Memory Management

Learning Outcomes

- Appreciate the need for memory management in operating systems, understand the limits of fixed memory allocation schemes.
- Understand fragmentation in dynamic memory allocation, and understand basic dynamic allocation approaches.
- Understand how program memory addresses relate to physical memory addresses, memory management in base-limit machines, and swapping
- An overview of virtual memory management.

Process

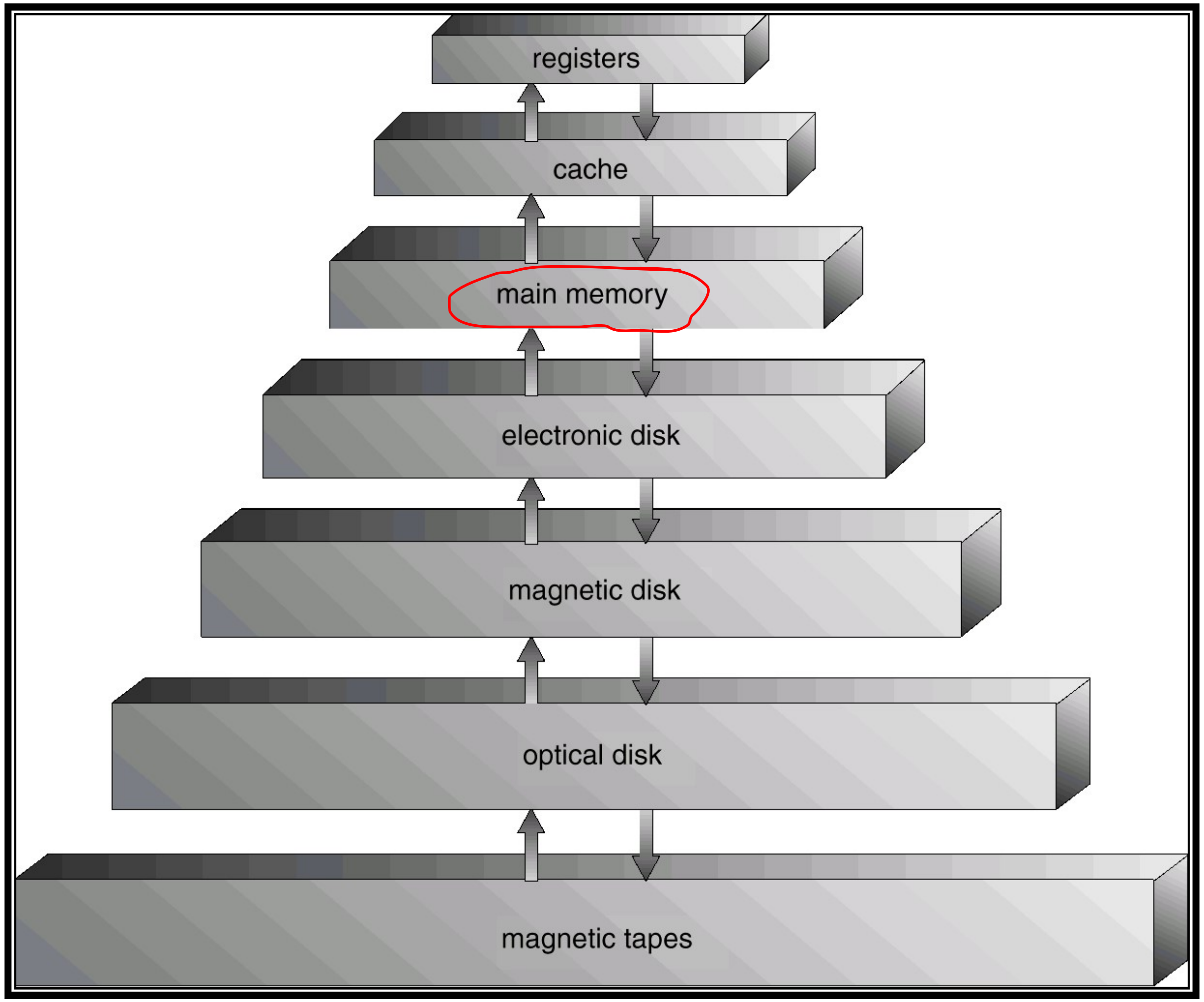
- One or more threads of execution
- Resources required for execution
  - Memory (RAM)
    - Program code ("text")
    - Data (initialised, uninitialised, stack)
    - Buffers held in the kernel on behalf of the process
  - Others
    - CPU time
    - Files, disk space, printers, etc.

OS Memory Management

- Keeps track of what memory is in use and what memory is free
- Allocates free memory to process when needed
  - And deallocates it when they don't
- Manages the transfer of memory between RAM and disk.

Memory Hierarchy

- Ideally, programmers want memory that is
  - Fast
  - Large
  - Nonvolatile
- Not possible
- Memory management coordinates how memory hierarchy is used.
  - Focus usually on RAM ⇔ Disk



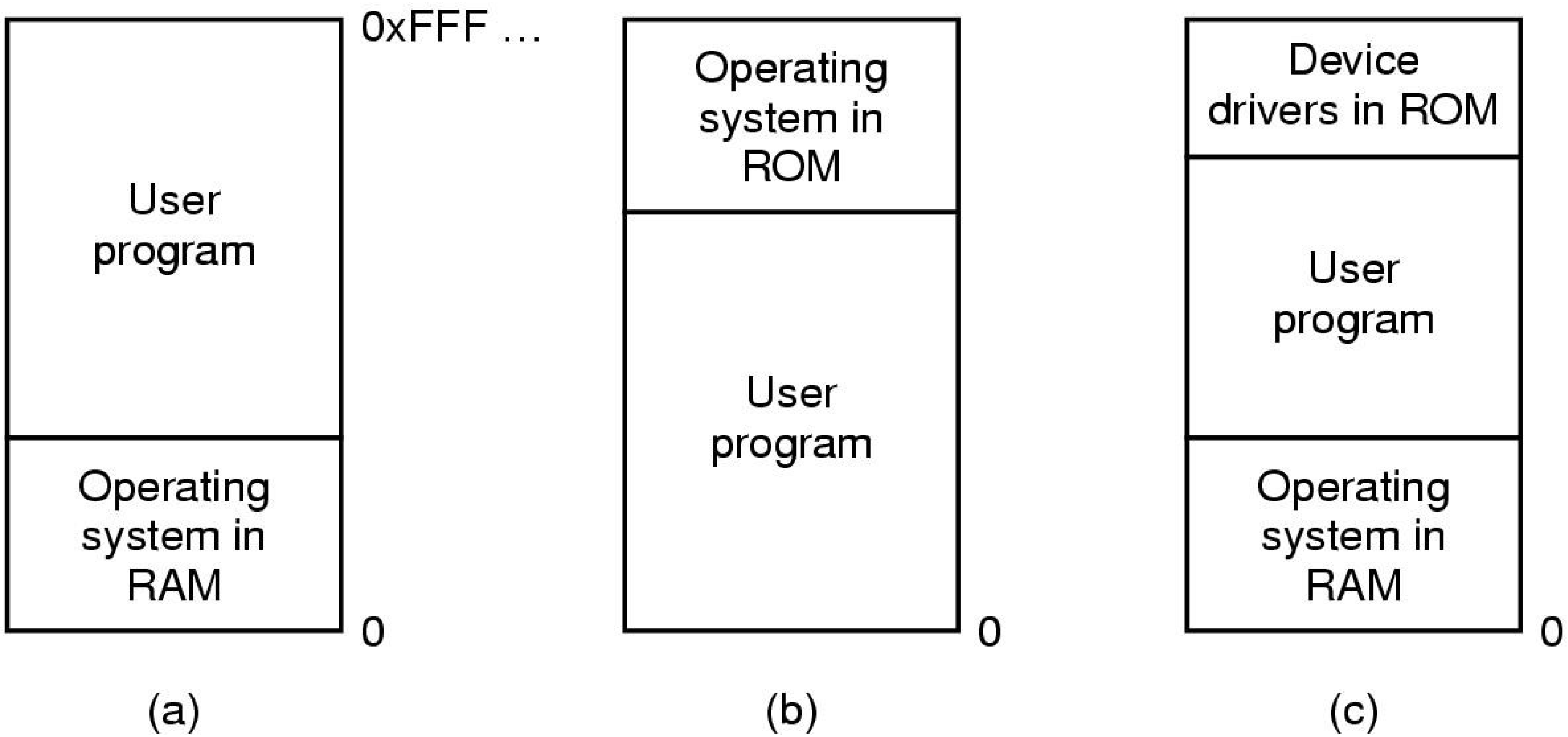
OS Memory Management

- Two broad classes of memory management systems
  - Those that transfer processes to and from external storage during execution.
    - Called swapping or paging
  - Those that don't
    - Simple
    - Might find this scheme in an embedded device, dumb phone, or smartcard.

Basic Memory Management

Monoprogramming without Swapping or Paging

bios



Three simple ways of organizing memory

- an operating system with one user process

Monoprogramming

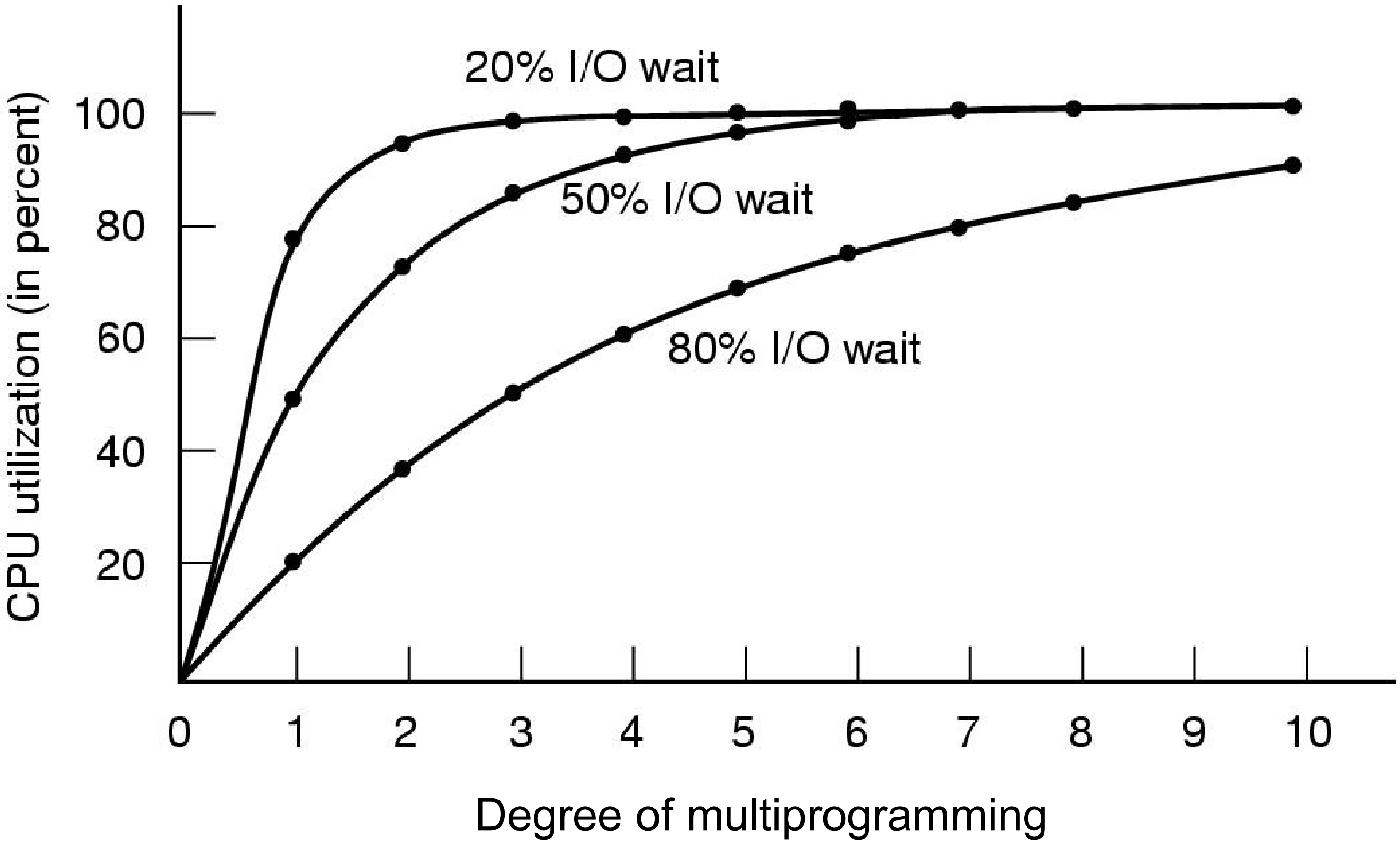
- Okay if
  - Only have one thing to do
  - Memory available approximately equates to memory required
- Otherwise,
  - Poor CPU utilisation in the presence of I/O waiting
  - Poor memory utilisation with a varied job mix

