Virtual Memory

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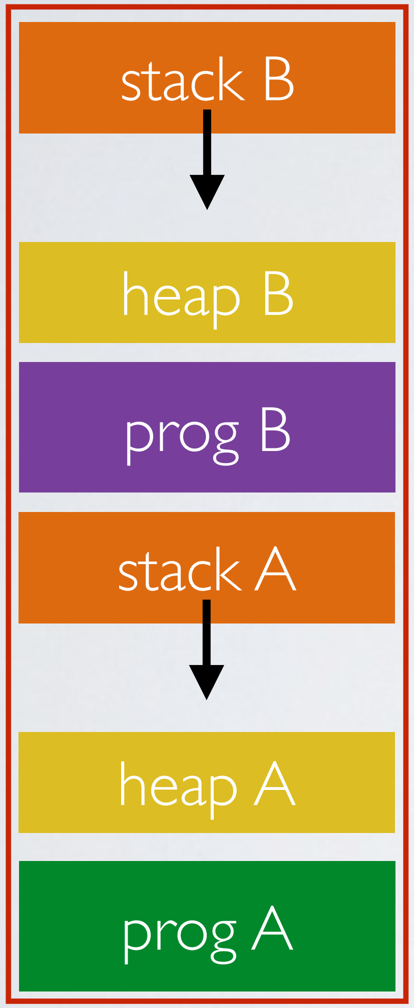
The problem of managing the memory



How to make programs and execution contexts co-exists in memory?

✓ Placing multiple execution contexts (stack and heap) at random locations in memory is not a problem ... ... well, as long as your have enough memory

◉ However having programs placed at random locations is problematic

(recap) Compiling and linking

- **Compiler** takes source code files and translates (binds) symbolic addresses to logical, relocatable addresses within compilation unit (object file)
- **Linker** takes collection of object files and translates addresses to logical, absolute addresses within executable (resolves references to symbols defined in other files/ modules)

Let's look at some C code and its binary

```c
#include <stdio.h>

int foo(){
    printf("hello world!");
}

int main(int argc, char **argv){
    foo();
}
```

Since function addresses and others are hard-encoded in the binary, the program cannot be placed at random locations in memory

```
0804840b <foo>:
 804840b:   55                      push   ebp
 804840c:   89 e5                   mov    ebp,esp
 804840e:   83 ec 08                sub    esp,0x8
 8048411:   83 ec 0c                sub    esp,0xc
 8048414:   68 d0 84 04 08          push   0x80484d0
 8048419:   e8 c2 fe ff ff          call   80482e0 <printf@plt>
 804841e:   83 c4 10                add    esp,0x10
 8048421:   90                      nop
 8048422:   c9                      leave
 8048423:   c3                      ret

08048424 <main>:
 8048424:   8d 4c 24 04             lea    ecx,[esp+0x4]
 8048428:   83 e4 f0                and    esp,0xfffffff0
 804842b:   ff 71 fc                push   DWORD PTR [ecx-0x4]
 804842e:   55                      push   ebp
 804842f:   89 e5                   mov    ebp,esp
 8048431:   51                      push   ecx
 8048432:   83 ec 04                sub    esp,0x4
 8048435:   e8 d1 ff ff ff          call   804840b <foo>
 804843a:   b8 00 00 00 00          mov    eax,0x0
 804843f:   83 c4 04                add    esp,0x4
 8048442:   59                      pop    ecx
 8048443:   5d                      pop    ebp
 8048444:   8d 61 fc                lea    esp,[ecx-0x4]
 8048447:   c3                      ret
 8048448:   66 90                   xchg   ax,ax
 804844a:   66 90                   xchg   ax,ax
 804844c:   66 90                   xchg   ax,ax
 804844e:   66 90                   xchg   ax,ax
```

Naive Idea : load time linking

How about doing the linking when process executed, not at compile time

- ➡ Determine where process will reside in memory and adjust all references within program

- How to relocate the program in memory during execution? (consider functions but also data pointers now)
- What if no contiguous free region fits program?
- How to avoid programs interfering with each others?

Issues in sharing physical memory

Transparency

- A process shouldn't require particular physical memory bits
- A process often require large amounts of contiguous memory (for stack, large data structures, etc.)

