NDSS'17

Deconstructing Xen

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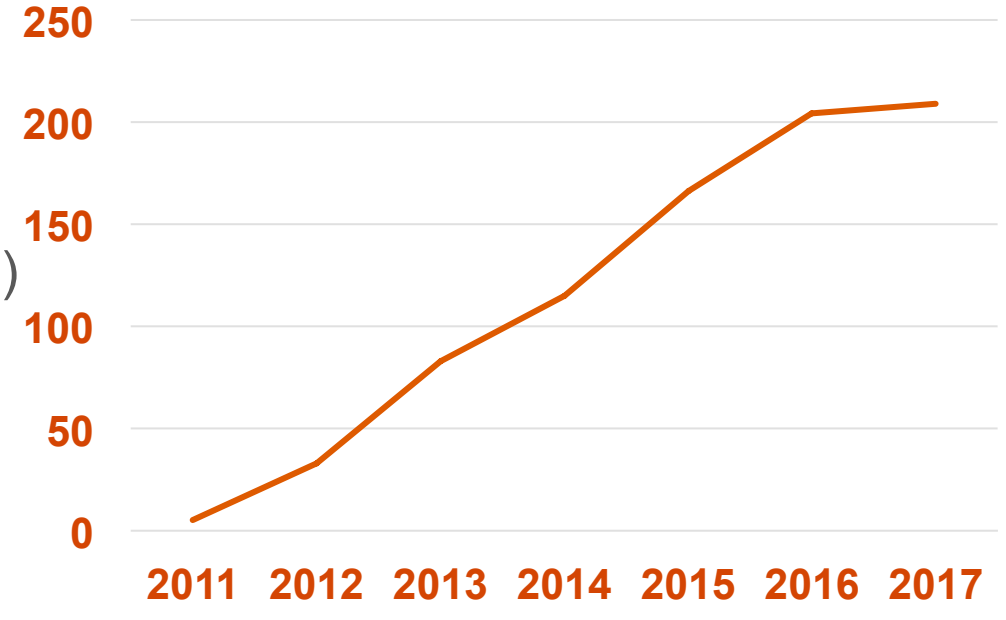
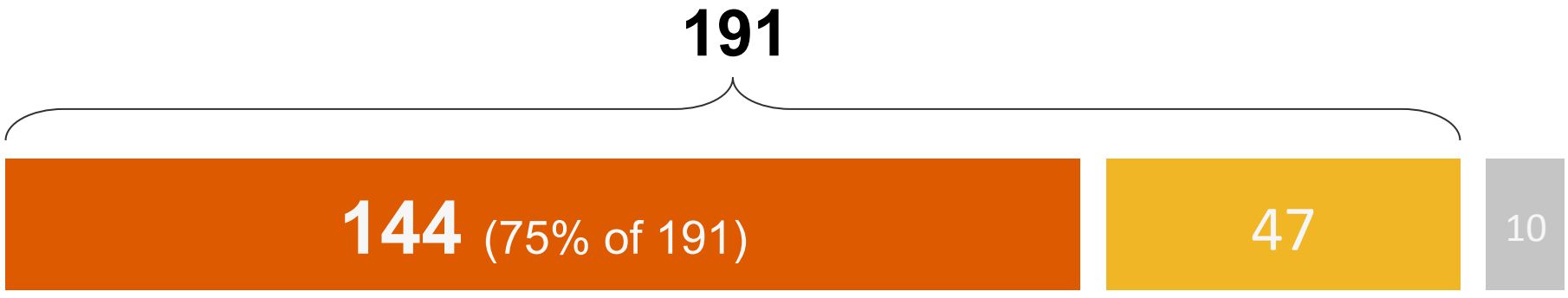
Hypervisors have Bugs

- Xen is used by Amazon EC2
- Xen's CVE is growing
  - 210 XSA (Xen Security Advisories)
  - Xen's LoC is growing from 45K (v2.0) to 270K (v4.0)
- KVM also has 100+ CVEs



Data from https://xenbits.xen.org/xsa/

Analyze 201 of Xen's Vulnerabilities (XSA)



144 are in the hypervisor

E.g., Host DoS, privilege escalation, etc.

Use hypervisor to attack VM

Focus on this part

47 are not in hypervisor

Some are in Domain-0

Some are in Qemu

10 are ignored

7 numbers are not used

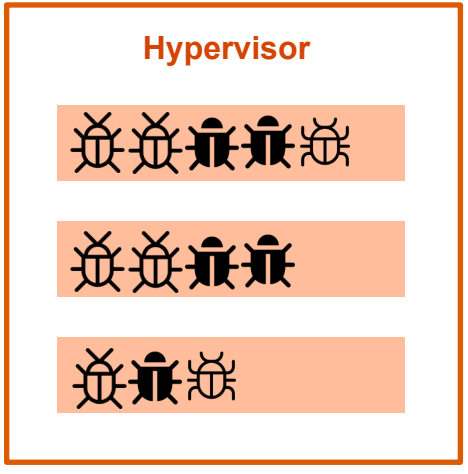
XSA-161 was withdrawn

XSA-99 is irrelevant

XSA-166 is too vague

3 Dimensions to Categorize (144 Hypervisor bugs)

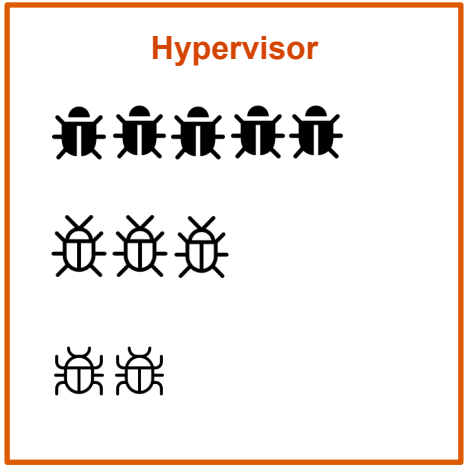
Which component to attack?



Attack targets

Memory management: 25.7%
CPU virtualization: 21.5%
Code emulation: 13.2%
...

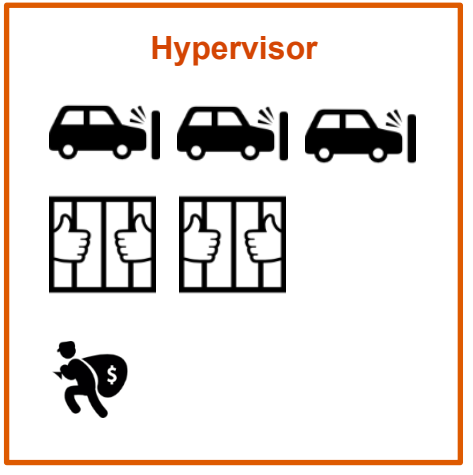
How to attack?



Key steps of attack

Memory corruption: 45.1%
Misuse of hardware: 22.2%
Live lock: 8.3%
...

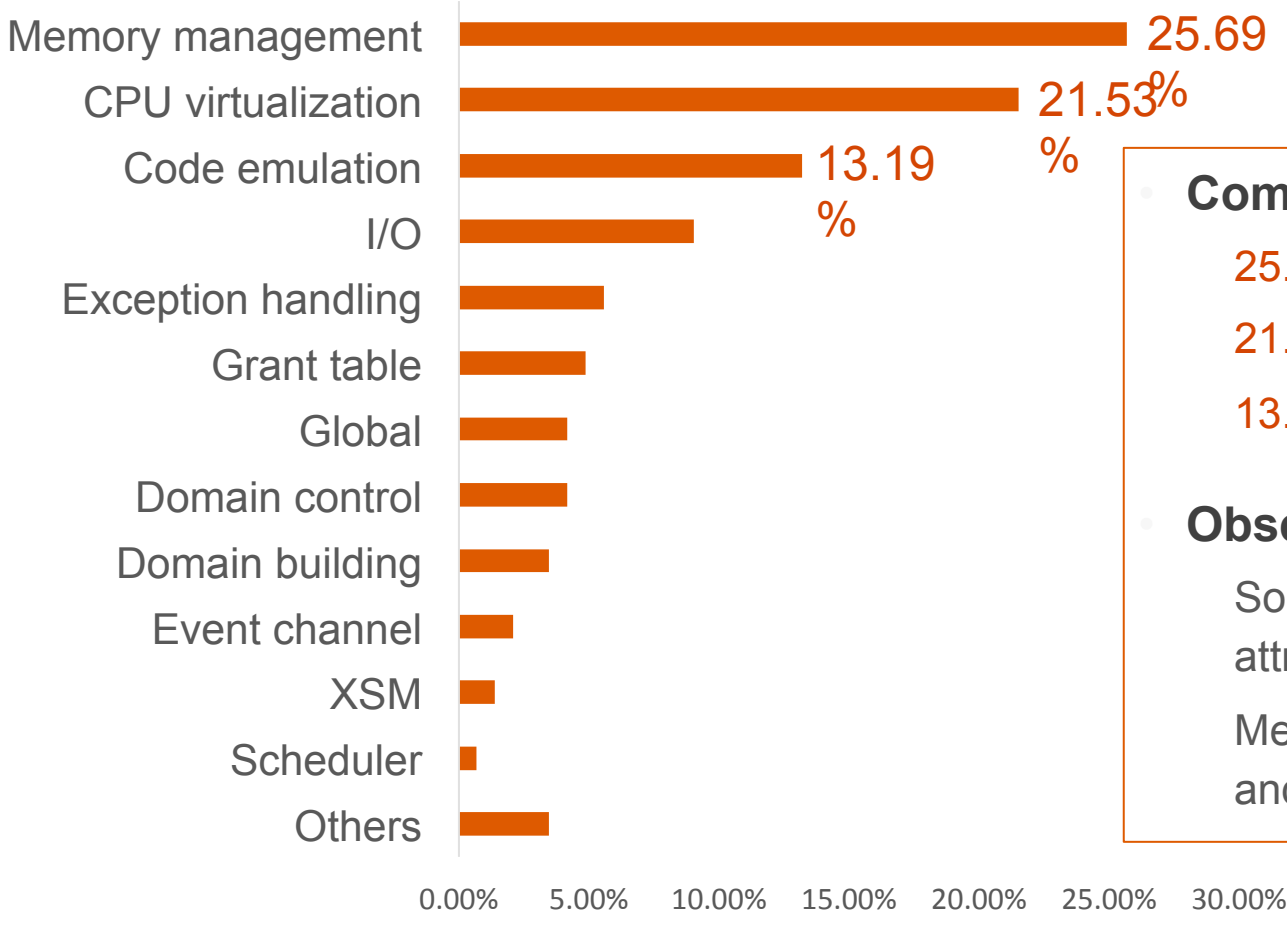
Attack for what?



