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

registers

cache

main memory

electronic disk

magnetic disk

optical disk

magnetic tapes
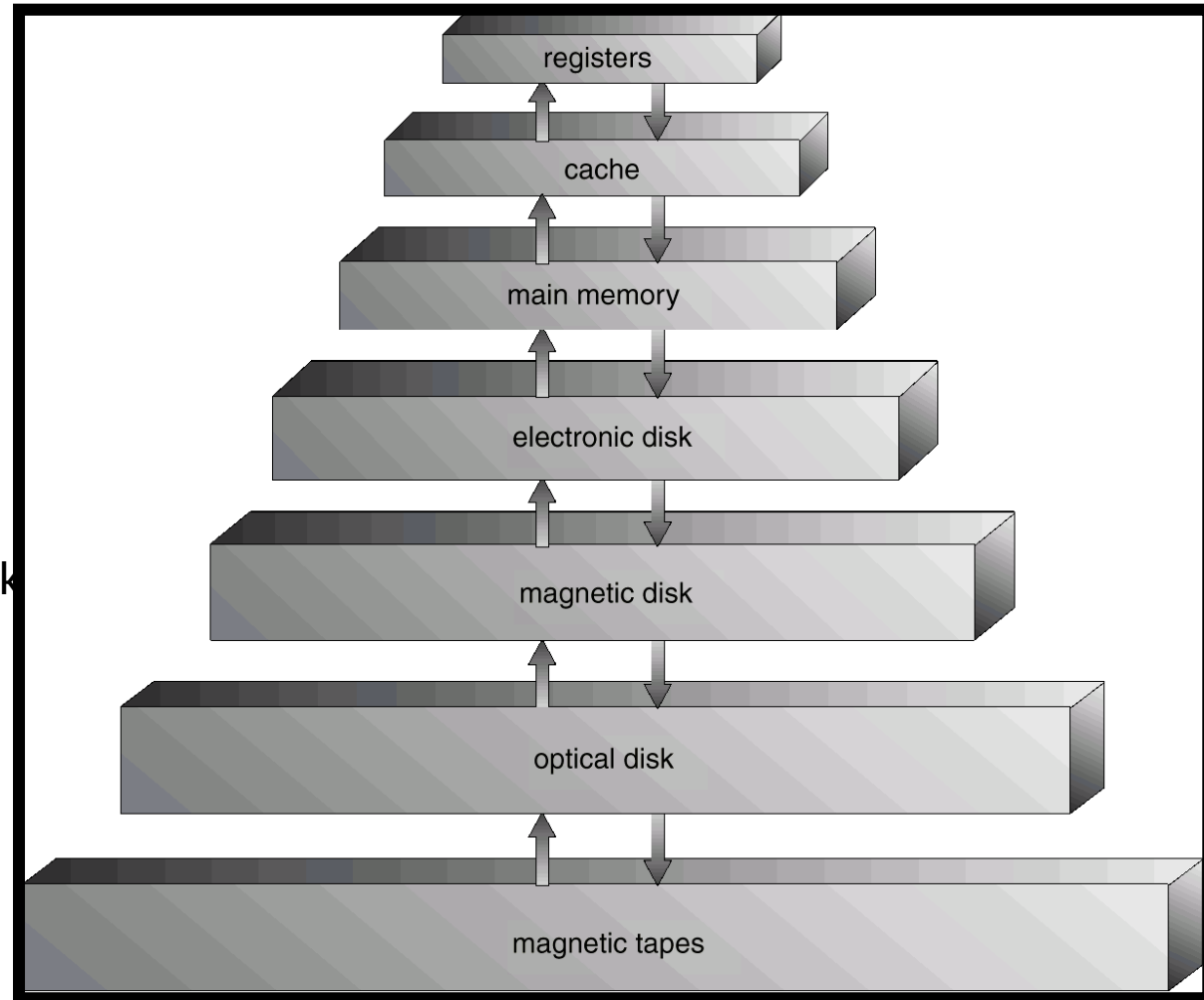
OS Memory Management

- 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.

- Like other topics in this course, let's start by considering and ruling out the simple approaches
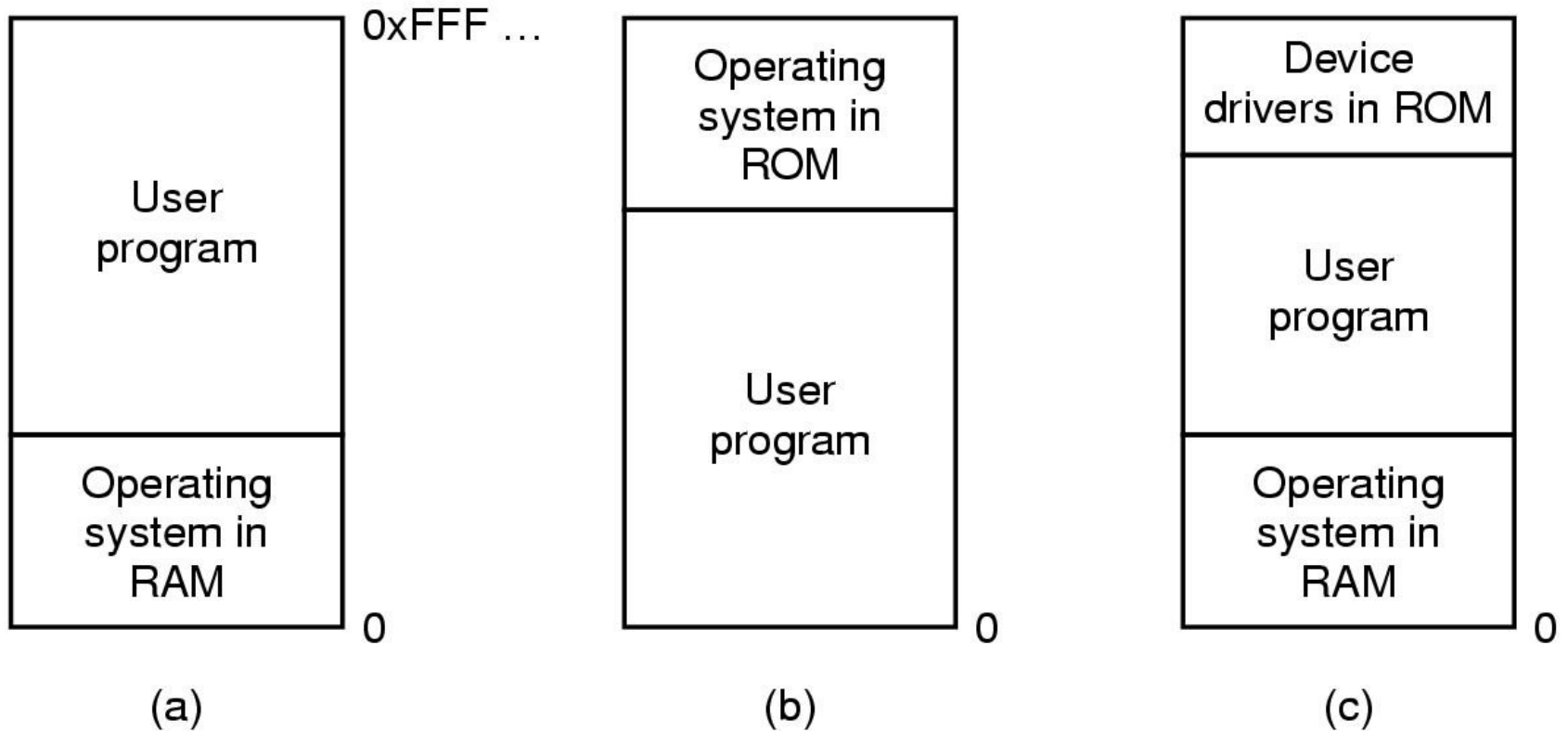
Basic Memory Management
Monoprogramming without Swapping or Paging

(a) | (b) | (c)
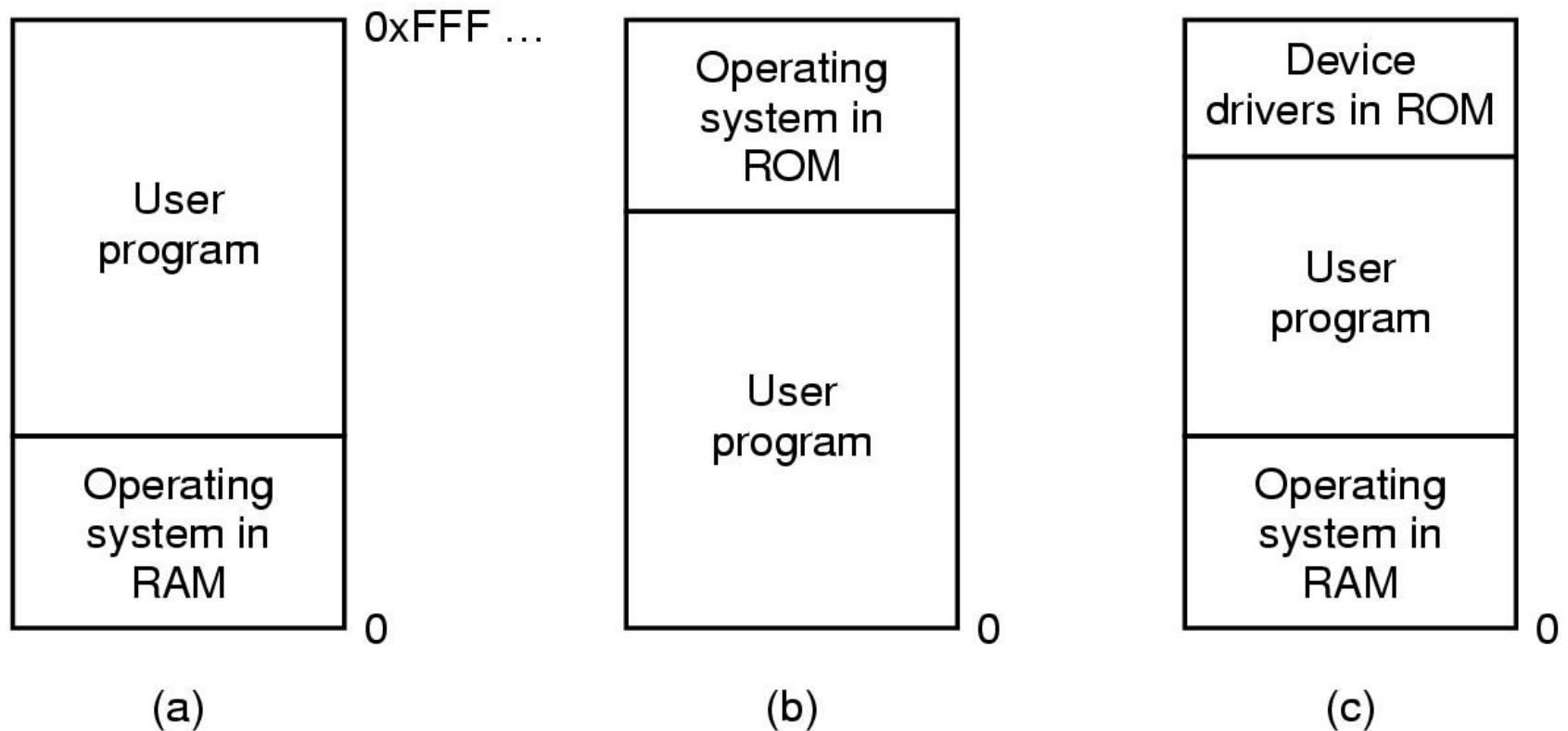
Three simple ways of organizing memory
- an operating system with one user process

