Revision of Memory management concepts

Revision

- Memory layout of C program
- Address binding times: compile, link, load
- MMU Schemes
  - No MMU, Base+Relocation, Multiple Base+Relocation = Segmentation, Paging
    - Hierarchical paging
    - TLB,
  - External and Internal fragmentation
- X86 memory management
- Xv6 paging + segmentation

More on Linking, Loading

More on Linking and Loading

- Static Linking: All object code combined at link time and a big object code file is created
- Static Loading: All the code is loaded in memory at the time of exec()
- Problems
  - Static linking: Big executable files,
  - Static loading: need to load functions even if they do not execute
- Solution: Dynamic Linking and Dynamic Loading

Dynamic Linking

- Linker is normally invoked as a part of compilation process
  - Links
    - function code to function calls
    - references to global variables with “extern” declarations
- Dynamic Linker
  - Does not combine function code with the object code file
  - Instead introduces a “stub” code that is indirect reference to actual code
  - At the time of “loading” (or executing!) the program in memory, the “link-loader” (part of OS!) will pick up the relevant code from the library machine code file (e.g. libc.so.6)

Dynamic Linking on Linux

```
#include <stdio.h>
int main() {
int a, b;
scanf("%d%d", &a, &b);
printf("%d %d\n", a, b);
return 0;
}
```

PLT: Procedure Linkage Table
used to call external procedures/functions whose address is to be resolved by the dynamic linker at run time.

Output of objdump -x -D

Disassembly of section .text:

```
0000000000001189 <main>:
    11d4:       callq  1080 <printf@plt>
```

Disassembly of section .plt.got:

```
0000000000001080 <printf@plt>:
    1080:     endbr64
    1084:     bnd jmpq *0x2f3d(%rip)       # 3fc8 <printf@GLIBC_2.2.5>
    108b:     nopl   0x0(%rax,%rax,1)
```

Dynamic Loading

- Loader
  - Loads the program in memory
  - Part of exec() code
  - Needs to understand the format of the executable file (e.g. the ELF format)
- Dynamic Loading
  - Load a part from the ELF file only if needed during execution
  - Delayed loading
  - Needs a more sophisticated memory management by operating system – to be seen during this series of lectures

Dynamic Linking, Loading

- Dynamic linking necessarily demands an advanced type of loader that understands dynamic linking
  - Hence called 'link-loader'
  - Static or dynamic loading is still a choice
- Question: which of the MMU options will alllow for which type of linking, loading ?

Virtual Memory

Introduction

- Virtual memory != Virtual address
  - Virtual address is address issued by CPU's execution unit, later converted by MMU to physical address
  - Virtual memory is a memory management technique employed by OS (with hardware support, of course)

Unused parts of program

```
int a[4096][4096]
int f(int m[][4096]) {
    int i, j;
    for(i = 0; i < 1024; i++)
        m[0][i] = 200;
}
int main() {
    int i, j;
    for(i = 0; i < 1024; i++)
```

