# Windows Kernel Internals II

## Virtual Machine Architecture

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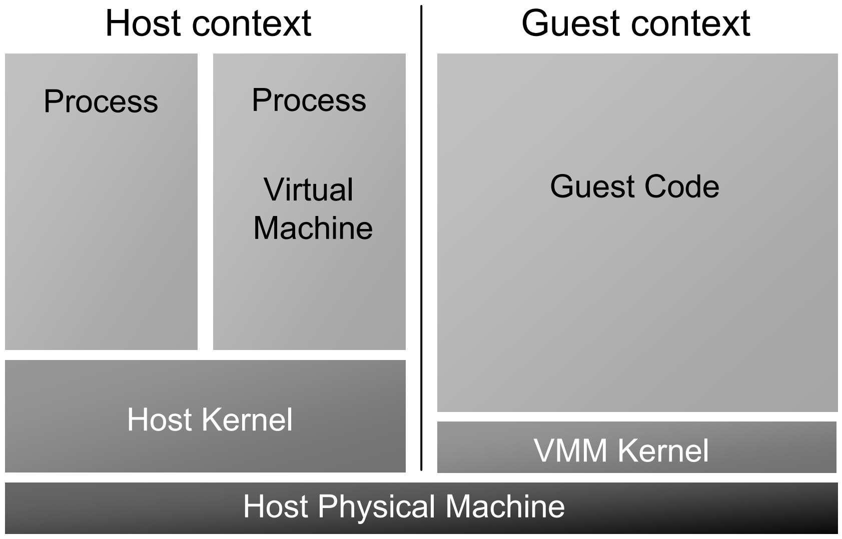
# Hosted VM Model

## Windows acts as a "host"

- Resources for each VM are allocated from the host
- All I/O with external devices is performed through the host

## "Guest" code runs within a separate context

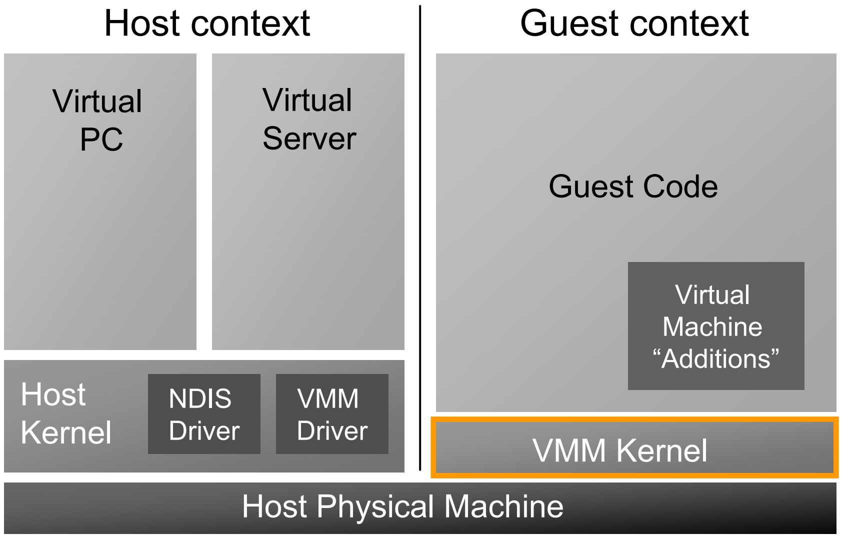
- Independent address space
- Specialized "VMM" kernel



# VM Components

## VMM Kernel

- Thin layer, all in assembly
- Code executed at ring-0
- Exception handling
- External Interrupt pass-through
- Page table maintenance
- Located within a 32MB area of address space known as the “VMM work area”
- Work area is relocatable
- One VMM instance per virtual processor