Results of attack

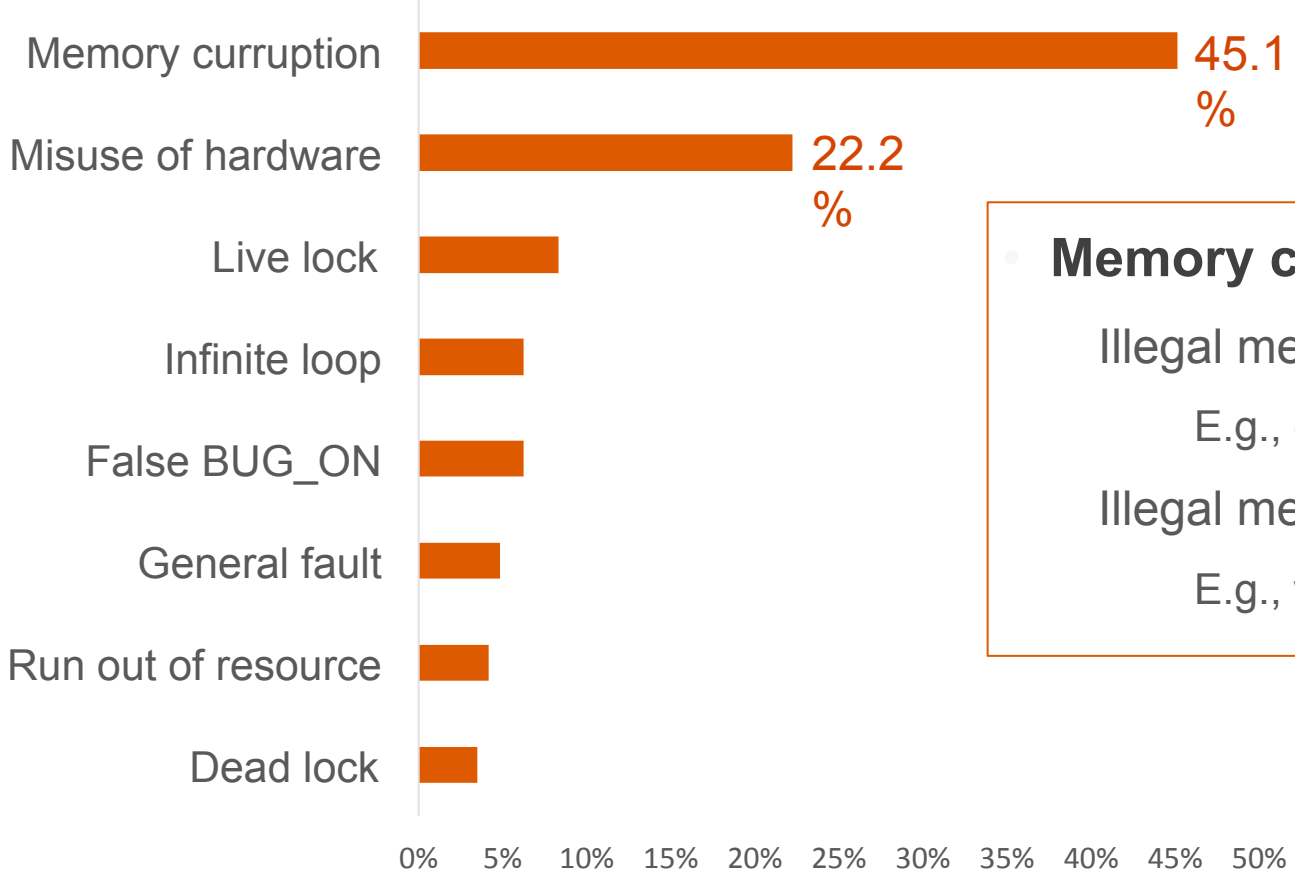
Host DoS: 61.8%
Privilege escalation: 15.3%
Info leak: 13.9%
...

1. Xen Components with Bugs



- **Components with bugs**
  - 25.69%: Memory management
  - 21.53%: CPU virtualization
  - 13.19%: Code emulation
- **Observations:**
  - Some components are more attractive to attackers
  - Memory management is critical and hard to get right

2. The Types of Key Step of Attack



Memory corruption: 45.14%

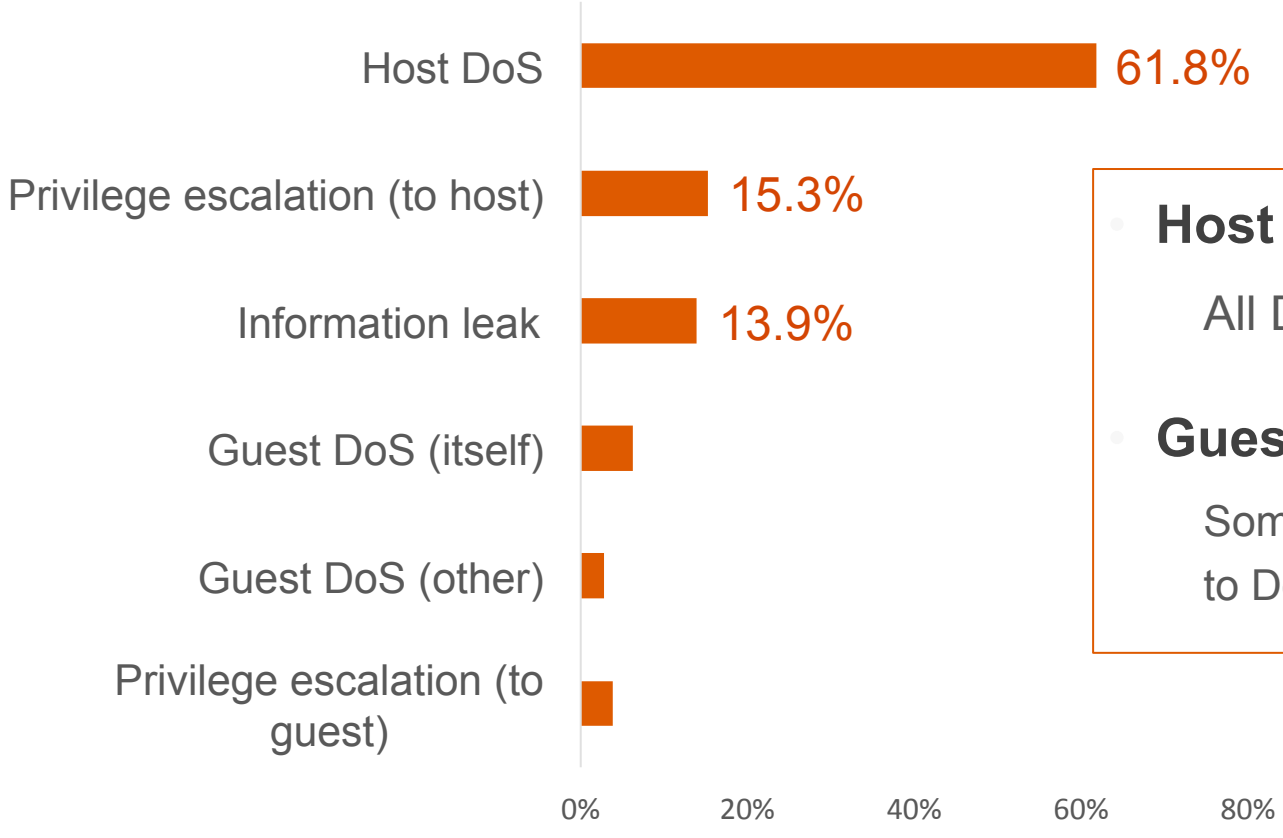
Illegal memory read

E.g., out-of-boundary

Illegal memory write

E.g., write to an invalid pointer

3. The Consequences of Attack



- **Host DoS: more than 60%**
  - All DoS: more than 70%
- **Guest to guest attack**
  - Some guest app leverages hypervisor to DoS its own guest VM

Summary: Observations

- **Hypervisors have bugs**
  - Some previous studies focused on bugs of dom-0 or host OS
  - Some systems (e.g., nested virtualization) can solve the problem but may cause performance overhead due to nested levels
- **Some components have more vulnerabilities (found)**
  - Take consideration on mem management, code emulation, etc.
- **DoS cannot be ignored**
  - Need to tolerant DoS for availability

Deconstruction for Isolation

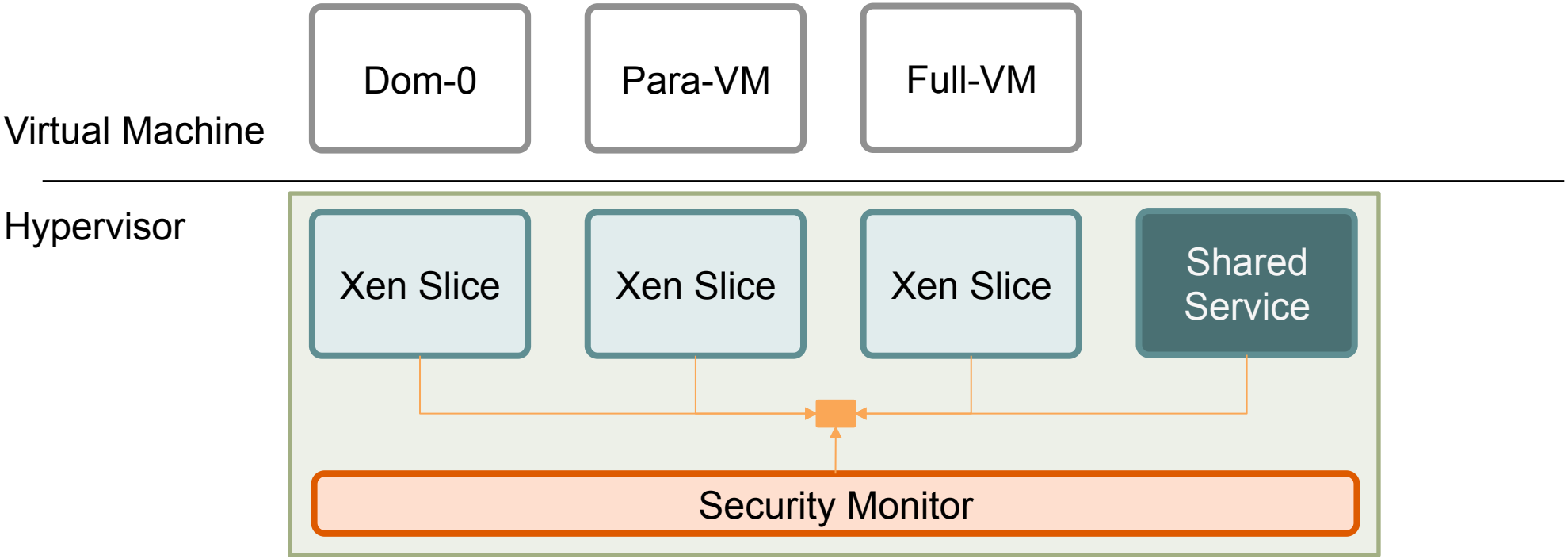
NEXEN: NESTED XEN

It's a palindrome!

