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
Memory Protection Key (MPK)

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  - Partition different memory domains within one address space
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

Virtual Page

<table>
<thead>
<tr>
<th>Domain-0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain-1</td>
</tr>
<tr>
<td>Domain-2</td>
</tr>
<tr>
<td>Domain-1</td>
</tr>
</tbody>
</table>

Page Table Entries (PTE)

New fields in PTE
4-bit Dom-ID (pkey)

- pkey-0
- pkey-1
- pkey-2
- pkey-1

A new register: PKRU
32-bit per-core register

<table>
<thead>
<tr>
<th>31</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

WRPKRU: set the register

Dom-1 rw
Dom-0 rw
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

![Diagram showing domain switching and pkey reuse](image-url)
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

```
PTE
   pkey | Physical Addr | Attributes

PKRU
31 3 2 1 0
Dom-1 rw Dom-0 rw

Takes more bits in the upcoming 5-level page table
Can we find 10 bits for using as pkey?

How to represent the domain permission efficiently?
```

2047?
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)

<table>
<thead>
<tr>
<th>Domain</th>
<th>pkey</th>
<th>EPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain-1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Domain-16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Domain-2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Domain-16</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Domain-31</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Process Virtual Address Space
Basic Design of EPK

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

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Basic Design of EPK

- Use the extended protection key as the domain ID
  - Domain ID: EPT-index (0-511) + pkey (1-15)
/* 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 virtual 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 \([ATC 20]\)
    - Limitation: small domain number due to the MPK limitation
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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