Memory

Address Space Abstraction

- Address space
  - All memory data
  - i.e., program code, stack, data segment
- Hardware interface (physical reality)
  - Computer has one small, shared memory
- Application interface (illusion)
  - Each process wants private, large memory

How can we close this gap?

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Address Space Illusions

- Address independence
  - Same address can be used in different address spaces yet remain logically distinct
- Protection
  - One address space cannot access data in another address space
- Virtual memory
  - Address space can be larger than the amount of physical memory on the machine

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Address Space Illusions

Illusion

Giant address space
Protected from others
(Unless you want to share)
More whenever you want it

Reality

Many processes sharing
One address space
Limited memory

Today:
The story of the Illusion

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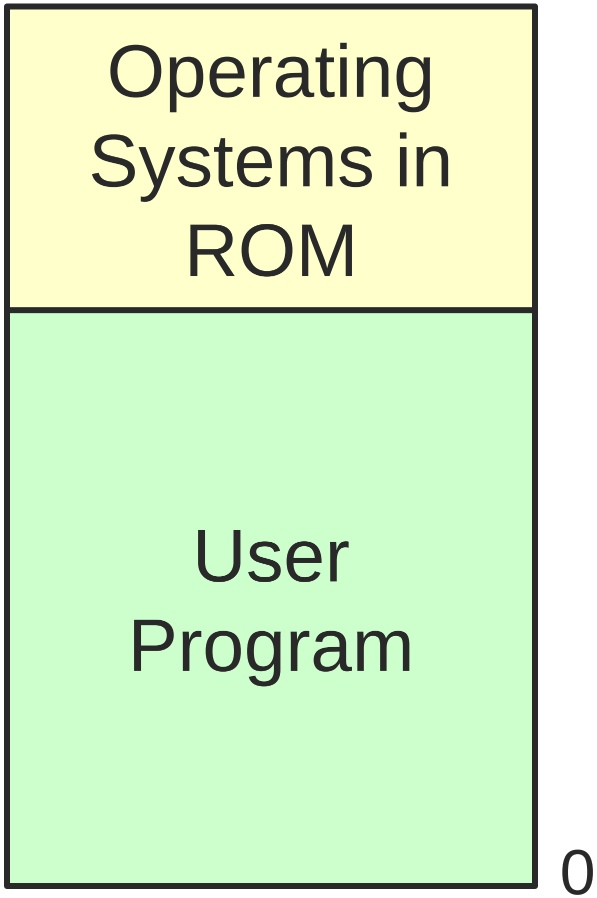
Uni-programming

- 1 process runs at a time
- Always load process into the same spot
- How do you switch processes?
- What illusions does this provide?
  - Independence, protection, virtual memory?



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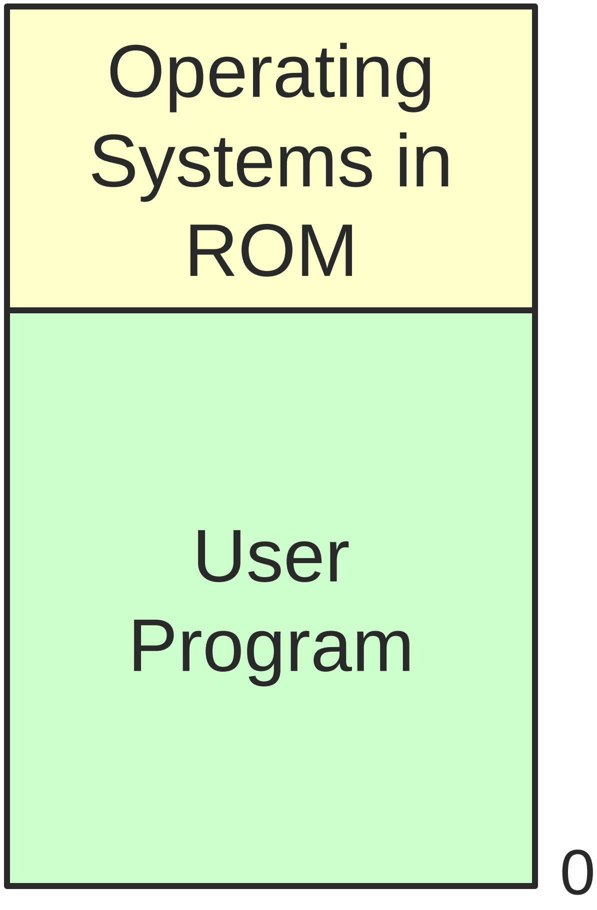
Uni-programming

- 1 process runs at a time
- Always load process into the same spot
- How do you switch processes?
- What illusions does this provide?
  - Independence, protection, virtual memory?
- Problems?
  - Slow, large time slices



Multi-Programming

- Multiple processes in memory at the same time
- Goals
  1. Layout processes in memory as needed
  2. Protect each process's memory from accesses by other processes
  3. Minimize performance overheads
  4. Maximize memory utilization

