Operating Systems

Memory Management

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Agenda

- Memory Management
- Real Mode
- Protected Mode and Virtual Memory
- Page Replacement Strategies

Agenda

Memory Management

- Essential function of OS
- Required for ...
  - allocating memory to programs at their request
  - Freeing memory which are allocated to programs once they are not needed any longer
- Three concepts for memory management:
  1. **Static partitioning**
  2. **Dynamic partitioning**
  3. **Buddy memory allocation**

Source: Andries L Steenkamp (Wikipedia), CC-BY-SA-4.0

Your Ideas

How would you implement a memory management?

Main Problem: Fragmentation

- When allocating memory for processes the memory may become fragmented, i.e., get *holes*
- Two types of fragmentation can happen:
  - **internal fragmentation:**
    The allocated chunk of memory is not entirely used
  - **external fragmentation:**
    There is unused (not allocated) memory between the allocated chunks of memory

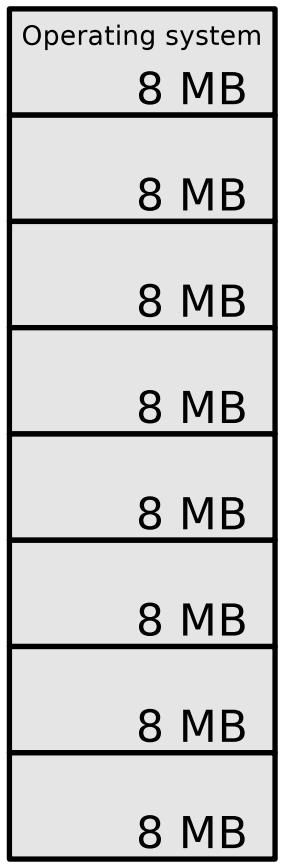
Concept 1: Static Partitioning

- The main memory is split into partitions
- Partitions can be of equal size or of different sizes
- **Drawbacks**:
  - **Internal fragmentation** occurs in any case $\Longrightarrow$ inefficient
    - The problem may be mitigated by partitions of different sizes
  - The number of partitions limits the number of possible processes
- Challenge:
  A process requires more memory than any partition provides
  $\Rightarrow$ The process must be implemented in a way that only a part of its program code is stored inside the main memory
  - When program code (modules) are loaded into the main memory *Overlay* occurs
    $\Longrightarrow$ modules and data may become overwritten

IBM OS/360 MFT in the 1960s implemented static partitioning

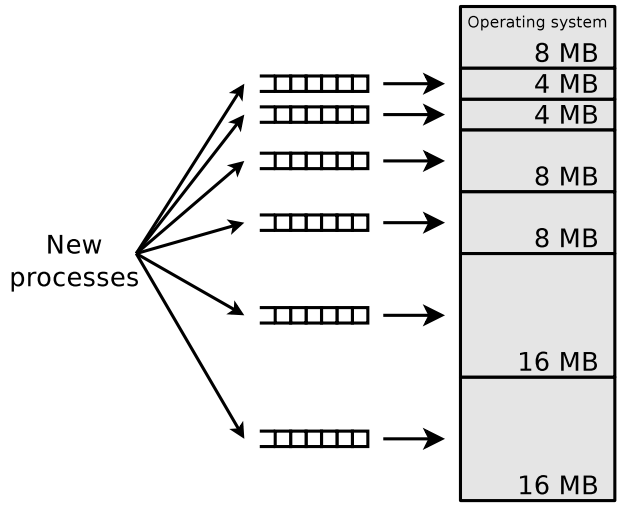
Static Partitioning: Partitions of Equal Size

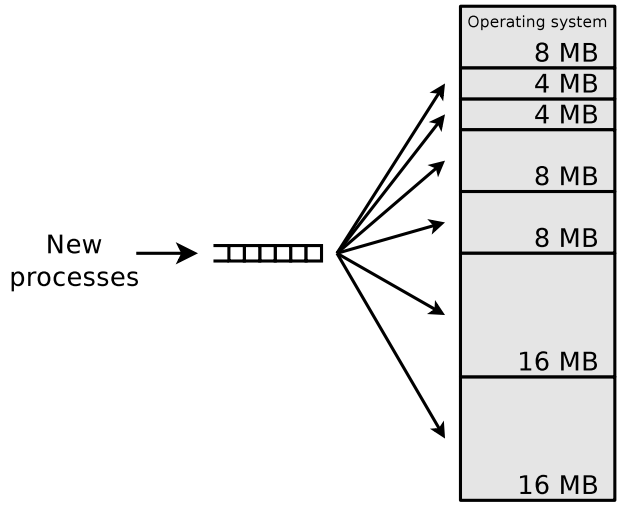
- If partitions of equal size are used, it does not matter which free partition is allocated to a process
- If no partition is free, a process from main memory need to be replaced
  - The decision of which process will be replaced depends on the $\longrightarrow$ **replacement** method used



Static Partitioning: Partitions of Different Sizes

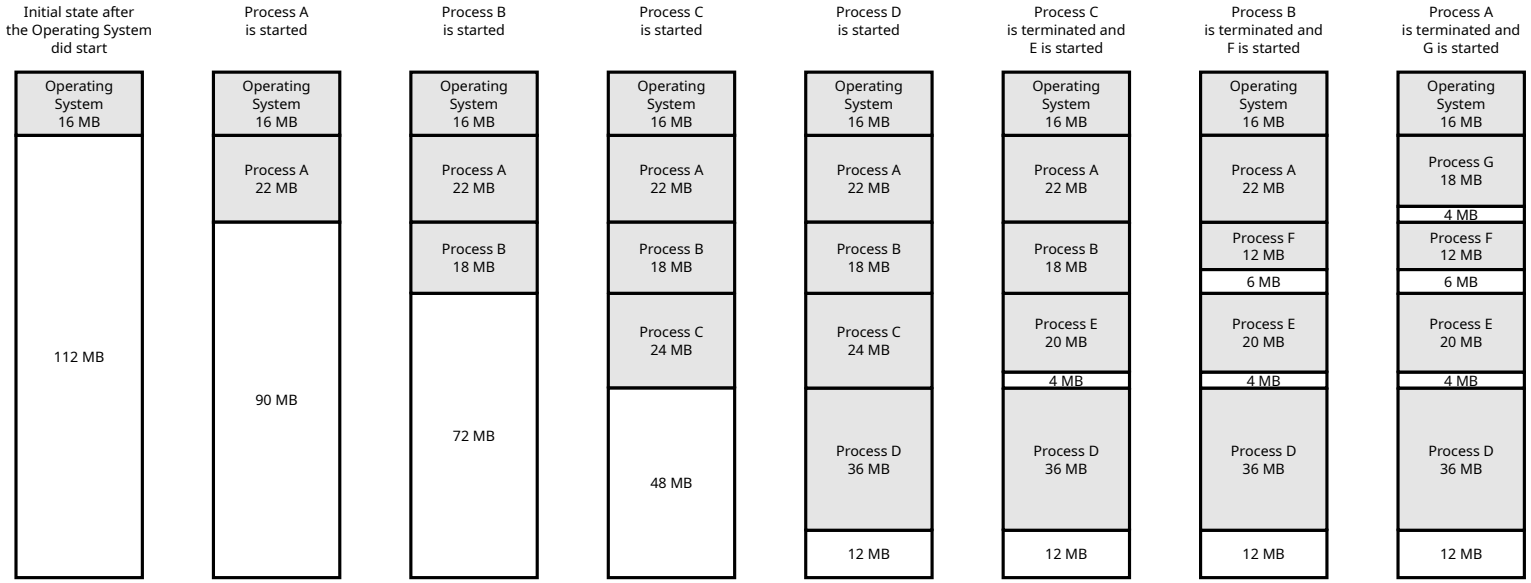
- To reduce internal fragmentation, partitions of different sizes may be used
- Processes should get a partition allocated, which fits as precise as possible
- Two possible ways exist to allocate partitions to processes:
  1. A separate process queue for each partition
     - **Drawback**: Some partitions may never used
  2. A single queue for all partitions
     - The allocation of partitions to processes can be carried out in a flexible way
     - To changed requirements of processes can be reacted quickly





Concept 2: Dynamic Partitioning

- Each process gets a partition of main memory with the exact required size allocated



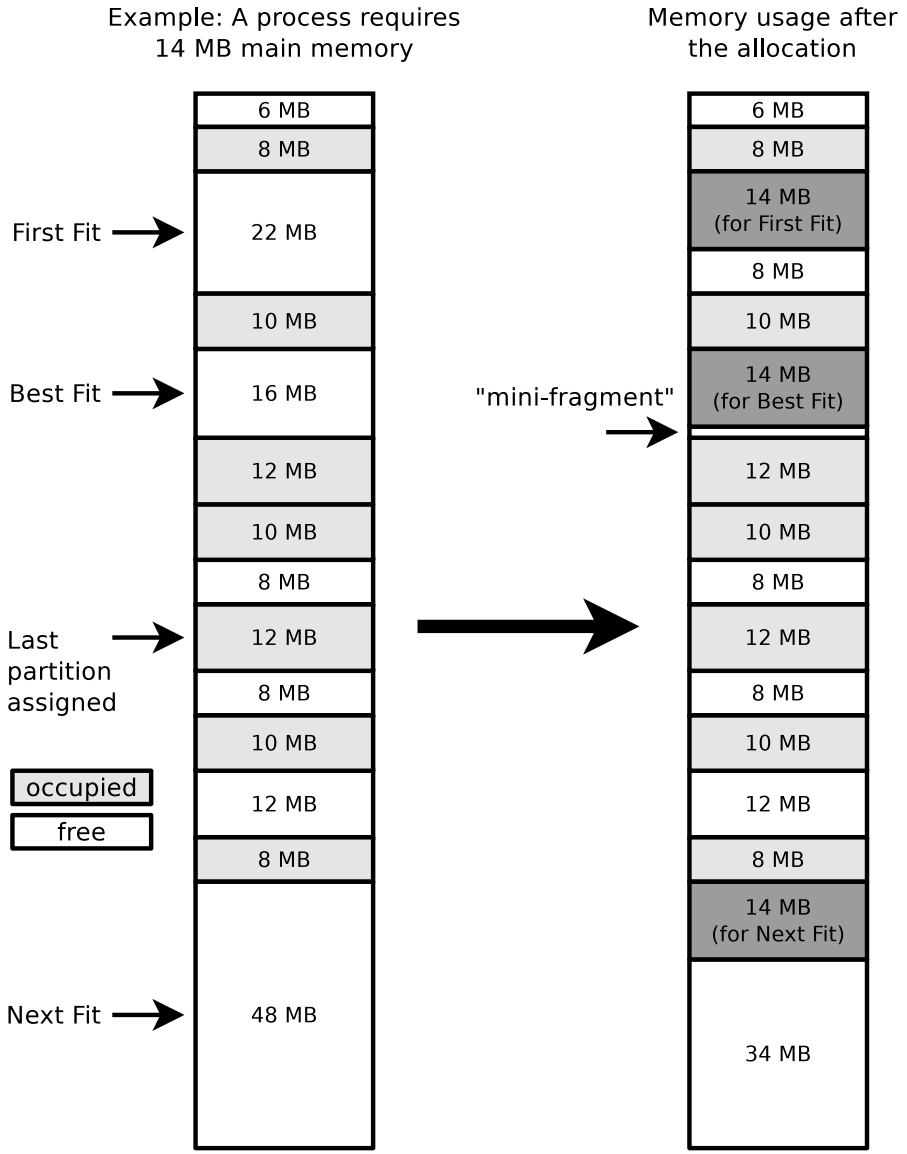
- **External fragmentation** occurs in any case $\Longrightarrow$ inefficient
  - Possible solution: *Defragmentation*
    - Requirement: Relocation of memory blocks must be supported
    - References in processes must not become invalid by relocating partitions

