Introduction to virtual memory
Segmentation

M1 MOSIG – Operating System Design

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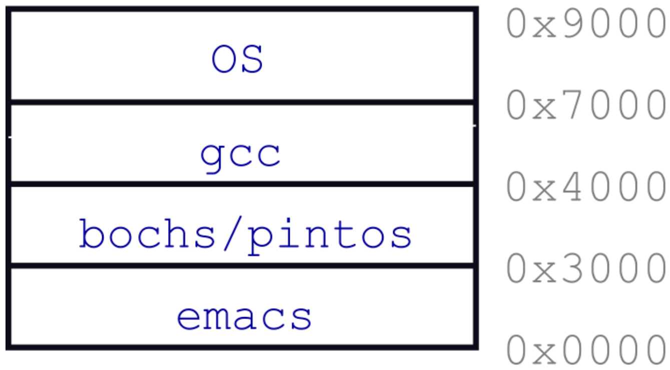
  - David Mazières (Stanford)
    - (most slides/figures directly adapted from those of the CS140 class)
  - Randall Bryant, David O'Hallaron, Gregory Kesden, Markus Püschel (Carnegie Mellon University)
    - Textbook: Computer Systems: A Programmer's Perspective (2nd Edition)
    - CS 15-213/18-243 classes (some slides/figures directly adapted from these classes)
  - Remzi and Andrea Arpaci-Dusseau (U. Wisconsin)
  - Textbooks (Silberschatz et al., Tanenbaum)

Outline

- **The need for virtual memory**

- How to implement virtual memory?
  - 1st attempt: Load-time linking
  - 2nd attempt: Registers and MMU
  - 3rd attempt: Segmentation

Motivating example
Processes coexisting in memory



- Consider multiprogramming in physical memory
  - What happens if one application needs to expand?
  - What happens if one application needs more memory than what is on the machine?
  - What happens if pintos is buggy and writes to 0x7100?
  - When does gcc have to know that it will run at 0x4000?
  - What if emacs is not using its whole memory range?

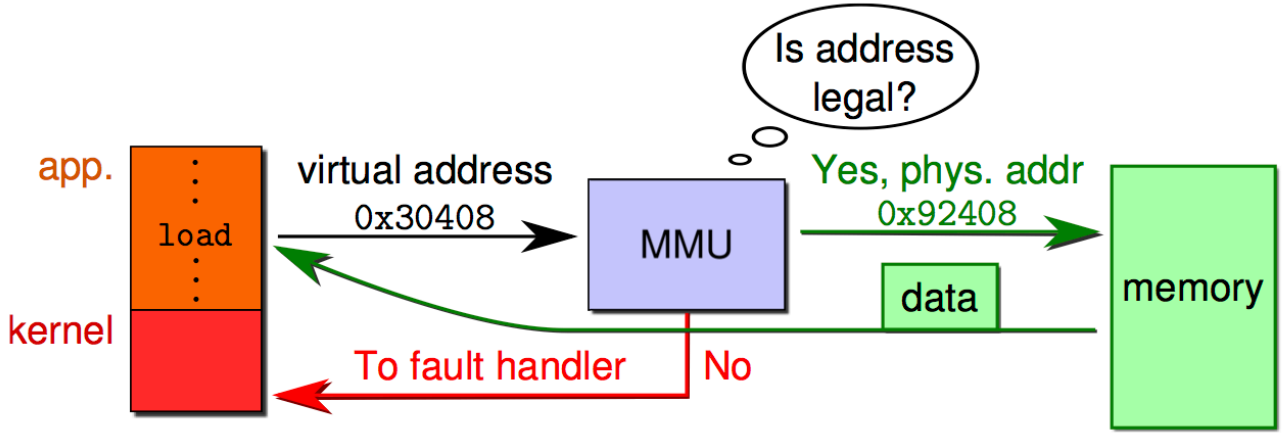
Issues in sharing physical memory

- **Protection**
  - A bug in one process can corrupt memory in another
  - How to prevent process A from trashing B’s memory?
  - How to prevent A from observing B’s memory?

