CS3281 / CS5281

Advanced Virtual Memory

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Spring 2024

**Some lecture slides borrowed and adapted from CMU's "Computer Systems: A Programmer's Perspective" and MIT's 6.S081 Course*

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Today

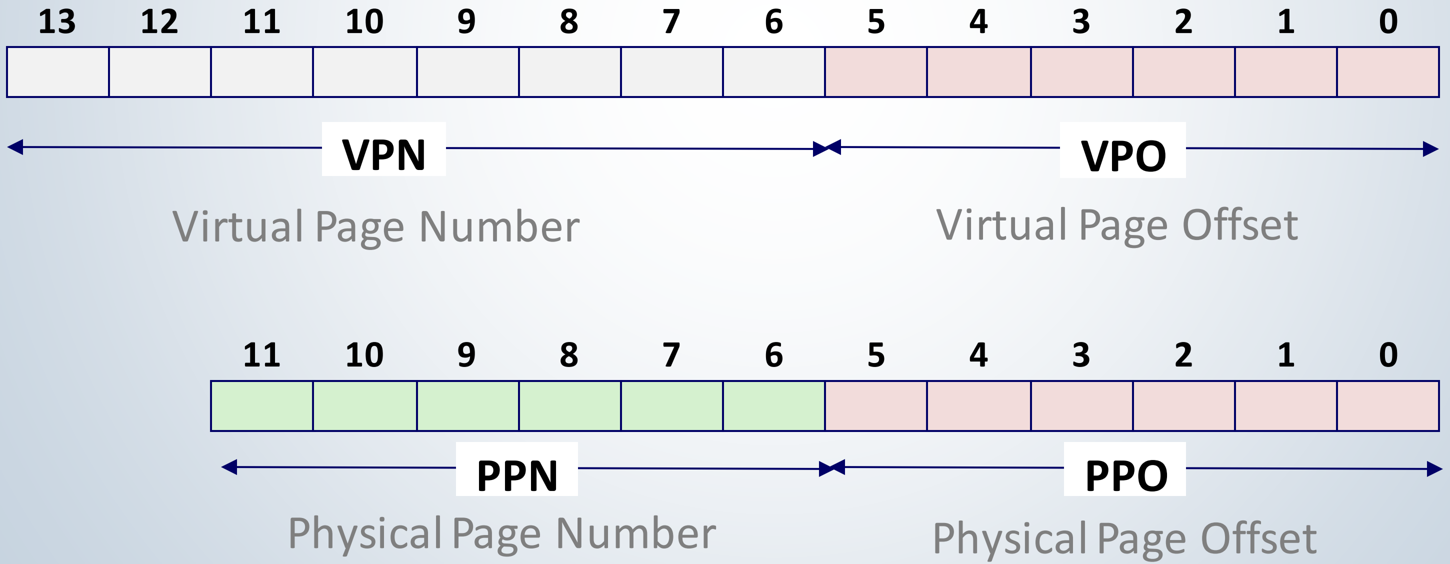
- Simple memory system example
- Case Study: RISC-V
- Memory mapping

Review of Symbols

- Basic Parameters
  - **$N = 2^n$** : Number of addresses in virtual address space
  - **$M = 2^m$** : Number of addresses in physical address space
  - **$P = 2^p$** : Page size (bytes)
- Components of the virtual address (VA)
  - **VPO**: Virtual page offset
  - **VPN**: Virtual page number
- Components of the physical address (PA)
  - **PPO**: Physical page offset (same as VPO)
  - **PPN:** Physical page number

Simple Memory System Example

- Addressing
  - 14-bit virtual addresses
  - 12-bit physical address
  - Page size = 64 bytes



Simply Memory System Page Table

- Only show first 16 entries (out of 256)

VPN	PPN	Valid
00	28	1
01	–	0
02	33	1
03	02	1
04	–	0
05	16	1
06	–	0
07	–	0

VPN	PPN	Valid
08	13	1
09	17	1
0A	09	1
0B	–	0
0C	–	0
0D	2D	1
0E	11	1
0F	0D	1

Address Translation Example #1

Virtual Address: 0x03D4

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	1	1	1	1	0	1	0	1	0	0

← **VPN** → ← **VPO** →

VPN: **0x0F**

Page Fault: N

PPN: **0x0D**

11	10	9	8	7	6	5	4	3	2	1	0
0	0	1	1	0	1	0	1	0	1	0	0

← **PPN** → ← **PPO** →

Address Translation Example #2

Virtual Address: 0x0020

13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	0	1	0	0	0	0	0
VPN								**VPO**					