All parts of array a[] not accessed

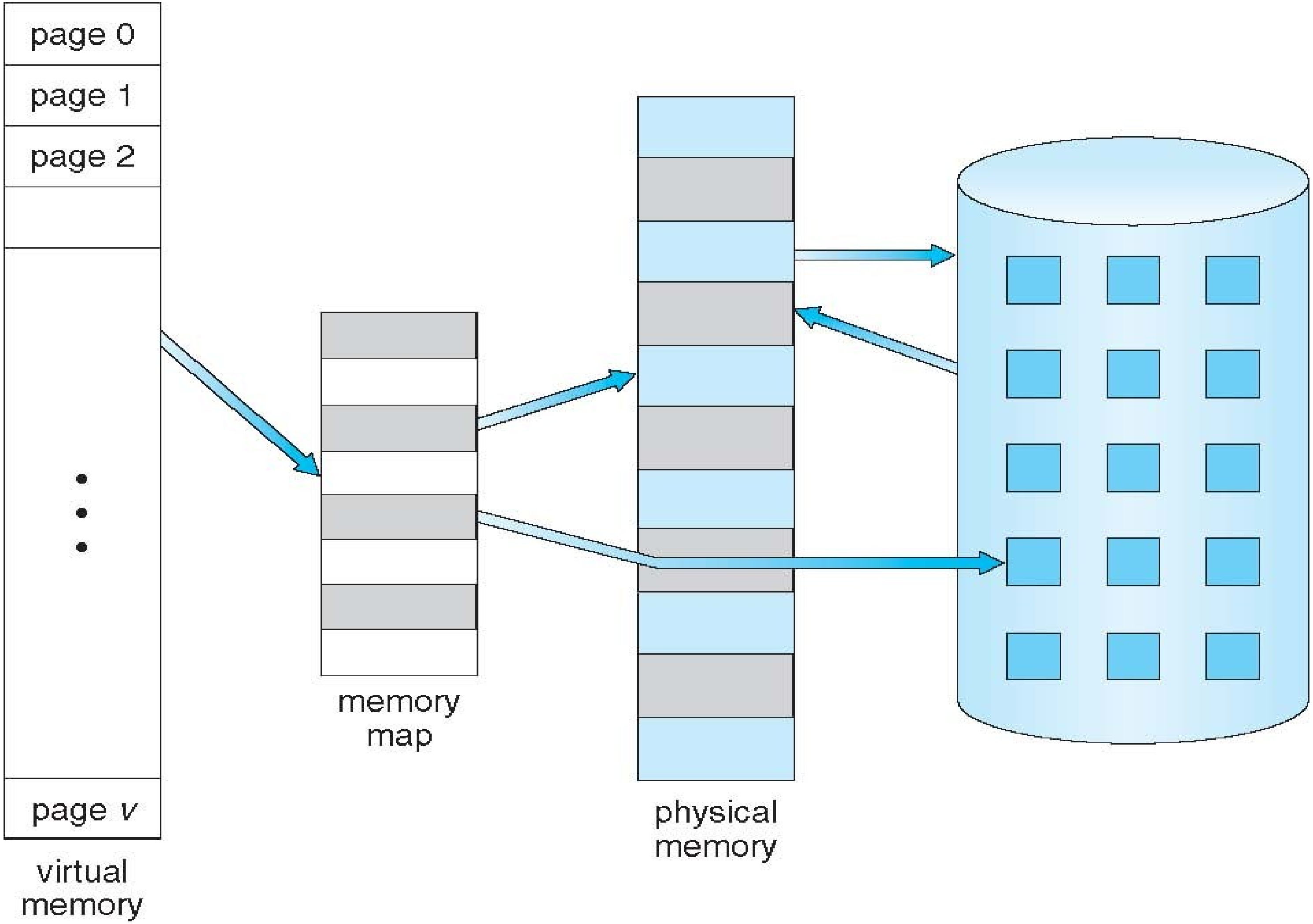
Function f() may not be called

Some problems with schemes discussed so far

- Code needs to be in memory to execute, But entire program rarely used
  - Error code, unusual routines, large data structures are rarely used
- So, entire program code, data not needed at same time
- So, consider ability to execute partially-loaded program
  - One Program no longer constrained by limits of physical memory
  - One Program and collection of programs could be larger than physical memory

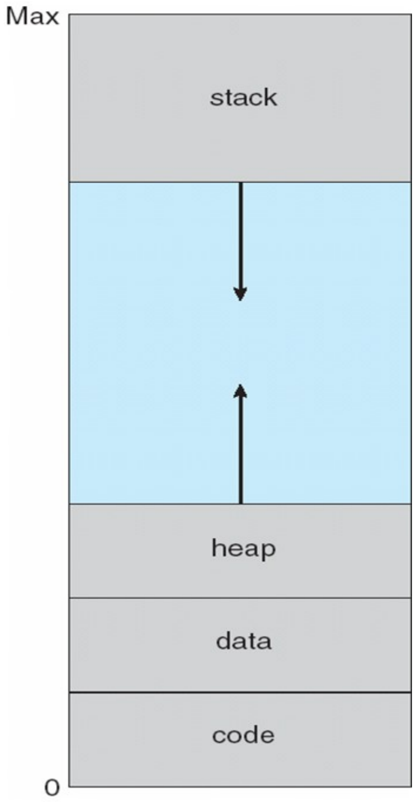
What is virtual memory?

