



## Memory management

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## Memory (ideally)

- Ideally...
  - Extremely fast (faster than the CPU in executing an instruction)
  - Abundantly large
  - Dirt cheap

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## Memory (for real)

Typical access time		Size
1 nsec	Registers	< 1K
2 nsec	Cache	~ 1M
10 nsec	Main memory	~ 1-4G
10 msec	Magnetic disk	~ 5-100G
100 sec	Magnetic tape	> 20G

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## Memory cntd.

- Registers: typical 32 in a 32 bit CPU
- Cache: divided into cache lines (64 bytes each)
  - Cache hit – no main memory access, no bus involvement
  - Cache miss – costly
- Main memory
- Disk (multiple plates, heads, arms)
  - Logical structure: sectors, tracks, cylinders
- Magnetic tape: backup, cheap, removable

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## OS management of memory

- The part of the OS that handles the management of the memory is called:
  - Surprise, surprise: memory manager!
- Various levels of complicity
  - Depending on the type of OS
- E.g. mono-programming, multiprogramming, and so forth

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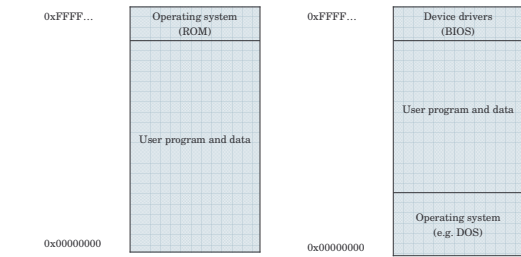
## Specifics of memory management

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## Mono-programming

- No swapping, a few options...

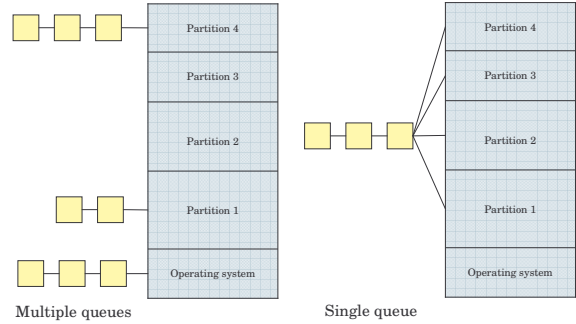


Some embedded systems (e.g. PALM)

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## Multiprogramming with fixed partitions



Multiple queues

Single queue

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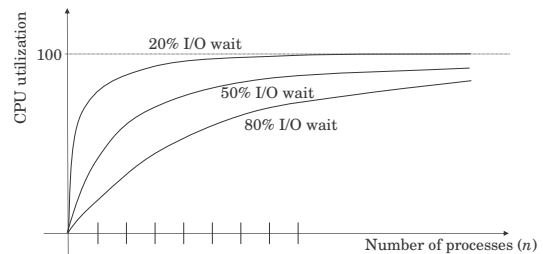
## Modeling multiprogramming

- Each process spends a fraction  $p$  of its time waiting for I/O to complete
- If we have  $n$  processes, the probability that all of them are simultaneously waiting for I/O is:  $p^n$
- CPU utilization is thus:  $1 - p^n$

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## CPU utilization



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## Example

- A system has 32Mbyte of RAM, OS takes 16Mbytes
- Each process occupies on average 4Mbytes (4 processes simultaneously in memory) and has 20% utilization time (80% blocked on I/O)
- CPU utilization approx 60%
- Buying 16M additional RAM will allow to increase multiprogramming to 8, CPU utilization will get to about 83%
- Another 16M will get from 83 to 93%, depending on memory price we can make an informed choice

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## Relocation and protection

- Relocation when loading the code. The linker stores some additional information which is used at load time to relocate (rewrite) every single instruction referencing memory.
- HW support through the use of base and limit registers
- Partial support, only base but no limit

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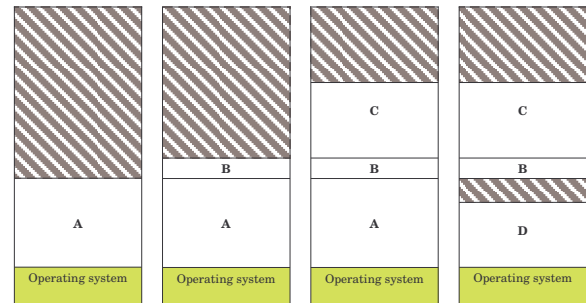
## Swapping and virtual memory

- Swapping: whole process data/code in memory when running
- Virtual memory: only part of the data/code in memory

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## Swapping



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## Swapping cntd.

- Memory compaction (remove holes)
- If processes could grow (by allocating memory on a heap like in many programming languages), how does the OS take care of it?
- Many different solutions: e.g. reserve room for growth or swap the process out and relocate it to a bigger memory partition, etc.

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## How is it implemented?

- Bitmaps
  - Memory is divided into allocation units
  - Each bit of the bitmap represents a unit ( $1 = \text{used}$ ,  $0 = \text{free}$ )
  - The size of allocation unit is an important design issue (less unused memory, bigger bitmap)
  - Search bitmaps when loading in a new process for  $k$  consecutive free allocation units

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## How is it implemented?