(a)   (b)   (c)

These concepts persist:
  - Firmware
 - BIOS

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 utilisation of memory if we switch between jobs with different memory needs

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

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
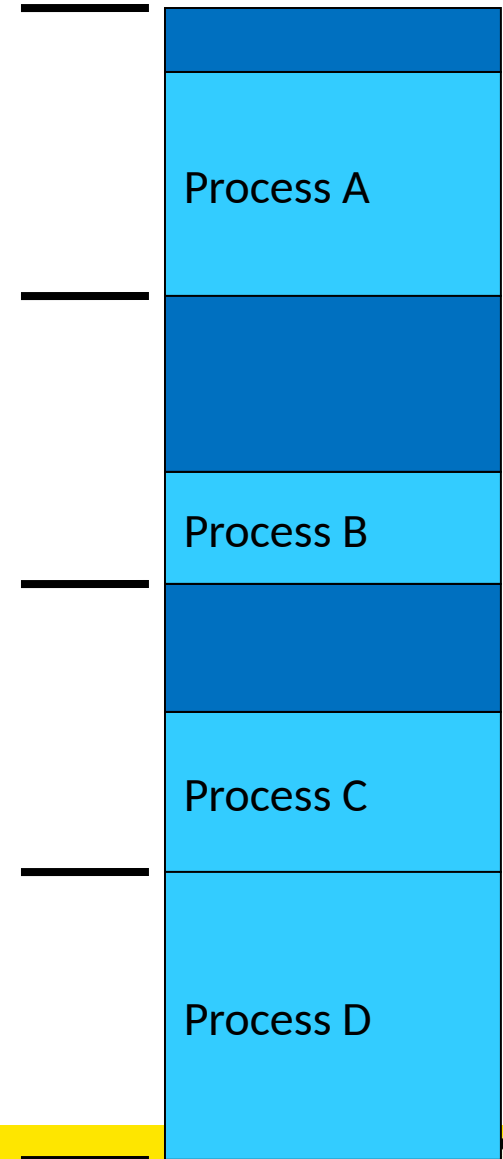
Process B

Process C

Process D

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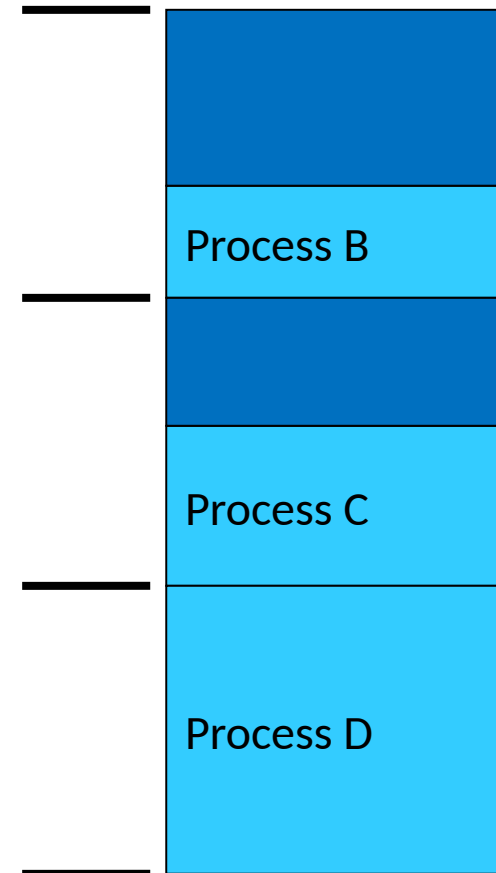
Problem: How to divide memory

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

Process A

Process B

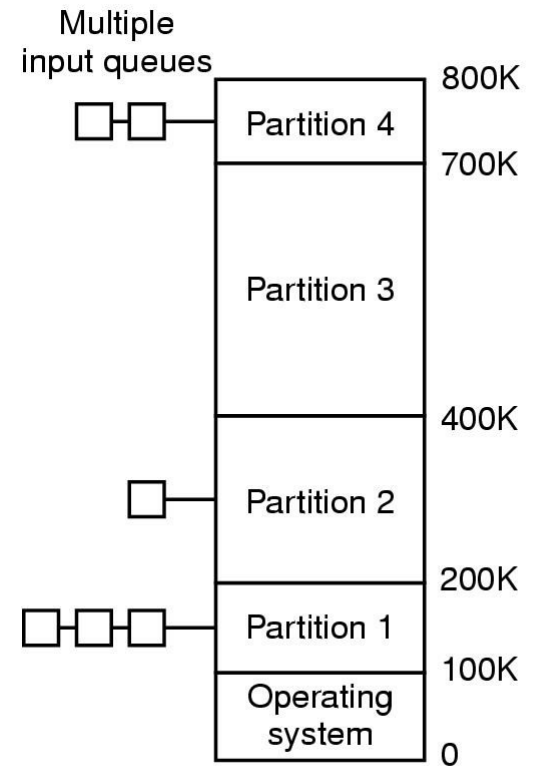Process C

Process D

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SYDNEY
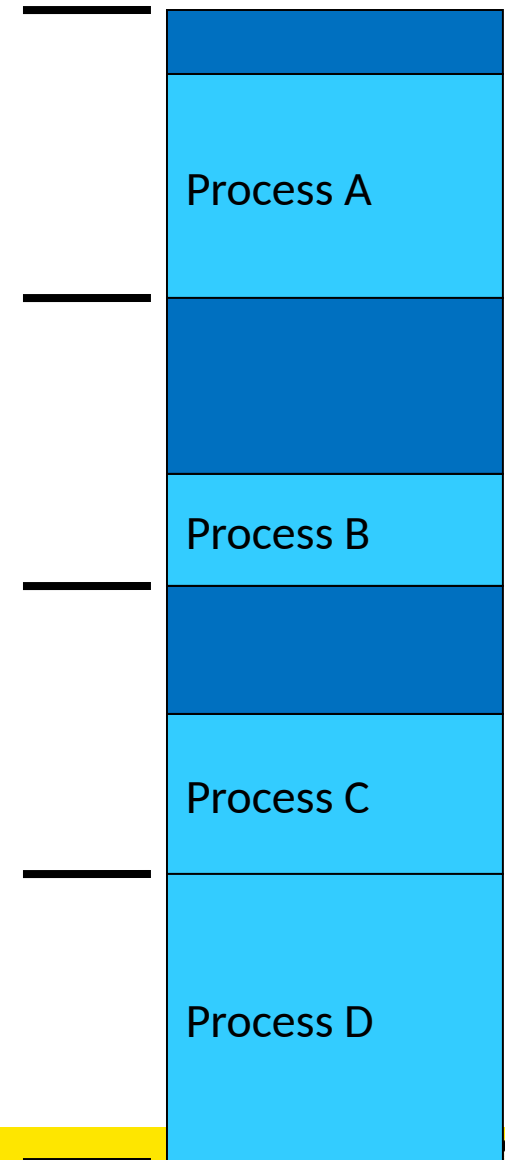
Simple MM: Fixed, equal-sized partitions

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

Process A

Process B

Process C

Process D

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

Multiple input queues

|	800K
Partition 4	700K
Partition 3	
	400K
Partition 2	
	200K
Partition 1	
	100K
Operating system	0

(a)

