Principles of Operating Systems

CS 446/646

3. Memory Management

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Principles of Operating Systems

CS 446/646

0. Course Presentation
1. Introduction to Operating Systems
2. Processes
3. **Memory Management**
4. **CPU Scheduling**
5. **Input/Output**
6. **File System**
7. **Case Studies**

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CS 446/646

3. Memory Management

a. Goals of Memory Management

b. Partitioning

c. Linking & Loading

d. Simple Paging & Segmentation

e. Virtual Memory

f. Page Replacement Algorithms

Principles of Operating Systems

CS 446/646

3. Memory Management

a. Goals of Memory Management

- ✓ How to distribute multiple processes in memory?
- ✓ Relocation of address references
- ✓ Protection & sharing of address spaces
- ✓ Logical vs. physical organization

b. Partitioning

c. Linking & Loading

d. Simple Paging & Segmentation

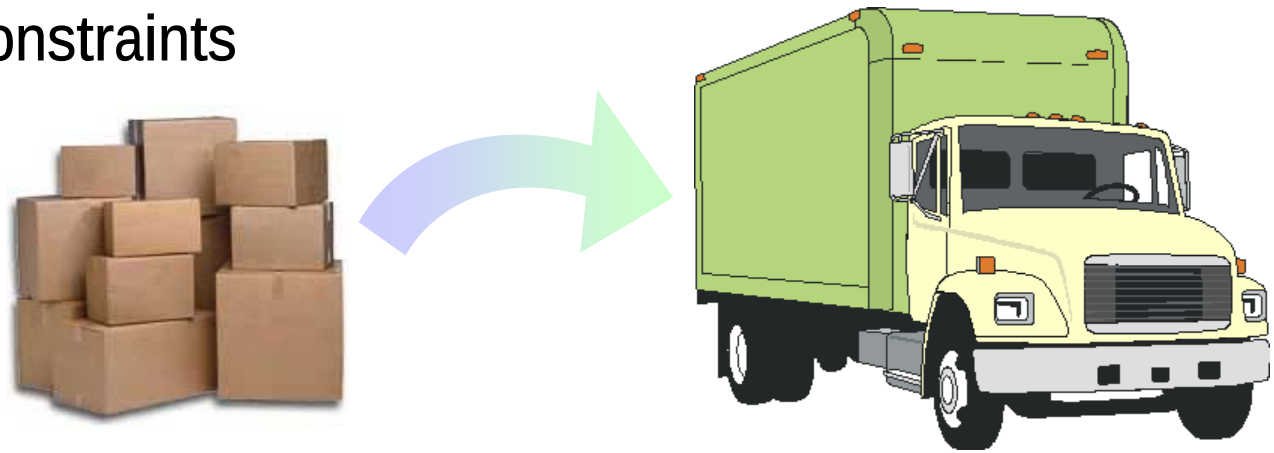
e. Virtual Memory

f. Page Replacement Algorithms

3.a Goals of Memory Management

How to distribute multiple processes in memory?

- The O/S must fit multiple processes in memory
  - ✓ memory needs to be subdivided to accommodate multiple processes
  - ✓ memory needs to be allocated to ensure a reasonable supply of ready processes so that the CPU is never idle
  - ✓ memory management is an **optimization** task under **constraints**



Fitting processes into memory is like fitting boxes into a fixed amount of space

3.a Goals of Memory Management

How to distribute multiple processes in memory?

- Memory management must satisfy various requirements
  - ✓ relocation of address references
    - must translate memory references to physical addresses
  - ✓ protection of memory spaces
    - forbid cross-process references
  - ✓ sharing of memory spaces
    - allow several processes to access a common memory area
  - ✓ logical organization (of programs)
    - programs are broken up into independent modules
  - ✓ physical organization (of memory)
    - fit multiple programs and modules in physical memory

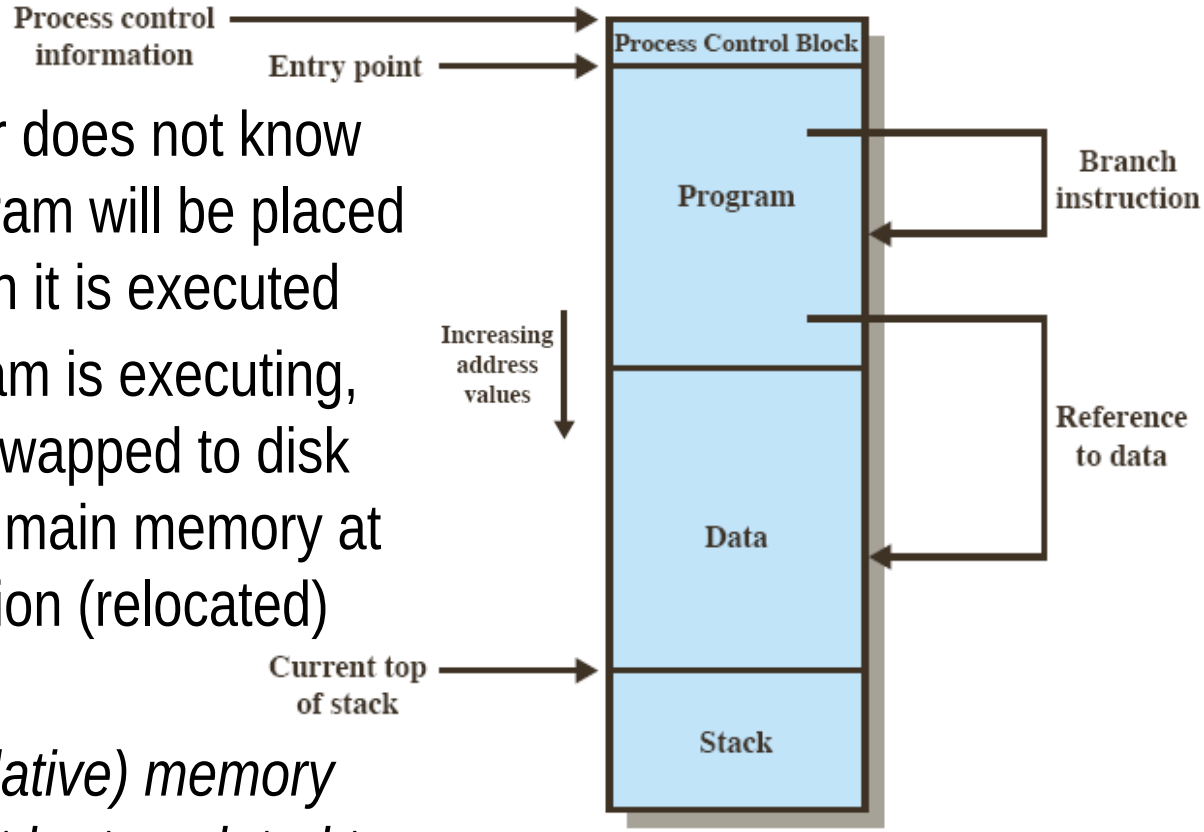
3.a Goals of Memory Management

Relocation of address references

➢ Relocation of address references

- ✓ the programmer does not know where the program will be placed in memory when it is executed
- ✓ while the program is executing, it may also be swapped to disk and returned to main memory at a different location (relocated)

→ *thus, logical (relative) memory references must be translated to physical (absolute) addresses*



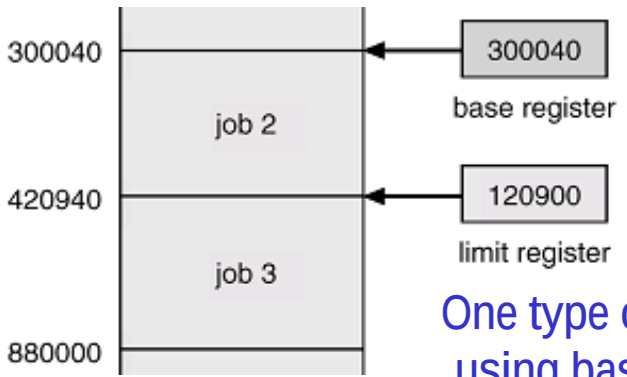
Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

Process addressing requirements

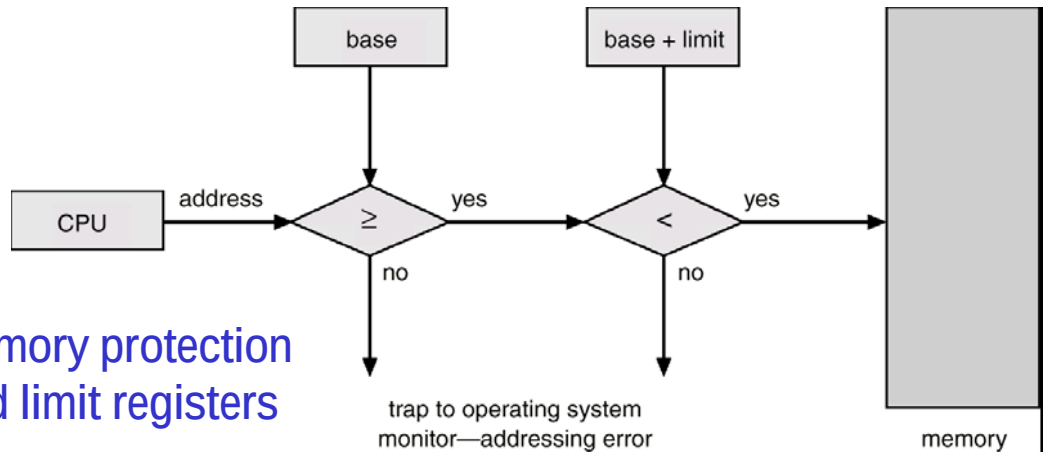
3.a Goals of Memory Management

Protection of address spaces

- Protection of address spaces
  - ✓ processes must not use memory locations in other processes
  - ✓ addressing must be checked at run time, as it is impossible to check physical addresses at compile time
  - ✓ however, the operating system cannot anticipate all of the (calculated) memory references a program will make
  - → *thus, fine-level protection is ultimately carried out in hardware*



One type of memory protection using base and limit registers



Silberschatz, A., Galvin, P. B. and Gagne, G. (2003) *Operating Systems Concepts with Java (6th Edition)*.

3.a Goals of Memory Management

Sharing of address spaces

- Sharing of address spaces
  - ✓ conversely, it should be possible to allow several processes to access the same portion of memory
    - for example, processes executing the same program can save resources by sharing the same copy of code in memory
    - also, processes cooperating on some task may need access to the same data structure
  - → *we will see that mechanisms supporting relocation also support sharing capabilities*

3.a Goals of Memory Management

Logical organization

- Logical organization (of programs)
  - ✓ the linear 1-D organization of memory does not reflect the way programs are typically constructed
  - ✓ large programs are often organized into modules and the O/S should be able to handle modular programs, so that:
    - modules can be written and compiled independently
    - different degrees of protection can be given to different modules: read-only, execute-only, read-and-write, etc.
    - modules can be shared among processes

  → *segmentation is a memory management technique that supports modularization*

3.a Goals of Memory Management

Physical organization

- Physical organization (of memory)
  - ✓ two-level scheme
    - main memory: fast access, high cost, volatile
    - secondary memory: slow access, cheaper, long-term storage
  - → *thus, a major O/S concern is the flow of information between main and secondary memory (it should not be a user concern)*

Principles of Operating Systems

CS 446/646

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- ✓ How to distribute multiple processes in memory?
- ✓ Relocation of address references
- ✓ Protection & sharing of address spaces
- ✓ Logical vs. physical organization

b. Partitioning

c. Linking & Loading

d. Simple Paging & Segmentation

e. Virtual Memory

f. Page Replacement Algorithms

Principles of Operating Systems

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3. Memory Management

a. Goals of Memory Management

b. Partitioning

- ✓ Fixed partitioning: shelving the boxes
- ✓ Dynamic partitioning: stacking the boxes
- ✓ "Buddy system": splitting & merging the shelves

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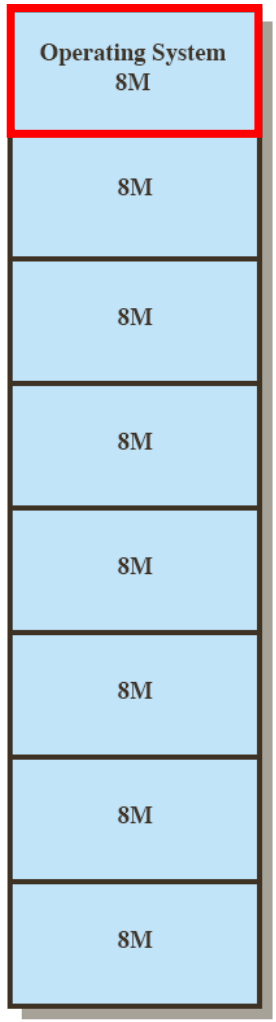
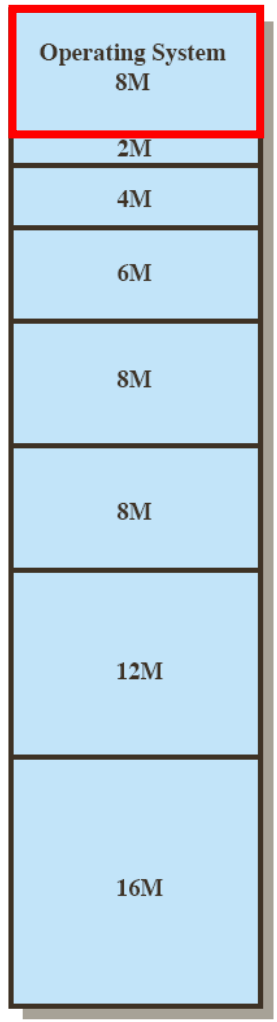
3.b Partitioning

