## Evolution in Memory Management

Programs used all physical memory & executed one at a time.

Programmers divided up their programs into **overlays**

- memory-size (or less) partitions of program and data that would not be used at the same time
- loaded into memory under user control

  $\Longrightarrow$ programs larger than physical memory could execute

**Multiprogramming**

- several programs were memory-resident at the same time
- one executed while another waited for I/O

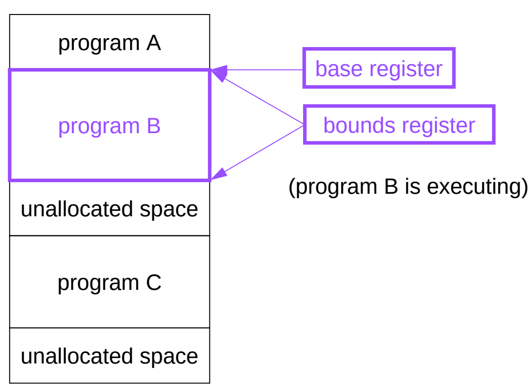
  $\Longrightarrow$ better utilization of the CPU



## Evolution in Memory Management

**Relocation**

- programs are compiled & linked wrt address 0
- relocated to some other address in physical memory
  - **base register**: contains the first location of the program
  - **bounds register**: contains the size of the program
- relocating a program address to physical memory
  - physical address = base register + program address
  - check if physical address is within the bounds (physical address $\leq$ base address + bounds value)
  - if not, an exception occurs



## Evolution in Memory Management

**Relocation,** cont'd.

- advantages of relocation
  - allows multiple programs to reside in memory
  - allows a program to reside anywhere in memory by separating program addresses & physical addresses
- problems with relocation
  - **memory fragmentation**
    - unallocated space between programs
    - fragmentation get worse as over time (smaller & more numerous "holes" in memory)
    - requires copying to remove the fragments
  - still requires overlays for large programs



## Virtual Memory

A model (a memory abstraction) to the programmer that:

- a program starts in location 0
- a program extends contiguously in memory
- a program has available to it the entire architectural memory space ($2^{wordsize}$ bytes):
  called the **virtual address space**

**Paging**

- implementation for virtual memory
- divide the virtual address space into fixed-size chunks,
  called **pages**
- divide physical memory into chunks of the same size,
  called **page frames**
- provide a mapping between addresses in pages & address in page frames,
  called **address translation**
- if no mapping exists
  (i.e., if a virtual address is on a page that does not have a page frame in physical memory),
  it is on disk and has to be **paged** into memory

## Address Translation

**Address translation**:

- maps addresses in the virtual address space (**virtual addresses**) to locations in physical memory (**physical addresses**)
  - CPU emits a virtual (program-generated) address
  - memory has physical addresses
- relocation mechanism is fully associative
  - a page can reside in any page frame
- mapping techniques in:
  - software data structure (**page tables**) &
  - hardware cache (**translation lookaside buffer**) (*we'll cover them both later*)



## Address Translation Using Page Tables

Operating systems data structure

- page tables are built & maintained by the OS
- one page table per process
  - process A's virtual addresses will map to different physical locations than process B's
- one entry in the page table per (virtual) page: called **page table entry (PTE)**
- PTE fields:
  - **valid bit**: whether the page is mapped into memory or still resides on disk
  - **page frame number** or disk location
  - **dirty bit**: indicates whether any address on the page has been written
  - **reference or use bit**: set if this page was used recently
  - **protection bits**: access privilege (read/write/execute) for user or kernel mode

## Page Table Size

Calculating page table size:

$$\text{number of page table entries} = \frac{\text{virtual address space}}{\text{page size}}$$

$$\text{size of page table} = \text{number of page table entries} \times \text{size of a PTE}$$

An example:

$$2^{32}/2^{12} = 2^{20} \text{page table entries}$$

$$2^{20} \times 2^{2} = 4\text{MB}$$

- there are several techniques to reduce the size of the page tables



## Design Trade-offs for Page SIze

Choosing a **page size**:

- big pages
  - \+ better throughput from disk
  - \+ smaller page tables
  - \- (internal) fragmentation
- small pages
  - \+ lower latency to fetch a page
  - \- larger page tables
    (but can use techniques to reduce page table size)

Current page sizes:

- 8KB
- some machines have larger ones too