- Virtual memory – separation of user logical memory from physical memory
  - Only part of the program needs to be in memory for execution
  - Logical address space can therefore be much larger than physical address space
  - Allows address spaces to be shared by several processes
  - Allows for more efficient process creation
  - More programs running concurrently
  - Less I/O needed to load or swap processes
- Virtual memory can be implemented via:
  - Demand paging
  - Demand segmentation

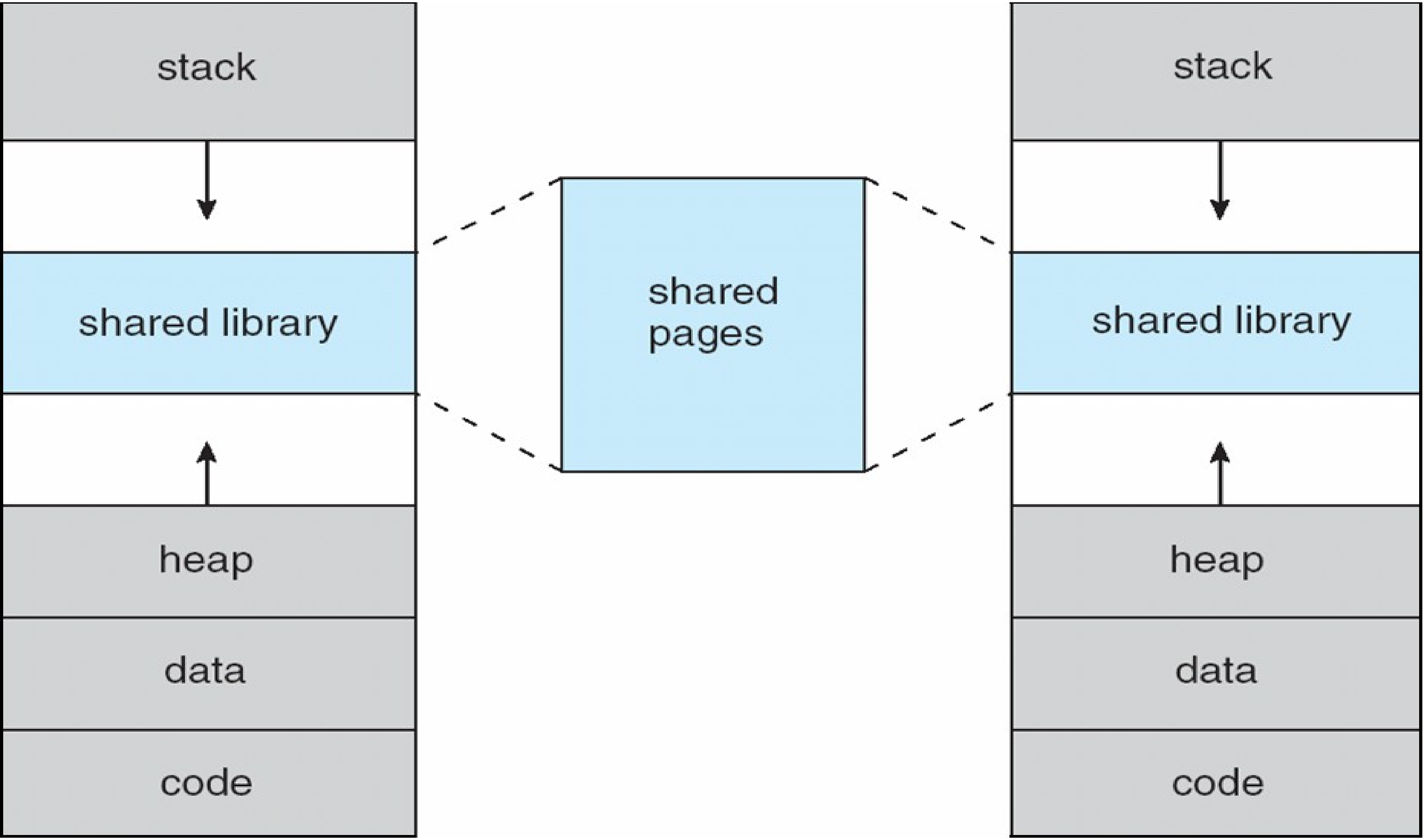


Virtual Memory Larger Than Physical Memory

Virtual Address space



Enables **sparse** address spaces with holes left for growth, dynamically linked libraries, etc