Fixed partitioning: shelving the boxes



(a) Equal-size partitions



(b) Unequal-size partitions

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

Example of fixed partitioning of a 64MB memory (the "shelves")

3.b Partitioning

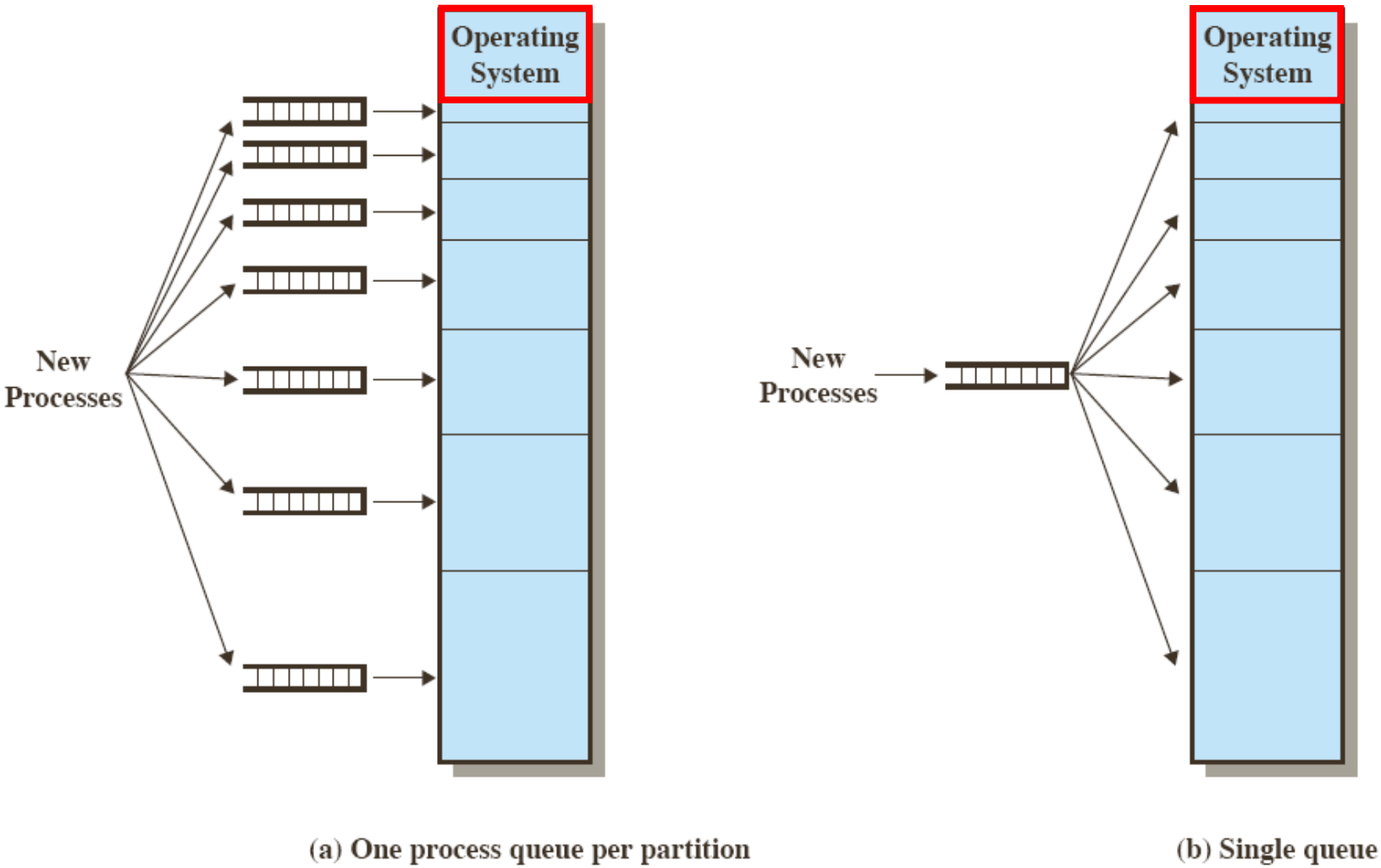
Fixed partitioning: shelving the boxes

- Fixed partition establishes fixed boundaries in memory
  - the oldest and simplest scheme to manage memory space
    - any process whose size is less than or equal to a partition size can be loaded into an available partition
    - if all partitions are full, the operating system can swap a process out of a partition
  - also the least adequate scheme
    - larger programs may not fit in any of the partitions, so the programmer must design “overlaying” modules
    - memory use is very inefficient: even small programs occupy entire partitions, thus wasting space internal to the partitions

    → this waste of space is called **internal fragmentation**

3.b Partitioning

Fixed partitioning: shelving the boxes



(a) One process queue per partition

(b) Single queue

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Placement algorithms for unequal-size fixed partitioning

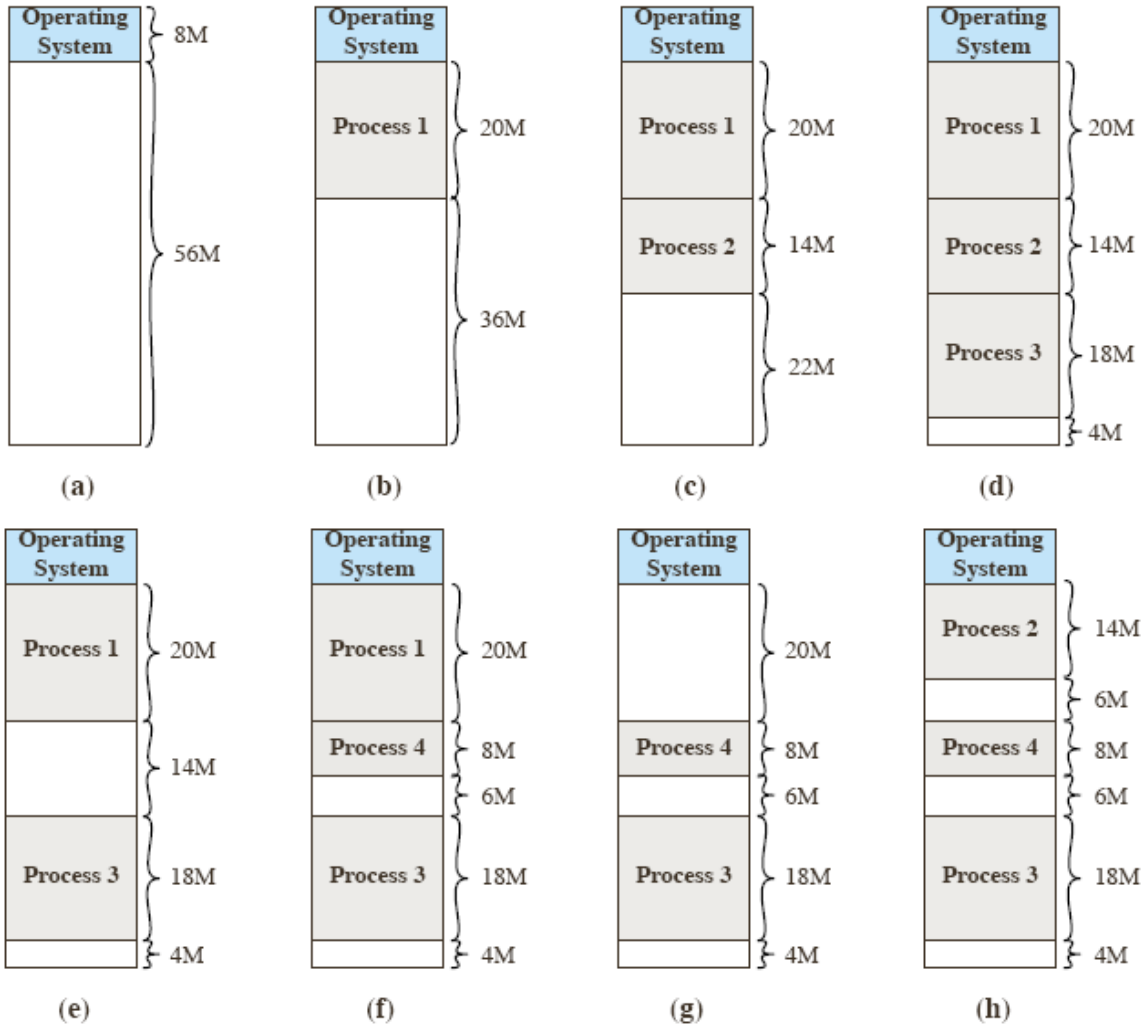
3.b Partitioning

Fixed partitioning: shelving the boxes

- Placement algorithms for fixed partitioning
  - ✓ equal-size partitions
    - because all partitions are of equal size, it does not matter which partition is used
    - → no special algorithm is needed
  - ✓ unequal-size partitions
    - per-partition queue: to minimize internal fragmentation, processes must wait for a partition that best fits their size
    - global queue: however, doing so needlessly prevents a process from running while another (bigger) partition might be available
    - → tradeoff between wasting space and wasting time

3.b Partitioning

Dynamic partitioning: stacking the boxes



The effect of dynamic partitioning

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

3.b Partitioning

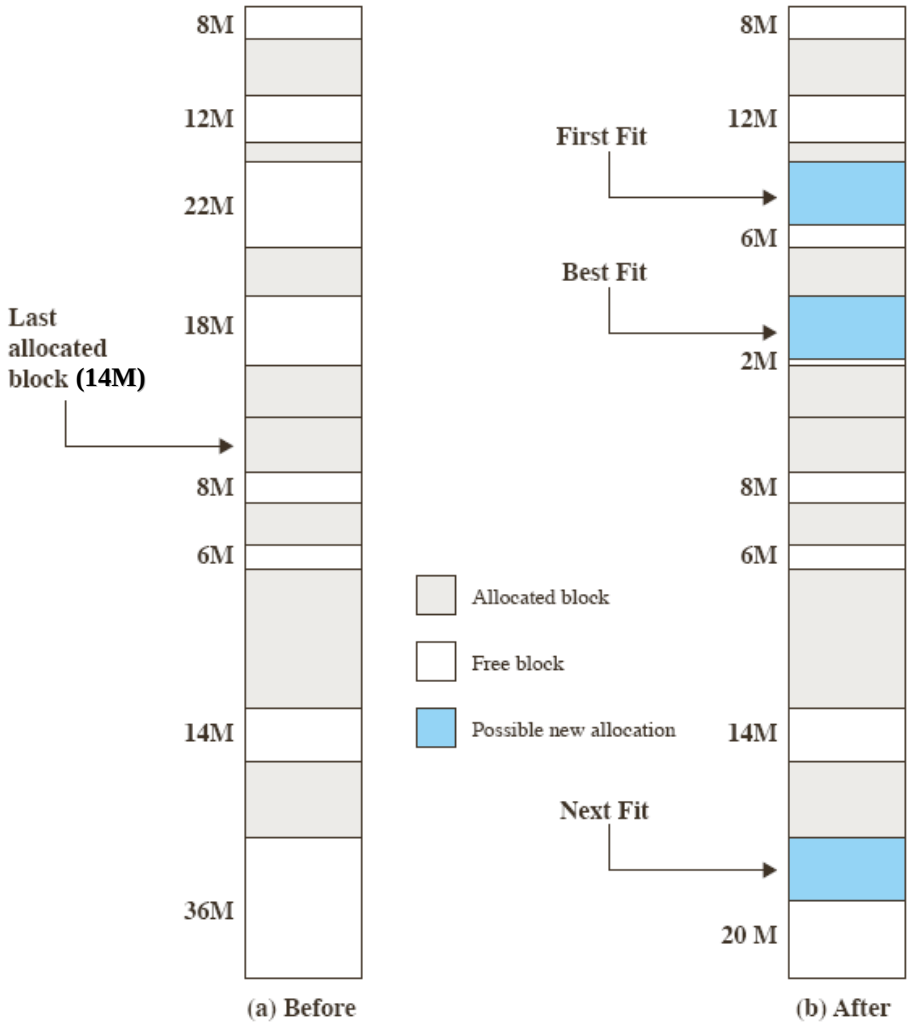
Dynamic partitioning: stacking the boxes

- Dynamic partitioning stacks processes contiguously
  - also an old and relatively simple allocation scheme
    - partitions are now of variable length and number
    - a process is allocated exactly as much memory as required
  - but also inadequate for today's standards
    - stacking processes will not prevent gaps as processes are continuously swapped in and out of memory

    → this is called **external fragmentation**
    - O/S **compaction** routines can shift processes from time to time, but this is time-consuming in read/write operations and relocation (re-translating references)

