Linking and Loading: Linking

These slides adapted from materials provided by the textbook authors.

Linking and Loading

- **Linking**
- **Loading**
- **Case study: Library interpositioning**

Example C Program

```c
int array[2] = {1, 2};

int sum(int *a, int n);

int main(){
    int val = sum(array, 2);
    return val;
}
```

main.c

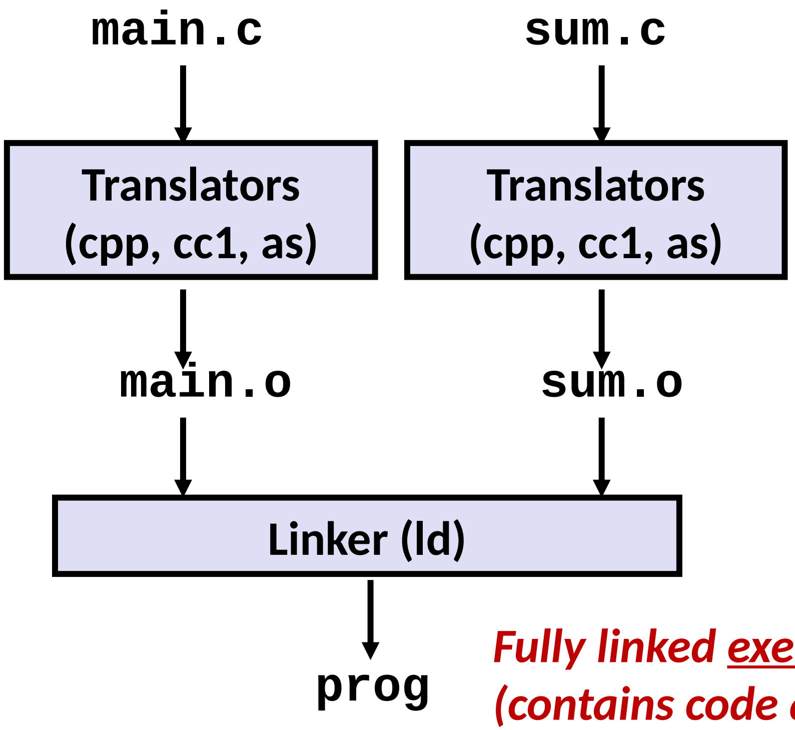
```c
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

sum.c

Static Linking

- Programs are translated and linked using a *compiler driver*:
  - `linux> gcc -Og -o prog main.c sum.c`
  - `linux> ./prog`



Source files

Separately compiled
<u>relocatable</u> object files

Fully linked <u>executable</u> object file
(contains code and data for all functions
defined in `main.c` and `sum.c`)

Why Linkers?

- **Reason 1: Modularity**
  - Program can be written as a collection of smaller source files, rather than one monolithic mass.
  - Can build libraries of common functions (more on this later)
    - e.g., Math library, standard C library

Why Linkers? (cont)

- **Reason 2: Efficiency**
  - Time: Separate compilation
    - Change one source file, compile, and then relink.
    - No need to recompile other source files.
  - Space: Libraries
    - Common functions can be aggregated into a single file...
    - Yet executable files and running memory images contain only code for the functions they actually use.

What Do Linkers Do?

- **Step 1: Symbol resolution**

  - Programs define and reference *symbols* (global variables and functions):

    ```
    void swap() {…}    /* define symbol swap */
    swap();            /* reference symbol swap */
    int *xp = &x;      /* define symbol xp, reference x */
    ```

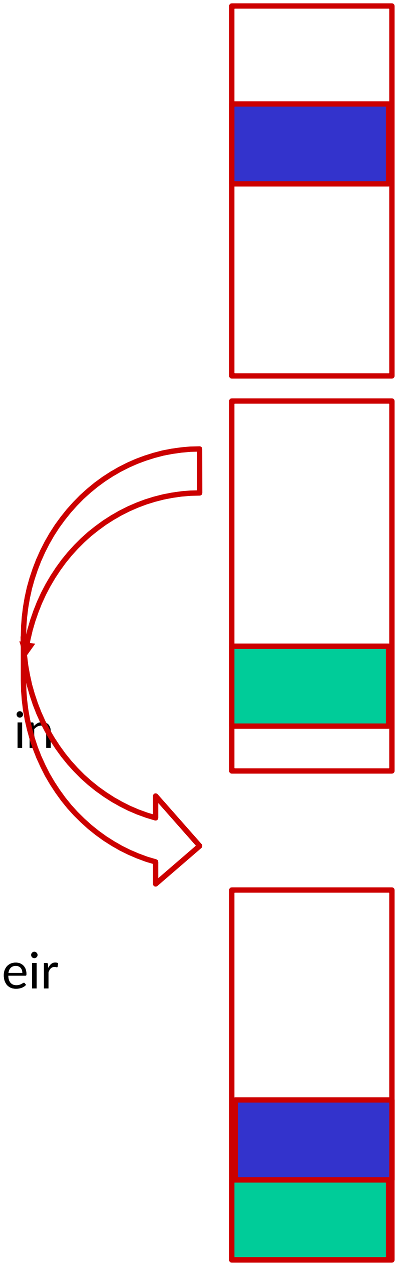
  - Symbol definitions are stored in object file (by assembler) in *symbol table*.
    - Symbol table is an array of `structs`
    - Each entry includes name, size, and location of symbol.

  - **During symbol resolution step, the linker associates each symbol reference with exactly one symbol definition.**

What Do Linkers Do? (cont)

- **Step 2: Relocation**
  - Merges separate code and data sections into single sections
  - Relocates symbols from their relative locations in the `.o` files to their final absolute memory locations in the executable.
  - Updates all references to these symbols to reflect their new positions.

Let’s look at these two steps in more detail….



Three Kinds of Object Files (Modules)

- **Relocatable object file (`.o` file)**
  - Contains code and data in a form that can be combined with other relocatable object files to form executable object file.
    - Each `.o` file is produced from exactly one source (`.c`) file

- **Executable object file (`a.out` file)**
  - Contains code and data in a form that can be copied directly into memory and then executed.

- **Shared object file (`.so` file)**
  - Special type of relocatable object file that can be loaded into memory and linked dynamically, at either load time or run-time.
  - Called *Dynamic Link Libraries* (DLLs) by Windows

Executable and Linkable Format (ELF)

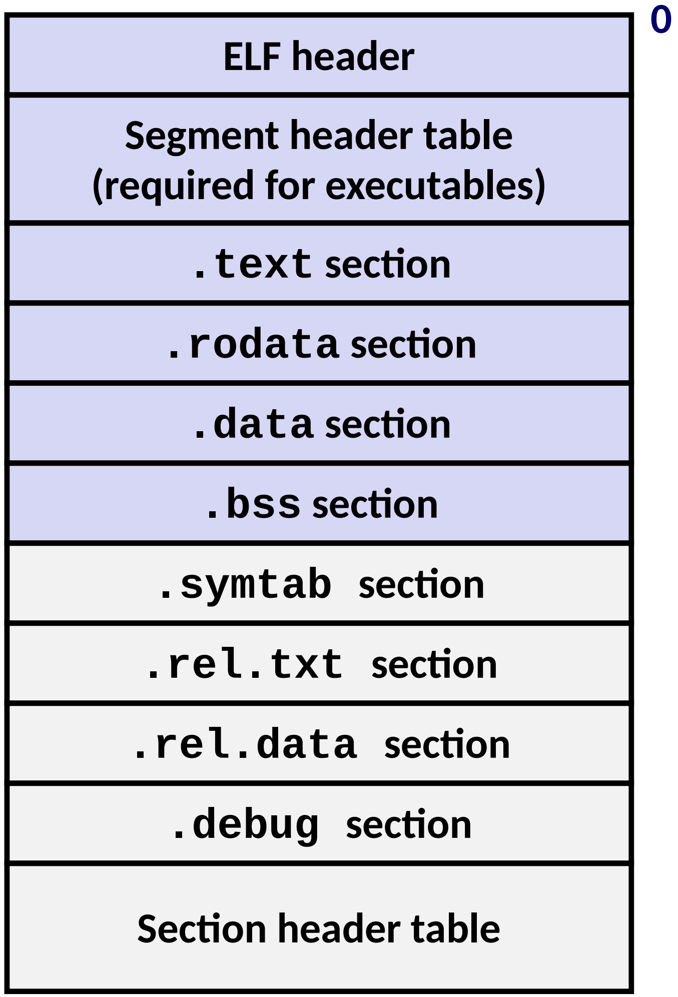
- **Standard binary format for object files**

- **One unified format for**
  - Relocatable object files (`.o`),
  - Executable object files (`a.out`)
  - Shared object files (`.so`)

- **Generic name: ELF binaries**

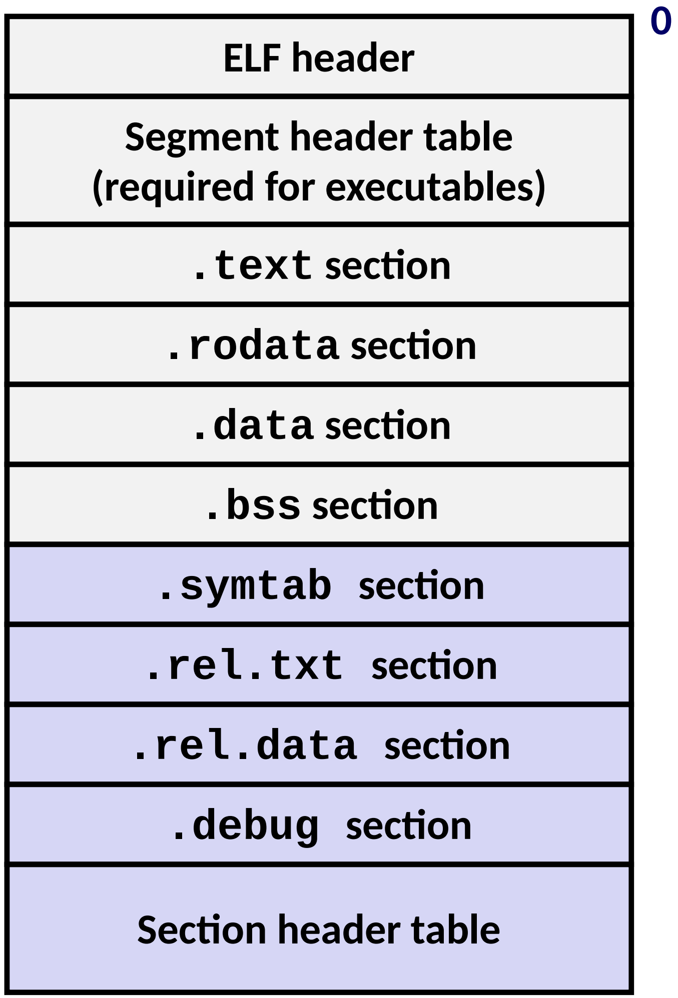
ELF Object File Format

- **Elf header**
  - Word size, byte ordering, file type (.o, exec, .so), machine type, etc.
- **Segment header table**
  - Page size, virtual addresses memory segments (sections), segment sizes.
- **`.text` section**
  - Code
- **`.rodata` section**
  - Read only data: jump tables, ...
- **`.data` section**
  - Initialized global variables
- **`.bss` section**
  - Uninitialized global variables
  - “Block Started by Symbol”
  - Has section header but occupies no space



ELF Object File Format (cont.)

- **`.symtab` section**
  - Symbol table
  - Procedure and static variable names
  - Section names and locations
- **`.rel.text` section**
  - Relocation info for **`.text`** section
  - Addresses of instructions that will need to be modified in the executable
  - Instructions for modifying.
- **`.rel.data` section**
  - Relocation info for **`.data`** section
  - Addresses of pointer data that will need to be modified in the merged executable
- **`.debug` section**
  - Info for symbolic debugging (**`gcc -g`**)
- **Section header table**
  - Offsets and sizes of each section



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ELF header

Segment header table
(required for executables)

`.text` section

`.rodata` section

`.data` section

`.bss` section

`.symtab` section

`.rel.txt` section

`.rel.data` section

`.debug` section

Section header table

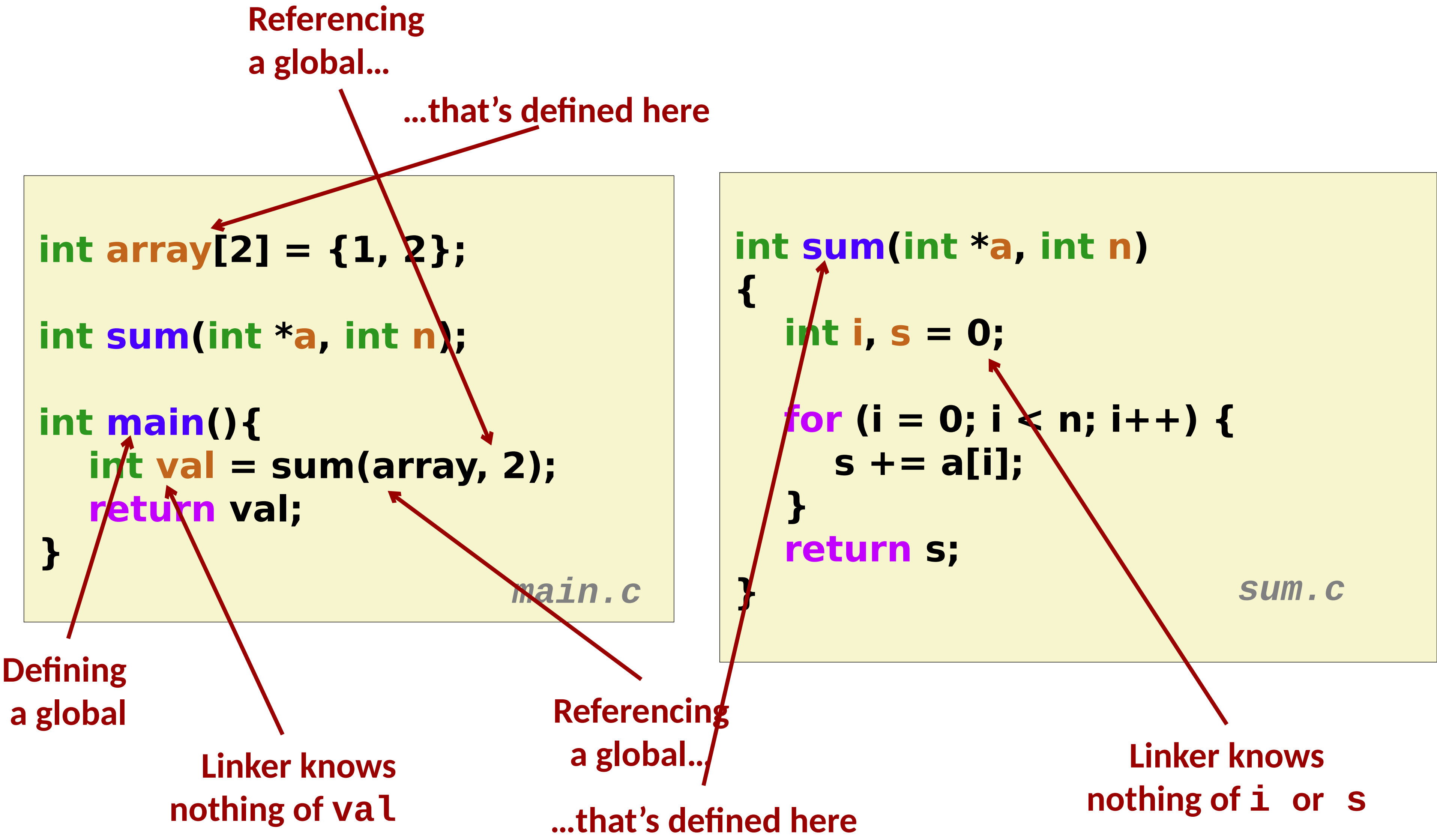
Linker Symbols

- **Global symbols**
  - Symbols defined by module *m* that can be referenced by other modules.
  - E.g.: non-**`static`** C functions and non-**`static`** global variables.

- **External symbols**
  - Global symbols that are referenced by module *m* but defined by some other module.

- **Local symbols**
  - Symbols that are defined and referenced exclusively by module *m*.
  - E.g.: C functions and global variables defined with the **`static`** attribute.
  - **Local linker symbols are *not* local program variables – those are allocated on the stack at runtime & not managed by linker**

Step 1: Symbol Resolution



