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EMT: An OS Framework for New Memory Translation Architectures

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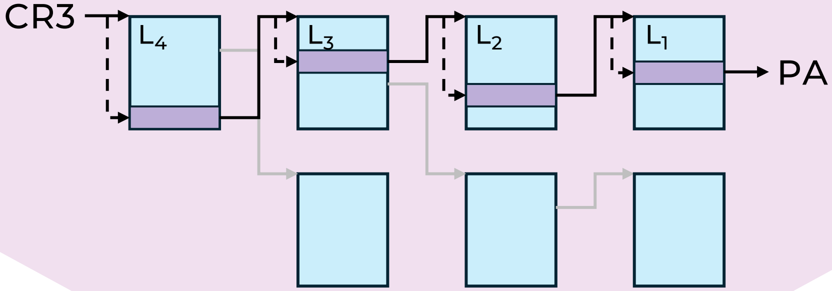
Radix tree was the de facto translation design

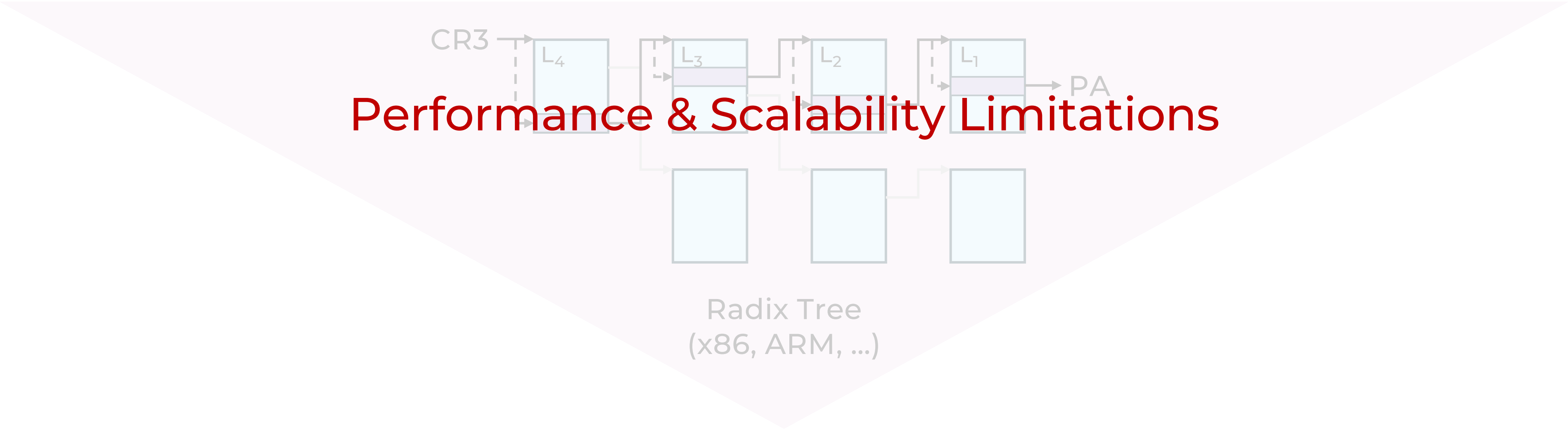


Radix Tree
(x86, ARM, …)

Today most commercial architectures
exclusively uses radix tree design.

x86, ARM64, RISC-V, LoongArch, s390, …

Radix tree was the de facto translation design



Performance & Scalability Limitations

Today most commercial architectures
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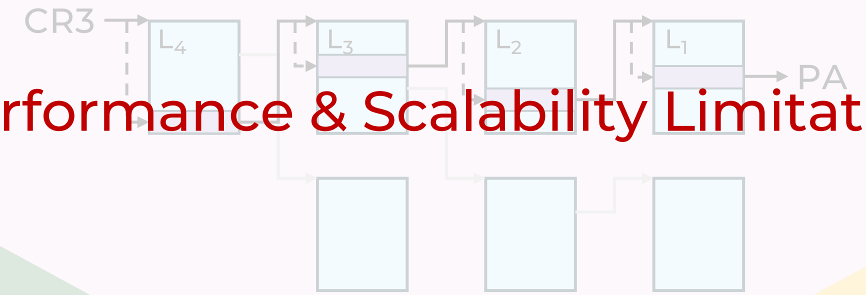
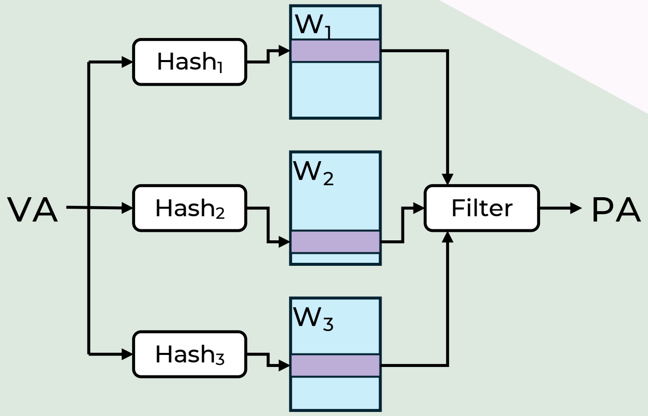
x86, ARM64, RISC-V, LoongArch, s390, ...

New translation architectures are emerging

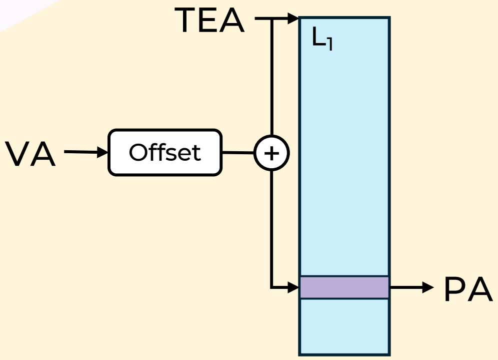


Performance & Scalability Limitations

Radix Tree
(x86, ARM, ...)

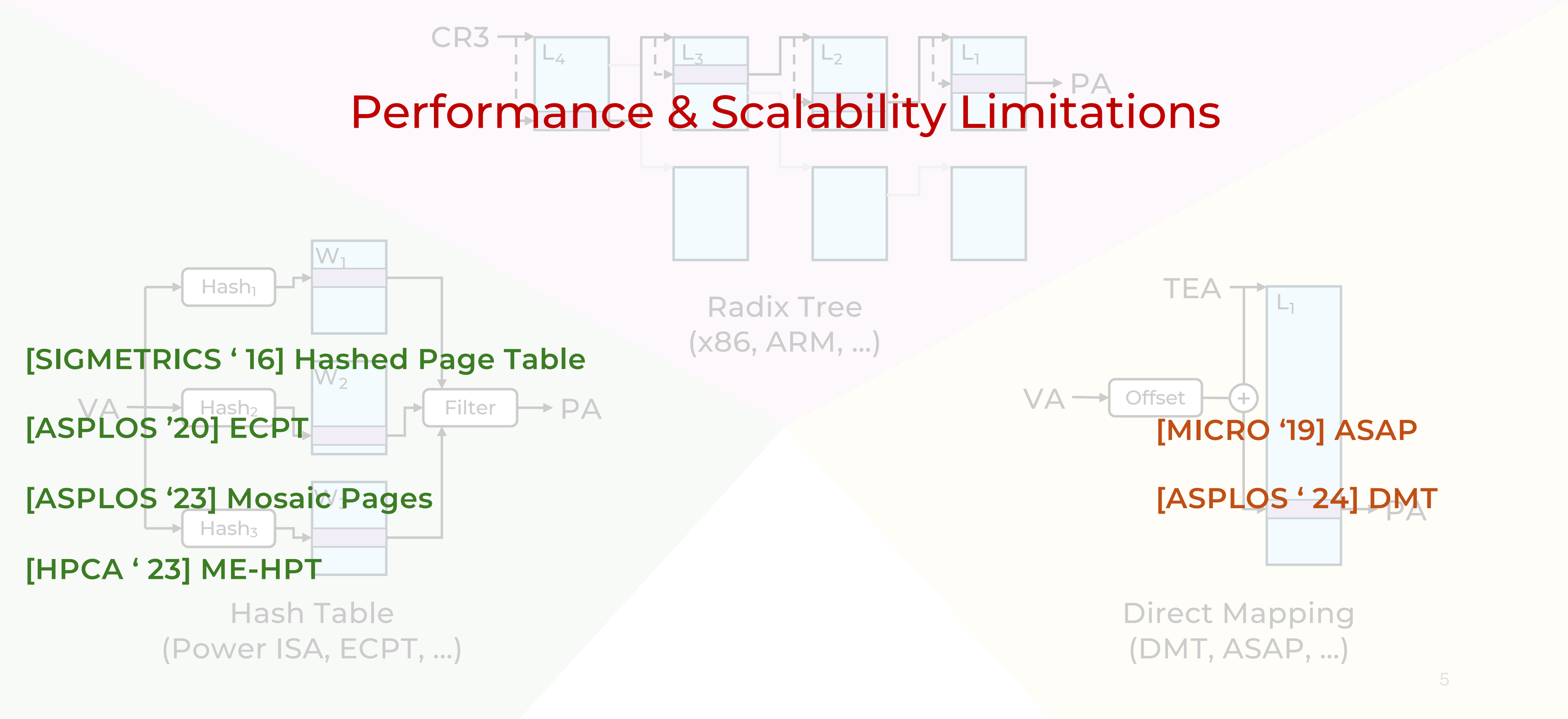


Hash Table
(Power ISA, ECPT, ...)



