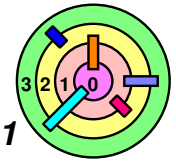
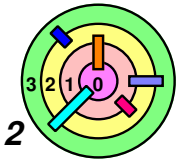
# 4.2 Rethinking Operating-System Structure

- Virtual Machines
- Microkernel



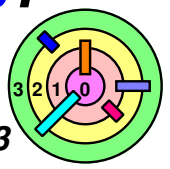
# Monolithic Kernel

- Major advantage of monolithic kernel
  - performance
- Major down side of monolithic kernel
  - reliability (i.e., buggy kernel)
- Proposal to fix the reliability problem
  - shrink the code in "privileged mode"
- Two major approaches
  - *virtual machines*
  - *microkernel*



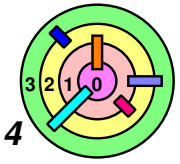
# Virtual Machines

- A nicely designed and implemented monolithic OS is great
  - but that's not the reality
- Major problem with a monolithic OS *implementation*
  - bugs in one component can adversely affect another component
    - worse if large number of programmers contribute code
      - some coders are not as good as others
      - good coders have bad days
- Modern OSs *isolate* applications from one another
  - code executing in the privileged mode can do things the user mode code cannot
    - e.g., invoking privileged instructions
  - if you invoke a privileged instruction in user mode, you will cause a violation and trap into the kernel
- Can the same kind of *isolation* be provided for *OS components*?
  - if yes, at what cost? (there is no free lunch)



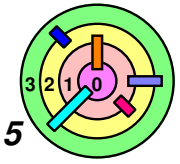
# Virtual Machines
# Part 1: > 45 Years Ago

- Had a different motivation

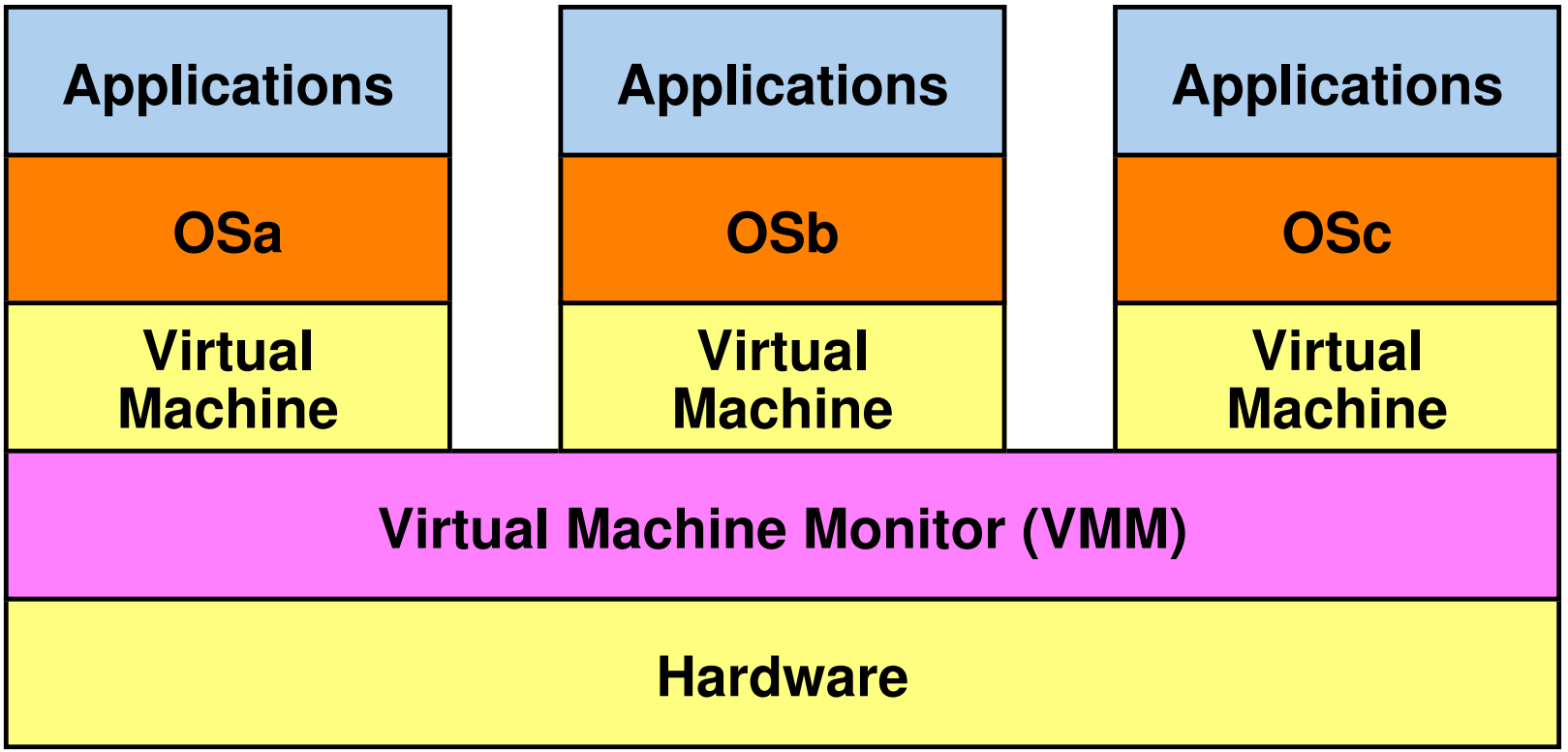


# It's 1964 ...

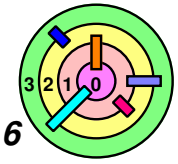
- IBM wants a *multiuser time-sharing system*
- TSS (Time-Sharing System) project
  - it's a very difficult system to build
  - large, monolithic system
  - lots of people working on it
  - for years
  - total, complete flop
- CMS
  - *single-user time-sharing system* for IBM 360
- CP67
  - *virtual machine monitor (VMM)*
  - supports multiple virtual IBM 360s
- Put the two together ...
  - a (working) *multiuser time-sharing system*



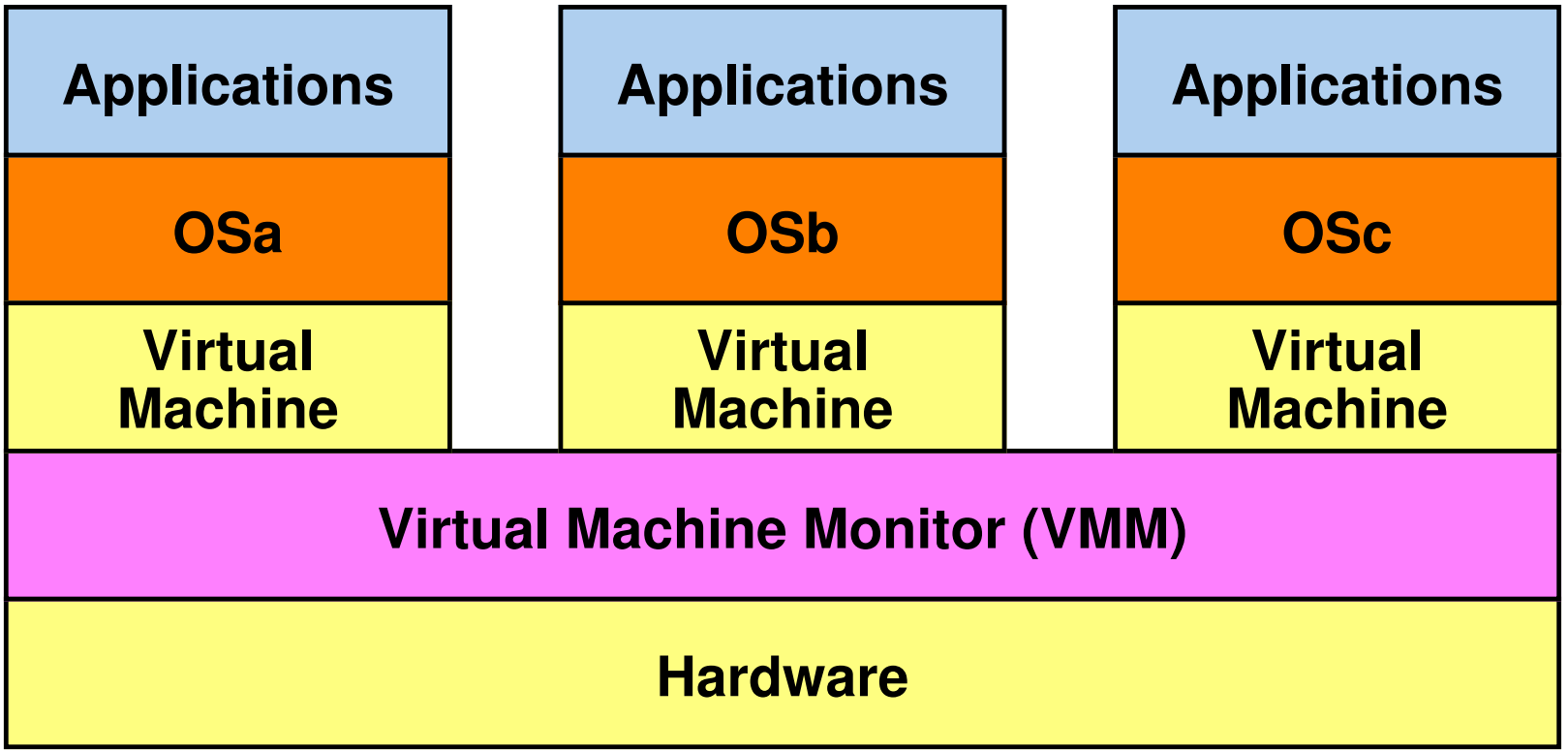
# Virtual Machines




- In OS, a *"monitor"* is a *synchronization construct* that allows executing entities to have both *mutual exclusion* and the ability to *wait* (block) for a certain condition to become true
- What abstraction does a *virtual machine* provide?



# Virtual Machines

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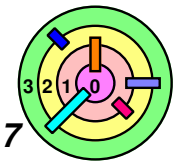
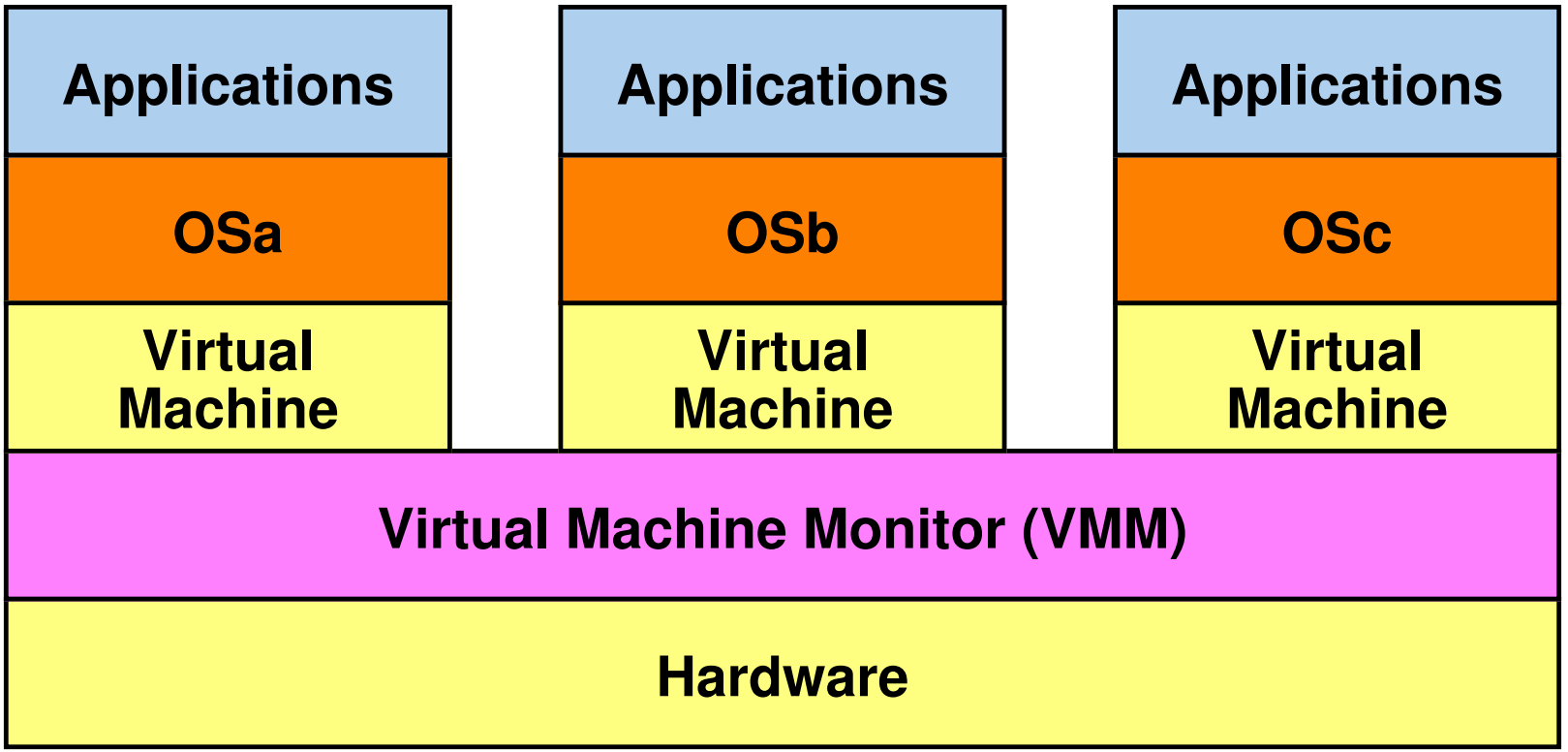
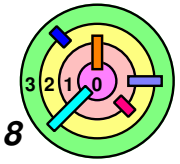
  - *hardware*



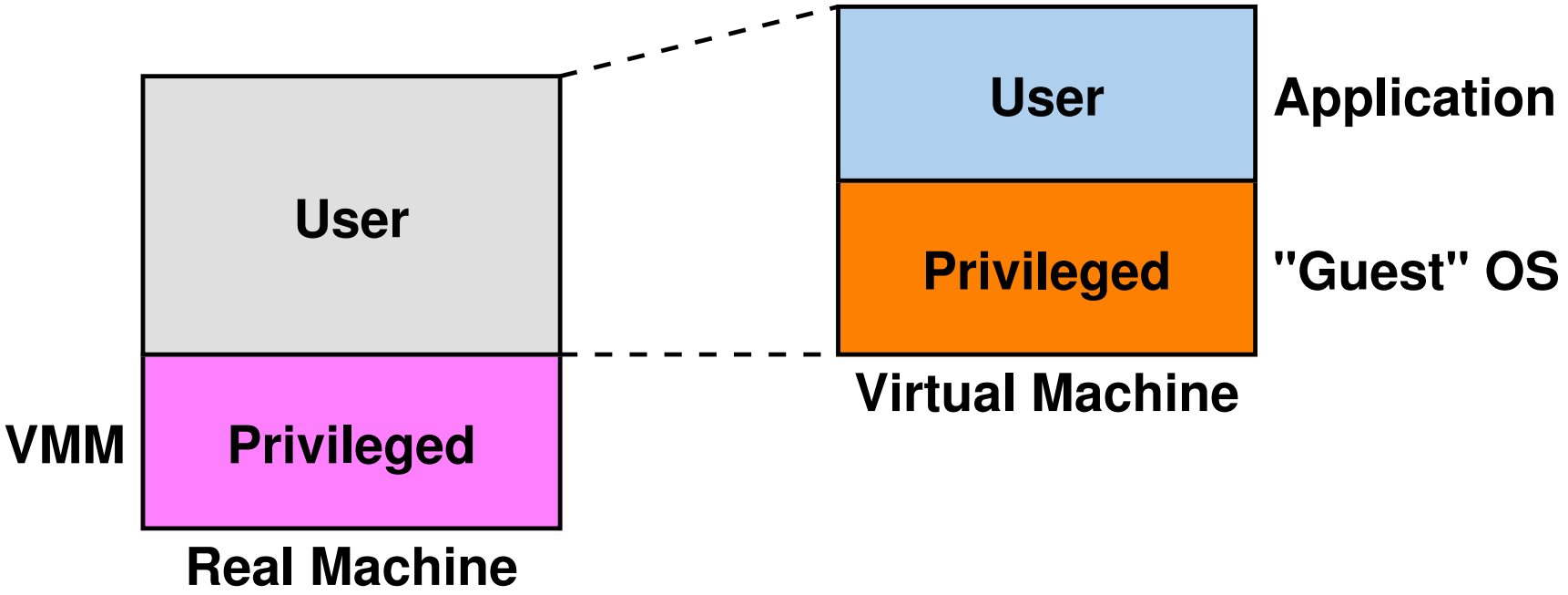
# Virtual Machines



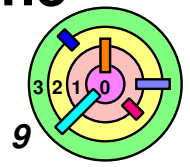

- A single user time-sharing system could be developed independently of the VMM
  - and it can be tested on a real machine (which behaves identical to the VM)
  - no ambiguity about the interface th VMM must provide to its applications - *identical* to the *real machine*!