Shared pages
Using Virtual Memory

System libraries shared via mapping into virtual address space

Shared memory by mapping same page-frames into page tables of involved processes

Pages can be shared during `fork()`, speeding process creation (more later)

Demand Paging

Demand Paging

- Load a “page” to memory when it’s neded (on demand)
  - Less I/O needed, no unnecessary I/O
  - Less memory needed
  - Faster response
  - More users
-

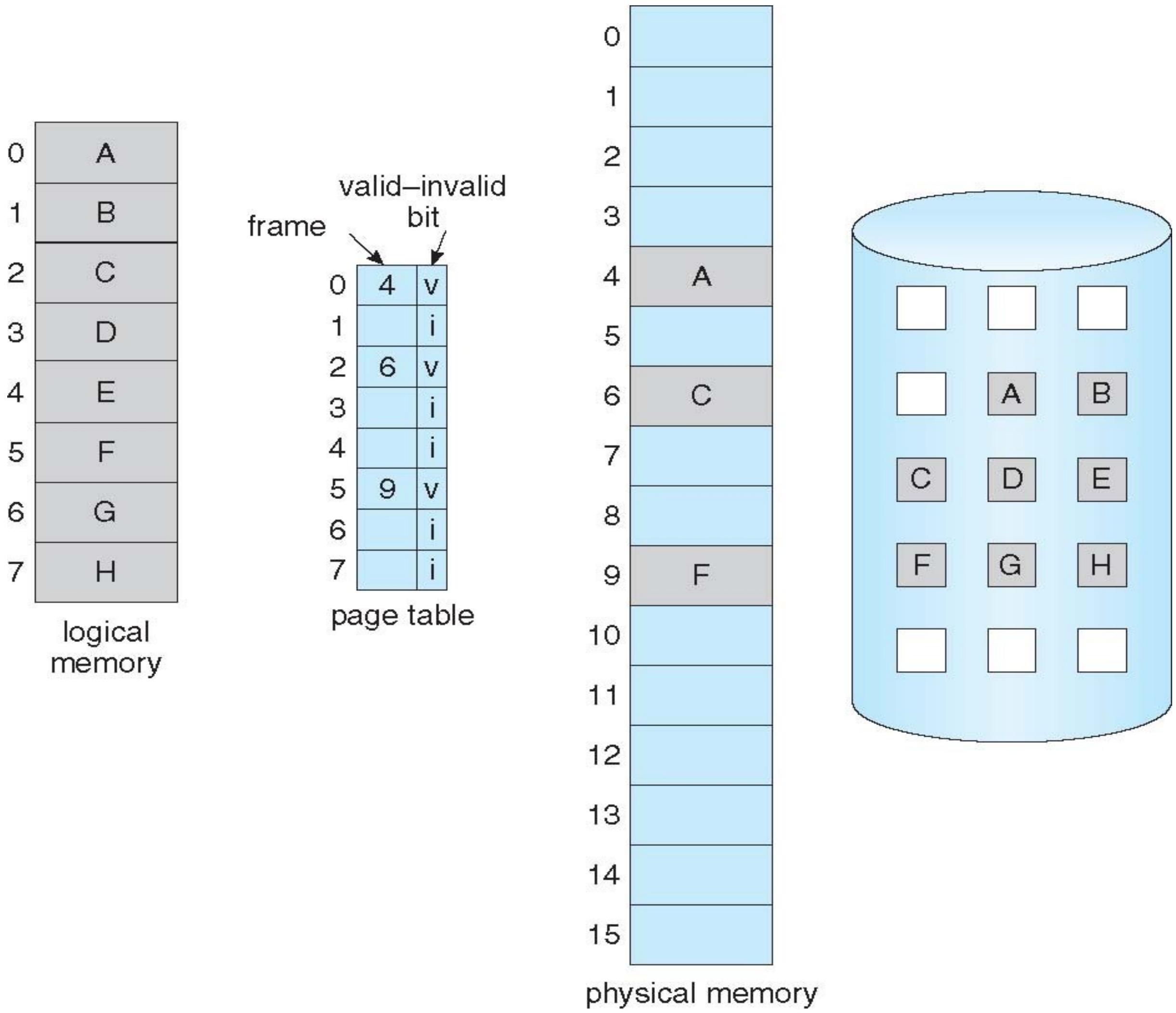
Demand Paging

- Options:
  - Load entire process at load time : achieves little
  - Load some pages at load time: good
  - Load no pages at load time: pure demand paging

