Memory Safety for Low-Level Software/Hardware Interactions

Montreal or Bust!

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Memory Safety Future is Bright

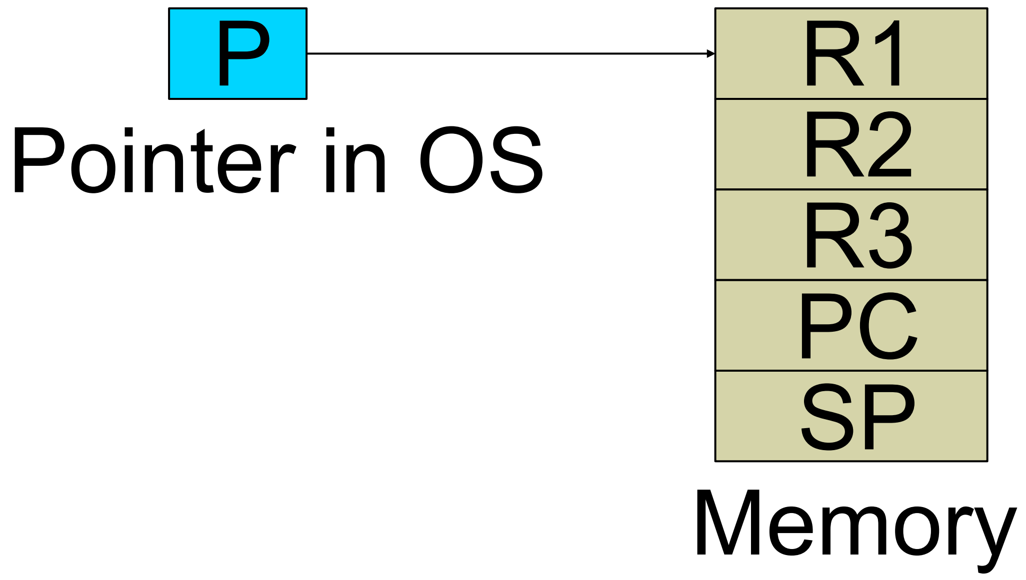
- User-space memory safety is improving
  - Safe languages
  - SAFECode, CCured, Baggy bounds checking, Softbound, etc
- Memory safety for operating systems exists!
  - Singularity (C#), SPIN (Modula-3)
  - Linux on Secure Virtual Architecture (C)

A New Enemy Arises: Software/Hardware Interactions

- What is a low-level software-hardware interaction?
  - Instruction that manipulates hardware resources
  - Below semantics of the programming language
- **Perfectly type-safe code**! But:
  - Can corrupt control-flow or data-flow
- Examples:
  - Processor State
  - I/O Objects
  - MMU mappings

Memory Safety: Processor State

- Operating systems explicitly manage Processor State
  - Processor states saved in memory buffers
- Type-safe stores can modify a saved processor state
  - Can subvert control/data-flow integrity



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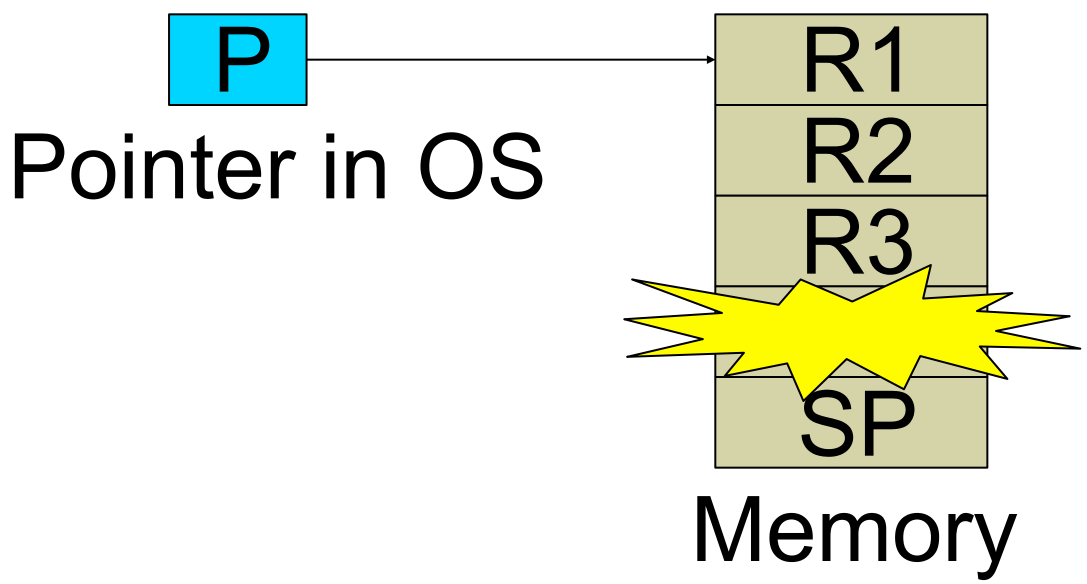

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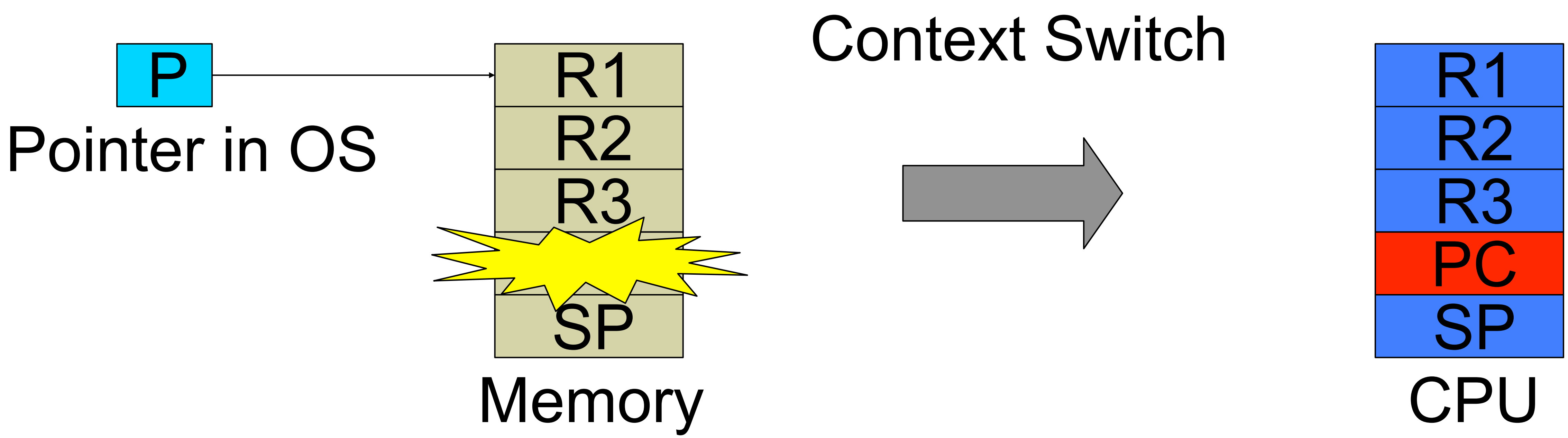


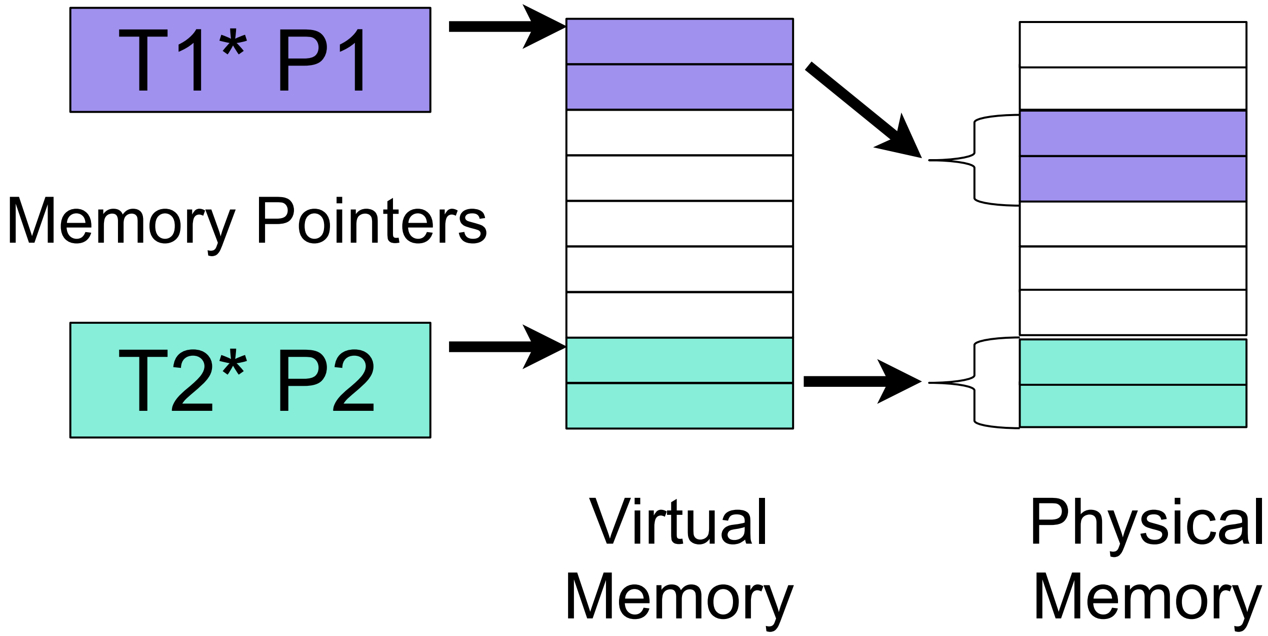
Memory Safety: I/O

- I/O device memory and RAM in same address space
- However, I/O memory *is* different
  - I/O memory incompatible with standard compiler analysis
  - I/O memory has side effects on hardware

