Systems and Networking I

Applied Computer Science and Artificial Intelligence

2025-2026

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Where Do We Stand?

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  - Processes and Threads
  - CPU Scheduling
  - Synchronization and Deadlock

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  - Memory Management
- … Later on:
  - File Systems and I/O Storage
  - Advanced Topics (?)

Part IV: Memory Management

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- Allocate memory resources among multiple competing processes
  - **maximizing memory utilization and system throughput**
- Guarantee isolation between processes
  - **addressability and protection**
- Provide a convenient abstraction to the programmer
  - **illusion of unlimited amount of memory**

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  2) **Loaded** from disk into main memory (RAM)

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NOTE:
In case of purely-interpreted language implementations, translation from source code to executable is done "on-the-fly" by the loaded interpreter

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How?

Generating Memory Addresses: Example

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1. Fetch instruction at address `128`
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3. Fetch instruction at address `136`
4. Execute instruction: addition (no memory reference)
5. Fetch instruction at address `144`
6. Execute instruction: store to address `[%R2]` (`1234`)

Symbolic Name vs. Logical vs. Physical Address

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physical address: actual memory address which memory chip operates on

Address Binding

Mapping from logical to physical address

Address Binding

Mapping from logical to physical address

Compile time

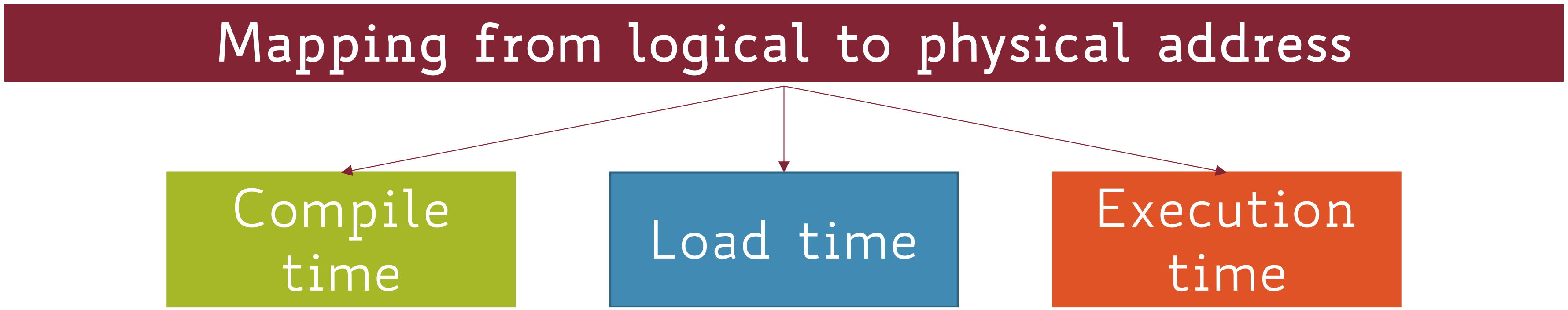
Address Binding

Mapping from logical to physical address

Compile time

Load time

Address Binding



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The program must be recompiled!

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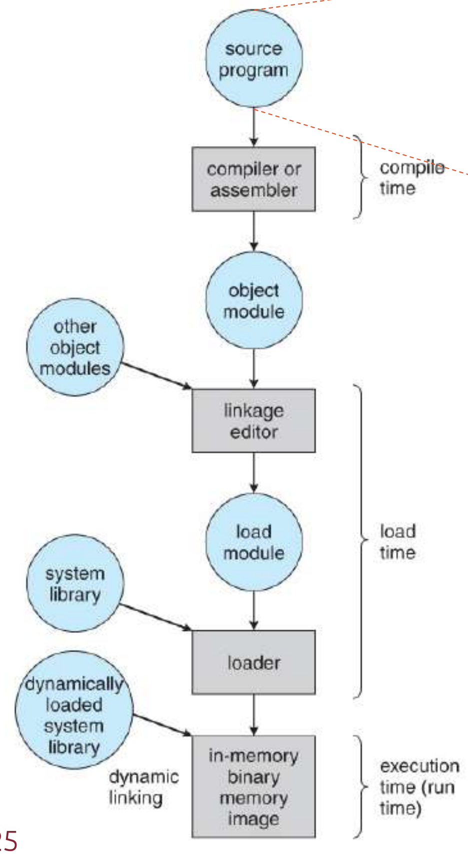


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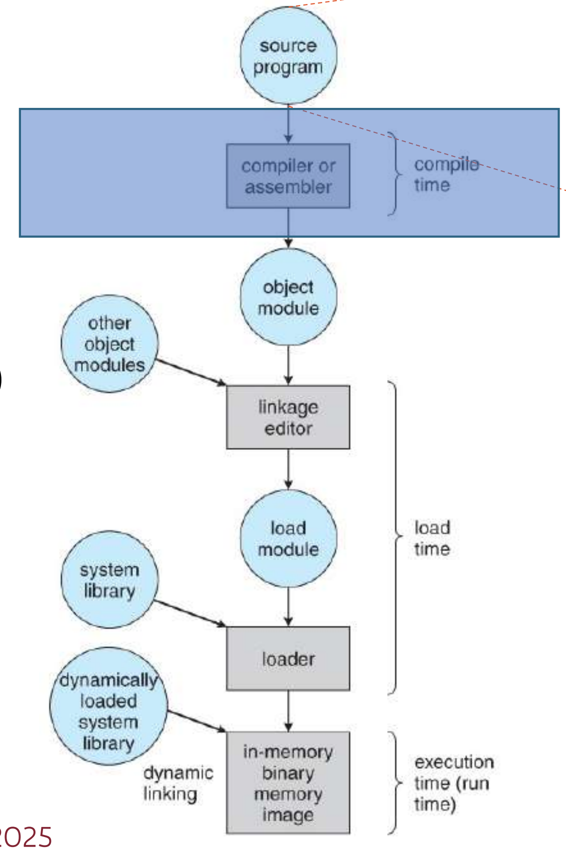


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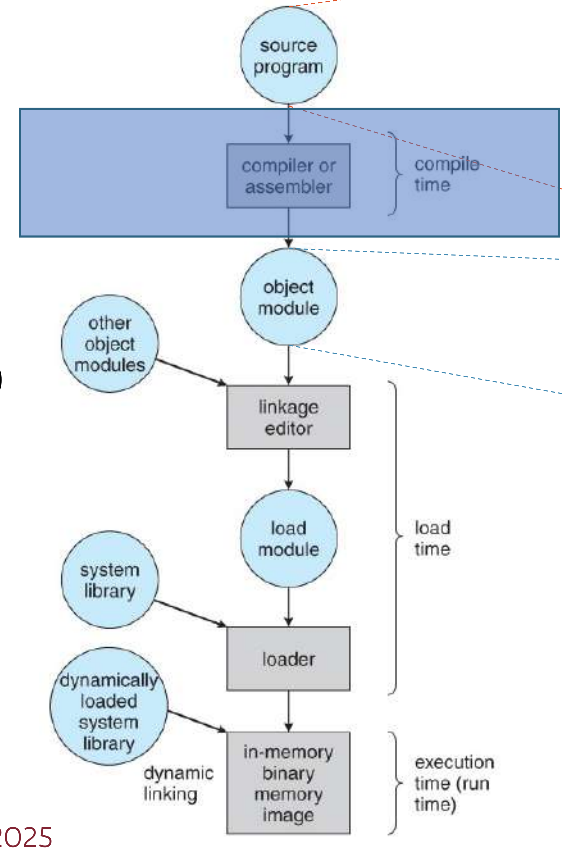


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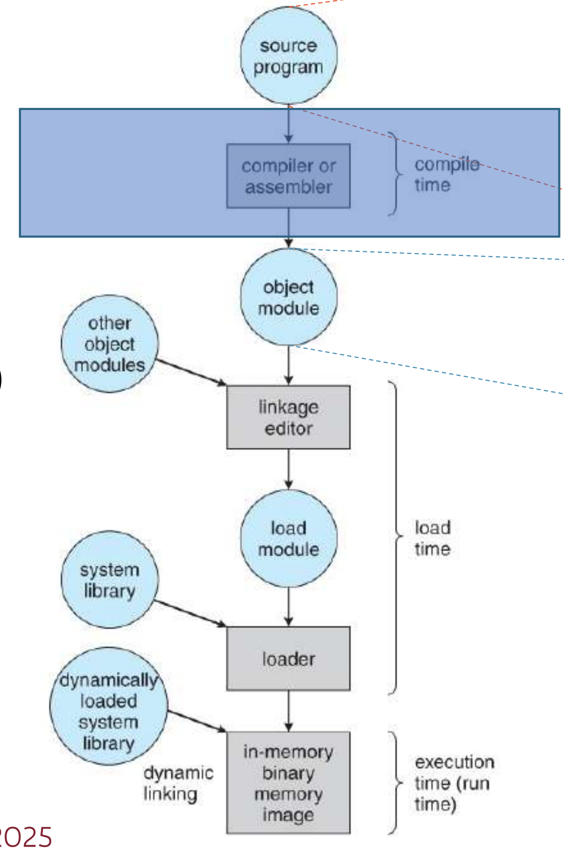


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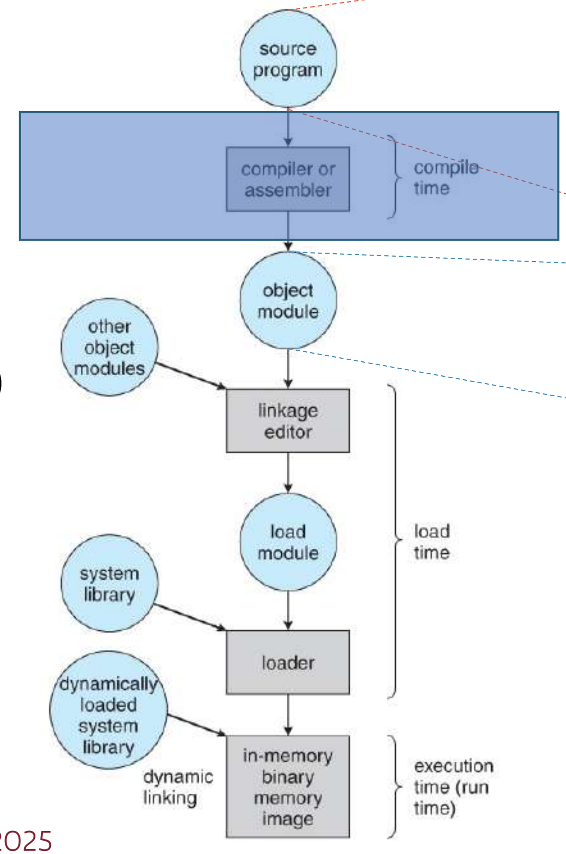


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The program must be reloaded but not recompiled!

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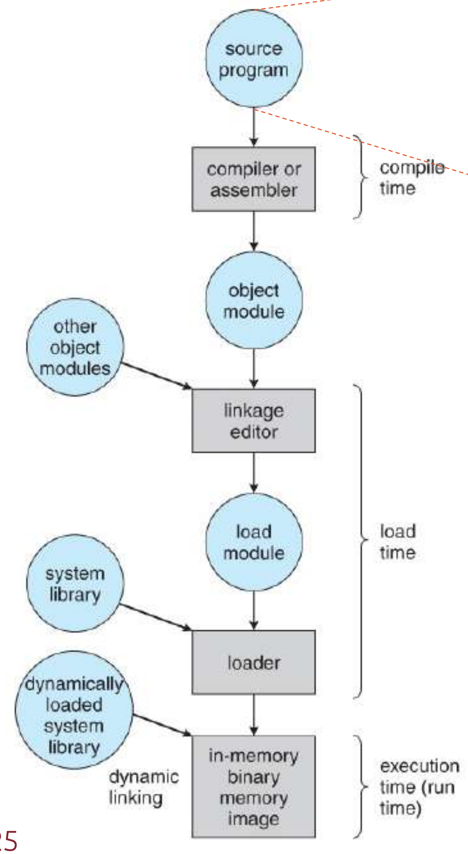


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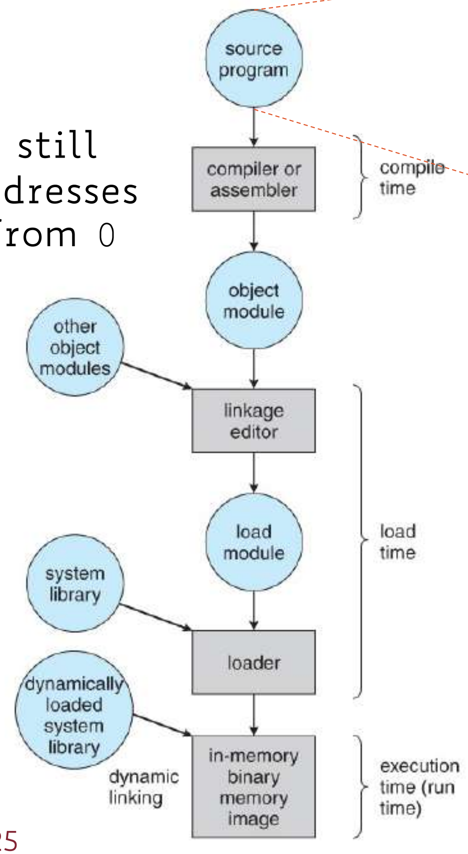


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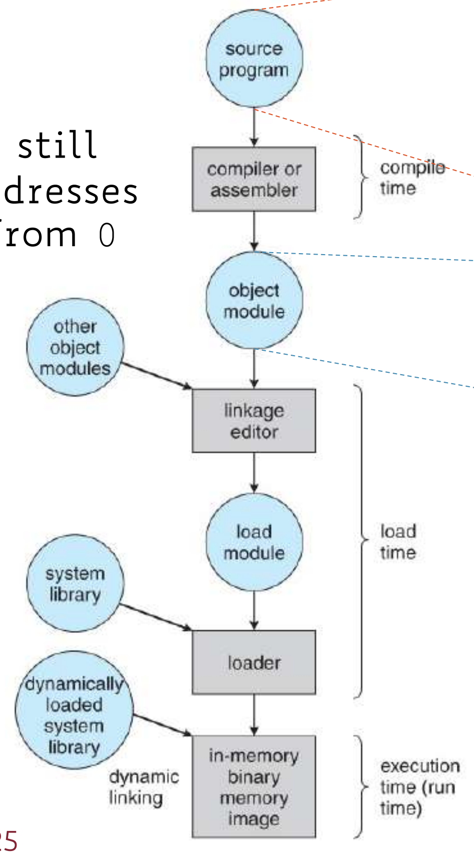