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

Multiple input queues

Partition 4 — 800K — 700K

Partition 3 — 400K

Partition 2 — 200K

Partition 1 — 100K

Operating system — 0

(a)
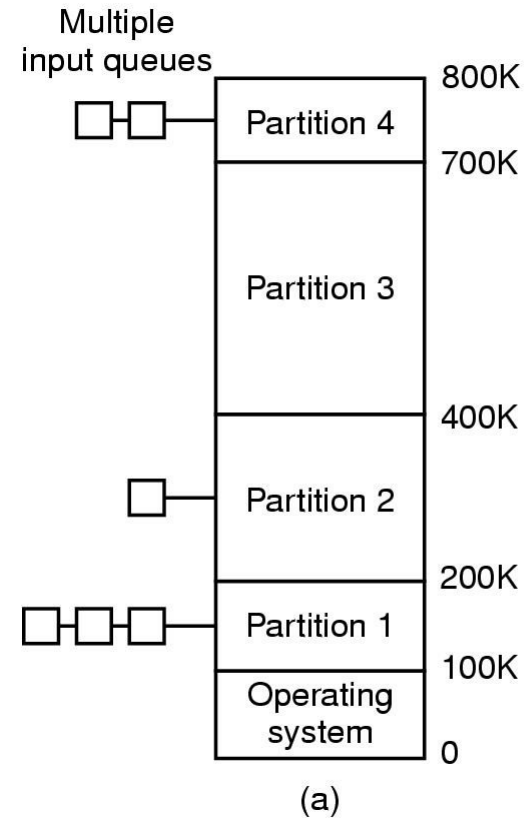
Alternative queue strategy

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

Single input queue

Partition 4

Partition 3

Partition 2

Partition 1

Operating system

(b)
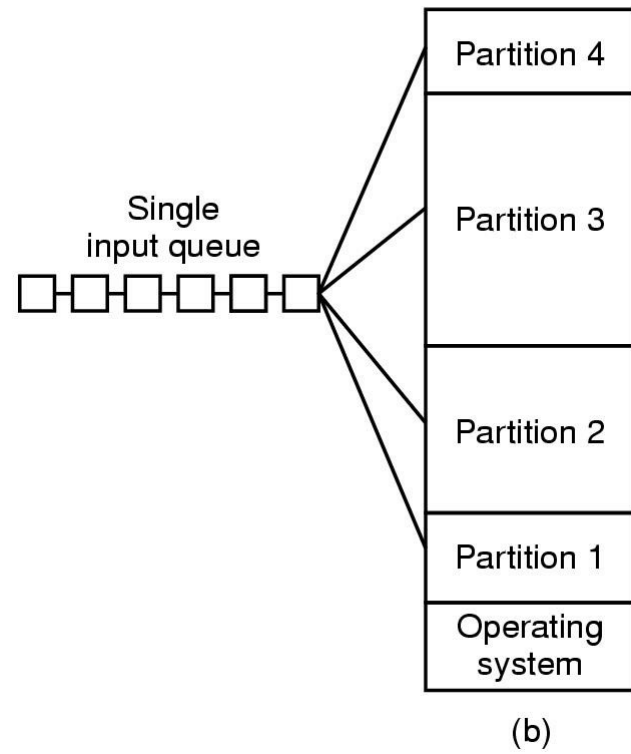
Fixed Partition Summary

- 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

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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
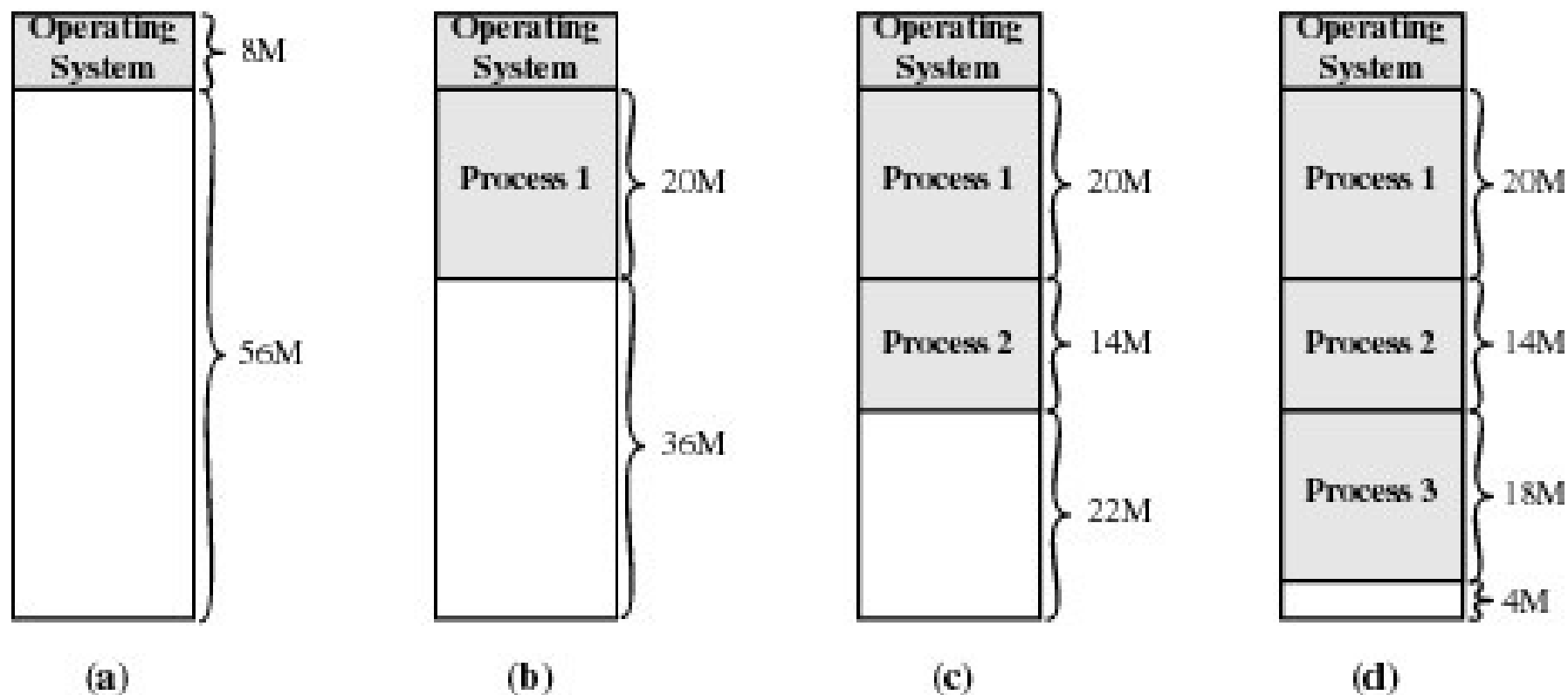 - Assumes a process knows what it needs

Figure 7.4 The Effect of Dynamic Partitioning
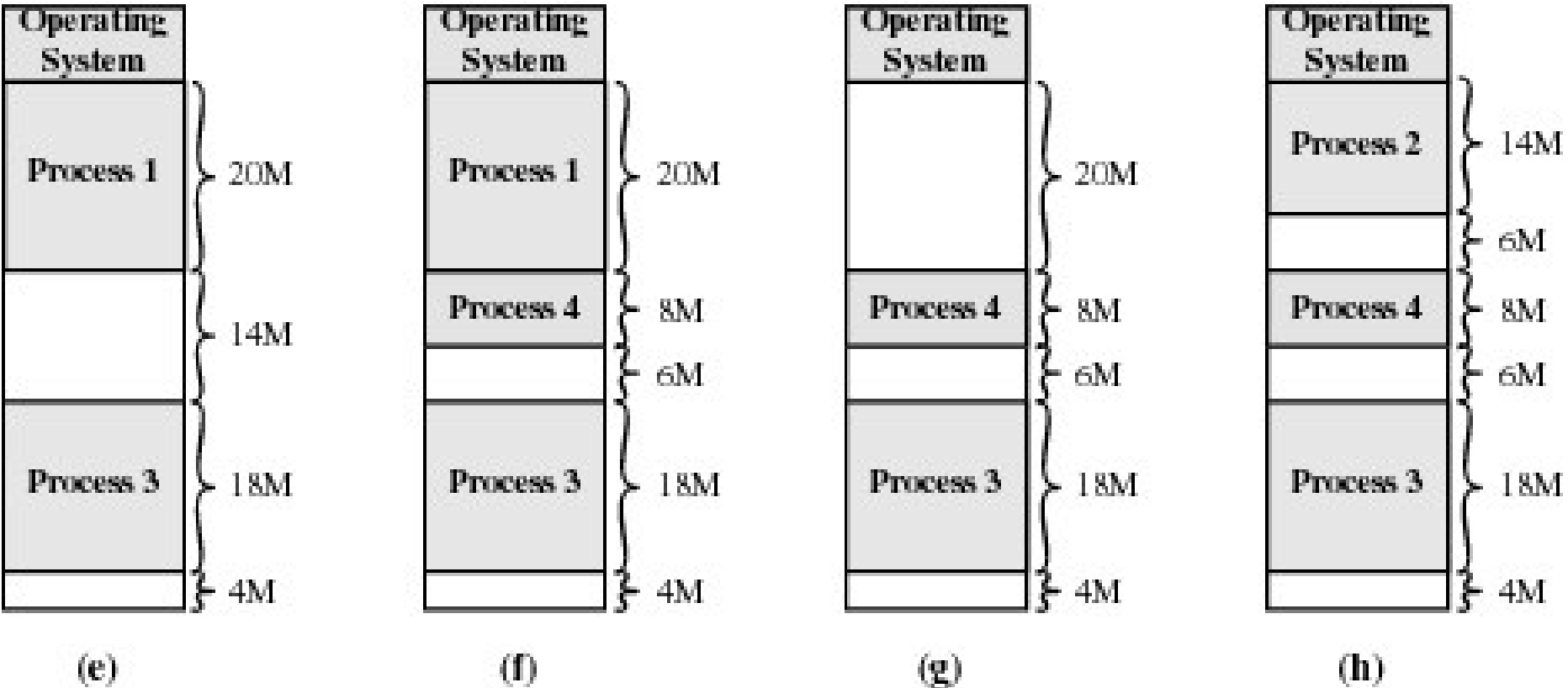
Figure 7.4 The Effect of Dynamic Partitioning