- **Transparency**
  - A process should not require particular/fixed memory locations
  - Processes often require large amount of contiguous memory (for stack, large data structures, etc.)

- **Resource exhaustion**
  - Programmers typically assume that a machine has “enough” memory
  - The sum of sizes of all processes is often greater than physical memory

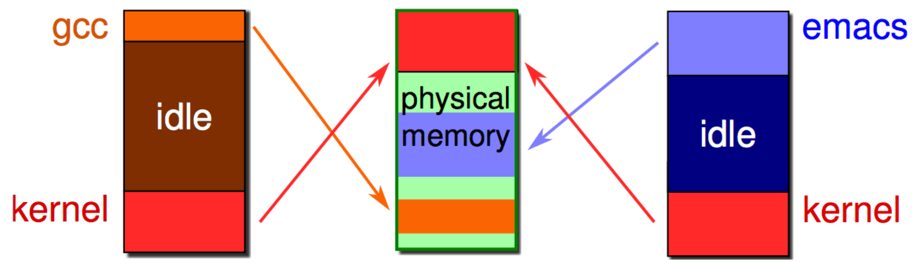
Introducing virtual memory
Goals



- **Give each program its own "virtual" address space**
  - At run time, redirect each load/store instruction to its actual memory
  - ... So that the application does not care what physical memory it is using
- **Enforce protection**
  - Prevent one application from messing with another's memory
- **Allow programs to see more memory than exists**
  - Somehow relocate some memory accesses to disk

Introducing virtual memory
Advantages

- Can re-locate program (code/data) while running
  - Run partially in memory, partially on disk
- In many cases, most of the memory of a process is idle (80/20 rule)

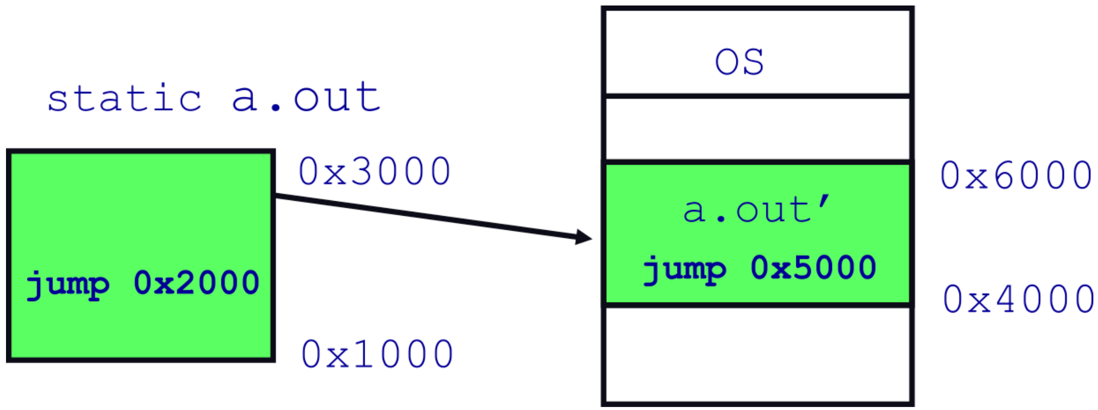


  - Write idle part to disk until needed
  - Let other processes use memory for idle part
  - Analogy with CPU virtualization:
    - When process not using CPU, switch
    - When not using a physical page, switch it to another process
  - Challenge: the virtual memory subsystem is an extra layer
    - Could cause slowdown

Introducing virtual memory
How to implement it it?

We will consider several approaches.

Idea 1: Load-time linking



- Link as usual, but keep the list of memory references
- Fix up a process when it starts
  - Determine where process will reside in memory
  - Adjust all references within program (using addition)
- Problems
  - How to enforce protection?
  - How to move data during execution (after startup)?
  - What if no contiguous free region fits program?