From Observations to Nexen

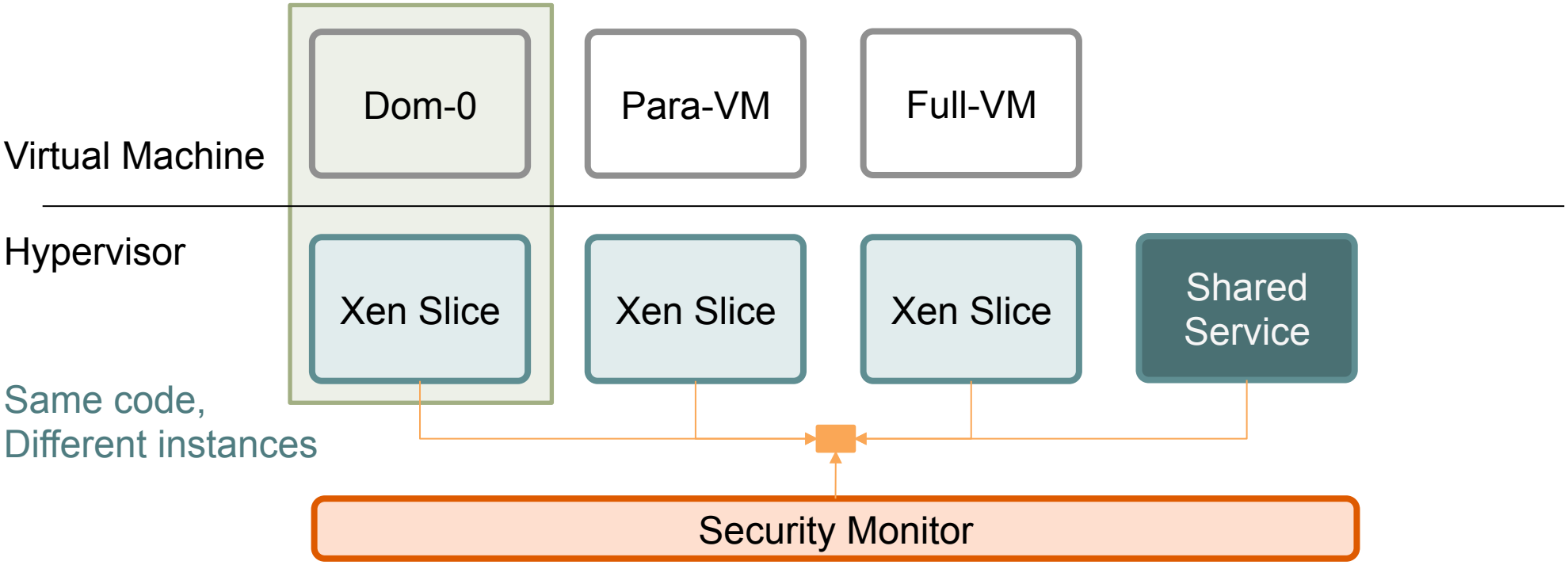
- **Hypervisors have bugs**
  - Deconstruct the hypervisor to isolated components
  - “Nesting” within single hardware privilege for performance
- **Some components have more vulnerabilities (found)**
  - Isolate vulnerabilities in the boundary of VM
- **DoS cannot be ignored**
  - Isolate failure in the boundary of VM

Deconstructing Xen



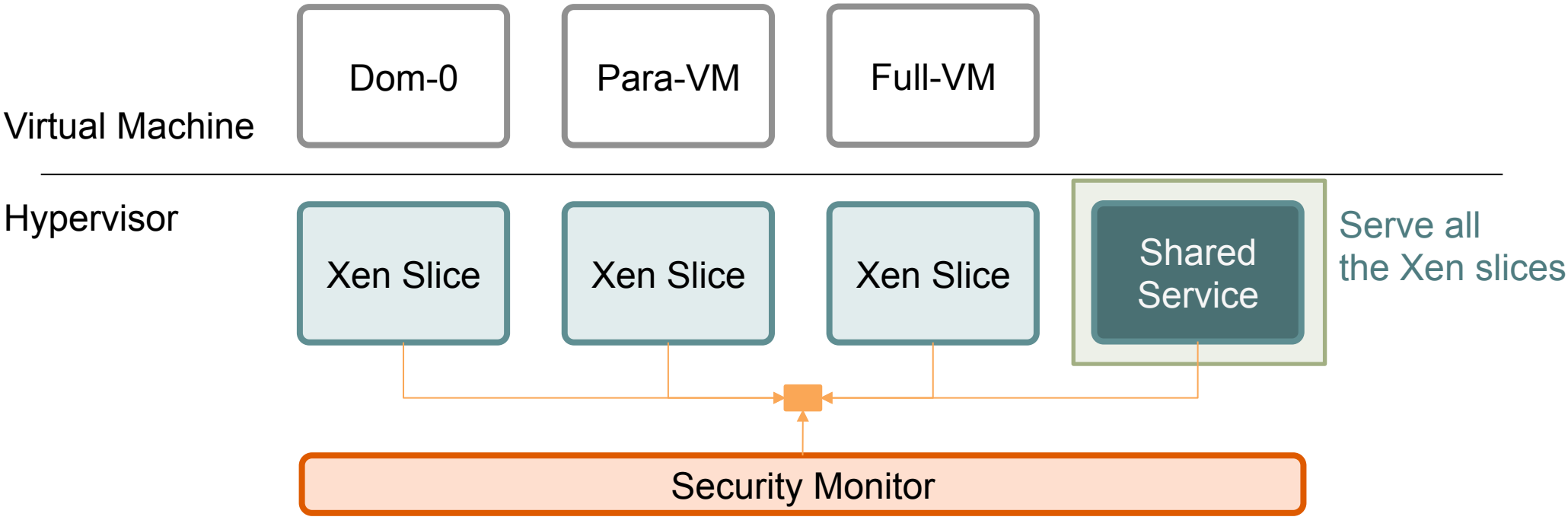
Partition Xen into several internal domains, all the domains run in the **same hardware privilege**

Xen Slice



Each Xen slice serves only one VM, containing the VM's metadata and handling its VMExits