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

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
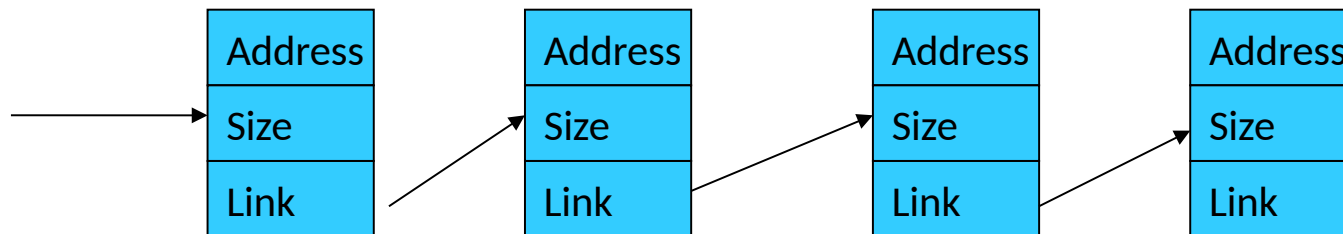
Coalescing Free Partitions with Linked Lists
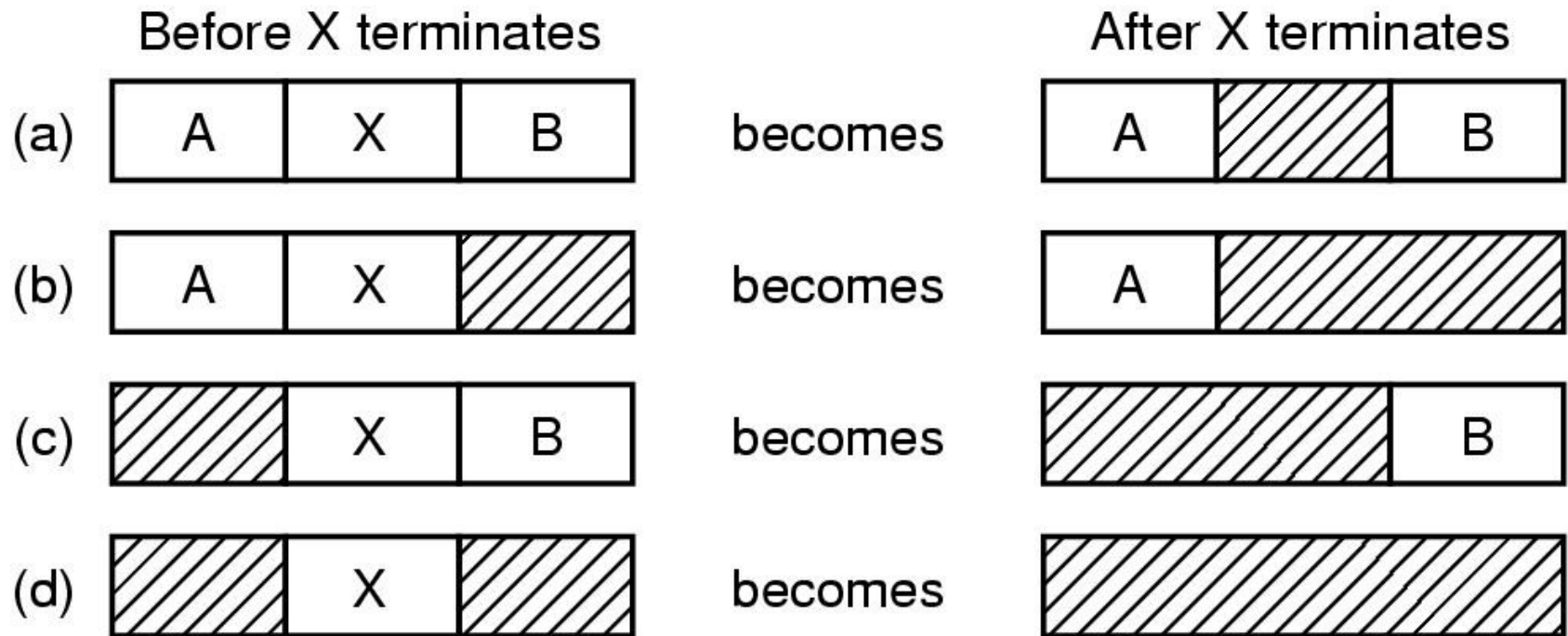
Four neighbor combinations for the terminating process X

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

Address
Size
Link

Address
Size
Link

Address
Size
Link

Address
Size
Link
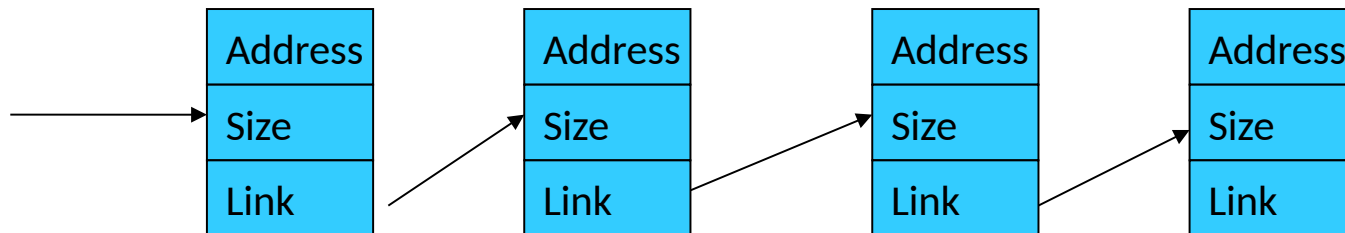
Dynamic Partitioning Placement Algorithm

- 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.

Address
Size
Link

Address
Size
Link

Address
Size
Link

Address
Size
Link

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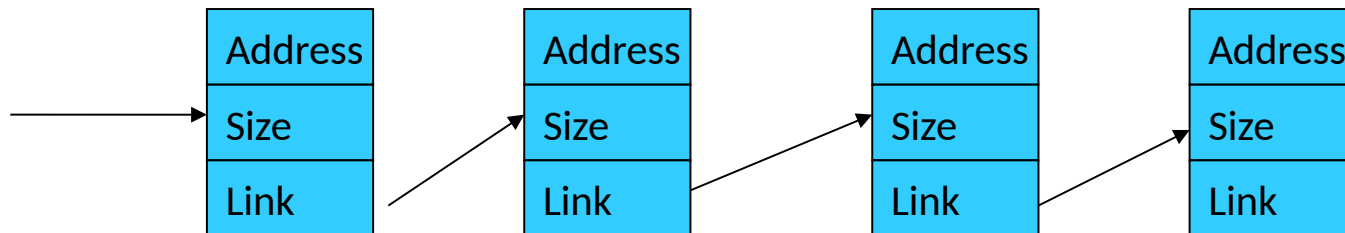
Dynamic Partitioning Placement Algorithm

- 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

Address		Address		Address		Address
Size		Size		Size		Size
Link		Link		Link		Link
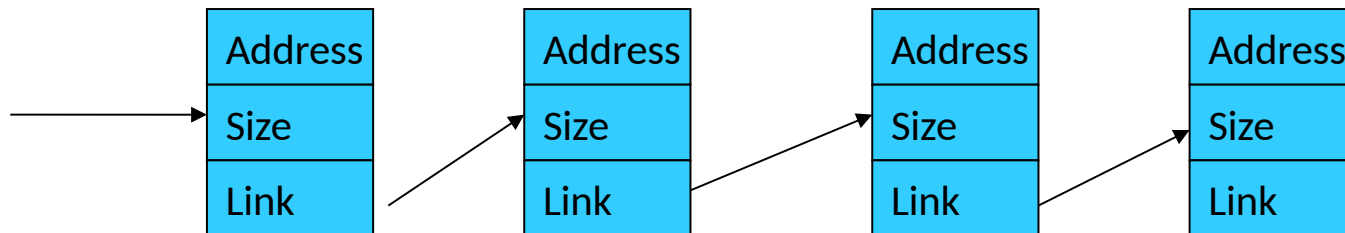
Dynamic Partitioning Placement Algorithm

- 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

Address
Size
Link

Address
Size
Link

Address
Size
Link

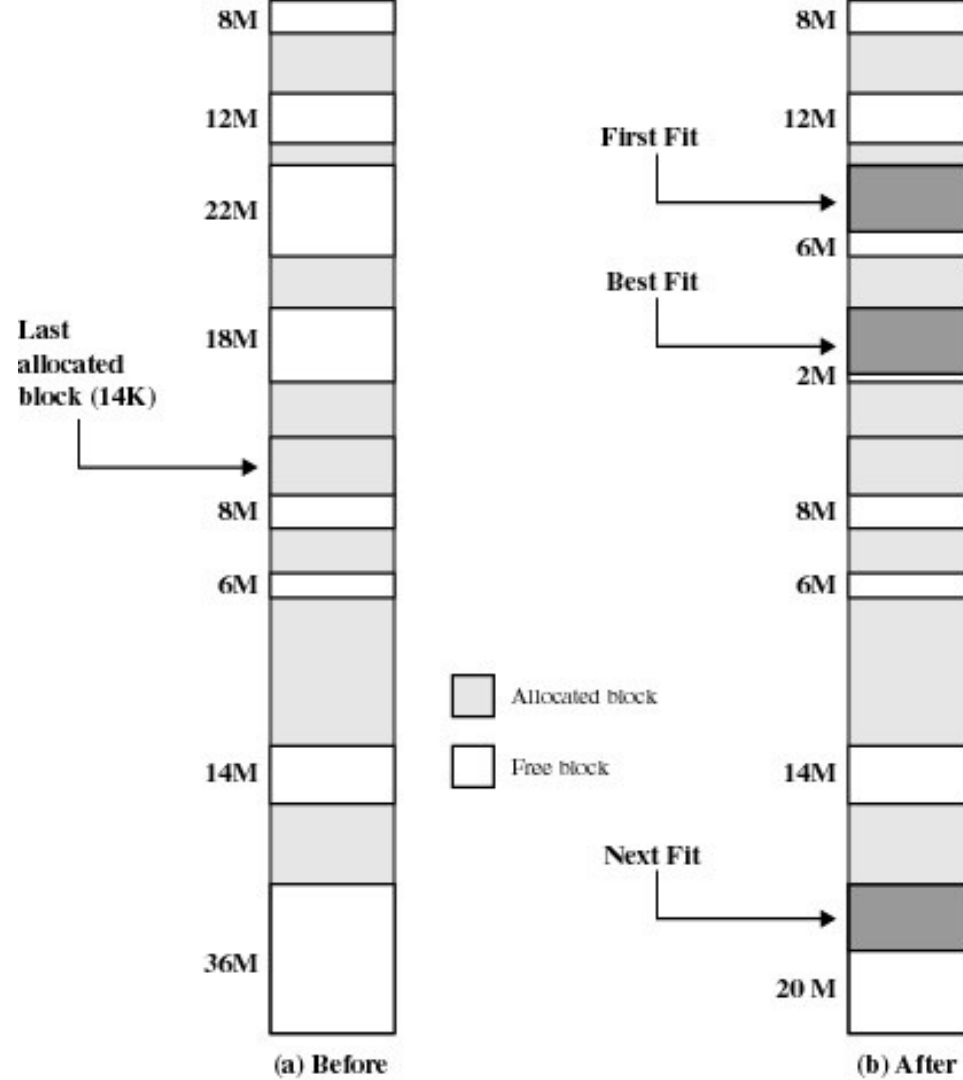| Address |
| --- |
| Size |
| Link |
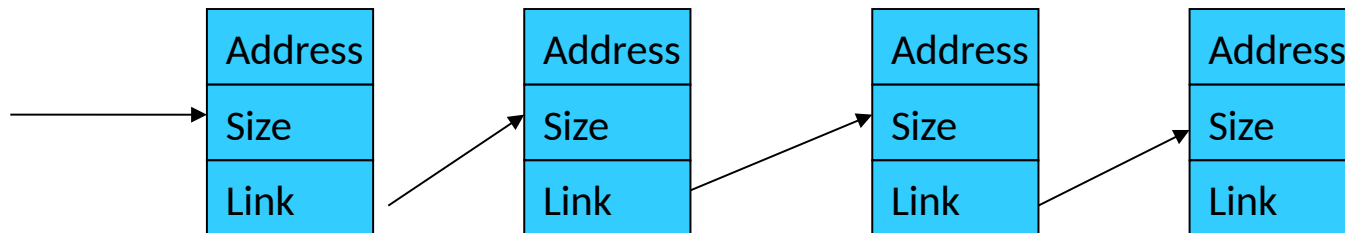
Figure 7.5 Example Memory Configuration Before and After Allocation of 16 Mbyte Block

