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

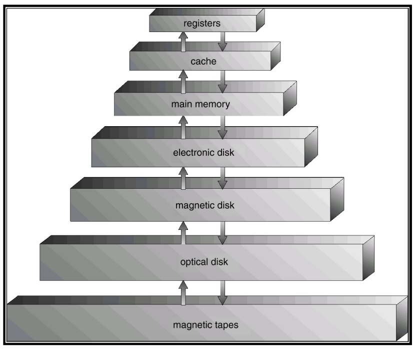
- One or more threads of execution
- Resources required for execution
  - Memory (RAM)
    - Program code ("text")
    - Data (initialised, uninitialised, stack)
    - Buffers held in the kernel on behalf of the process
  - Others
    - CPU time
    - Files, disk space, printers, etc.

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 content between RAM and disk.

Memory Hierarchy

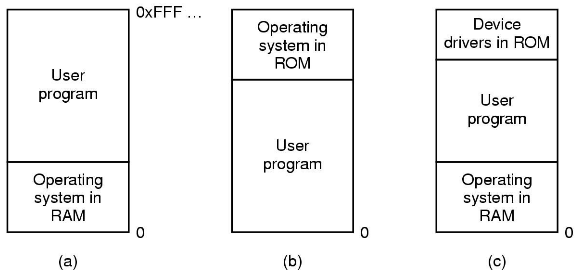
- Ideally, programmers want memory that is
  - Fast
  - Large
  - Nonvolatile
- Not possible
- Memory management coordinates how memory hierarchy is used.
  - Focus usually on RAM ⇔ Disk



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



Three simple ways of organizing memory

- an operating system with one user process

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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

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Idea

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

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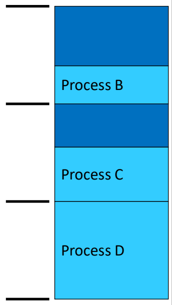
General problem: How to divide memory between processes?

- 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



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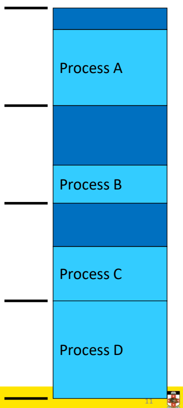
Problem: How to divide memory

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



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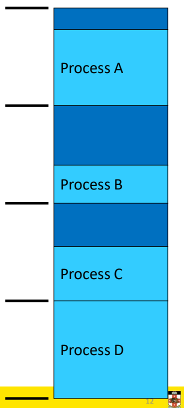
Simple MM: Fixed, equal-sized partitions

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



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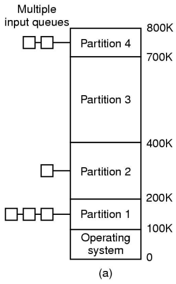
Simple MM: Fixed, variable-sized partitions

- 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



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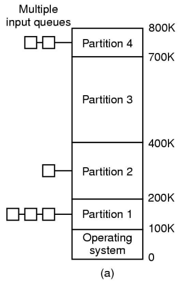
- Issue
  - Some partitions may be idle
    - Small jobs available, but only large partition free
    - Workload could be unpredictable



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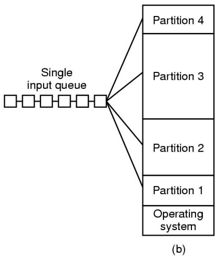
Alternative queue strategy

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



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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

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Dynamic Partitioning

- 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

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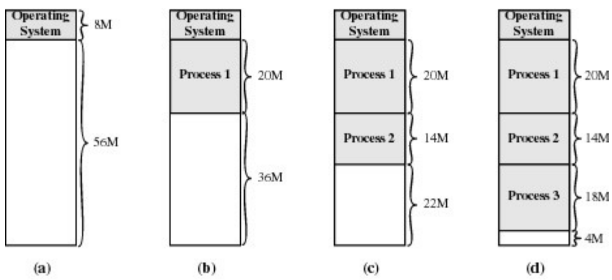