# How?

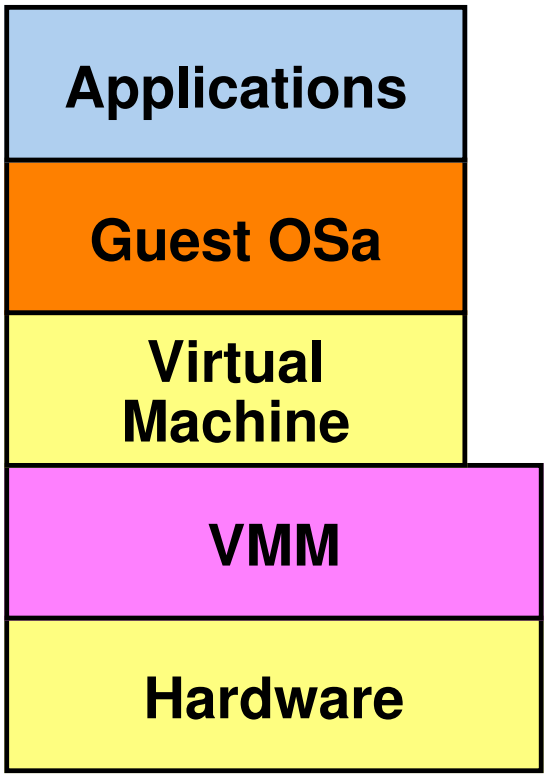


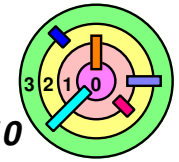

- Run the *entire virtual machine* in *user mode* of the real machine
  - *VMM* runs in the *privileged* mode of the *real* machine
- VMM keeps track of whether each virtual machine is in the *virtual privileged mode* or in the *virtual user mode*
  - *OS* runs in the *(virtual) privileged* mode of the *virtual* machine
  - Applications runs in the *(virtual) user* mode of the *virtual* machine



# VMM

- Processor in the virtual machine is the *real* processor
  - instructions are *executed* (and not interpreted or emulated)
  - traps are generated just as they are on real machines
    - in a real machine, trap handler is indexed by the trap number into a hardware-mandated jump table



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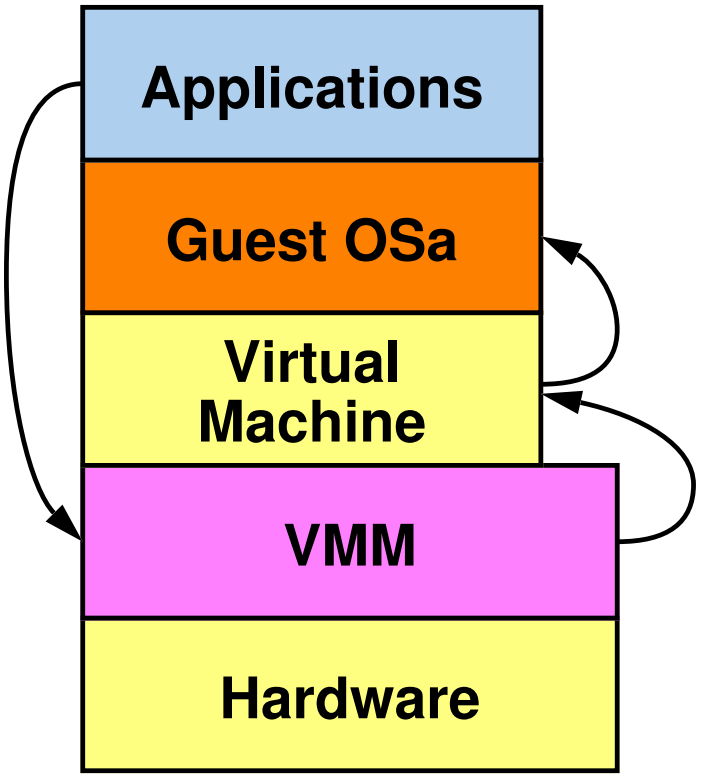
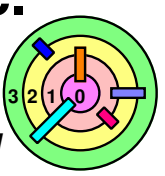
    - the VMM needs to find the address of the virtual machine's trap handler in the table and transfer control to it
    - interrupts pretty much work the same way

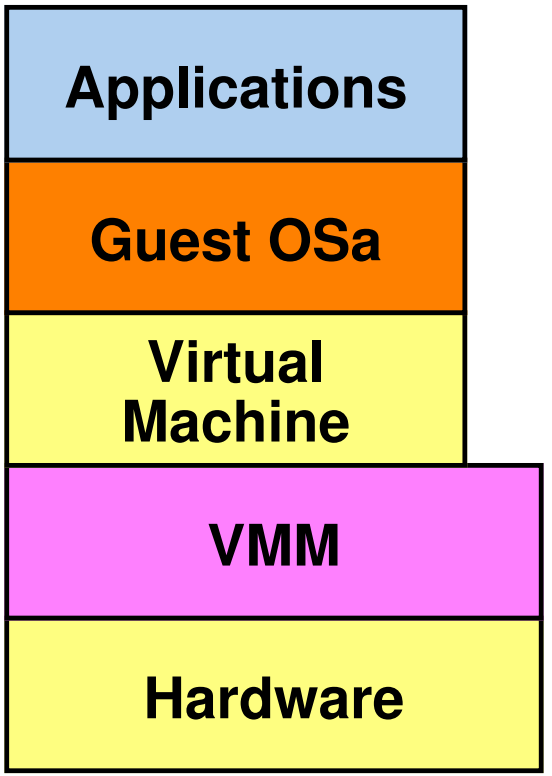


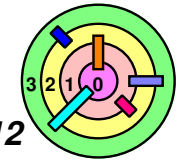

- "Virtual Machine" in the picture contains:
  - virtual CPU, virtual disk, virtual display, virtual keyboard, etc.
    - *data structures* that *represent HW components*



# VMM Operations

- Execute a *non-privileged* instruction
  - e.g., "add", "mul"



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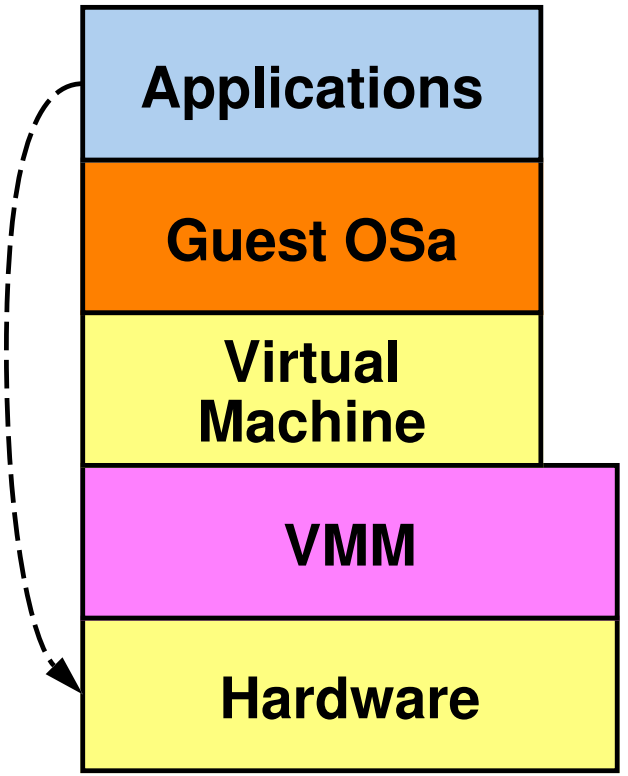


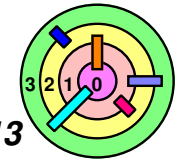

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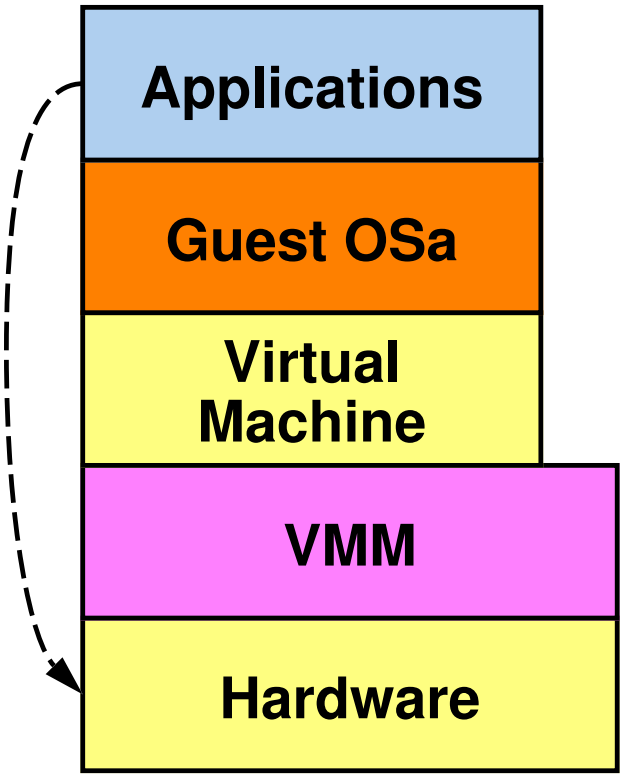
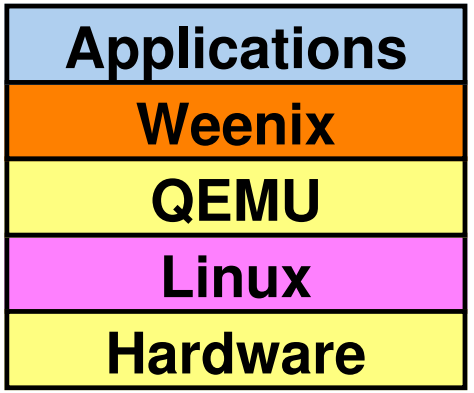



- Note: this is kind of like our kernel assignments (but quite different)




a *software emulator* for the x86 instruction set

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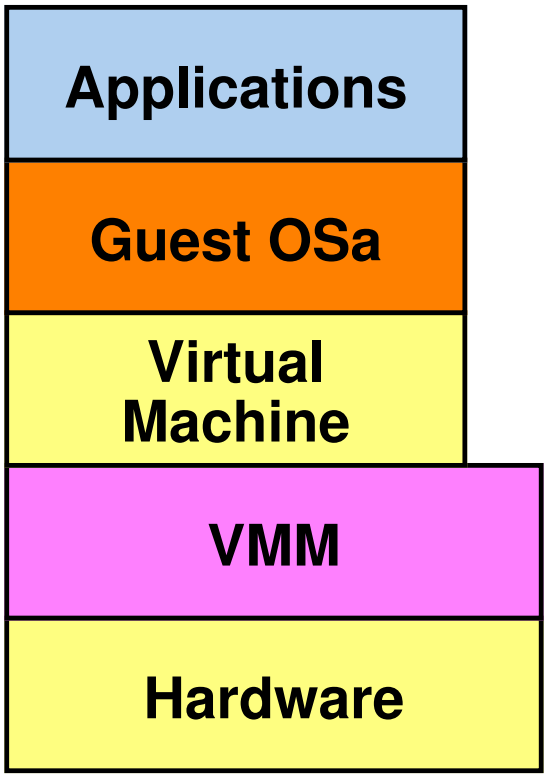
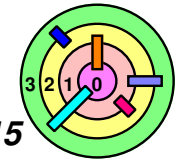
- Execute a ***privileged*** instruction
  - e.g., "trap" (due to "fork")



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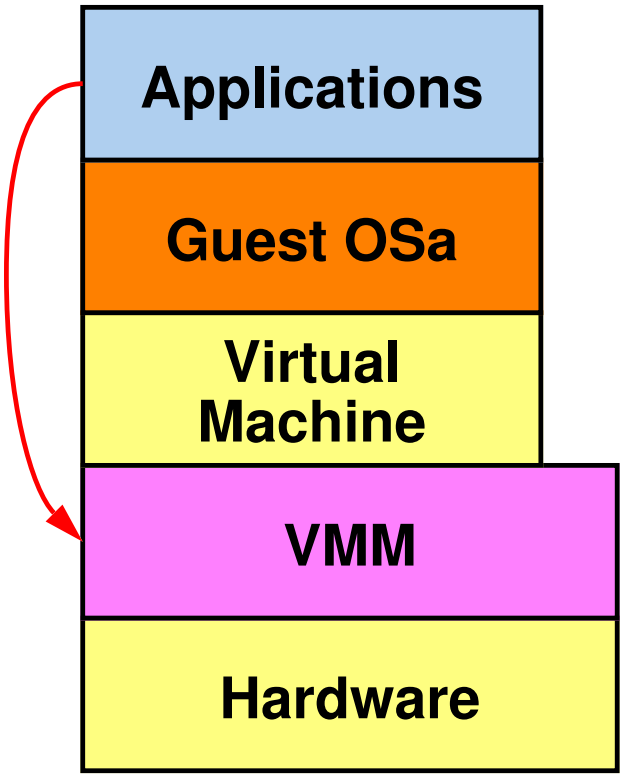


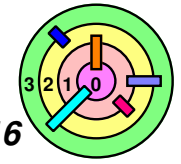

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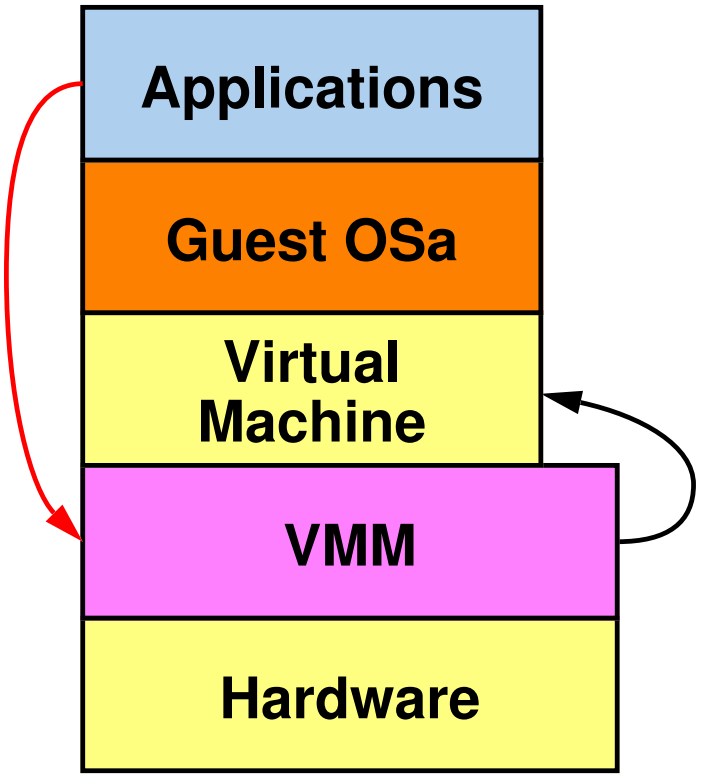


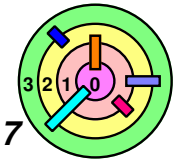

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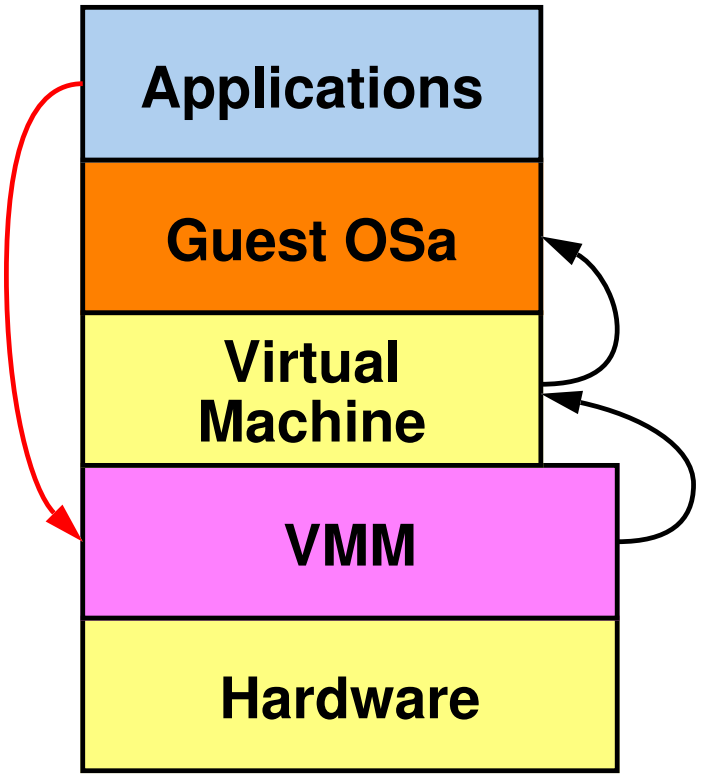
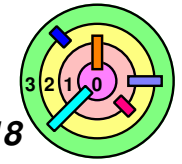


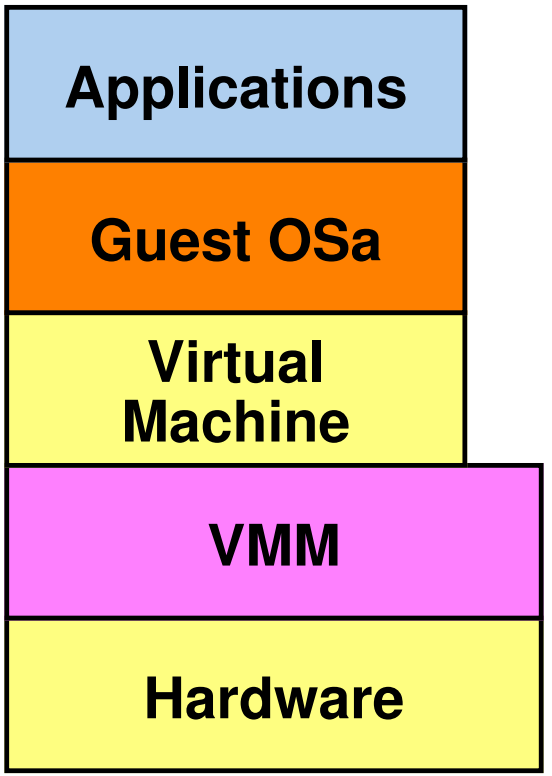

- Note that without VM, the application will simply traps into the OS directly
  - now it's a lot more involved

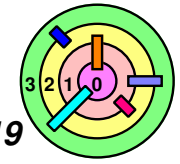
- Note that most instructions the trap handler executes are *not* privileged (such as the code to setup PCB, TCB, etc.)
  - clearly, these instructions can run in non-privileged mode
  - what type of code *must* execute in *privileged* mode?



# VMM Operations

- A *sensitive* instruction must execute in the privilege mode *(in the kernel)*
  - a *sensitive* instruction is an instruction that will change something in the *hardware/processor*
    - e.g., insturctions that change the mapping of virtual to real memory



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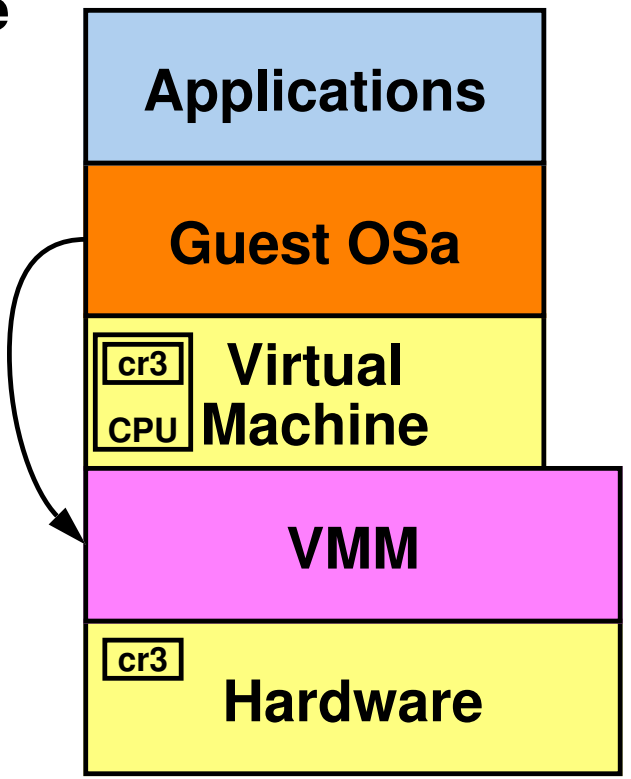
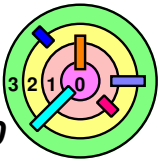



Guest OS runs in the *user* mode of the *real* processor
- executing a *sensitive* instruction will cause a trap into the VMM
- must *not* execute such instruction
- the VMM *emulates* the instruction



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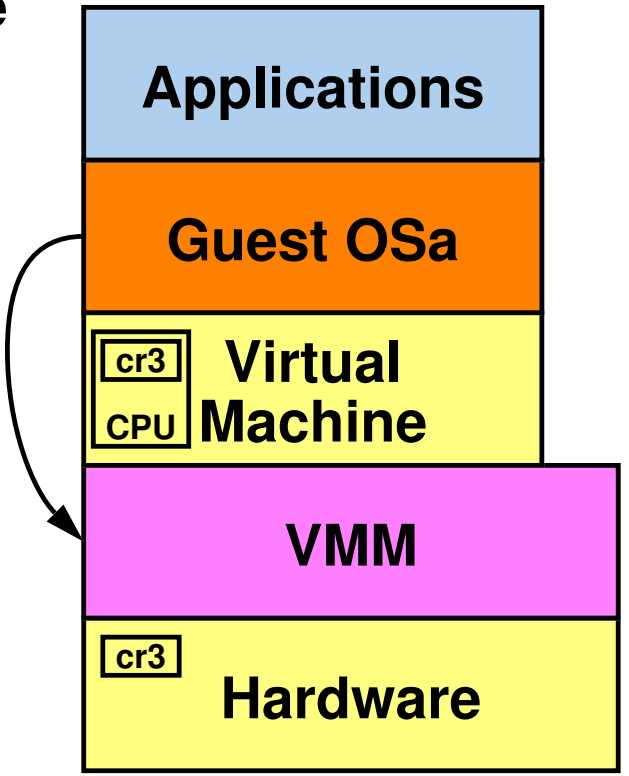
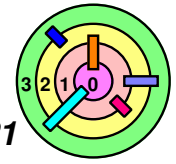
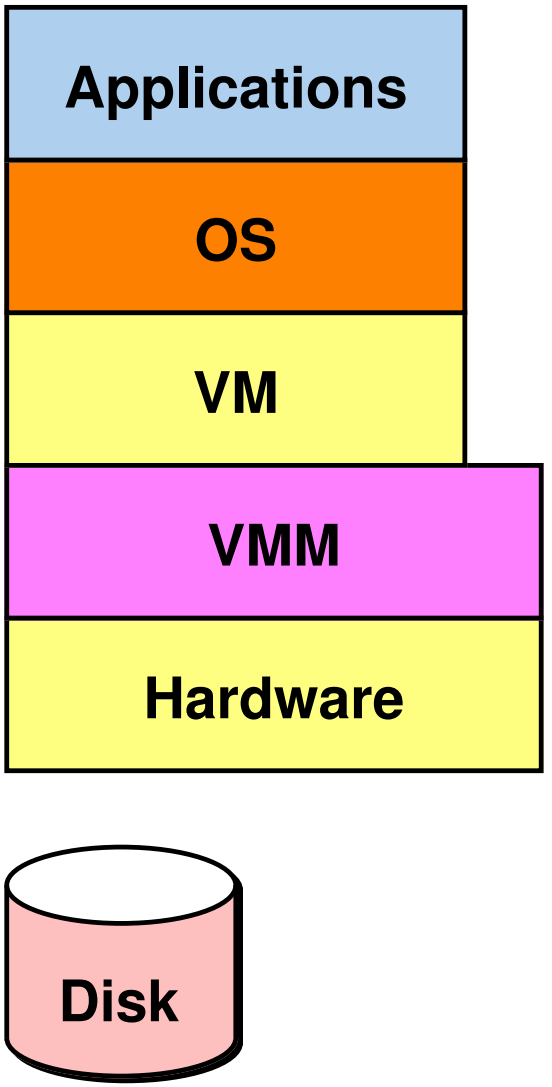