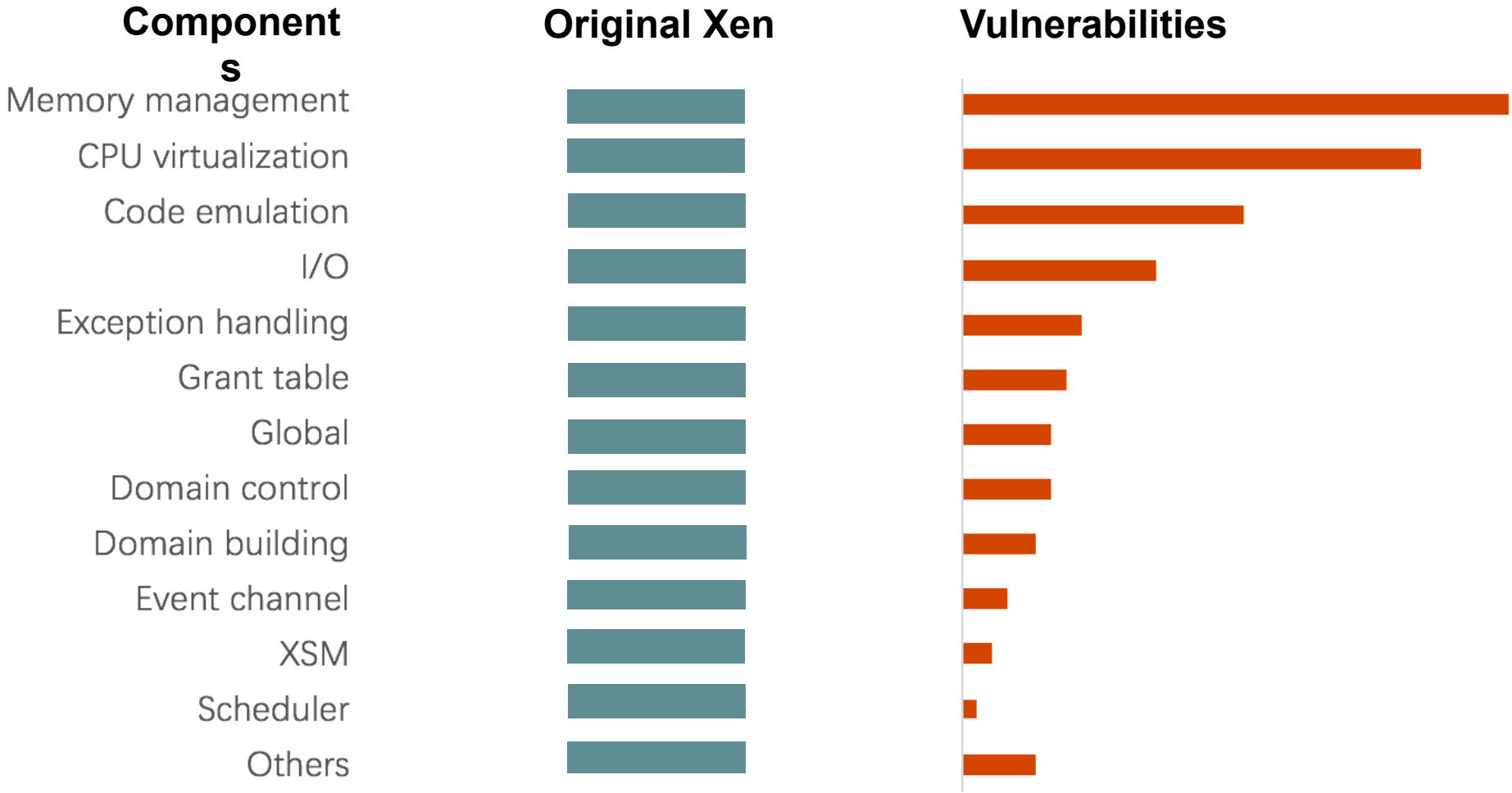
Shared Service

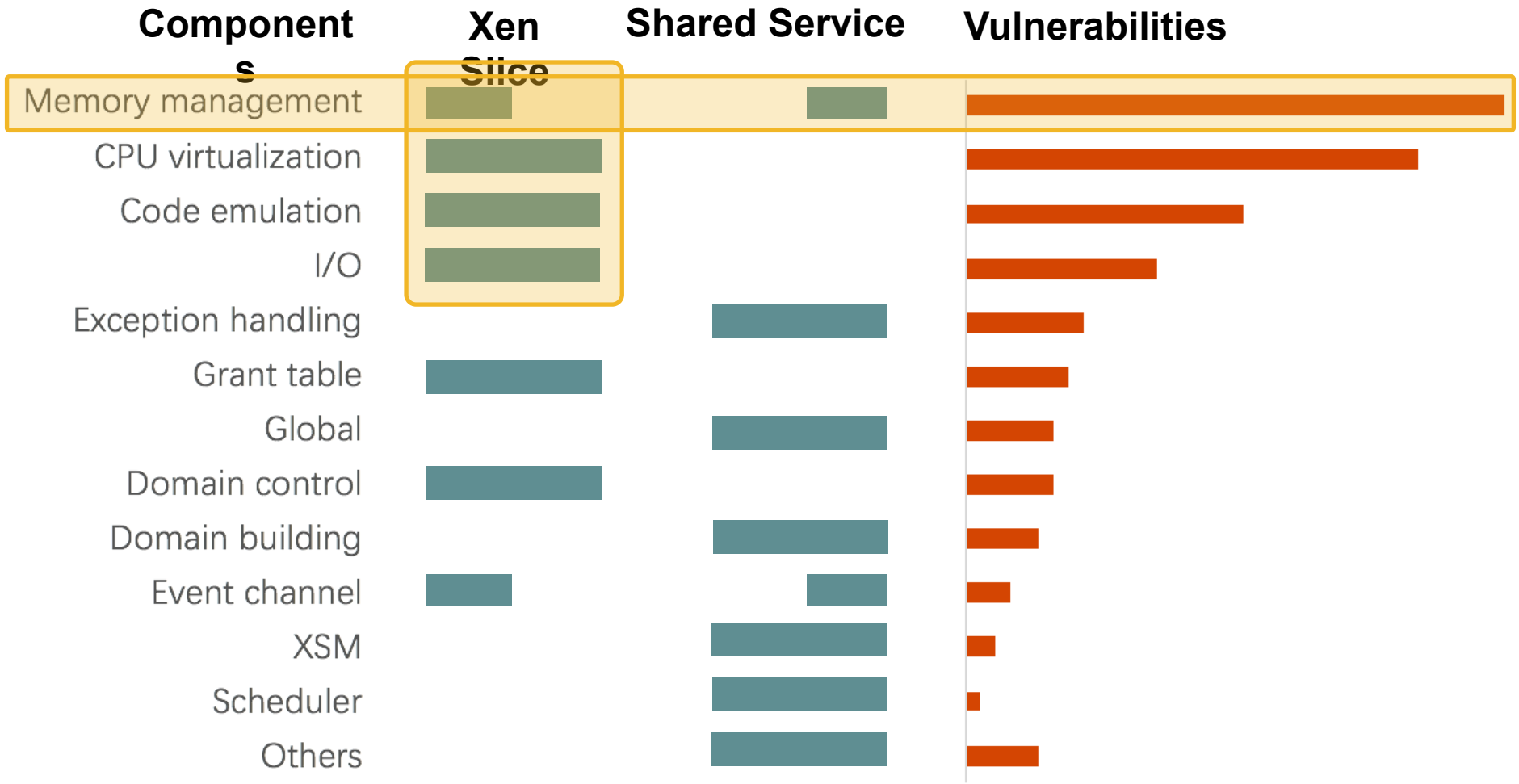


Only one shared service. It does not interact directly with VM, just serves Xen slices.

Xen Destruction

- Questions
  - Which parts to put in Xen slices?
  - Which parts to put in shared service?
- Principles
  - Least privilege
  - Minimize runtime communication
  - Separate mechanism from policy


Components
Original Xen
Vulnerabilities
Memory management
CPU virtualization
Code emulation
I/O
Exception handling
Grant table
Global
Domain control
Domain building
Event channel
XSM
Scheduler
Others


Components
Xen Slice
Shared Service
Vulnerabilities
Memory management
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I/O
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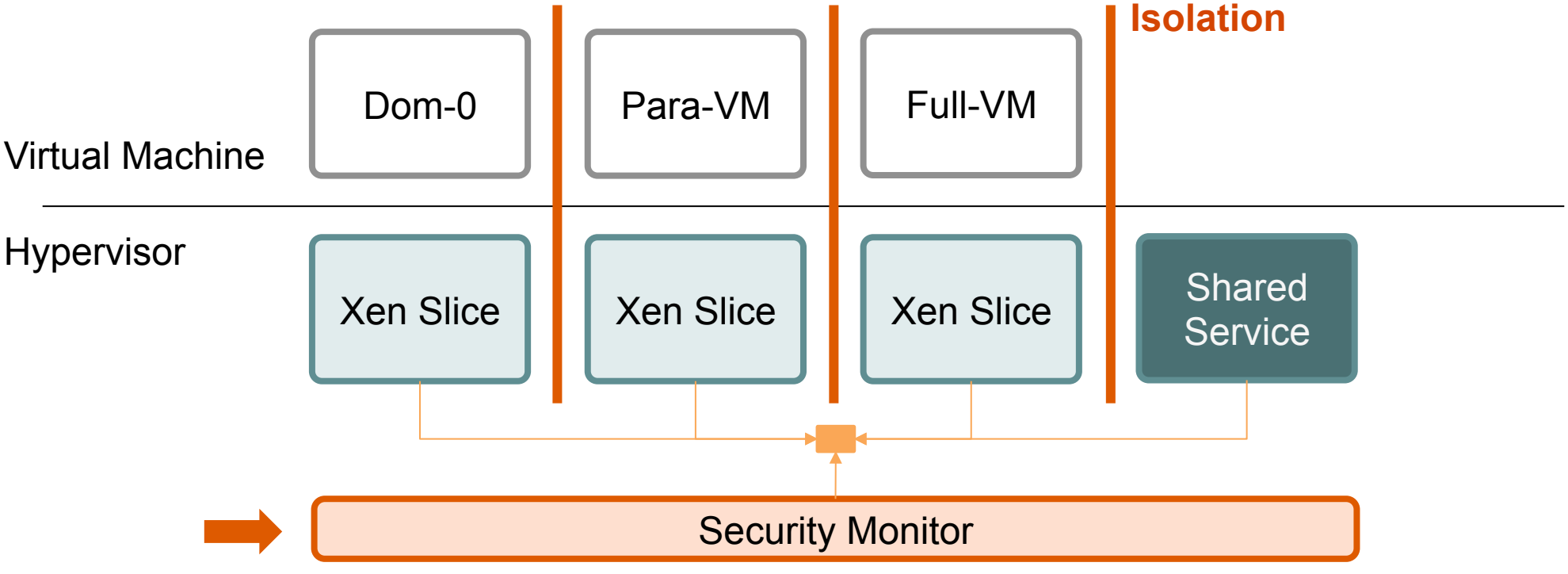
Grant table
Global
Domain control
Domain building
Event channel
XSM
Scheduler
Others

Security Monitor: Controls the MMU

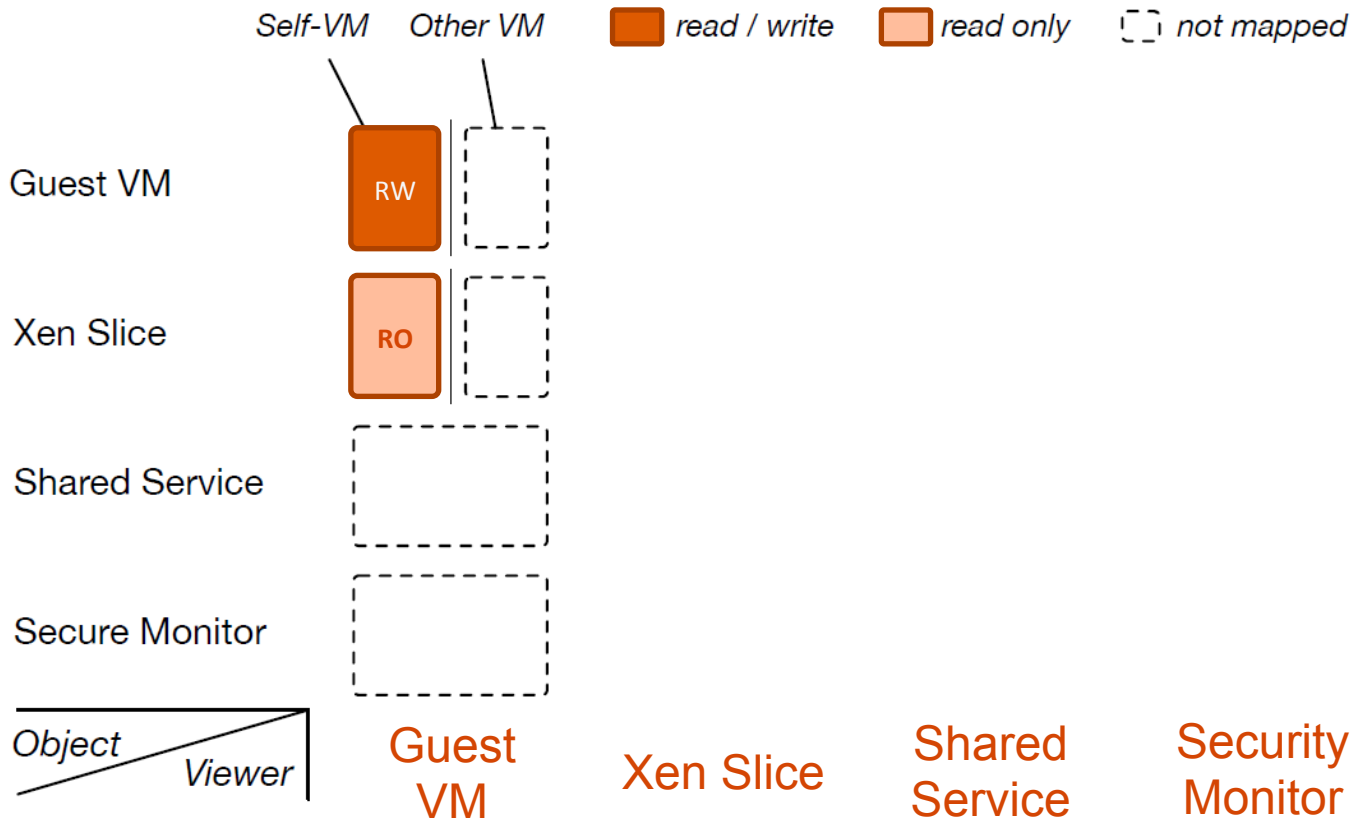


The **security monitor** controls guest page tables and EPTs. It offers interfaces & does security che