Resource exhaustion

- Programmers typically assume machine has "enough" memory
- Sum of sizes of all processes often greater than physical memory

Protection

- How to prevent A from even observing B's memory
- How to prevent process A from corrupting B's memory (whether it is intentional or not)

Virtual Memory Goals

- Provide a convenient abstraction for programming by giving each program its own virtual address space
- Allow programs to see more memory than exists
- Allocate scarce memory resources among competing processes to maximize performance with minimal overhead
- Enforce protection by preventing one process from messing with another's memory

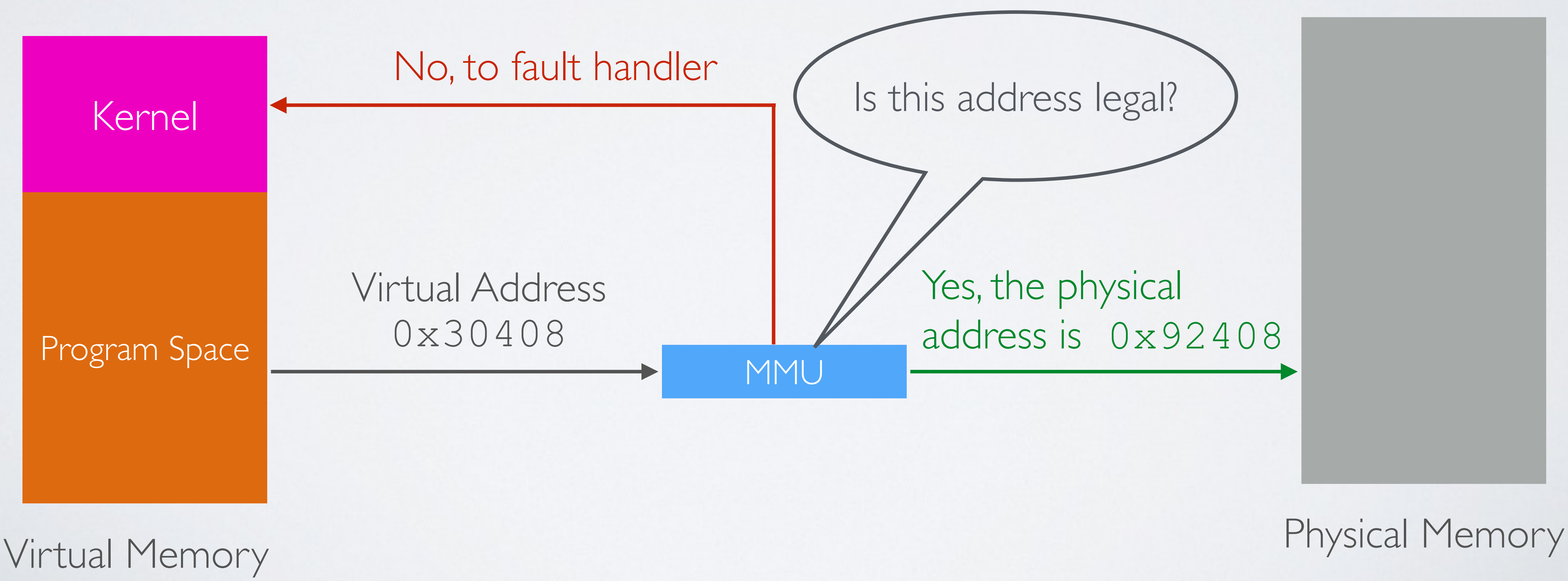
Definitions

- Programs load/store to **virtual addresses**
- Actual memory uses **physical addresses**
- Virtual memory hardware is the **MMU (Memory Management Unit)**
  - Usually part of CPU and configured through privileged instructions (e.g., `load bound reg`)
  - Translates from virtual to physical addresses
  - Gives per-process view of memory called **address space**

Virtual Memory in a nutshell

The application does not see physical memory addresses

➡ **Memory-Management Unit** (MMU) relocates each load/store at runtime



Virtual Memory Advantages

✓ Can re-locate process while running either in memory or to disk (a.k.a swap)

Techniques for implementing virtual memory

- Basic address translation
- Segmentation (the old way)
- **Paging (the new way)**

Basic Address Translation

Base & Bound registers

Two special privileged registers : `base` and `bound`

On each load/store/jump

- **Physical address = virtual address +** `base`
- Check **$0 \le$ virtual address <** `bound`, else trap to kernel

