# 5th Slide Set
# Operating Systems

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# Learning Objectives of this Slide Set

- At the end of this slide set You know/understand...
  - fundamental concepts of **memory management**
    - **Static partitioning**
    - **Dynamic partitioning**
    - **Buddy memory allocation**
  - how operating systems **access the memory** (address it!)
    - **Real mode**
    - **Protected mode**
  - components and concepts to implement **virtual memory**
    - Memory Management Unit (**MMU**)
    - Paged memory management (**paging**)
    - Segmented memory management (**segmentation**)
- the possible results if memory is requested
  - **Hit** and **Miss**
- the functioning and characteristics of common **replacement strategies**

Exercise sheet 5 repeats the contents of this slide set which are relevant for these learning objectives

# Memory Management

- An essential function of operating systems
- Required for allocating portions of memory to programs at their request
- Also frees memory portions, which are allocated to programs, when they are not needed any longer
- 3 concepts for memory management:
  1. **Static partitioning**
  2. **Dynamic partitioning**
  3. **Buddy memory allocation**

These concepts are already somewhat older...

Image source: unknown (perhaps IBM)

A good description of the memory management concepts provides...

- **Operating Systems – Internals and Design Principles**, *William Stallings*, 4th edition, Prentice Hall (2001), P.305-315
- **Moderne Betriebssysteme**, *Andrew S. Tanenbaum*, 3rd edition, Pearson (2009), P.232-240

# Concept 1: Static Partitioning

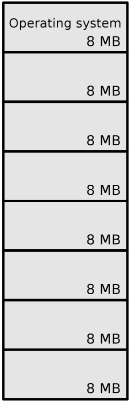
- The main memory is split into **partitions of equal size** or of **different sizes**
- Drawbacks:
  - **Internal fragmentation** occurs in any case $\Longrightarrow$ inefficient
    - The problem is moderated by partitions of different sizes, but not solved
  - The number of partitions limits the number of possible processes
- Challenge: A process requires more memory than a partition is of size
  - Then 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 (1/2)

- 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 scheduling method ($\Longrightarrow$ slide set 8) used

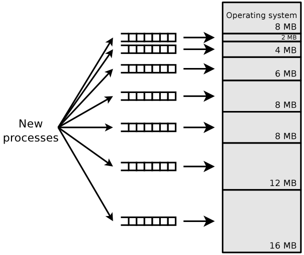


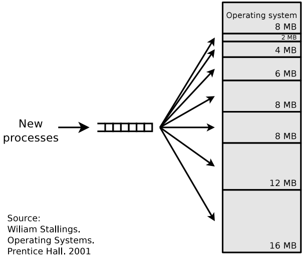

Partitions of equal size

Source:
Wiliam Stallings.
Operating Systems.
Prentice Hall. 2001

# Static Partitioning (2/2)

- Processes should get a partition allocated, which fits as precise as possible
  - Objective: Little internal fragmentation
- If **partitions of different sizes** are used, 2 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

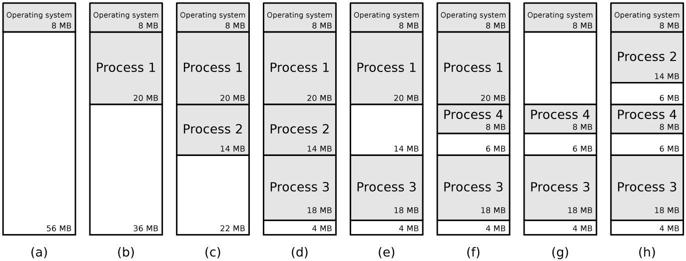



Source:
Wiliam Stallings.
Operating Systems.
Prentice Hall. 2001

# Concept 2: Dynamic Partitioning

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



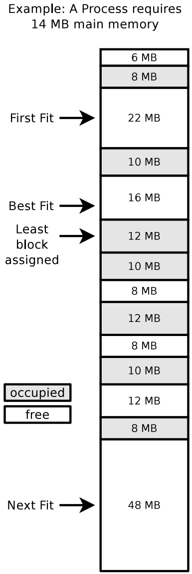

Source:
Wiliam Stallings.
Operating Systems.
Prentice Hall. 2001

- **External fragmentation** occurs in any case $\Longrightarrow$ inefficient
  - Possible solution: Defragmentation
    - Requirement: Relocation of memory blocks must be supported
    - References inside processes are not allowed to become invalid because of the relocation of partitions