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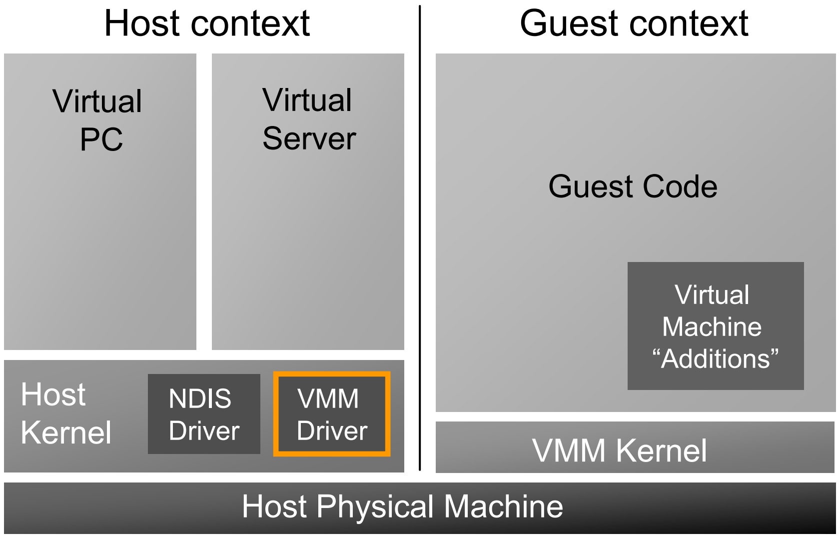
# VM Components

## VMM Driver

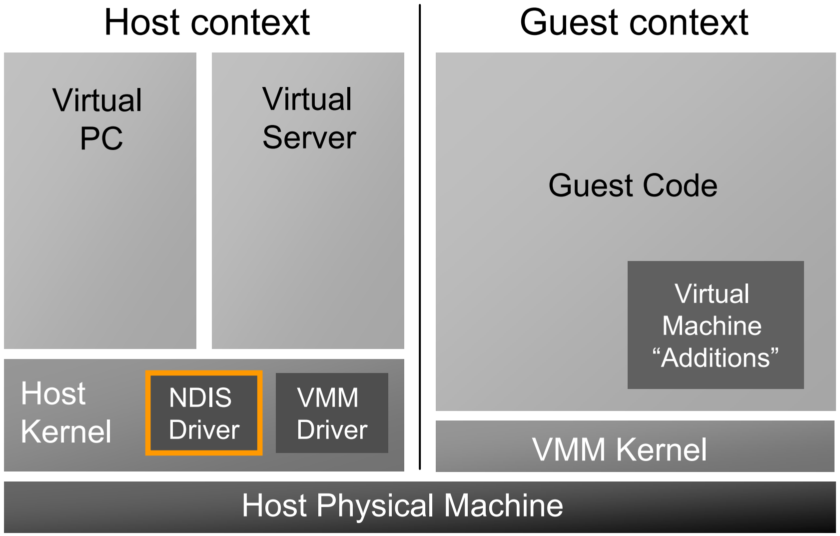
- Provides kernel-level VM-related services
  - CreateVirtualMachine
  - CreateVirtualProcessor
  - ExecuteVirtualProcessor
- Implements context switching mechanism between the host and guest contexts
- Loads and bootstraps the VMM kernel
- Much of the security work we've done recently involved repackaging the VMM kernel code into the VMM driver



# VM Components

## NDIS Filter Driver

- Allows VM to send and receive
  Ethernet packets via physical
  Ethernet hardware
- Spoofs unique MAC addresses
  for virtual NICs
- Injects packets into host Ethernet stack for guest-to-host
  networking