Idea 2: base + bound registers

- Introduce two special privileged (hardware) registers: base and bound

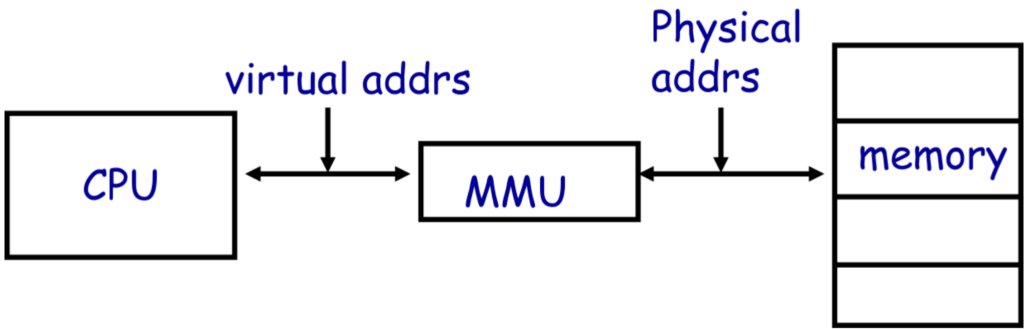
- On each load/store:
  - Compute phys. addr. = virt. addr. + base
  - Check $0 \le$ virt. addr. $<$ bound, else trap to kernel

- How to move a process in memory?
  - Change base register

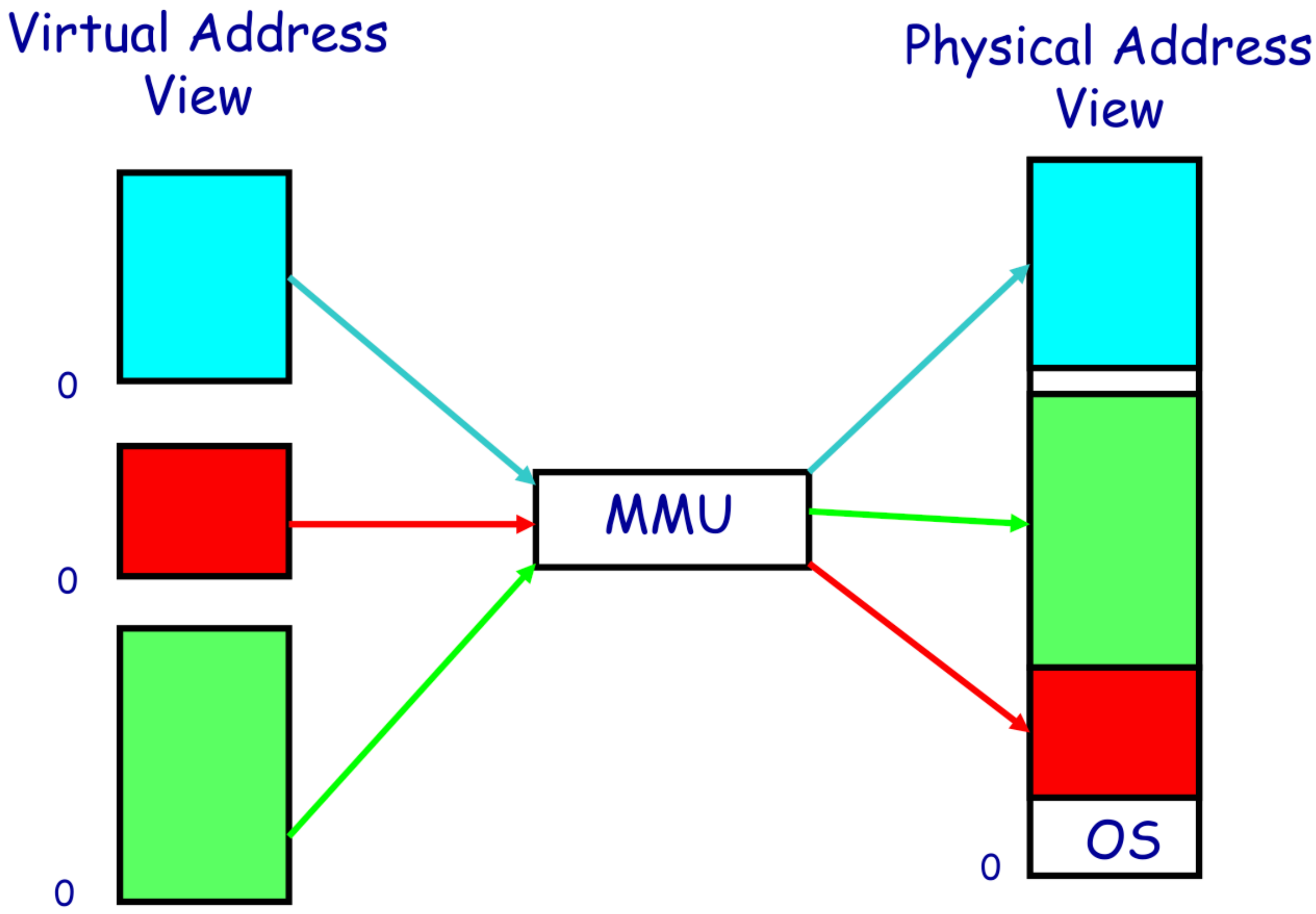
- What happens on context switch?
  - OS must reload/modify base and bound registers