- Intel E1000E Bug on Linux 2.6
  - Invalid write on I/O memory
  - Damaged Intel E1000E Network Cards
  - Potential DoS Attack

Memory Safety: MMU

- MMU can violate type safety



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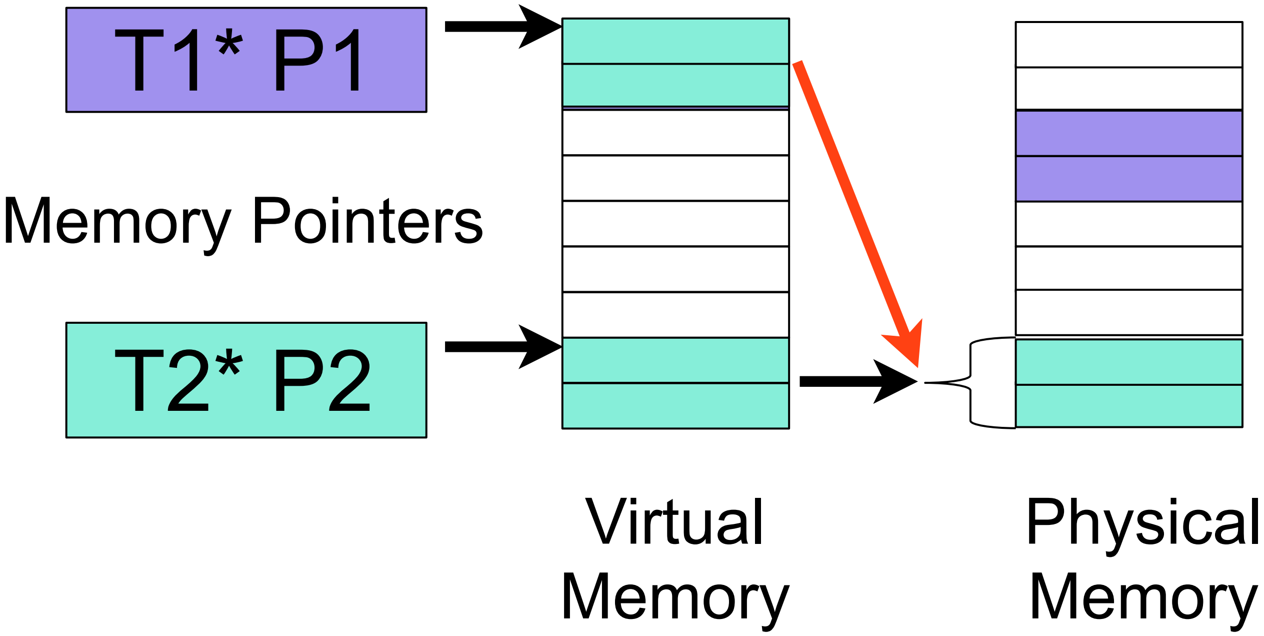

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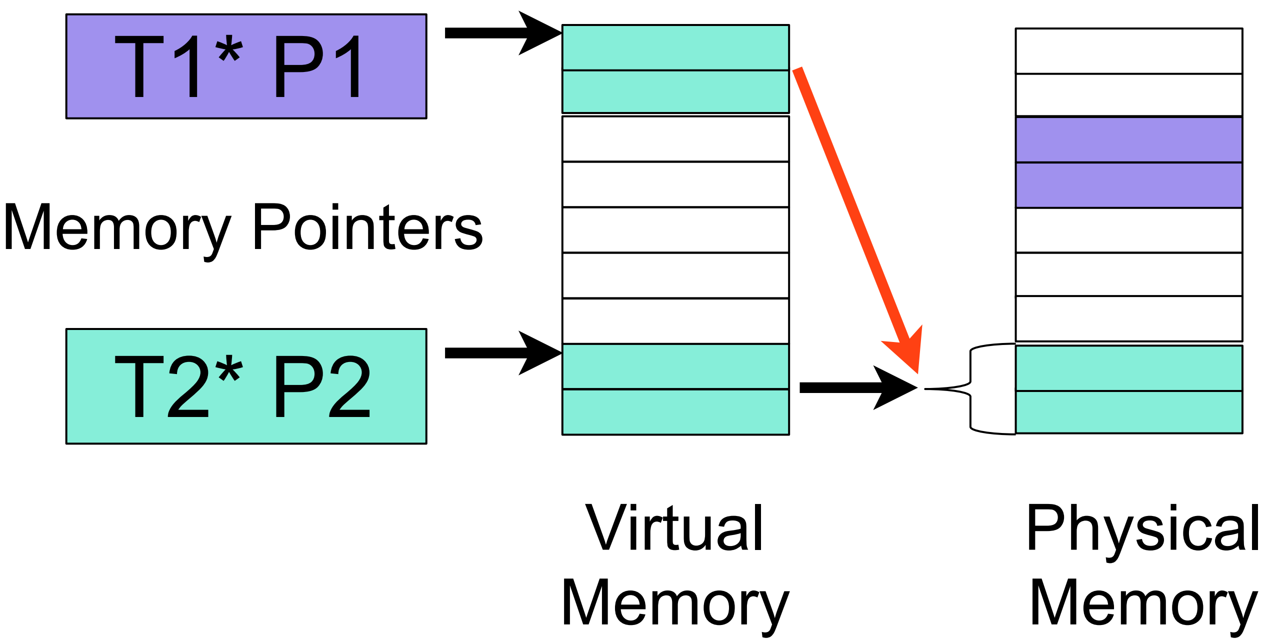
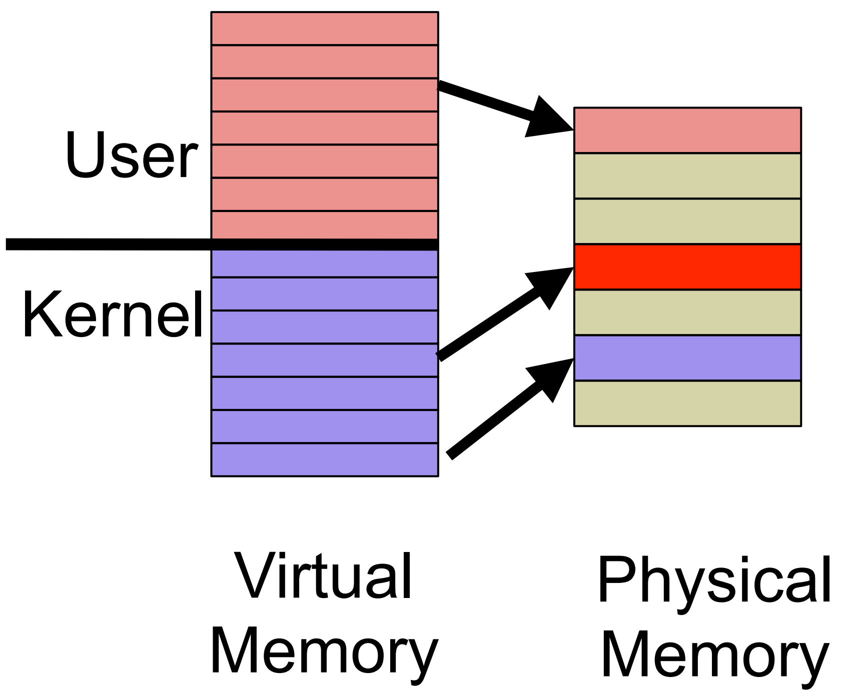


- MMU can make kernel pages accessible to user-space
  - BID9356, BID9686, BID18177 (www.securityfocus.com)



