Non-examinable Learning Outcomes ☺

- An appreciation that the abstract interface to the system can be at different levels.
  - Virtual machine monitors (VMMs) provide a low-level interface
- An understanding of trap and emulate
- Knowledge of the difference between type 1 (native) and type 2 VMMs (hosted)

1

Virtual Machines

References:

Smith, J.E.; Ravi Nair; , "The architecture of virtual machines," *Computer* , vol.38, no.5, pp. 32- 38, May 2005

Chapter 7 – 7.3 Textbook “Modern Operating Systems”, 4th ed.

All of chapter 7, if you’re interested.

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Observations

- Operating systems provide well defined interfaces
  - Abstract hardware details
    - Simplify
    - Enable portability across hardware differences
- Hardware instruction set architectures are another will defined interface
  - Example AMD and Intel both implement (mostly) the same ISA
  - Same software can run on both

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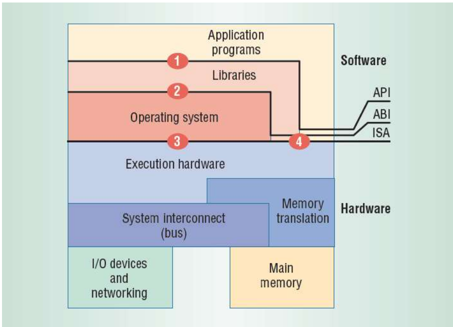
Interface Levels



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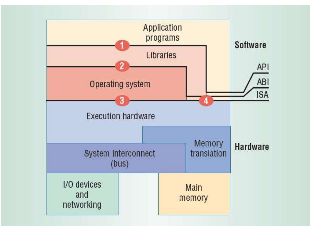
Instruction Set Architecture

- Interface between software and hardware
  - label 3 + 4
- Divided between privileged and un-privileged parts
  - Privileged a superset of the un-privileged



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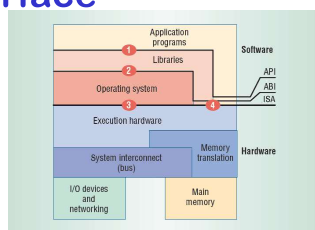
Application Binary Interface

- Interface between programs ↔ hardware + OS
  - Label 2+4
- Consists of system call interface + un-privileged ISA



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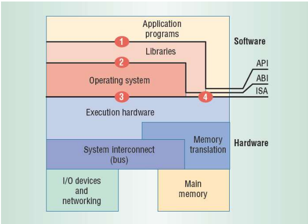
Application Programming Interface

- Interface between high-level language ↔ libraries + hardware + OS
- Consists of library calls + un-privileged ISA
  - Syscalls usually called through library.
- Portable via re-compilation to other systems supporting API
  - or dynamic linking



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Some Interface Goals

- Support deploying software across all computing platforms.
  - E.g. software distribution across the Internet
- Provide a platform to securely share hardware resources.
  - E.g. cloud computing

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OS is an extended virtual machine

- Multiplexes the "machine" between applications
  - Time sharing, multitasking, batching
- Provided a higher-level machine for
  - Ease of use
  - Portability
  - Efficiency
  - Security
  - Etc….

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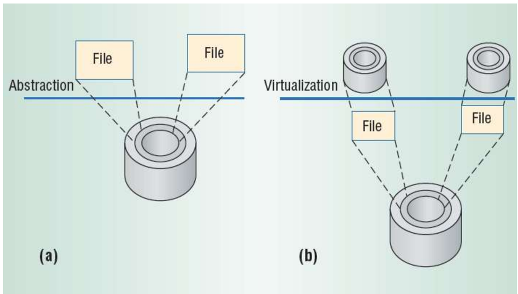
Abstraction versus Virtualisation



