Introduction to the Course

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Why this Course?

- Today, virtualization is very used in computing systems
  - From “low-power” devices (traditionally considered as embedded)...
  - ...To big clouds!
- Used for various reasons:
  - Security / safety
  - Running multiple OSs on the same machine
  - Server consolidation
  - “On-demand” allocation of computing resources
- Lots of very different technologies...

Virtualization?

- "Virtualization" is often used as a generic term, to indicate lots of different things
  - Different kinds of requirements and features...
  - ...Different levels of performance, security, flexibility
- People sometimes consider virtualization solutions and VMs as "black boxes"
  - Without caring about the used mechanisms or implementation details
- As a result, it becomes difficult to exactly understand the security and performance implications
- Need for better understanding of the various virtualization technologies and soltions!

Overview — 1

- Introduction to virtualization
- Various levels of virtualization
  - Hardware virtualization
  - OS-level virtualization
    - Containers
  - language-level virtualization, ...
- Virtualizing computing and non-computing resources
  - CPU virtualization
    - Emulation
    - Trap and emulate
    - Hardware-assisted virtualization
  - I/O devices virtualization, ...

Overview — 2

- Virtual abstractions
  - VMs vs containers
  - Containers as an abstraction (as opposite to containers as a technology)
- Virtualization architectures
- Real-Time virtualization
  - Latencies
  - Hierarchical scheduling
- Modern technologies
  - Lightweight VMs / MicroVMs
  - Unikernels, specialized/reduced monitors

Virtualization

- Virtualization: creation of a *virtual instance* of a computing system
  - Computer (PC, server, embedded board, ...)
  - Operating System
  - Storage device / other
- Separate / independent from the physical system(s) hosting it
- This mainly requires two activities:
  1. Pooling: consolidating possibly distributed resources into a single logical entity
  2. Isolation: creating the impression that the virtualized application has a private copy of the resources

Resource Pooling

- Set of multiple, possibly distributed, resources
- Single “virtual resource”, that can be used to transparently access them
  - Pool of physical servers hosting VMs in a cloud; accessed by starting a VM $\Leftarrow$ load balancing
  - Pool of storage devices (disks, databases, ...) accessed as a single virtual storage device $\leftarrow$ I do not know where data are really stored...
  - ...
- Used for automatically distributing the load, for building powerful machines based on less powerful ones, for making computation independent on data placement, ...

Resource Isolation

- The usage of virtual resources must be controlled by the virtualization software
  - Example: applications running in a VM should not be able to access resources outside of the VM...
  - ...Nor to directly access physical resources!
  - Or: applications using a virtual storage device should not be able to even see the physical storage devices
  - ...
- Virtual resources should not even be distinguishible from physical ones
  - Example: applications running in a VM should have the impression to run on a physical machine...

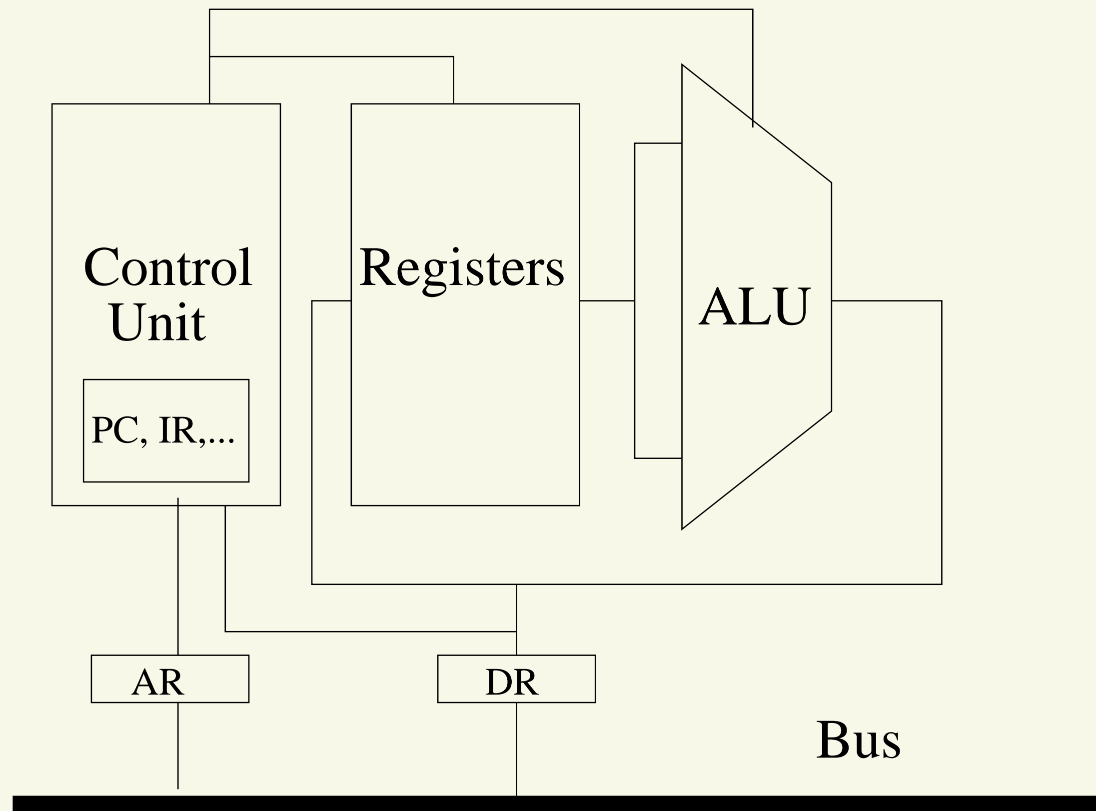
Different Kinds of Isolation...