3.b Partitioning

Dynamic partitioning: stacking the boxes



Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

Before and after allocation of a 16M block under dynamic partitioning

3.b Partitioning

Dynamic partitioning: stacking the boxes

- Placement algorithms minimize external fragmentation
  - ✓ in order to minimize costly compaction ("garbage-collection" of fragmentation), position the processes cleverly; alternatives are:
  - ✓ **best-fit** placement
    - chooses the block that is closest in size to the request, so as to leave the smallest amount of fragmentation
  - ✓ **first-fit** placement
    - scans the memory from the beginning and chooses the first available block that is large enough
  - ✓ **next-fit** placement
    - scans the memory from the last placement and chooses the next available block that is large enough

3.b Partitioning

Dynamic partitioning: stacking the boxes

- Placement algorithms: comparative results
  - ✓ while performance depends on the exact sequence of process requests and sizes, statistical conclusions can be reached:
  - 👎 **best-fit** placement
    - paradoxically, the worst performer! it quickly litters memory with small fragments and requires compaction frequently
  - 👍 **first-fit** placement
    - the best and fastest
  - ✌ **next-fit** placement
    - the runner-up: slightly worse than first-fit, because it spreads fragmentation more evenly (whereas first-fit has a tendency to preserve big blocks at the end of memory)

3.b Partitioning

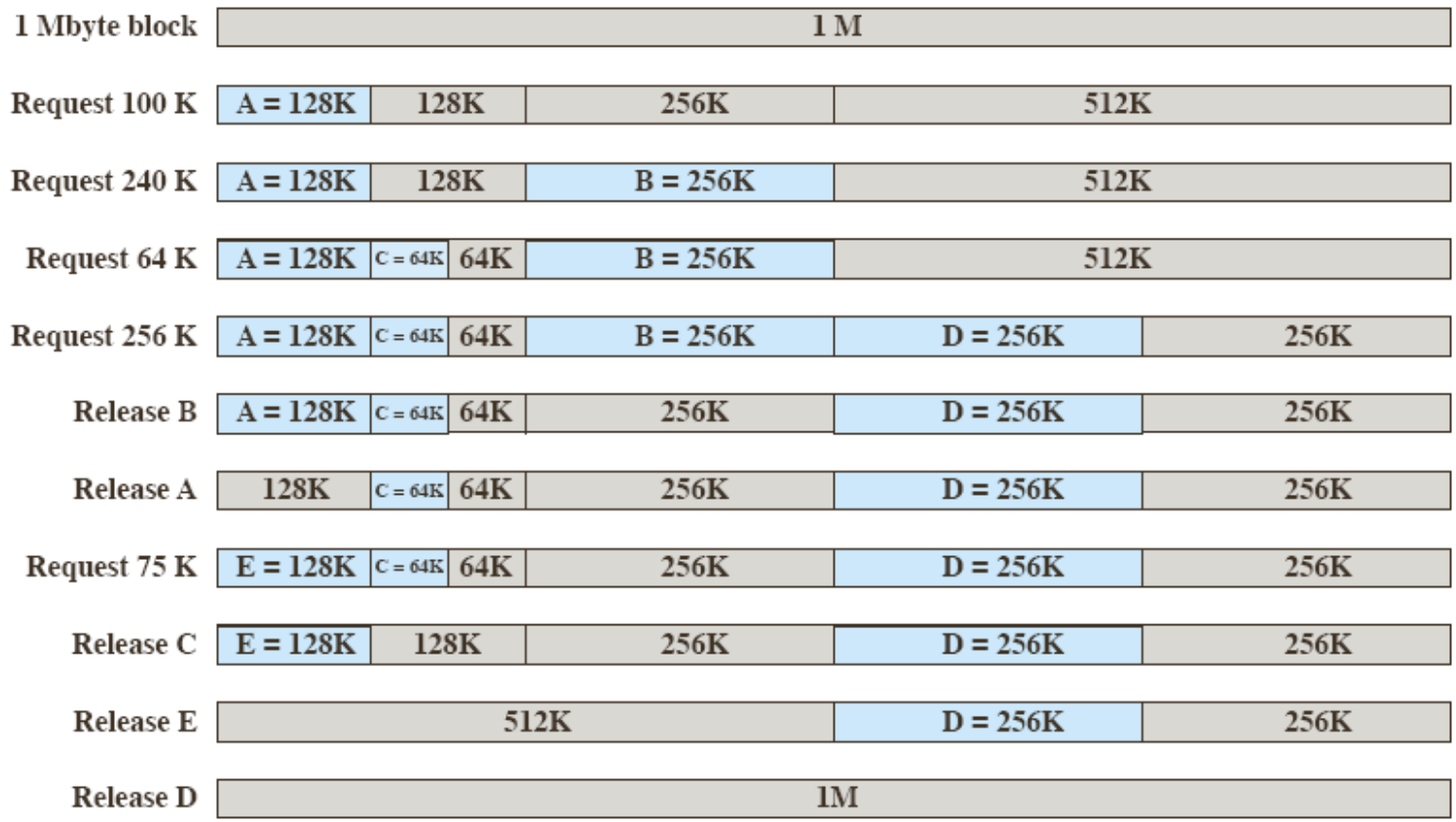
Dynamic partitioning: stacking the boxes

- Summary: fixed vs. dynamic partitioning
  - ✓ both fixed and dynamic partitioning schemes have drawbacks
  - ✓ fixed partitioning
    - limits the number of active processes
    - wastes space through internal fragmentation
  - ✓ dynamic partitioning
    - more complex to maintain
    - wastes space through external fragmentation
    - requires the overhead of compaction

3.b Partitioning

"Buddy system": splitting & merging the shelves

- The buddy system: splitting and coalescing



Example of buddy system

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Principles of Operating Systems

CS 446/646

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- ✓ From object codes to executable in memory
- ✓ Loading: binding logical references to physical addresses
- ✓ Linking: weaving logical addresses together

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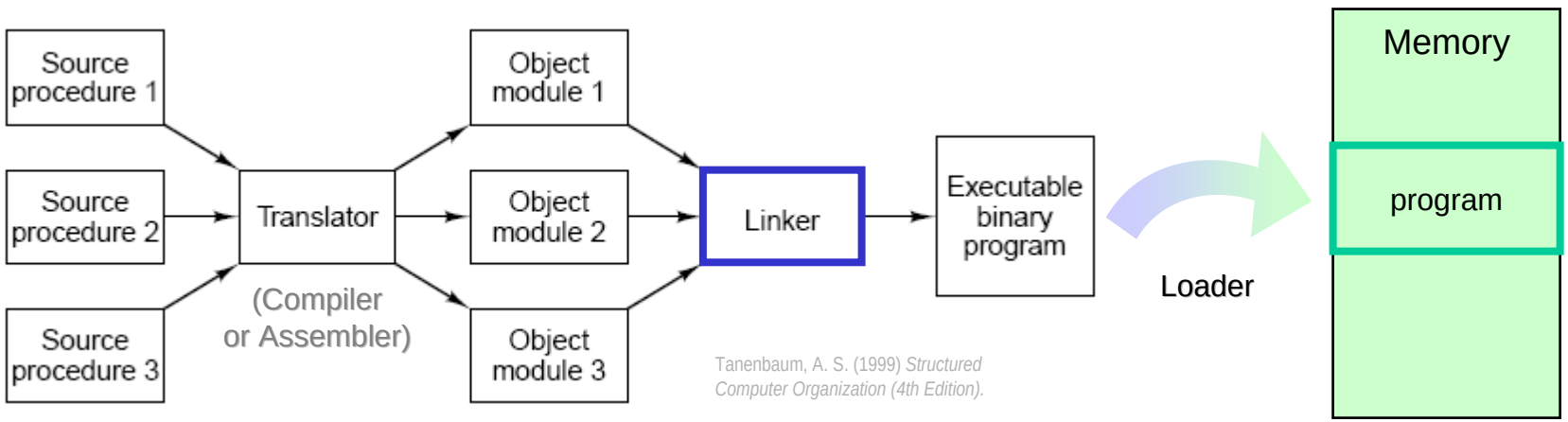
3.c Linking & Loading

From object codes to executable

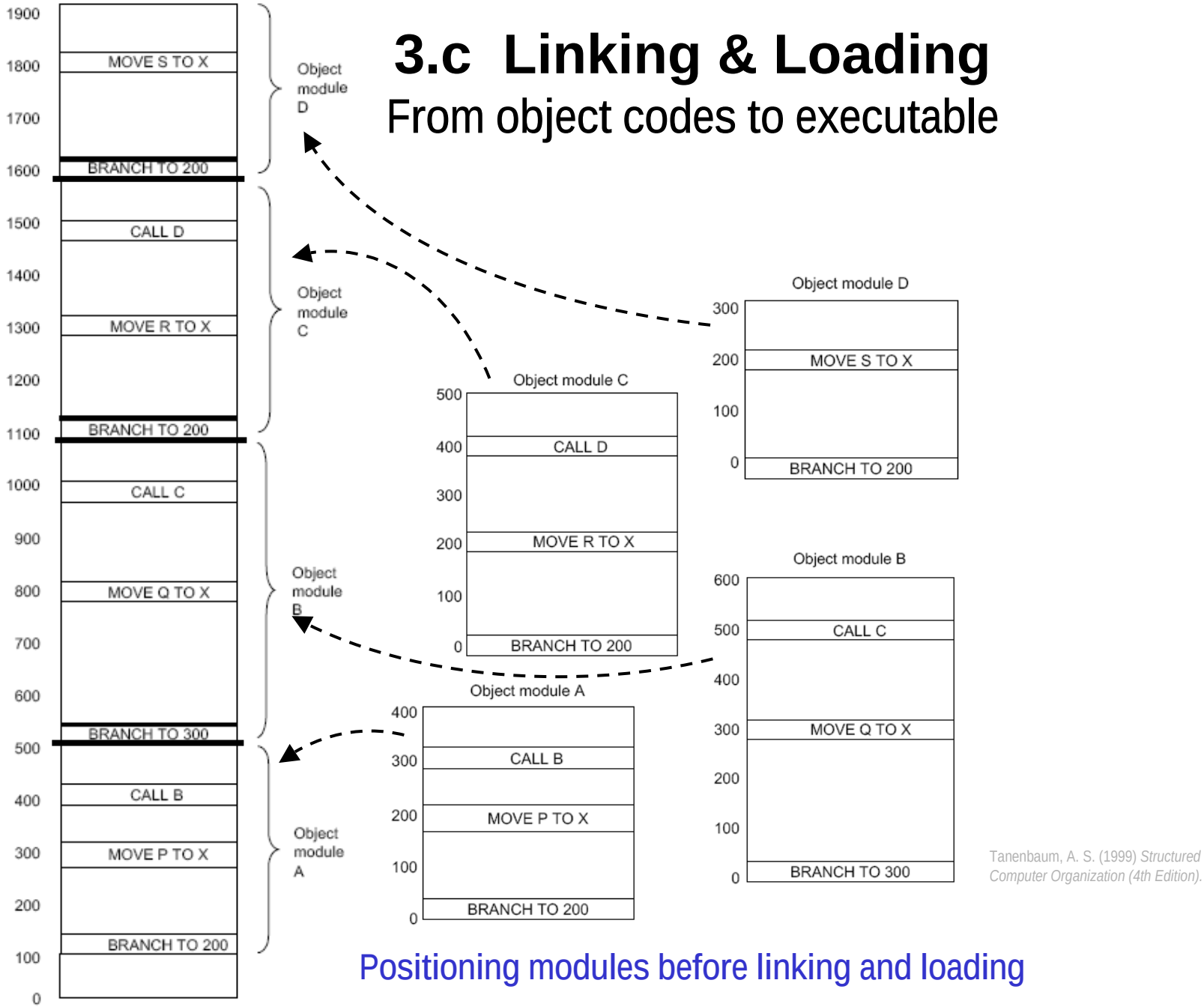
- Linkers and loaders
  - ✓ a **linker** or "link editor" is a program that takes a collection of object modules (created by compilers or assemblers) and combines them into a single executable program
  - ✓ a **loader** places the linked program in memory, possibly translating (relocating) addresses on the way



