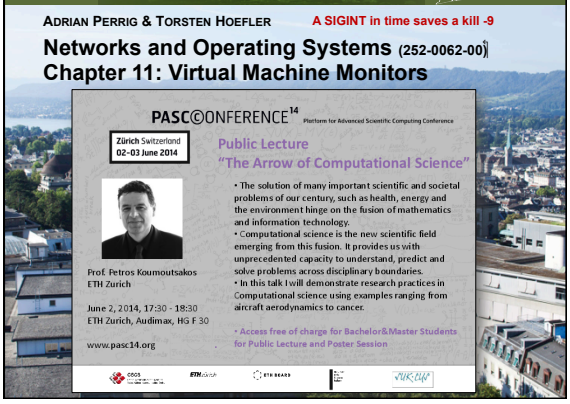
ADRIAN PERRIG & TORSTEN HOEFLER A SIGINT in time saves a kill -9

# Networks and Operating Systems (252-0062-00)
# Chapter 11: Virtual Machine Monitors






## Our Small Quiz

- **True or false (raise hand)**
  - Spooling can be used to improve access times
  - Buffering can cope with device speed mismatches
  - The Linux kernel identifies devices using a number
  - From userspace, devices in Linux are identified through files
  - Standard BSD sockets require two or more copies at the host
  - Protocols are processed in the first level interrupt handler
  - The second level interrupt handler copies the packet data to userspace
  - Deferred procedure calls can be executed in any process context
  - Unix mbufs (and skbufs) enable protocol-independent processing
  - Network I/O is not performance-critical
  - NAPI's design aims to reduce the CPU load
  - NAPI uses polling to accelerate packet processing
  - TCP offload reduces the server CPU load
  - TCP offload can accelerate applications





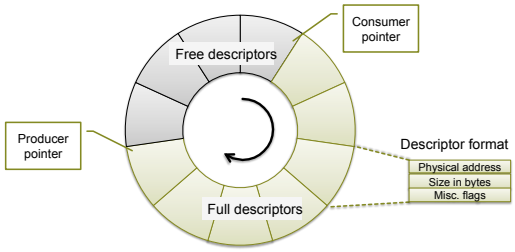
## Buffering

**Key ideas:**

- **Decouple sending and receiving**
  - Neither side should wait for the other
  - Only use interrupts to unblock host
- **Batch together requests**
  - Spread cost of transfer over several packets



## Producer-consumer buffer descriptor rings






## Buffering for network cards

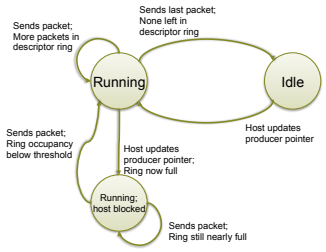
**Producer, consumer pointers are NIC registers**

- **Transmit path:**
  - Host updates producer pointer, adds packets to ring
  - Device updates consumer pointer
- **Receive path:**
  - Host updates consumer pointer, adds empty buffers to ring
  - Device updates producer pointer,
  - fills buffers with received packets.

**More complex protocols are possible…**

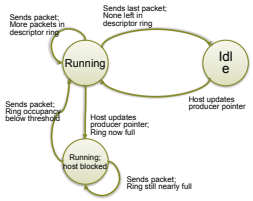


## Example transmit state machine



## Transmit interrupts

- **Ring empty**
  - ⇒ all packets sent
  - ⇒ device going idle
- **Ring occupancy drops**
  - ⇒ host can now send again
  - ⇒ device continues running




Exercise: devise a similar state machine for receive!

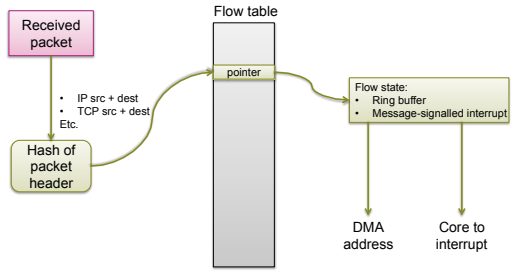
## Buffering summary

- **DMA used *twice***
  - Data transfer
  - Reading and writing descriptors
- **Similar schemes used for any fast DMA device**
  - SATA/SAS interfaces (such as AHCI)
  - USB2/USB3 controllers
  - etc.
- **Descriptors send *ownership* of memory regions**
- **Flexible – many variations possible:**
  - Host can send lots of regions in advance
  - Device might allocate out of regions, send back subsets
  - Buffers might be used out-of-order
- **Particularly powerful with multiple send and receive queues…**

