A COMPARISON OF SOFTWARE AND HARDWARE TECHNIQUES FOR X86 VIRTUALIZATION

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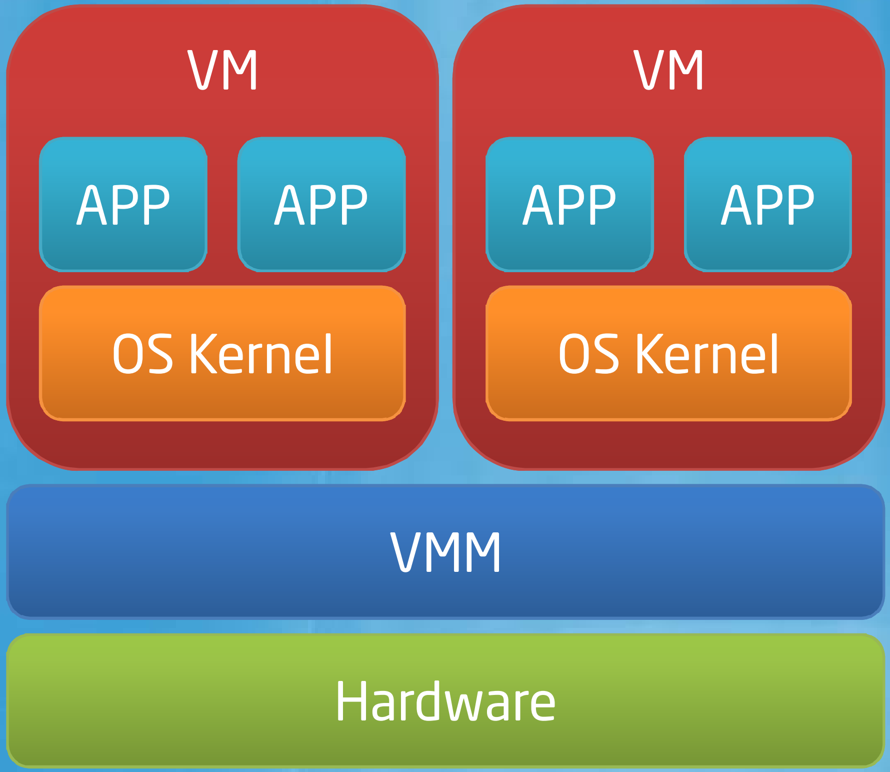
Content

- Introduction
- Virtualization
  - Classical
  - Software
  - Hardware
- Comparison
- Opportunities
- Conclusion

Introduction and Terminology

- Virtualization
- Virtual Machine
  - Guest
- Virtual Machine Monitor
  - Host
- Motivation
  - Resource utilization
  - Development
  - ...



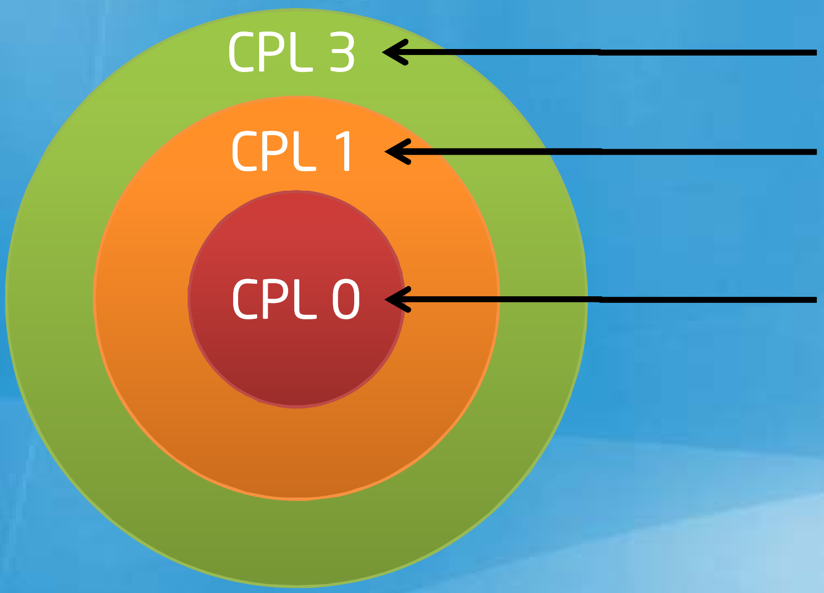
CLASSICAL VIRTUALIZATION

Classical Virtualization

- Three essential characteristics (Popek and Goldberg)
  - Fidelity – runs any software
  - Performance – fairly fast
  - Safety – VMM manages hardware
- Trap-and-Emulate
  - Only real solution until recently