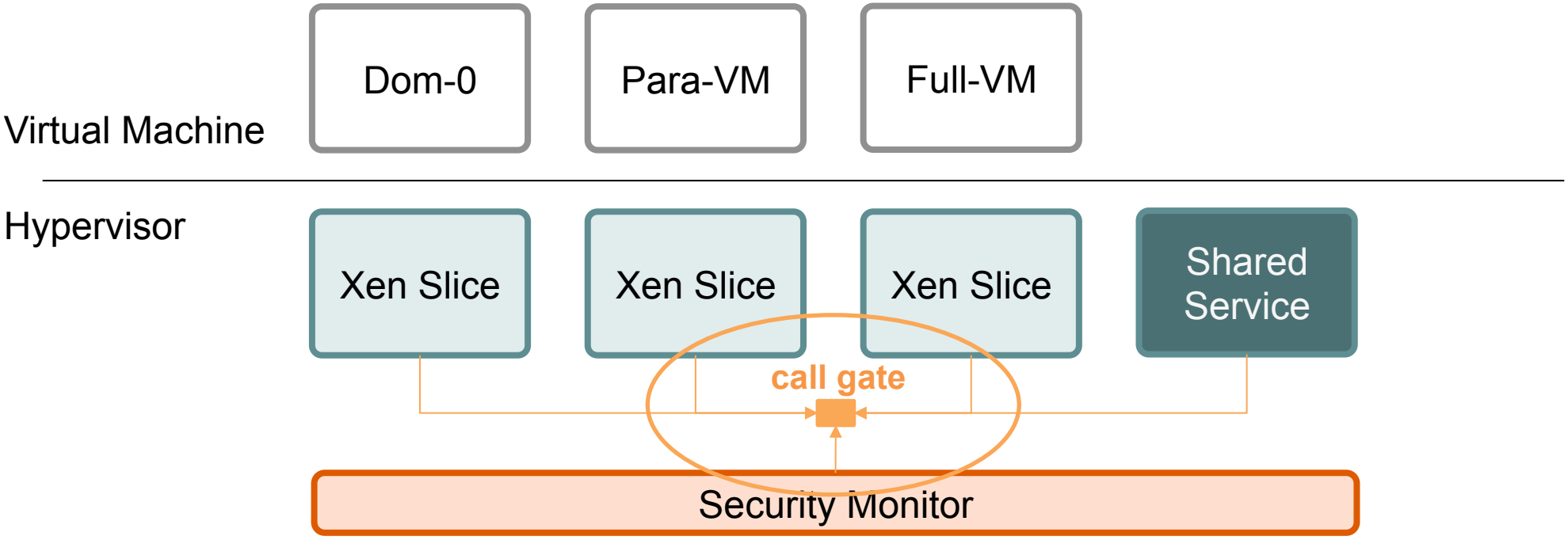
Protecting the Security Monitor

- MMU virtualization
  - Get higher software privilege in the same hardware privilege
  - Similar with the *nested-kernel* architecture [ASPLOS'16]
- Only the monitor can modify page tables
  - Page tables are mapped as read-only to other components
  - No page table operation instructions out of the monitor
  - Enforce security policies on each operation of page table
  - Bootstrap security: through Intel TXT or TPM

Same Memory, Different Views



Call Gate: Intercept Switches between Slices



Intercept switches between Xen slices & shared service, as well as VM & its Xen slice

Summary: What Nexen can/cannot Defend?

Malicious Component	Steal or tamper with VM's data	Host DoS	Guest DoS
VM (user)	N.A.	Considered	Considered
VM (kernel)	Not considered	Considered	N.A.
Other VM	Considered	Considered	Considered
Xen Slice	Considered	Considered	Not considered
Shared Service	Considered	Not considered	Not considered

Nexen cannot defend against attacks through legal interfaces (aka., Iago attack)

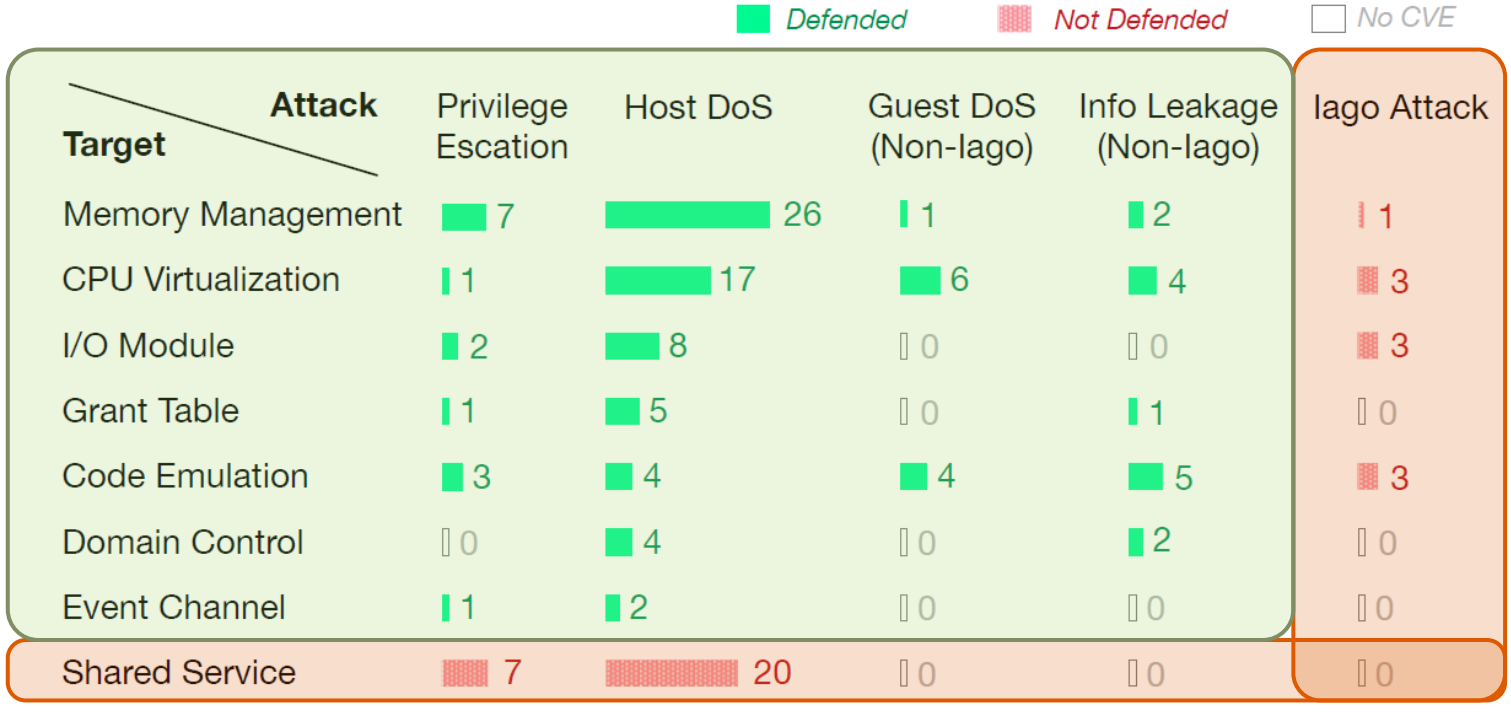
Security & Performance

EVALUATION

Security Evaluation on 144 XSAs

107/144 (74%): Defended

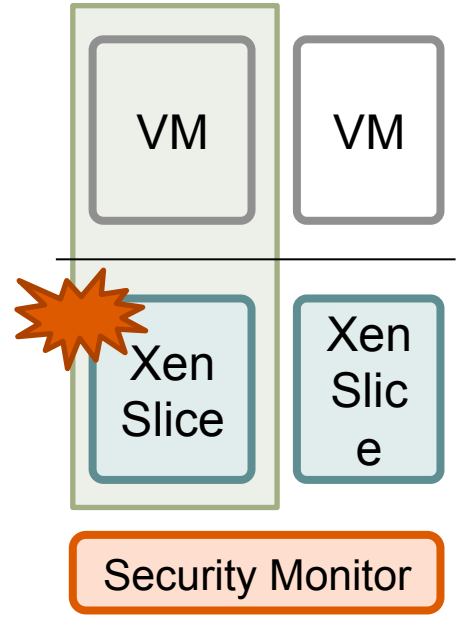
10/144 (7%): attack through interface, depends on semantic