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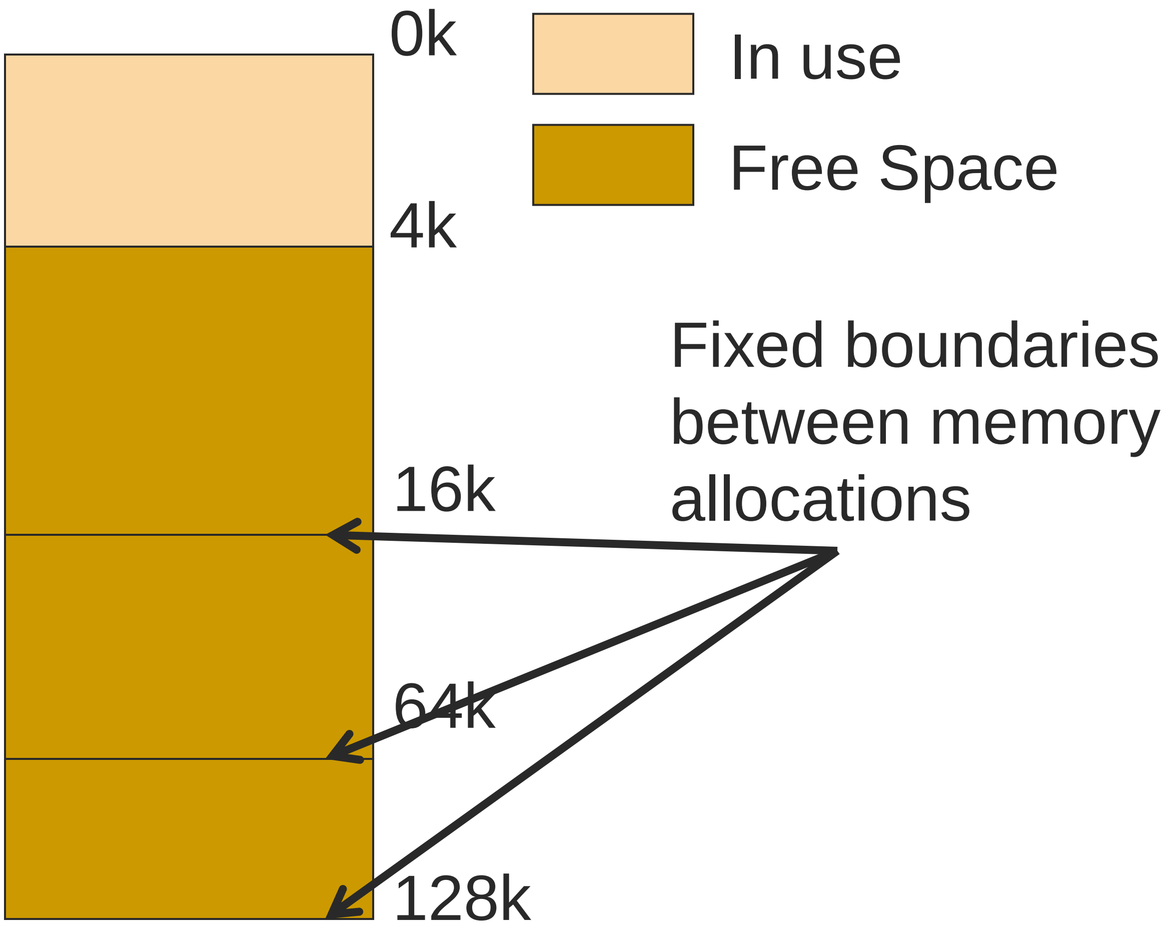
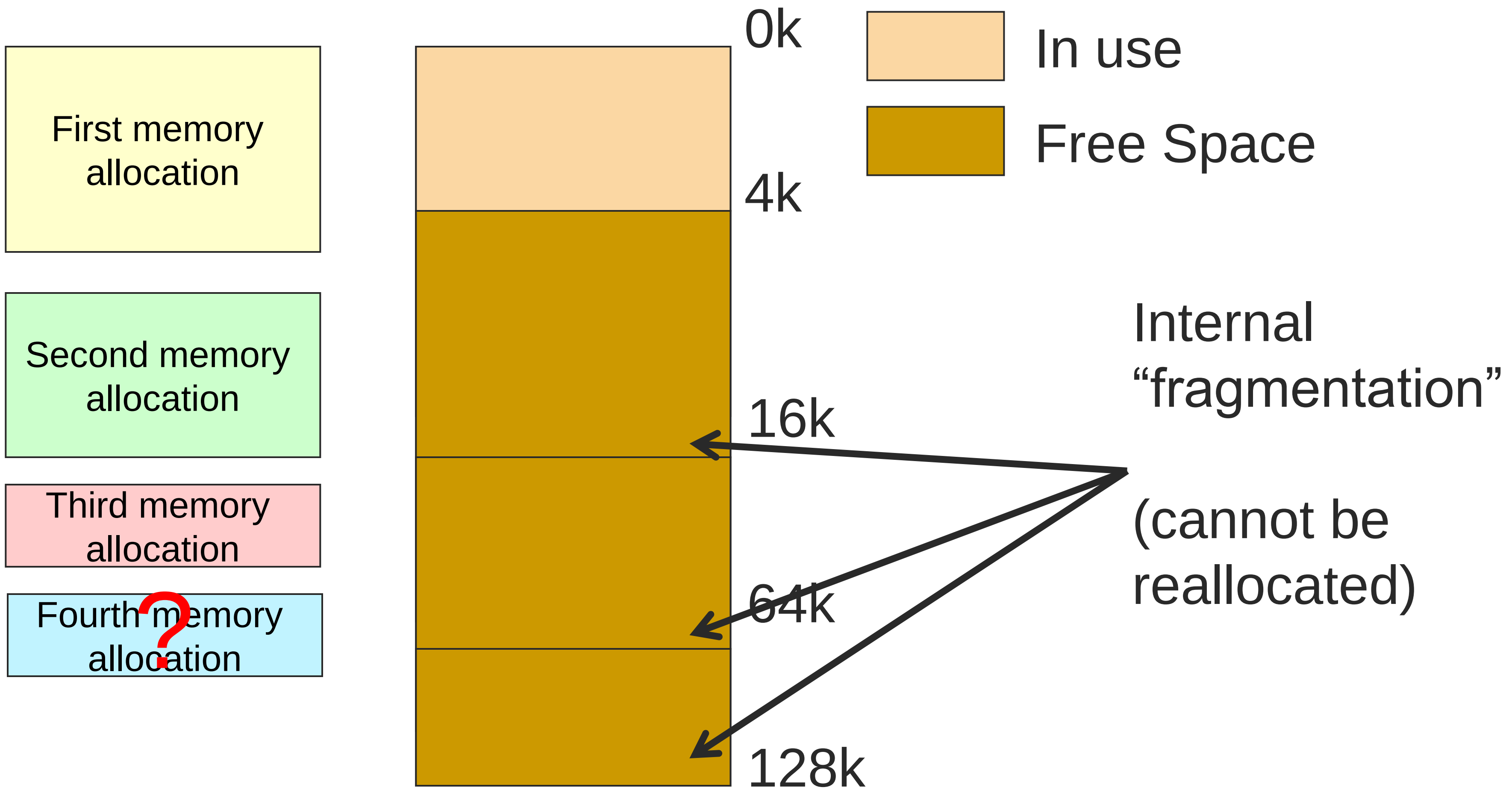
Multiple Fixed Partitions

Divide memory into *n* (possibly unequal) partitions.



Multiple Fixed Partitions



Problems with Fixed Partitions

1. Program addresses vary across runs
2. Internal fragmentation
3. Not all processes may fit in memory

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Problem 1: Insufficient Memory

- What if there are more processes than could fit into the memory?
- Swapping
- Impact: Memory allocation changes as
  - Processes come into memory
  - Processes leave memory
    - Swapped to disk
    - Complete execution

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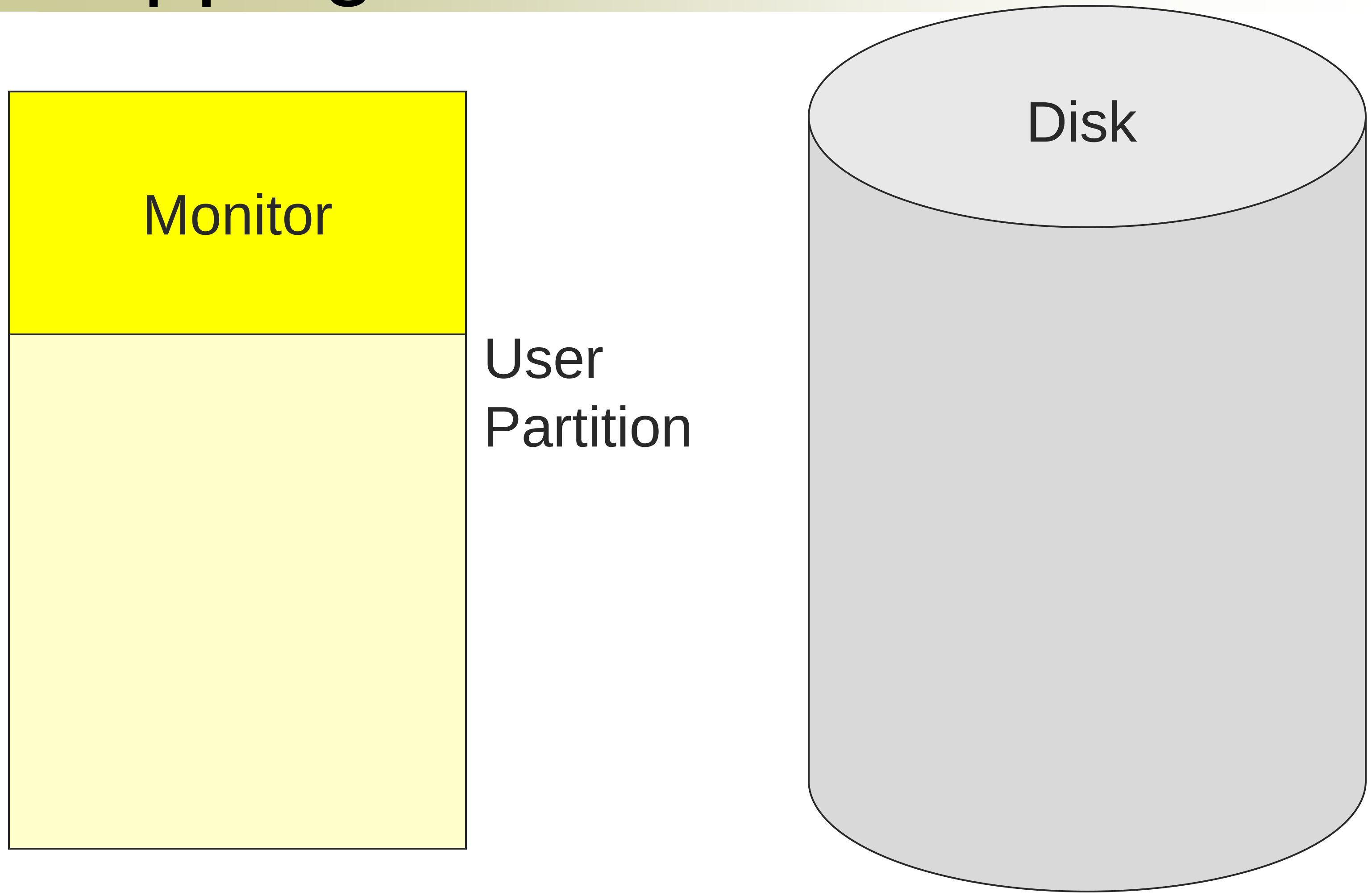
Swapping