IBM OS/360 MVT in the 1960s implemented dynamic partitioning

How to find a free Block?

Implementation Concepts for Dynamic Partitioning

- First Fit
  - Searches for a free block, starting from the beginning of the address space
  - Quick method
- Next Fit
  - Searches for a free block, starting from the latest allocation
  - Fragments quickly the large area of free space at the end of the address space
- Best Fit
  - Searches for the free block, which fits best
  - Produces many mini-fragments and is slow



Concept 3: Buddy Memory Allocation

- Originally invented by *Harry Markowitz* in 1965 (according to *Donald Knuth*)
- **Main idea:**
  - Recursively split memory into halfes
  - Each memory block has its buddy, a block of equal size
  - If two buddies are free, they are merged again

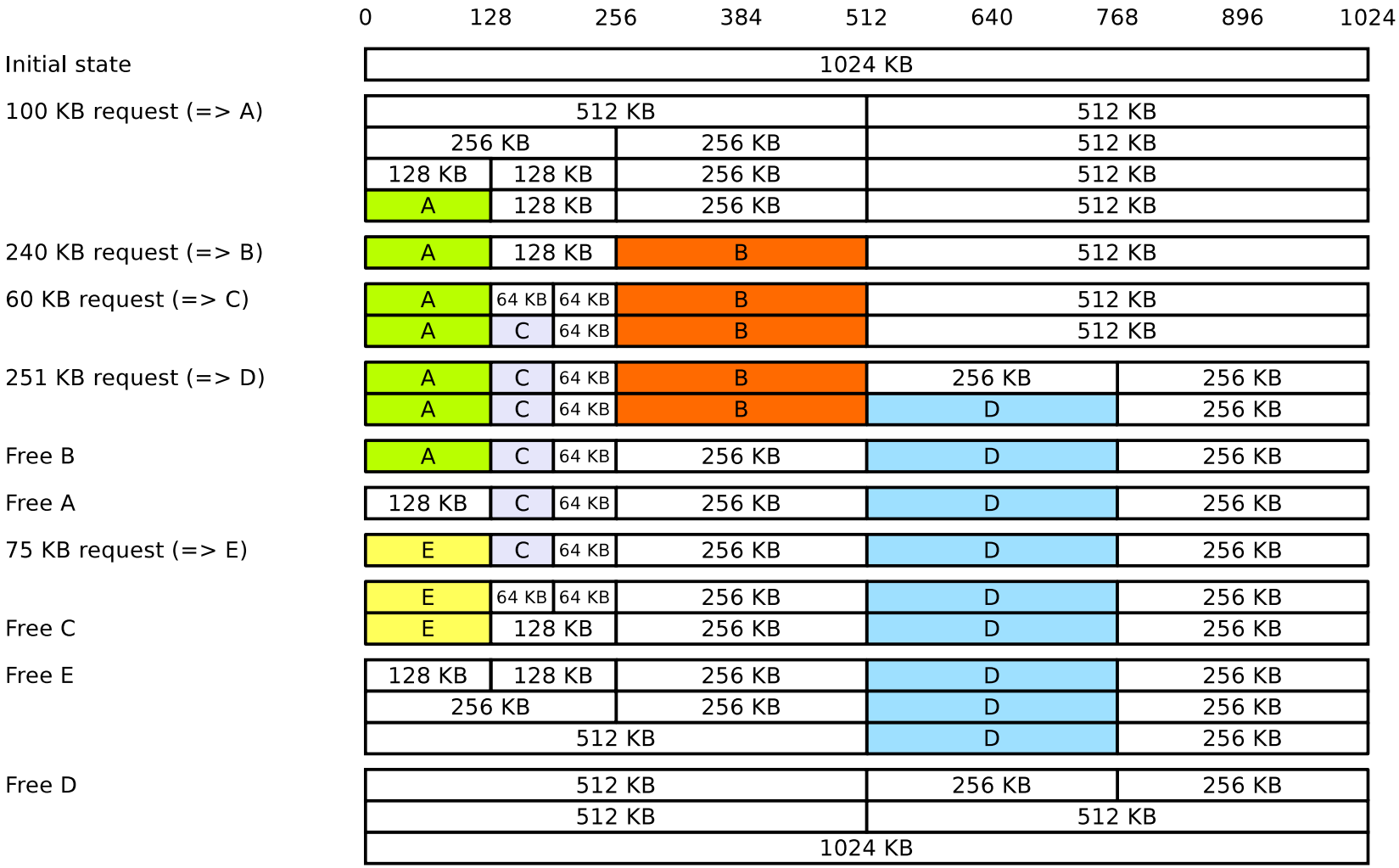
Buddy memory management in practice

- The Linux kernel implements a variant of the buddy memory management for the page allocation
- The operating system maintains for each possible block size a list of free blocks
- `https://www.kernel.org/doc/gorman/html/understand/understand009.html`

Buddy Memory Allocation: Algorithm

- Initially, a single block covers the entire memory
- Each memory request is rounded up to the next higher power of two and a matching free block is searched
  - If no matching block is found, a block of double the size is searched and split into halves (so-called *buddies*)
    - The first block is then allocated to the process
  - If no block of double size exists, a block of four times size is searched, etc. . .
- When memory is freed, it is checked whether the corresponding buddy is free, too
  - If yes, the buddies are merged again

Buddy Memory Allocation Example



- **Drawback:** Internal and external fragmentation

Information about the Memory Fragmentation

- The row labeled `DMA` shows the first 16 MB of the system
  - The size of the address bus of the Intel 80286 is 2^{24} => 16 MB memory can be addressed maximum
- The row labeled `DMA32` shows all memory > 16 MB and < 4 GB
  - The address bus size of 32 bit x86 CPUs is 2^{32} => 4 GB memory can be addressed
- The row labeled `Normal` shows all memory > 4 GB
  - The size of the address bus of modern computer systems is usually 36, 44 or 48 bits

Further information about the rows: `https://utcc.utoronto.ca/~cks/space/blog/linux/KernelMemoryZones`

```
$ cat  /proc/buddyinfo
Node 0, zone      DMA      1      0      0      0      0      0      0      1      2      2
Node 0, zone    DMA32  22898  13478   4609   2950    786    561    191     80     27     27     24
Node 0, zone   Normal   4700   2609   1564    860    641    277    104     46     16      9      1
```

- **column 1** $\Longrightarrow$ number of free memory chunks (buddies) of size $2^0 * PAGESIZE \Longrightarrow 4\,kB$
- **column 2** $\Longrightarrow$ number of free memory chunks (buddies) of size $2^1 * PAGESIZE \Longrightarrow 8\,kB$
- **column 3** $\Longrightarrow$ number of free memory chunks (buddies) of size $2^2 * PAGESIZE \Longrightarrow 16\,kB$
- ...
- **column 11** $\Longrightarrow$ number of free memory chunks (buddies) of size $2^{10} * PAGESIZE \Longrightarrow 4096\,kB = 4\,MB$

PAGESIZE = 4096 Bytes = 4 kB
The pagesize of a Linux system can be checked via the command: `$ getconf PAGESIZE`