- Resource isolation can be used for different reasons
  - Security $\leftarrow$ reduce the impact of compromised subsystems
  - Application sandboxing $\leftarrow$ execute non-trusted software
  - Performance guarantees $\leftarrow$ isolate the performance of a component from interference of other components
  - ...
- Different kinds of requirements

...And Different Kinds of Virtualization

- Example: Compute virtualization $\leftarrow$ virtualization of a computing element
- Different kinds of abstractions, ranging from Virtual Machine (virtual instance of a PC) to "virtual language runtime"
  - Abstraction: virtual PC $\rightarrow$ probably strongest type of isolation, but some overhead
  - Abstraction: JVM $\rightarrow$ much less isolation (but the virtualization overhead can be reduced)
- Common concept: Abstract Machine... Let's look at it
  - Starting from the very beginning: physical machine

Example of (Toy) CPU

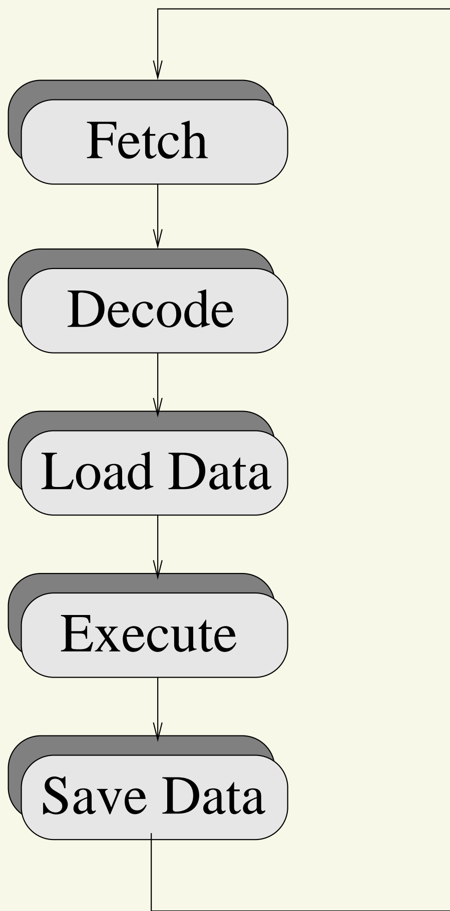


- Toy CPU: just an example with many simplifications
- Modern (real) CPUs are much more complex!
  - Pipeline
  - Parallel execution
  - ...

CPUs, Programs, & Friends

- CPU $\rightarrow$ executes programs
  - Stored in main memory
  - Use data from main memory
- Program: formal description of an algorithm
  - Using a programming language
- Sequence of machine instructions
  - Actions having effects on some objects
  - "Object": data stored in main memory
- Instance of program in execution: sequence of actions on objects
  - Example: `int mcd(int a, int b)` and its execution

Executing a Program



- CPU: cyclical execution (fetch / decode / load / execute / save)
  - Machine instructions are executed (mainly) sequentially
- Machine designed to execute its own language!
  - Machine Language

Physical Machines...