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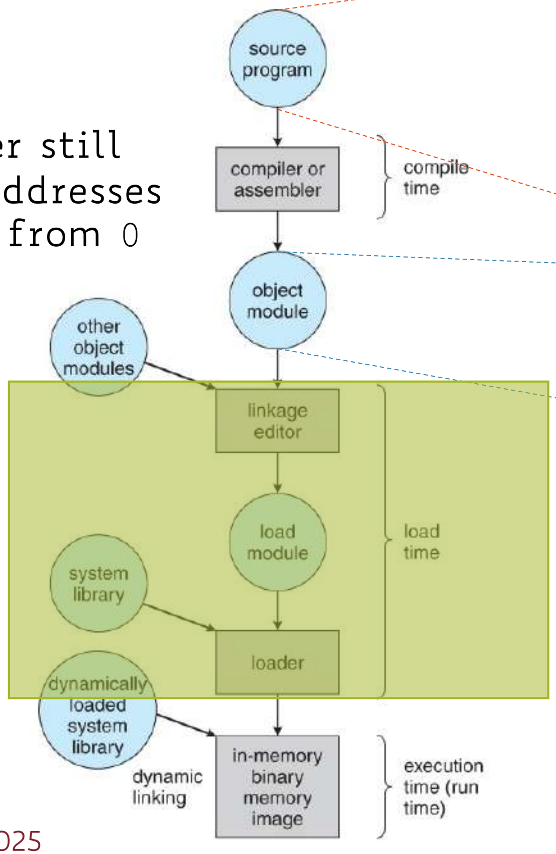


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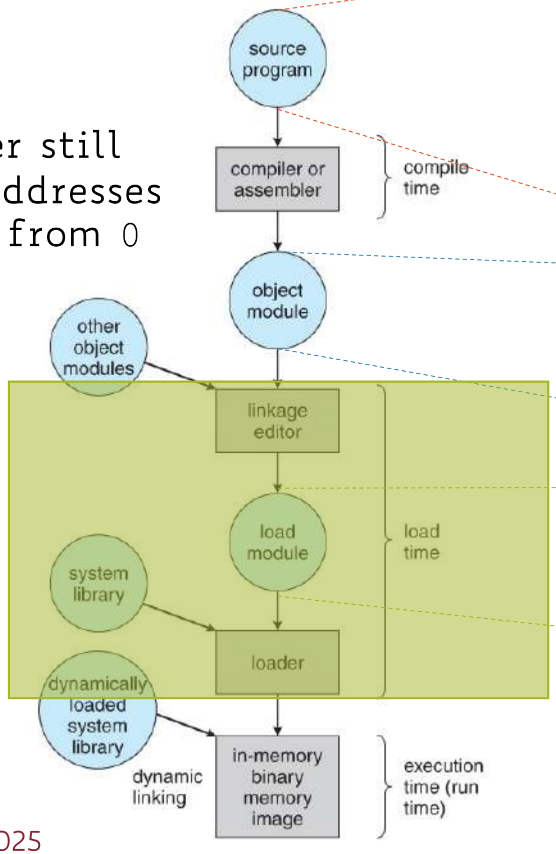


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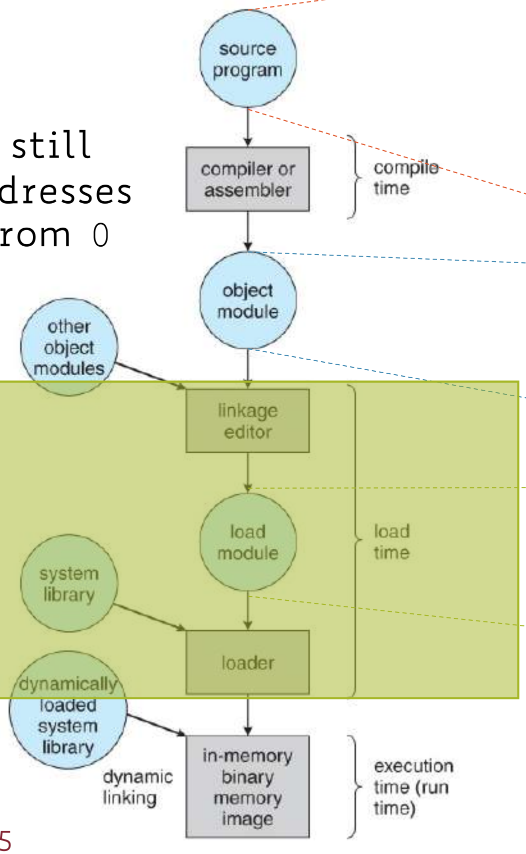


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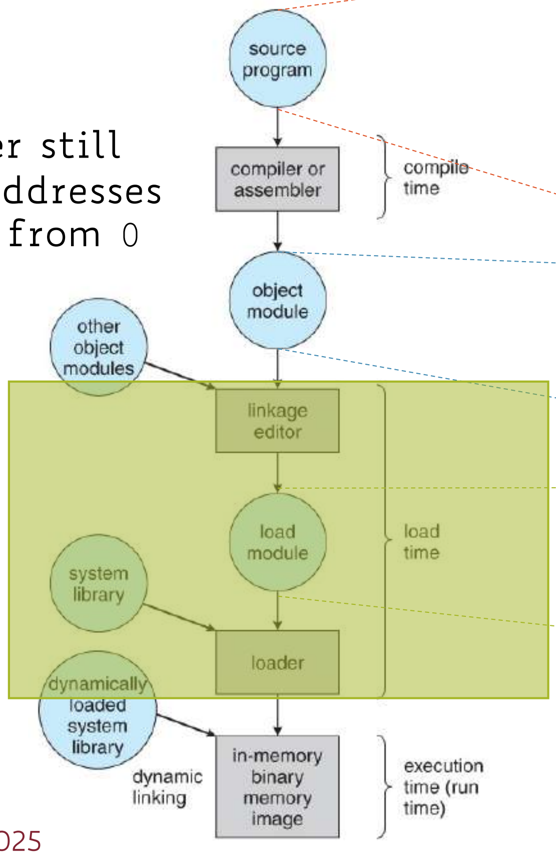


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Most flexible solution implemented by the majority of modern OSs

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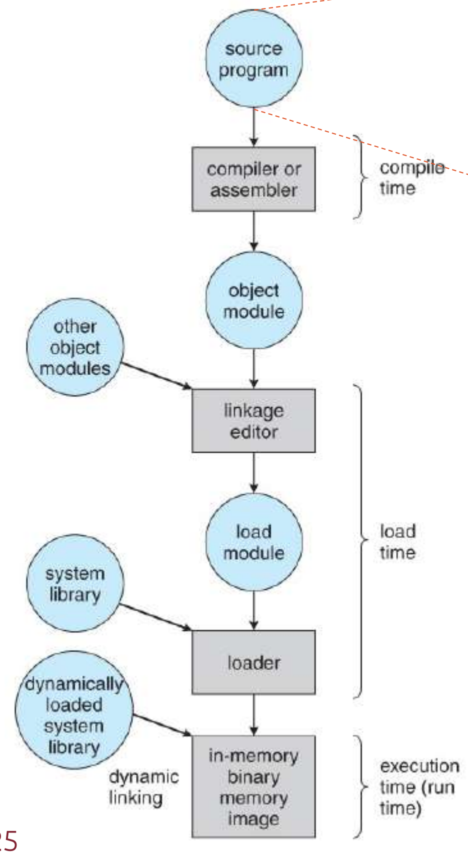


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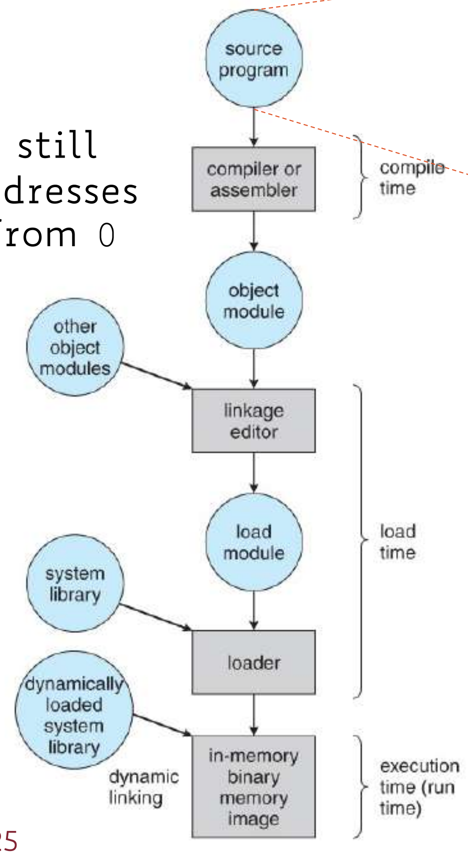


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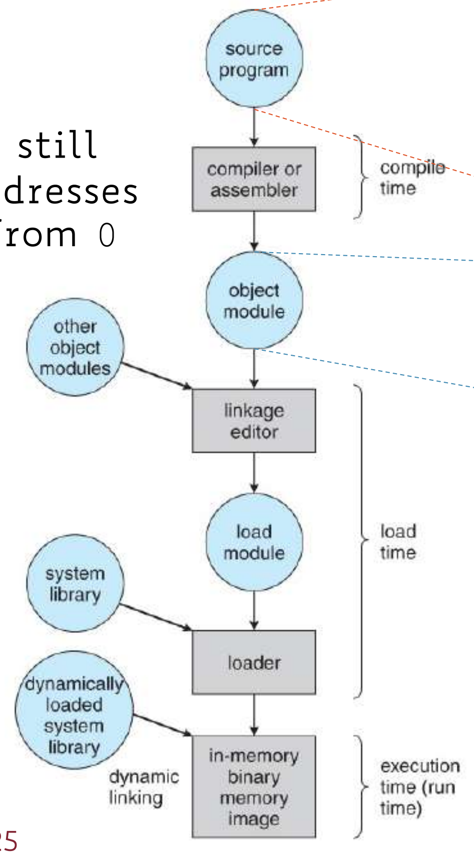


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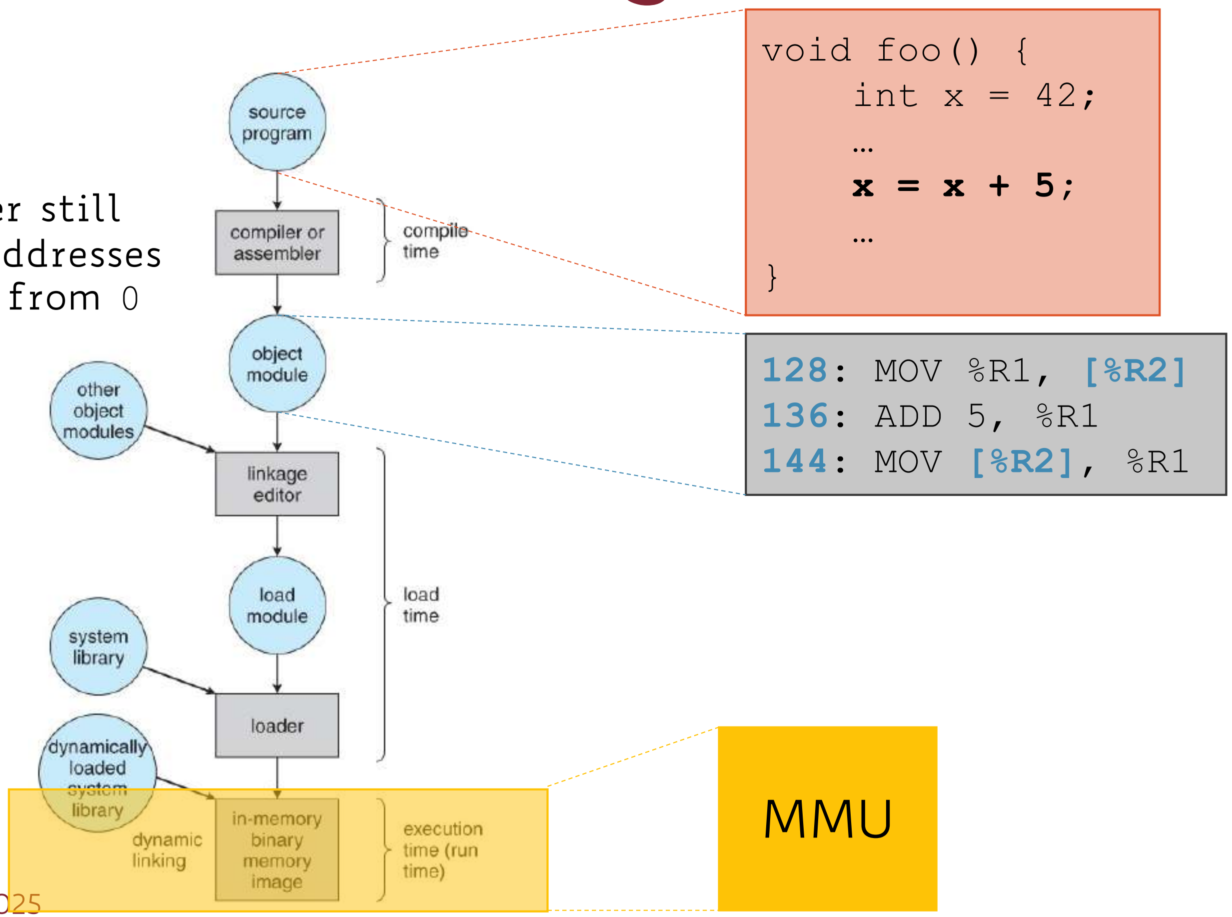