Idea

- Recall, an OS aims to
  - Maximise memory utilisation resource utilisation
  - Maximise CPU utilization
    - (ignore battery/power-management issues)
- Subdivide memory and run more than one process at once!!!!
  - Multiprogramming, Multitasking

KE1

Modeling Multiprogramming



CPU utilization as a function of number of processes in memory

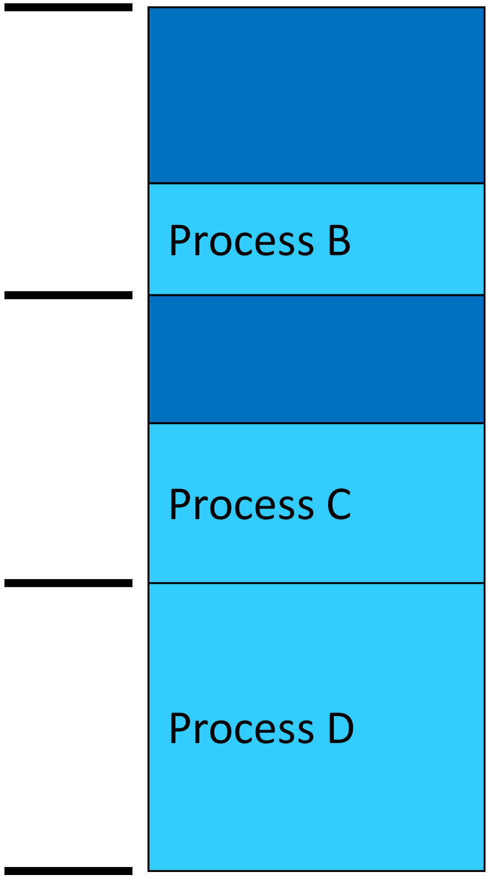
Slide 10

KE1 Kevin Elphinstone, 30/03/2020

General problem: How to divide memory between processes?

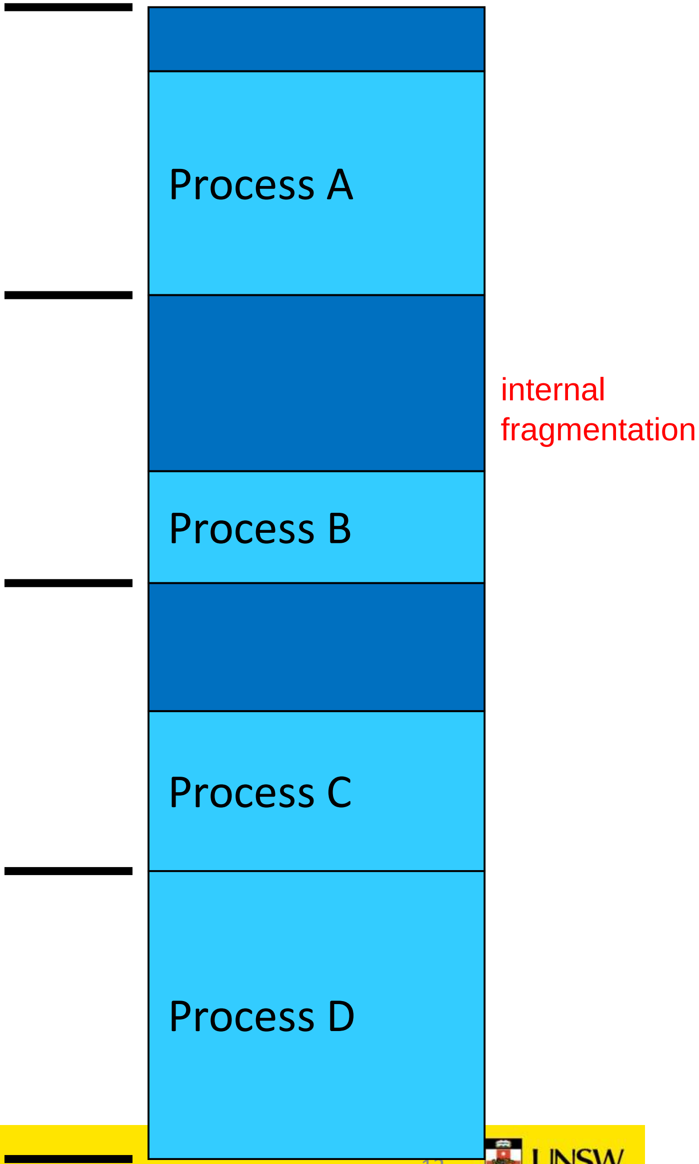
where is the free memory
how do we allocate the free memory for programs to run

- Given a workload, how to we
  - Keep track of free memory?
  - Locate free memory for a new process?
- Overview of evolution of simple memory management
  - Static (fixed partitioning) approaches
    - Simple, predicable workloads of early computing
  - Dynamic (partitioning) approaches
    - More flexible computing as compute power and complexity increased.
- Introduce virtual memory
  - Segmentation and paging



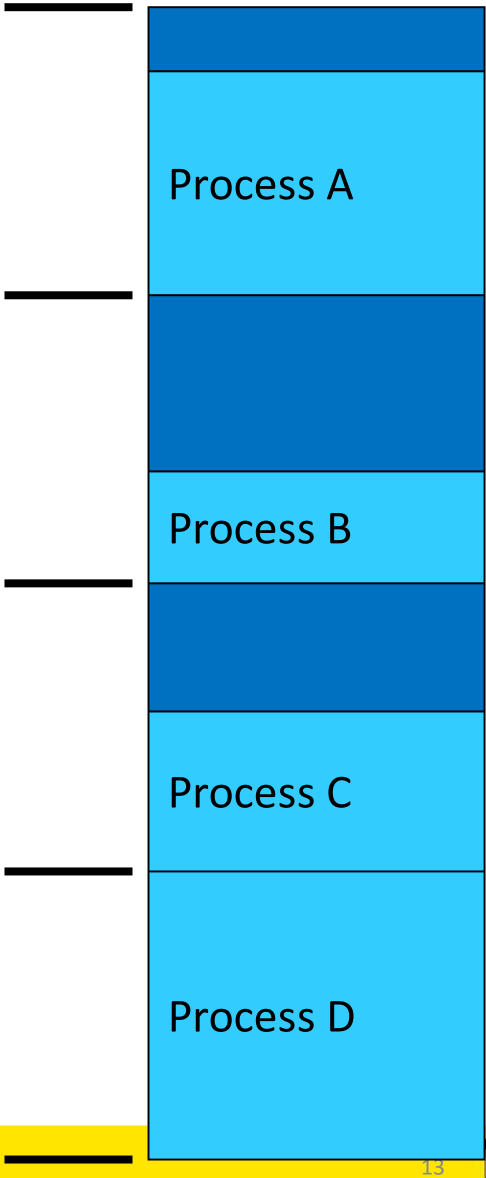
Problem: How to divide memory

- One approach
  - divide memory into fixed equal-sized partitions
  - Any process <= partition size can be loaded into any partition
  - Partitions are free or busy



Simple MM: Fixed, equal-sized partitions

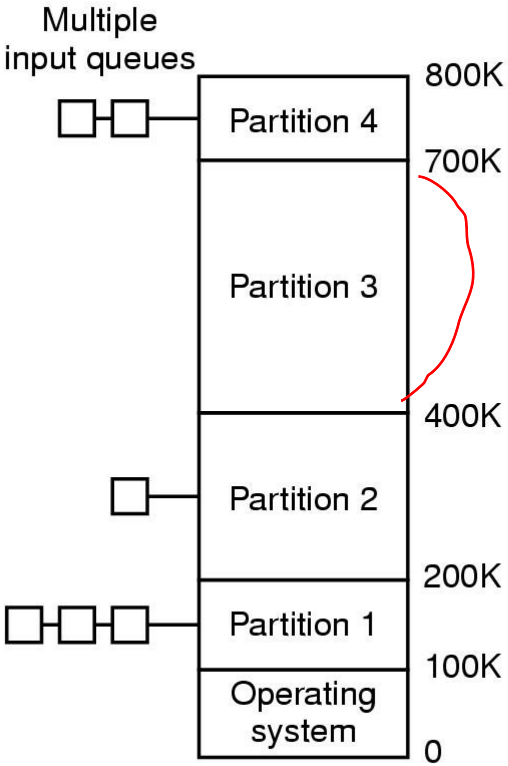
- Any unused space in the partition is wasted
  - Called internal fragmentation
- Processes smaller than main memory, but larger than a partition cannot run.



Simple MM: Fixed, variable-sized partitions

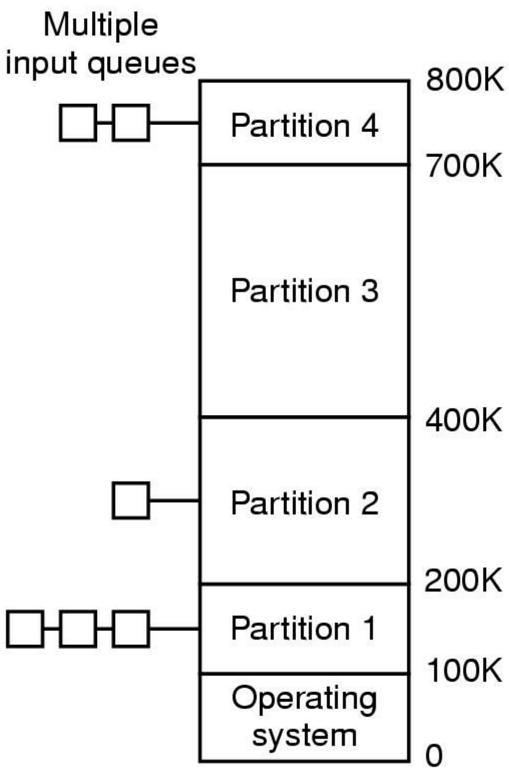
best-fit: variable sized, less internal fragmentation

- Divide memory at boot time into a selection of different sized partitions
  - Can base sizes on expected workload
- Each partition has queue:
  - Place process in queue for smallest partition that it fits in.
  - Processes wait for when assigned partition is empty to start



(a)

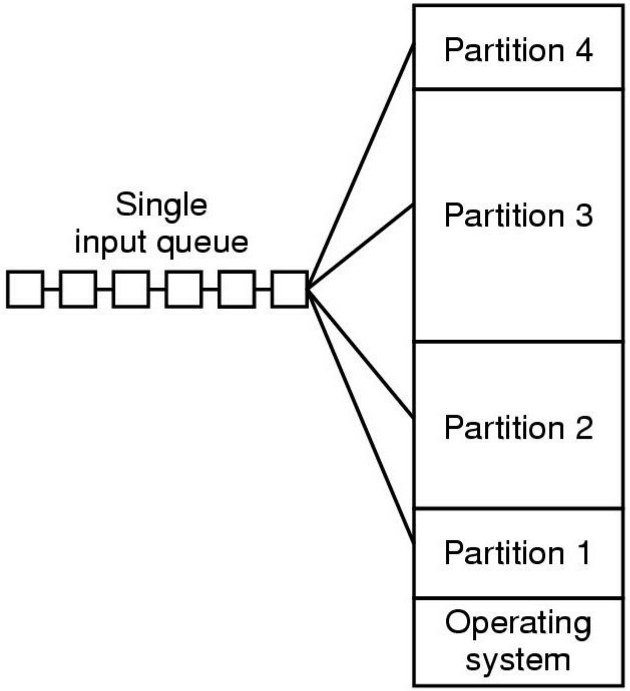
- Issue
  - Some partitions may be idle
    - Small jobs available, but only large partition free
    - Workload could be unpredictable



(a)

Alternative queue strategy

- Single queue, search for any jobs that fit
    - Small jobs in large partition if necessary
  - Increases internal memory fragmentation



(b)

Fixed Partition Summary

- Simple
- Easy to implement ✓
- Can result in poor memory utilisation
  - Due to internal fragmentation
- Used on IBM System 360 operating system (OS/MFT)
  - Announced 6 April, 1964
- Still applicable for simple embedded systems
  - Static workload known in advance

Dynamic Partitioning

get rid of the internal fragmentation program

- Partitions are of variable length
  - Allocated on-demand from ranges of free memory
- Process is allocated exactly what it needs
  - Assumes a process knows what it needs

