Systems and Networking I

Applied Computer Science and Artificial Intelligence

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SAPIENZA
UNIVERSITÀ DI ROMA

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Paging + Segmentation

- Paging (OS' view of memory)
  - Divide memory into fixed-size pages and map them to physical frames
- Segmentation (compiler's view of memory)
  - Divide process into logical segments (e.g., code, data, stack, heap)
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So far, the entire virtual address space of a process was assumed to fit and be all in memory

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Virtual Memory uses backing storage (i.e., disk) to store unused pages and give the illusion of "infinite" space

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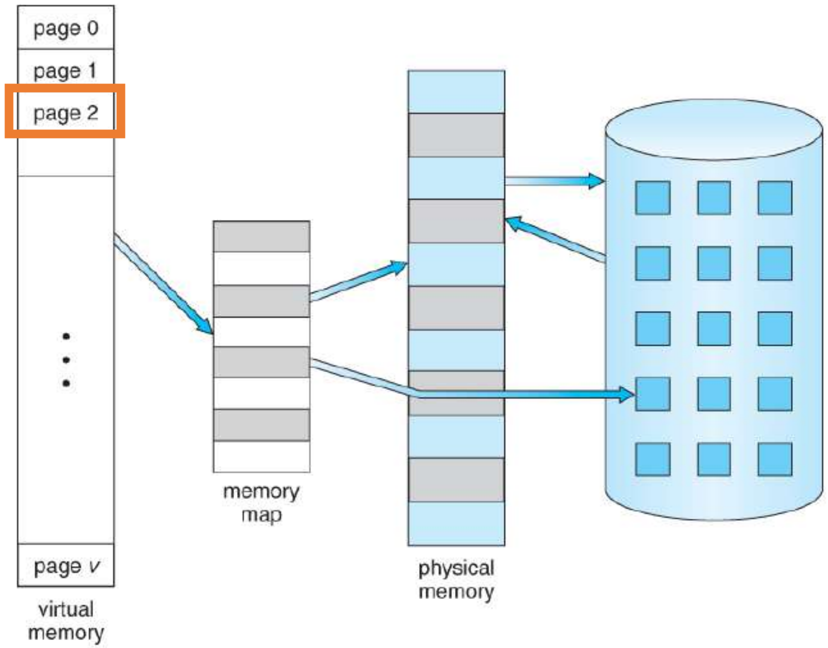
  - Less I/O is needed for swapping processes in and out of memory, speeding things up

Virtual Memory: The Big Picture



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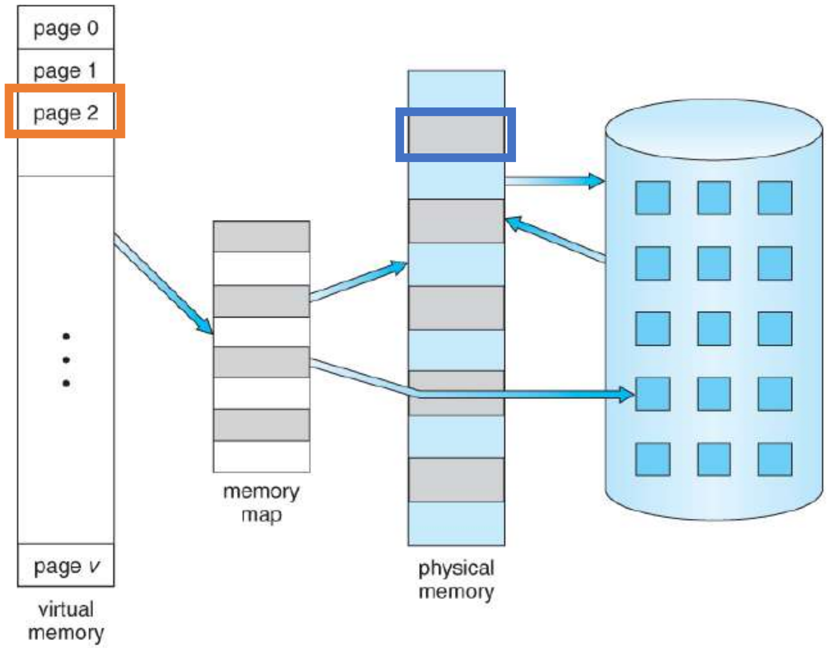