- All *sensitive* instructions must also be *privileged*
  - but what if it's not?
    - you cannot build a virtual machine for this processor
  - this gives us another definition of "sensitive instruction"
    - it's an instruction that if it's not privileged, it will cause the guest OS (inside a virtual machine) to execute incorrectly
      - this definition may be more useful



# VMM Operations

- What about I/O?
  - e.g., `read()`



# VMM Operations

- What about I/O?
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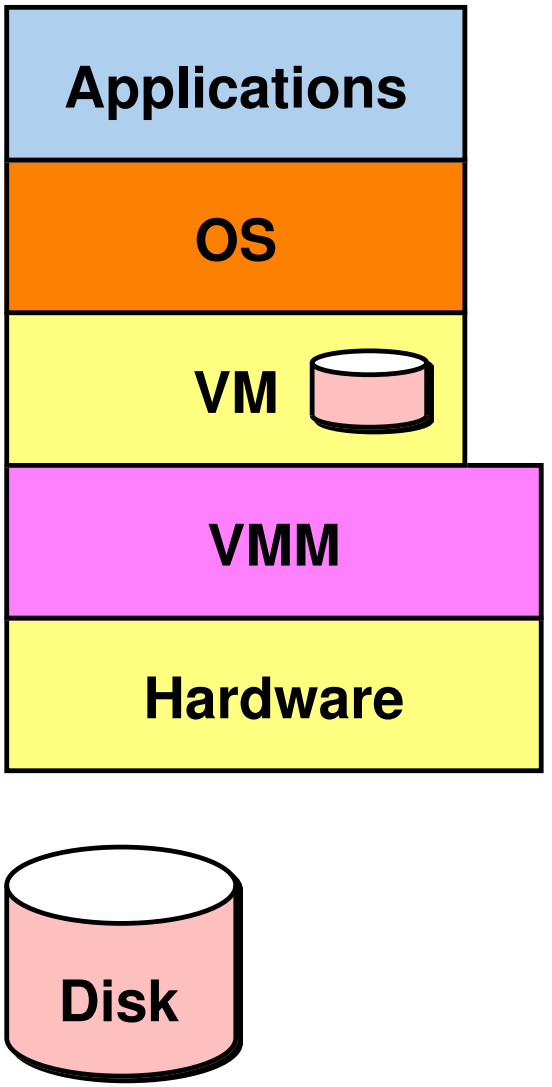
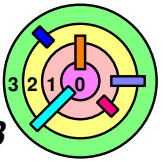
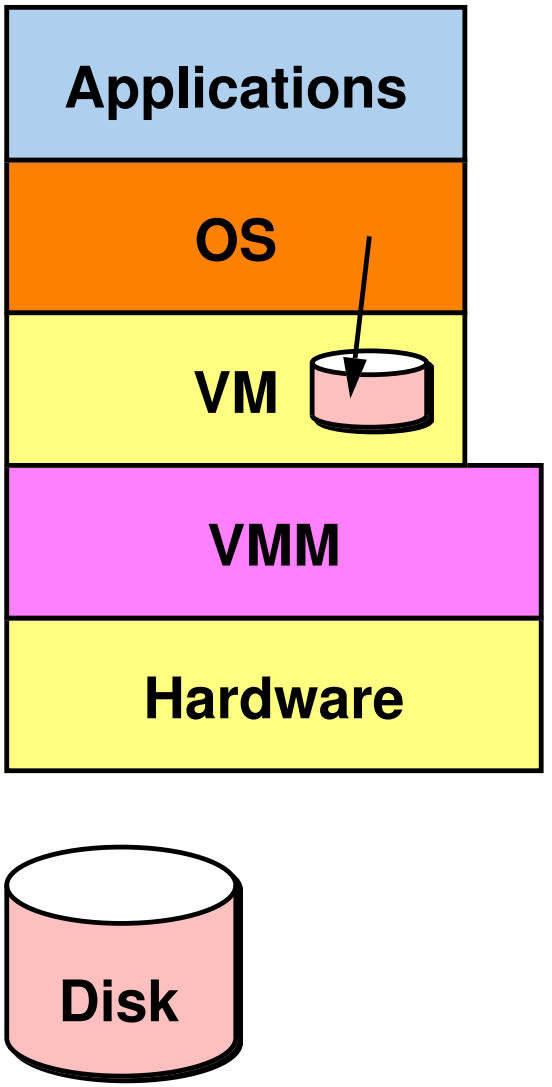
real disk is divvy up among the virtual machines
- each VM has a virtual disk

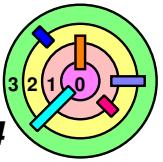


# VMM Operations

- What about I/O?
  - e.g., `read()`
  - `read()` eventually reaches the OS
  - the OS asks for a block on the virtual disk

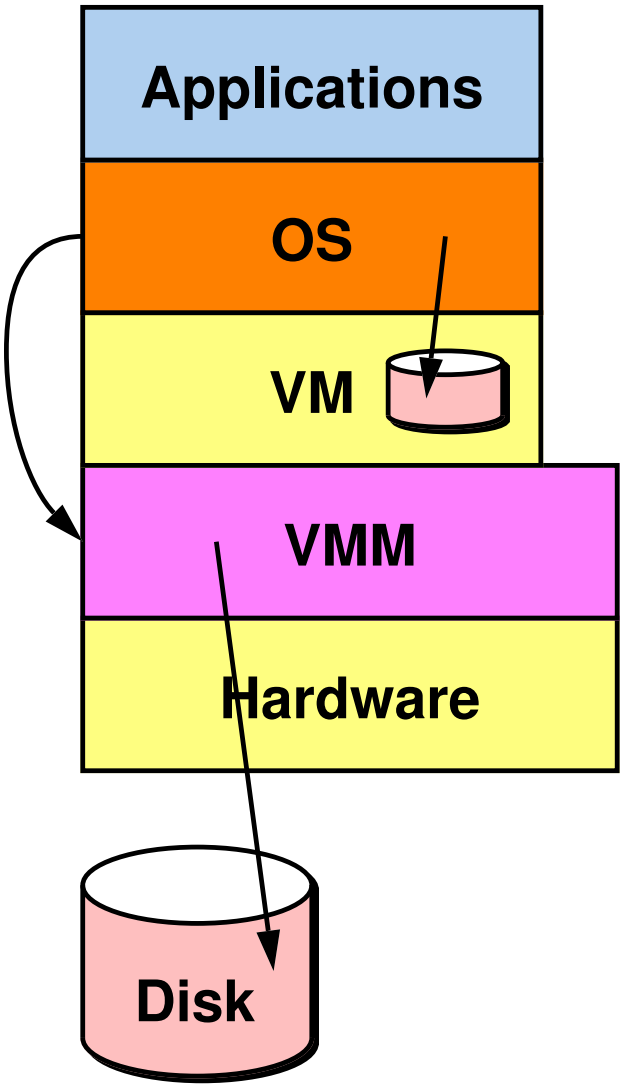


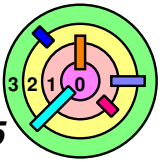



# VMM Operations

- What about I/O?
  - e.g., `read()`
  - `read()` eventually reaches the OS
  - the OS asks for a block on the virtual disk

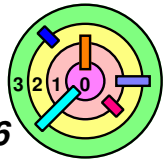
traps into VMM
- the VMM *emulates* the instruction (i.e., translates it into a request for the real disk)
- there's really *no* disk in the VM



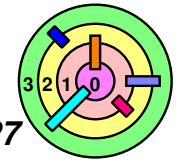
# Why Virtual Machine?

- It's a good structuring technique for a multi-user system
  - many advantages
- OS debugging and testing
  - run a production OS in a VM, accessible to users
  - test a new OS in a separate VM, accessible to developers
- Adapt to hardware changes in software
- Multiple OSes on one machine
  - one type of applications run really well in one OS
  - another type of applications run really well in a different OS
  - one physical machine can support both, no user need to suffer
  - today, it's common that a machine in the cloud would run multiple Linux OS instances and multiple Windows OS instances
- Server consolidation and service isolation
  - web hosting, security concerns
  - cloud computing



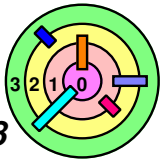
# Requirements

- A virtual machine is an efficient, isolated duplicate of real machine
  - requires faithful virtualization of pretty much all components
    - processor
    - memory
    - interval timers
    - I/O devices
    - etc.
  - this is "*pure*" virtualization
    - costly
- *Paravirtualization:*
  - virtualized entity is a bit different from the real entity
    - so as to enhance scalability, performance, and simplicity
    - it is probably aware that it's not running on a real machine



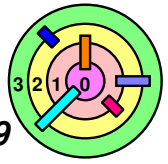
# Processor Virtualization Requirements

- Virtualizing the processor requires:
  1) multiplexing the real processor among the virtual machines
     - relatively straightforward
  2) making each virtual machine behaves just like a real machine
     - all instructions must work identically
     - generation of and response to traps and interrupts must be identical as well



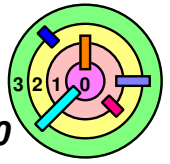
# Processor Virtualization Requirements

- Processor in the virtual machine is the real processor
  - instructions are executed (and not interpreted or emulated)
  - traps are generated just as they are on real machines
    - in a real machine, trap handler is indexed by the trap number into a hardware-mandated jump table
    - the VMM needs to find the address of the virtual machine's trap handler in the table and transfer control to it
    - interrupts pretty much work the same way
- Pretty much everything can be worked out except for one problem
  - if a virtual machine is executing in the privileged mode, what's to prevent it from changing how the memory-mapping resources that have been set up?
- Need to distinguish between ***sensitive instructions*** and ***privileged instructions***



# Processor Virtualization Requirements

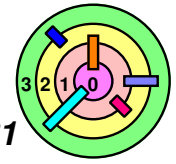
- ***Privileged Instructions:***
  - cause privileged-instruction trap when executed in user mode
  - execute fully when the processor is in privileged mode
- ***Sensitive Instructions:***
  - ***Control-sensitive instructions:***
    1) instructions that affect allocation of (real) system resources
       - such as insturctions that change the mapping of virtual to real memory
  - ***Behavior-sensitive instructions:***
    2) instructions whose effect depends on the allocation of (1)
       - such as insturctions that returns the real address of a location in virtual memory
    3) instructions whose effect depends on the current processor mode
       - such as x86's `popf` insturctions that sets a set of processor flags when run in privileged mode, but set a different set of flags otherwise



# Processor Virtualization Requirements

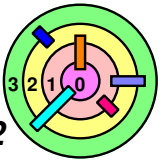
- [Popek and Goldberg, 1974] *proved* that the *sufficient condition* to be able to construct a virtual machine is simply the following:
  - a computer's set of *sensitive instructions* is a *subset* of its *privileged instructions*
  - i.e., if you execute a sensitive insturction in user mode, you will trap into the kernel
    - more importantly, if you execute a sensitive insturction in *virtual user or virtual privileged mode*, you will trap into *VMM*

- The above theorem holds for the IBM 360
  - virtual machines can be constructed for it
- The above theorem does not hold for the x86 processors
  - cannot build virtual machines for x86

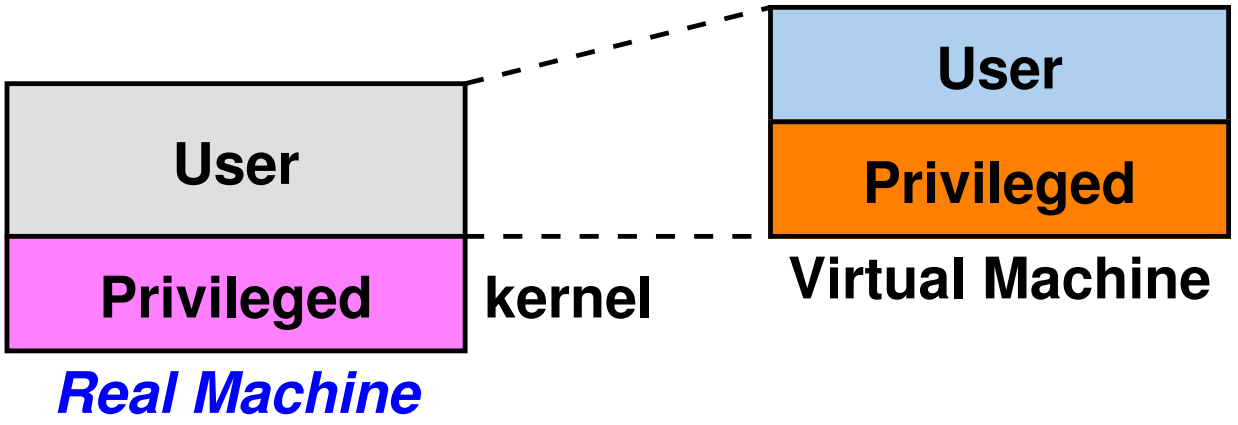


# The (Real) 360 Architecture

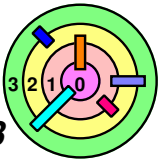
- Two execution modes
  - supervisor and problem (user)
  - all sensitive instructions are privileged instructions
- Memory is protectable: 2KB granularity
- All interrupt vectors and the clock are in first 512 bytes of memory
- I/O done via channel programs in memory, initiated with privileged instructions
- Dynamic address translation (virtual memory) added for Model 67



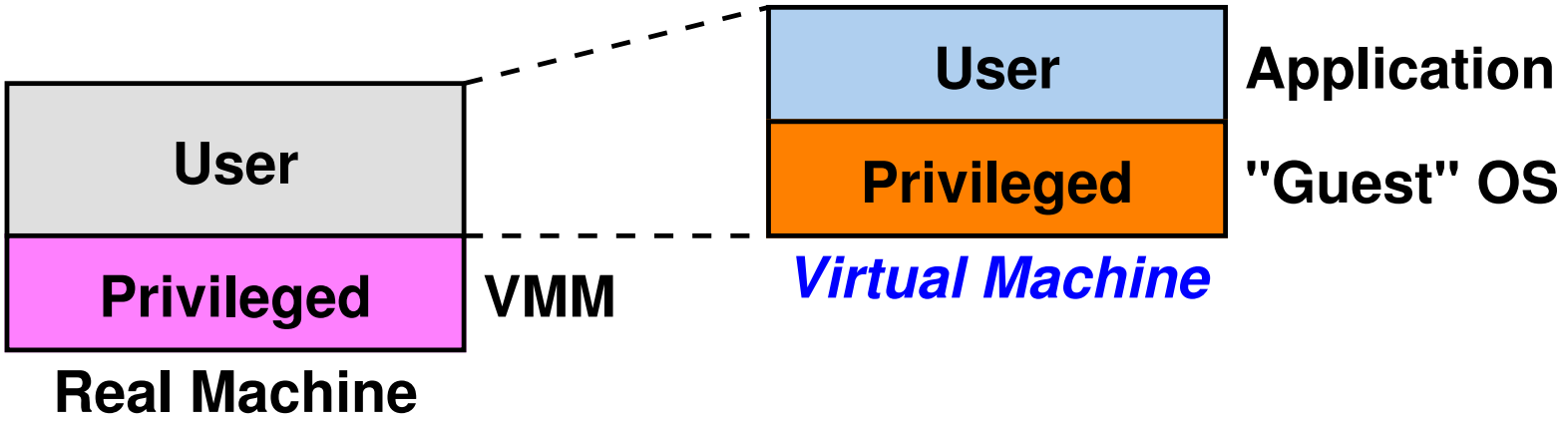
# Actions on Real 360



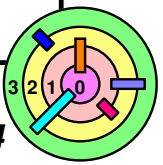

| | User mode | Privileged mode |
|---|---|---|
| non-sensitive instruction | executes fine | executes fine |
| errant instruction | traps to kernel | traps to kernel |
| sensitive instruction | traps to kernel | executes fine |



# Actions on Virtual 360

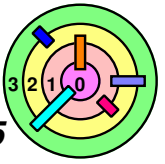



| | Virtual user mode | Virtual privileged mode |
|---|---|---|
| non-sensitive instruction | executes fine | executes fine |
| errant instruction | traps to VMM; VMM causes trap to occur on Guest OS | traps to VMM; VMM causes trap to occur on Guest OS |
| sensitive instruction | traps to VMM; VMM causes trap to occur on Guest OS | traps to VMM; VMM verifies and *emulates* instruction |

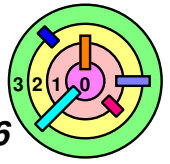


# Virtual Devices?

- Terminals
  - connecting (real) people
- Networks
  - didn't exist in the 60s
  - (how did virtual machines communicate?)
- Disk drives
  - CP67 supported "mini disks"
  - extended at Brown into "segment system"
- Interval timer
  - virtual or real?



