Virtualization and memory hierarchy

Computer Architecture

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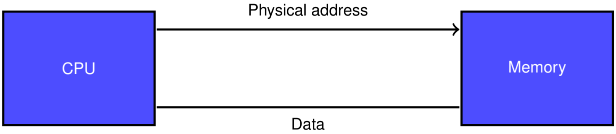
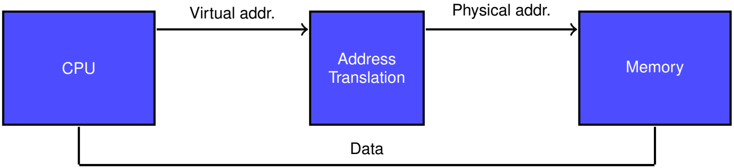
Limits of physical memory addressing



- All programs share a single addressing space.
  - **Physical address space**.
- There is no way to prevent a program to access a resource.

Overcoming the physical limit



- Programs run in a **normalized virtual addresses space**.
- **Address translation**:
  - Performed by hardware.
  - Managed by OS.
- **Supported features**:
  - Protection, Translation, Sharing.

Advantages of virtual memory (I)

- **Translation**:
  - Programs may have a **consistent view** of memory.
  - Decreases **cost** of **multi-threaded** applications.
  - Only the **working set** is needed in main memory.
  - Dynamic structures only use the physical memory that they **really need** (e.g. stack).

Advantages of virtual memory (II)

- **Protection**:
  - Allows to **protect** a process from others.
  - **Attributes** can be set at **page level**.
    - Read only, execution, ...
  - **Kernel** data protected from programs.
  - Improves protection against **malware**.

- **Sharing**:
  - **A page** can be **mapped** to several processes.
    - e.g. Memory mapped files.

Differences with cache

- **Replacement**:
  - **Cache**: Hardware controlled.
  - **VM**: Software controlled.
- **Size**:
  - Cache size independent from address length.
  - VM size dependent from address length.

Parameters

Parameter	L1 Cache L1	Virtual memory
Block size	16 – 128 bytes	4096 – 65,536 bytes
Hit time	1 – 3 cycles	100 – 200 cycles
Miss penalty	8 – 200 cycles	10^6 – 10^7 cycles
Access time	6 – 160 cycles	$8 \cdot 10^5$ – $8 \cdot 10^6$ cycles
Transfer time	2 – 40 cycles	$2 \cdot 10^5$ – $2 \cdot 10^6$ cycles
Miss rate	0.1% – 10%	0.00001% – 0.001%

Four questions on memory hierarchy

1. Where can a block be placed in the upper level?
   - **Block placement**.
2. How is a block found in the upper level?
   - **Block identification**.
3. Which block must be replaced on miss?
   - **Block replacement**.
4. What happens on a write?
   - **Write strategy**.

Four questions on **virtual memory**

1. Where can a **page** be placed in **main memory**?
   - **Page placement**.
2. How is a **page** found in **main memory**?
   - **Page identification**.
3. Which **page** must be replaced on miss?
   - **Page replacement**.
4. What happens on a **write**?
   - **Write strategy**.

Where is a page placed in main memory?

- A page may be placed in **any page frame** in main memory.
  - Fully associative mapping.
- Managed by the operating system.
- **Goal**: **Minimize miss rate**.
  - Cannot do much with miss penalty.
  - Very high penalty due to slow magnetic disks.

How is a page found in main memory?

- Keep in main memory a **page table per process**.
  - **Mapping table** between **page identifier** and **page frame identifier**.

- Decreasing translation time.
  - **TLB**: *Translation Lookaside Buffer*.
  - Avoids accesses to page table in main memory.

Which page should be replaced on a miss?

- Replacement policy defined by Operating System.
  - Typically **LRU** (*Least-recently used*).