Direct Mapping
(DMT, ASAP, ...)

New translation architectures are emerging



Performance & Scalability Limitations

[SIGMETRICS ‘ 16] Hashed Page Table

[ASPLOS ’20] ECPT

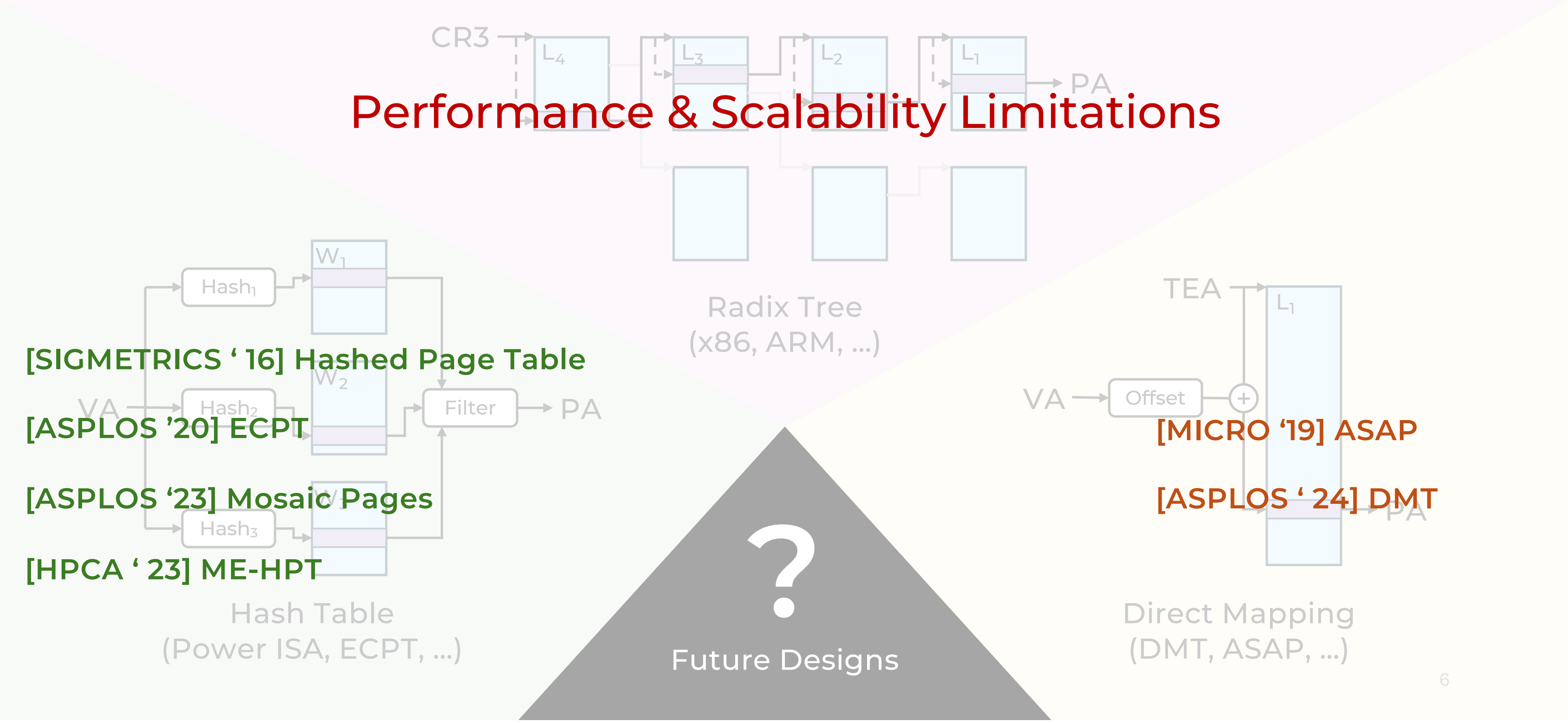
[ASPLOS ‘23] Mosaic Pages

[HPCA ‘ 23] ME-HPT

[MICRO ‘19] ASAP

[ASPLOS ‘ 24] DMT

New translation architectures are emerging



Performance & Scalability Limitations

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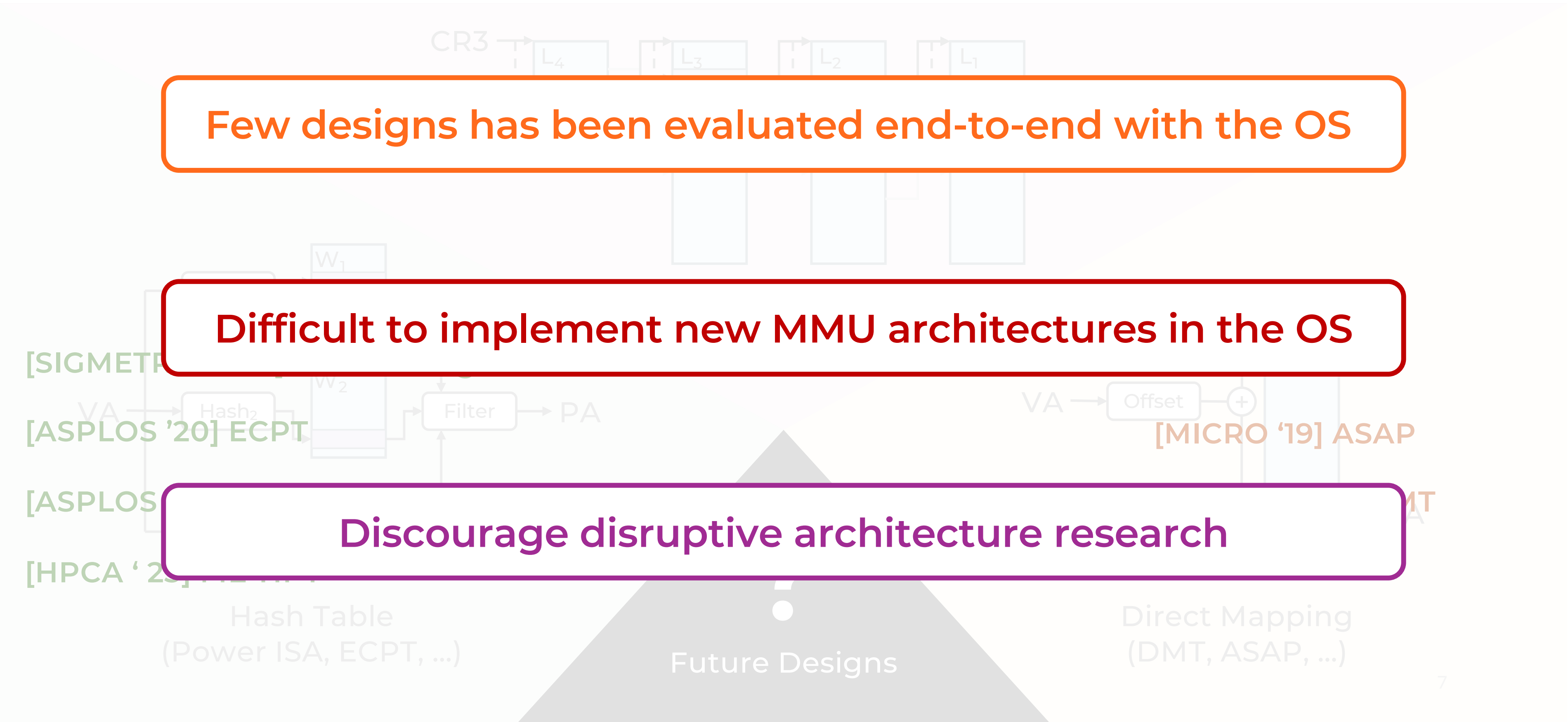
[ASPLOS ‘ 24] DMT