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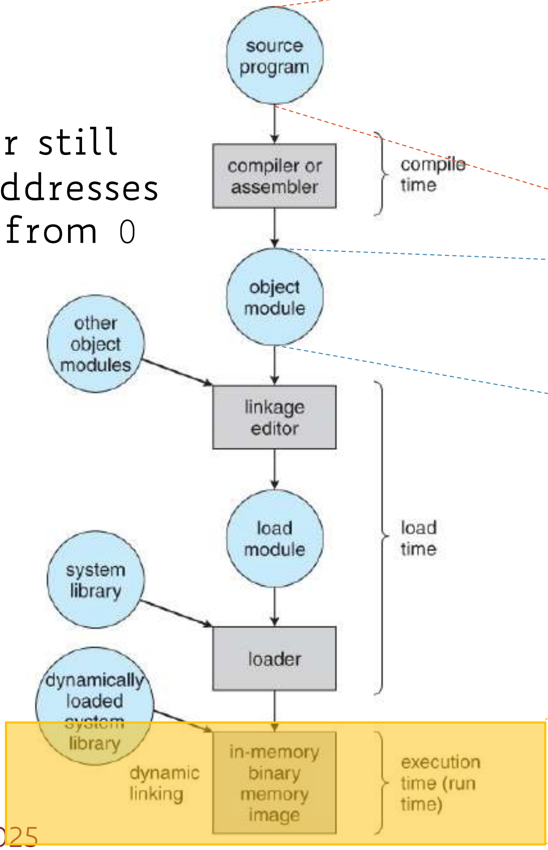


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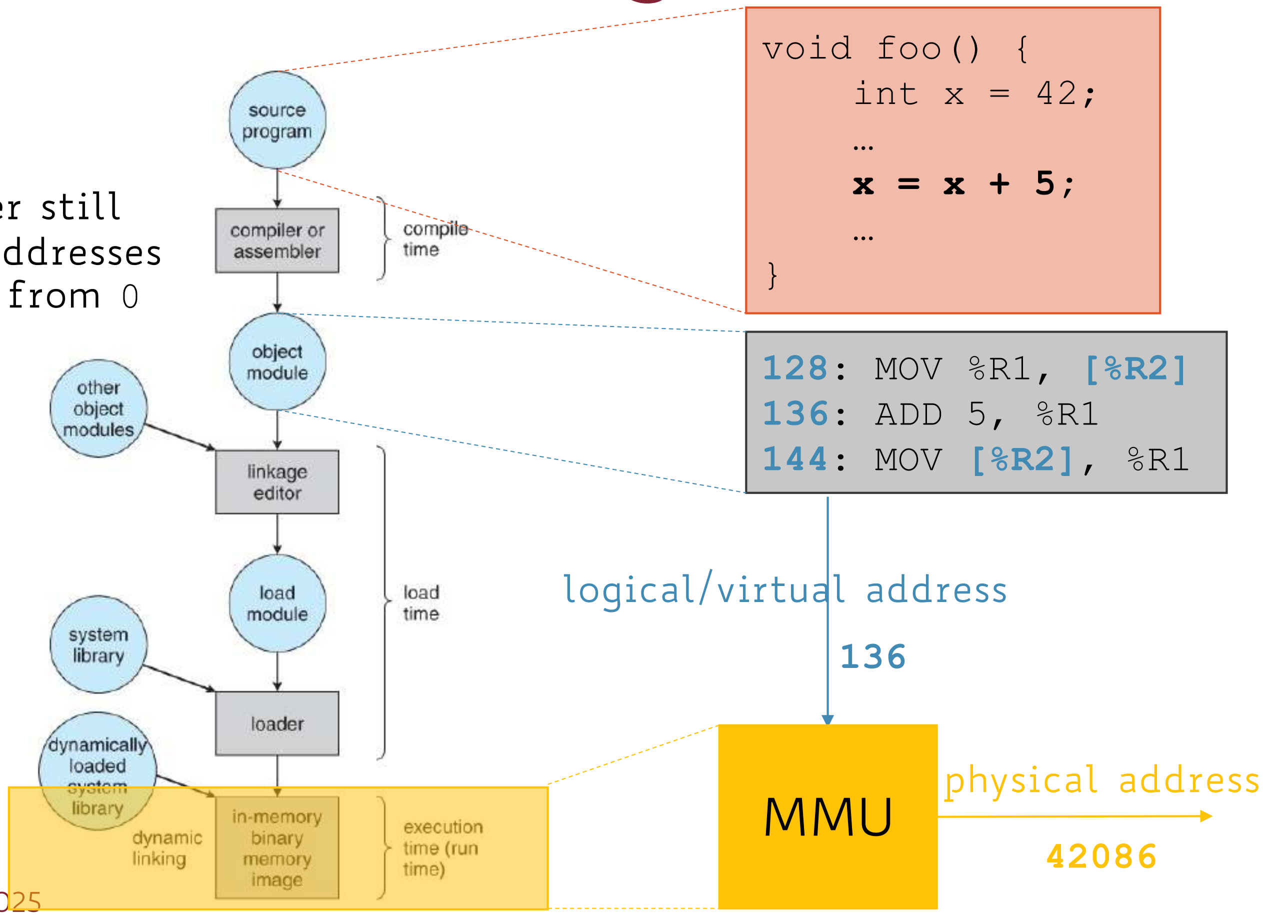

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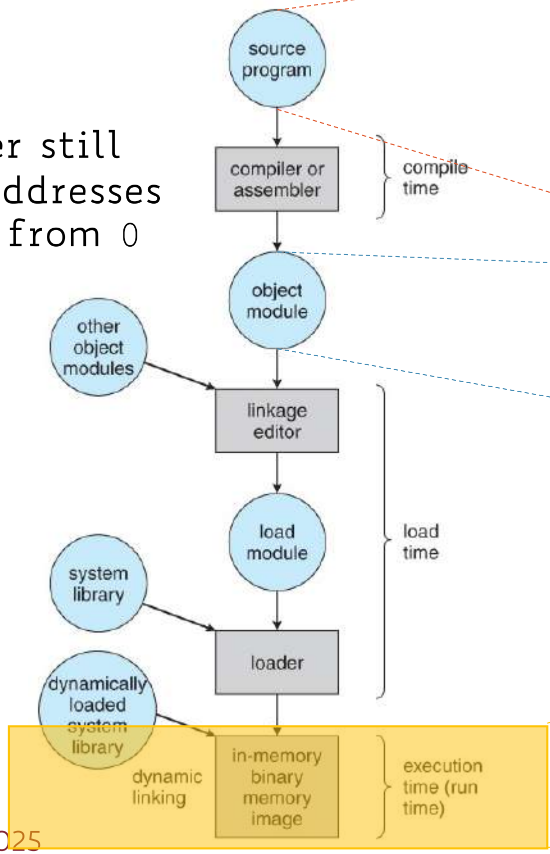


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Every logical address referenced by the CPU is translated by HW at run time

physical addresses != logical addresses

MMU

physical address

42086

Managing Memory

- <u>Key Assumptions:</u>
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  - VAS must be entirely placed contiguously in main memory
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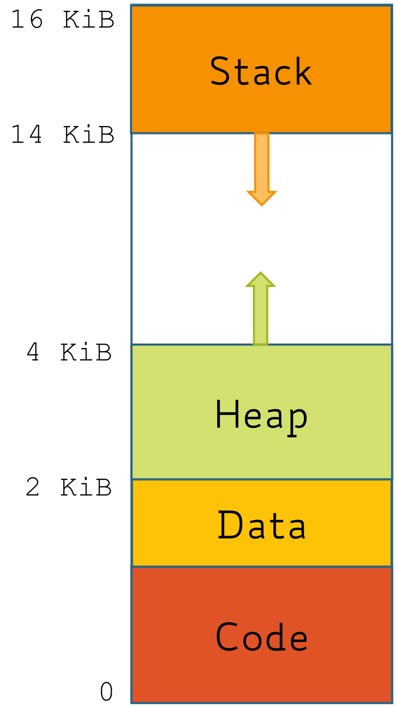
Don't worry! We will soon relax those assumptions

Managing Memory: VAS

`virtual address space = 16 KiB`



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- Transparency
  - Processes should not be aware that memory is shared
  - Processes should not be aware of which portions of physical memory they are assigned to

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- **Protection/Security**
  - Processes must not be able to corrupt each other or the OS
  - Processes must not be able to read data of other processes
- **Efficiency**
  - CPU and memory performance should not degrade badly due to sharing
  - Keep memory fragmentation low

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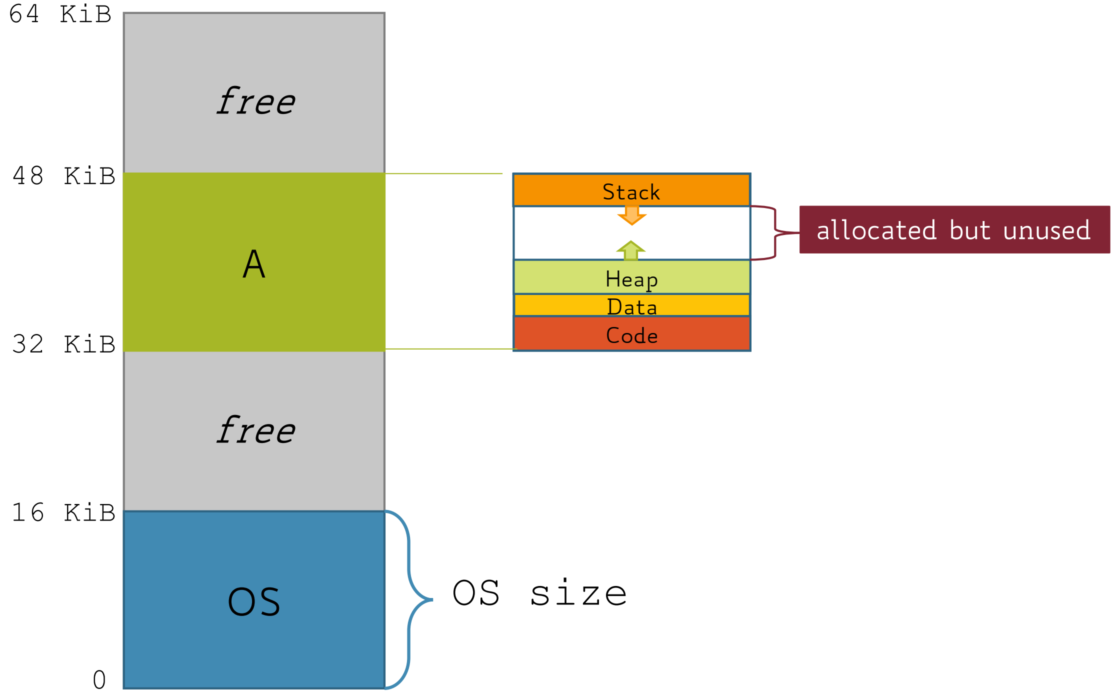
- Allow transparent sharing of memory: each process' address space may be placed anywhere in memory

Managing Memory: VAS Relocation

RAM size = 64 KiB

OS size = 16 KiB



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- CONs:
  - No protection/privacy → processes can corrupt the OS or other processes
  - Address space must be entirely allocated contiguously → free space between stack and heap can be huge and wasted!
  - The OS cannot move a process (address space) once allocated in memory

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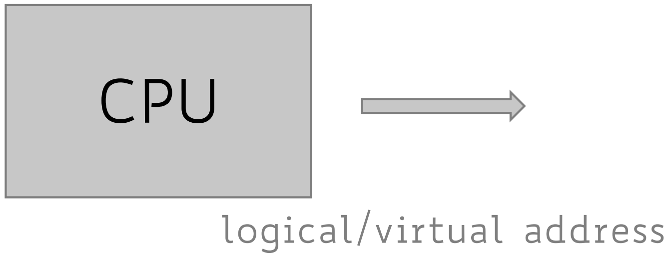

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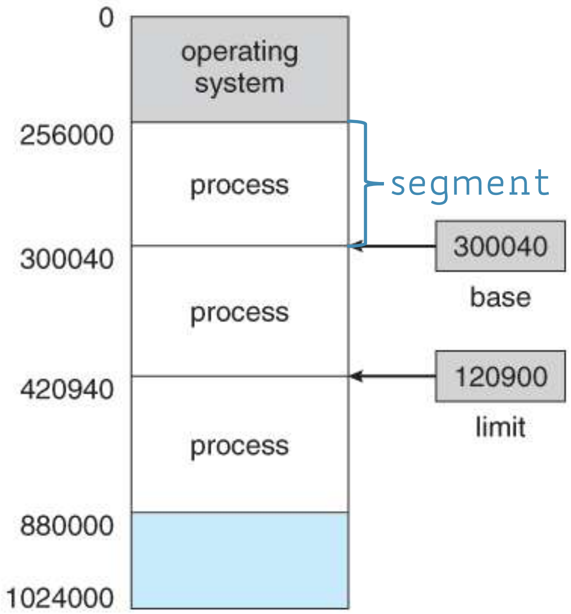
    - while executing process instructions on the CPU

Base and Limit Registers: Idea



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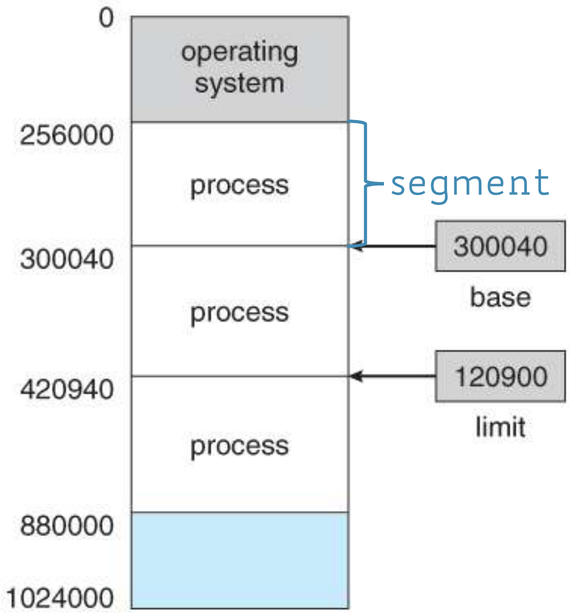

