Operating System Concepts

Lecture 23: Memory Management

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MWF 12:00-12:50 VVC 2 215

Today's class

- diving deeper into the concepts and mechanisms of memory sharing and address translation
  - how memory addresses generated by CPU are mapped to physical addresses?
  - what's the difference between static and dynamic relocation?
  - what are the policies for contiguous memory allocation?
  - what is internal/external fragmentation and how to eliminate it?

Closer look at the instruction execution cycle

- instruction execution cycle
  - **step 1**: fetch instruction from memory according to the value stored in the program counter
  - **step 2**: decode the instruction; this may cause operands to be fetched from memory
  - **step 3**: execute the instruction
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- CPU can directly access main memory and registers built into each core, for example: memory direct to register: **`MOV r1, @0xfffa620e`**
  - instructions cannot take disk addresses; hence, the program's code and data must be loaded into memory before the CPU can operate on them
  - registers are accessible within one cycle, but memory access can take many cycles of the CPU clock (CPU needs to **stall** in such cases)
  - cache is used for faster access

Basics of memory addressing

- a k-bit address allows referencing 2^k locations
  - each location can be one byte, 2 bytes, or 4 bytes (one word)
  - 2^{32} = ~4 billion addresses on a 32-bit machine
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Basics of memory addressing

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- each program operates in an address space distinct from the physical memory space of the machine
- protection: prevent access to private memory of other processes
- translation: map accesses from one address space (virtual) to a different one (physical)

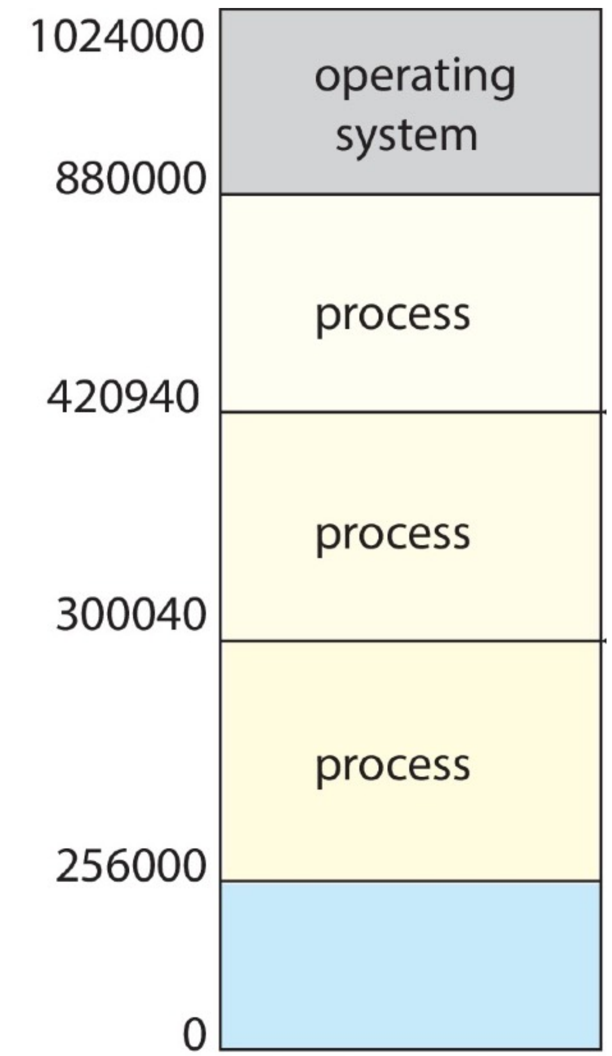
Uniprogramming

- works in simple systems, e.g., embedded computers, micro-controllers
- one program shares memory with the OS; it always runs at the same place in physical memory (no translation)
    - load application into low memory and OS into high memory
    - application can address <u>any physical memory location</u>
        - they can corrupt OS and even the disk (no protection)

Multiprogramming

multiprogramming without translation or protection (e.g., Windows 95)

- need to load multiple processes in memory for concurrent execution
  - they are unaware of sharing the memory with each other
  - translation is done by linker/loader; adjusts addresses while program loaded into memory
- compiler generates .o file with code starting at location 0
- linker scans through each .o file, changing addresses to point to where each module goes in the larger program
- loader loads the executable (a.out) to the memory and runs the program
- problem with just using linker-loader? still no protection
  - bugs in any program can cause other programs (even OS) to crash



Address translation terminology

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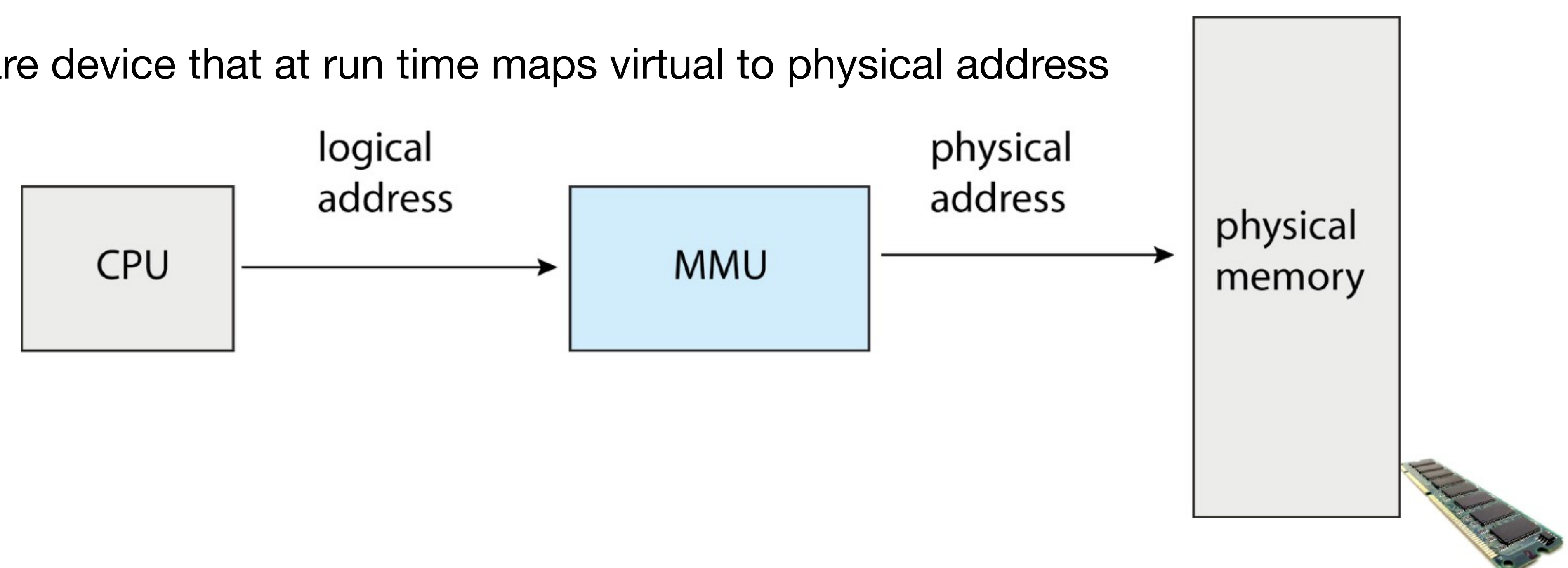
- memory management unit (MMU)
  - hardware device that at run time maps virtual to physical address



Address binding schemes

- can happen at three different stages
  - **compile time**: if memory location known a priori, absolute code can be generated; code must be recompiled if starting location changes
    - logical and physical addresses are the same
  - **load time**: must generate relocatable code if memory location is not known at compile time
    - logical and physical addresses can be the same
  - **execution time**: binding delayed until run time if the process can be moved during its execution from one memory segment to another
    - needs hardware support for address mapping (e.g., base and limit registers)

Multiprogramming with protection

- protection is necessary
  - separate per-process memory space
  - processes don't care what physical portion of memory they are assigned to
- there are different options:
  - base and bounds
  - segmentation
  - paging
  - multi-level translation