- Computer: (physical) machine designed to execute programs
- Every machine executes programs written in its own language
- Relationship between machine and language
  - A machine has its own language (the language it can parse and execute)
  - A language can be “understood” (parsed and executed) by multiple different machines
- Program execution: (infinite) cycle fetch/decode/load/execute/save
  - CPU: hw implementation of this cycle

...And Abstract Machines!

- The fetch/decode/load/execute/save cycle can be implemented in hw or in sw...
- Software Implementation: Abstract Machine
  - Algoritmhms and data structures used to store and execute programs
- Once upon a time referred as "*Virtual Machine*"
  - Today, the term "Virtual Machine" (VM) is used with a slightly different meaning

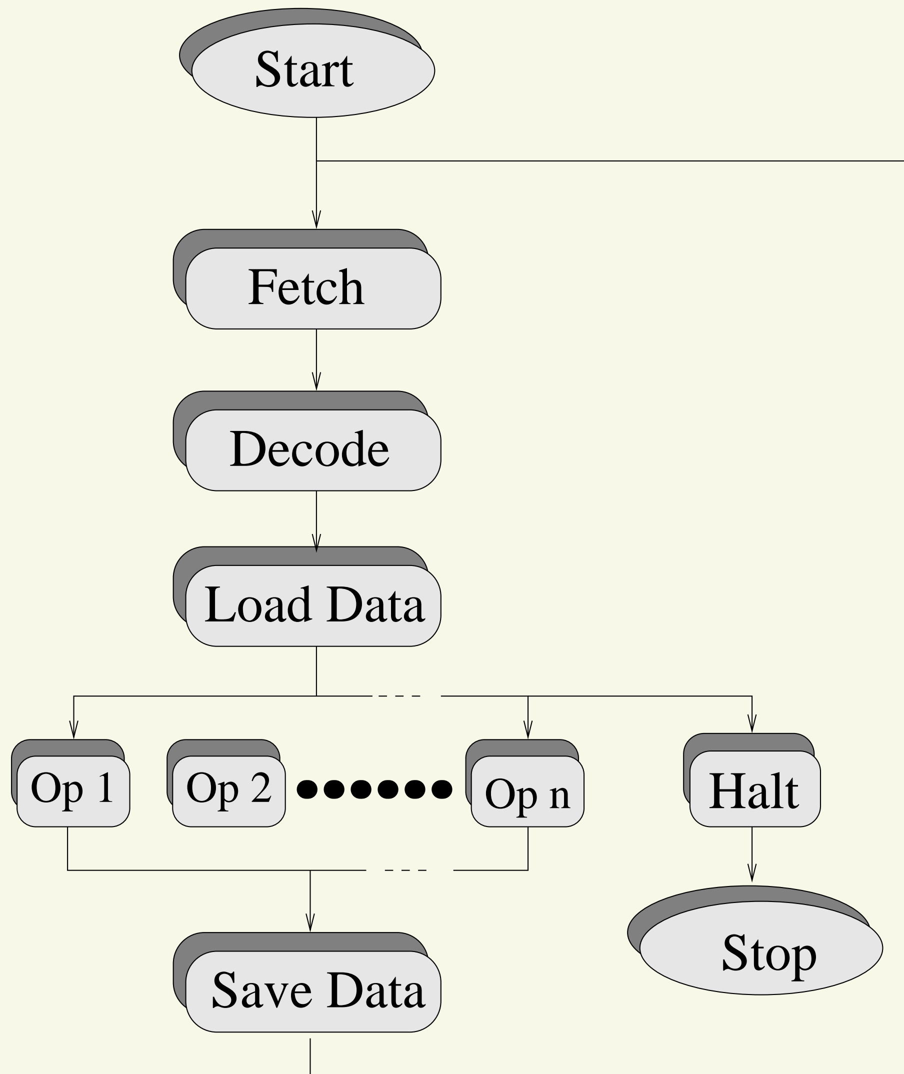
Abstract Machines and Languages

- Similarly to physical machines (CPUs), each abstract machine has its own machine language
  - Machine language for a CPU: sequence of 0 / 1
    - Assembly makes it more readable
  - Abstract machines generally have higher level machine languages (C, Java, etc...)
- $\mathcal{M}_\mathcal{L}$: abstract machine understanding language $\mathcal{L}$
  - $\mathcal{L}$ is the *machine language* of $\mathcal{M}_\mathcal{L}$
  - Program: sequence of instructions written in $\mathcal{L}$
- $\mathcal{M}_\mathcal{L}$ is just a possibile way to describe $\mathcal{L}$

Abstract Machines Behaviour

- To execute a program written in $\mathcal{L}$, $\mathcal{M}_{\mathcal{L}}$ has to:
  1. Execute some “elementary operations”
     - In hw, ALU
  2. Manage the execution flow
     - Execution is not only sequential (jumps, loops, etc...)
     - In hw, PC handling
  3. Move data from / to memory
     - Addressing modes, ...
  4. Take care of memory management
     - Dynamic allocation, stack management, etc...