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.
    - They are similar to issues in disk block 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
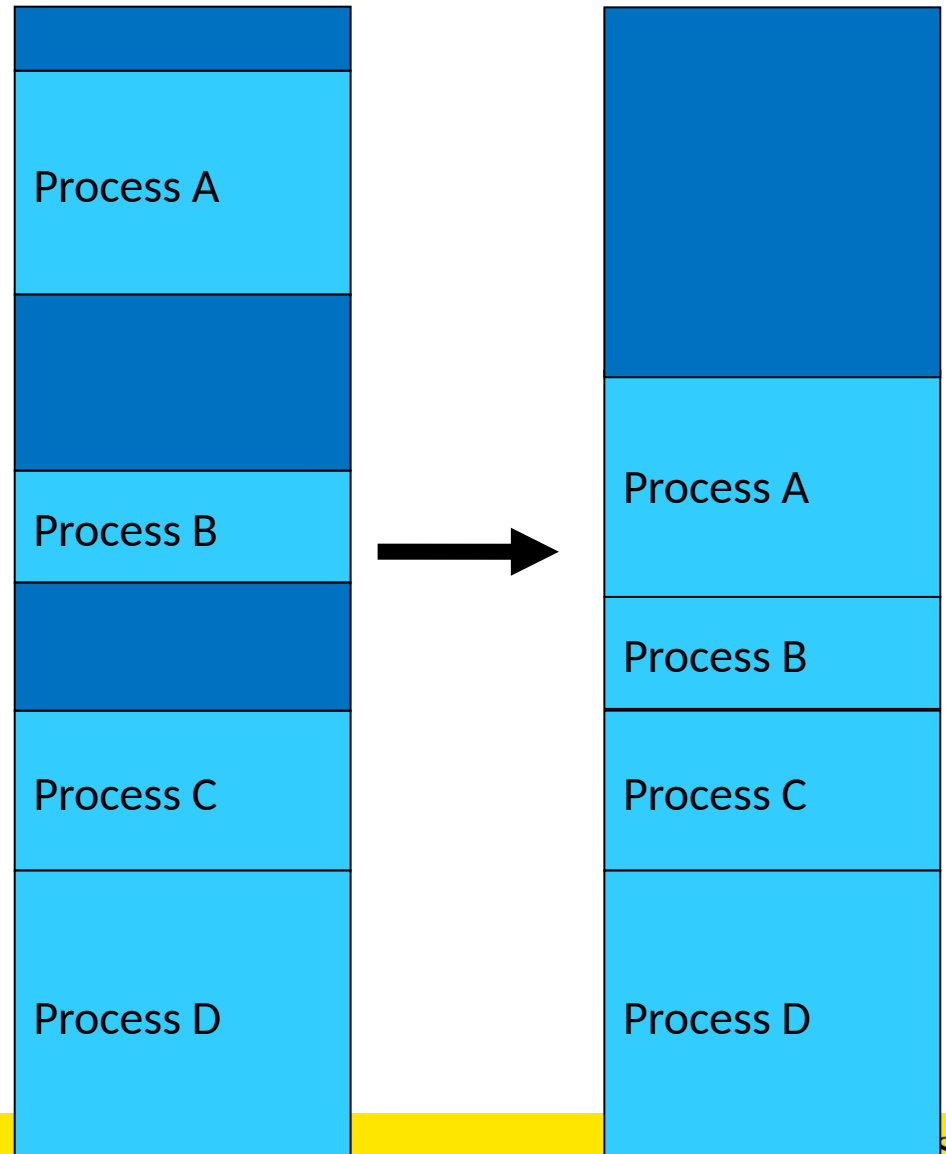
Some Remaining Issues with Dynamic Partitioning

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

Process A
Process B
Process C
Process D

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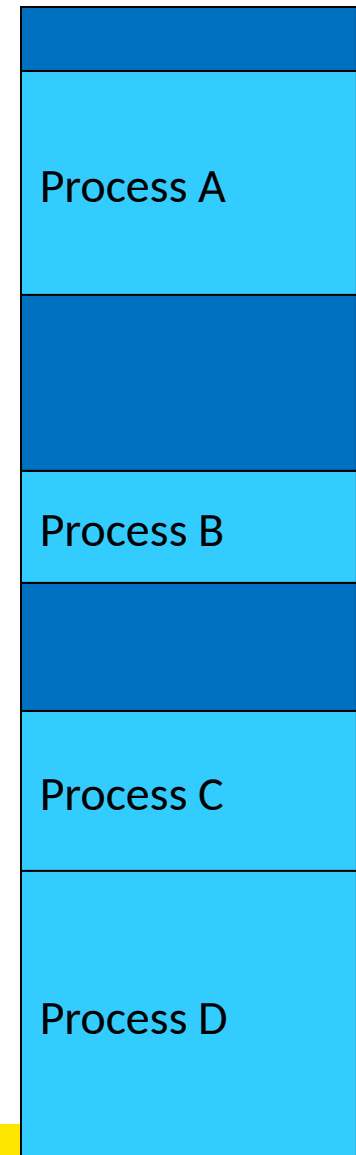
Example Logical Address-Space Layout

- 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?