## Receive-side scaling

- **Insight:**
  - Too much traffic for one core to handle
  - Cores aren't getting any faster
    - ⇒ Must parallelize across cores
- **Key idea: handle different flows on different cores**
  - But: how to determine flow for each packet?
  - Can't do this on a core: same problem!
- **Solution: demultiplex on the NIC**
  - DMA packets to per-flow buffers / queues
  - Send interrupt only to core handling flow

## Receive-side scaling




## Receive-side scaling

- **Can balance flows across cores**
  - Note: doesn't help with one big flow!
- **Assumes:**
  - *n* cores processing *m* flows is faster than one core
- **Hence:**
  - Network stack and protocol graph must *scale* on a multiprocessor.
- **Multiprocessor scaling: topic for later (see DPHPC class)**

## Virtual Machine Monitors

## Virtual Machine Monitors

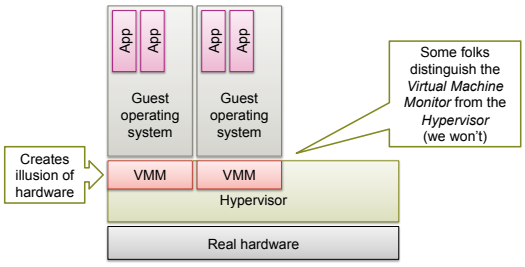
- **Basic definitions**
- **Why would you want one?**
- **Structure**
- **How does it work?**
  - CPU
  - MMU
  - Memory
  - Devices
  - Network

• Acknowledgement: Thanks to Steve Hand for some of the slides!


## What is a Virtual Machine Monitor?

- **Virtualizes an entire (hardware) machine**
  - Contrast with OS processes
  - Interface provided is "illusion of real hardware"
  - Applications are therefore complete Operating Systems themselves
  - Terminology: ***Guest Operating Systems***
- **Old idea: IBM VM/CMS (1960s)**
  - Recently revived: VMware, Xen, Hyper-V, kvm, etc.

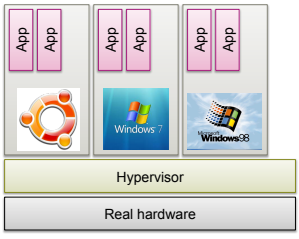
## VMMs and Hypervisors




## Why would you want one?

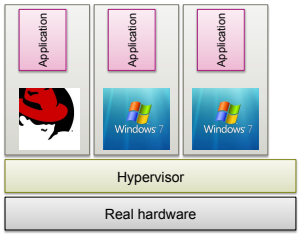
- **Server consolidation (program assumes own machine)**
- **Performance isolation**
- **Backward compatibility**
- **Cloud computing (unit of selling cycles)**
- **OS development/testing**
- **Something under the OS: replay, auditing, trusted computing, rootkits**

## Running multiple OSes on one machine




- **Application compatibility**
  - I use Debian for almost everything, but I edit slides in PowerPoint
  - Some people compile Barrelfish in a Debian VM over Windows 7 with Hyper-V
- **Backward compatibility**
  - Nothing beats a Windows 98 virtual machine for playing old computer games

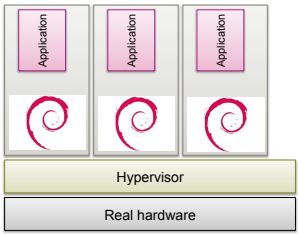
## Server consolidation




- **Many applications assume they have the machine to themselves**
- **Each machine is mostly idle**

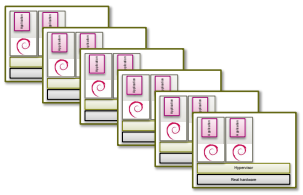
⇒ **Consolidate servers onto a single physical machine**