```
int array[2] = {1, 2};

int sum(int *a, int n);

int main(){
    int val = sum(array, 2);
    return val;
}
```

main.c

```
int sum(int *a, int n)
{
    int i, s = 0;

    for (i = 0; i < n; i++) {
        s += a[i];
    }
    return s;
}
```

sum.c

Referencing a global…

…that's defined here

Defining a global

Linker knows nothing of `val`

Referencing a global…

…that's defined here

Linker knows nothing of `i` or `s`

Local Symbols

- **Local non-static C variables vs. local static C variables**
  - local non-static C variables: stored on the stack
  - local static C variables: stored in either `.bss,` or `.data`

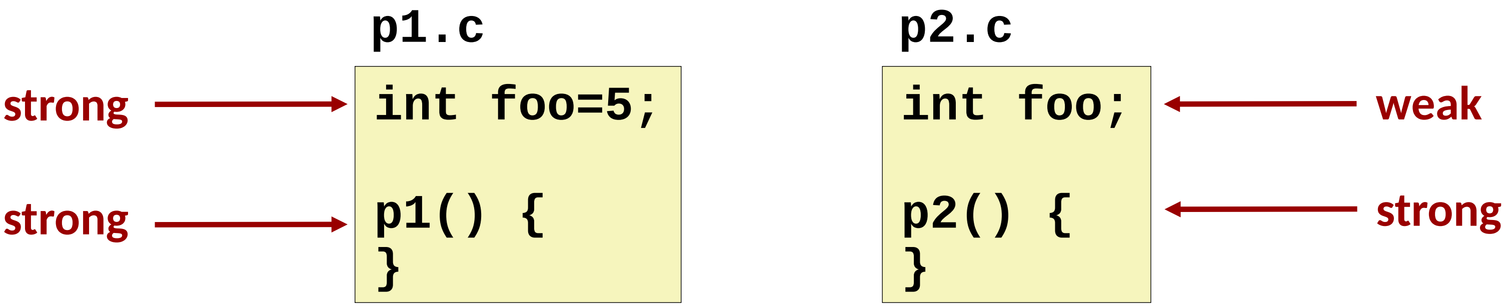
```
int f()
{
   static int x = 0;
   return x;
}

int g()
{
   static int x = 1;
   return x;
}
```

Compiler allocates space in `.data` for each definition of `x`

Creates local symbols in the symbol table with unique names, e.g., `x.1` and `x.2`.

How Linker Resolves Duplicate Symbol Definitions

- **Program symbols are either *strong* or *weak***
  - ***Strong***: procedures and initialized globals
  - ***Weak***: uninitialized globals



p1.c

```
int foo=5;

p1() {
}
```

p2.c

```
int foo;

p2() {
}
```

Linker’s Symbol Rules

- **Rule 1: Multiple strong symbols are not allowed**
  - Each item can be defined only once
  - Otherwise: Linker error

- **Rule 2: Given a strong symbol and multiple weak symbols, choose the strong symbol**
  - References to the weak symbol resolve to the strong symbol

- **Rule 3: If there are multiple weak symbols, pick an arbitrary one**
  - Can override this with **`gcc –fno-common`**

Linker Puzzles

```
int x;
p1() {}
```

```
p1() {}
```

Link time error: two strong symbols (**`p1`**)

```
int x;
p1() {}
```

```
int x;
p2() {}
```

References to **`x`** will refer to the same uninitialized int. Is this what you really want?

```
int x;
int y;
p1() {}
```

```
double x;
p2() {}
```

Writes to **`x`** in **`p2`** might overwrite **`y`**!
Evil!

```
int x=7;
int y=5;
p1() {}
```

```
double x;
p2() {}
```

Writes to **`x`** in **`p2`** will overwrite **`y`**!
Nasty!

```
int x=7;
p1() {}
```

```
int x;
p2() {}
```

References to **`x`** will refer to the same initialized variable.

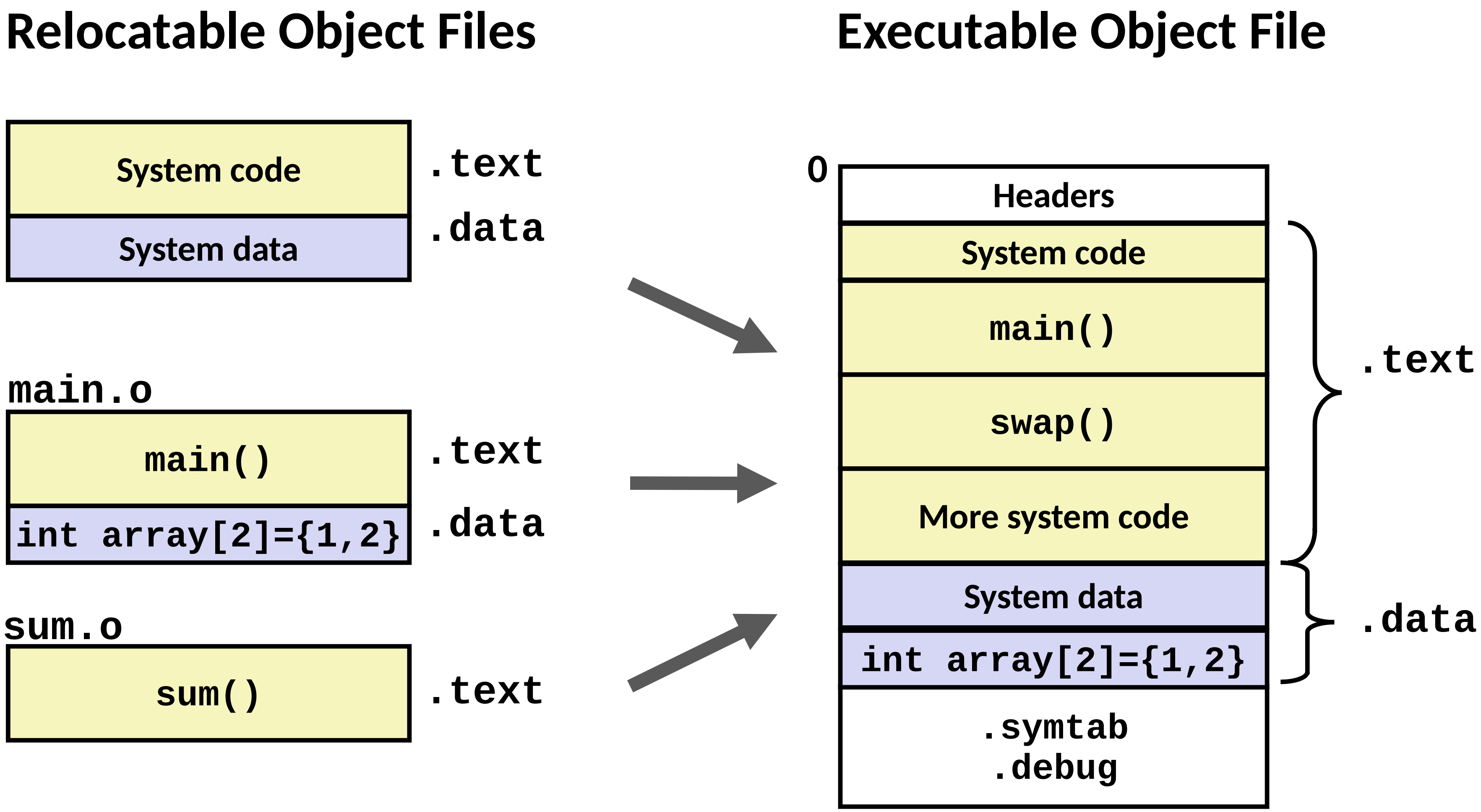
Nightmare scenario: two identical weak structs, compiled by different compilers with different alignment rules.

Global Variables

- **Avoid if you can**

- **Otherwise**
  - Use **`static`** if you can
  - Initialize if you define a global variable
  - Use **`extern`** if you reference an external global variable

Step 2: Relocation



Relocation Entries

```c
int array[2] = {1, 2};

int main()
{
    int val = sum(array, 2);
    return val;
}
```

main.c

```
0000000000000000 <main>:
   0:   48 83 ec 08             sub    $0x8,%rsp
   4:   be 02 00 00 00          mov    $0x2,%esi
   9:   bf 00 00 00 00          mov    $0x0,%edi      # %edi = &array
                        a: R_X86_64_32 array          # Relocation entry

   e:   e8 00 00 00 00          callq  13 <main+0x13> # sum()
                        f: R_X86_64_PC32 sum-0x4      # Relocation entry
  13:   48 83 c4 08             add    $0x8,%rsp
  17:   c3                      retq
```

main.o

Relocated .text section

```
00000000004004d0 <main>:
  4004d0:       48 83 ec 08          sub    $0x8,%rsp
  4004d4:       be 02 00 00 00       mov    $0x2,%esi
  4004d9:       bf 18 10 60 00       mov    $0x601018,%edi  # %edi = &array
  4004de:       e8 05 00 00 00       callq  4004e8 <sum>     # sum()
  4004e3:       48 83 c4 08          add    $0x8,%rsp
  4004e7:       c3                   retq