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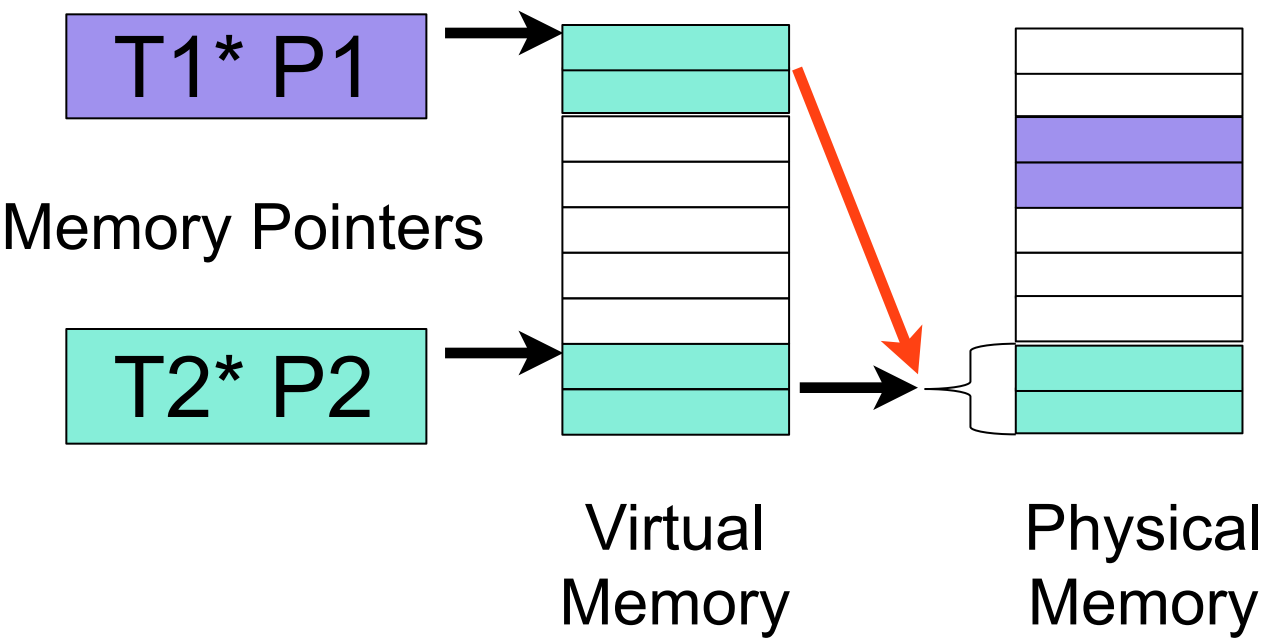

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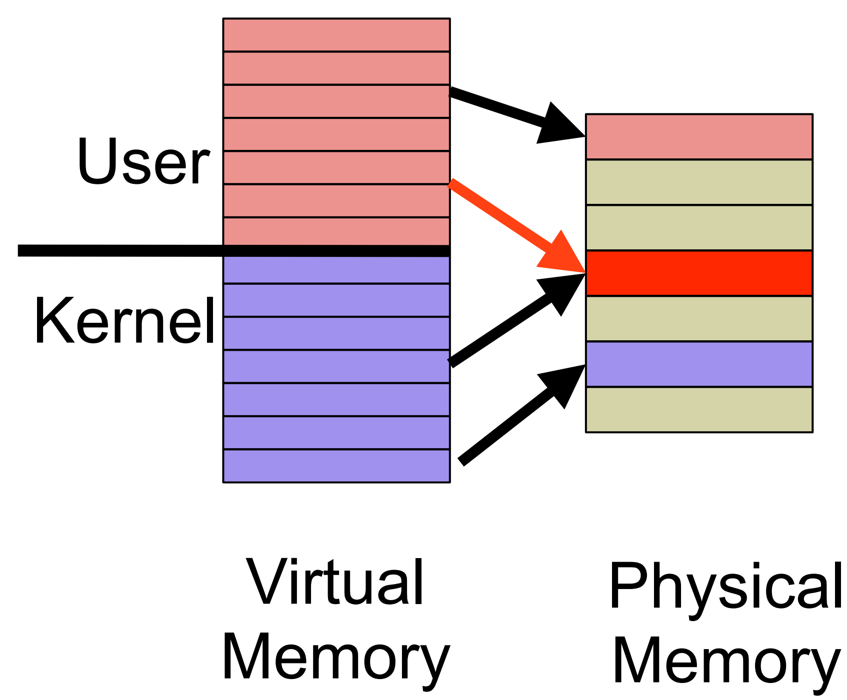
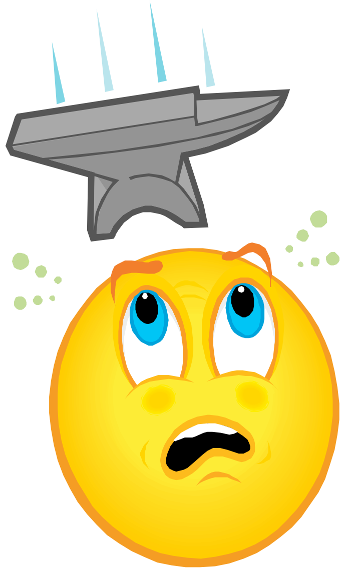


It’s Already Here!

- Intel E1000E Bug
- MMU exploits in Linux

Need solutions ***before*** these attacks become more sophisticated and commonplace!



SVA-OS: Memory Safety for Low-Level Software-Hardware Interactions

- First system to provide comprehensive memory safety for low-level software/hardware interactions
  - Linux 2.4.22 on Secure Virtual Architecture (SVA)
- Compiler analysis and runtime checks
  - Little overhead above and beyond traditional memory safety
- Effective at preventing software/hardware exploits

Outline

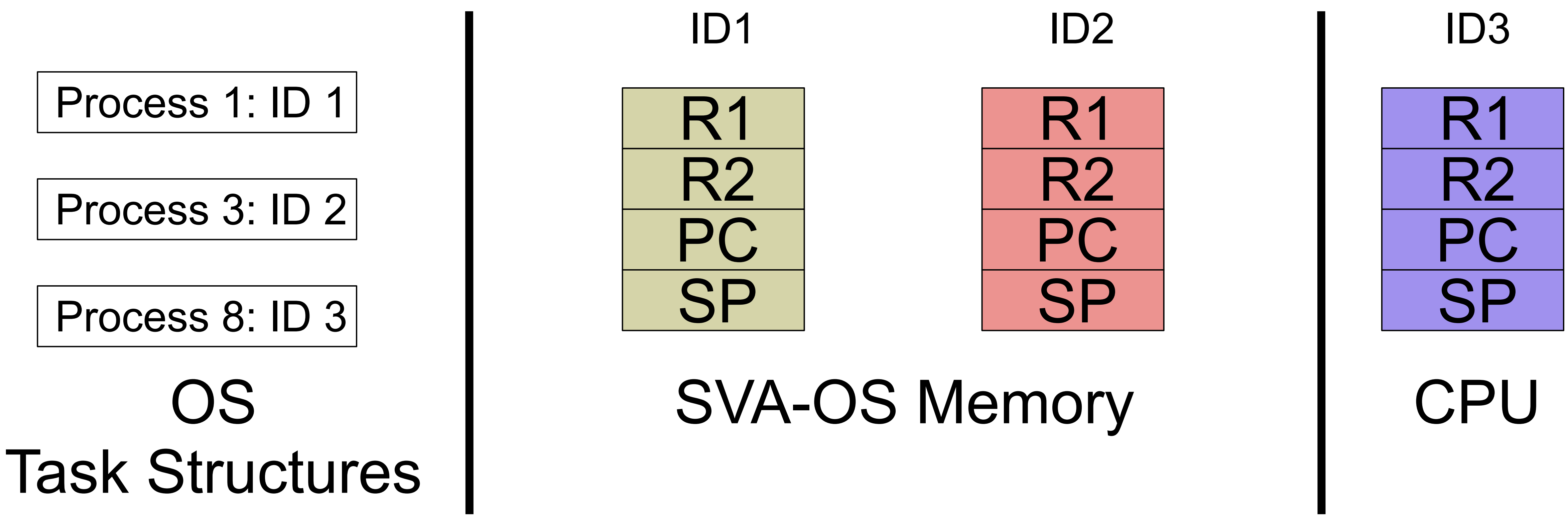
- Motivation
- **High-level Solutions**
- Design of SVA-OS
- Experimental Results
- Future Work and Conclusions

Foundations: What Do We Need?

- System that provides traditional memory safety
  - SVA-OS *will preserve* memory safety
- Examples
  - Type-safe languages, e.g. Singularity
  - Compiler techniques for commodity operating systems, e.g. Secure Virtual Architecture (SVA)

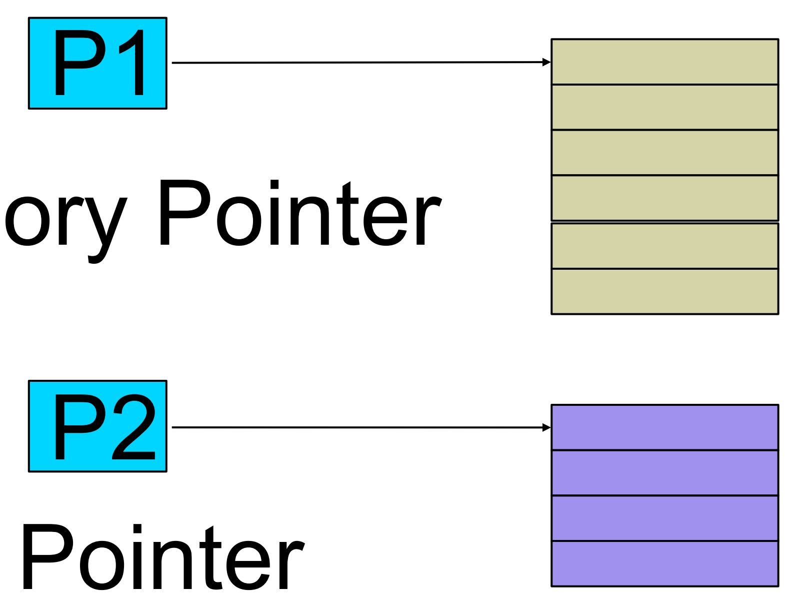
Solution: Processor State

- New instruction to save old state and restore new state
  - State saved in internal SVA-OS memory
  - State referenced by ID returned from VM
- Policy left to OS
  - Scheduling, context switching, signal delivery