From source code to memory, via translating, linking and loading

3.c Linking & Loading

From object codes to executable

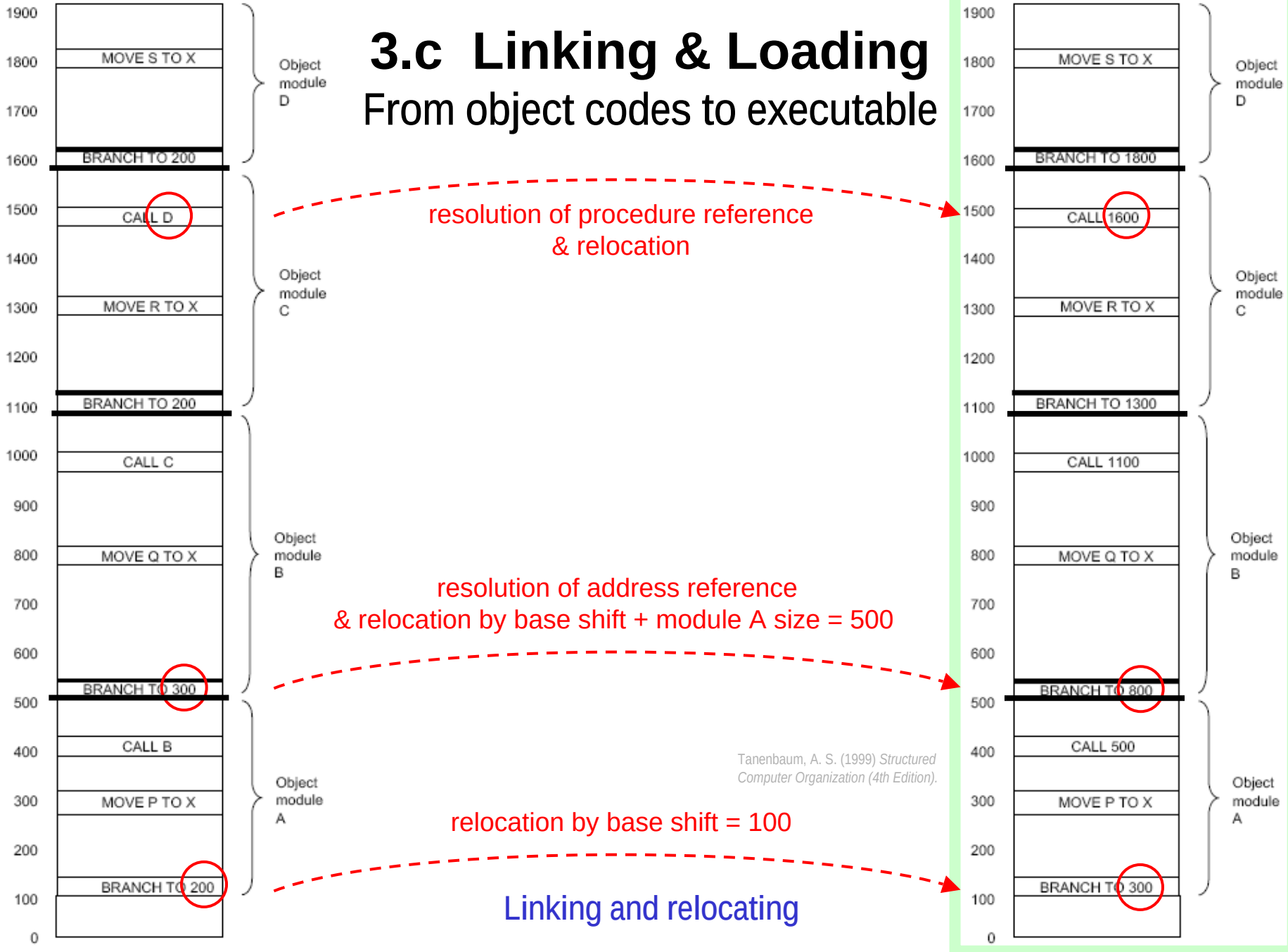


Tanenbaum, A. S. (1999) *Structured Computer Organization (4th Edition).*

Positioning modules before linking and loading

3.c Linking & Loading

From object codes to executable



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3.c Linking & Loading

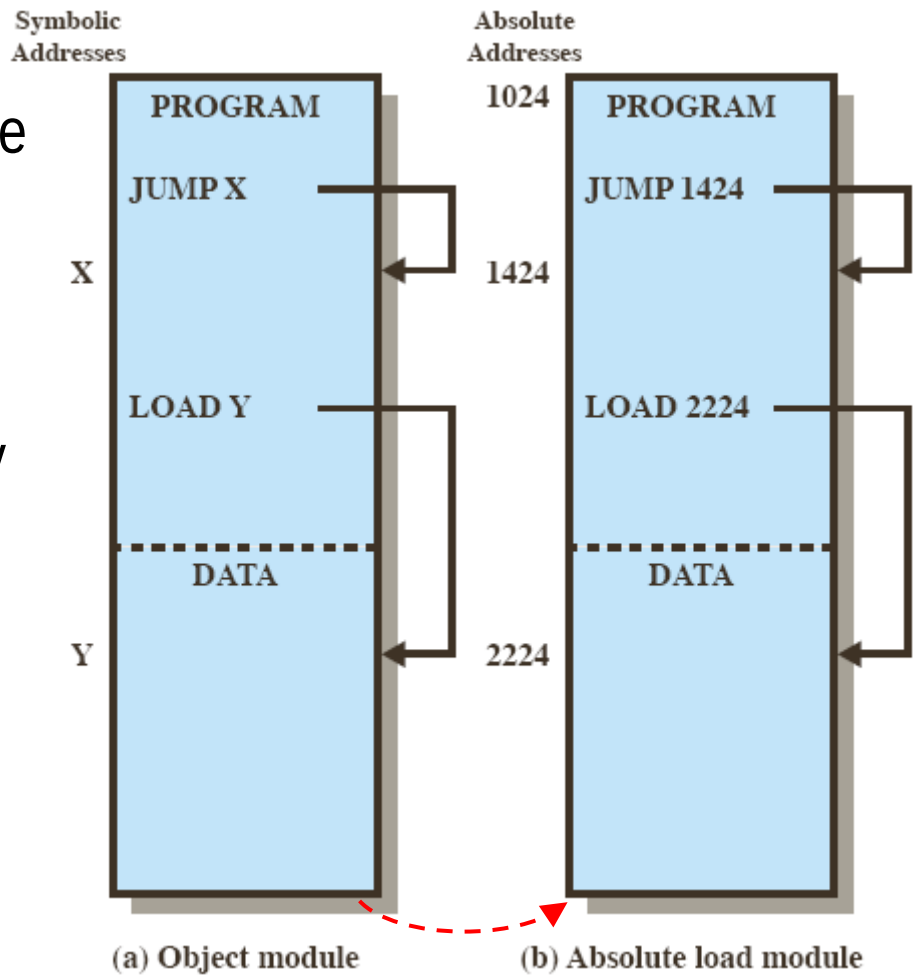
Loading: binding logical references to physical addresses

- Loading involves binding instructions and data to physical memory addresses
  - ✓ once an executable is finished compiling or is stored on disk, the loader places it in memory
  - ✓ modern systems allow a user process image to reside in any part of physical memory
  - ✓ three approaches to loading:
    - 👎 absolute loading = binding can be done beforehand, at compile time *(writing once)*
    - ✌ relocatable loading = binding is done <u>at</u> load time *(rewriting)*
    - 👍 dynamic runtime loading = binding is postponed until execution time *(not writing)*

3.c Linking & Loading

Loading: binding logical references to physical addresses

- Absolute loading
  - ✓ requires that a given module always be loaded into the same location in memory
  - ✓ thus, the compiler can bind symbolic addresses directly to absolute addresses
  - ✓ this was the case of the `.COM` format programs in MS-DOS
  - → *not acceptable: prevents swapping and/or multi-tasking, etc.*



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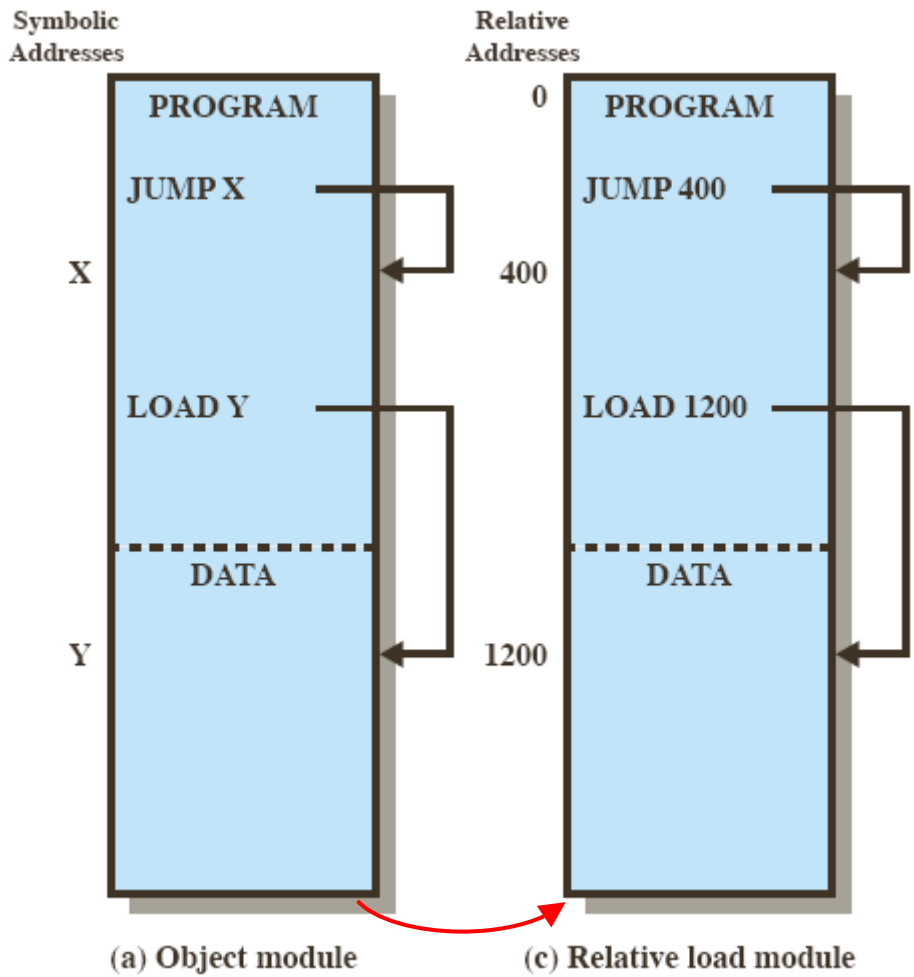
Absolute load module

3.c Linking & Loading

Loading: binding logical references to physical addresses

Relocatable loading

- ✓ we need modules that can be located and relocated anywhere in memory
- ✓ for this, the compiler must produce relative addresses
- ✓ then the task of the loader is basically to add one or several fixed offset(s) to all address references
- ✓ problem: swapping in and out requires delocating and relocating every time



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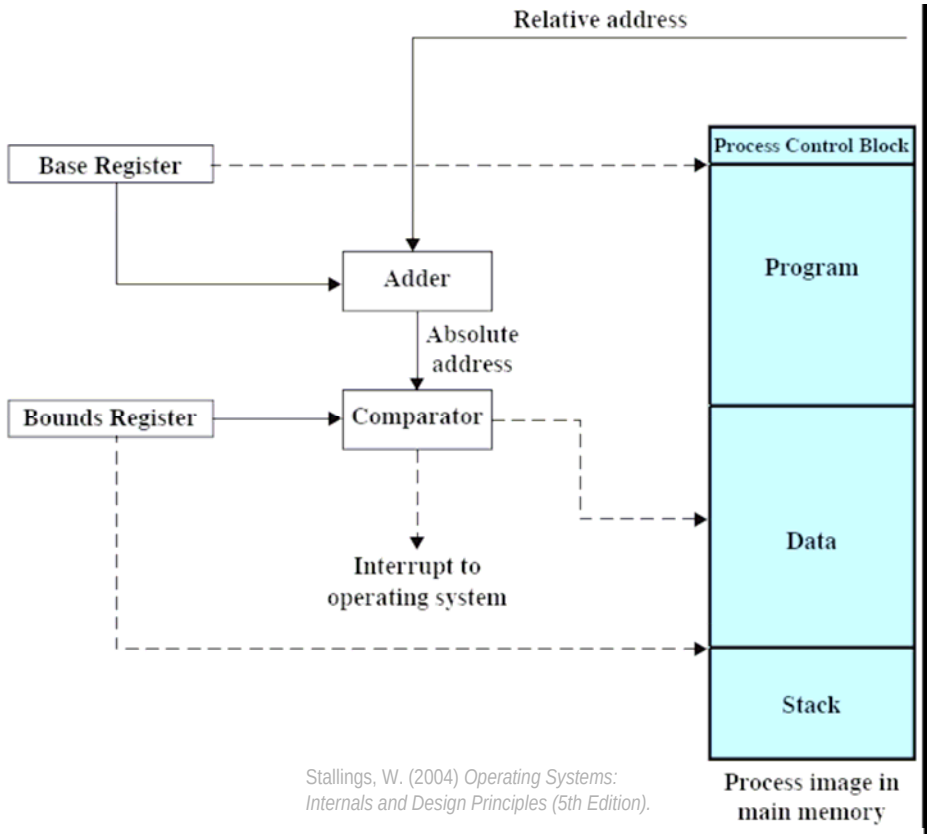
Relocatable load module

3.c Linking & Loading

Loading: binding logical references to physical addresses

- Dynamic runtime loading
  - ✓ physical address binding does not happen until the very last moment, when the instruction is executed
  - ✓ done by special processor hardware (combined with protection)
  - ✓ gives the most freedom



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Hardware support for relocation

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d. **Simple Paging & Segmentation**

e. **Virtual Memory**

f. **Page Replacement Algorithms**

Principles of Operating Systems

CS 446/646

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d. Simple Paging & Segmentation