✓ OS can change these registers to move the process in memory

✓ OS must re-load base these register on context switch

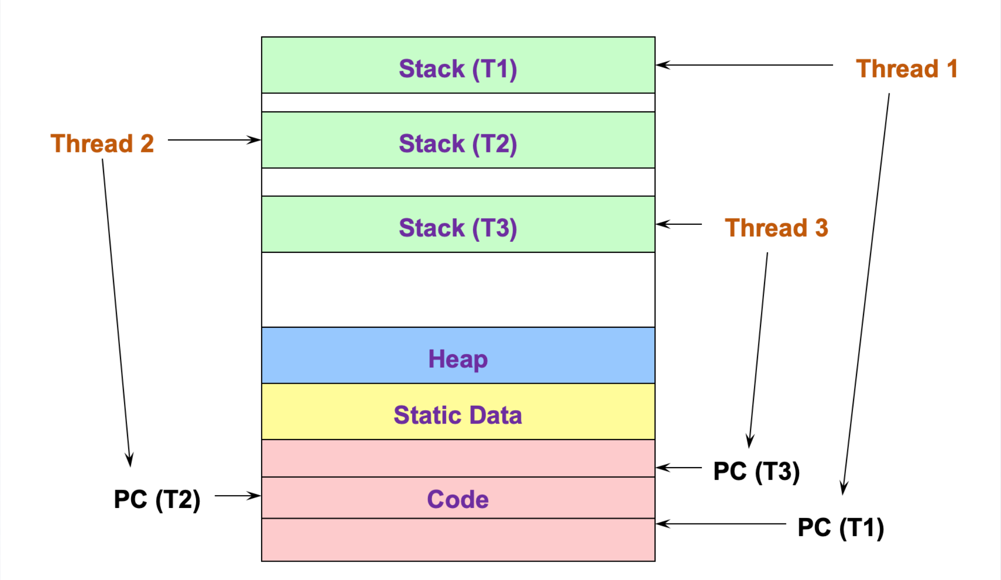
Base + Bound Trade-offs

Advantages

✓ Cheap in terms of hardware : only two registers

✓ Cheap in terms of cycles : do add and compare in parallel

Disadvantages



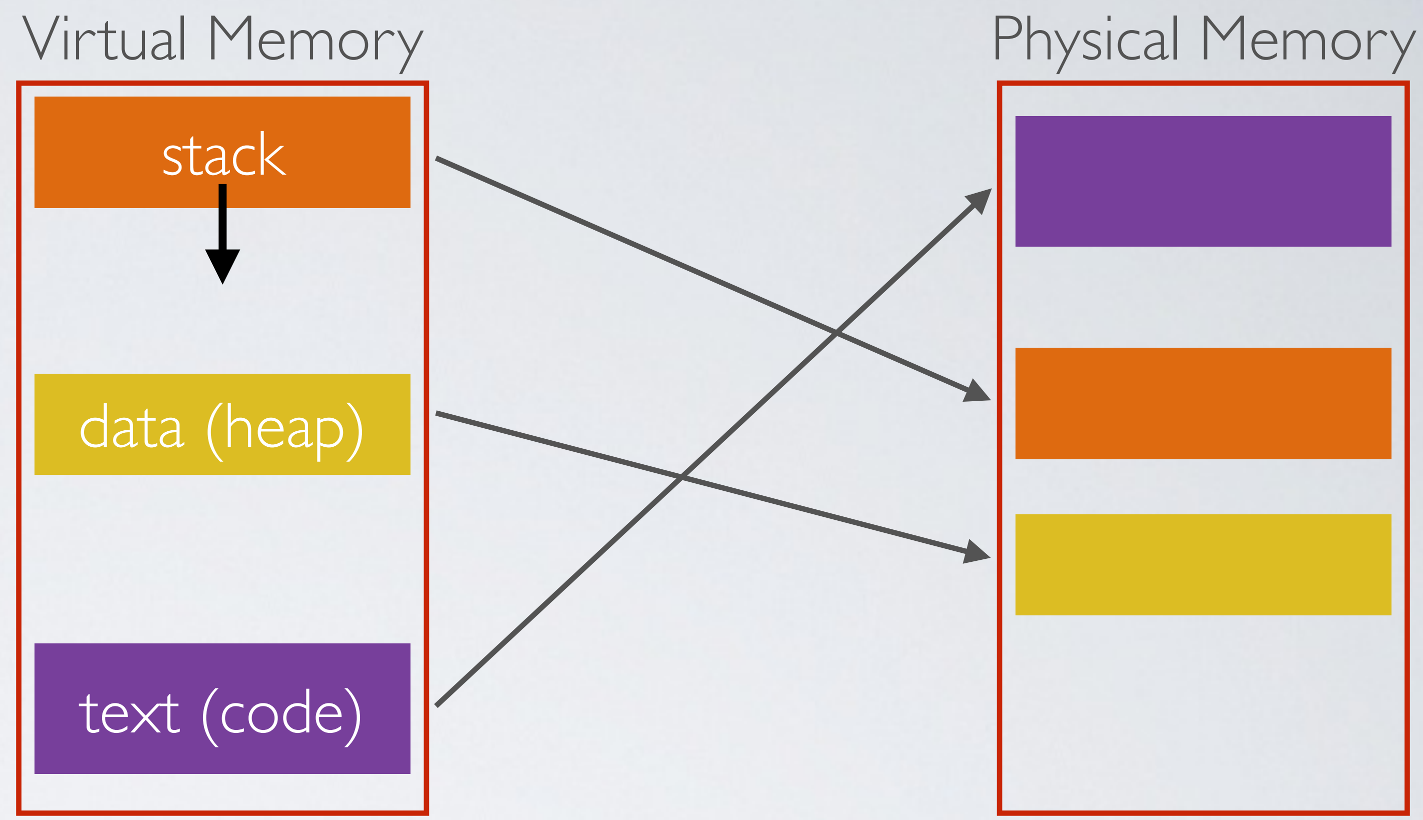