VPN: **0x00**

Page Fault: N

PPN: **0x28**

11	10	9	8	7	6	5	4	3	2	1	0
1	0	1	0	0	0	1	0	0	0	0	0
PPN						**PPO**					

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Virtual Memory in RISC-V

- Supports different addressing modes:
  - Sv32, Sv39, sV48 -> number of virtual address bits
  - We focus on Sv39, which has a 3-level page table
- Register called supervisor address translation and protection (satp) points to the page root
- satp is set using a special instruction called control status register write (csrw)
- Only allowed in kernel model. Why?

satp

63 — 60	59 — 44	43 — 0
MODE (WARL)	ASID (WARL)	PPN (WARL)
4	16	44

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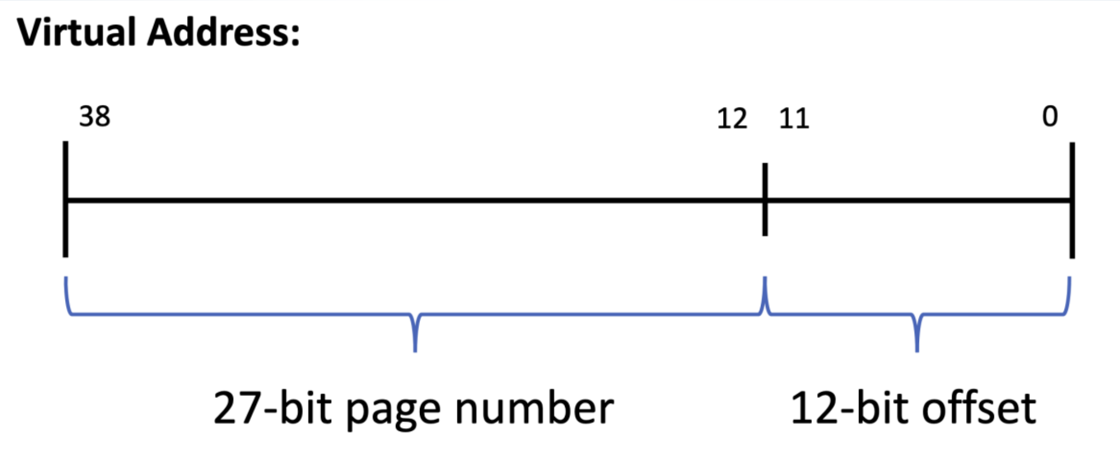
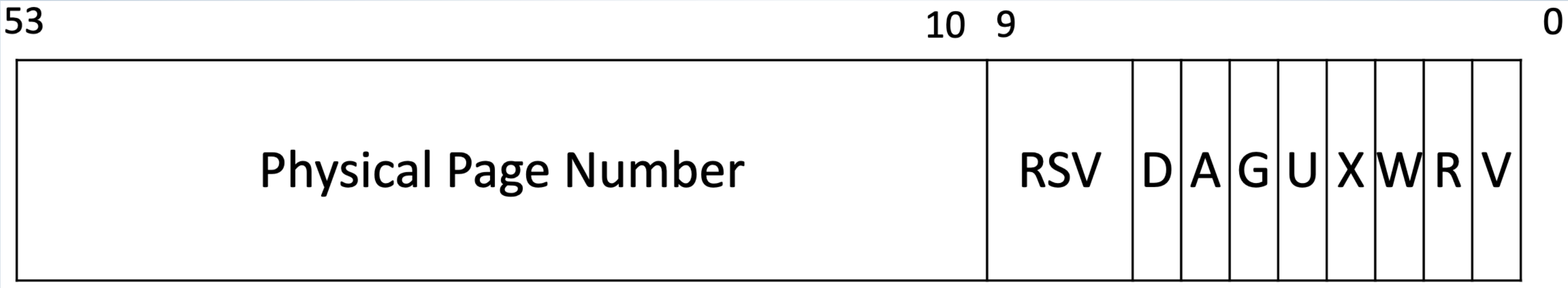
Virtual Memory in RISC-V (Sv39)

- Virtual addresses are divided in 4-KB pages
- 39 bit address
- 4KB = 2^12
- 39 – 12 = 27 bits for page number



Page Table Entries



- Some important information
- Physical page number: 44-bit physical page location
- U: If set, userspace can access this virtual address
- W: if set, the CPU can write to this virtual address
- V: if set, an entry for this virtual address exists (is valid)
- RSV: Ignored by MMU

What if we store PTEs in a single array?