Hardware support

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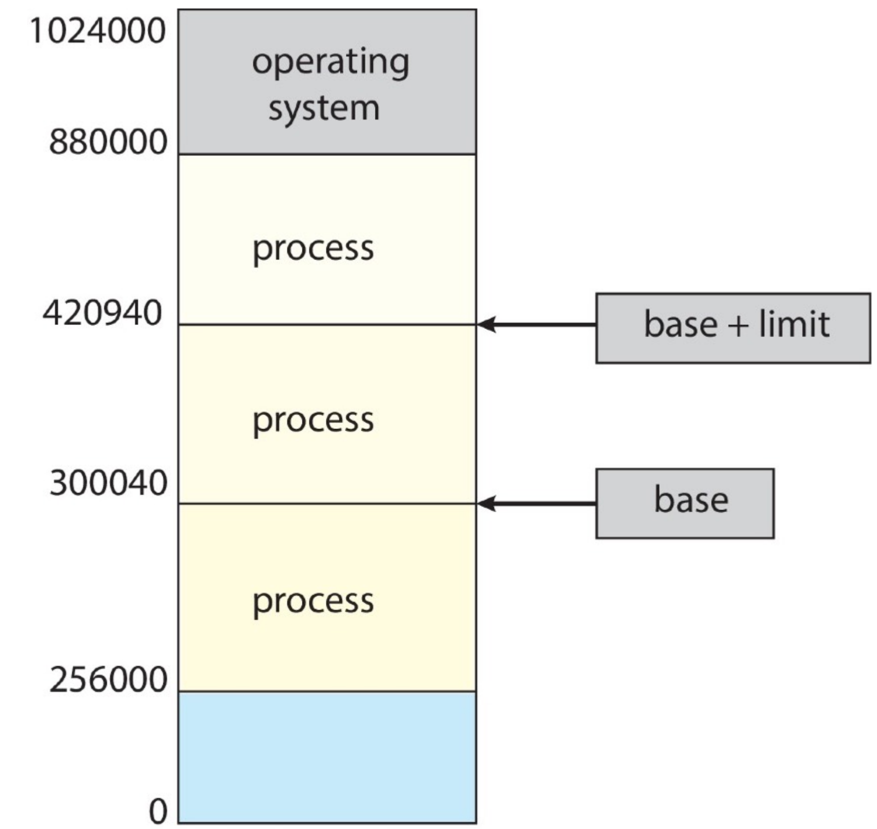

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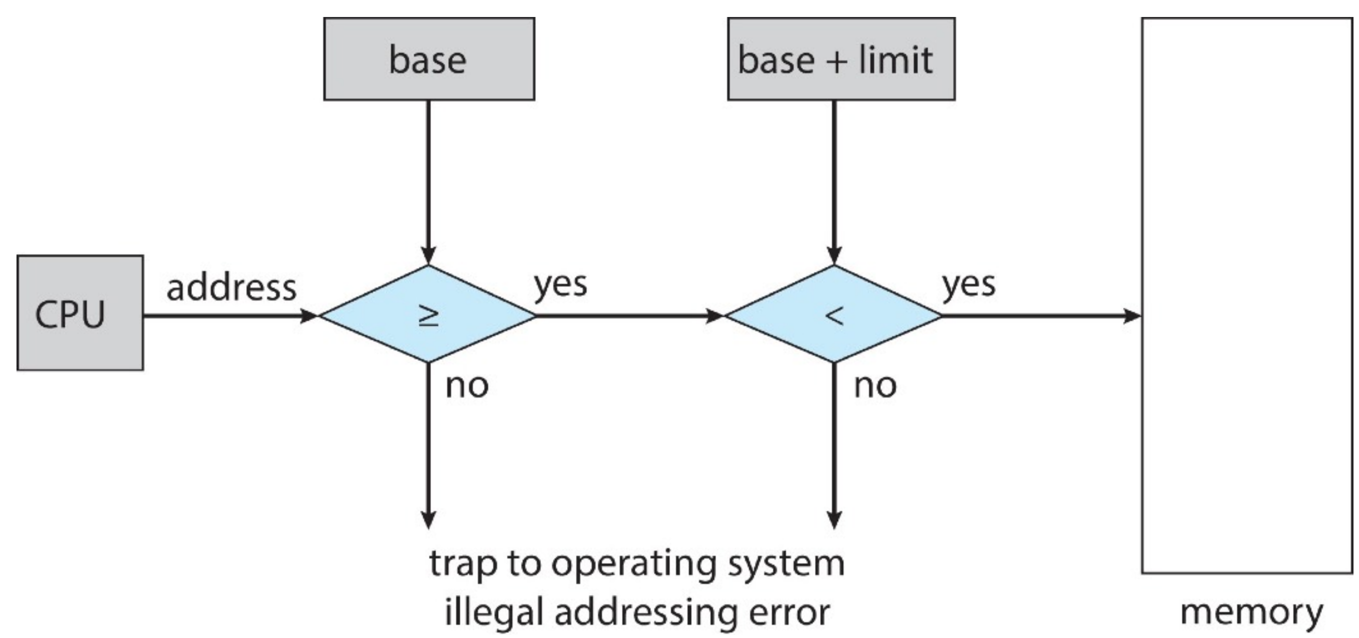
- an attempt to access an address outside this range results in a trap to the OS



Relocation

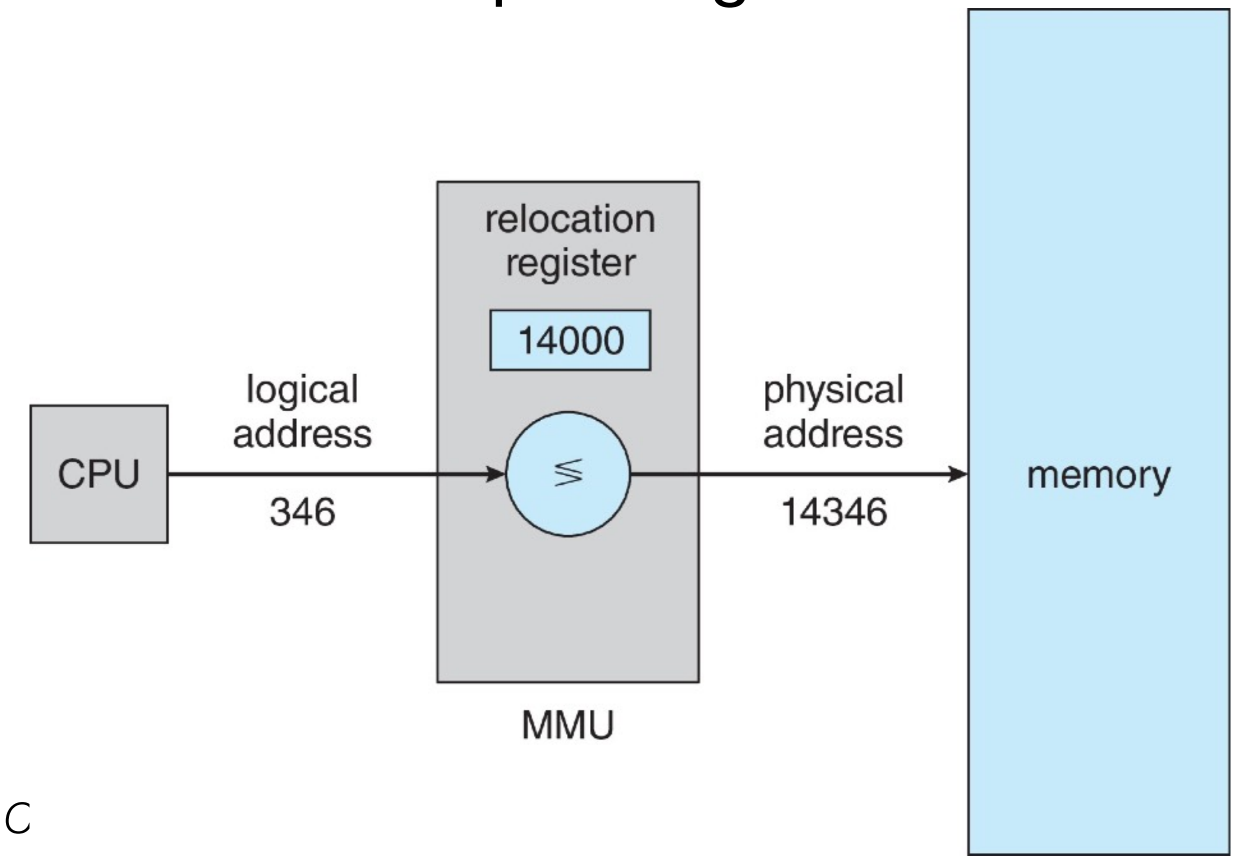
- program contains virtual addresses but the machine understands physical addresses
- if physical address==virtual address then
  - we cannot have multiple programs residing in memory at once
- hence, virtual addresses must be relocated to physical addresses at run time