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

# 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



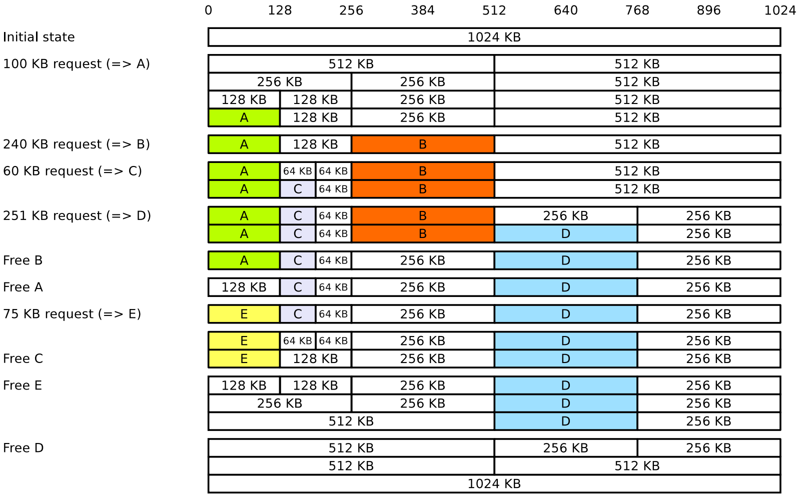
# Concept 3: Buddy Memory Allocation of Donald Knuth

- Initially, a single block covers the entire memory
- If a process requires memory, the request is rounded up to the next higher power of two and an appropriate free block is searched
    - If no block of this size exists, a block of double size is searched and this block is split into 2 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...
- If memory is freed, it is checked whether 2 halves of the same size can be re-combined to a larger block
    - Only previously made subdivisions are reversed!

**Bddy 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

# Buddy Memory Allocation Example




- Drawback: Internal and external fragmentation

# Information about the Memory Fragmentation

- The DMA row shows the first 16 MB on a system
- The DMA32 row shows all memory > 16 MB and < 4 GB on a system
- The Normal row shows all memory > 4 GB on a system

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

```
$ cat /proc/buddyinfo
Node 0, zone      DMA      1      1      1      0      2      1      1      0      1      1      3
Node 0, zone    DMA32    208    124   1646    566    347    116    139    115     17      4    212
Node 0, zone   Normal     43     62    747    433    273    300    254    190     20      8    287
```

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

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

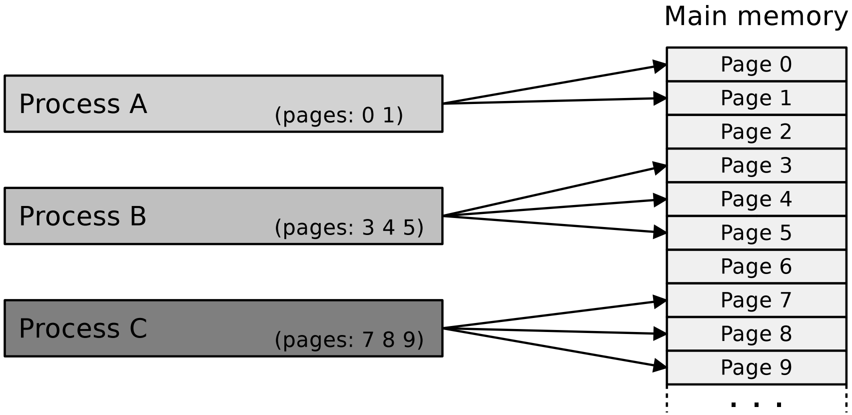
# Accessing Memory

- With 16-bit architectures, $2^{16}$ memory addresses and therefore up to $65,536$ Bytes can be addressed
- With 32-bit architectures, $2^{32}$ memory addresses and therefore up to $4,294,967,296$ Bytes $=$ **4 GB** can be addressed
- With 64-bit architectures, $2^{64}$ memory addresses and therefore up to $18,446,744,073,709,551,616$ Bytes $=$ **16 Exabyte** can be addressed

**! ! ! Question ! ! !**

How is the memory accessed by the processes

# Idea: Direct Memory Access




- Most obvious idea: Direct memory access by the processes
  $\Longrightarrow$ **Real Mode**
- Unfortunately, this is impossible in multitasking systems