New meaning for valid/invalid bits in page table

Frame #	valid-invalid bit
	v
	v
	v
	v
	i
….	
	i
	i

- With each page table entry a valid–invalid bit is associated
  - v: in-memory – memory resident
  - i : not-in-memory or illegal
- During address translation, if valid–invalid bit in page table entry is I : **raises trap called page fault**



Page

Table

With

Some pages

Not

In memory

Page fault

Page fault

- Page fault is a hardware interrupt
- It occurs when the page table entry corresponding to current memory access is “i”
- All actions that a kernel takes on a hardware interrupt are taken!
  - Change of stack to kernel stack
  - Saving the context of process
  - Switching to kernel code

Important (not all) steps on a Page fault

1) Operating system looks at another data structure (table), most likely in PCB itself, to decide:

    If it's Invalid reference -> abort the process (segfault)

    Just not in memory -> Need to get the page in memory

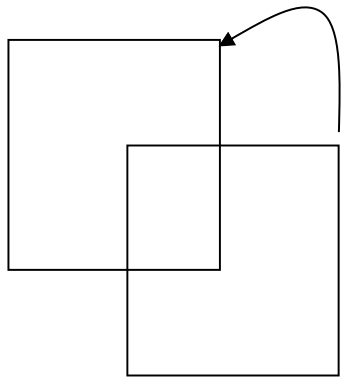
2) Get empty frame (this may be complicated, may need evicting a frame if no free frames available!)
3) Swap page into frame via scheduled disk/IO operation
4) Reset tables to indicate page now in memory.
5) Set validation bit = v
6) Restart the instruction that caused the page fault