Process control information → Process Control Block 0x0000

Entry point to program →

Program

Increasing address values

Branch instruction

Reference to data

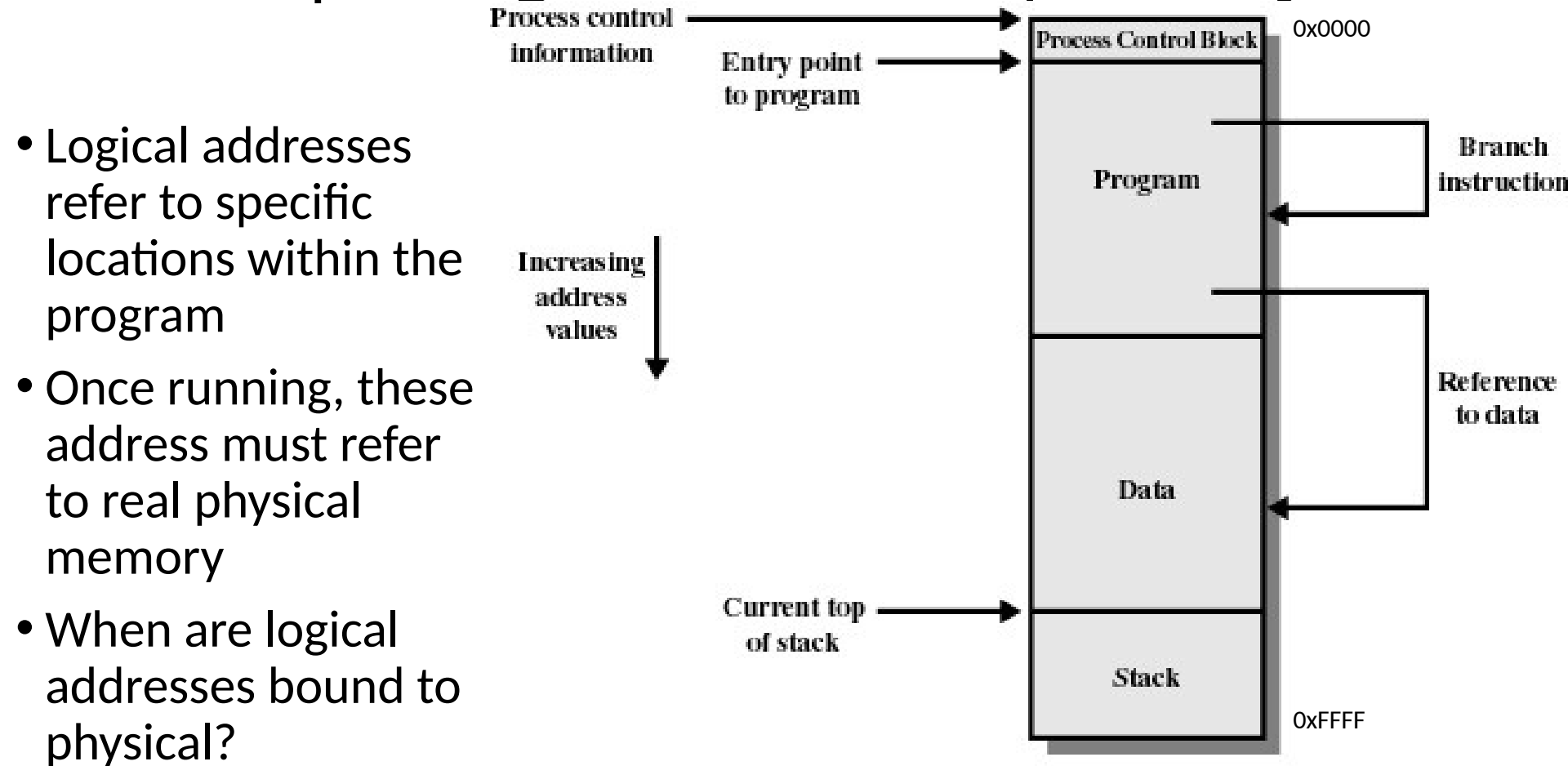Data

Current top of stack →

Stack

0xFFFF

Figure 7.1 Addressing Requirements for a Process
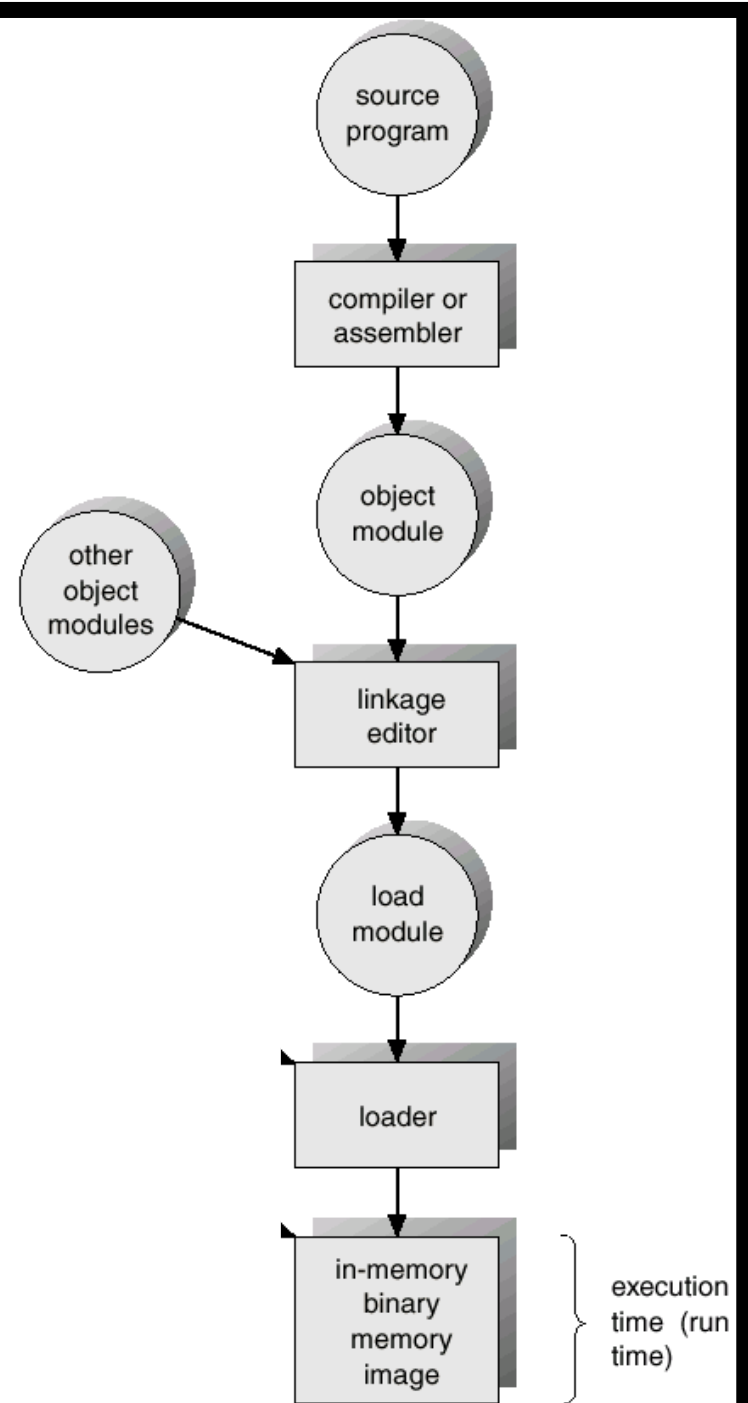
When are memory addresses bound?

- 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
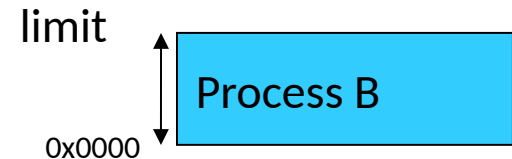
limit

0x0000

Process B

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

0xFFFF

limit | Process B | base

0x0000

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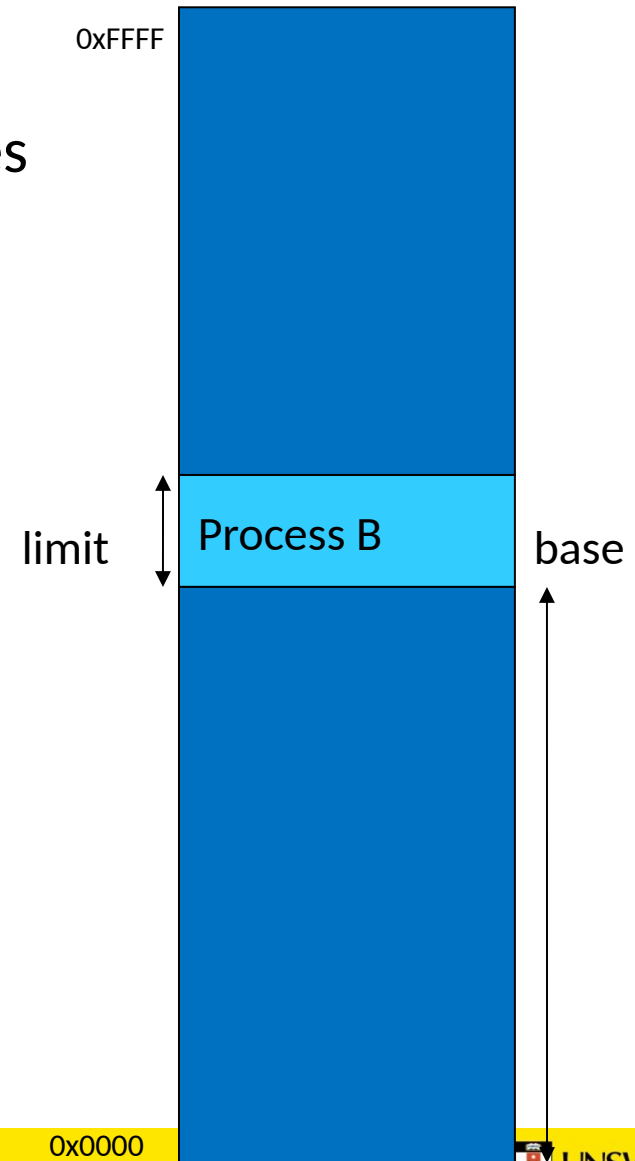
Hardware Support for Relocation and Limit Registers
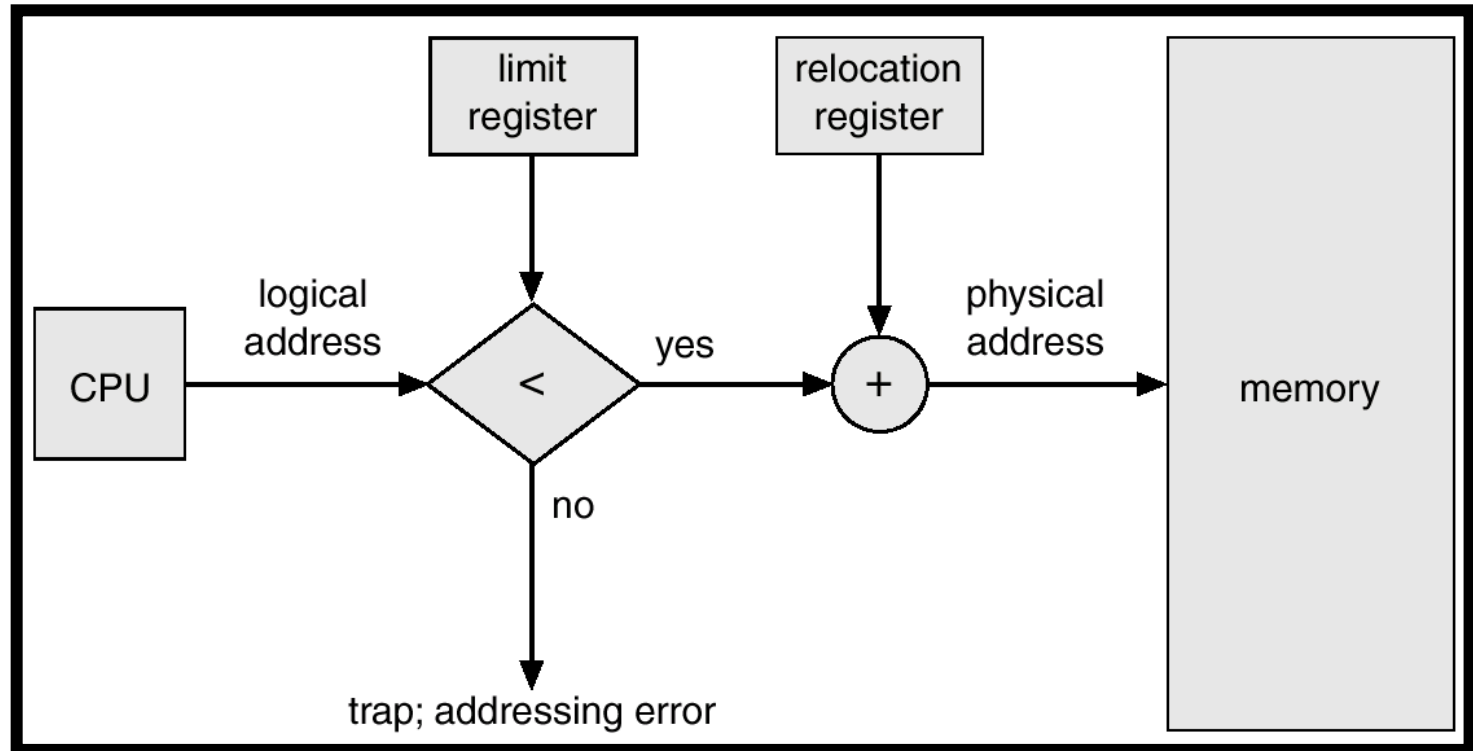
Base and Limit Registers