◉ Growing a process is expensive

◉ No way to share code or data

➡ **Solution :** segmentation i.e separate code, stack and data segments

Segmentation

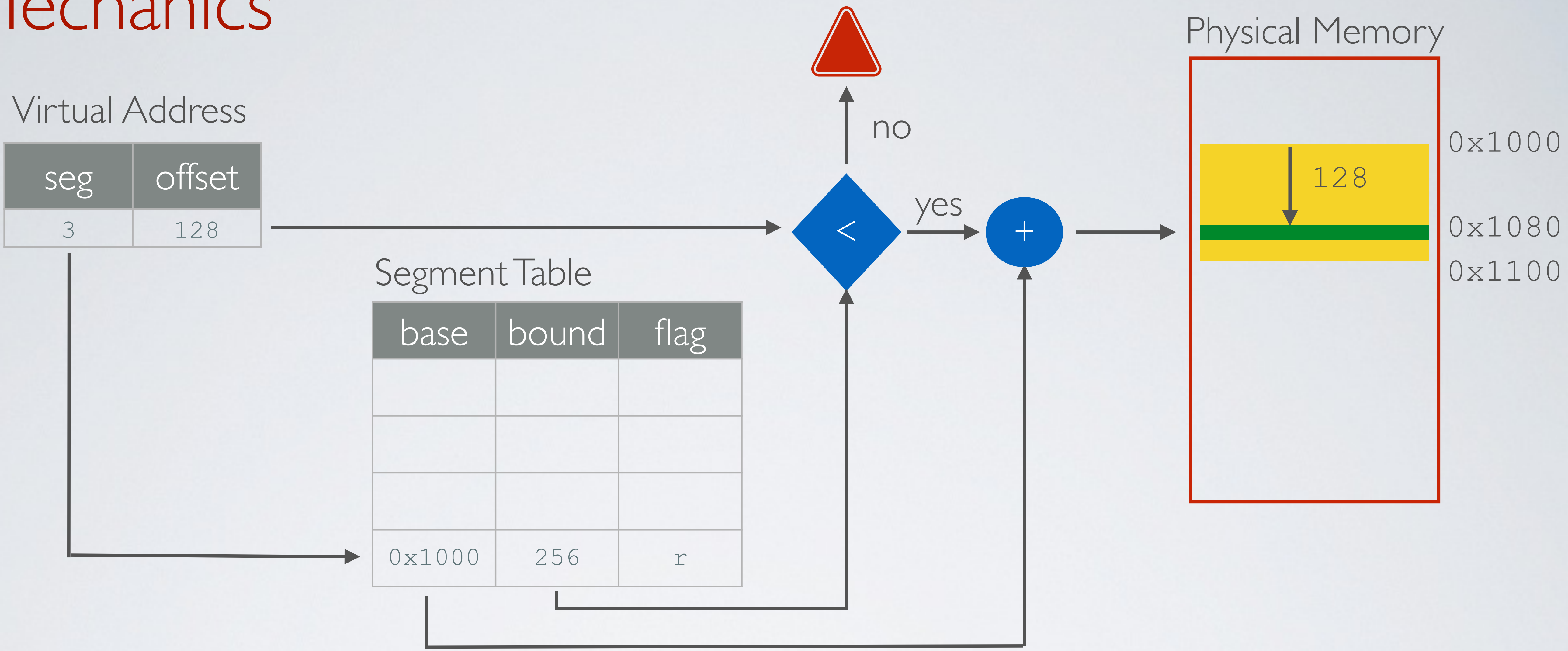
Idea



Each process has a collection of multiple base/bound registers

- ➡ Address space is built from many segments (a.k.a segmentation table)
- ✓ Can share/protect memory at segment granularity