Static relocation

- at load time, the OS adjusts the addresses in a process to reflect its position in memory
- once a process is assigned a place in memory and starts executing it, the OS cannot move it

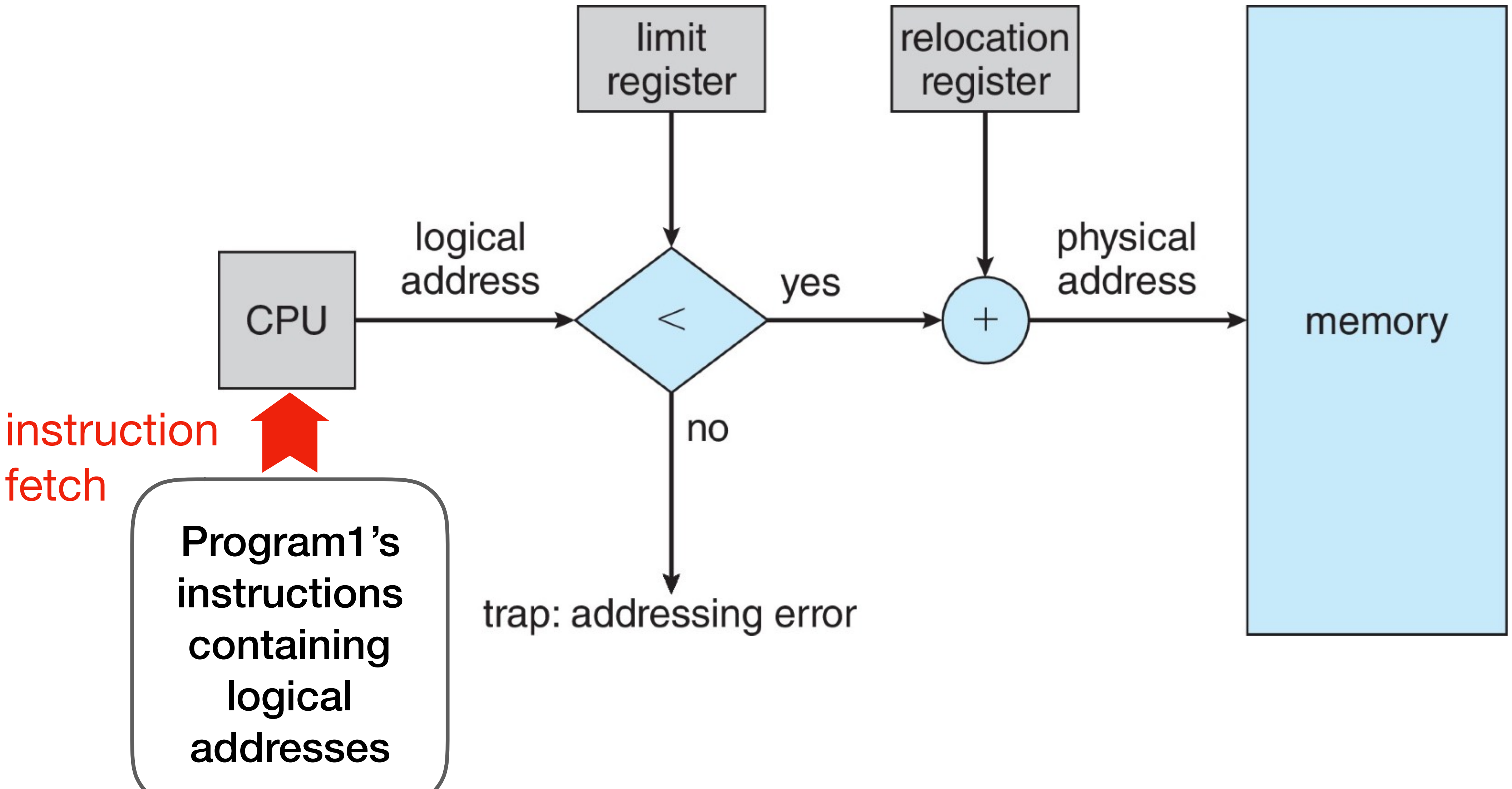
Dynamic relocation

- hardware adds the content of the **relocation register** (base register) to virtual addresses to get the corresponding physical addresses
  - addresses within program do not have to be relocated when program placed in different region of RAM
- hardware compares address with limit register (address must be less than limit)
- if test fails, the processor takes an address trap and ignores the physical address



Protection

- each memory reference is checked
- the base register is called the relocation register



Evaluating dynamic relocation

- advantages
  - OS can easily move a process in memory during its execution
  - simple: requiring two special registers, an add and a comparison
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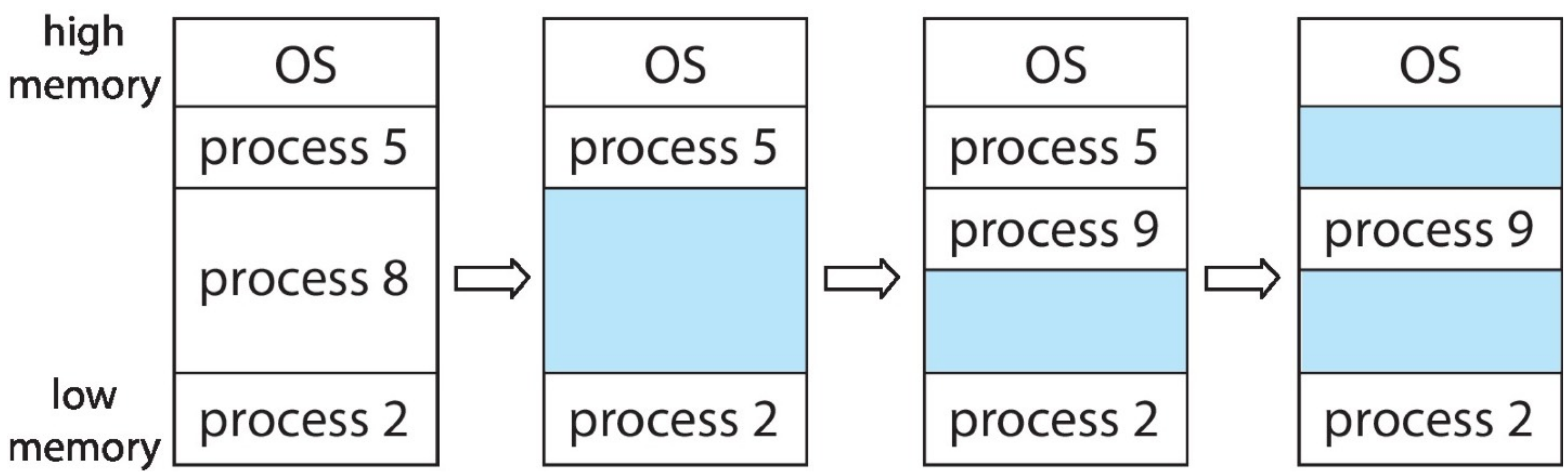
  - simple: requiring two special registers, an add and a comparison
  - OS can allow a process to grow over time (it can be slow)
- disadvantages
  - slow: every memory reference requires adding the content of the relocation register to the logical address
  - doesn't allow code sharing between processing
  - all memory of an active process must fit in the memory, reducing the degree of multiprogramming
  - the size of the memory image of a process is limited to physical memory size