# Real Mode (Real Address Mode)

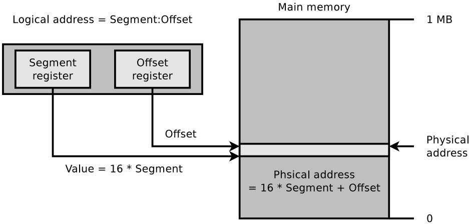
- Operating mode of x86-compatible CPUs
- **No memory protection**
  - Each process can access the entire memory, which can be addressed
    - Unacceptable for multitasking operating systems
- **A maximum of 1 MB main memory can be addressed**
  - Maximum main memory of an Intel 8086
  - Reason: The address bus of the 8088 contains only 20 lines
    - 20 lines $\Longrightarrow$ 20 Bits long memory addresses $\Longrightarrow 2^{20} =$ 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*) contains the BIOS of the graphics card, the memory window to the graphics card memory and the BIOS ROM of the motherboard
- 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

Helpful source: `http://www.internals.com/articles/protmode/realmode.htm`

# Real Mode – Addressing

- The main memory is split into 65,536 segments
  - The memory adress length is 16 Bits
  - The size of each segment is 64 Bytes ($= 2^{16} = 65,536$ bits)
- 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**)

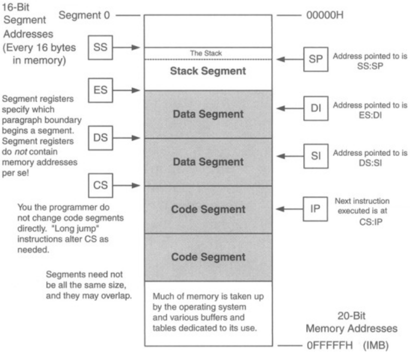
- The **segment register** stores the segments number
- The **offset register** points to an address between 0 and $2^{16}$ (=65,536), relative to the address of the segment register



# Real Mode – Segment Registers since the 8086

Image Source: http://www.c-jump.com

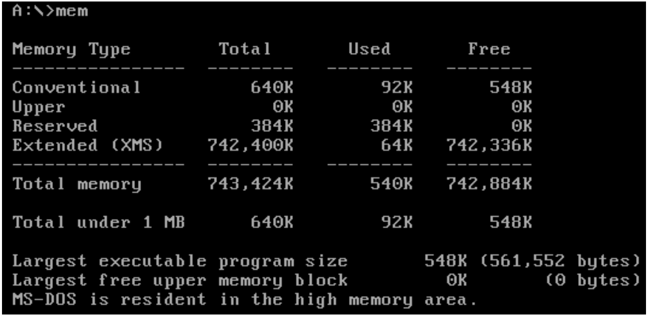
- The 8086 contains 4 **segment registers**
- `CS` (Code Segment)
  - Segment with the source code of the program
- `DS` (Data Segment)
  - Segment with the global data, of the current program
- `SS` (Stack Segment)
  - Segment with the stack for the local data of the program
- `ES` (Extra Segment)
  - Segment for further data



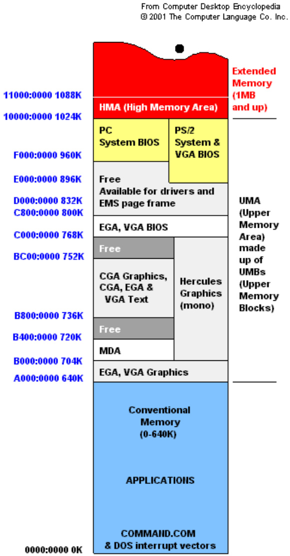

- Since the Intel 80386, 2 further segment registers (`FS`, and `GS`) for additional extra segments exist
- The segments implement a simple form of **memory protection**

# Real Mode in MS-DOS

Image Source: Google Image Search



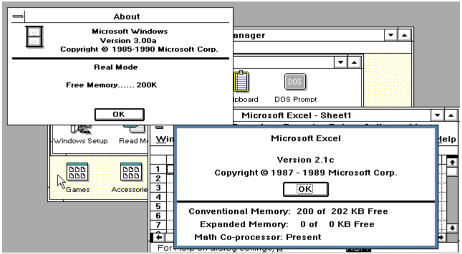
```
A:\>mem

Memory Type        Total      Used       Free
----------------  ---------  ---------  ---------
Conventional          640K        92K       548K
Upper                   0K         0K         0K
Reserved              384K       384K         0K
Extended (XMS)    742,400K        64K   742,336K
----------------  ---------  ---------  ---------
Total memory      743,424K       540K   742,884K

Total under 1 MB      640K        92K       548K

Largest executable program size       548K (561,552 bytes)
Largest free upper memory block         0K         (0 bytes)
MS-DOS is resident in the high memory area.
```