Mechanics

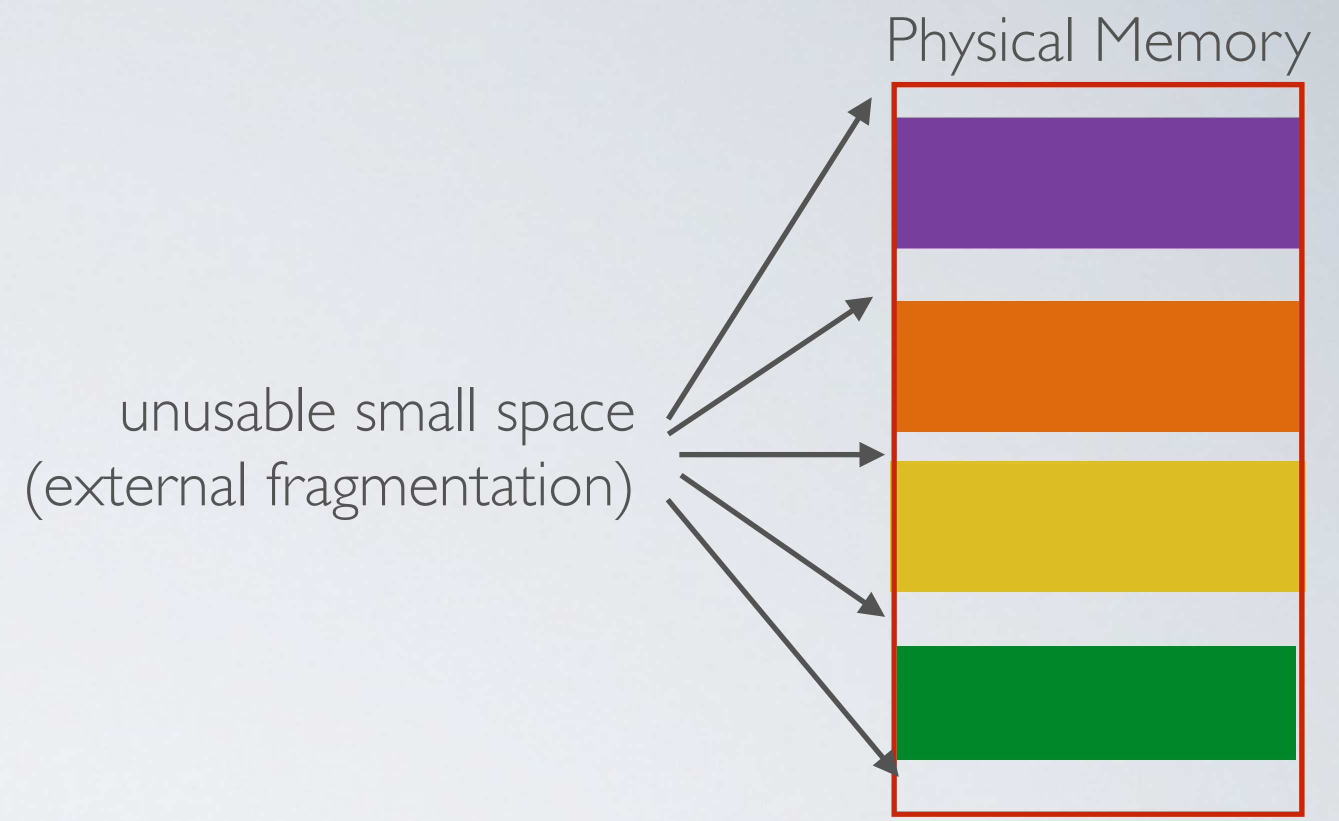


Each virtual address indicates

- a segment index in the table (top bits)
- and an offset (low bits)

➡ x86 stores segment #s in registers (CS, DS, SS, ES, FS, GS)

Segmentation Trade-offs



Advantages

- ✓ Multiple segments per process (sparse memory)
- ✓ Can easily share memory
- ✓ Do not need entire process in memory (swap)

Disadvantages

- Requires translation, which could limit performance
- Makes external **fragmentation** a real problem