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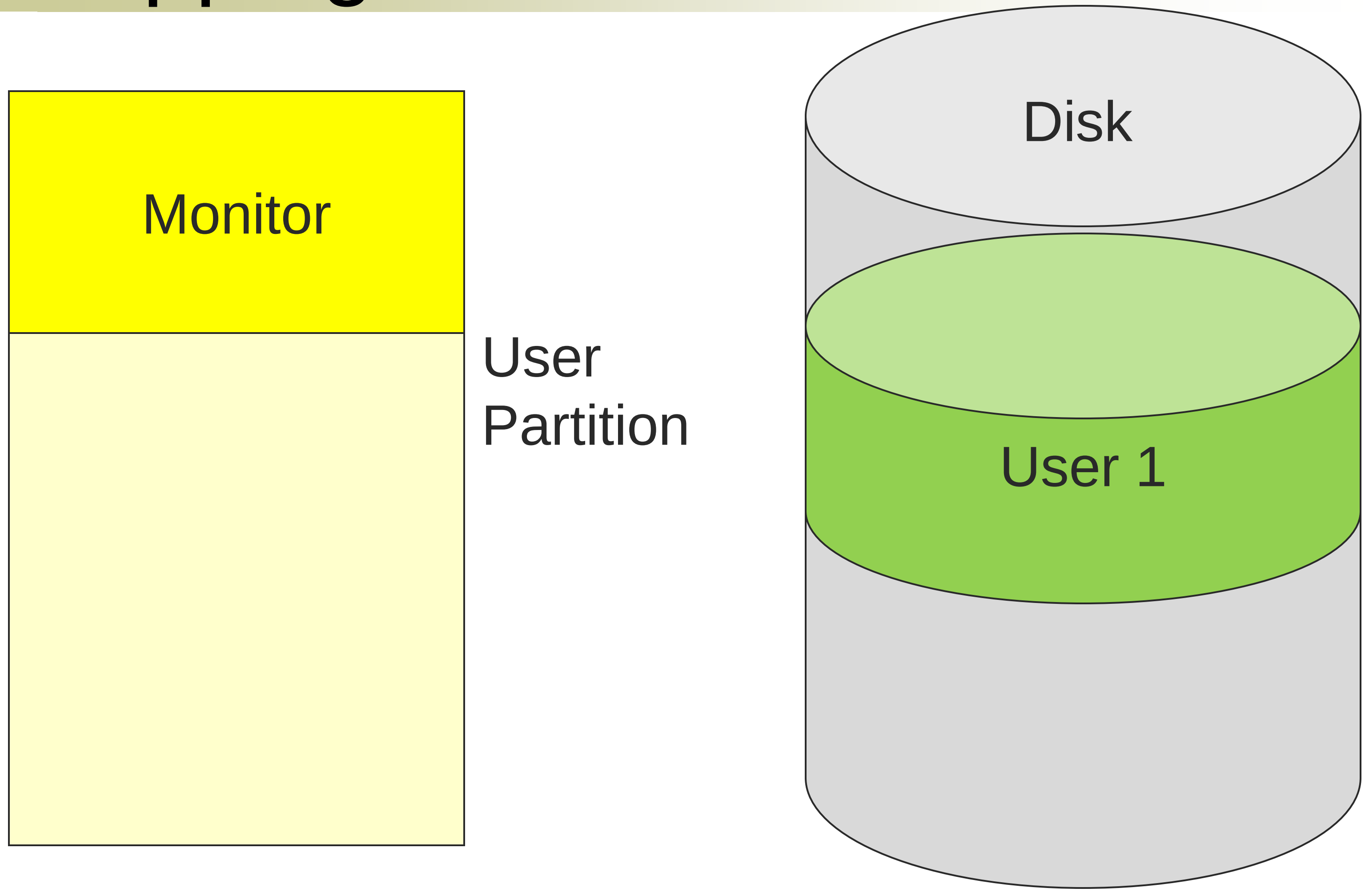
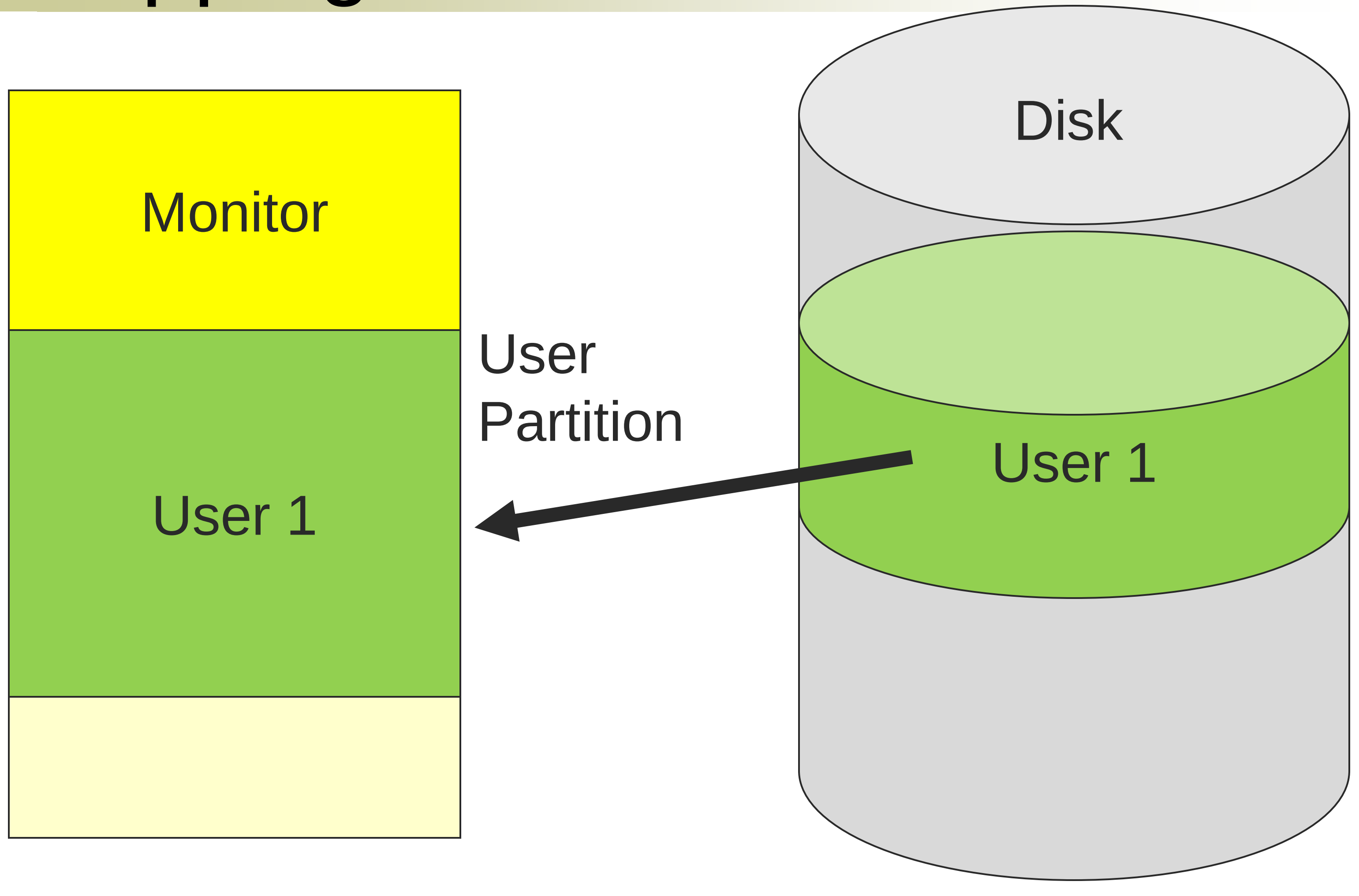
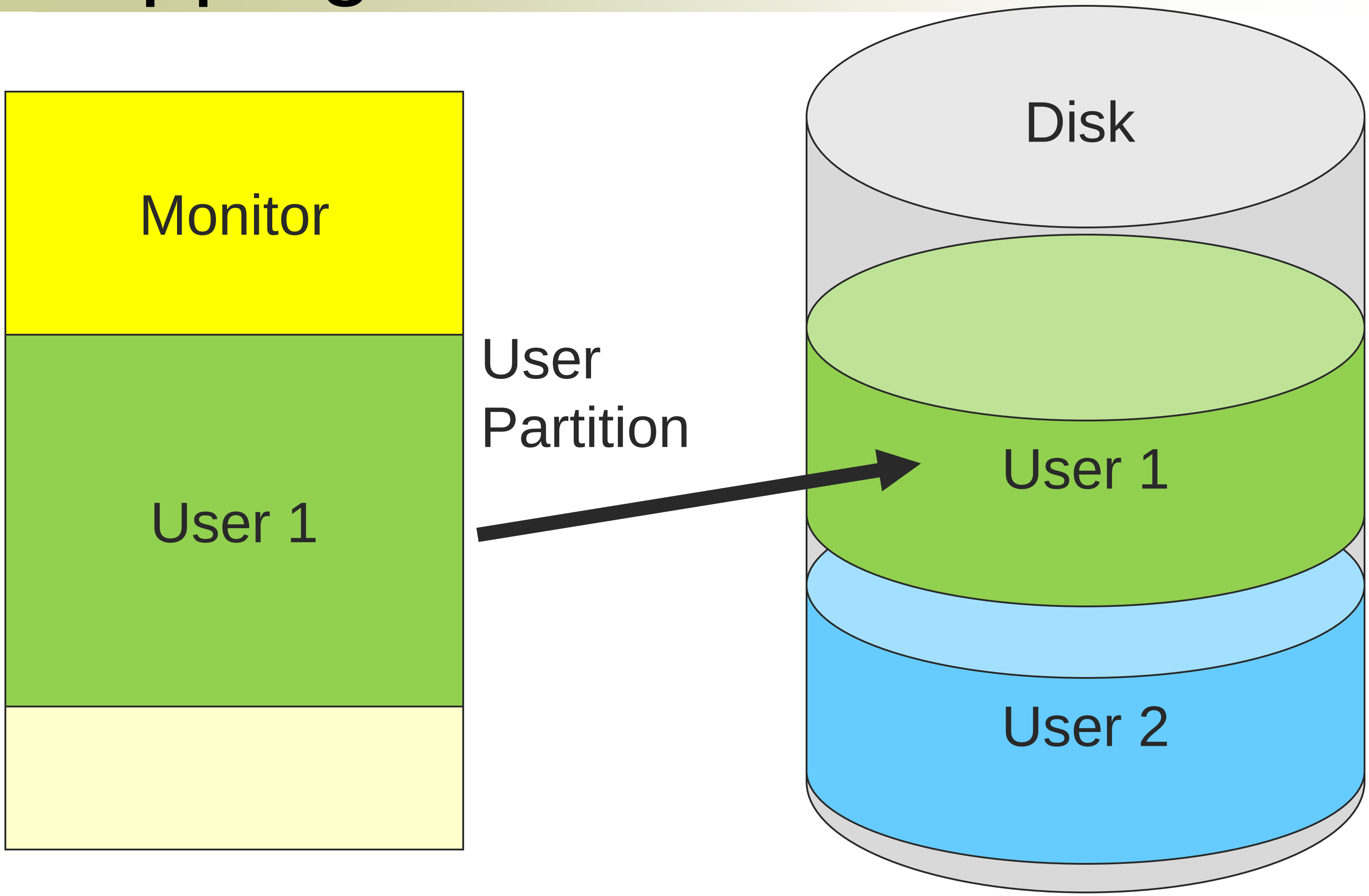
Swapping