## Resource isolation



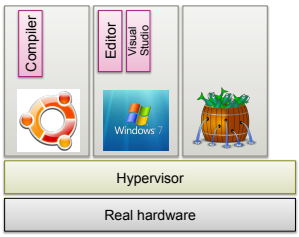

- **Surprisingly, modern OSes do not have an abstraction for a single application**
- **Performance isolation can be critical in some enterprises**
- **Use virtual machines as *resource containers***

## Cloud computing



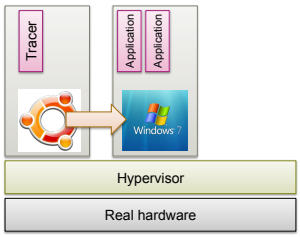
- **Selling computing capacity on demand**
  - E.g. Amazon EC2, GoGrid, etc.
- **Hypervisors decouple *allocation* of resources (VMs) from *provisioning* of infrastructure (physical machines)**

## Operating System development




- **Building and testing a new OS without needing to reboot real hardware**
- **VMM often gives you more information about faults than real hardware anyway**

## Other cool applications…

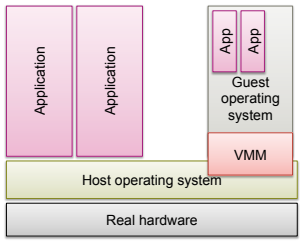



- **Tracing**
- **Debugging**
- **Execution replay**
- **Lock-step execution**
- **Live migration**
- **Rollback**
- **Speculation**
- **Etc.…**

## How does it all work?

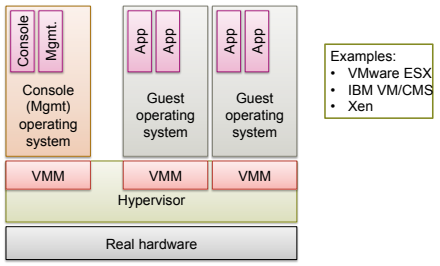
- **Note: a hypervisor is basically an OS**
  - With an "unusual API"
- **Many functions quite similar:**
  - Multiplexing resources
  - Scheduling, virtual memory, device drivers
- **Different:**
  - Creating the illusion of hardware to "applications"
  - Guest OSes are less flexible in resource requirements

## Hosted VMMs




Examples:
- VMware workstation
- Linux KVM
- Microsoft Hyper-V
- VirtualBox

## Hypervisor-based VMMs




## How to virtualize…

- **The CPU (s)?**
- **The MMU?**
- **Physical memory?**
- **Devices (disks, etc.)?**
- **The Network**

**and?**

## Virtualizing the CPU

- **A CPU architecture is *strictly virtualizable* if it can be perfectly emulated over itself, with all non-privileged instructions executed natively**
- **Privileged instructions ⇒ trap**
  - Kernel-mode (i.e., the VMM) emulates instruction
  - Guest's kernel mode is actually user mode
    *Or another, extra privilege level (such as ring 1)*
- **Examples: IBM S/390, Alpha, PowerPC**

## Virtualizing the CPU

- **A strictly virtualizable processor can execute a complete native Guest OS**
  - Guest applications run in user mode as before
  - Guest kernel works exactly as before
- **Problem: x86 architecture is not virtualizable ⊗**
  - About 20 instructions are sensitive but not privileged
  - Mostly segment loads and processor flag manipulation

## Non-virtualizable x86: example

- **`PUSHF`/`POPF` instructions**
  - Push/pop condition code register
  - Includes interrupt enable flag (`IF`)
- **Unprivileged instructions: fine in user space!**
  - `IF` is ignored by `POPF` in user mode, not in kernel mode

**⇒ VMM can't determine if Guest OS wants interrupts disabled!**

- Can't cause a trap on a (privileged) `POPF`
- Prevents correct functioning of the Guest OS

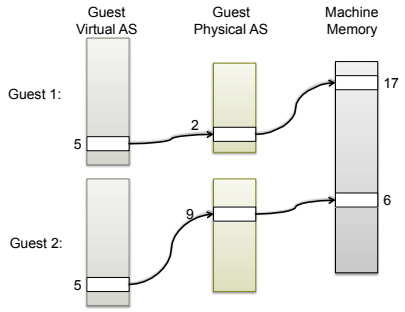
## Solutions

1. **Emulation: emulate all kernel-mode code in software**
   - Very slow – particularly for I/O intensive workloads
   - Used by, e.g., SoftPC
2. ***Paravirtualization*: modify Guest OS kernel**
   - Replace critical calls with explicit trap instruction to VMM
   - Also called a "HyperCall" (used for all kinds of things)
   - Used by, e.g., Xen
3. **Binary rewriting:**
   - Protect kernel instruction pages, trap to VMM on first IFetch
   - Scan page for POPF instructions and replace
   - Restart instruction in Guest OS and continue
   - Used by, e.g. VMware
4. **Hardware support: Intel VT-x, AMD-V**
   - Extra processor mode causes `POPF` to trap

