EPK: Scalable and Efficient Memory Protection Keys

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Memory Protection Key (MPK)

- **A hardware feature for intra-process memory isolation**
  - It has been introduced into Intel CPUs since 2019

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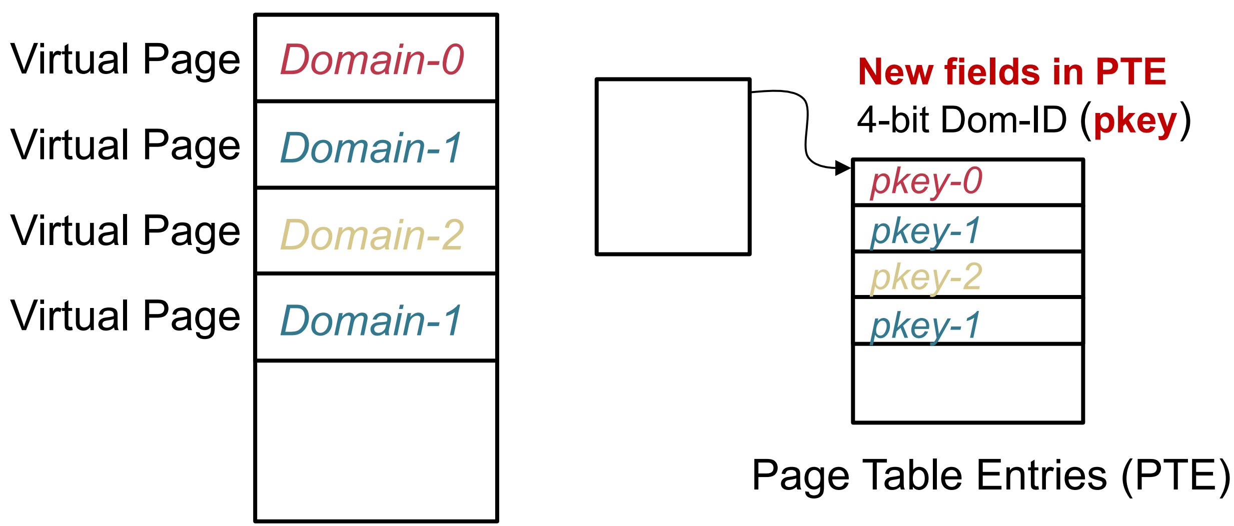
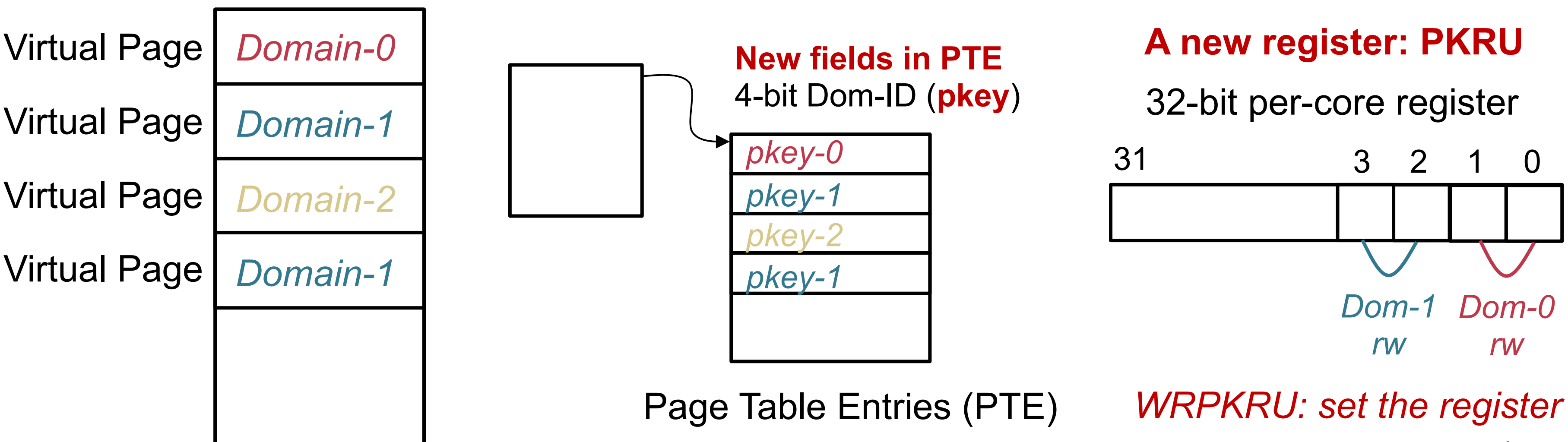