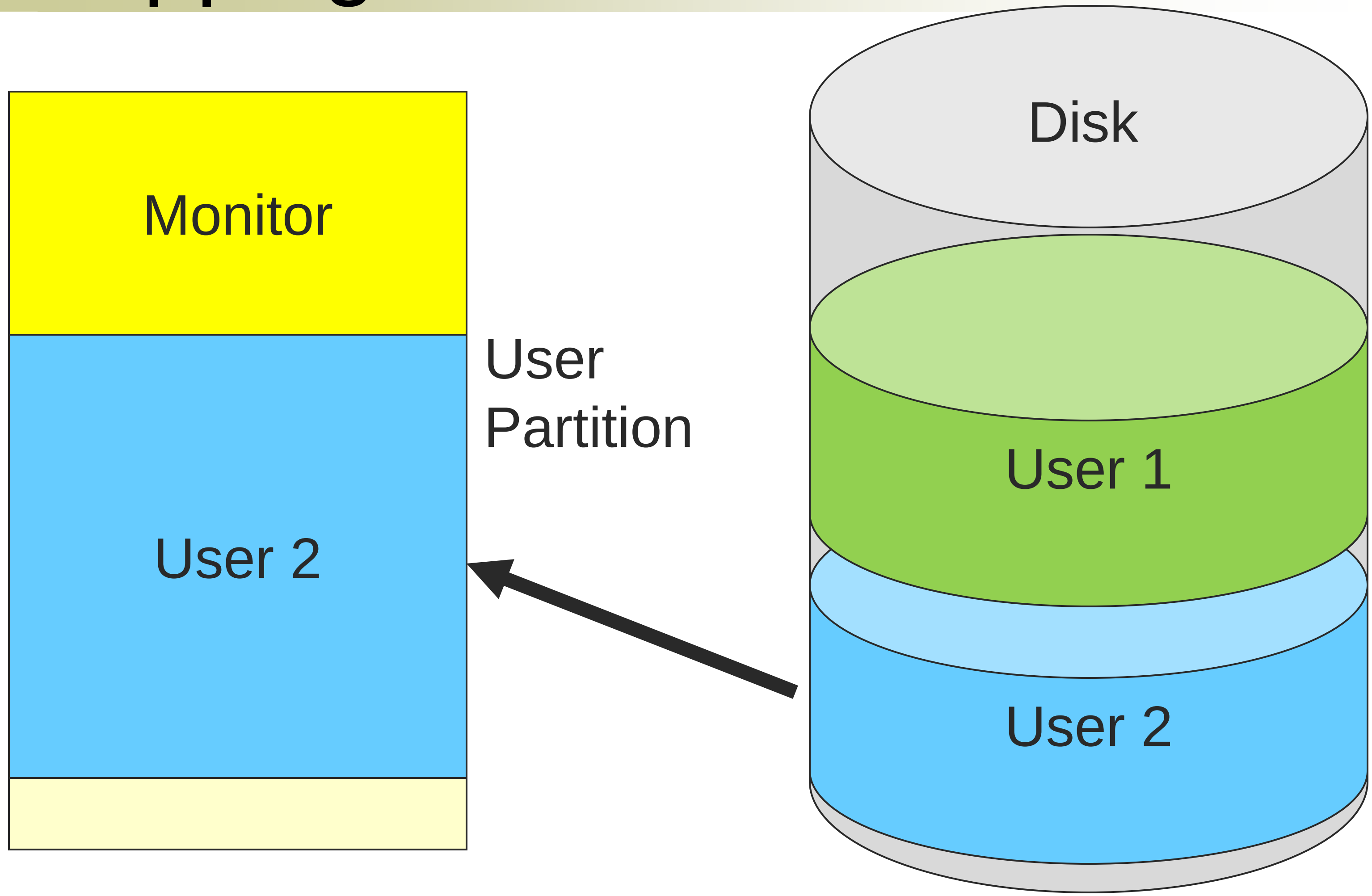
Swapping



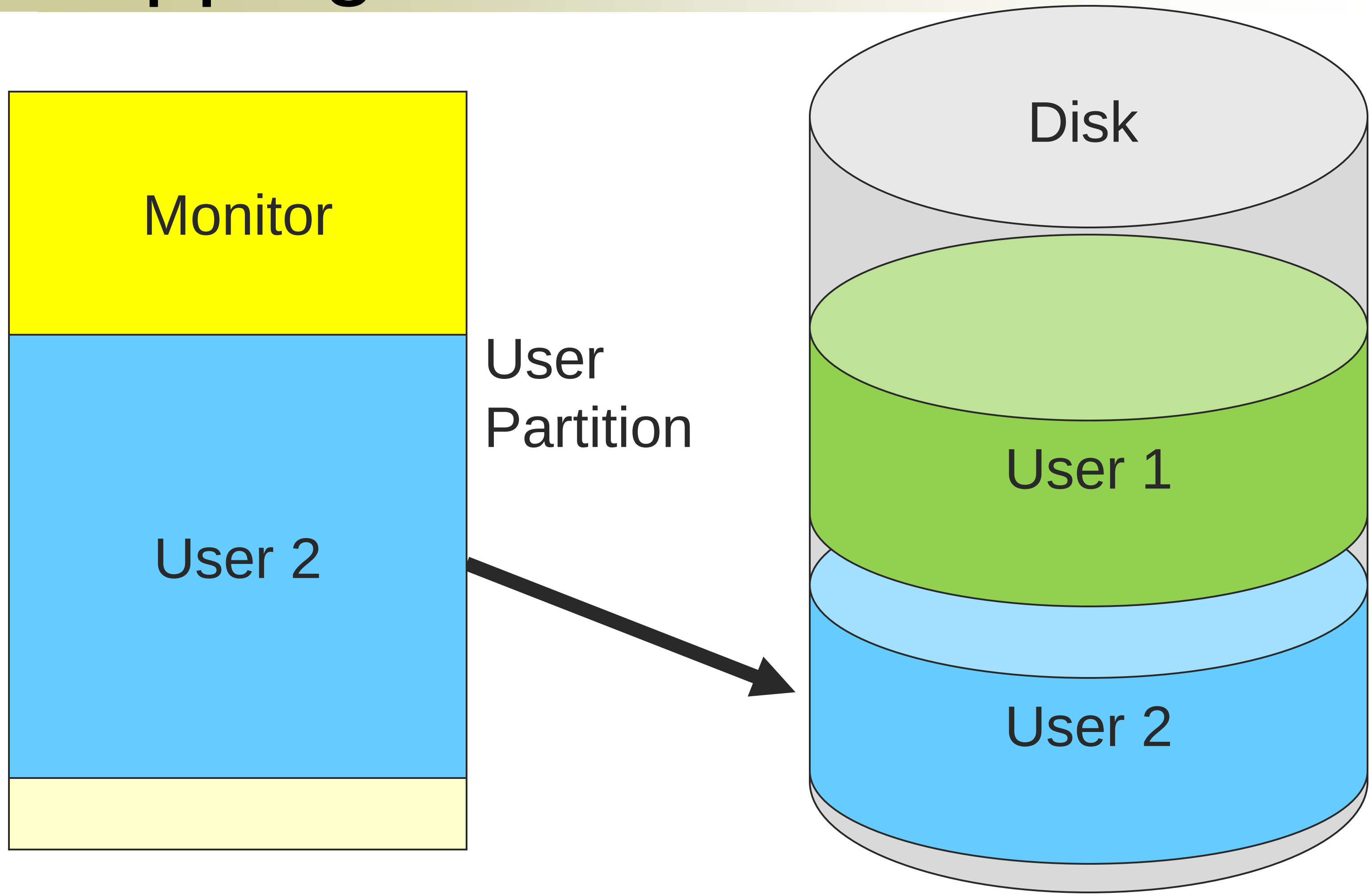
Swapping



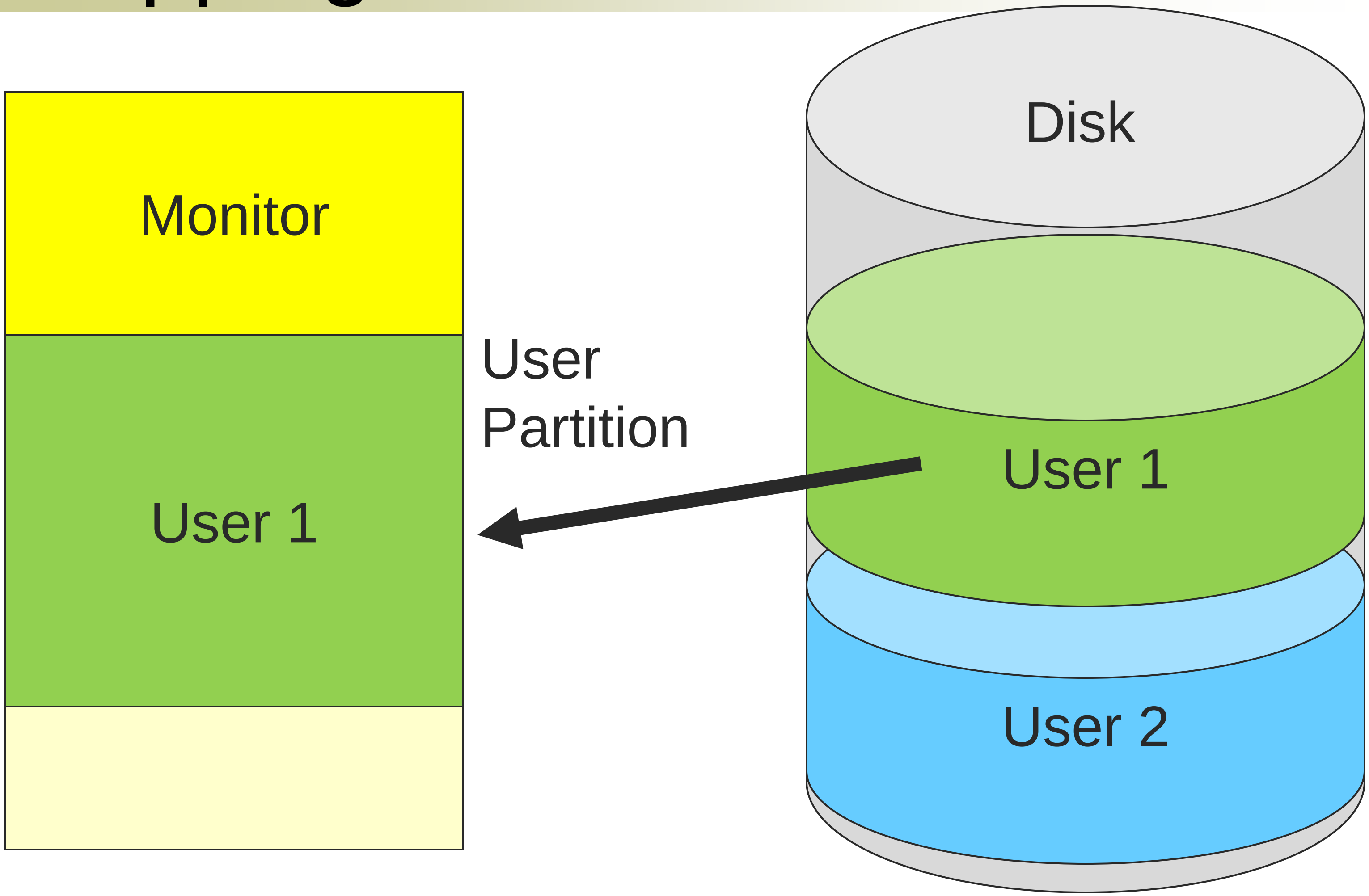
Swapping



Swapping



Swapping



Storage Placement Strategies

- First fit
  - Use the first available hole whose size is sufficient to meet the need
  - Rationale?
- Best fit
  - Use the hole whose size is equal to the need, or if none is equal, the hole that is larger but closest in size
  - Rationale?
- Worst fit
  - Use the largest available hole
  - Rationale?

Example

- Consider a swapping system in which memory consists of the following hole sizes in memory order:
  - 10K, 4K, 20K, 18K, 7K, 9K, 12K, and 15K.
  - Which hole is taken for successive segment requests of:
    - 12K
    - 10K
    - 9K

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Example

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    - 12K
    - 10K
    - 9K

First fit: 20K, 10K, 18K.	Best fit: 12K, 10K, 9K.	Worst fit: 20K, 18K, and 15K.