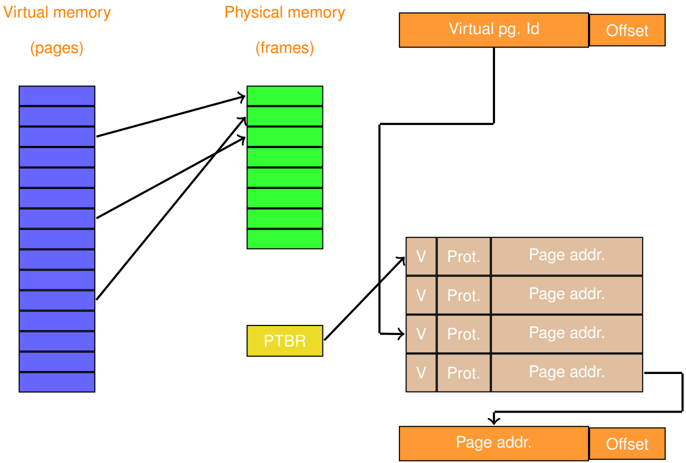
- Architecture must supply support to operating system.
  - **Use bit**: Enabled when page is accessed.
    - Really, only when TLB miss.
  - Operating system periodically zeroes this bit.
    - Records values later.
    - Allows to determine pages that have been modified within an interval.

What happens on a miss?

- Write strategy is always **write-back**.
  - No VM systems with write-through ever built.
  - **Don't be tempted!**

- Disk write costs extremely high.
  - Disk writes minimization.
  - Use **dirty bit** to annotate when a page has been modified.

Page table


Virtual memory
(pages)
Physical memory
(frames)
Virtual pg. Id
Offset
PTBR
V
Prot.
Page addr.
V
Prot.
Page addr.
V
Prot.
Page addr.
V
Prot.
Page addr.
Page addr.
Offset

Page table size

- Assuming **32 bits virtual addresses**, **4 KB pages** and **4 bytes** per **table entry**:
  - **Table size**:

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

- **Alternatives**:
  - Multi-level page tables.
  - Inverted page tables.
- **Example**: IA-64
  - Offers both alternatives to OS developer.

TLB: Translation Lookaside Buffer

- **Ideal case**.
  - Each access requires two memory accesses.
    1. Access to page table.
    2. Access to memory.
  - Worse scenario in case of multi-level pages.

- **Solution**:
  - Use translation cache to avoid accesses to page table.
    - **Tag**: Portion of virtual address.
    - **Data**: Frame number, protection bits, validity bit, and dirty bit.

Virtual machines

- Developed in late 60's.
  - Used since in *mainframe* environments.
  - Ignored in single user machines until late 90's.

- Recovered popularity due to:
  - Increasing importance of **isolation** and **security** in modern systems.
  - **Security** and **reliability** failures in operating systems.
  - **Sharing** a single computer by multiple unrelated users.
  - Dramatic increase in processor **performance**.
    - Overhead of VMMs more acceptable now.

Virtual Machine Monitor

A virtual machine is taken to be an efficient, isolated duplicate of the real machine. We explain these notions through the idea of a Virtual Machine Monitor (VMM) ...
...a VMM has three essential characteristics.

- First, the VMM provides an environment for programs which is essentially identical with the original machine,
- second, programs run in this environment show at worst only minor decreases in speed;
- and last, the VMM is in complete control of system resources.

Source: Popek, G. y Goldberg, R. **Formal requirements for virtualizable third generation architectures**.

Communications of the ACM, July 1974

Virtualization

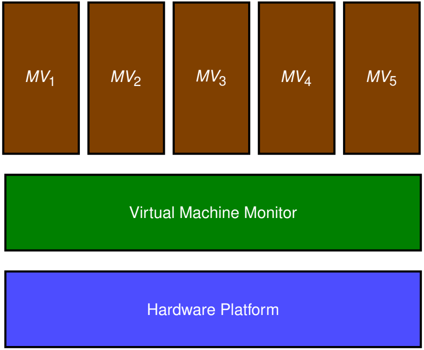
- **General definition**: Any emulation method offering a standard software interface to the physical machine.
  - Java VM? .NET?

- **System level virtual machines**: Offer a complete system environment at binary ISA level.
  - Usually assuming that VM ISA and hardware ISA are identical.
  - **Examples**:
    - IBM VM/370.
    - VMWare ESX Server.
    - Xen.

Virtual machine

- Offers to the user the illusion that they have a **complete computer**.
  - Including their own copy of the operating system.
- A computer can run **several virtual machines**.
  - May support several operating systems.
  - All operating systems sharing same hardware.
- **Terminology**:
  - **Host**: Underlying hardware platform.
  - **Guest**: Each virtual machine sharing resources.

