CSL373: Operating Systems
Virtual Memory

Lecture overview

- Virtual memory

  Maps virtual addresses to physical pages & disk blocks.

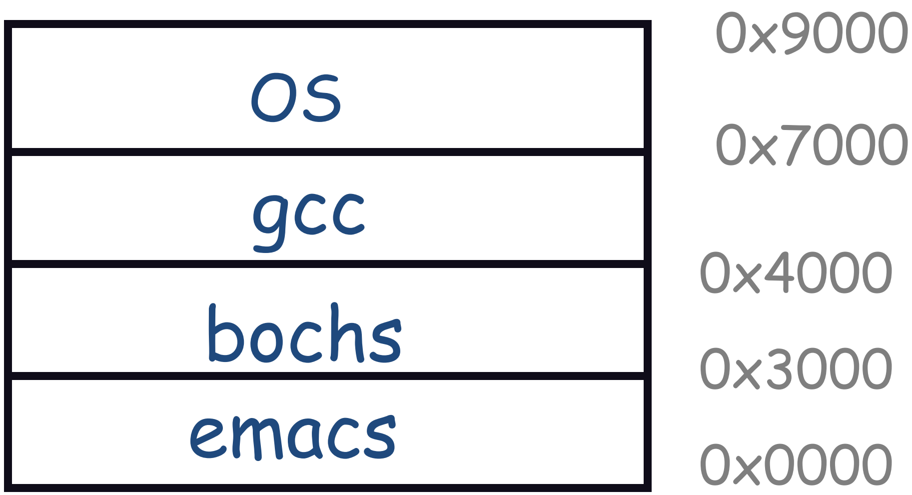
  Like processes, a well-proven OS abstraction: ~40 years old

  Today: what it's good for, how to build one

- Readings: Silberschatz Chapter 8

Problem: we want processes to co-exist

- Consider a primitive system running three processes in physical memory:

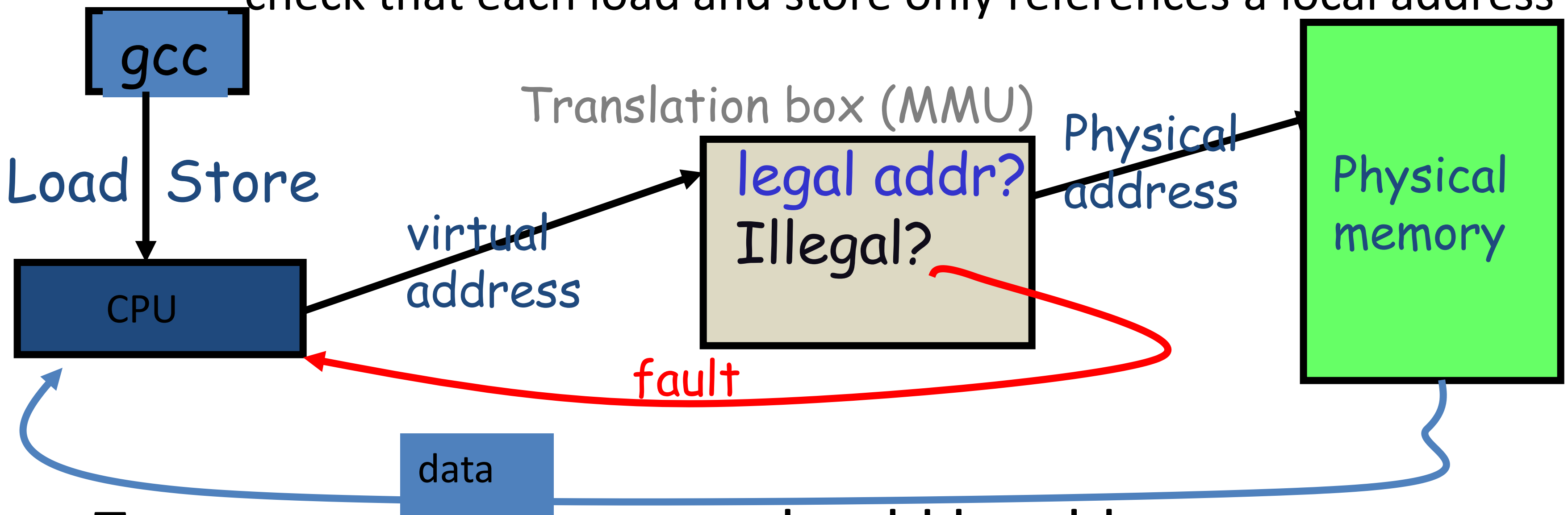


  - What happens if bochs wants to expand?
  - If emacs needs more memory than is on the machine??
  - If bochs has an error and writes to address 0x7100?
  - When does gcc have to know it will run at 0x4000?
  - What if emacs isn't using its memory?

Issues in sharing physical memory

- Protection: errors in one process should only affect it

  all systems conceptually: record process's legal address range(s), check that each load and store only references a local address