Agenda

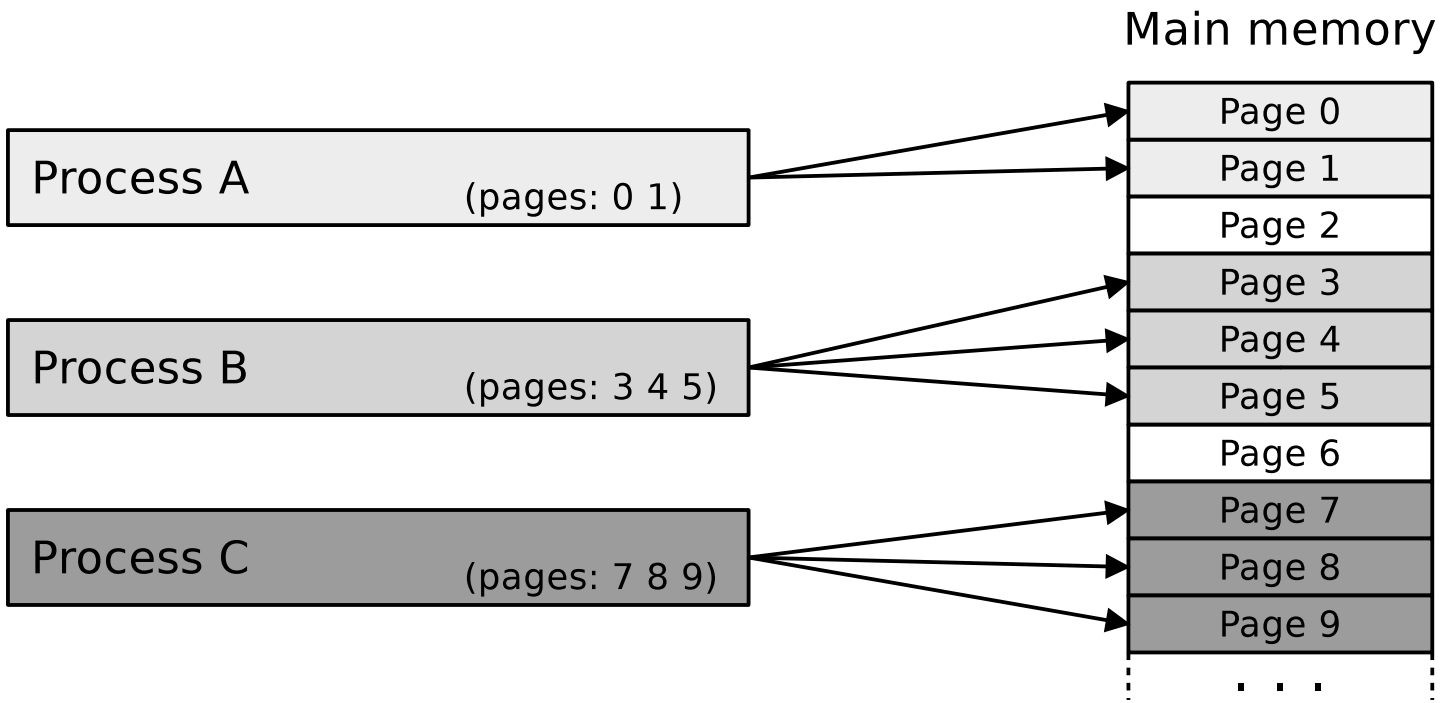
Accessing Memory

How do processes access (allocate) memory?

Recap

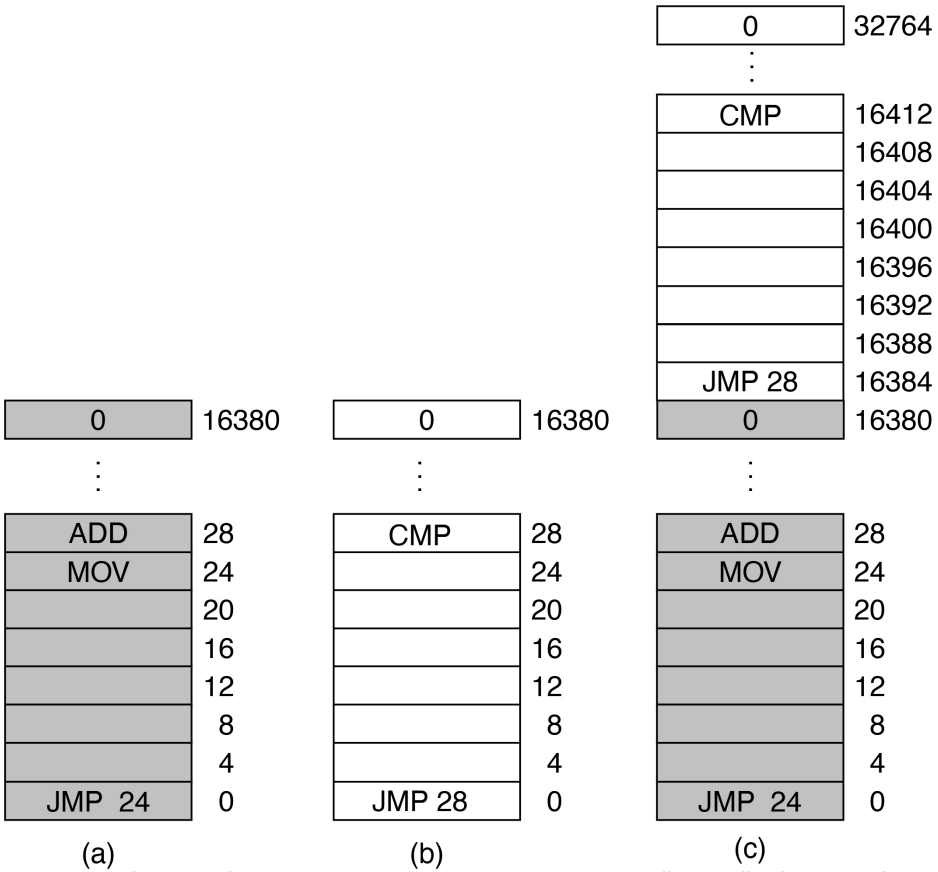
- In 16-bit architectures 2^{16} memory addresses, i.e., up to $65,536$ Bytes can be addressed
- In 32-bit architectures 2^{32} memory addresses, i.e., up to $4,294,967,296$ Bytes $= 4\,\text{GB}$ can be addressed
- In 64-bit architectures, 2^{64} memory addresses, i.e., up to $18,446,744,073,709,551,616$ Bytes $=$ 16 Exabyte can be addressed

Idea: Direct Memory Access



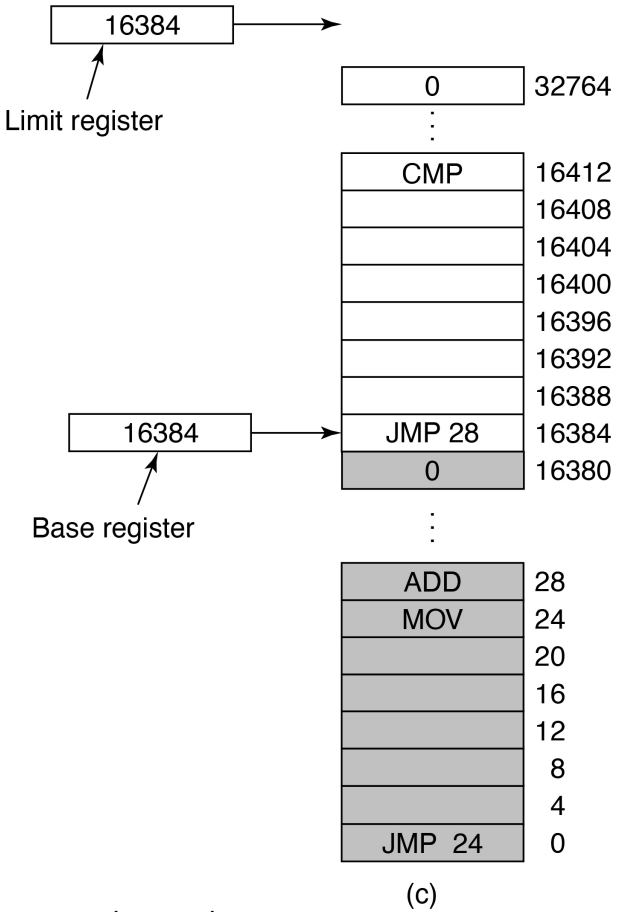
- Most obvious idea: Direct memory access by the processes
  $\Longrightarrow$ **Real Mode (Real Address Mode)**
- Operating mode of x86-compatible CPUs
- No memory protection!
  - Each process can access the entire memory, which can be addressed
    - Not ideal for general-purpose multitasking OS

Relocation Problem



- Two problems occur when processes access physical memory addresses
  - One process can overwrite data from another process
  - Access (e.g., jumps) to absolute addresses require knowledge about the position in memory

Base and Limit Register



(c)

- Base and limit registers can be used for separating the address spaces for processes
  - The base register contains the physical address of the program start
  - The limit register contains its length

Real Mode (Real Address Mode)

- A maximum of 1 MB main memory can be addressed
  - Maximum main memory of an Intel 8086
  - **Reason:** The address bus of the 8088 contains only 20 lines
    - 20 lines $\Rightarrow$ 20 bit memory addresses $\Rightarrow$ $2^{20} \approx 1$ MB memory can be addressed by the CPU
  - Only the first 640 kB (lower memory) can be used by the operating system (MS-DOS) and the applications
    - The remaining 384 kB (upper memory) contain the BIOS and *add-on* devices like the graphic card
- The term *real mode* was introduced with the Intel 80286
  - In real mode, a CPU accesses the main memory equal to a 8086
  - Each x86-compatible CPU starts in real mode

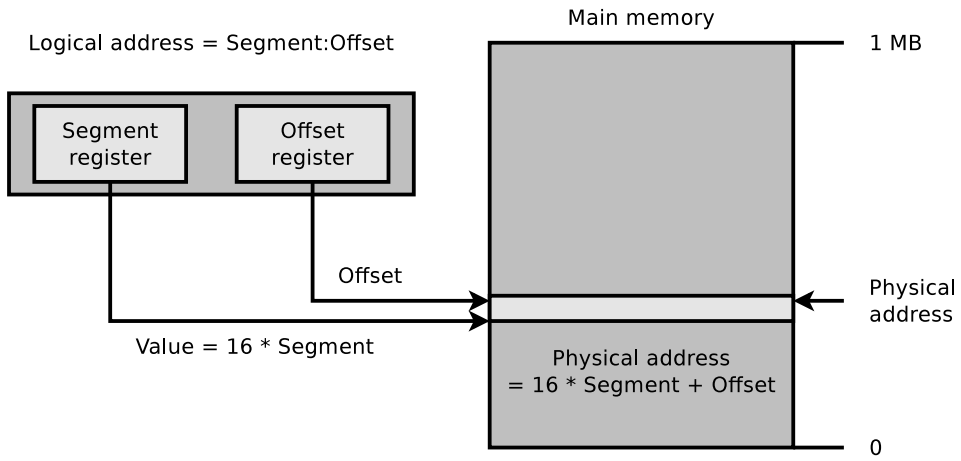
https://wiki.osdev.org/UEFI

- On a legacy system with a BIOS firmware, after the BIOS has done the system initialization (memory controller configuration, PCI bus configuration, graphics card initialization, etc.), the Real Mode ist started. The bootloader or the operating system has to switch to protected mode (paging)
- On a system with an UEFI firmware (Unified Extensible Firmware Interface), the firmware does all these initialization steps and switches into protected mode (paging)

