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Seeing Through the Same Lens: Introspecting Guest Address Space at Native Speed

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Outline

- Problem
- Design
- Implementation
- Evaluations

Problem

- Considering introspecting kernel objects
  - Untrusted live VM
  - VMI tool running outside of the VM
- The VMI tool and the target objects are in different address spaces.
- The VMI tool needs to perform a sequence of operations for every kernel object access.

Problem

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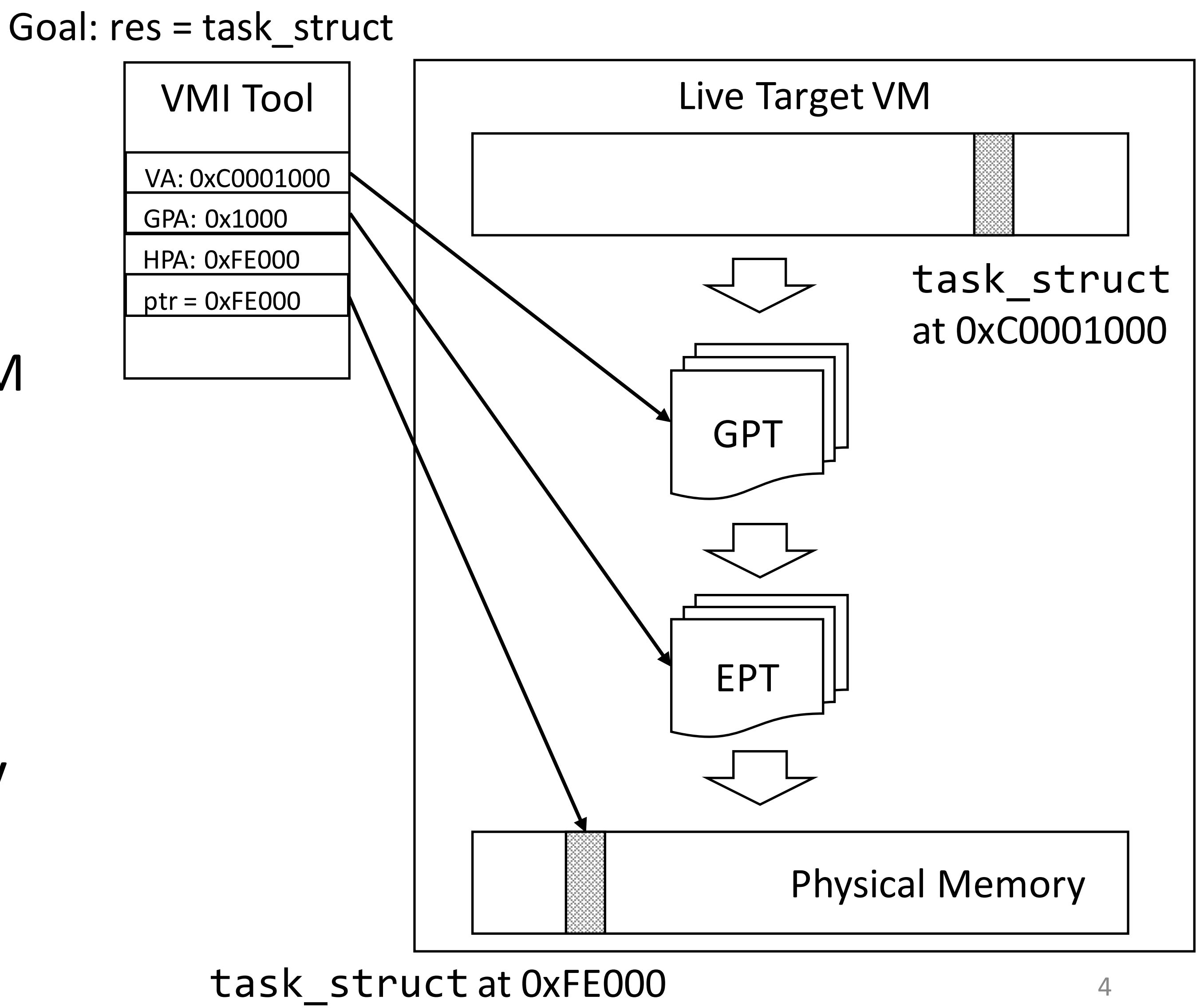
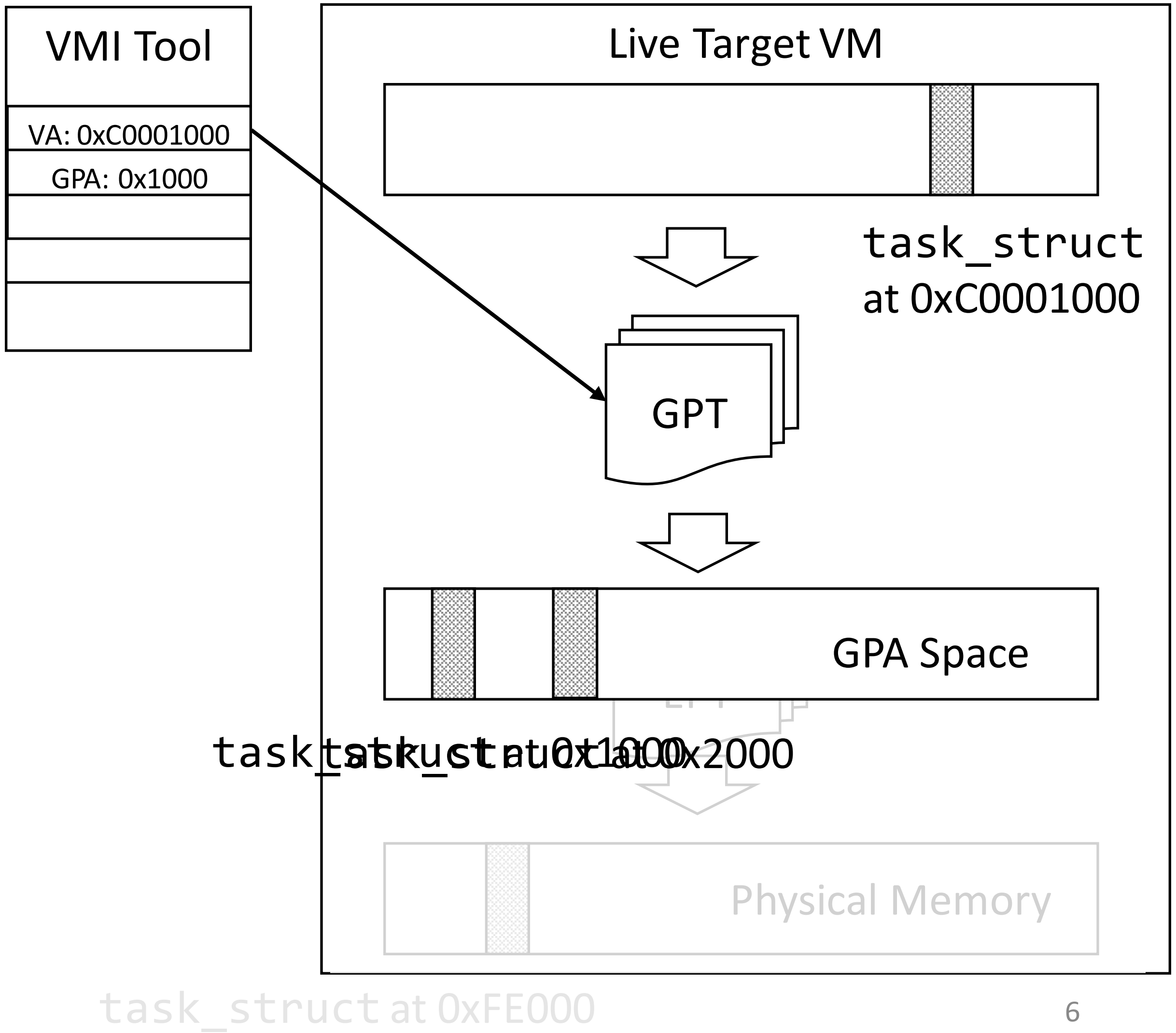