## Virtualizing the MMU

- **Hypervisor allocates memory to VMs**
  - Guest assumes control over all physical memory
  - VMM can't let Guest OS to install mappings
- **Definitions needed:**
  - *Virtual* address: a virtual address in the guest
  - *Physical* address: as seen by the guest
  - *Machine* address: real physical address
    *As seen by the Hypervisor*

## Virtual/Physical/Machine




## MMU Virtualization

- **Critical for performance, challenging to make fast, especially SMP**
  - Hot-unplug unnecessary virtual CPUs
  - Use multicast TLB flush paravirtualizations etc.
- **Xen supports 3 MMU virtualization modes**
  1. Direct ("Writable") pagetables
  2. Shadow pagetables
  3. Hardware Assisted Paging
- **OS Paravirtualization compulsory for #1, optional (and very beneficial) for #2&3**

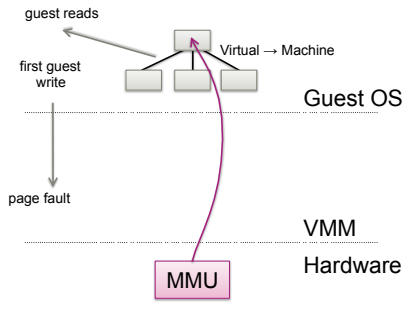
## Paravirtualization approach

- **Guest OS creates page tables the hardware uses**
  - VMM must validate all updates to page tables
  - Requires modifications to Guest OS
  - Not quite enough…
- **VMM must check *all* writes to PTEs**
  - Write-protect all PTEs to the Guest kernel
  - Add a HyperCall to update PTEs
  - Batch updates to avoid trap overhead
  - OS is now aware of machine addresses
  - Significant overhead!

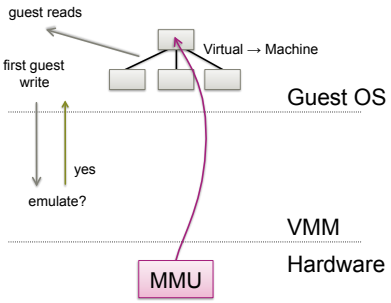
## Para-Virtualizing the MMU

- **Guest OSes allocate and manage own PTs**
  - Hypercall to change PT base
- **VMM must validate PT updates before use**
  - Allows incremental updates, avoids revalidation
- **Validation rules applied to each PTE:**
  - 1. Guest may only map pages it owns*
  - 2. Pagetable pages may only be mapped RO
- **VMM traps PTE updates and emulates, or 'unhooks' PTE page for bulk updates**

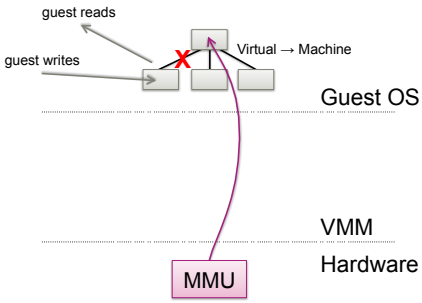
## Writeable Page Tables : 1 – Write fault



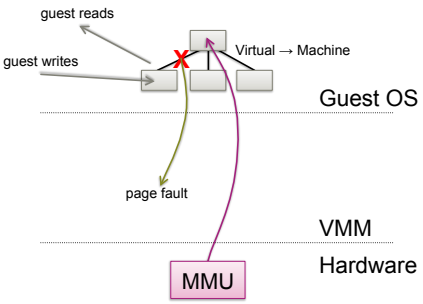
## Writeable Page Tables : 2 – Emulate?