Virtual memory
Definitions

- Programs manipulate virtual (a.k.a. "logical") addresses
- The actual memory uses physical (a.k.a. "real") addresses
- Hardware uses a special component: **Memory Management Unit (MMU)**
  - Usually part of the CPU
  - Accessed with privileged instructions
  - Translates from virtual to physical addresses
  - Provides a per-process view of the memory, called address space

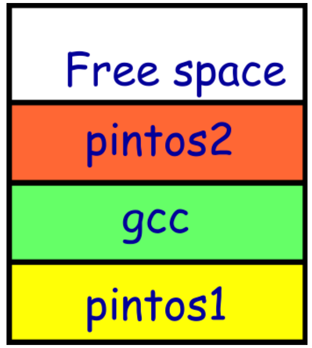


Address space



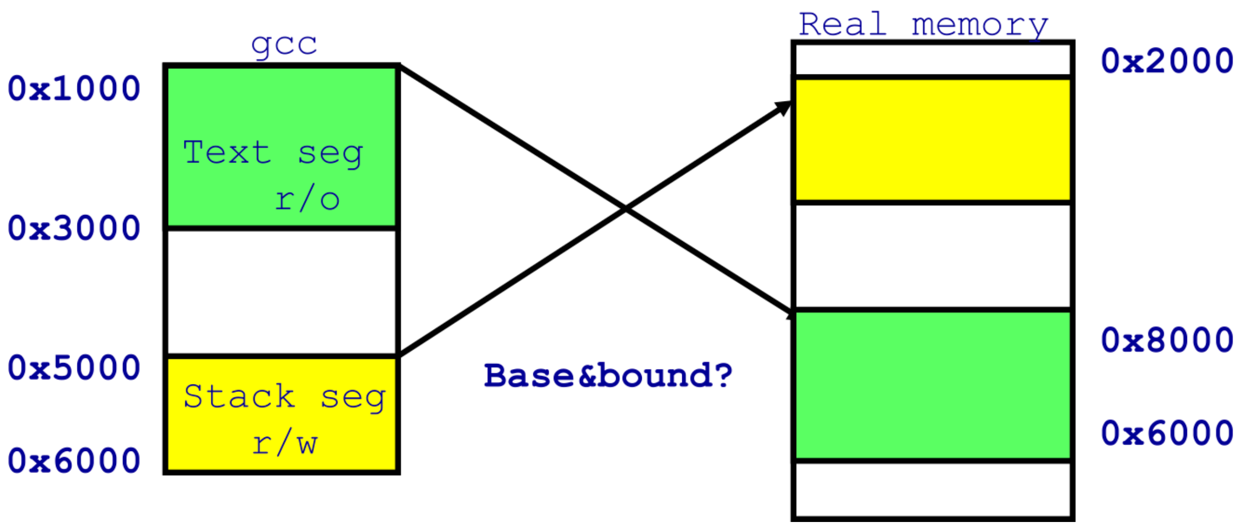
Base+bound trade-offs

- Advantages
  - Cheap to implement in hardware
  - Cheap in terms of cycles: do add and compare in parallel
- Disadvantages
  - Growing the memory of a process is expensive or impossible
  - No way to share code or data
    - (e.g., multiple copies of the same application and/or multiple applications accessing the same file)