Solution: Memory Mapped I/O

- New instruction to map I/O memory into address space
- New instructions to load/store I/O objects
- Add run-time checks to ensure that:
  - Regular load/stores access memory
  - I/O accesses access I/O memory



Memory Pointer

iostore (v, *p1);

I/O Pointer

store (v, *p2);

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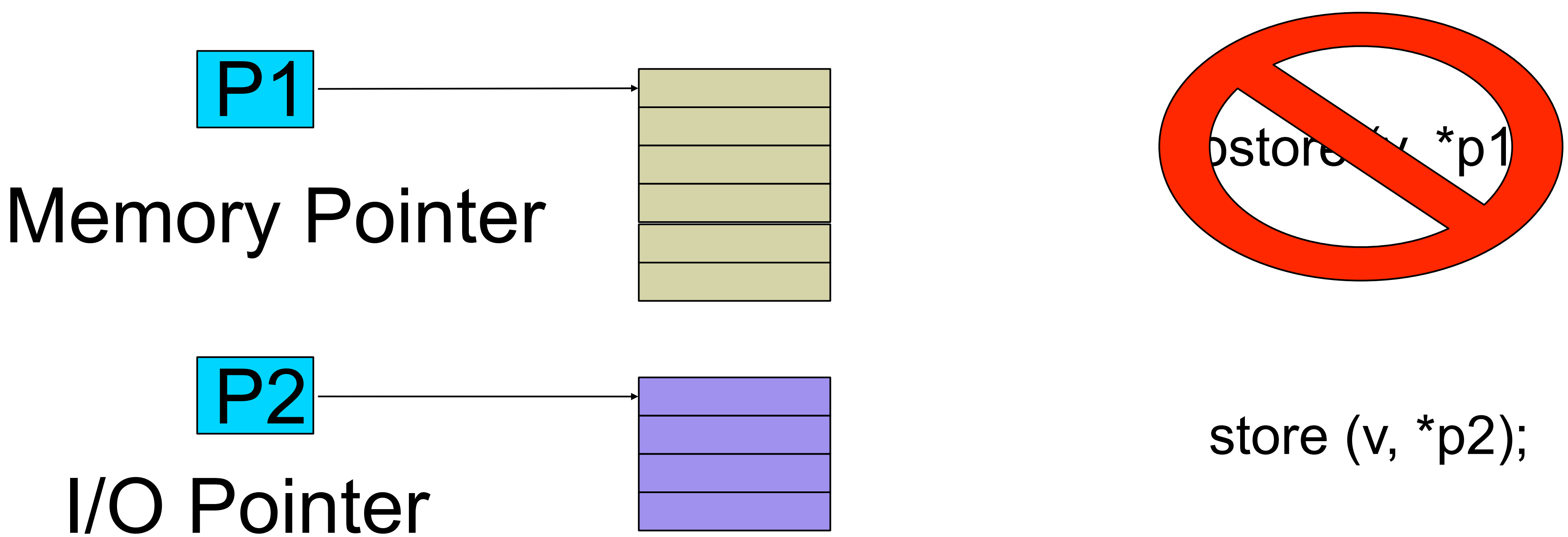

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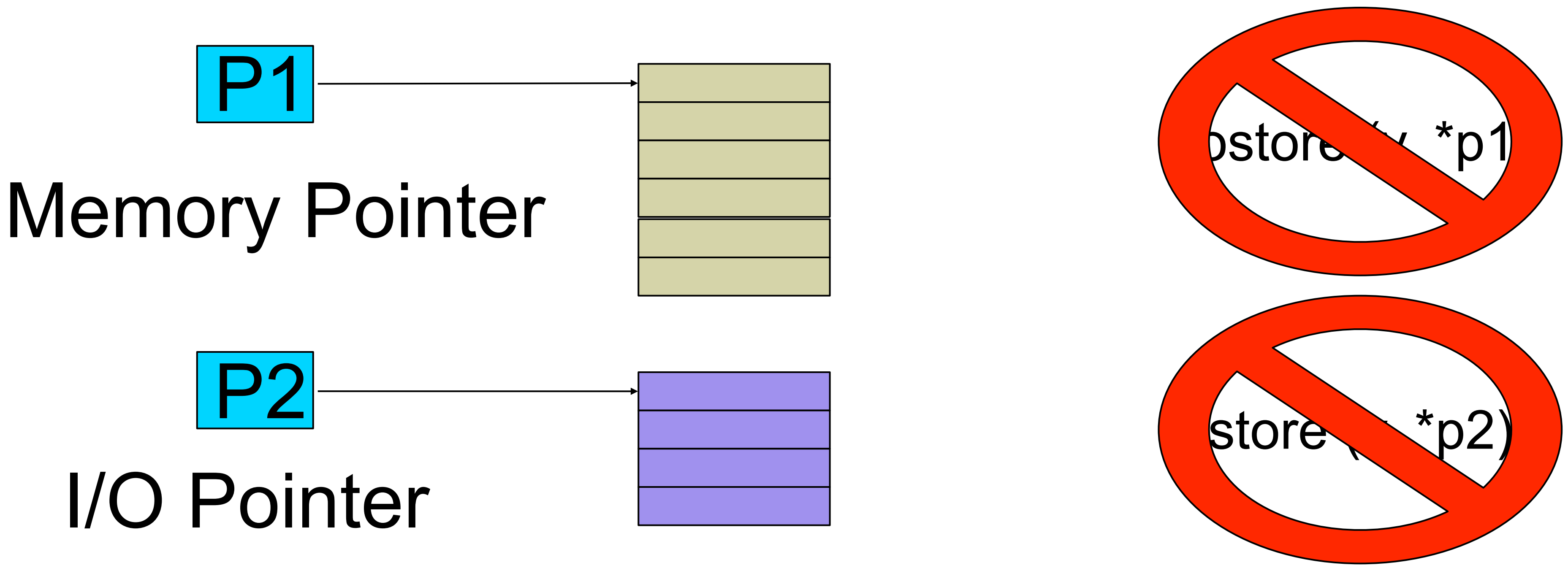
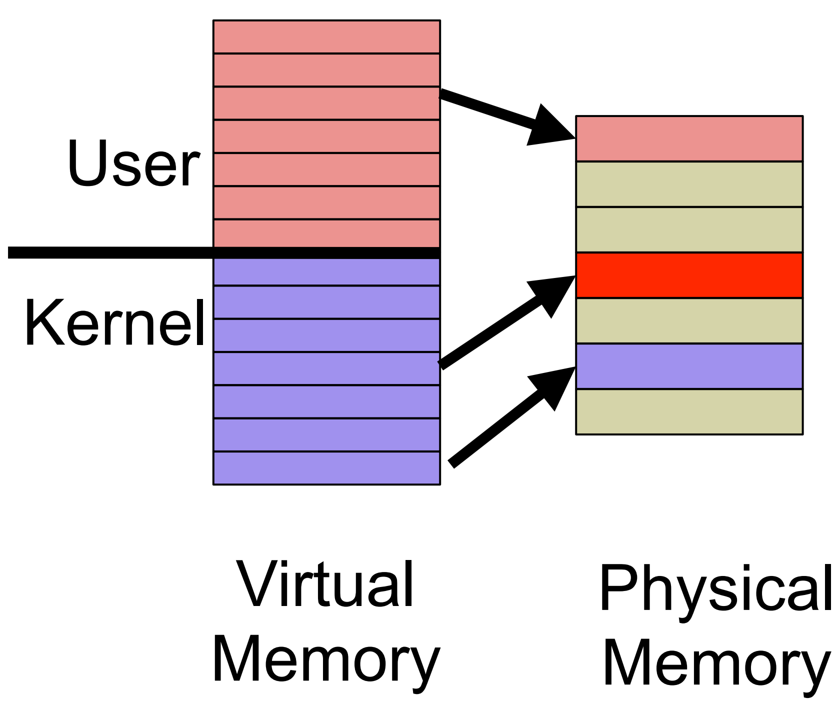
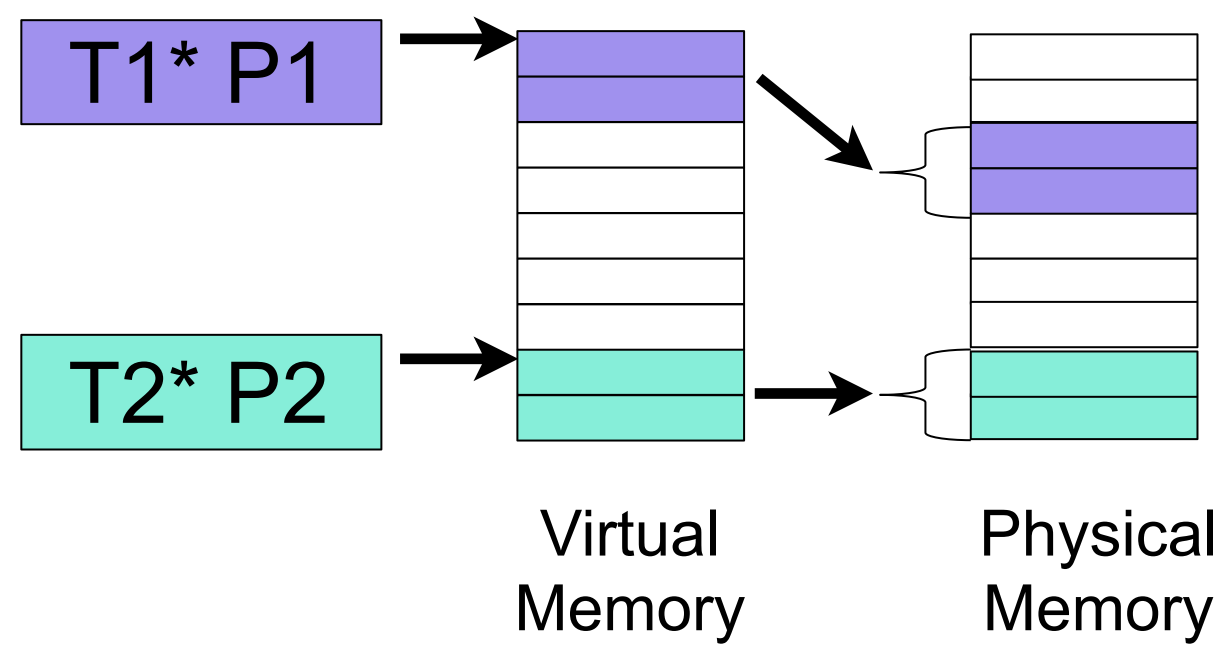