00000000004004e8 <sum>:
  4004e8:       b8 00 00 00 00          mov    $0x0,%eax
  4004ed:       ba 00 00 00 00          mov    $0x0,%edx
  4004f2:       eb 09                   jmp    4004fd <sum+0x15>
  4004f4:       48 63 ca                movslq %edx,%rcx
  4004f7:       03 04 8f                add    (%rdi,%rcx,4),%eax
  4004fa:       83 c2 01                add    $0x1,%edx
  4004fd:       39 f2                   cmp    %esi,%edx
  4004ff:       7c f3                   jl     4004f4 <sum+0xc>
  400501:       f3 c3                   repz retq
```

Using PC-relative addressing for sum(): 0x4004e8 = 0x4004e3 + 0x5

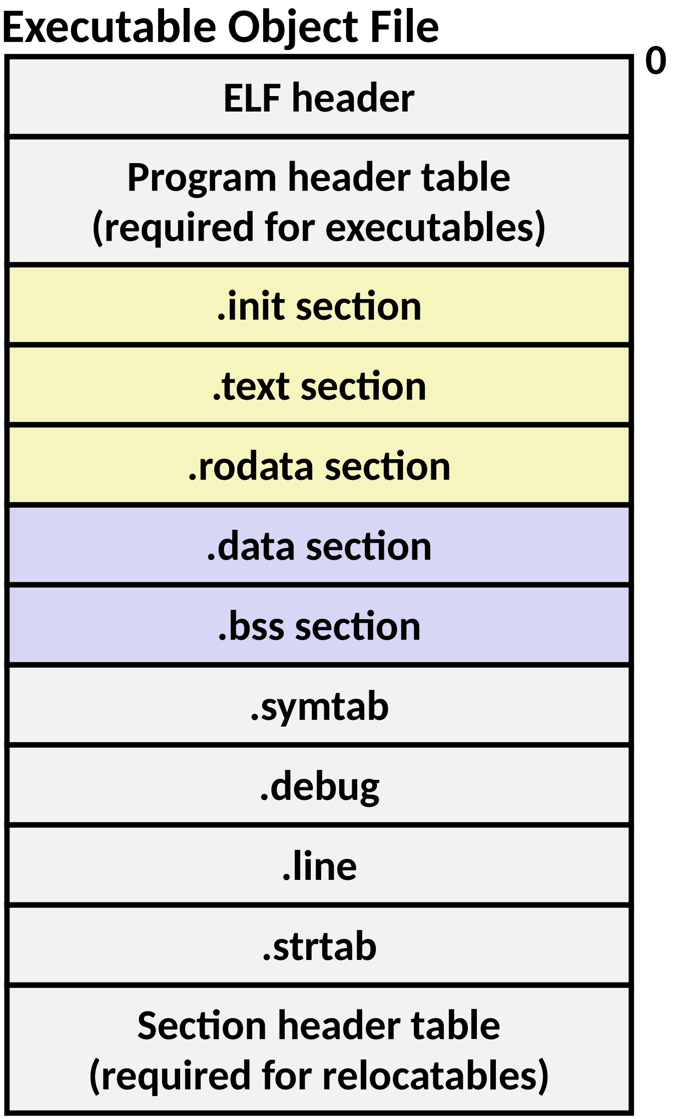
Linking and Loading: Loading & Libraries

These slides adapted from materials provided by the textbook authors.

Linking and Loading

- Linking
- **Loading**
- Case study: Library interpositioning

Loading Executable Object Files



Executable Object File

0

ELF header

Program header table
(required for executables)

.init section

.text section

.rodata section

.data section

.bss section

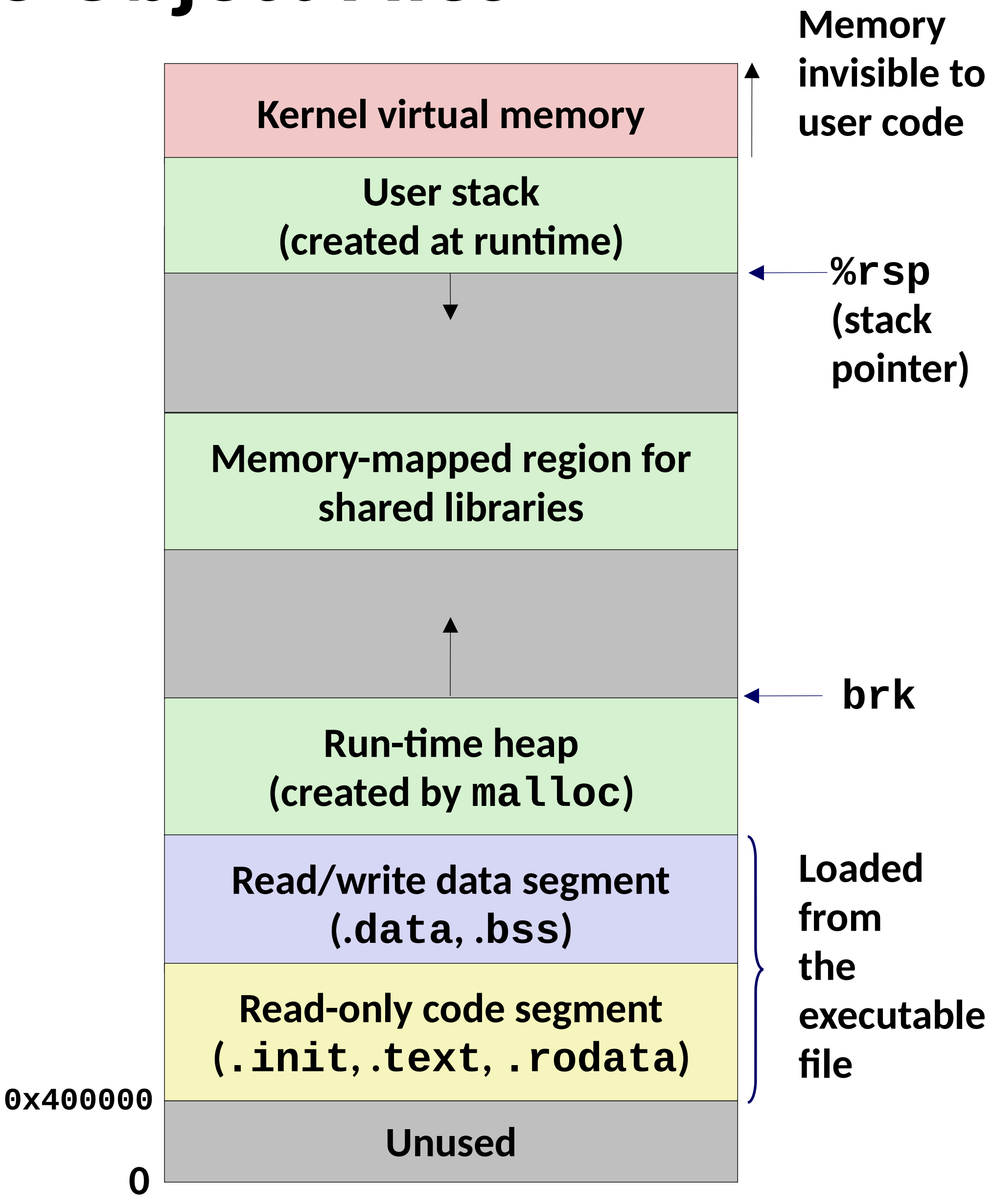
.symtab

.debug

.line

.strtab

Section header table
(required for relocatables)



Memory invisible to user code

Kernel virtual memory

User stack
(created at runtime)

`%rsp`
(stack pointer)

Memory-mapped region for shared libraries

`brk`

Run-time heap
(created by `malloc`)

Read/write data segment
(`.data`, `.bss`)

Read-only code segment
(`.init`, `.text`, `.rodata`)

Loaded from the executable file

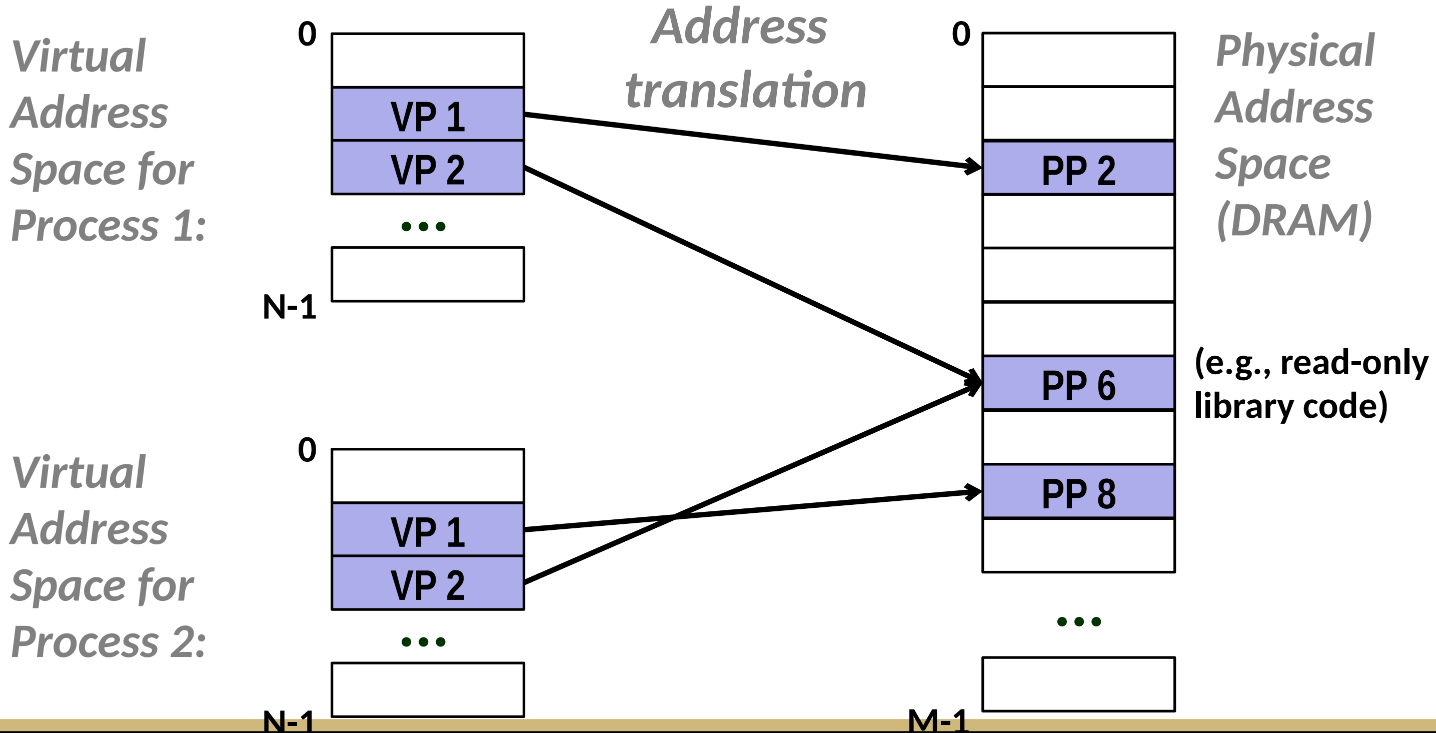
`0x400000`

Unused

0

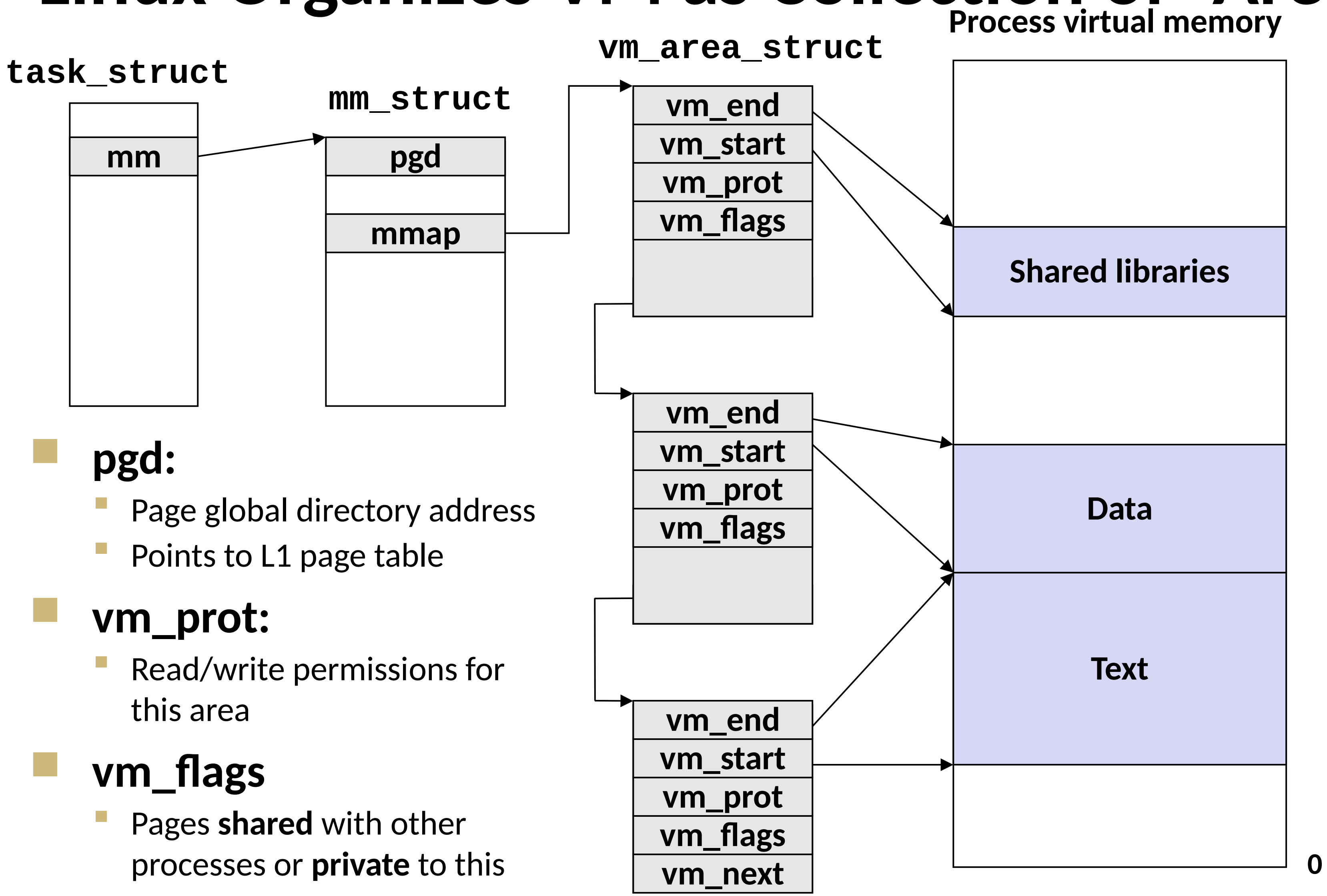
VM as a Tool for Memory Management

- **Simplifying memory allocation**
  - Each virtual page can be mapped to any physical page
  - A virtual page can be stored in different physical pages at different times
- **Sharing code and data among processes**
  - Map virtual pages to the same physical page (here: PP 6)


Virtual Address Space for Process 1:
0
VP 1
VP 2
...
N-1
Address translation
0
PP 2
PP 6
PP 8
...
M-1
Physical Address Space (DRAM)
Virtual Address Space for Process 2:
0
VP 1
VP 2
...
N-1

(e.g., read-only library code)

Linux Organizes VM as Collection of “Areas”



- **pgd:**
  - Page global directory address
  - Points to L1 page table
- **vm_prot:**
  - Read/write permissions for this area
- **vm_flags**
  - Pages **shared** with other processes or **private** to this process

Packaging Commonly Used Functions

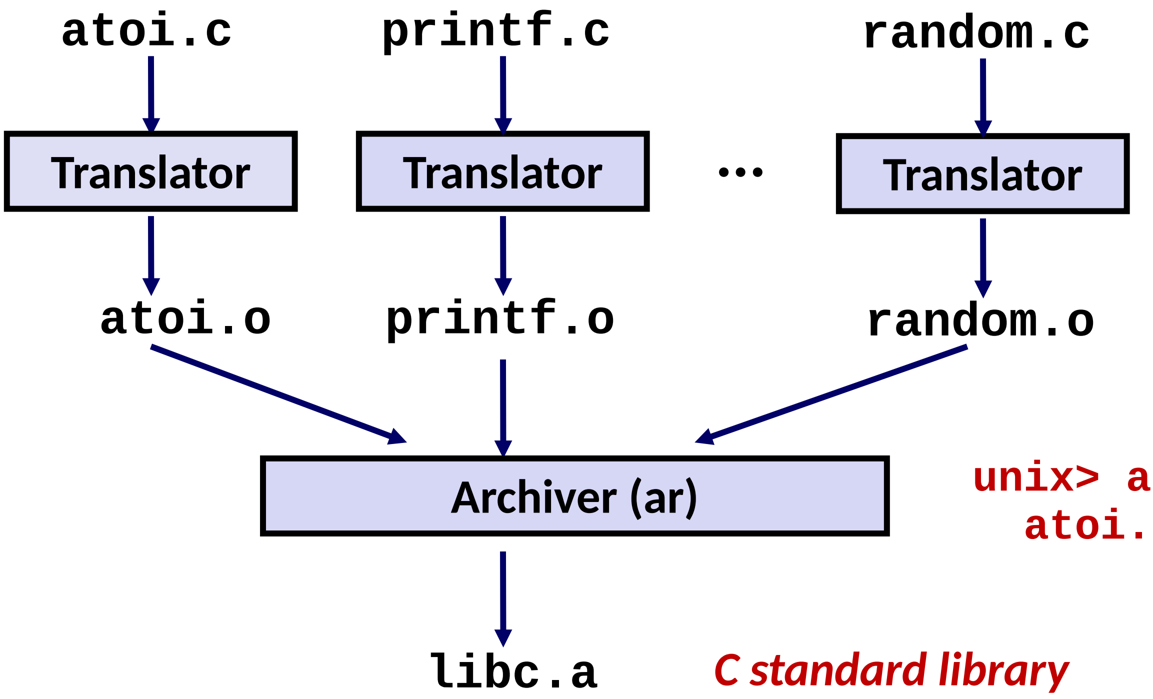
- **How to package functions commonly used by programmers?**
  - Math, I/O, memory management, string manipulation, etc.

- **Awkward, given the linker framework so far:**
  - **Option 1:** Put all functions into a single source file
    - Programmers link big object file into their programs
    - Space and time inefficient
  - **Option 2:** Put each function in a separate source file
    - Programmers explicitly link appropriate binaries into their programs
    - More efficient, but burdensome on the programmer

Old-fashioned Solution: Static Libraries

- **Static libraries (.a archive files)**
  - Concatenate related relocatable object files into a single file with an index (called an *archive*).
  - Enhance linker so that it tries to resolve unresolved external references by looking for the symbols in one or more archives.
  - If an archive member file resolves reference, link it into the executable.

Creating Static Libraries



```
unix> ar rs libc.a \
   atoi.o printf.o … random.o
```

C standard library

- **Archiver allows incremental updates**
- **Recompile function that changes and replace .o file in archive.**

Commonly Used Libraries

libc.a (the C standard library)

- 4.6 MB archive of 1496 object files.
- I/O, memory allocation, signal handling, string handling, data and time, random numbers, integer math

libm.a (the C math library)

- 2 MB archive of 444 object files.
- floating point math (sin, cos, tan, log, exp, sqrt, …)

```
% ar –t libc.a | sort
…
fork.o
…
fprintf.o
fpu_control.o
fputc.o
freopen.o
fscanf.o
fseek.o
fstab.o
…
```

```
% ar –t libm.a | sort
…
e_acos.o
e_acosf.o
e_acosh.o
e_acoshf.o
e_acoshl.o
e_acosl.o
e_asin.o
e_asinf.o
e_asinl.o
…
```

Linking with Static Libraries