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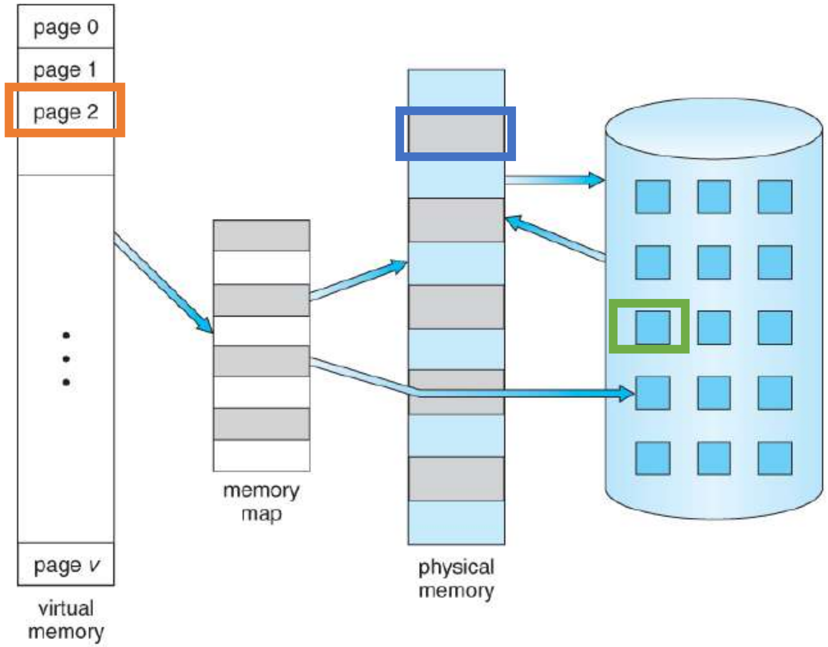

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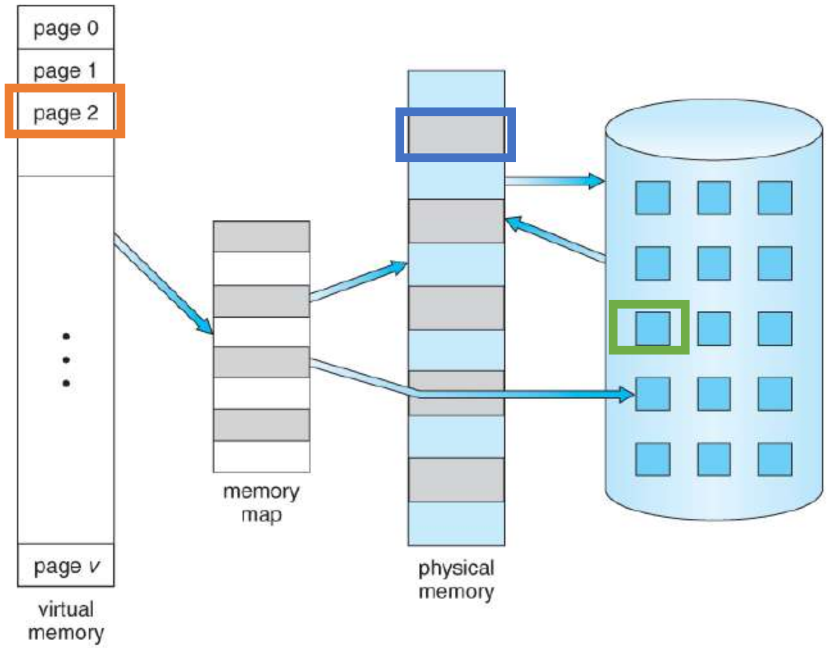
Virtual Memory: The Big Picture

virtual memory can be much larger than physical memory



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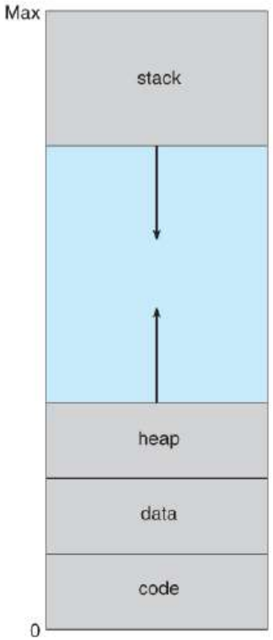
The Sparseness of Virtual Address Space



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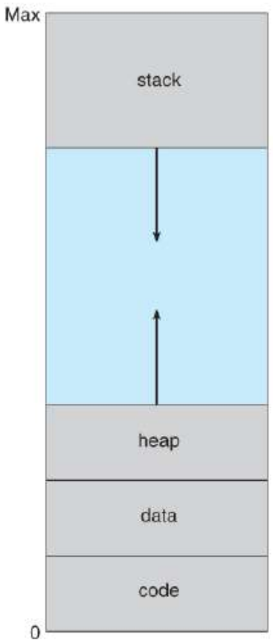

Typically, virtual address space is highly sparse

A lot of virtual memory addresses remain unreferenced

```
int *arr = malloc(4 TB);
arr[0] = 1;
arr[500000000] = 2;
```

```
void f() {
    char big[4 * 1024 * 1024];    // 4 MB array
    big[0] = 1;                   // first page touched only
}
```

