CS3281 / CS5281

Advanced Virtual Memory

Will Hedgecock
Sandeep Neema
Bryan Ward

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

Tel (615) 343-7472 | Fax (615) 343-7440
1025 16th Avenue South Nashville, TN 37212
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Today

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

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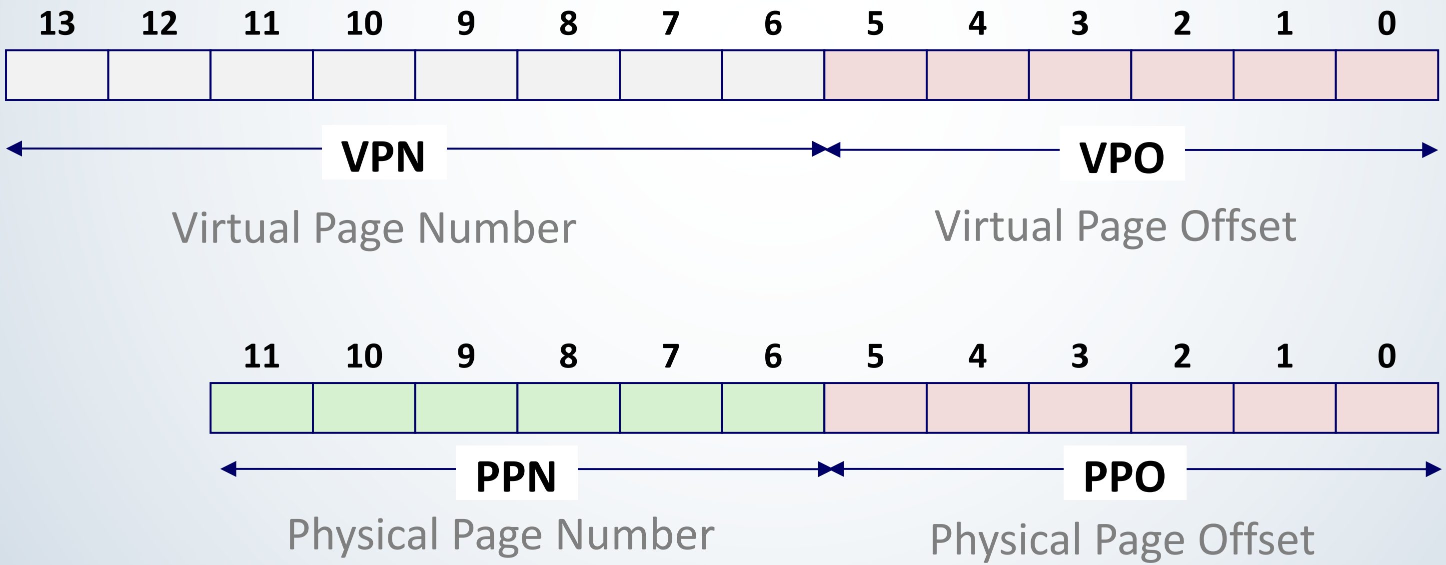
Review of Symbols

- 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 (bits 13–6) | VPO (bits 5–0)

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 (bits 11–6) | PPO (bits 5–0)

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 (bits 13–6) **VPO** (bits 5–0)

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 (bits 11–6) **PPO** (bits 5–0)