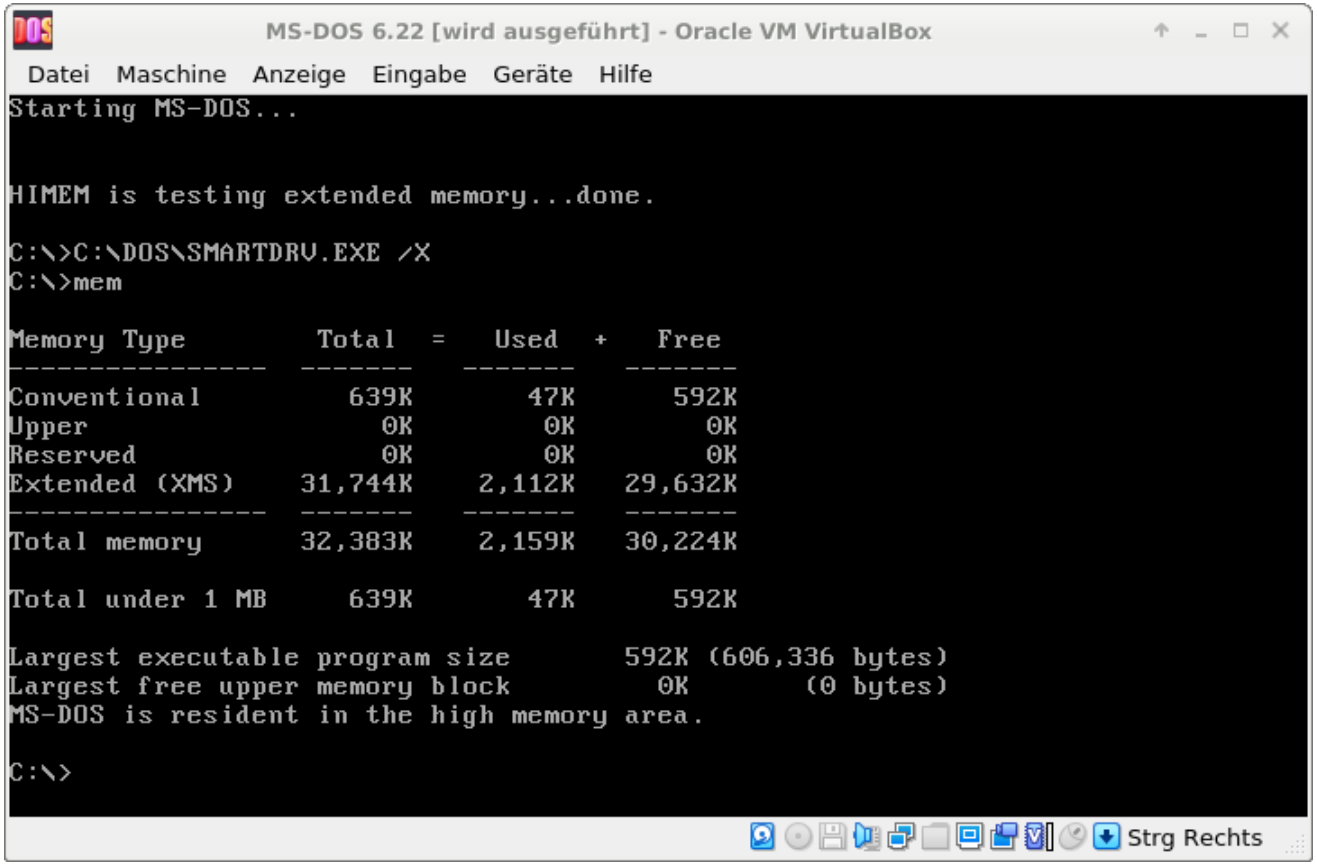
Real Mode – Addressing

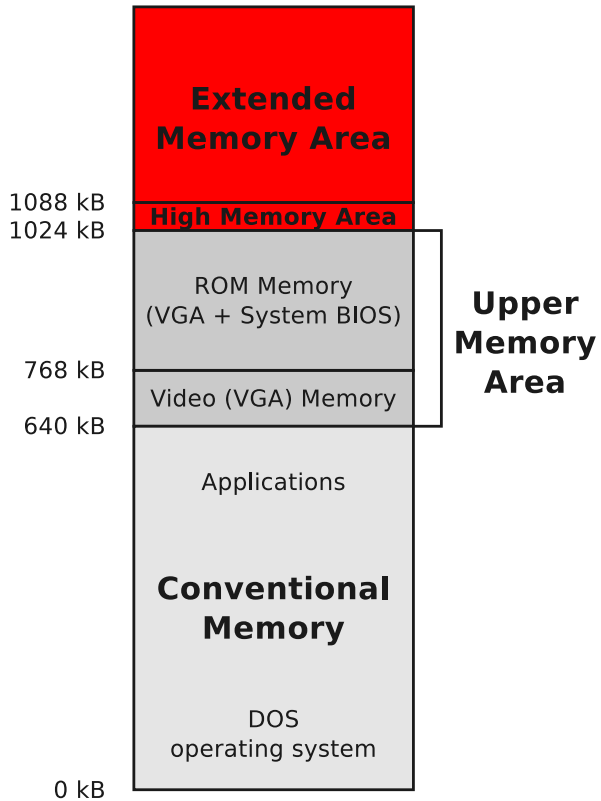
- The main memory is split into **segments** of equal size
  - The memory address length is 16 Bits
  - The size of each segment is 64 kBytes ($= 2^{16} = 65,536$ Bytes)
- Main memory addressing is implemented via segment and offset
  - Two 16 bits long values, which are separated by a colon `Segment:Offset`
  - Segment and offset are stored in the two 16-bit large registers segment register (= base address register) and offset register (= index register)

- The segment register stores the segments number
- The offset register points to an address between 0 and 2^{16} (=65,536), relative to the address in the segment register



Real Mode in MS-DOS

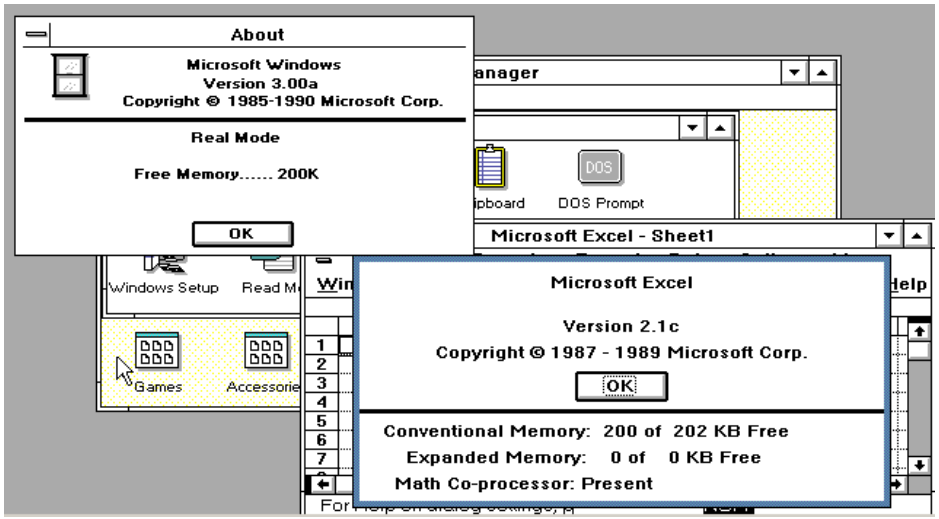


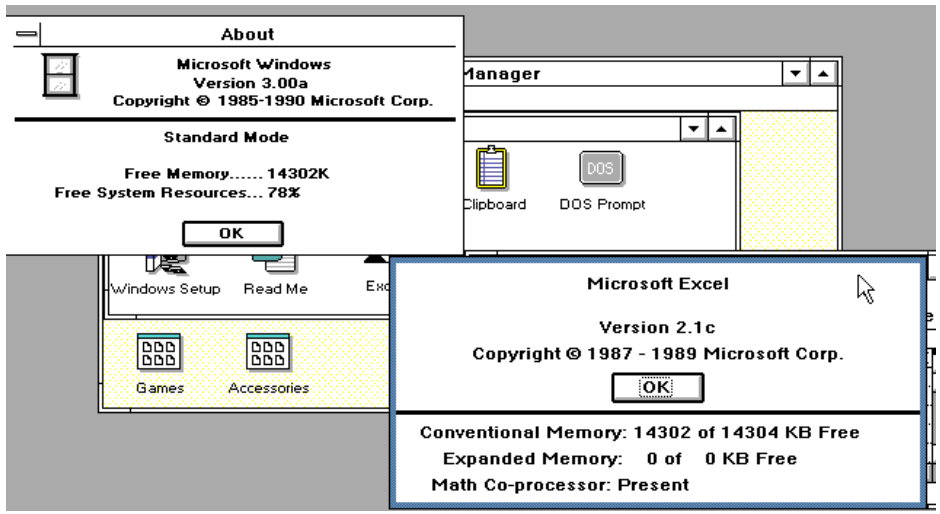


- Real mode is the default mode of MS-DOS and compatible operating systems (e.g. PC-DOS, DR-DOS and FreeDOS)

Real Mode in Microsoft Windows

- Newer operating systems only use it during the start phase and then switch to the protected mode





- Windows 2.0 runs only in real mode
- Windows 2.1 and 3.0 can run either in real mode or protected mode
- Windows 3.1 and later revisions run only in protected mode

Image Source: neozeed. https://virtuallyfun.com/wordpress/2011/06/01/windows-3-0/

Agenda

- Memory Management
- Real Mode
- Protected Mode and Virtual Memory
- Page Replacement Strategies

Memory Addressing

- With **singletasking** the main memory is split into two areas
  - **Kernel space** = area for the operating system
  - **User space** = area for the currently running process
- With **multitasking** the user space can be further subdivided so that other processes can be stored in the memory
- The following requirements must be considered:
  - Relocation
  - Protection
  - Shared usage