VM y VMM: Layers



- **VMM** $\rightarrow$ Software system layer.
  - Monitor runs on hardware platform.
  - Allows execution of multiple virtual machines on single hardware platform.
  - Each virtual machine has its own operating system and applications.
  - Allows running applications without modification.

VMM

- **Virtual Machine Monitor** or **hypervisor**:
  - Software supporting virtual machines.

- VMM determines mapping between: **virtual resources** and **physical resources**.

- **Alternatives for physical resource sharing**:
  - Time sharing.
  - Partitioning.
  - Software emulation.

- A VMM is **smaller** than a traditional OS.

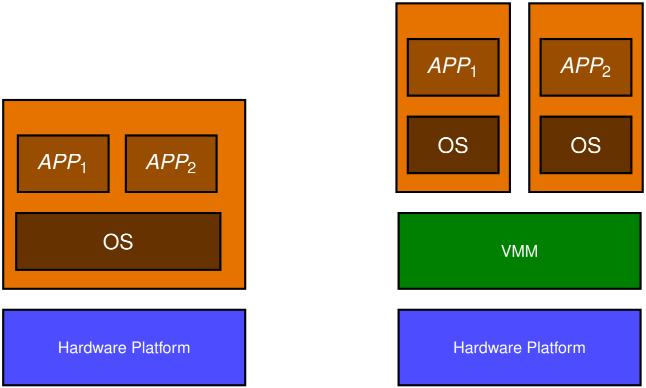
Overhead of VMM

- Depends on workloads.
- User level**processor bound** programs:
  - **Example**: SPEC.
  - **Overhead**: 0.
  - Invocations to OS are rare.
- **I/O intensive** programs $\rightarrow$ **OS intensive**.
  - Many system calls $\rightarrow$ Privileged instructions.
  - May lead to **a lot of virtualization overhead**.
- **I/O intensive** and **I/O bound** programs.
  - Low processor utilization.
  - **Virtualization** may be **hidden**.
  - **Low virtualization overhead**.

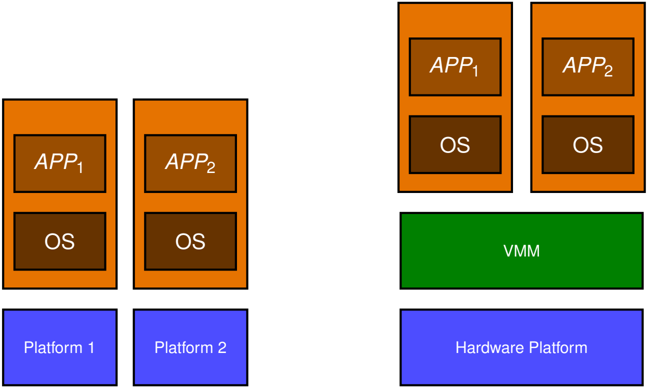
Other uses (in addition to protection)

- **Software management.**
  - VM offers an **abstraction** allowing to run a **complete software stack**.
    - Old operating Systems (DOS?).
  - **Combined** deployment:
    - Stable OS, legacy OS, and next OS version.
- **Hardware management.**
  - VM allows to run **separate software stacks** but on top of a single hardware platform.
    - Servers consolidation.
    - Independence *rightarrow* Higher reliability.
  - **Migrating** VMs in execution.
    - Load balancing.
    - Hardware evacuation due to failures.

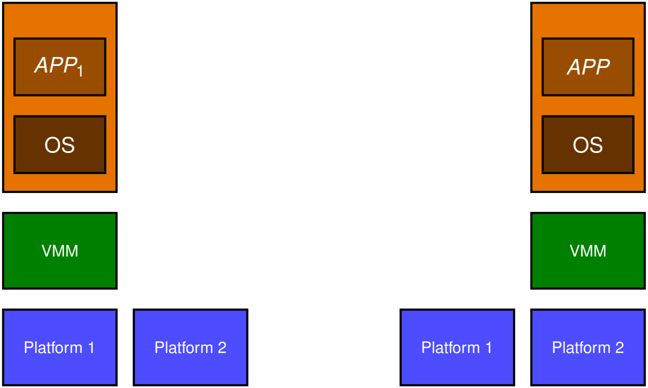
Uses: isolation



Uses: consolidation



Uses: migration



VMM requirements (I)

- A **VMM**:
  - Offers a **software interface** to guest software.
  - **Isolates** a guest state from the rest.
  - **Protects** itself form guests.