De-Privileging

- Read/Write privileged state Instruction
- Direct Execution but reduced privileged level
- VMM intercepts traps and emulates



CPL 3 Applications

CPL 1 Operating System

CPL 0 Virtual Machine Monitor

Shadow Structures

- Virtual state differs from physical state
- VMM provides basic Execution Environment
- Shadow Structures
- On-CPU privileged state
  - Maintained as Image
- Off-CPU privileged data
  - Resides in Memory

Memory Traces

- Use of hardware page protection mechanisms for coherency of shadow structures
- Protection for memory-mapped devices
- Handling a trace fault:
  - Decode guest instruction
  - Emulate its effect in the primary structure
  - Apply change to the shadow structure

Tracing Example

- Use of Shadow Page Tables to run guest
- Vmware manages SPTs as cache
- True Page Fault
  - Violation of the protection policy
  - Forwarded to guest
- Hidden Page Fault
  - Missing Page in SPT
  - No guest-visible effect

Refinements

- Flexibility in VMM/guest OS Interface
  - Modify guest OS
  - Performance Gains
  - Extended Features
- Flexibilty in VMM/hardware Interface
  - Hardware Execution mode for guest OS
- “Paravirtualization”

SOFTWARE VIRTUALIZATION

x86 Obstacles

- Visibility of privileged state
- Lack of Traps at user-level
- Example: Unprivileged popf
    - Privileged level: ALU & system flags
    - De-privileged level: ALU changes
    - No trap in de-privileged level

Simple Binary Translation – Interpreter

- Use of an interpreter
- Prevent leakage of privileged state
- Correct implementation of non-trapping instructions
- Separation of virtual state from physical state
- Fails Performance Criteria