Solution: MMU

- Add run-time checks on MMU updates
  - Mapping kernel memory into user-space
  - Mapping data inconsistent with types
- Same mechanism as VMMs
  - Finer-grain checks





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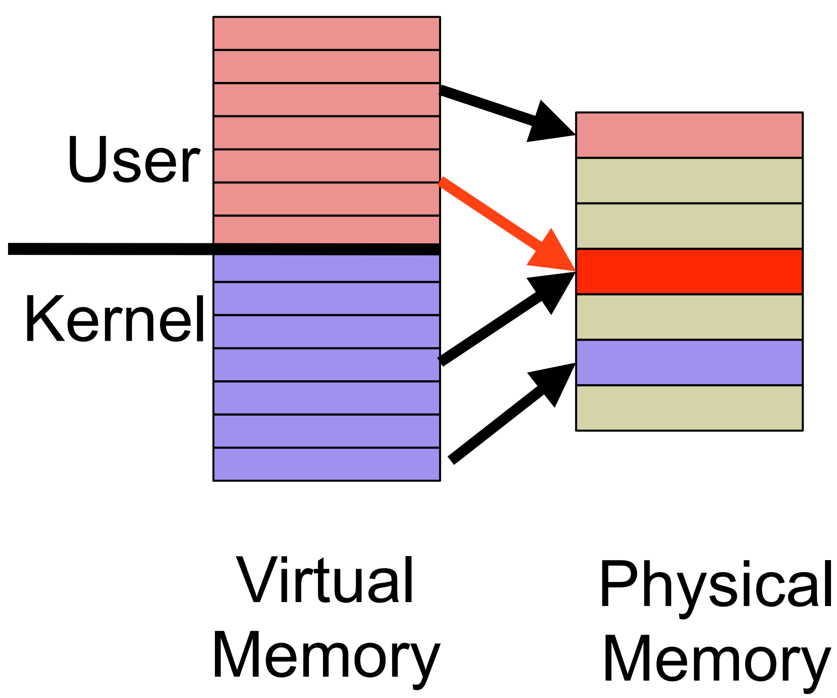

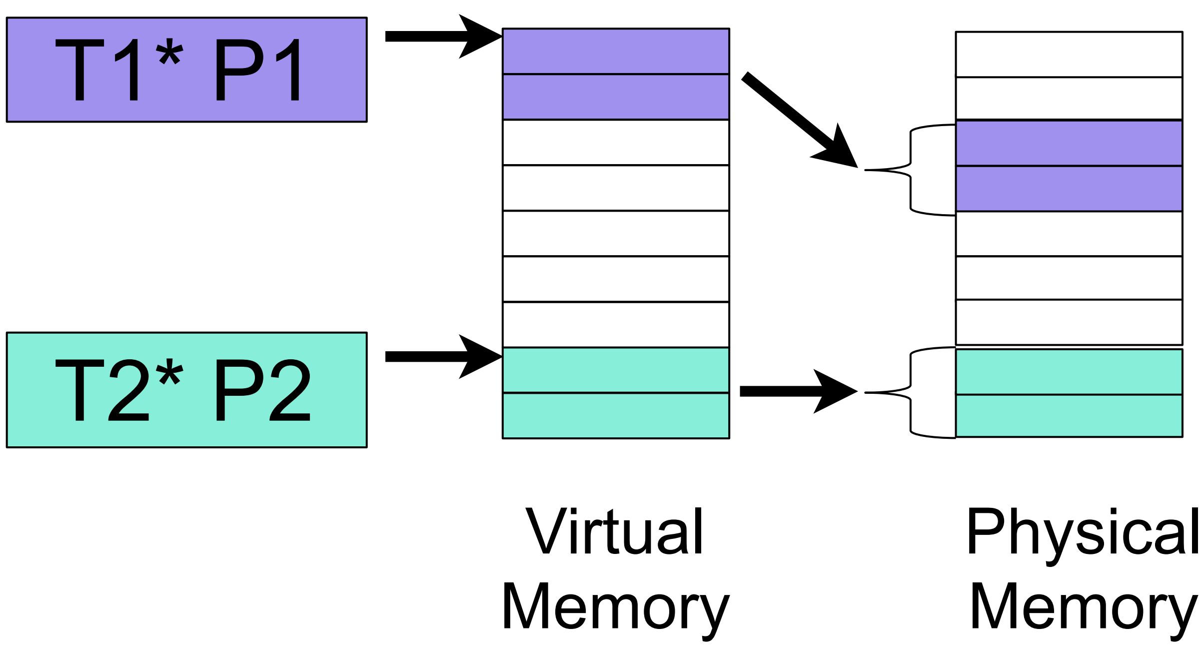

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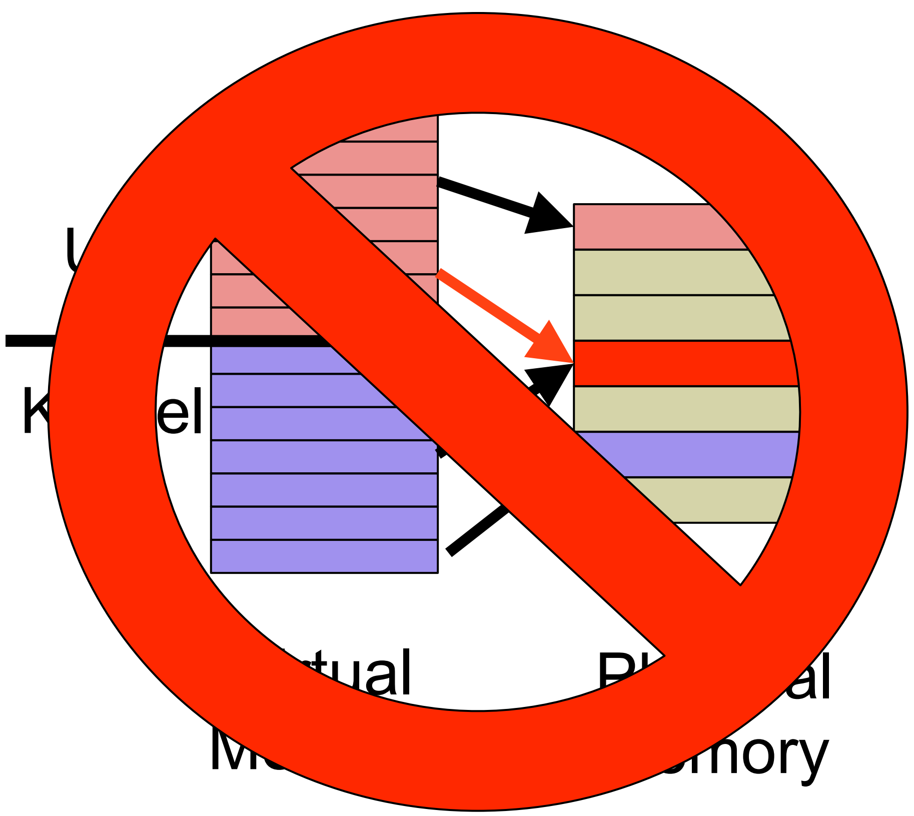