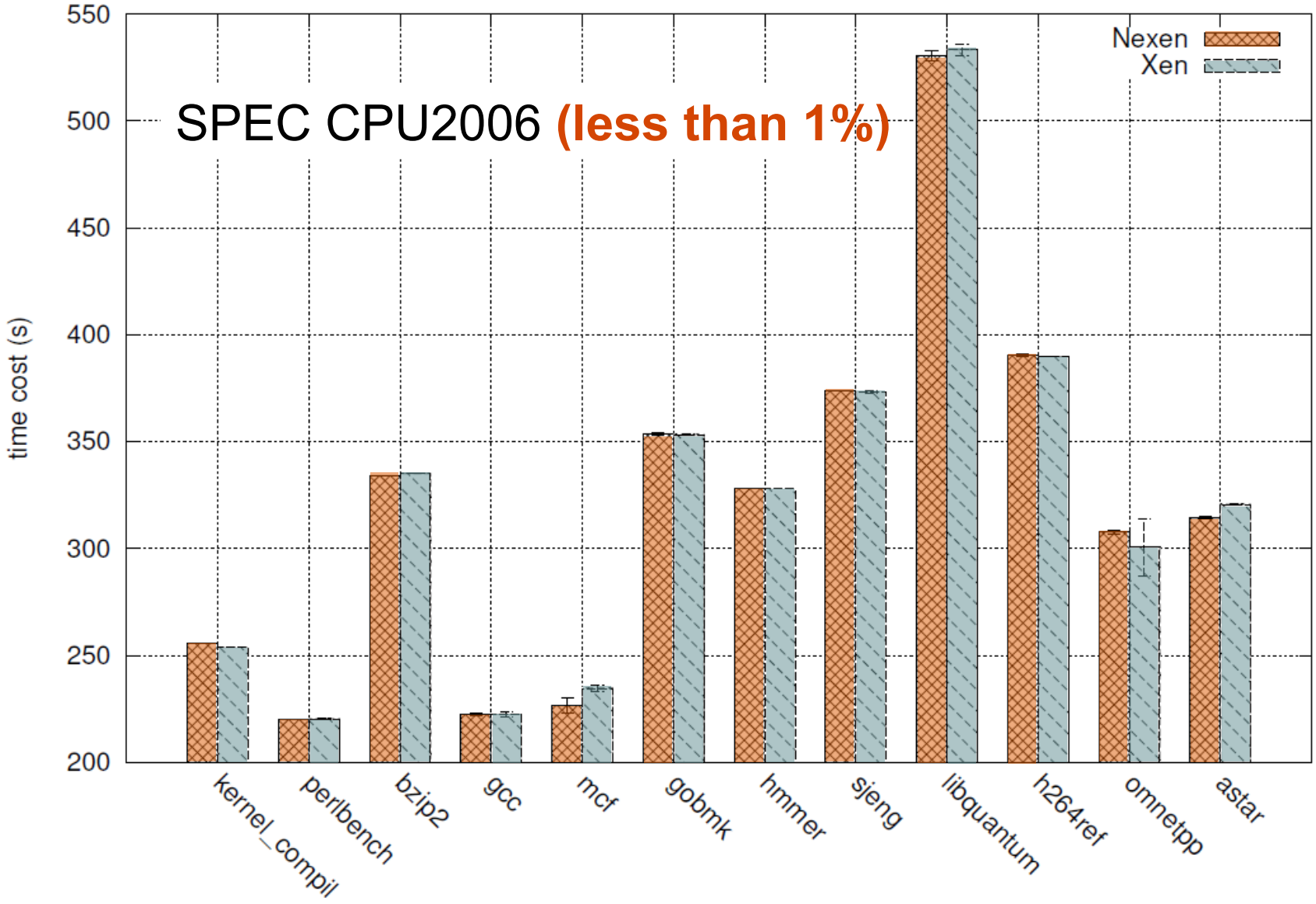
27/144 (19%): target the shared service and can cause host failure

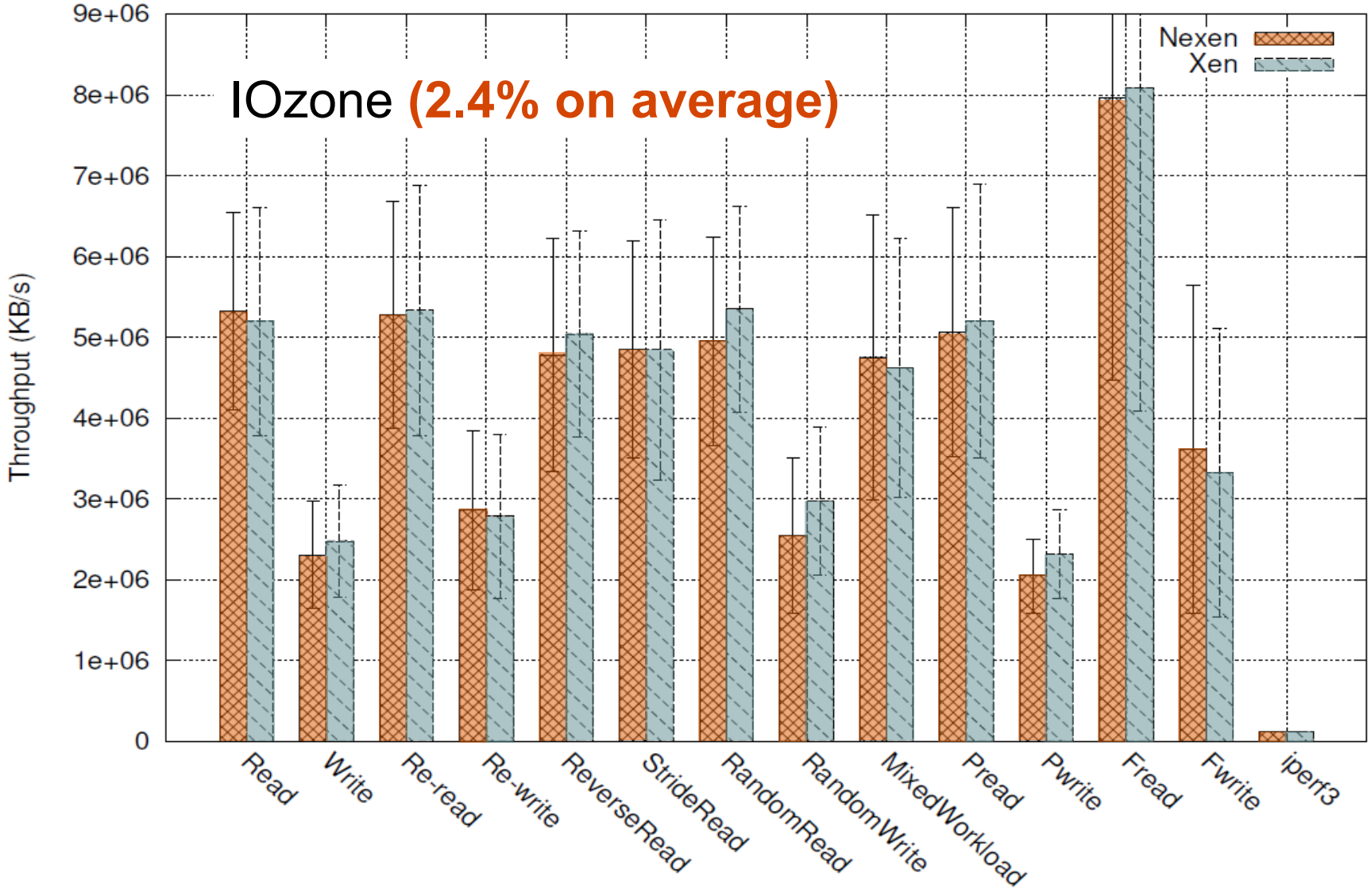
Case Study: XSA-108

- Type: Out-of-boundary mem access in code emulation causes info leak
- Description
  - Xen's code emulation for APIC erroneously emulates read and write permissions for 1024 MSRs where there are actually 256 MSRs. A read operation can go beyond the page set up and potentially get sensitive data from the hypervisor or other VMs

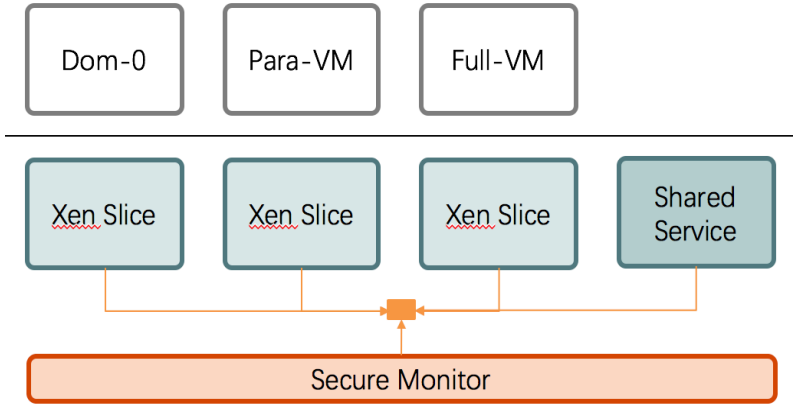



```
- case MSR_IA32_APICBASE_MSR ... MSR_IA32_APICBASE_MSR +
0x3ff: + case MSR_IA32_APICBASE_MSR ... MSR_IA32_APICBASE_MSR
+ 0xff:
```


SPEC CPU2006 (less than 1%)
Nexen
Xen
time cost (s)
550
500
450
400
350
300
250
200
kernel_compil
perlbench
bzip2
gcc
mcf
gobmk
hmmer
sjeng
libquantum
h264ref
omnetpp
astar


IOzone (2.4% on average)
Nexen
Xen
Throughput (KB/s)
9e+06
8e+06
7e+06
6e+06
5e+06
4e+06
3e+06
2e+06
1e+06
0
Read
Write
Re-read
Re-write
ReverseRead
StrideRead
RandomRead
RandomWrite
MixedWorkload
Pread
Pwrite
Fread
Fwrite
iperf3