Simple Binary Translation

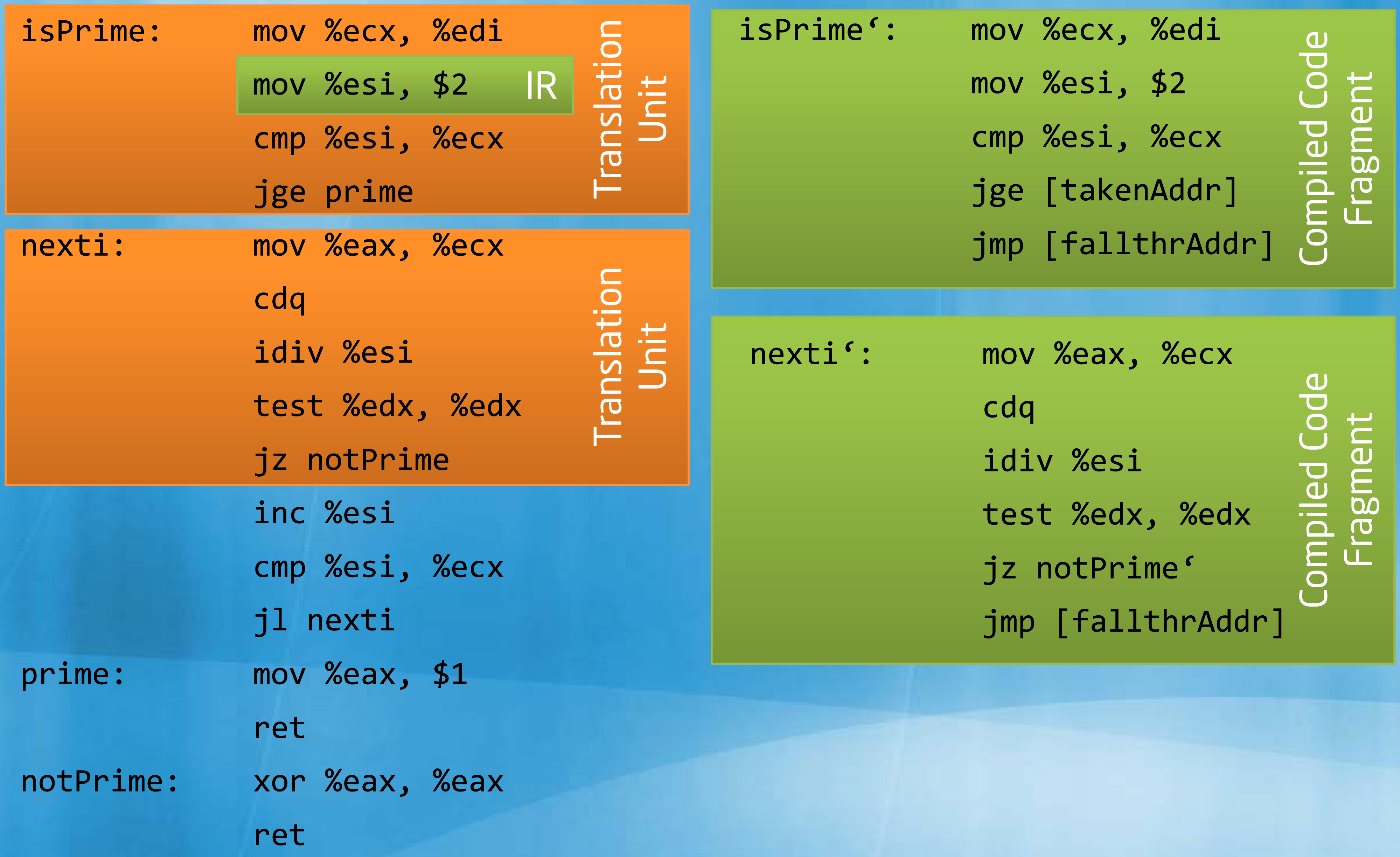
- Binary Translation combines Interpreter with Performance
- VMware's Translator offers this properties:
  - Binary
  - Dynamic
  - On Demand
  - System Level
  - Sub-Setting
  - Adaptive

Simple Binary Translation – Example

- Simple prime validation
- Invoke `isPrime(49)`

```
int isPrime(int a) {
    for (int i = 2; i < a; i++) {
        if (a % i == 0) return 0;
    }
    return 1;
}
```

Simple Binary Translation – Example



```
isPrime:      mov %ecx, %edi
              mov %esi, $2
              cmp %esi, %ecx
              jge prime
nexti:        mov %eax, %ecx
              cdq
              idiv %esi
              test %edx, %edx
              jz notPrime
              inc %esi
              cmp %esi, %ecx
              jl nexti
prime:        mov %eax, $1
              ret
notPrime:     xor %eax, %eax
              ret
```

```
isPrime‘:     mov %ecx, %edi
              mov %esi, $2
              cmp %esi, %ecx
              jge [takenAddr]
              jmp [fallthrAddr]
```

```
nexti‘:       mov %eax, %ecx
              cdq
              idiv %esi
              test %edx, %edx
              jz notPrime‘
              jmp [fallthrAddr]
```