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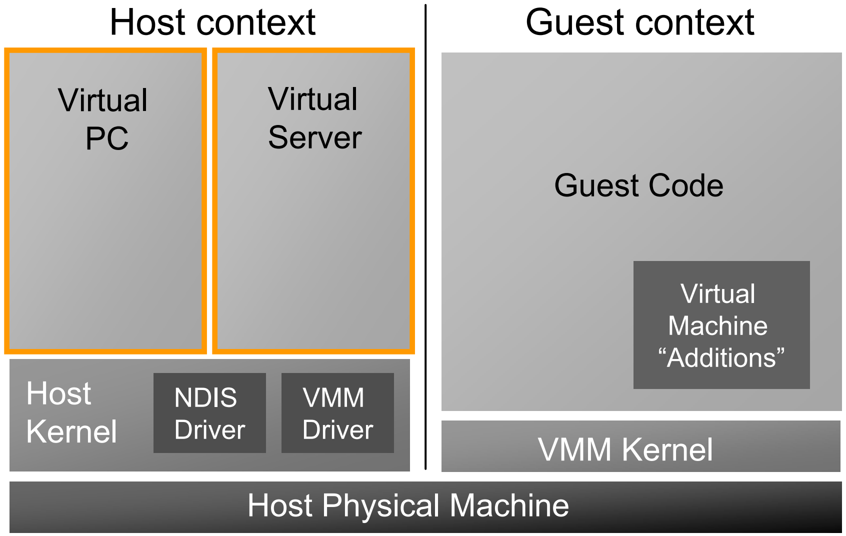
# VM Components

**Virtual PC / Virtual Server executables**

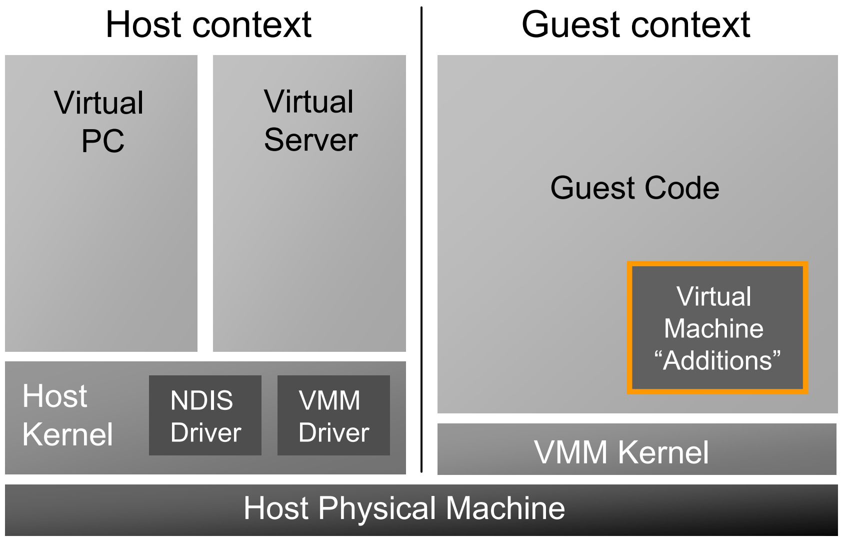
- Device emulation modules
- Resource allocation
- VM configuration creation & editing
- VM control (start, stop, pause, save)
- Scripting APIs
- User interaction
- Host side of guest/host integration features



# VM Components

## Virtual Machine "Additions"

- Collection of components installed within the guest environment by the user
- Implement optimizations
  - Video
  - SCSI
  - Networking (in the future)
  - Guest kernel patches
- Implement guest half of guest/host integration features
  - Clipboard sharing
  - File drag and drop
  - Arbitrary video resizing

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# VM Execution Loop

- **Host code repeatedly calls ExecuteVirtualProcessor**
- **VMM acts as "co-routine" (i.e. VMM state is saved and restored each time ExecuteVirtualProcessor is called)**
- **Cycles spent inside guest context are counted against the calling thread**
  - Host code can control how much time is spent in guest
- **Return code indicates why ExecuteVirtualProcessor returned**
  - Time slice complete
  - IN or OUT instruction encountered
  - HLT instruction encountered

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# Processor Virtualization

## x86 Virtualization

- Processor is non-virtualizable
  - Poor privileged and user state separation
    - For example, EFLAGS register contains condition codes (user state) and interrupt mask (privileged state)
  - Some instructions that access privileged state are non-trapping
- Overly complex and messy architecture
  - Many modes, legacy protection mechanisms and general “warts”