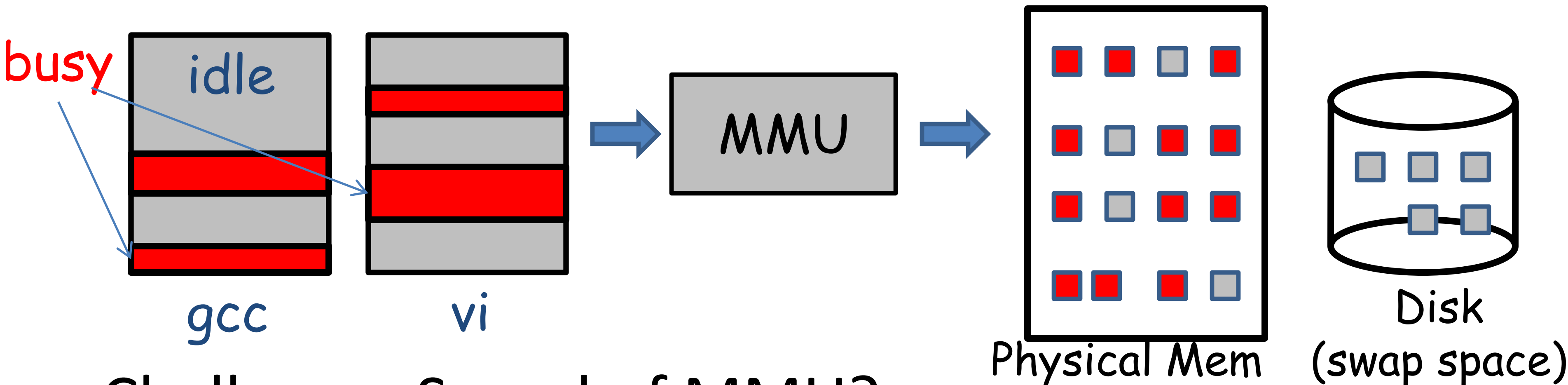


- Transparency: a process should be able to run regardless of its location in or the size of physical memory

  Give each process a large, static "fake" address space; as process runs, relocate each load and store to its actual memory

Clever? We get both flexibility and speed!

- VM = indirection between apps and actual memory
  - Flexibility: process can be moved in memory as it executes, run partially in memory and on disk, …
  - Simplicity: drastically simplifies applications
  - Efficiency: most of a process's memory will be idle (80/20 rule)



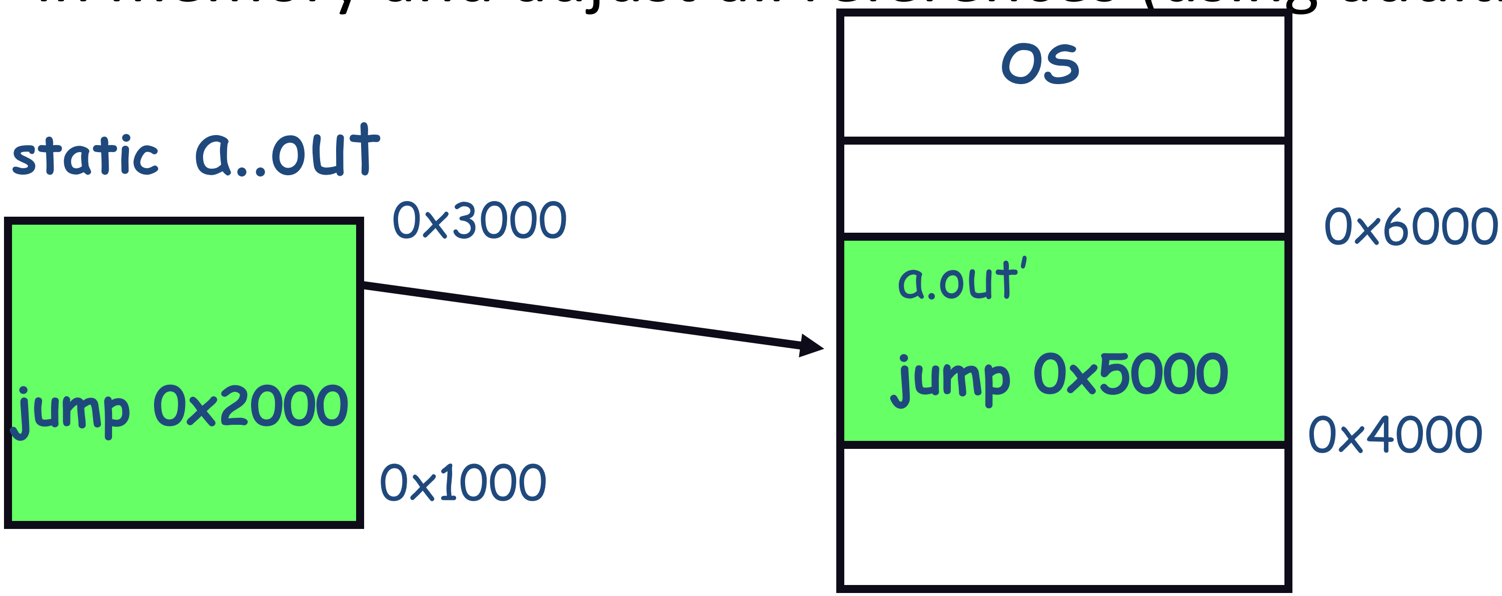
- Challenge: Speed of MMU?

Our main questions

- How is protection enforced?
- How are processes reolcated?
- How is memory partitioned?

Simple idea 1: load-time linking

- Link as usual, but keep the list of references
- At load time, determine where processes will reside in memory and adjust all references (using addition)