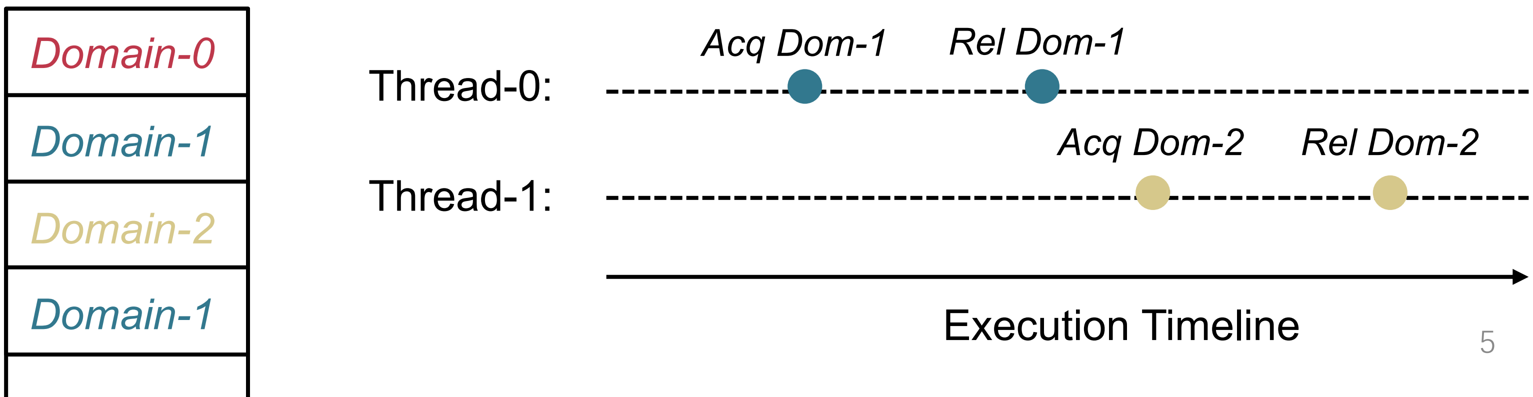
Memory Protection Key (MPK)

- **A hardware feature for intra-process memory isolation**
  - Partition different memory domains within one address space
  - Allow different threads have different memory views



Common Usage Model

- Create memory domains for separating the memory data
- A thread acquires/releases the access permission of one specific domain before/after accessing the data in it
- Acquire/release the domain access permission is efficiently achieved in the user mode (domain switching)