Inadequacy of Page Table Walk

- Page table walk lies at the heart of VMI
- Slow, compared to native address translation by MMU
  - A number of loads from memory
- An experiment to evaluate the slowness of software based page table walk
  - Periodically modifies one `task->cred` pointer
  - Closely monitor the value of the pointer by repeatedly reading it from outside
  - Cannot catch up with frequent transient guest state changes

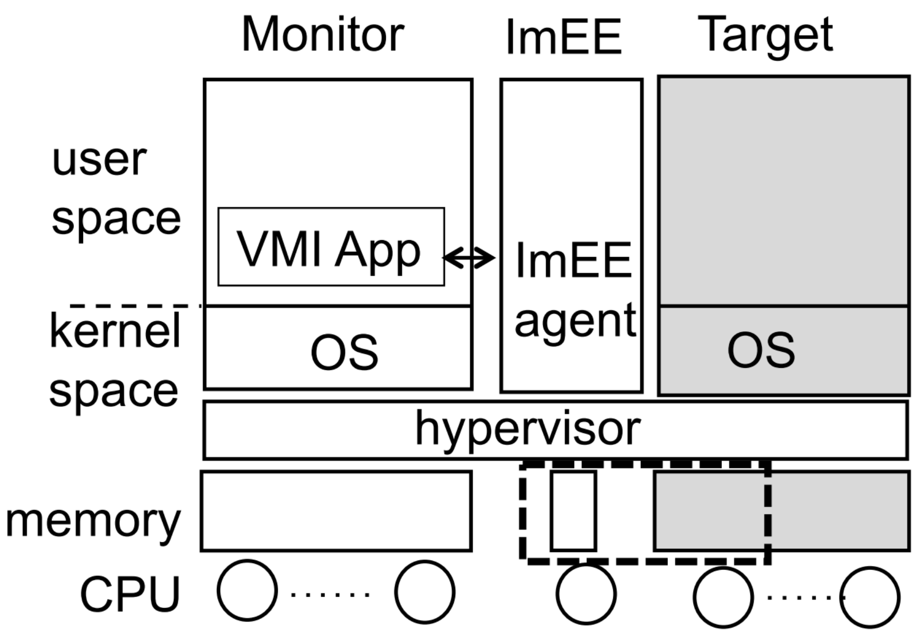
Inadequacy of Page Table Walk

- Mapping consistency with the target is not maintained
  - Uses any mappings: ample room for the guest to present false mappings
  - The target VM may also make transient changes to the page table
  - Caching techniques that aim to enhance efficiency further deteriorate the situation, giving up consistency for efficiency.