Issues with page fault handling

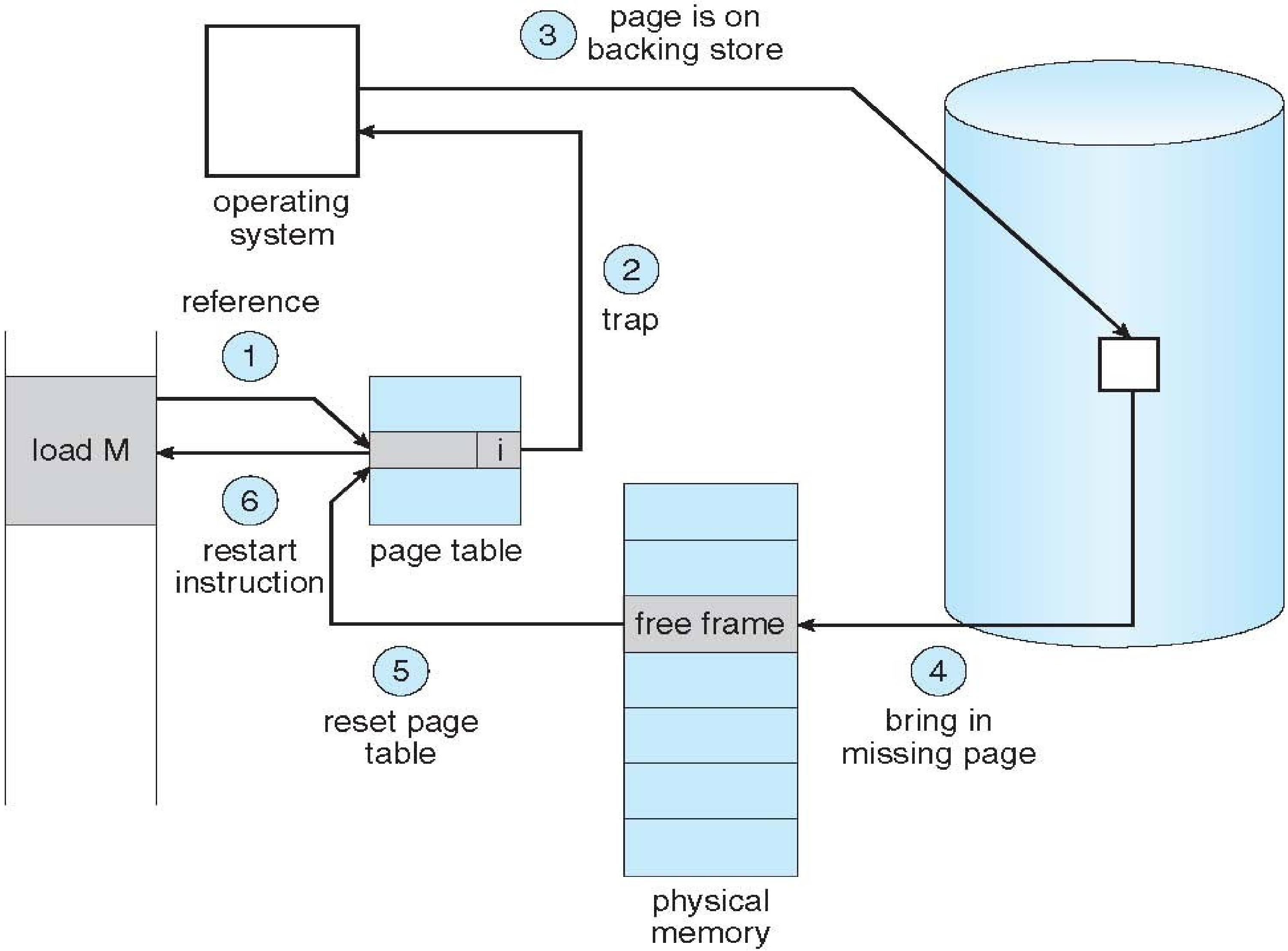
- Extreme case – start process with *no* pages in memory
  - OS sets instruction pointer to first instruction of process, non-memory-resident -> page fault
  - And for every other process pages on first access
  - **Pure demand paging. Less response time ?**
- Actually, a given instruction could access multiple pages -> multiple page faults
  - Pain decreased because of **locality of reference**
- Hardware support needed for demand paging
  - Page table with valid / invalid bit
  - Secondary memory (swap device with **swap space**)
  - Instruction restart

Problem with Instruction restart

- A critical Problem
- Consider an instruction that could access several different locations
  - `movarray 0x100, 0x200, 20`
  - # copy 20 bytes from address 0x100 to address 0x200
  - `movarray 0x100, 0x110, 20`
  - # what to do in this case?



Handling A Page Fault



Page fault handling (detailed)

1) Trap to the operating system
2) Default trap handling():
    - Save the process registers and process state
    - Determine that the interrupt was a page fault. Run page fault handler.
3) Page fault handler(): Check that the page reference was legal and determine the location of the page on the disk. If illegal, terminate process.
4) Find a free frame. Issue a read from the disk to a free frame:
    - Process waits in a queue for disk read. Meanwhile many processes may get scheduled.
    - Disk DMA hardware transfers data to the free frame and raises interrupt in end

Page fault handling (detailed)

6) (as said on last slide) While waiting, allocate the CPU to some other process
7) (as said on last slide) Receive an interrupt from the disk I/O subsystem (I/O completed)
8) Default interrupt handling():
   - Save the registers and process state for the other user
   - Determine that the interrupt was from the disk
9) Disk interrupt handler():
   - Figure out that the interrupt was for our waiting process
   - Make the process runnable
10) Wait for the CPU to be allocated to this process again
    - Kernel restores the page table of the process, marks entry as “v”
    - Restore the user registers, process state, and new page table, and then resume the interrupted instruction

Performance of demand paging

Page Fault Rate 0 <= p <= 1

if p = 0 no page faults

if p = 1, every reference is a fault

Effective (memory) Access Time (EAT)

EAT = (1 – p) * memory access time +

p * (page fault overhead // Kernel code execution time

+ swap page out // time to write an occupied frame to disk

+ swap page in // time to read data from disk into free frame

+ restart overhead) // time to reset process context, restart it

Performance of demand paging

Memory access time = 200 nanoseconds

Average page-fault service time = 8 milliseconds

EAT = (1 – p) x 200 + p (8 milliseconds)

= (1 – p x 200 + p x 8,000,000

= 200 + p x 7,999,800

If one access out of 1,000 causes a page fault, then

EAT = 8.2 microseconds.

