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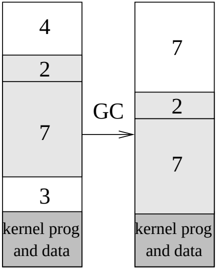
The OS stops all running processes (i.e., stops scheduling processes); shifts their code and data around to close up the gaps; then lets the processes continue (i.e., starts scheduling again)

Memory

Physical Memory



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- the pause while things are moved is bad for interactive and real-time behaviour
- the erratic nature of when GCs are needed leads to unpredictable behaviour from the OS
- given the right kind of hardware support, better solutions completely avoiding the need for GC are possible

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Exercise Reflect on whether it would be a good idea to implement an OS in Java (Hint: nobody serious does so!)

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Better is to *preempt* memory: take it away from one process and give it to another

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Physical Memory

Remember that preemption takes a resource away from a process and returns it later in the same state

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Even though that memory has been used by some other process and written its own data or code into it

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Physical Memory

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This is a tradeoff of speed (time spent copying to and from disk) against process size (memory allocation)

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Physical Memory

Swapping

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This is where one or more other processes are selected by the OS and they are copied out to disk to make space

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When a process makes a request for an allocation that the OS cannot immediately satisfy the OS can try *swapping*

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The best choice is usually a blocked process that couldn’t have been run right now anyway

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Data is retrieved from where it was saved, while code is copied back from the original program file—this is why some OS's don't like you deleting programs while they are running

Memory

Physical Memory

This differs from overlays in that it is the OS that does the swapping, not the process doing it to itself

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Something that often is forgotten these days!

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Physical Memory

The OS will take swapping into account when scheduling

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There is a clear interaction of scheduling and swapping processes: each will affect the other

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Physical Memory

Variants:

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- Only one process ever in memory, swapped as a whole when scheduled: simple, and used on very early systems
- Swapping of processes: only marginally harder, and fits well with a partitioning system and fits well with scheduling
- Swapping *parts* of a process: not so easy as the OS has to work harder to determine which parts of a process's code or data might not be needed in the near future

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Virtual Memory

Paging

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Virtual Memory

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This is all augmented by the idea of *paging*

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To describe paging we must first go back to pages

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Hardware is designed so copying pages in and out of memory from disk is as efficient as possible

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Virtual Memory

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A virtual address is a per-process fictional address

The user process sees only the virtual addresses: the system will translate them on the fly into physical addresses

Memory

Virtual Memory

The OS has tables, one per process, called *page tables*, that contains the virtual-physical address mappings for each page in each process

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Under the entry for page 3 in the page table for this process we might find the number 7, meaning physical page 7

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So virtual address 12298 **in this process** refers to physical byte $7 \times 4096 + 10 = 28682$

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In another process, virtual page 3 could be mapped to physical page 42

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We use pages, of course, to make this translation manageable

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Virtual Memory

The table only contains entries for pages that are actually in use by that process: this keeps the tables to a reasonable size

V page	P page
3	7
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5	121
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etc.	

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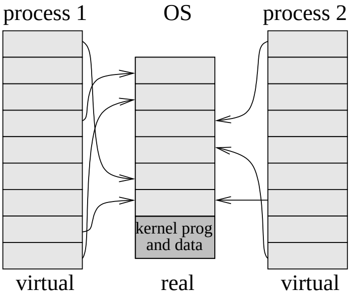
Note: though still called “tables”, in modern OSs they are likely to be more sophisticated datastructures, such as trees

Memory

Virtual Memory



Every process gets its own complete and separate address space, mapped into the physical address space

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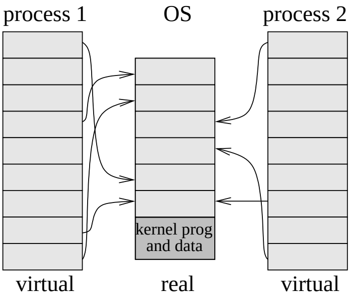