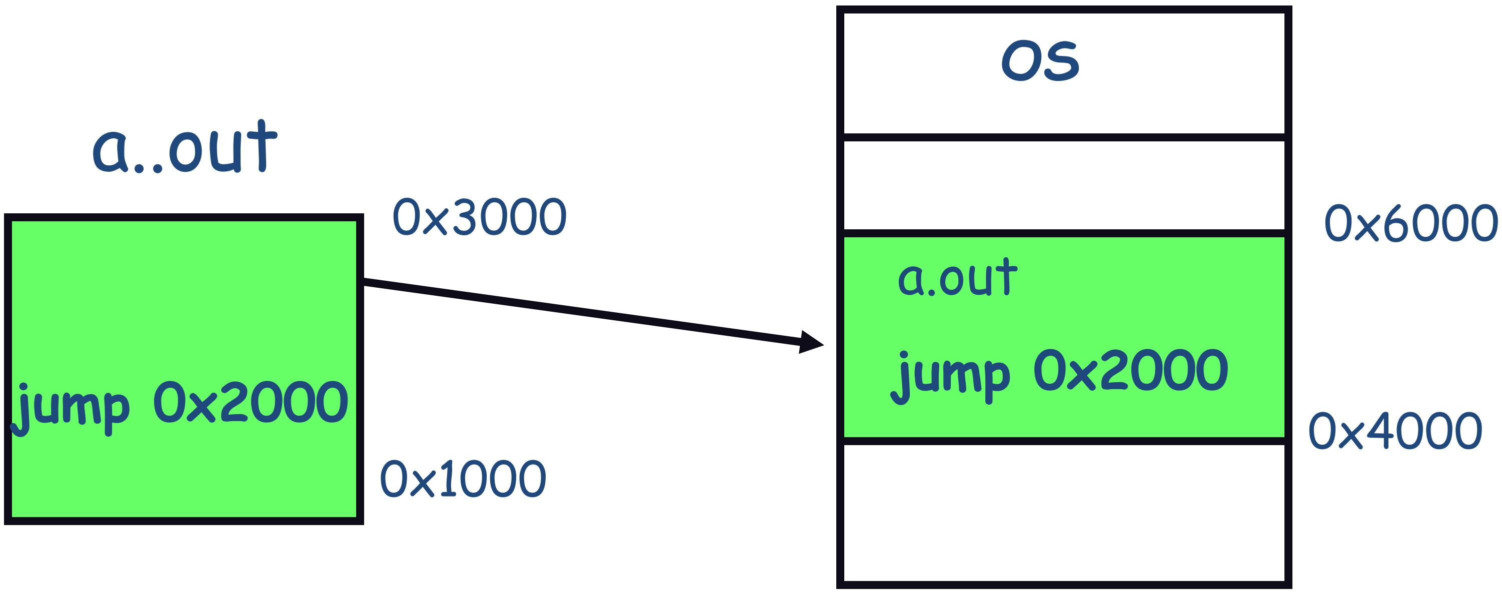
- Prob 1: protection?
- Prob 2: how to move in memory? (Consider: data pointers)
- Prob 3: more than one segment?

Simple idea 2: base + bound register

- Use hardware to solve problem: on every load and store

  relocation: physical addr = virtual addr + base register

  protection: check that address falls in [base, base+bound)



When process runs, base register = 0x3000, bounds register = 0x6000. Jump addr = 0x2000+0x3000=0x5000

How to move process in memory? What happens on process switch?

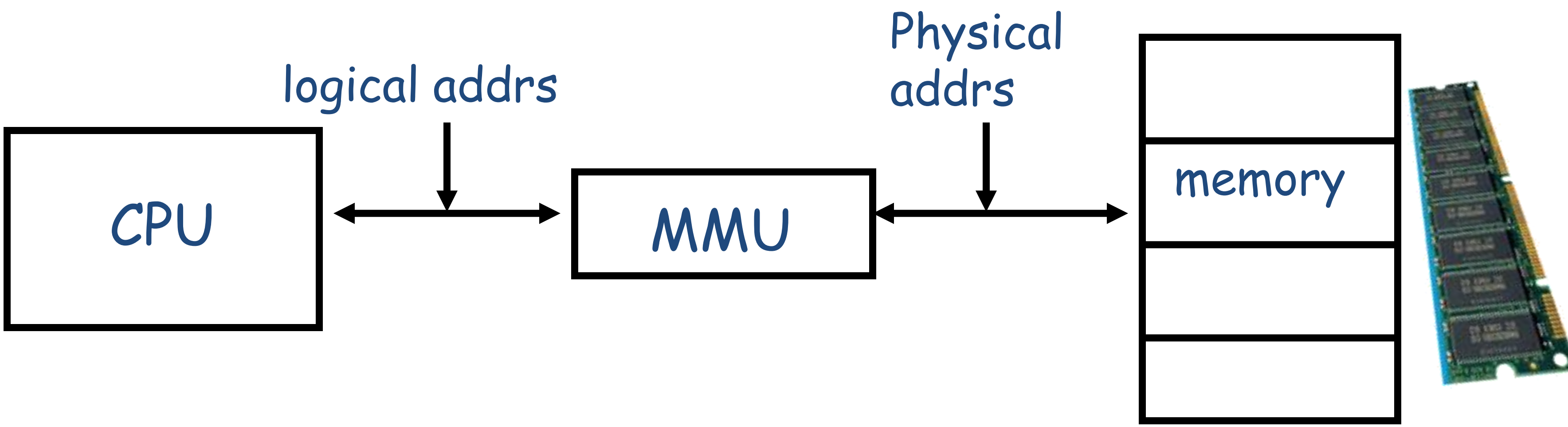
Some terminology

- Definitions:

  program addresses are called logical or virtual addresses

  actual addresses are called physical or real addresses

- Translation (or relocation) mechanism: MMU



Each load and store supplied virtual address translated to real address by MMU (memory management unit)

All other mechanisms for dynamic relocation use a similar organization. All lead to multiple (per process) view of memory, called address spaces

Protection mechanics

- How to prevent users from changing base/bound register?
- General mechanism: privileged instructions

  OS runs in privileged mode (set a bit in process status word)

  application processes run in user mode

  Certain instructions can only be issued in privileged mode

  (checked by hardware: illegal instruction trap)

- How to switch? ("usually" how its done, many variations)

  User->OS: application issues a system call, hardware then:

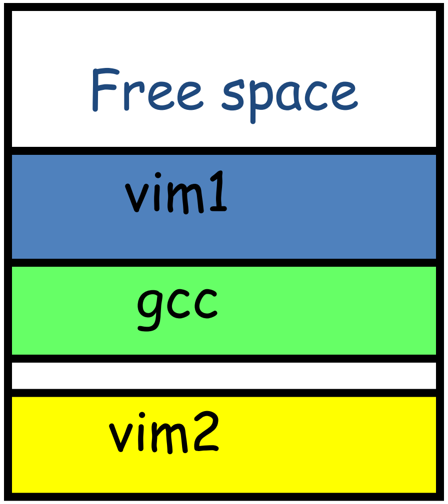
  - sets program counter to known address (can't trust user to)
  - updates process status word
  - and disables relocation (OS has different address space)