- **Guest software** should behave as if there was no VMM, except for:
  - Performance dependent behavior.
  - Limitations of fixed resources when shared among multiple VMMs.

VMM requirements (II)

- Guest software must not be able to modify directly real resources allocation.
- VMM must control everything, even if used by guests.
  - Access to privileged state, address translation, I/O, exceptions, interruptions, ...
- VMM must run in a more privileged mode than guests.
  - Execution of privileged instructions by VMM.
- Requirements of VMM (equivalent to requirements for virtual memory).
  - A minimum of two processor modes.
  - Subset of privileged instructions, only in privileged mode.
    - Trap if executed in user mode.

ISA support

- If VM considered in ISA design, it is easy to reduce instructions that VMM must execute and emulation time.
  - **But**, Most desktop ISAs designed before VMs.
- VMM must ensure that guests only interact with virtual resources.
  - Guest OS running in user mode.
  - Trying to access hardware leads to a trap.
- If ISA is not VM-aware, VMM must intercept problematic instructions.
  - Introduction of virtual resource.

Impact on virtual memory

- Each guest manages virtual memory.
  - Virtualizing virtual memory?
- VMM distinguishes between **real memory** and **physical memory**.
  - **Real Memory**: Intermediate level between **virtual memory** and **physical memory**.
  - **Guest**: Mapping between **virtual memory** and **real memory**.
  - **VMM**: Mapping between **real memory** and **physical memory**.
- To decrease indirection level, VMM keeps a **shadow page table**.
  - Mapping between **virtual memory** and **physical memory**.
  - VMM must capture changes in **page table** and **pointer to page table**.

ISA support for virtual memory virtualization

- IBM 370 includes additional indirection level managed by VMM.
  - Eliminates the need of shadow the page table.

- TLB virtualization.
  - VMM manages TLB and keeps copies of TLB in each guest.
  - TLB accesses generate a trap.
  - TLB with process identifiers simplifies management.
    - Allow entries from multiple VMs over the VMM at the same time.

Input/Output impact

- **Most complex** part in virtualization.
  - Increasing number of I/O devices.
  - Increasing diversity of I/O devices.
  - Sharing devices among VMs.
  - Support for an increasing variety of drivers.
- **General part** of driver remains on the guest side.
  - **Specific part** in VMM.
- **Device dependent** method.
  - **Disks**: Partitioned by VMM for creating virtual disks.
  - **Network interfaces**: Multiplexed over time.
    - VMM manages **virtual network addresses**.

7 Virtualization technologies

- Impure virtualization
- ISA Technologies

Impure virtualization

- Solution for **non-virtualizable** architectures and for decreasing **performance problems**:
- **Approaches**:
  - **Paravirtualization**: Port guest OS code to a modified ISA.
    - Development effort.
    - Need to adapt code for every OS.
    - Source code must be available.
  - **Binary translation**: Replace non-virtualizable instructions by emulation code or VMM calls.
    - Does not require source code.
    - Some emulations are possible in user space.

Example: XEN

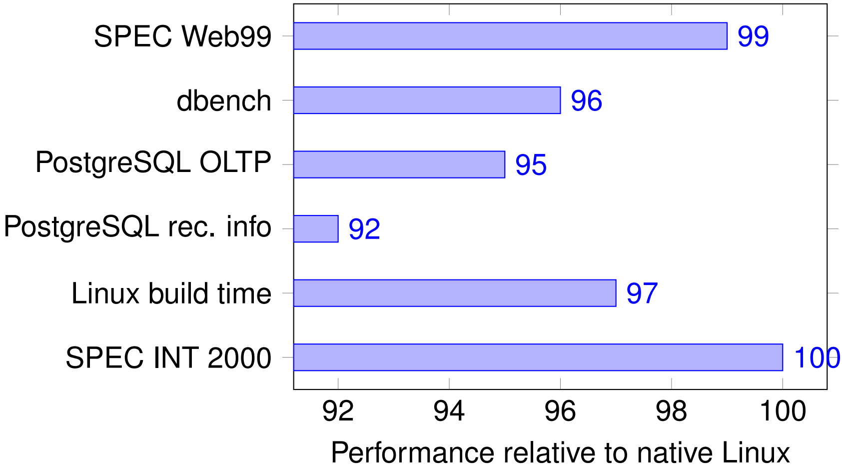
- **Xen**: VMM *open-source* for x86.
- **Strategy**: **Paravirtualization**.
  - Small modifications into the OS to simplify virtualization.
- **Examples of paravirtualization**:
  - Avoid TLB **flush** when the VMM is invoked.
    - Xen mapped to upper 64MB in each VM.
  - Allow guest to **allocate** pages.
    - Check if protection restrictions are not violated.
  - **Protection** between programs and guest → Use **protection levels** from x86:
    - Xen (0), Guest (1), Programs (3).