The missed evaluation of new architectures

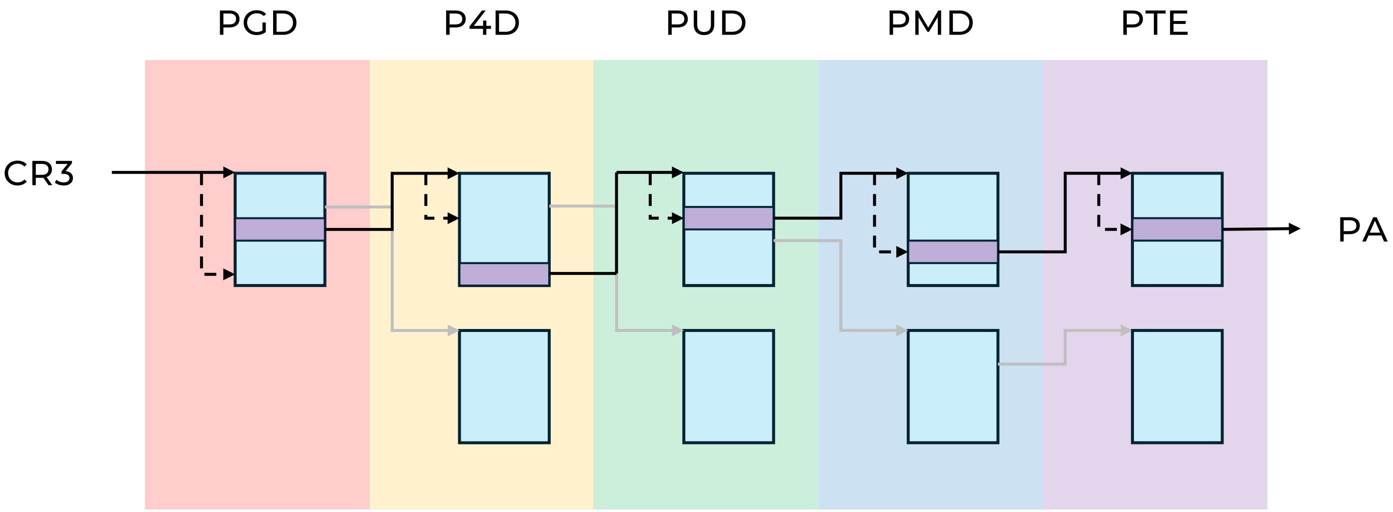


Few designs has been evaluated end-to-end with the OS

Difficult to implement new MMU architectures in the OS

Discourage disruptive architecture research

The Linux kernel assumes radix design

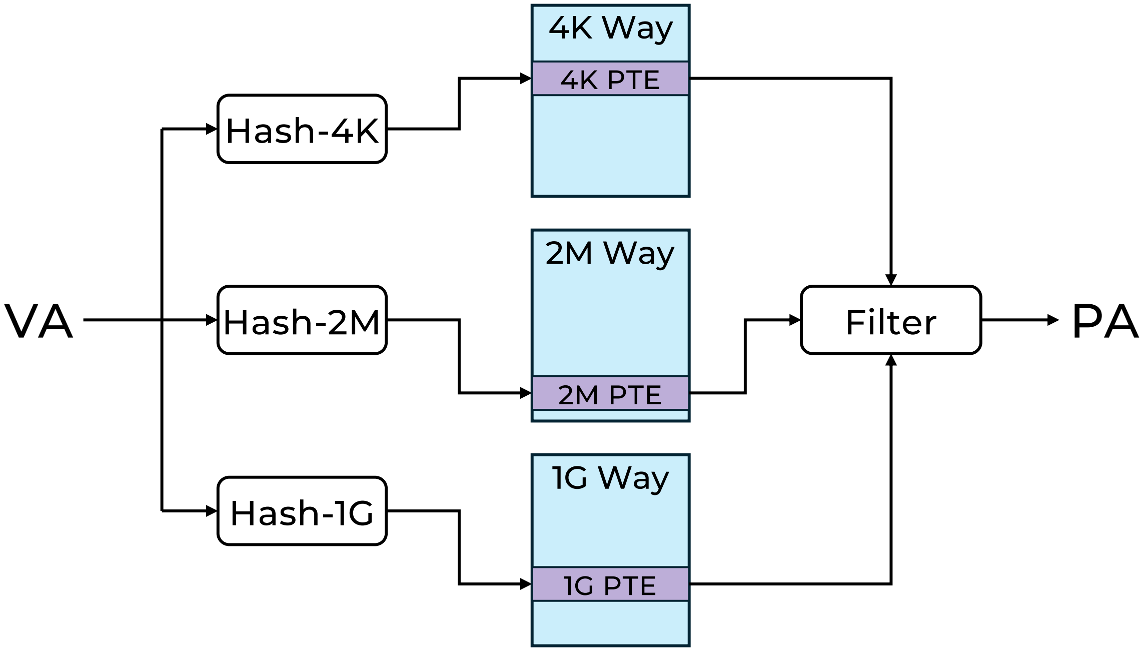


“It so happens that a tree format is the only sane format…”

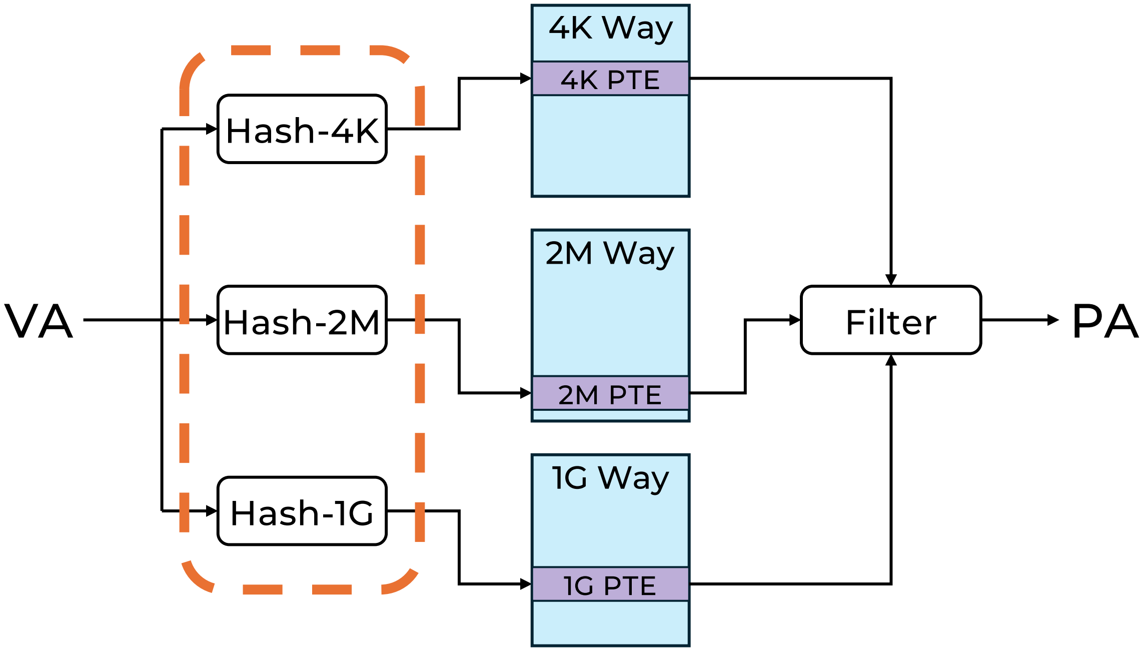
— Linus Torvalds, 2002

🤔

ECPT: A different design from radix schemes



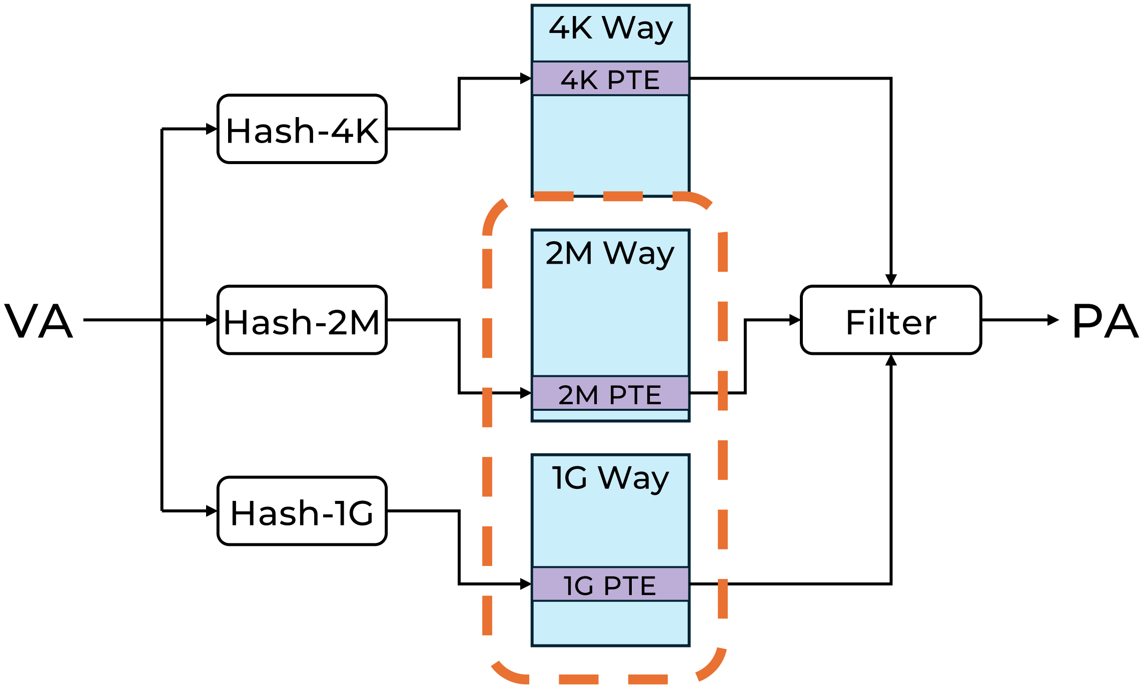
ECPT: A different design from radix schemes