Simple Binary Translation – Example

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isPrime:      mov %ecx, %edi
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              jge prime
nexti:        mov %eax, %ecx
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              idiv %esi
              test %edx, %edx
              jz notPrime
              inc %esi
              cmp %esi, %ecx
              jl nexti
prime:        mov %eax, $1
              ret
notPrime:     xor %eax, %eax
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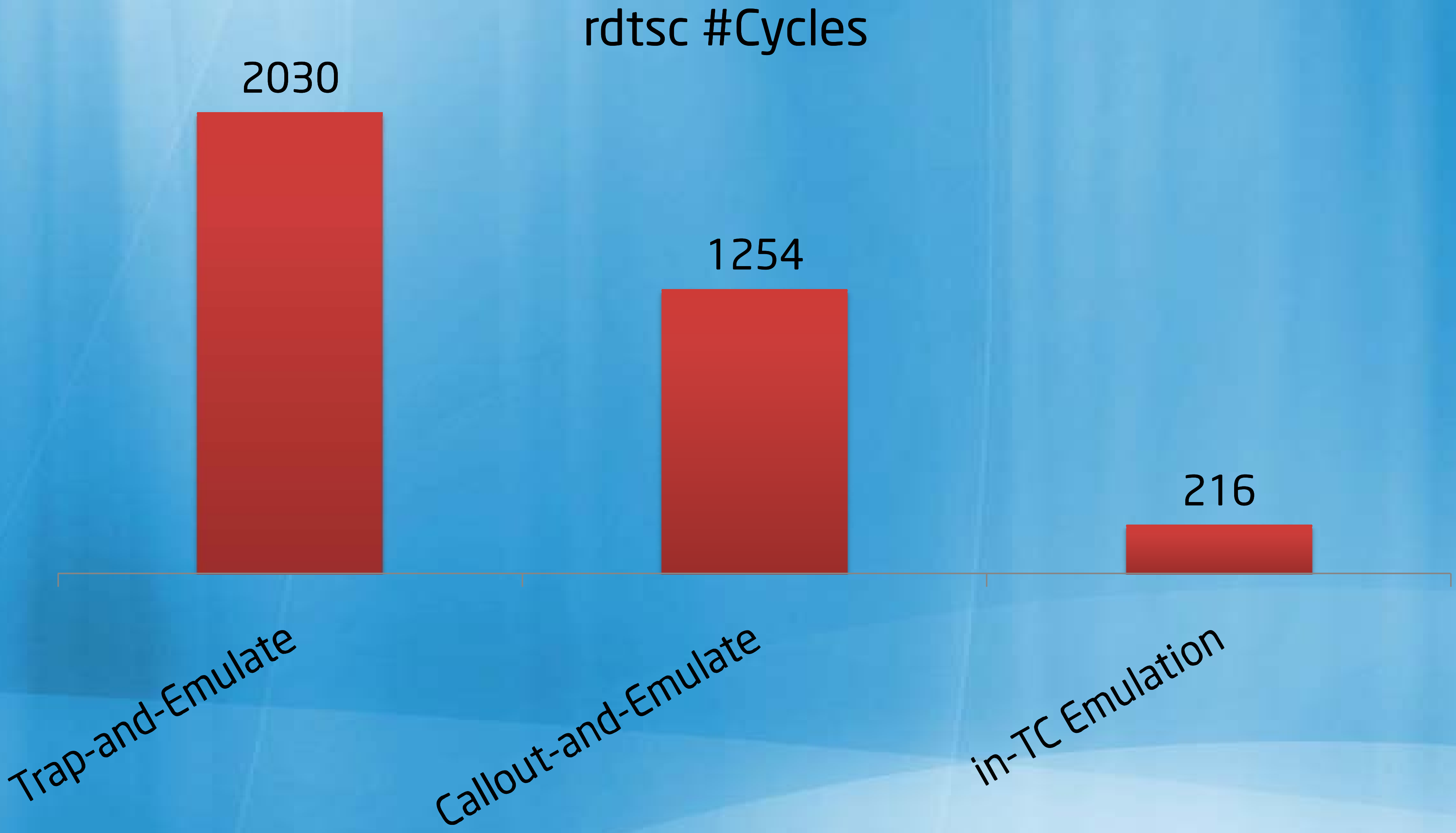
```