Changes in Xen

- Changes needed in Linux $\rightarrow$ around $3,000$ lines of code.
  - 1% x86 specific code.

Operating System	Runs as *host*	Runs as *guest*
Linux 2.4	Yes	Yes
Linux 2.6	Yes	Yes
NetBSD 2.0	No	Yes
NetBSD 3.0	Yes	Yes
Plan 9	No	Yes
FreeBSD 5	No	Yes

Performance in Xen

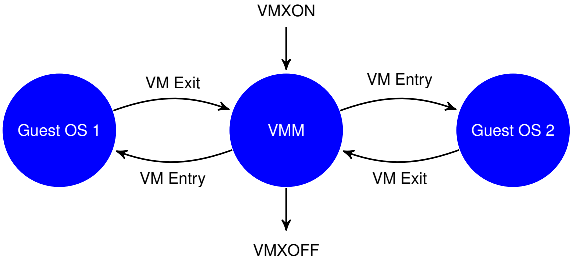


7 Virtualization technologies

- Impure virtualization
- ISA Technologies

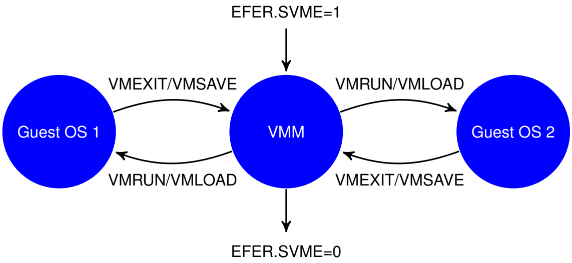
Intel Virtualization Technology

- Adds new instructions:
  - VMXON
  - VMXOFF
  - VMLAUNCH
  - VMRESUME
  - ...



AMD Secure Virtual Machine

- Adds new instructions:
  - VMRUN/VMLOAD.
  - VMCALL/VMSAVE.
  - ...



Operation modes

- **VMX root**:
  - Fully privileged.
  - Designed to be used with VMM.

- **VMX non-root**:
  - Non privileged.
  - Designed to be used by guest software.

Entering and exiting virtual machines

- **VM Entry**:
  - Transition from VMM to host.
  - Enters non-root mode.
  - Loads guest state.
  - **VMLAUNCH** instruction used for initial entry.
  - **VMRESUME** instruction used for subsequent entries.

- **VM Exit**:
  - **VMEXIT** instruction used to enter VMM mode.
  - Enters in root mode.
  - Saves guest state.
  - Loads VMM state.
  - There are instructions and events that cause a **VMEXIT**.

Benefits from VT technology

- Decreases OS dependency.
  - Removes needs for binary translation.
  - Facilitates the support for old operating systems.
- Improves robustness.
  - Removes need for complex techniques.
  - Smaller and simpler VMMs.
- Improves performance.
  - Less transitions to VMM.

Summary

- Virtual memory offers a mechanism for **translation**, facilitating **protection** and **sharing**.
- Virtual memory policies:
  - Placement: Fully associative.
  - Identification: Page Table.
  - Replacement: Usually LRU with TLB support.
  - Writing: Always write-back.
- Virtual machines: isolation, security, reliability, and sharing.
- Uses of VMM: protection, management sw/hw (isolation, consolidation, migration).
- Technologies: Impure virtualization and solutions in ISA.

References

- **Computer Architecture. A Quantitative Approach**
  5th Ed.
  Hennessy and Patterson.
  Sections: B.4, 2.4.

- **Recommended exercises**:
  - B.12, B.13, B.14, 2.20, 2.21, 2.22, 2.23

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