+ Index with hash function values
- Index with bits in virt. address

Elastic Cuckoo Page Table (ECPT) vs. Radix-Tree Page Table

ECPT: A different design from radix schemes



+ Index with hash function values
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+ PTEs points to the actual page
- PTEs points to the next level PT

Elastic Cuckoo Page Table (ECPT) vs. Radix-Tree Page Table

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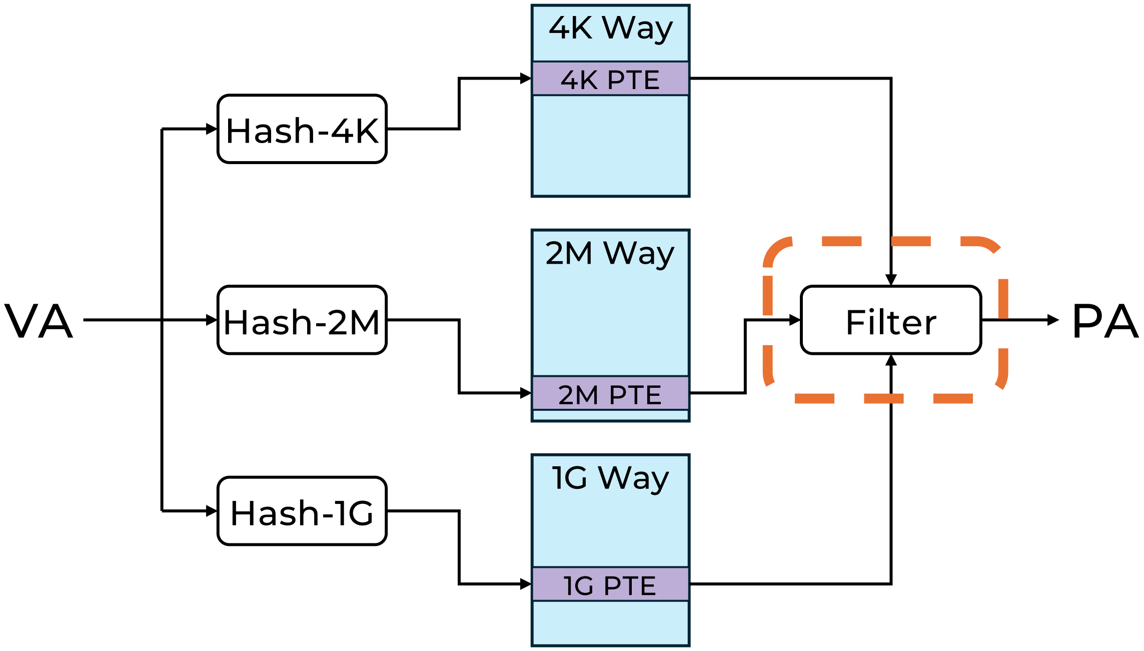

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+ Page walk returns many PTEs
- Page walk returns one final PTE

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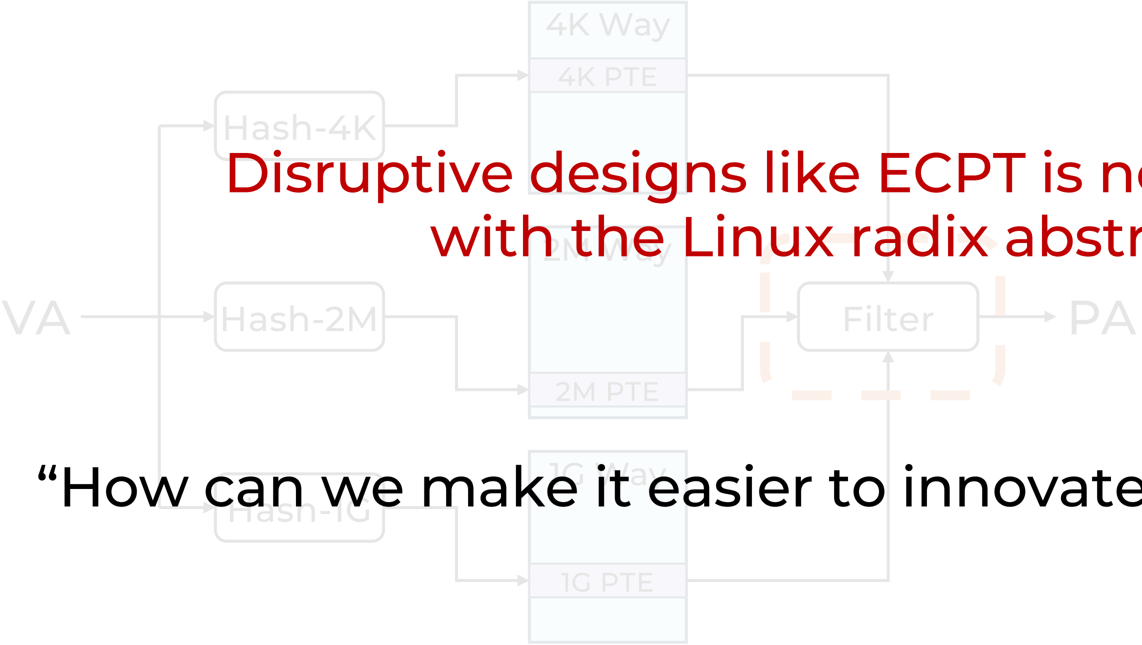
ECPT: A different design from radix schemes



Disruptive designs like ECPT is not compatible with the Linux radix abstraction

“How can we make it easier to innovate in virtual memory?”

+ Index with hash function values
- Index with bits in virt. address

+ PTEs points to the actual page
- PTEs points to the next level PT

+ Page walk returns many PTEs
- Page walk returns one final PTE

Elastic Cuckoo Page Table (ECPT) vs. Radix-Tree Page Table

Contributions

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EMT: an OS framework for new memory translation architectures

Hardware neutral design with no assumption on page table structures

Extensible interface that enables hardware-specific optimizations

Accurate profiling with near-zero (<0.2%) performance overhead

Contributions

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EMT: an OS framework for new memory translation architectures

- Hardware neutral design with no assumption on page table structures
- Extensible interface that enables hardware-specific optimizations
- Accurate profiling with near-zero (<0.2%) performance overhead

An open platform for memory translation research

- Research ready for full system prototyping, development, and evaluation
- Open source available at https://github.com/xlab-uiuc/emt

Contributions

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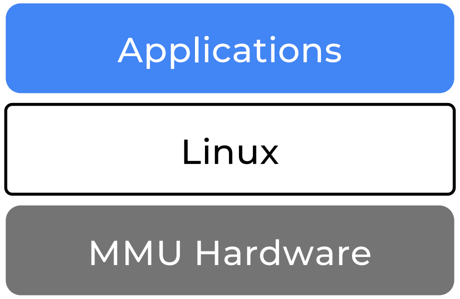
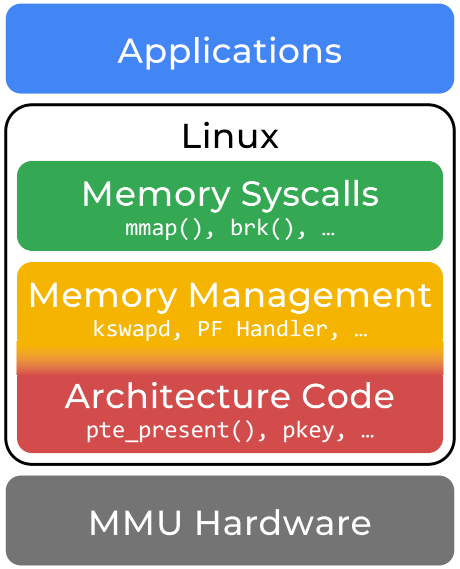
New insights on hashing-based designs from the OS perspective