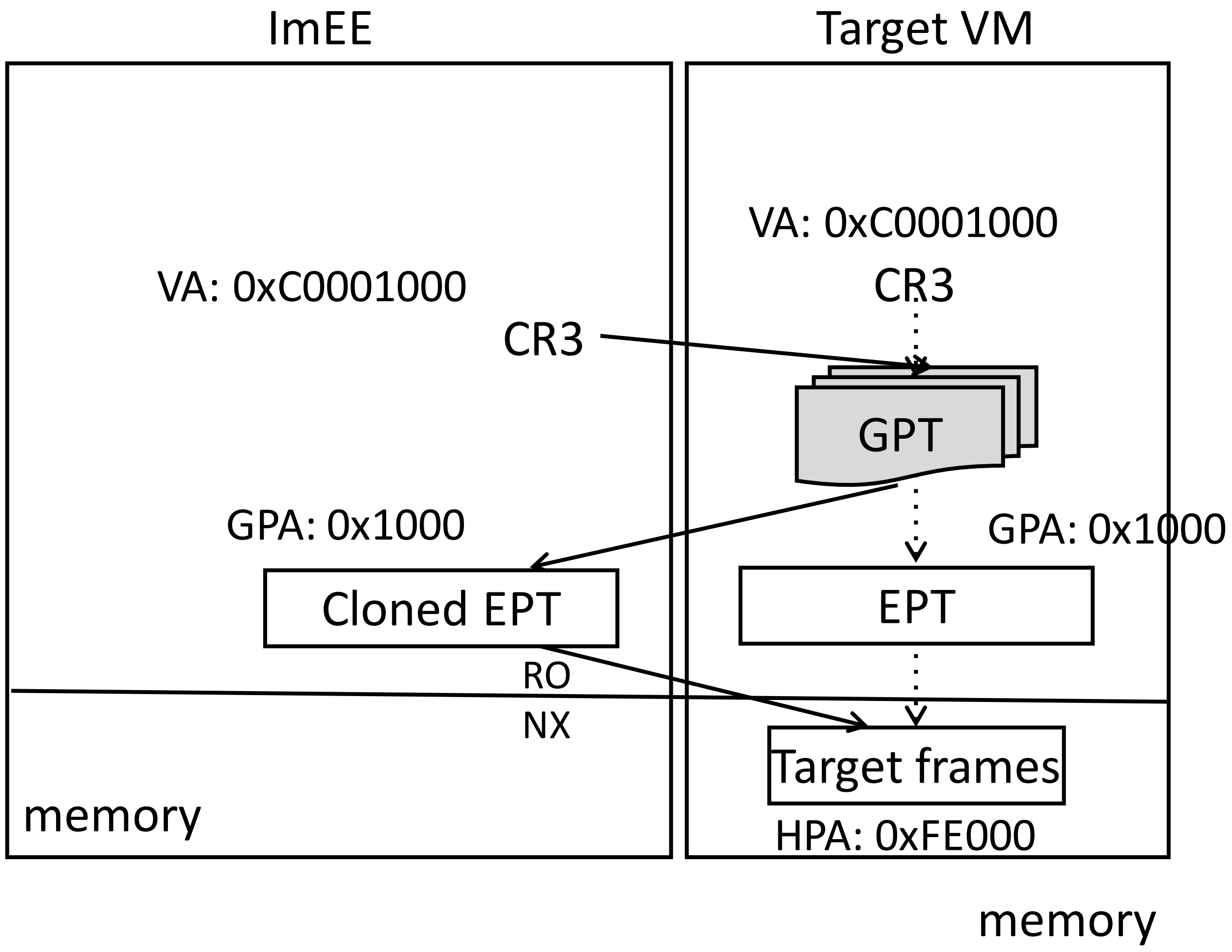
Immersive Execution Environment (ImEE) Architecture

- ImEE is essentially a special VM created on-demand by VMI applications.
- Scheduled by the hypervisor
- Consists of only a vCPU and a small amount of memory: code and data
- ImEE hosts a piece of code called *ImEE agent* that actually performs introspection
- ImEE acts as a memory access engine for VMI applications
  - Only perform memory read
  - Native speed read
  - Page table is consistent with target at any moment