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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 call 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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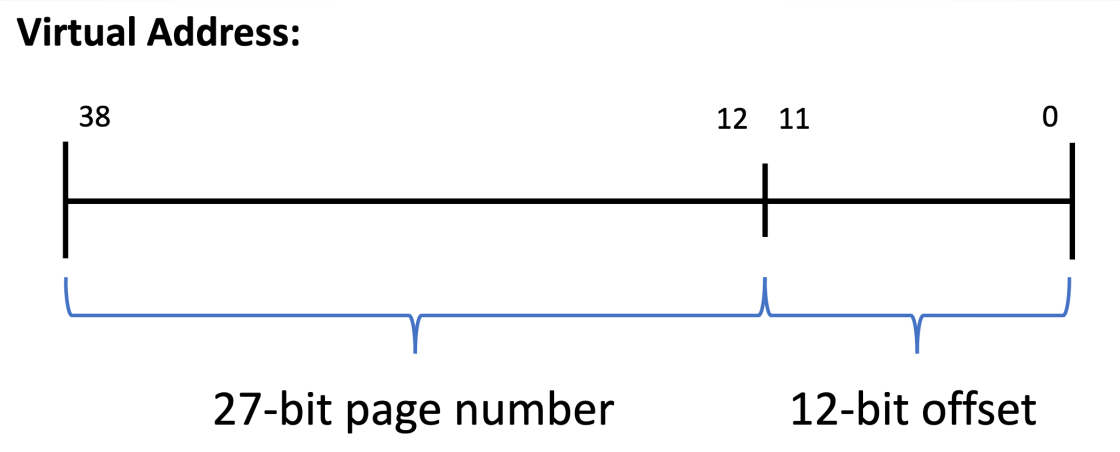
Virtual Memory in RISC-V (Sv39)

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



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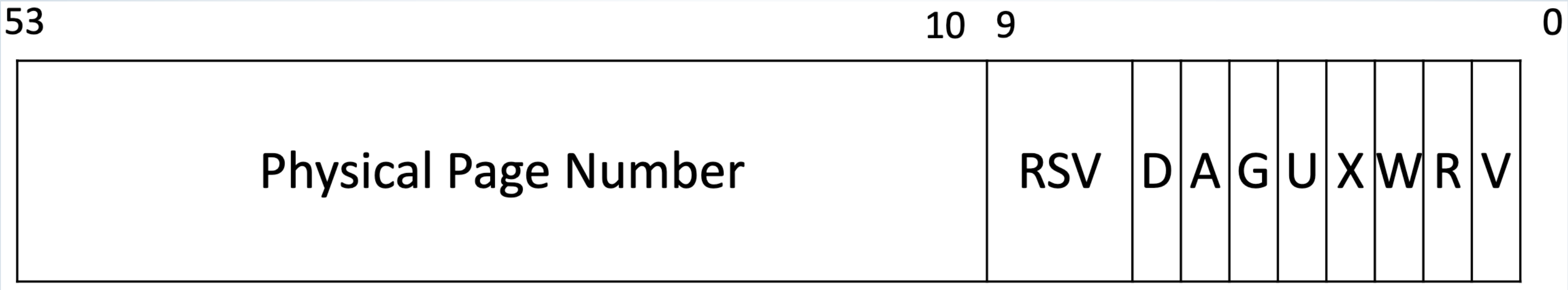
Page Table Entries



- 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

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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?