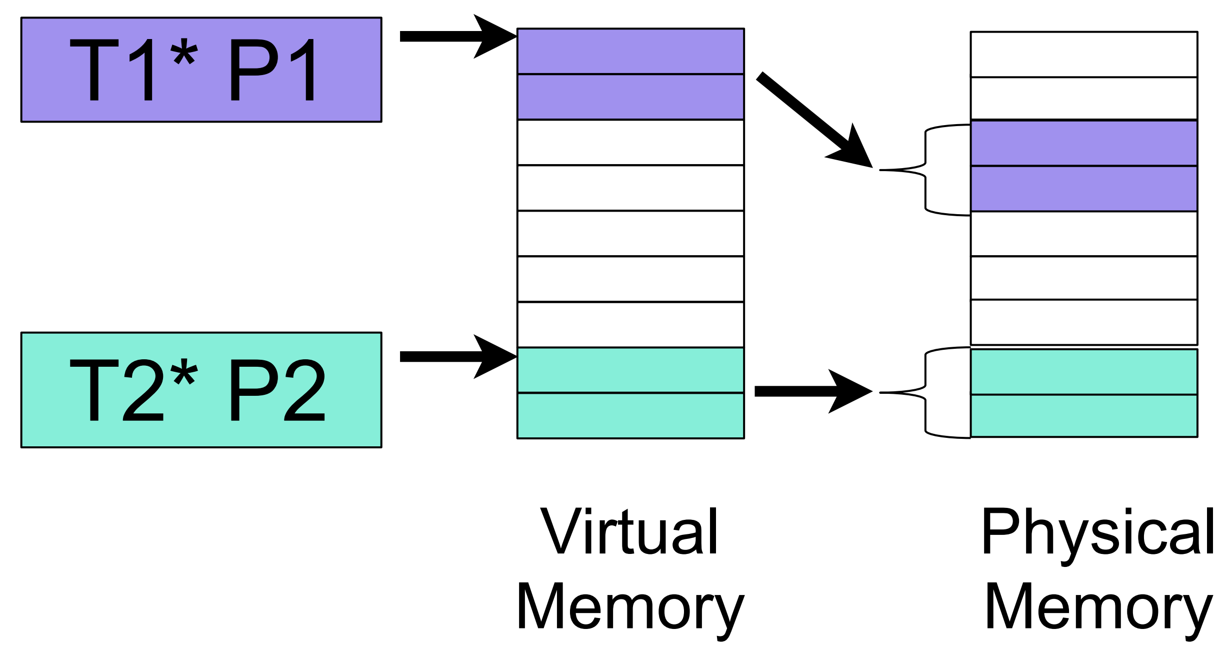

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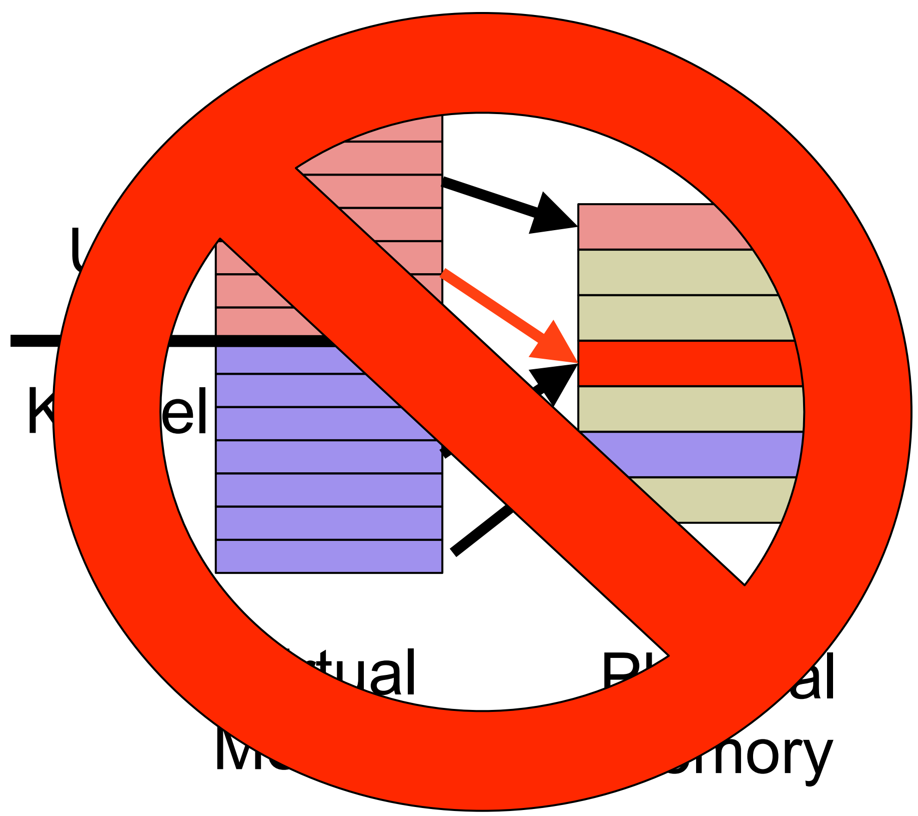

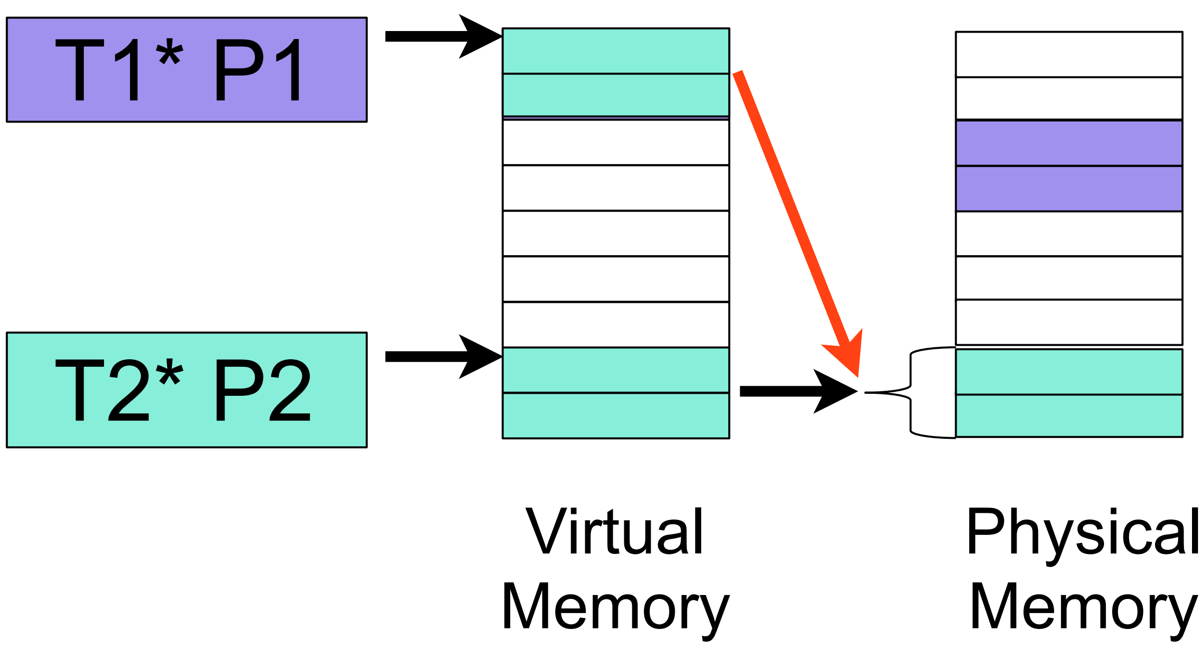

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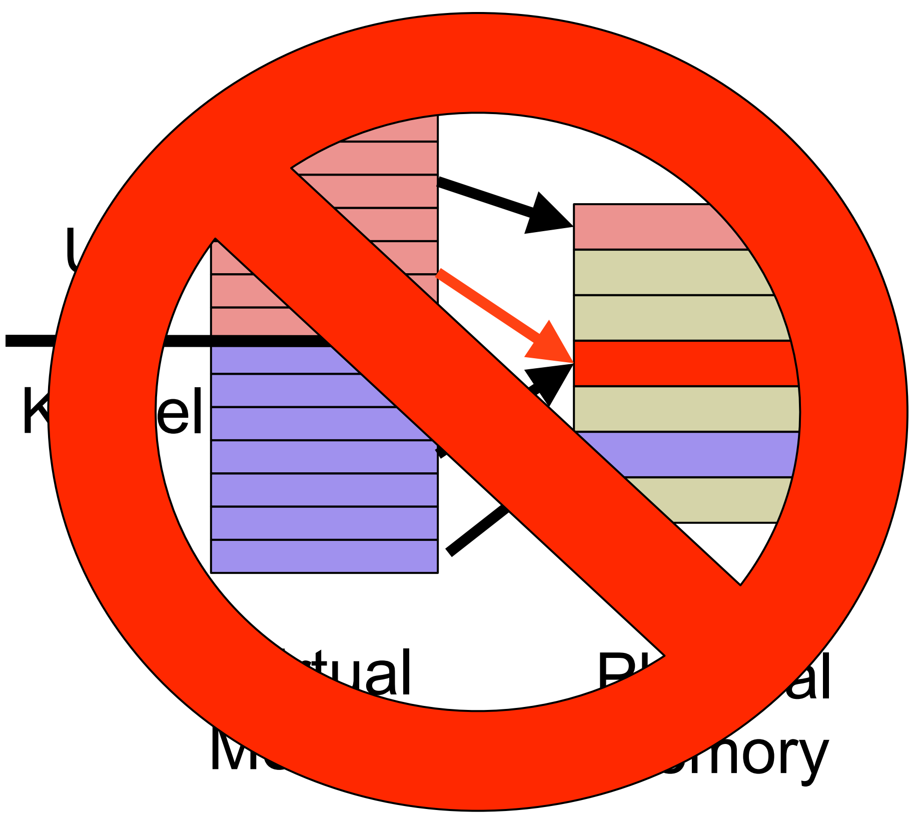