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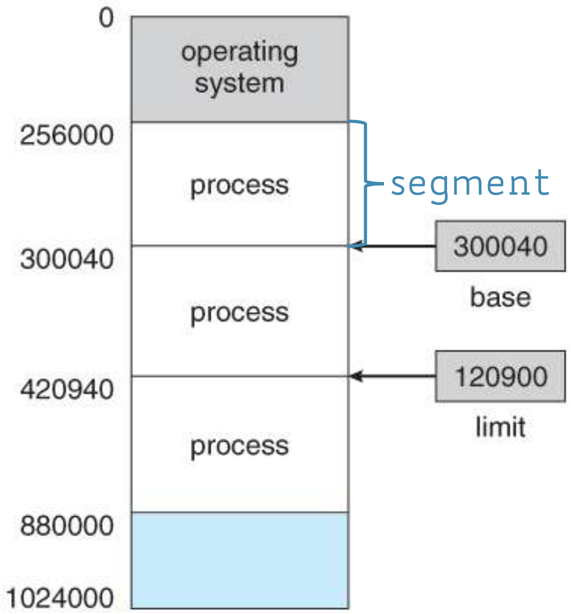

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Protection implemented using two MMU registers: base and limit

Implementing Dynamic Relocation

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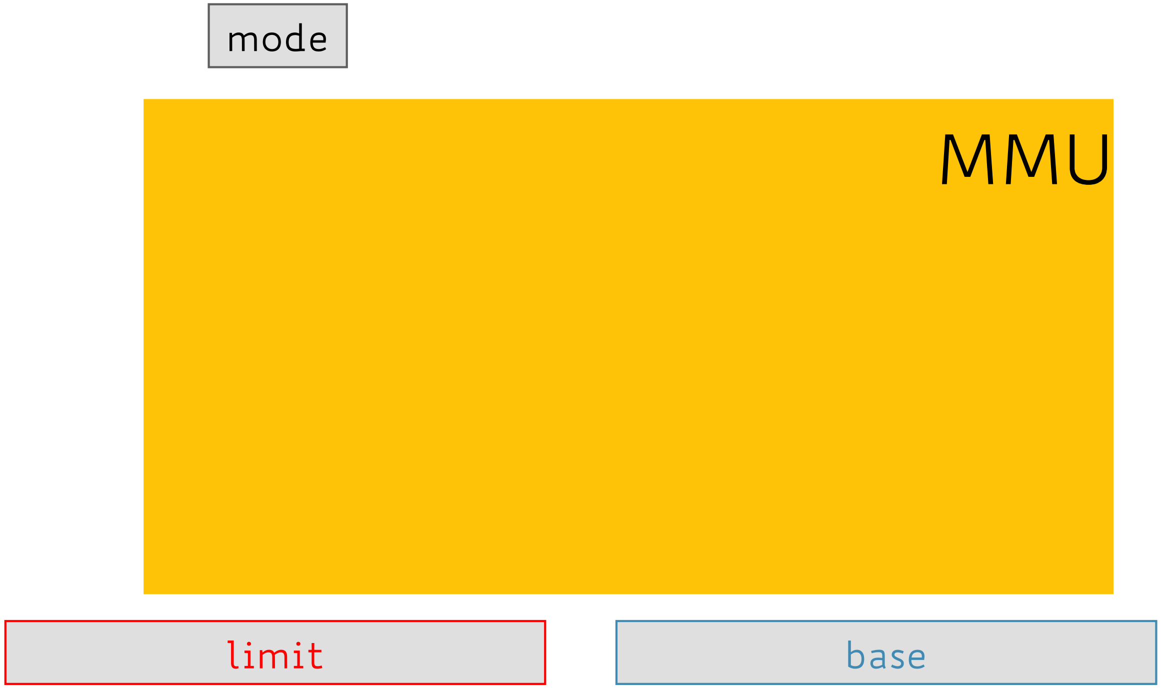

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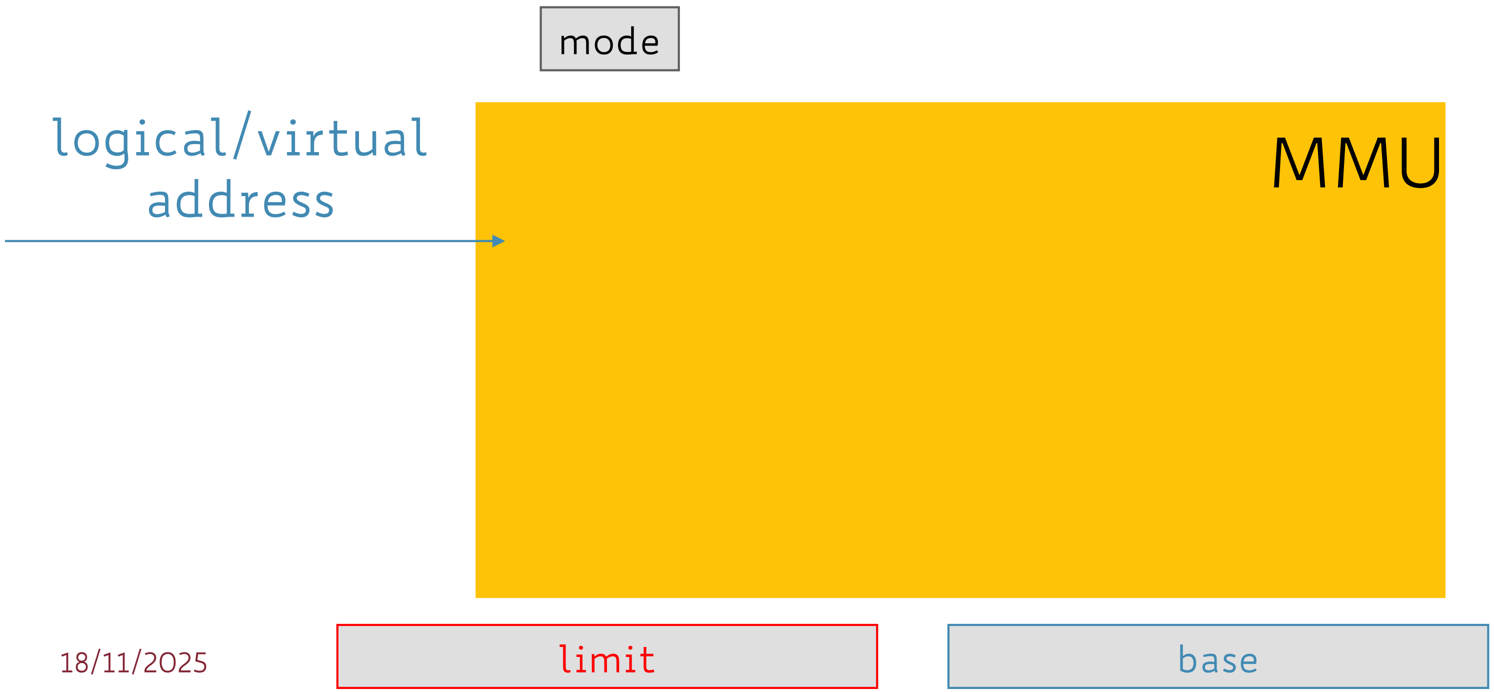

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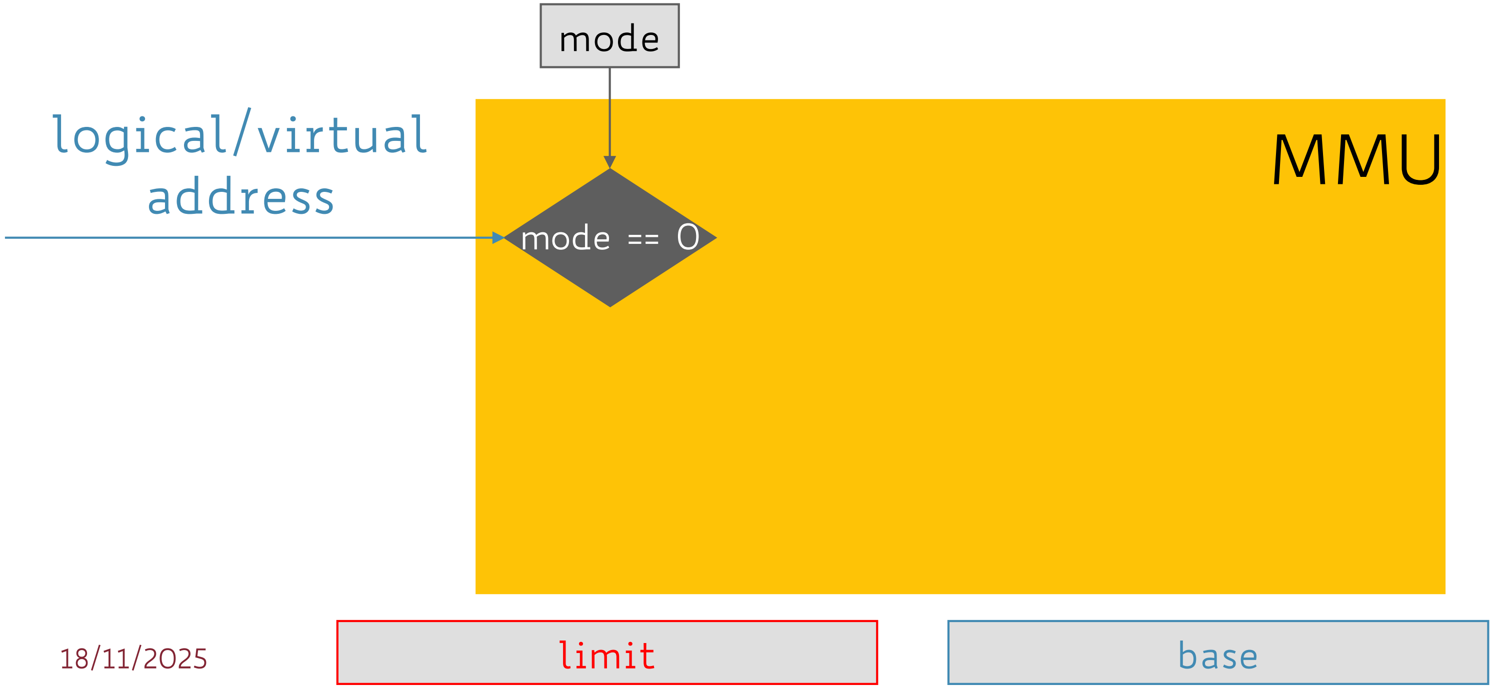

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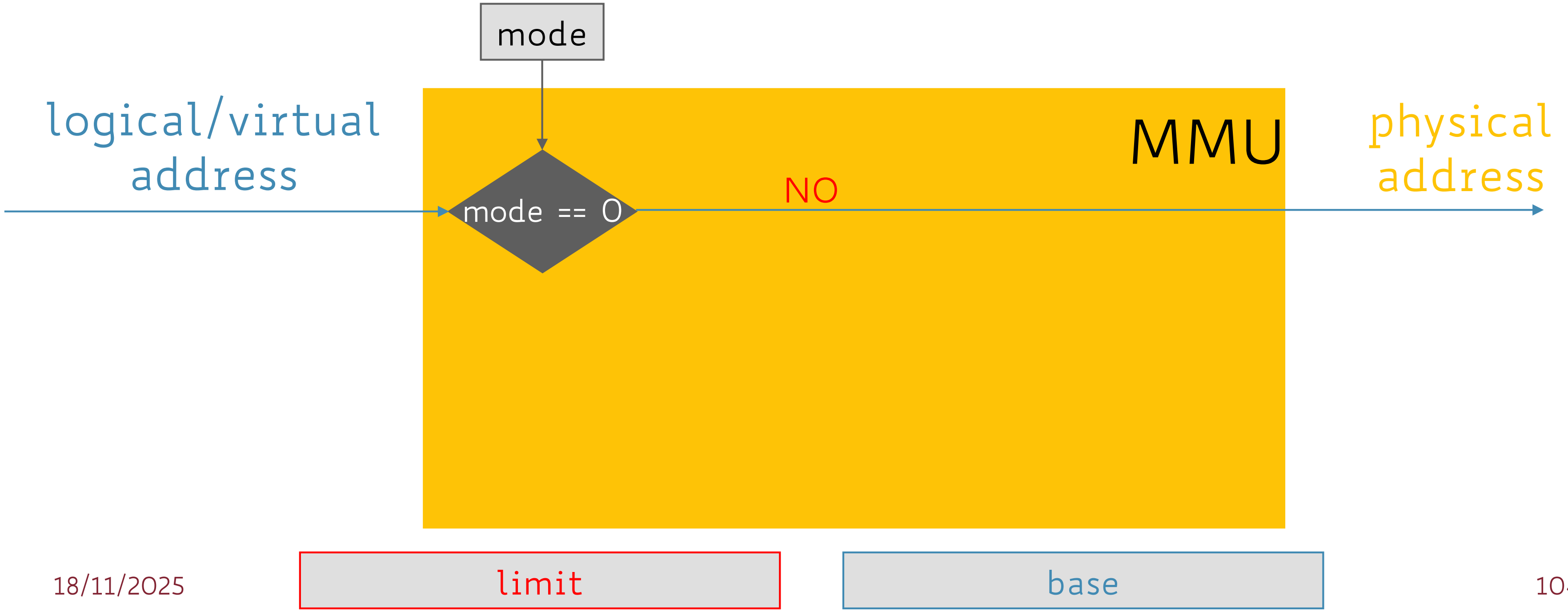