- ✓ Paging
- ✓ Hardware support for paging
- ✓ Segmentation

e. Virtual Memory

f. Page Replacement Algorithms

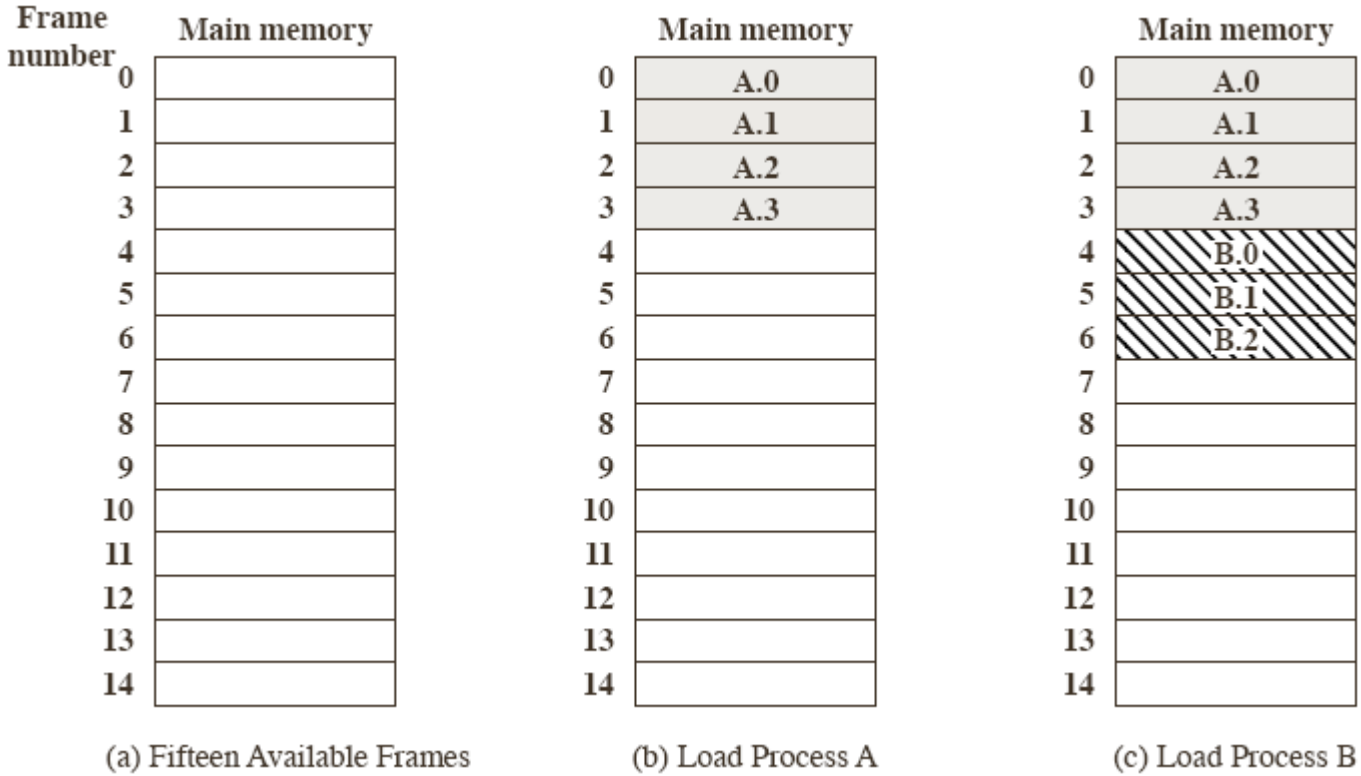
3.d Simple Paging & Segmentation

Paging

- (Sub)divide and conquer
  - ✓ new idea: partition process images, too, so that their physical domain doesn't have to be contiguous anymore
    - memory is partitioned into small, equal-size chunks
    - process images or also subdivided into the same size chunks
  - ✓ the chunks of a process are called **pages** and chunks of memory are called **frames**
  - ✓ the O/S maintains a page table for each process

3.d Simple Paging & Segmentation

Paging



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3.d Simple Paging & Segmentation

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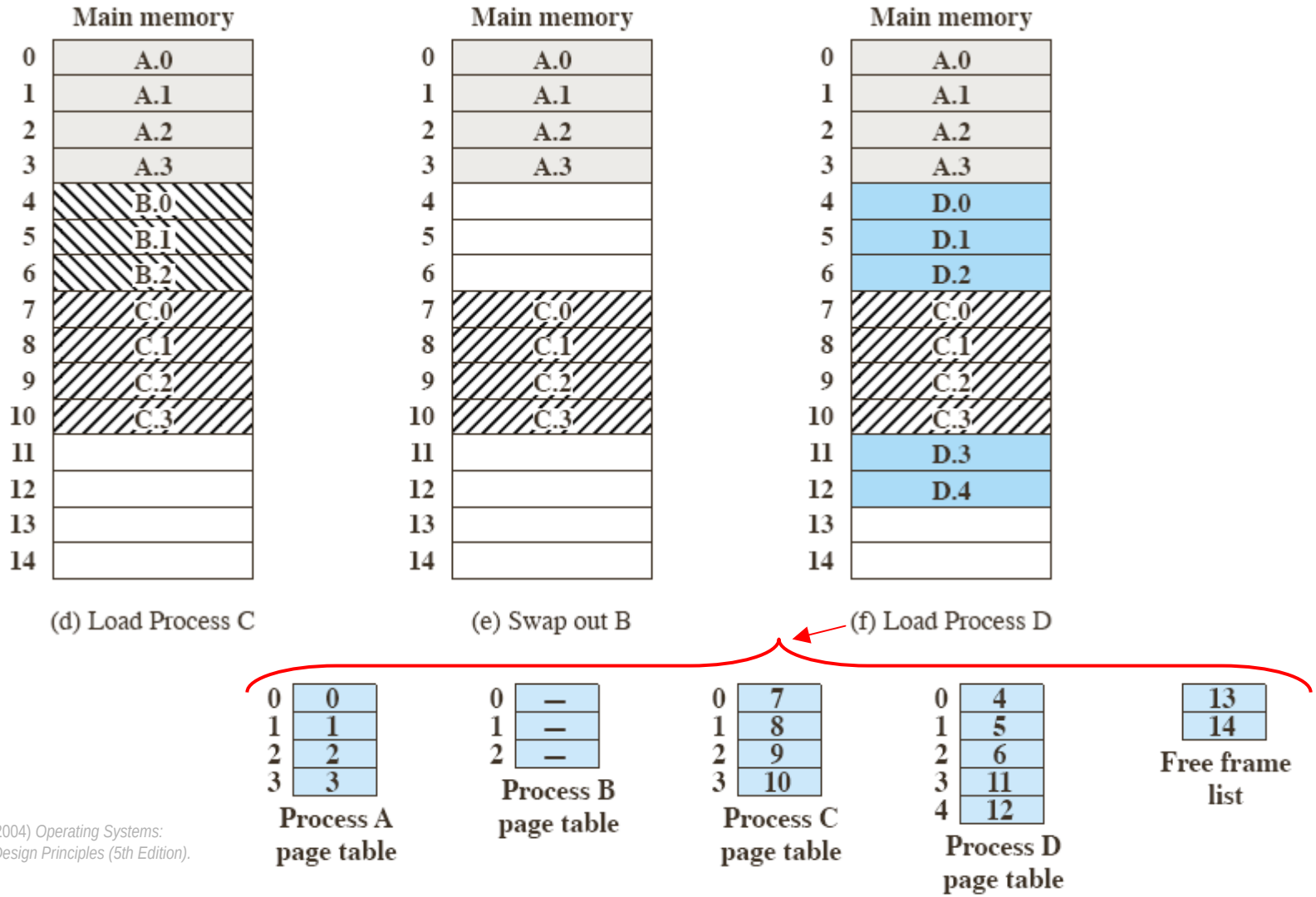

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3.d Simple Paging & Segmentation

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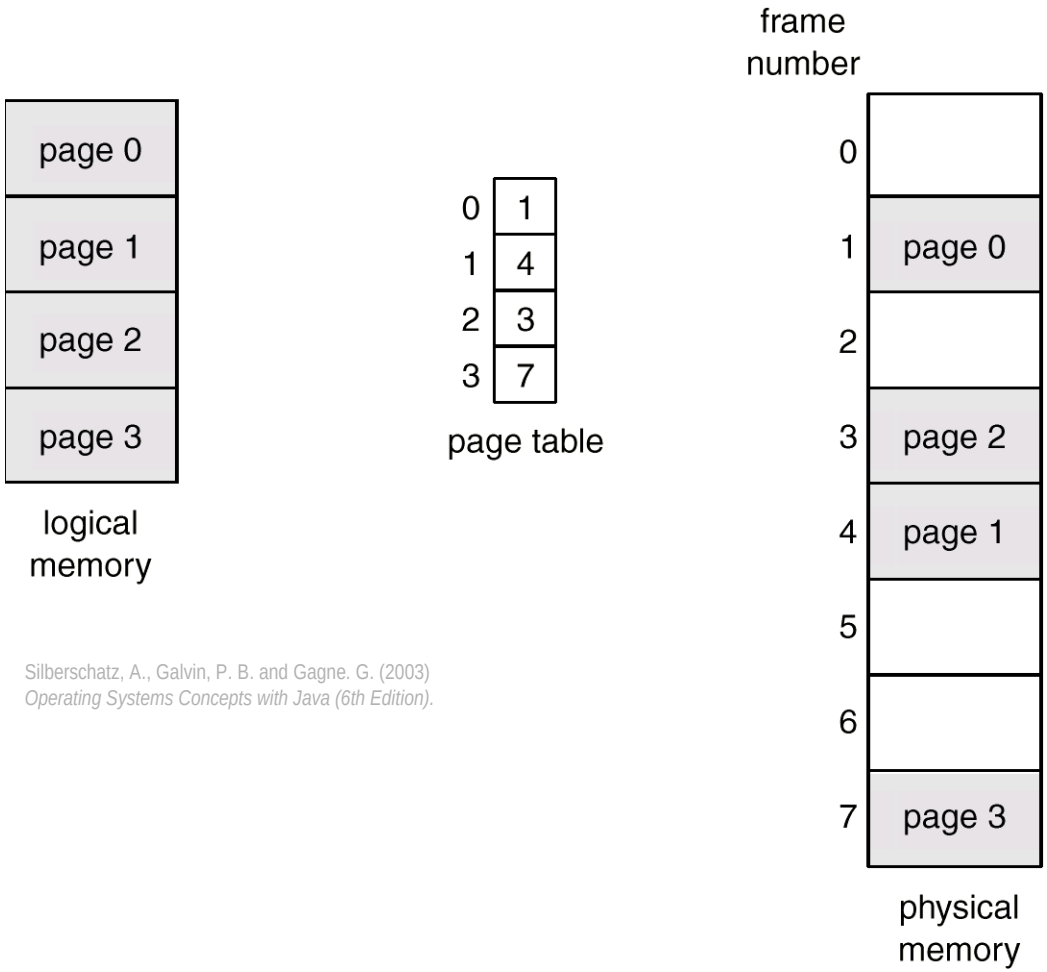

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3.d Simple Paging & Segmentation

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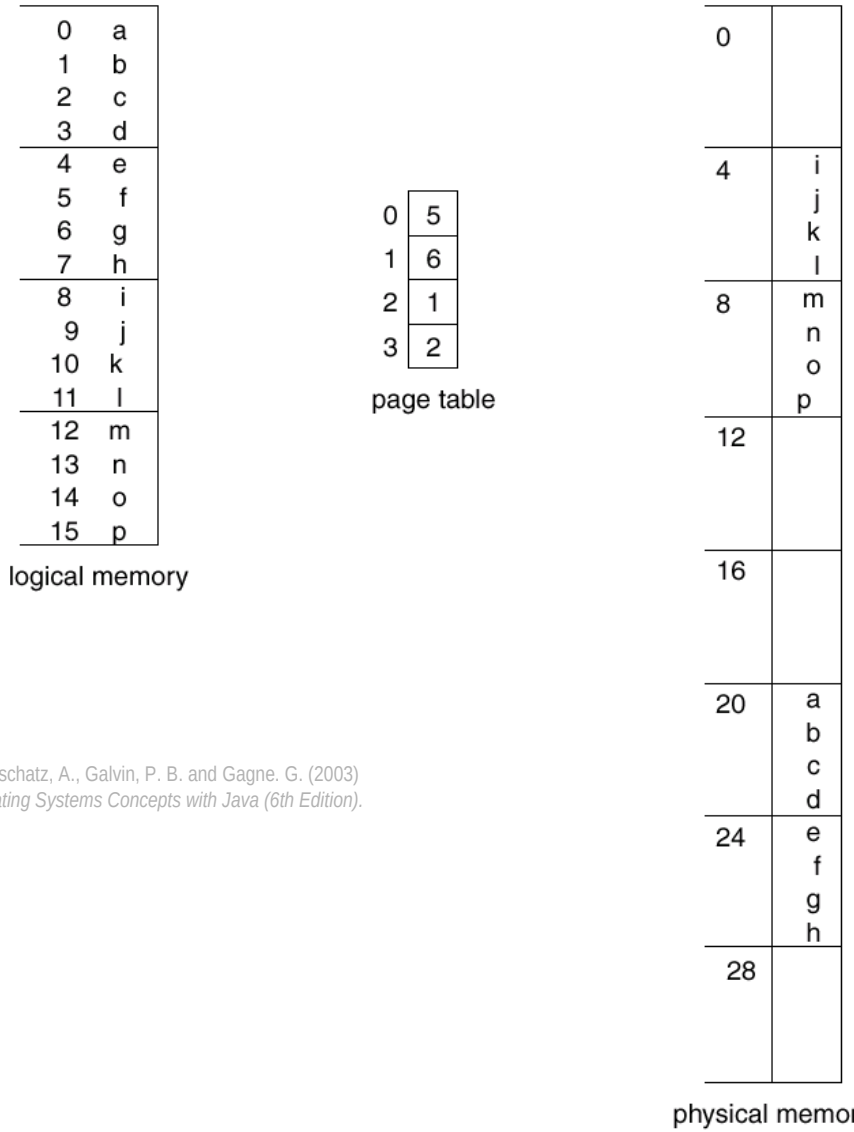