- Linked lists
  - A linked list may store:
    - Information about a process or a hole
    - Address where it starts
    - Length
    - Pointer to the next element
  - Merging operation (e.g. two consecutive holes)
  - Process' table entry will contain a pointer to the element in the list relative to it

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## Different algorithms

- First fit: the first hole that fits the process is used (hole is broken down into two pieces)
- Next fit: it doesn't start from the beginning, simply restart from where it left the previous search
- Best fit: search the whole list for the smallest hole that fits
- Performance: best fit creates a lot of fragmentation in practice, first fit tends to leave larger holes (less fragmentation)

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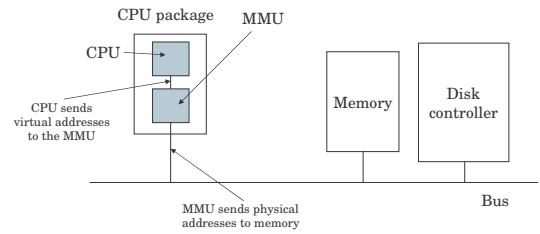
## Virtual memory

- Once upon a time there was the “overlay”
- In practice programmer divided the program (by hand) into many parts that could be swapped in and out from disk
- Why don't we delegate this function to the machine itself?
- Virtual memory was born!

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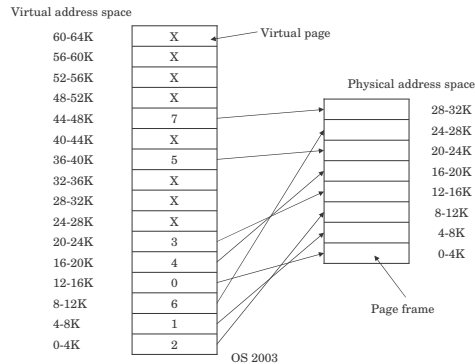
## Paging



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## MMU's internals



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## Example

- `MOV REG,0`
  - CPU sends request for address 0
  - MMU looks for 0 and sees that the page containing virtual address 0 is at frame 2
  - It thus adds 8192 (frame 2 start address)
  - MMU finally sends 8192 on the bus

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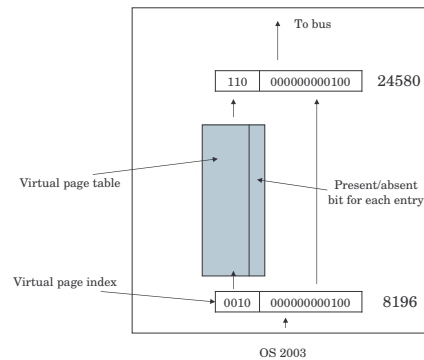
## Since memory is finite

- Present/absent bit in the virtual page table (the X's in the picture)
- Same as before:
  - `MOV REG,32780` what happens?
- Page fault, the page is not in physical memory but rather on the disk
- The OS needs to evict a page from main memory and to replace it with the missing page, to update the MMU's tables, and to restart the instruction that caused the fault

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## Operation of the MMU



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## Is it a simple task?

- The page table can be extremely large
  - 32bits systems with a 4K-page size has more than a million pages
  - 64bits  $2^{52}$  pages? Gosh!
- The mapping must be fast (VERY fast)
  - Every memory reference requires a virtual to physical conversion, a single instruction might have >1 reference

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## Where's the page table?

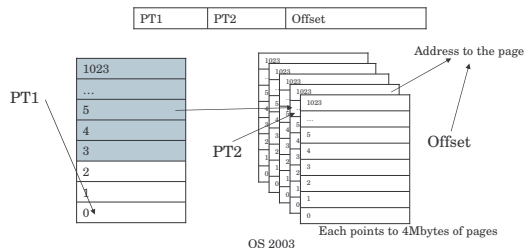
- Within the MMU
  - Every context switch requires loading the whole page table into the MMU registers, good because it doesn't require more memory reference afterwards
- Memory
  - A single pointer to the table needs to be reloaded in a context switch, more memory references (to the page table) are required for mapping each memory reference

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## Multi-level page tables

- Example: 32 bits could be partitioned as a 10-bit pointer to level 1 table, 10-bit to level 2 and 12-bit offset fields



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## About the page table

- Present/absent: in memory?
- Protection bits: e.g. read/write/execute
- Modified: whether any address has been changed, rewrite to disk is required before evicting the page
- Referenced: used by the OS to decide which page to evict
- Caching: may be used to avoid caching pages required for I/O

Caching disabled	Referenced	Modified	Protection	Present/Absent	Page frame #
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## TLBs

- Translation Lookaside Buffers
  - Page tables in memory require additional memory accesses, unpractical
  - Most programs tend to make a large number of references to a small number of pages
  - Use something called a TLB or Associative Memory

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## What does the TLB do?

- Small number of entries, within the MMU, fast
- Association (direct) of virtual page to page frame
- Parallel compare over the whole table, if virtual page is not there, do the normal lookup (over memory) and then evict an entry and replace with the new one

Valid	Virtual page	Modified	Protection	Page frame
1	140	1	RW	31
1	20	0	RX	38
1	860	1	RW	14

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## Additional issues

- Software TLB management
  - Some microprocessors don't have the TLB completely in HW, the handling of the TLB fault is done in SW (i.e. the OS does it)
- Inverted Page Tables
  - Imagine a 64 bit computer: page tables would be too big
  - Inverted table, one per page frame rather than per page
  - It requires a search (potentially slow), needs a good implementation (fast) and a possibly large TLB