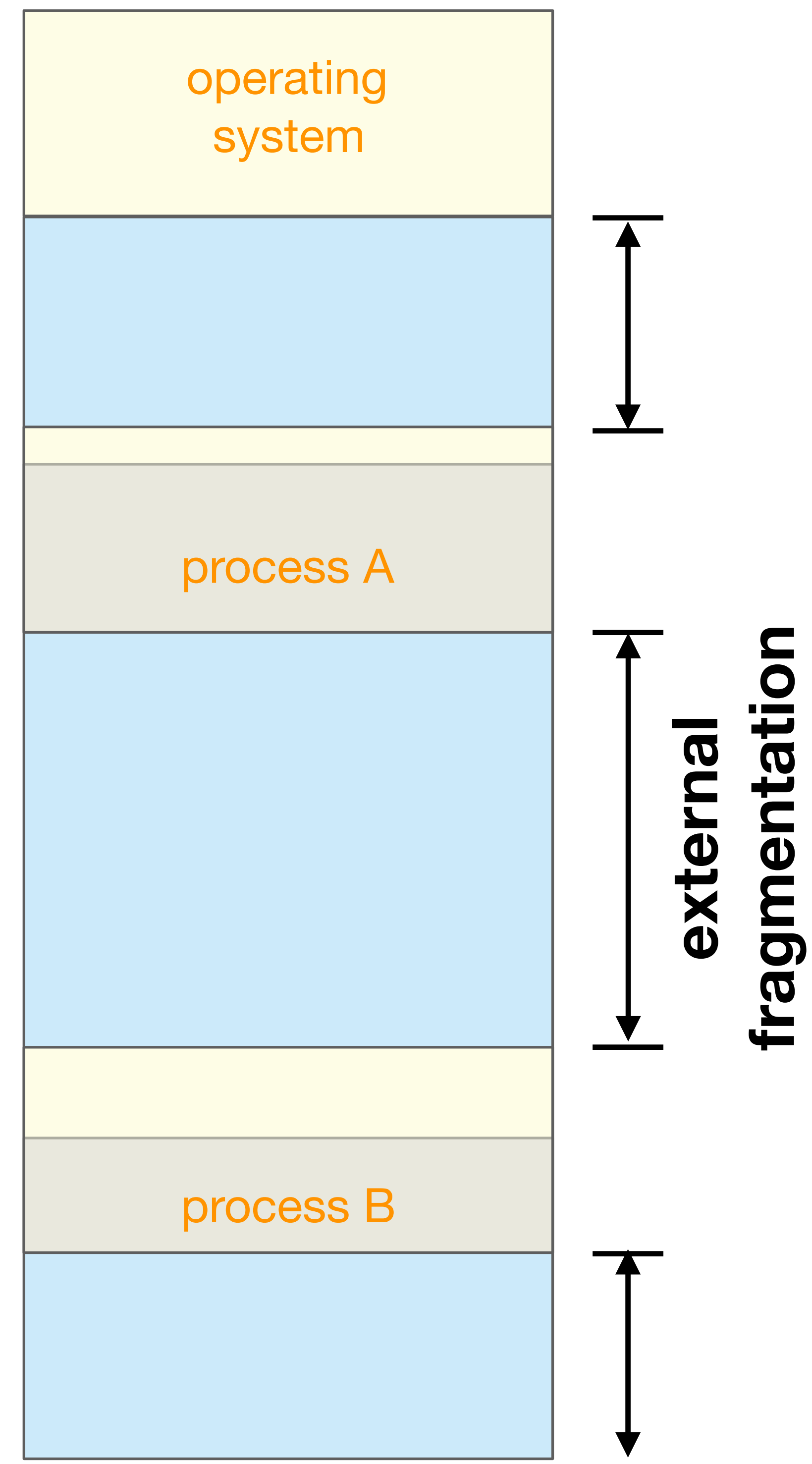
Memory allocation

- allocate a partition when a process is admitted into the system
  - which partition? depends on the allocation policy
- allocate a contiguous memory partition to the process
  - user variable-partition sizes for efficiency (sized to a given process' needs)
- OS keeps track of full blocks and empty blocks (i.e., holes)
  - using a linked list of empty blocks, for example



What is fragmentation?

- external fragmentation
  - unused memory between units of allocation
  - there is enough memory to fit a process in memory, but the space is not contiguous
  - **50-percent rule**: simulations show that N blocks are lost due to fragmentation for every 2N allocated blocks (33% wasted space)



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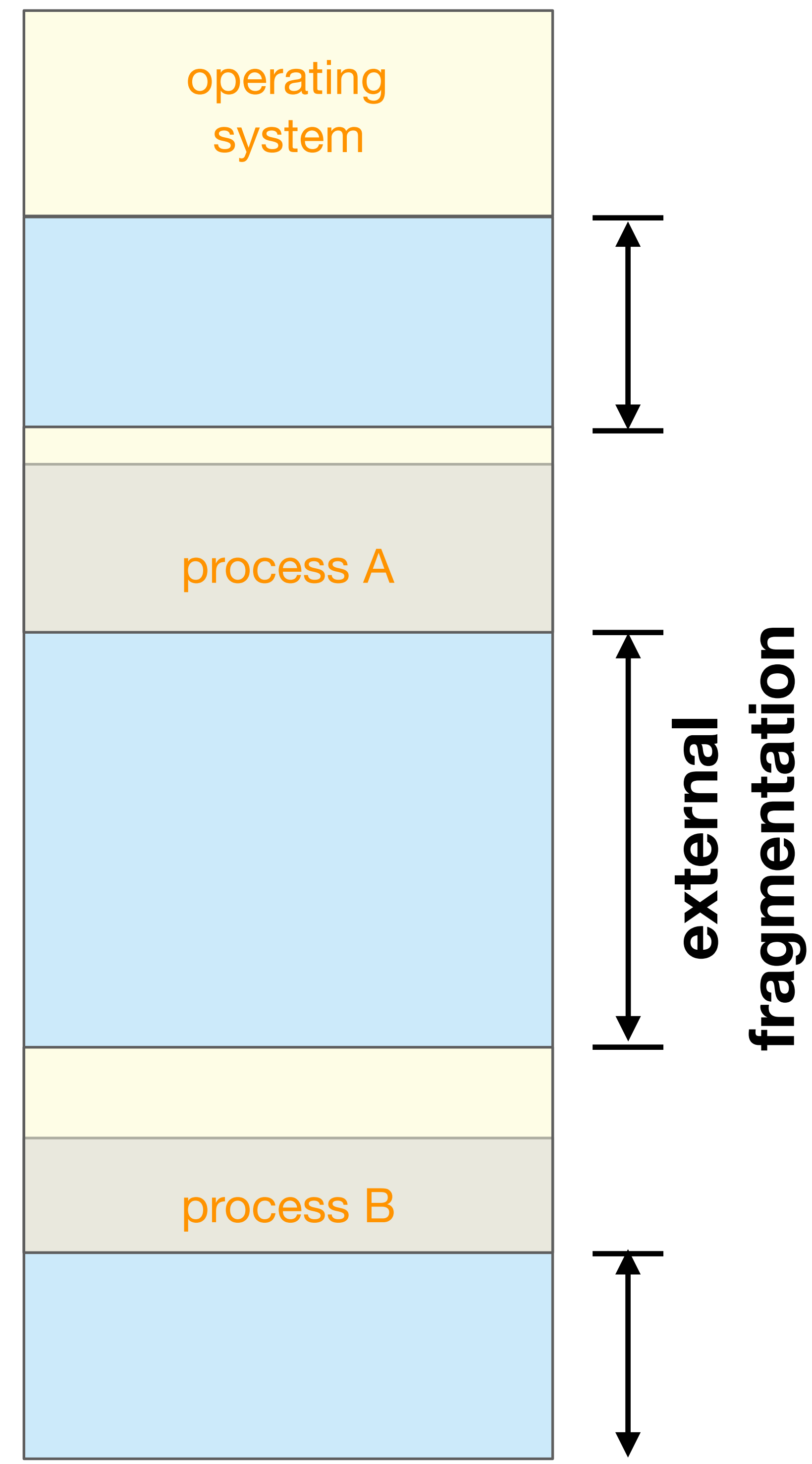
  - unused memory within a unit of allocation
  - consider a block size of 8192 bytes and a process of size 8128 bytes
    - it is more efficient to allocate the process the entire block than to keep track of 64 free bytes