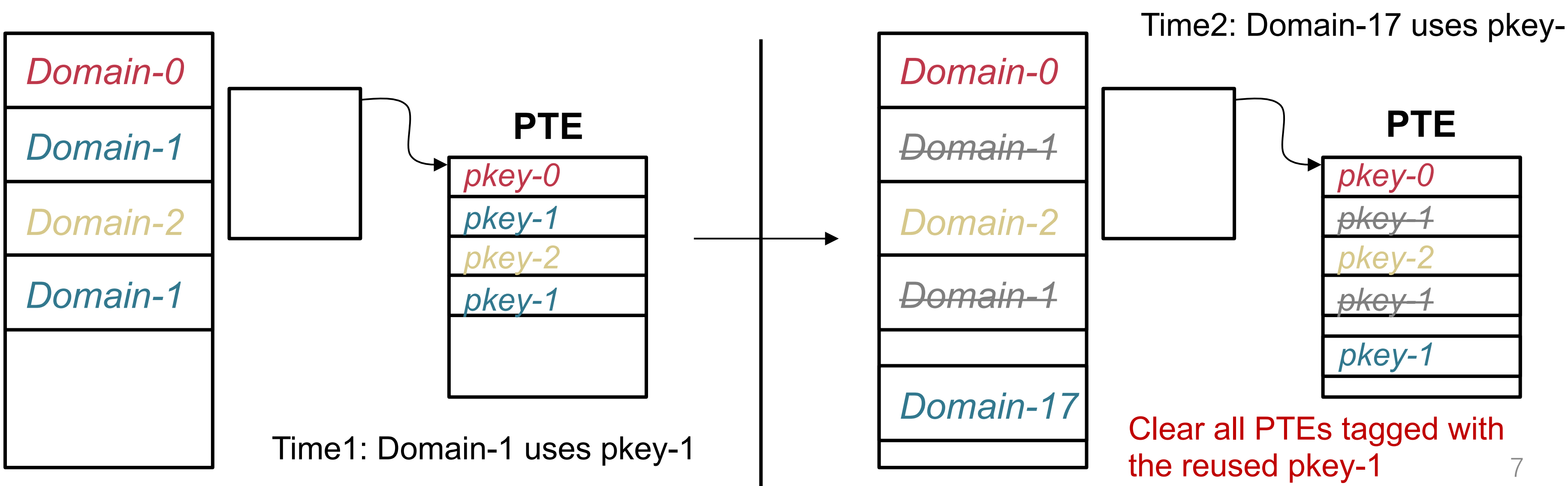


The Limitation of MPK

- **Contradiction**
  - Small (16) MPK domain number vs. Scalable domain requirements
- 😒 **Introduce isolation among different clients**
  - The client number is usually far more than 16
- 😒 **Introduce isolation to persistent memory data**
  - More domains can benefit stray access protection
- 😒 **Introduce isolation to more mutual-distrust modules**
  - Both applications and system software may contain more than 16 components that need to be isolated

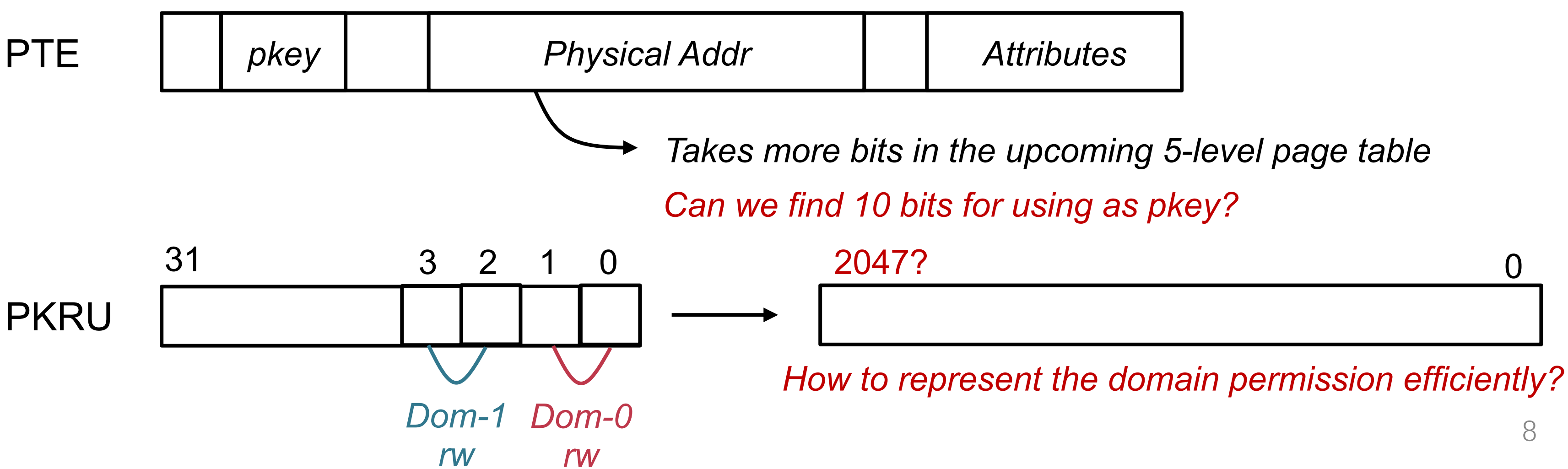
Candidate Solution 1

- **Solution-1: Resource time-division multiplexing**
  - Letting different domains use the same pkey at different times
  - **Performance issue**: Domain switching requires modifying page table entries and TLB flushing



Candidate Solution 2

- **Solution-2: Using 10 bits in the PTE as the pkey field**
  - 10 bits pkey can offer 1,024 memory domains
  - **Compatibility issue**: Non-achievable in existing CPUs; significantly reduce the usable bits in the PTE; PKRU register