GET_PTE(va) = &ptes[va >> 12]

PPN										
...										
...										
...										
...										
...										
...										
...										
...										

How large is this array?

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What if we store PTEs in a single array?

GET_PTE(va) = &ptes[va >> 12]

PPN										
...										
...										
...										
...										
...										
...										
...										
...										

How large is this array?

Each entry is (padded to) 64 bits (8 bytes)

2^27 Virtual Page Numbers (2^39/2^12)

2^27 * 8 = 2^30 = 1GB!

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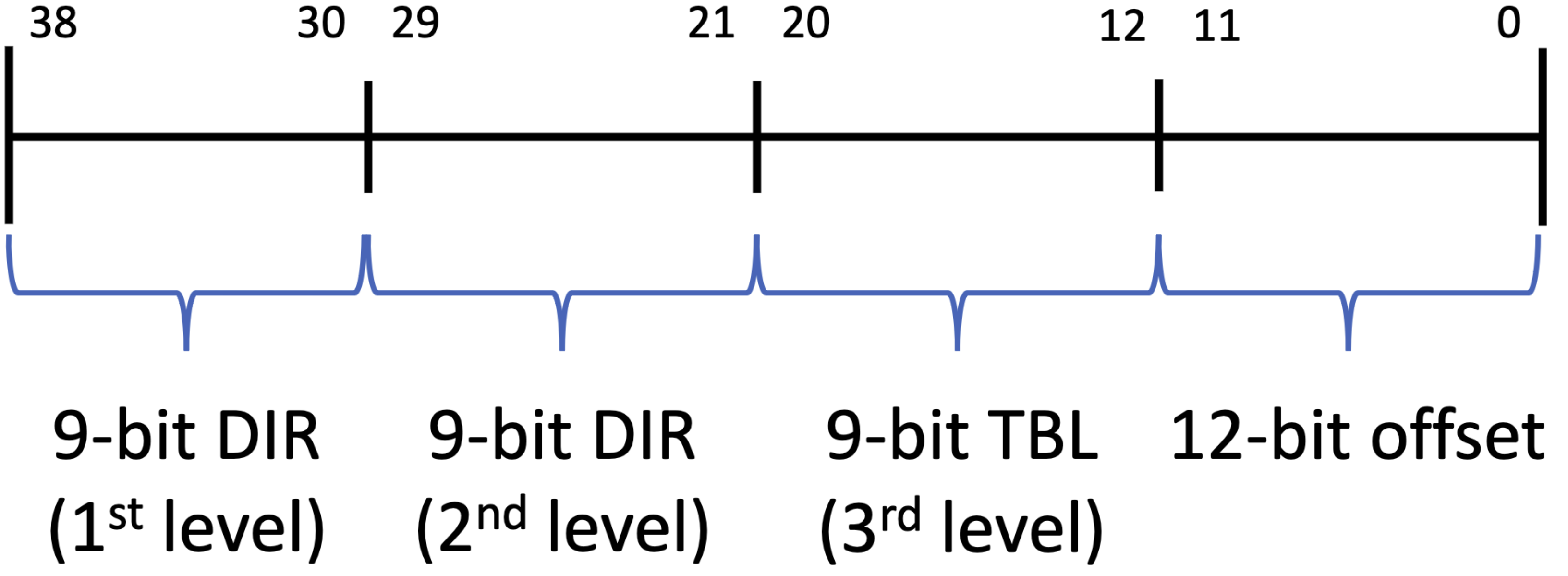
RISC-V Solution: Use three levels to save space