Memory Management Demands

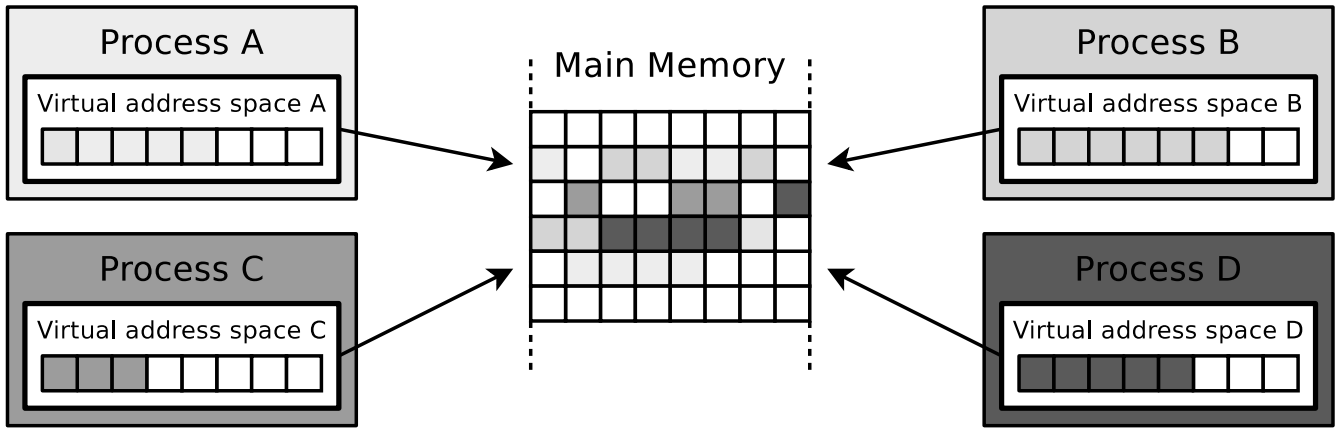
- **Relocation**
  - If processes are replaced from the main memory, it is unknown at which address they will be inserted later into the main memory again
  - Finding: Processes must not refer to physical memory addresses
- **Protection**
  - Memory areas must be protected against accidental or unauthorized access by other processes
  - Finding: Access attempts must be verified (by the CPU)
- **Shared use**
  - Despite memory protection, it must be possible for processes to collaborate via shared memory
- **Increased capacity**
  - 1 MB is not enough
  - It should be possible to use more memory as physically exists
  - Finding: If the main memory is full, parts of the data can be swapped
- Solution: Protected mode and virtual memory

Protected Mode

- Operating mode of x86-compatible CPUs
  - Introduced with the Intel 80286
- Increases the amount of memory, which can be addressed
  - 16-bit protected mode at 80286 $\Longrightarrow$ 16 MB main memory
  - 32-bit protected mode at 80386 $\Longrightarrow$ 4 GB main memory
  - For later processors, the amount of addressable memory depends on the number of bus lines in the address bus
- Implements the **virtual memory** concept
  - Processes do not use physical memory addresses
  - Each process has its own separate **address space**
    - Independent from the storage technology
    - Consists of logical memory addresses (numbered from address 0 upwards)

Virtual Memory (1/2)

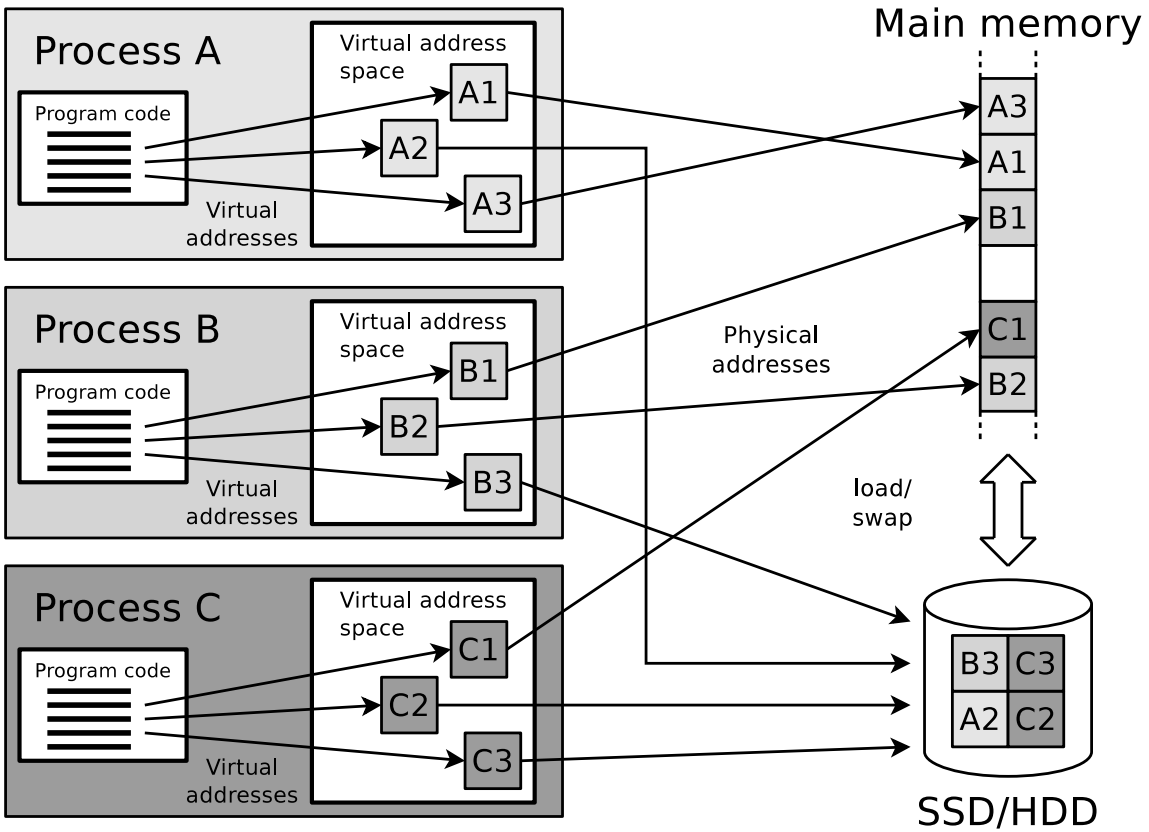
- **Address spaces** can be created or erased as necessary and they are protected
  - I.e., the memory within this address space can only be accessed by the owning process
- The virtual memory is **mapped** to the physical memory



- Virtual memory improves the utilization of the main memory
  - The memory for a process does not need to be contiguous in main memory

  $\Rightarrow$ fragmentation of the main memory is not a problem

Virtual Memory (2/2)



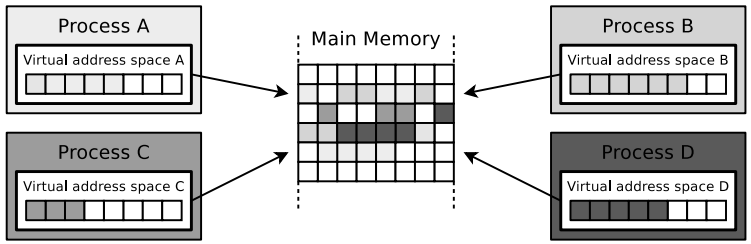
- More memory than physically available in the system can be addressed and used
- **Swapping** is performed transparently for users and processes

In protected mode, the CPU supports two memory management methods

- Segmentation exists since the 80286 (not relevant any more)
- **Paging** (see slide 32) exists since the 80386
- Both methods are implementation variants of the **virtual memory** concept

Paging: Paged Memory Management

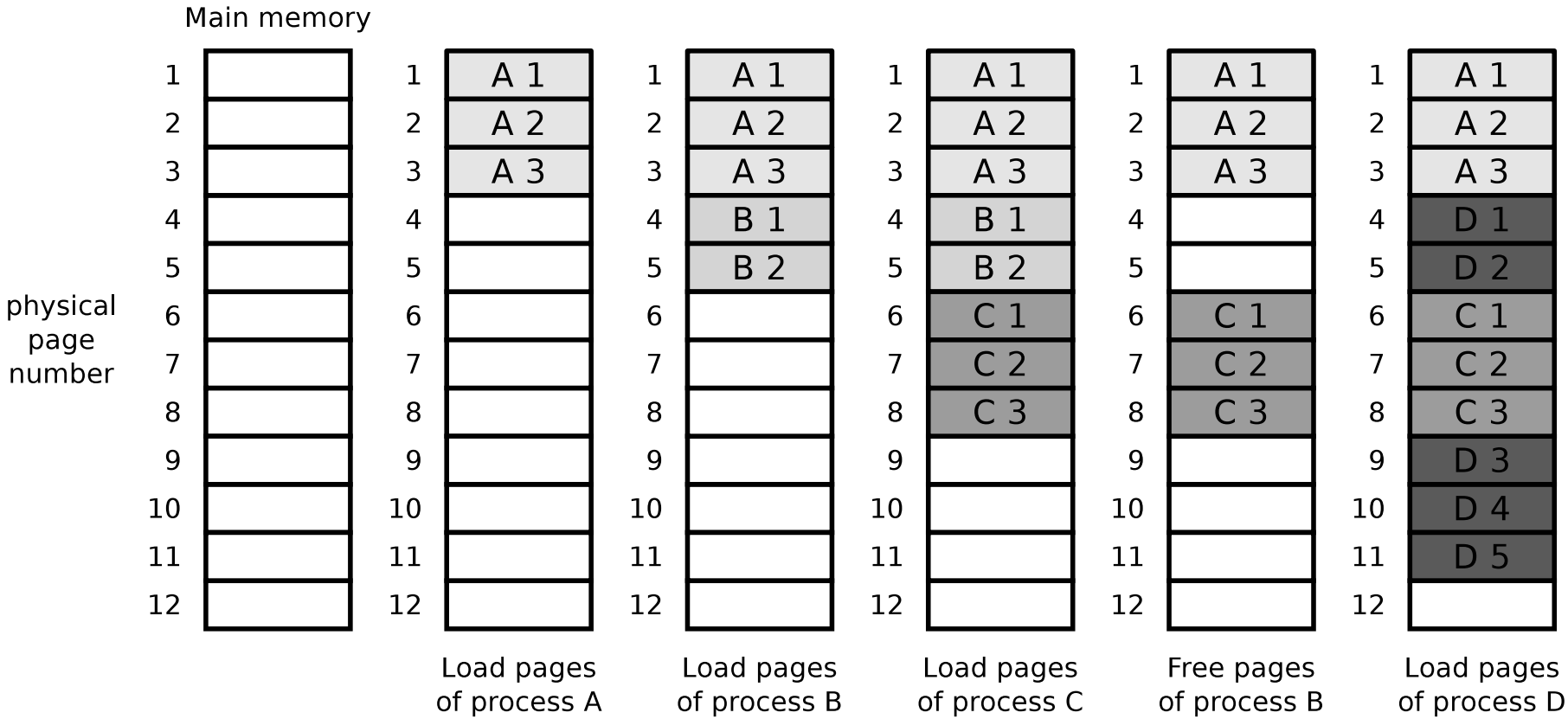
- **Virtual pages** of the processes are mapped to **physical pages** in the main memory
  - All pages have the same length
    - The page size is usually 4 kB (at the Alpha architecture and the UltraSPARC architecture: 8 kB, at Apple Silicon: 16 kB)
- Benefits:
  - External fragmentation is irrelevant
  - Internal fragmentation can only occur in the last page of each process