Our Idea: EPK

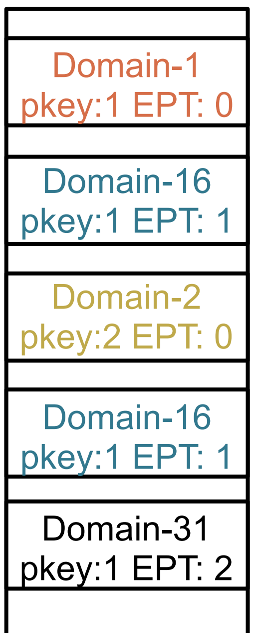
- **Design goals**
  - 😊 Scalable number of memory domains
  - 😊 No hardware modifications
  - 😊 Low performance overhead (support scalable memory domain size)
- **Observation**
  - MPK and VMFUNC share similarities in decoupling privilege-mode management and non-privilege-mode fast switching
- **Idea**
  - Reuse the same pkey in different extended page tables (EPT)
  - EPK: Extended Protection Keys

A Quick Intro of VMFUNC

- **EPT: Extended Page Table**
  - Map guest physical addresses (GPA) to host physical addresses (HPA)
  - Managed by the hypervisor
- **VMFUNC: A hardware virtualization extension**
  - VM functions: EPT switching in the VM
  - Load one EPT from a list of 512 EPTs configured by the hypervisor
  - No TLB flushing is needed when executing VMFUNC

Basic Design of EPK

- **Use the extended protection key as the domain ID**
  - Domain ID: EPT-index (0-511) + pkey (1-15)



Process Virtual Address Space

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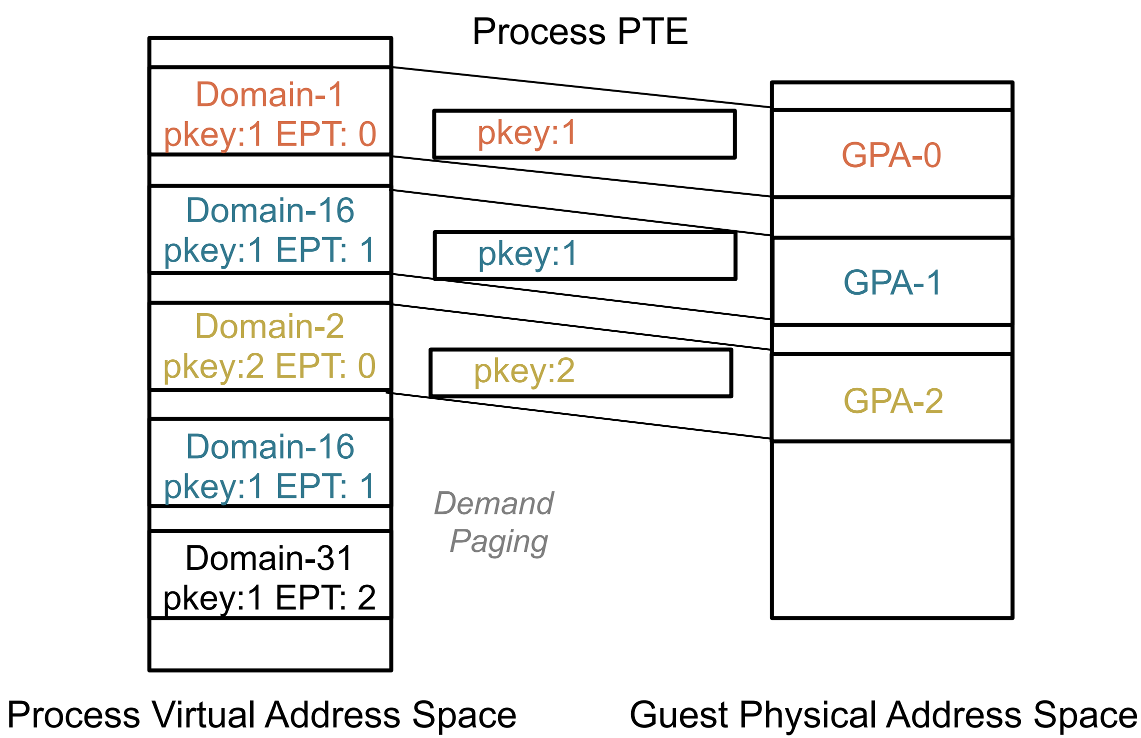