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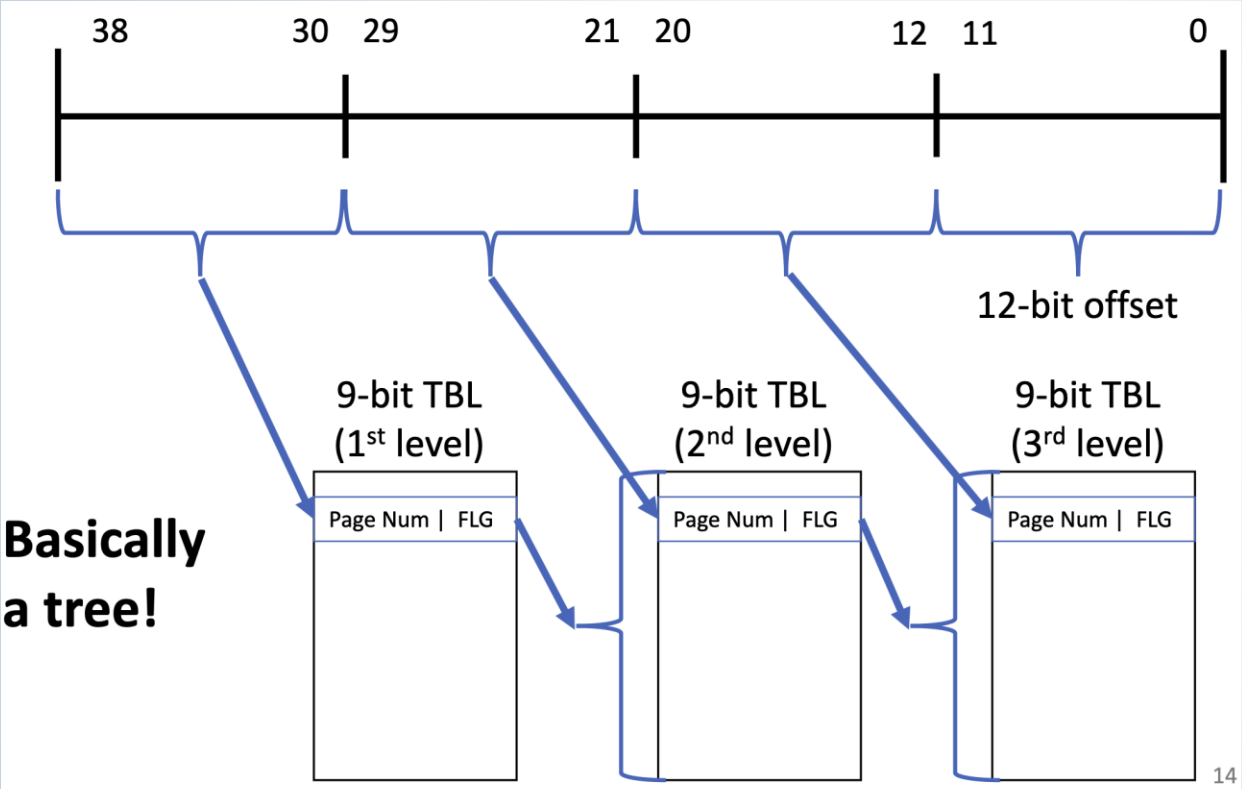
RISC-V multi-level page tables



Each table is 1 page = 4096B

Each PTE is 64 bits

How many PTEs per table?

How do we use this in practice?

- CPU sets satp register to point to the first-level page directory
- There is only 1 first-level page directory per process
- By swapping the satp register, you completely change the functional address space
- Operating system modifies page tables and directories to layout memory as desired
- Hardware “walks” this page-table tree data structure to translate from virtual address to physical address and actually fetch memory

More about flags in RISC-V

- If U is cleared, only kernel can access
- If flag permission is violated, we get a page fault

X	W	R	Meaning
0	0	0	Pointer to next level of page table.
0	0	1	Read-only page.
0	1	0	*Reserved for future use.*
0	1	1	Read-write page.
1	0	0	Execute-only page.
1	0	1	Read-execute page.
1	1	0	*Reserved for future use.*
1	1	1	Read-write-execute page.

Today

- Simple memory system example
- Case Study: RISC-V
- Shared Memory and Copy-on-Write
- Memory mapping