- The operating system maintains **for each process a page table**
  - Storing the locations of the individual pages of the process
- Processes **only** work with **virtual memory addresses**
  - Virtual memory addresses consist of two parts
    - The more significant part is the page number
    - The lower significant part is the offset (address inside a page)
  - The length of the virtual addresses is architecture dependent (depends on the number of bus lines in the address bus), and is 16, 32, or 64 bits

Allocation of Process Pages to free Physical Pages

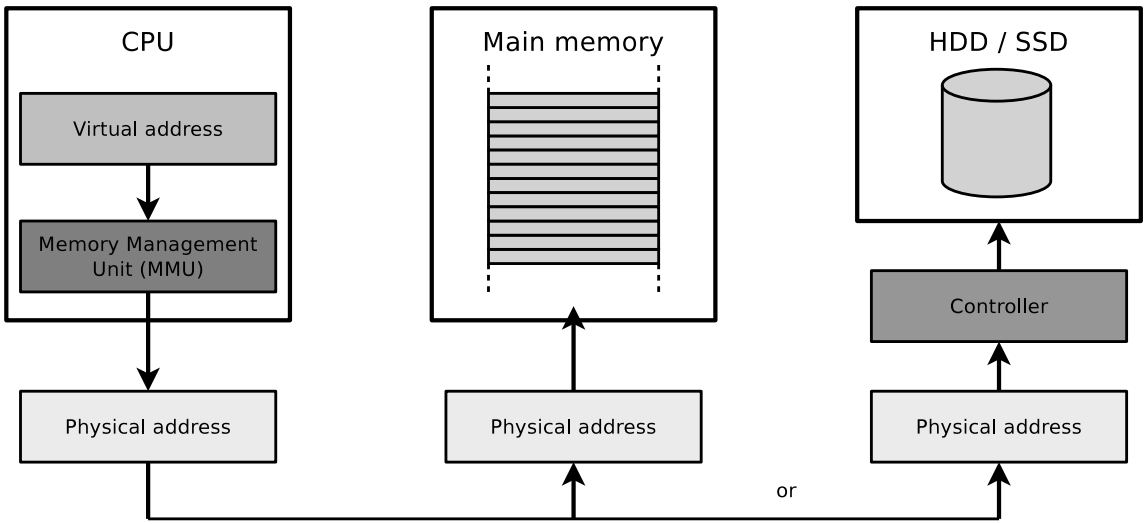
- Processes do not need to be located contiguous inside main memory
  $\Longrightarrow$ No external fragmentation



The topic is well explained in: Operating Systems, *William Stallings*, 4th edition, Prentice Hall (2001)

Address Translation by the Memory Management Unit

- The CPU translates virtual memory addresses via the MMU and the page table into physical addresses
  - The OS determines whether the physical address belongs to the main memory or to a SSD/HDD



- If the desired data is located on the SSD/HDD, the operating system must copy the data into the main memory
- If the main memory has no more free capacity, the operating system must relocate (*swap*) data from the main memory to the SDD/HDD

The topic MMU is clearly explained by...

- Modern Operating Systems, *Andrew S. Tanenbaum*, 2nd edition, Pearson (2009), P. 223-226

Implementation of the Page Table

- Impact of the page length:
  - **Short pages**: Less capacity loss caused by internal fragmentation, but bigger page table
  - **Long pages**: Shorter page table, but more capacity loss caused by internal fragmentation
- Page tables are stored inside the main memory

$$\text{Maximum page table size} = \frac{\text{Virtual address space}}{\text{Page size}} * \text{Size of each page table entry}$$

- Maximum page table size with 32 bit operating systems:

$$\frac{4\,\text{GB}}{4\,\text{kB}} * 4\,\text{Bytes} = \frac{2^{32}\,\text{Bytes}}{2^{12}\,\text{Bytes}} * 2^2\,\text{Bytes} = 2^{22}\,\text{Bytes} = 4\,\text{MB}$$

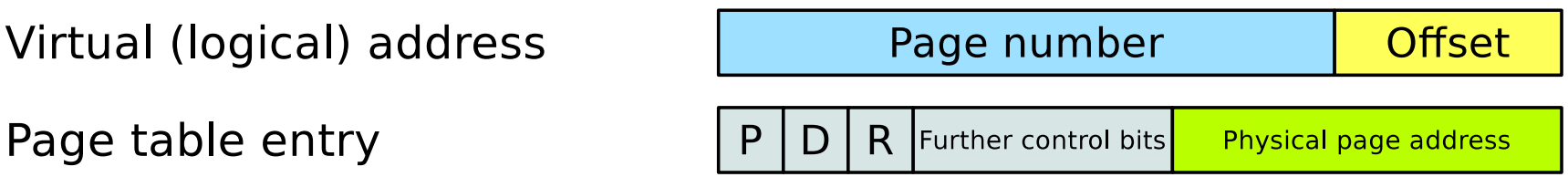
- Each process in a multitasking operating system requires a page table

In 64 bit operating systems, the page tables of the individual processes can be significantly larger

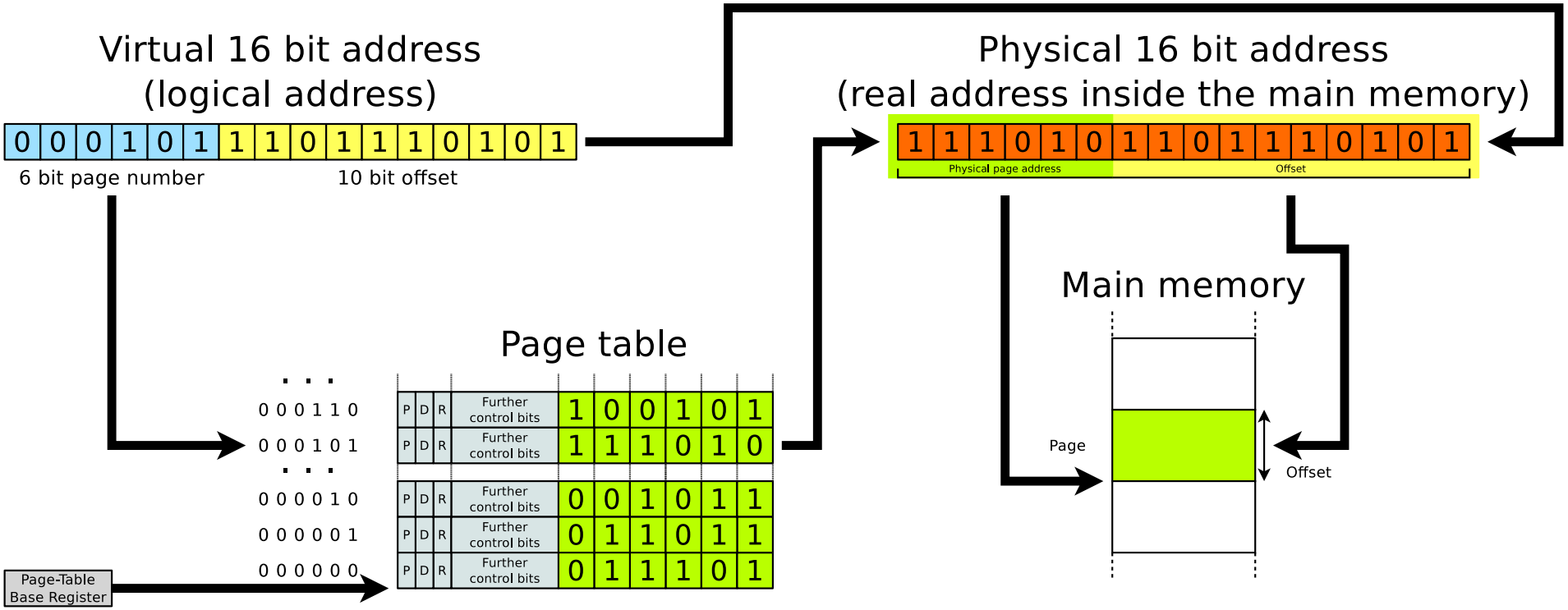
However, since most everyday processes do not require several gigabytes of memory, the overhead of managing the page tables on modern computers is low

Page Table Structure

- Each page table record contains among others:
  - Present bit: Specifies whether the page is stored inside the main memory
  - Dirty bit (*Modified-Bit*): Specifies whether the page has been modified
  - Reference bit: Specifies whether the page was referenced (even read operations!) $\Longrightarrow$ this is eventually relevant for the page replacement strategy used
  - Further control bits: Here is among others specified whether...
    - User mode processes have only read access to the page or write access too (read/write bit)
    - User-mode processes are allowed to access the page (user/supervisor bit)
    - Modifications are immediately passed down (write-through) or when the page is removed (write-back) from main memory (write-through bit)
    - The page may be loaded into the cache or not (cache-disable bit)
  - Physical page address: Is concatenated with the offset of the virtual address



Address Translation with Paging (single level)