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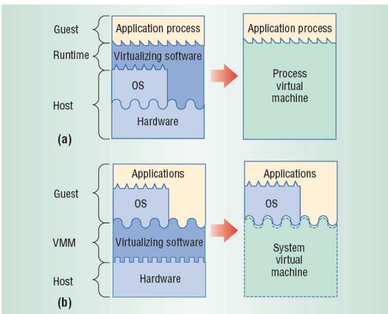
Process versus *System* Virtual Machine



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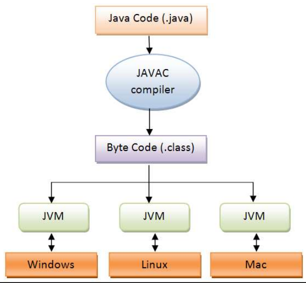
JAVA – Higher-level Virtual Machine

- write a program once, and run it anywhere
  - Architecture independent
  - Operating System independent
- Language itself was clean, robust, garbage collection
- Program compiled into bytecode
  - Interpreted or just-in-time compiled.
  - Lower than native performance



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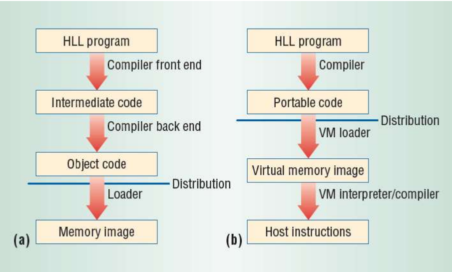
Comparing Conventional code execution versus Emulation/Translation



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Aside: Just In-Time compilation (JIT)

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JAVA and the Interface Goals

- Support deploying software across all computing platforms. ✔
- Provide a platform to securely share hardware resources. ✘

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Issues

- Legacy applications
- No isolation nor resource management between applets
- Security
  - Trust JVM implementation? Trust underlying OS?
- Performance compared to native?

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Is the OS the “right” level of extended machine?

- Security
  - Trust the underlying OS?
- Legacy application and OSs
- Resource management of existing systems suitable for all applications?
  - Performance isolation?
- What about activities requiring “root” privileges

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Virtual Machine Monitors

Also termed a *hypervisor*

- Provide scheduling and resource management
- Extended “machine” is the actual machine interface.

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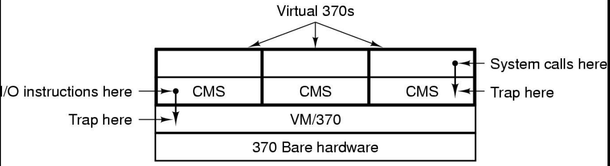
IBM VM/370

- CMS a light-weight, single-user OS
- VM/370 multiplex multiple copies of CMS



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Advantages

- Legacy OSes (and applications)
- Legacy hardware
- Server consolidation
  - Cost saving
  - Power saving
- Server migration
- Concurrent OSes
  - Linux – Windows
  - Primary – Backup
    - High availability
- Test and Development
- Security
  - VMM (hopefully) small and correct
- Performance near bare hardware
  - For some applications

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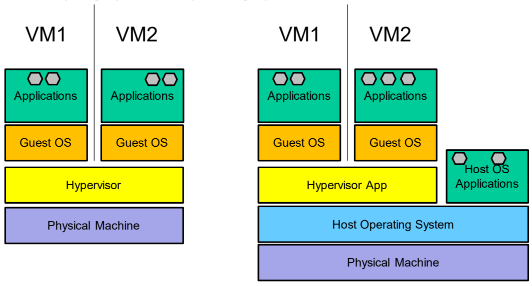
Native (Type 1) vs. Hosted (Type 2) Hypervisor



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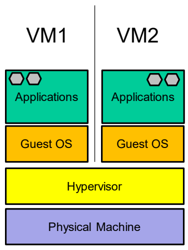
Type 1 (Native) Hypervisor

- Hypervisor (VMM) runs in most privileged mode of processor
  - Manage hardware directly
  - Also termed classic…, bare-metal…, native…
- Guest OS runs in non-privileged mode
  - Hypervisor implements a virtual kernel-mode/virtual user-mode
  - Or, CPU provides three privilege levels (e.g. Intel VT-x)
- What happens when guest OS executes native privileged instructions?