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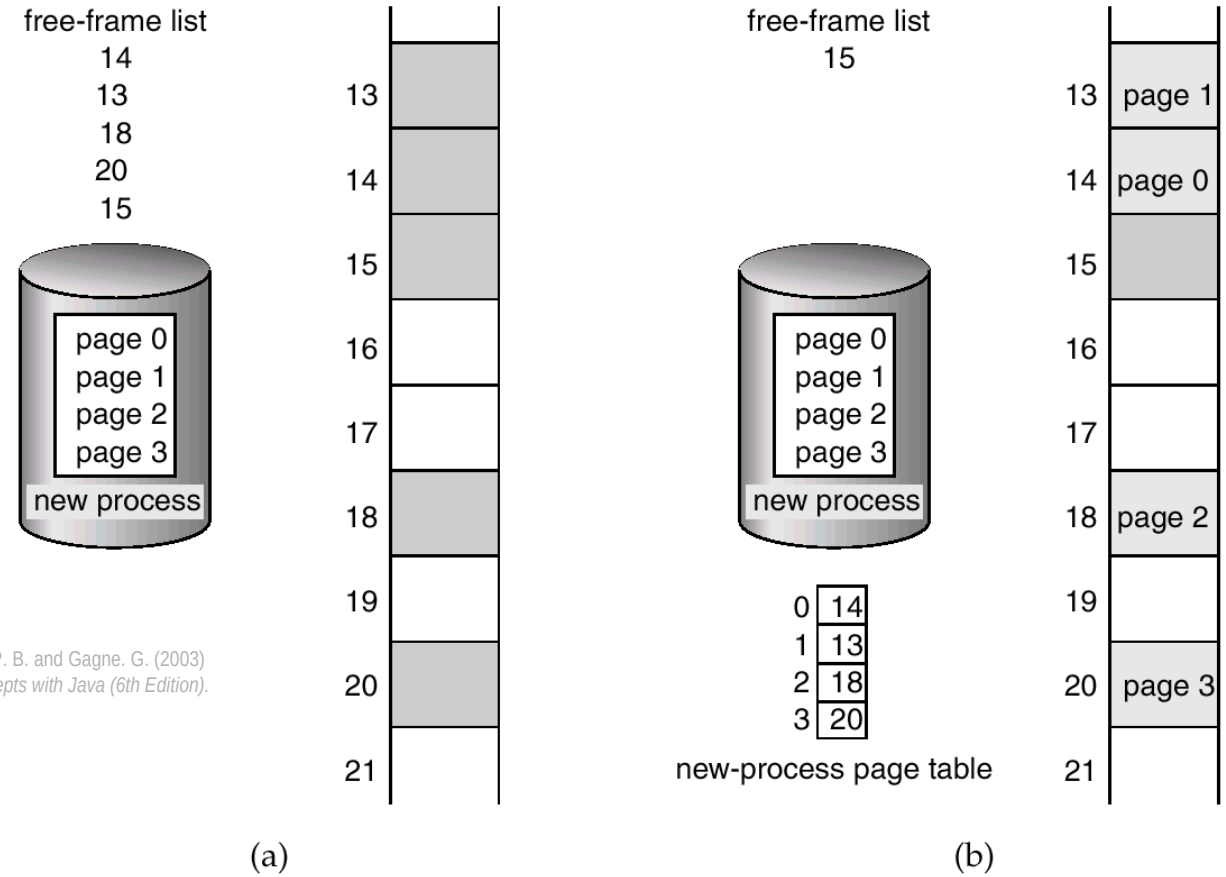

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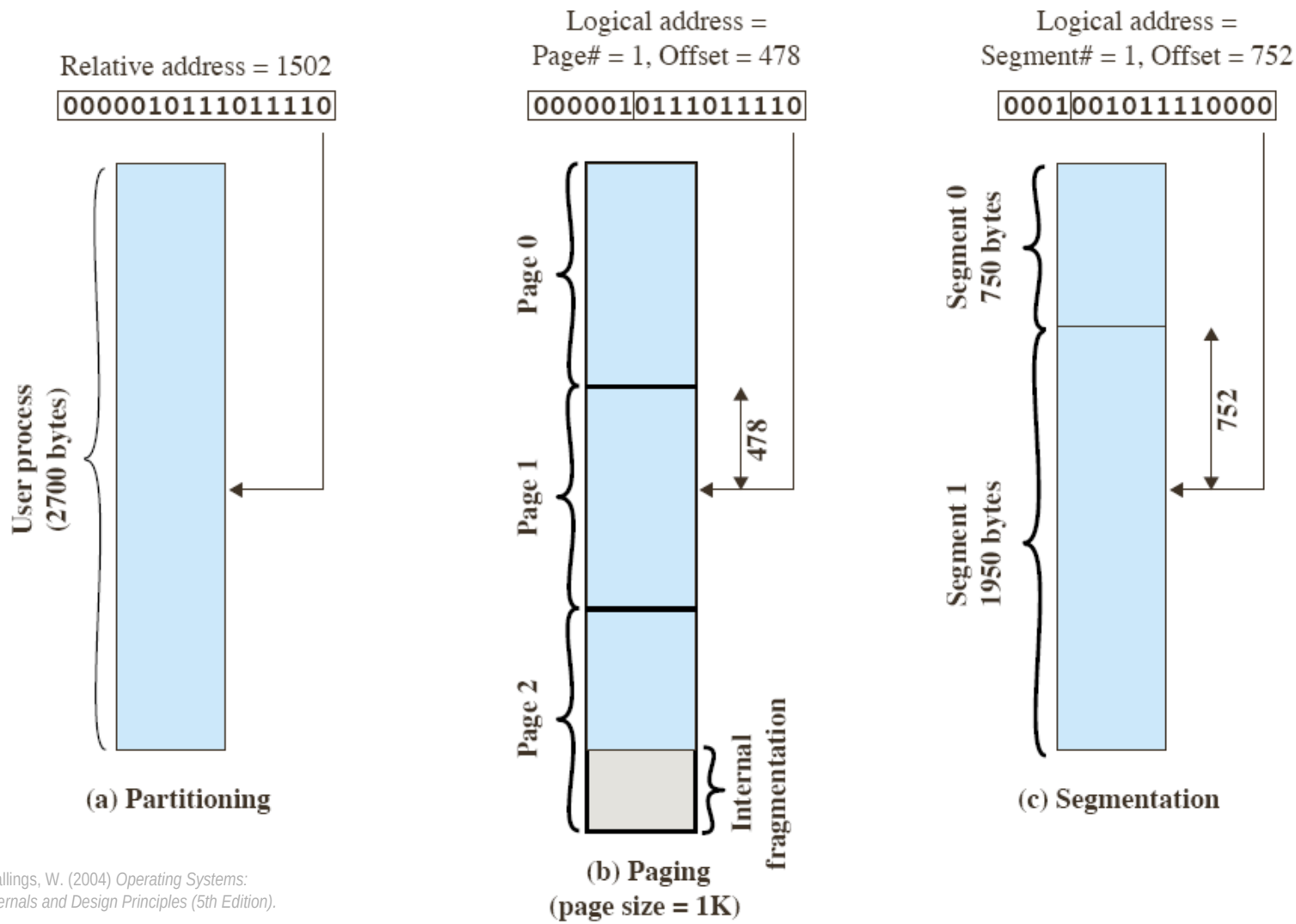
3.d Simple Paging & Segmentation

Hardware support for paging



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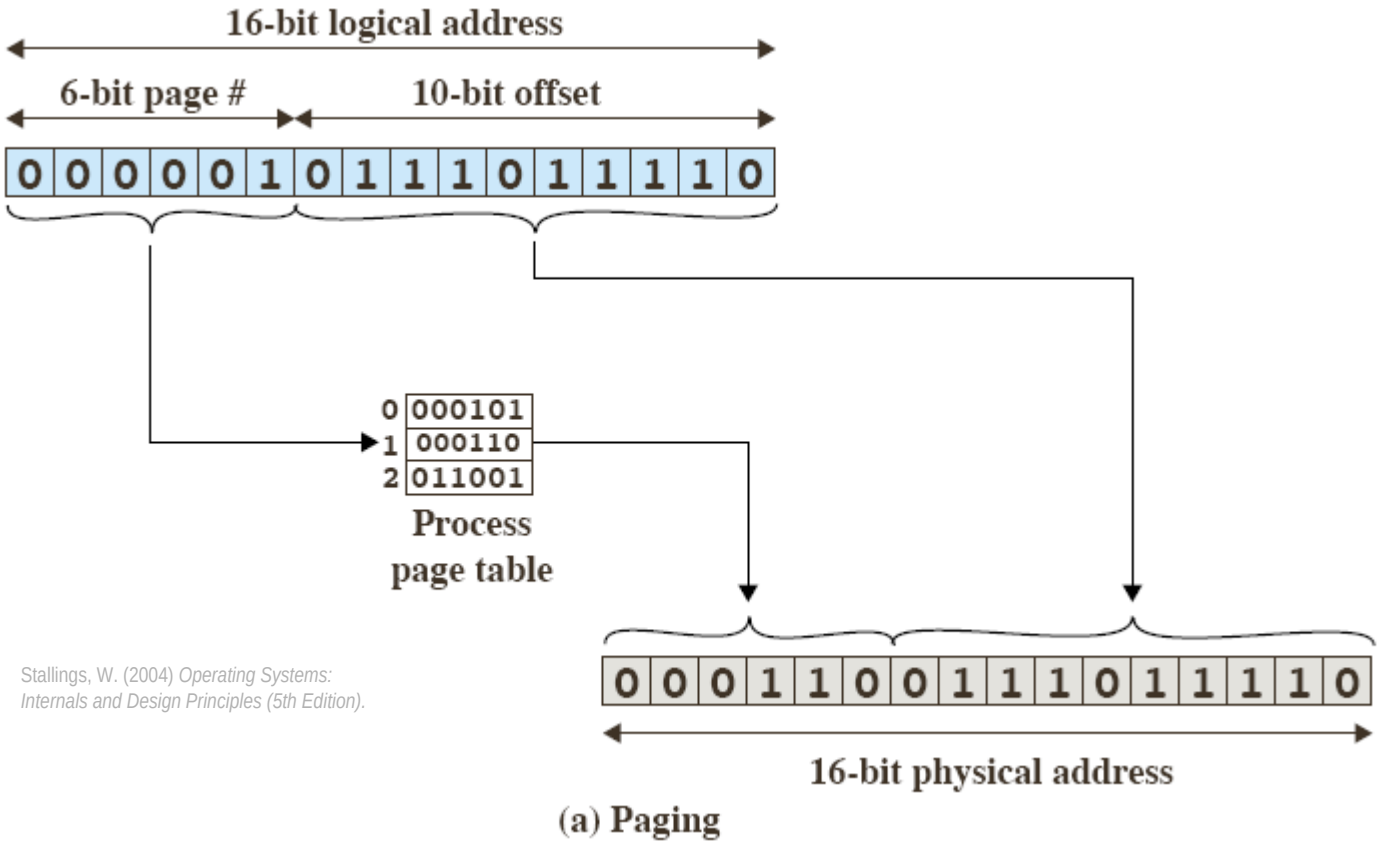
Hardware support for paging

