VIRTUALIZATION

Andrew Herbert

Cambridge University
ANSA
Microsoft Research
EDSAC Replica Project

DEFINITION (In context of SOSP)

- *Virtualization* is a property of operating systems that gives the illusion of efficiently running multiple independent computers known as *virtual machines*.
- The virtual machines be directly executed by (i.e., exactly mimic) the underlying physical machine, or they may comprise a more abstract system, parts, or all, of which are simulated by the physical machine.
- The part of the operating system that provides the virtual machine abstraction is commonly called a *virtual machine monitor* or *hypervisor.*

SOSP & VIRTUALIZATION

- Virtual Machine Monitors
- Layered Abstract Machines
- OS Process as a Virtual Environment
- Addressing Virtual Resources

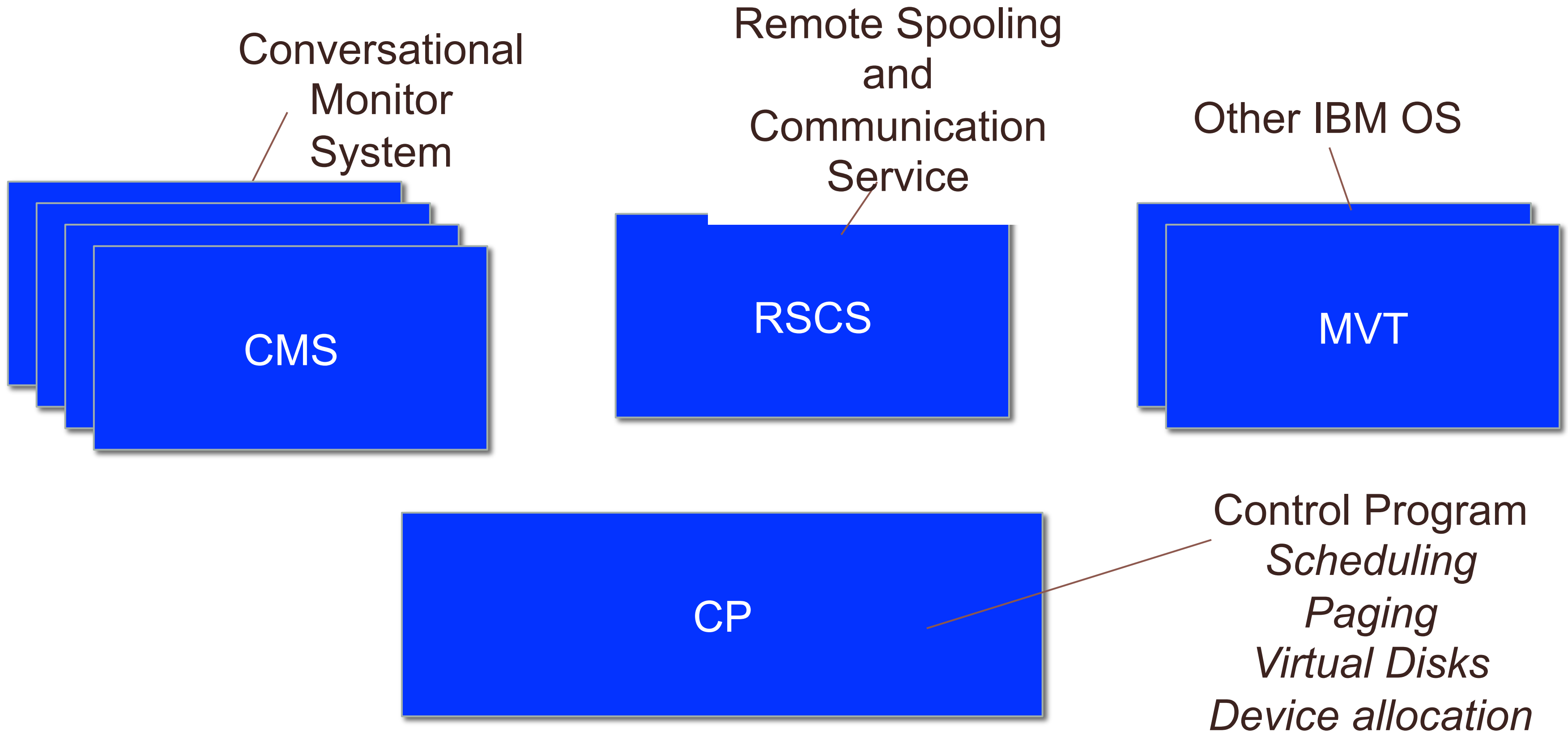
Note: referenced systems, papers are exemplars, not an exhaustive list.