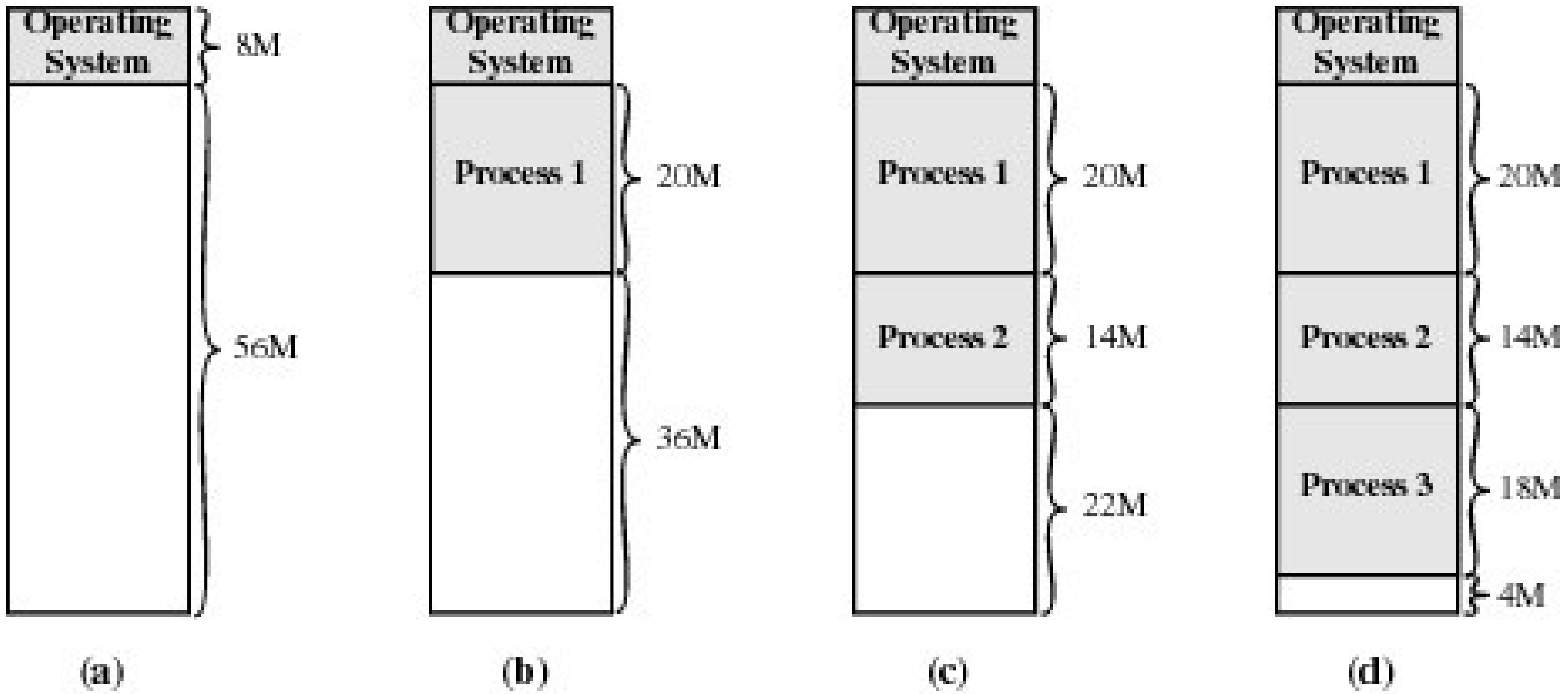


Figure 7.4 The Effect of Dynamic Partitioning

this leaves a lot of small holes on our memory

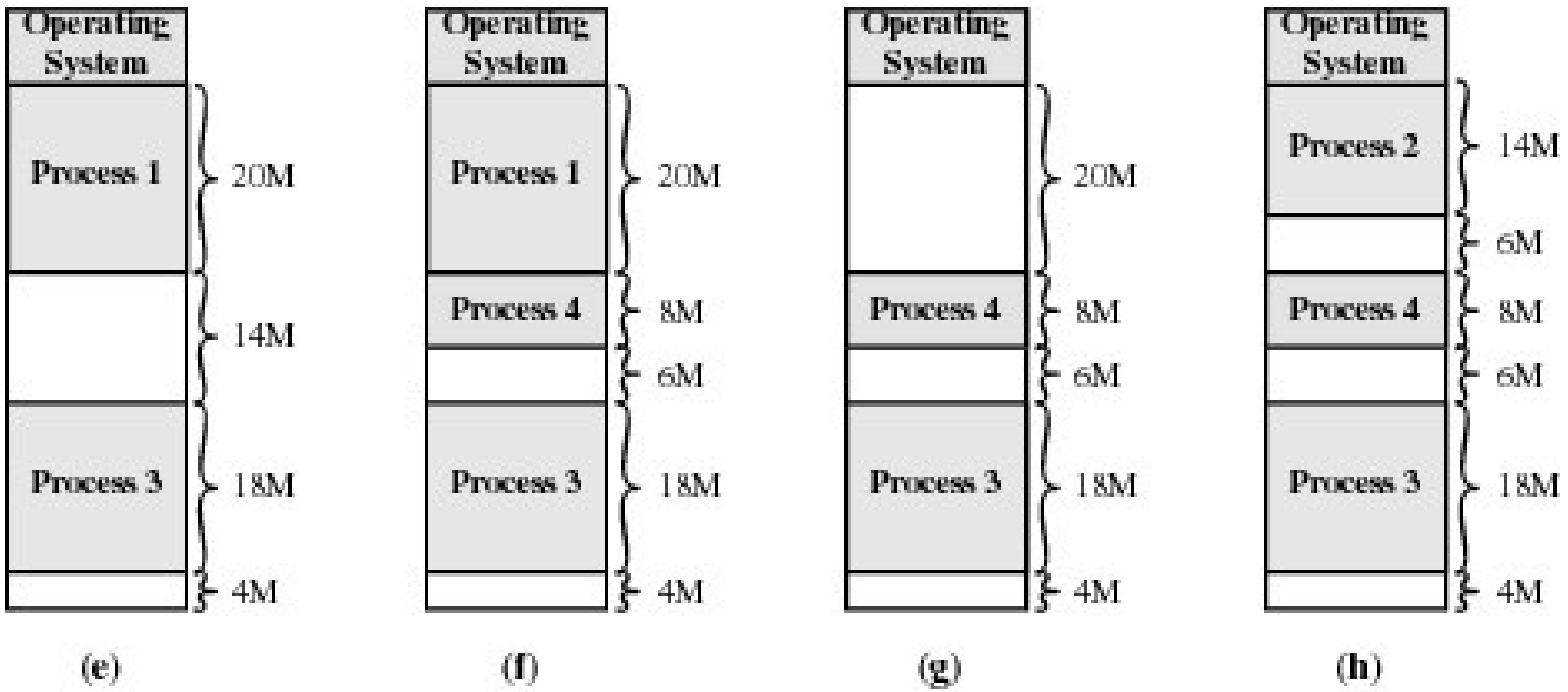


Figure 7.4 The Effect of Dynamic Partitioning

Dynamic Partitioning

- In previous diagram
  - We have 16 meg free in total, but it can’t be used to run any more processes requiring > 6 meg as it is fragmented
  - Called *external fragmentation*
- We end up with unusable holes

Recap: Fragmentation

- **External Fragmentation**:
  - The space wasted external to the allocated memory regions.
  - Memory space exists to satisfy a request, but it is unusable as it is not contiguous.
- **Internal Fragmentation:**
  - The space wasted internal to the allocated memory regions.
  - allocated memory may be slightly larger than requested memory; this size difference is wasted memory internal to a partition.

Dynamic Partition Allocation Algorithms

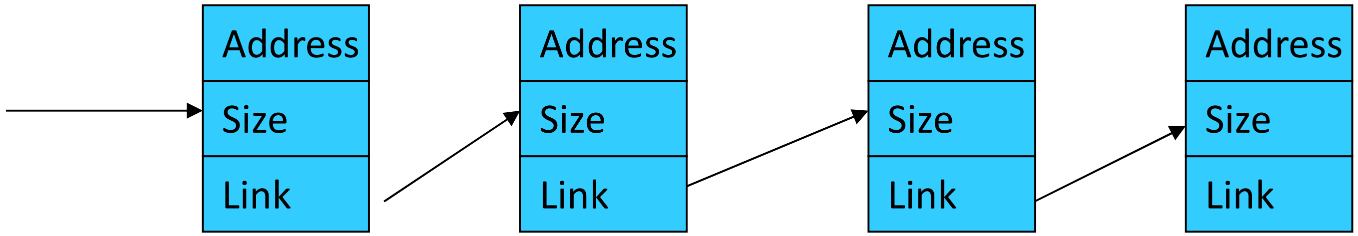
- Also applicable to `malloc()`-like in-application allocators
- Given a region of memory, basic requirements are:
  - Quickly locate a free partition satisfying the request
    - Minimise CPU time search
  - Minimise external fragmentation
  - Minimise memory overhead of bookkeeping
  - Efficiently support merging two adjacent free partitions into a larger partition

4

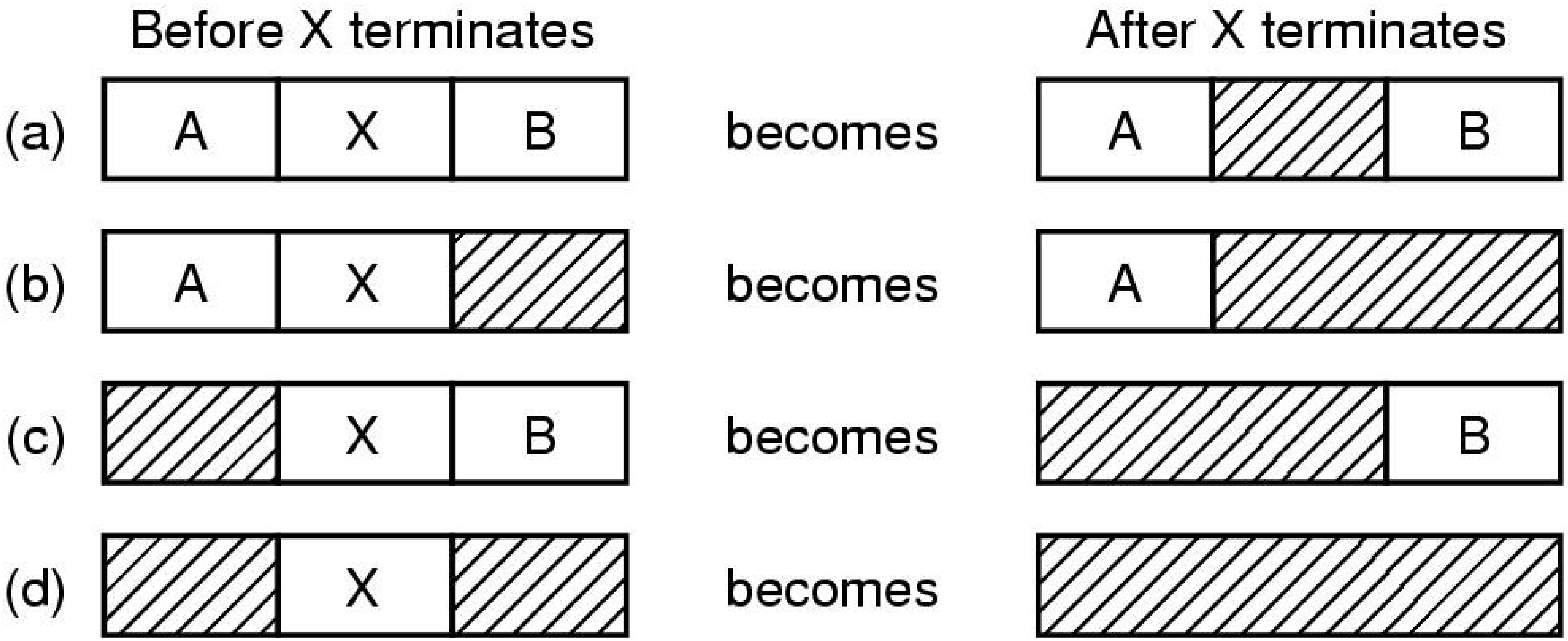
Classic Approach

- Represent available memory as a linked list of available "holes" (free memory ranges).
  - Base, size
  - Kept in order of increasing address
    - Simplifies merging of adjacent holes into larger holes.
  - List nodes be stored in the "holes" themselves