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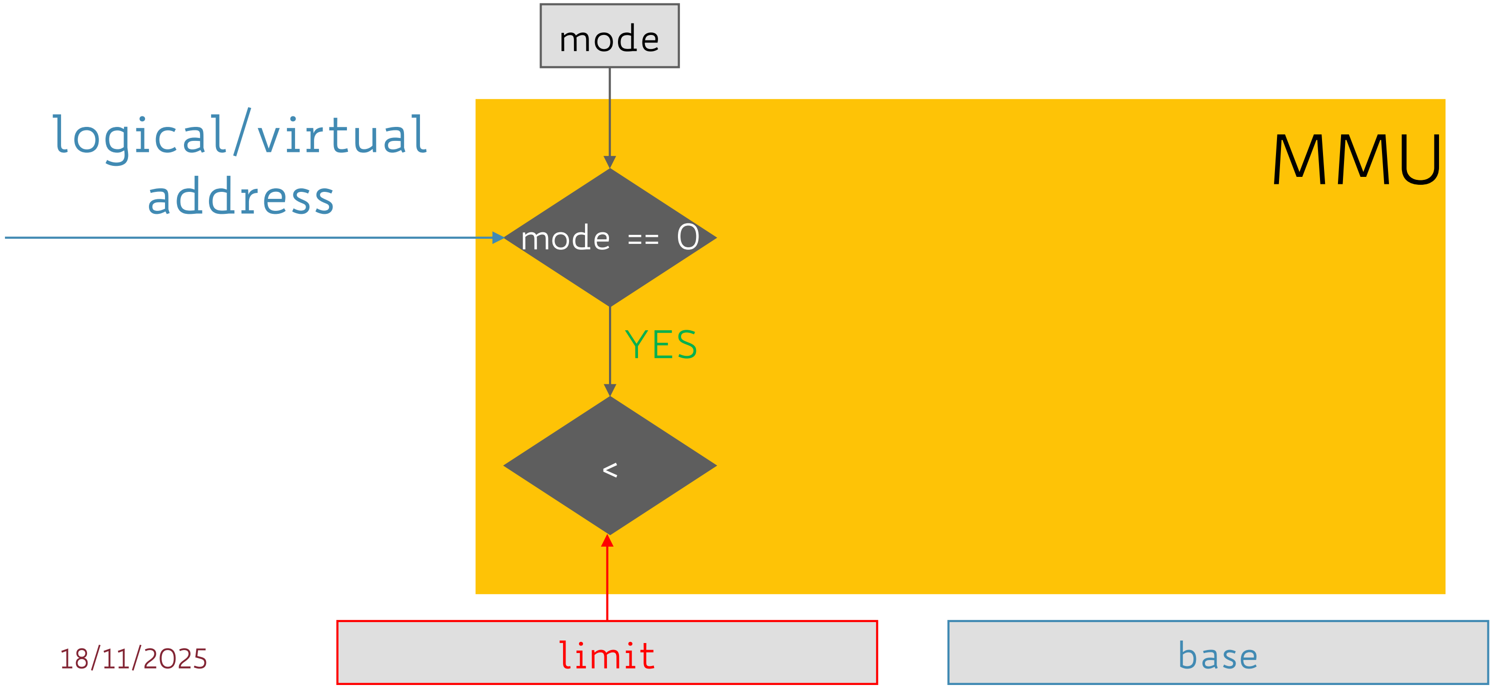

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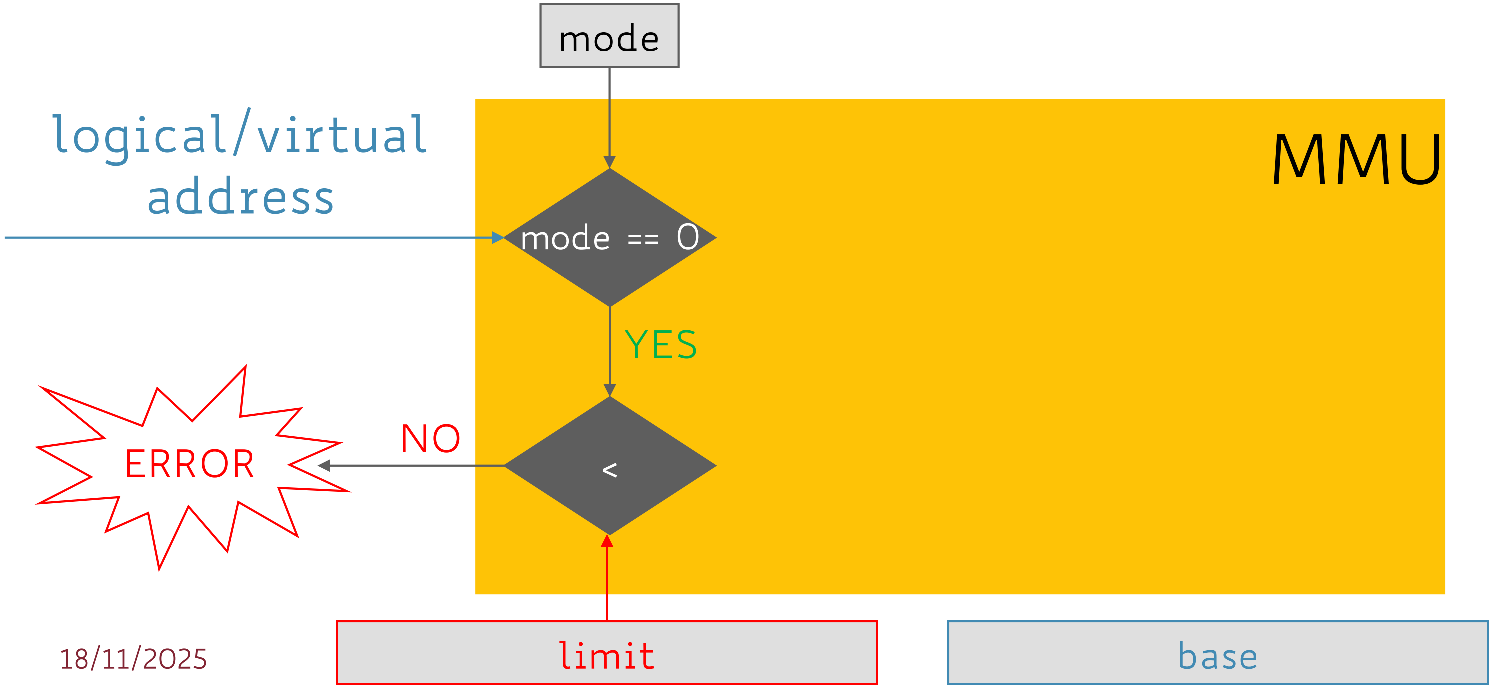

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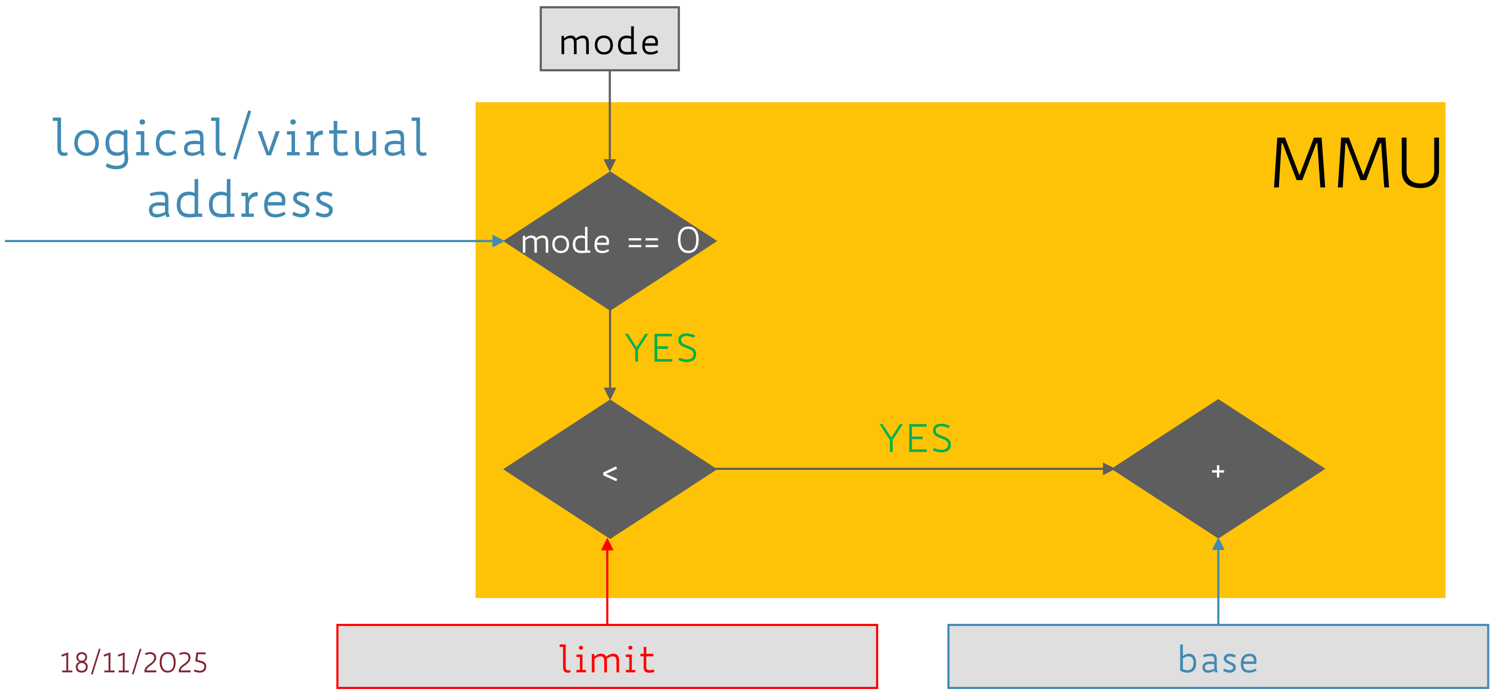

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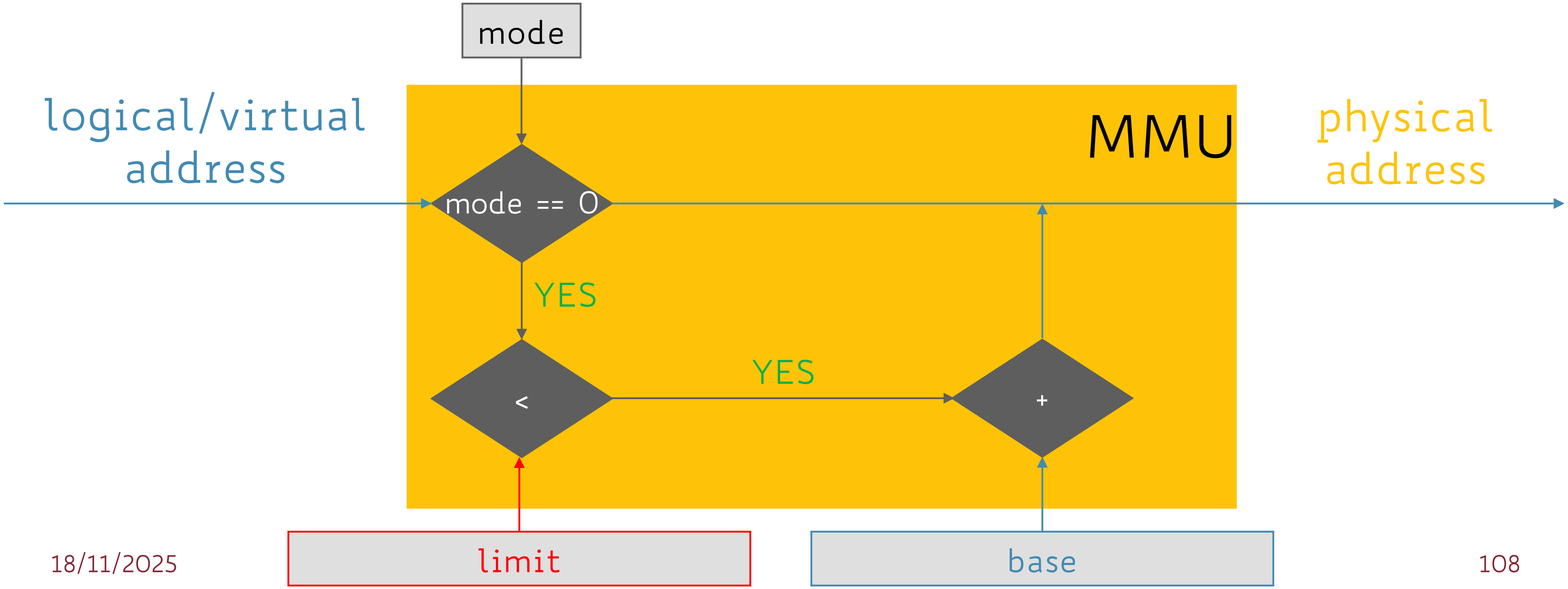

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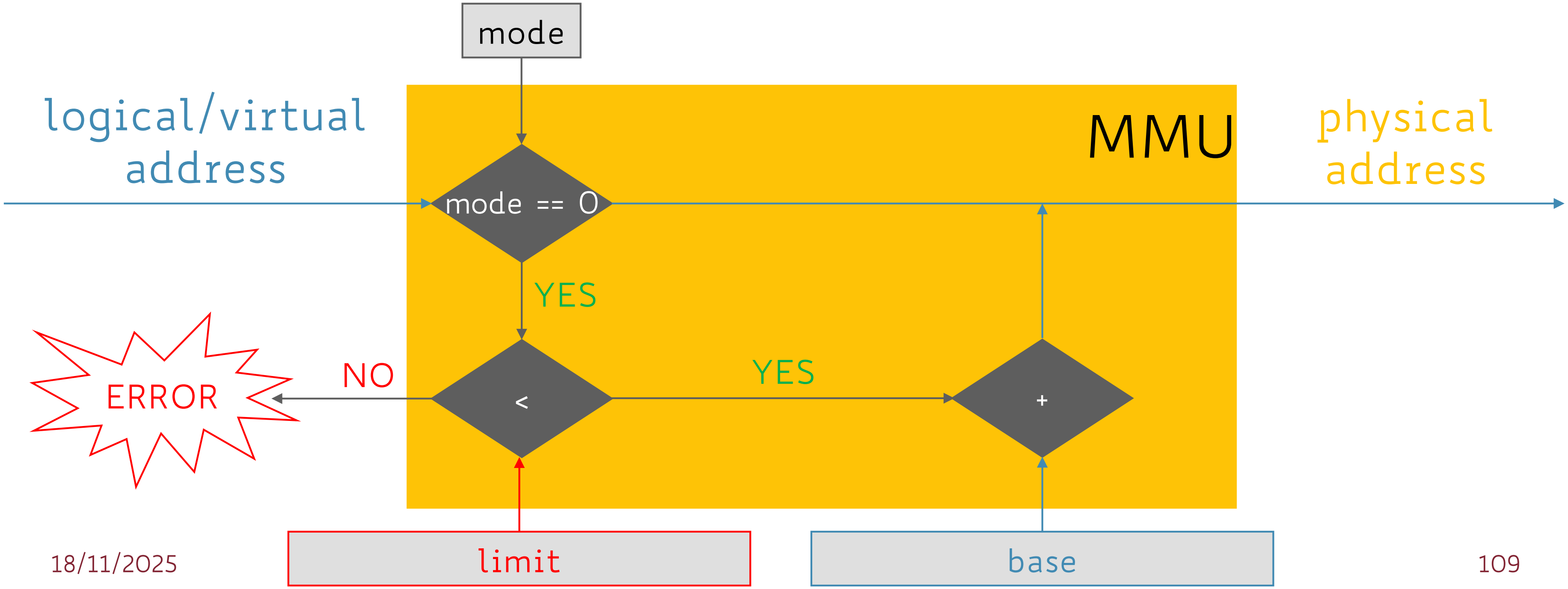