- New challenges previously undiscovered regarding their OS implications
- New solutions to these challenges evaluated in our ECPT implementation

EMT Overview

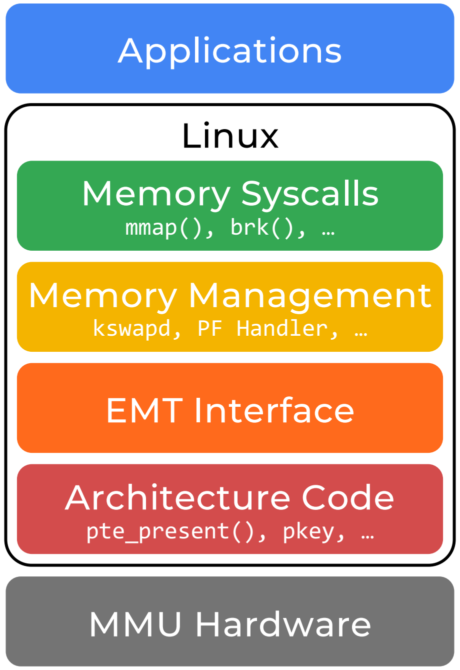


EMT Overview



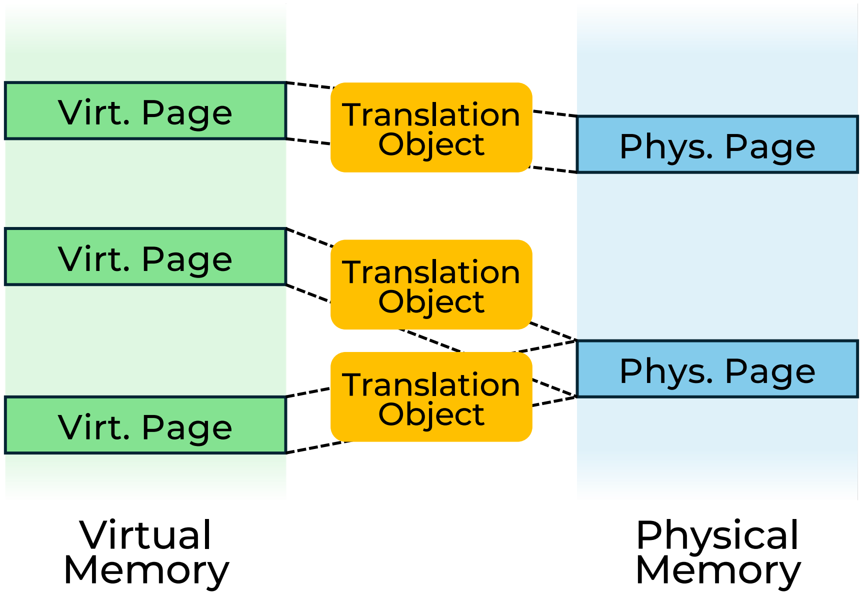
Linux coupled memory management and arch-specific code

EMT Overview



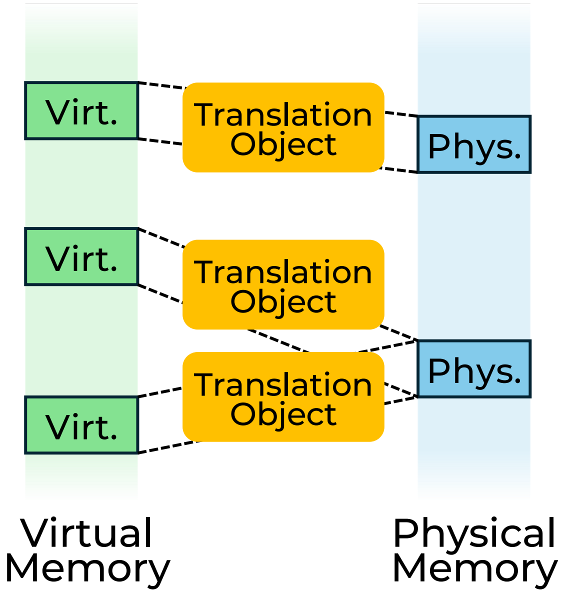
EMT decoupled memory management and arch-specific code

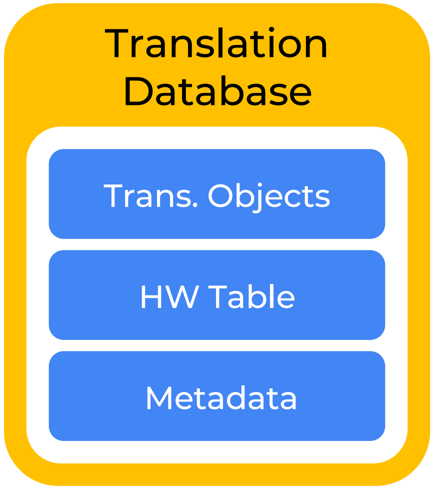
EMT models functionality, not structure



Translation Object
Models a *page mapping*

EMT models functionality, not structure

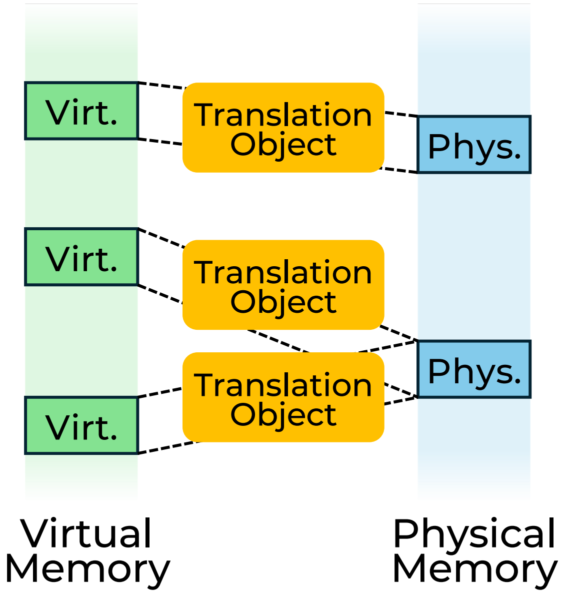




Translation Object
Models a *page mapping*

Translation Database
Models an *address space*

EMT models functionality, not structure



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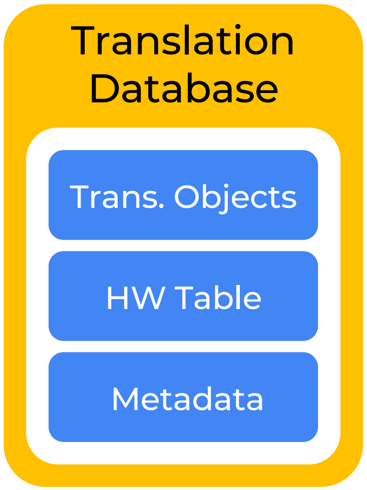
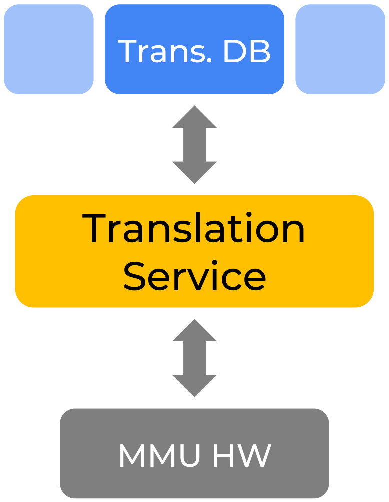
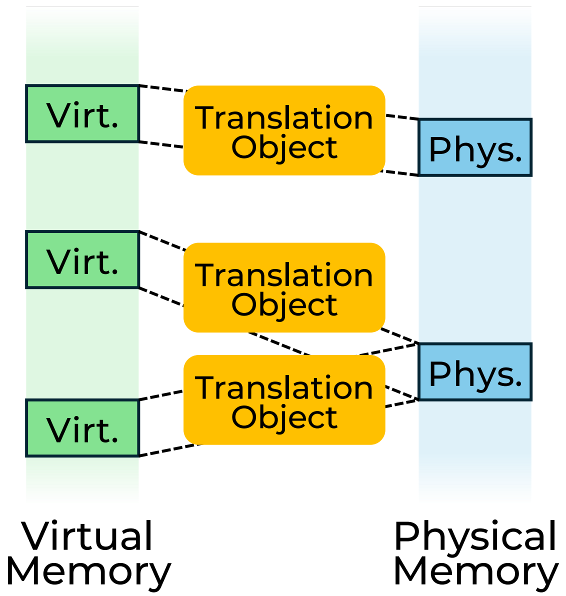