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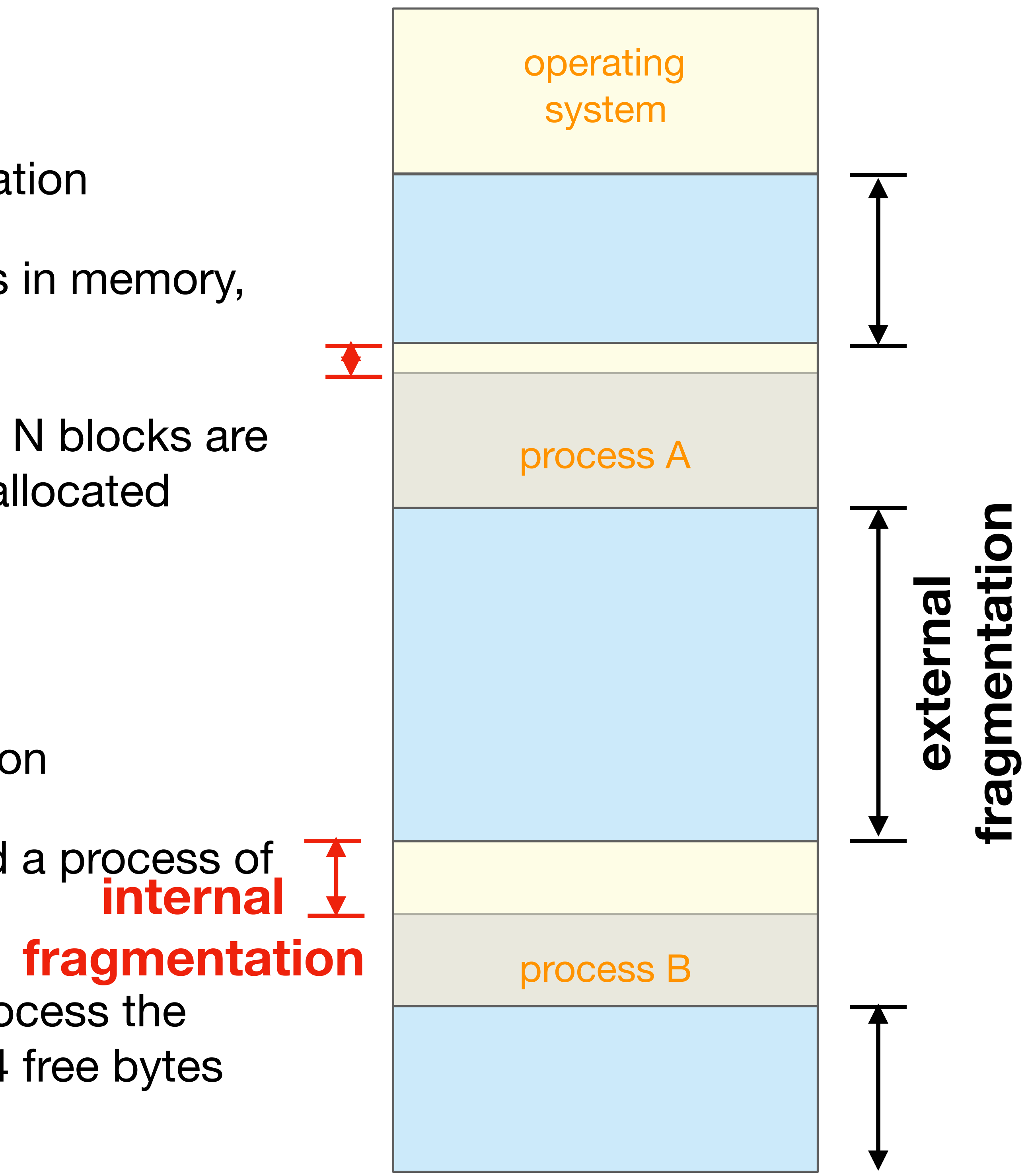

First-fit allocation

- use the first available free block larger than `n`
- implementation
  - requires a free block list sorted by address
  - allocation requires a search for the first partition that is large enough
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- advantages
  - simple implementation
  - results in larger free blocks towards the end of the address space
- disadvantages
  - slow allocation
  - external fragmentation

Best-fit allocation

- use the smallest available free block larger than `n` to minimize the size of external fragments produced
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Best-fit allocation

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  - allocation requires a search for the first partition that is large enough
  - deallocation requires checking if the freed blocks can be merged with other adjacent free blocks (more expensive than first fit)
- advantages
  - works best if most allocations are small sized
- disadvantages
  - slow deallocation
  - external fragmentation
  - tends to produce many tiny fragments

Worst-fit allocation

- use the largest available free block larger than `n` to avoid having too many tiny fragments
- implementation
    - requires a free block list sorted by size (descending)
    - allocation requires a search for the first (largest) partition
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Worst-fit allocation

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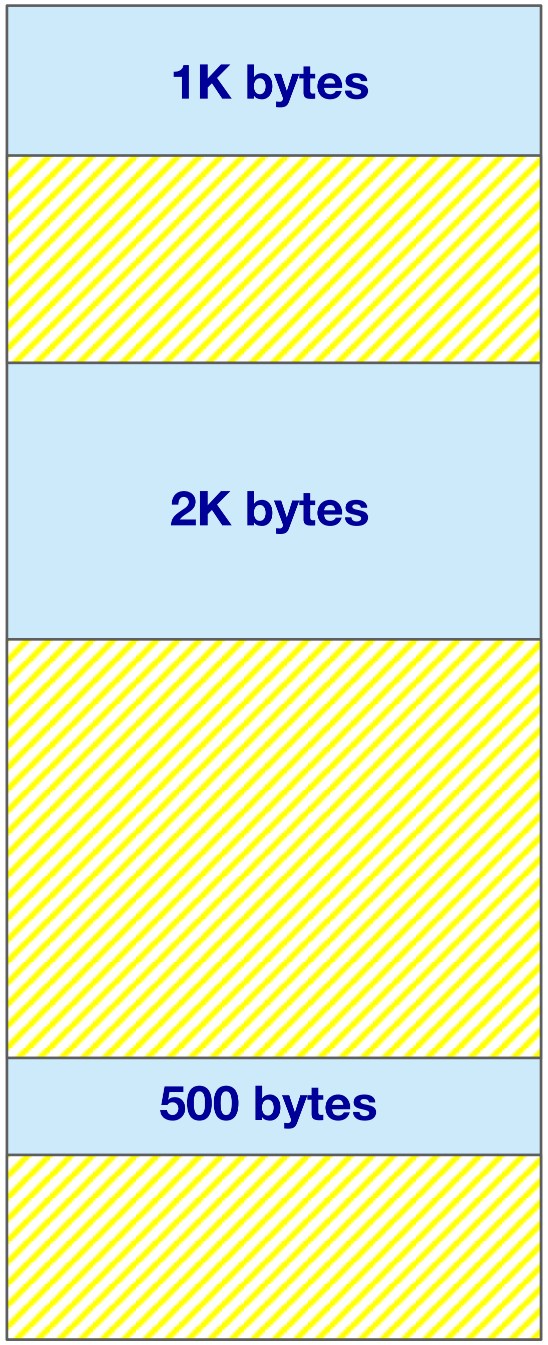
  - requires a free block list sorted by size (descending)
  - allocation requires a search for the first (largest) partition
  - deallocation requires checking if the freed blocks can be merged with other adjacent free blocks (more expensive than first fit)
- advantages
  - works best if most allocations are medium sized
- disadvantages
  - slow deallocation
  - external fragmentation
  - may run into problem allocating large partitions because large free blocks are used for smaller allocations