- One solution: Multiple segments
  - E.g., separate code, stack and data segments
  - Possibly multiple data segments per process

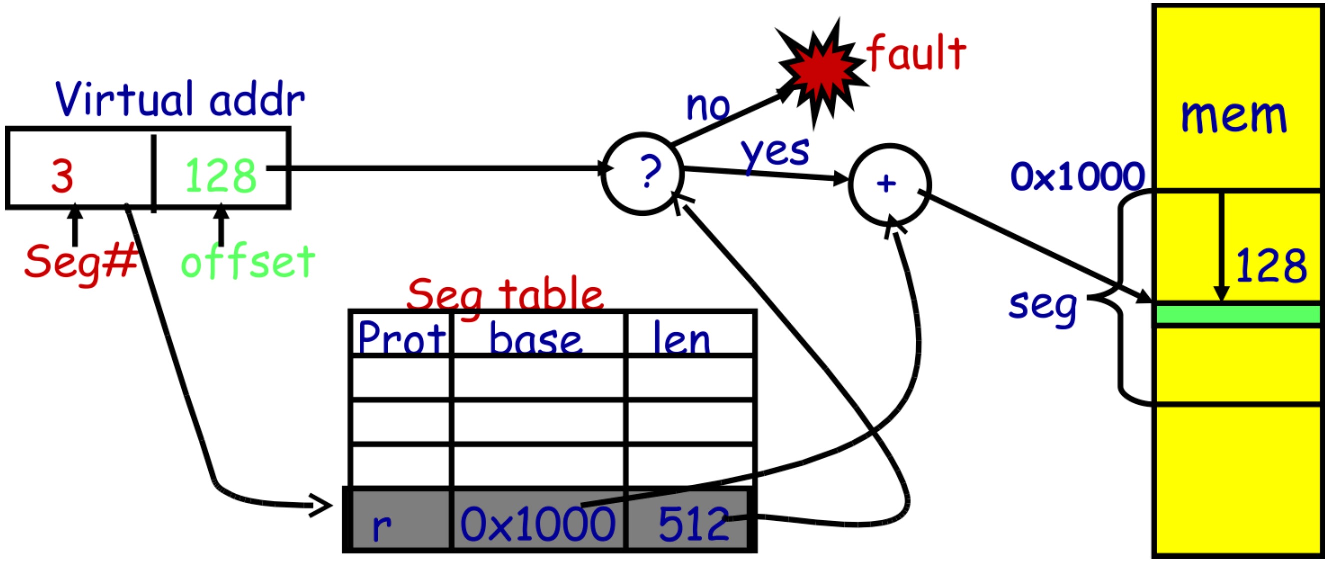
Segmentation



- Let processes have many base/bound registers
  - Address space built from many segments
  - Can share/protect memory on segment granularity

