Pre-Virtualization with Compiler Afterburning

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http://l4ka.org

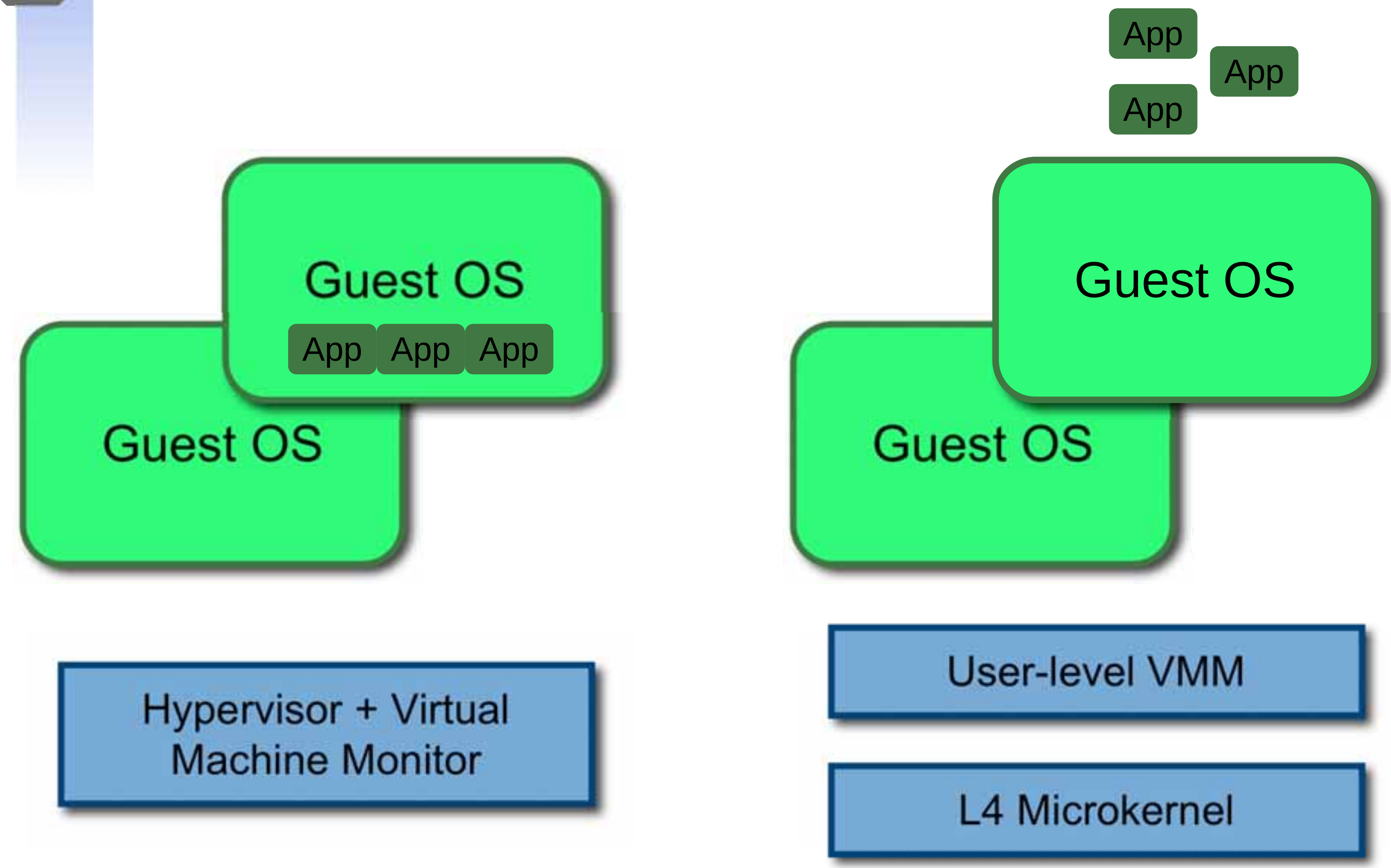
Overview

- Virtualization background
- Basics of pre-virtualization
- Virtualization kit
- Analysis

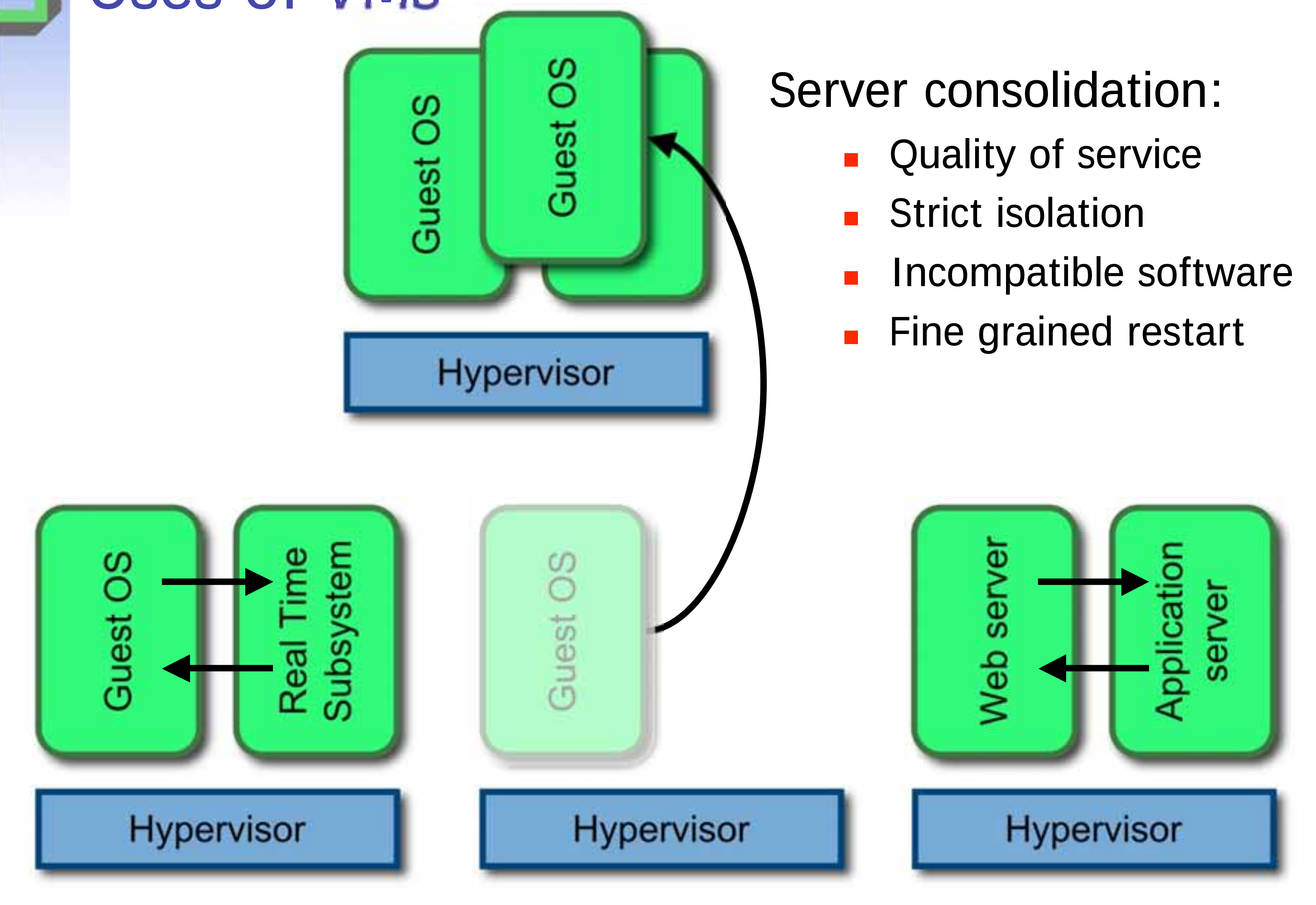
Virtual Machine (VM)

- A software duplicate of the hardware
  - Indistinguishable from real hardware
    - Except for timing
- Statistically, most instructions execute directly on real CPU
  - Faster than full emulation

Basic VM Structure



Uses of VMs



Server consolidation:

- Quality of service
- Strict isolation
- Incompatible software
- Fine grained restart

Legacy Reuse

- VMs enhance legacy code
- Modular encapsulation
  - Guest OS is nearly a black box
  - Well defined interface (but sometimes buggy)
  - Communication with the black box via platform interfaces (network, disk, ...)
- Tr … able
  ke …