How to allocate 300 bytes?



initial memory image

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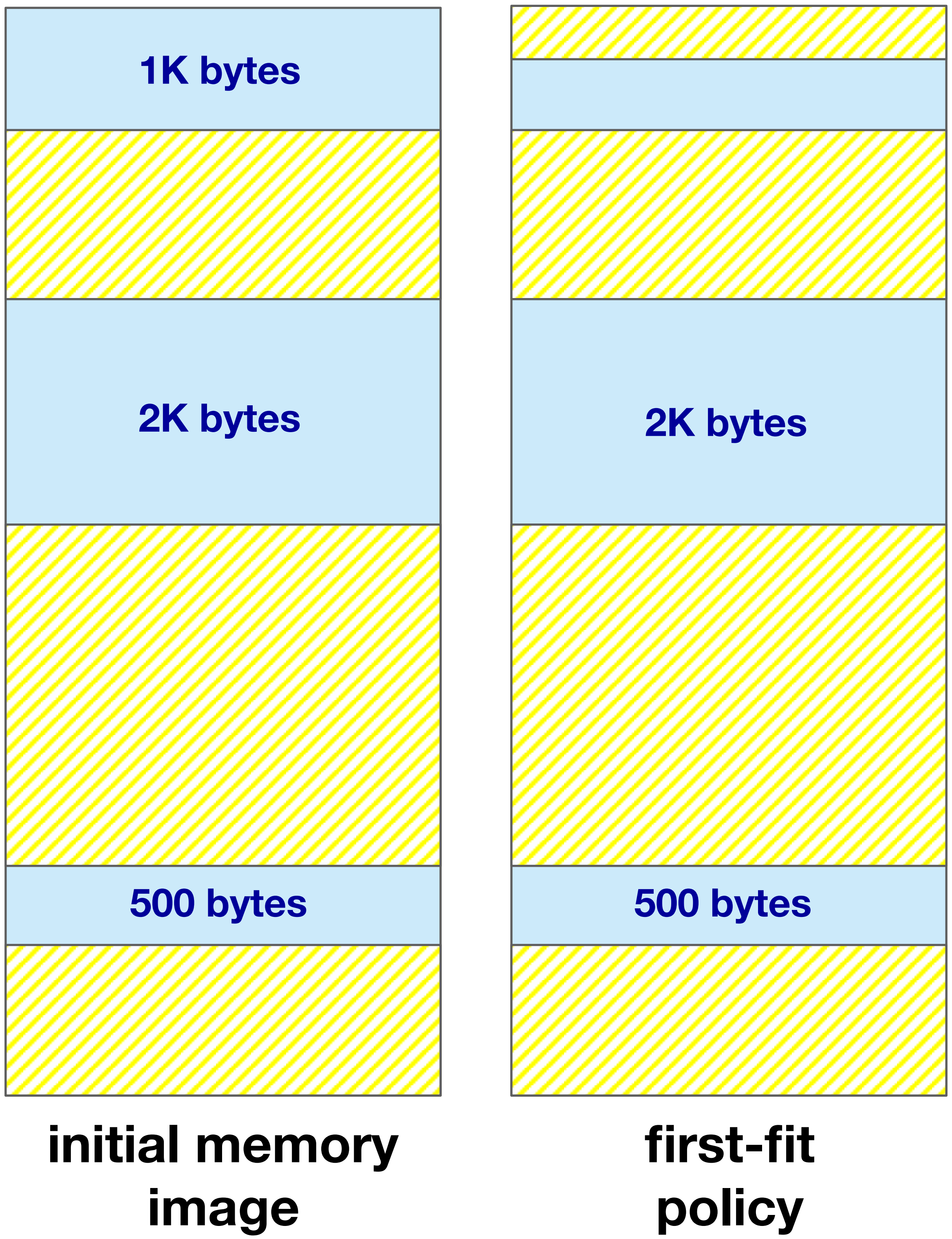

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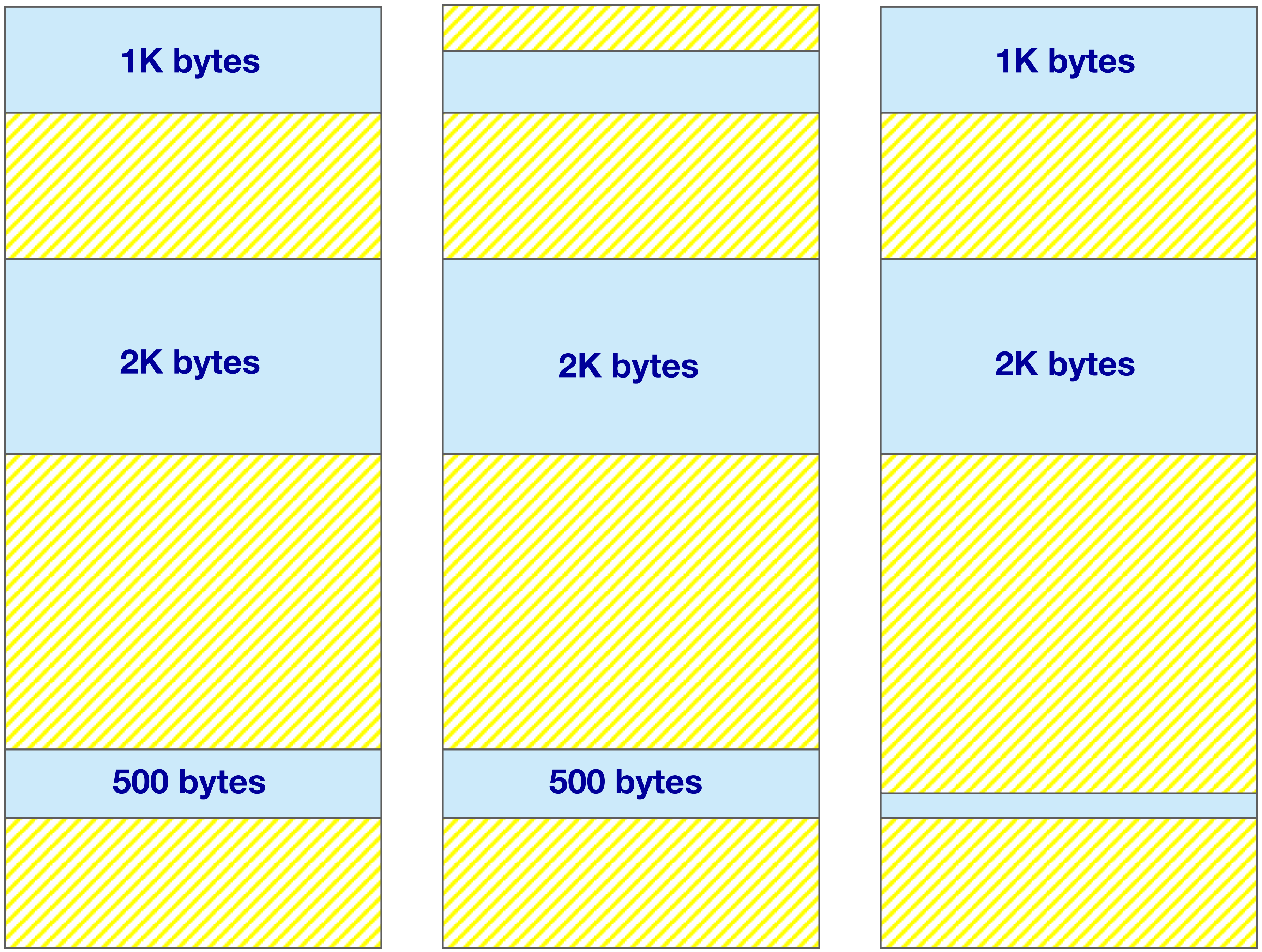