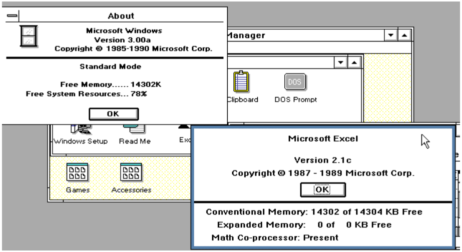



- Real mode is the default mode of MS-DOS and compatible operating systems (e.g. PC-DOS, DR-DOS and FreeDOS)

# 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: `http://virtuallyfun.superglobalmegacorp.com`

# 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 $\Longrightarrow$ slide set 10
- **Increased capacity**
  - 1 MB is not enough
  - It should be possible to use more memory as physically exists
  - Finding: If the main memory is filled, parts of the data can be swapped
- Solution: **Protected mode** and **virtual memory**

# Protected Mode

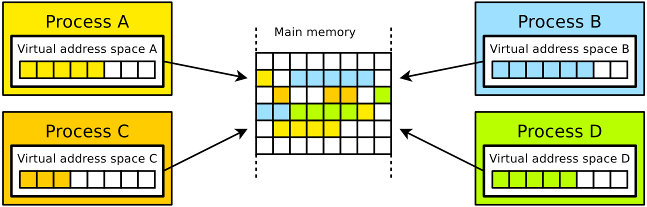
- Operating mode of x86-compatible CPUs
  - Introduced with the Intel 80286
- Increases the amount of memory, which can be addressed
  - 16-bit protected mode at 80286 $\Longrightarrow$ 16 MB main memory
  - 32-bit protected mode at 80386 $\Longrightarrow$ 4 GB main memory
- Implements the **virtual memory** concept
  - Each process is executed in its own copy of the physical address space, which is protected from other processes
    - Each process can only access its own virtual memory
  - With the Memory Management Unit (MMU), processes get address spaces provided, equal to the real mode
    - Virtual memory addresses translates the CPU with the MMU into physical memory addresses
- x86-CPUs contain 4 privilege levels ($\Longrightarrow$ slide set 7) for processes
  - Objective: Implementing memory protection to improve stability and security

# Virtual Memory (1/3)

- Modern operating systems operate in protected mode
- In protected mode, the CPU supports 2 memory management methods
  - **Segmentation** exists since the 80286
  - **Paging** exists since the 80386
  - Both methods are implementation variants of the **virtual memory** concept
- Processes do not use physical memory addresses
  - This would cause issues in multitasking systems
- Instead, each process has a separate **address space**
  - This address space is an abstraction of the physical memory
    - It implements **virtual memory**
    - It is independent from the storage technology used and the existing expansion options
    - It consists of logical memory addresses, which are numbered from address 0 upwards

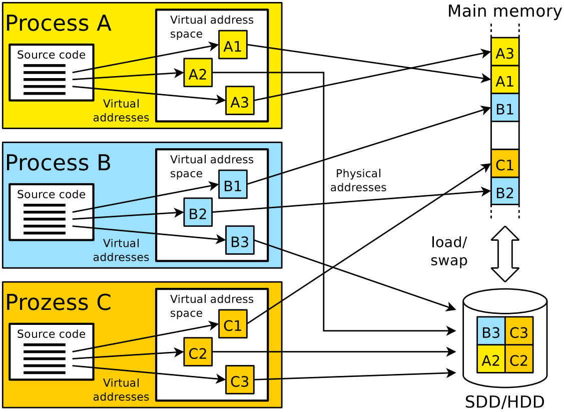
# Virtual Memory (2/3)

- Address spaces can be created or erased as necessary and they are protected
  - No process can access the address space of another process without prior agreement
- The virtual memory is **mapped** to the physical memory




- With virtual memory, the main memory is utilized better
  - Processes do not need to be located in a row inside the main memory
  - Therefore, the fragmentation of the main memory is not a problem

# Virtual Memory (3/3)




- Thanks to virtual memory, more memory can be accessed and used, as is physically present in the system
- **Swapping** is performed transparently for users and processes

The topic Virtual Memory is clearly explained by...