Fragmentation

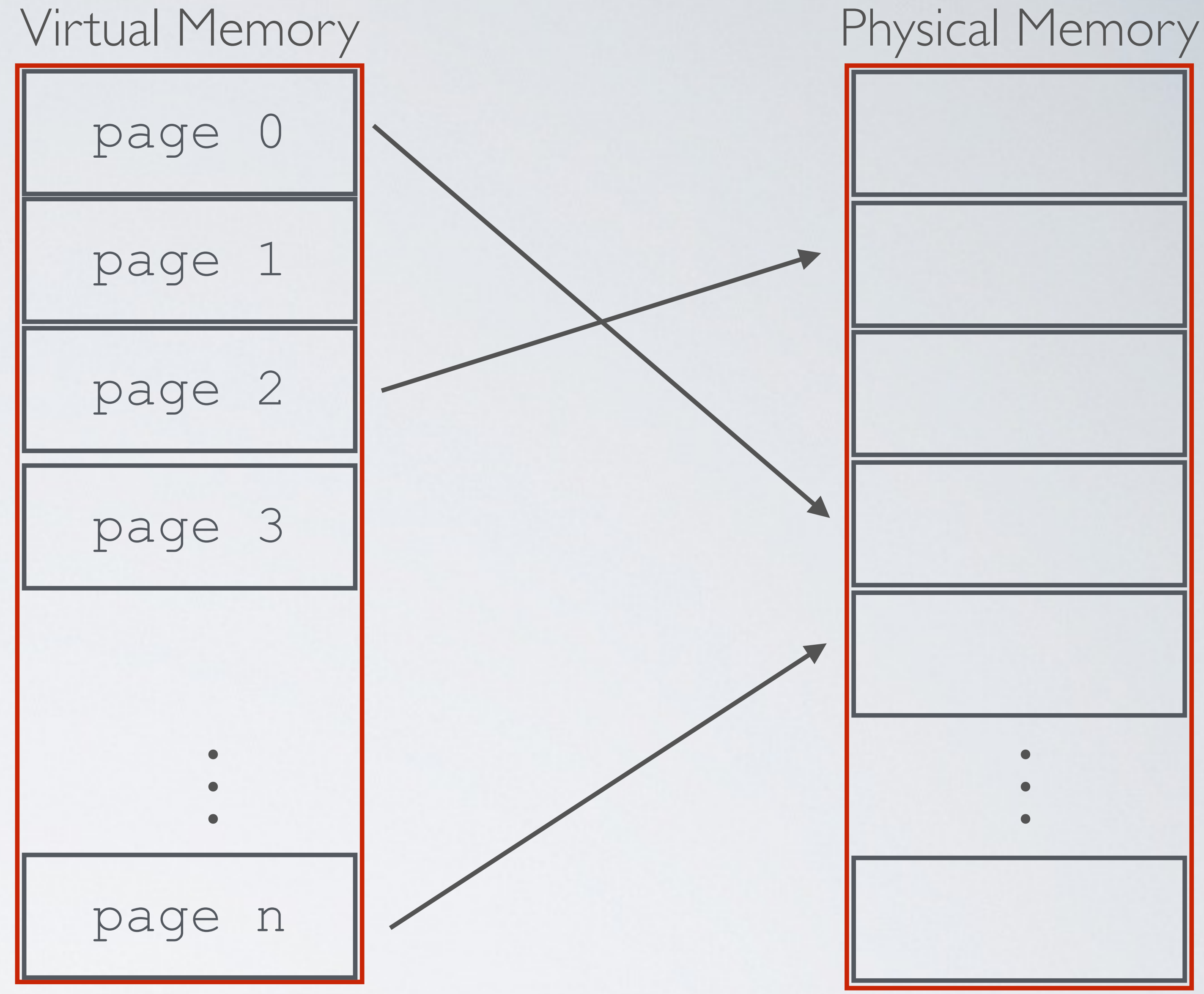
Fragmentation is the inability to use free memory

➡ Over time

- **External fragmentation**
  because of variables sized pieces (i.e many small holes)
- **Internal fragmentation**
  because of fixed size pieces (i.e no external hole but internal waste of space)

Paging
(Introduction)