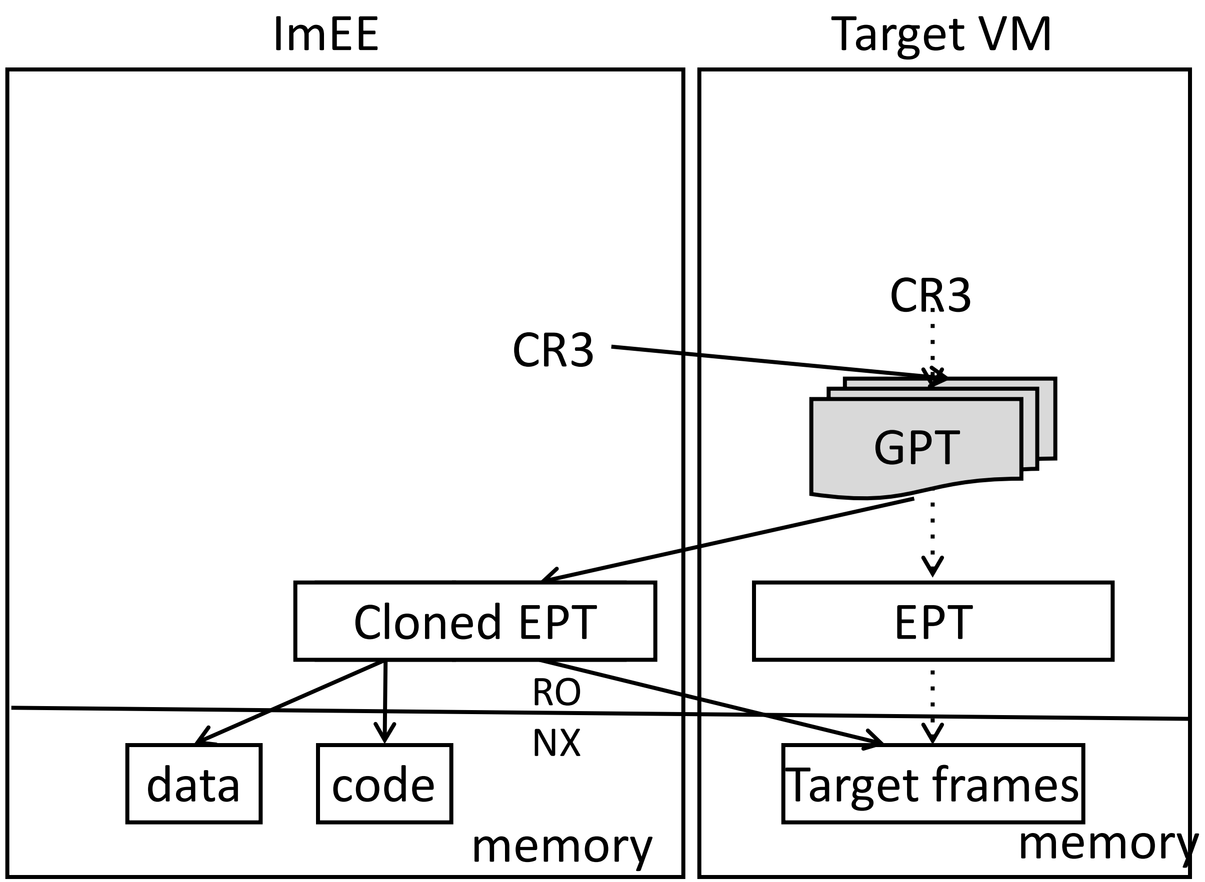
Basic Idea

- An environment with a twisted address mappings
  - Cloned CR3 content
  - Cloned EPT, with mappings from target EPT and restricted permission
- The result: a VA is translated to the same HPA by the MMU in both environments



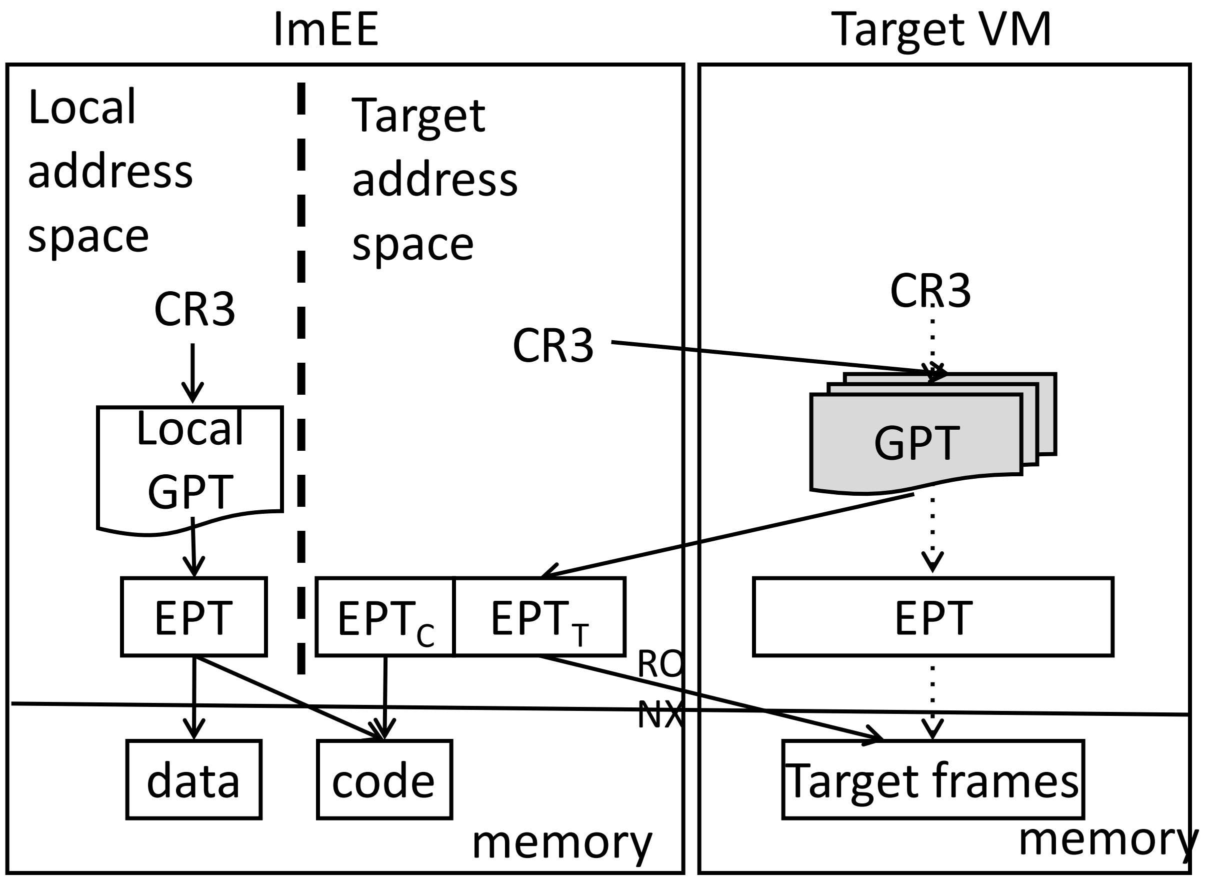
Making it work

- Implementation issues:
  - Need room in the virtual address space for
    - our own code
    - exchanging data with VMI tool
  - We want to avoid touching GPT
- What about the number of redirected pages?