- **Betriebssysteme**, *Carsten Vogt*, 1st edition, Spektrum Akademischer Verlag (2001), P. 152

# 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: 8 kB)
- Benefits:
  - No external fragmentation
  - Internal fragmentation can only occur in the last page of each process
- The operating system maintains **for each process a page table**
  - The page table stores the information where the individual pages of the process are located
- Processes only work with **virtual memory addresses**
  - Virtual memory addresses consist of 2 parts
    - The more significant part contains the page number
    - The lower significant part contains the offset (address inside a page)
  - The length of the virtual addresses is architecture dependent, and is therefore 16, 32, or 64 bits

# Allocation of Process Pages to free Physical Pages

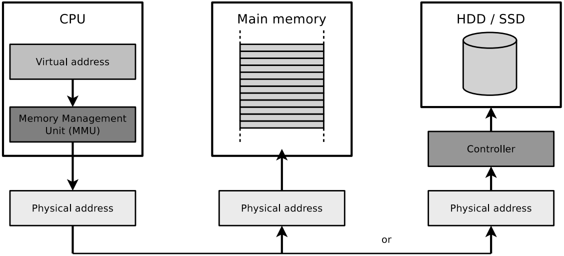
- Processes do not need to be located in a row inside the main memory
  $\Longrightarrow$ No external fragmentation

| Physical page number | Main memory | Load process A | Load process B | Load process C | Swap process B | Load process D |
|---|---|---|---|---|---|---|
| 0 | | A 0 | A 0 | A 0 | A 0 | A 0 |
| 1 | | A 1 | A 1 | A 1 | A 1 | A 1 |
| 2 | | A 2 | A 2 | A 2 | A 2 | A 2 |
| 3 | | A 3 | A 3 | A 3 | A 3 | A 3 |
| 4 | | | B 0 | B 0 | | D 0 |
| 5 | | | B 1 | B 1 | | D 1 |
| 6 | | | B 2 | B 2 | | D 2 |
| 7 | | | | C 0 | C 0 | C 0 |
| 8 | | | | C 1 | C 1 | C 1 |
| 9 | | | | C 2 | C 2 | C 2 |
| 10 | | | | C 3 | C 3 | C 3 |
| 11 | | | | | | D 3 |
| 12 | | | | | | D 4 |
| 13 | | | | | | |
| 14 | | | | | | |

Image source: **Operating Systems**, *William Stallings*, $4^{th}$ edition, Prentice Hall (2001)

# Address Translation by the Memory Management Unit

- Virtual memory addresses translates the CPU with the **MMU** and the page table into physical addresses
  - The operating system investigates 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...

- **Betriebssysteme**, *Carsten Vogt*, 1st edition, Spektrum Akademischer Verlag (2001), P. 152-153
- **Moderne Betriebssysteme**, *Andrew S. Tanenbaum*, 2nd edition, Pearson (2009), P. 223-226

# Implementation of the Page Table

- Impact of the page length:
  - **Short pages**: Less loss caused by internal fragmentation, but bigger page table
  - **Long pages**: Shorter page table, but more 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:

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

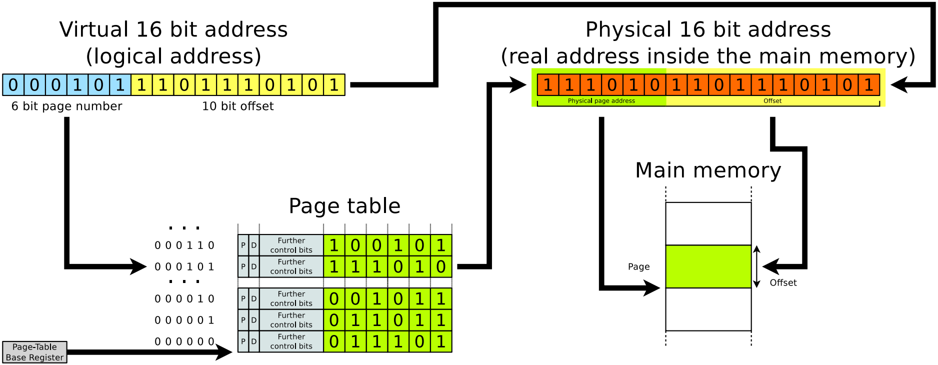
- Each process in a multitasking operating system requires a page table