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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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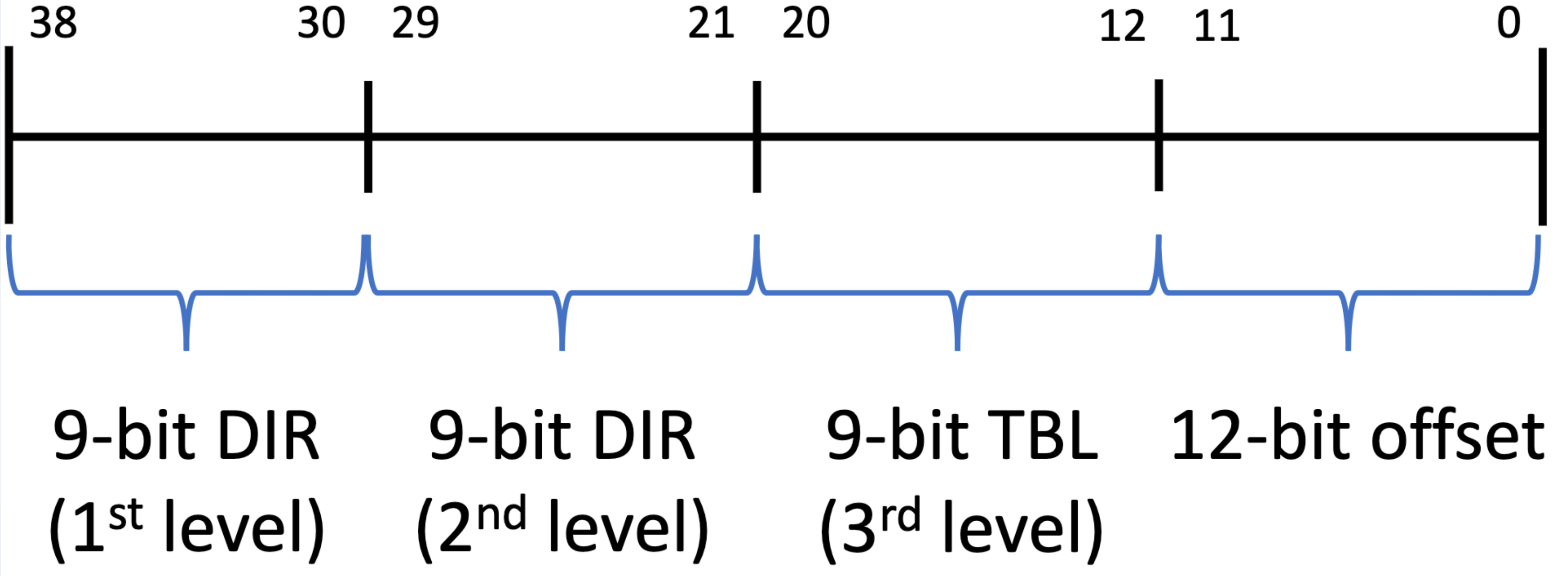
RISC-V Solution: Use three levels to save space



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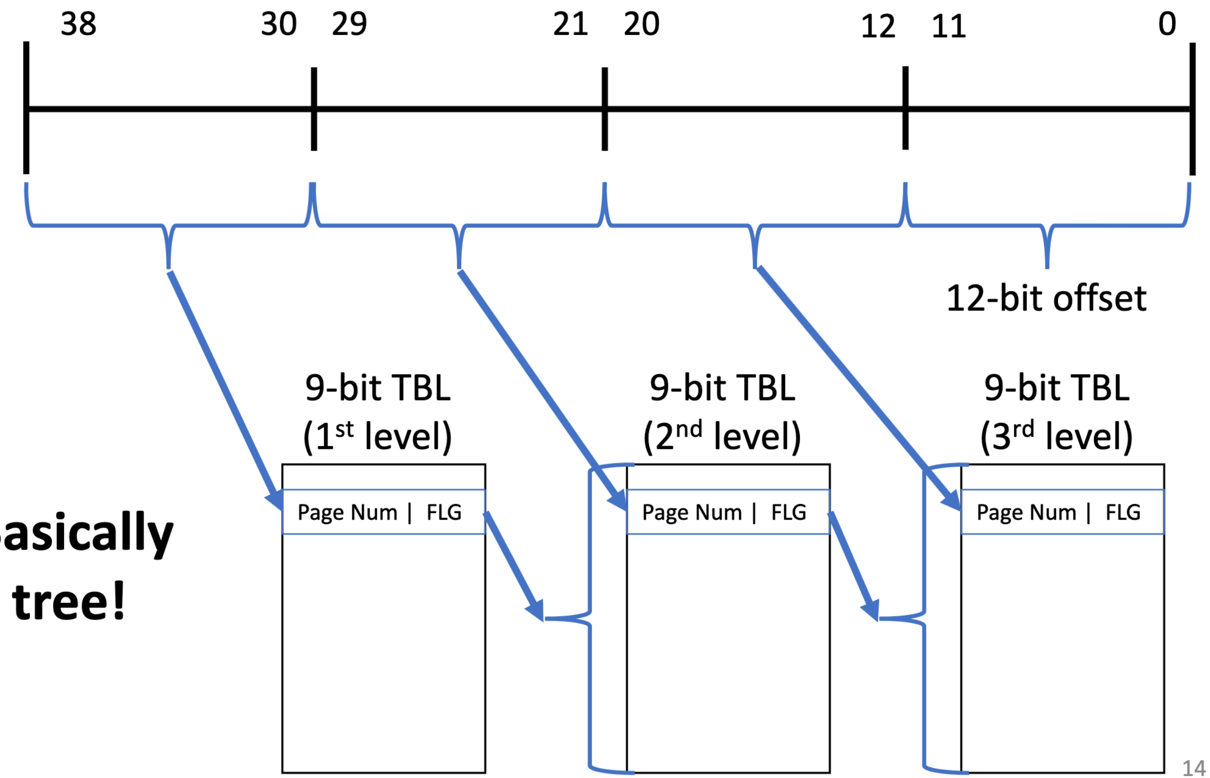
RISC-V multi-level page tables