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- Therefore, memory accesses must reference pages that are in memory **with high probability**

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- We call this area as the **working set** of the process
- Since the working set is fairly small compared to the whole virtual address space, it will likely fit in memory

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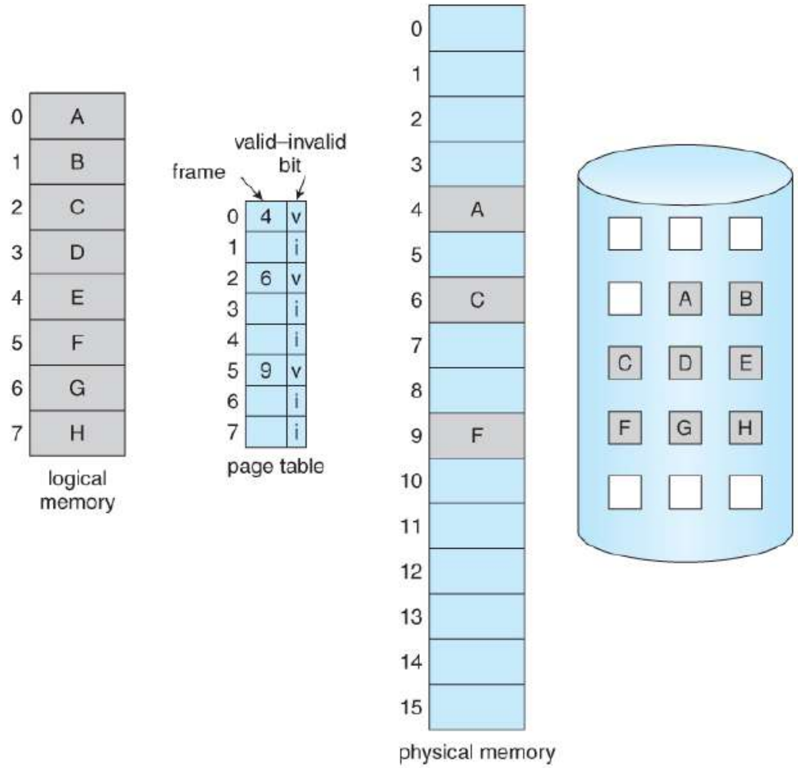
- But in a reasonably small time frame, the working set stays "the same"

Virtual Memory: Basic Concepts



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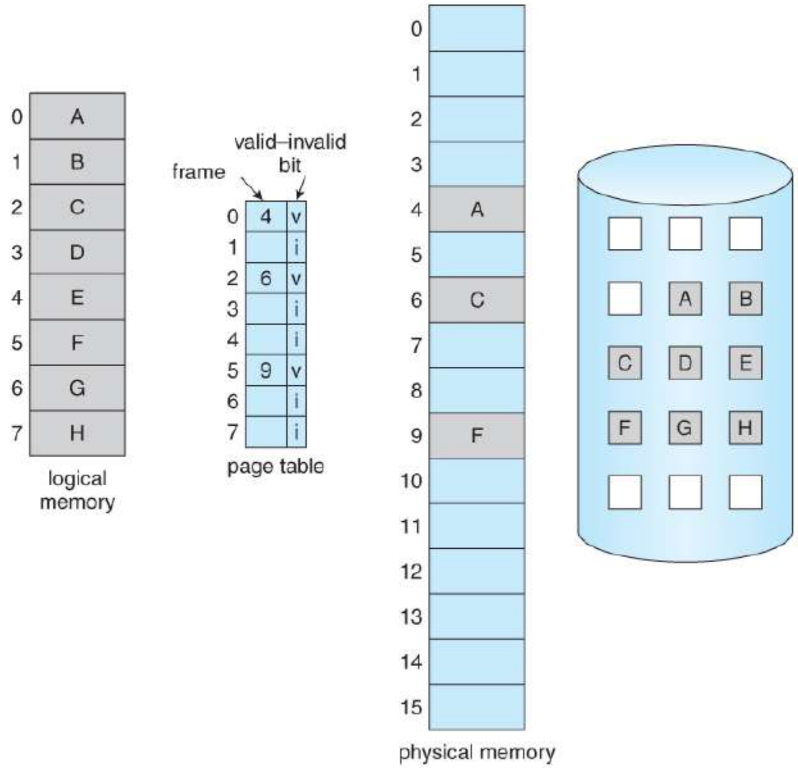