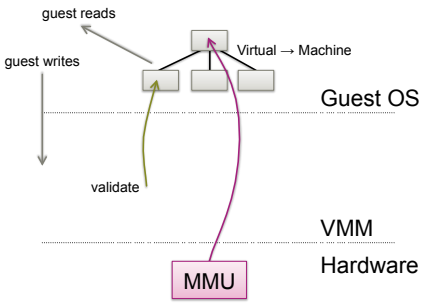

## Writeable Page Tables : 3 - Unhook



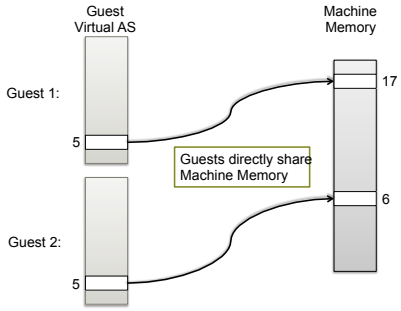

## Writeable Page Tables : 4 - First Use




## Writeable Page Tables : 5 – Re-hook



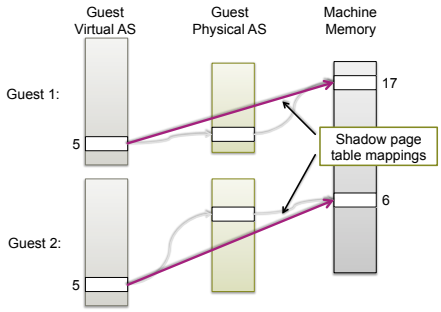

## Writeable page tables require paravirtualization



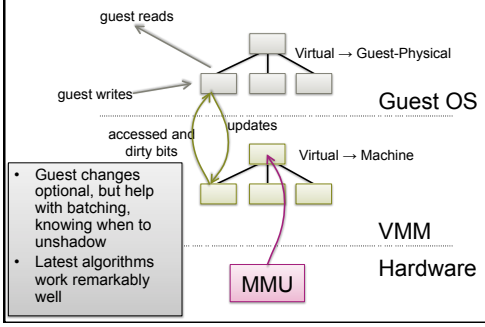

## Shadow Page Tables

- **Guest OS sets up its own page tables**
  - Not used by the hardware!
- **VMM maintains *shadow page tables***
  - Map directly from Guest VAs to Machine Addresses
  - Hardware switched whenever Guest reloads PTBR
- **VMM must keep V→M table consistent with Guest V→P table and it's own P→M table**
  - VMM write-protects all guest page tables
  - Write ⇒ trap: apply write to shadow table as well
  - Significant overhead!

## Shadow Page Tables




## Shadow page tables




- Guest changes optional, but help with batching, knowing when to unshadow
- Latest algorithms work remarkably well

## Hardware support

- **"Nested page tables"**
  - Relatively new in AMD (NPT) and Intel (EPT) hardware
- **Two-level translation of addresses in the MMU**
  - Hardware knows about:
    *V→P tables (in the Guest)*
    *P→M tables (in the Hypervisor)*
  - Tagged TLBs to avoid expensive flush on a VM entry/exit
- **Very nice and easy to code to**
  - One reason kvm is so small
- **Significant performance overhead…**

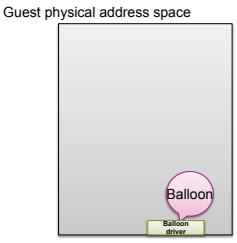
## Memory allocation

- **Guest OS is not expecting physical memory to change in size!**
- **Two problems:**
  - Hypervisor wants to overcommit RAM
  - How to reallocate (machine) memory between VMs
- **Phenomenon: Double Paging**
  - Hypervisor pages out memory
  - GuestOS decides to page out physical frame
  - (Unwittingly) faults it in via the Hypervisor, only to write it out again

## Ballooning

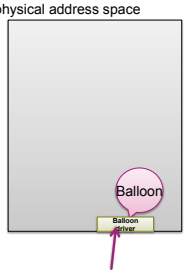
- **Technique to reclaim memory from a Guest**
- **Install a "balloon driver" in Guest kernel**
  - Can allocate and free kernel physical memory
    *Just like any other part of the kernel*
  - Uses HyperCalls to return frames to the Hypervisor, and have them returned
    *Guest OS is unware, simply allocates physical memory*

## Ballooning: taking RAM away from a VM



## Ballooning: taking RAM away from a VM

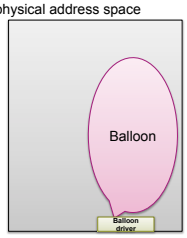
Guest physical address space




1. **VMM asks balloon driver for memory**
2.
3.
4.