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# Processor Emulation

**In general, emulation is necessary**

- VM uses a binary translation mechanism
  - Most instructions are copied directly
  - Non-virtualizable ("dangerous") instructions are modified
- Binary translation execution imposes ~50% performance overhead

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# Direct Execution

**In some processor modes, it's safe to use direct execution, others require emulation**

| | |
|---|---|
| Real Mode | Emulation |
| Virtual 8086 (v86) mode | Direct Execution |
| Protected Mode Ring 3 | Direct Execution (with a few exceptions) |
| Protected Mode Ring 0 | Emulation, unless known to be safe |

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# Direct Execution

**"Ring Compression"**

- Guest ring-0, 1, 2 code is executed at ring 1
- Guest ring-3 code is executed at ring 3
- Provides correct MMU protection semantics (since ring 0-2 can access privileged pages)

**Direct execution of ring-0 code is only allowed if the VMM is notified that it's "safe"**

- This requires patching certain "dangerous" instruction sequences in the Windows kernel and HAL
- Patching is performed at runtime in memory only
- Patches are different for each version of Windows kernel & HAL

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# Guest OS Patching

**Examples:**

- PUSHFD / POPFD
- CLI / STI
- Spin lock acquisition failure (in the future)

Original Code

```
pushfd
cli
mov      eax,[ebp+8]
call     [eax]
popfd
ret
```

pushfd never traps (breaks IF virtualization)

cli traps, but cannot be easily patched with a jmp because it only takes up one byte

popfd never traps (breaks IF virtualization)

This sequence prevents correct behavior in direct execution

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# Guest OS Patching

## Synthetic instructions

- Use an illegal instruction form (reserved for us by Intel)
- Five bytes in length (for ease in patching)
- Exhibit same side effects of real instruction

Original Code

```
pushfd
cli
mov      eax,[ebp+8]
call     [eax]
popfd
ret
```

With Synthetic Instructions

```
vmpushfd
vmcli
mov      eax,[ebp+8]
call     [eax]
vmpopf
ret
```

All synthetic instructions trap and are five bytes long so they can be replaced with jmp or call instructions at runtime

This sequence allows correct behavior in direct execution, but generates three traps

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# Guest OS Patching

## Runtime Guest OS Patching

- Replace synthetic instructions with subroutine calls
- This technique prevents us from exposing internal VMM implementation details to OS vendors. We can change the subroutine implementations in the future.

Original Code

```
pushfd
cli
mov      eax,[ebp+8]
call     [eax]
popfd
ret
```

With Synthetic Instructions

```
vmpushfd
vmcli
mov      eax,[ebp+8]
call     [eax]
vmpopf
ret
```

With Runtime Patches

```
call     _vmpushfd
call     _vmcli
mov      eax,[ebp+8]
call     [eax]
call     _vmpopfd
ret
```

This patched sequence is correct and fast

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# Direct Execution Overhead

**Necessary to trap into the VMM kernel on some instructions**

- IN & OUT for I/O device emulation
- STI & CLI for interrupt mask virtualization
- INT & IRET to catch ring transitions
- INVLPG and MOV to CR3 for page table virtualization

**Traps are expensive – and getting worse**

- ~500 cycles on Pentium III or AMD processors; ~2000 cycles on Pentium 4
- Runtime patching of some trapping instructions is possible

# Physical Memory & RAM

**Virtualized RAM**

- User decides how much RAM is associated with each virtual machine

**Physical pages**

- Allocated by VMM from host OS
- Currently allocated at the time the VM starts, but could be allocated on demand
- Host physical addresses don't match guest physical addresses

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# Logical Page Mappings

**Logical Memory**

- Logical mappings defined by guest page tables (mostly)
- VMM finds 32MB unused area for the VMM code and data (the “VMM work area”).
- VMM monitors guest OS address space usage and relocates itself if necessary