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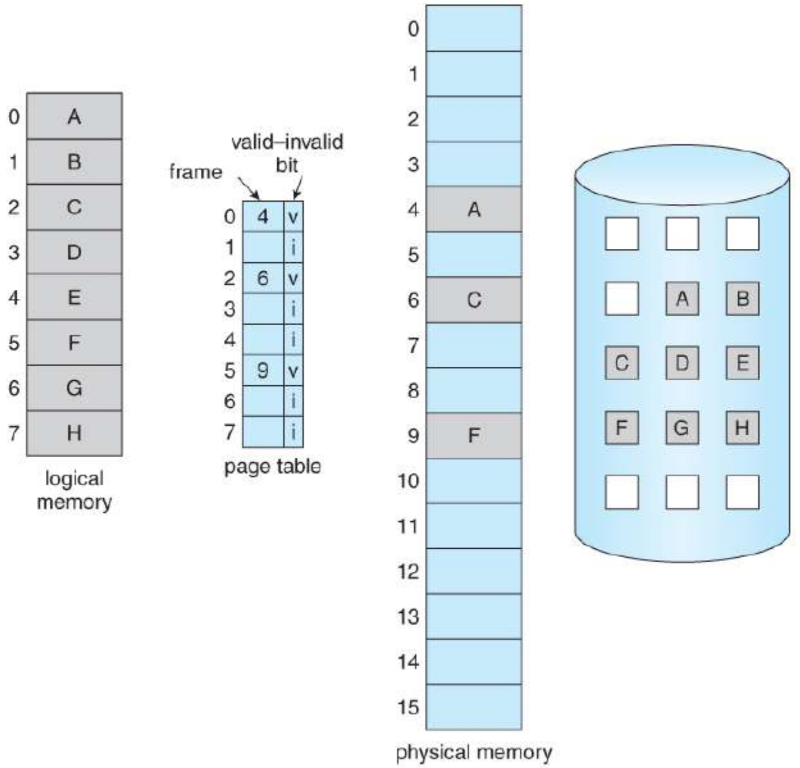

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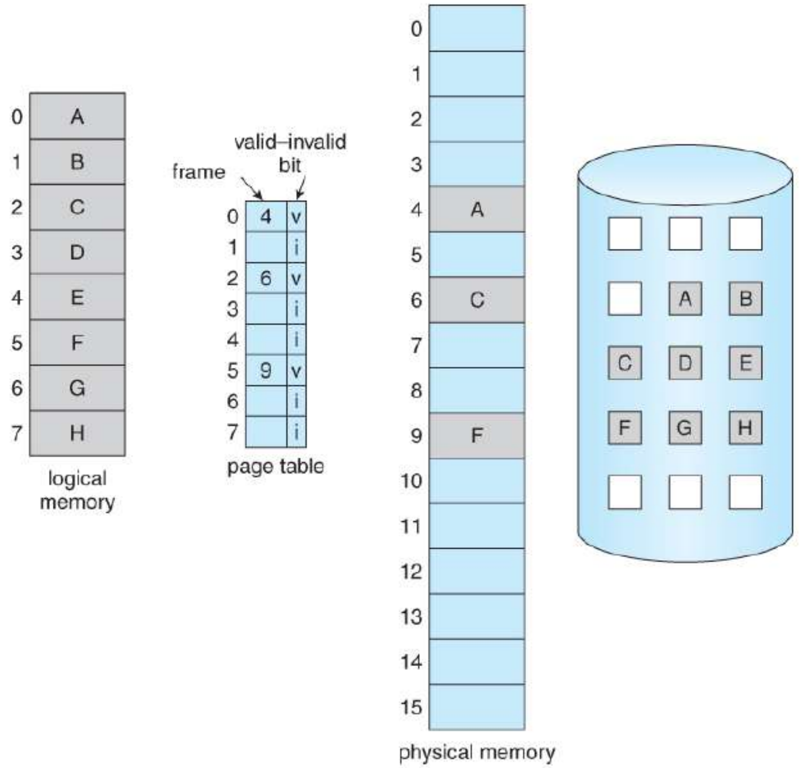

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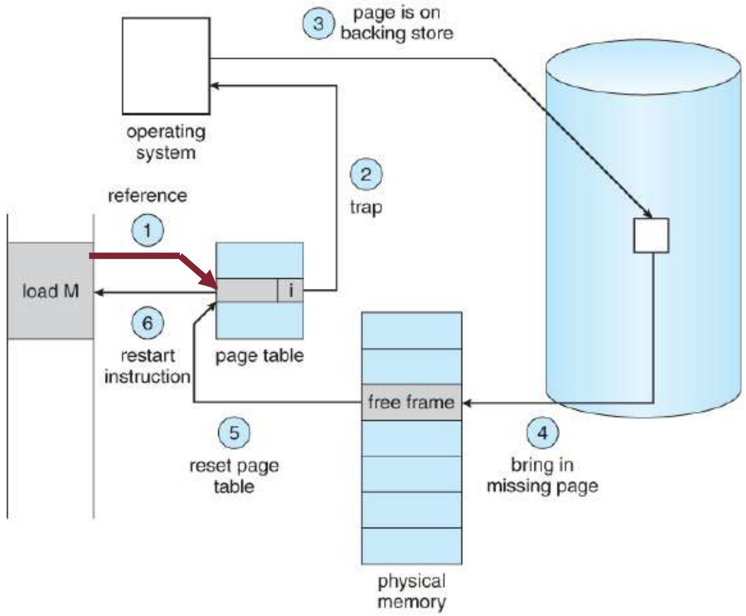
If the bit is set to 1 it means the page entry is valid (i.e., the requested page is in memory)