## Ballooning: taking RAM away from a VM

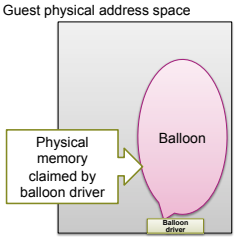
Guest physical address space




1. **VMM asks balloon driver for memory**
2. **Balloon driver asks Guest OS kernel for more frames**
   - "inflates the balloon"
3.
4.

## Ballooning: taking RAM away from a VM

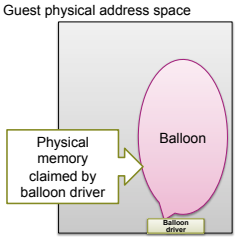
Guest physical address space




1. **VMM asks balloon driver for memory**
2. **Balloon driver asks Guest OS kernel for more frames**
   - "inflates the balloon"
3. **Balloon driver sends physical frame numbers to VMM**
4.

## Ballooning: taking RAM away from a VM

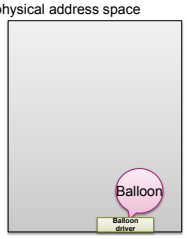
Guest physical address space




1. **VMM asks balloon driver for memory**
2. **Balloon driver asks Guest OS kernel for more frames**
   - "inflates the balloon"
3. **Balloon driver sends physical frame numbers to VMM**
4. **VMM translates into machine addresses and claims the frames**

## Returning RAM to a VM

Guest physical address space




1. **VMM converts machine address into a physical address previously allocated by the balloon driver**
2. **VMM hands PFN to balloon driver**
3. **Balloon driver frees physical frame back to Guest OS kernel**
   - "deflates the balloon"

## Virtualizing Devices

- **Familiar by now: trap-and-emulate**
  - I/O space traps
  - Protect memory and trap
  - "Device model": software model of device in VMM
- **Interrupts → upcalls to Guest OS**
  - Emulate interrupt controller (APIC) in Guest
  - Emulate DMA with copy into Guest PAS
- **Significant performance overhead!**

## Paravirtualized devices

- **"Fake" device drivers which communicate efficiently with VMM via hypercalls**
  - Used for block devices like disk controllers
  - Network interfaces
  - "VMware tools" is mostly about these
- **Dramatically better performance!**

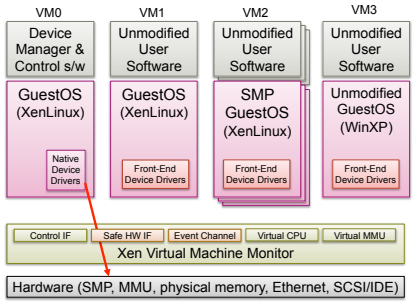
## Networking

- **Virtual network device in the Guest VM**
- **Hypervisor implements a "soft switch"**
  - Entire virtual IP/Ethernet network on a machine
- **Many different addressing options**
  - Separate IP addresses
  - Separate MAC addresses
  - NAT
- **Etc.**

## Where are the real drivers?

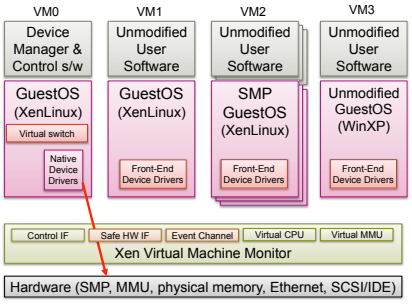
1. **In the Hypervisor**
   - E.g. VMware ESX
   - Problem: need to rewrite device drivers (new OS)
2. **In the console OS**
   - Export virtual devices to other VMs
3. **In "driver domains"**
   - Map hardware directly into a "trusted" VM
   - ***Device Passthrough***
   - Run your favorite OS just for the device driver
   - Use IOMMU hardware to protect other memory from driver VM
4. **Use "self-virtualizing devices"**