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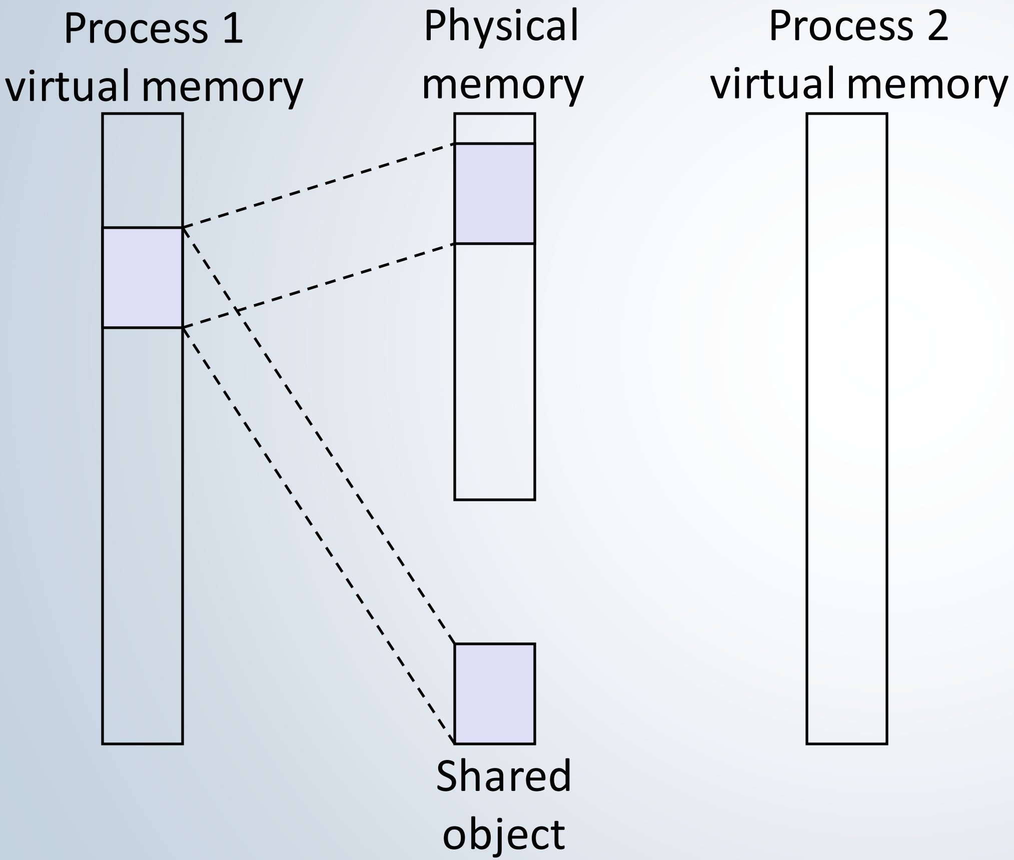
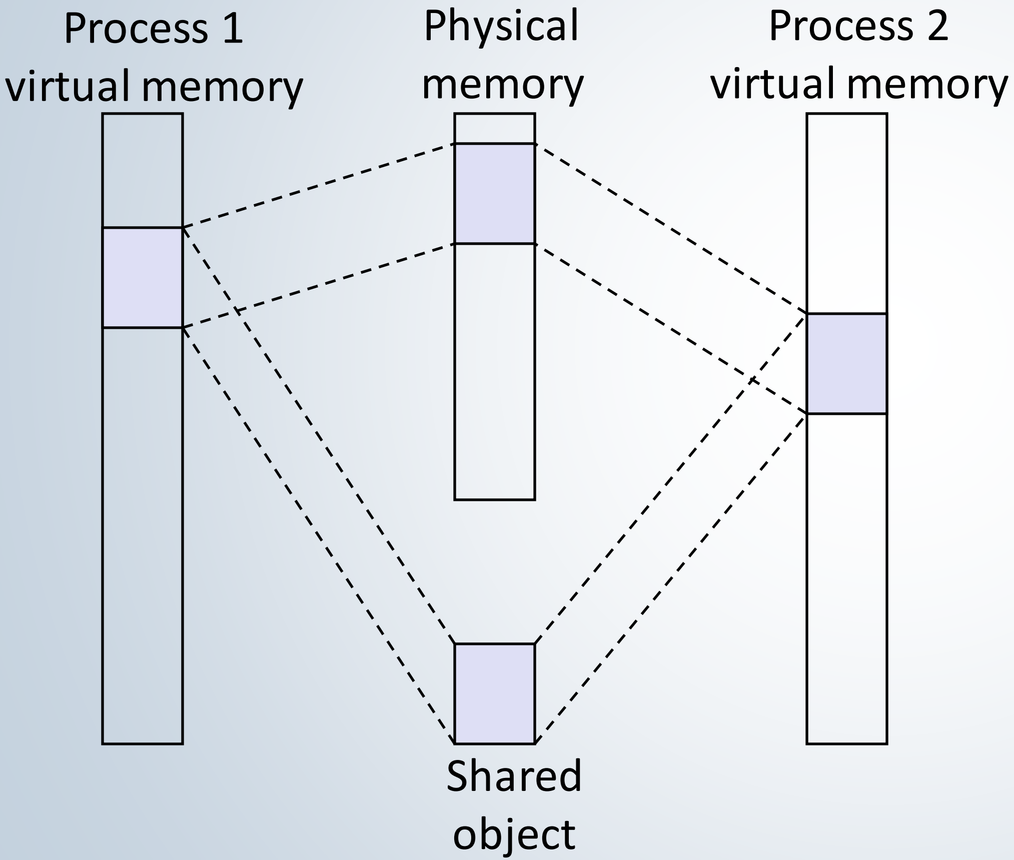
Sharing Revisited: Shared Objects