# Page Table Structure

- Each page table record contains among others:
  - **Present bit**: Specifies whether the page in stored inside the main memory
  - **Dirty bit** (*Modified-Bit*): Specifies whether the page was 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

| | | | | | |
|---|---|---|---|---|---|
| Virtual (logical) address | Page number | | | | Offset |
| Page table entry | P | D | R | Further control bits | Physical page address |

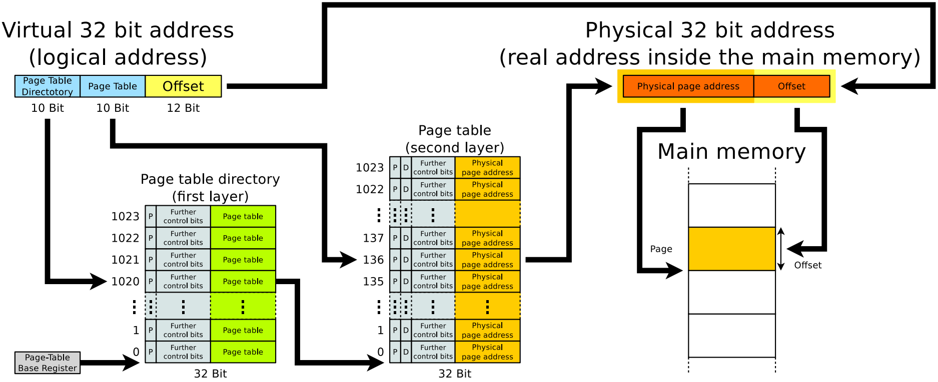
# Address Translation with Paging (single level)




## 2 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 (2 levels)




## The topic Paging is clearly explained by. . .

- **Betriebssysteme**, *Eduard Glatz*, 2nd edition, dpunkt (2010), P.450-457
- **Betriebssysteme**, *William Stallings*, 4th edition, Pearson (2003), S.394-399
- `http://wiki.osdev.org/Paging`

# Page Fault Exception

- A program tries to access a page, which is not located in the physical main memory
  - The **present bit** in each page table record indicates whether a page is located inside main memory or not

- The operating system handles the page fault, while it carries out these steps:
  - Determine the location of the data in secondary storage (SSD/HDD)
  - Obtain free main memory pages
  - Load requested data into the pages
  - Update the page table of the process
  - Return control to the program, which retries the instruction that caused the page fault

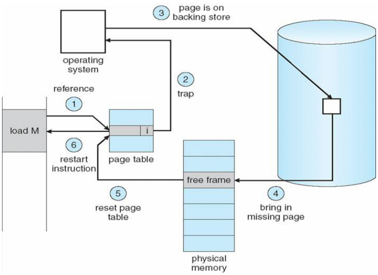
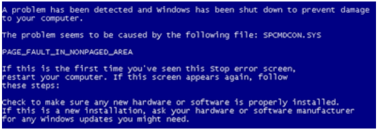


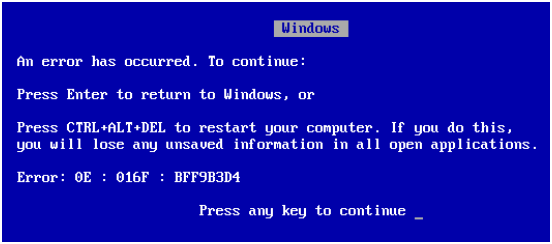

Image source: `http://www.cs.odu.edu/~cs471w/spring10/lectures/virtualmemory.htm`

# 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 access a virtual memory address, which it is not allowed to access $\Longrightarrow$ crash
  - Example: A process tries to carry out a write access to a read-only page



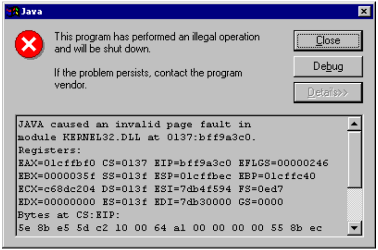




Image source: Wikipedia, http://telcontar.net/store/archive/CrashGallery/images/crash/m/crash13.png and http://www.dtec-computers.com/images/jpg/computer_repair/blue-screen-of-death.gif