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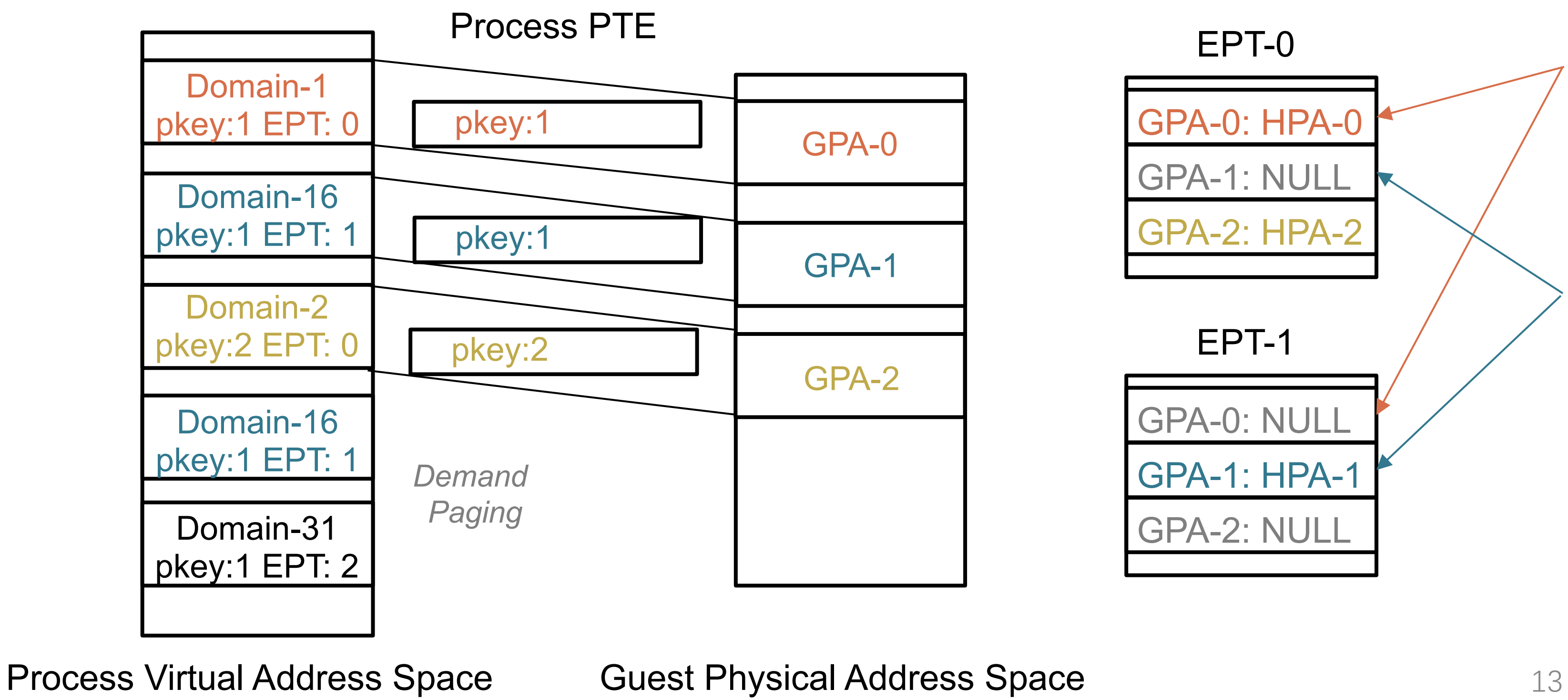