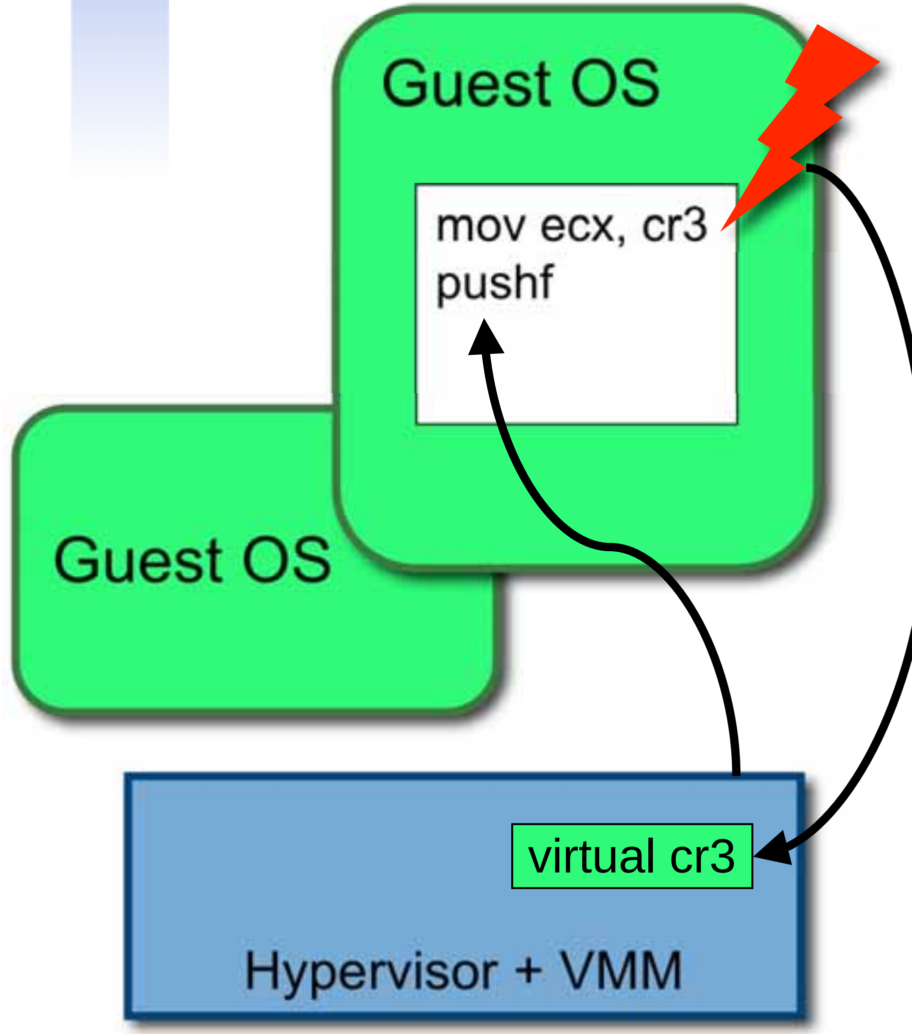
Current OS design is deficient.

The VM is a hack to fix the problems.

Virtualization Definitions

- Sensitive instruction:
  - Destroys the illusion of virtualization
- Innocuous instruction:
  - Safe to execute within a VM
- Privileged instruction:
  - No side effects when executed at user level; raises a fault
- Virtualizable ISA: all sensitive instructions are privileged

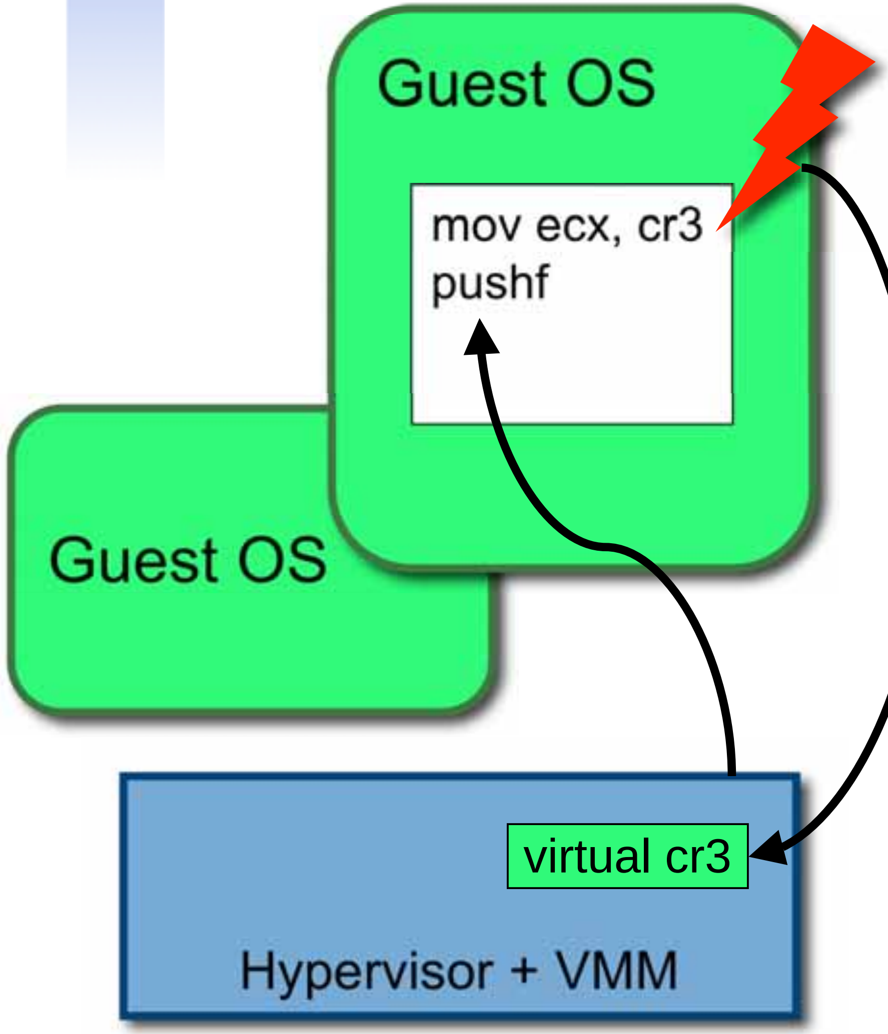
Pure Virtualization



Advantages:

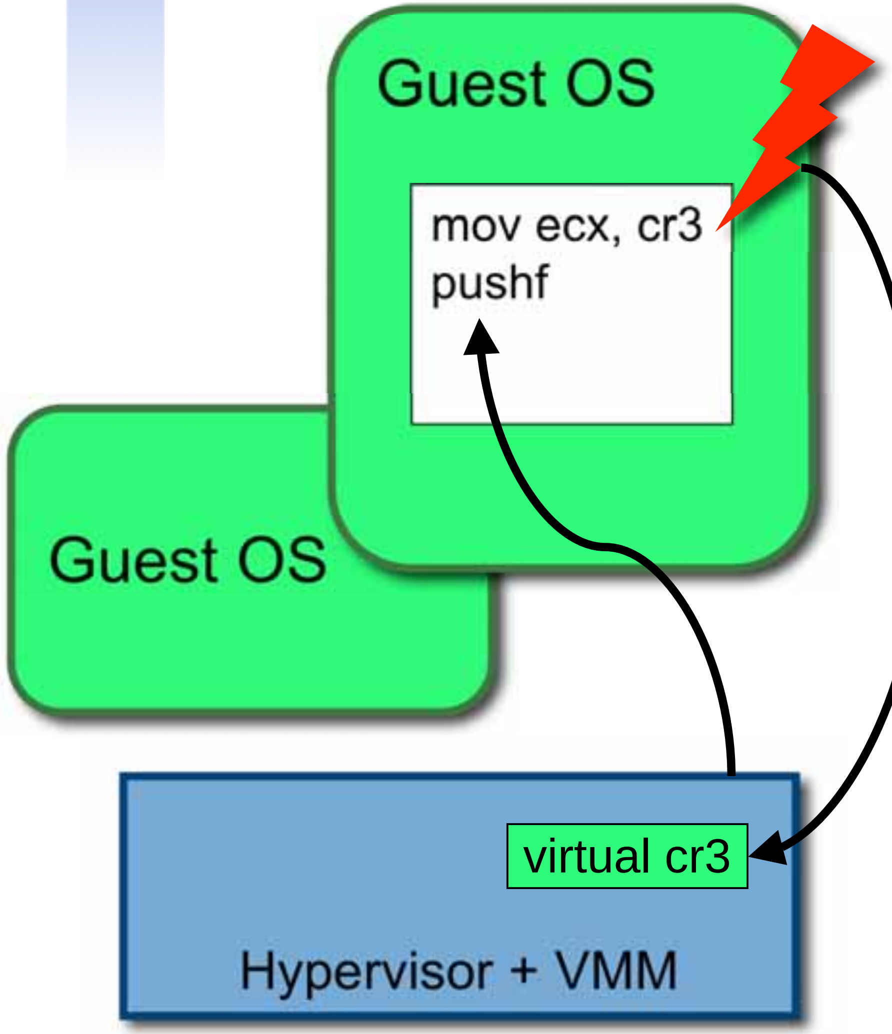
- ✓ Trustworthy emulation
- ✓ Hypervisor diversity
  - Raw hardware
  - VMware
  - VirtualPC
- ✓ Guest OS diversity
  - 1 x engineering effort
  - N x guest OS