This is a slowdown by a factor of 40!!

If want performance degradation < 10 percent

220 > 200 + 7,999,800 x p

20 > 7,999,800 x p

p < .0000025

< one page fault in every 400,000 memory accesses

An optimization: Copy on write

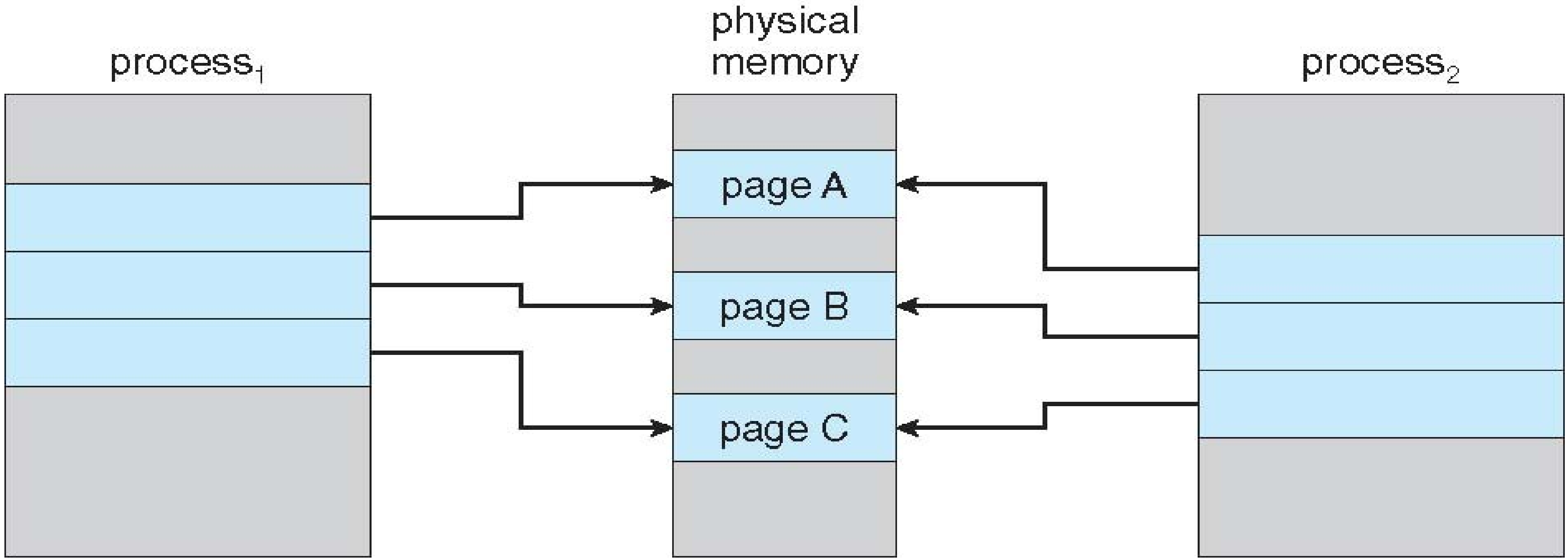
The problem with fork() and exec(). Consider the case of a shell

```
scanf("%s", cmd);
if(strcmp(cmd, "exit") == 0)
    return 0;
pid = fork(); // A->B
if(pid == 0) {
    ret = execl(cmd, cmd, NULL);
    if(ret == -1) {
        perror("execution failed");
        exit(errno);
    }
} else {
    wait(0);
}
```