Conclusion



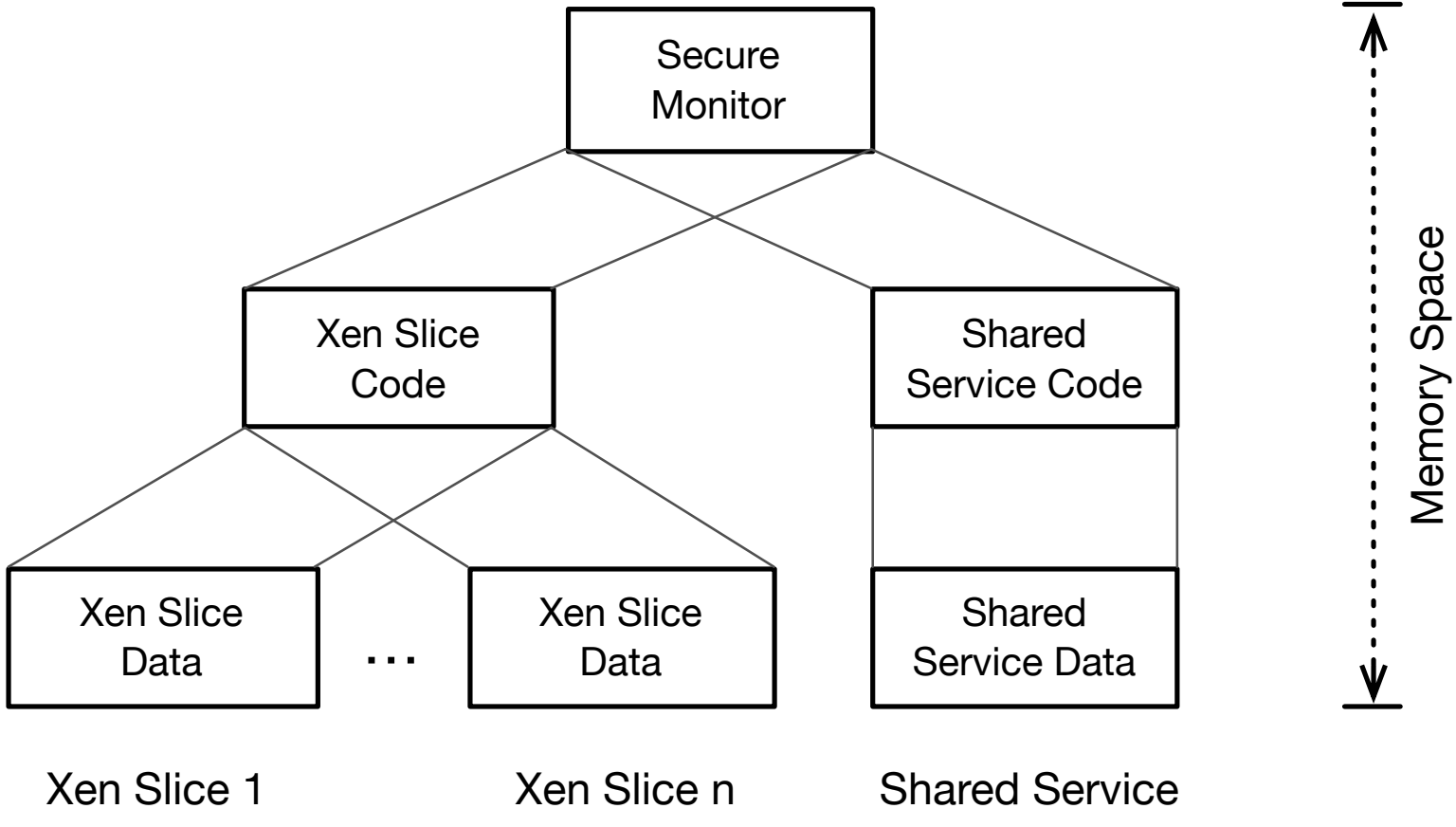
- Methodology of deconstruction
  - Analyze 201 Xen's vulnerabilities
  - Derive boundary of isolation from the result
  - Deconstructing system to internal domains and security monitor
- Nexen implementation
  - Deconstruct Xen to multiple *Xen slices* and one *shared service*
  - Using nested kernel design to protect the *security monitor*

- More info: *http://ipads.se.sjtu.edu.cn/xsa*

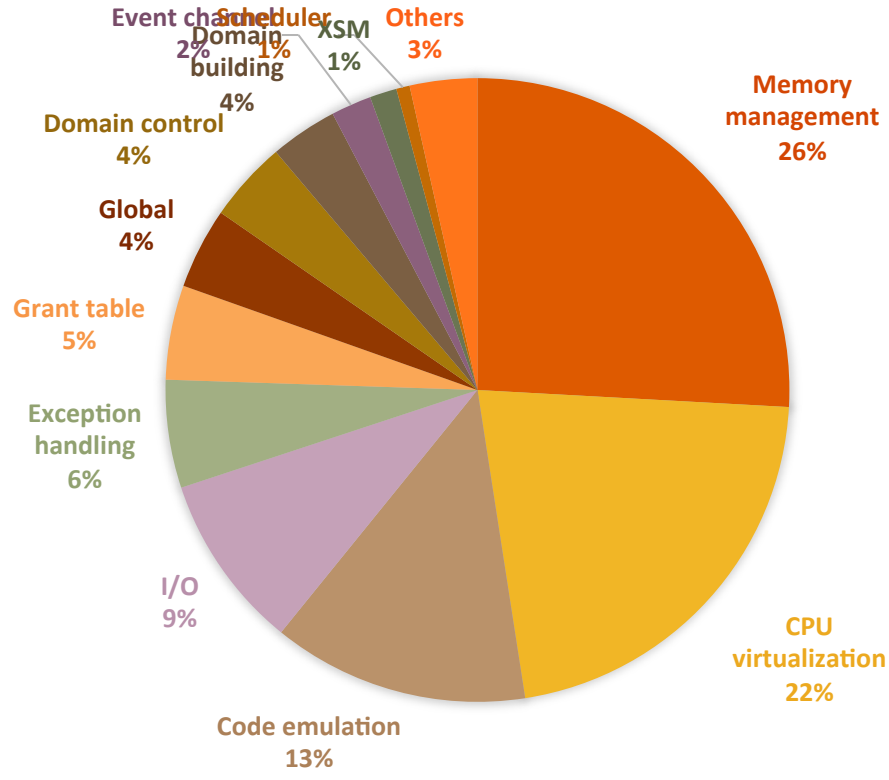
Thanks!

BACKUP SLIDES

Same Memory, Different Views

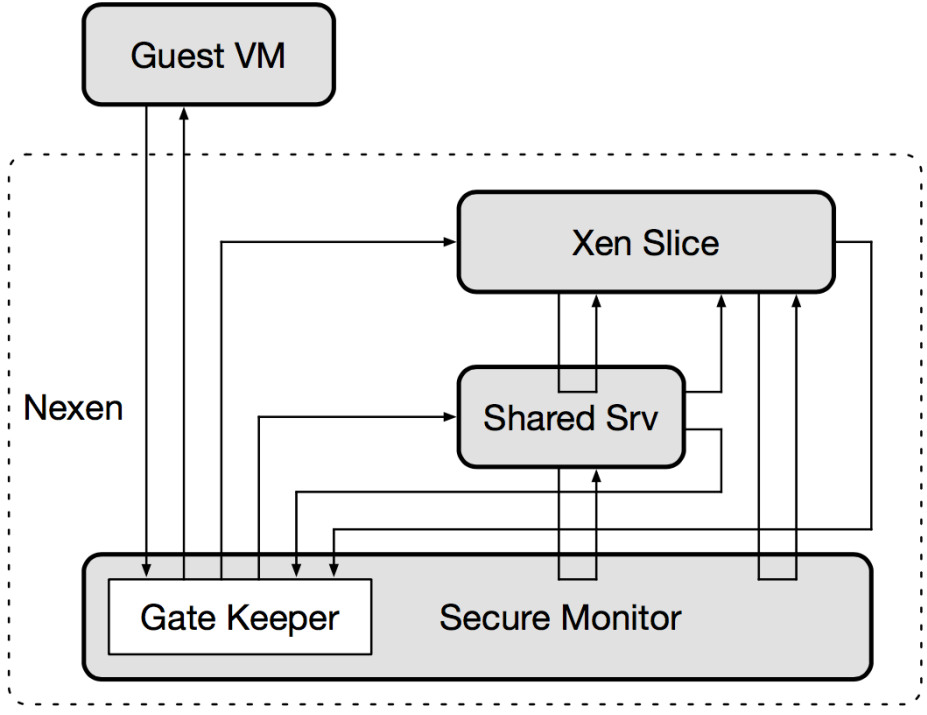


Target	Ratio
Memory management	25.69%
CPU virtualization	21.53%
Code emulation	13.19%
I/O	9.03%
Exception handling	5.56%
Grant table	4.86%
Global	4.17%
Domain control	4.17%
Domain building	3.47%
Event channel	2.08%
XSM	1.39%
Scheduler	0.69%
Others	3.47%



The Control Flow

- Gate keeper in the monitor
  - Switch between memory spaces
- Intercept transferring between:
  - Guest VM & Hypervisor
  - Xen slice & shared service
- Complete mediation
  - Cannot be bypassed



Case Study: XSA-191

- Type
  - Misuse of H/W feature in code emulation causes privilege escalation to guest kernel
- Description
  - Intel hardware uses NULL segment selectors to prevent access. Xen code emulator fails to check this condition and may erroneously permit invalid access. An unprivileged guest user program may be able to elevate its privilege to that of the guest operating system

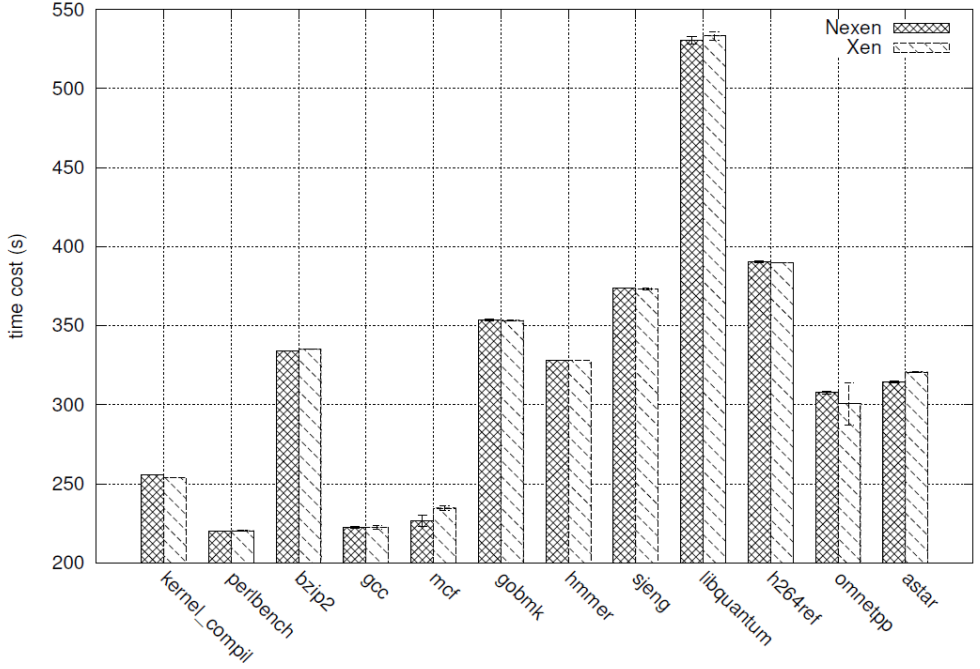
Case Study: XSA-191

- How to trigger?
  1. try to set kernel data segment selector to NULL
  2. trigger an instruction that requires emulation, the side effect of which changes an entry of kernel page table
  3. the instruction emulated, changing the page table entry, giving the user program access to some kernel data