# Virtual Machines
# Part 2: Now



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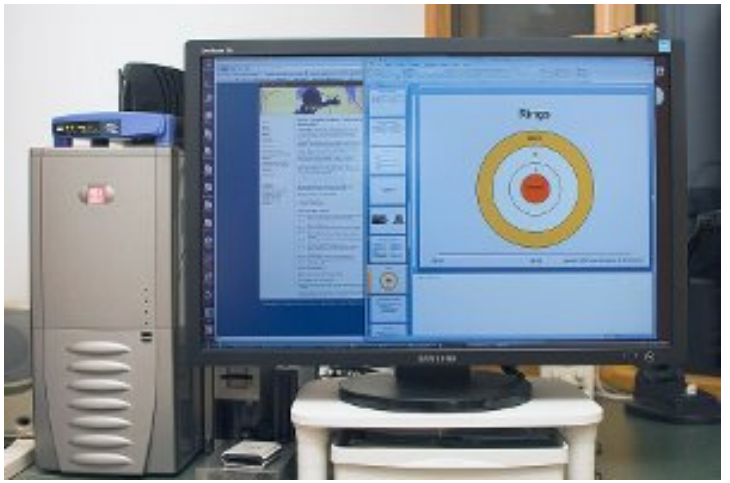
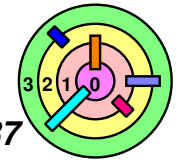




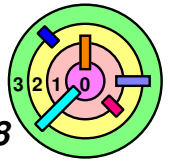
# How They Are Different

## *IBM 360*

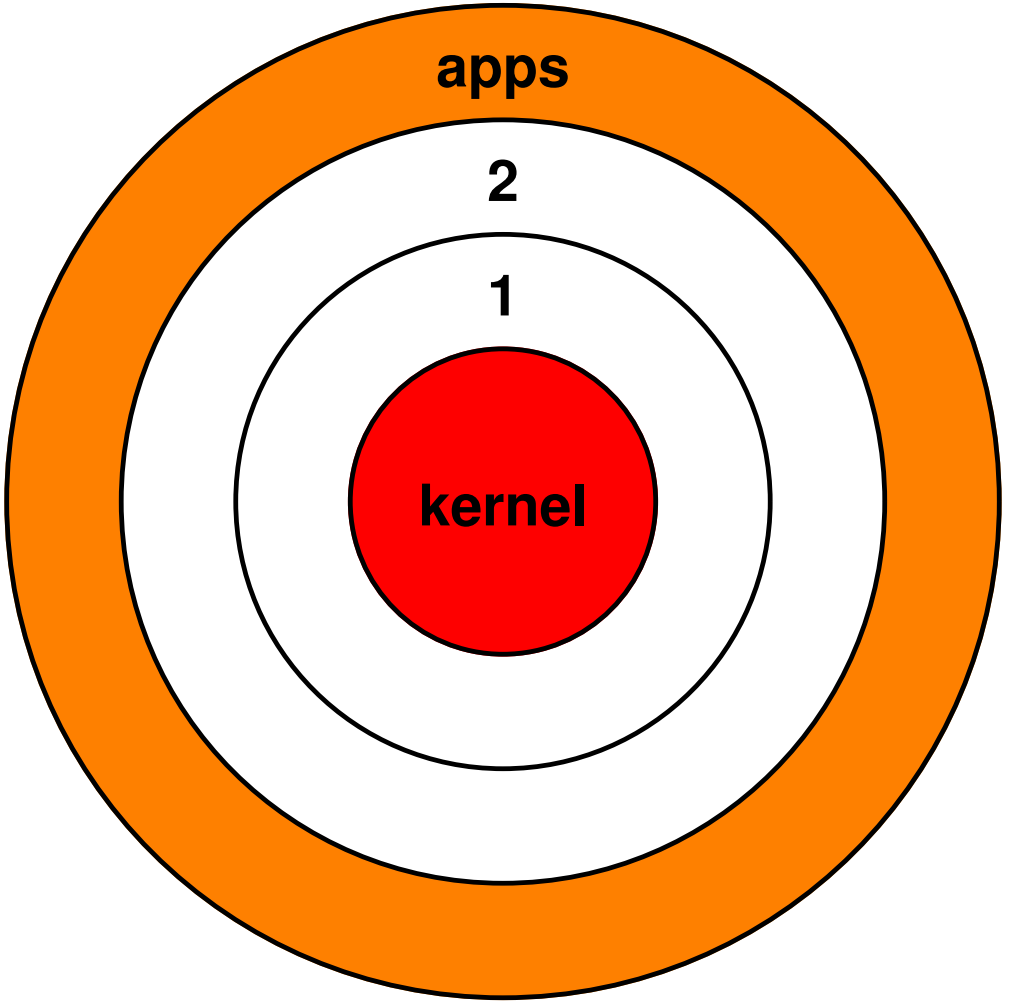
- Two execution modes
  - supervisor and problem (user)
  - *all* sensitive instructions are privileged instructions
- Memory is protectable: 2k-byte granularity
- All interrupt vectors and the clock are in first 512 bytes of memory
- I/O done via *channel programs* in memory, initiated with privileged instructions
- Dynamic address translation (virtual memory) added for Model 67

## *Intel x86*

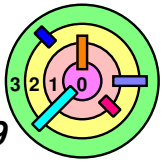
- Four execution modes
  - rings 0 through 3
  - *not all* sensitive instructions are privileged instructions
- Memory is protectable: segment system + virtual memory
- Special register points to interrupt table
- I/O done via *memory-mapped* addresses
- Virtual memory is standard



# Rings

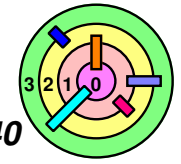



An x86 processor can be in one of 4 *modes*



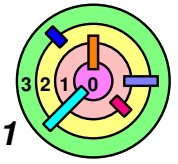
# A Sensitive x86 Instruction

- `popf`
  - pops flags (word) off stack, setting processor flags according to word's content
    - sets all flags if in ring 0
      - including interrupt-disable flag
    - just some of them if in other rings
      - ignores interrupt-disable flag
  - bad news: if invoked in *user* mode, does *not* cause a *trap!*
    - therefore, this instruction will execute differently in the OS when it's running on top of a VM (as compared to running on a real machine)
      - since the OS is running in user mode under the virtual memory scheme
    - this is one of the major problem to virtualize x86 systems
    - there is another major problem (related to device I/O)



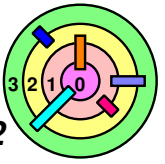
# What to Do?

- ***Binary rewriting***
  - rewrite kernel binaries of guest OSes
    - replace sensitive instructions with hypercalls
    - do so dynamically (i.e., ***dynamic*** binary rewriting)
      - VMware does this
    - no need to modify guest OS
- ***Hardware virtualization***
  - fix the hardware so it's virtualizable
- ***Paravirtualization***
  - virtual machine differs from real machine
    - provides more convenient interfaces for virtualization
    - ***hypervisor*** interface between virtual and real machines
      - please note that some would use the term ***"hypervisor"*** to simply mean ***"VMM"*** (even without paravirtualization)
    - guest OS ***source code*** is ***modified*** (and recompiled)



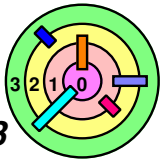
# Binary Rewriting

- Privilege-mode code run via binary translator
  - guest OS is unmodified
  - replaces sensitive instructions with hypercalls
  - translated code is cached
    - usually translated just once
  - *VMWare*
  - U.S. patent 6,397,242
- VirtualBox appears to do something similar to VMWare
  - see https://www.virtualbox.org/manual/ch10.html#idp58764736 for more details



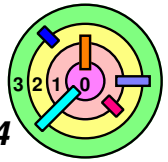
# Fixing the Hardware

- Intel Vanderpool technology: VT-x
  - new processor mode
    - "ring -1"
      - *root* mode
      - other modes are *non-root*
  - certain operations and events in non-root mode cause *VM-exit* to root mode
    - essentially a hypercall
    - code in root mode specifies which operations and events cause VM-exits
      - e.g., `popf`, page fault
  - non-VMM OSes must not be written to use root mode!

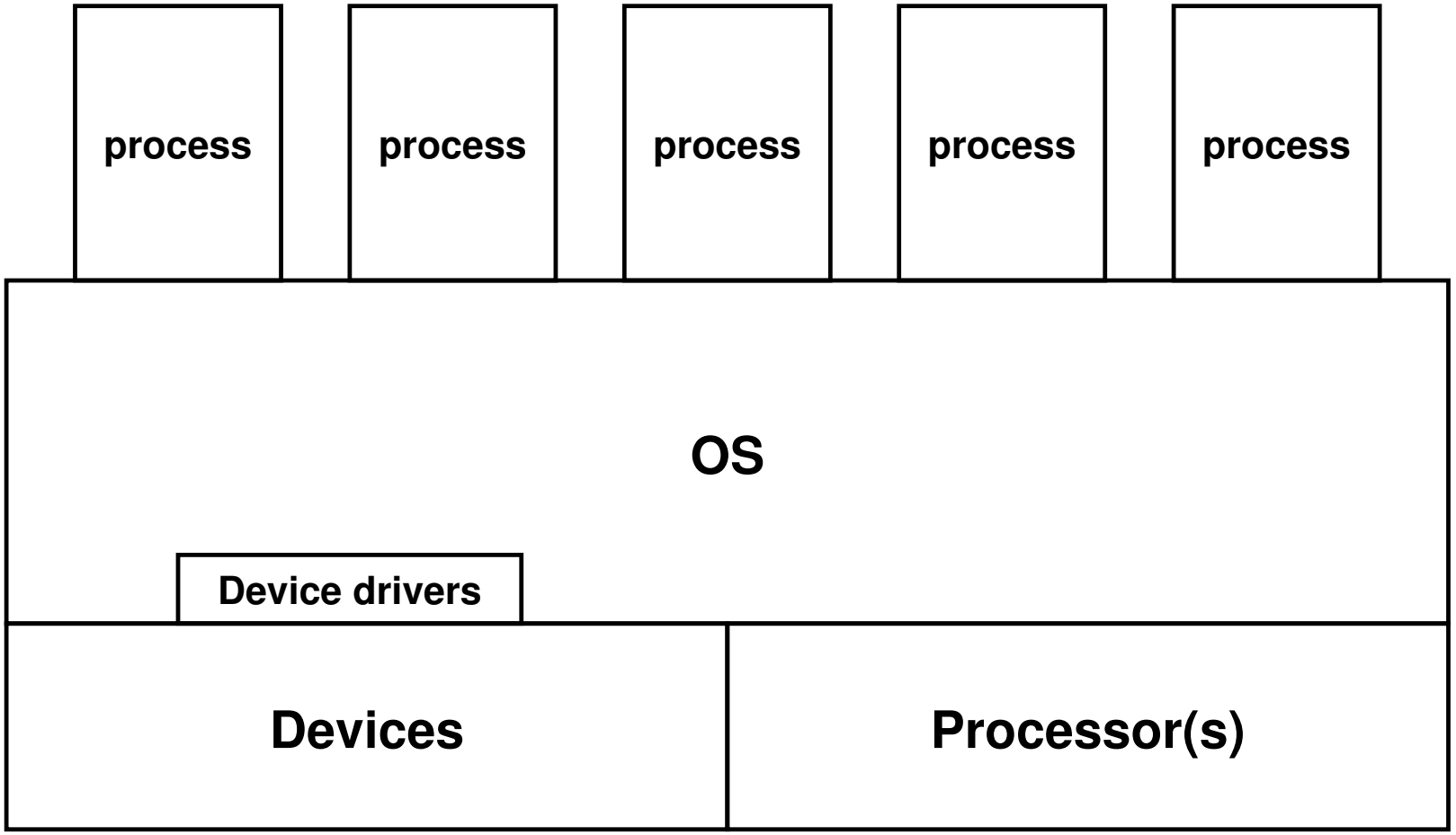


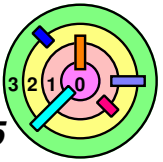
# I/O Virtualization

- Channel programs were generic for IBM 360
  - can be emmulated in the VMM
- I/O via memory-mapped registers is not
  - lots and lots and lots of device drivers
  - must VMM handle all of them?