Basically a tree!

Each table is 1 page = 4096B

Each PTE is 64 bits

How many PTEs per table?

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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

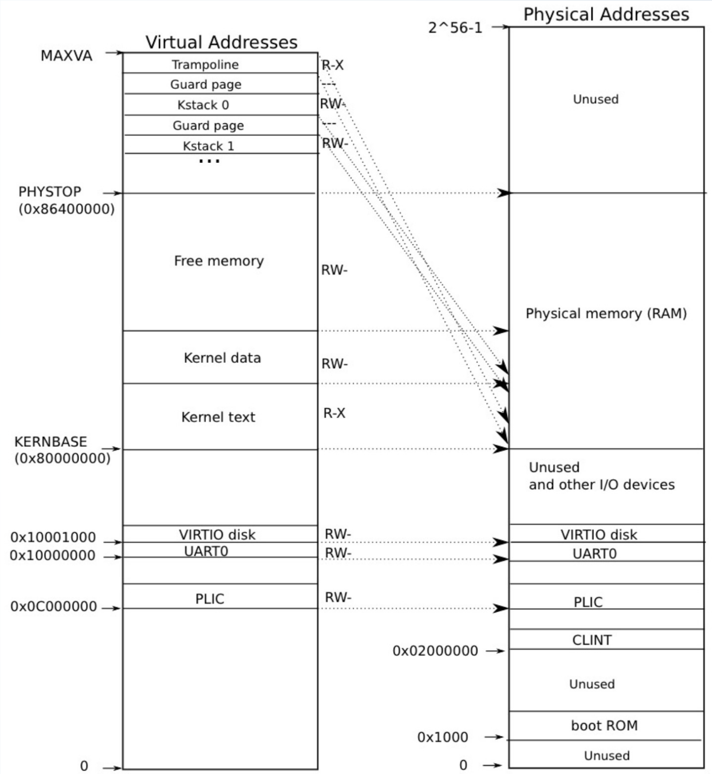
More about flags in RISC-V

- 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.

Kernel memory layout

- Kernel memory layout is largely direct mapped
- i.e., page tables are setup such that PPN = VPN
- <u>Implication: address of memory page in kernel space is different than in user space!</u>