Otherwise, a page fault trap occurs, and the page has to be loaded (i.e., fetched) from disk

Page Fault Handling



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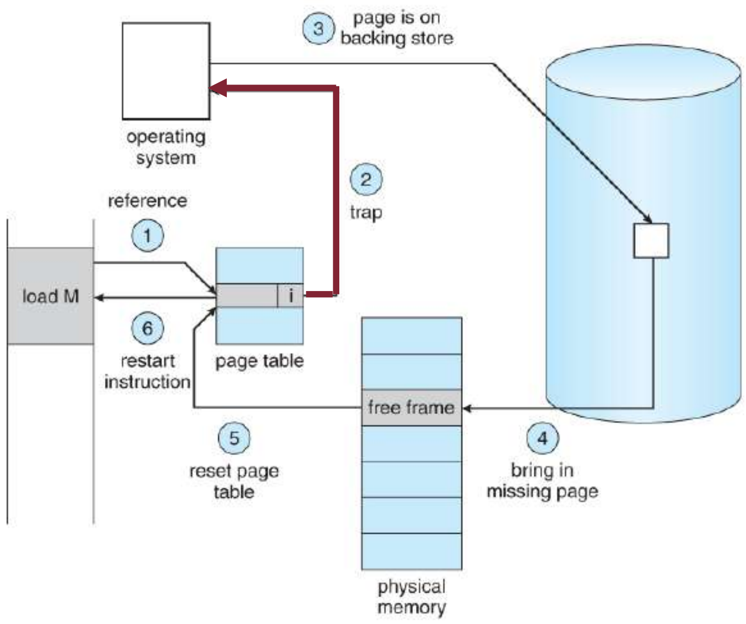

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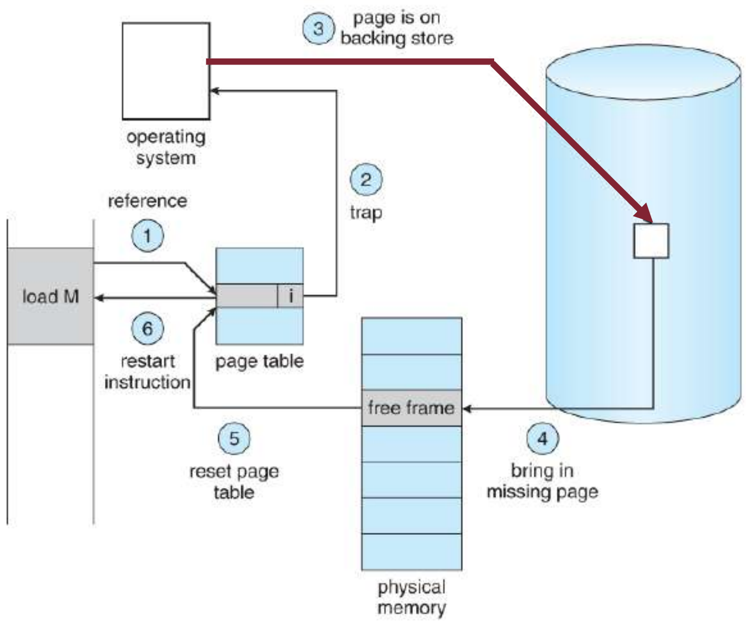