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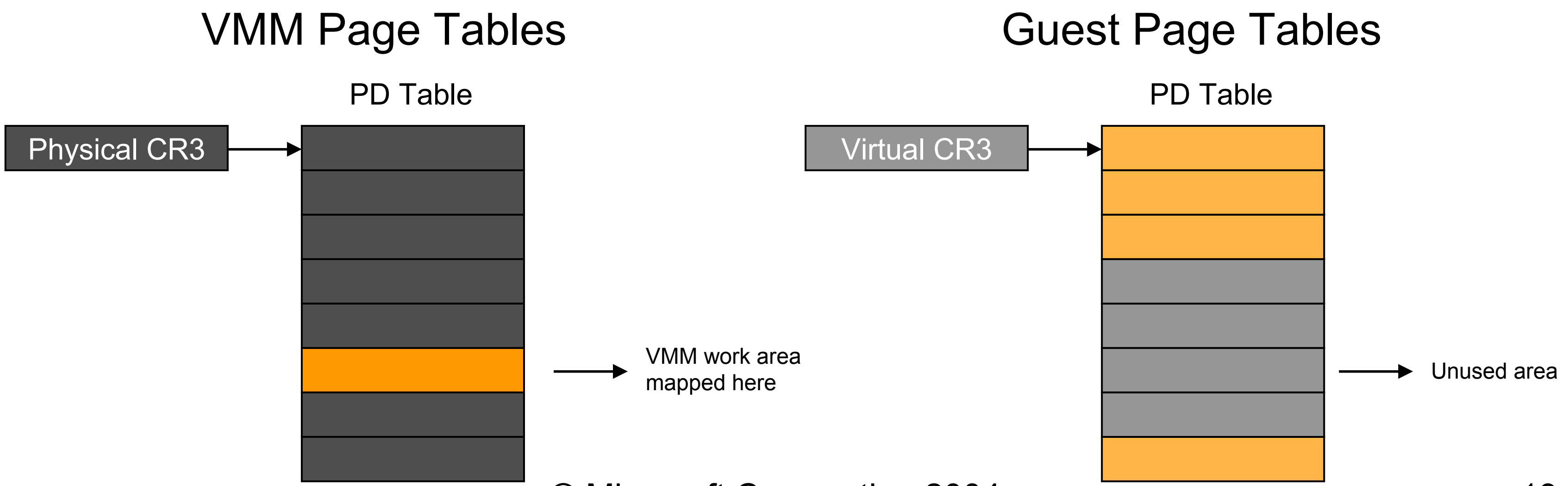
# VMM Page Tables