Pure Virtualization



- Problems:
  - Trapping is costly (cycles, pipe flush)
  - x86 isn't fully virtualizable
- VMware's solution:
  - ✓ Dynamic code rewriting
  - Difficult

Pure Virtualization



- Harsh requirements on hypervisor:
  - 4GB address space
  - Hide differences in CPUs [MMX vs. SSE2]
  - Burdensome legacy emulation
- High perf. devices:
  - Custom device drivers

Para-virtualization

```
mov ecx, cr3
pushf
```

↓ Manual source modifications

```
mov ecx, ebx
mov $1, eax
sysenter

push virtual_flags
```

- L4Linux, Denali, Xen
- Replace sensitive instructions with hypercalls
  - ✓ Avoids costs of trapping
  - ✓ Batch state changes into single hypercall
  - ✓ Relax requirements on hypervisor
- Problems:
  - ✗ Engineering effort
  - ✗ Reduces trustworthiness of guest OS
  - ✗ Ties guest OS directly to a single hypervisor

Para-virtualization

```
mov ecx, cr3
pushf
```

Manual source modifications

```
mov ecx, ebx
mov $1, eax
sysenter

push virtual_flags
```

- Problems:
  - Migrations
    - Only possible between ABI compatible hypervisors
    - MMX vs. SSE2
  - No support for raw hardware
  - High perf. devices:
    - Custom device drivers

Transparent virtualization

```
mov ecx, cr3
pushf
```

↓ Manual source modifications

```
if (VMM) {
  call VMM_load_cr3
  call VMM_pushf
} else {
  mov ecx, cr3
  pushf
}
```

- VMware's VMI
- Replace sensitive instructions with hooks
  - ✓ Avoids costs of trapping
  - ✓ Hypervisor diversity
  - ✓ Potential industry standard
- Problems:
  - × Manual engineering effort
  - × Reduces trustworthiness of guest OS [unless done by kernel architects]

The Interface Difference

- Pure virtualization: lowest level interface
- Para-virtualization: high-level interface
  - ✓ Semantic assists
  - ✓ Higher performance
  - ✓ Supports unfriendly architectures
  - ✗ But hypervisor specific
- The semantic-assists cost modularity
  - The ISA is the modular interface

What is Virtualization About?

- Customization:
  - I want my features
  - You want your features
- Decentralized development:
  - Enhance a guest OS without the architect’s permission
- Modularity:
  - Layering
  - Software reuse
- Conclusion: para-virtualization is inferior

Why not standardize Para-virtualization?

- What is the perfect interface?
  - Ex: Xen changed their API: 2.0 ⇒ 3.0. But wasn't 2.0 already the ultimate?
- Domain specific trade-offs:
  - Classic: security vs. performance
- Different philosophies:
  - Ex: Run guest kernel at
    - user-level
    - intermediate privilege via x86's segments
- Conclusion: a standardized para-virtualization interface is not possible
  - The platform ISA is a standard.

Uniting Two Worlds

Pure virtualization

- Trustworthiness
- Layered engineering
- Hypervisor diversity
- Guest OS diversity