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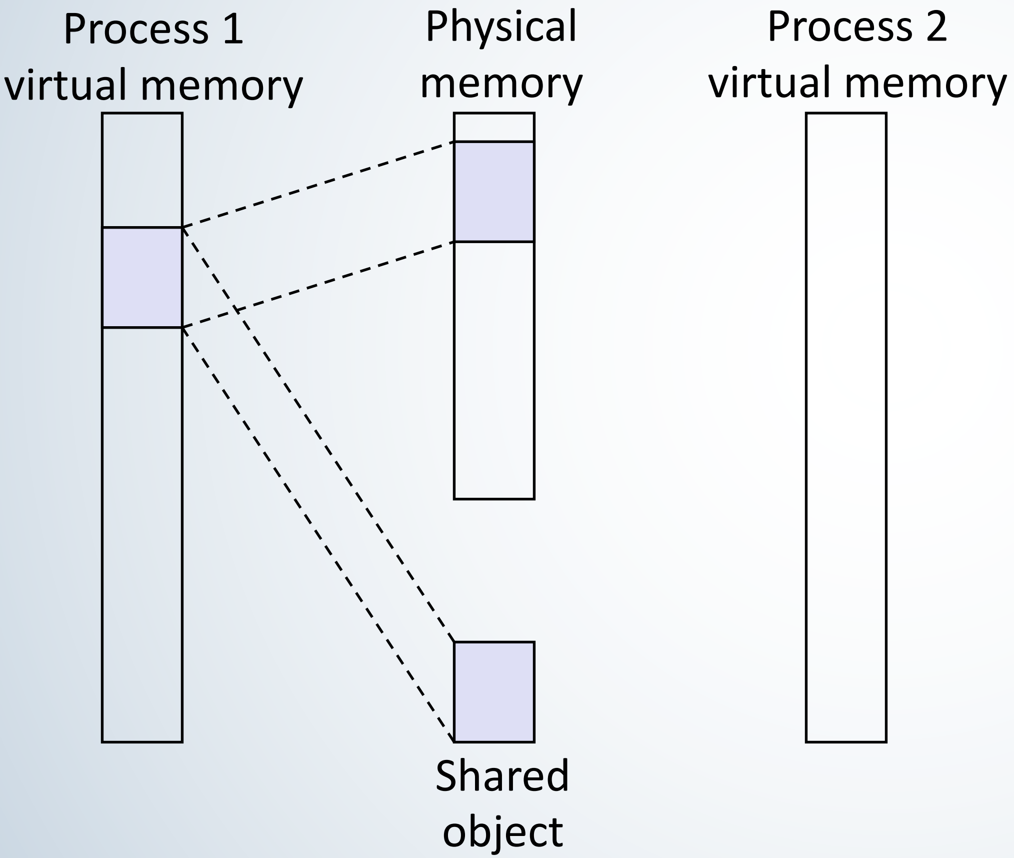
Memory Mapping (not in xv6)

- 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

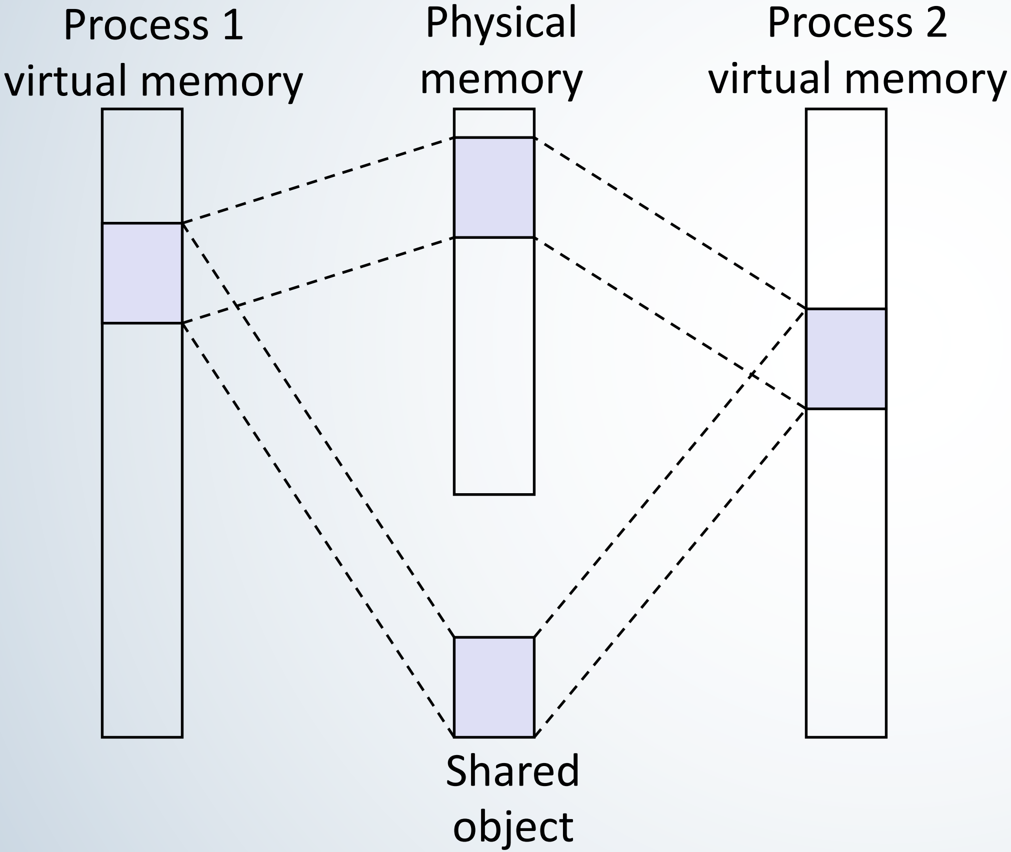
- Dirty pages are copied back and forth between memory and a special *swap file*.