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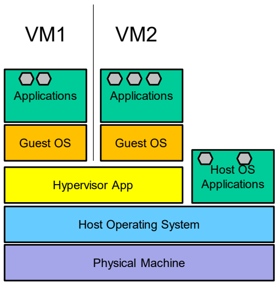
Type 2 (Hosted) Hypervisor

- Hypervisor runs as user-mode process above the privileged host OS
  - Also termed hosted hypervisor
- Again, provides a virtual kernel-mode and virtual user-mode
- Can leverage device support of existing host OS.
- What happens when guest OS execute privileged instructions?



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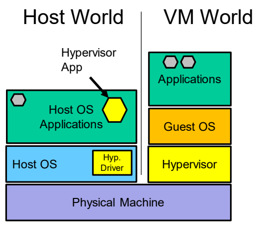
Hosted Hypervisor Details

- Jeremy Sugerman, Ganesh Venkitachalam and Beng-Hong Lim, "Virtualizing I/O Devices on VMware Workstation's Hosted Virtual Machine Monitor", USENIX ATC 2001
- Hypervisor application installs driver (part of the hypervisor) into the Host OS
- Driver intercepts hypervisor related activities from Hyp. App.
- It "world switches" when guest OS needs to runs
  - Unloads Host OS state from processor
  - Loads hypervisor state and gives it control of machine
- Hypervisor "world switches" when Host OS is needed
  - Regularly to allow interactivity with Host OS.
  - When hypervisor needs Host OS service (e.g. file system)



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Gerald J. Popek and Robert P. Goldberg (1974). "Formal Requirements for Virtualizable Third Generation Architectures". Communications of the ACM 17 (7): 412 –421.

- Sensitive Instructions
  - The instructions that attempt to change the configuration of the processor.
  - The instructions whose behaviour or result depends on the configuration of the processor.
- Privileged Instructions
  - Instructions that trap if the processor is in user mode and do not trap if it is in system mode.
- Theorem
  - Architecture is virtualisable if sensitive instructions are a subset of privileged instructions.

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Example: mtc0/mfc0 MIPS

- mfc0: load a value in the system coprocessor
  - Can be used to observer processor configuration
- mtc0: store a value in the system coprocessor
  - Can be used to change processor configuration
- Example: disable interrupts

```
mfc0 r1, C0_Status
andi r1, r1, CST_IEc
mtc0 r1, C0_Status
```

- Sensitive?
- Privileged?

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Approach: Trap & Emulate?

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Example: cli/sti x86

- CLI: clear interrupt flag
  - Disable interrupts
- STI: set interrupt flags
  - Enable interrupts
- Sensitive?
- Privileged?

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X86 POPF

31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
0	0	0	0	0	0	0	0	0	0	ID	VIP	VIF	AC	VM	RF	0	NT	IOPL		OF	DF	IF	TF	SF	ZF	0	AF	0	PF	1	CF

- Pop top of stack and store in EFLAGS register
  - IF bit disables interrupts

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X86 POPF

- Is not privileged (does not trap)
  - In kernel mode – enable/disables interrupts
  - In user-mode – silently ignored
- POPF is not virtualisable
- X86 (pre VT extensions) is not virtualisable

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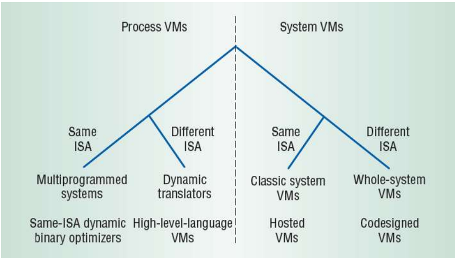
Taxonomy of Virtual Machines



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What is System/161?

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