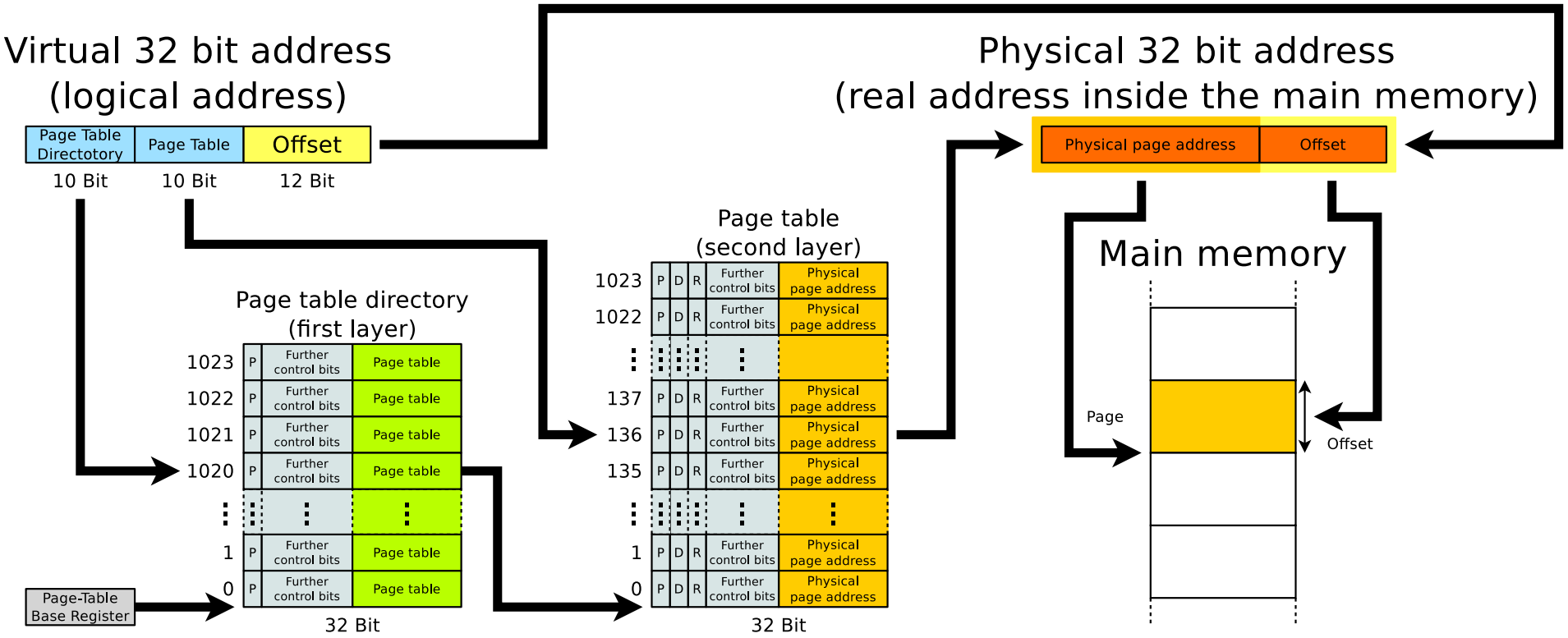


- Single level paging is sufficient in 16 bit architectures
- For architectures $\geq$ 32 bit the operating systems implement multi-level paging

Two registers enable the MMU to access the page table

- Page-Table Base Register (PTBR): Address where the page table of the current process starts
- Page-Table Length Register (PTLR): Length of the page table of the current process

Address Translation with Paging (Two levels)



The topic Paging is clearly explained by...

- Operating Systems, *William Stallings*, 4th edition, Pearson (2003), S.394-399
- `http://wiki.osdev.org/Paging`

Why multi-level Paging?

We already know...

- In 32 bit operating systems with 4 kB page length, the page table of each process can be 4 MB in size (see slide 35)
- In 64 bit operating systems, the page tables can be much larger

- Multi-level paging reduces the main memory usage
  - When calculating a physical address, the operating system scans the pages of the different levels step by step
  - If required, individual pages of the different levels can be relocated to the swap storage to free up storage capacity in the main memory

Architecture	Page Table	Virtual Address Length	Partitioning[a]
IA32 (x86-32)	2 levels	32 Bits	10+10+12
IA32 with PAE[b]	3 levels	32 Bits	2+9+9+12
PPC64	3 levels	41 Bits	10+10+9+12
AMD64 (x86-64)	4 levels	48 Bits	9+9+9+9+12
Intel Ice Lake Xeon Scalable[c]	5 levels	57 Bits	9+9+9+9+9+12

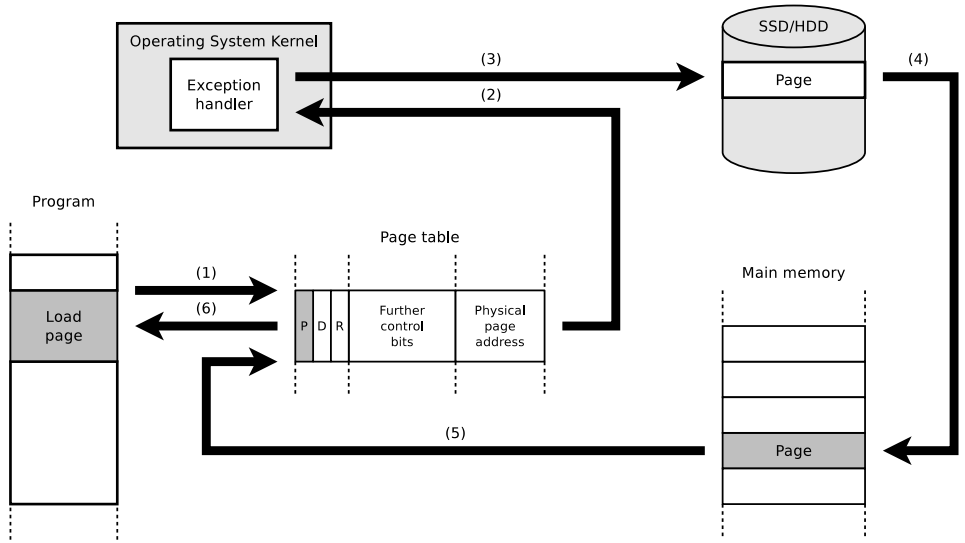
[a] The last number indicates the length of the offset in bits. The remaining numbers indicate the lengths of the page

[b] PAE = Physical Address Extension. With this paging extension of the Pentium Pro processor, more than 4 GB of R can be addressed by the operating system. However, the memory usable per process is still limited to 4 GB.

[c] `https://software.intel.com/content/dam/develop/public/us/en/documents/5-level-paging-white-paper.pdf`

Page Fault Exception

- A process tries (1) to request a page which is currently not located in physical main memory
  - The **present bit** in each page table record indicates whether the page is located inside main memory or not

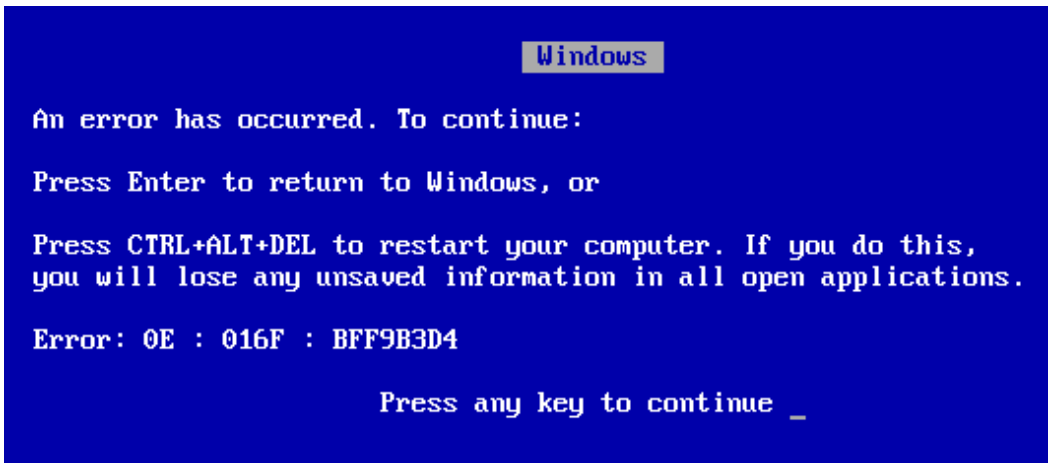


- A **software interrupt (exception)** is triggered (2) to switch from **user mode** to **kernel mode**
- The operating system...
  - locates (3) the page by using the controller and the device driver on the swap memory (SSD/HDD)
  - copies (4) the page into a free page of the main memory
  - updates (5) the page table
  - returns control to the process (6)
    - The process again executes the instruction that caused the page fault

Access Violation Exception or General Protection Fault Exception

- Also called Segmentation fault or Segmentation violation
  - A paging issue which has nothing to do with segmentation!