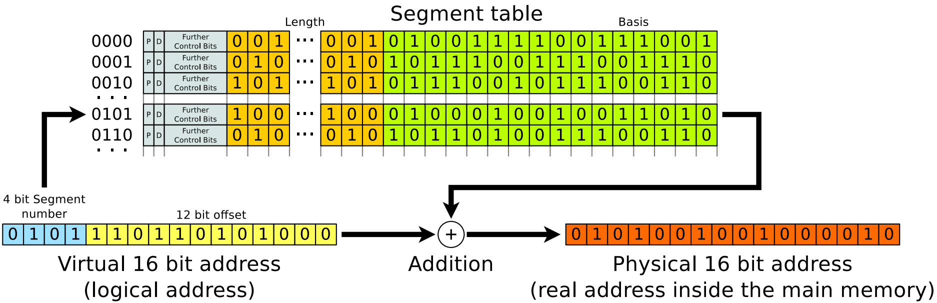
# Segmentation

- A further virtual memory management method
- The virtual memory of the processes consists of **segments** of different length

The maximum segment length explains the example on the next slide

- The operating system maintains **for each process a segment table**
  - Each record in the segment table contains the length of the segment and the start address in the main memory
  - Virtual addresses of the processes are translated into physical addresses by using the segment tables
- No internal fragmentation
- External Fragmentation occurs as with dynamic partitioning
  - But not so much of it

# Address Translation with Segmentation




- The **maximum segment length** is determined by the length of the offset of the virtual addresses
  - In this example, the length of the offset is 12 bits
    $\Longrightarrow$ maximum segment length $= 2^{12} = 4,096$ bits $= 512$ Bytes

# Segment Table Structure

- Each segment table record contains among others:
  - **Present bit**: Specifies whether the segment in stored inside the main memory
  - **Dirty bit** (*Accessed bit* or *Modified bit*): Specifies whether the segment was modified
  - **Further control bits**: Specifies e.g. access control privileges
  - **Length**: Length of the segment
  - **Segment basis**: Is added to the offset of the virtual address

Virtual (logical) address

| Segment number | Offset |
|---|---|

Segment table entry

| P | D | Further control bits | Length | Segment basis |
|---|---|---|---|---|

- If a program tries to access a segment, which is not in the physical main memory, a **segment not present** exception is raised
  - The **present bit** in each segment table record indicates whether a segment is located inside main memory or not

# 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**
  - Operating mode of x86-compatible CPUs
  - Implements the **virtual memory** concept
  - **16 bit protected mode** (introduced with the Intel 80286)
    - Only **segmentation**
    - With the 24 bits address bus, a maximum of $2^{24}$ Bytes = 16 MB of physical main memory can be addressed
    - Main memory is split into segments of $2^{16}$ Bytes = 64 kB maximum each
  - **32 bit protected mode** (introduced with the Intel 80386)
    - Main memory is split into segments of $2^{32}$ Bytes = 4 GB maximum each
    - **Paging** can be used in addition to the segmentation
    - A maximum of 4 GB physical main memory can be addressed

# Virtual Memory in Modern Operating Systems (1/2)

- Modern operating systems (for x86) operate in protected mode and use only paging
  - Segmentation is no longer used
- This method is called **flat memory model**
  - Data, code, extra and stack segment cover the entire address space
  - This way, the entire address space of each process is addressable via the offset
    - Segmentation does not provide memory protection any more
    - But this is not a problem, because of the paging

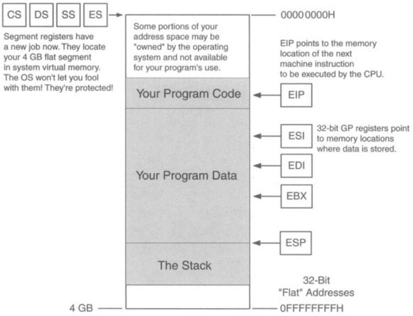



Image Source: `http://www.c-jump.com`

- Benefit: Operating systems can be ported more easily to other CPU architectures, which do not implement segmentation