VIRTUAL MACHINE MONITORS

- Origins in 1965 IBM M44/44X to explore page replacement algorithms
- M44/44X allowed each “virtual machine” to have its own paging strategy to allow measurement and comparison
- Evolved via CP/40 and CP/67 to VM/370

IBM VM/370

- Addressed three needs
  - Time-sharing computer utility
  - Running legacy applications and their operating systems alongside new applications and systems
  - Developing and debugging new operating systems using same time-sharing environment as for applications


Conversational Monitor System
Remote Spooling and Communication Service
Other IBM OS
CMS
RSCS
MVT
CP
Control Program
Scheduling
Paging
Virtual Disks
Device allocation

VIRTUALIZATION APPROACHES

- Semi-formal model by Popek and Goldberg (1974)
  - Notion of *sensitive instructions* which reveal processor state
- IBM 360/370 enabled *pure* virtualization
  - Only *privileged* instructions in virtual supervisor mode have to be simulated by the VMM
- In contrast to *hybrid* virtualization
  - Some unprivileged instructions have to be simulated in virtual supervisor mode in addition
  - x86 only became pure with Intel VT-x / AMD SVM (2006)

1975-1995

1975-1995

- IBM VM/370 continues...
- Recursive virtual machines...
  - Lauer & Weyth, 1973
  - CAP (Needham & Walker, 1977)
- Then...

“SPECIAL EFFECT” VMMs

- *Hypervisor-based fault tolerance*
  - (Schneider & Bressoud 1996)
- *ReVirt: enabling intrusion analysis…*
- (Dunlap, King, Cinar, Basrai & Chen 2002)

HOSTED VMMs (TYPE 2)

- Enable desktop OS coexistence
- VMM runs as app on host OS
  - Often with associated kernel driver
  - Uses host OS services (file, network)
  - VMs run guest OS image
- DEC-10 VMM for ITS (Galley, 1973)
- VMWare Desktop for Windows (1999)

NATIVE/BARE METAL VMMs (TYPE 1)

- DISCO (Buignon, Devine, et al. 1997)
  - *Hybrid virtualization with binary rewriting and shadowing in place of simulation*
- VMWare ESX Server (Waldspurger 2002)
  - *System-wide resource multiplexing*
  - *Ballooning, Content-based Page Sharing*
- Xen (Barham et al. 2003)
  - *Paravirtualization*

BENEFITS OF VIRTUAL MACHINES

- Desktop virtualization
  - OS coexistence
  - Desktop checkpoint/restore, migration
- Server virtualization
  - Server consolidation
  - Multi-tenancy with strong isolation
  - Statistical multiplexing of resources across multiple virtual servers
  - Management framework for server workloads

LAYERED ABSTRACT MACHINES

- Design and implement an operating system as a hierarchical series of abstract machines
- *'THE' multiprogramming system* (Dijkstra, 1967)
  - Layer 0: concurrency and interrupt handling (processes and semaphores)
  - Layer 1: automatic memory paging
  - Layer 2: operator's console
  - Layer 3: input-output
  - Layer 5: Algol batch system

WHY LAYER?