  OS-> User:

  - sets base and bounds register (recall: relocation off)
  - issues an instruction that simultaneously (1) sets pc to given address, (2) turns relocation back on, and (3) lowers privilege

Base & bound tradeoffs

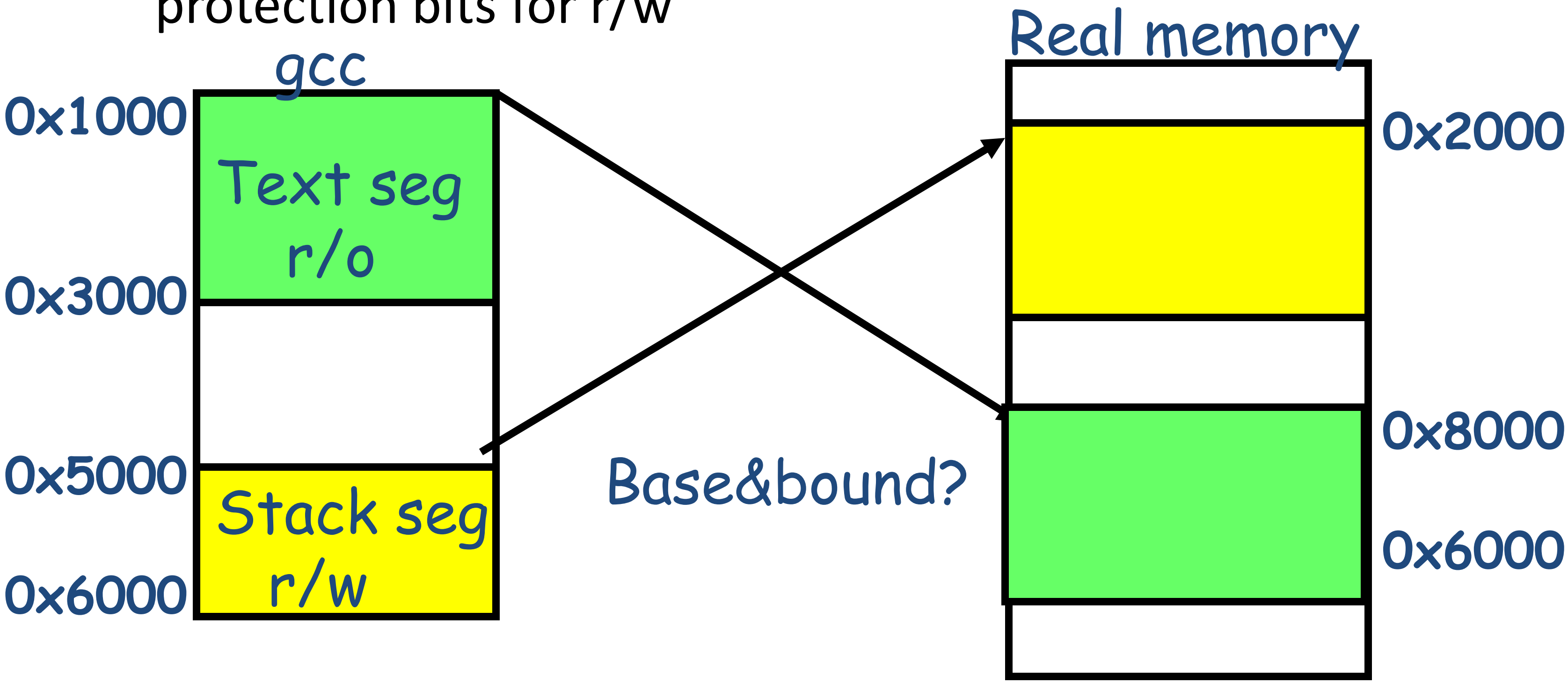
- Pro:
  - Cheap in terms of hardware: only two registers
  - Cheap in terms of cycles: do add and compare in parallel
  - Examples: Cray-1
- Con: only one segment
  - prob 1: growing processes
    - How to expand gcc?
  - prob 2: how to share code and data??
    - how can copies of "vi" share code?
  - prob 3: how to separate code and data?
- A solution: multiple segments
  "segmentation"