initial memory image	first-fit policy	best-fit policy

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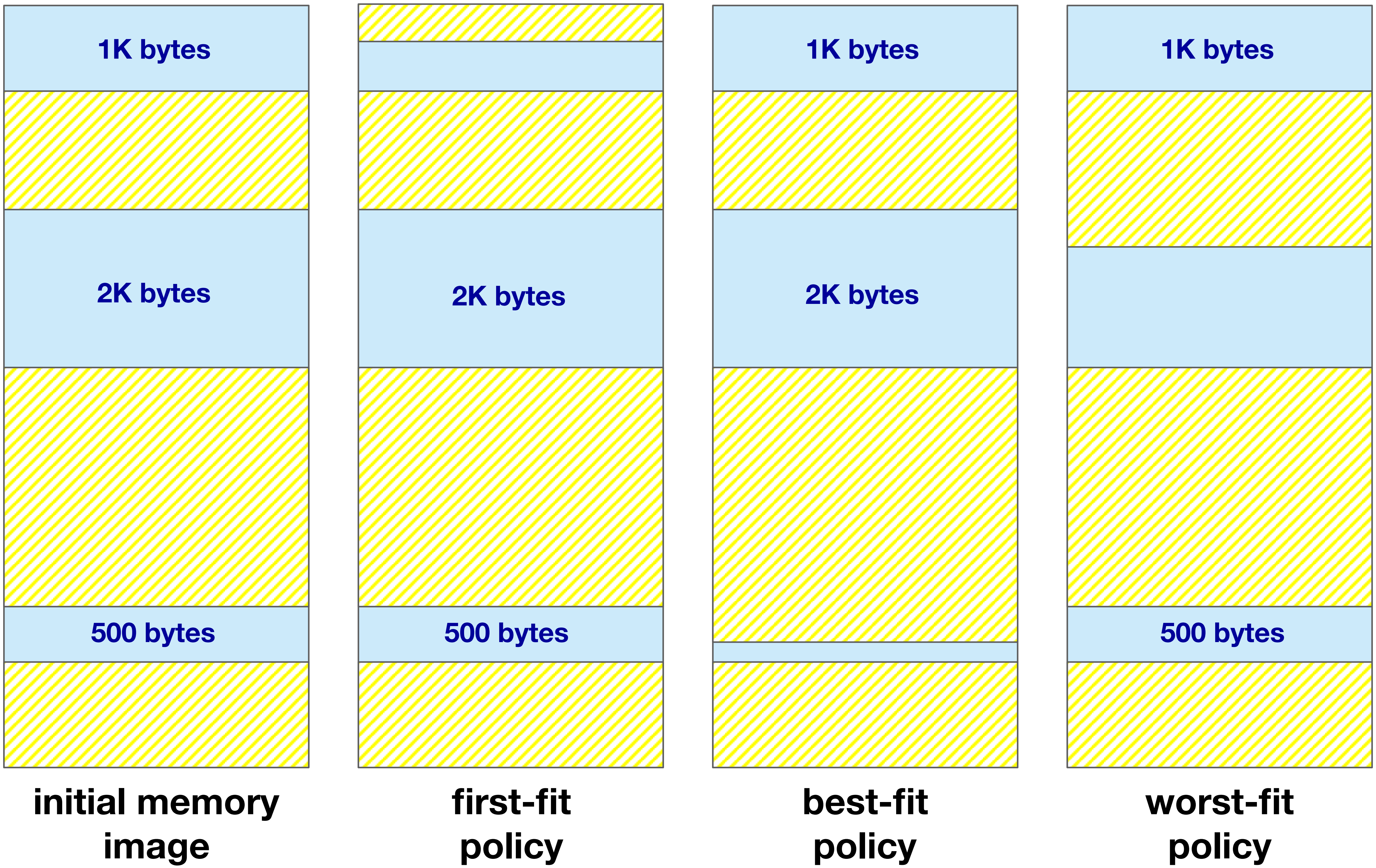
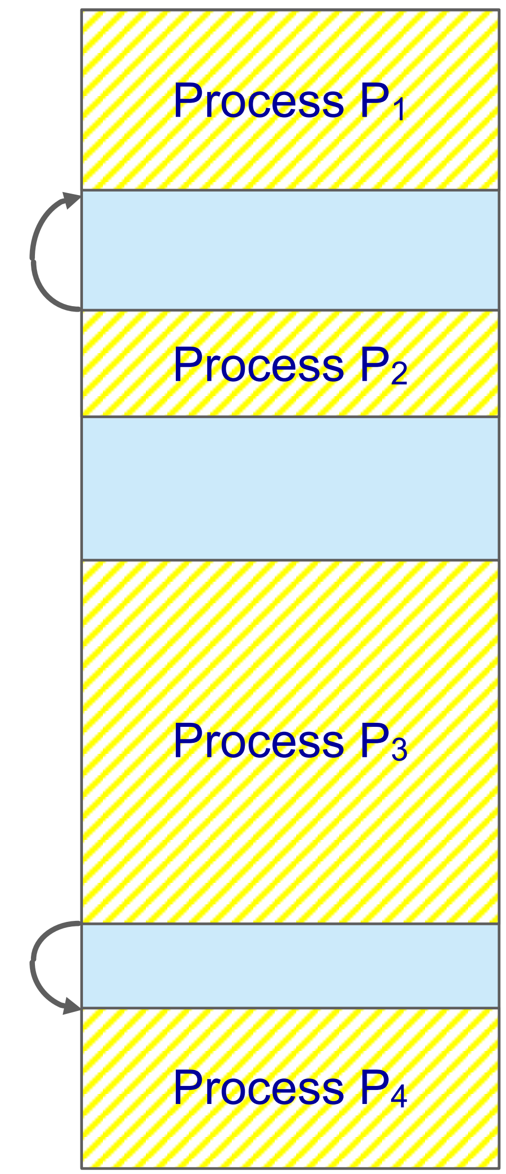


What's a good allocation policy?

- a policy that minimizes wasted space due to fragmentation
- simulations show first-fit and best-fit usually yield better storage utilization than worst-fit
  - first-fit is faster than best-fit