Sharing Revisited: Shared Objects



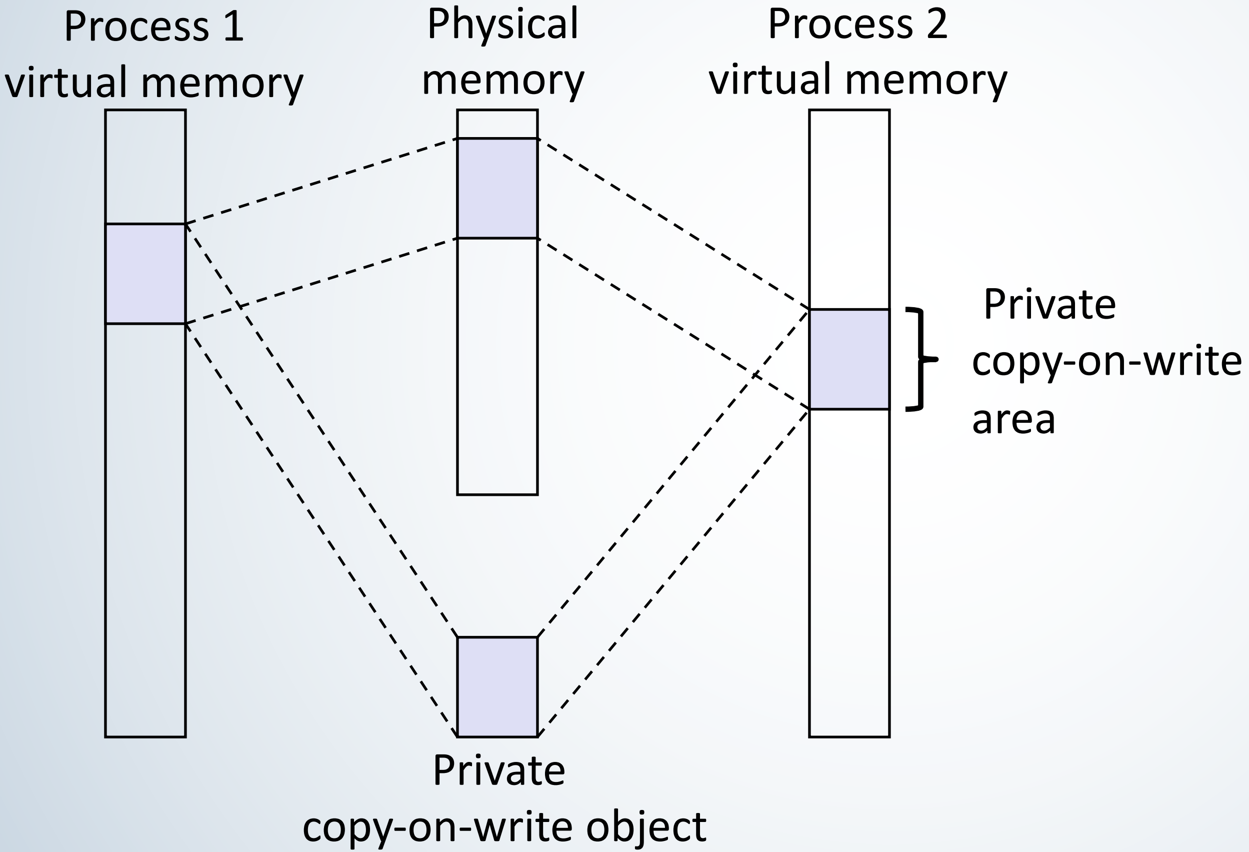
- **Process 2 maps the shared object.**

Sharing Revisited: Shared Objects