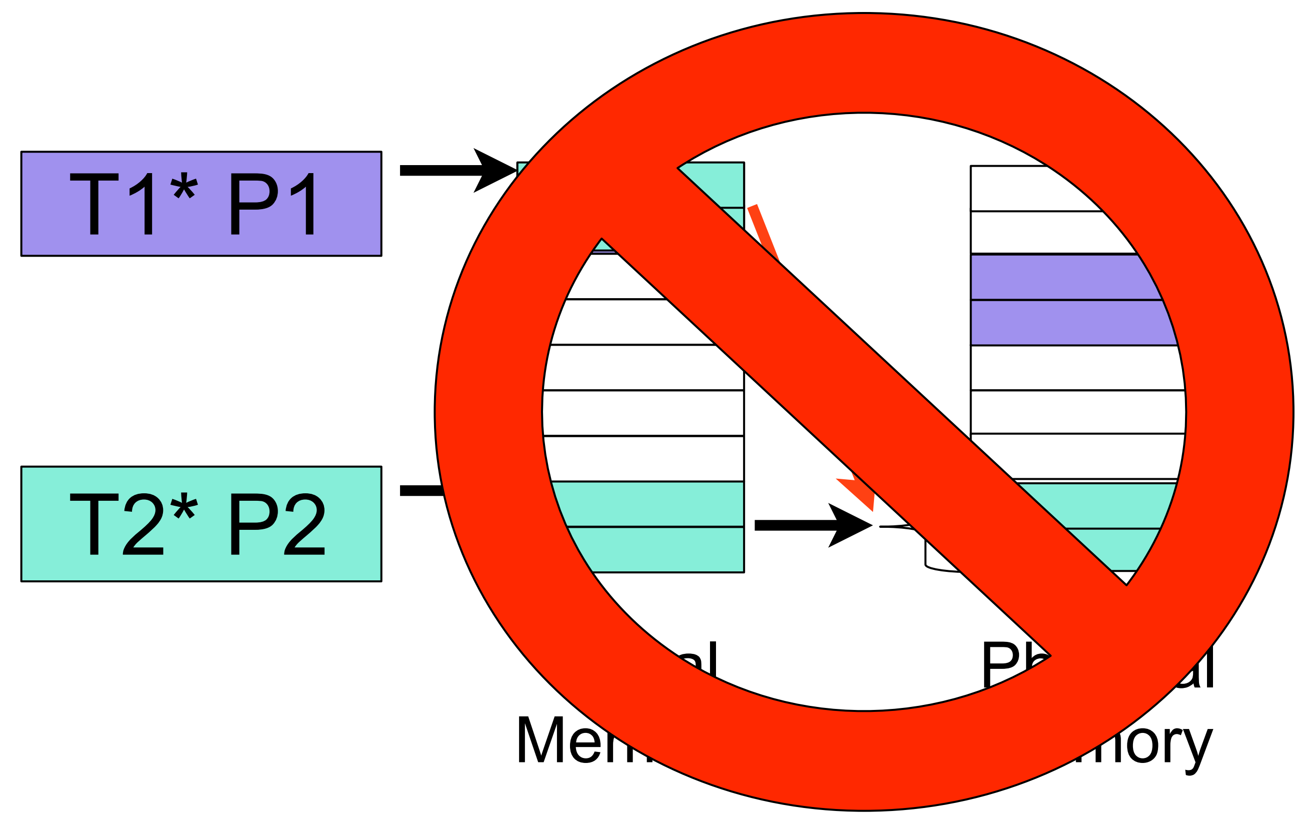

Outline

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- **Design of SVA-OS**
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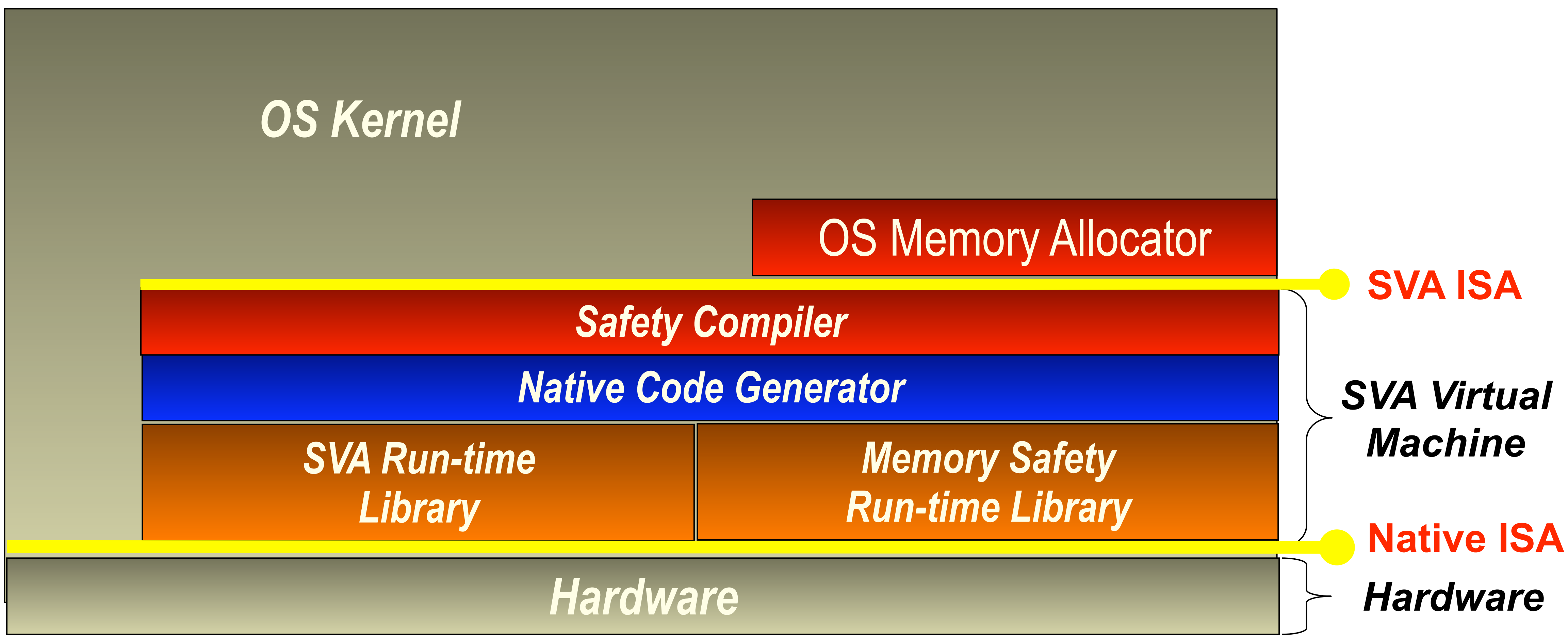
Secure Virtual Architecture[1]

- Compiler-based virtual machine
  - Hosts a commodity OS (e.g., Linux)
  - Provides traditional memory safety guarantees (control-flow and data-flow integrity)



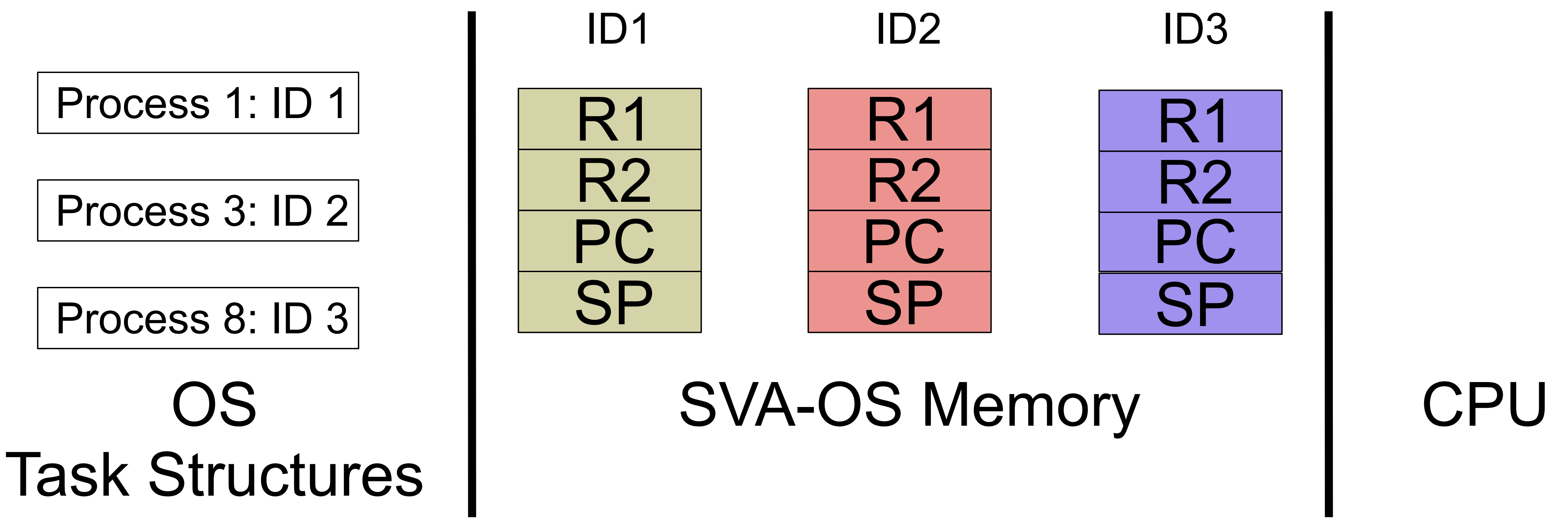
[1]Criswell et al. [SOSP 2007]