- 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=0x8000

limit = 0x2000

0xFFFF

Process A

0x9FFF
limit
0x8000

0x1FFF
0x0000   Process B   base

Process C

Process D

0x0000

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=0x4000

limit = 0x3000

0xFFFF

Process A

Process B

0x6FFF
0x2FFF

limit   Process C   base

0x4000
0x0000

Process D

0x0000

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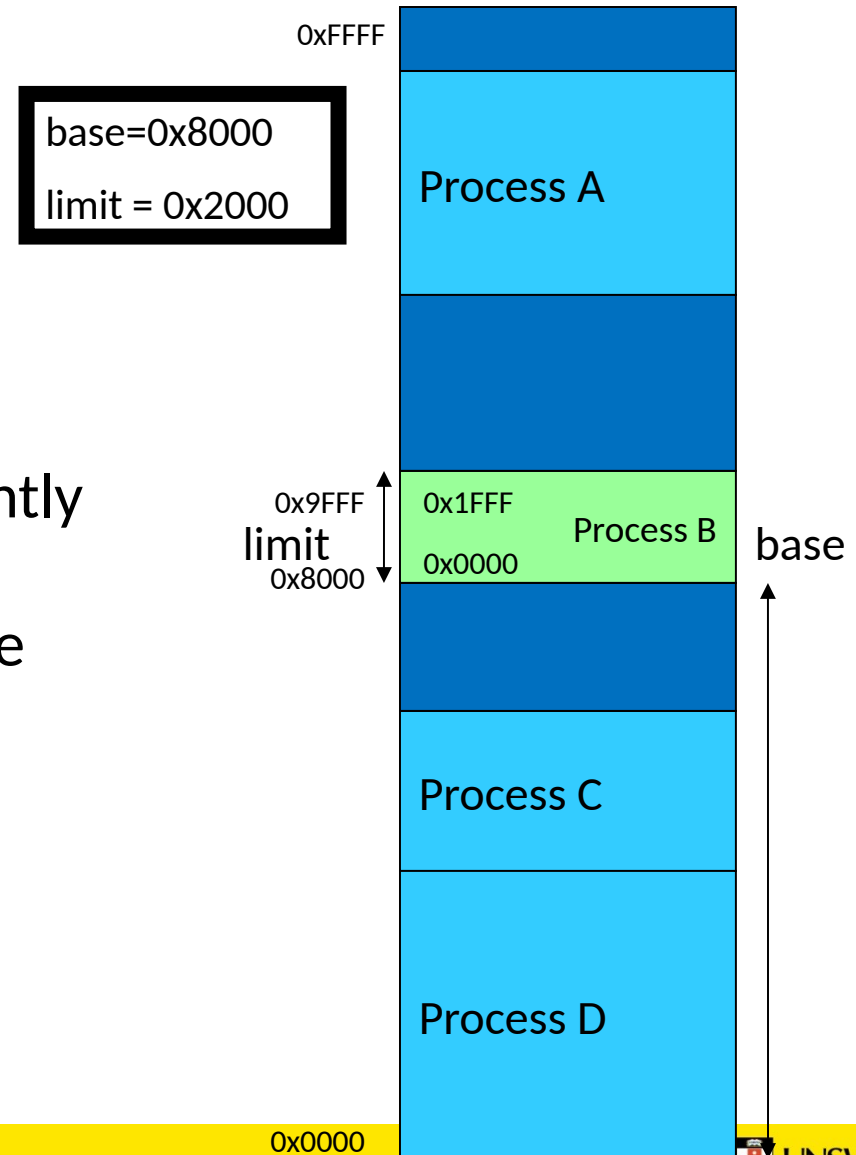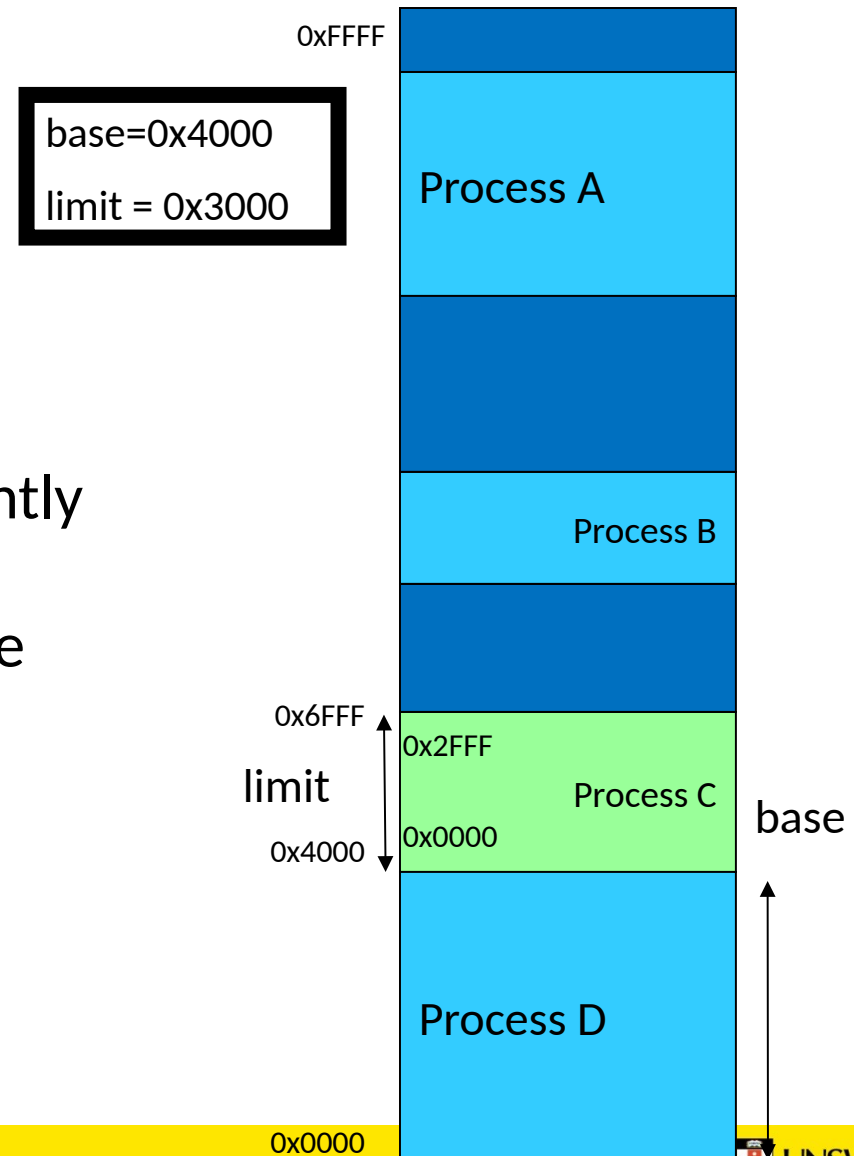
Base and Limit Registers