Translation Database
Models an *address space*

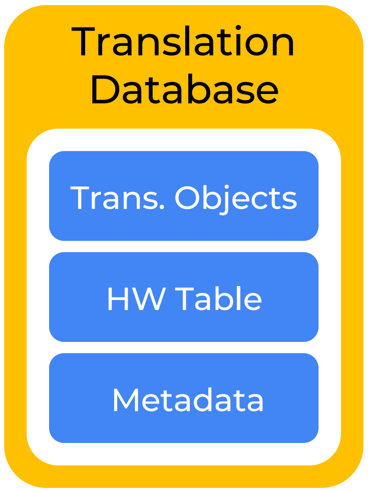


Translation Service
Models the *MMU*

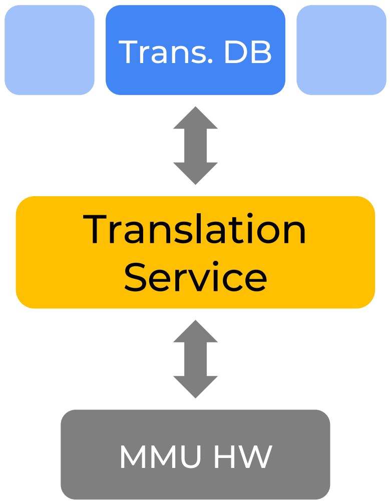
EMT models functionality, not structure



Translation Object
Models a *page mapping*

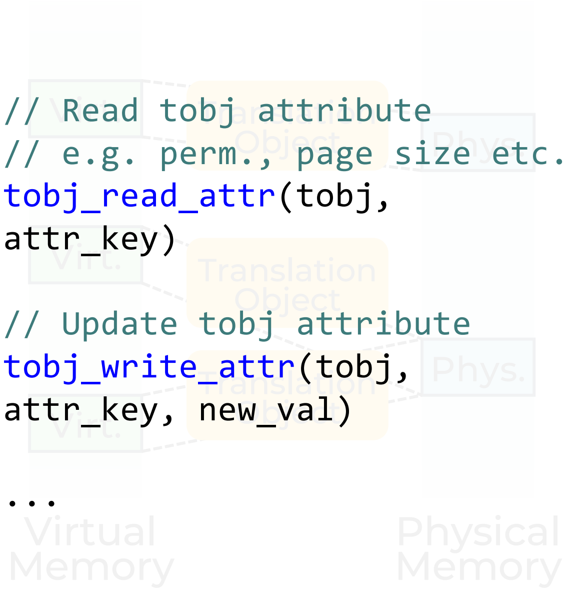


Translation Database
Models an *address space*



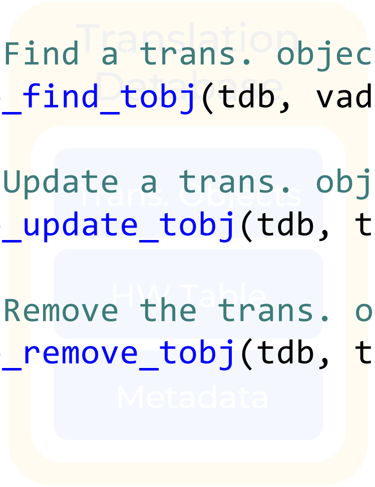
Translation Service
Models the *MMU*

EMT Basic Functions



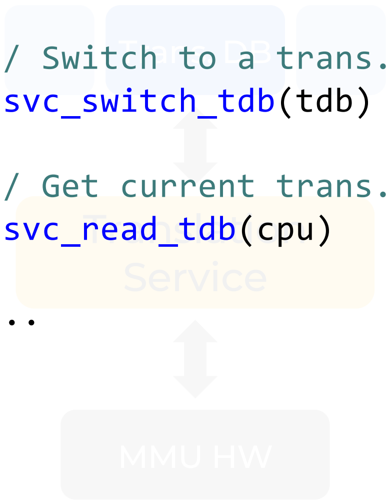
```
// Read tobj attribute
// e.g. perm., page size etc.
tobj_read_attr(tobj,
attr_key)

// Update tobj attribute
tobj_write_attr(tobj,
attr_key, new_val)

...
```

Translation Object
Models a *page mapping*



```
// Find a trans. object
tdb_find_tobj(tdb, vaddr)

// Update a trans. object
tdb_update_tobj(tdb, tobj)

// Remove the trans. object
tdb_remove_tobj(tdb, tobj)

...
```

Translation Database
Models an *address space*

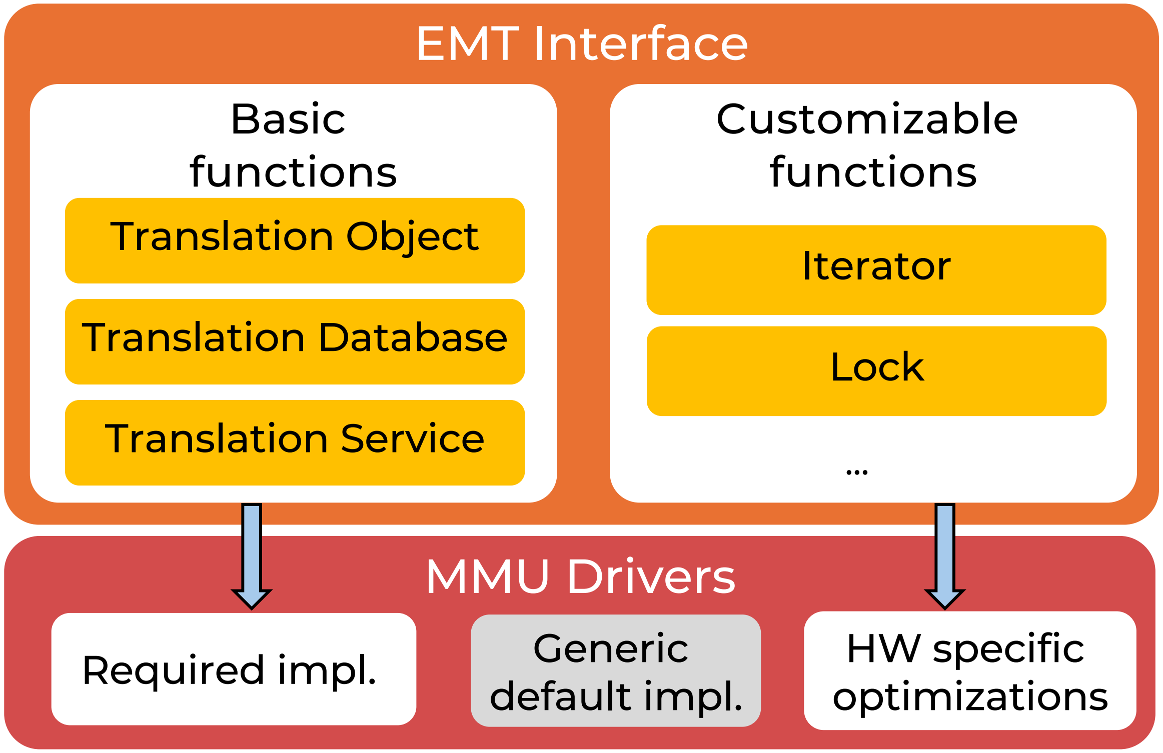


```
// Switch to a trans. db
tsvc_switch_tdb(tdb)

// Get current trans. db
tsvc_read_tdb(cpu)

...
```

Translation Service
Models the *MMU*

EMT Customizable Functions

HW neutral



Exploit HW features ***and*** guarantee HW neutrality

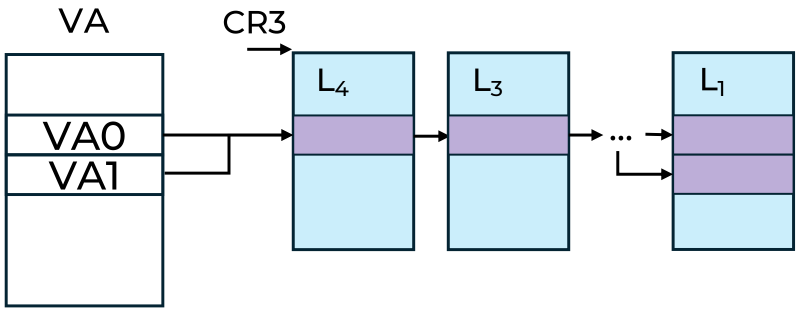
EMT enables HW-specific optimizations

Customizable functions: iterator

Iterate over a range of virtual address

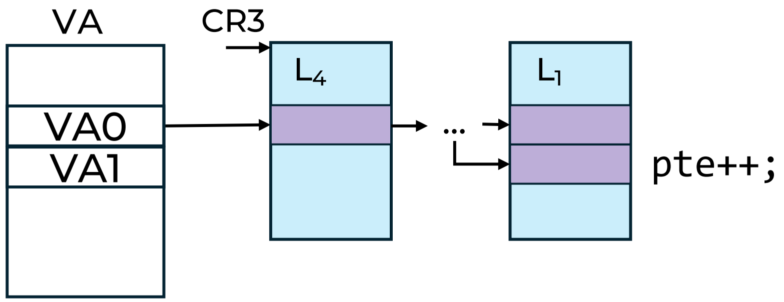
`tobj_iter_next` gets the next trans. object

