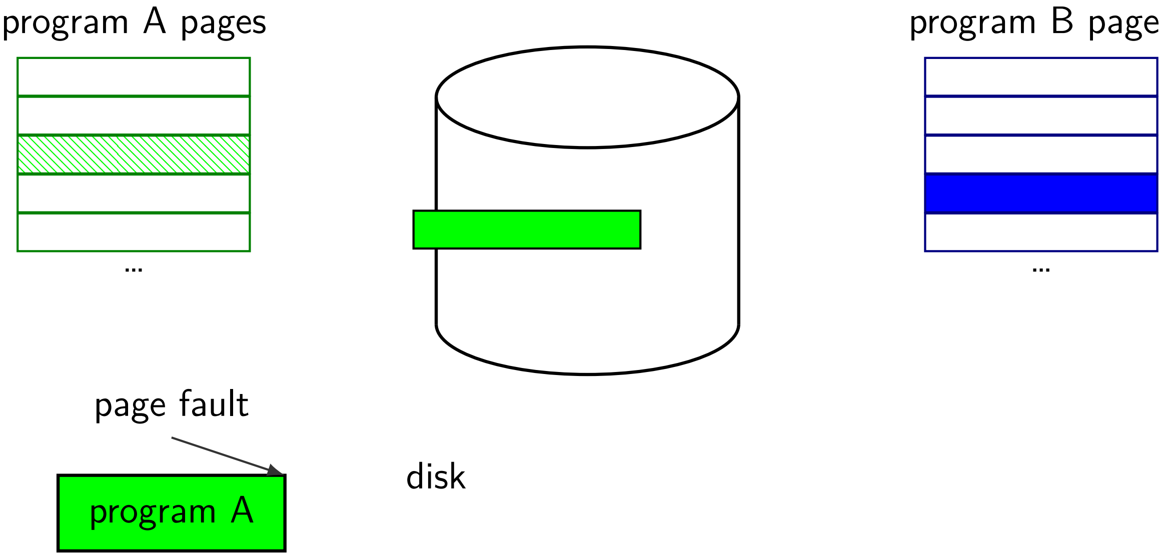
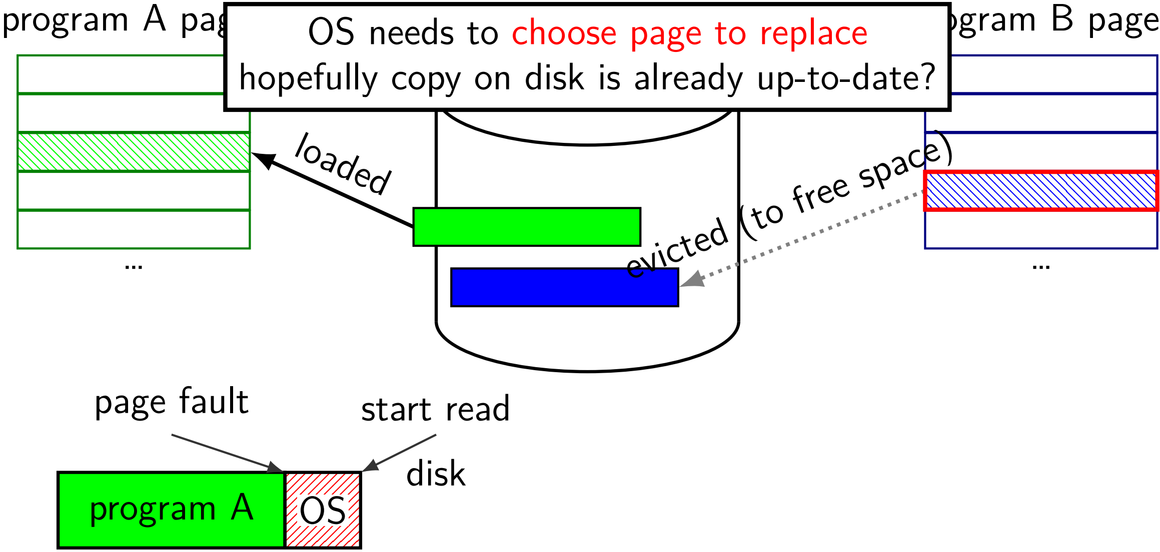
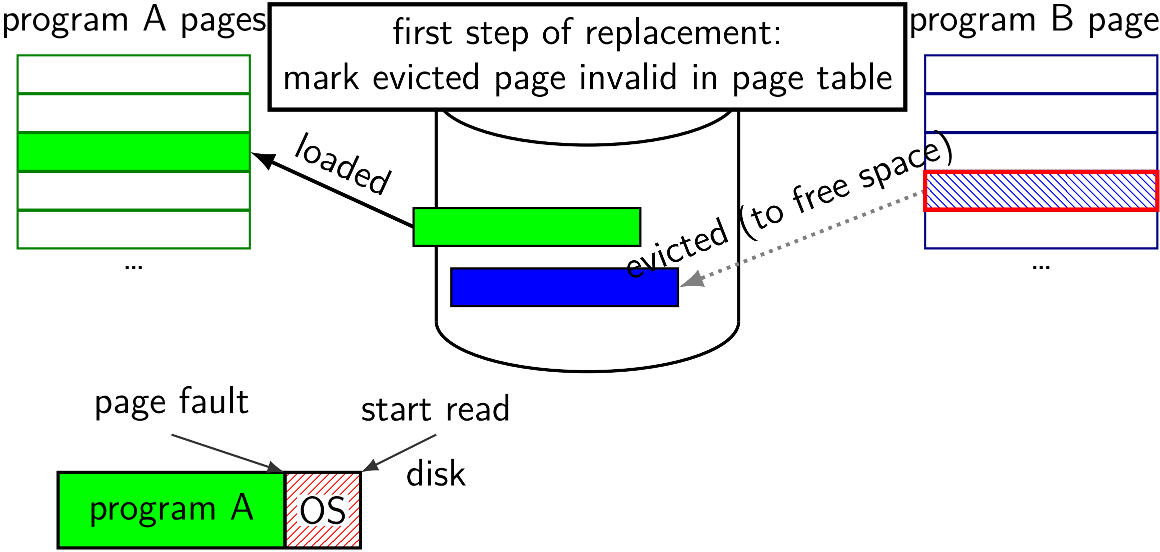
swapping timeline