Idea

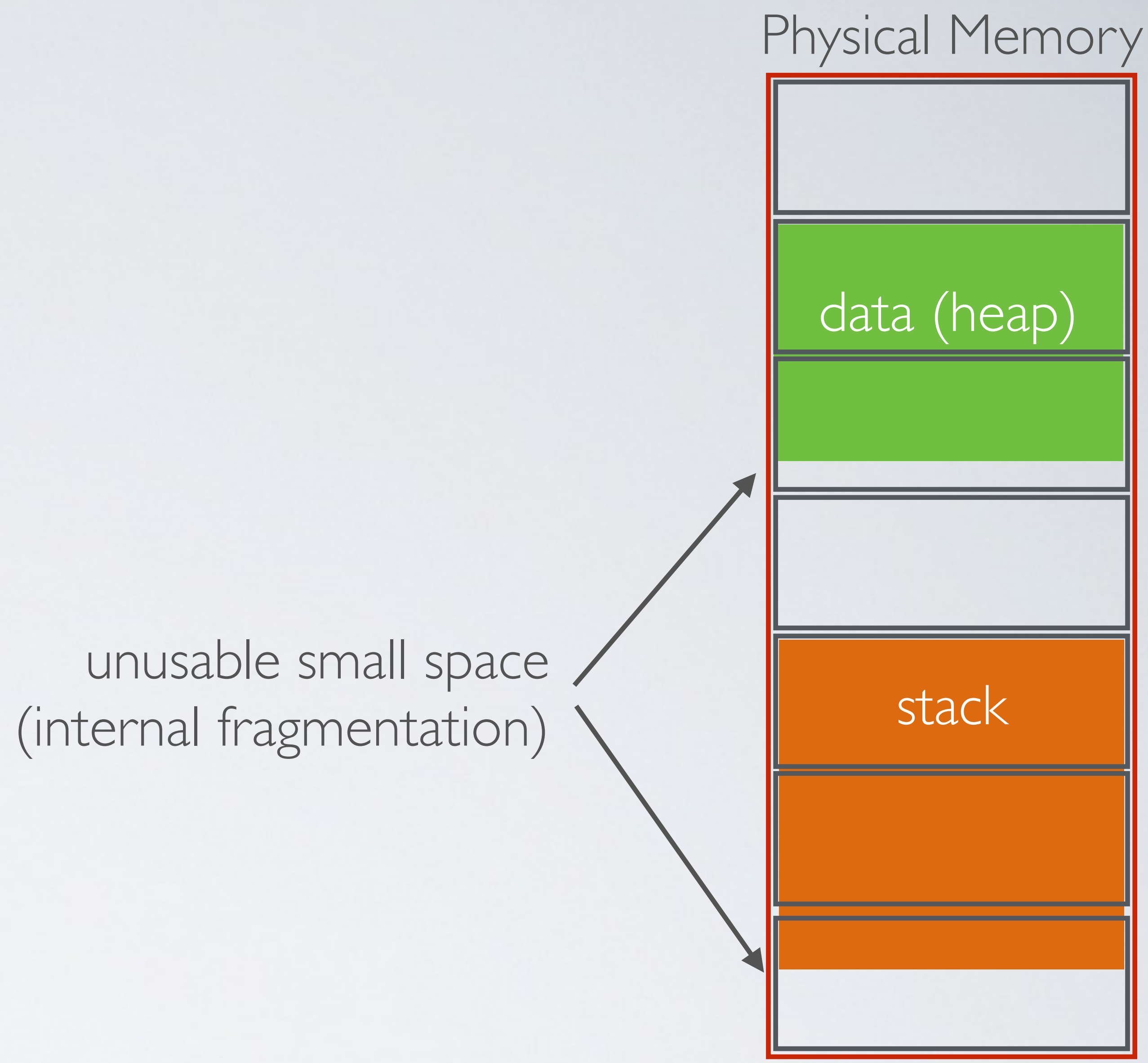


➡ Divide memory up into fixed-size pages to eliminate external fragmentation

Each process has a collection of maps from virtual pages to physical pages

✓ Can share/protect memory at page granularity

Paging Trade-offs



- ✓ Eliminates external fragmentation
- ✓ Simplifies allocation, free, and backing storage (swap)
- ◉ Average internal fragmentation of .5 pages per "segment"

Paging Data Structures

Pages are fixed size (e.g. 4K) so a virtual address has two parts:

- **virtual page number** : most significant bits
- and the **page offset** : least significant 12 bits ($\log_2 4k$)