Storage Placement Strategies

- Best fit
  - Produces the smallest leftover hole
  - Creates small holes that cannot be used
- Worst Fit
  - Produces the largest leftover hole
  - Difficult to run large programs
- First Fit
  - Creates average size holes

- First-fit and best-fit better than worst-fit in terms of speed and storage utilization

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Fragmentation

- External Fragmentation
  - Memory space exists to satisfy a request, but it is not contiguous
- Internal Fragmentation
  - Allocated memory may be larger than requested memory
  - The extra memory internal to a partition, but not being used

How Bad Is Fragmentation?

- Statistical analysis - Random job sizes
- First-fit
  - Given N allocated blocks
  - 0.5∗N blocks will be lost *on average*, because of fragmentation

- Known as 50% RULE

Compaction

- Reduce external fragmentation by compaction
  - Move jobs in memory to place all free memory together in one large block
  - Compaction is possible only if relocation is dynamic, and is done at execution time

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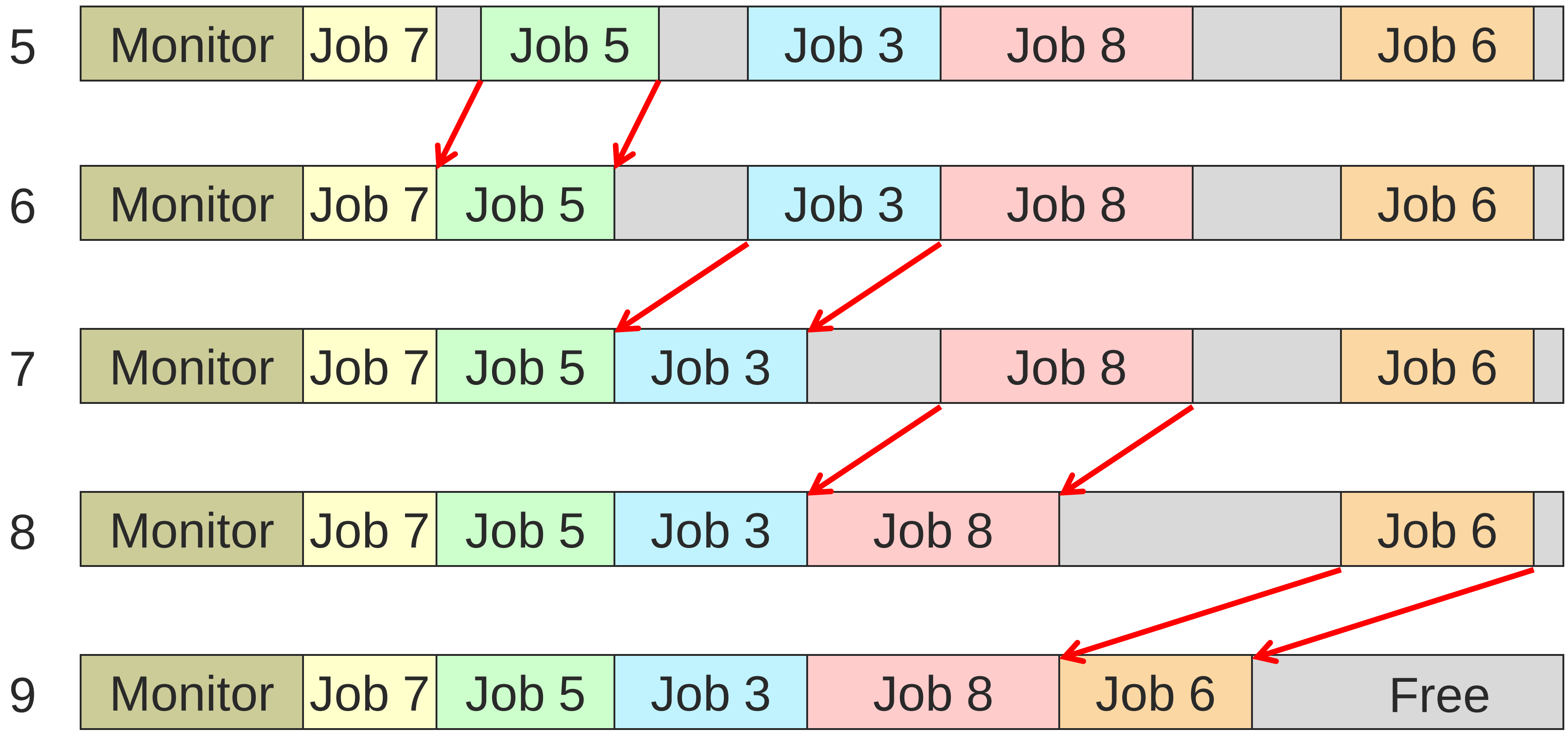
Compaction



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Storage Management Problems

- Fixed partitions suffer from
- Variable partitions suffer from
- Compaction suffers from

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Storage Management Problems

- Fixed partitions suffer from
  - Internal fragmentation
- Variable partitions suffer from
  - External fragmentation
- Compaction suffers from
  - Overhead

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Limitations of Swapping

- Problems with swapping under Partitioning
  - Process must fit into physical memory (impossible to run larger processes)
  - Memory becomes fragmented
    - External fragmentation
      - Lots of small free areas
    - Need compaction
      - Reassemble larger free areas
  - Processes are either in memory or on disk
    - Half and half doesn't do any good

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Problem 2: Varying Addresses

- Problem addresses for a job are unknown until start time
  - At link-time, linker must know memory address at which the program will begin
  - These addresses must be adjusted at run time

Solution?

Virtual Memory

- Basic idea
  - Allow the OS to hand out more memory than exists on the system
  - Keep recently used stuff in physical memory
  - Move less recently used stuff to disk
  - Keep all of this hidden from processes
- Process view
  - Processes still see an address space from 0 – max address
  - Actual physical location (and movement) of memory handled by the OS without process help

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Virtual Addresses

- Virtual address
  - An address meaningful to the user process
- Physical address
  - An address meaningful to the physical memory
- Different jobs run at different phy. addresses
  - But virtual address can be the same
  - Program never sees physical address
  - Linker must know program's starting memory address

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Indirection

"Any programming problem can be solved by adding a level of indirection …

…except for the problem of too many layers of indirection."

David Wheeler

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Multi-programming

- Multiple processes in memory at the same time
- What do we really need?
  - Address translation
    - Translate every memory reference from virtual address to physical address
    - Static before execution, or dynamic during execution?
  - Protection
    - Support independent addresses spaces

Dynamic Address Translation

- Load each process into contiguous regions of physical memory

- Logical or "Virtual" addresses
  - Logical address space
  - Range: 0 to MAX

- Physical addresses
  - Physical address space
  - Range: R+0 to R+MAX for base value R

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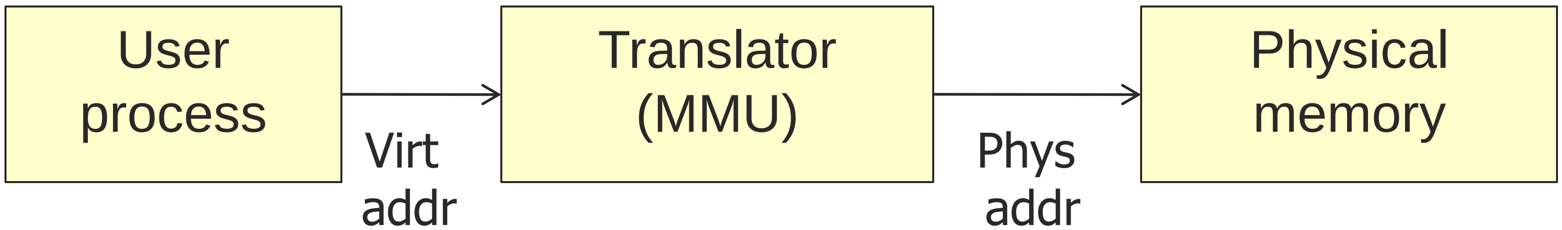
Dynamic Address Translation



- Translation enforces protection
  - One process can't even refer to another process's address space
- Translation enables virtual memory
  - A virtual address only needs to be in physical memory when it is being accessed
  - Change translations on the fly as different virtual addresses occupy physical memory