```
#include <stdio.h>
#include "vector.h"

int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];

int main()
{
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n”,
           z[0], z[1]);
    return 0;
}
```

main2.c

libvector.a

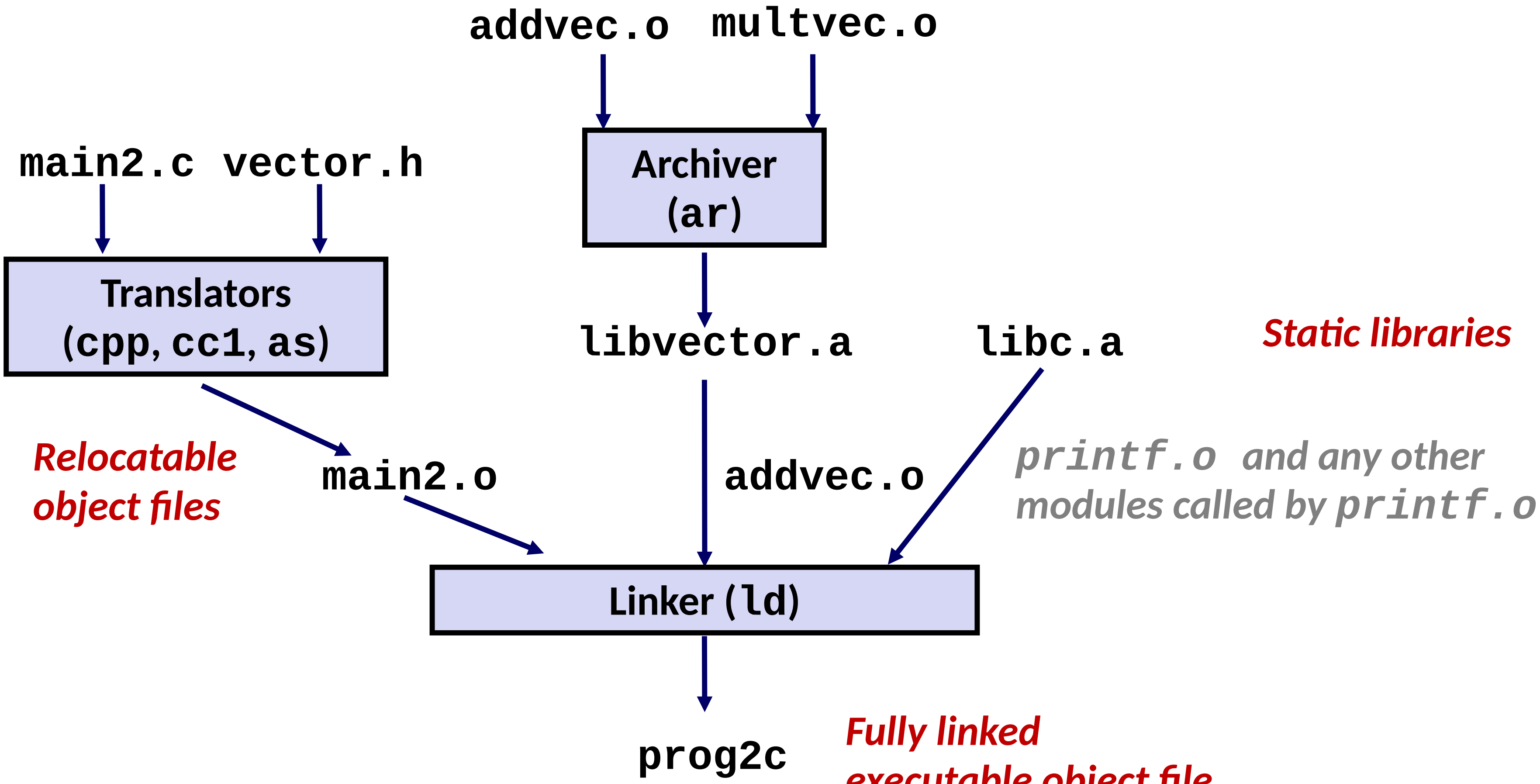
```
void addvec(int *x, int *y,
            int *z, int n) {
    int i;

    for (i = 0; i < n; i++)
        z[i] = x[i] + y[i];
}
```

addvec.c

```
void multvec(int *x, int *y,
             int *z, int n)
{
    int i;

    for (i = 0; i < n; i++)
        z[i] = x[i] * y[i];
}
```

multvec.c

Linking with Static Libraries



"c" for "compile-time"

Using Static Libraries

- **Linker's algorithm for resolving external references:**
  - Scan **.o** files and **.a** files in the command line order.
  - During the scan, keep a list of the current unresolved references.
  - As each new **.o** or **.a** file, *obj*, is encountered, try to resolve each unresolved reference in the list against the symbols defined in *obj*.
  - If any entries in the unresolved list at end of scan, then error.

- **Problem:**
  - Command line order matters!
  - Moral: put libraries at the end of the command line.

```
unix> gcc -L. libtest.o -lmine
unix> gcc -L. -lmine libtest.o
libtest.o: In function `main':
libtest.o(.text+0x4): undefined reference to `libfun'
```

Modern Solution: Shared Libraries

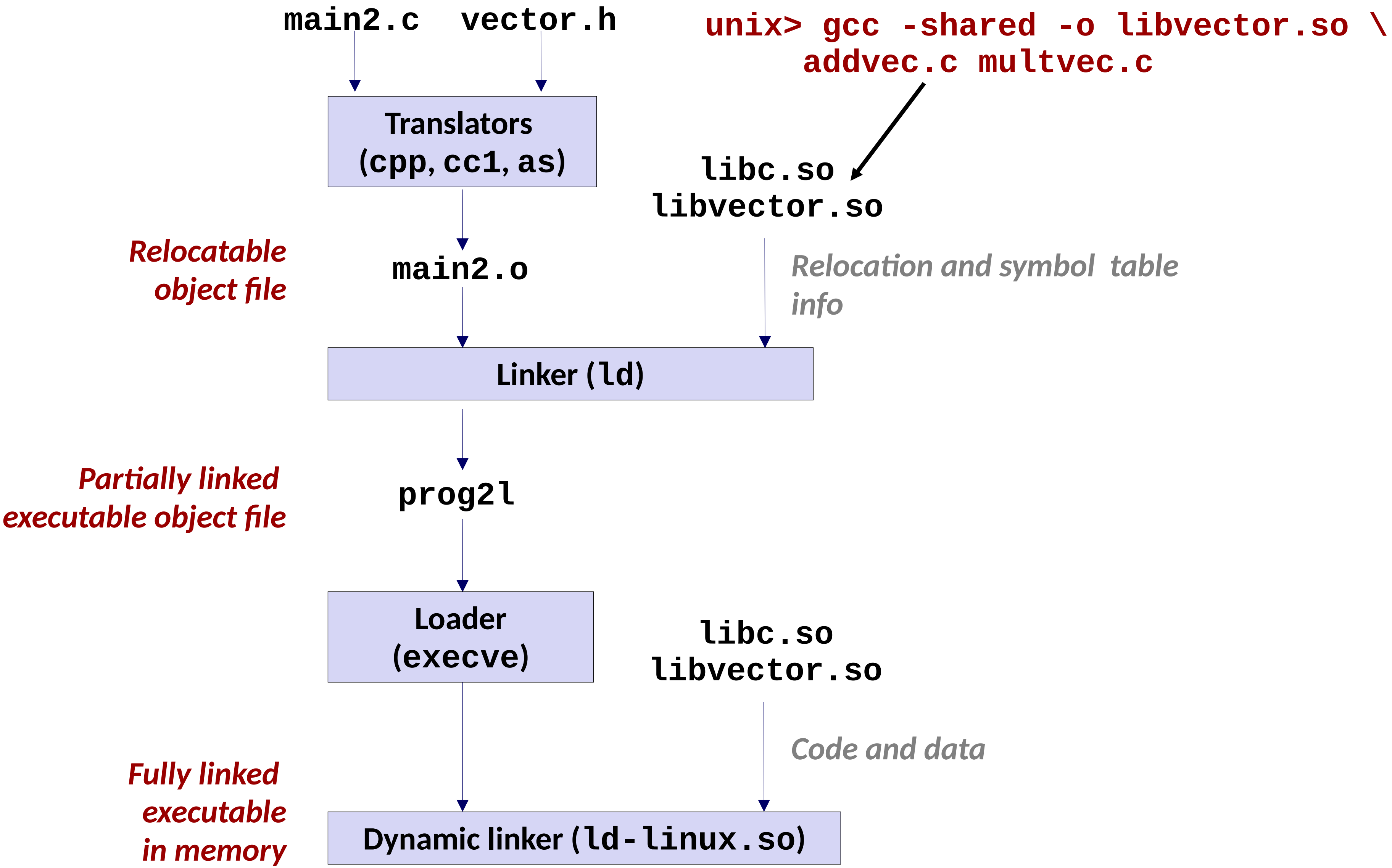
- **Static libraries have the following disadvantages:**
  - Duplication in the stored executables (every function needs libc)
  - Duplication in the running executables
  - Minor bug fixes of system libraries require each application to explicitly relink

- **Modern solution: Shared Libraries**
  - Object files that contain code and data that are loaded and linked into an application *dynamically*, at either *load-time* or *run-time*
  - Also called: dynamic link libraries, DLLs, `.so` files

Shared Libraries (cont.)

- **Dynamic linking can occur when executable is first loaded and run (load-time linking).**
  - Common case for Linux, handled automatically by the dynamic linker (**`ld-linux.so`**).
  - Standard C library (**`libc.so`**) usually dynamically linked.
- **Dynamic linking can also occur after program has begun (run-time linking).**
  - In Linux, this is done by calls to the **`dlopen()`** interface.
    - Distributing software.
    - High-performance web servers.
    - Runtime library interpositioning.
- **Shared library routines can be shared by multiple processes.**
  - More on this when we learn about virtual memory

Dynamic Linking at Load-time



```
unix> gcc -shared -o libvector.so \
        addvec.c multvec.c
```

Dynamic Linking at Run-time

```
beast-1$ strace /bin/echo hi
execve("/bin/echo", ["/bin/echo", "hi"], [/* 34 vars */]) = 0
brk(NULL)                               = 0xa32000
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file
access("/etc/ld.so.preload", R_OK)      = -1 ENOENT (No such file
open("/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, {st_mode=S_IFREG|0644, st_size=77306, ...}) = 0
mmap(NULL, 77306, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7f34318f7000
close(3)                                = 0
access("/etc/ld.so.nohwcap", F_OK)      = -1 ENOENT (No such file
open("/lib/x86_64-linux-gnu/libc.so.6", O_RDONLY|O_CLOEXEC) = 3
read(3, "\177ELF\2\1\1\3\0\0\0\0\0\0\0\0\3\0>\0\1\0\0\0P\t\2\0\0\
fstat(3, {st_mode=S_IFREG|0755, st_size=1868984, ...}) = 0
mmap(NULL, 4096, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP_ANONYMOUS,
mmap(NULL, 3971488, PROT_READ|PROT_EXEC, MAP_PRIVATE|MAP_DENYWRIT
mprotect(0x7f34314db000, 2097152, PROT_NONE) = 0
mmap(0x7f34316db000, 24576, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP
mmap(0x7f34316e1000, 14752, PROT_READ|PROT_WRITE, MAP_PRIVATE|MAP
close(3)
```

Dynamic Linking at Run-time

```
#include <stdio.h>
#include <stdlib.h>
#include <dlfcn.h>

int x[2] = {1, 2};
int y[2] = {3, 4};
int z[2];

int main()
{
   void *handle;
   void (*addvec)(int *, int *, int *, int);
   char *error;

   /* Dynamically load the shared library that contains addvec() */
   handle = dlopen("./libvector.so", RTLD_LAZY);
   if (!handle) {
      fprintf(stderr, "%s\n", dlerror());
      exit(1);
   }
```

dll.c

Dynamic Linking at Run-time

```
        ...

    /* Get a pointer to the addvec() function we just loaded */
    addvec = dlsym(handle, "addvec");
    if ((error = dlerror()) != NULL) {
        fprintf(stderr, "%s\n", error);
        exit(1);
    }

    /* Now we can call addvec() just like any other function */
    addvec(x, y, z, 2);
    printf("z = [%d %d]\n", z[0], z[1]);

    /* Unload the shared library */
    if (dlclose(handle) < 0) {
        fprintf(stderr, "%s\n", dlerror());
        exit(1);
    }
    return 0;
}
```

dll.c

Linking Summary

- **Linking is a technique that allows programs to be constructed from multiple object files.**

- **Linking can happen at different times in a program's lifetime:**
  - Compile time (when a program is compiled)
  - Load time (when a program is loaded into memory)
  - Run time (while a program is executing)

- **Understanding linking can help you avoid nasty errors and make you a better programmer.**

Loading Executable Object Files