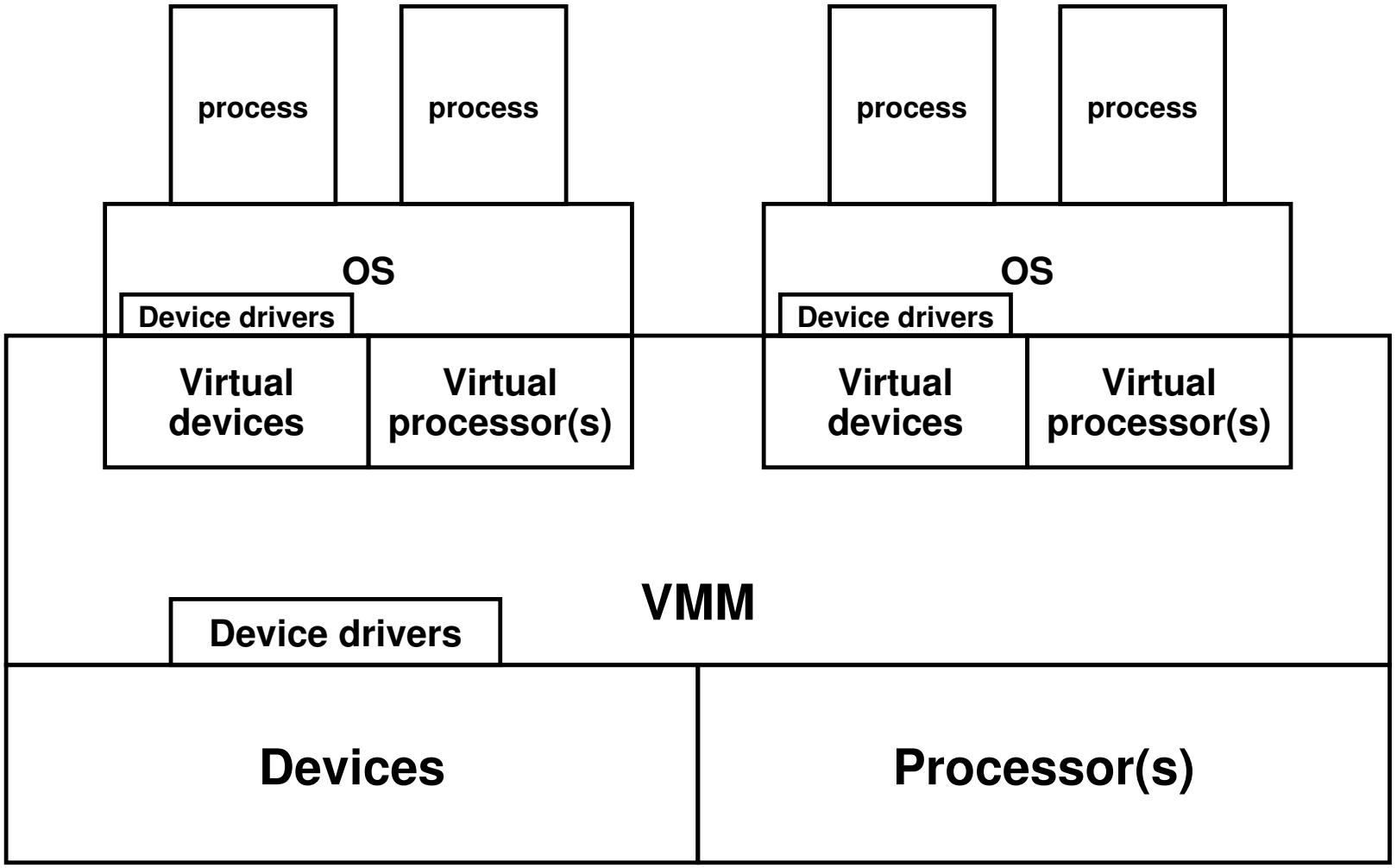


# Real-Machine OS Structure

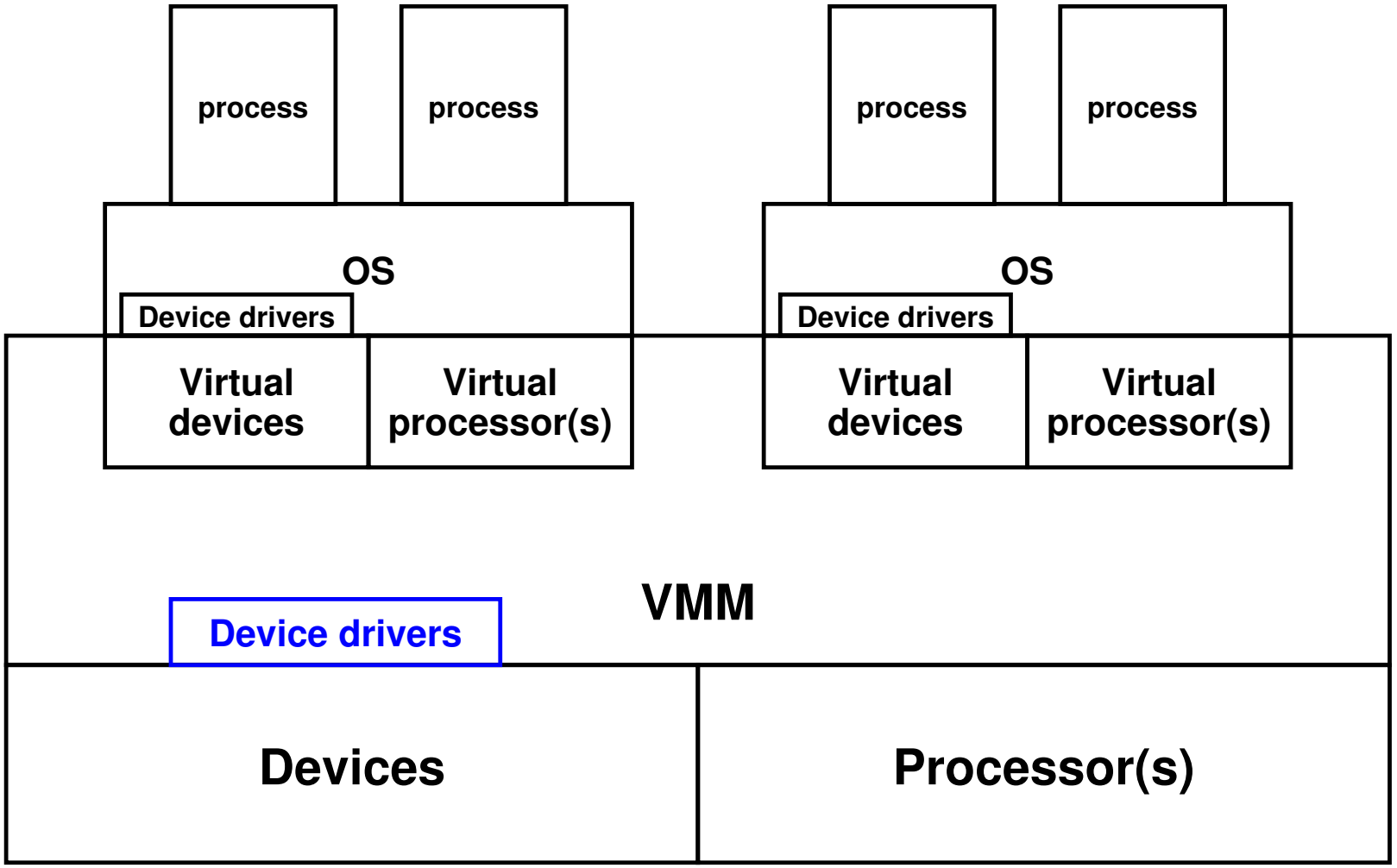


# On a Virtual Machine ...

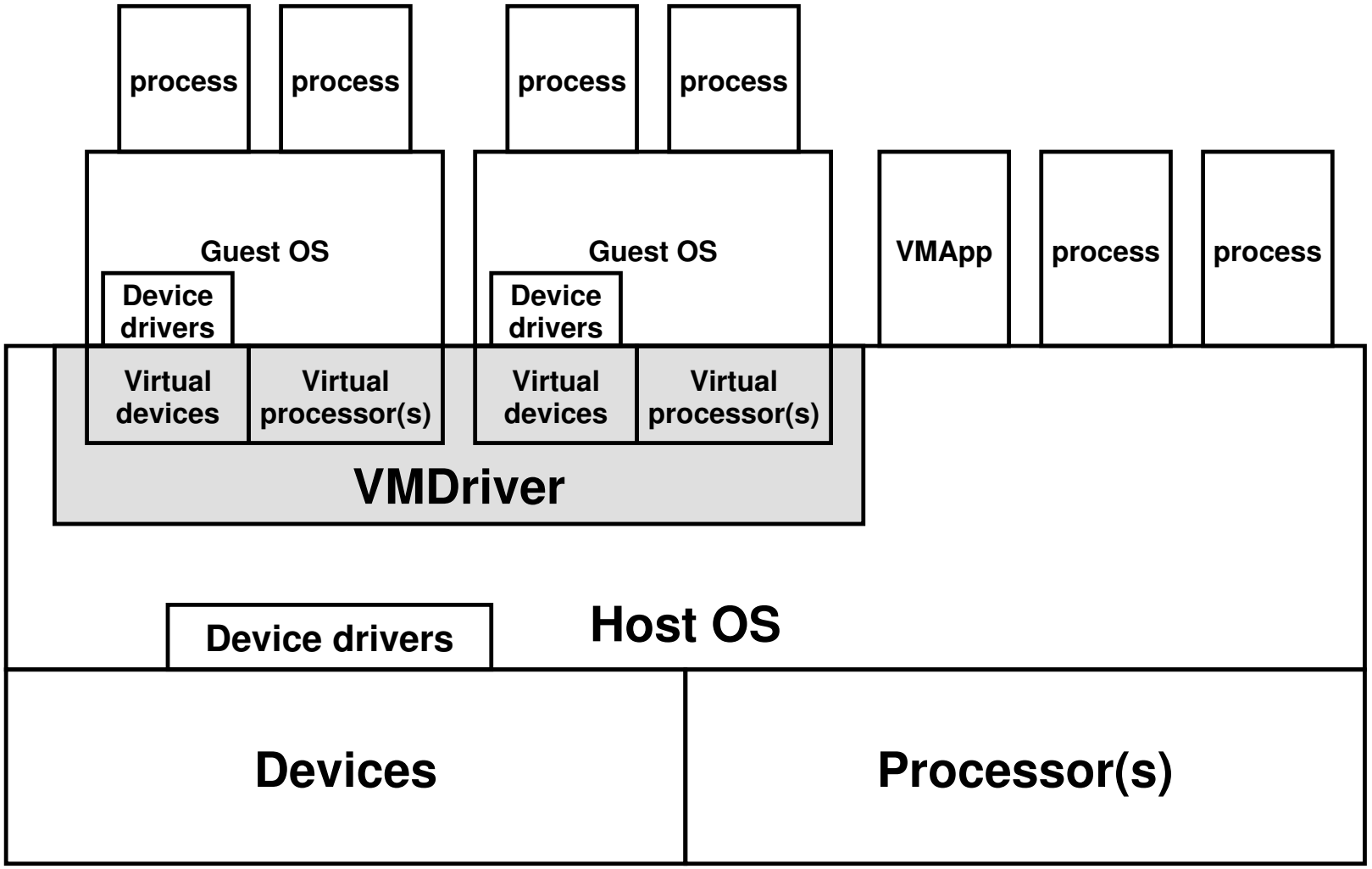


# On a Virtual Machine ...



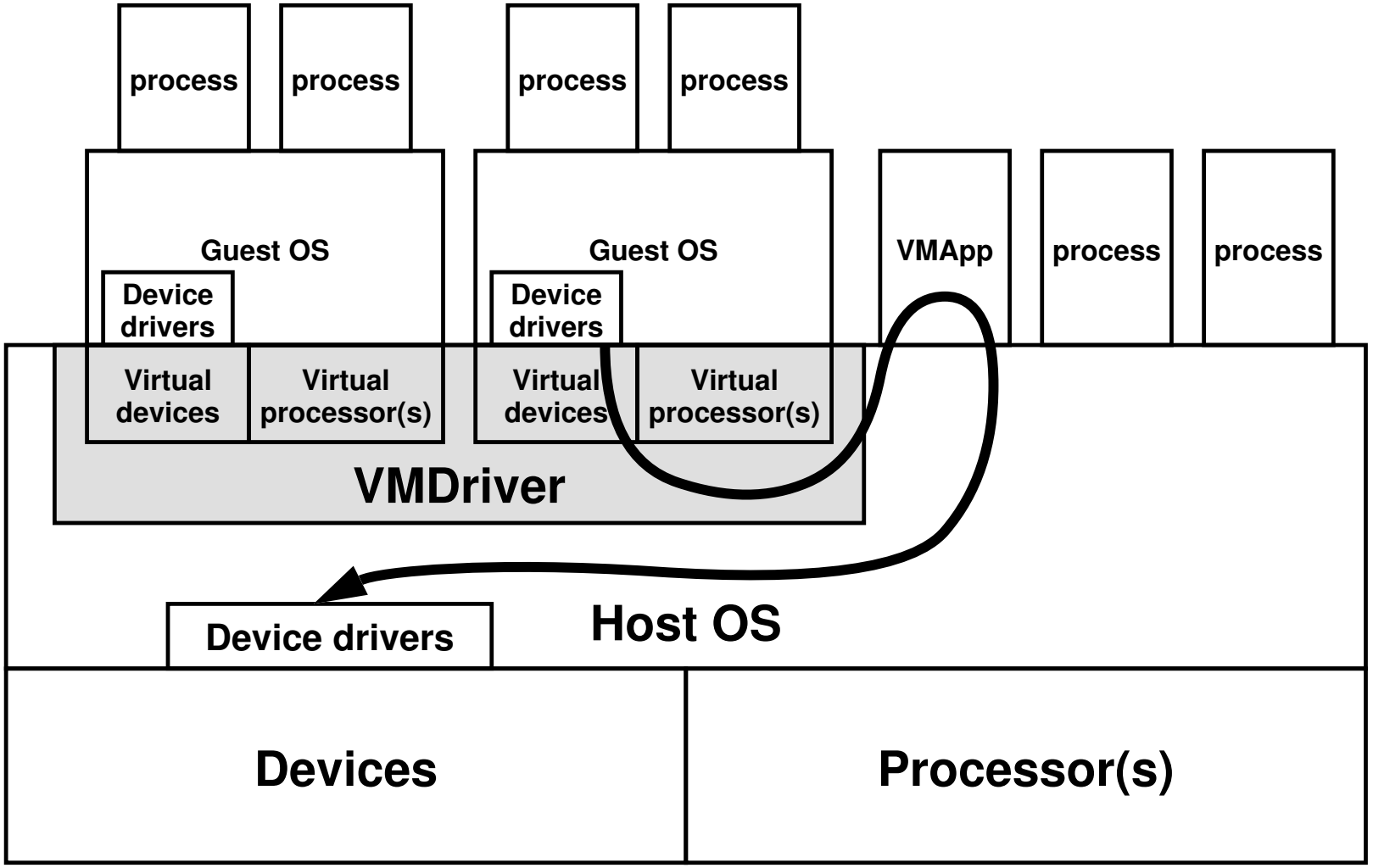

- More suitable for server machines (higher performance)
  - problem: who is going to write device drivers for VMM in lower-end machines?

# VMware Workstation - Host/Guest Model




- VMware's solution is to use a host/guest model
  - VMDriver takes the place of the VMM
  - plenty of device drivers already available on host OS

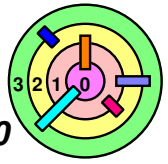
# VMware Workstation - Host/Guest Model



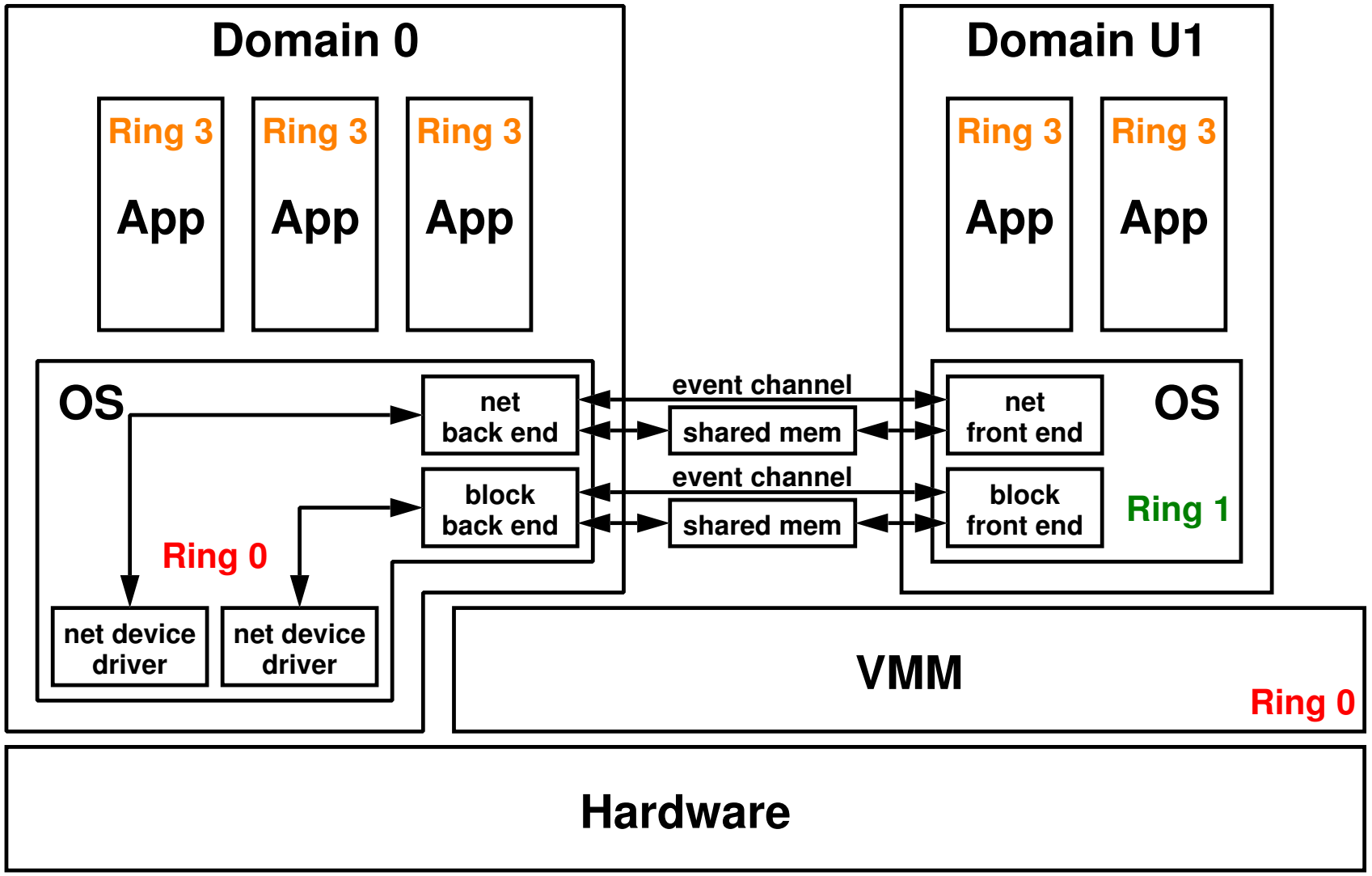

- More suitable for "workstations" - more variety of devices
  - *convenience* over *performance*

# Paravirtualization

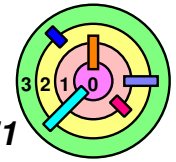
- Sensitive instructions replaced with hypervisor calls
  - traps to VMM
- Virtual machine provides higher-level device interface
  - guest machine has *no device drivers*
    - OS is changed already, might as well change I/O, if there are sufficient benefits



# Xen

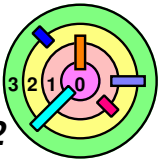



- In a way, the Domain 0 OS is like the Host OS in VMware
  - it directly talks to the hardware

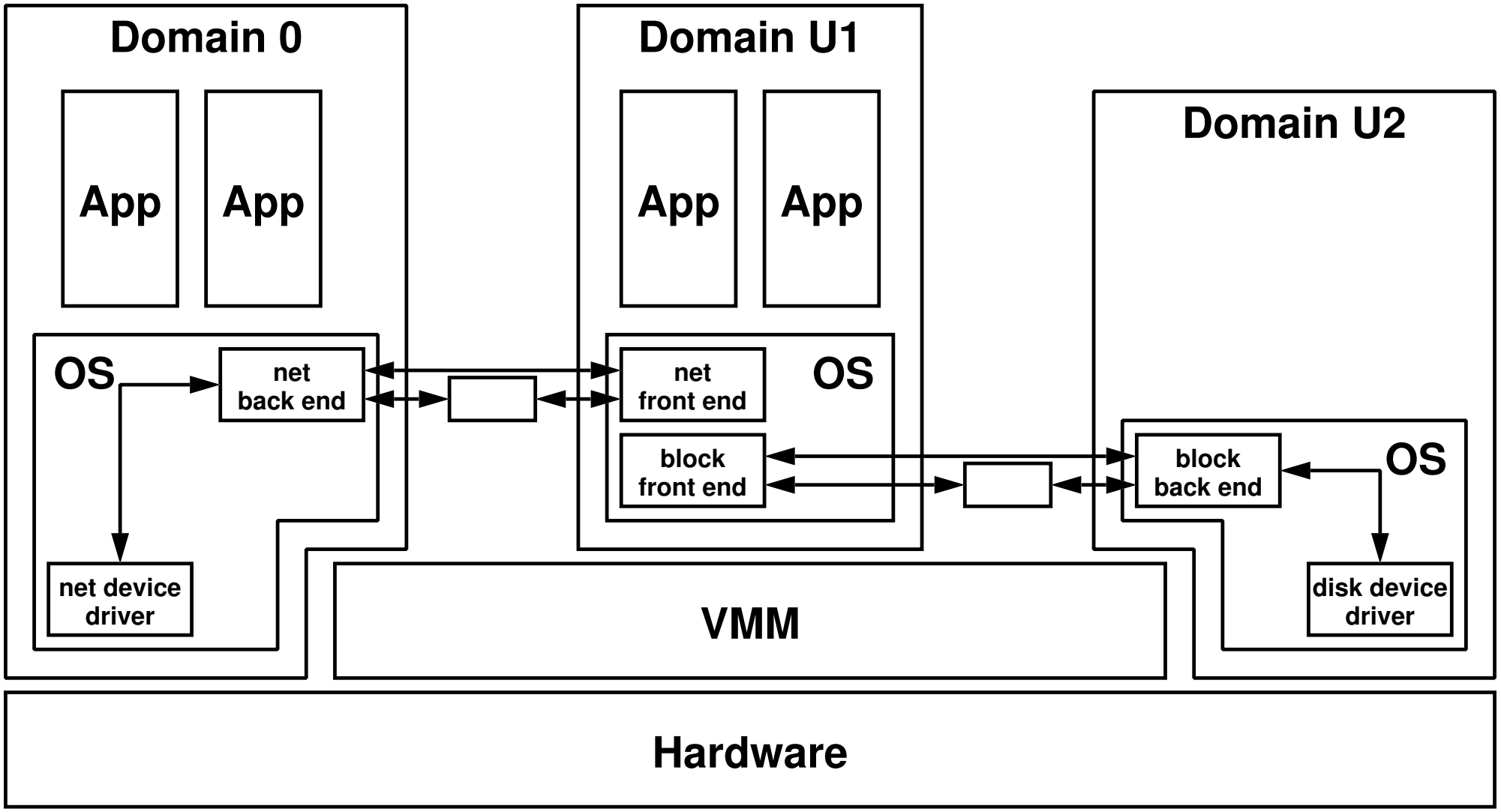


# Additional Applications

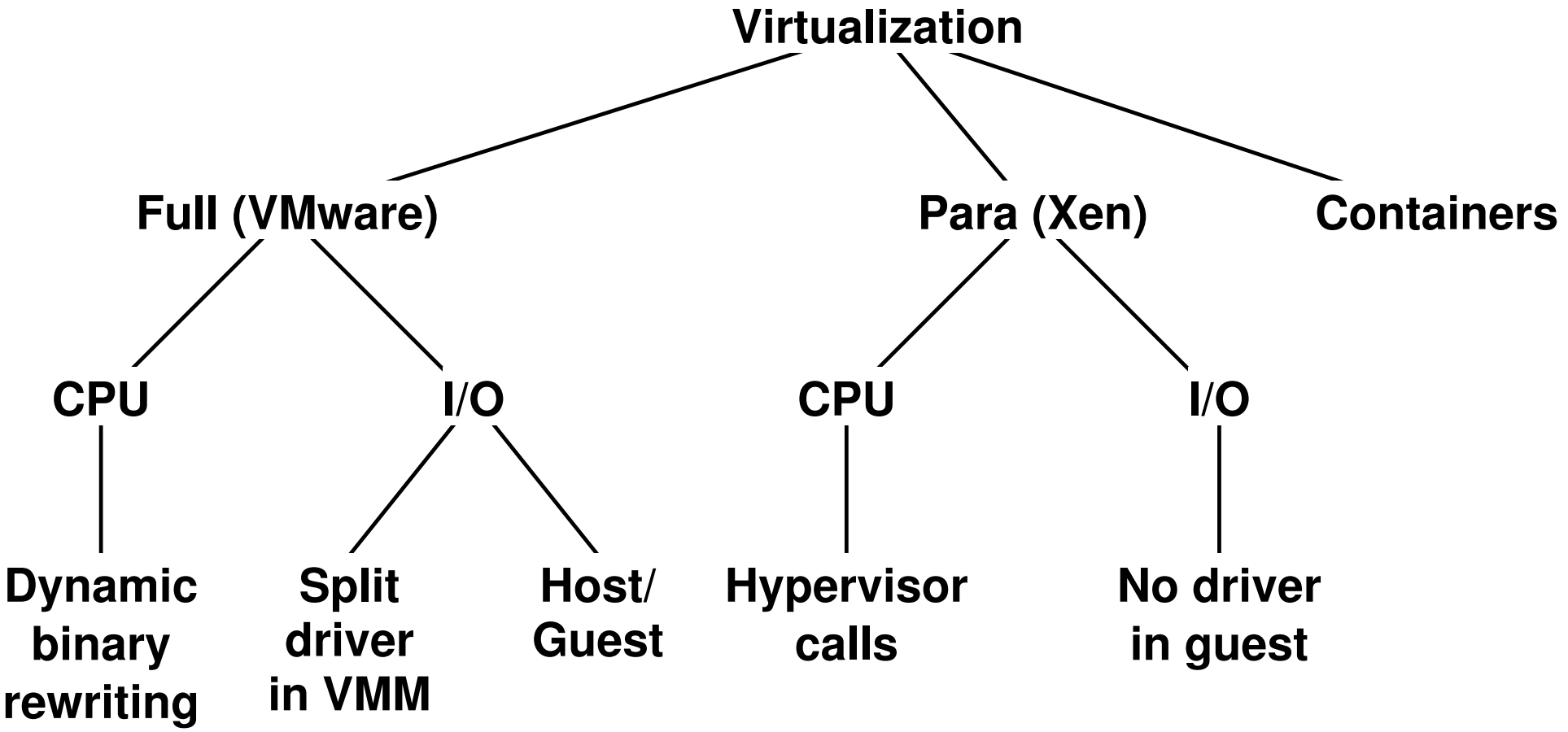
- **Sandboxing**
  - isolate web servers
  - isolate device drivers
- **Migration**
  - VM not tied to particular hardware
  - easy to move from one (real) platform to another