Dynamic Relocation

- PROs:
  - Provides protection (both read and write) across address spaces
  - OS can easily move a process during execution
  - OS can allow process to dynamically grow over time
  - Simple, fast hardware implementation (MMU):
    - 2 special registers, one add and one compare operation (can be done in parallel)

Dynamic Relocation

- CONs:
  - Little hardware overhead to pay at each memory reference
  - Each VAS of a process must still be allocated contiguously in physical memory (possible memory waste, e.g., stack/heap) → **segmentation**
  - Degree of multiprogramming is bound since all VAS of all active processes must fit entirely in memory → **paging**
  - Process is still limited to physical memory size → **virtual memory**

To Wrap Up

- Modern OSs manage memory ensuring:
  - Transparency → logical/virtual vs. physical address space
  - Protection/Flexibility → dynamic relocation
  - Efficiency → hardware support (e.g., MMU)
- We are still assuming the whole virtual address space of a process is fully and contiguously loaded in main memory → **serious limitation!**

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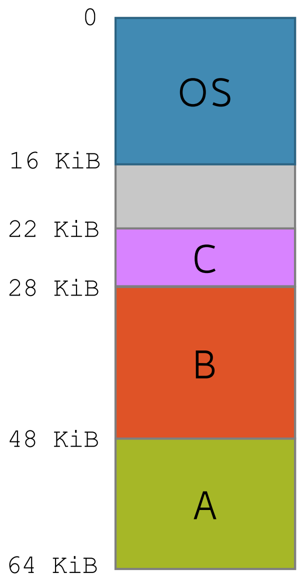

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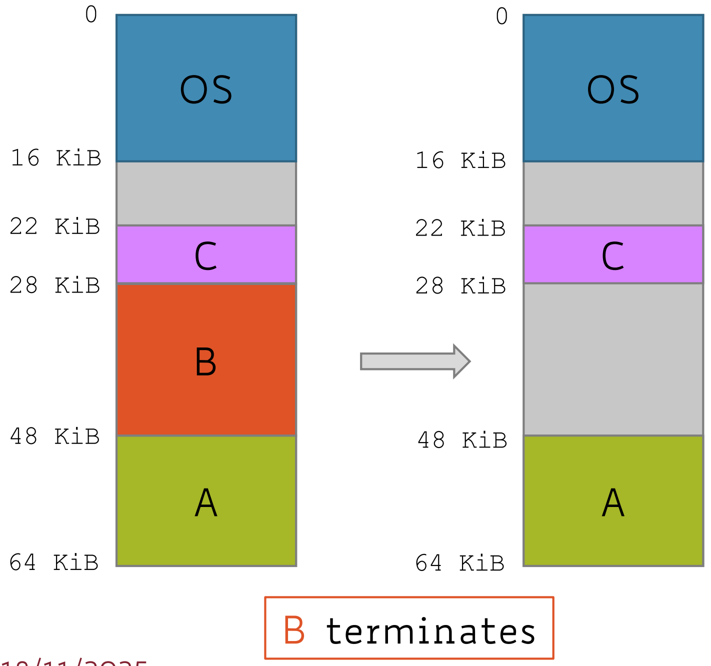

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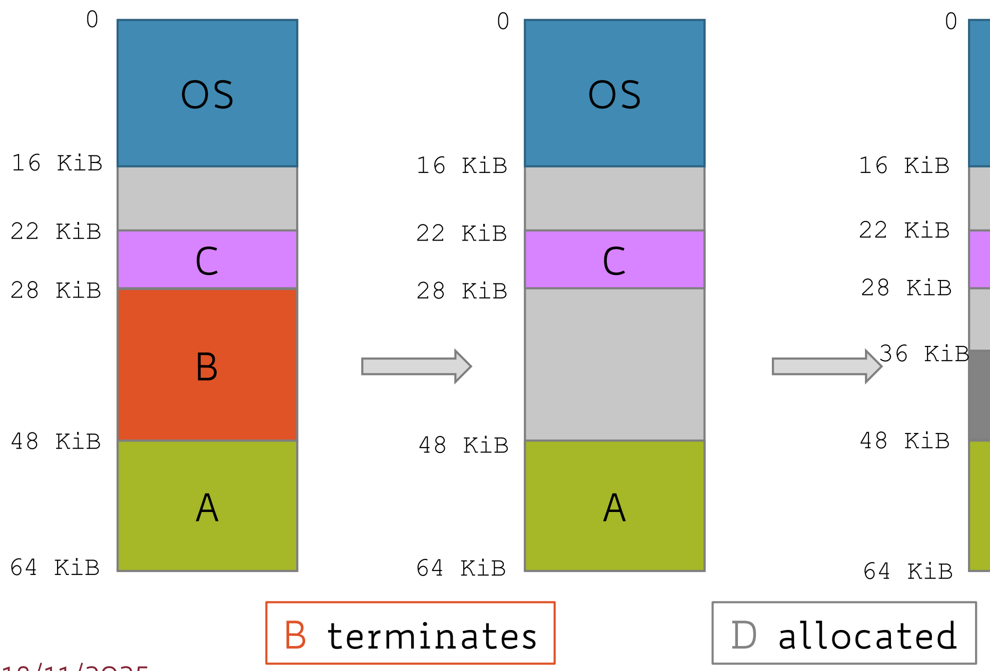

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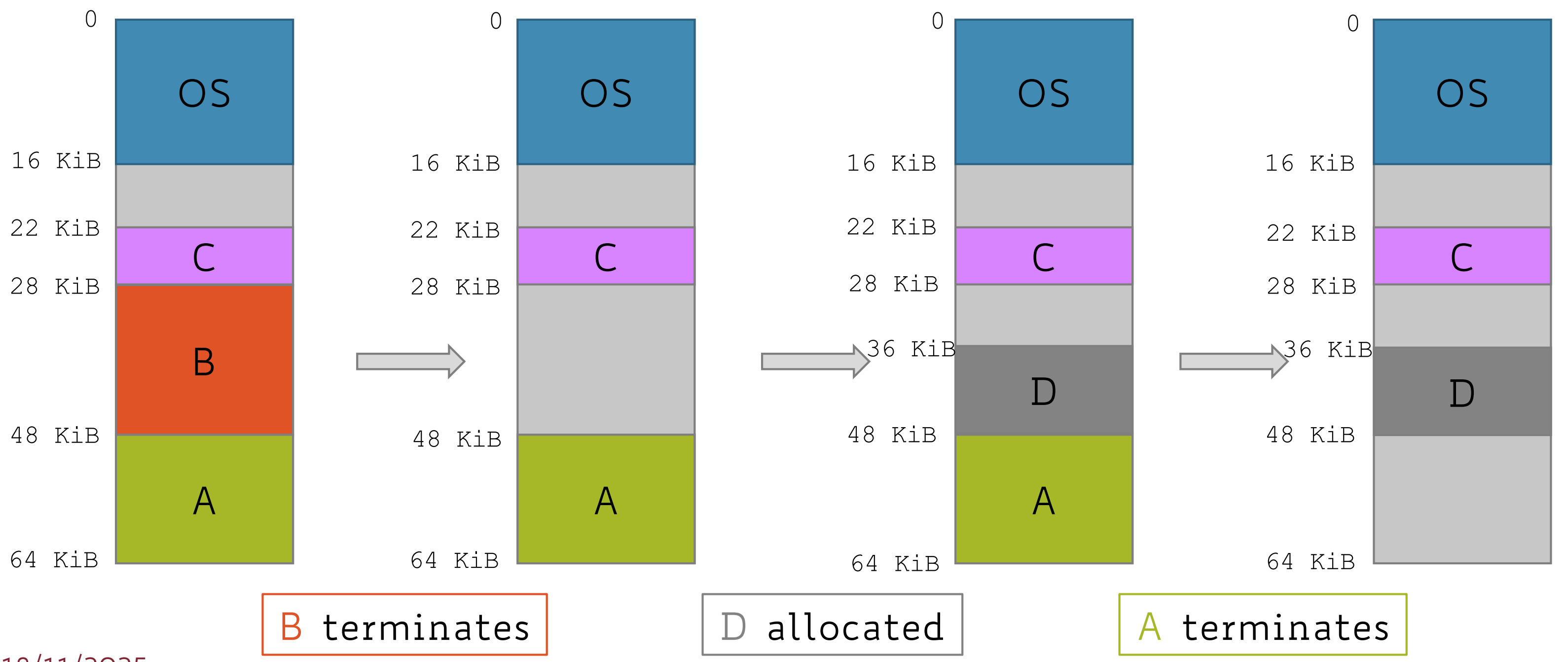

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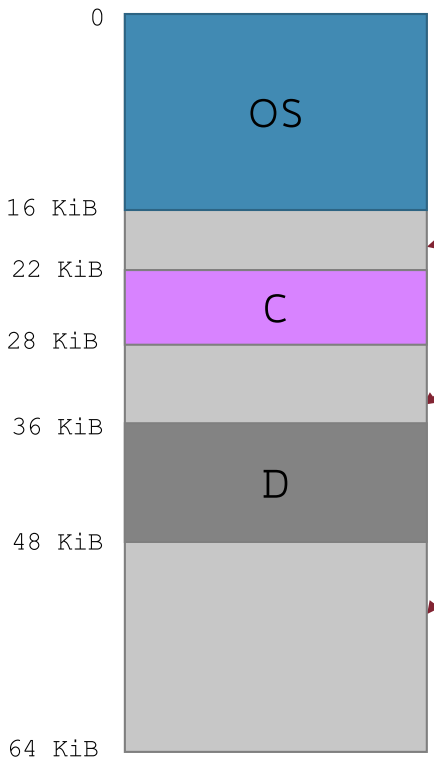

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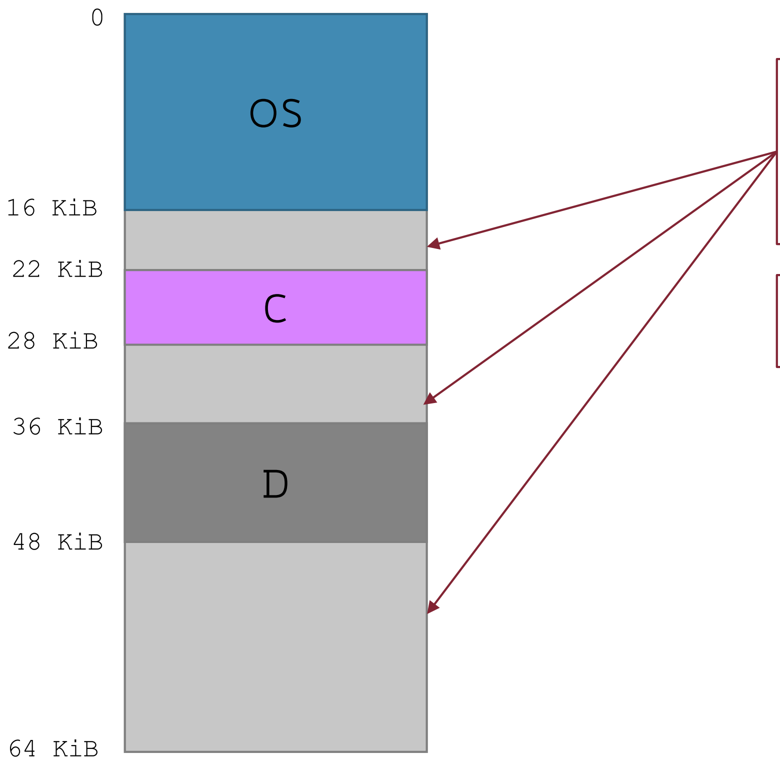

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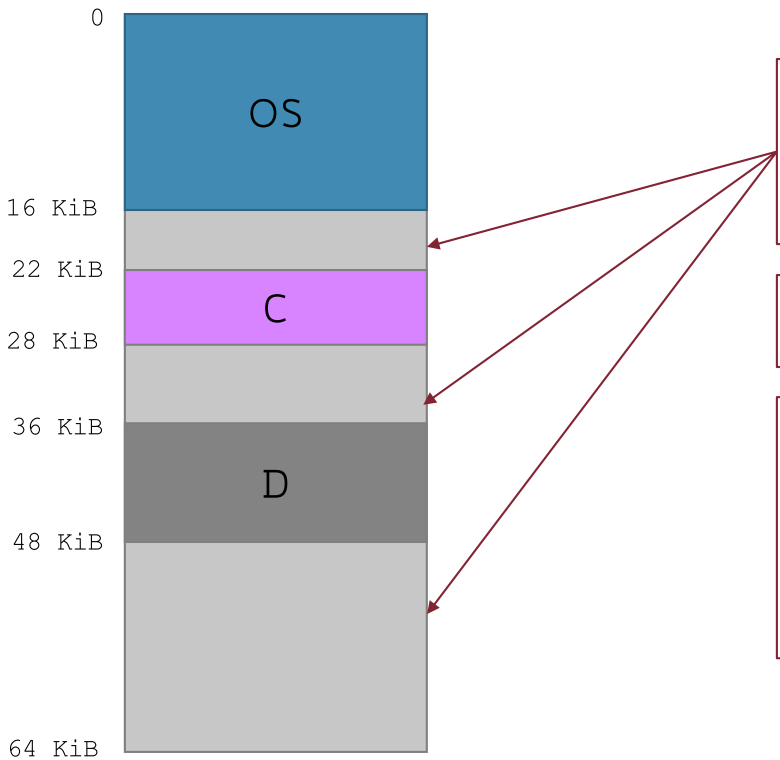