```
unix> ./dll
```

What’s happening?

- **Invokes the ‘loader’, which:**
  - Copies code and data sections to memory
  - (`.init`, `.text`, `.rodata`, `.data`, `.bss`)
  - jumps to first instruction (‘entry point’)
  - For c, this is __libc_start_main, defined in libc.so
- **If there are dynamically-linked libraries:**
  - Loader copies code and data sections to memory, as before.
  - Then copies the code and data sections of the libraries to memory as well.
  - Then relocates any references to symbols in ‘dll’ to the definitions provided by the libraries.

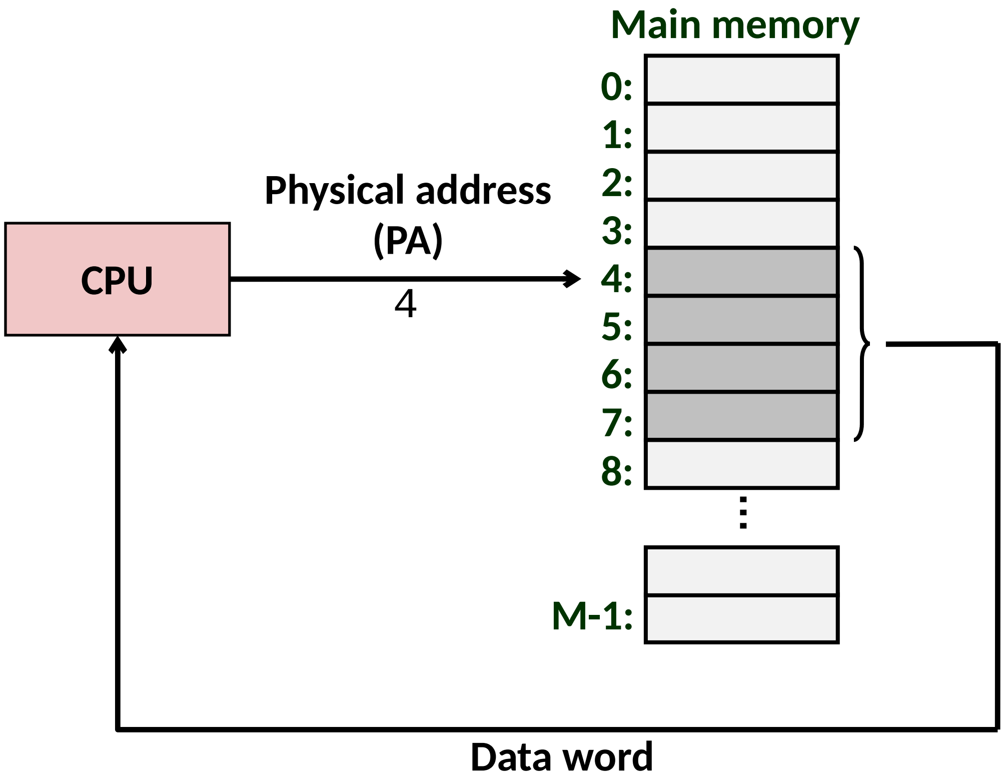
Virtual Memory: Concepts

These slides adapted from materials provided by the textbook authors.

Virtual Memory

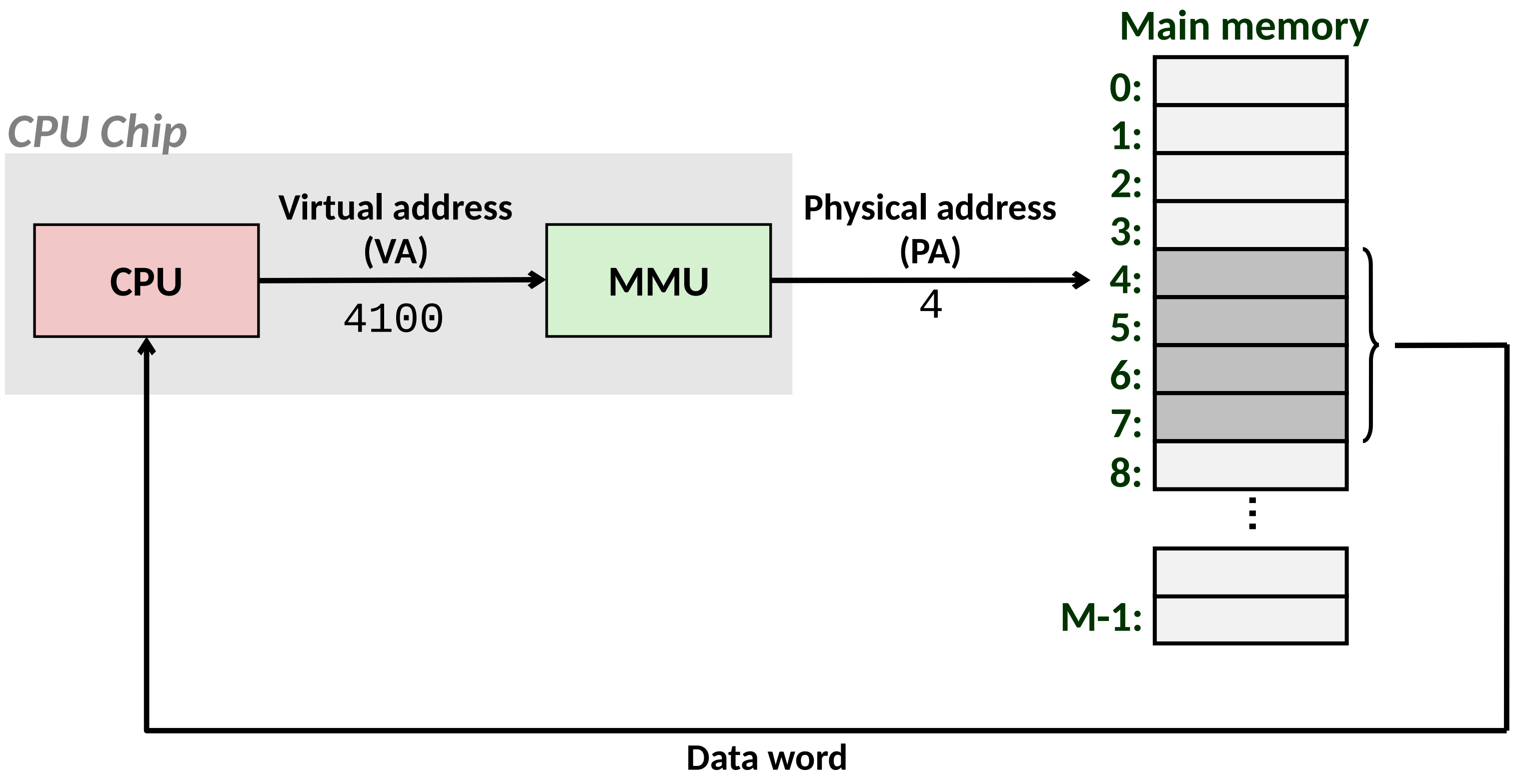
- **Address spaces**
- VM as a tool for caching
- VM as a tool for memory management
- VM as a tool for memory protection
- Address translation

A System Using Physical Addressing



- **Used in "simple" systems like embedded microcontrollers in devices like cars, elevators, and digital picture frames**

A System Using Virtual Addressing



- Used in all modern servers, laptops, and smart phones
- One of the great ideas in computer science

Address Spaces

- **Linear address space:** Ordered set of contiguous non-negative integer addresses:

  {0, 1, 2, 3 … }

- **Virtual address space:** Set of N = 2^n virtual addresses

  {0, 1, 2, 3, …, N-1}

- **Physical address space:** Set of M = 2^m physical addresses

  {0, 1, 2, 3, …, M-1}

Why Virtual Memory (VM)?

- **Uses main memory efficiently**
  - Use DRAM as a cache for parts of a virtual address space

- **Simplifies memory management**
  - Each process gets the same uniform linear address space

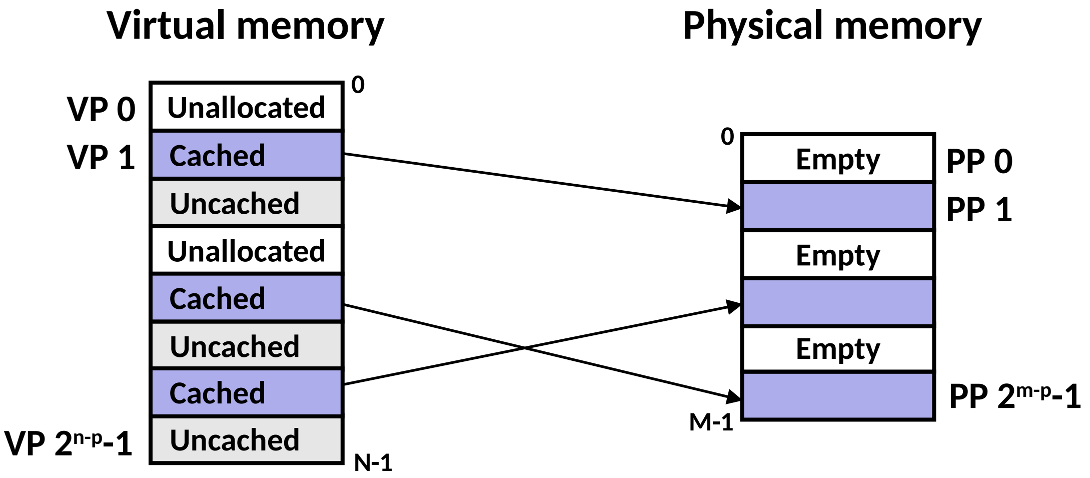
- **Isolates address spaces**
  - One process can't interfere with another's memory
  - User program cannot access privileged kernel information and code

Virtual Memory

- Address spaces
- **VM as a tool for caching**
- VM as a tool for memory management
- VM as a tool for memory protection
- Address translation