0 memory overhead



Coalescing Free Partitions with Linked Lists



Four neighbor combinations for the terminating process X

Dynamic Partitioning Placement Algorithm

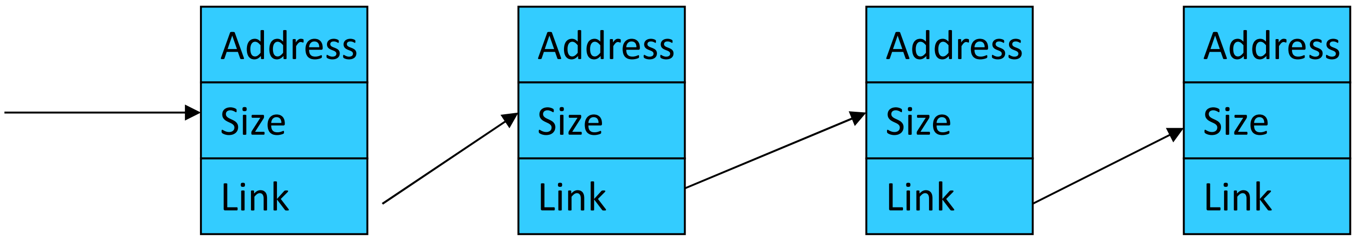
- First-fit algorithm

find something fast

  - Scan the list for the first entry that fits
    - If greater in size, break it into an allocated and free part
    - Intent: Minimise amount of searching performed
  - Aims to find a match quickly

holds tend to locate towards the head of the list

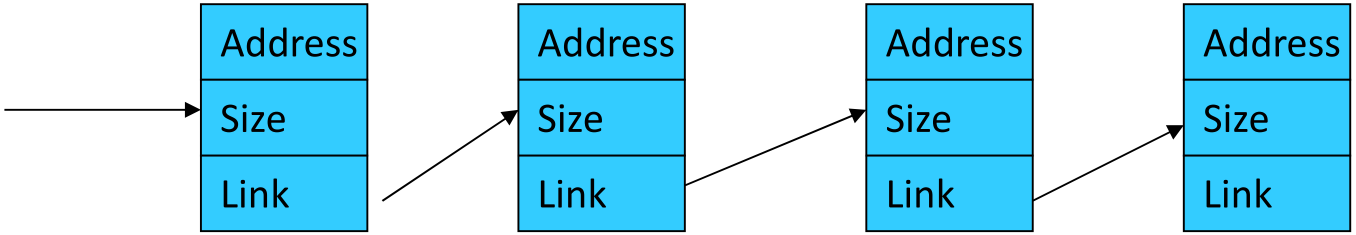
  - Biases allocation to one end of memory
  - Tends to preserve larger blocks at the end of memory



UNSW SYDNEY

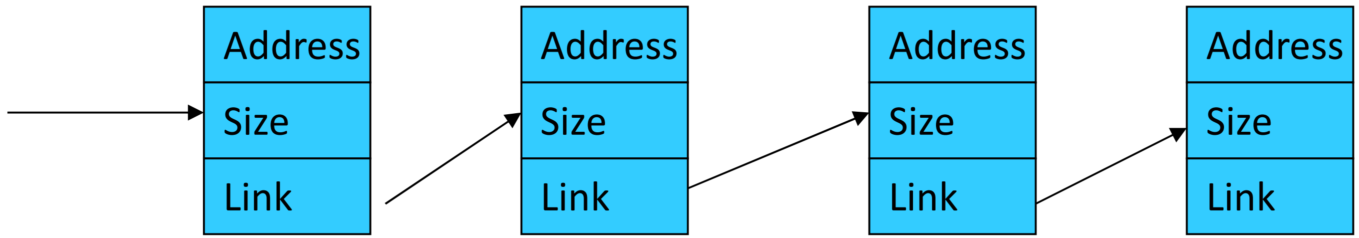
Dynamic Partitioning Placement Algorithm

- Next-fit
  - Like first-fit, except it begins its search from the point in list where the last request succeeded instead of at the beginning.
    - (Flawed) Intuition: spread allocation more uniformly over entire memory to avoid skipping over small holes at start of memory
    - Performs worse than first-fit as it breaks up the large free space at end of memory.



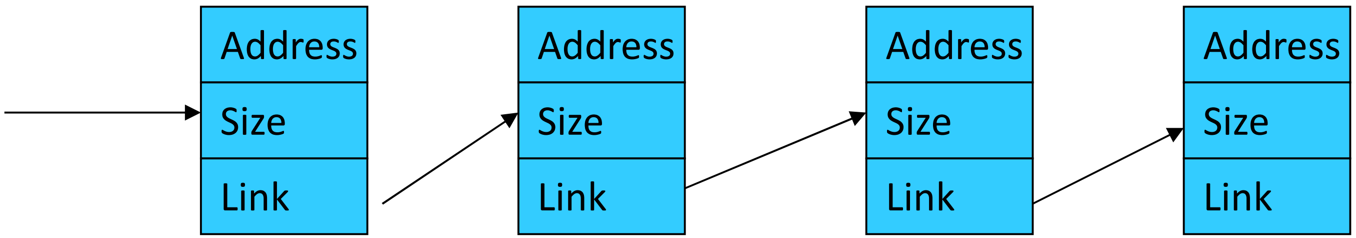
Dynamic Partitioning Placement Algorithm

- Best-fit algorithm
  - Chooses the block that is closest in size to the request
  - Performs worse than first-fit
    - Has to search complete list
      - does more work than first-fit
      - Since smallest block is chosen for a process, the smallest amount of external fragmentation is left
      - Create lots of unusable holes



Dynamic Partitioning Placement Algorithm

- Worst-fit algorithm
  - Chooses the block that is largest in size (worst-fit)
    - (whimsical) idea is to leave a usable fragment left over
  - Poor performer
    - Has to do more work (like best fit) to search complete list
    - Does not result in significantly less fragmentation



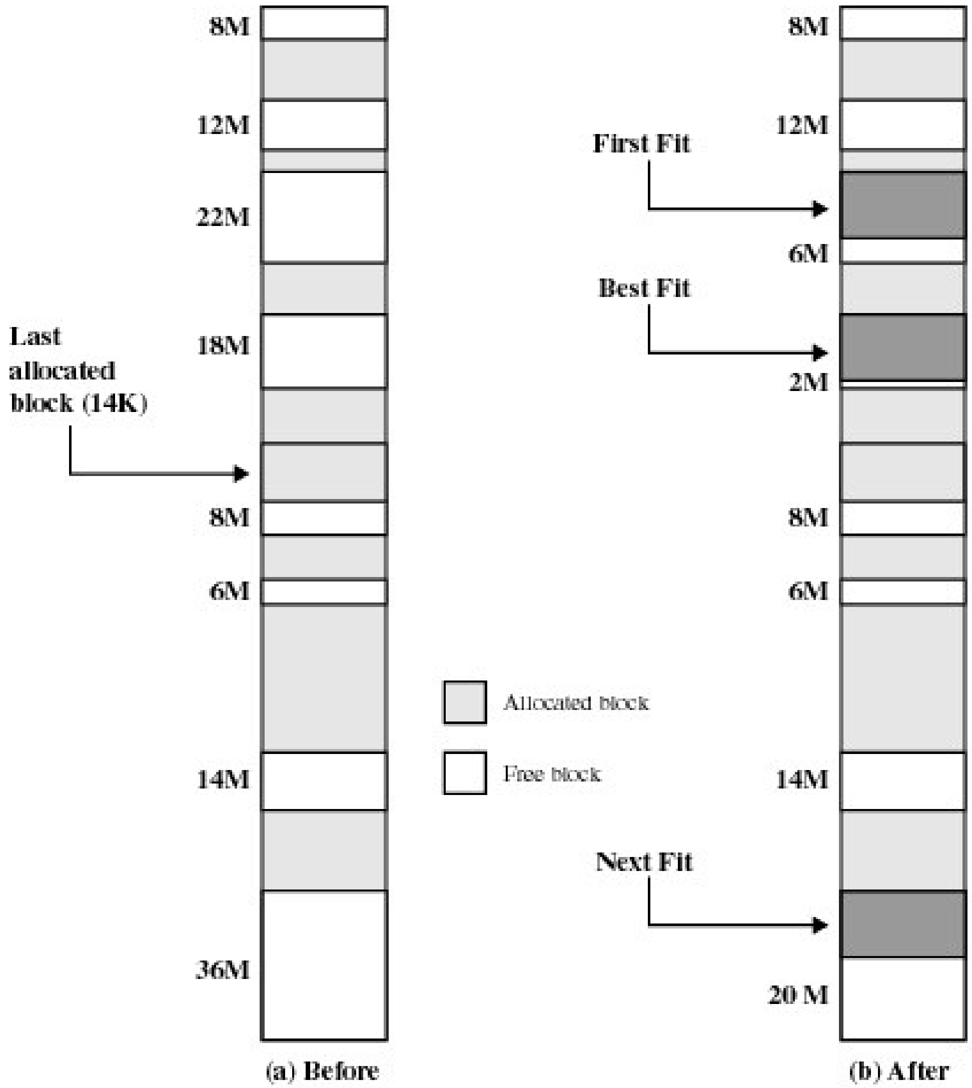


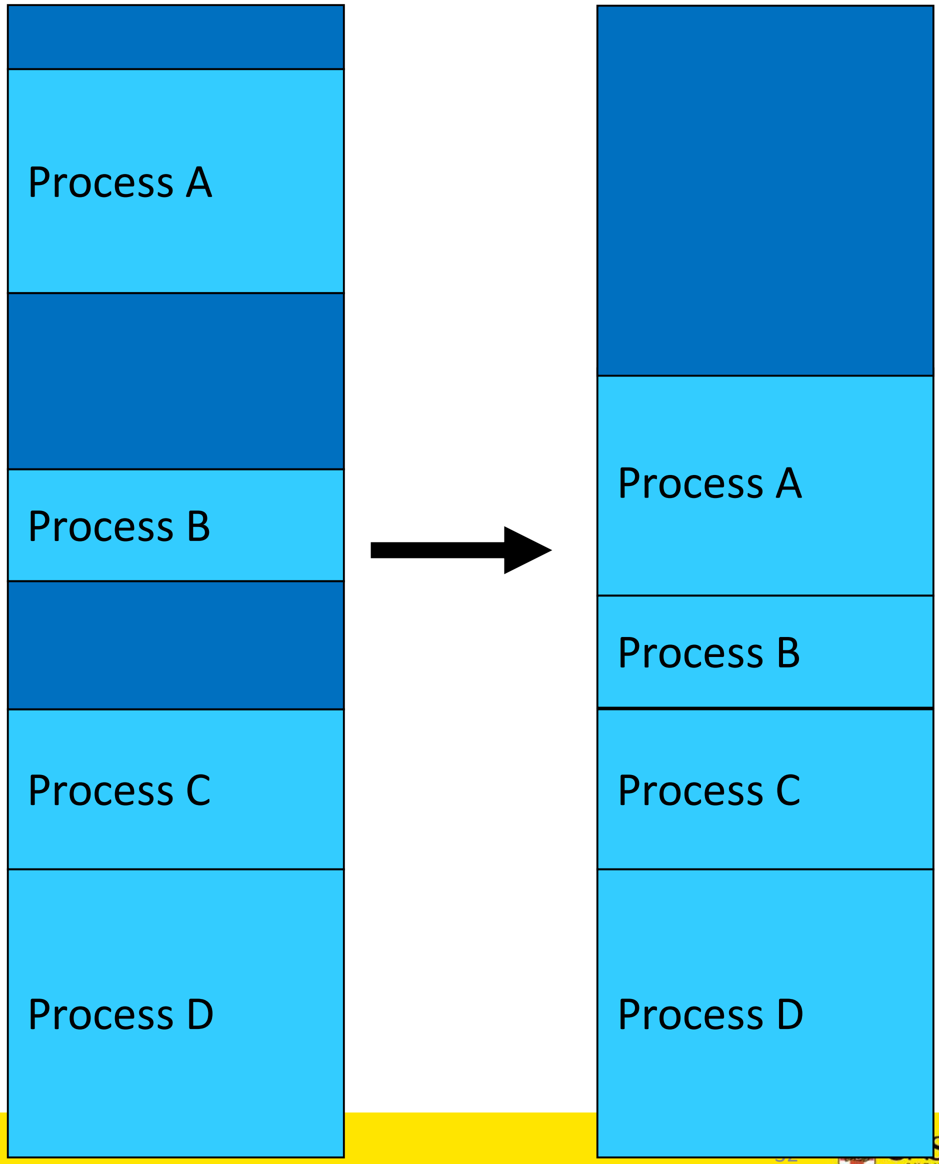
Figure 7.5 Example Memory Configuration Before and After Allocation of 16 Mbyte Block

Dynamic Partition Allocation Algorithm

- Summary next fit
  - First-fit generally better than the others and easiest to implement
- You should be aware of them
  - They are simple solutions to a still-existing OS or application service/function – memory allocation.
- Note: Largely have been superseded by more complex and specific allocation strategies
  - Typical in-kernel allocators used are *lazy buddy,* and *slab* allocators

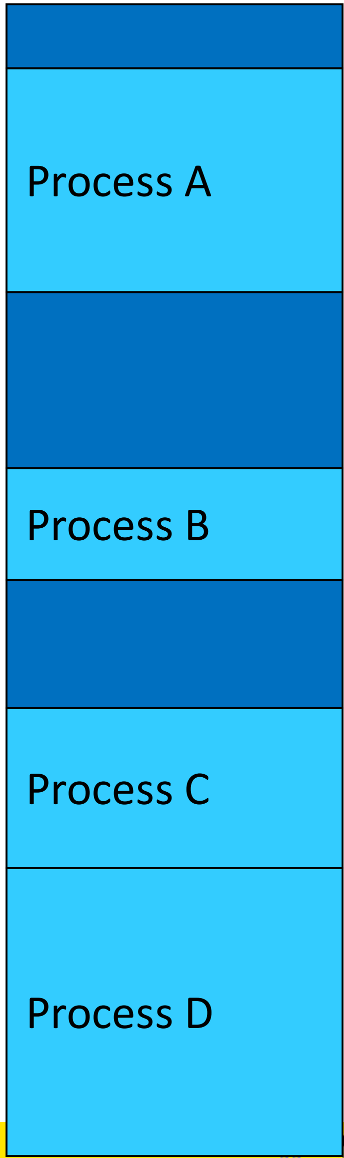
Compaction

- We can reduce external fragmentation by compaction
  - Shuffle memory contents to place all free memory together in one large block.
  - this is not easy Only if we can relocate running programs?
    - Pointers?
  - Generally requires hardware support



Some Remaining Issues with Dynamic Partitioning

- We have ignored
  - Relocation
    - How does a process run in different locations in memory?
  - Protection
    - How do we prevent processes interfering with each other



Example Logical Address-Space Layout

- Logical addresses refer to specific locations within the program
- Once running, these address must refer to real physical memory
- When are logical addresses bound to physical?