Abstract Machine Example



- Execution cycle: very similar to a CPU...
- ... But it is implemented in software!

Virtualized Resources

- Virtual Machine: efficient, isolated duplicate of a physical machine
  - Why focusing on *physical* machines?
  - What about abstract machines?
- Software stack: hierarchy of abstract machines
  - ...
  - Abstract machine: language runtime
  - Abstract machine: OS (hardware + system library calls)
  - Abstract machine: OS kernel (hardware + syscalls)
  - Physical machine (hardware)

Hardware Virtualization

- Can be full hardware virtualization or paravirtualization
  - Paravirtualization requires modifications to guest OS (kernel)
- Can be based on trap and emulate
- Can use special CPU features (hardware assisted virtualization)
- In any case, the hardware (whole machine) is virtualized!
  - Guests can provide their own OS kernel
  - Guests can execute at various privilege levels

OS-Level Virtualization

- The OS kernel (or the whole OS) is virtualized
  - Guests can provide the user-space part of the OS (system libraries + binaries, boot scripts, ...) or just an application...
  - ...But continue to use the host OS kernel!
- One single OS kernel (the host kernel) in the system
  - The kernel virtualizes all (or part) of its services
- OS kernel virtualization: container-based virtualization
- Example of OS virtualization: wine

Virtualization at Language Level

- The language runtime is virtualized
  - Often used to achieve independence from hardware architecture
- Example: Java Virtual Machine
- Often implemented by using emulation techniques
  - Interpreter or just-in-time compiler

Hardware Virtualization

- Virtual Machine: efficient, isolated duplicate of a physical machine
  - Execution environment essentially identical to the physical machine
  - Programs only see a small decrease in speed
  - A “monitor” or “hypervisor” is in full control of physical resources
- Programs running in a VM should not see differences respect to real hw
- Virtualization should be efficient
- Programs should not be able to access resources outside of the VM

VMs and OSs

- How is an OS related to Virtual Machines?
  - The OS should provide support for the Virtual Machine Monitor / hypervisor
  - The OS *could* be optimized to run inside a VM
- OS suport for virtualization (as host or as guest)
  - Impact on resource management
  - Impact on the exposed features
  - Impact on the I/O devices support
- Impact on the OS architecture?
  - Host: type-I hypervisors, μ-kernel systems
  - Guest: library OSs, unikernels, vertically structured OSs

CPU Virtualization

- First idea: simulate the CPU hw in software
  - Software implementation of an abstract machine implementing the fetch-decode-execute-(write) cycle
  - Fails the efficency requirement!!!
- Other idea: directly execute the virtualized instructions on the CPU
  - Virtual ISA: exact copy of the host ISA
  - Might fail the third (VMM is in control) requirement
  - Limited to unprivileged instructions (with VMM executing at a high privilege level)
  - What to do for privileged instructions?

Virtualizable CPU Architectures

- The monitor should be able to “intercept” some machine instructions
  - Some kind of trap / exception / software interrupt must be generated
  - Not always possible (think about x86 ring 0)
- The CPU must provide some support for full virtualization
  - “More than supervisor” mode $\rightarrow$ hypervisor mode
  - Introduce two operating modes: “root mode” and “non-root mode”; non-root mode can only modify a shadow copy of the CPU privileged state
  - ...

OSs for Virtualizable Architectures

- Virtualizable ISA: how to use it?
  - VMM or hypervisor responsible for managing VMs and other resources
  - Re-invent an OS, or using an existing one?
- OS support for hypervisors
  - Hosted hypervisor
  - Dom0
  - ...
- Difference between a hypervisor and a μ-kernel???
  - Are we reinventing an old idea?
  - ...And, what are μ-kernels, after all???