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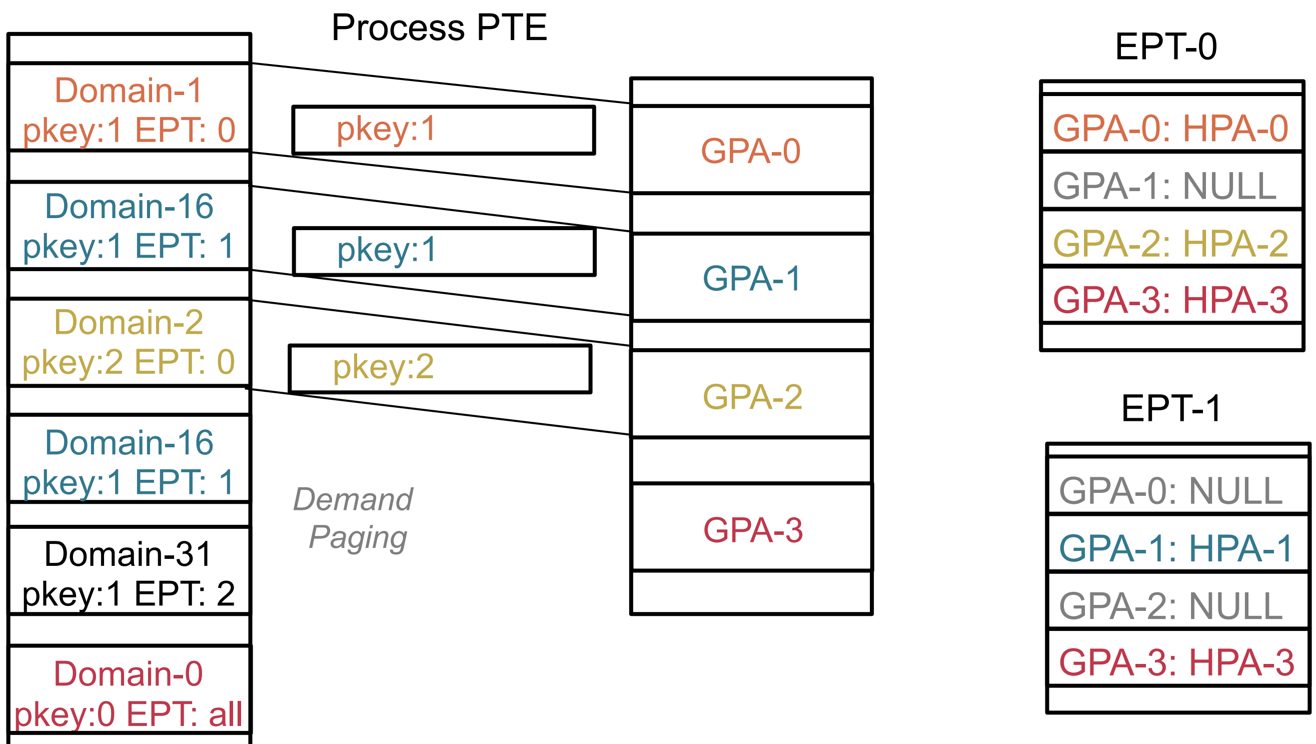


APIs

```
/* Allocate domain IDs with affinity */
int alloc_domains(int num, int dom_ids[]);

/* Free domain IDs */
int free_domains(int num, int dom_ids[]);

/* Allocate a virutal memory range for a domain */
void *domain_mmap(int dom_id, void *addr, size_t len,
                 int prot, int flags);

/* Remove some mappings */
void domain_munmap(void *addr, size_t len);

/* Retrieve the access permission of a domain */
void domain_begin(int id, int prot);

/* Release the domain permission */
void domain_end(int id);
```

Challenges

- **Challenge-1: EPT management**
  - How to make a VM seamlessly run with different EPTs
  - How to bridge the semantic gap for filling EPT mapping
- **Challenge-2: Multi-domain access**
  - How to transparently access multiple domains across different EPTs

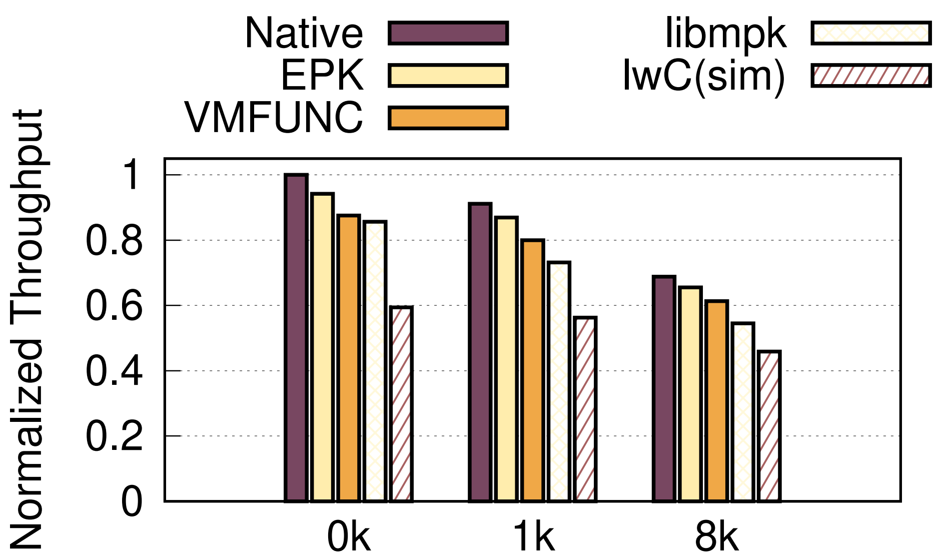
Please refer to the paper if interested

Evaluation Setup

- **Platform**
  - Dell PowerEdge R640 Server
  - Intel Xeon Gold 6138 CPU (HT disabled, 2.0GHz fixed)
  - EPK implemented on Linux/KVM-4.19.88
- **Comparison**
  - Vanilla VM process (with no isolation)
  - A VMFUNC solution (Use one EPT as one domain)
  - libmpk (time-division MPK pkey multiplexing) *[ATC 19]*