Segmentation

- Big idea: let processes have many base & bound ranges

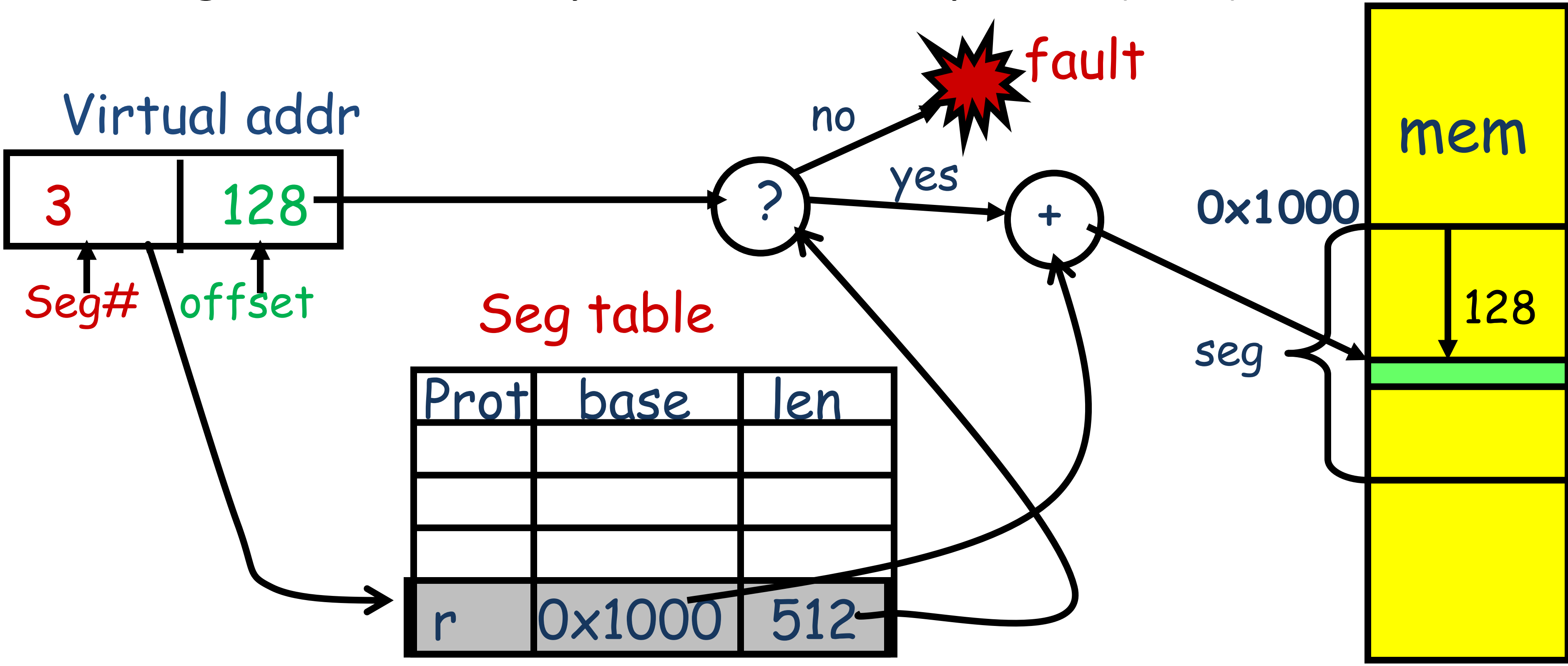
  Process address space built from multiple “segments”. Each has its own base & bound values. Since we can now share, add protection bits for r/w



- Problem: how to specify what segment address refers to?

Segmentation Mechanics

- Each process has an array of its segments (segment table)
- Each memory reference indicates a segment and offset:
  - Top bits of addr select segment, low bits select offset (PDP-10)
  - Segment selected by instruction, or operand (Intel)

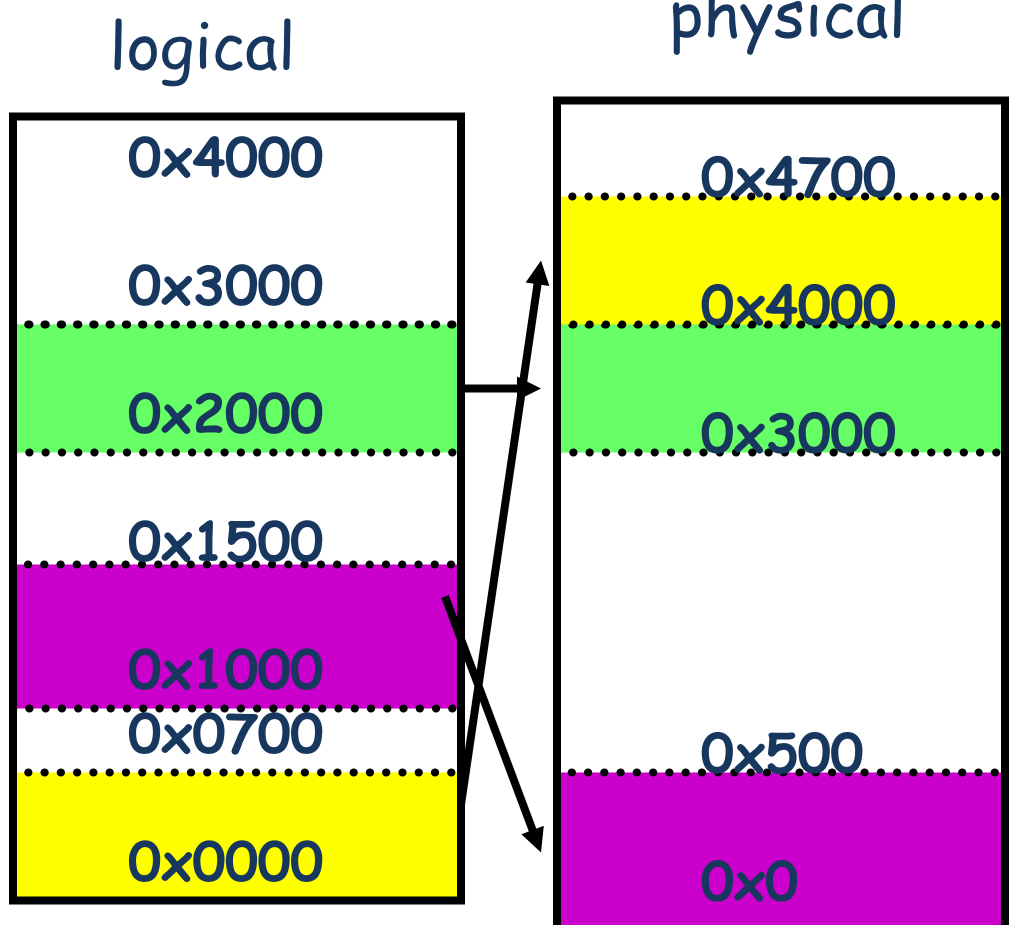


Segmentation example

- 2-bit segment number (1st digit), 12 bit offset (last 3)

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

- Where is 0x0240?
- 0x1108?
- 0x265c?
- 0x3002?
- 0x1600?