**VMM maintains its own private page table**

– Initially, only the VMM work area is mapped

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# VMM Page Tables

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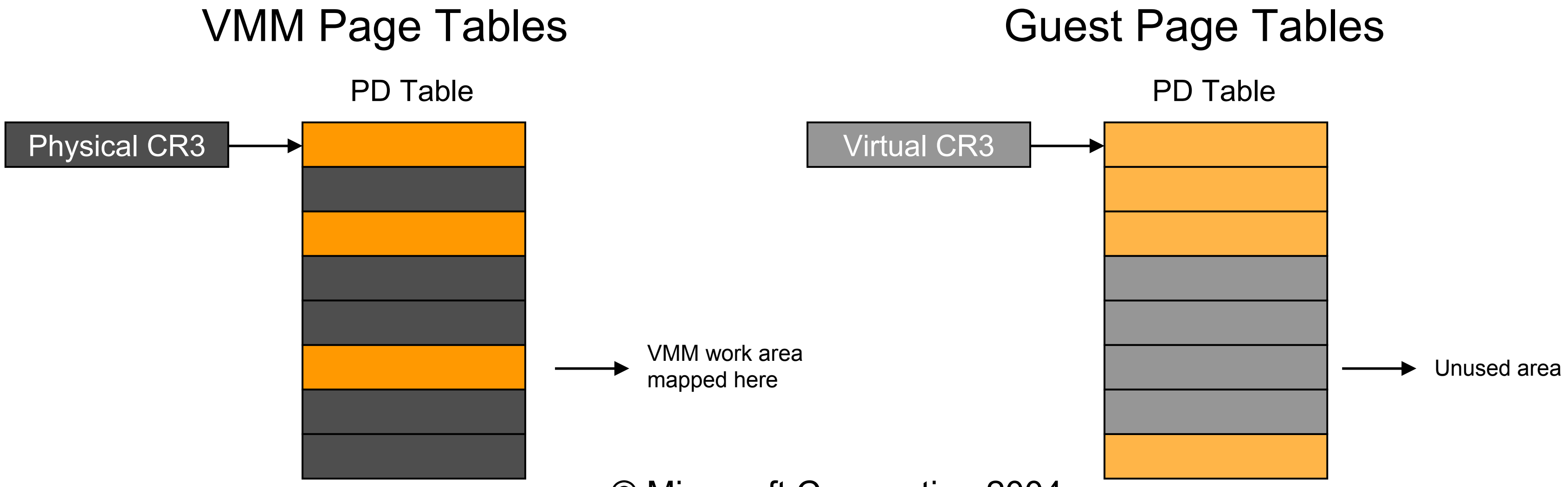
– Guest pages are mapped on demand as they are accessed

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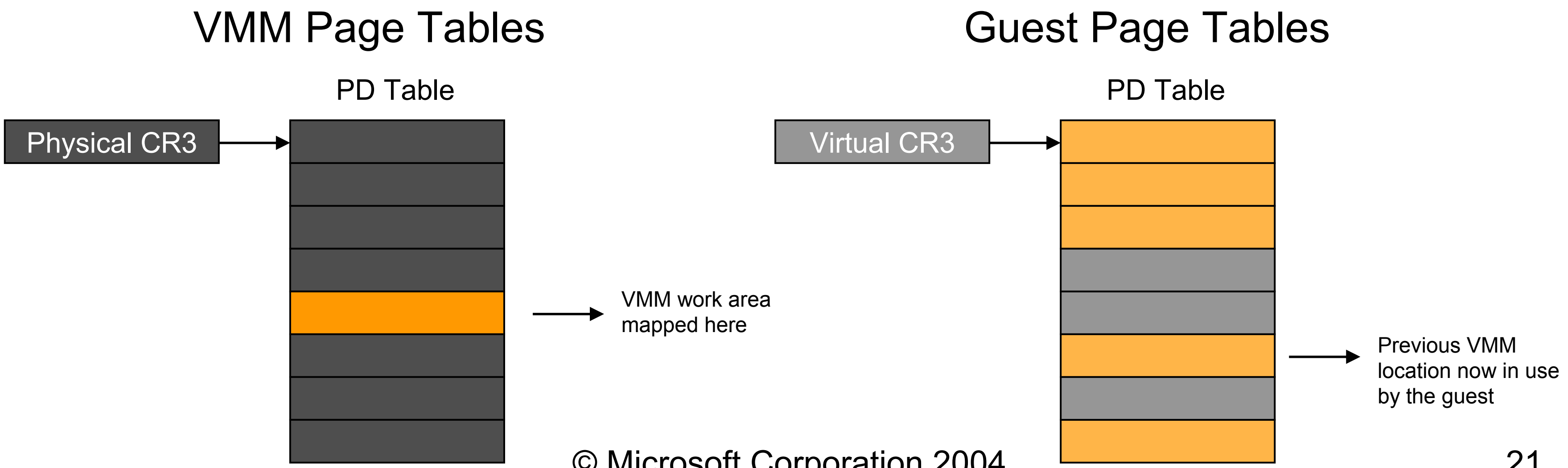
# VMM Page Tables

**VMM maintains its own private page table**

- Initially, only the VMM work area is mapped
- Guest pages are mapped on demand as they are accessed
- Guest pages are unmapped when guest flushes its TLB
- VMM work area is relocated as necessary