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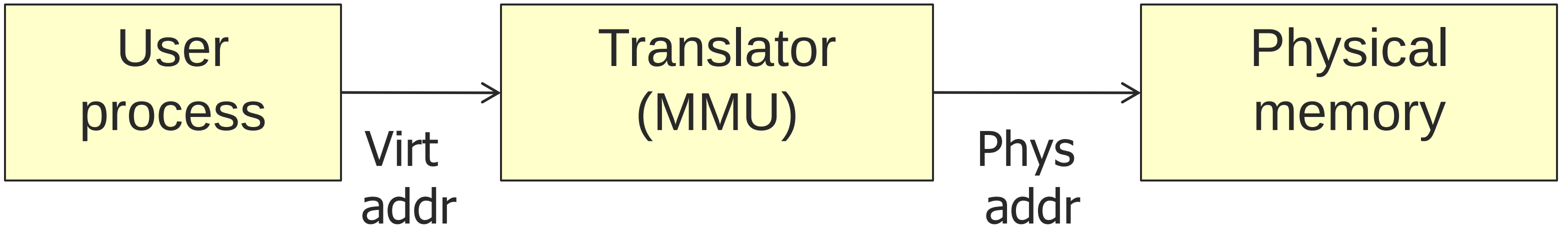
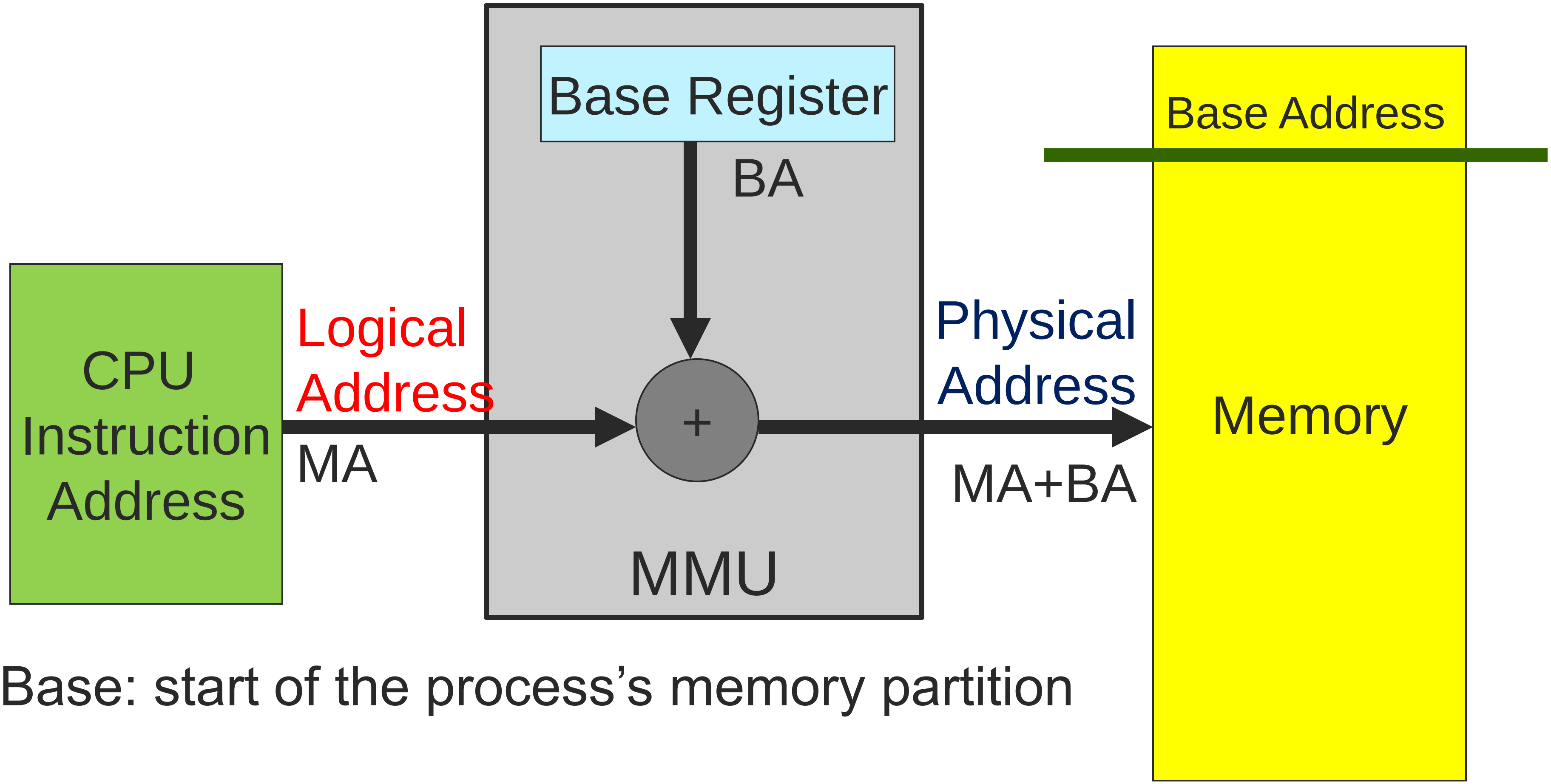
Dynamic Address Translation



- Implementation tradeoffs
  - Flexibility (e.g., sharing, growth, virtual memory)
  - Size of translation data
  - Speed of translation

Base Register



Base: start of the process's memory partition

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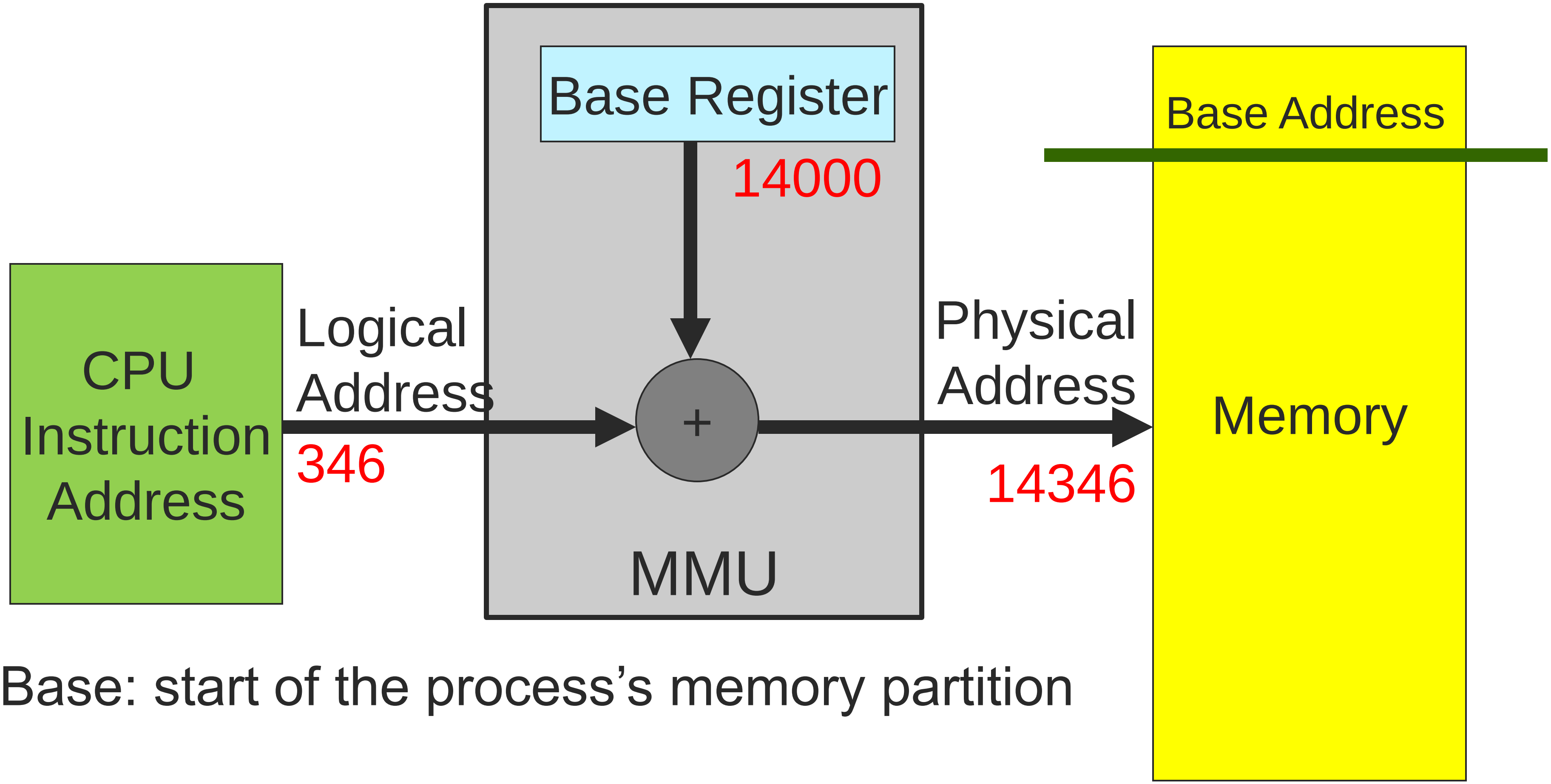
Base Register