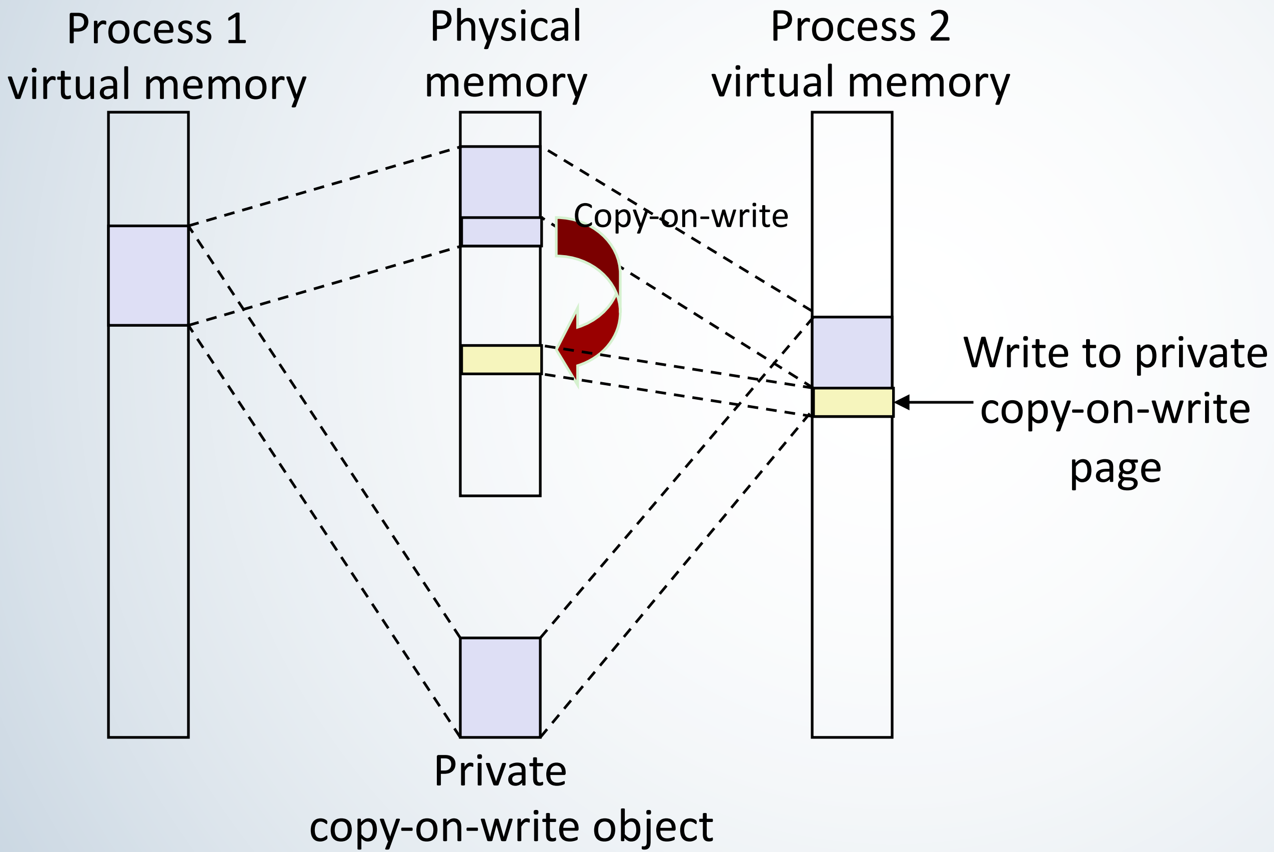
- **Process 2 maps the shared object.**
- Notice how the virtual addresses can be different.