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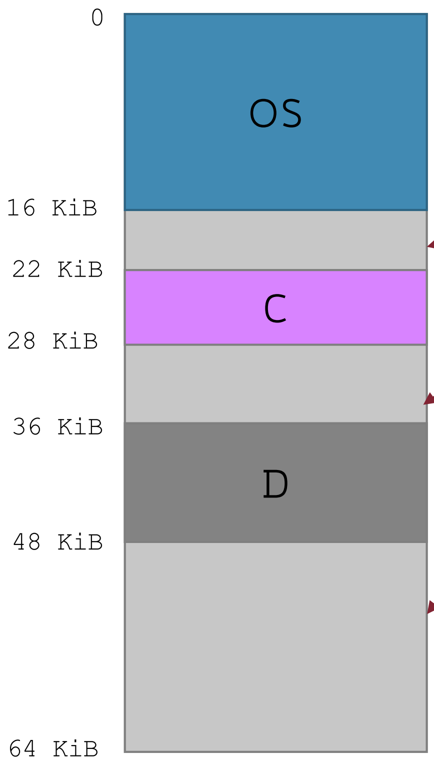

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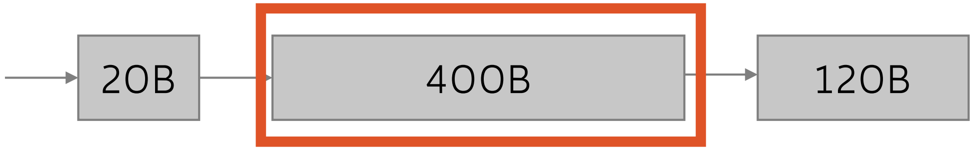

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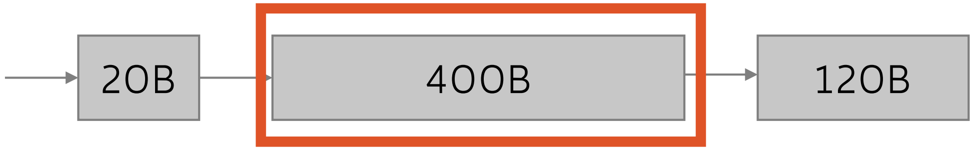

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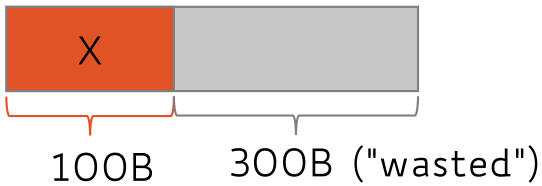

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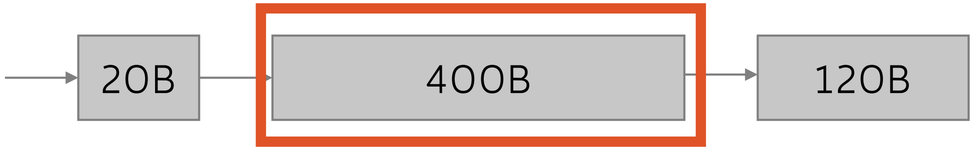

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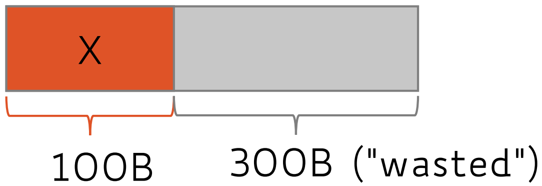

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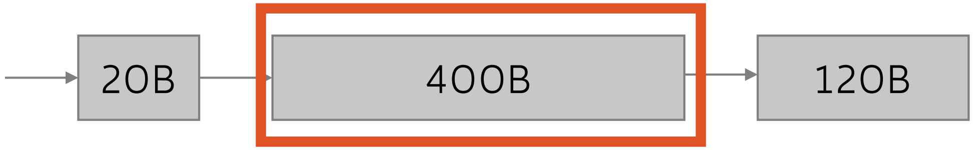

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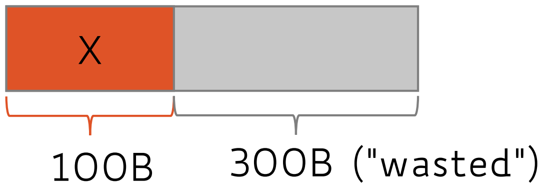

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We will not be able to satisfy this request even if theoretically we could

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Binary Search Tree (BST)

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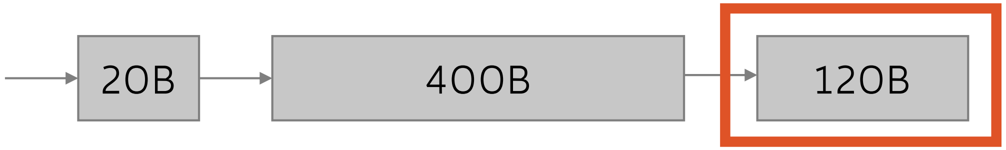

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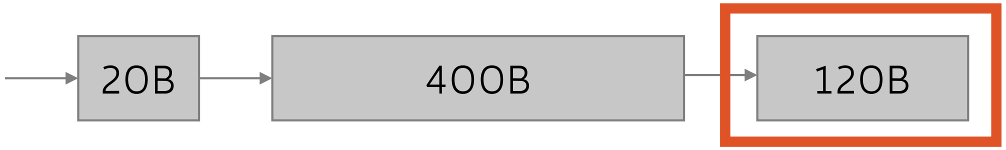

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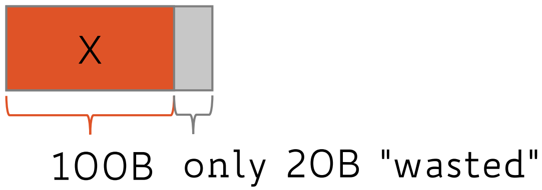

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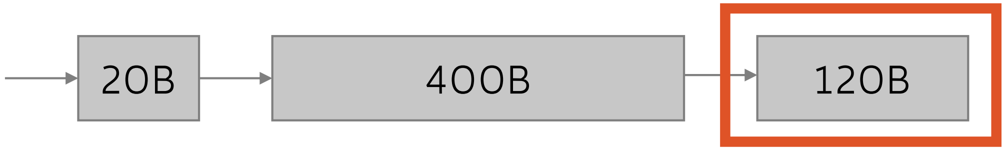

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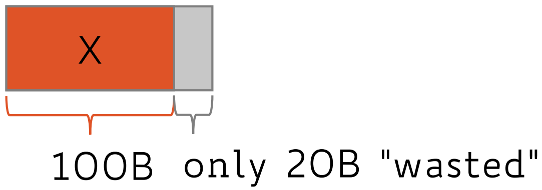

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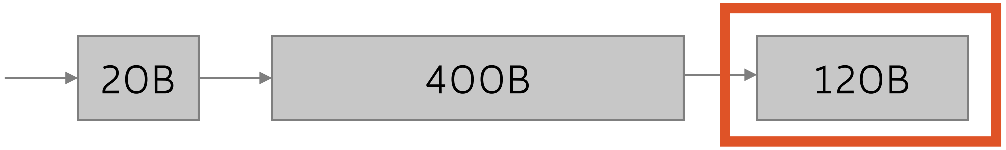

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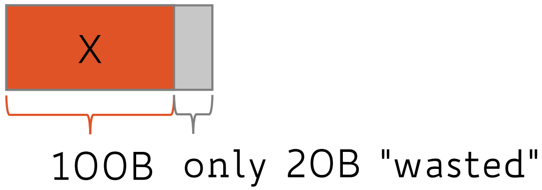

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We can now assign it the second available hole segment (400B)

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- First-Fit is also generally faster than Best-Fit

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Problem

Individual holes may be too small to serve a process request but they can be large enough if combined together

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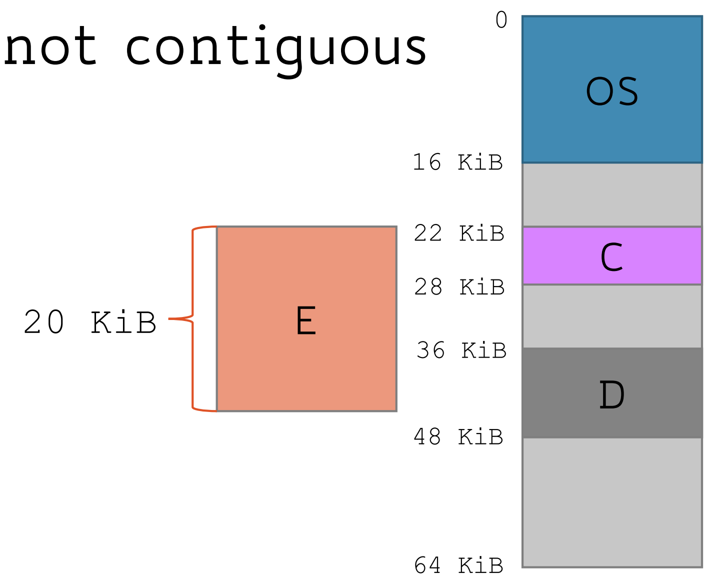

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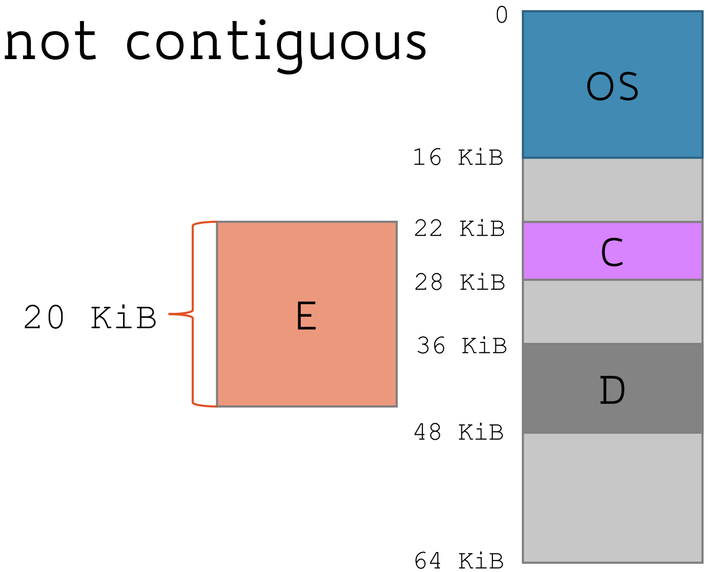

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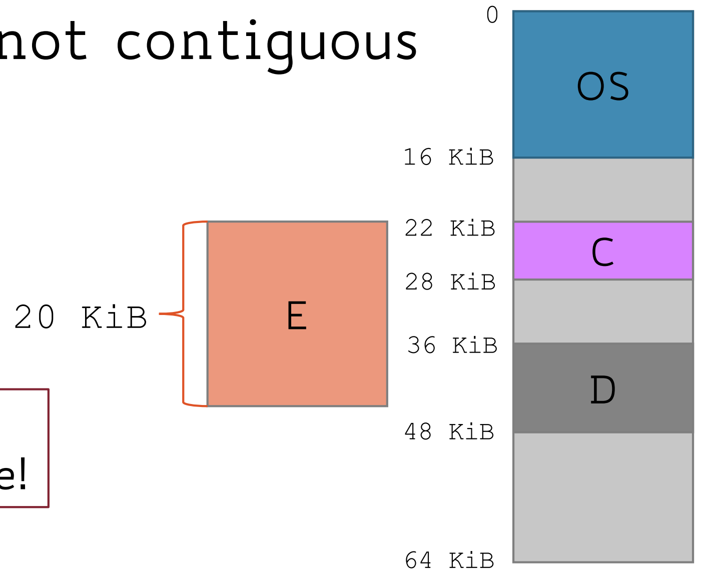
Goal:
Allocation policy that minimizes wasted space!



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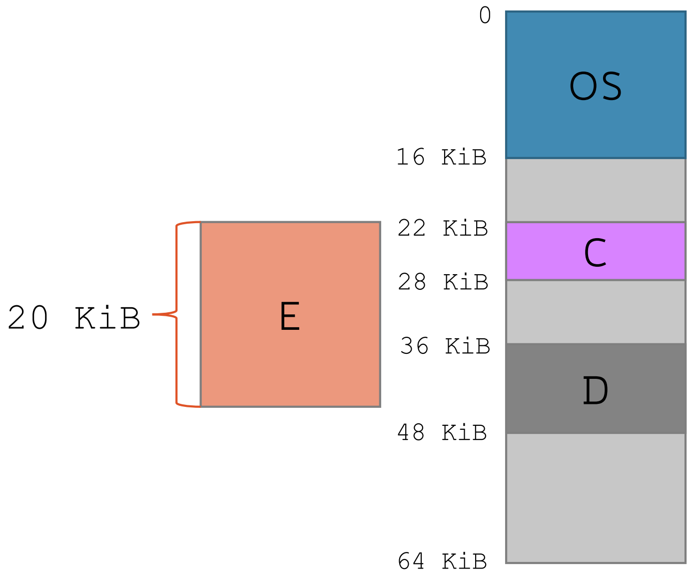
- It may be much more efficient to allocate the process the whole block (and waste 2B) rather than keep track of a tiny 2B hole