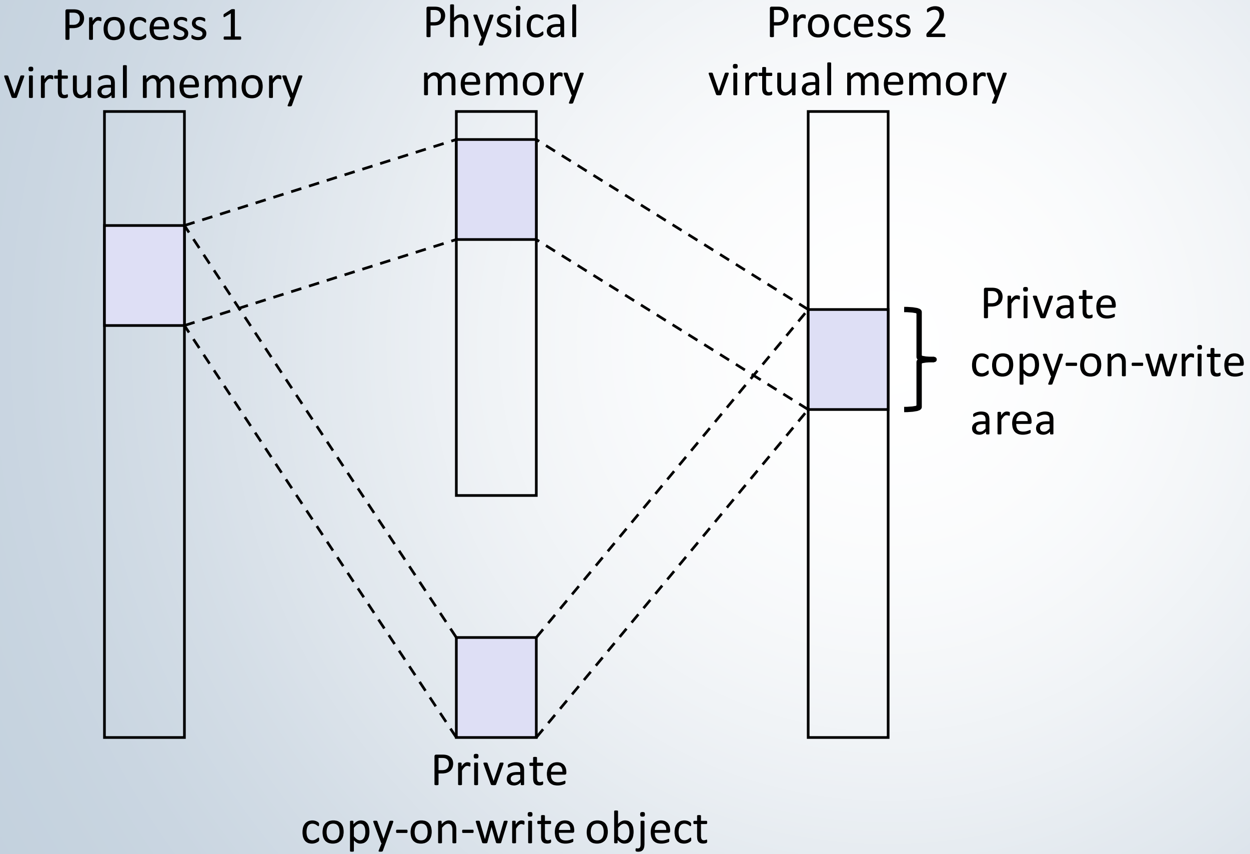
- **Process 2 maps the shared object.**

Sharing Revisited: Shared Objects



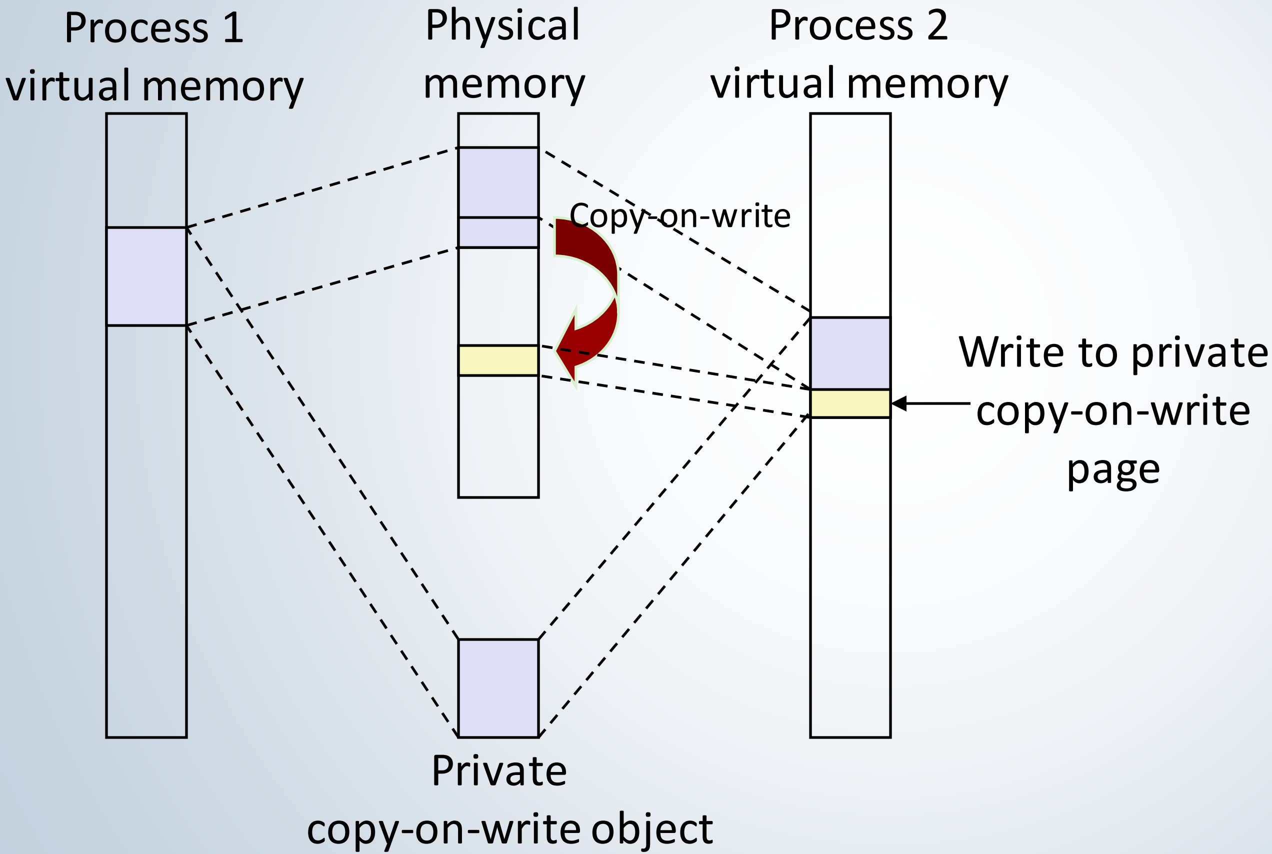
- **Process 2 maps the shared object.**
- Notice how the virtual addresses can be different.

Sharing Revisited: Copy-On-Write (COW) Objects



- Two processes mapping a *private copy-on-write (COW)* object
- Area flagged as private copy-on-write
- PTEs in private areas are flagged as read-only

Sharing Revisited: Copy-On-Write (COW) Objects



- Instruction writing to private page triggers protection fault
- Handler creates new R/W page
- Instruction restarts upon handler return
- Copying deferred as long as possible!

The fork() Function Revisited

- Can use COW memory mapping in `fork()` to provides private address space for each process without duplicating physical memory unnecessarily

- To create virtual address for new process
  - Create exact copies of current page tables
  - Flag each page in <u>both processes</u> as read-only (clear `write` flag)
  - Flag each `writeable page` in both processes as private COW

- On return, each process has identical view of memory but only one copy of physical memory exists

- Subsequent writes trigger COW mechanism and force pages to be duplicated when needed

Memory Mapping (not in xv6)

- VM areas initialized by associating them with disk objects.
  - Process is known as ***memory mapping***.

- Area can be *backed by* (i.e., get its initial values from) :
  - ***Regular file*** on disk (e.g., an executable object file)
    - Initial page bytes come from a section of a file
  - ***Anonymous file*** (e.g., nothing)
    - First fault will allocate a physical page full of 0's (***demand-zero page***)
    - Once the page is written to (***dirtied***), it is like any other page

- Dirty pages are copied back and forth between memory and a special *swap file*.