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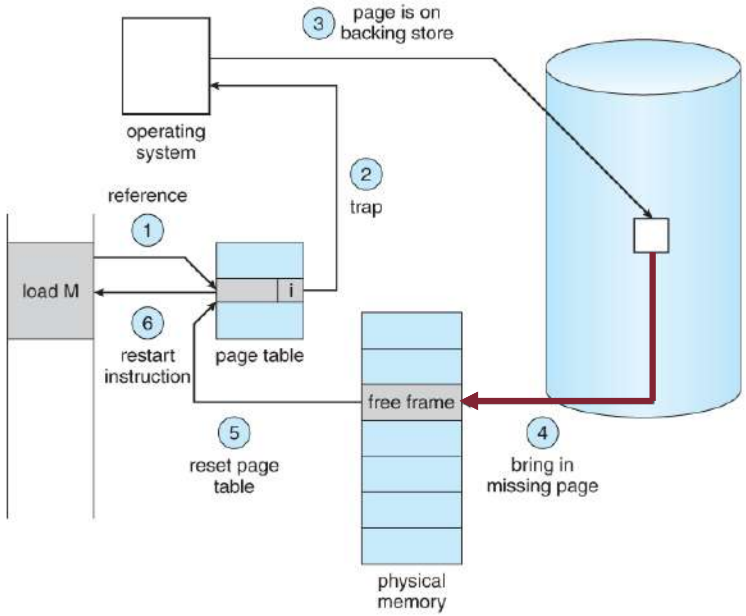

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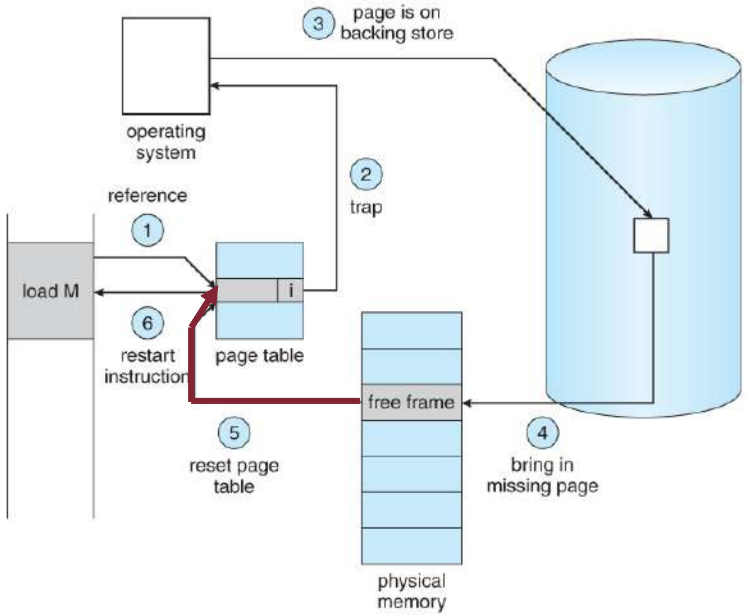

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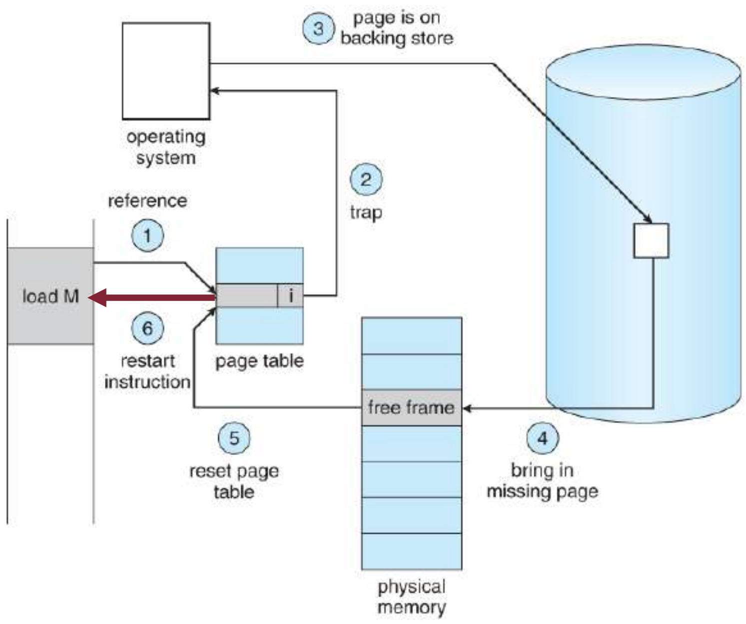

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5. When the I/O operation is complete, the process's page table is updated with the new frame number, and the bit is set to valid
6. The current process gets interrupted and the instruction that caused the page fault must be restarted from the beginning

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- If we get a TLB hit but the frame is not actually in main memory, we have to go fetch the page from disk anyway!
- TLB hit means the requested page entry is in the cache **and** the referenced frame is also in memory

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- If the requested page is not in the cache (TLB miss) **and it is not even in memory** (i.e., it is on disk):
  - The OS picks a TLB entry to replace and fills it with the new entry as follows
    - invalidates the TLB entry
    - performs page fault trap operations
    - updates the TLB entry
    - restarts the faulting instruction

Page Fault Handling: Faulty Address

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- How does the OS figure out which page generated the fault?
- Architecture-dependent:
  - x86: hardware saves the virtual address that caused the fault (CR2 register)
  - On some platforms, OS gets only address of faulting instruction, must simulate the instruction and try every address to find the one that generated the fault