```
isPrime':     *mov %ecx, %edi
              mov %esi, $2
              cmp %esi, %ecx
              jge [takenAddr]
nexti':       *mov %eax, %ecx
              cdq
              idiv %esi
              test %edx, %edx
              jz notPrime'
              *inc %esi
              cmp %esi, %ecx
              jl nexti'
              jmp [fallthrAddr3]
notPrime':    *xor %eax, %eax
              pop %r11 ; RET
              mov %gs:0xff39eb8(%rip), %rcx
              movzx %ecx, %r11b
              jmp %gs:0xfc7dde0(8*%rcx)
```

Simple Binary Translation – Exceptions

- PC-relative addressing
  - Translator output on different location
- Direct control flows
  - Code layout changes need reconnection
- Indirect control flows
  - Dynamically computed targets
- Privileged instructions

Comparison


rdtsc #Cycles
2030
1254
216
Trap-and-Emulate
Callout-and-Emulate
in-TC Emulation

HARDWARE VIRTUALIZATION

x86 Architecture Extensions

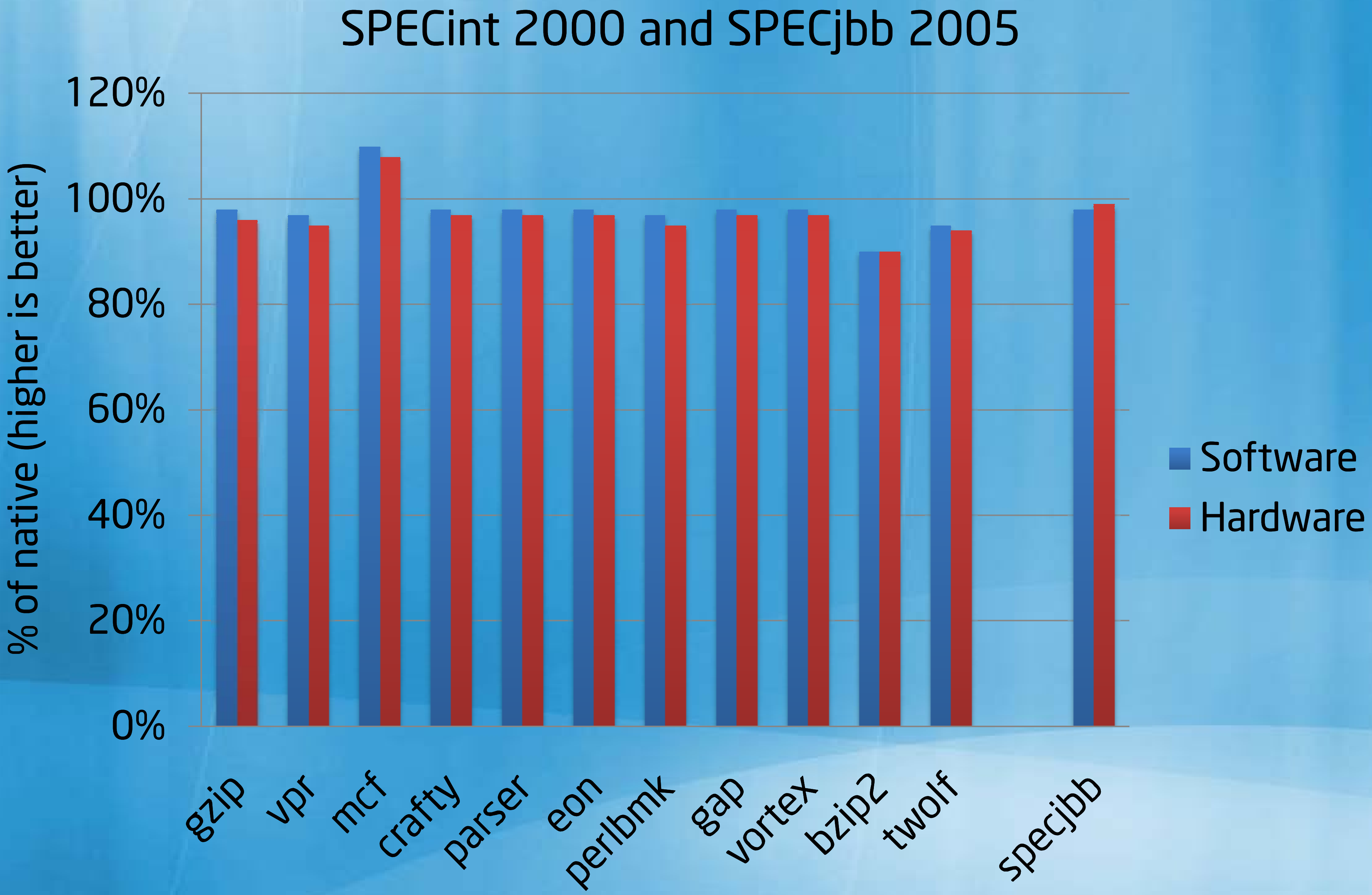
- Allows classical Trap-and-Emulate
- Virtual Machine Control Block
  - Diagnostics Fields
- Guest Mode (VMX) vs. Host Mode
- `vmrun` Command

Qualitative Comparision

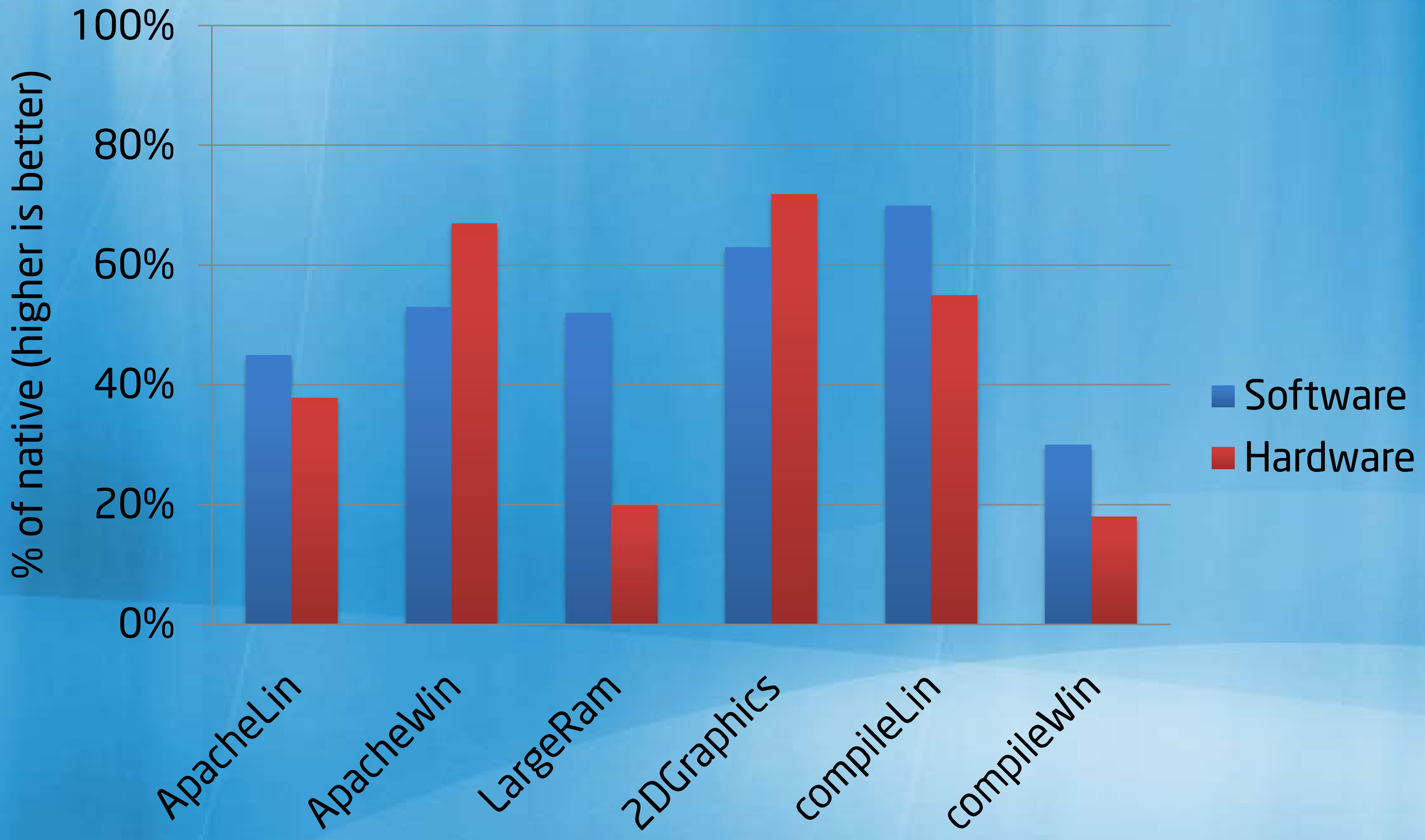
- Binary Translator