VM as a Tool for Caching

- Conceptually, *virtual memory* is an array of N contiguous bytes stored on disk.
- The contents of the array on disk are cached in *physical memory* (*DRAM cache*)
  - These cache blocks are called *pages* (size is P = 2^p bytes)



Virtual pages (VPs) stored on disk

Physical pages (PPs) cached in DRAM

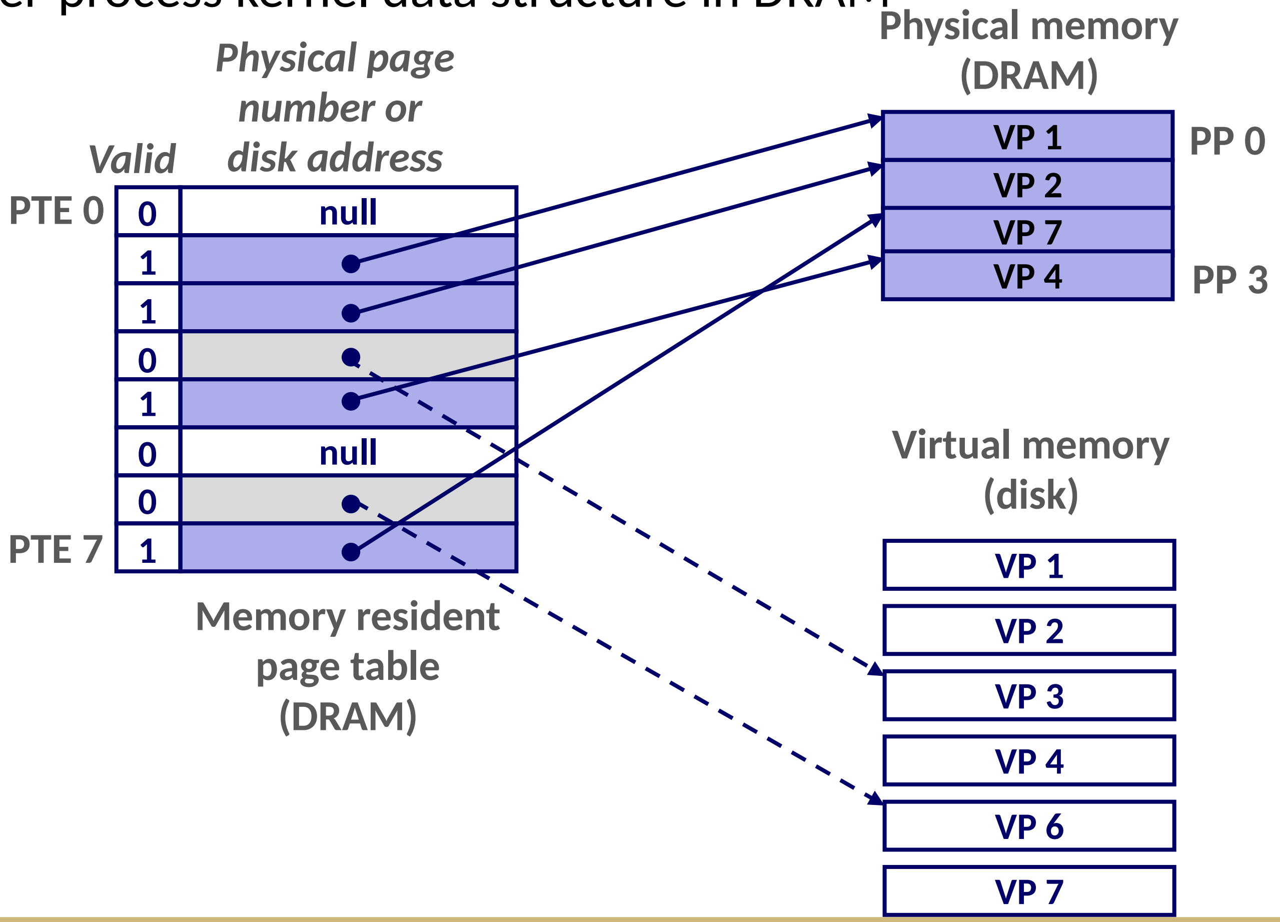
DRAM Cache Organization

- **DRAM cache organization driven by the enormous miss penalty**
  - DRAM is about ***10x*** slower than SRAM
  - Disk is about ***10,000x*** slower than DRAM

- **Consequences**
  - Large page (block) size: typically 4 KB, sometimes 4 MB
  - Fully associative
    - Any VP can be placed in any PP
    - Requires a "large" mapping function – different from cache memories
  - Highly sophisticated, expensive replacement algorithms
    - Too complicated and open-ended to be implemented in hardware
  - Write-back rather than write-through

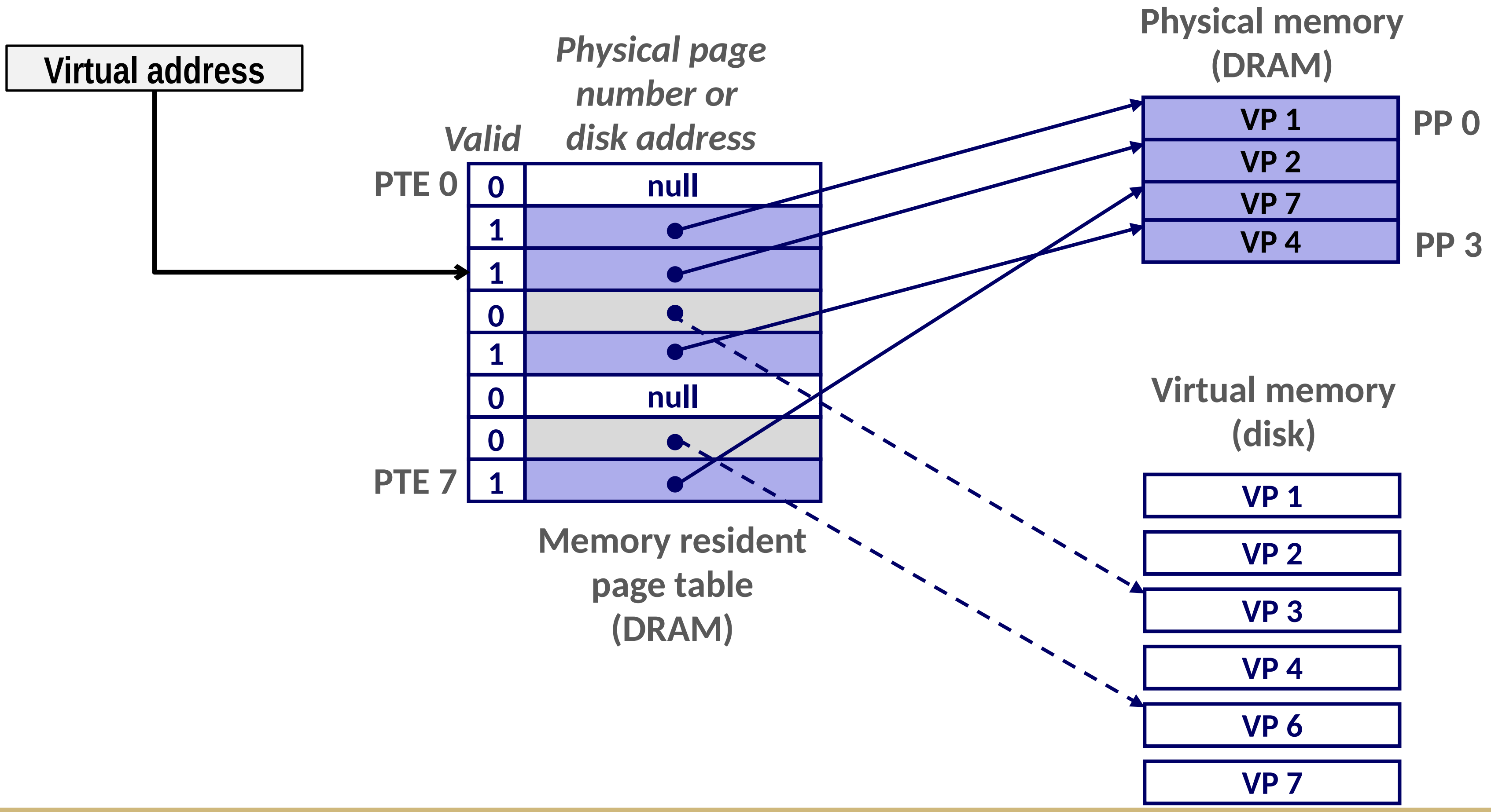
Enabling Data Structure: Page Table

- **A *page table* is an array of page table entries (PTEs) that maps virtual pages to physical pages.**
  - Per-process kernel data structure in DRAM



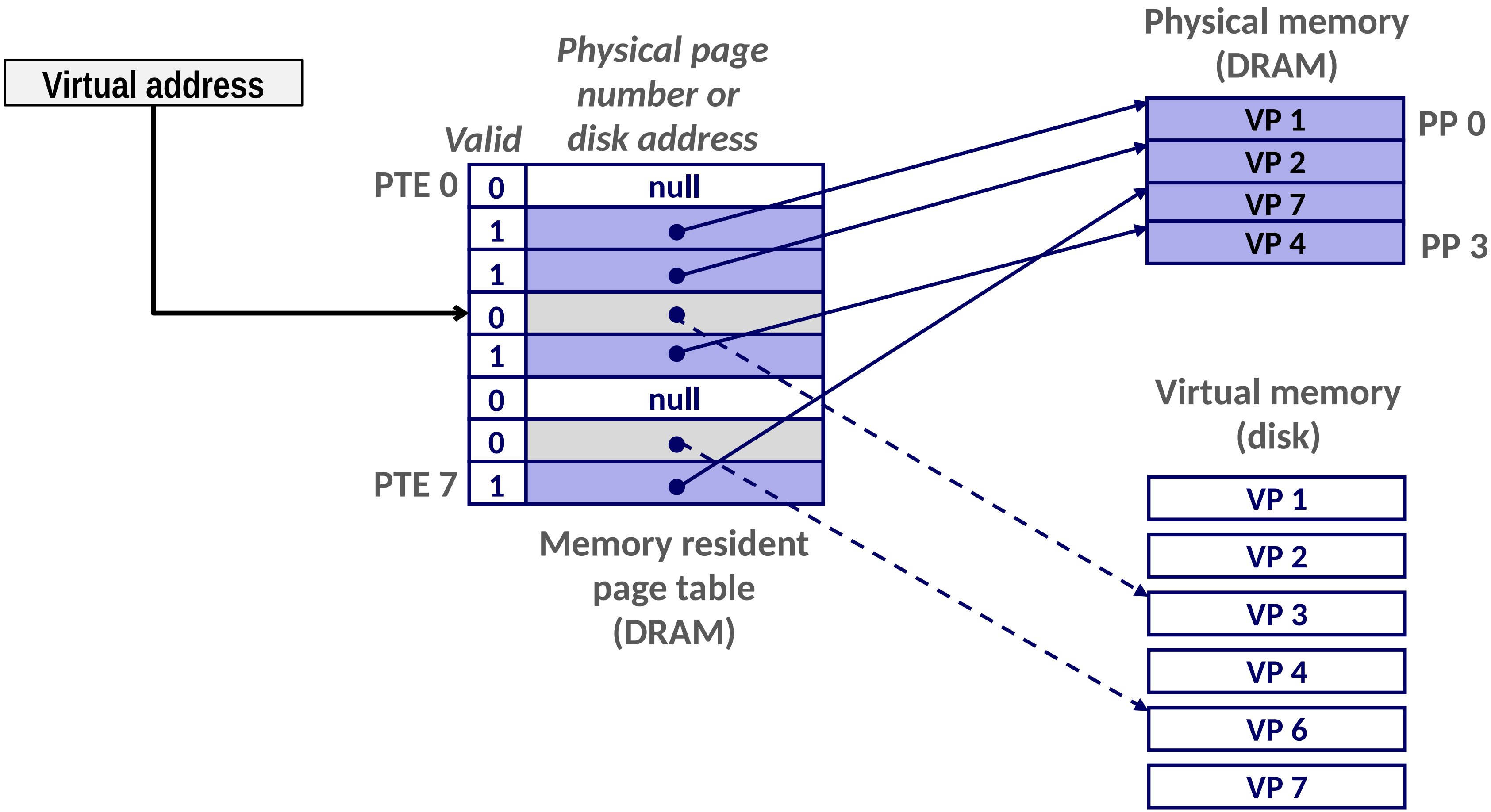
Page Hit

- ***Page hit:*** **reference to VM word that is in physical memory (DRAM cache hit)**



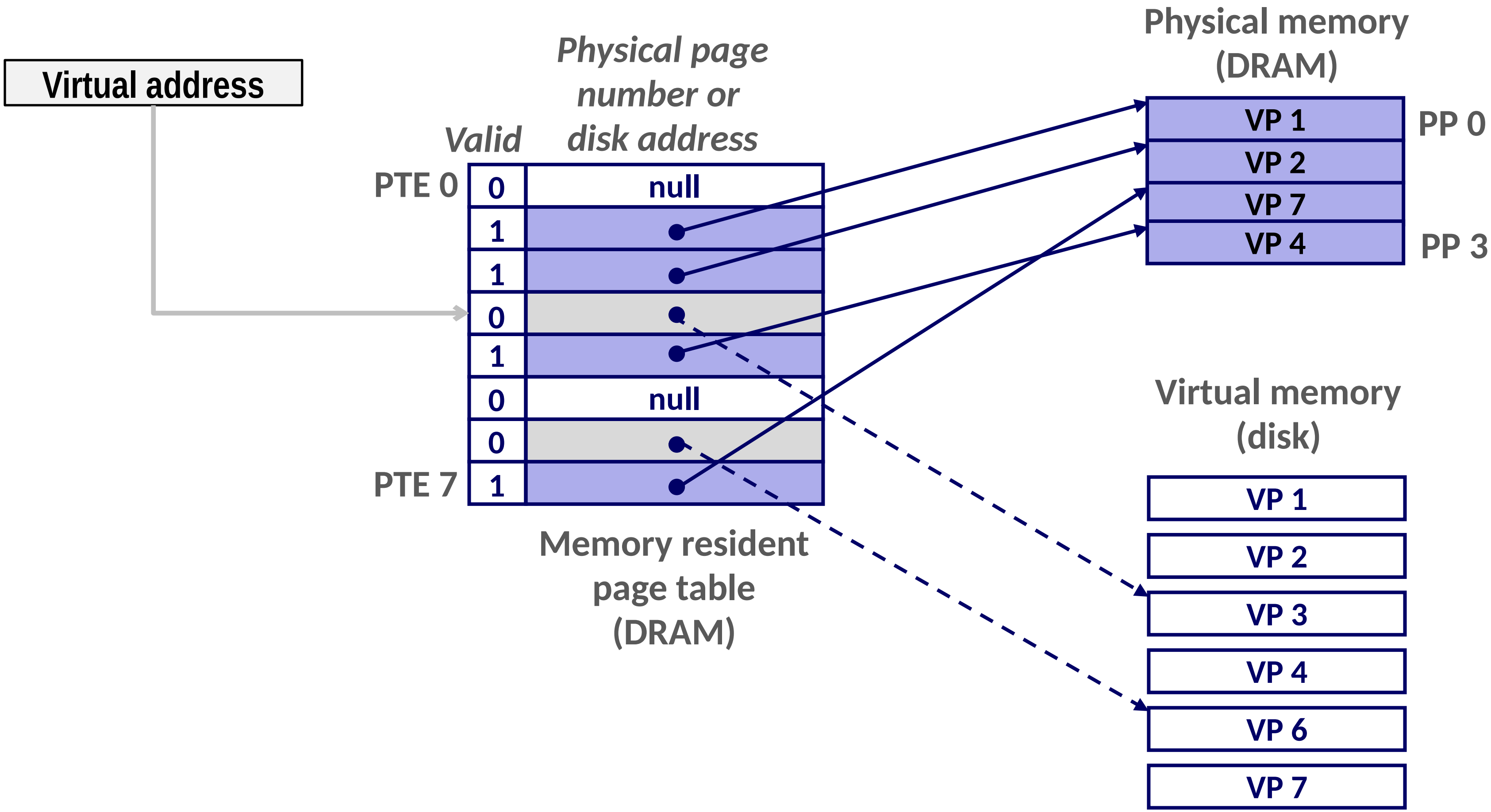
Page Fault

- ***Page fault:*** **reference to VM word that is not in physical memory (DRAM cache miss)**



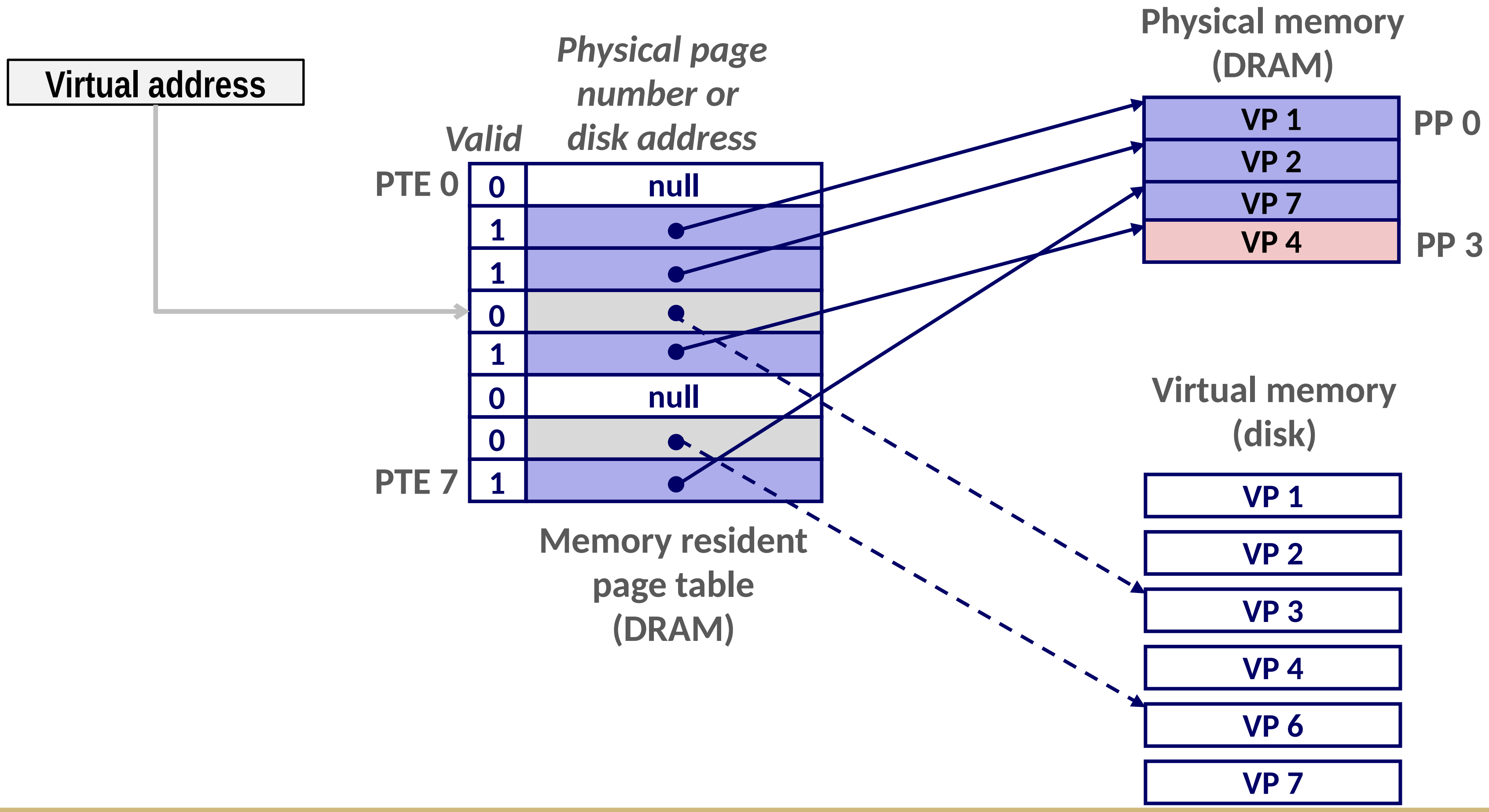
Handling Page Fault

- Page miss causes page fault (an exception)



Handling Page Fault

- Page miss causes page fault (an exception)
- Page fault handler selects a victim to be evicted (here VP 4)



Handling Page Fault

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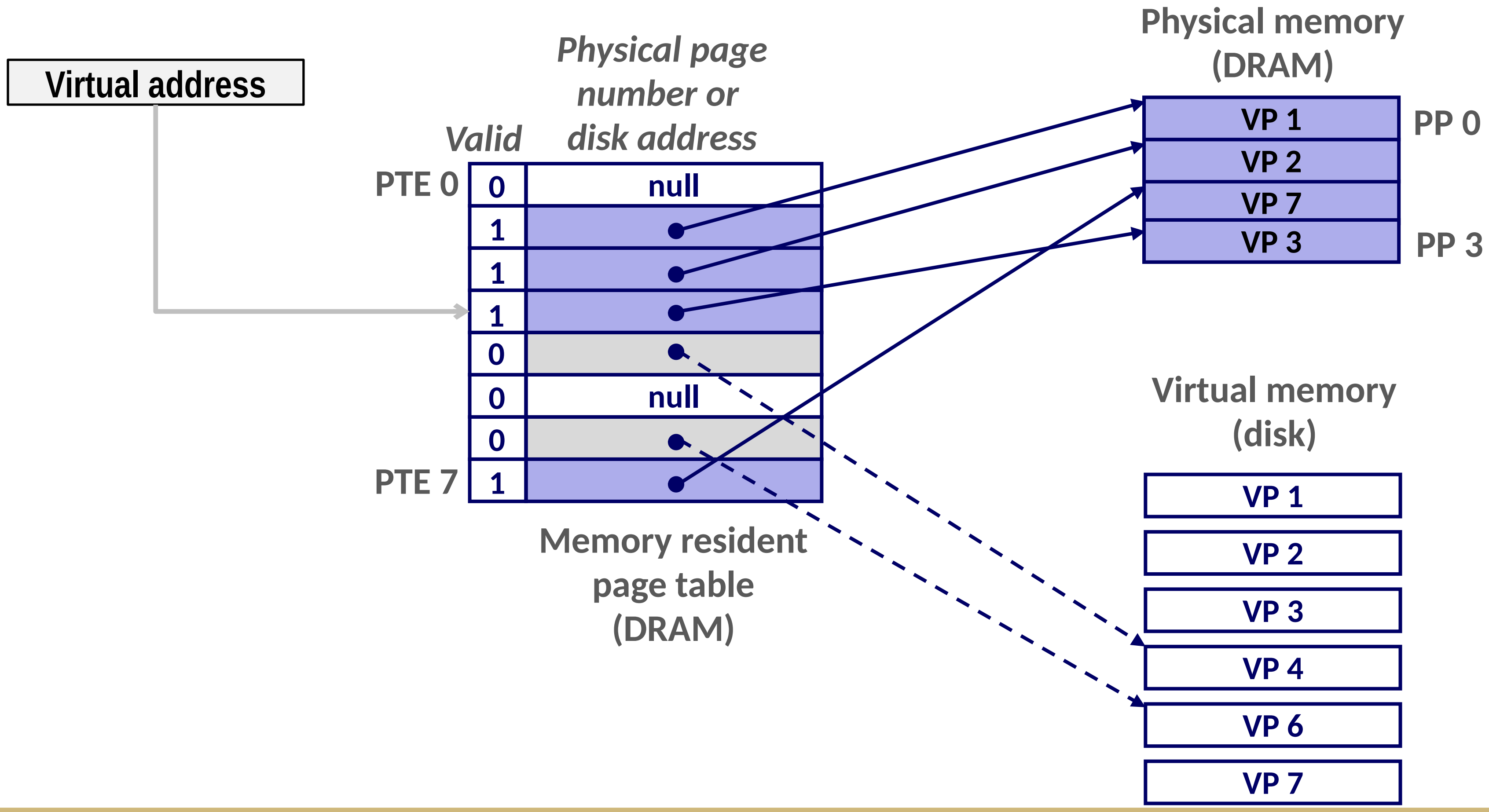
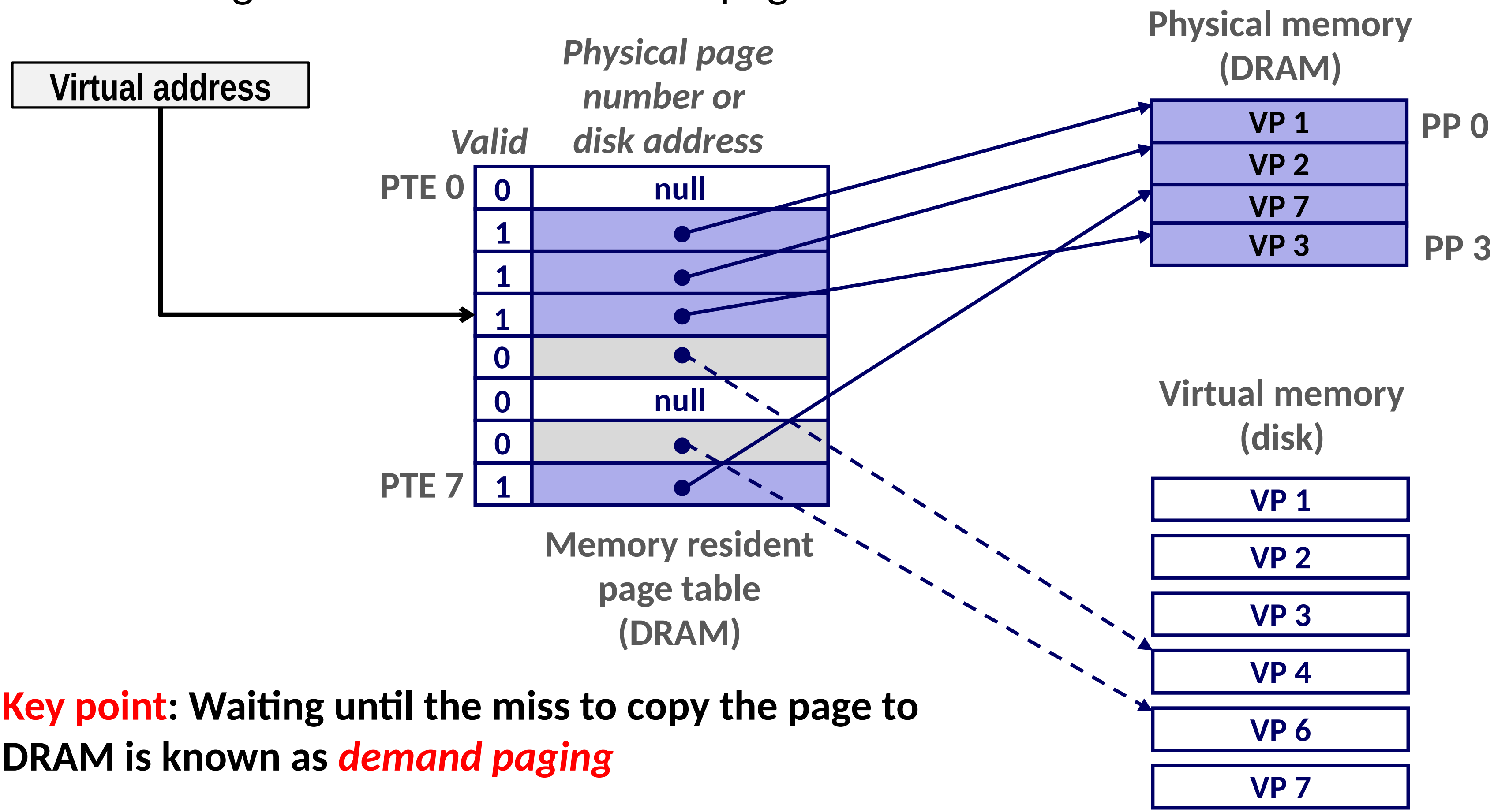


Handling Page Fault

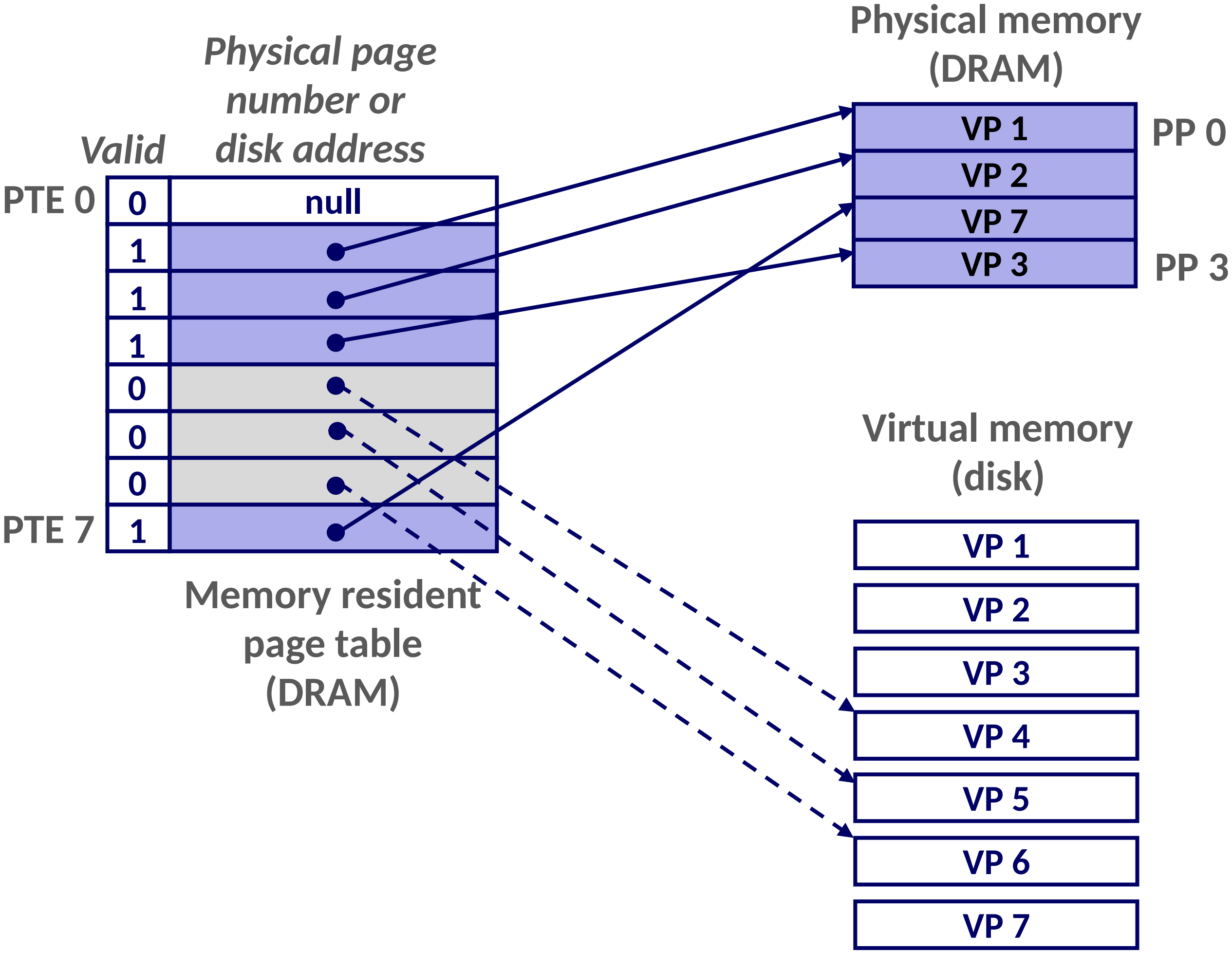
- Page miss causes page fault (an exception)
- Page fault handler selects a victim to be evicted (here VP 4)
- Offending instruction is restarted: page hit!