# Virtual Memory in Modern Operating Systems (2/2)

- Some architectures:
  - IA32 (see slide 30)
    - 2-level page table
    - Length of virtual addresses: 32 bits
    - 10+10+12 $\Longrightarrow$ 10 bits for the 2 page tables plus 12 bits offset
  - IA32 mit Physical Address Extension (PAE) $\Longrightarrow$ Pentium Pro
    - 3-level page table
    - Length of virtual addresses: 32 bits
    - 2+9+9+12 $\Longrightarrow$ 2 bits for the first page table and 9 bits each for the 2 further page tables plus 12 bits offset
  - PPC64
    - 3-level page table
    - Length of virtual addresses: 41 bits
    - 10+10+9+12 $\Longrightarrow$ 10 bits for the first two page tables, 9 bits for the third page table plus 12 bits offset
  - AMD64 (x86−64)
    - 4-level page table
    - Length of virtual addresses: 48 bits
    - 9+9+9+9+12 $\Longrightarrow$ 9 bits each for the 4 page tables plus 12 bits offset

# Hit Rate and Miss Rate

- In case of a request to a computer memory, 2 results are possible:
  - **Hit**: Requested data is available
  - **Miss**: Requested data is missing
- 2 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

- It makes sense to keep the data ($\Longrightarrow$ **pages**) inside main memory, which is frequently 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 seplacement strategies. . .

- OPT, FIFO, LRU and Clock provides **Operating Systems**, *William Stallings*, 4th edition, Prentice Hall (2001), P.355-363
- FIFO, LRU, LFU and Clock provides **Betriebssysteme**, *Carsten Vogt*, 1st edition, Spektrum Verlag (2001), P.162-163
- FIFO, LRU and Clock provides **Moderne Betriebssysteme**, *Andrew S. Tanenbaum*, 2nd edition, Pearson (2009), P.237-242
- FIFO, LRU, LFU and Clock provides **Betriebssysteme**, *Eduard Glatz*, 2nd edition, dpunkt (2010), P.471-476

# Optimal strategy (OPT)

Image Source: Lukasfilm Games

- Replaces the page, which is **not accessed for the longest time in the future**
- Impossible to implement!
  - Reason: Nobody can predict the future
    - Therefore, the operating system must take into account the past
- 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 accessed 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 accesses

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

→ 10 Miss

# Least Frequently Used (LFU)

- Replaces the page, which was **least often accessed**
- For each page in memory, a reference counter exists in the page table, which stores the number of accesses
- 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 accesses
- Drawback: Pages which have been accessed often in the past, may block the memory

| Requests: | **1** | **2** | **3** | **4** | **1** | **2** | **5** | **1** | **2** | **3** | **4** | **5** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Page 1: | ${}_{1}1$ | ${}_{1}1$ | ${}_{1}1$ | ${}_{1}4$ | ${}_{1}4$ | ${}_{1}4$ | ${}_{1}5$ | ${}_{1}5$ | ${}_{1}5$ | ${}_{1}3$ | ${}_{1}4$ | ${}_{1}5$ |
| Page 2: | | ${}_{1}2$ | ${}_{1}2$ | ${}_{1}2$ | ${}_{1}1$ | ${}_{1}1$ | ${}_{1}1$ | ${}_{2}1$ | ${}_{2}1$ | ${}_{2}1$ | ${}_{2}1$ | ${}_{2}1$ |
| Page 3: | | | ${}_{1}3$ | ${}_{1}3$ | ${}_{1}3$ | ${}_{1}2$ | ${}_{1}2$ | ${}_{1}2$ | ${}_{2}2$ | ${}_{2}2$ | ${}_{2}2$ | ${}_{2}2$ |

$\longrightarrow$ 10 Miss

# First In First Out (FIFO)

- Replaces the page, which is stored **in memory for the longest time**
- Assumption: increasing the memory results in fewer or, at worst, the same miss number
- Problem: Laszlo Belady demonstrated in 1969 that for certain access patterns, FIFO creates with an increased memory capacity more miss ($\Longrightarrow$ **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 28), which exists in the page table for each page
  - If a page is loaded into memory $\Longrightarrow$ reference bit $= 0$
  - If a page is accessed $\Longrightarrow$ reference bit $= 1$
- A pointer indicates the last accessed 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 will be 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 by Digital Equipment Corporation) and Windows NT 4.0 on uniprocessors 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
- **Random**: Random pages are replaced
  - Benefits Simple and resource-saving replacement strategy
    - Reason: No need to store information about the access behavior

**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
- The Intel i860 RISC CPU uses the Random replacement strategy for the cache