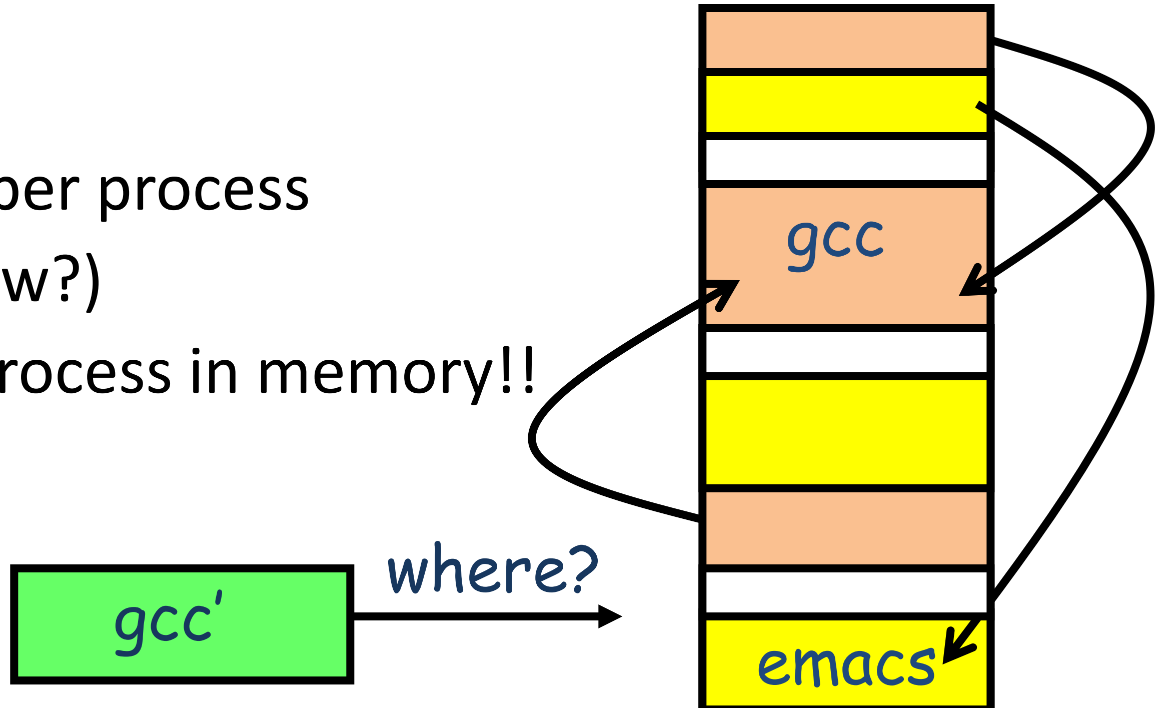
Segmentation Tradeoffs

- Pro:

  Multiple segments per process

  Allows sharing! (how?)

  Don't need entire process in memory!!



- Con:

  Extra layer of translation

  speed = hardware support

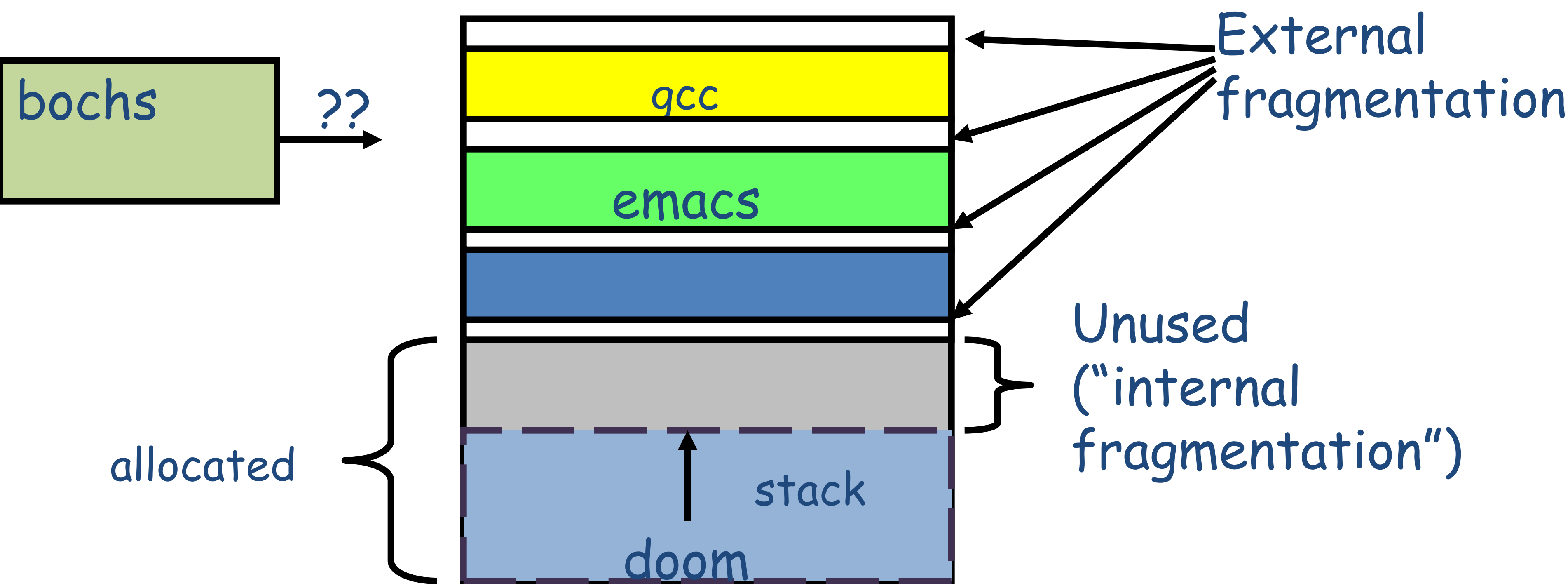
  An "n" byte segment requires n *contiguous* bytes of physical memory. (why?) Makes fragmentation a real problem.