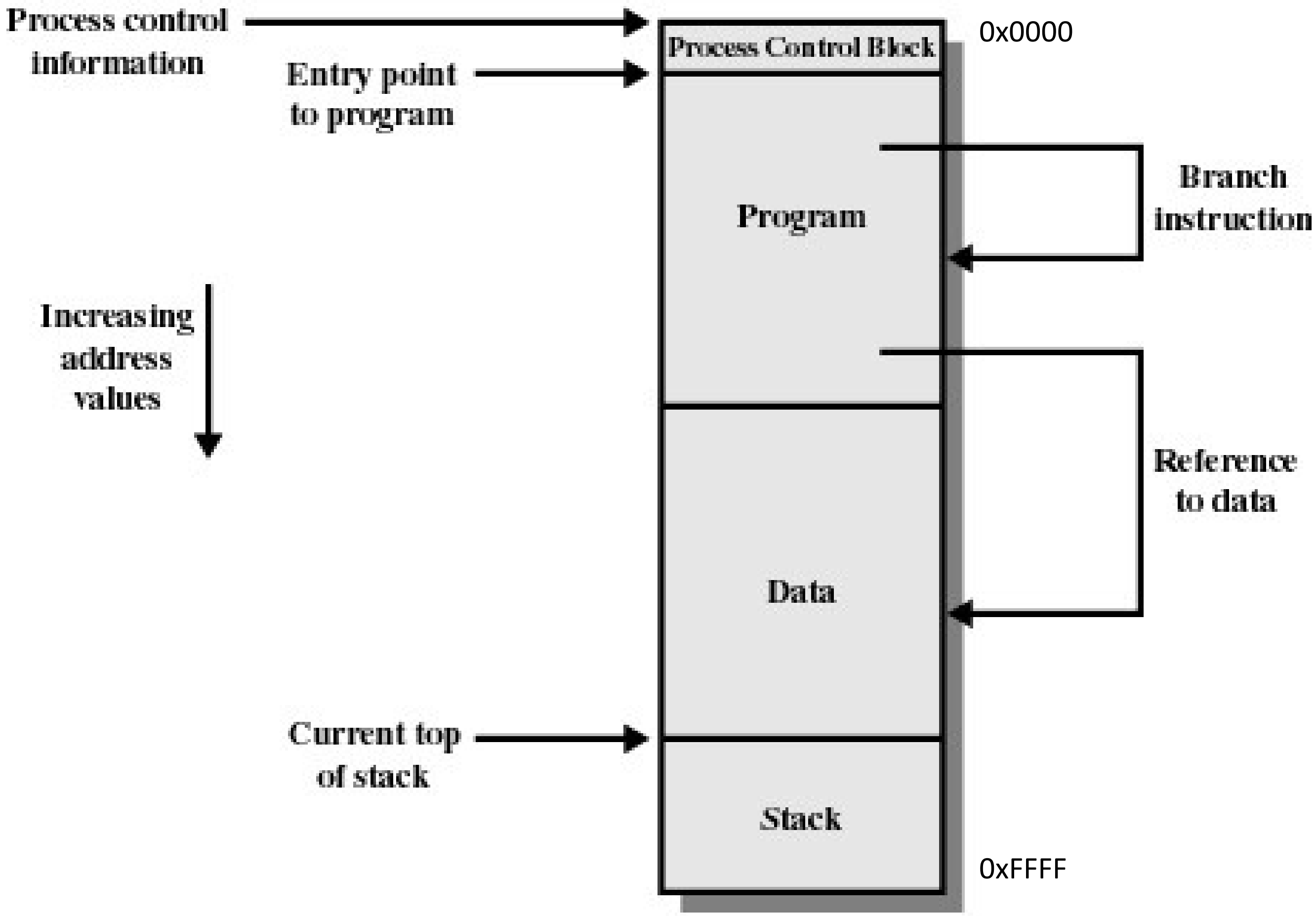
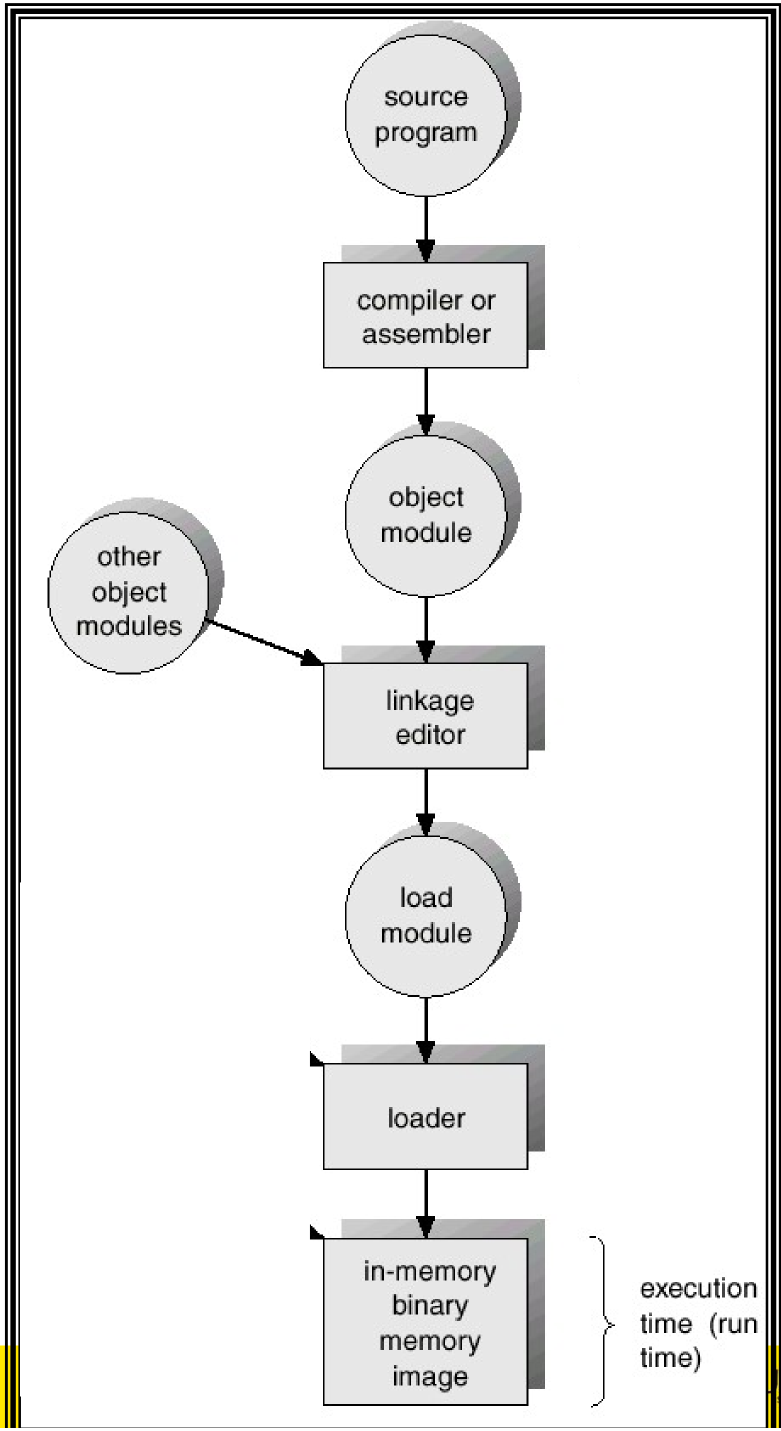


Figure 7.1 Addressing Requirements for a Process

layer of indirection,

When are memory addresses bound?

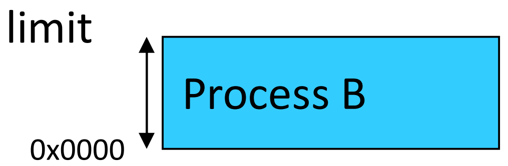
- Compile/link time
  - Compiler/Linker binds the addresses
  - Must know “run” location at compile time
  - Recompile if location changes
- Load time
  - Compiler generates *relocatable* code
  - Loader binds the addresses at load time
- Run time
  - Logical compile-time addresses translated to physical addresses by *special hardware.*



Hardware Support for Runtime Binding and Protection

- For process B to run using logical addresses
  - Process B expects to access addresses from zero to some limit of memory size

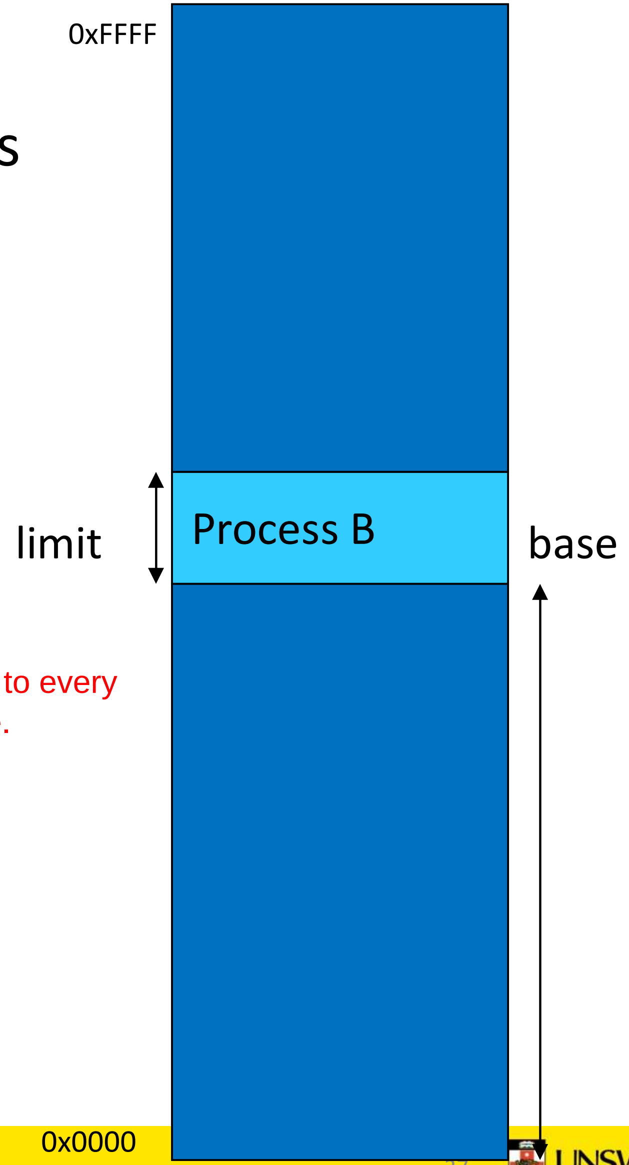
process b expects to run from 0 up. We told the compiler linker that this process will grow from 0 up to some limit. If the internal references point to the right location