Figure 7.4 The Effect of Dynamic Partitioning

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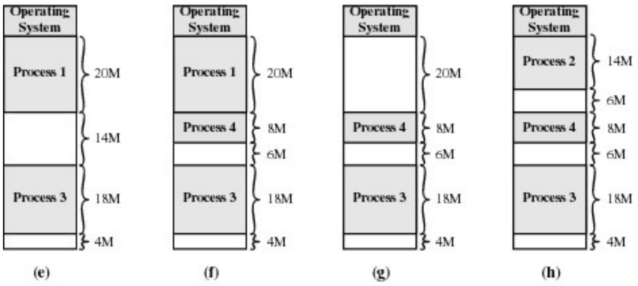

Figure 7.4 The Effect of Dynamic Partitioning

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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

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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.

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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

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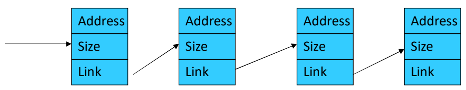
Classic Approach

- 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 can be stored in the "holes" themselves



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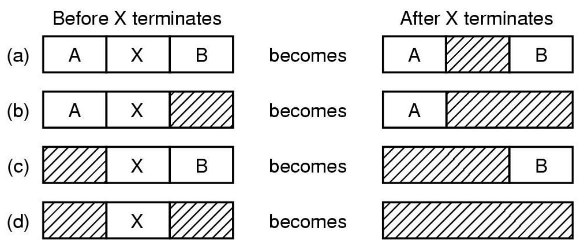
Coalescing Free Partitions with Linked Lists



Four neighbor combinations for the terminating process X

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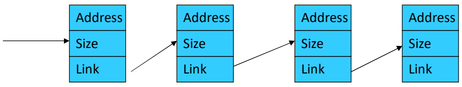
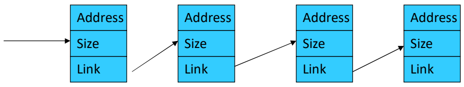
Dynamic Partitioning Placement Algorithm

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



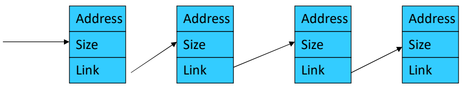
Dynamic Partitioning Placement Algorithm

- 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.



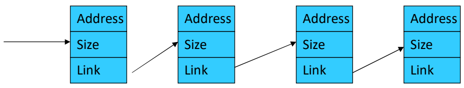
Dynamic Partitioning Placement Algorithm

- 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



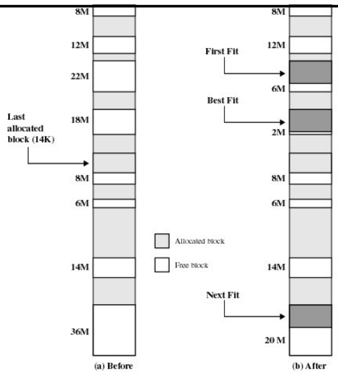


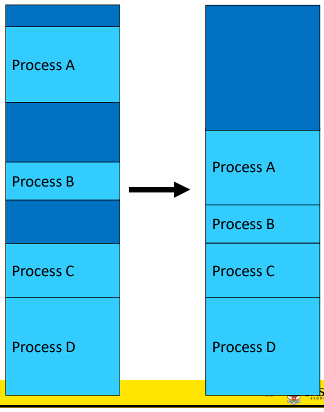
Figure 7.5 Example Memory Configuration Before and After Allocation of 16 Mbyte Block

Dynamic Partition Allocation Algorithm

- Summary
  - 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.
  - Only if we can relocate running programs?
    - Pointers?
  - Generally requires hardware support



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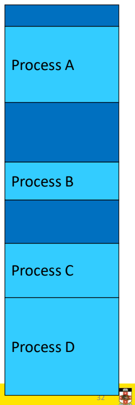
Some Remaining Issues with Dynamic Partitioning

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



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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?