Fragmentation

- "The inability to use memory that is free".
- Over time:

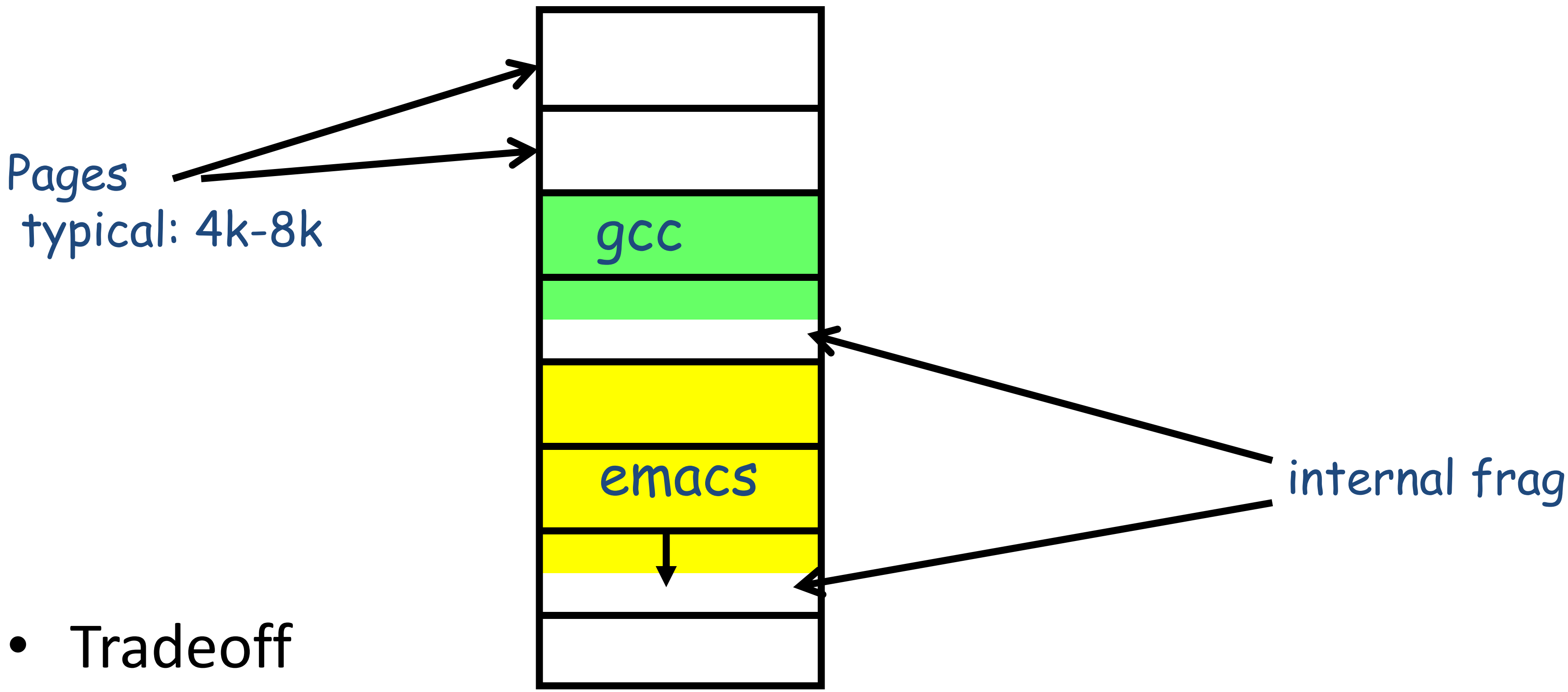
  variable-sized pieces = many small holes (external frag)

  fixed-sized pieces = no external holes, but force internal waste (internal fragmentation)



Page based virtual memory

- Quantize memory into fixed sized pieces (“pages”)



- Tradeoff

  pro: eliminates external fragmentation

  pro: simplifies allocation, free and swapping

  con: internal fragmentation (~.5 page per “segment”)