Hardware Support for Runtime Binding and Protection

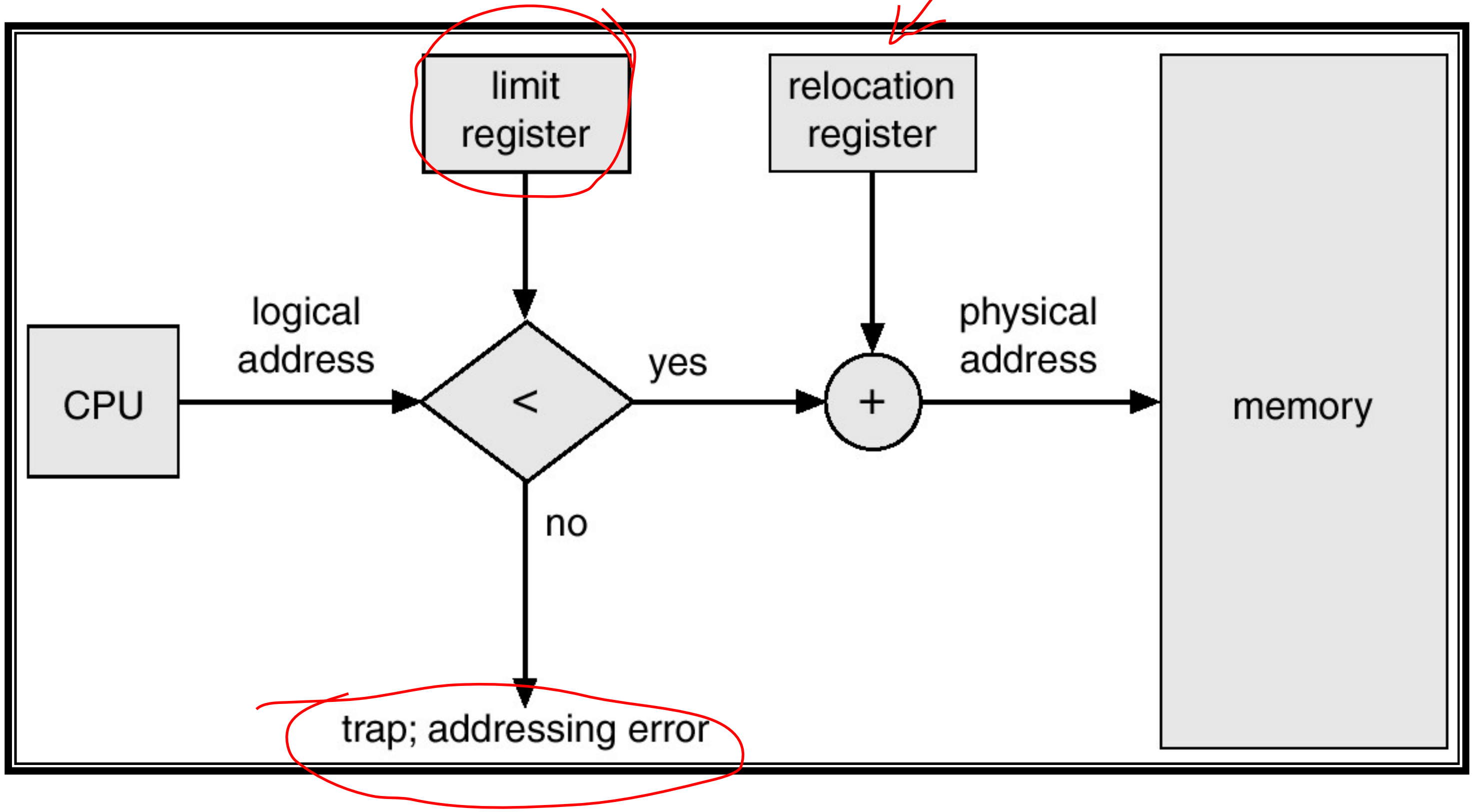
- For process B to run using logical addresses
  - Need to add an appropriate offset to its logical addresses
    - Achieve relocation
    - Protect memory “lower” than B
  - Must limit the maximum logical address B can generate
    - Protect memory “higher” than B

we can trick process B to think that it is running at address 0 if we add an offset to every address B issues that pushes the reference address down to where it should be.



Hardware Support for Relocation and Limit Registers

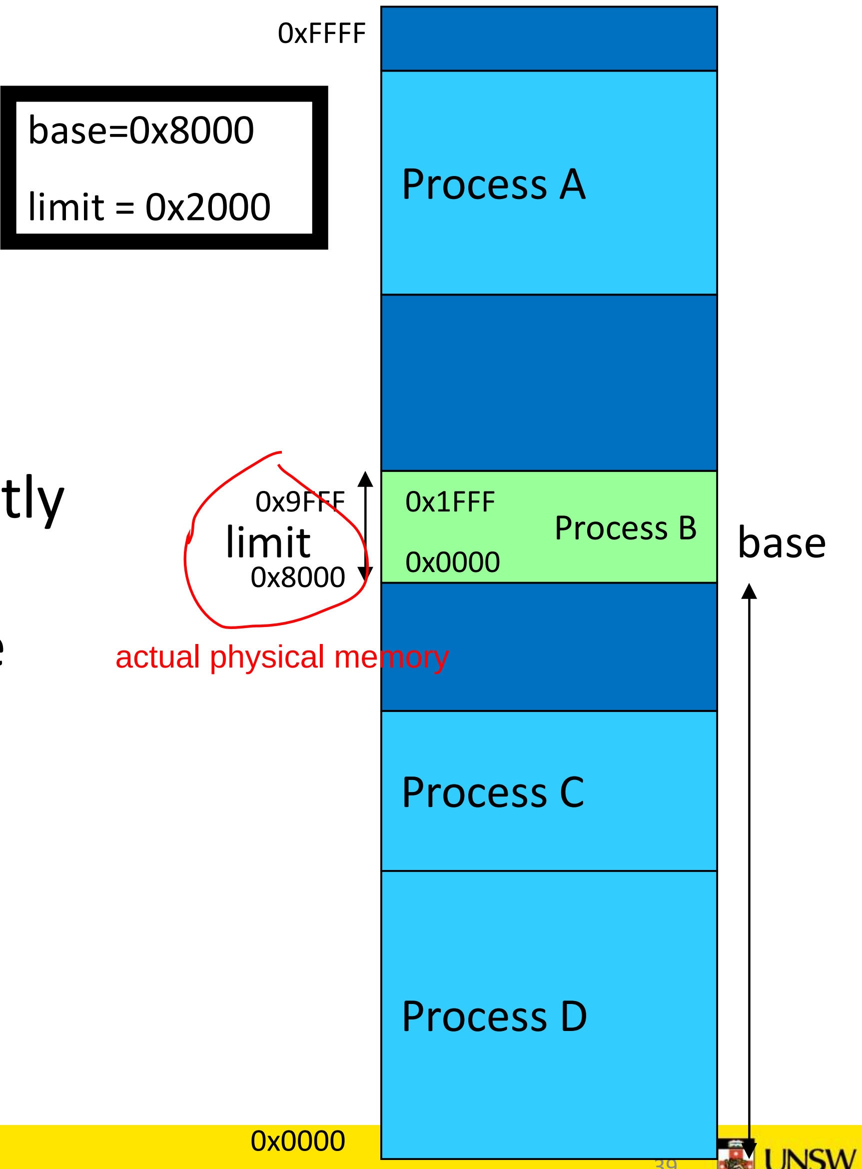
add the offset to the logical address



if the address is bigger than the limit, the os can terminate this process

Base and Limit Registers

- Also called
  - Base and bound registers
  - Relocation and limit registers
- Base and limit registers
  - Restrict and relocate the currently active process
  - Base and limit registers must be changed at
    - Load time
    - Relocation (compaction time)
    - On a context switch



Base and Limit Registers

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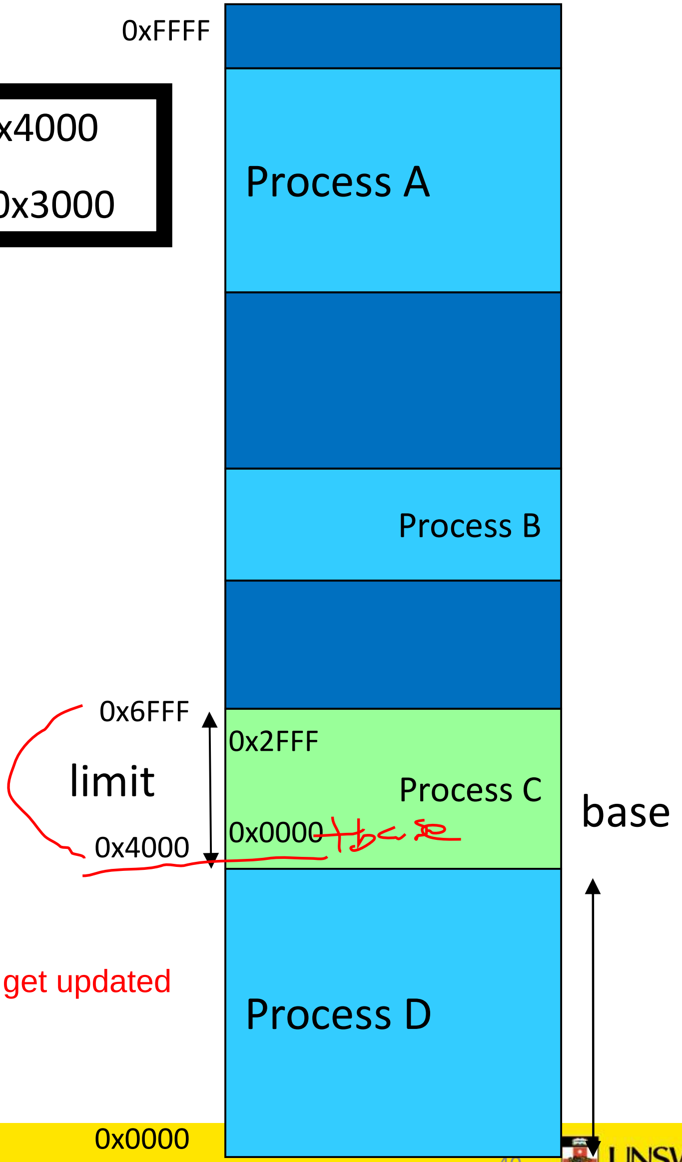
  - Restrict and relocate the currently active process
  - Base and limit registers must be changed at
    - Load time
    - Relocation (compaction time)
    - On a context switch

if I context switch back and forth between the two, the base and limit registers get updated

base=0x4000

limit = 0x3000



Base and Limit Registers

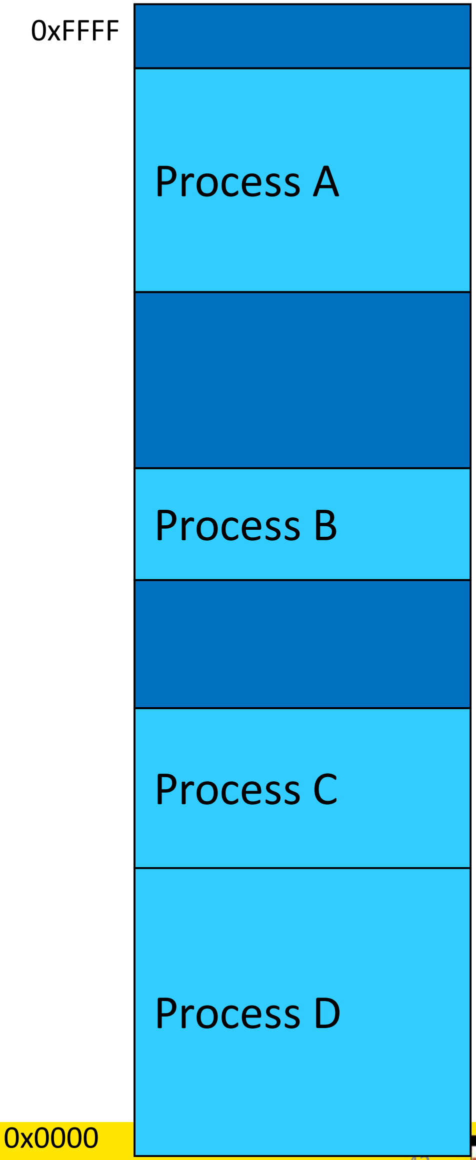
- Pro
  - Supports protected multi-processing (-tasking)
- Cons
  - Physical memory allocation must still be contiguous
  - The entire process must be in memory
  - Do not support partial sharing of address spaces
    - No shared code, libraries, or data structures between processes

hard to share - serious limitation

In a timesharing machine, there is a mix of active and inactive programs running at the same time. Compared to base and limit machine

Timesharing

- Thus far, we have a system suitable for a batch system
  - Limited number of dynamically allocated processes
    - Enough to keep CPU utilised
  - Relocated at runtime
  - Protected from each other
- But what about timesharing?
  - We need more than just a small number of processes running at once
  - Need to support a mix of active and inactive processes, of varying longevity