Key point: Waiting until the miss to copy the page to DRAM is known as *demand paging*

Allocating Pages

- **Allocating a new page (VP 5) of virtual memory.**



Locality to the Rescue Again!

- **Virtual memory seems terribly inefficient, but it works because of locality.**

- **At any point in time, programs tend to access a set of active virtual pages called the *working set***
  - Programs with better temporal locality will have smaller working sets

- **If (working set size < main memory size)**
  - Good performance for one process after compulsory misses

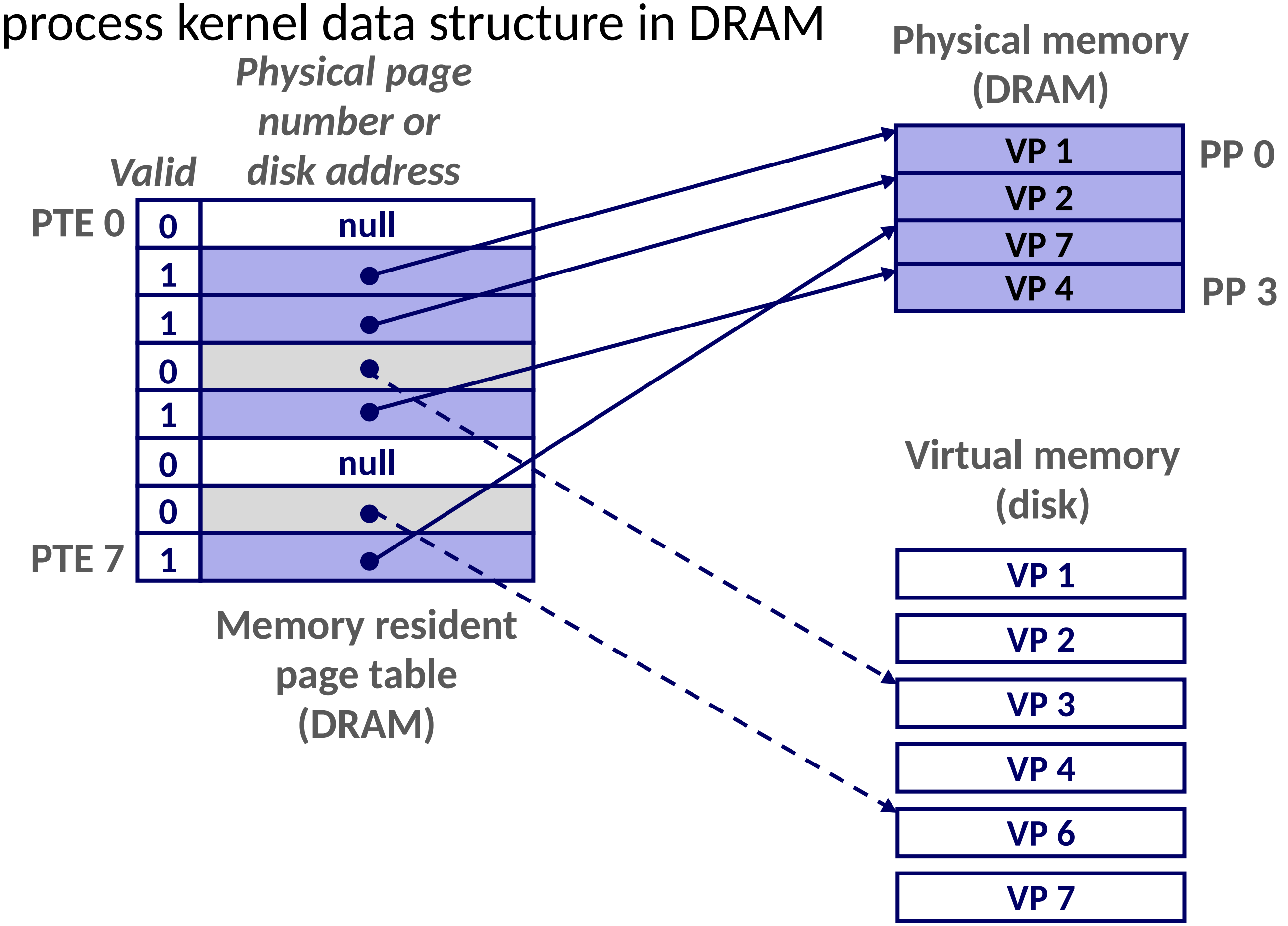
- **If (SUM(working set sizes) > main memory size)**
  - *Thrashing:* Performance meltdown where pages are swapped (copied) in and out continuously

Review of Terms

- **Virtual address space:** Set of $N = 2^n$ virtual addresses
- **Physical address space:** Set of $M = 2^m$ physical addresses
  - Physical: actually fits in Memory (DRAM)
- Memory is divided in to pages. Page: Set of $P = 2^p$ bytes
- **Page hit:** reference to VM word that is in physical memory
- **Page fault:** reference to VM word that is not in physical memory (DRAM cache miss)
- **Working set:** a set of active virtual pages in use by a program
- **Thrashing:** Performance meltdown where pages are swapped (copied) in and out continuously
  - Occurs when working set is larger than physical memory.

Enabling Data Structure: Page Table

- A ***page table*** **is an array of page table entries (PTEs) that maps virtual pages to physical pages.**
  - Per-process kernel data structure in DRAM

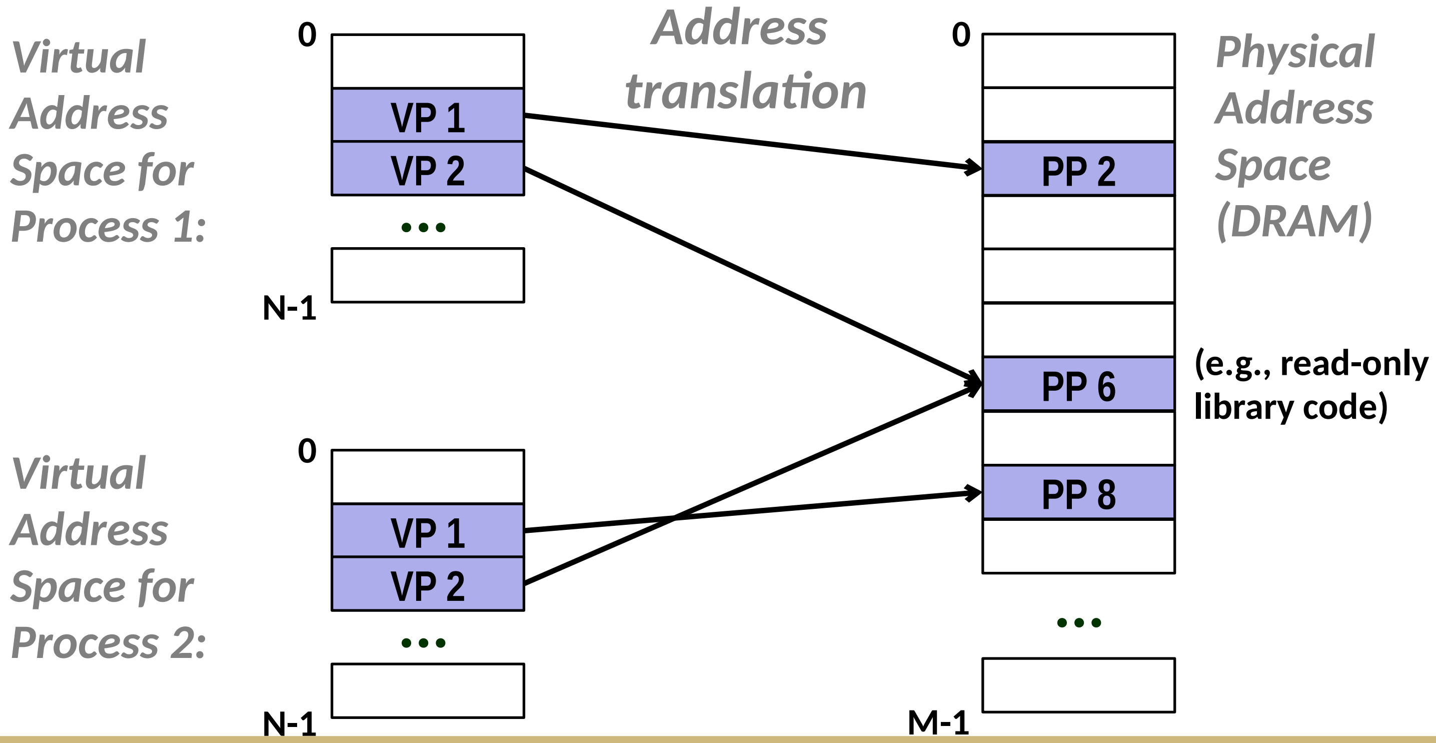


Virtual Memory

- Address spaces
- VM as a tool for caching
- **VM as a tool for memory management**
- VM as a tool for memory protection
- Address translation

VM as a Tool for Memory Management

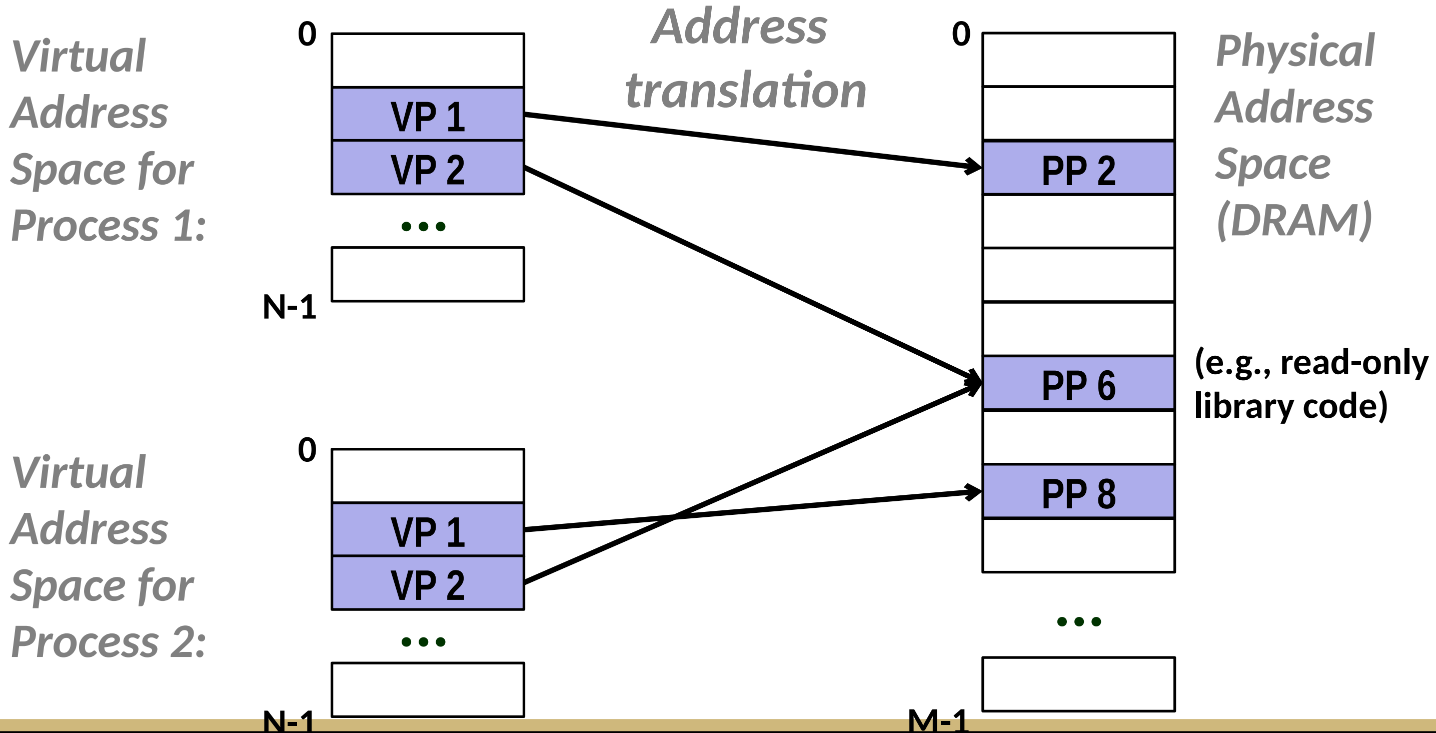
- **Key idea: each process has its own virtual address space**
  - It can view memory as a simple linear array
  - Mapping function scatters addresses through physical memory
    - Well-chosen mappings can improve locality