swapping timeline

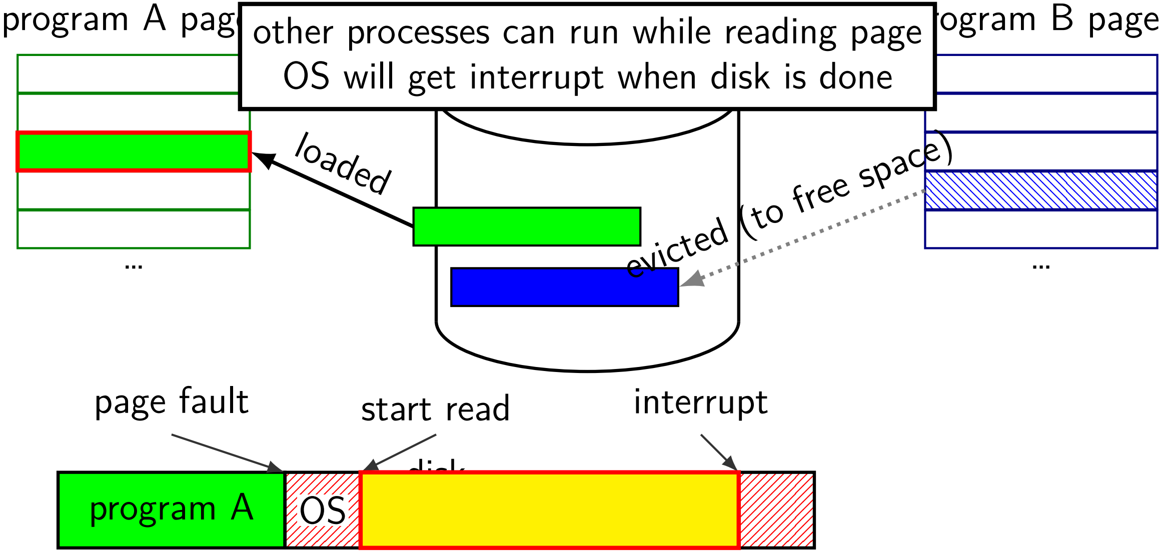


swapping timeline

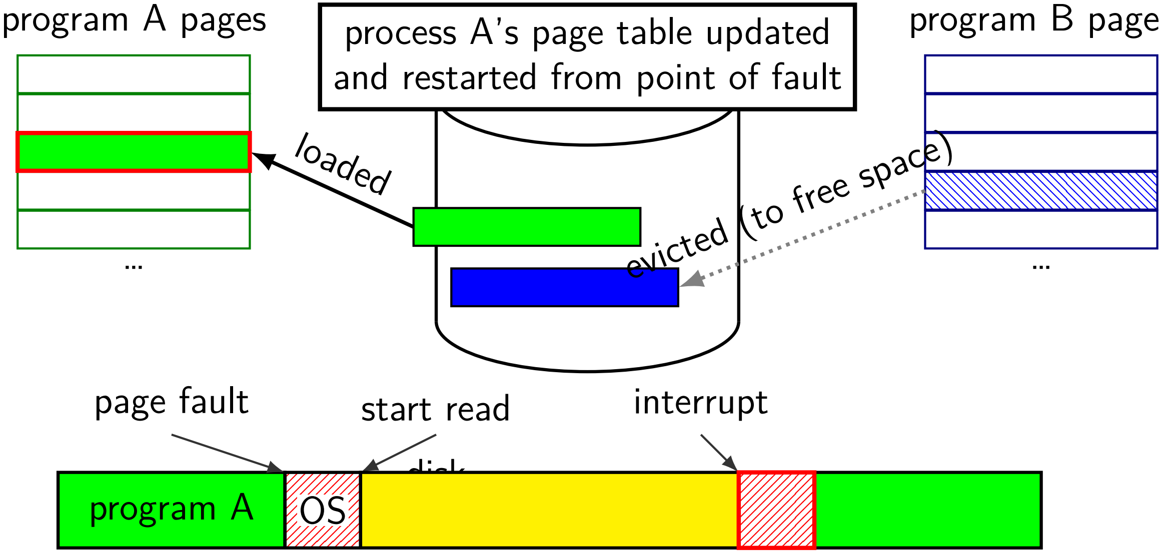


swapping timeline

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



swapping timeline



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