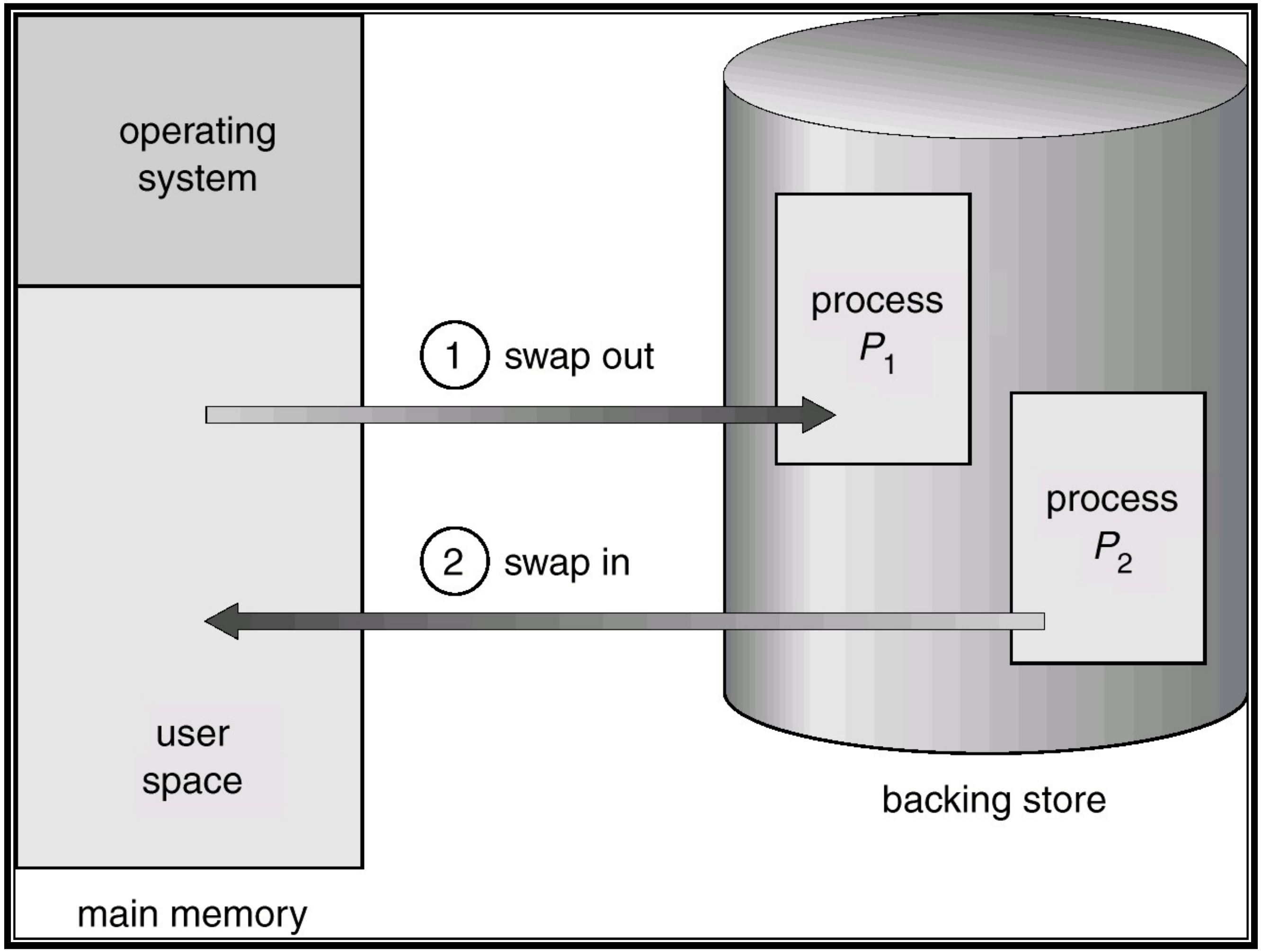


Swapping

an inactive program can be copied out from the memory to secondary storage, and copied back to ram in the future.

- A process can be *swapped* temporarily out of memory to a *backing store*, and then brought back into memory for continued execution.
- Backing store – fast disk large enough to accommodate copies of all memory images for all users; must provide direct access to these memory images.
- Can prioritize – lower-priority process is swapped out so higher-priority process can be loaded and executed.
- Major part of swap time is transfer time; total transfer time is directly proportional to the *amount* of memory swapped.
  - slow issue with swapping technique

Schematic View of Swapping



So far we have assumed a process is smaller than memory

- What can we do if a process is larger than main memory?

Virtual Memory

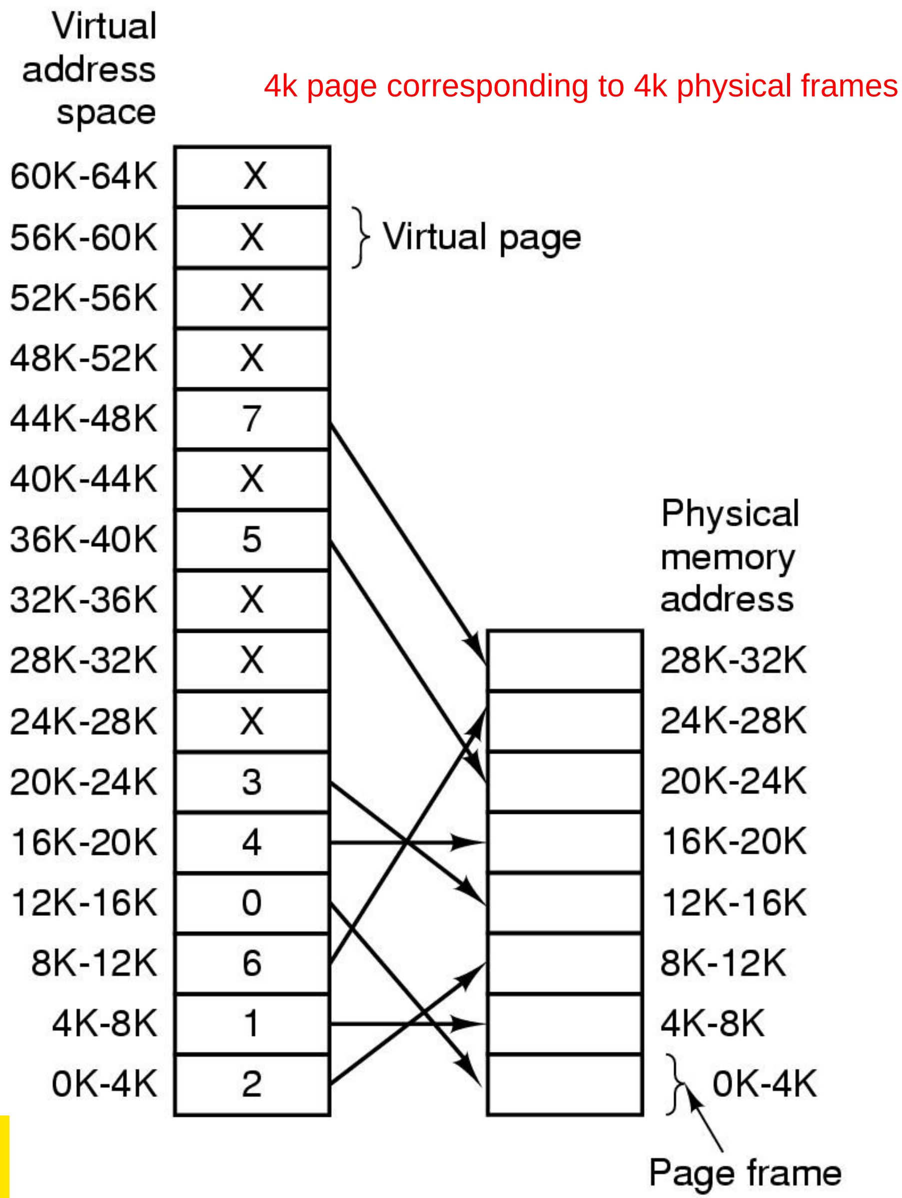
- Developed to address the issues identified with the simple schemes covered thus far.
- Two classic variants
  - Paging
  - Segmentation
    - (no longer covered in course, see textbook if interested)

- Paging is now the dominant one of the two
  - We'll focus on it
- Some architectures support hybrids of the two schemes
  - E.g. Intel IA-32 (32-bit x86) segment architecture with paging in it
    - Becoming less relevant

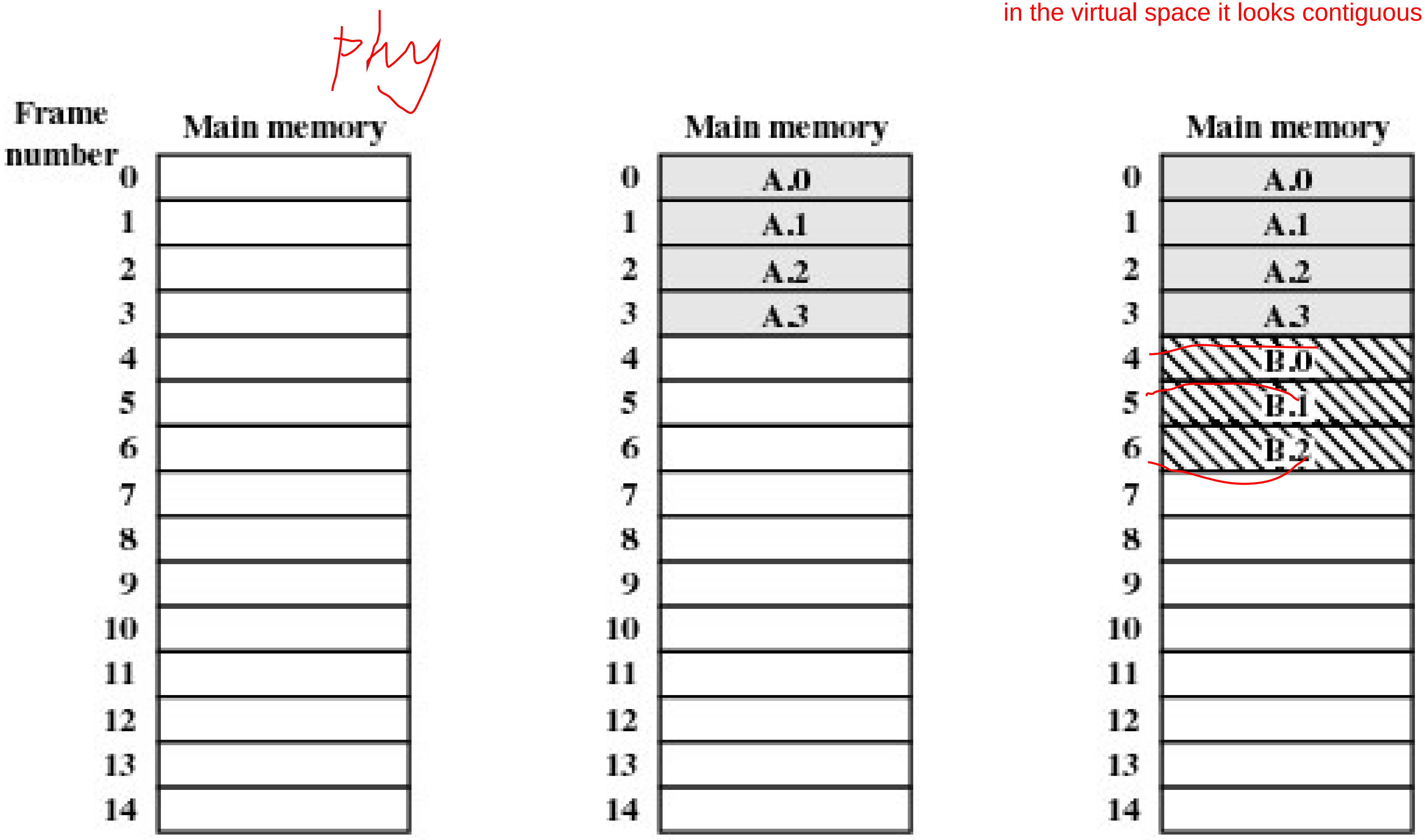
Virtual Memory – Paging Overview

- Partition physical memory into small equal sized chunks
  - Called *frames*
- Divide each process’s virtual (logical) address space into same size chunks
  - Called pages
  - Virtual memory addresses consist of a *page number* and *offset* within the page
- OS maintains a *page table*
  - contains the frame location for each page
  - Used by *hardware* to translate each virtual address to physical address
  - The relation between virtual addresses and physical memory addresses is given by page table
- Process’s physical memory does **not** have to be contiguous