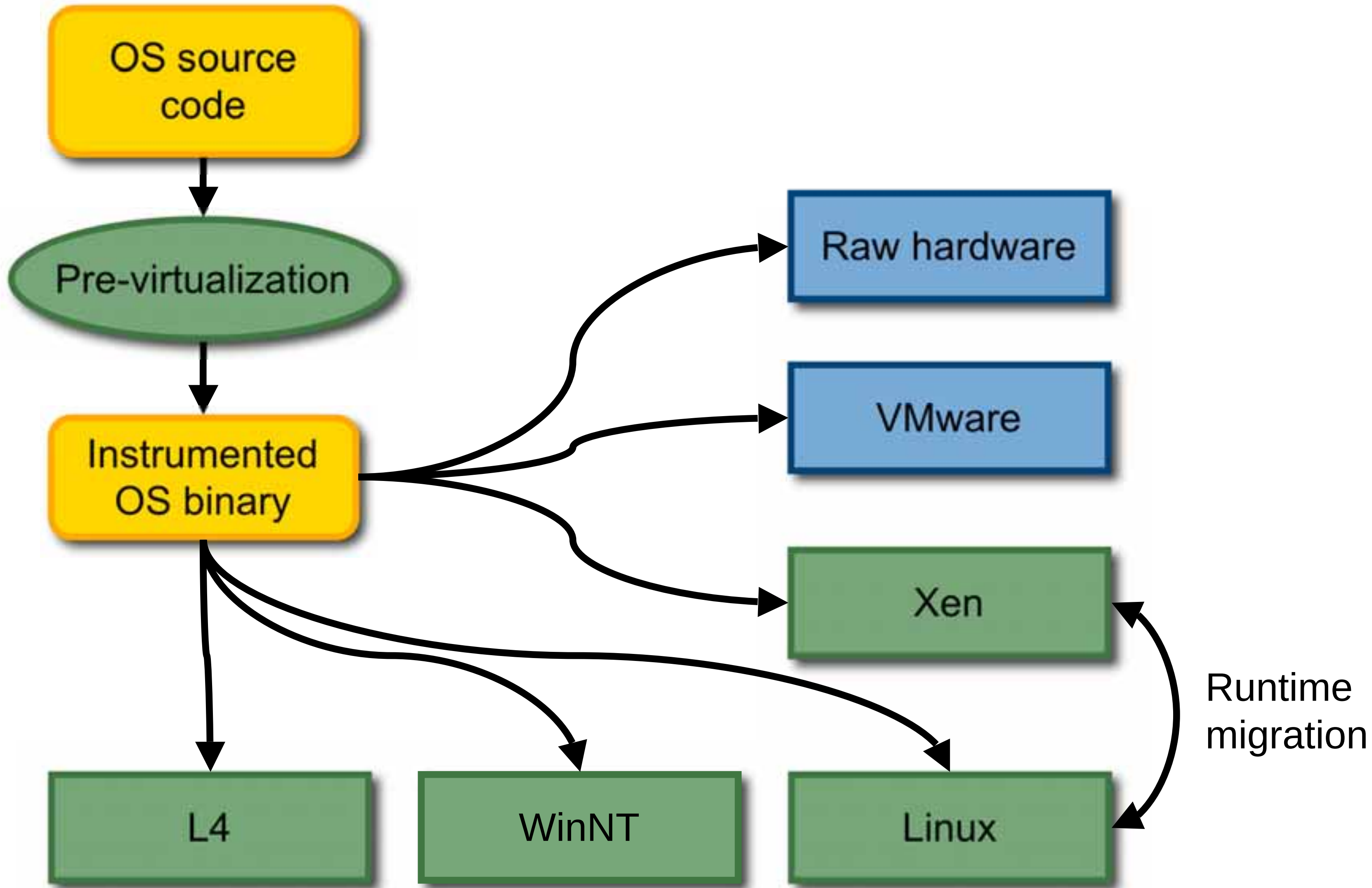
Para-virtualization

- Performance
- Scalability
- Supports unfriendly architectures

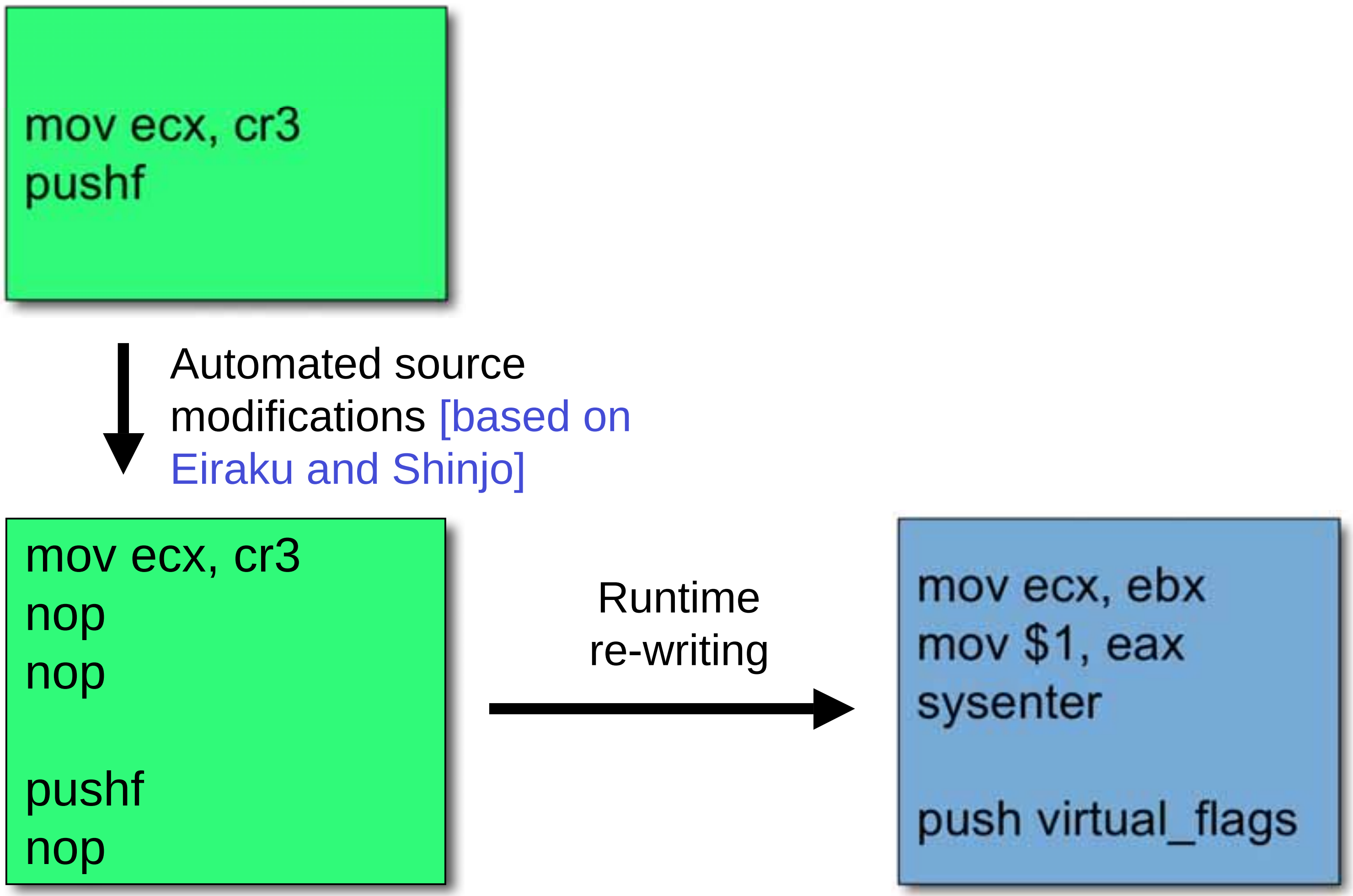
+

Pre-virtualization

Pre-virtualization Overview



Pre-virtualization Basics



Pre-Virtualization: Eiraku and Shinjo

- Static
  - Replace sensitive ops with emulation code
  - Supports a single hypervisor
- Trapping
  - Replace sensitive ops with trapping instructions
  - Via trapping, hypervisor diversity

Pre-Virtualization: Dynamic Rewriting

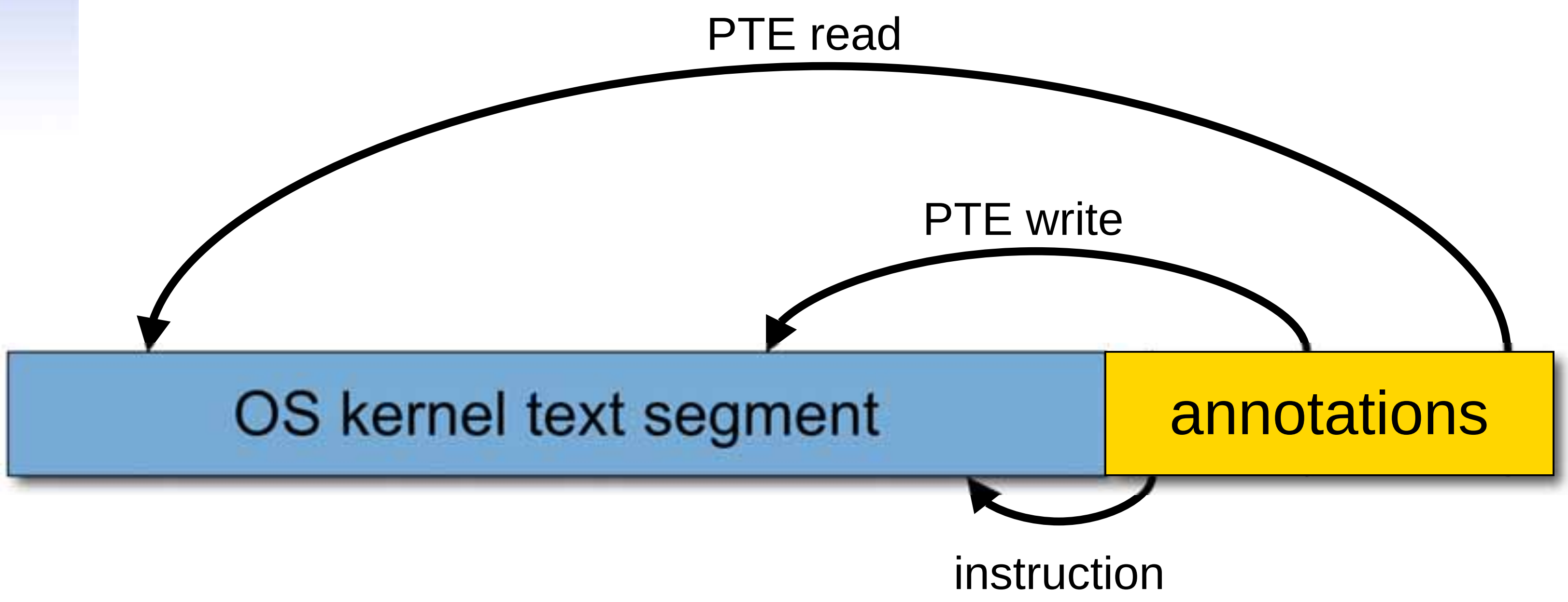
- Runs on raw hardware
- Hypervisor diversity

1. Instruction padding
   - Pad sensitive ops with NOPs
   - Rewrite instruction at runtime
   - Special sequences: sti ; hlt
2. Basic-block padding
   - Pad basic-blocks with NOPs
   - Rewrite entire basic block at runtime

Pre-Virtualization: Dynamic Rewriting

3. Basic-block bypass
   - Write a jump instruction at beginning of b.b., and jump to emulation code
4. Basic-block dynamic link
   - Rewrite all jump sources to the basic-block, so that they jump to the replacement basic-block

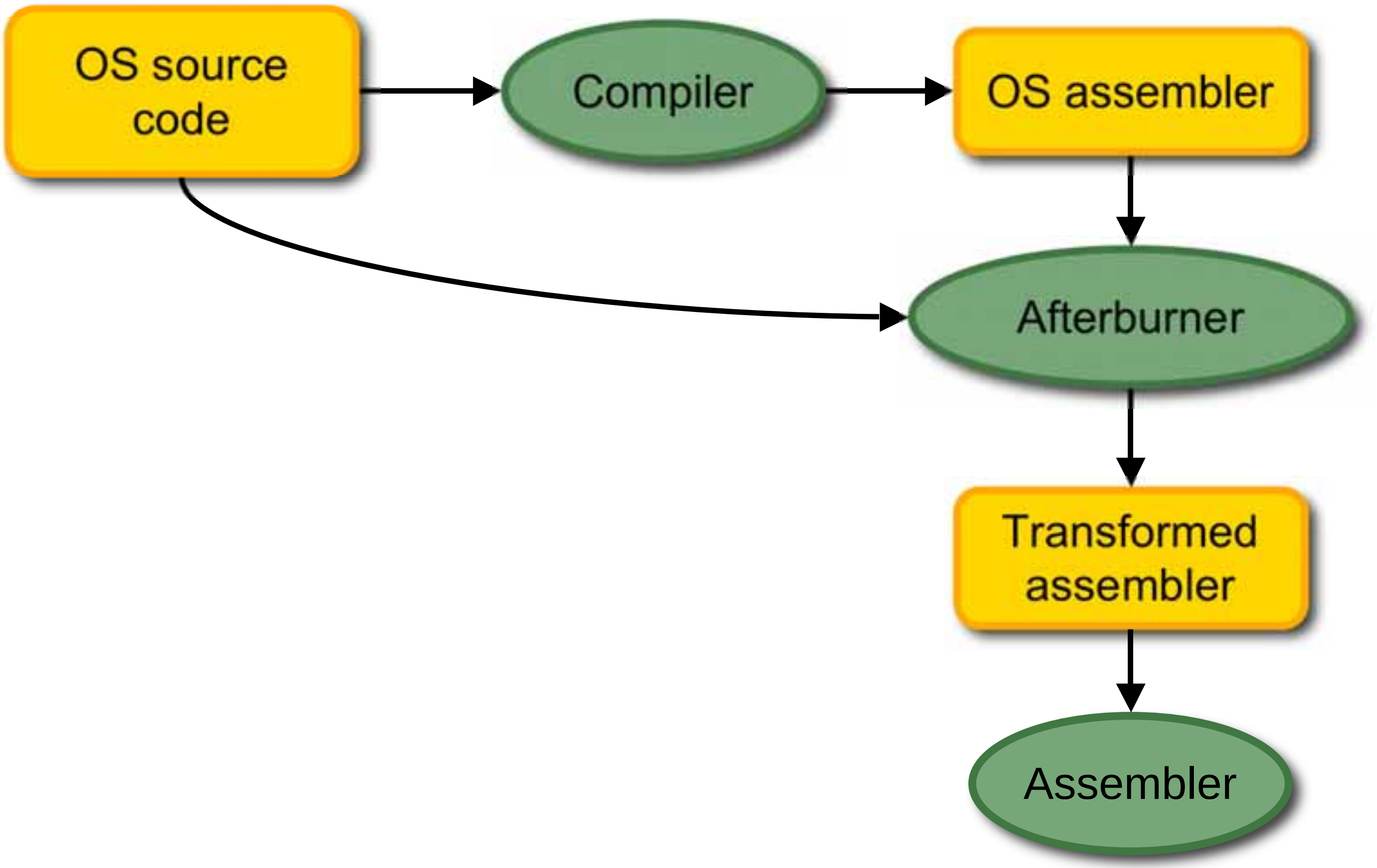
Dynamic Rewriting



Rich annotations possible:

- Register liveness
- Basic block boundaries
- Function boundaries

Phase 1: Afterburner

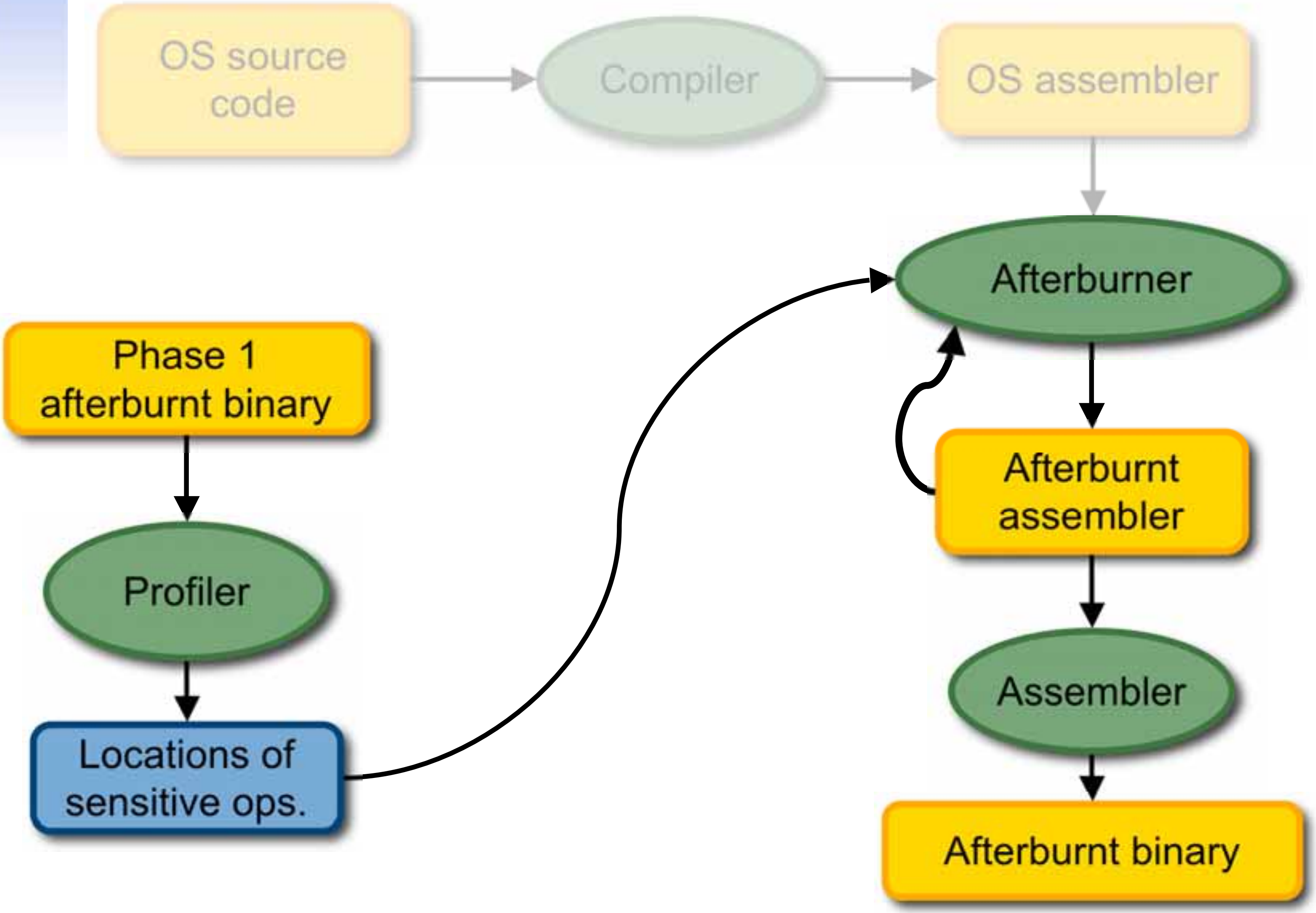


Phase 2: Profiler Feedback

- Virtualization-sensitive memory:
  - Page tables, tss, idt, gdt, etc.
  - Memory mapped devices
  - Important for performance

- Use a profile-feedback loop
  - Instrument and annotate the instructions that access sensitive memory
  - Or compiler data-flow analysis?

Phase 2: Profiler Feedback



Profiler Problems

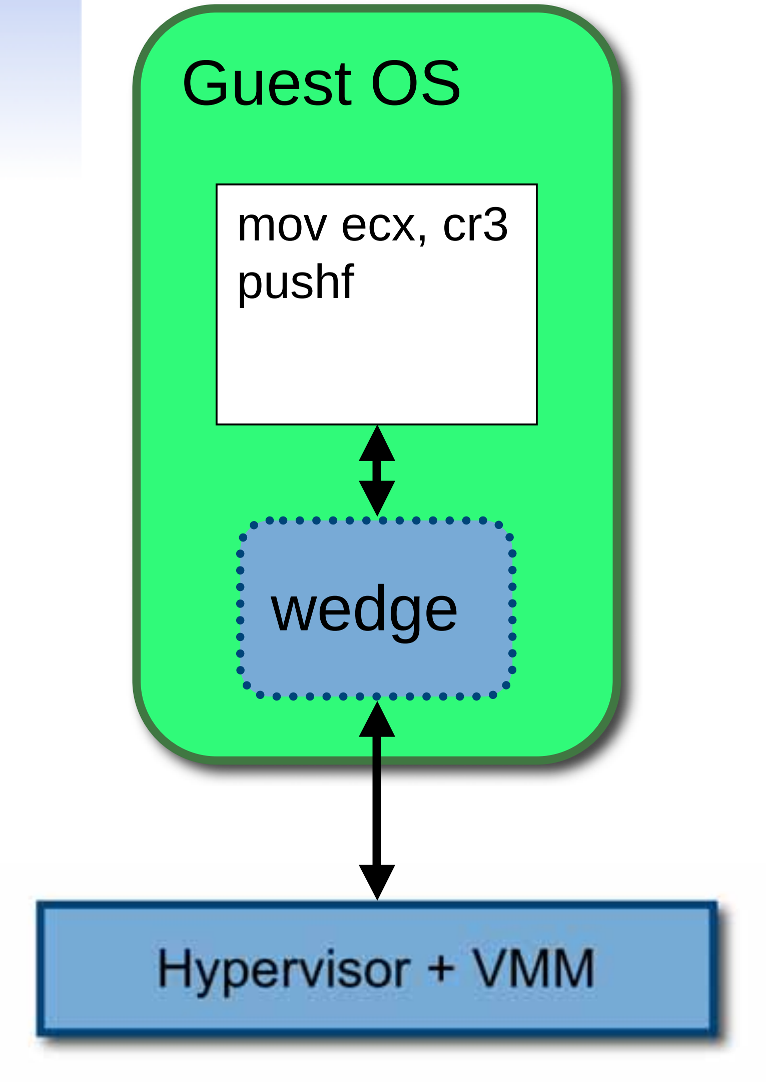
- Profiling is imperfect
  - Incomplete coverage
  - Captures only the common case
- In production environment:
  - Guest kernel could access sensitive memory
  - To detect sensitive accesses, use page faults
    - Easy to implement for devices
    - Suboptimal for guest’s page tables
- Long term solution: data flow analysis

Is Pre-virtualization Good Enough?