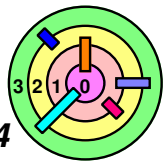


# Xen with Isolated Driver



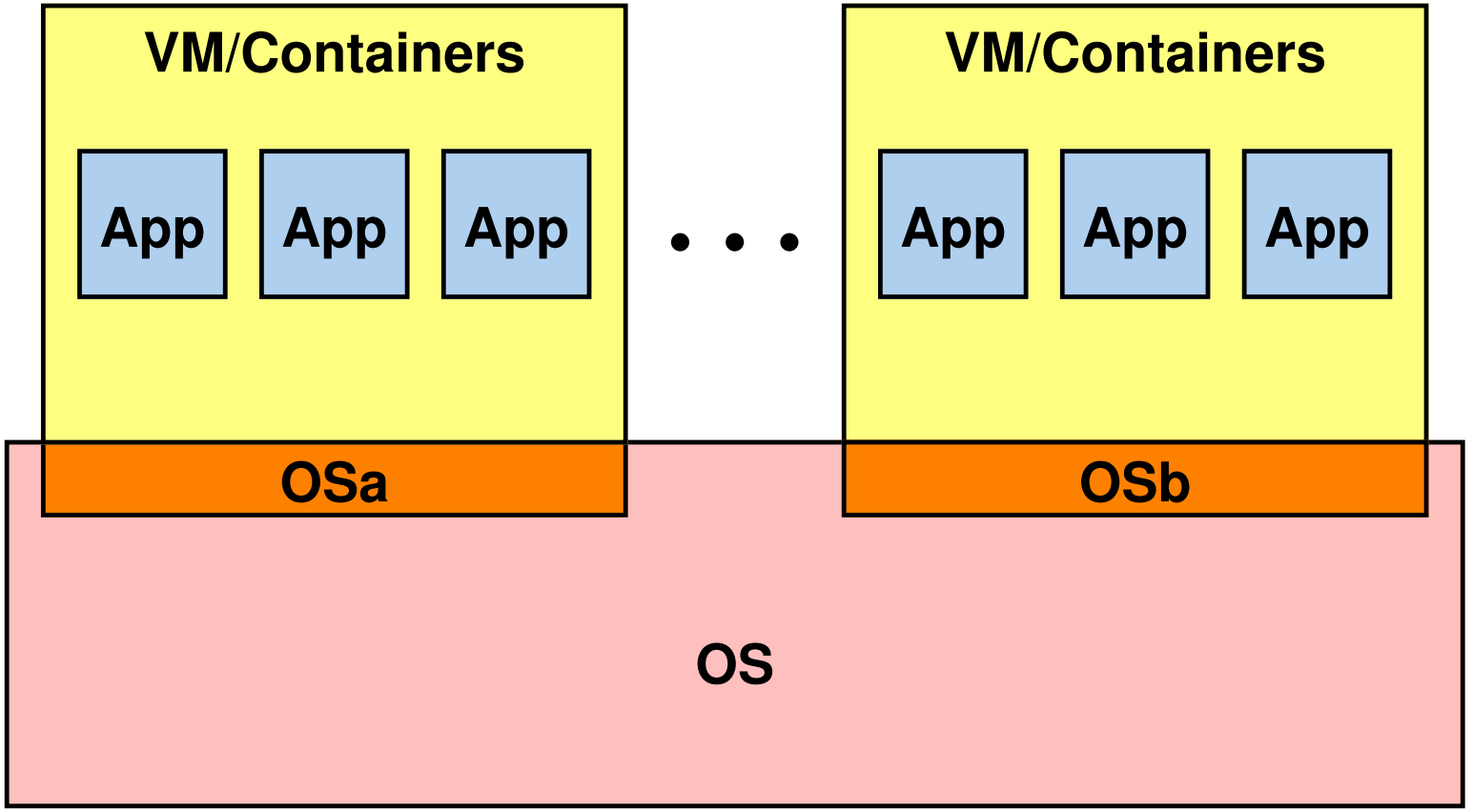
# Summary



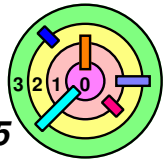



# One More Kind Of Virtualization

- Containerized OS (or OS Containers)
  - not covered in textbook

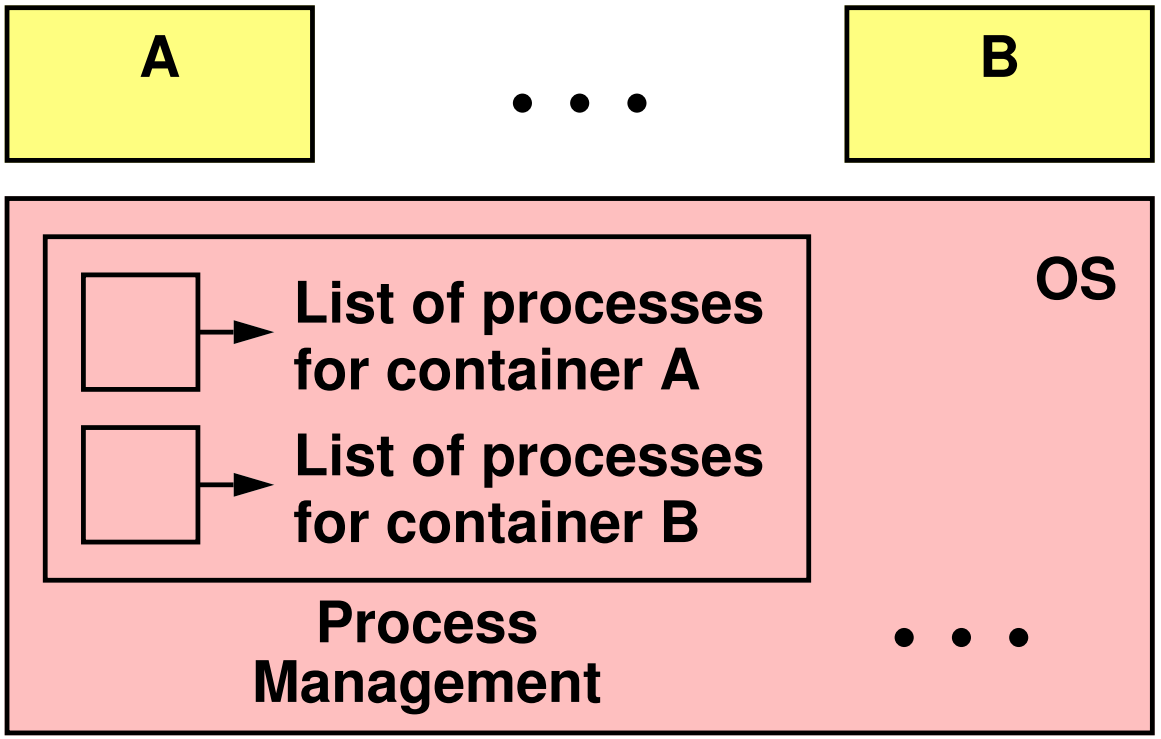



  - the OS provides the abstraction that each container runs on top of a separate OS (but there is really only one OS)
  - e.g., OpenVZ, Linux Containers (LXC), Docker

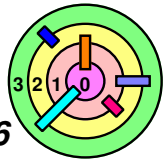


# Containerized OS

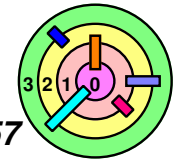
- Within the OS, the management of resources for each container is separated
  - e.g., processes for container A is kept separate from processes for container B



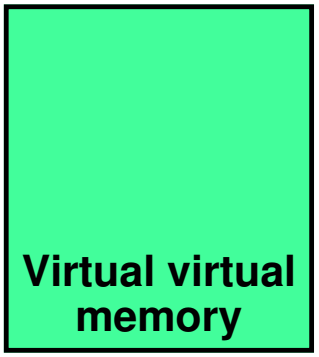

- Others may consider this "virtual machine", but we shouldn't
  - because "guest OS" does not run in user space



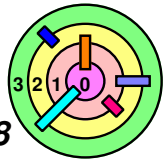
# 7.2.6 Virtualizing Virtual Memory



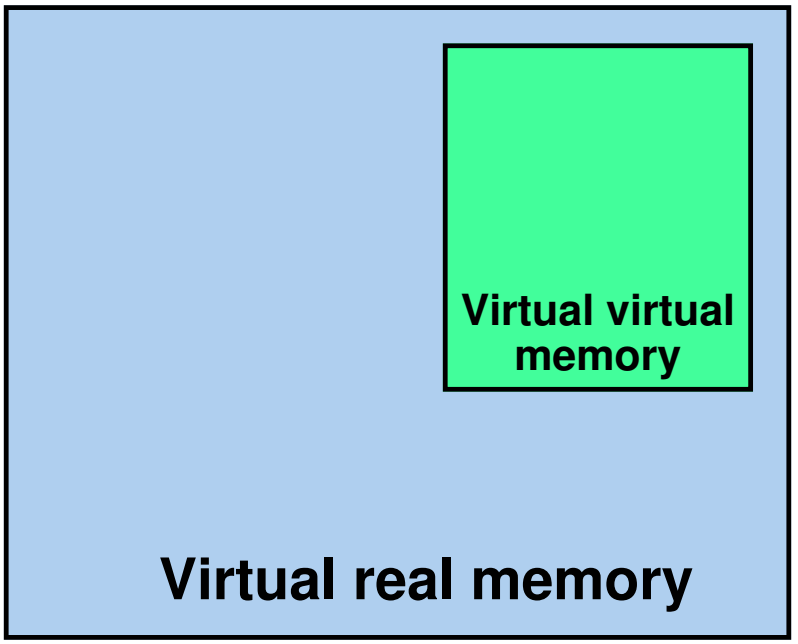
# Virtual Machines Meet Virtual Memory



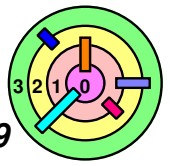

- A user process thinks it's accessing virtual memory
  - but it's really dealing with *virtual virtual memory*



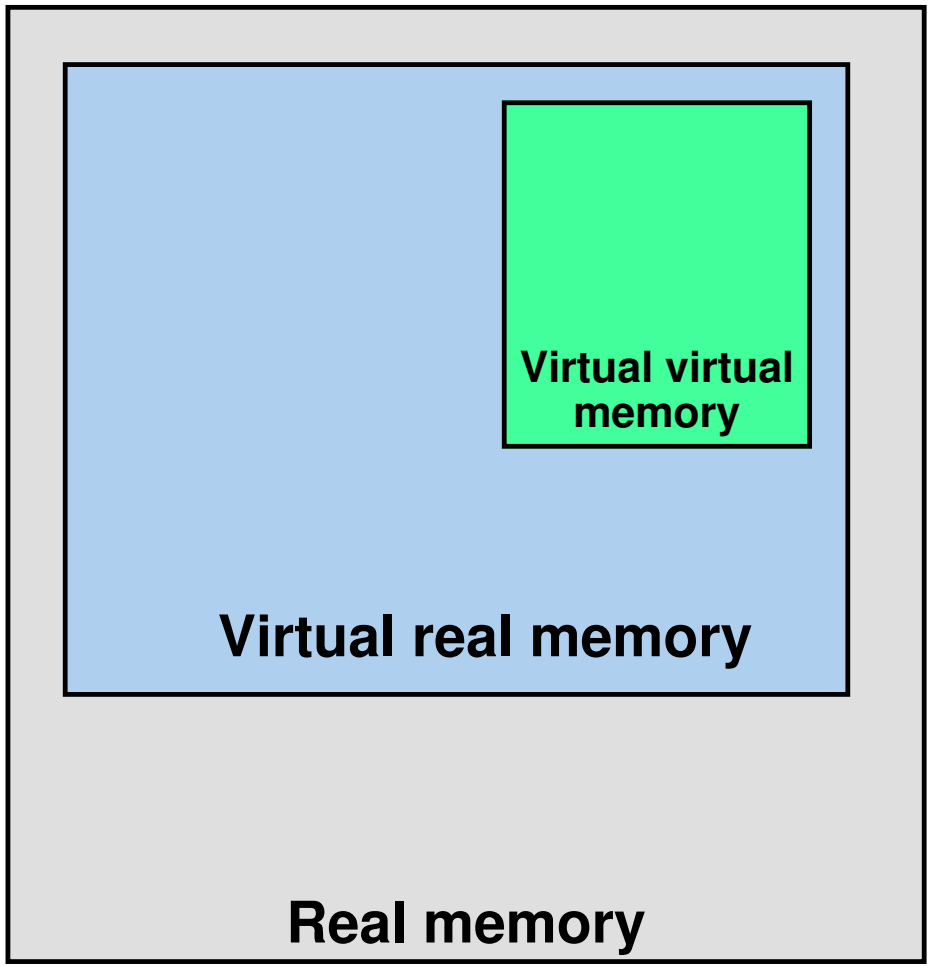
# Virtual Machines Meet Virtual Memory



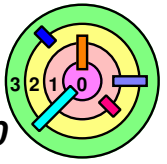

- A user process thinks it's accessing virtual memory
  - but it's really dealing with *virtual virtual memory*
- The OS in a VM thinks it's managing real memory
  - but it's really dealing with *virtual real memory*



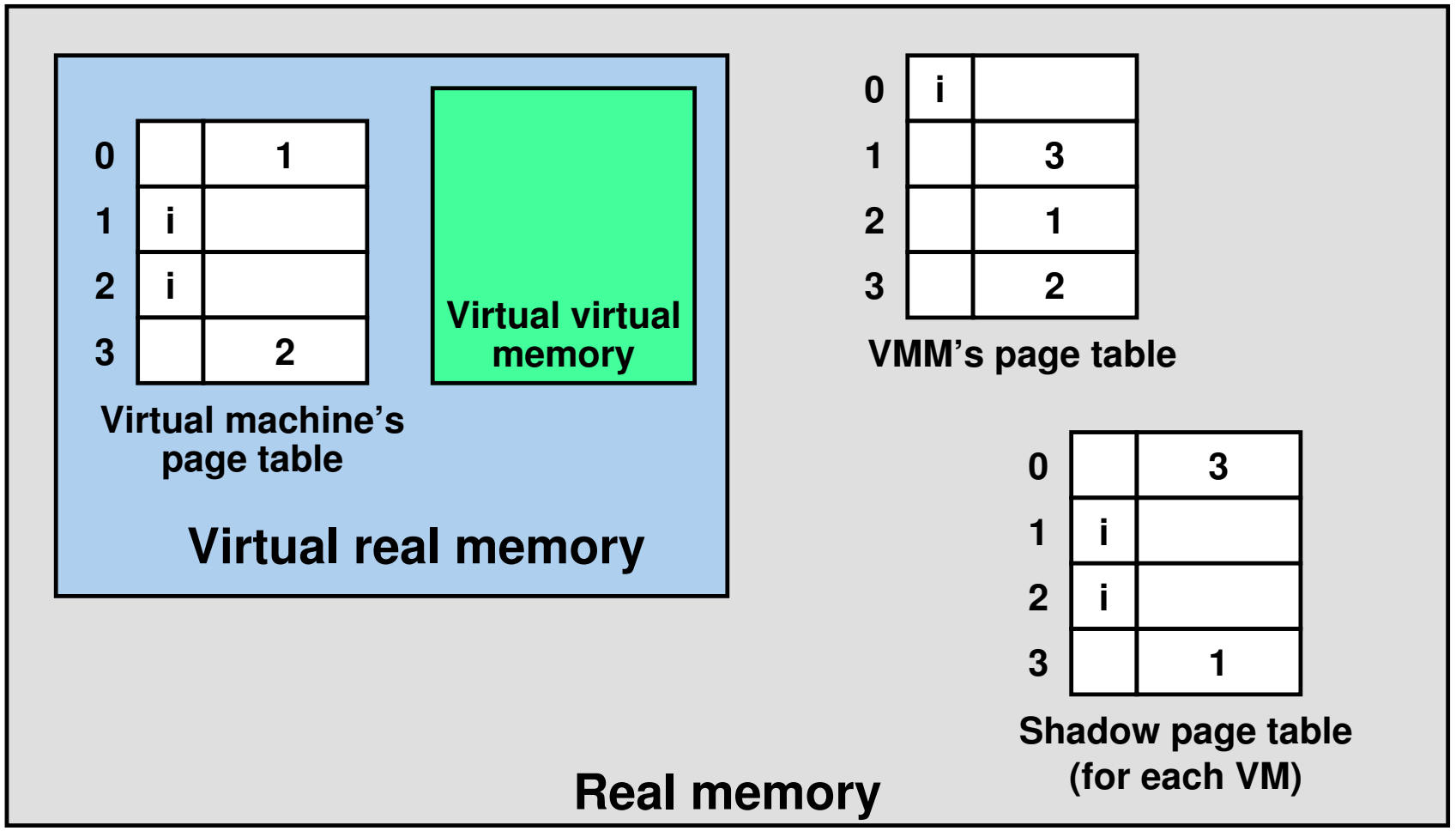
# Virtual Machines Meet Virtual Memory



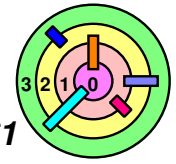

- A user process thinks it's accessing virtual memory
  - but it's really dealing with *virtual virtual memory*
- The OS in a VM thinks it's managing real memory
  - but it's really dealing with *virtual real memory*
- VMM needs to manage real memory
  - how can we *virtualize virtual memory*?