Default implementation
HW neutral but less performant



Full page table walk for every VA

Radix MMU driver
Customized to exploit locality



EMT enables HW-specific optimizations

Customizable functions: iterator

Iterate over a range of virtual address

`tobj_iter_next` gets the next trans. object

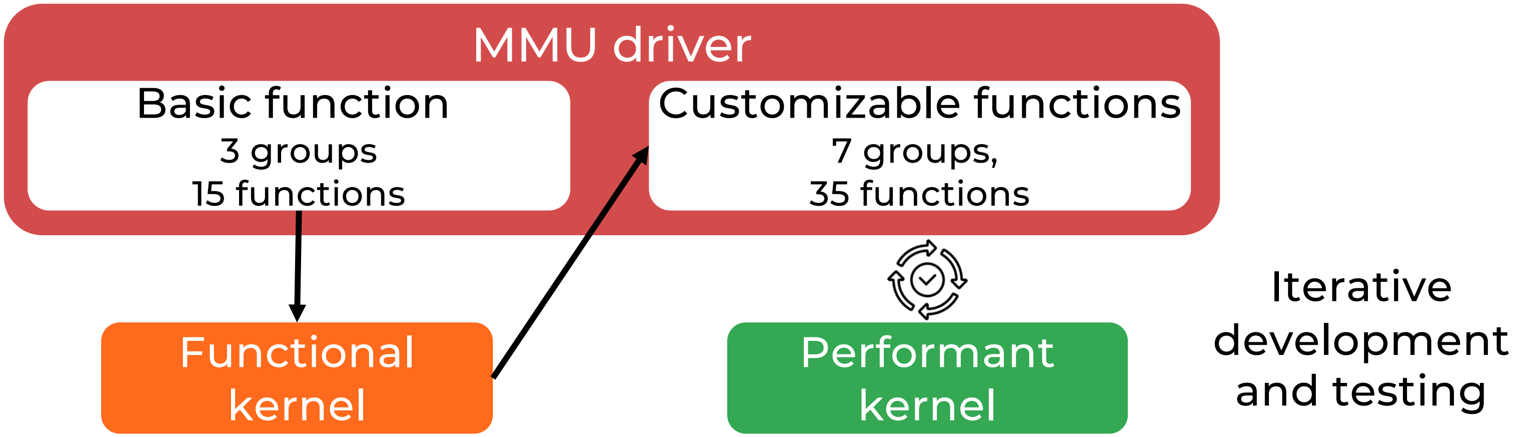
Default implementation
HW neutral but less performant

```
tdb_find_tobj(iter->tdb, iter->va,
    tobj); /* full page walk on Radix */
tobj_read_attr(tobj, TOBJ_ATTR_SIZE,
   &size);
iter->va += size
...
```

Radix MMU driver
Customized to exploit locality

```
... /* update tobj */
if ((iter->va + PAGE_SIZE) &
   (~PMD_MASK)) {
   iter->va += PAGE_SIZE;
   iter->pte++;
   return 0;
} /* handle other cases */
```

EMT simplifies OS support for different MMUs



MMU driver

Basic function
3 groups
15 functions

Customizable functions
7 groups,
35 functions

Functional kernel

Performant kernel

Iterative development and testing

EMT supports tree- and hash-based translations (e.g., Radix and ECPT)

Flattened page table support implemented with < 700 LOC

- No changes to Linux memory management routines
- Reuse part of the x86 MMU driver