ParaVirtualization

- So, CPU virtualization can be easy and efficient
  - Provided that the ISA is virtualizable
  - Provided host OS support / hypervisor
- What about I/O devices?
  - Virtualizing real hardware can be complex and inefficient
  - Idea: device passthrough
  - Other possibility: paravirtulization
- Paravirtualization: the guest knows that it is running in a VM
  - Memory buffers can be (securely) shared between guest and host
  - ...

Different Kinds of VMMs/Hypervisors

- Software implementation of $\mathcal{M}_{\mathcal{L}}$ (hardware machine): executes on a Host Machine $\mathcal{M}h_{\mathcal{L}h}$
- $\mathcal{M}h_{\mathcal{L}h}$ is of course an abstract machine...
  - Is it the hardware machine?
  - Is it a higher-level abstract machine (implemented by kernel, OS, ...)?
- In other words: where does the hypervisor run?
  - Does it run directly on the hardware?
  - Does it run on an OS kernel?
  - Does it uses other services provided by a host OS?

Bare Metal Hypervisors

- The host machine $\mathcal{M}h_{\mathcal{L}h}$ is the hardware machine, without extensions
  - The hypervisor directly accesses the hardware
  - Loaded by some kind of bootloader, controls the execution of guest kernels/OSs
  - No functionalities provided by a "host kernel"
- Examples: Xen, but also Jailhouse (funny detail: Linux is the bootloader!)
- How to access the physical devices?
  - Must implement device drivers...
  - ...Or rely on a "special" guest OS that provides the drivers
  - Generally uses pass-through techniques

Hosted Hypervisors

- The host machine is the hardware machine + a host kernel (or even a host OS!)
  - The hypervisor can rely on functionalities provided by the host kernel
  - No need to re-implement memory management, drivers, CPU scheduler, ...
- Examples: KVM, VirtualBox, ...
- The hypervisor can be started only after the guest OS is booted
  - There generally is a kernel-level hypervisor + a user-level management tool (sometimes named VMM)

OS-Level Virtual Machines

- Virtual Machine: efficient, isolated duplicate of an operating system (or operating system kernel)
- Do not virtualise the whole hardware
  - Only OS services are virtualised
  - Host kernel: virtualise its services to provide isolation among guests
- Container: isolated execution environment to encapsulate one or more processes/tasks
  - Sort of “chroot on steroids”
- Two aspects: resource control (scheduling) and visibility

More on “Containers”

- Container: resource control and visibility
  - Control how many resources a VM is using
  - Make sure that virtual resources of a VM are not visible in other VMs
- “Resource Containers: A New Facility for Resource Management in Server Systems” (Banga et al, 1999)
  - Operating system abstraction containing all the resources used by an application to achieve a particular independent activity
- Today, “container” == execution environment
  - Used to run a whole OS $\rightarrow$ VM (with OS-level virtualization)
  - Used to run a single application / micro-service

Linux Containers

- The Linux kernel does not directly provide the "container" abstraction
- Containers can be built based on lower-level mechanisms: *control groups* (`cgroups`) and *namespaces*
  - namespaces: isolate and virtualise system resources
  - cgroups: limit, control, or monitor resources used by groups of tasks
- Namespaces are concerned with resources' visibility, cgroups are concerned with scheduling

Linux Namespaces

- Used to isolate and virtualise system resources
  - Processes executing in a namespace have the illusion to use a dedicated copy of the namespace resources
  - Processes in a namespace cannot use (or even see) resources outside of the namespace
- Processes in a network namespace only see network interfaces that are assigned to the namespace
  - Same for routing table, etc...
- Processes in a PID namespace only see processes from the same namespace
  - PIDs can be“private to the namespace”

Linux Control Groups

- Used to restrict (limit, control) or monitor the amount of resources used by “groups of processes”
  - Processes can be organized in groups, to control their accesses to resources
- Example: CPU control groups for scheduling
  - Limit the amount of CPU time that processes can use, etc...
- Similar cgroups for other resources
  - memory, IO, pids, network, ...

Building a Container

- Namespaces and control group give fine-grained control on processes and resources
  - Per-resource control groups and/or namespaces
  - Lower level abstractions respect to other OSs (for example, FreeBSD jails)
- More powerful than other mechanisms, but more difficult to use
- To build a container, it is necessary to:
  - Setup all the needed namespaces and control groups
  - Create a “disk image” for the container (directory containing the container’s fs)

Running in a Container

- Chroot to the container fs
  - Must contain the whole OS, or the libraries/files needed to execute the program to containerize
- Start init, or the program to containerize
  - Thanks to the PID namespace, it will have PID 1 in the container!
- Note: init can mount procfs or other pseudo-filesystems
  - Namespaces allow to control the information exported in those pseudofilesystems!