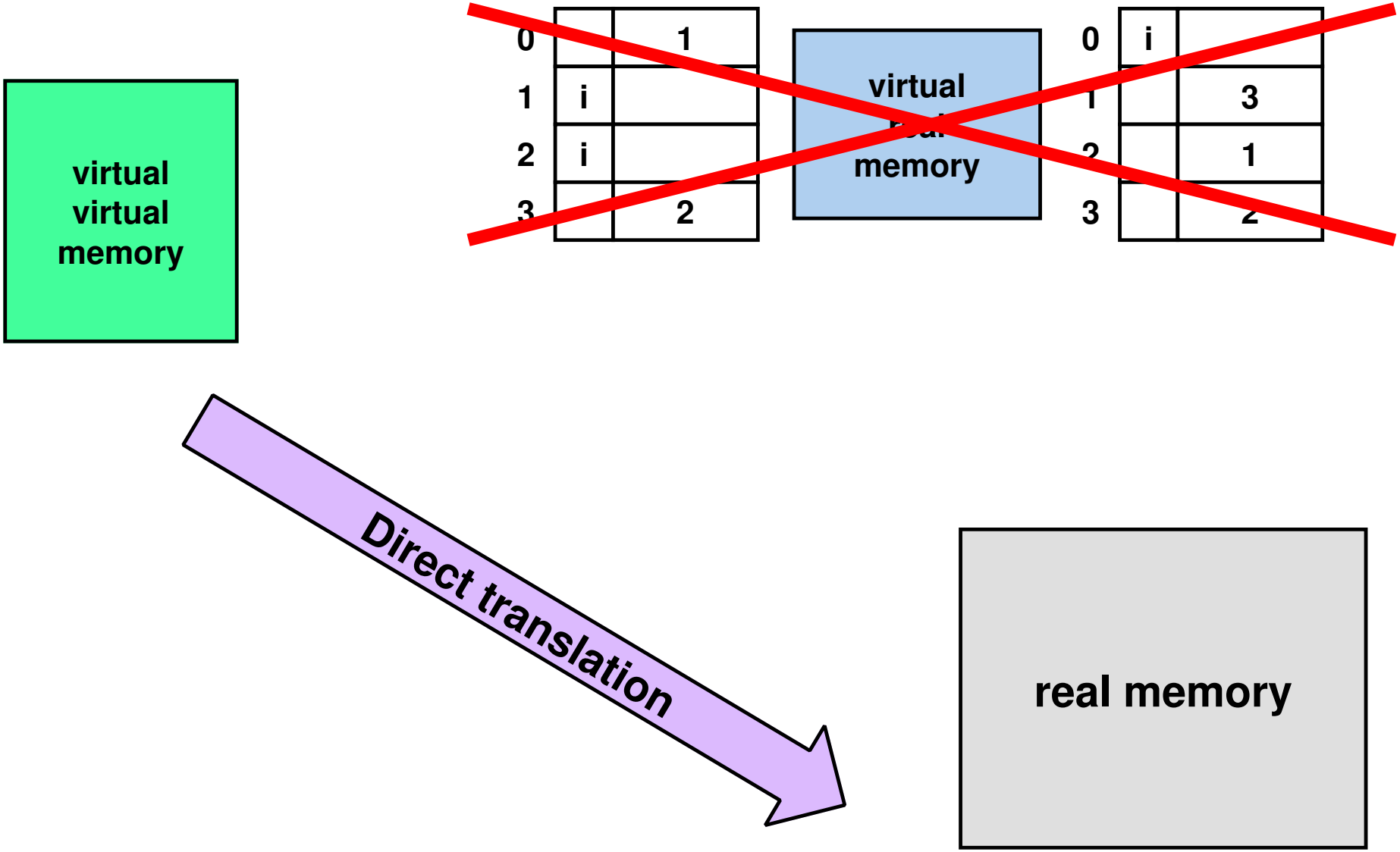
# Virtual Machines Meet Virtual Memory



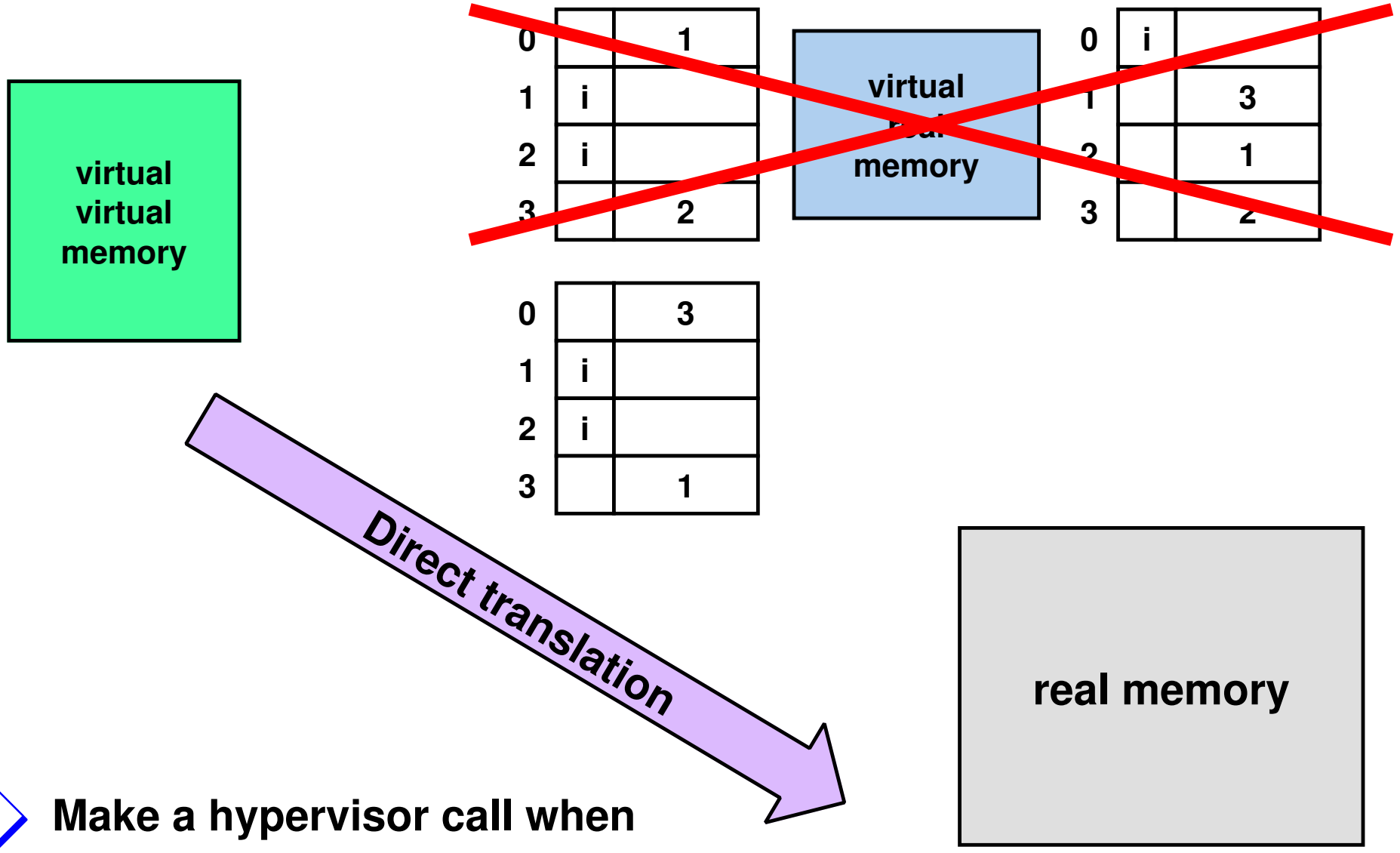

- When a VM changes its page table, VMM must update the corresponding *Shadow Page Table*
  - main problem: poor performance



# Solution 1: Paravirtualization to the Rescue

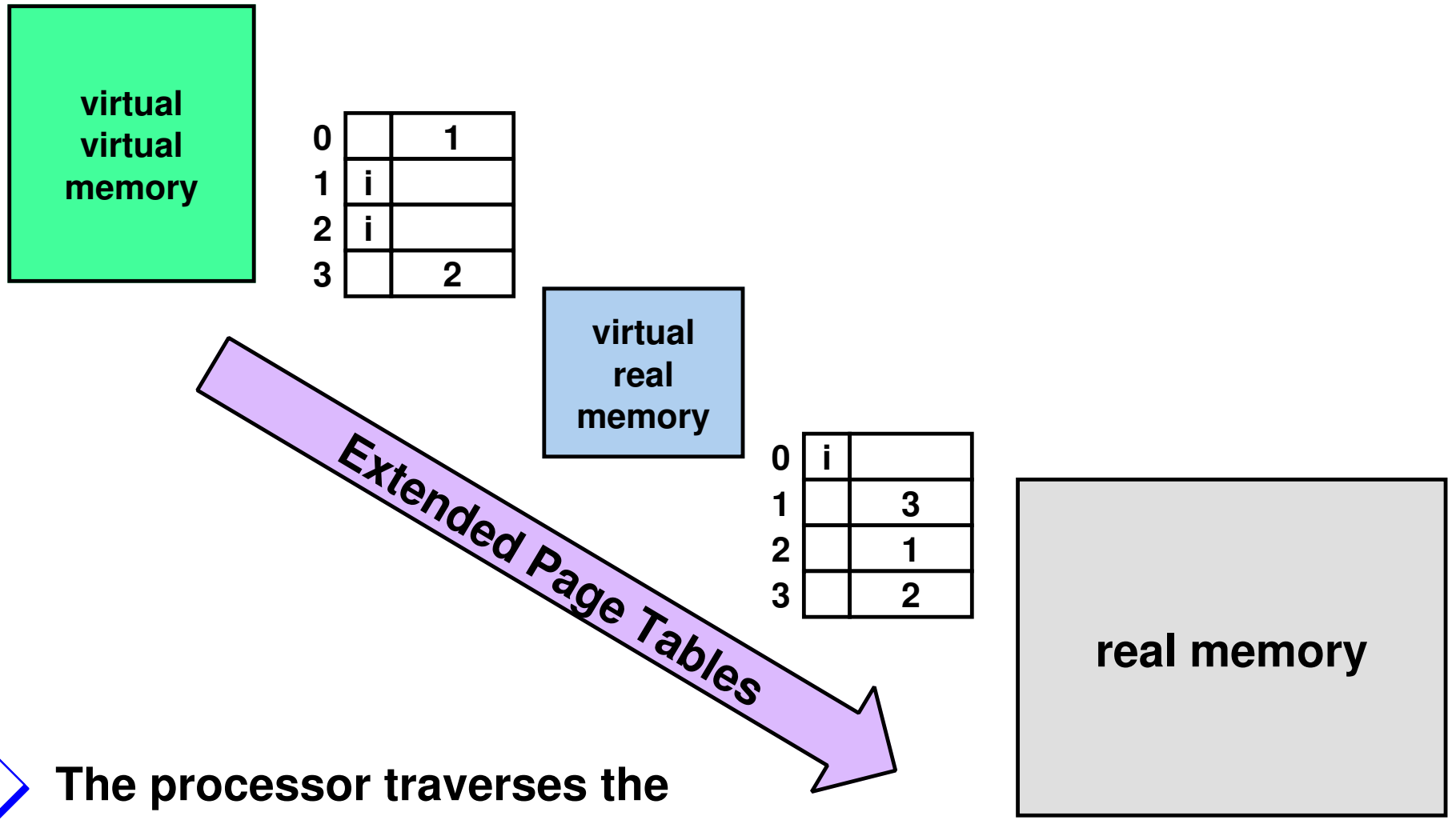


# Solution 1: Paravirtualization to the Rescue



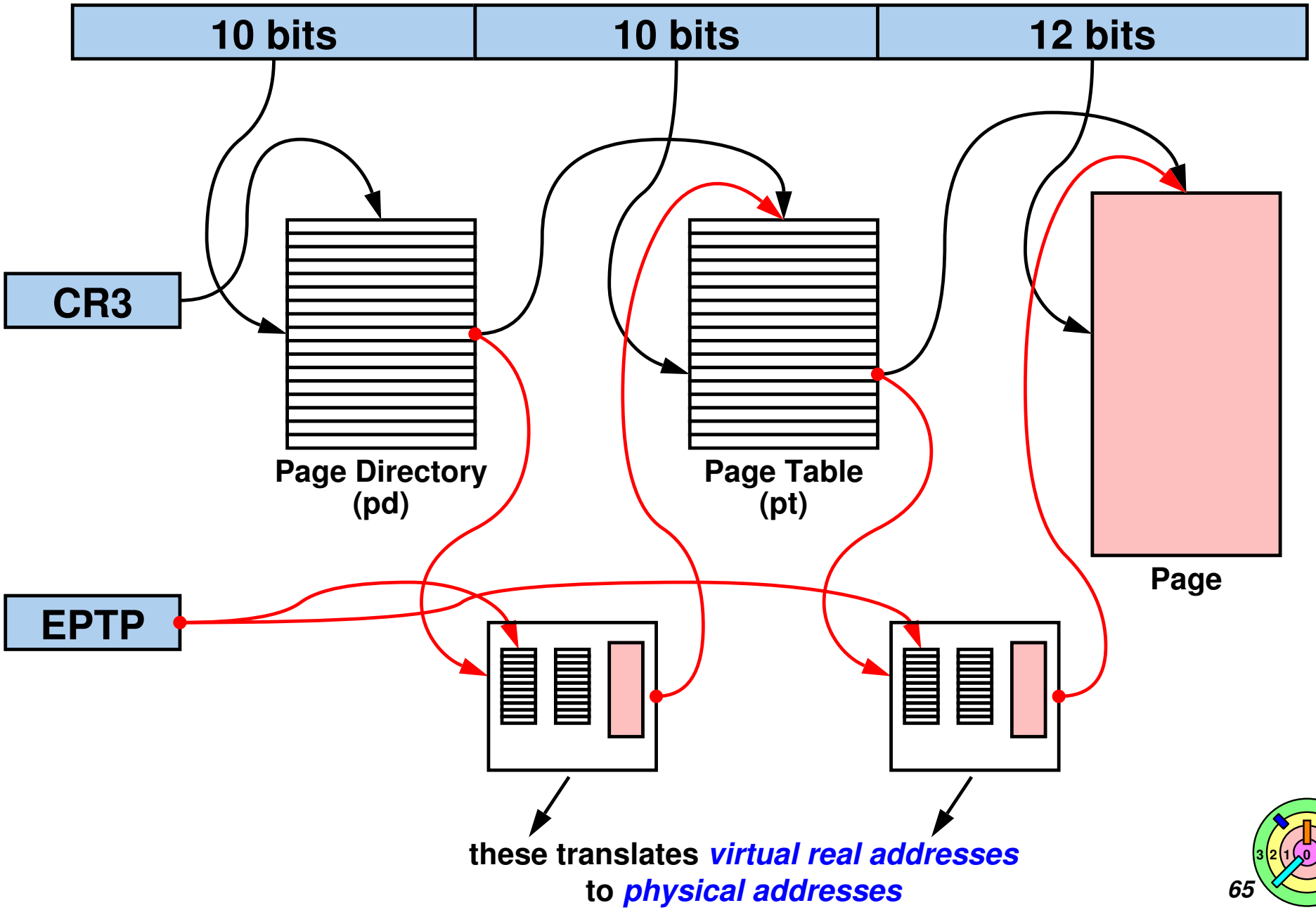

- Make a hypervisor call when page table needs to be modified
  - helps a bit, but not much faster

# Solution 2: Hardware to the Rescue

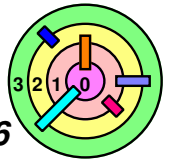



The processor traverses the two tables in sequence and does the conversion all by itself

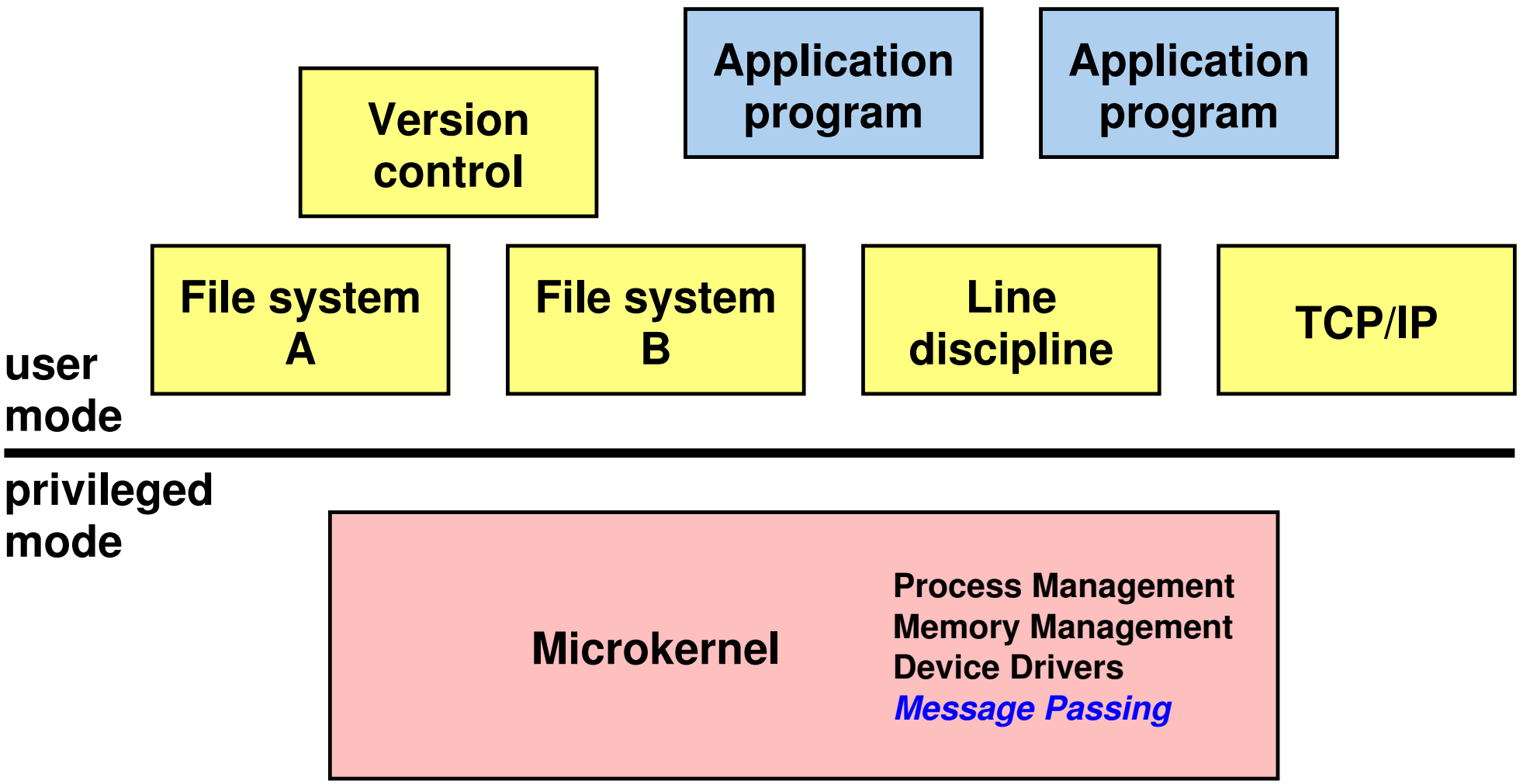
# x86 Paging with EPT



# Microkernels (Back to Section 4.2)

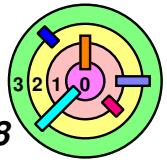


# OS Services as User Apps



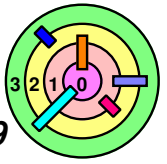
# Why?

- It's cool ...
- Assume that OS coders are incompetent, malicious, or both ...
  - OS components run as protected user-level applications
- Extensibility
  - easier to add, modify, and extend user-level components than kernel components



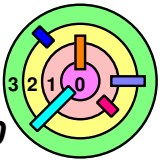
# Implementation Issues

- How are modules linked together?
  - e.g., how would you implement `read()/write()`?
    - can't use system calls any more!
  - e.g., which file system supports `read()/write()`?
- How is data moved around efficiently?



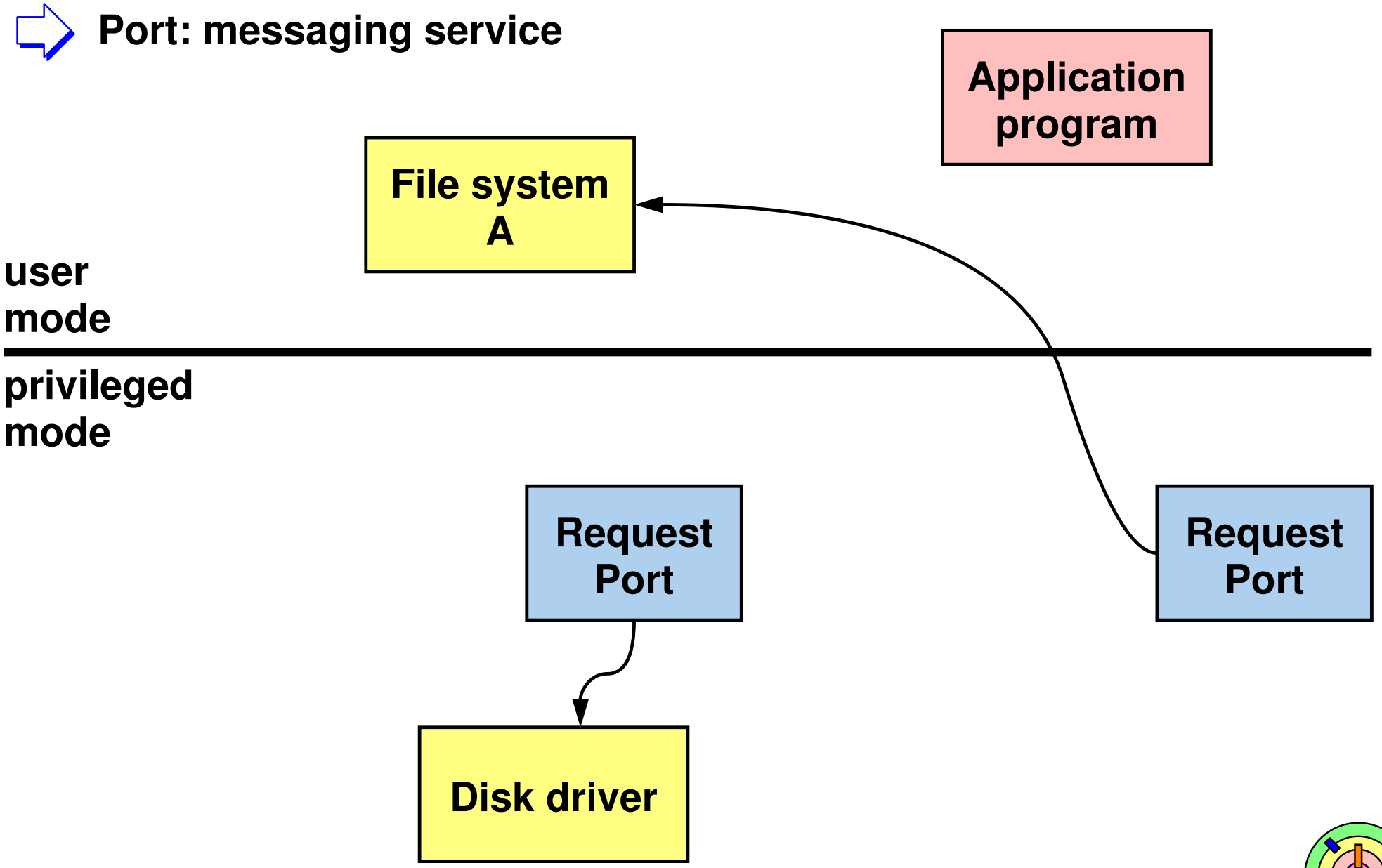
# Mach

- Developed at CMU, then Utah
- Early versions shared kernel with Unix
  - basis of NeXT OS
- Later versions still shared kernel with Unix
  - basis of OSF/1
    - basis of Macintosh OS X
- Even later versions actually functioned as working microkernel
  - basis of GNU/HURD project
    - HURD: HIRD of Unix-replacing daemons
    - HIRD: HURD of interfaces representing depth