Base: start of the process's memory partition

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Protection

- Problem
  - How to prevent a malicious process from writing or jumping into another user's or OS partitions
- Solution
  - Base bounds register

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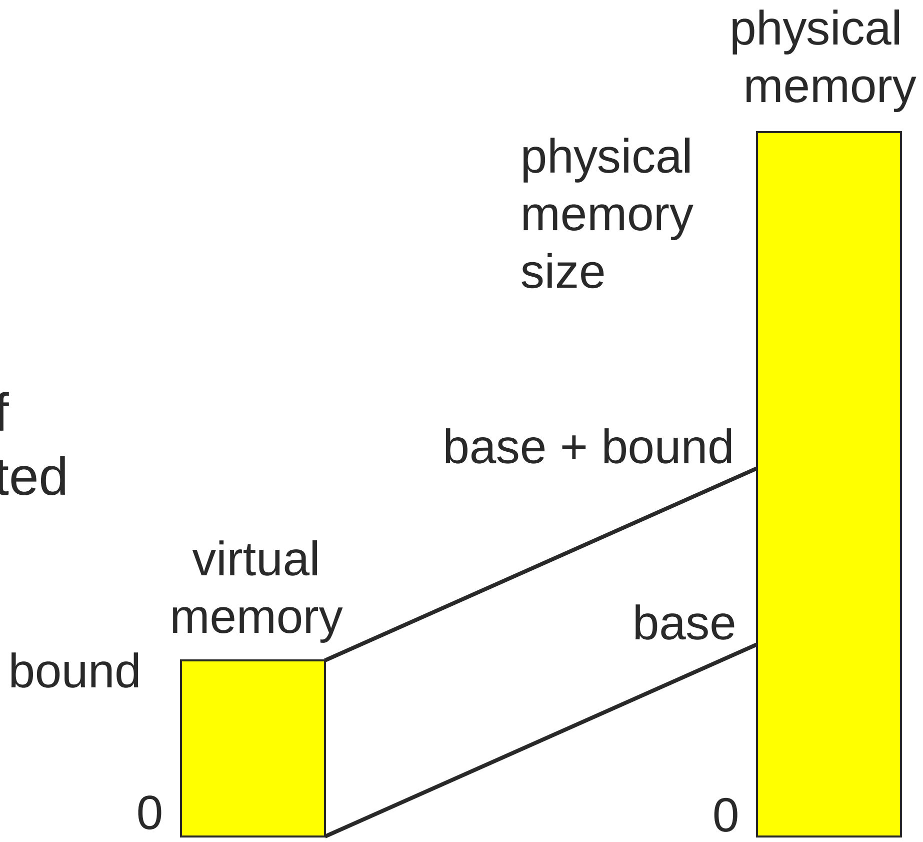
Base and bounds

```
if (virt addr > bound)
    trap to kernel
} else {
    phys addr =
      virt addr + base
}
```

- Process has the illusion of running on its own dedicated machine with memory [0,bound)
- Provides protection from other processes also currently in memory



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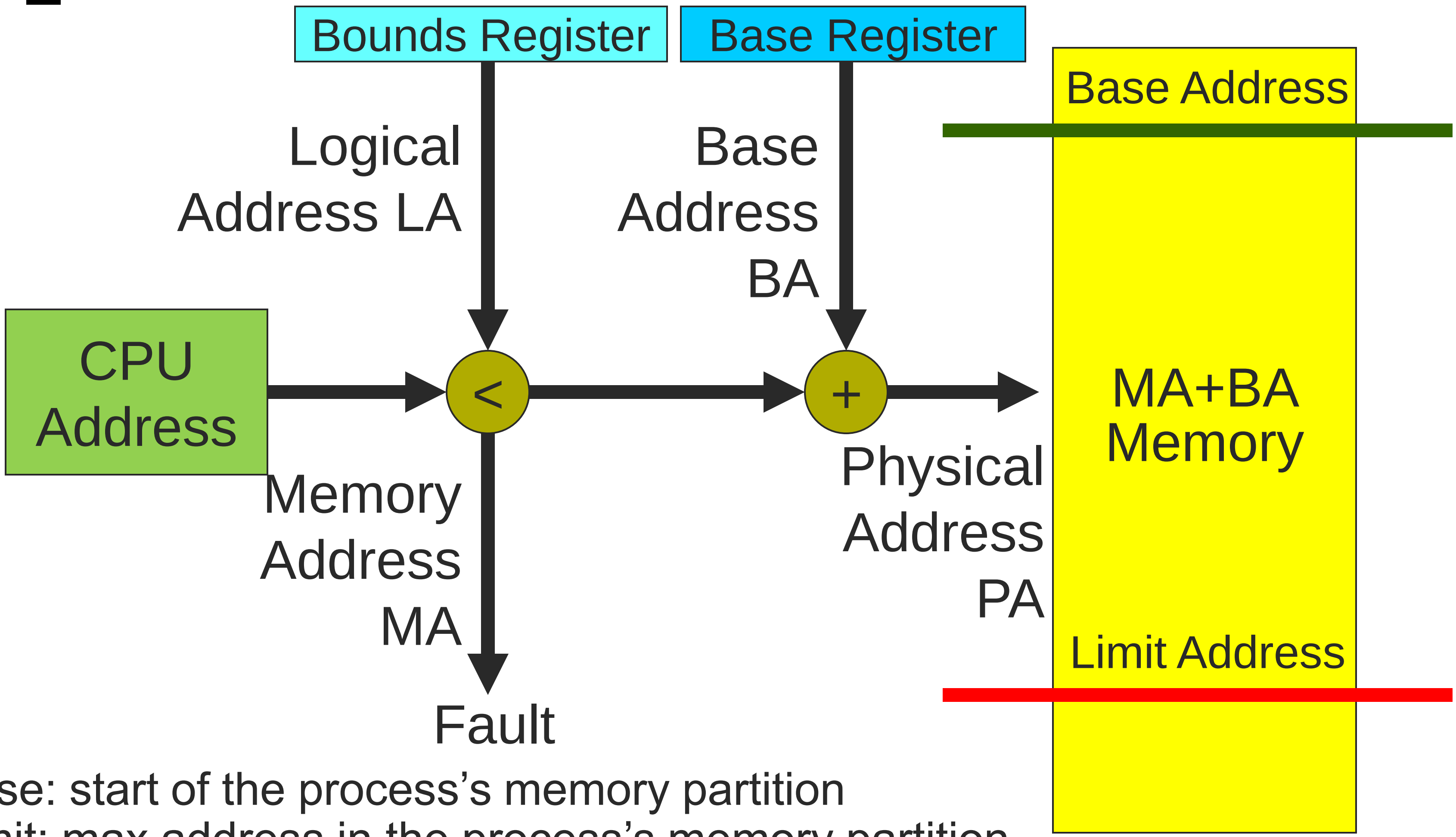
Base and Bounds Registers



Base: start of the process's memory partition
Limit: max address in the process's memory partition

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Base and bounds

- What must change during a context switch?
  - The base and the bounds registers
- Can a process change its own base and bound?
  - No, only the OS can change these registers
  - The program can do it indirectly (e.g., ask for more memory in stack)

Base and bounds

- Problem: Process needs more memory over time
- How does the kernel handle the address space growing?
  - You are the OS designer
  - Design algorithm for allowing processes to grow