Solution to Fragmentation: Full Compaction



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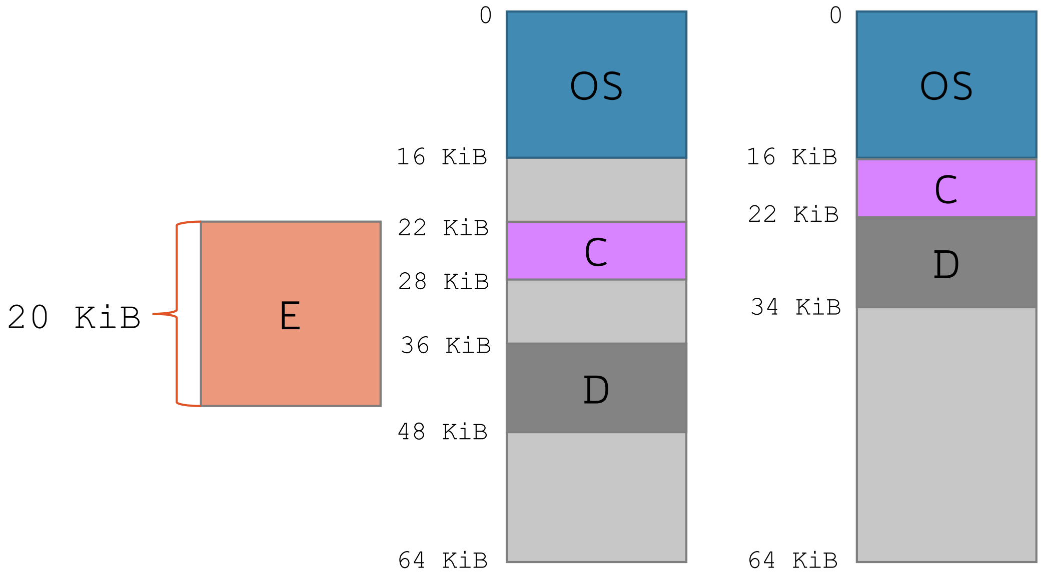

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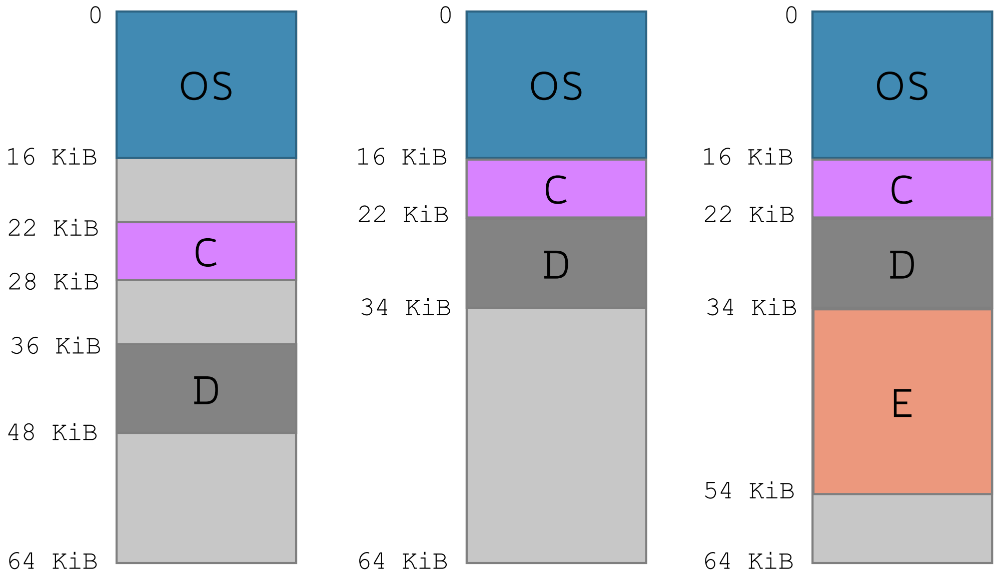

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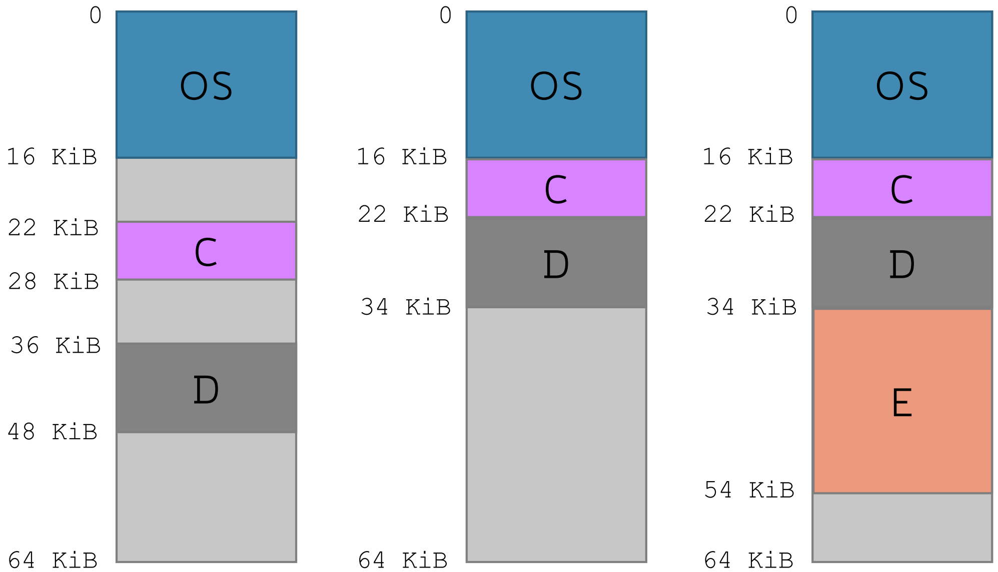
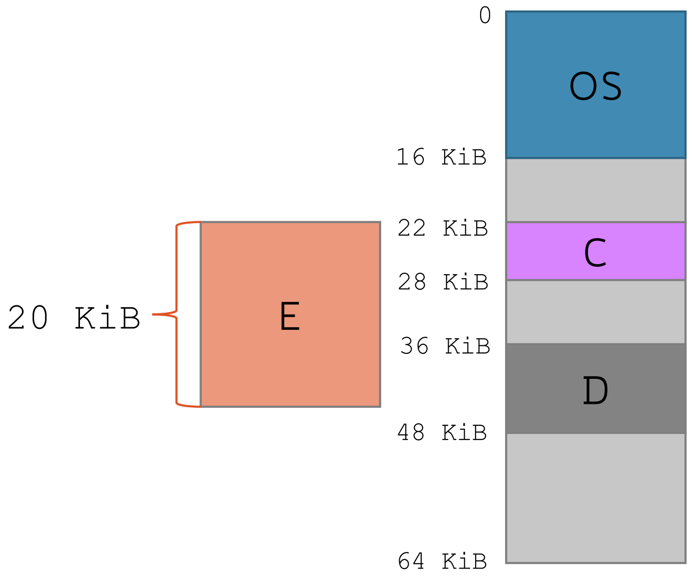


Only one hole is left but two processes need to be moved (C and D)

Solution to Fragmentation: Partial Compaction



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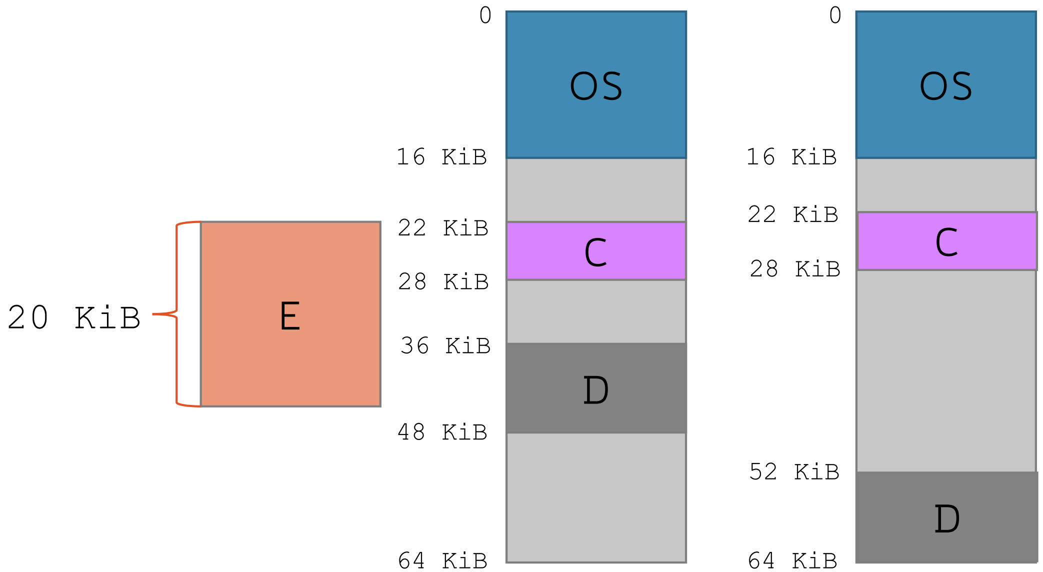

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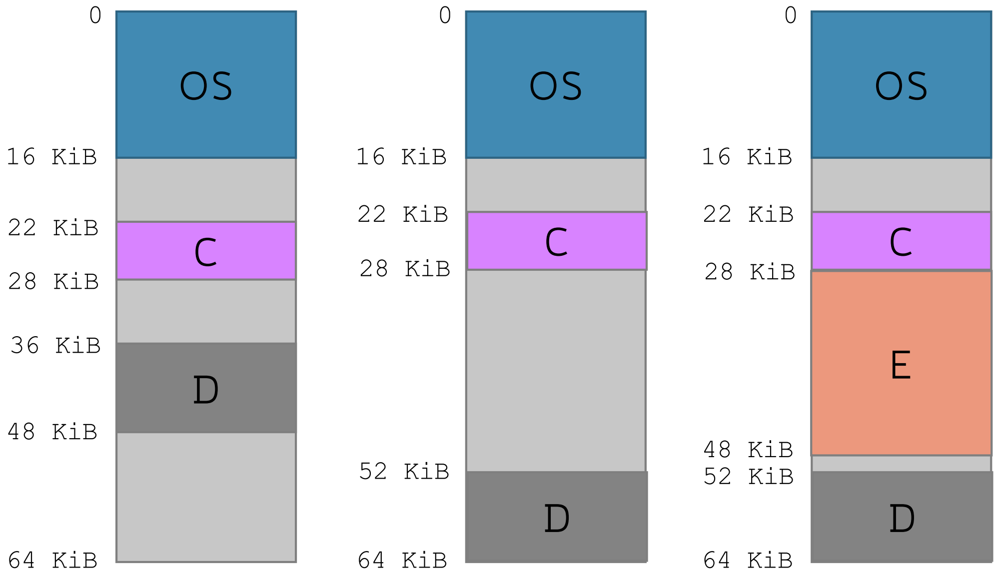

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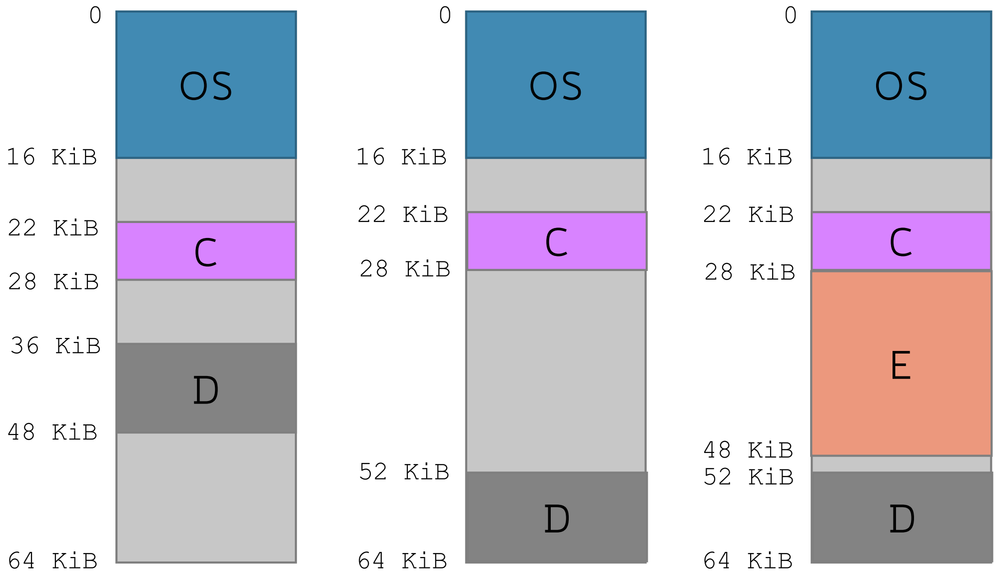

Still some holes left but only one process is moved (D) rather than two

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- That process can be "swapped out" from memory to disk to make room for other processes

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- Using swapping, fragmentation can be tackled easily
  - Just run compaction before swapping-in a process

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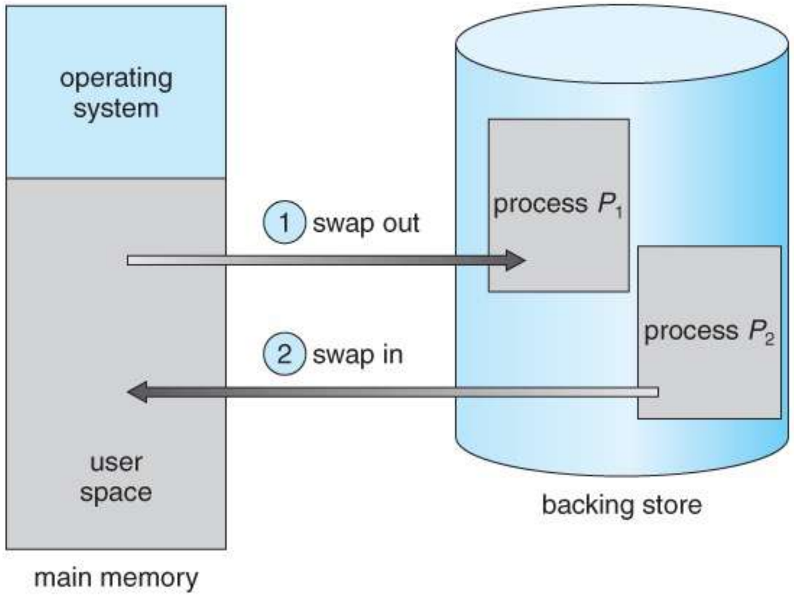
- Time slice is usually way smaller than that!

Swapping



Most modern OSs no longer use swapping, because it is too slow and there are faster alternatives available (e.g., paging)

Summary

- Contiguous memory allocation may cause fragmentation
  - External vs. Internal Fragmentation
- Existing countermeasures (compaction) exist but they are costly
- We may want to relax the constraint on having an entire process loaded in main memory
- Paging solves all these issues!