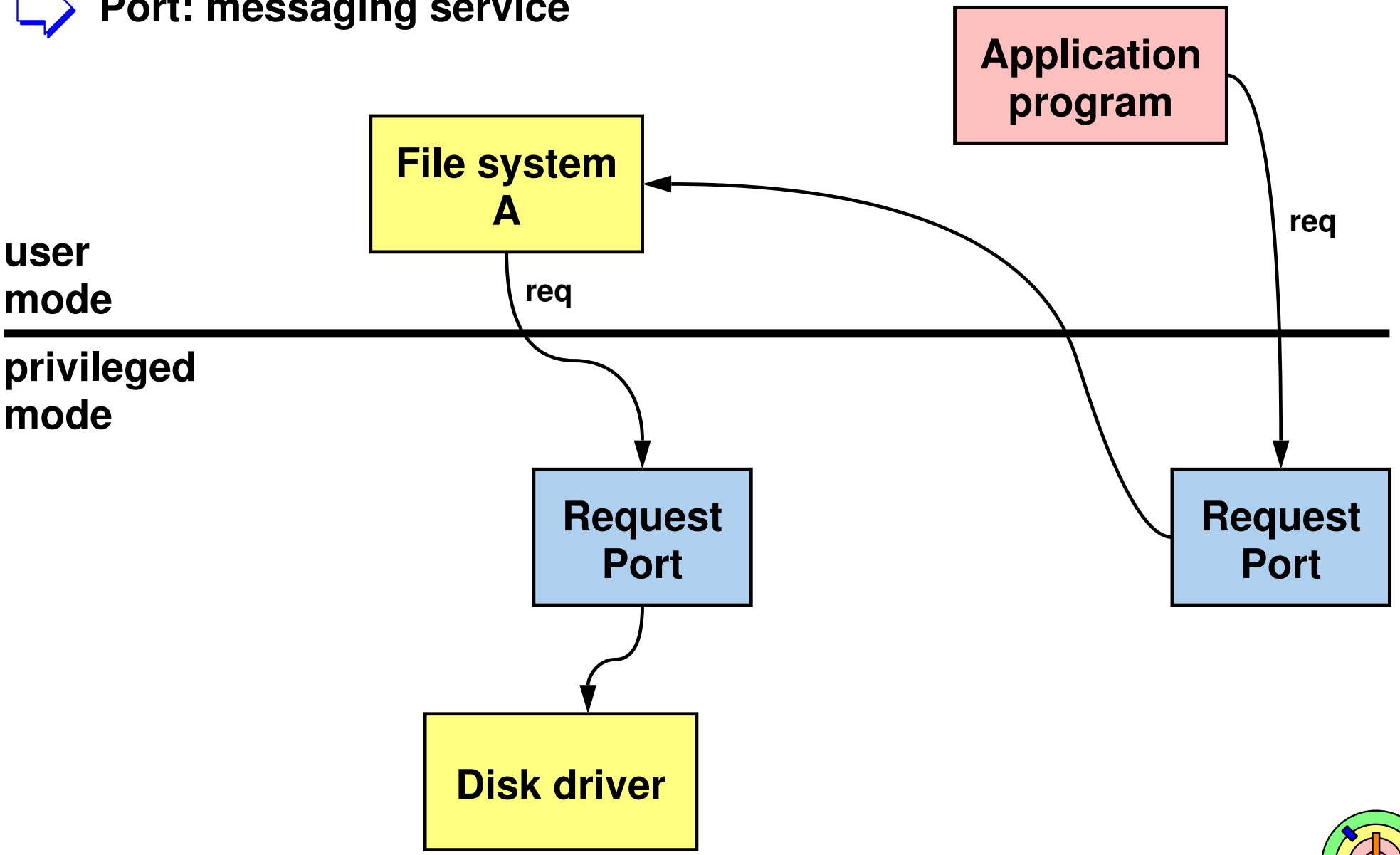
# Example

- Port: messaging service



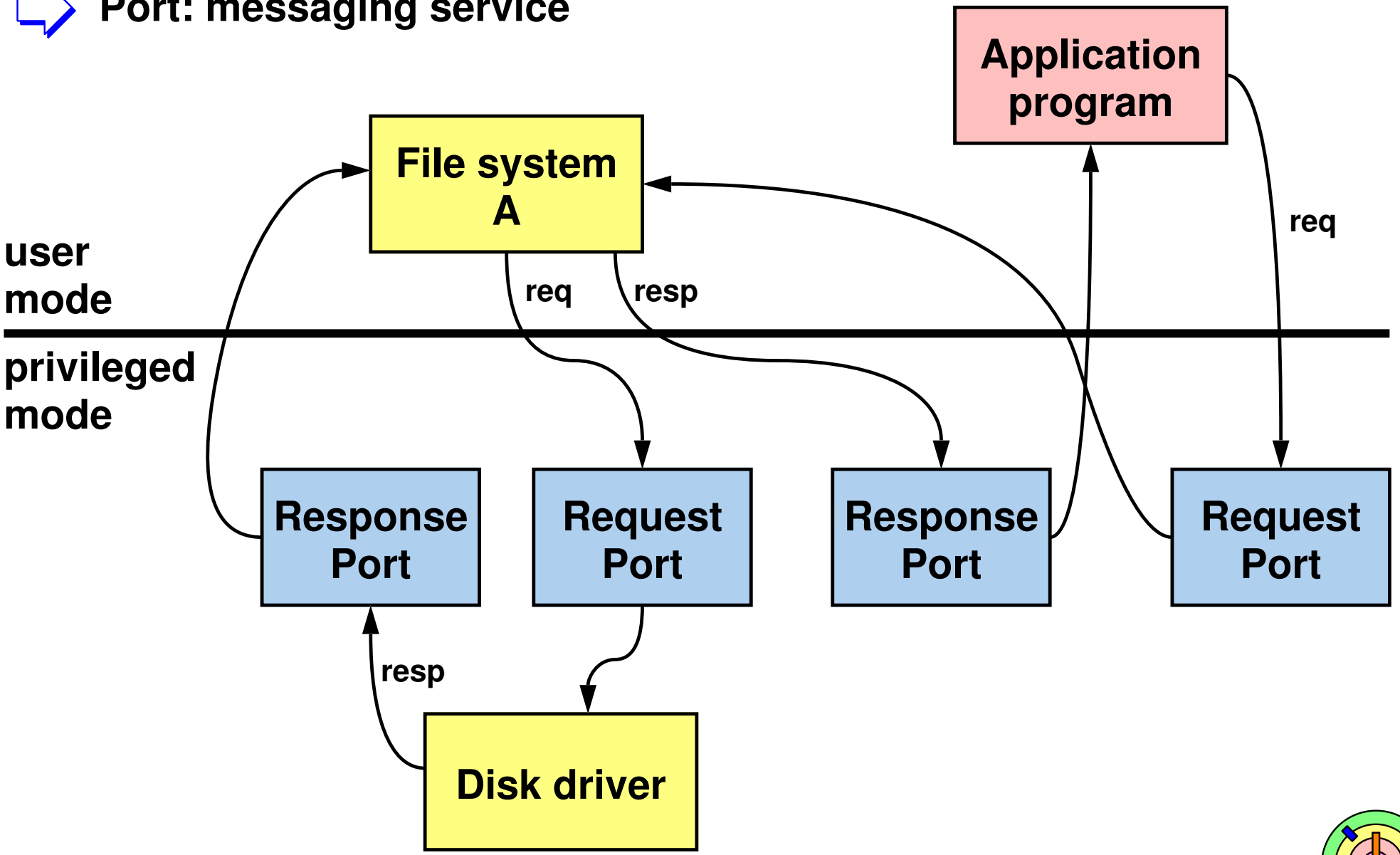
# Example

- Port: messaging service



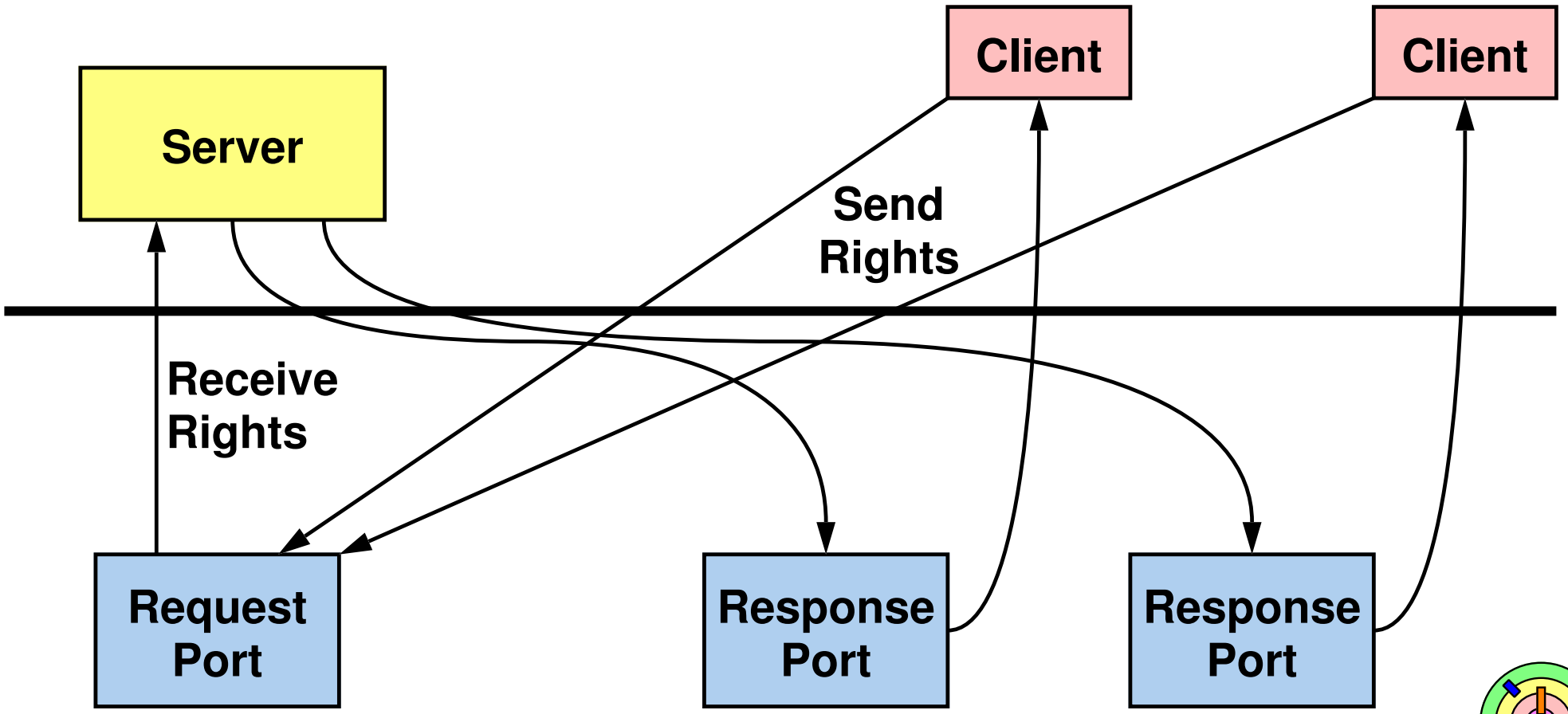
# Example

- Port: messaging service



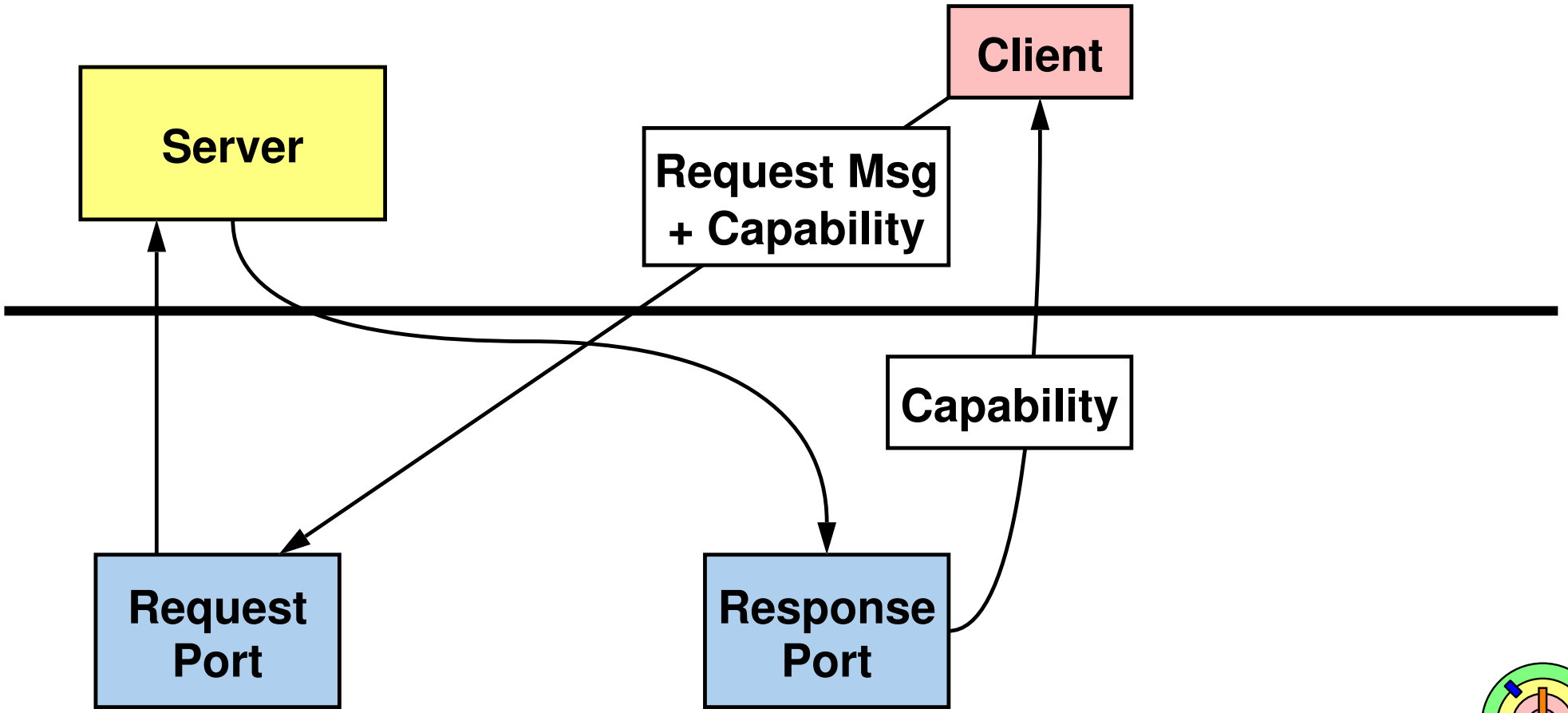
# Mach Ports (1)

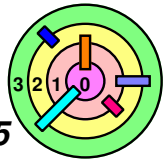
- Linkage construct



# Mach Ports (1)

- Communication construct
  - client create *response port* and *capability* (like a key) to send data through it
    - include capability in the request message to server



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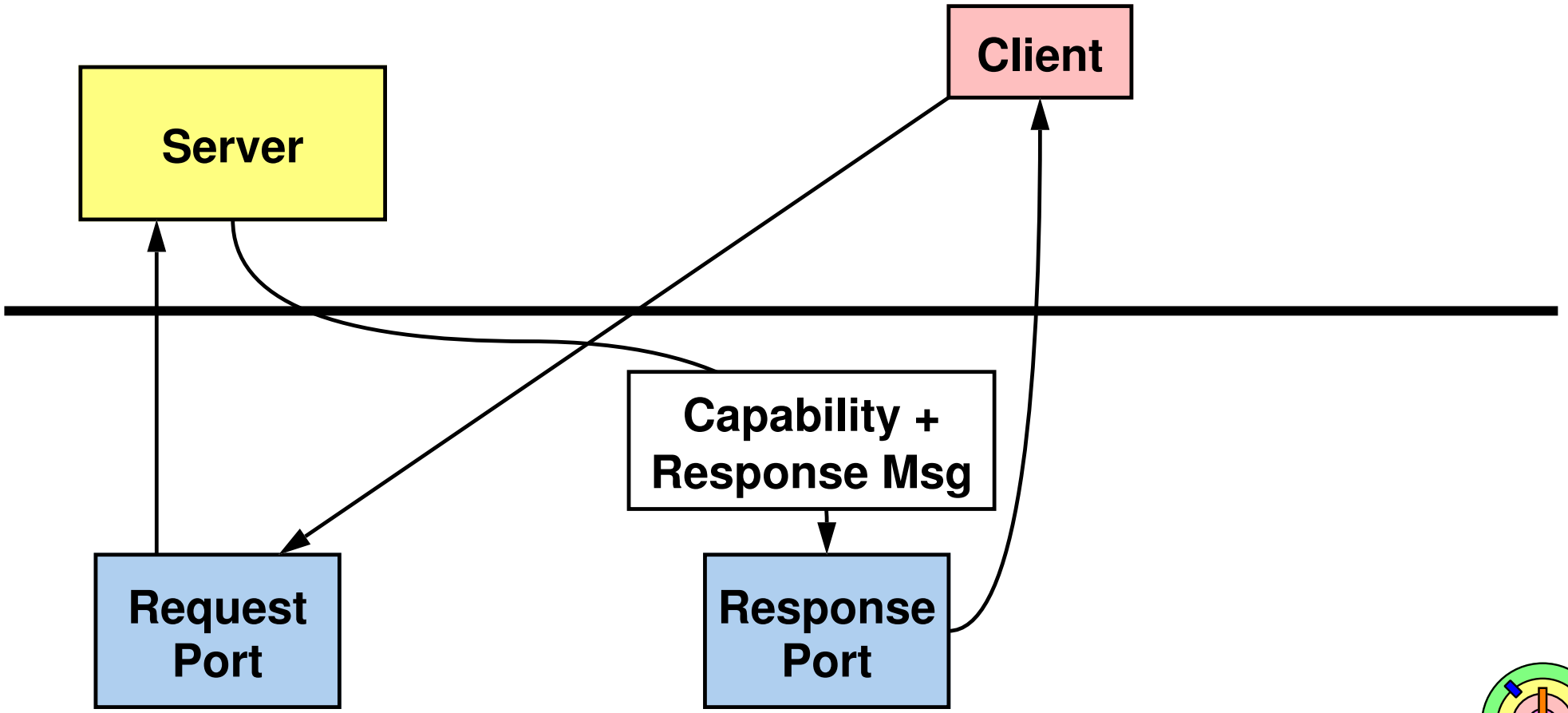
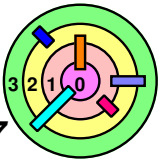


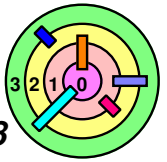
# RPC

- Ports used to implement *remote procedure calls*
  - communication across process boundaries
  - if procedures are on same machine ...
    - local RPC



# Successful Microkernel Systems

- ?
- ?
- ...



# Attempts

- Windows NT 3.1
  - graphics subsystem ran as user-level process
  - moved to kernel in 4.0 for performance reasons
- Macintosh OS X
  - based on Mach
  - all services in kernel for performance reasons
- HURD
  - based on Mach
  - services implemented as user processes
  - no one uses it, for performance reasons ...