EMT has negligible performance overhead

EMT-Linux on the Radix MMU driver vs. vanilla Linux

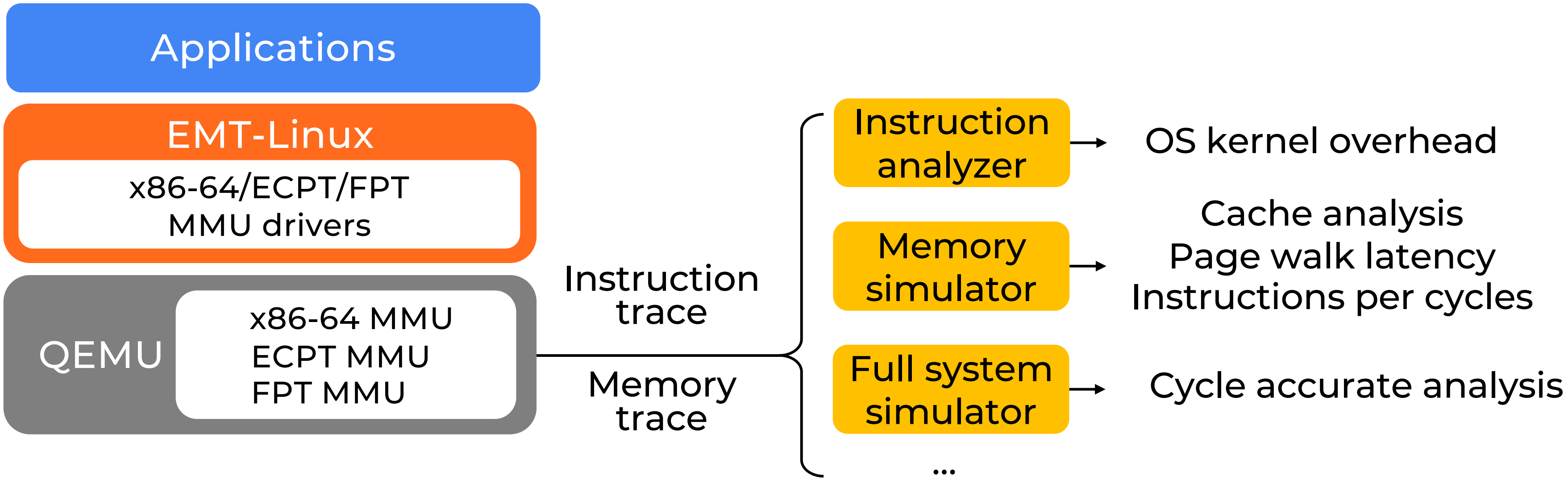
Benchmarks

EMT is carefully engineered to minimize performance overhead

Minimize call stacks depth and keep a similar cache efficiency

EMT enables all HW-specific optimizations for radix

An open platform for virtual memory research



EMT enables end-to-end system evaluations in the absence of hardware

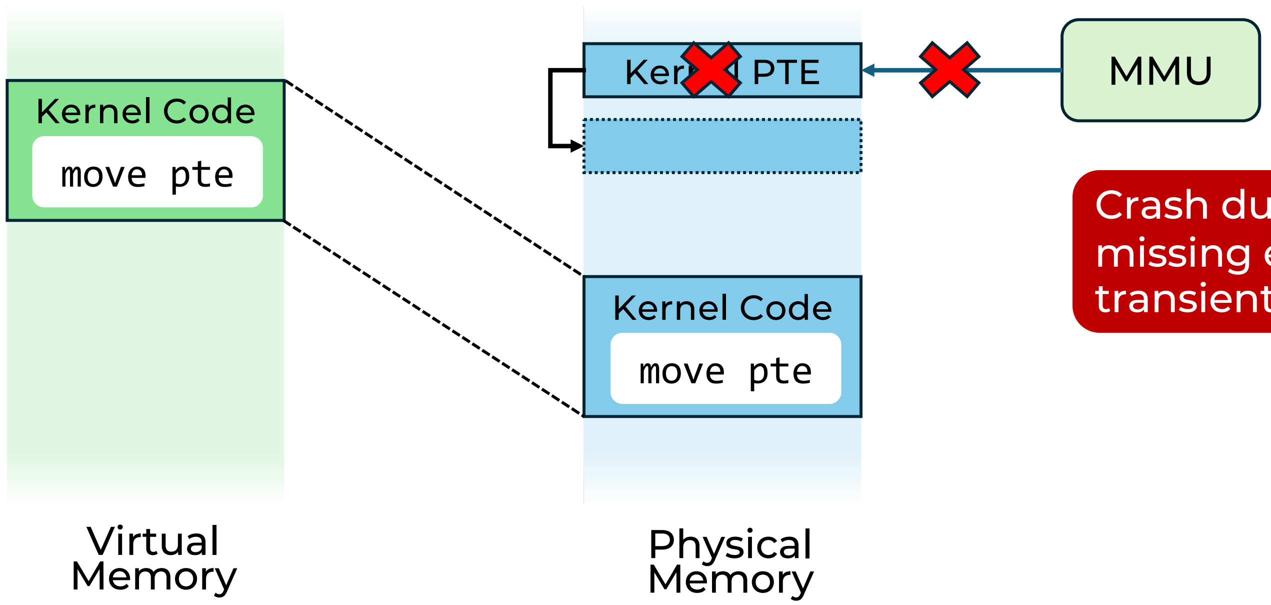
EMT supports rich performance analysis

EMT brings insights from the OS perspective

Hash page table: self-reference paradox

Approach 1: invalidation before copy

Kernel PTEs may move due to hash collisions

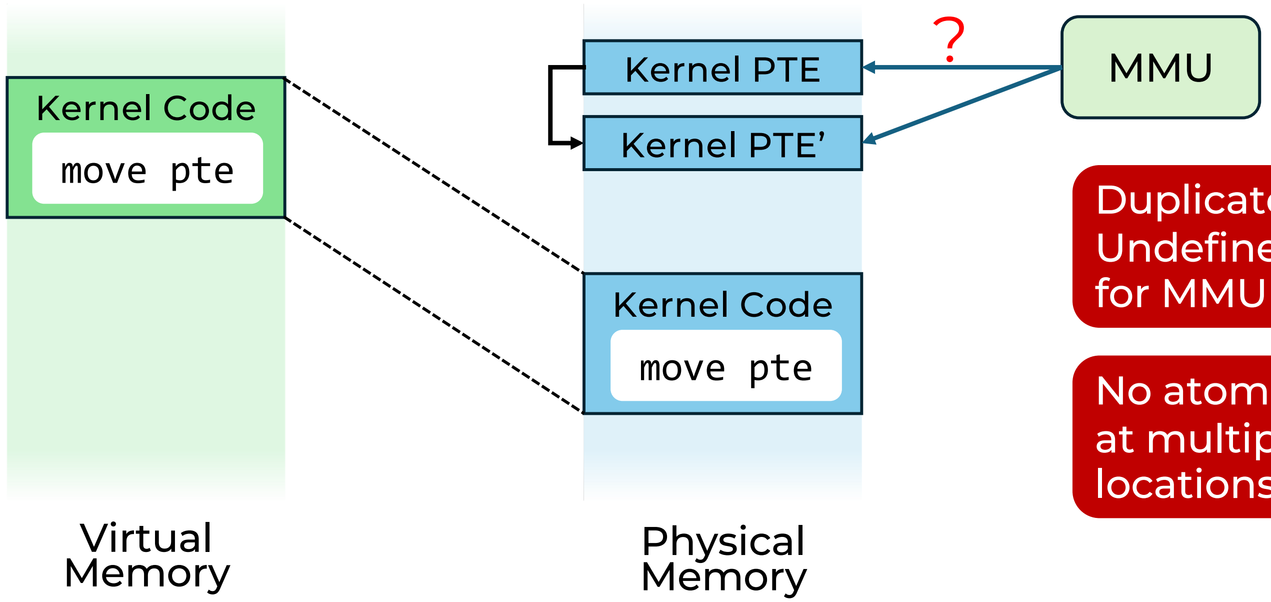


Crash due to missing entries in transient window

EMT brings insights from the OS perspective

Hash page table: self-reference paradox

Approach 2: copy before invalidation



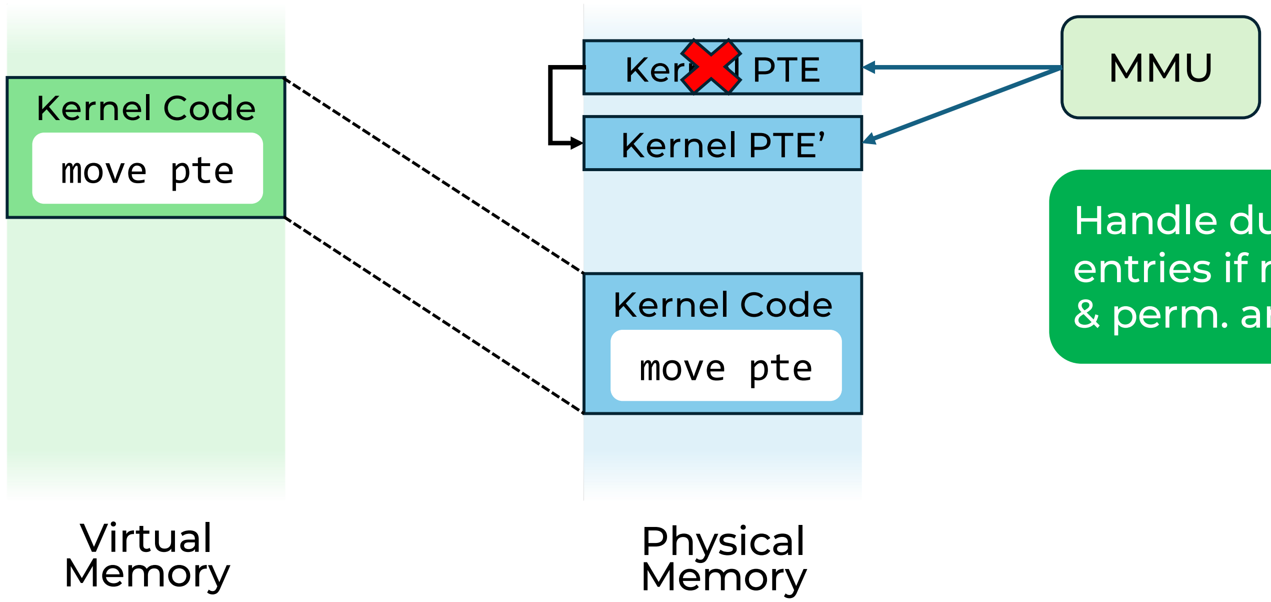
Duplicated entries
Undefined behavior for MMU

No atomic updates at multiple locations

EMT brings insights from the OS perspective

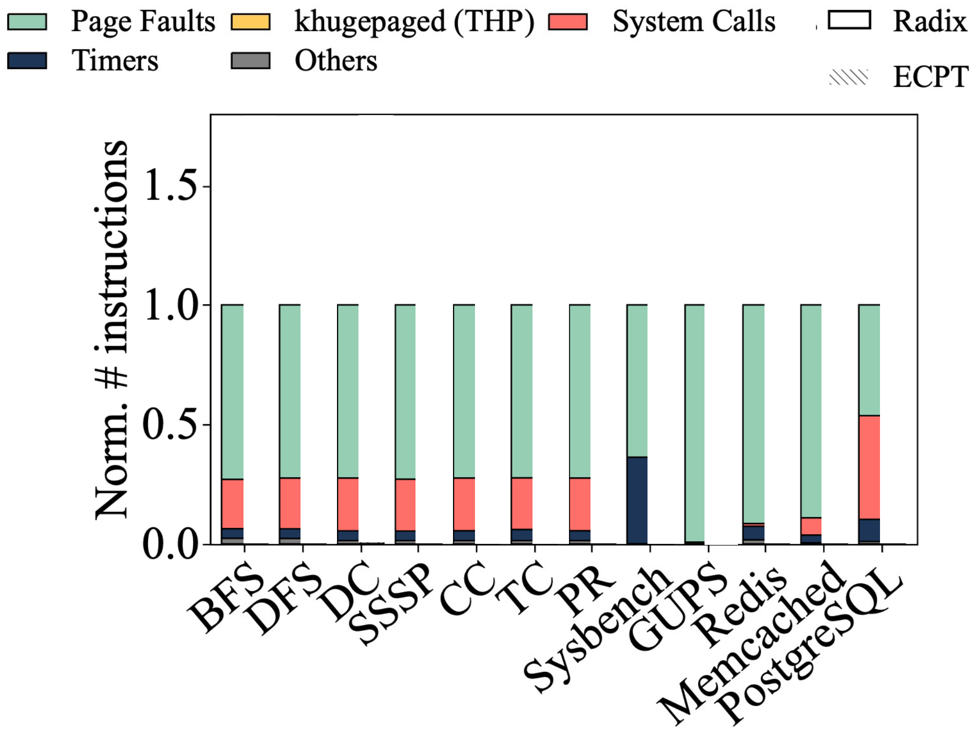
Hash page table: self-reference paradox

Solution: copying before invalidation + extend MMU logic



Handle duplicated entries if mapping & perm. are same

EMT helps analyze MMU design tradeoffs



ECPT is faster than x86 Radix on hardware metrics

ECPT incurs 1.74x page fault handling overhead over Radix

Conclusion

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OS support is essential for memory translation designs

- Understanding OS implications is very beneficial
- Experimenting with modern Oses is strongly encouraged
- OS extensibility is crucial to foster diverse memory translation research

EMT: an OS framework for new memory translation architectures

- Hardware neutral design with no assumption on page table structures
- Extensible interface that enables hardware-specific optimizations
- Accurate profiling with near-zero (<0.2%) performance impacts

An open platform for memory translation research

- Research ready for full system prototyping, development, and evaluation
- Open source available at https://github.com/xlab-uiuc/emt