- Pre-virtualization:
  - Instruction-level transformations
  - At best, basic-block transformations
- Para-virtualization:
  - High-level interface
  - Semantic assists

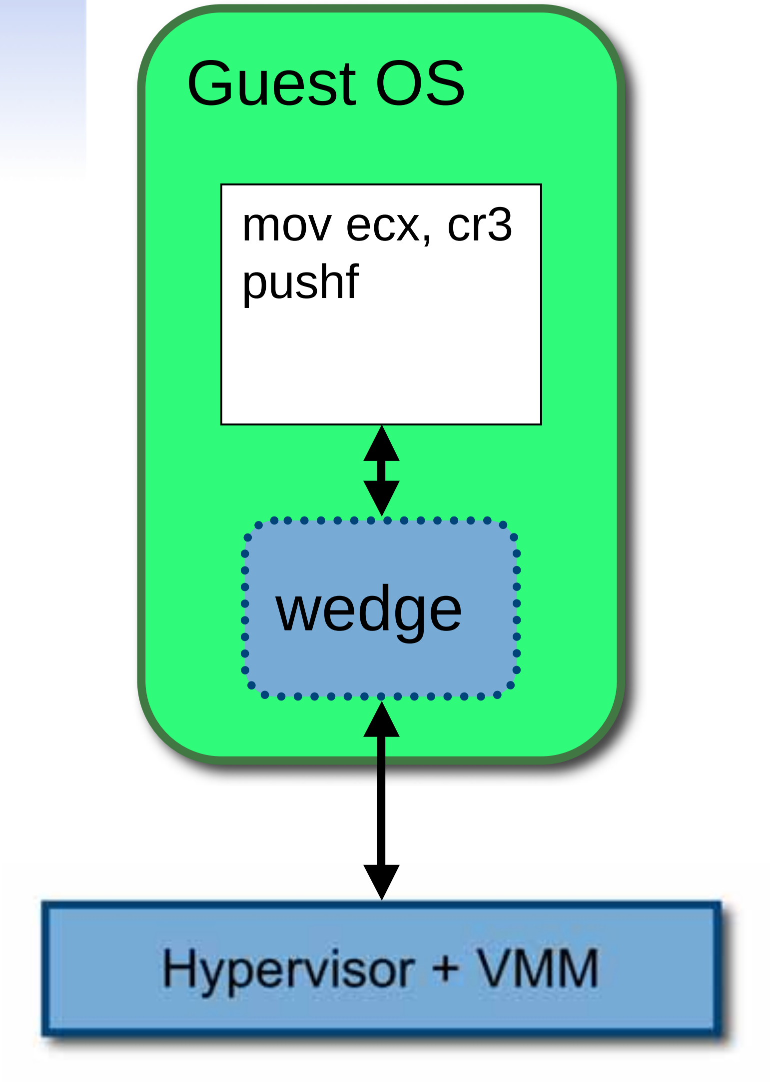
We need more from pre-virtualization!

In-Place Virtualization: Approximating Para-virtualization



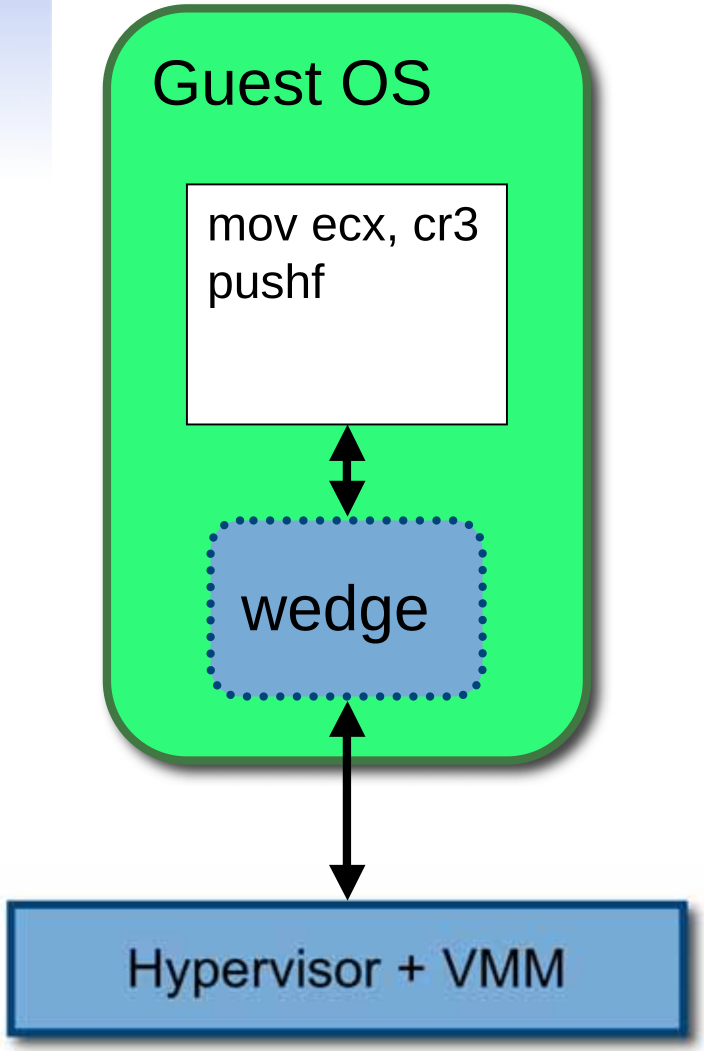
- The wedge creates a virtual CPU
- Invokes hypercalls only when necessary
- Frequent operations, such as cli/sti, emulated in the wedge
- Loose state consistency
- Use heuristics
- No licensing issues

In-Place Virtualization: Examples



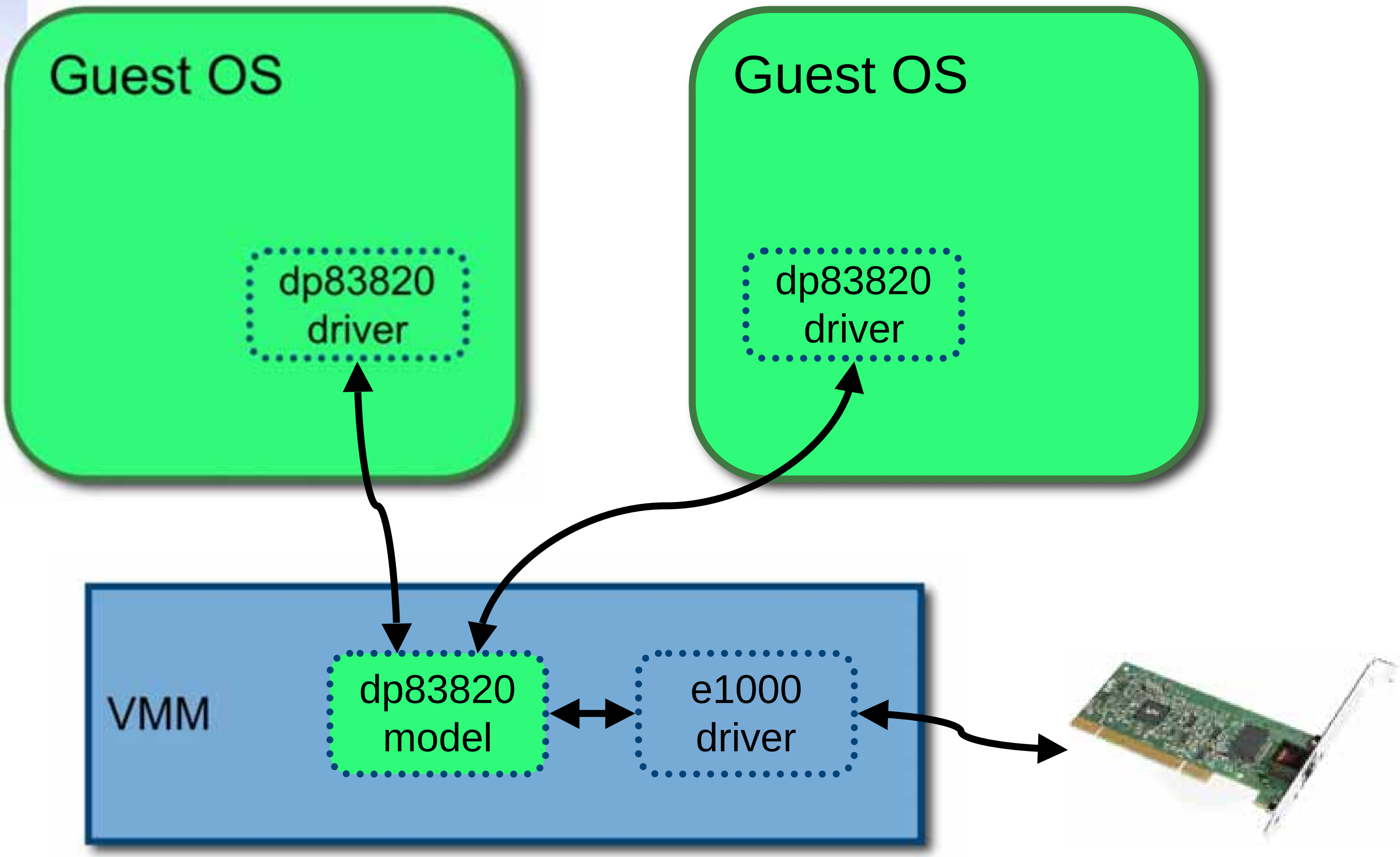
- Interrupts: accumulate in wedge, delivered on guest's iret, thus cheap masking
- PTE updates: synchronize page tables on TLB flushes
- PTE scanning: read referenced+dirty bits in batches
- fork() + exec() : heuristics