- A process tries to request a virtual memory address which it is not allowed to request



- Result: Legacy Windows systems crash (blue screen), Linux returns the signal `SIGSEGV`
- **Example:** A process tries to carry out a write operation on a read-only page

Source: Herold H. (1996) *UNIX-Systemprogrammierung*. 2nd. Addison-Wesley
Image source (top): Reader781. Wikimedia (CC0)
Image source (bottom): Akhristov. Wikimedia (CC0)

Summary: Real Mode and Protected Mode

- **Real mode**
  - Operating mode of x86-compatible CPUs
  - The CPU accesses the main memory equal to an Intel 8086 CPU
  - No memory protection
    - Each process can access the entire main memory
- **Protected mode**
  - Modern operating systems (for x86) operate in protected mode and implement paging
  - Operating mode of x86-compatible CPUs
  - Implements the **virtual memory** concept

Kernel Space and User Space (only on 32-bit systems)

- 32-bit operating systems split the virtual address space of each process into **kernel space** and user space
  - Kernel space = area for the kernel and kernel extensions (drivers)
  - User space = area for the currently running process, which is extended with *swap* (Windows: *Page file*) memory
- The virtual address space (virtual memory) of 32-bit CPUs is limited to 4 GB per process
- **Linux**
  - 25% are reserved per default for the system (kernel) and 75% for the user-mode processes
- **Windows**
  - 50% are reserved per default for the system (kernel) and 50% for the user-mode processes

On 64-bit architectures, the 3G/1G or 2G/2G split doesn't apply anymore! When using a 64 bit operating system on x86, all available virtual addresses can be assigned to user mode processes
Sources: `http://stackoverflow.com/questions/1115033/` and `http://stackoverflow.com/questions/19006376`

Agenda

- Memory Management
- Real Mode
- Protected Mode and Virtual Memory
- Page Replacement Strategies

Page Replacement

- If the main memory is not big enough to store all pages of running processes, **swapping** is required

$\Rightarrow$ Pages in main memory are replaced by pages from **swap memory**

- An efficient memory management method for the main memory and cache...
  - keeps those pages inside the memory that are requested frequently
  - identifies those pages that are unlikely to be requested in the near future and replaces them if capacity is needed

Hit Rate and Miss Rate

- In case of a request to a computer memory, two results are possible:
  - **Hit**: Requested data is available
  - **Miss**: Requested data is missing
- Two key figures are used to evaluate the efficiency of a computer memory
  - **Hit rate**: The number of requests to the computer memory, with result in hit, divided by the total number of requests
    - Result is between 0 and 1
    - The greater the value, the better is the efficiency of the computer memory
  - **Miss rate**: The number of requests to the computer memory, with result in miss, divided by the total number of requests
    - Miss rate $= 1 -$ hit rate

Page Replacement Strategies

- **Objective:** Keep the data ($\Longrightarrow$ pages) in main memory that is frequently requested (accessed)
- Some replacement strategies:
  - OPT (Optimal strategy)
  - LRU (Least Recently Used)
  - LFU (Least Frequently Used)
  - FIFO (First In First Out)
  - Clock / Second Chance
  - TTL (Time To Live)
  - Random

A well understandable explanation of the page replacement strategies...

- OPT, FIFO, LRU and Clock provides Operating Systems, *William Stallings*, 4th edition, Prentice Hall (2001), P.355-363

Optimal strategy (OPT)

- Replaces the page, which is not requested for the longest time in the future
- Impossible to implement!
  - **Reason:** Nobody can predict the future
- OPT is used to evaluate the efficiency of other replacement strategies

Requests:	**1**	**2**	**3**	**4**	**1**	**2**	**5**	**1**	**2**	**3**	**4**	**5**
Page 1:	1	1	1	1	1	1	1	1	1	3	3	3
Page 2:		2	2	2	2	2	2	2	2	2	4	4
Page 3:			3	4	4	4	5	5	5	5	5	5

→ 7 Miss

The requests are requests for pages inside the virtual address space of a process. If the requested page is not inside the cache, it is read from the main memory or the swap

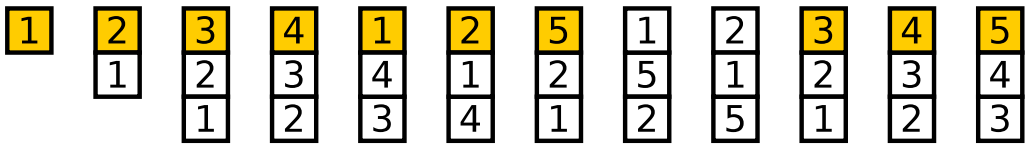
Least Recently Used (LRU)

- Replaces the page, which was not requested for the longest time
- All pages are referenced in a queue
  - If a page is loaded into memory or referenced, it is moved to the front of the queue
  - If the memory has no more free capacity and a miss occurs, the page at the end of the queue is replaced
- **Drawback:** Ignores the number of requests

Requests:	**1**	**2**	**3**	**4**	**1**	**2**	**5**	**1**	**2**	**3**	**4**	**5**
Page 1:	1	1	1	4	4	4	5	5	5	3	3	3
Page 2:		2	2	2	1	1	1	1	1	1	4	4
Page 3:			3	3	3	2	2	2	2	2	2	5

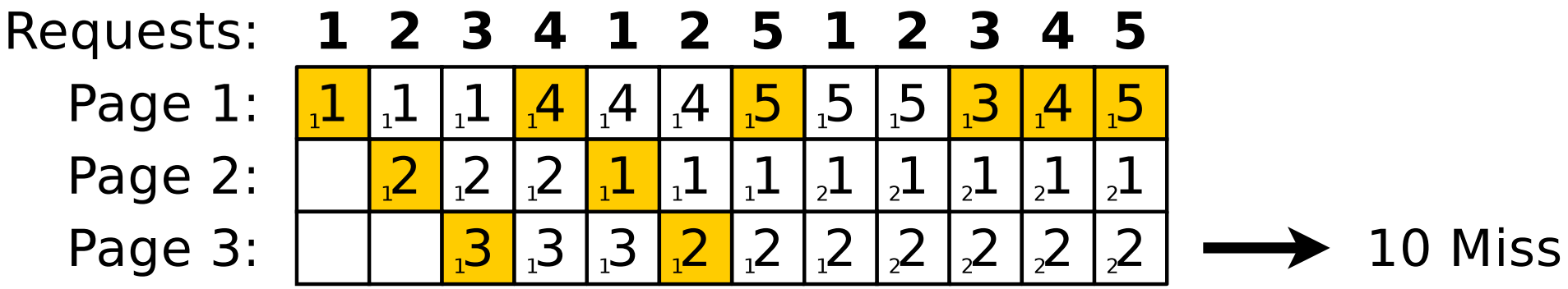
→ 10 Miss

Queue:



Least Frequently Used (LFU)

- Replaces the page, which was least often requested
- For each page inside the memory, a reference counter exists in the page table, in which the operating system stores the number of requests
  - If the memory has no more free capacity and a miss occurs, the page is replaced, which has the lowest value in its reference counter
- **Benefit:** Takes into account the number of times pages are requested
- **Drawback:** Pages which have been requested often in the past, may block the memory



First In First Out (FIFO)

- Replaces the page, which is stored in memory for the longest time
- Common assumption: increasing the memory results in fewer or, at worst, the same miss number
- **Problem:** Laszlo Belady demonstrated in 1969 that for certain request patterns, FIFO causes with an expanded memory capacity more miss events ($\Longrightarrow$ Belady's anomaly)
  - Until the discovery of Belady's Anomaly, FIFO was considered a good replacement strategy

Belady's Anomaly (1969)

Requests:	**1**	**2**	**3**	**4**	**1**	**2**	**5**	**1**	**2**	**3**	**4**	**5**
Page 1:	1	1	1	4	4	4	5	5	5	5	5	5
Page 2:		2	2	2	1	1	1	1	1	3	3	3
Page 3:			3	3	3	2	2	2	2	2	4	4

→ 9 Miss

Page 1:	1	1	1	1	1	1	5	5	5	5	4	4
Page 2:		2	2	2	2	2	2	1	1	1	1	5
Page 3:			3	3	3	3	3	3	2	2	2	2
Page 4:				4	4	4	4	4	4	3	3	3

→ 10 Miss

More information about Belady's anomaly

Belady, Nelson and Shedler. *An Anomaly in Space-time Characteristics of Certain Programs Running in a Paging Machine*. Communications of the ACM. Volume 12 Issue 6. June 1969

Clock/Second Chance

- This strategy uses the reference bit (see slide 36), which exists in the page table for each page
  - If a page is loaded into memory $\Longrightarrow$ reference bit = 0
  - If a page is requested $\Longrightarrow$ reference bit = 1
- A pointer indicates the last requested page
- In case of a miss, the memory is searched from the position of the pointer for the first page, whose reference bit has value 0
  - This page is replaced
  - For all pages, which are examined during the searching, where the reference bit has value 1, it is set to value 0

Requests:	**1**	**2**	**3**	**4**	**1**	**2**	**5**	**1**	**2**	**3**	**4**	**5**
Page 1:	$_0 1^X$	$_0 1$	$_0 1$	$_0 4^X$	$_0 4$	$_0 4$	$_0 5^X$	$_0 5$	$_0 5$	$_0 3^X$	$_0 4^X$	$_0 4$
Page 2:		$_0 2^X$	$_0 2$	$_0 2$	$_0 1^X$	$_0 1$	$_0 1$	$_1 1^X$	$_1 1$	$_1 1$	$_0 1$	$_0 5^X$
Page 3:			$_0 3^X$	$_0 3$	$_0 3$	$_0 2^X$	$_0 2$	$_0 2$	$_1 2^X$	$_1 2$	$_0 2$	$_0 2$

$\longrightarrow$ 10 Miss

Linux, BSD-UNIX, VAX/VMS (originally from Digital Equipment Corporation), Windows NT 4.0 on uniprocessors systems and modern Windows operating systems implement the clock replacement strategy or variants of this strategy

Further Replacement Strategies

- TTL (Time To Live): Each page gets a time to live value, when it is stored in the memory
  - If the TTL has exceeded, the page can be replaced

This concept is not used in operating systems but it is useful for the caching of Web pages (Internet contents)

Interesting source: Caching with expiration times. *Gopalan P, Harloff H, Mehta A, Mihail M, Vishnoi N* (2002) `https://www.cc.gatech.edu/~mihail/www-papers/soda02.pdf`

- Random: Random pages are replaced
  - **Benefits:** Simple and resource-saving replacement strategy
    - Reason: No need to store information about the requests

The random replacement strategy is (was) used in practice

- The operating systems IBM OS/390 and Windows NT 4.0 on SMP systems use the random replacement strategy
  (Source OS/390: Pancham P, Chaudhary D, Gupta R. (2014) *Comparison of Cache Page Replacement Techniques to Enhance Cache Memory Performance*. International Journal of Computer Applications. Volume 98, Number 19)
  (Source NT4: `http://www.itprotoday.com/management-mobility/inside-memory-management-part-2`)
- The Intel i860 RISC CPU uses the Random replacement strategy for the cache
  (Source: Rhodehamel M. (1989) *The Bus Interface and Paging Units of the i860 Microprocessor*. Proceedings of the IEEE International Conference on Computer Design. P. 380-384)

You should now be able to answer the following questions:

- What are the fundamental concepts of memory management?
  - How do static and dynamic partitioning and how does Buddy memory allocation work?
- What is the difference between memory access via real mode and protected mode
- Which components and concepts are required to implement virtual memory?
- What are the characteristics of common replacement strategies?