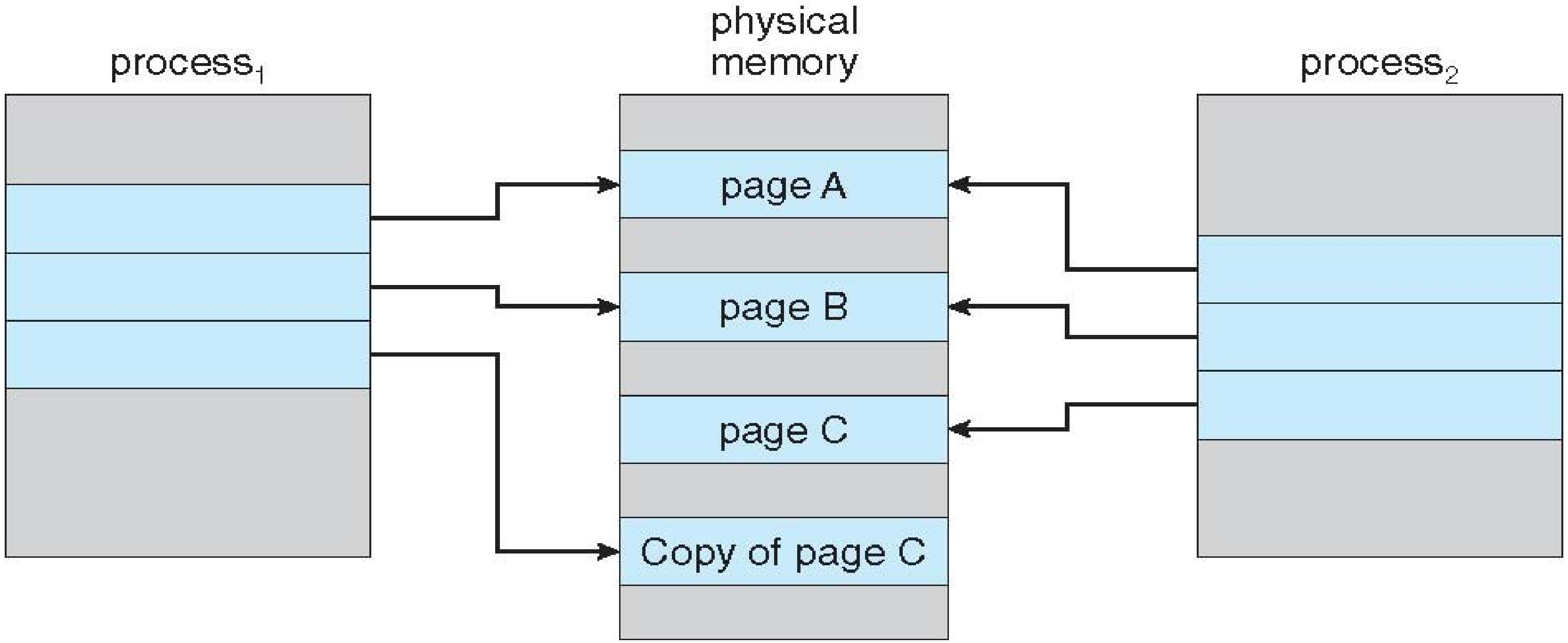
- During fork()
  - Pages of parent were duplicated
  - Equal amount of page frames were allocated
  - Page table for child differed from parent (as it has another set of frames)
- In exec()
  - The page frames of child were taken away and new frames were allocated
  - Child’s page table was rebuilt!
- Waste of time during fork() if the exec() was to be called immediately

An optimization: Copy on write

- Copy-on-Write (COW) allows both parent and child processes to initially share the same pages in memory
  - If either process modifies a shared page, only then is the page copied
- COW allows more efficient process creation as only modified pages are copied
- vfork() variation on fork() system call has parent suspend and child using copy-on-write address space of parent
  - Designed to have child call exec()
  - Very efficient



Before Process 1 Modifies Page C



After Process 1 Modifies Page C

Challenges and improvements in implementation

- Choice of backing store
  - For stack, heap pages: on swap partition
  - For code, shared library? : swap partition or the actual executable file on the file-system?
  - If the choice is file-system for code, then the page-fault handler needs to call functions related to file-system
- Is the page table itself pagable?
  - If no, good
  - If Yes, then there can be page faults in accessing the page tables themselves! More complicated!
- Is the kernel code pagable?
  - If no, good
  - If yes, life is very complicated ! Page fault in running kernel code, interrupt handlers, system calls, etc.