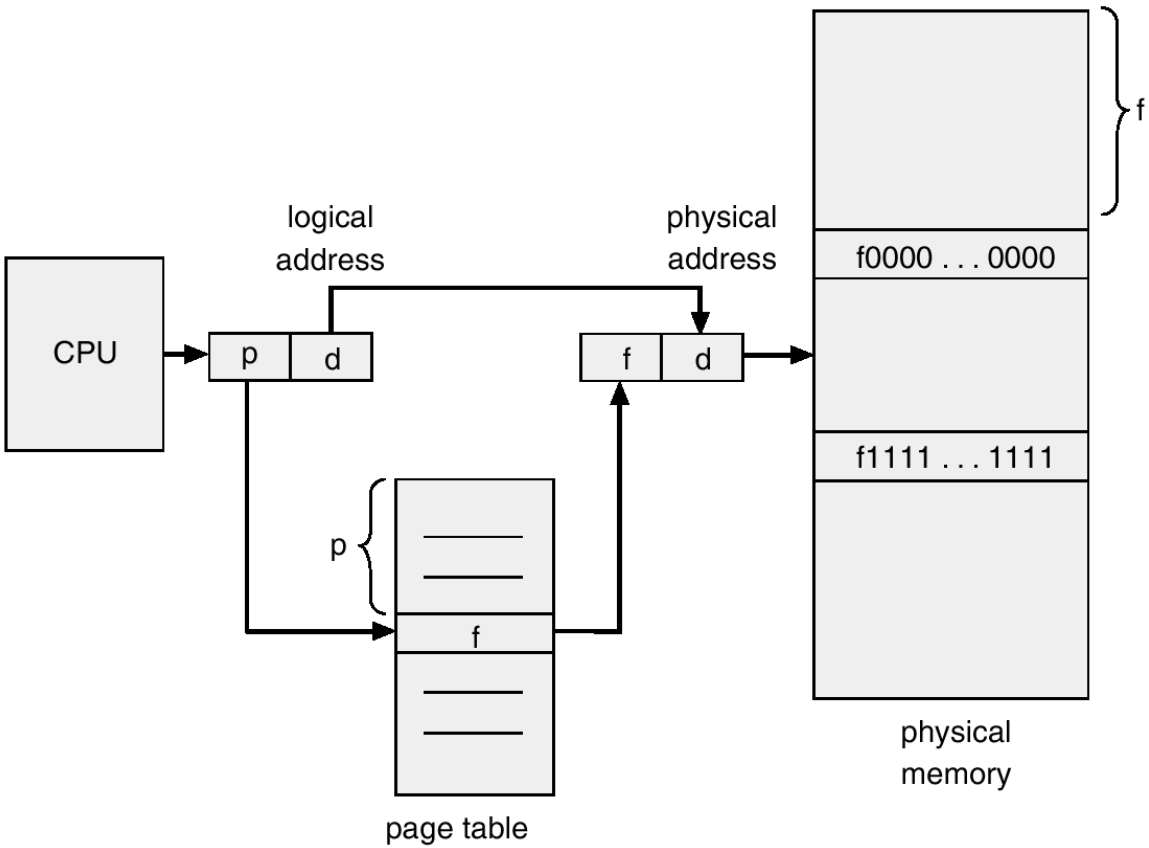


(a) Paging

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

3.d Simple Paging & Segmentation

Hardware support for paging



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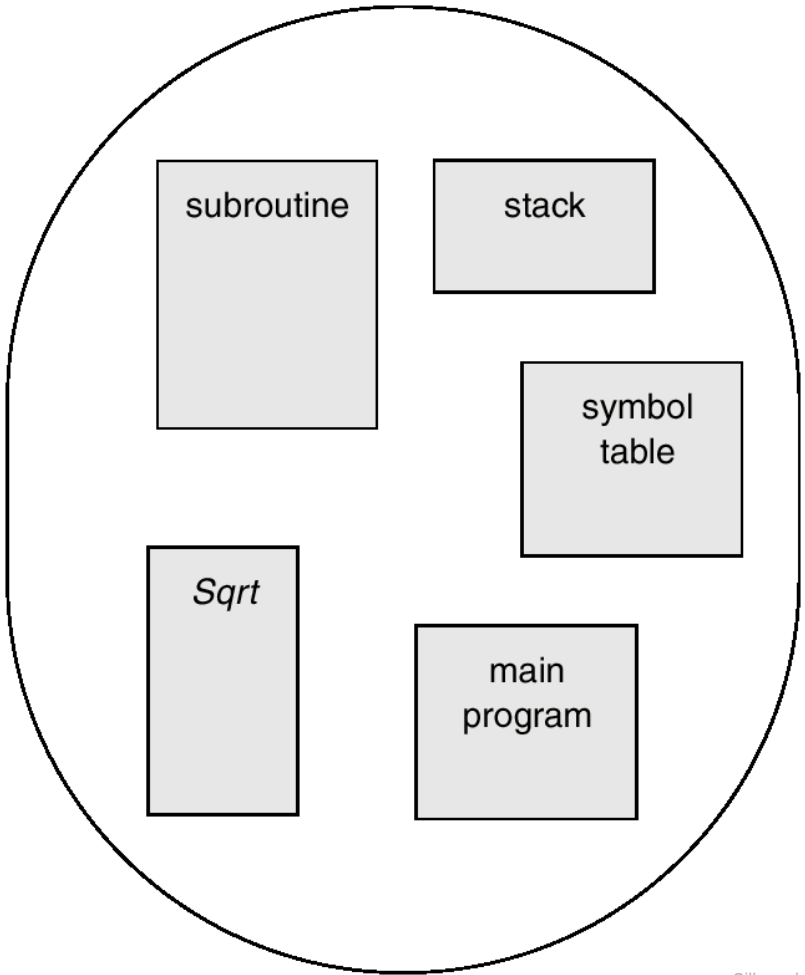
3.d Simple Paging & Segmentation

Segmentation



logical address space

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3.d Simple Paging & Segmentation

Segmentation

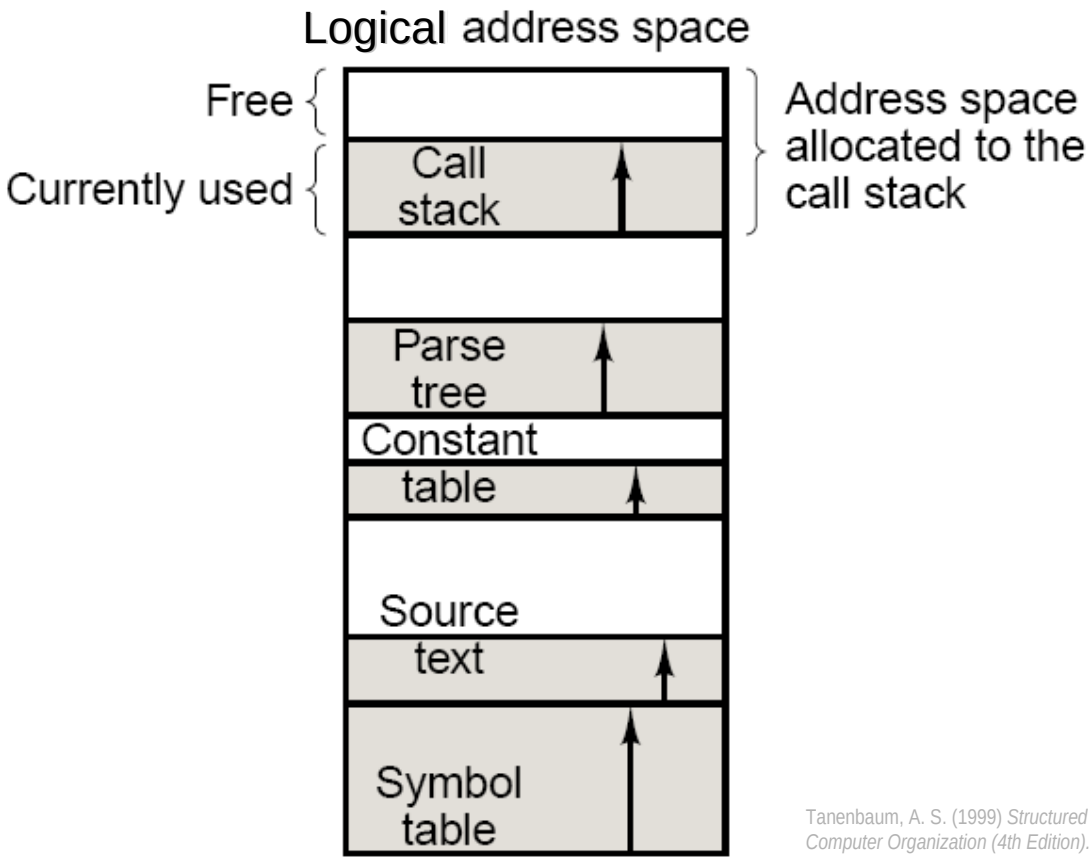


Figure 6-7. In a one-dimensional address space with growing tables, one table may bump into another.

3.d Simple Paging & Segmentation

Segmentation

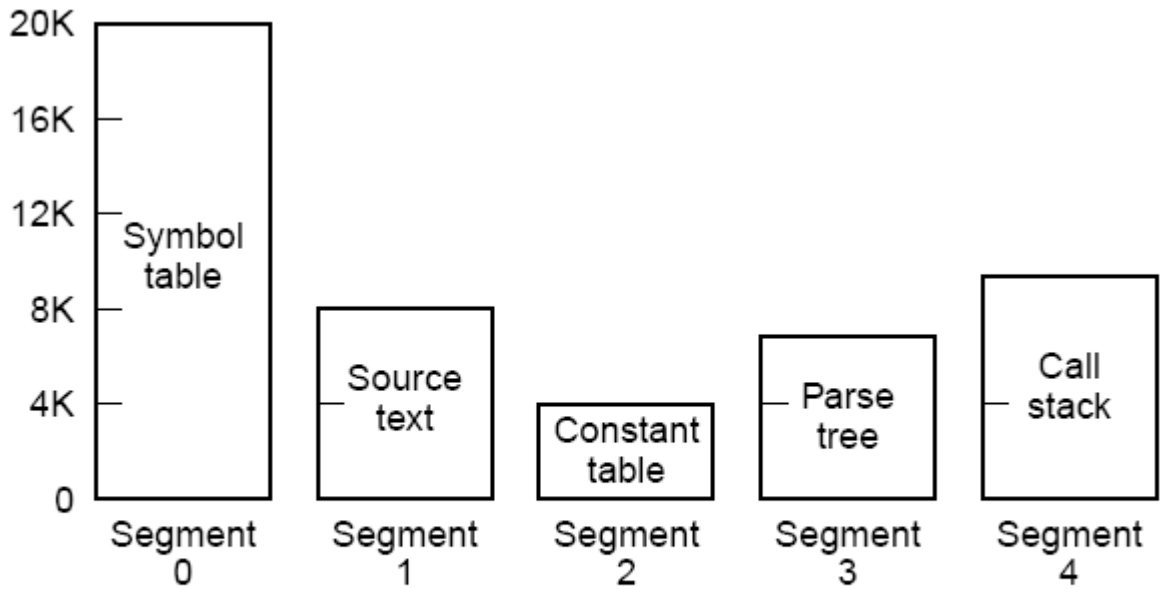
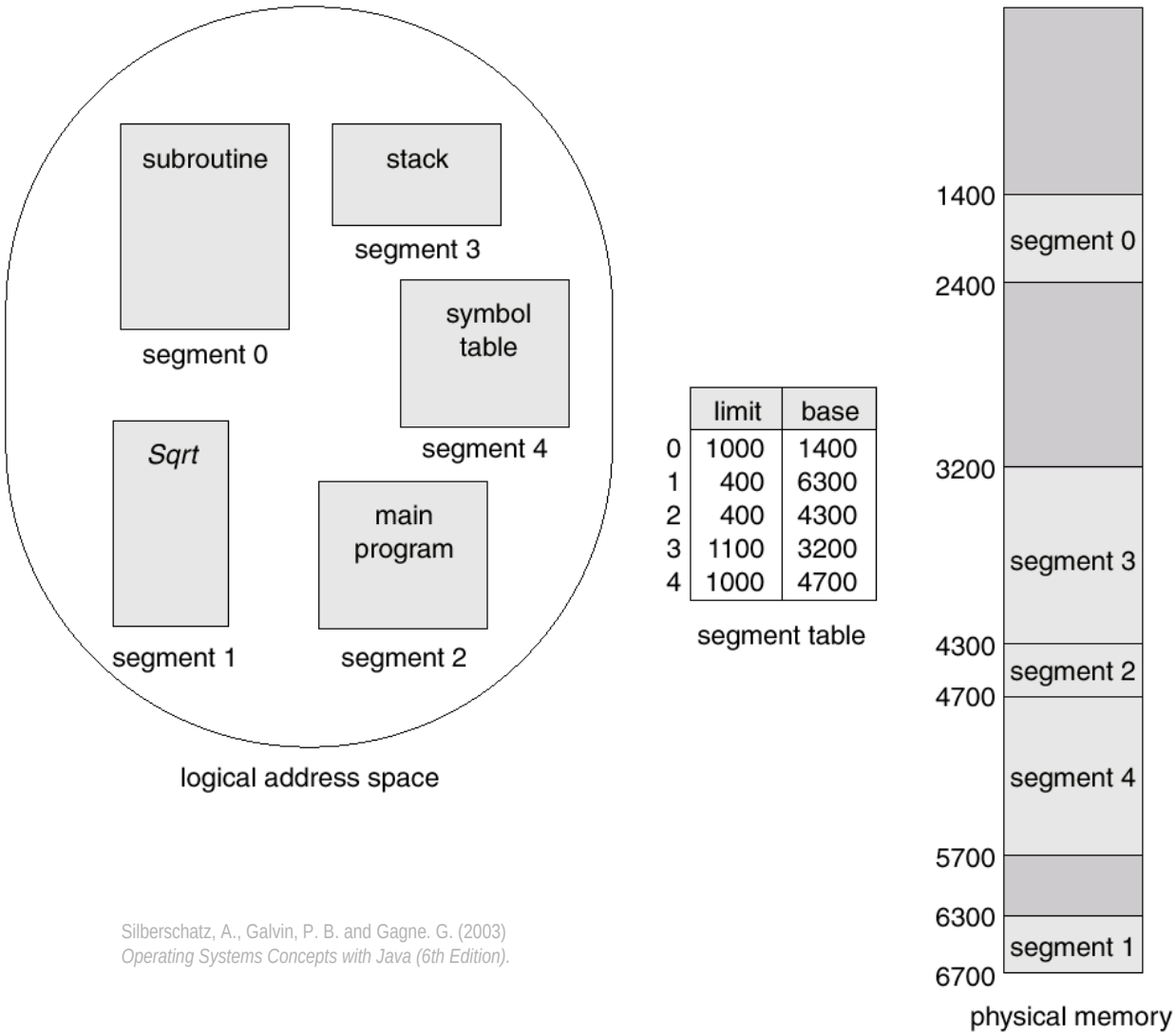


Figure 6-8. A segmented memory allows each table to grow or shrink independently of the other tables.