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

- VM and memory mapping explain how `fork` provides private address space for each process.

- To create virtual address for new new process
  - Create exact copies of current `mm_struct`, `vm_area_struct`, and page tables.
  - Flag each page in both processes as read-only
  - Flag each `vm_area_struct` in both processes as private COW

- On return, each process has exact copy of virtual memory

- Subsequent writes create new pages using COW mechanism.

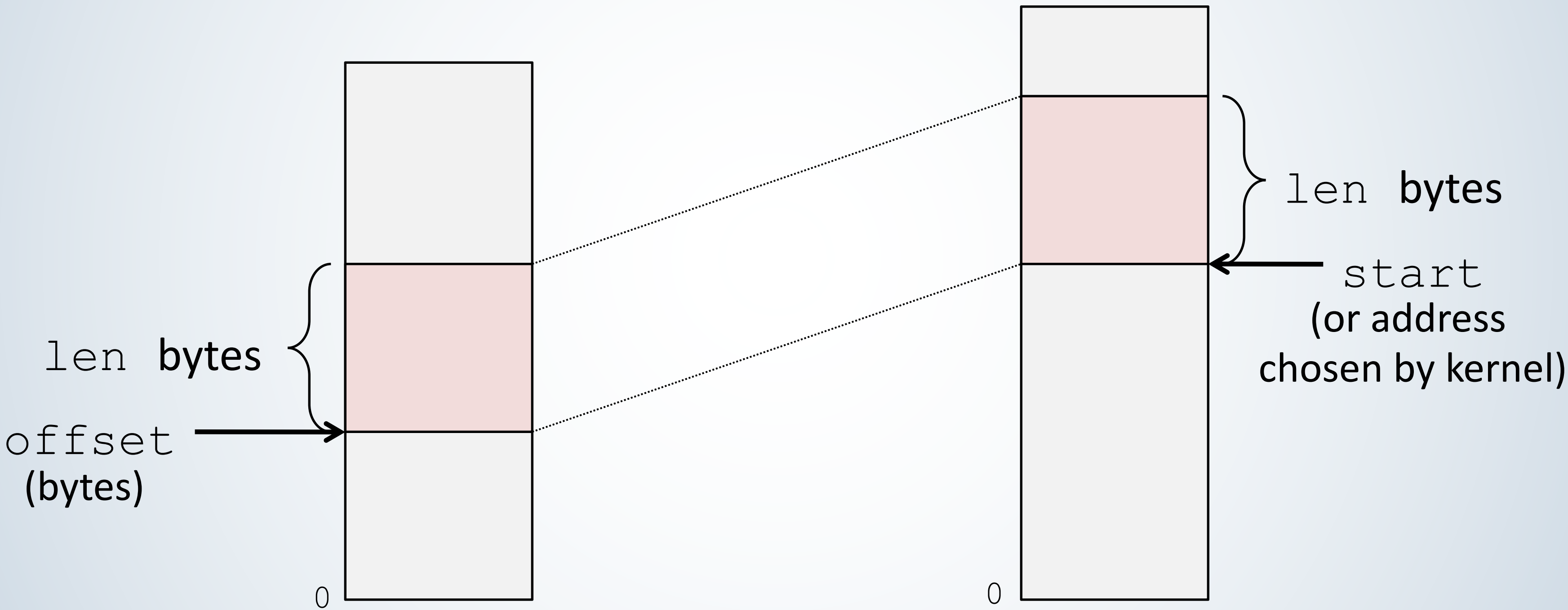
User-Level Memory Mapping

```
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`**)

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

- 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);
}
```