Case-Study: Intra-Process Isolation

NGINX v1.12.1: One worker thread
Workload: Use ab generate 300 clients sending file requests
Isolation: isolate each client's session key in one domain



Overhead

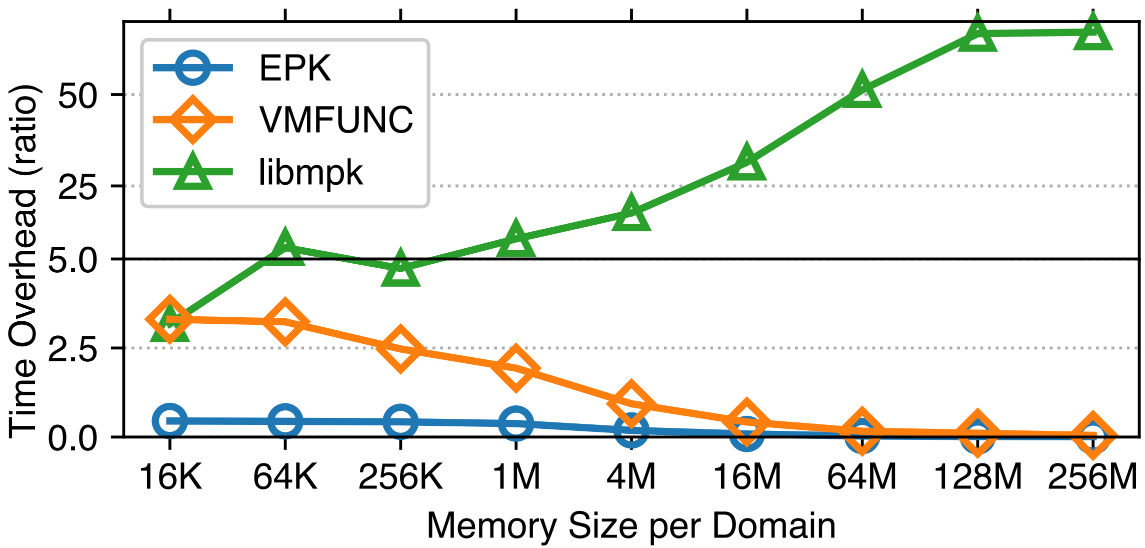
EPK: 5%

VMFUNC: 12%

libmpk: 18%

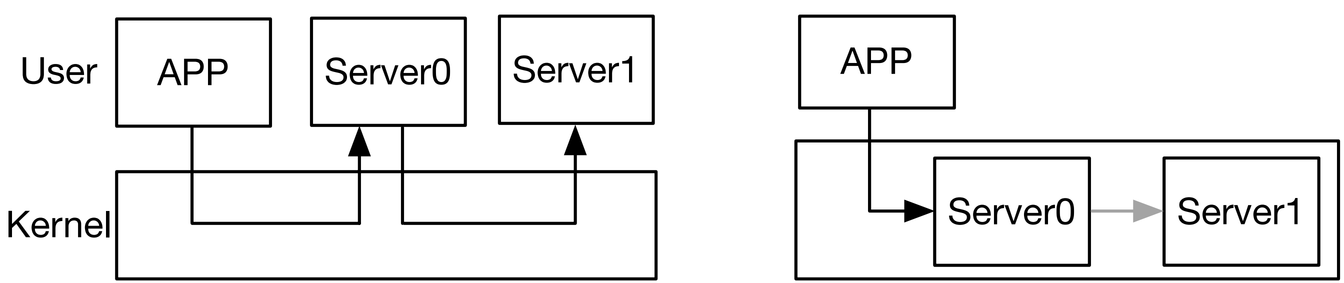
Case-Study: Memory Data Isolation

Hash-table
Workload: switch to random domain repeatedly and operate the hash-table in it
Isolation: separate each hash table in one individual memory domain