## Xen 3.x Architecture




Thanks to Steve Hand for some of these diagr

## Xen 3.x Architecture

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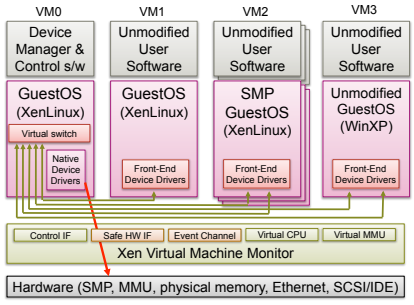
## Xen 3.x Architecture



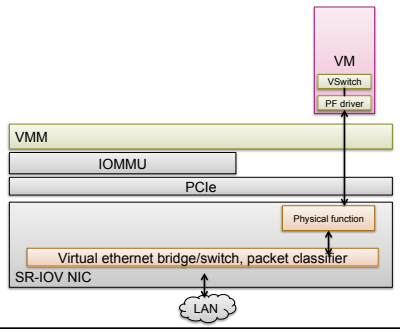

Thanks to Steve Hand for some of these diagrams

## Remember this card?

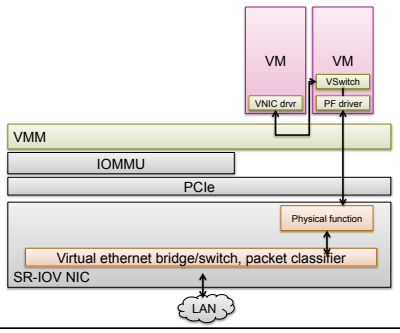
## SR-IOV

- **Single-Root I/O Virtualization**
- **Key idea: dynamically create new "PCIe devices"**
  - Physical Function (PF): original device, full functionality
  - Virtual Function (VF): extra "device", limited funtionality
  - VFs created/destroyed via PF registers
- **For networking:**
  - Partitions a network card's resources
  - With direct assignment can implement passthrough

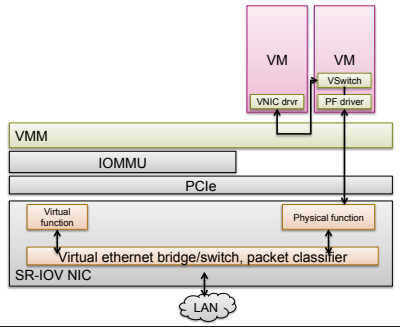
## SR-IOV in action



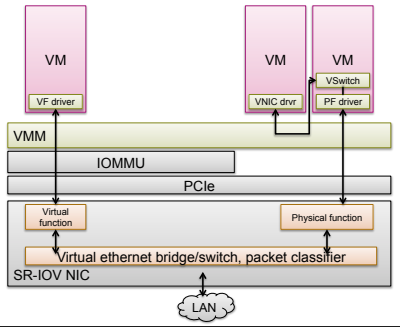

## SR-IOV in action



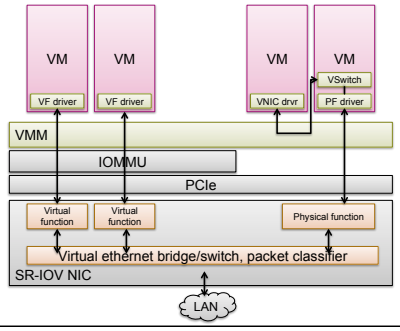

## SR-IOV in action



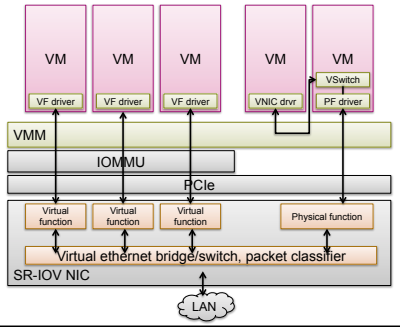

## SR-IOV in action



## SR-IOV in action




## SR-IOV in action




## Self-virtualizing devices

- **Can dynamically create up to 2048 distinct *PCI devices* on demand!**
  - Hypervisor can create a virtual NIC for each VM
  - Softswitch driver programs “master” NIC to demux packets to each virtual NIC
  - PCI bus is virtualized in each VM
  - Each Guest OS appears to have “real” NIC, talks direct to the real hardware

## Tomorrow

**Reliable storage**
**OS Research/Future™**