Virtual Address Space for Process 1:
0
VP 1
VP 2
...
N-1
Address translation
0
PP 2
PP 6
PP 8
...
M-1
Physical Address Space (DRAM)
(e.g., read-only library code)
Virtual Address Space for Process 2:
0
VP 1
VP 2
...
N-1

VM as a Tool for Memory Management

- **Simplifying memory allocation**
  - Each virtual page can be mapped to any physical page
  - A virtual page can be stored in different physical pages at different times
- **Sharing code and data among processes**
  - Map virtual pages to the same physical page (here: PP 6)



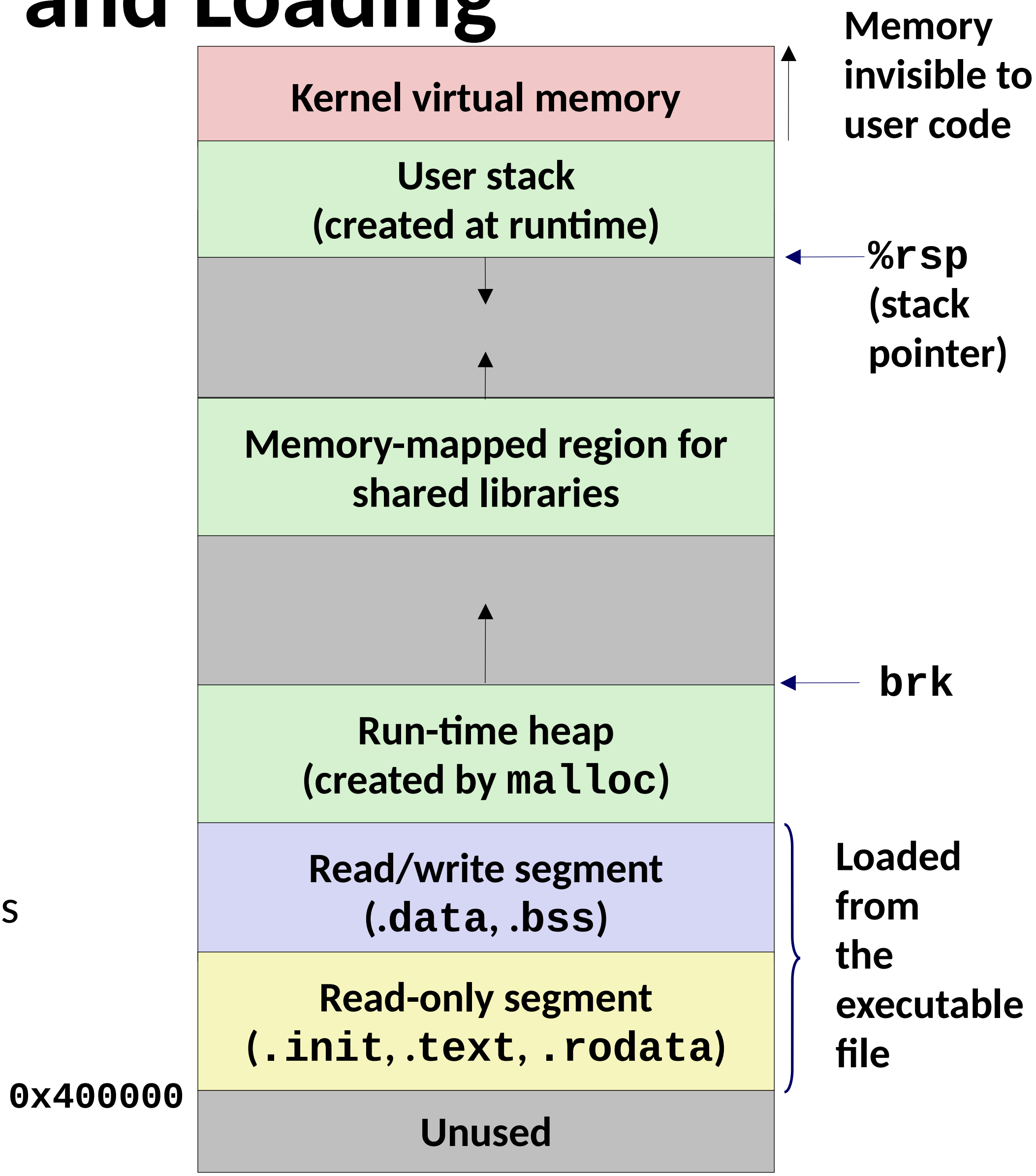
Virtual Address Space for Process 1:
0
VP 1
VP 2
...
N-1
Address translation
0
PP 2
PP 6
PP 8
...
M-1
Physical Address Space (DRAM)
Virtual Address Space for Process 2:
0
VP 1
VP 2
...
N-1

(e.g., read-only library code)

Simplifying Linking and Loading

- **Linking**
  - Each program has similar virtual address space
  - Code, data, and heap always start at the same addresses.

- **Loading**
  - **`execve`** allocates virtual pages for .text and .data sections & creates PTEs marked as invalid
  - The **`.text`** and **`.data`** sections are copied, page by page, on demand by the virtual memory system



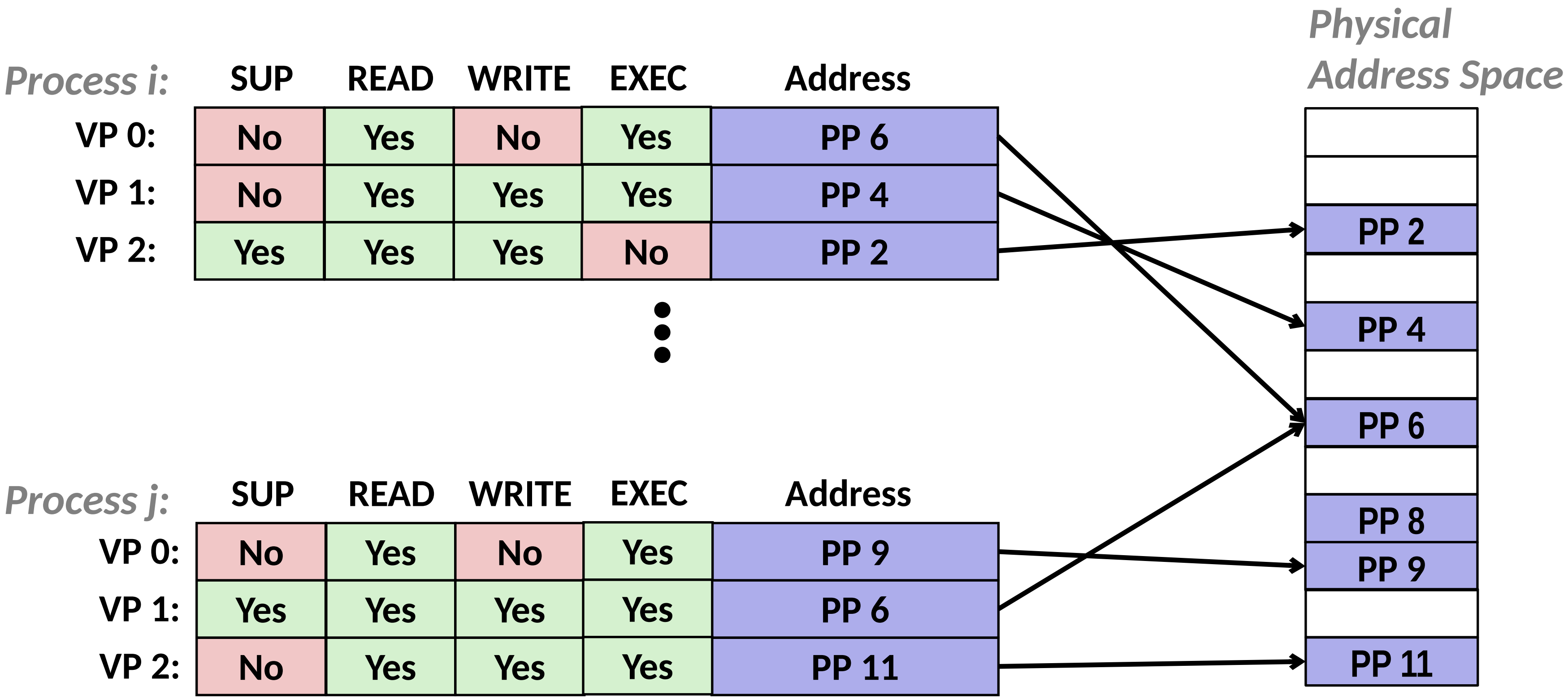
Kernel virtual memory
Memory invisible to user code
User stack (created at runtime)
%rsp (stack pointer)
Memory-mapped region for shared libraries
brk
Run-time heap (created by malloc)
Read/write segment (.data, .bss)
Read-only segment (.init, .text, .rodata)
Loaded from the executable file
0x400000
Unused

Virtual Memory

- Address spaces
- VM as a tool for caching
- VM as a tool for memory management
- **VM as a tool for memory protection**
- Address translation

VM as a Tool for Memory Protection

- Extend PTEs with permission bits
- MMU checks these bits on each access



Process i:	SUP	READ	WRITE	EXEC	Address
VP 0:	No	Yes	No	Yes	PP 6
VP 1:	No	Yes	Yes	Yes	PP 4
VP 2:	Yes	Yes	Yes	No	PP 2

⋮

Process j:	SUP	READ	WRITE	EXEC	Address
VP 0:	No	Yes	No	Yes	PP 9
VP 1:	Yes	Yes	Yes	Yes	PP 6
VP 2:	No	Yes	Yes	Yes	PP 11