4k page corresponding to 4k physical frames

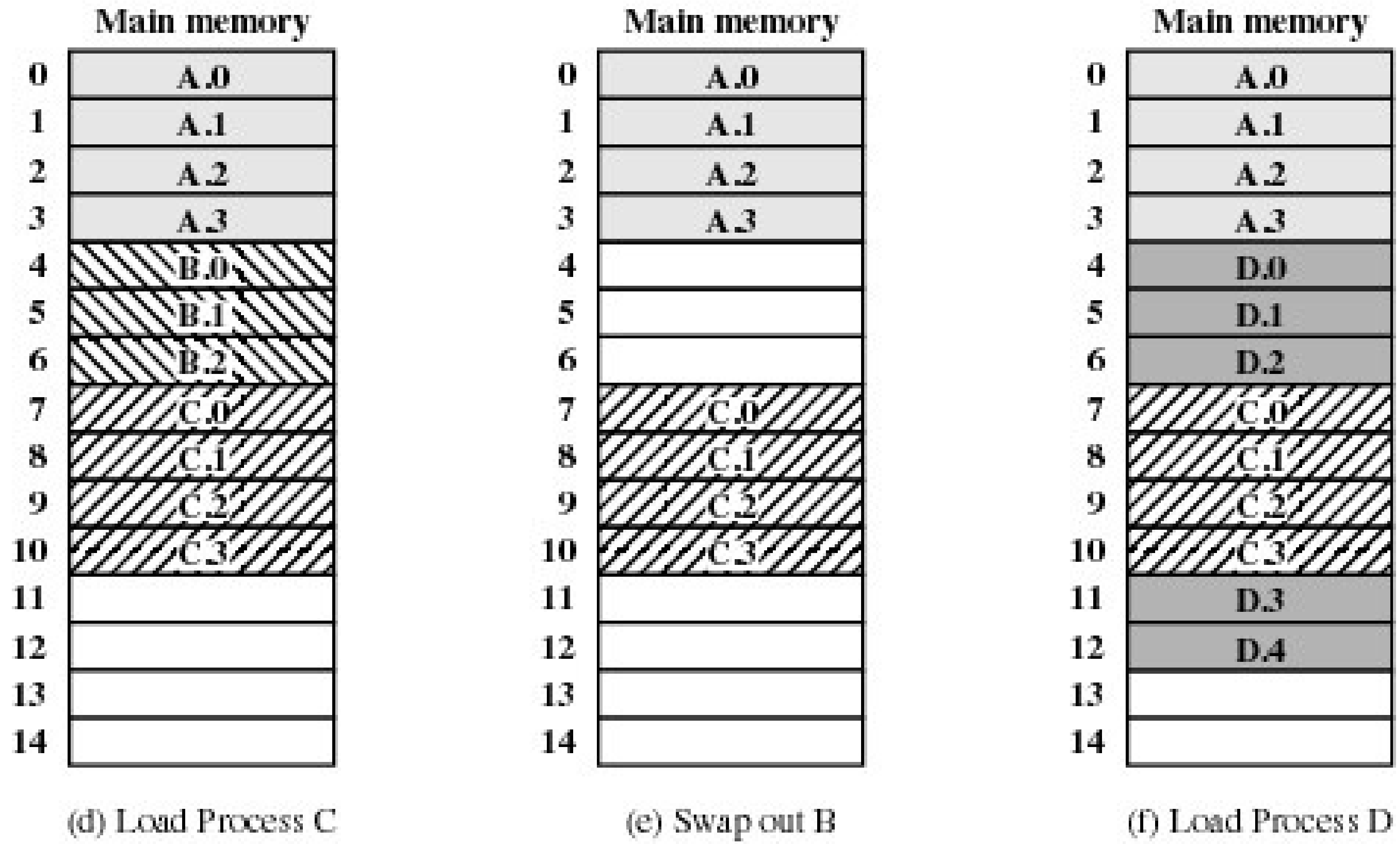


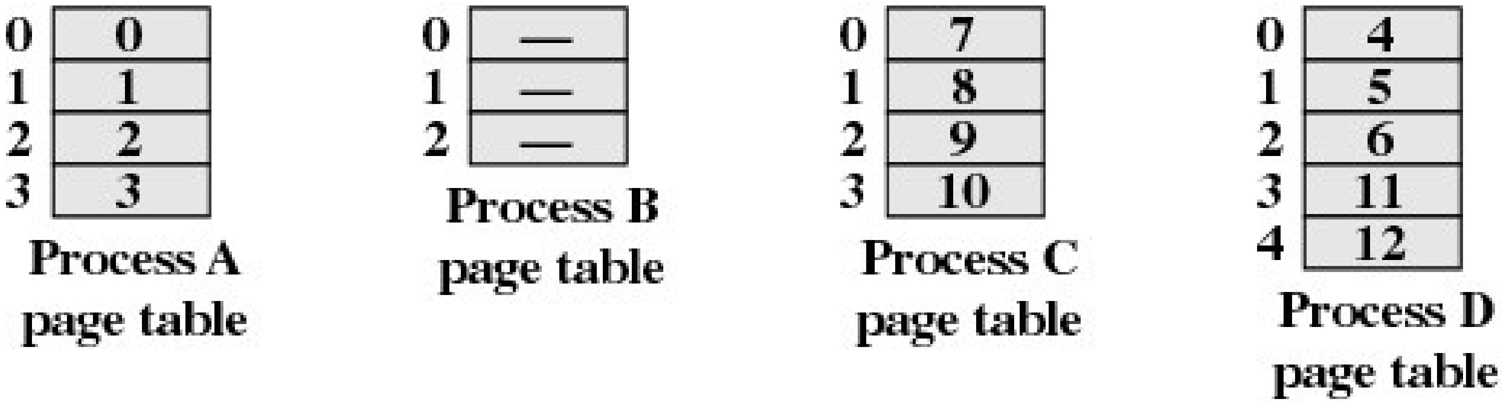
in the virtual space it looks contiguous



(a) Fifteen Available Frames (b) Load Process A (b) Load Process B

Figure 7.9 Assignment of Process Pages to Free Frames





free frame list
process page table
main memory physical memory table

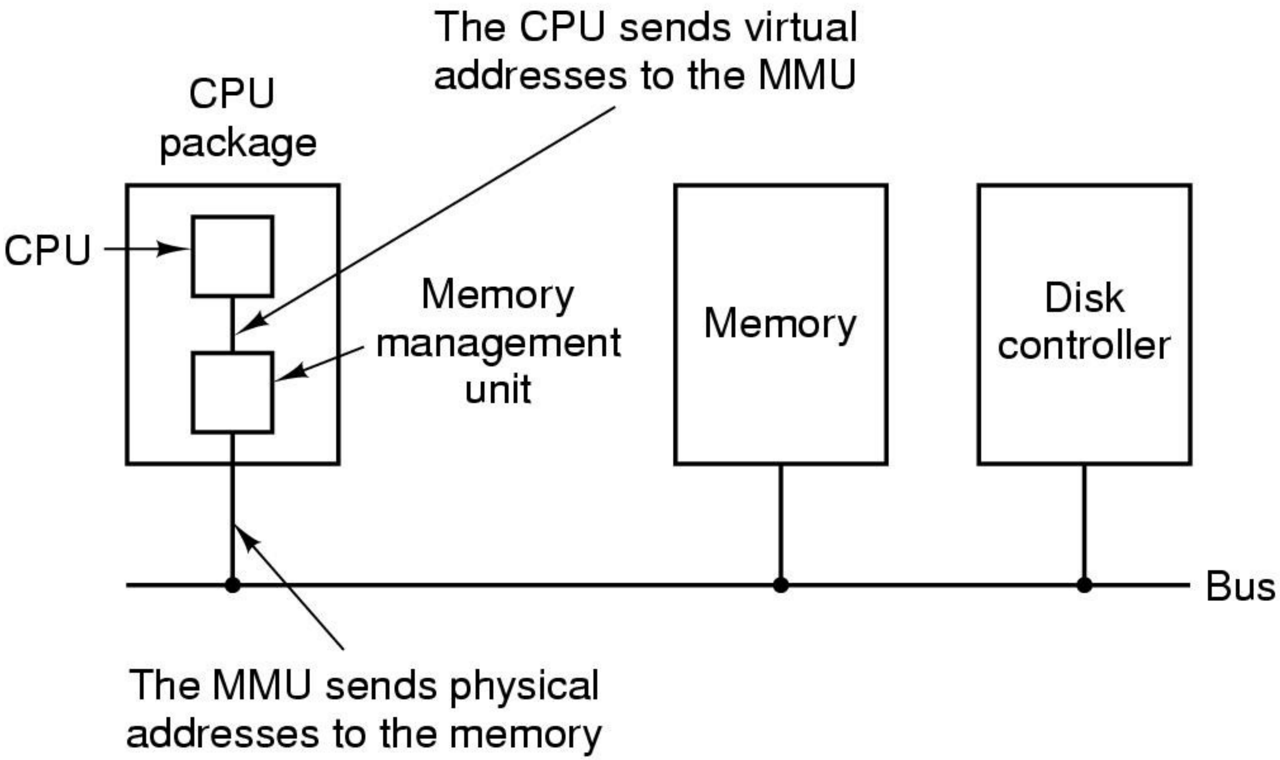
Paging

- No external fragmentation
- Small internal fragmentation (in last page)
- Allows sharing by *mapping* several pages to the same frame
- Abstracts physical organisation
  - Programmer only deal with virtual addresses

we only play with the virtual addresses

- Minimal support for logical organisation
  - Each unit is one or more pages

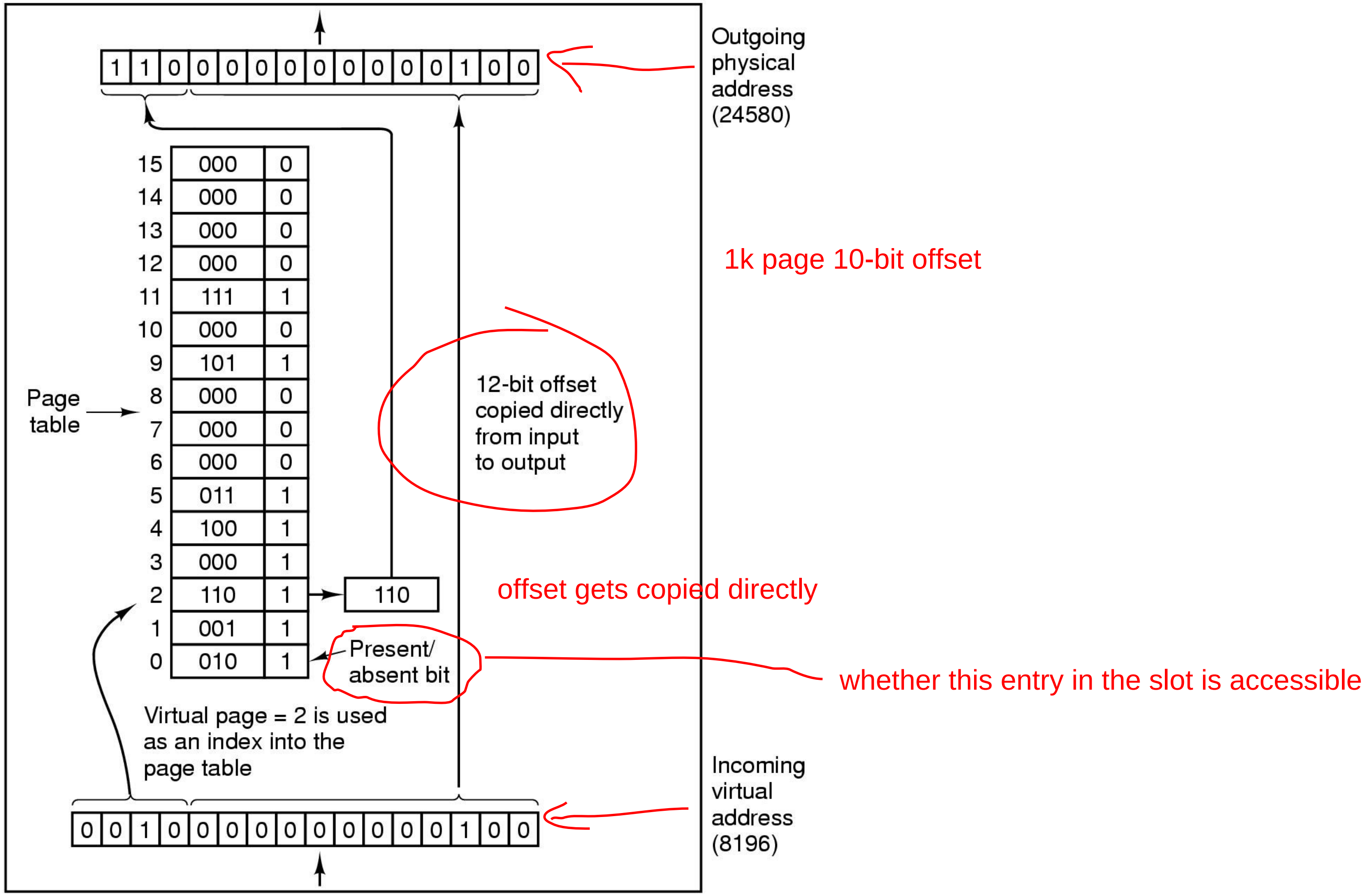
Memory Management Unit
(also called Translation Look-aside Buffer – TLB)



The position and function of the MMU

MMU Operation

Assume for now that the page table is contained wholly in registers within the MMU – in practice it is not



Internal operation of simplified MMU with 16 4 KB pages