Every process gets its own complete and separate address space, mapped into the physical address space

Even for the same userid: this is usually what you want, protection of one process from another

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Virtual Memory

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This is clearly not sensible as it would be very slow

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Virtual Memory

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The TLB maintains its own copy of *a few* of the virtual-physical mappings from the page table of the current process and can translate very quickly between them

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Virtual Memory

To repeat that: the table in the TLB is a *small subset* of the OS's page table mappings of the current process

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Only a small subset as TLB memory is very limited in size since it is very expensive to make memory that runs fast enough to make this mechanism practical: it contains perhaps just a few dozens of the virtual to physical mappings

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Note (again): the TLB contains copies of the page *mappings*, not pages

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The Intel Nehalem architecture has a 64 entry data TLB (and a 512 entry level 2 TLB); and a separate 64 entry instruction TLB

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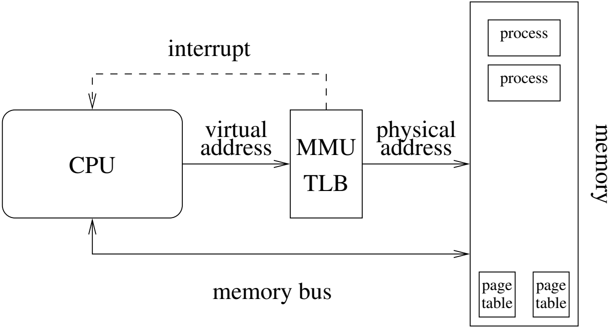
Note that 64 entries typically corresponds to an area of $64 \times 4\text{k page} = 256\text{k}$ bytes, so while not huge, this isn't so bad as it might seem as first

Memory

Virtual Memory



The MMU and TLB are often physically part of the CPU package, for speed of access

Memory

Virtual Memory

When presented with an address from the CPU the TLB first looks the virtual page up in its table. If it is there is—a *TLB hit*—the memory access goes ahead at full speed using the physical address computed from the real page index found there

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There are two popular techniques used

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Virtual Memory

In a *hardware managed* TLB, the CPU/TLB itself stops what it is doing and searches for the page number in the page table (in memory) for the current process: this is called a *page walk*

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If it finds it, it installs it in the TLB table and carries on with the memory access

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If it finds it, it installs it in the TLB table and carries on with the memory access

The OS is not involved in the page walk, it is purely hardware

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Virtual Memory

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The OS then takes over and has to do the page walk

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Virtual Memory

This deals with the case of when the requested page has already been allocated by the OS to the current process, so there is an entry in the page table for the page walk to find

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In either software or hardware case, if the requested virtual page is not yet allocated by the OS to the process and so not in its page table, the OS needs to allocate a page

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Virtual Memory

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(When the process is rescheduled) the memory access can then proceed

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Of course, the OS may choose not to allocate a page and it could then send a segmentation violation signal to the process

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Terminology warning: a TLB miss when the page is already allocated and indexed in the page table is sometimes called a *minor* or *soft* page fault; while a miss on an unallocated page is a *major* or *hard* page fault

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Virtual Memory

Speed relies crucially on the TLB containing a good proportion of the addresses currently being used: if a process writes wildly all over memory we are guaranteed to get TLB misses and slow memory access: lots of TLB misses and page walks or page fault interrupts

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After a while, the TLB settles down, caching the indices of the pages the process is using, the *working set*

Memory

Virtual Memory

Note that a page fault can cost a lot of time

Register access	1 cycle
(L1 memory cache hit	≈ 2 cycles)
(L3 memory cache hit	≈ 50 cycles)
Main memory access	≈ 200 cycles
TLB miss (page in memory)	$\approx 10,000$ cycles
Page fault (page on disk)	$\approx 1,000,000,000$ cycles

These are very rough figures and are the combined overhead of OS operations and memory architecture