- Segment must be specified as part of virtual address

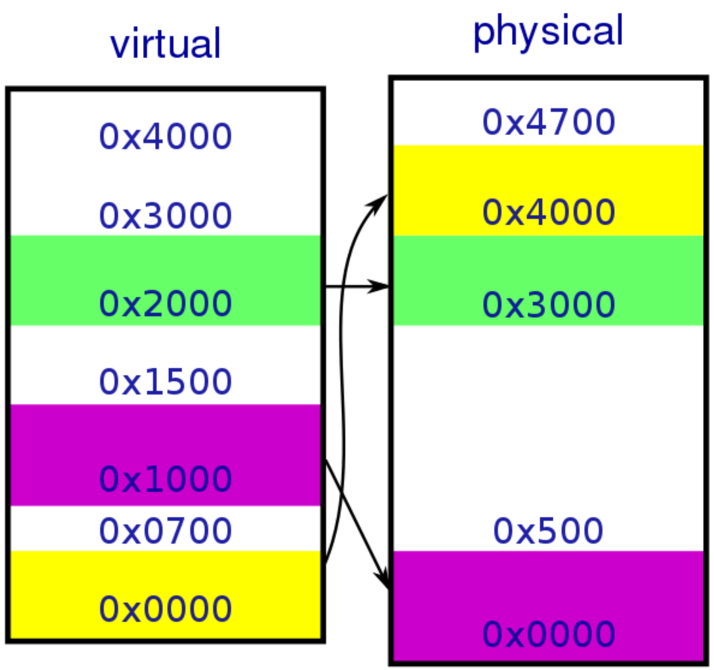
Segmentation mechanics



- Each process has a segment table
- Each virt. addr. (VA) indicates a segment and an offset
  - Top bits of addr. select segment, low bits select offset
  - Or segment selected implicitly by instruction or operand
    - This means you need wider pointers ("far pointers") to specify segment

Segmentation example

Seg	base	bounds	rw
0	0x4000	0x6ff	10
1	0x0000	0x4ff	11
2	0x3000	0xfff	11
3			00



- 2-bit segment number (1st digit), 12-bit offset (last 3 digits)
  - Where is 0x0240? 0x1108? 0x265c? 0x3002? 0x1600?

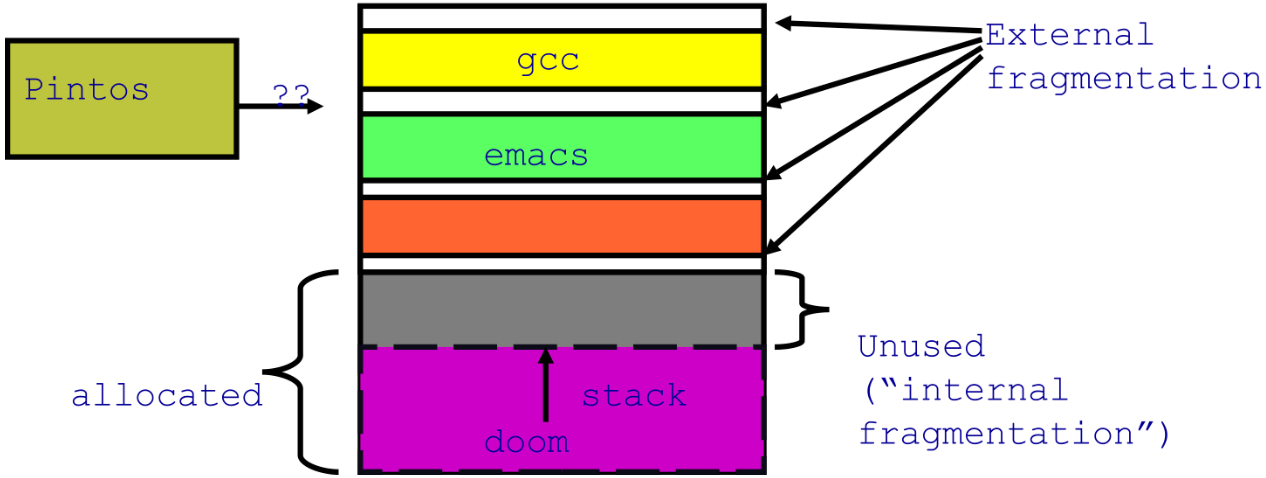
Segmentation trade-offs

- Advantages
  - Multiple segments per process
  - Allows sharing (how?)
  - Does not need to store entire process in memory at any moment

- Disadvantages
  - Requires translation hardware, which could limit performance
  - N-byte segment needs N contiguous bytes of physical memory
  - Makes *fragmentation* a real problem

Fragmentation

- Fragmentation: inability to use free memory
- Over time :
  – Variable-sized pieces: many small holes (***external fragmentation***)
  – Fixed-size pieces: no external holes, but force internal waste (***internal fragmentation***)



- In the next lecture, we will study a better solution for the virtual memory implementation problem, which does not suffer from fragmentation