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- To restart (from scratch) a faulty instruction the OS needs hardware support for saving:
  - The faulting instruction
  - The CPU state

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- idempotent → just restart the faulting instruction (hardware saves instruction address during page fault)
- non-idempotent → much more difficult to restart
  - MOV [%R1], +(%R2) → increment the value of R2 and store it to memory address in R1
  - What if memory address [%R1] causes the page fault?
  - Cannot naively redo the instruction from scratch, otherwise R2 gets incremented twice

Page Fault Handling: Transparency

- Even harder when using instructions that are not easily undoable
  - E.g., instructions that are used to move a block of memory at once
  - The block may span multiple pages: some of them can be in memory while some others not
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How to unwind those complicated side-effects?

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Ensure all the addresses within the block to be moved are in memory before executing the instruction

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  - **spatial** → if a process accesses an item in memory, it will tend to reference a close item again soon

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$$t_{MA} = \text{physical memory access time}$$
$$t_{FAULT} = \text{time to handle a page fault}$$
$$p \in [0, 1] = \text{probability of page fault}$$
$$t_{ACCESS} = \text{effective time for each memory reference}$$

$$t_{ACCESS} = (1 - p) * t_{MA} + p * t_{FAULT}$$

Let's assume: $t_{MA} = 100$ nsec and $t_{FAULT} = 20$ msec $= 20,000,000$ nsec

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This heavily depends on p!

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The access time increases from just 100 nsec up to ~20.1 microsec

200 times slowdown factor

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$$1.1 * 100 = 100 - 100p + 20,000,000p =$$
$$19,999,900p = 110 - 100 =$$

To achieve that goal, we can tolerate at most 1 page fault every about 2 million accesses!

$$p = \frac{10}{19,999,900} = \frac{1}{1,999,990} \boxed{\approx 0,0000005 = 5 * 10^{-7}}$$

Virtual Memory: Performance Example

More generally, given t_{MA}, t_{FAULT}, and a threshold $\varepsilon > 0$ if we want to find p s.t.:

$$t_{ACCESS} = (1 + \epsilon) * t_{MA}$$

We substitute t_{ACCESS} and solve for p the resulting equation:

$$(1 - p) * t_{MA} + p * t_{FAULT} = (1 + \epsilon) * t_{MA} =$$
$$t_{MA} - p * t_{MA} + p * t_{FAULT} = t_{MA} + \epsilon * t_{MA}$$
$$p(t_{FAULT} - t_{MA}) = \epsilon * t_{MA} =$$

$$\boxed{p = \frac{\epsilon * t_{MA}}{t_{FAULT} - t_{MA}}}$$

Virtual Memory: Considerations

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- So far, we have described how the OS (with the support of HW) manages page faults
- Still, the OS has to answer 2 fundamental questions:
  - When to load process' pages into main memory (**page fetching**)
  - Which page to remove from memory if this gets filled (**page replacement**)

Page Fetching Goals

- The overall goal is still to make physical memory look larger than it is
- Exploiting the locality reference of programs
- Keep in memory only those pages that is being used
- Keep on disk those pages that are unused
- Ideally, producing a memory system with the performance of main memory and the cost/capacity of disk!

Page Fetching Strategies

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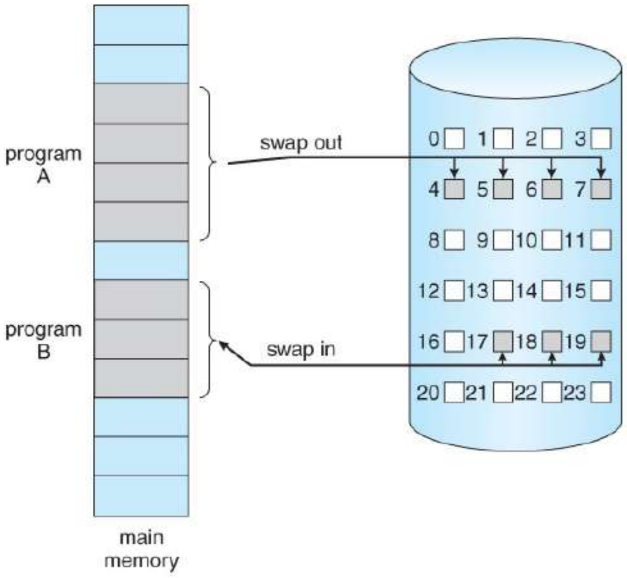
Most modern OSs use demand fetching

(Pure) Demand Paging

- When a process starts up, **none** of its pages are loaded
- Rather, a page is swapped in only when the process references it (upon a page fault)
- This is termed a **lazy swapper** or **pager**
- Opposite of loading all the pages at process startup!