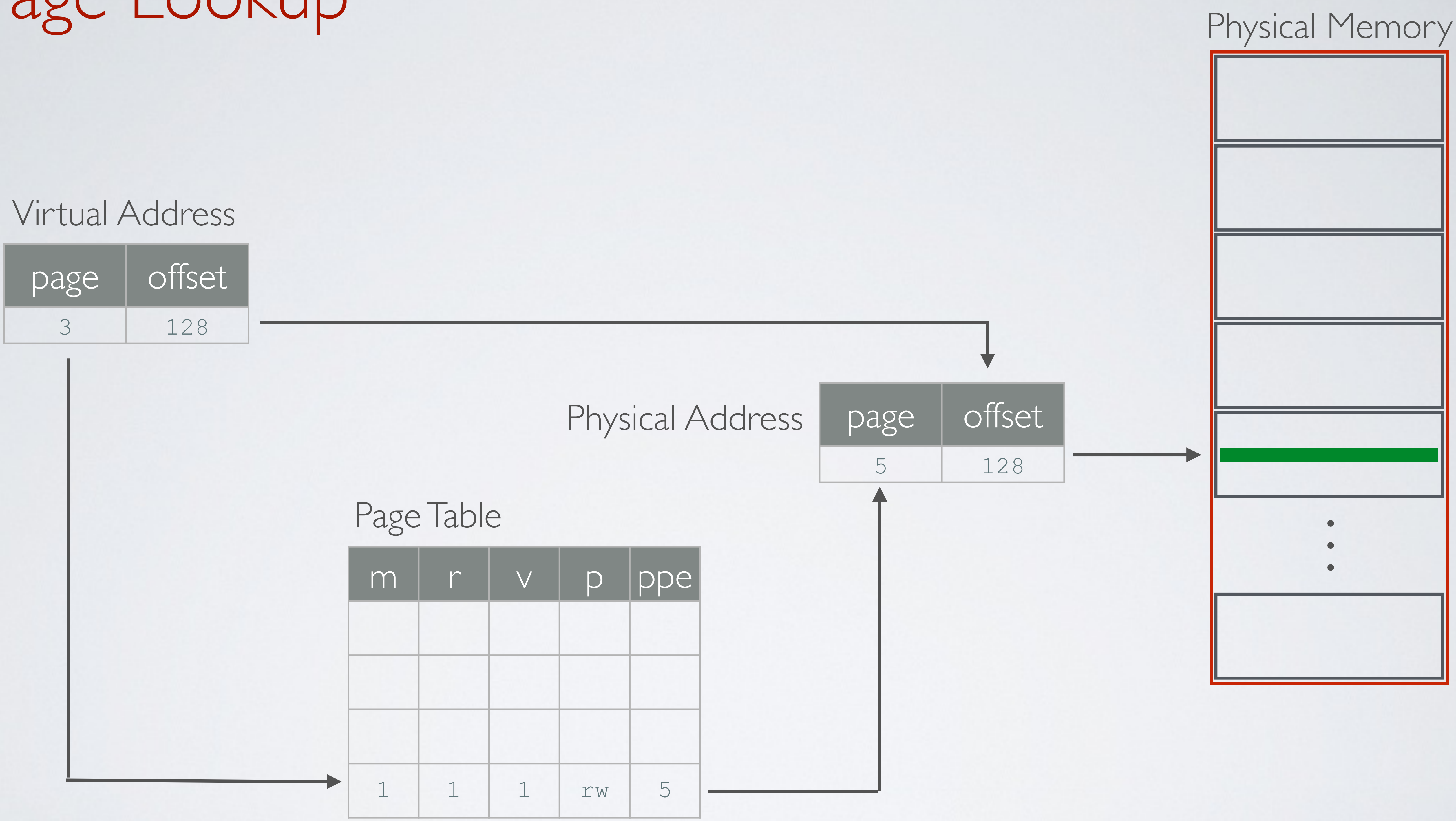
The page table is a collection of **page table entry (PTE)** that maps

- a **virtual page number (VPN)**
  i.e the index in the page table
- to **physical page numbers (PPN)** a.k.a frame number
- and includes bits for protection, validity, etc ...

Page Table Entries (PTEs)

- The **Modify bit** says whether or not the page has been written (set when the write to a page occurs)
- The **Reference bit** says whether the page has been accessed (set when a read or write to a page occurs)
- The **Valid bit** says whether or not the PTE can be used (checked each time the virtual address is used)
- The **Protection bits** say what operations (read, write, execute) are allowed on page
- The **Physical page number (PPN)** determines the physical page

Page Lookup


Virtual Address
page
offset
3
128
Physical Address
page
offset
5
128
Page Table
m
r
v
p
ppe
1
1
1
rw
5
Physical Memory

Paging Advantages

- ✓ Easy to allocate memory
  - Memory comes from a free list of fixed size chunks
  - Allocating a page is just removing it from the list
  - External fragmentation not a problem
- ✓ Easy to swap out chunks of a program
  - All chunks are the same size
  - Use valid bit to detect references to swapped pages
  - Pages are a convenient multiple of the disk block size

Paging Limitations

- Can still have internal fragmentation
- Requires 2 or more references, which could limit performance

➡ **Solution**: use a hardware cache of lookups (coming next)

- The amount of memory to store the page table is significant
  - Need one PTE per page, with 32 bit address space w/ 4KB pages = 2^20 PTEs
  - 4 bytes/PTE = 4MB/page table
  - 25 processes = 100MB just for page tables!

➡ **Solution** : page the page tables (coming next)

x86 Paging and Segmentation

x86 architecture supports both paging and segmentation

- Segment register base + pointer val = linear address
- Page translation happens on linear addresses

- Two levels of protection and translation check
  - Segmentation model has four privilege levels (CPL 0–3)
  - Paging only two, so 0–2 = kernel, 3 = user

Acknowledgments

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