- 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

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

0xFFFF

Process A

Process B

Process C

Process D

0x0000
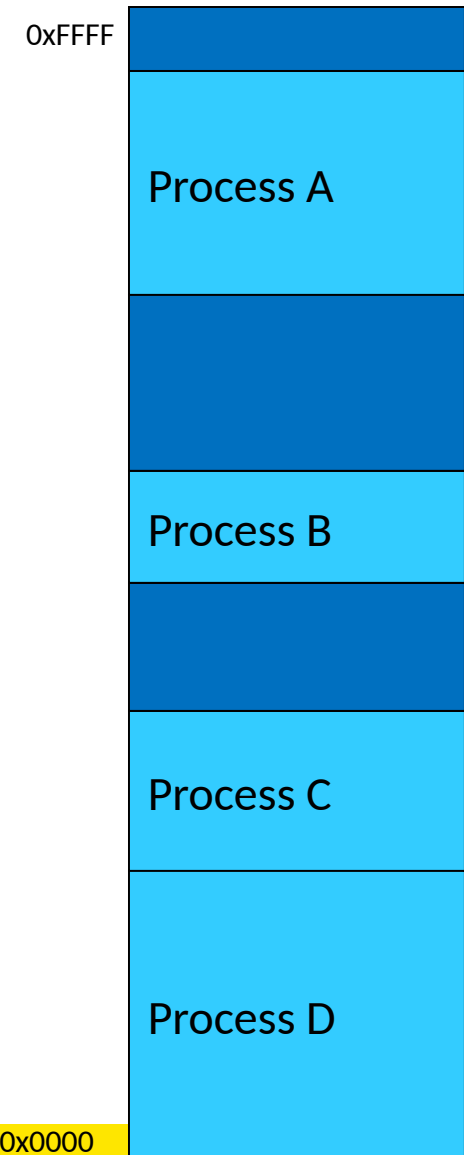
Swapping

- 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

Schematic View of Swapping
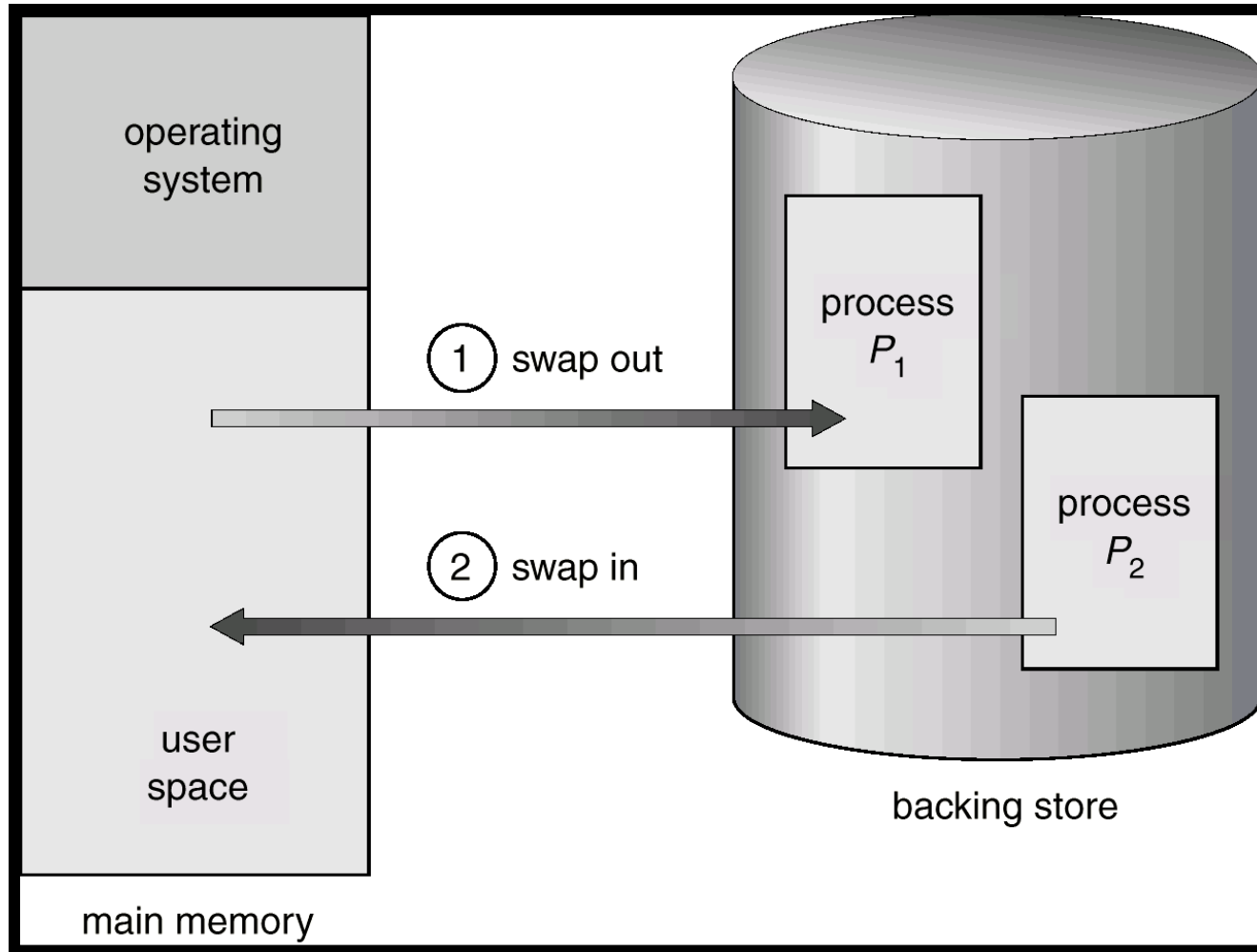
So far we have assumed a process is smaller than memory

- 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)
    - 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

Virtual address space

Virtual address range	Value
60K-64K	X
56K-60K	X
52K-56K	X
48K-52K	X
44K-48K	7
40K-44K	X
36K-40K	5
32K-36K	X
28K-32K	X
24K-28K	X
20K-24K	3
16K-20K	4
12K-16K	0
8K-12K	6
4K-8K	1
0K-4K	2

} Virtual page

Physical memory address

28K-32K
24K-28K
20K-24K
16K-20K
12K-16K
8K-12K
4K-8K
0K-4K

Page frame

Frame number	Main memory		Main memory		Main memory
0		0	A.0	0	A.0
1		1	A.1	1	A.1
2		2	A.2	2	A.2
3		3	A.3	3	A.3
4		4		4	B.0
5		5		5	B.1
6		6		6	B.2
7		7		7	
8		8		8	
9		9		9	
10		10		10	
11		11		11	
12		12		12	
13		13		13	
14		14		14	

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

Figure 7.9 Assignment of Process Pages to Free Frames

Main memory

0	A.0
1	A.1
2	A.2
3	A.3
4	B.0
5	B.1
6	B.2
7	C.0
8	C.1
9	C.2
10	C.3
11	
12	
13	
14	

(d) Load Process C

Main memory

0	A.0
1	A.1
2	A.2
3	A.3
4	
5	
6	
7	C.0
8	C.1
9	C.2
10	C.3
11	
12	
13	
14	

(e) Swap out B

Main memory

0	A.0
1	A.1
2	A.2
3	A.3
4	D.0
5	D.1
6	D.2
7	C.0
8	C.1
9	C.2
10	C.3
11	D.3
12	D.4
13	
14	

(f) Load Process D

0	0
1	1
2	2
3	3

Process A
page table

0	—
1	—
2	—

Process B
page table

0	7
1	8
2	9
3	10

Process C
page table

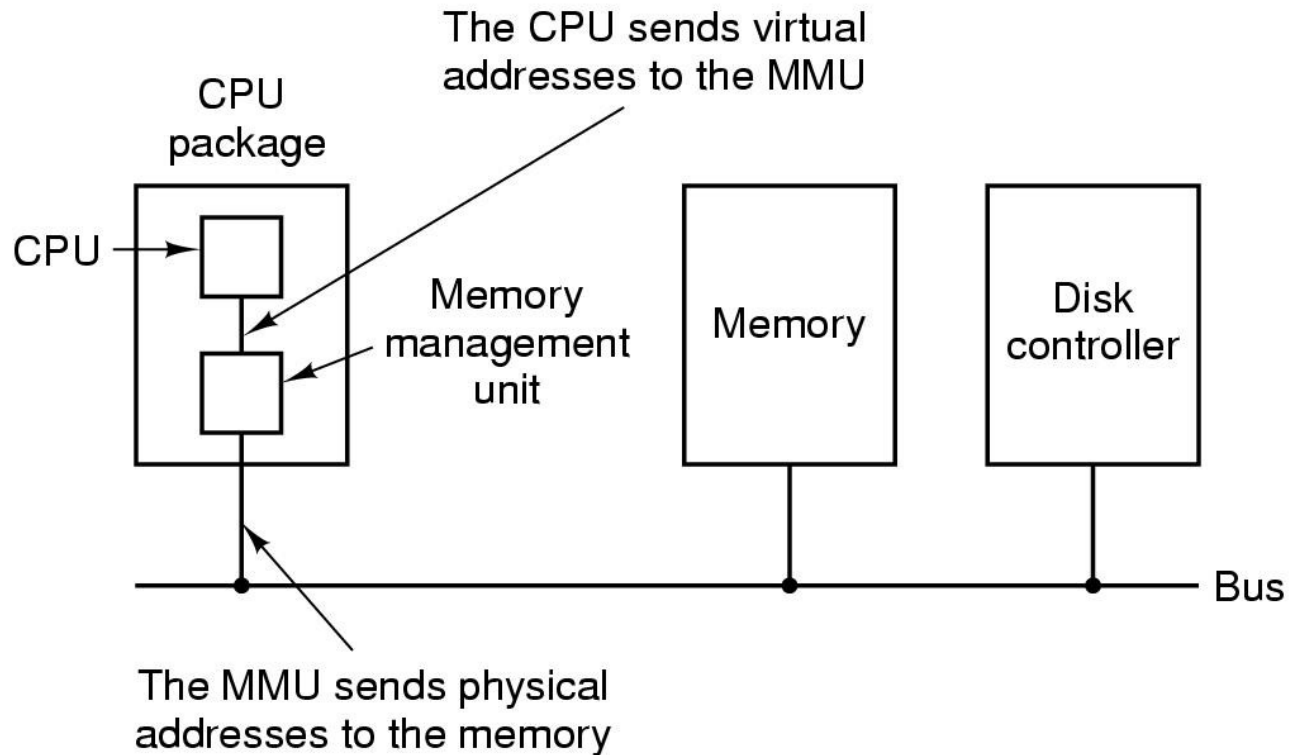|	
0	4
1	5
2	6
3	11
4	12

Process D
page table

13
14

Free frame
list

Paging

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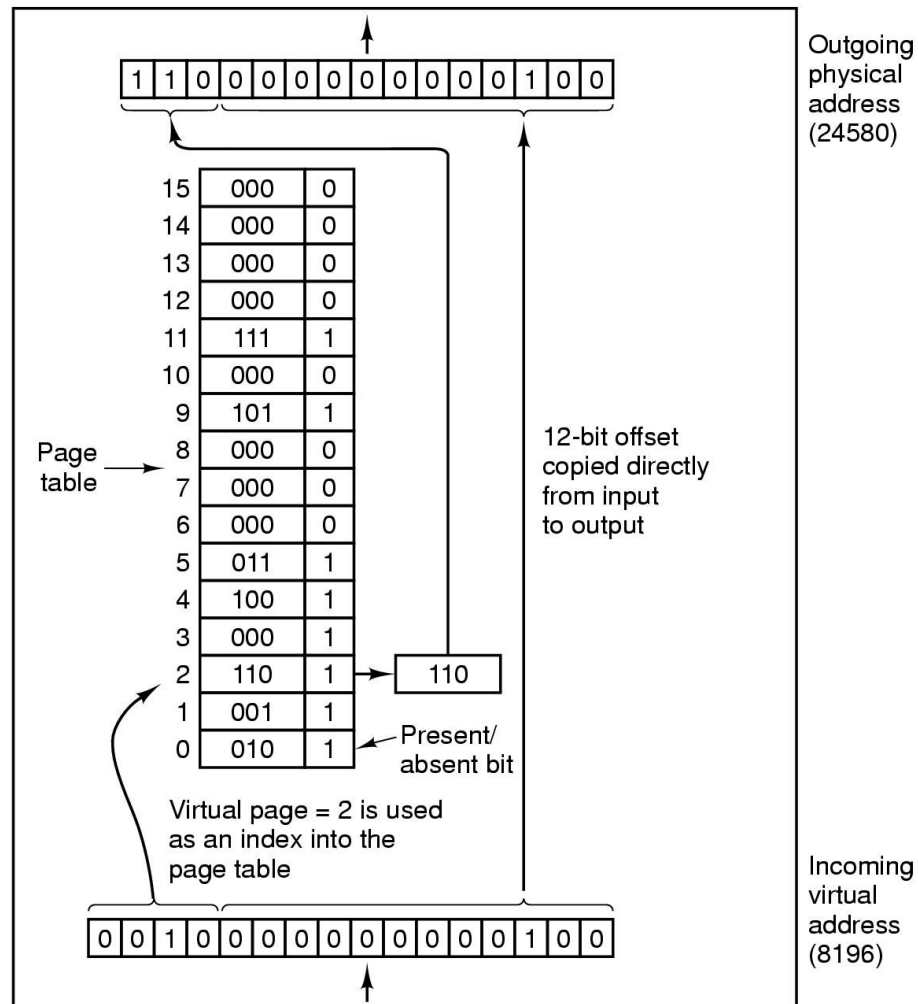 - Programmer only deal with virtual addresses

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

Today

(if we get to the end)

- The need to manage memory
- More on allocation and fragmentation
- Various schemes for static and dynamic allocation of regions
- Simple relocation
    - Base and limit
    - Offset
- Paging