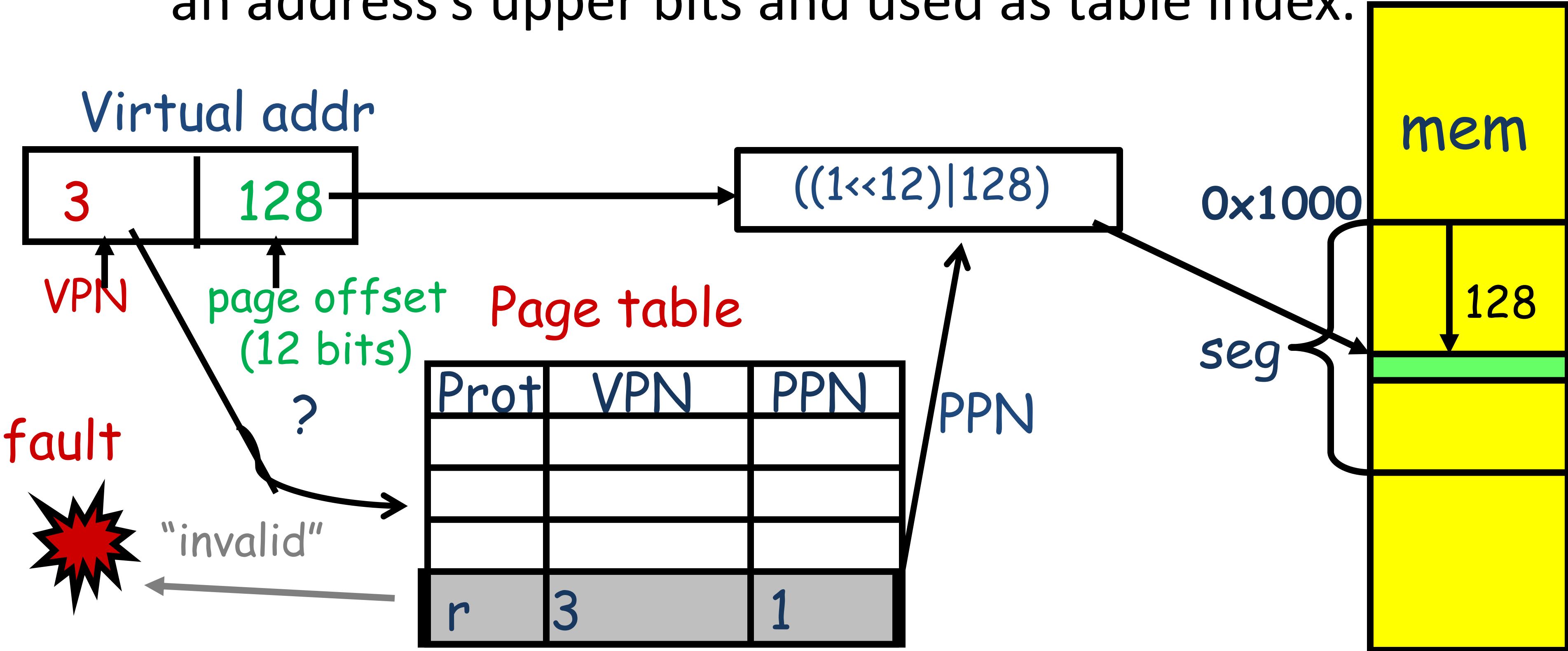
Page-based mechanics

memory is divided into chunks of the same size (pages)

each process has a table ("page table") that maps virtual page numbers to corresponding physical page numbers

- PT entry also includes protection bits (r, w, valid)

translation process: virtual page number extracted from an address's upper bits and used as table index.



Page-based translation example

- MIPS R2000: 32 bit addr space, 20-bit VPN and 12-bit offset:

Page number	page offset
20 bits	12 bits

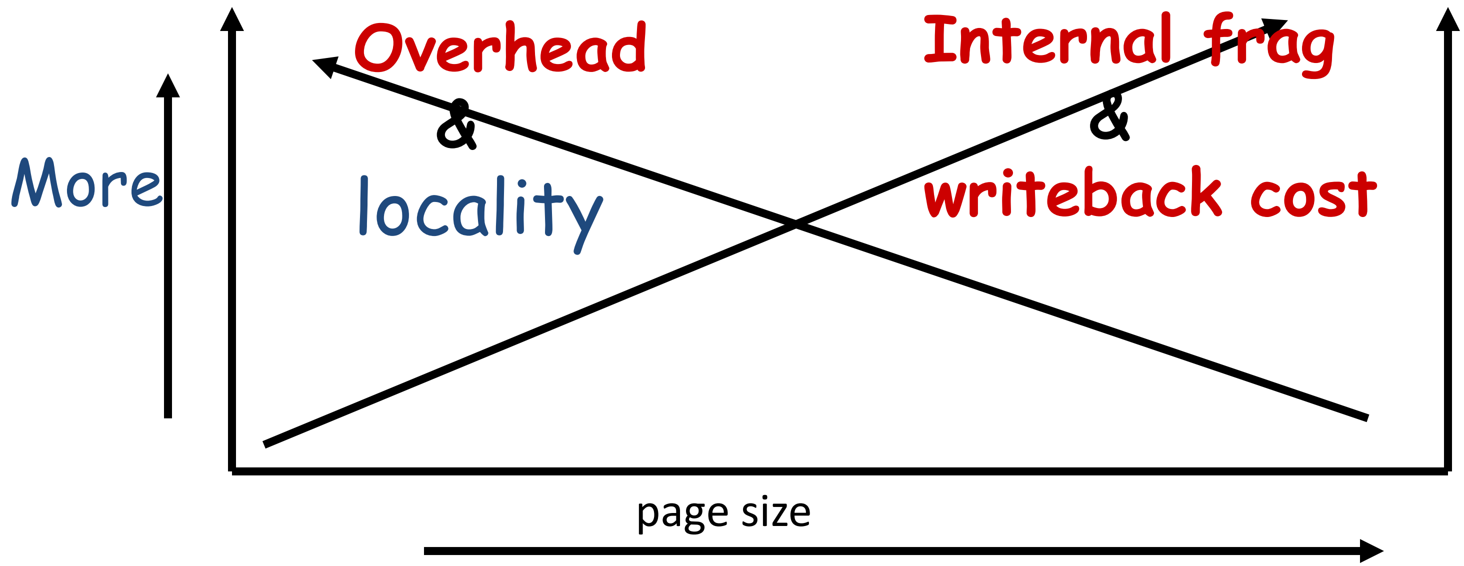
```
/* partial page table entry */
struct pte { unsigned ppn:20, valid:1, writeable:1…; };

/* given virtual address and r/w indication, return physical
   addr. Uses a simple "direct" page table (I.e., an array) with
   (conceptually) an entry for every possible vpn */
unsigned xlate(unsigned va, int wr) {
        struct pte *pte = &page_table[va >> 12];
        if(!pte->valid || (wr && !pte->writeable))
                raise address_fault;
        return (pte->ppn << 12) | (va & 0xfff);   }
```

Page tables vs segmentation

- Good:
  - Easy to allocate: keep a free list of available pages and grab the first one
  - Easy to swap since everything is the same size and since pages usually same size as disk blocks
- Bad:
  - size: PTs need one entry for each page-sized unit of virtual memory, vs one entry for every contiguous range
    - e.g., given a range [0x0000, 0xffff] need one segment descriptor but, assuming 4K pages, 16 page table entries

Page size tradeoffs



- Small page = large page-table overhead
  32-bit address space with 1k pages. How big PT?
- Large page = internal fragmentation
  Most UNIX processes have few segments (code, data, stack, heap) so not much of a problem
  But more expensive disk transfers, poorer (cache) locality

Virtual memory summary

- VM gives
  - Flexibility + protection + speed (if clever)
- Base & bounds = simple relocation+protection
  - Pro: simple, fast
  - Con: inflexible
- Segmentation = generalization of base & bounds
  - Pro: Gives more flexible sharing and space usage
  - Con: segments need contiguous physical memory ranges
- Paging: instead of using extents, use fixed size units
  - Quantize memory into pages & use (page) table to map virtual to physical pages
  - Pro: eliminates external fragmentation; flexible mappings
  - Con: internal frag; mapping contiguous ranges more costly