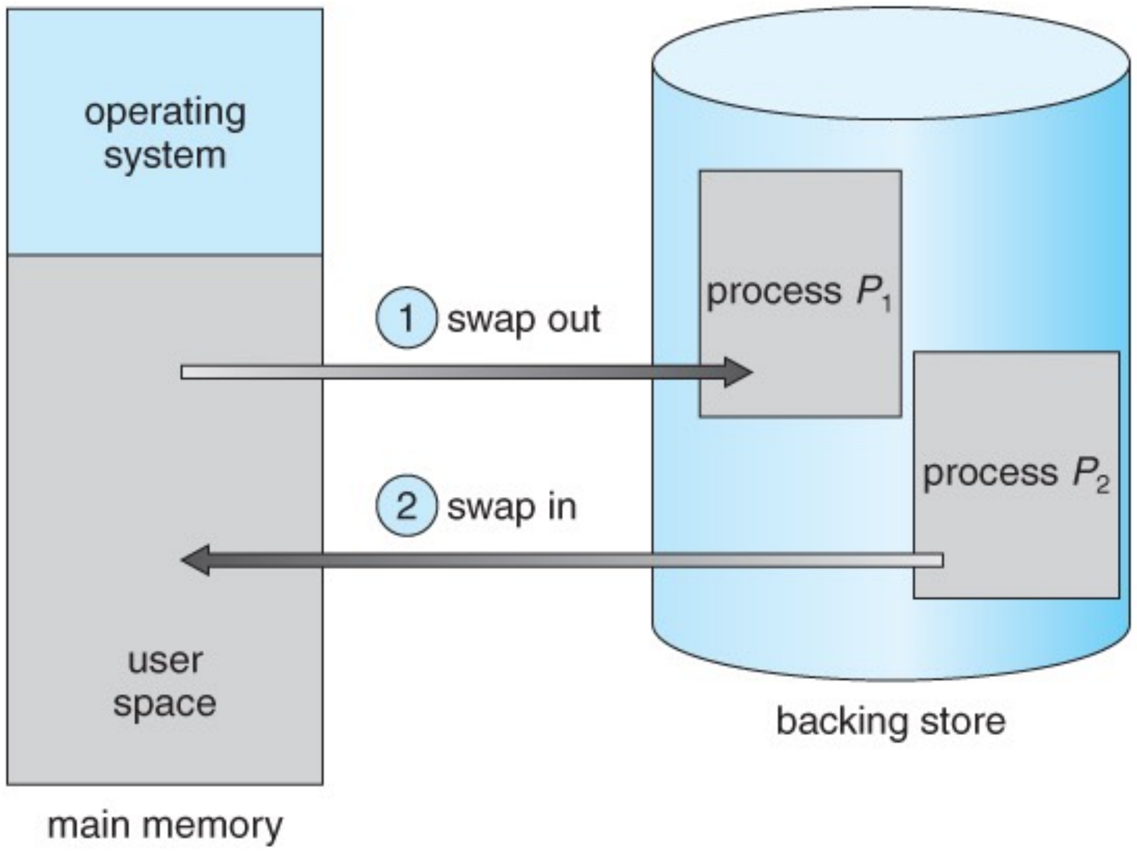
Compaction

- relocate processes to coalesce holes
  - the process shouldn't notice the change
  - requires logical addressed to be relocated at execution time
  - if addresses are relocated at load time, we cannot compact storage
- it can be done in different ways
  - how much memory is moved?
  - how big a hole is created?



What if not all processes fit into memory?

- swapping: preempt processes and reclaim their memory
  - frequency is dictated by the CPU scheduling algorithm



processes are copied from main memory to a backing store and are later copied back to main memory

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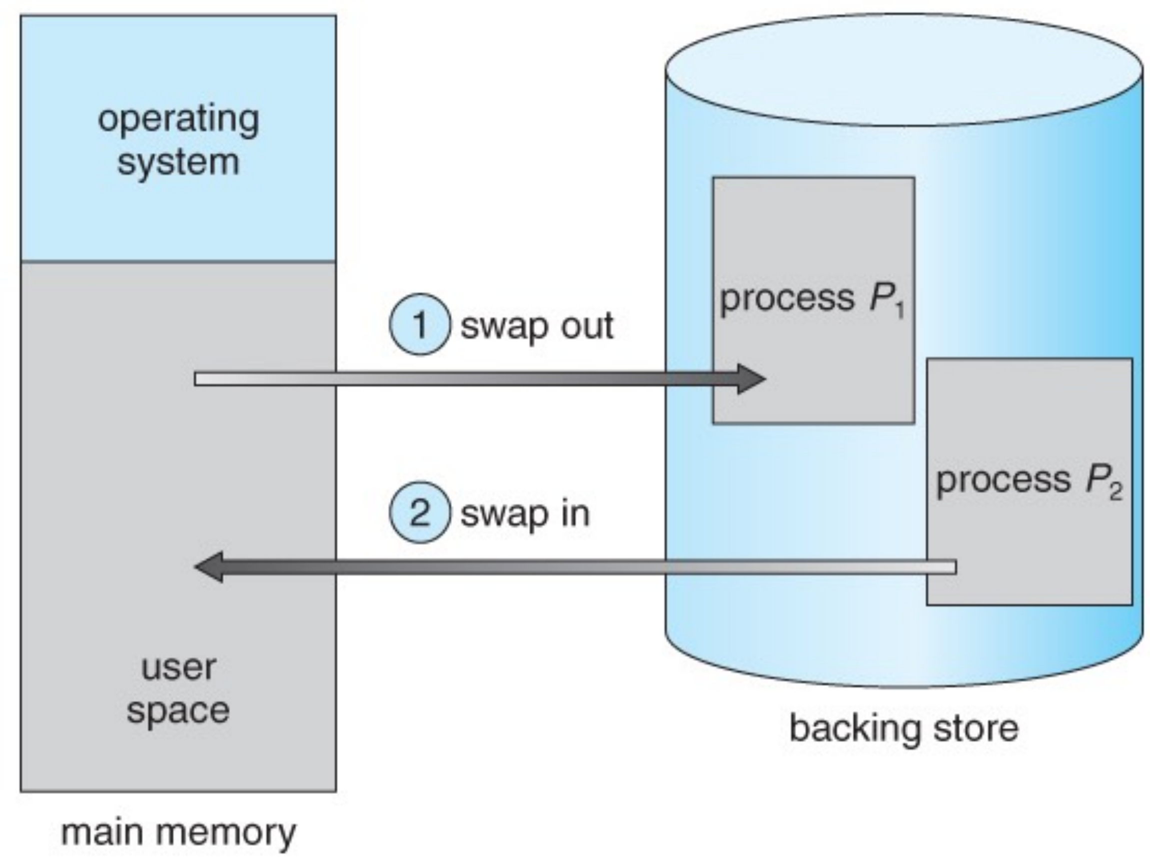

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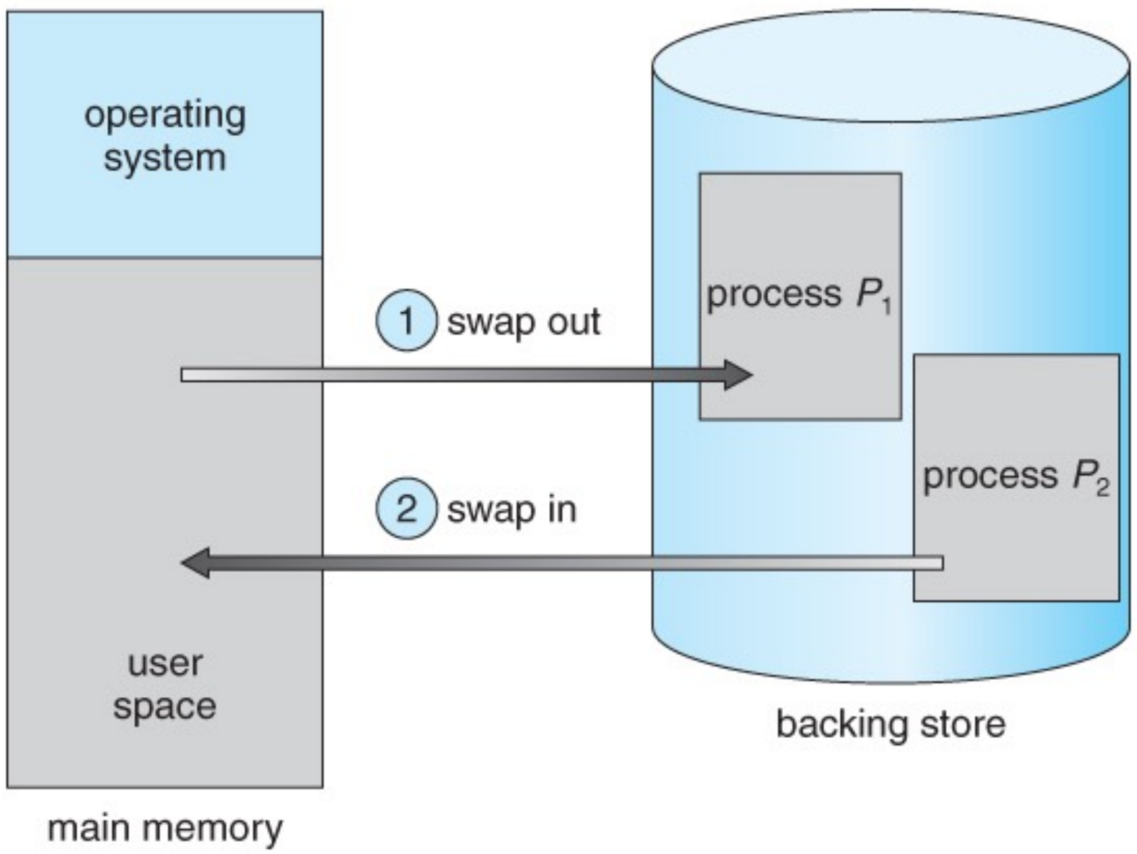
- compaction is easier with swapping



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