Example: Networking in Containers

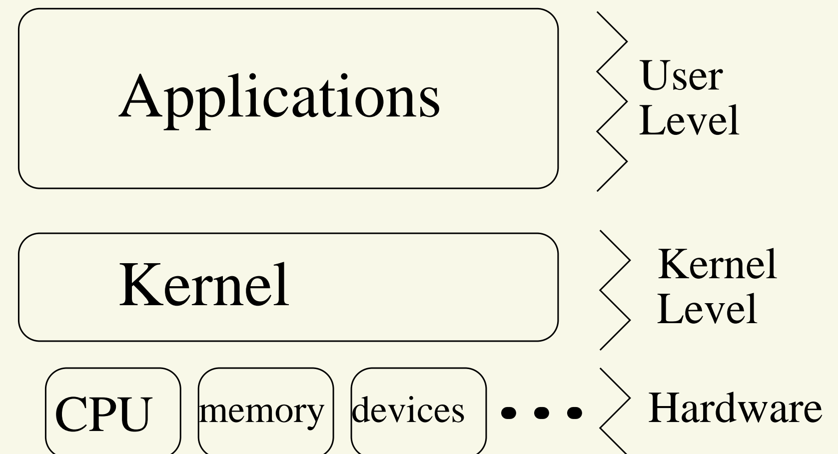
- Thanks to the network namespace, processes running in a container do not see the host's network interfaces
  - How to do networking, then?
- Create a *virtual ethernet pair*
  - Two virtual ethernet interfaces, connected point-to-point
  - Packets sent on one interface are received on the other, and vice-versa
- Associate one of the two virtual ethernet interfaces to the network namespace of the container
- Bind the other one to a software bridge

Virtual Operating Systems

- Instead of virtualizing kernel services, it is possible to virtualize the whole OS!
  - With containers, software implementation of an abstract macine $\mathcal{M}_\mathcal{L}$ corresponding to the OS kernel (understanding machine language + system calls)
  - Possible to implement an abstract machine $\mathcal{M}_\mathcal{L}$ understanding machine language + standard OS runtime (libc, ...)
- Possible to execute (for example) Windows applications on Linux (or vice-versa!)
  - How can this be implemented in practice?
  - Re-implement the system libraries...

The Kernel

- Kernel $\rightarrow$ OS component interacting with hardware
  - Runs in privileged mode (Kernel Space $\rightarrow$ KS)
  - User Level $\Leftrightarrow$ Kernel Level switch through special CPU instructions (INT, TRAP, ...)
  - User Level invokes *system calls* or IPCs
- Kernel Responsibilities
  - Process management
  - Memory management
  - Device management
  - System Calls



System Libraries

- Applications generally don't invoke system calls directly
- They generally use *system libraries* (like glibc), which
  - Provide a more advanced user interface (example: `fopen()` vs `open()`)
  - Hide the US $\Leftrightarrow$ KS switches
  - Provide some kind of stable ABI (application binary interface)

Static vs Shared Libraries - 1

- Libraries can be *static* or *dynamic*
  - `<libname>.a` vs `<libname>.so`
- Static libraries (`.a`)
  - Collections of object files (`.o`)
  - Application linked to a static library $\Rightarrow$ the needed objects are included into the executable
  - Only needed to compile the application

Static vs Shared Libraries - 2

- Dynamic libraries (`.so`, shared objects)
  - Are not included in the executable
  - Application linked to a dynamic library $\Rightarrow$ only the library symbols names are written in the executable
  - Actual linking is performed at loading time
  - `.so` files are needed to execute the application
- Linking static libraries produces larger executables...
- ...But these executables are “self contained”

OS ABI Virtualization

- A modified executable loader load some “special” system libraries instead of the standard ones
  - On Windows, when loading an ELF Linux executable dynamically link a “libc.so” implementing the Linux ABI on the windows kernel
  - On Linux, when loading a PE Windows executable dynamically link some special “win32.dll”/“win64.dll” implementing the Windows ABI on Linux
  - ...
- Of course, the devil is in the details (look at Wine!)
- What to do for statically linked applications / applications directly invoking syscalls?