- Build and test layer by layer
- Structured (informal) proof of correctness

- 1972, Liskov, Venus

- 1980s, Comer, XINU

LAYERING FOR SECURITY

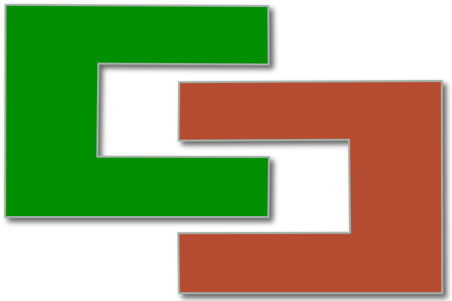
- US DoD Trusted Systems – Orange Book
  - A1 – Verified design
  - B2 – Structured protection
  - B3 – Security domains (reference monitor)
- *The foundations of a provably secure operating system (PSOS)* (Feiertag, Neumann, SRI, 1979)
  - Hierarchical Design Methodology, SPECIAL
  - 17 Nominal layers for verification, collapsed to 9 in the implementation

MULTICS KERNEL DESIGN

- 1977, MIT redesign and reimplementation of Multics to meet B2/B3 criteria (Schroeder, Clark & Saltzer, 1977)
- Added additional layers to system in order to remove code from the Multics supervisor so it could be reduced to be a reference monitor suitable for inspection
- *Type Extension*: treat each module as a *type manager*
  - Ensure type dependency graph does not contain cycles
  - Often had to split original modules into upper and lower types

LAYERS AND MODULES

- 1976, Haberman et al., FAMOS
  - *Modularization and hierarchy in a family of operating systems*
  - Set of components for building a family of (related) operating systems
  - Explored conflict between *layers* and *modules*
  - Similar model to Multics *type extension*



LAYERING AND NETWORKS

- Abstraction layering is not unique to systems
- Protocols defined as interacting peer entities at increasing levels of abstraction
- But Open Systems Interconnection 7-layer model regarded as overblown
- Virtualization by layering
  - Virtual Private Networks
  - Virtual LANs

OBSERVATIONS

- Most of these systems were done by people with a background in programming languages and formal specification and verification
- Some claim layering leads to inefficiency but XINU gives good evidence otherwise

VIRTUAL ENVIRONMENTS

- A process is a program executing in a virtual environment (Saltzer, 1966)
- 1950s & 60s – Tyranny of the instruction set
  - Each new machine required everything to be re-written
  - Emulate older machines e.g., IBM 360 – IBM 1400
- Atlas *Extracodes*
  - Undefined instructions that execute subroutines in fast memory – e.g., supervisor calls, library functions

LIBRARIES

- 1970s Emergence of practical general purpose / systems programming languages
- 1980s Unix marked transition to the standard library becoming the virtual environment
  - High level abstract interface for applications
  - Low level concrete interface for the library
- UNIX (via Multics) gave us the byte stream as the universal *virtual device* abstraction replacing messy record-oriented structures of earlier systems

DISTRIBUTED UNIX

- Distributed *single image* implementations of UNIX virtual environment didn't last, e.g. Locus (Popek, 1981)
    - Caching/Scaling problems (see Satya on file systems)
    - Autonomy of network of workstations model outweighed benefits of centralized management

NAMING VIRTUALIZED RESOURCES

- Useful to have a uniform context [location] independent way of naming sharable [virtual] resources
- Capabilities (see Lampson for security aspects)
  - C-lists (Dennis, Van Horn 1966)
  - *Capability-based addressing* (Fabry 74)
  - *Amoeba* (Tanenbaum et al. 1986)
- Grew out of Codewords / descriptors
  - Rice R1, R2 (1959-71), B5000 (1963)
  - Tagged Architectures (Feustal 1972)

PLAN 9

- Bell Labs 1991
  - Every resource is a file
  - Name spaces are mountable, stackable, ...

ACCESSING VIRTUAL RESOURCES

- Lots of arguments about how to access virtual resources
- See Kaashoek, Liskov on threads vs events
- Custom protocol vs optimized RPC vs TCP/IP
- Active versus passive objects (OMG CORBA)
- Workstations versus Processor Banks
  - PARC, MIT Athena, CMU Andrew, Cambridge Distributed System
  - GUI windows as virtual resources, e.g. X window system

TALKING POINTS

- More mileage from using virtualization to modify operating system semantics?
- VMM ≠ TCB, especially for type 2
- Revisit layered abstract machines as a systems design and implementation principle?
- Prove systems correct by default?
  - seL4 (Klein, Elpinstone, Heiser, Andronick, ..., 2009)
  - Verve (Yang & Hawblitzel, 2010)