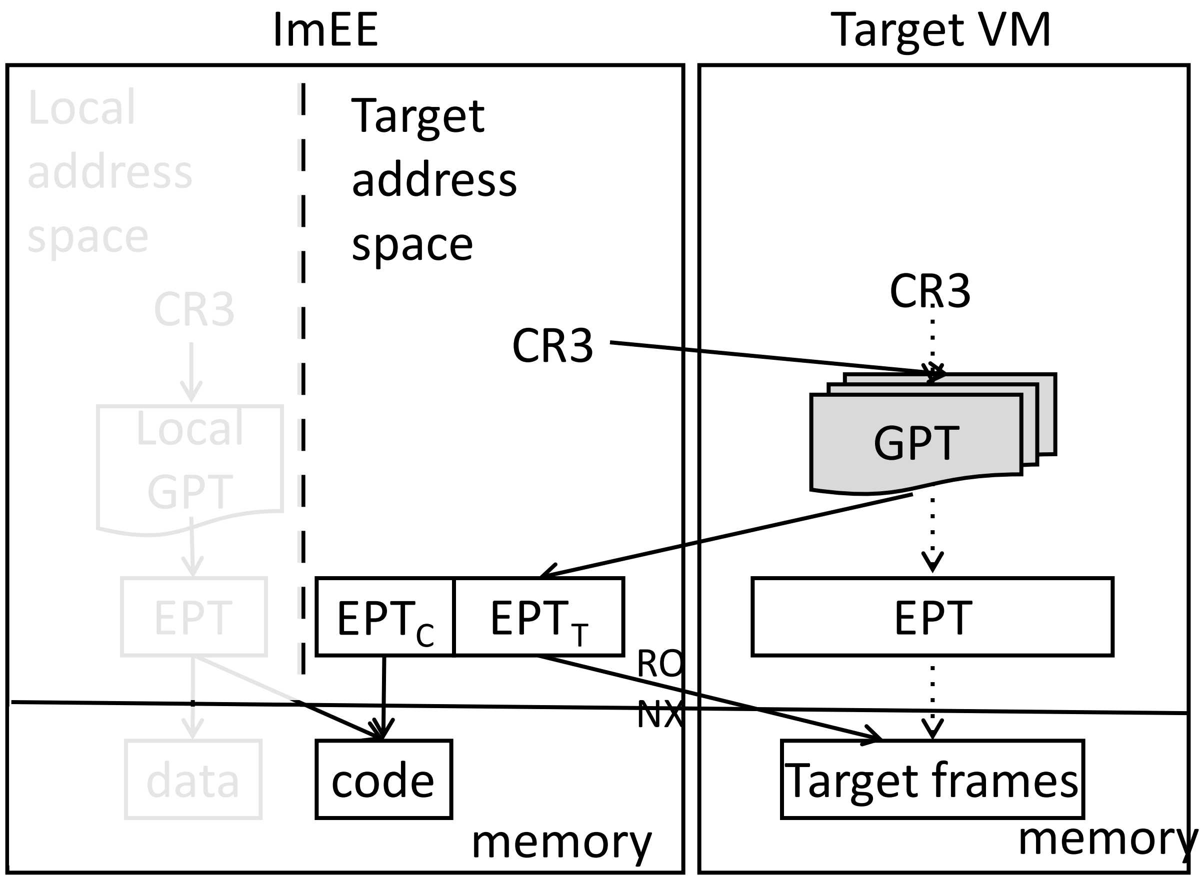
Immersive Execution Environment (ImEE)

- Two address spaces in the ImEE
- Local address space is for the ImEE agent to interact with the VMI application
- The idea 'incarnates' as the target address space in ImEE.
- Introspection is only performed in the target address space



Target Address Space

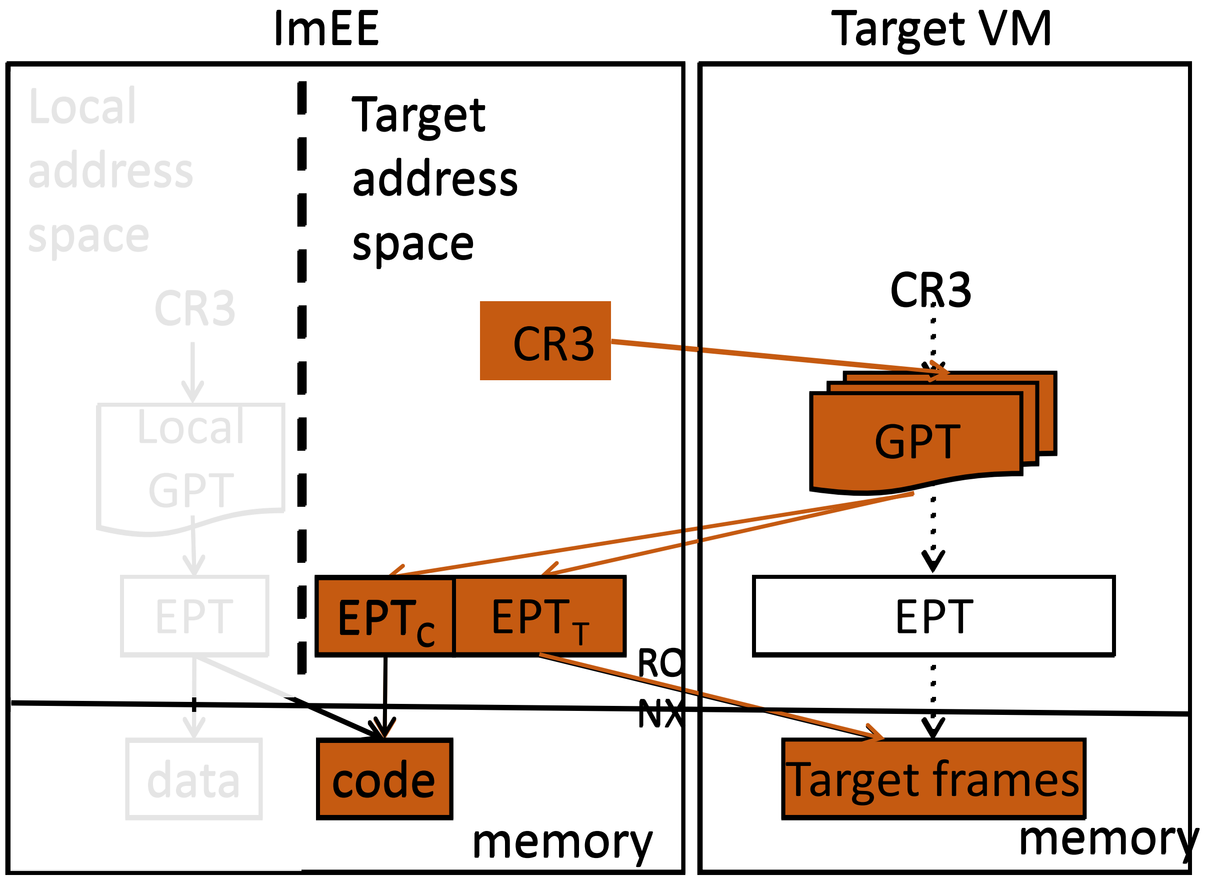
- GPA space is split by the EPT
  - All address mappings are the same as in the target VM, with read-only permission
  - One page is redirected by EPT to the agent's code page, with execute-only permission
- Two possible kinds of translation in the target address space:
  - Instruction fetch
  - Memory read