In-Place Virtualization: Problems

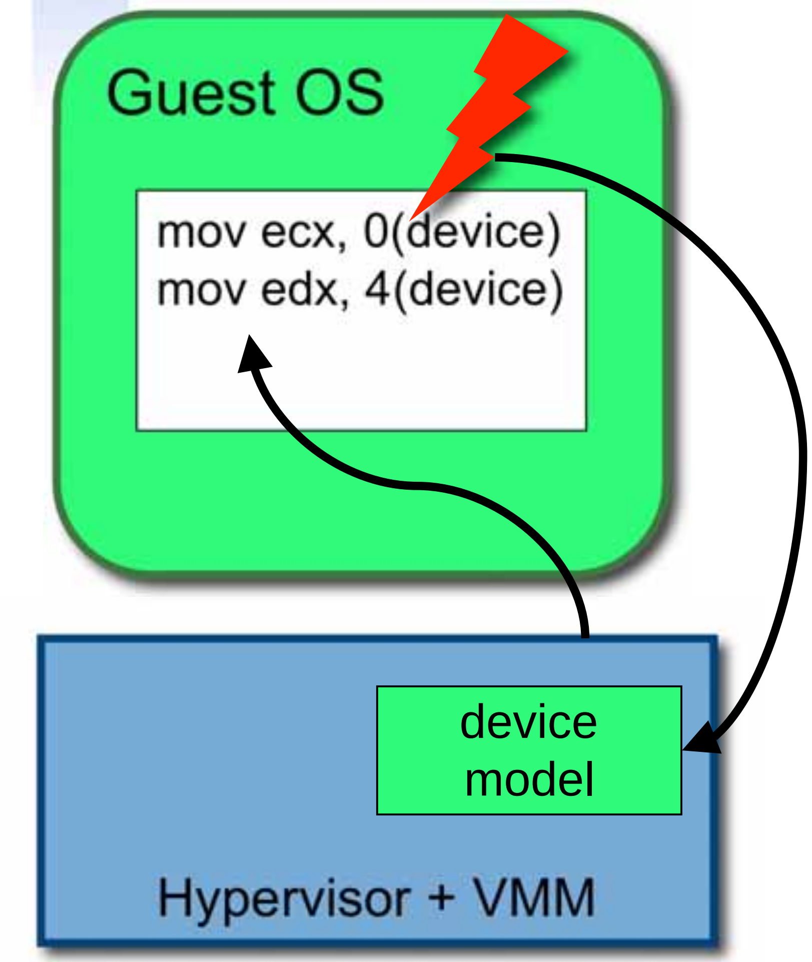


- Share the address space
  - May require support from guest kernel
- Large wedges:
  - User-level on Linux/BSD: 1GB
  - User-level on WinNT: 2GB
  - Requires relinking of the guest kernel
- Assumes valid guest stack

Device Access: Multiplexing

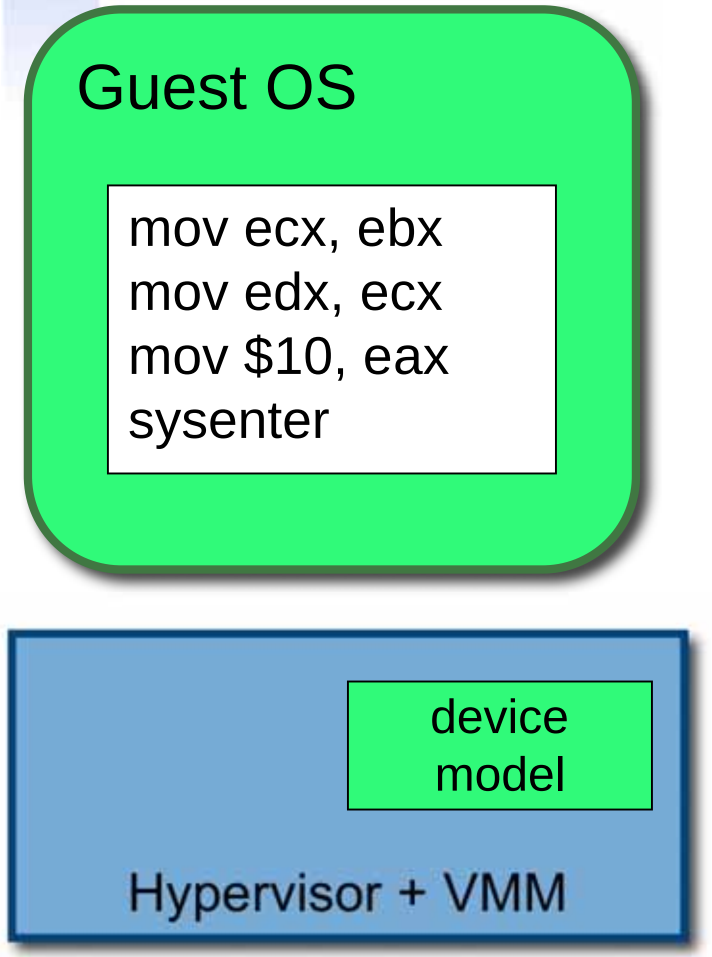


Device Emulation: Brute Force



- Trapping is expensive
- Trapping is frequent
  - Many small state updates

Device Emulation: Custom Drivers



- Traditional solution
- High performance
- Problems:
  - Specific to hypervisor
  - Different config for hypervisor and hardware
  - Unable to migrate between different hypervisors

Device Emulation: Pre-virtualization

- Rewrite sensitive ops
  - Replace with calls to the wedge
- Choose well behaved device interface:
  - network: dp83820
  - disk: SATA? SCSI?
- Can migrate between different hypervisors
- Good engineering leverage:
  - 1x engineering
  - Multiple guests

Device Emulation: Batching

- Device ops cause synchronization:
  - Hyper call
  - Potential address space switch
  - Expensive
- Solution:
  - ✓ Batching
  - ✓ Producer consumer rings
- Batching is difficult:
  - No semantic information
  - OS might send a file, but we see only packets

Device Emulation: Batching Heuristics

- We know:
  - When guest OS performs low-level ops
- Map low-level ops to high-level ops?
  - High device activity in interrupt handlers
  - When interrupt handler completes, device activity is paused briefly
  - Use hlt and iret

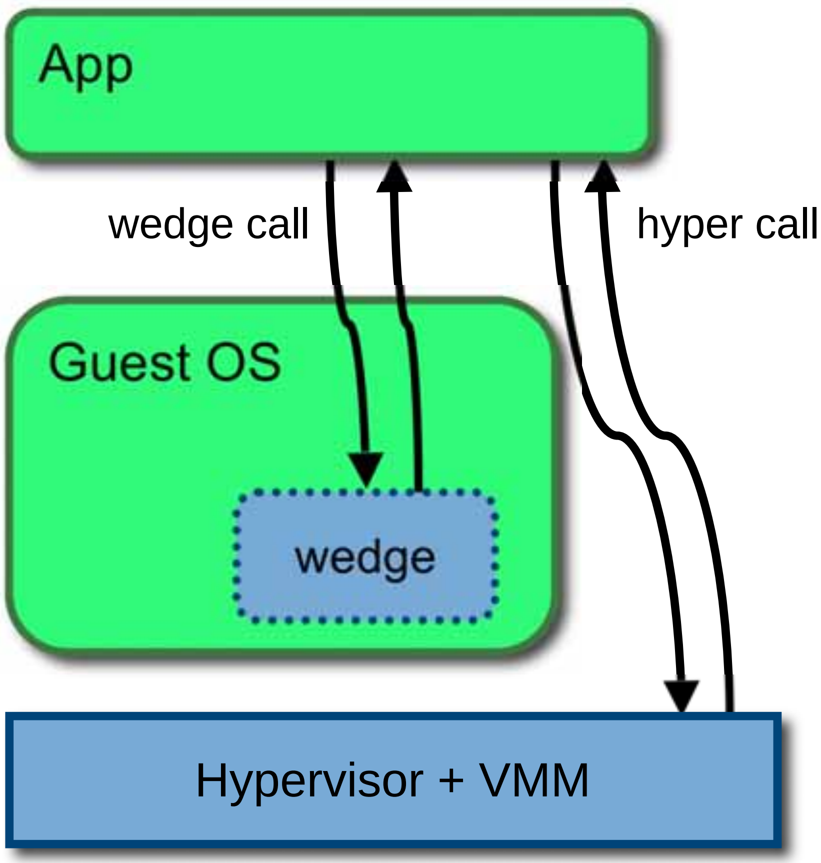
Transparent Virtualization: Safety Net

- Pre-virtualization is unfinished
  - Use manual annotations for memory operations
- Some hypervisors need high-level hooks for performance:
  - L4, Linux/BSD/WinNT user level
- Performance problems:
  - Signals
  - Process delete
  - Access to user memory
  - Thread local data

