Virtualizing I/O

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Administrivia

- Quiz next Mon: cover everything until (including) today’s lecture
  - Open everything (you can also use google), but no communication to anyone else
  - Quiz will be on Canvas, and you’ll need to join Zoom with camera turned on during the quiz (so that we can proctor)
  - Quiz will be 15 minutes (only few small questions, e.g., T/F, MC, short answers)
- Project proposal due on 1/24
- Finalize project topic choice (and update Google form if needed)
- Breakout room for project discussion at the end of the lecture
Leftover: Memory Sharing

• Motivation
  • Multiple VMs running same OS, apps
  • Collapse redundant copies of code, data, zeros

• Transparent page sharing
  • Map multiple PPNs to single MPN (copy-on-write)
  • Pioneered by Disco, but required guest OS hooks

• New twist: content-based sharing
  • General-purpose, no guest OS changes
  • Background activity saves memory over time
Leftover: Page Sharing: Scan Candidate PPN

![Diagram of page sharing and hash page contents](image-url)
Leftover: Page Sharing: Successful Match
Outline

• Device virtualization techniques
• Storage virtualization
• Network virtualization

Acknowledgment: some slides from Scott Devine’s lectures at Columbia, Teemu Koponen’s NSDI’14 presentation, and Ben Pfaff’s Network Virtualization lecture
I/O Virtualization

• Goal
  • Multiplexing device across guest VMs

• Challenges
  • Each guest OS has its own device driver
  • How can one device be controlled by multiple drivers?
  • What if one guest OS tries to format its disk?
Possible Solutions of I/O Virtualization

- Direct access: VM exclusively owns a device
- Device emulation: VMM emulates device in software
- Para-virtualization: split driver into guest part and host part
- Hardware assisted: hardware devices offer isolated “virtual interfaces”
Sol-1: Direct Access Device Virtualization

- CPU
  - MMU
- Memory
  - Controller
- Local Bus
  - Interface
- High-Speed I/O Bus
  - NIC
  - Controller
  - Bridge
  - Frame Buffer
- Low-Speed I/O Bus
  - LAN
  - CD-ROM
  - USB
Sol-1: Direct Access Device Virtualization
Sol-1: Direct Access Device Virtualization

VM
Guest
OS
CPU
MMU
Memory
Controller
Local Bus
Interface

NIC
Controller
Bridge
Frame Buffer

High-Speed I/O Bus

Low-Speed I/O Bus

LAN
CD-ROM
USB

DMA
memory
int
control
config

PCIe

serial
Direct Access Device Virtualization

• Positives
  • Fast, since the VM uses device just as native machine
  • Simplify monitor: limited device drivers needed

• Negatives
  • Hardware interface visible to guest (bad for migration)
  • Interposition is hard by definition (no way to trap & emulate)
  • Now you need much more devices! (imagine 100 VMs)
Sol-2: Emulating Devices

- Emulate a device
  - Implement device logic in pure software
  - Can even emulate non-existing devices
Example: Emulating Serial Port

Device Emulator

- Serial Chip ABC Emulation
- Generic Serial Layer

Guest

- Serial Chip ABC Driver

Host OS

Serial Chip XYZ

LAN
Emulated Devices

• Positives
  • Platform stability (good for migration)
  • Allows interposition
  • No special hardware support is needed

• Negatives
  • Can be slow (it’s software emulated)
Sol-3: Para-Virtualized Devices

- VMM offers new types of device
- The guest OS runs a new driver (*front-end driver*)
- VMM runs a *back-end* driver for each front-end
- VMM finally runs the real device driver to drive the device
virtio: Linux’s paravirtualized I/O solution

- **Front-end Driver**
  - A kernel module in the guest OS
  - Accepts I/O requests from the user process
  - Transfer I/O requests to back-end driver

- **Back-end Driver**
  - Accepts I/O requests from front-end driver
  - Perform I/O operation via physical device

- **Virtqueue**
  - A memory region accessible from both guest and host OS
  - An interface implemented as vring
A virtualization-enabled device can be configured to appear in the PCI configuration space as multiple virtual functions (VFs).

The VMM assigns one or more VFs to a VM by mapping the actual configuration space of the VFs to the configuration space presented to the VM by the VMM.
SR-IOV (Single Root I/O Virtualization)

- Hardware support for guest to access device without going through VMM
- Physical Function (PF)
  - A standard PCIe function
  - Can be associated with multiple VFs
- Virtual Function (VF)
  - A lightweight PCIe function (a unique PCIe xact source)
  - Each VF is isolated from other VFs
  - Has dedicated access to certain hardware resources
  - Share some other resources
- IOVM and PF driver: set up VFs and provide full features to each VF
## Virtualization Technologies Summary

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<th>Hardware Solution</th>
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Outline

- Device virtualization techniques
- Storage virtualization
- Network virtualization
Virtual Disk

- A virtual disk is just a file in host file system

- Hypervisor maps disk blocks to file offsets
  - Flat file (fix sized virtual disk)
  - Indexed file (virtual disk can grow on demand)
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VMware Workstation’s Network Subsystem

Figure 3: VMware's network subsystem provides virtual Ethernet adapters, hubs and bridges. A hub can be either bridged to a physical Ethernet adapter, or connected to a virtual network interface in the host OS. The virtual bridge and hub are implemented via a VMNet driver that is loaded into the host OS.
Data Center Network Design with VMs

Internet

Core Switch

Aggregation Switch

"Top of Rack" Switch

Machine 1
VM VM VM

Machine 2
VM VM VM

... Machine 40
VM VM VM

virtual switch (= vswitch)

up to 128 VMs each

One rack of machines

other agg switches

other ToRs
Virtualizing Network Functionalities

<table>
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<tr>
<th>VLAN</th>
<th>NAT</th>
<th>MPLS</th>
<th>VRF</th>
<th>Network Elements as VMs</th>
<th>FlowVisor</th>
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<td>IP address space</td>
<td>Path</td>
<td>L3 FIB</td>
<td>Elements</td>
<td>ASIC</td>
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</table>

L2
Plenty of primitives but no network virtualization per se.
Problems?

- A physical topology is hard to support different virtual topologies
- Virtualized workloads stay in the physical network address space (L2)
  - Slow provisioning
  - Limited mobility
  - Limited VM placement
  - Hardware dependent
  - Operationally intensive
Goals (Paraphrase with Machine Virtualization)
Network Virtualization

Packet Abstraction

Mgmt
Mgmt
Mgmt

Control Abstraction

Logical Network
Logical Network
Logical Network
Network Hypervisor

Packet Abstraction + Control Abstraction = Network Hypervisor
A Network Virtualization Distributed System

The Internet

- Wires
- Control protocols

Core Switch

Aggregation Switch

"Top of Rack" Switch

Machine 1

OVS

VM VM VM

Machine 2

OVS

VM VM VM

Machine 3

OVS

VM VM VM

Machine 4

OVS

VM VM VM

Data Center 1

Data Center 2
Management, Control, and Data Planes

[Diagram showing a network architecture with Management Plane, Control Plane, and Data Plane interconnected through SDN Controller, Network Virtualization Application, and API.]
Virtual Network Encapsulation (Data Plane Solution)
Distributed Network Services

middlebox
Open vSwitch (OVS)

- Software-based virtual multi-layer switch, open source
- ovsdb for storing configurations
- Uses a flow cache in kernel for fast processing
- First packet goes to the user-space ovs-vswitchd
Open vSwitch: Design Details