Target Address Space

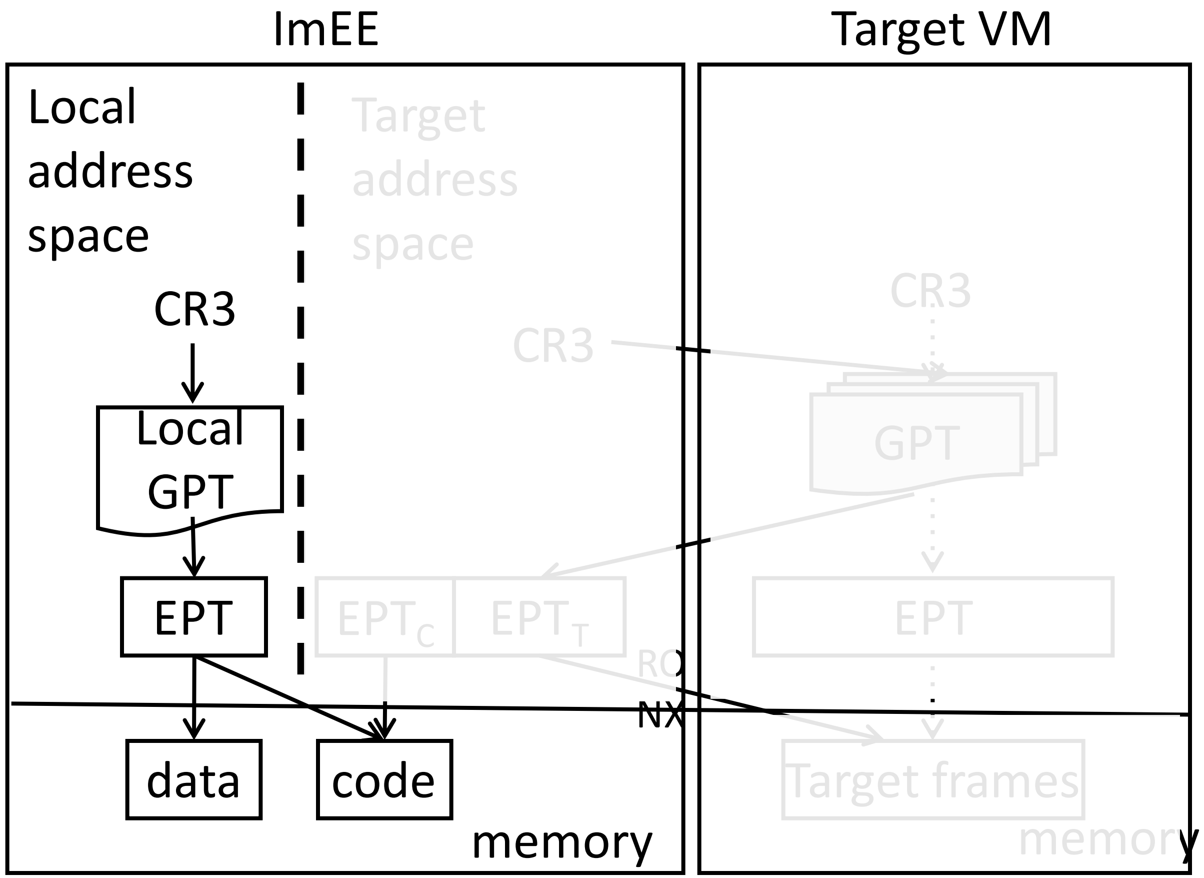
- Example:

0xBFF0: mov (0x1000), %eax



Local Address Space

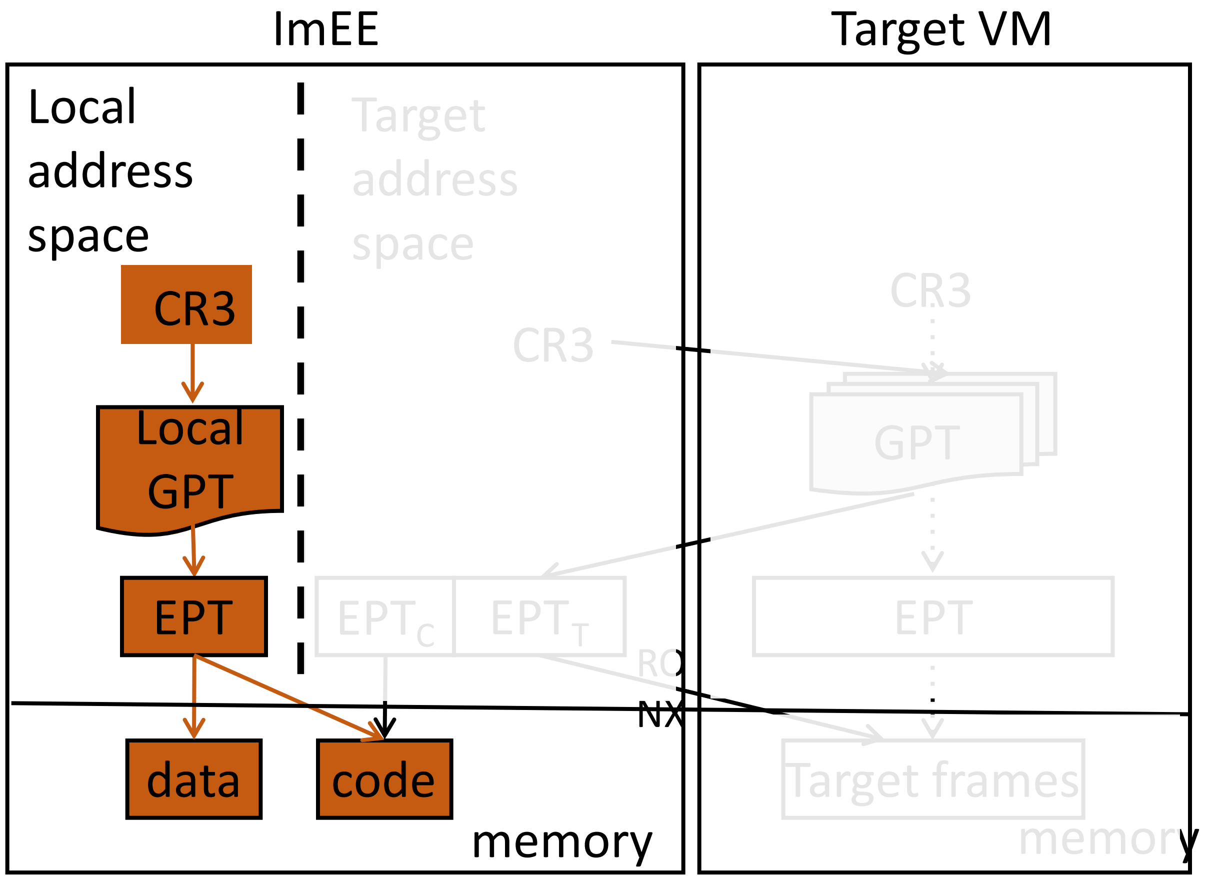
- Minimizes the number of redirected page in the target address space
- Only two pages are mapped
  - All pages except one are mapped to code
  - The remaining one is mapped to data
  - Allowing the agent to be executed almost anywhere, because we do not know the load address beforehand



Local Address Spaces

- Example:

0xBFFA: mov %eax, (0x2000)



The ImEE Agent

- The ImEE agent is the only code that runs inside ImEE
  - Reside within one page, self-contained
  - Position independent
  - Granted ring 0 privilege
- Initially, the agent is loaded at a page whose VA is mapped as executable in the guest page tables.
  - The hypervisor uses the page that the current IP points to

The ImEE Agent

- The agent's execution straddles between the two address spaces.
- Simplified pseudo-code:

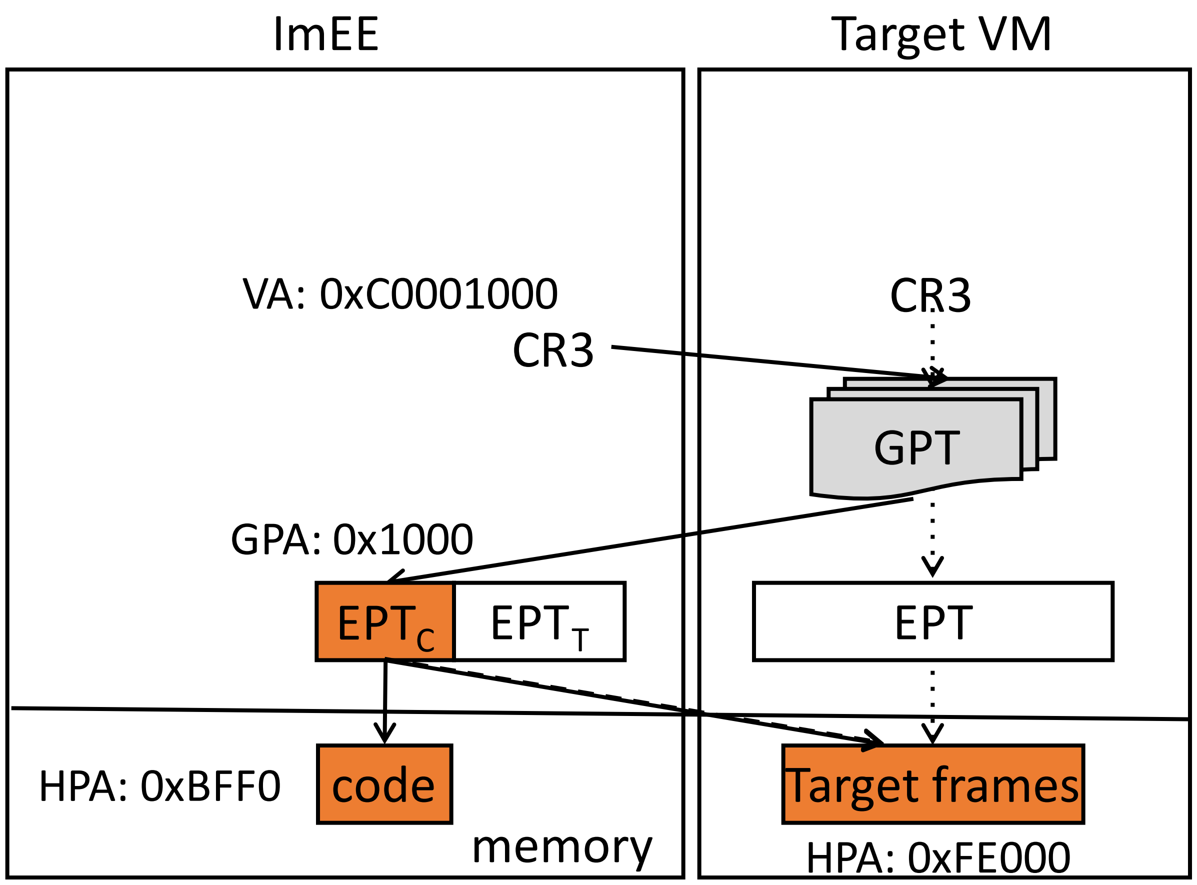
```
1.  eax = data[request]
2.  cr3 = target_cr3   /* switch to target address space */

3.  xmm0 = *eax
4.  cr3 = imee_cr3    /* switch to local address space */

5.  data[result] = xmm0
```

Other Issues

- Blind spot
  - The code page in the target GPA space is redirected
  - Any virtual address mapped to this GPA cannot be read
- Cannot be eliminated
- Only detected when introspection is on the blind spot
  - Relying on EPT mappings
  - Relocate agent once detected



Advantages

- Native speed
  - Address translation is performed at native speed by hardware.
- Consistency
  - Page table used is kept consistent with the current one in the target.
  - CR3 is synchronized

Implementation

- We implemented a prototype of ImEE
  - Hypervisor changes: modified KVM module
  - Consists of around 1400 SLOC
  - Two new IOCTLs as interface to user space
  - Optimized code path that handles ImEE specific VM exit
  - Agent: specially crafted assembly code
    - Within one page, a few tens of instructions
    - Position independent
    - One data page for exchange data with VMI tool

Evaluation

- We use LibVMI as the base line.
  - LibVMI: the only open source tool
  - Serves as building block for various other tools such as Volatility
- Experiment setup:
  - Hardware: Intel Core i7-2600, 4GB DDR3 RAM
  - Guest VM: 1GB RAM and one vCPU

Evaluation

- ImEE Overhead
  - Launch time: time taken for the hypervisor to prepare relevant data such as the EPT
  - Activation time: time for a launched, but not running, ImEE to begin execute the agent code

	ImEE	LibVMI	Speedup
Launch time	97 µs	100 ms	**1031 times**
Activation time	3.2 µs	-	

Evaluation

- Guest access speed
  - We measure the time take to read a number of bytes from the target
  - LibVMI's translation cache is on, data cache off

# of Bytes	ImEE	LibVMI (µs)	Speedup
4	0.353	18.4	**52 times**
64	0.358	18.5	**52 times**
128	0.389	18.4	**47 times**
512	1.643	18.9	**11 times**
1024	1.715	38.1	**22 times**

Tools

- `syscalldmp`: dumps totally 351 entries of the guest's system call table
- `pidlist`: lists all process identifiers in the guest.
- `pslist`: lists all tasks' identifiers and task names stored in task struct.
- `credlist`: lists all tasks' credential structures referenced by the task struct's cred pointer.

Evaluation

- We ran our four tools in four setups: ImEE, kernel, LibVMI on KVM and LibVMI on Xen
- Measure time taken to complete the task
- Results:
  - Comparable to kernel
  - Significant speedup compared to LibVMI

	Kernel (µs)	LibVMI / KVM (µs)	LibVMI / Xen (µs)	ImEE (µs)	Speedup (KVM)	Speedup (Xen)
syscalldmp	0.2	28.2	43	2.9	**9 times**	**15 times**
pidlist	10	5887	2180	31.6	**186 times**	**68 times**
pslist	10.4	8319	1477	38.6	**215 times**	**38 times**
credlist	25.3	8234	2274	25.6	**321 times**	**88 times**

Evaluation

- Scanning multiple VMs
  - We setup four VMs and measure:
    - Time to scan every VM
    - Time to switch scan target
  - Results:

	LibVMI	ImEE	Speedup
Scanning all VMs	561 ms	377 µs	**1400 times**
Switching target VM	19 ms	4.4 µs	**4300 times**

Conclusion

- ImEE is a novel memory access engine for out-of-VM introspeciton applications for live VM.
- Based on hardware virtualization, ImEE shows remarkable speed up compared to existing approaches.
- ImEE maintains mapping consistency during introspection. Complemented by its high speed, ImEE is suitable for security sensitive VMI applications.

Questions?