Prefetching



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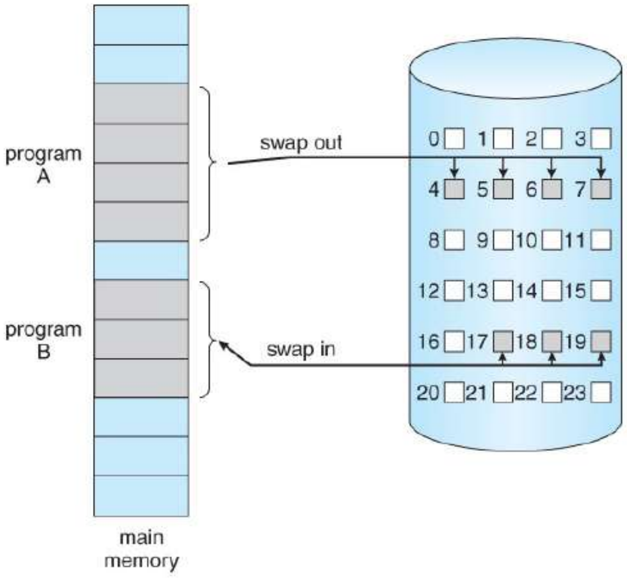

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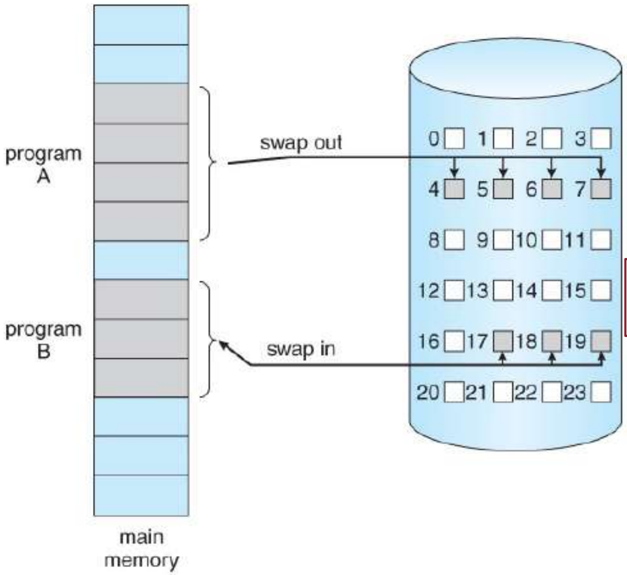

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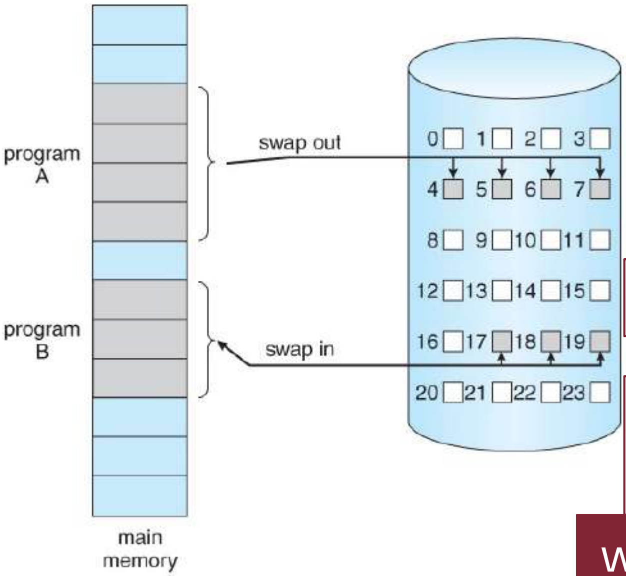

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Possible approach: upon page fault, load many pages instead of only the faulty one

works if program accesses memory sequentially

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- On Linux there exists a dedicated **contiguous swap partition** (on disk)
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- On Mac, instead, swap space is part of the file system (**swap files**) yet subject to fragmentation

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- The pages for a process are divided into **2 groups**:
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  - Data (initialized/uninitialized)
- Based on which kind of page is removed, different optimizations may apply upon page swap-out

Swap Out Optimizations

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  - Code content does not change!
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- Code page (read-only):
  - Code content does not change!
  - Just remove and load it back from executable file stored on disk
- Data page:
  - Data content does actually change!
  - Save it to the swap area/swap file, so that no changes are lost when it will be loaded in the future

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- Combined to paging, uses secondary storage (i.e., disks) as backup for unallocated frames
- Whenever a process requests a page, this could either be in main memory or on disk (**page fault**)
- Ideally, the OS should keep in main memory each process' **working set** to lower the chance of a page fault