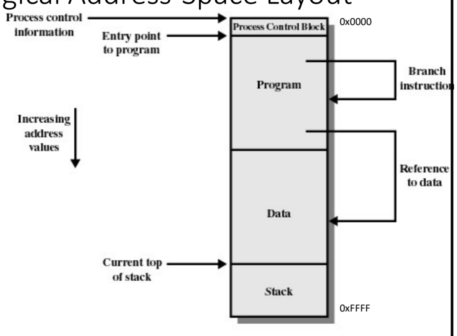

Figure 7.1 Addressing Requirements for a Process

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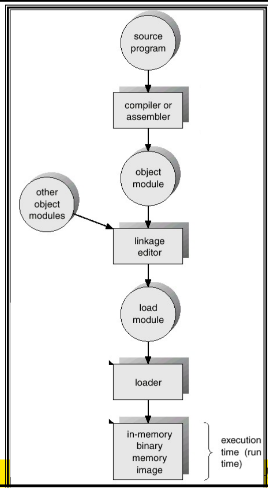
When are memory addresses bound?

- 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.*



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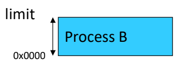
Hardware Support for Runtime Binding and Protection

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



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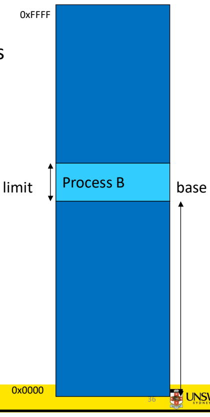
Hardware Support for Runtime Binding and Protection

- 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



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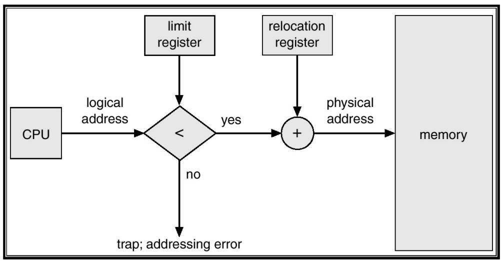
Hardware Support for Relocation and Limit Registers



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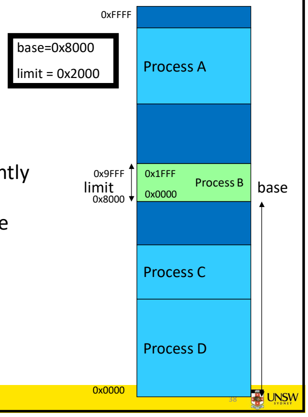
Base and Limit Registers

- 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



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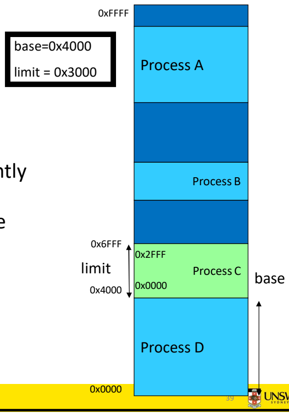

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Base and Limit Registers

- 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

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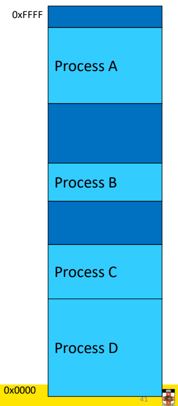
Timesharing

- 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



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Swapping

- A process can be *swapped* temporarily out of memory to a *backing store*, and then brought back into memory for continued execution.
- Swapping involves transferring the whole process
- 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