  - Trap Elimination
  - Emulation Speed
  - Callout avoidance
- Hardware-assisted VMM
  - Code density
  - Precise exceptions
  - System calls

EXPERIMENTS AND RESULTS

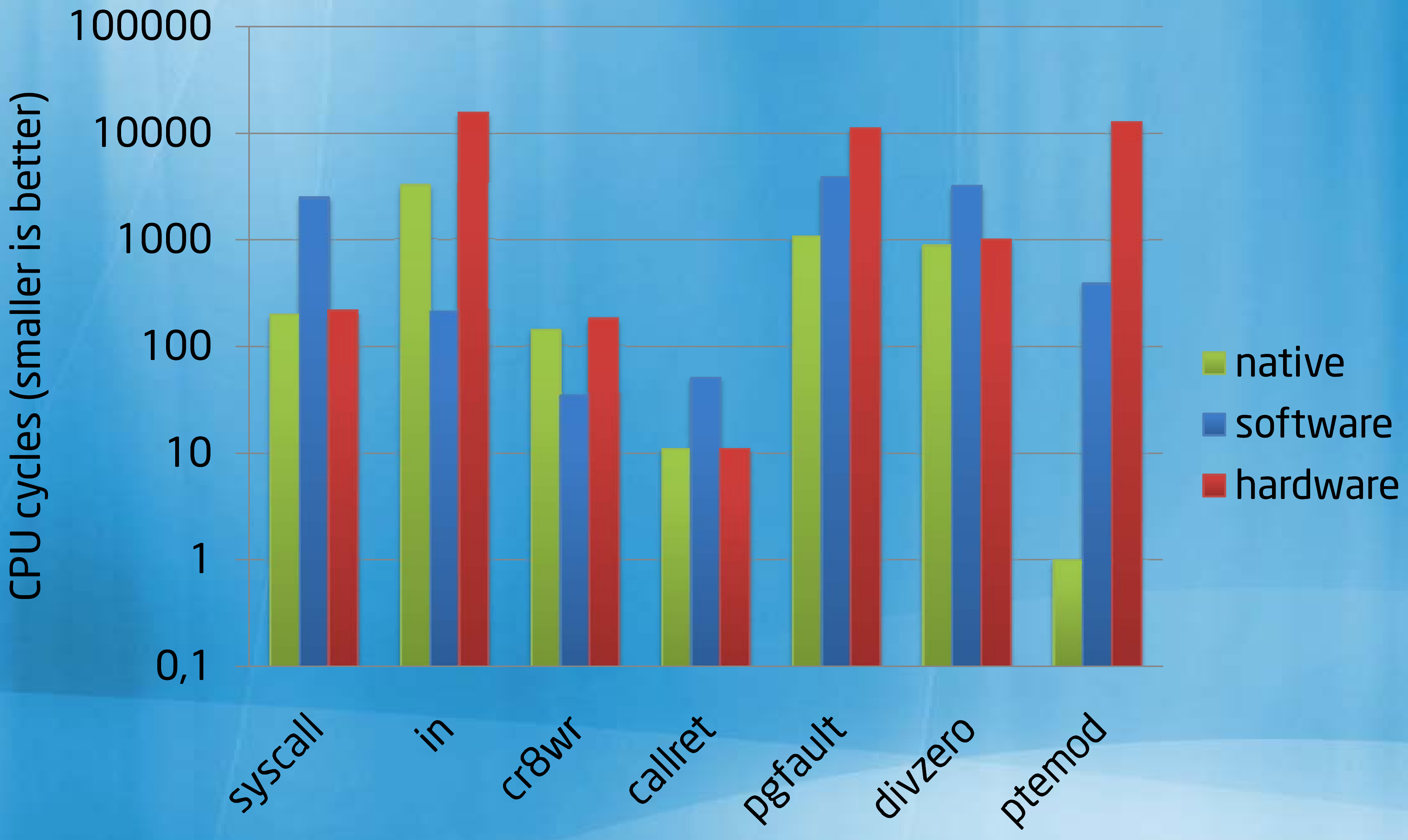
Initial Measuring



Macrobenchmarks



Cost of Operations



Opportunities

- Faster MicroCoreArchitecture Implementations
- Hardware VMM Algorithms
- Hybrid VMM
- Hardware MMU

Conclusions

- First generation of hardware support
  - Permit tran-and-emulate
- No real performance decrease
  - Only at system calls
- New MMU algorithms could help

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