Dune: Safe User-level Access to Privileged CPU Features

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The power of privilege

- Privileged CPU features are fundamental to kernels
- But other, compelling uses:
  - Speed up garbage collection (Azul C4)
    - Page tables provide memory access information
  - Privilege separation within a process (Palladium)
    - MMU hardware isolates compartments
  - Safe native code in web browsers (Xax)
    - System call handler intercepts system calls
Should we change the kernel?

- Problem: stability concerns, challenging to distribute, composability concerns
What about an Exokernel?

- Problem: must replace entire OS stack
What about a virtual machine?

- Problem: virtual machines have strict partitioning
Dune in a Nutshell

- Provide safe user-level access to privileged CPU features
- Still a normal process in all ways (POSIX API, etc)
- Key idea: leverage existing virtualization hardware (VT-x)
Garbage collection in Dune

• Solution: control the page table directly within a process
Outline

• Overview
• Design
• Evaluation
Available CPU features

• Privilege Modes
  – SYSRET, SYSEXIT, IRET

• Virtual Memory
  – MOV CRn, INVLPG, INVPCID

• Exceptions
  – LIDT, LTR, IRET, STI, CLI

• Segmentation
  – LGDT, LLDT
Dune architecture

- Host mode -> VMX root mode on Intel
- Normally used for hypervisors
- In Dune, we run the kernel here
  - Reason: need access to VT-x instructions
Dune architecture

• Guest mode -> VMX non-root mode on Intel
• Normally used by the guest kernel
• In Dune, we run ordinary processes here
  – Reason: need access to privileged features
• Dune Module (~2500 LOC)
  – Configures and manages virtualization hardware
  – Provides integration with the rest of the kernel in order to support a process abstraction
  – Uses Intel VT-x (could easily add AMD SVM)
libDune (~10,000 LOC)

- A utility library to help applications manage privileged hardware features
- Completely untrusted
- Exception handling, system call handling, page allocator, page table management, ELF loader
Providing a process abstraction

• Memory management
• System calls
• POSIX Signals
Memory management in Dune

- Configure the EPT to provide process memory
- User programs can then directly access the page table

```
Kernel
  Host-Virtual
  Kernel Page Table

Dune Process
  Guest-Virtual
  User Page Table

EPT

Guest-Physical

Host-Physical (RAM)
```
System calls in Dune

- **SYSCALL** will only trap back into the process
- **Use VMCALL** (i.e. a hypercall) to perform normal kernel system calls
But SYSCALL is still useful

- Isolate untrusted code by running it in a less privileged mode (i.e. ring 3 on x86)
- Leverage the ‘supervisor’ bit in the page table to protect memory
Signals in Dune

• Signals should only be delivered to ring 0
• What happens if process is in ring 3?
• Possible solution: have the Dune module manually transition the process to ring 0
  – Works but slow and somewhat complex
• Our solution: deliver signals as injected interrupts
  – Hardware automatically switches to ring 0
  – Can use CLI and STI to efficiently mask signals
Many implementation challenges

• Reducing VM exit and VM entry overhead
• Pthread and fork were tricky to integrate with the Linux kernel
• EPT does not support enough address space
• Check the paper for details
Outline

• Overview
• Design
• Evaluation
Evaluation

• How much overhead does Dune add?
• What potential does Dune create for optimization?
• What is Dune’s performance in end-to-end use cases?
Overhead analysis

• Two sources of overhead
  – VMX transitions
  – EPT translations

<table>
<thead>
<tr>
<th></th>
<th>Getpid</th>
<th>Page fault</th>
<th>Page walk</th>
</tr>
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<tbody>
<tr>
<td>Linux</td>
<td>138</td>
<td>2,687</td>
<td>36</td>
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<tr>
<td>Dune</td>
<td>895</td>
<td>5,093</td>
<td>86</td>
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</table>
Optimization analysis

• Large opportunities for optimization
  – Faster system call interposition and traps
  – More efficient user-level virtual memory manipulation

<table>
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<tr>
<th>(cycles)</th>
<th>ptrace (getpid)</th>
<th>trap (TRAP, PROT1, UNPROT)</th>
<th>Appel 1 (PROTN, TRAP, UNPROT)</th>
<th>Appel 2 (PROTN, TRAP, UNPROT)</th>
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<td>Linux</td>
<td>27,317</td>
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<td>701,413</td>
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<td>Dune</td>
<td>1,091</td>
<td>587</td>
<td>94,496</td>
<td>94,854</td>
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End-to-end case studies

• We built and evaluated three systems
  • Application sandbox (~1300 LOC)
    – Constrained the system calls performed by an untrusted binary
  • Garbage collection (less than 100 LOC change)
    – Improved dirty page detection through direct access to dirty bits
  • Privilege separation (~750 LOC)
    – Supported several protection domains within a single process through use of multiple page roots (with TLB tagging)
Sandbox: SPEC2000 performance

- Only notable end-to-end effect is EPT overhead
- Can be eliminated through use of large pages
Sandbox: lighttpd performance

- Slight reduction in throughput (less than 2%) due to VMCALL overhead
Performance of other use cases

• Up to 40% improvements in garbage collection performance (less than 100 LOC)

• Privilege separation system can context switch between subdomains 3x faster than Linux can switch between processes (750 LOC)
Conclusions

• Applications can benefit from access to privileged CPU features
• Virtualization hardware allows us to provide such access safely
• Dune creates new opportunities to build and improve applications without kernel changes
• Dune has modest performance overhead
• Download Dune at http://dune.scs.stanford.edu
Xax - kernel hack

- Implement “picoprocess” system call support
Xax – the Dune approach

- handle system calls directly within a process
Suppose we wanted to build a faster garbage collector

- leverage OS virtual memory support?
- Technique: memory remapping
  - Problem: mmap() is too slow (TLB invalidations)
- Technique: dirty page detection
  - Problem: Linux does not expose dirty page information
Application: sandboxing

Untrusted Process
Id-linux ELF Loader

Sandbox
Mini ELF Loader
Syscall Filter
Checkpoint System

Kernel
Dune Module
Application: garbage collection

Application

Garbage Collector

PGTBL

READ/CLEAR DIRTY BITS

VMCALL

Kernel

Dune Module
Could Dune Run in a VM?
What about Libra?

- Works but very complex and overhead is high
Why Dune is Safe

• Two key ideas
  – Memory protected by EPT
  – Privileged state protected by VT-x
VT-x: shadows privileged state

1.) save guest state
2.) load host state

1.) save host state
2.) load guest state

VM Exit

VM Enter
SPEC2000 - different sandboxing approaches

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Dune</th>
<th>Linux LGPG</th>
<th>Dune LGPG</th>
<th>32-bit Linux</th>
<th>32-bit NaCl</th>
<th>64-bit NaCl</th>
<th>KVM</th>
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<tr>
<td></td>
<td>3.1</td>
<td>-4.3</td>
<td>-4.1</td>
<td>12.7</td>
<td>37.6</td>
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Slowdown Percentage

-10 -5 0 5 10 15 20 25 30 35 40