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# Memory Sharing

**Memory allocated with VMM APIs can be used in three ways**

- Mapped within the VMM work area
- As guest virtual RAM (mapped into the guest address space according to the guest page tables)
- Mapped within the host context (for emulated DMA operations)

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# Device Emulation

## Device emulation modules

- Emulate behaviors of a real hardware device
- Register "callbacks" for I/O port accesses
- Can access virtualized "RAM" for emulated DMA operations
- Communicate among themselves (e.g. Ethernet module "plugs into" the PCI bus module and communicates with the PIC module to assert interrupts)
- May call host services to perform emulation
- Can be suspended, saved and restored

**Device Emulation Models**

440BX chipset with PIIX4
System BIOS (AMI)
PCI Bus
ISA Bus
Power Management
SM Bus
8259 PIC
PIT
DMA Controller
CMOS
RTC
Memory Controller
RAM & VRAM
COM (Serial) Ports
LPT (Parallel) Ports
IDE/ATAPI Controllers
SCSI Adapters (Adaptec 2940)
SVGA Video Adapter (S3 Trio64)
VESA BIOS
2D Graphics Accelerator
Hardware Cursor
Ethernet Adapters (DEC 21140)
SoundBlaster Sound Card
Keyboard
Mouse

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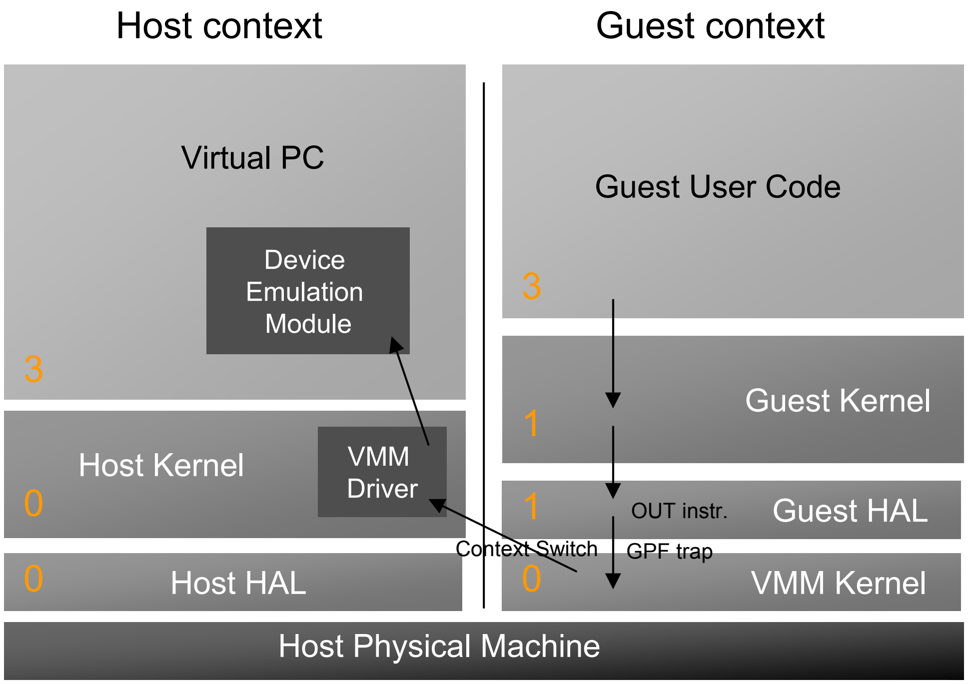
# Device I/O Accesses

**I/O accesses (IN & OUT instructions)**

- Trap into VMM kernel
- Force a context switch back to the host context where device emulation module is invoked
- “Fast I/O handlers” can be called from within the VMM context
- Some OUTs can be batched

**MMIO accesses**

- Caught in VMM’s page fault handler
- Very expensive



# Discussion

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