Transparent Virtualization: Safety Net

- Bypass platform init
  - BIOS
  - 16-bit code
- Make guest kernel relocatable
- Limited address space
  - Linux/BSD/WinNT user

Extensibility



- Wedge call:
  - Management utilities
  - Introspection
  - Filters
  - Enhancements
- Hyper call
  - IPC
  - Management utilities
  - Enhancements

Loadable Kernel Modules

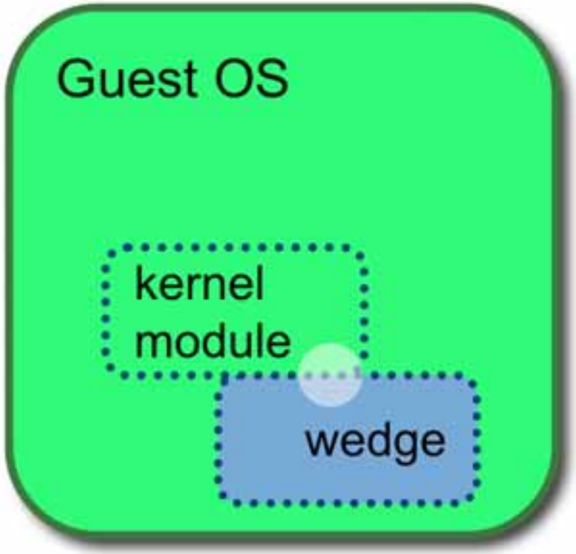
- Kernel modules are pre-virtualizated
  - When are they rewritten?
  - The rewriter needs the annotations ...

A. User-level utility
   1. Rewrites the module via wedge calls
   2. Guest kernel loads the module

B. Transparent kernel hook
   - Unmodified user-level tool chain
   - Guest kernel invokes rewrite hook

Loadable Wedge Modules

- Efficient interaction with the wedge:
  - Permit kernel modules to link against the wedge
  - Avoids expensive hyper calls
- Requirement:
  - Wedge symbol resolution
- Uses:
  - Memory ballooning module
  - Virtual device drivers



Evaluation

- Hypervisors:
  - L4Ka::Pistachio microkernel
  - Xen 2.0.2
- Guest OS: Linux 2.6.9
- Comparison:
  - afterburnt Linux on hypervisors
  - para-virtualized Linux: L4Linux, XenoLinux
  - native Linux
  - afterburnt Linux on hardware

(all execute with direct device access)

Implementation

- Simple implementation in C++
  - Contrast para-virtualization: must use language of the guest OS
- Reserved 64MB of address space
- Hooks added to guest OS:
  - page table — manual annotations
  - DMA translation — manual hooks
  - thread-local-storage
  - thread exit
  - user access

  L4 optimizations

Benchmark: Netperf

- System-under-test:
  - 2.8 GHz Pentium 4
  - gigabit ethernet
  - 256 MB of RAM, 64 MB RAM disk
- Client system
  - 1.4 GHz Pentium 4
  - gigabit ethernet
  - native Linux 2.4
  - 256 MB of RAM, 64 MB RAM disk
- Netperf send + receive: one gigabyte

Netperf Results

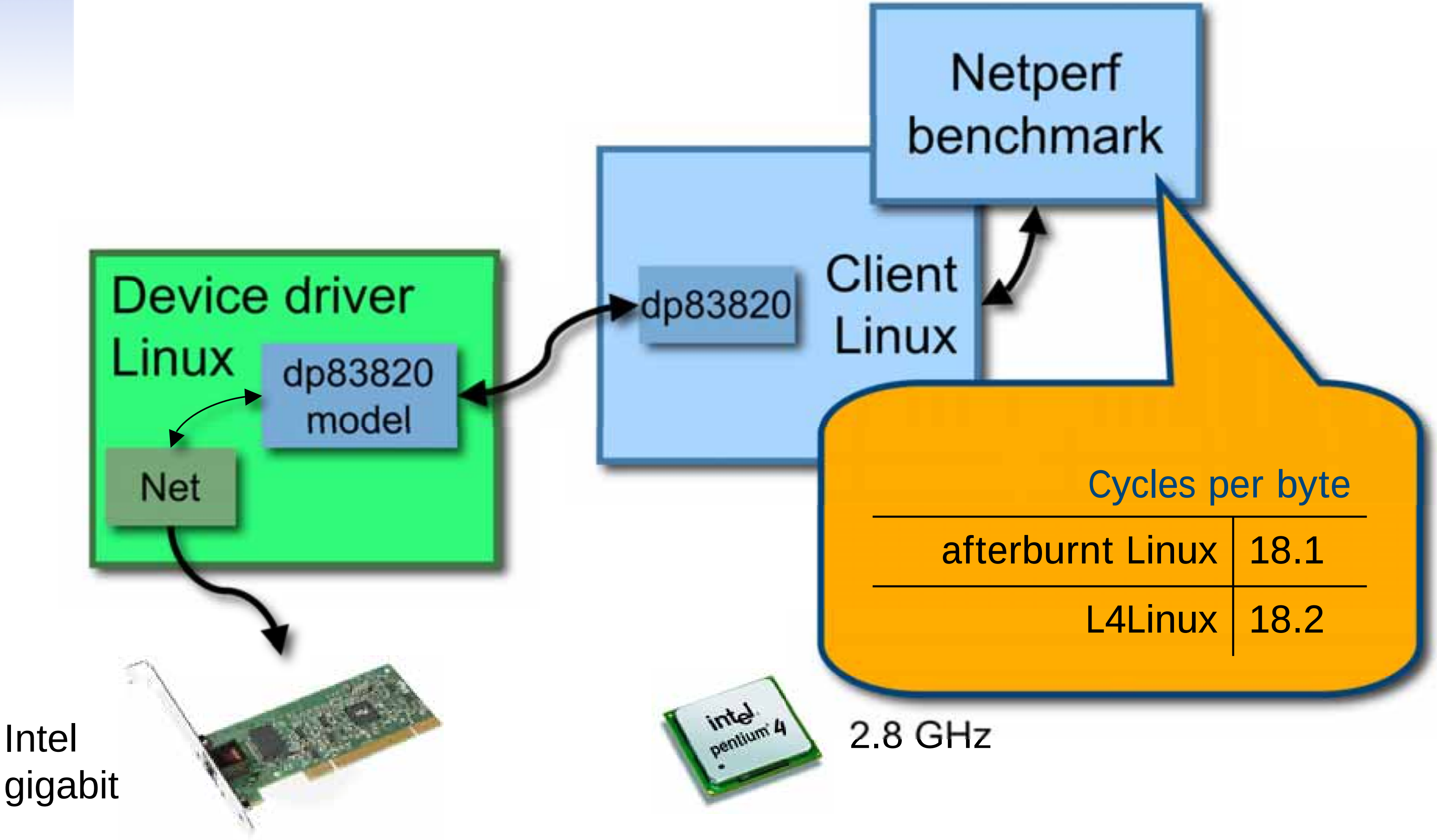
	Send		Receive	
	MB/s	CPU	MB/s	CPU
hardware	108.3	28.8%	97.6	35.4%
afterburnt hardware	108.5	27.4%	97.5	33.8%
XenoLinux	108.4	33.8%	97.6	41.6%
afterburn Xen	107.9	33.5%	96.6	41.1%
L4Ka::Linux	96.98	34.4%	97.5	35.6%
afterburnt L4	108.3	30.1%	97.5	37.2%

95% confidence interval is ± 0.21%

Netperf Instruction Expansion

operation	count	per interrupt
cli	6772992	74
sti	1572769	17
pushf	6715828	73
popf	5290060	58
hlt	91528	1
iret	184760	2
write ds	369520	4
write es	369520	4
read ds	184760	2
read es	184760	2
read fs	182866	2
read gs	182866	2
port out	278737	3

Device Pre-Virtualization Performance



	Cycles per byte
afterburnt Linux	18.1
L4Linux	18.2

Implementation: Afterburner

- Assembler macros
  - Walks the AST
  - But too inflexible (ex: sti ; hlt)
- Added new assembler operator: !
  - Prevents recursive macro expansion

```
.macro pushfl
9998:   !pushfl ; nop ; nop ; nop ; nop ; nop
9999:
.pushsection .afterburn
.long 9998b
.long 9999b
.popsection
.endm
```

Implementation: Architecture

- Front-ends:
  - Architecture specific
  - x86, ia32e, Itanium, PowerPC
- Back-ends:
  - Hypervisor specific
  - L4, Xen, Linux-user, WinNT-user
- Code reuse

Lines of Code

type	headers	source
common	686	1380
device	650	1476
x86	815	4436
L4	615	3655
Xen	677	2670
Linux	168	3405

Join the Fun

- Lots of pre-virtualization projects
- http://l4ka.org
- Source code available on the web
  - includes a ‘make world’
    - retrieves all packages
    - configures all packages
    - builds everything
    - prepares for QEMU emulator