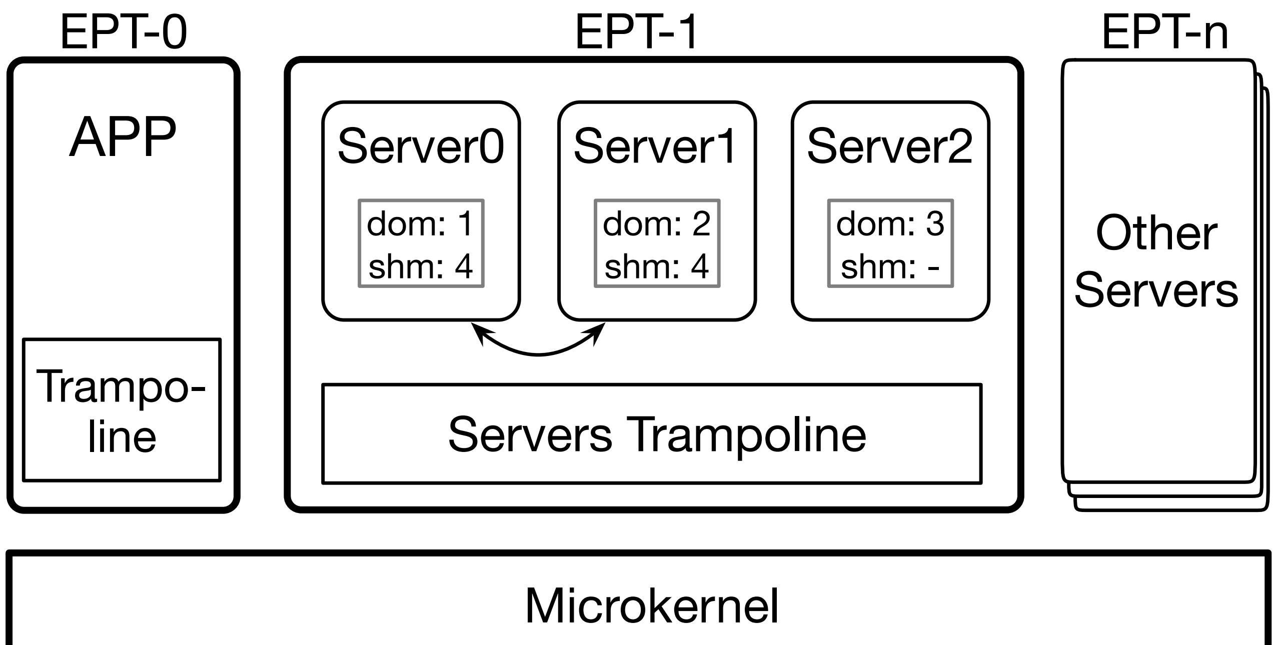
Case-Study: Boosting IPCs

- **Microkernel OS**
  - Implement OS functionalities in different user-space system servers
  - Isolation vs. Communication cost
  - UnderBridge: isolate servers with MPK-based domains *[ATC 20]*
    - <u>Limitation: small domain number due to the MPK limitation</u>



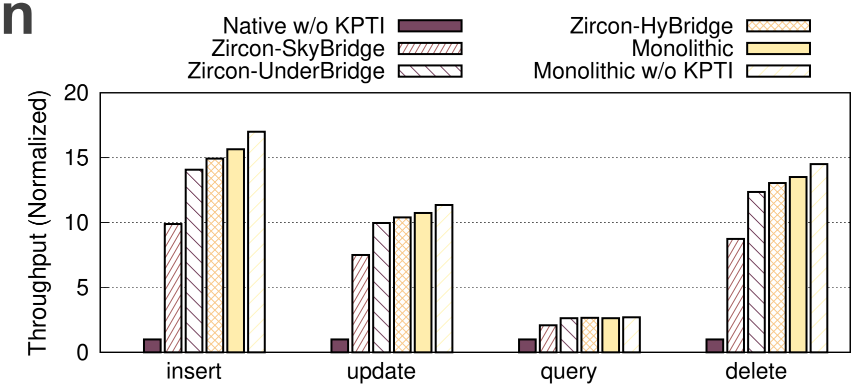
Case-Study: Boosting IPCs

- **HyBridge: A microkernel IPC design based on EPK**



Case-Study: Boosting IPCs

- **Application-to-Server IPC**
  - 527 cycles in HyBridge vs. 723 cycles in UnderBridge *[ATC 20]*
- **Cross-Server IPC**
  - 110 cycles in HyBridge vs. 437 cycles in SkyBridge *[EuroSys 19]*
- **Sqlite3 performance on Zircon**
  - 9x speedup than native
  - 66% speedup than SkyBridge



Conclusion

- **EPK**
  - First combines MPK and hardware virtualization features
  - Scalable and efficient memory domain mechanism
  - Three case studies to show the potential usages

Thanks!

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