Tanenbaum, A. S. (1999) *Structured Computer Organization (4th Edition).*

3.d Simple Paging & Segmentation

Segmentation



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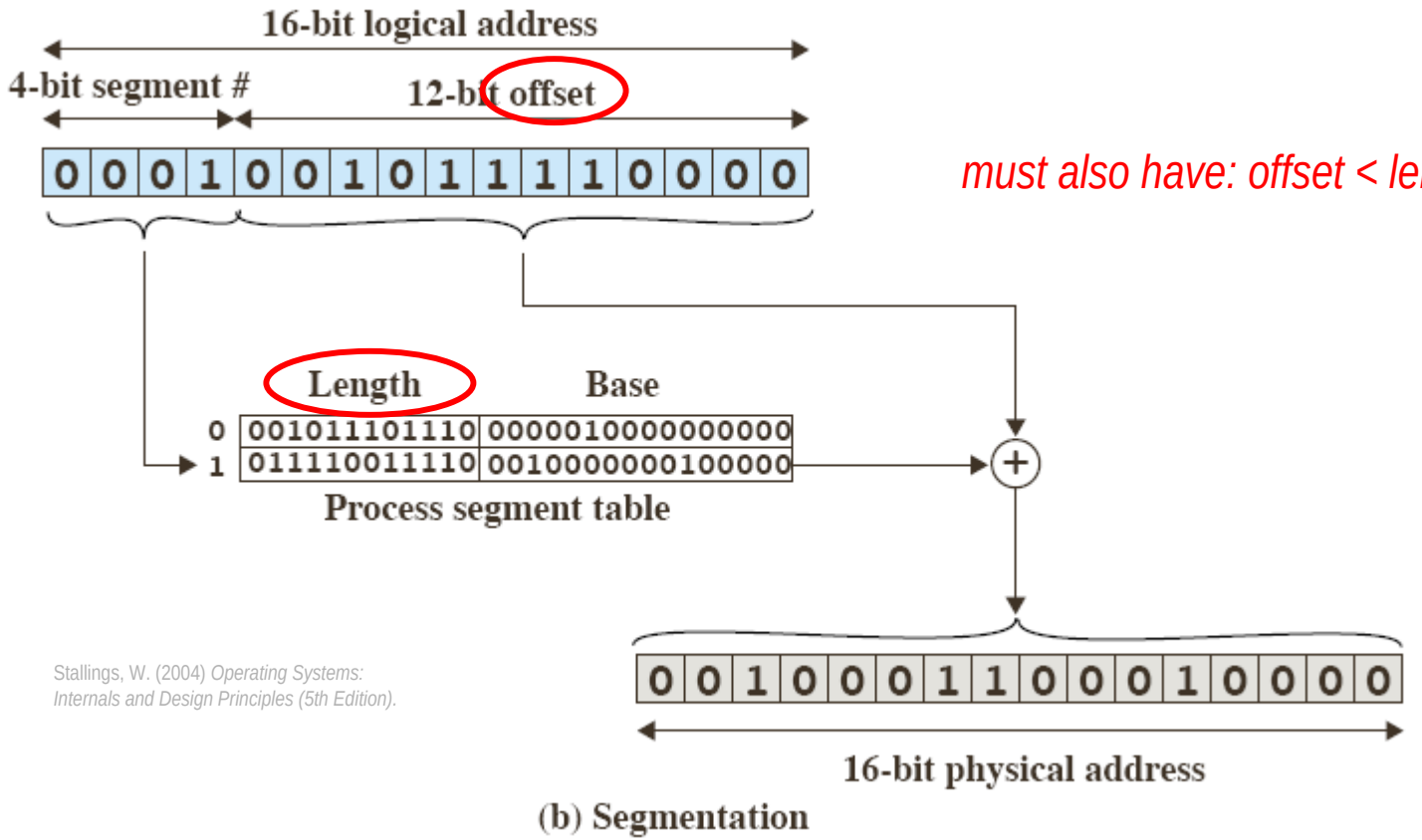
3.d Simple Paging & Segmentation

Segmentation



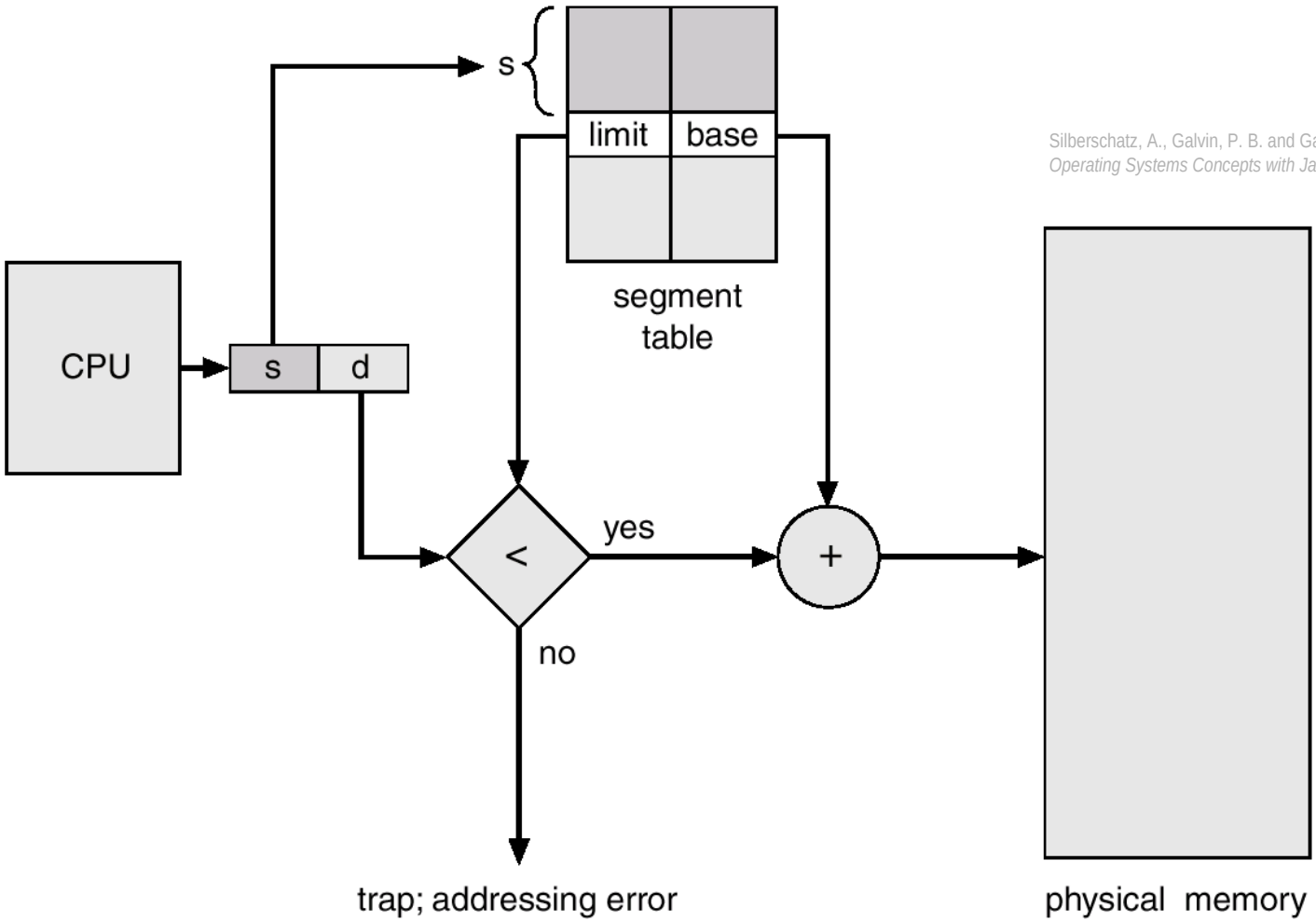
(b) Segmentation

must also have: offset < length

Stallings, W. (2004) *Operating Systems: Internals and Design Principles (5th Edition).*

3.d Simple Paging & Segmentation

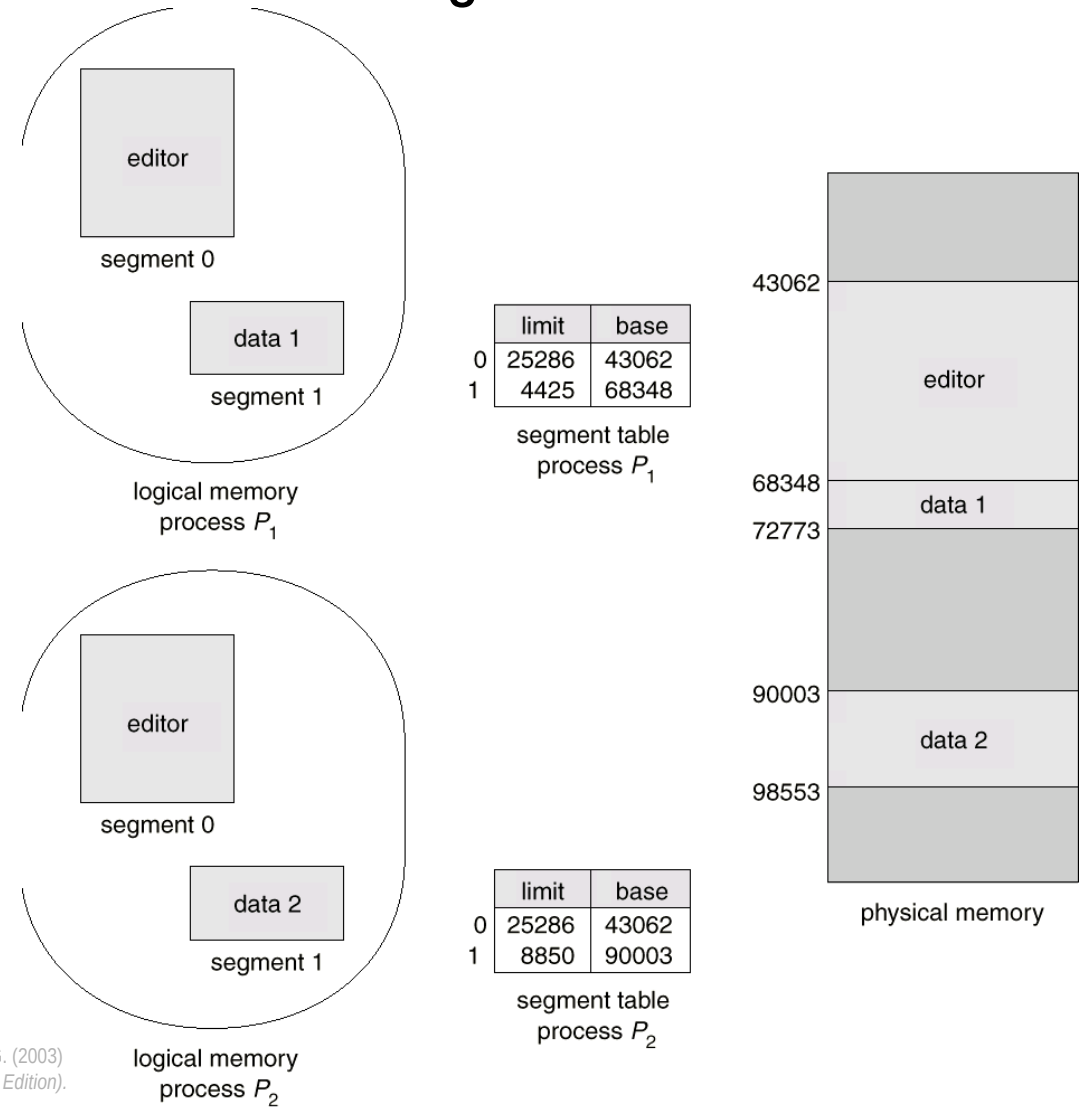
Segmentation



Silberschatz, A., Galvin, P. B. and Gagne. G. (2003)
Operating Systems Concepts with Java (6th Edition).

3.d Simple Paging & Segmentation

Segmentation



Silberschatz, A., Galvin, P. B. and Gagne. G. (2003) *Operating Systems Concepts with Java (6th Edition).*

Principles of Operating Systems

CS 446/646

3. Memory Management

a. Goals of Memory Management

b. Partitioning

c. Linking & Loading

d. Simple Paging & Segmentation

- ✓ Paging
- ✓ Hardware support for paging
- ✓ Segmentation

e. Virtual Memory

f. Page Replacement Algorithms