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User-Level Memory Mapping (Linux)

```
void *mmap(void *start, int len,
           int prot, int flags, int fd, int offset)
```

- Map **`len`** bytes starting at offset **`offset`** of the file specified by file description **`fd`**, preferably at address **`start`**
  - **`start`**: may be 0 for "pick an address"
  - **`prot`**: PROT_READ, PROT_WRITE, ...
  - **`flags`**: MAP_ANON, MAP_PRIVATE, MAP_SHARED, ...
- Return a pointer to start of mapped area (may not be **`start`**)

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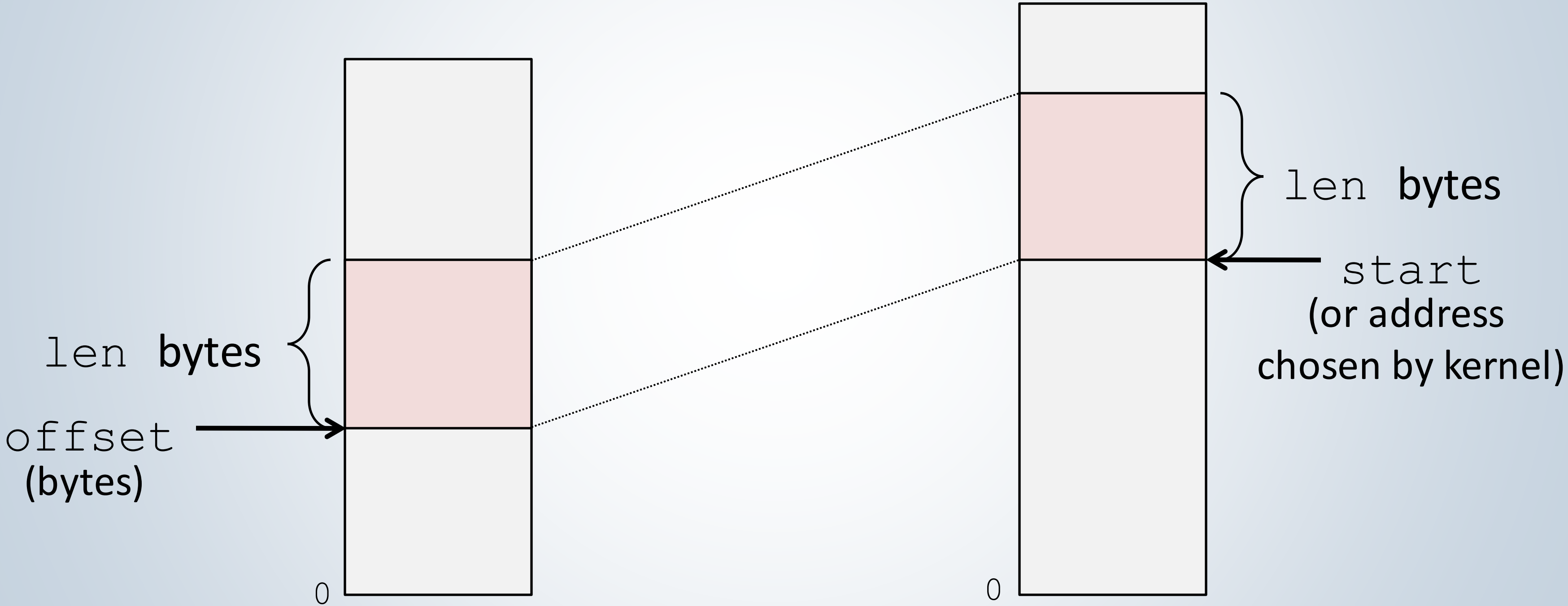
User-Level Memory Mapping

`void *mmap(void *start, int len, int prot, int flags, int fd, int offset)`



Disk file specified by file descriptor `fd`

Process virtual memory

Using mmap() to Copy Files (Linux)

- Copying a file to `stdout` without transferring data to user space

```c
#include "csapp.h"

void mmapcopy(int fd, int size)
{

   /* Ptr to memory mapped area */
   char *bufp;

   bufp = mmap(NULL, size,
               PROT_READ,
               MAP_PRIVATE,
               fd, 0);
   Write(1, bufp, size);
   return;
}
```

```c
/* mmapcopy driver */
int main(int argc, char **argv)
{
   struct stat stat;
   int fd;

   /* Check for required cmd line arg */
   if (argc != 2) {
      printf("usage: %s <filename>\n",
            argv[0]);
      exit(0);
   }

   /* Copy input file to stdout */
   fd = Open(argv[1], O_RDONLY, 0);
   Fstat(fd, &stat);
   mmapcopy(fd, stat.st_size);
   exit(0);
}
```