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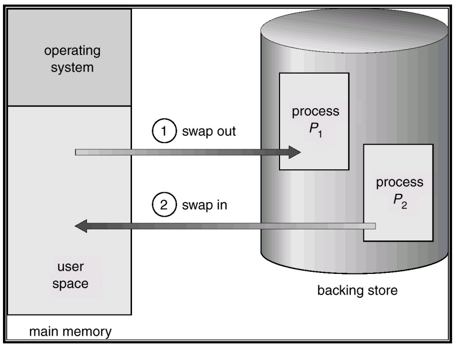
Schematic View of Swapping



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So far we have assumed a process is smaller than memory

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

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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)
    - Becoming less relevant

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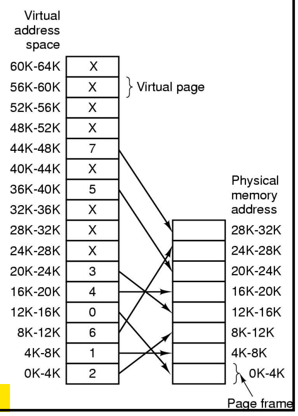
Virtual Memory – Paging Overview

- 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



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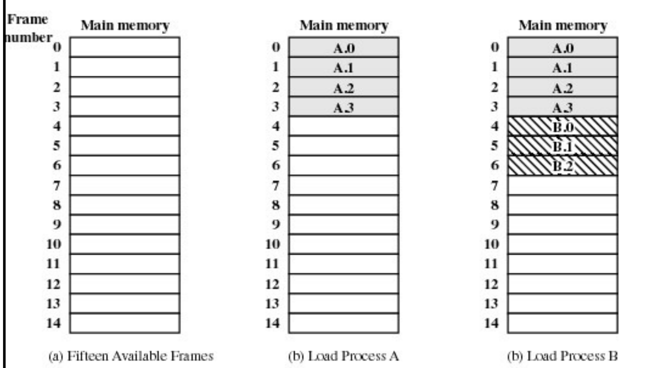

Figure 7.9 Assignment of Process Pages to Free Frames

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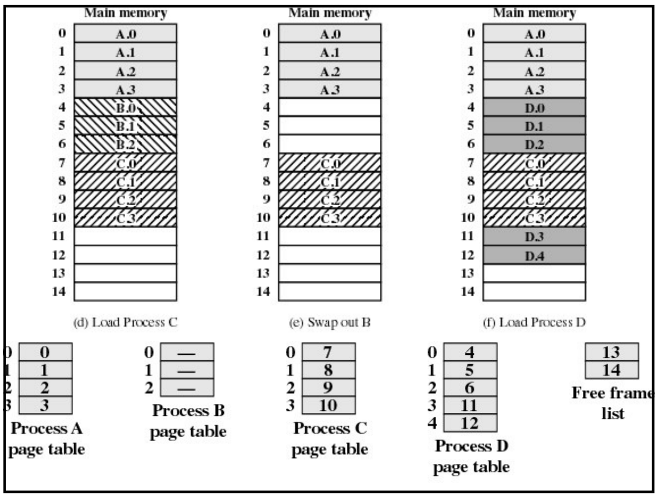

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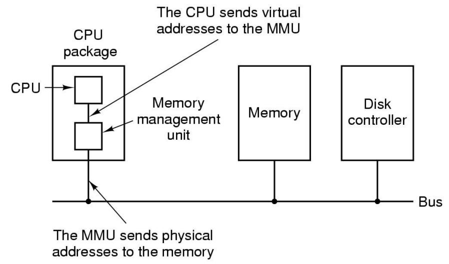
Paging

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

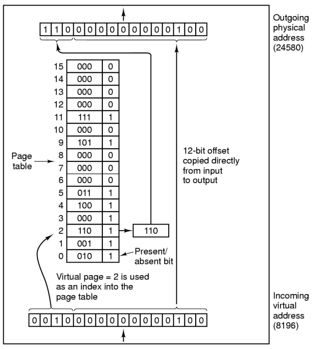
Memory Management Unit
(also called Translation Look-aside Buffer – TLB)



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