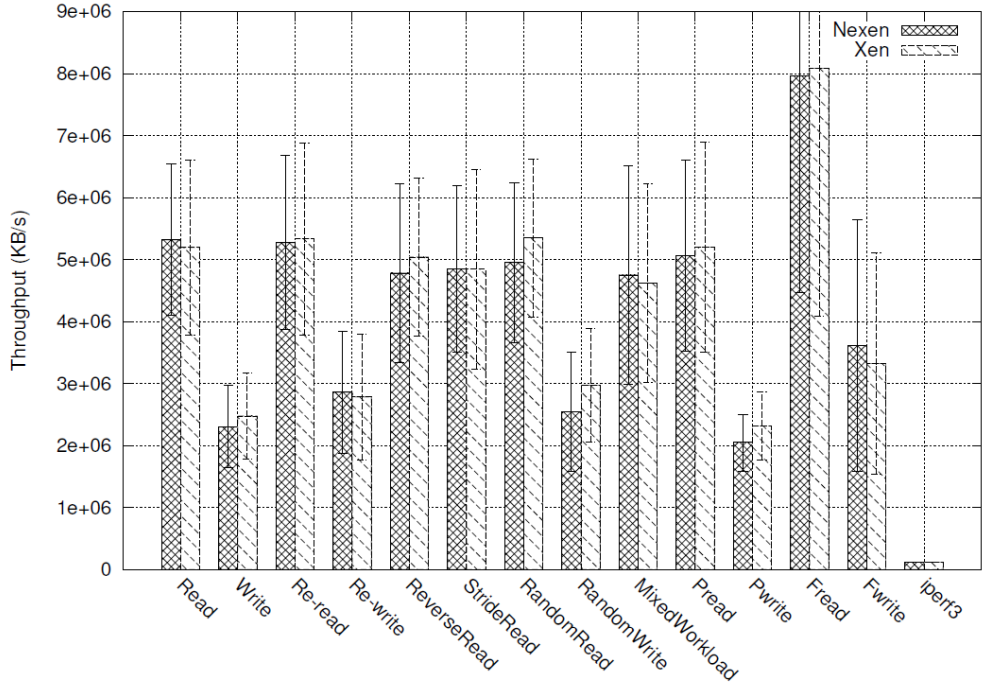
Case Study: XSA-191

- Why cannot defend?
  - Not harming other VMs: the process completely finish in code emulator of one VM
  - Iago attack: logic error of code emulator

Performance Evaluation: Negligible Overhead



SPEC CPU2006 (less than 1%)



IOzone (2.4% on average)

Case Study: XSA-83

- Type
  - Memory corruption in shared service causes privilege escalation
- Description
  - Out-of-memory condition yielding memory corruption during IRQ setup. When setting up the IRQ for a passed through physical device, a flaw in the error handling could result in a memory allocation being used after it is freed, and then freed a second time

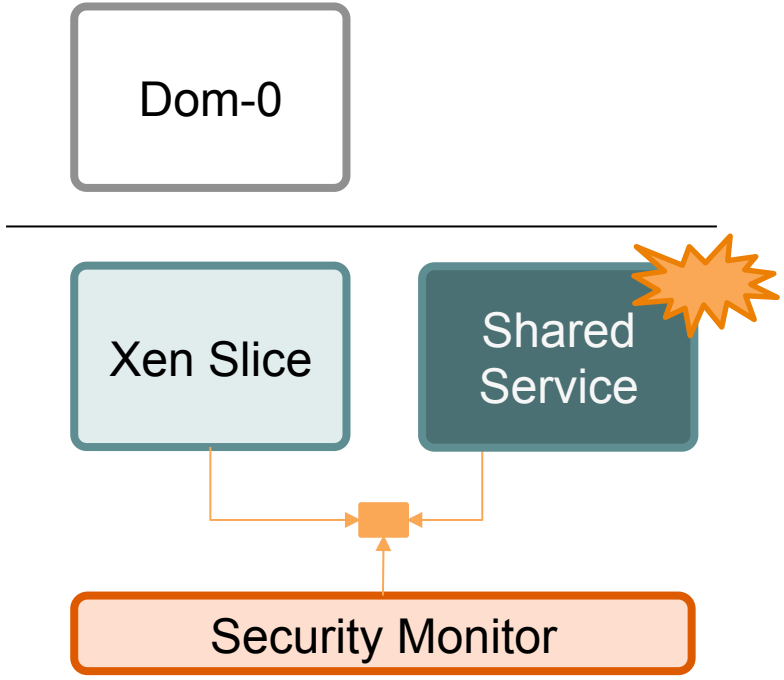
Case Study: XSA-83

- Patch

```
@@ -1590,8 +1590,7 @@ int pirq_guest_bind(struct vcpu *v, stru
          printk(XENLOG_G_INFO
                 "Cannot bind IRQ%d to dom%d. Out of memory.\n",
                 pirq->pirq, v->domain->domain_id);
-         rc = -ENOMEM;
-         goto out;
+         return -ENOMEM;
      }
```

Case Study: XSA-83

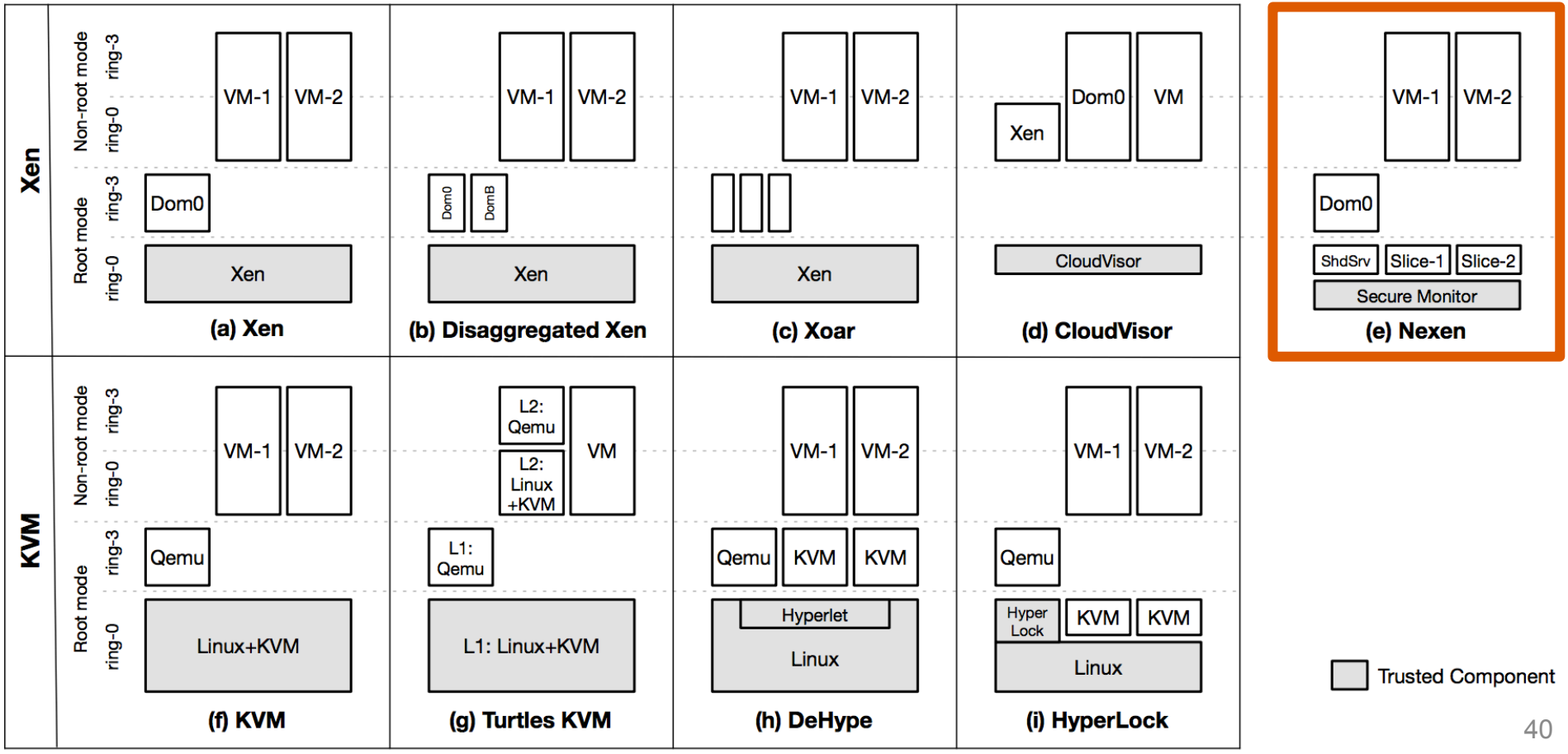
- Why cannot Nexen defend?
  - Since the shared service is critical in Nexen, exploiting a bug in this part will allow the attacker to do almost anything destructive towards the whole system
  - VM's data are still protected



Comparing with Related Work

	Hypervisor illegally accesses guest's data	Guest causes host DoS	Guest apps attack its own VM by hypervisor
Disaggregated Xen	No	No	No
Xoar	No	No	No
Turtles KVM	No	Yes	No
DeHype	No	Yes	No
HyperLock	No	Yes	No
CloudVisor	Yes	No	Yes
Nexen	Yes	Yes	Yes

Comparing with Related Work



Internal Domain API

- Domains interaction
  - Create a Xen slice
  - Allocate protected memory to a Xen slice
  - Specify policy for a piece of memory

Case Study: XSA-111

- Type
  - False BUG_ON in CPU virtualization causes host DoS
- Description
  - A piece of hypercall parameter translation code assumes that only the lower 32 bits of a 64-bit register variable are used, violation of which will trigger a BUG_ON that kills the hypervisor

Case Study: XSA-111

- How to trigger?
  - This condition can be deliberately violated by an HVM guest by temporarily changing to 64-bit mode and passing an invalid 64-bit parameter

```
int hypercall_xlat_continuation(unsigned int
*id, unsigned int nr, unsigned int mask, ...) {
    ...
     regs = guest_cpu_user_regs();
     ...
    BUG_ON(*reg != (unsigned int)*reg);
}
```

Case Study: XSA-111

- How to defend?
  - In Nexen, the vulnerable code runs in the context of a Xen slice
  - The modified BUG_ON logic will only kill current Xen slice VM when it is triggered