From SVA to SVA-OS

- Extend the SVA software/hardware interface
  - New instructions control software/hardware interactions
- Enforce memory safety for low-level operations
  - Use static analysis when possible
  - Add run-time checks when necessary

Solution: Processor State

- Save old state and place new state in a single instruction
  - **sva_swap_integer**
- Return opaque handle
- Buffer saved in SVA-OS memory
  - Buffer released on **sva_swap_integer** call



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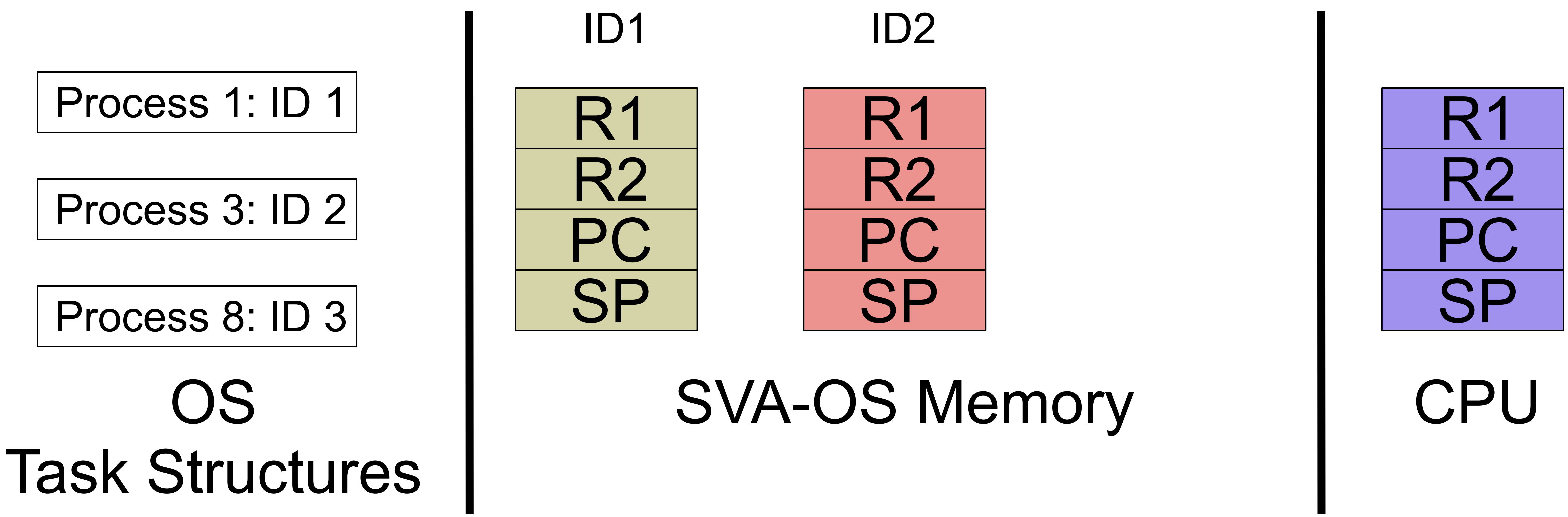

Solution: Memory Mapped I/O

- Operating system uses a pseudo-allocator
  - Map I/O objects into virtual address space
- New instructions for I/O reads and writes
  - **sva_io_readb**, **sva_io_writeb**
- Compiler marks I/O memory as type-unknown
  - Load/store check on each access
  - Load/store checks on memory objects that alias

Solution: MMU

- VMM-like interface to declare and update MMU mappings
  - **sva_declare_l1_page**, **sva_declare_l2_page**
  - **sva_update_l1_mapping**, **sva_update_l2_mapping**
- Runtime checks for typed memory
  - Pointer analysis in SVA segregates data by types
  - SVA-OS ensures this stays consistent
- Run-time checks for dividing memory
  - SVA-OS memory and kernel memory
  - Kernel memory and user-space memory
  - I/O memory and regular kernel memory

Linux 2.4 Port on SVA-OS

- Less than **100 lines changes** from original SVA Linux port
  - switch_to → sva_swap_integer
  - readb → sva_io_readb
  - set_pte → sva_update_l1_mapping
  - pte_alloc_one → sva_declare_l1_page
- Compiler changes:
  - Allocation of I/O objects: ioremap

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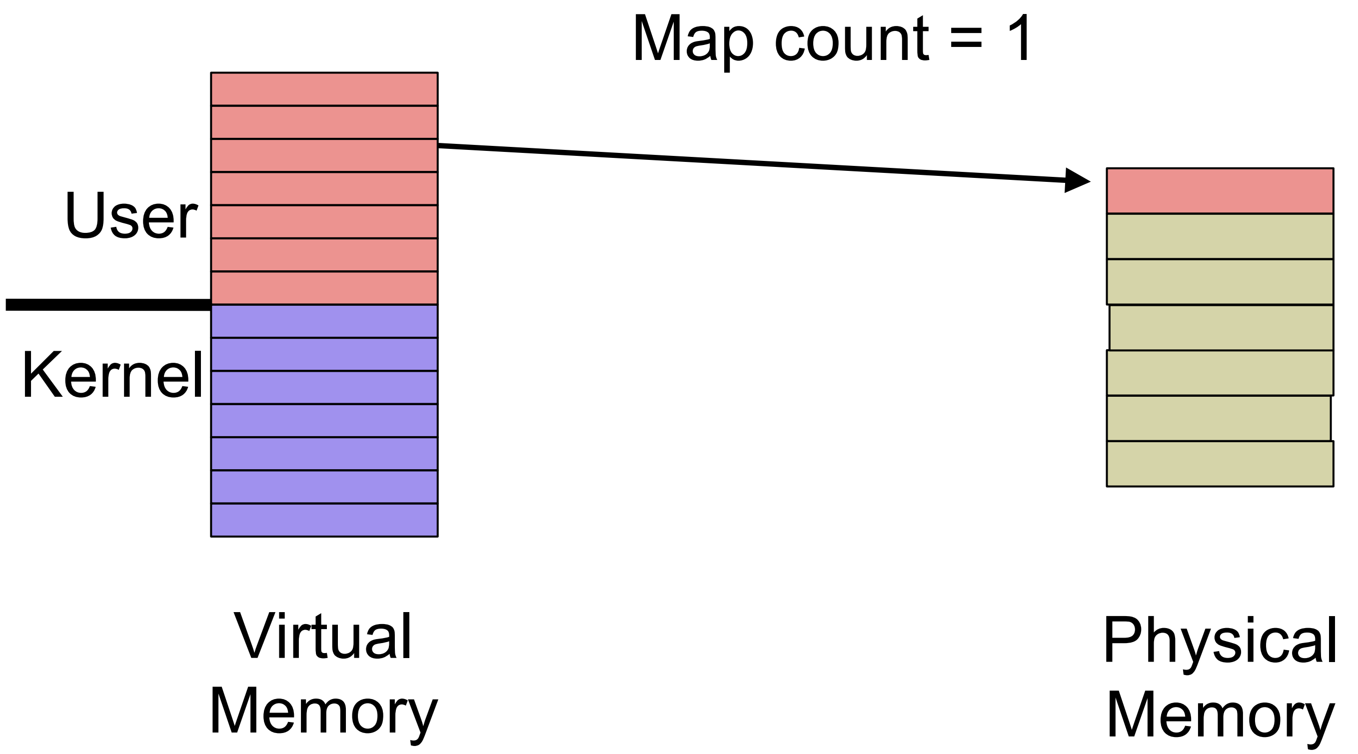
Does It Work?

- Tested two real world MMU exploits
  - BID9356, BID9686 on Linux 2.4
  - BID18177 exploit code not available
- Injected errors into our Linux 2.4 port
  - New system calls
- Studied the E1000E Intel Network bug
  - Paper study because only on Linux 2.6

MMU Exploits on Linux 2.4

- BID9356
  - **fork**, **mmap**



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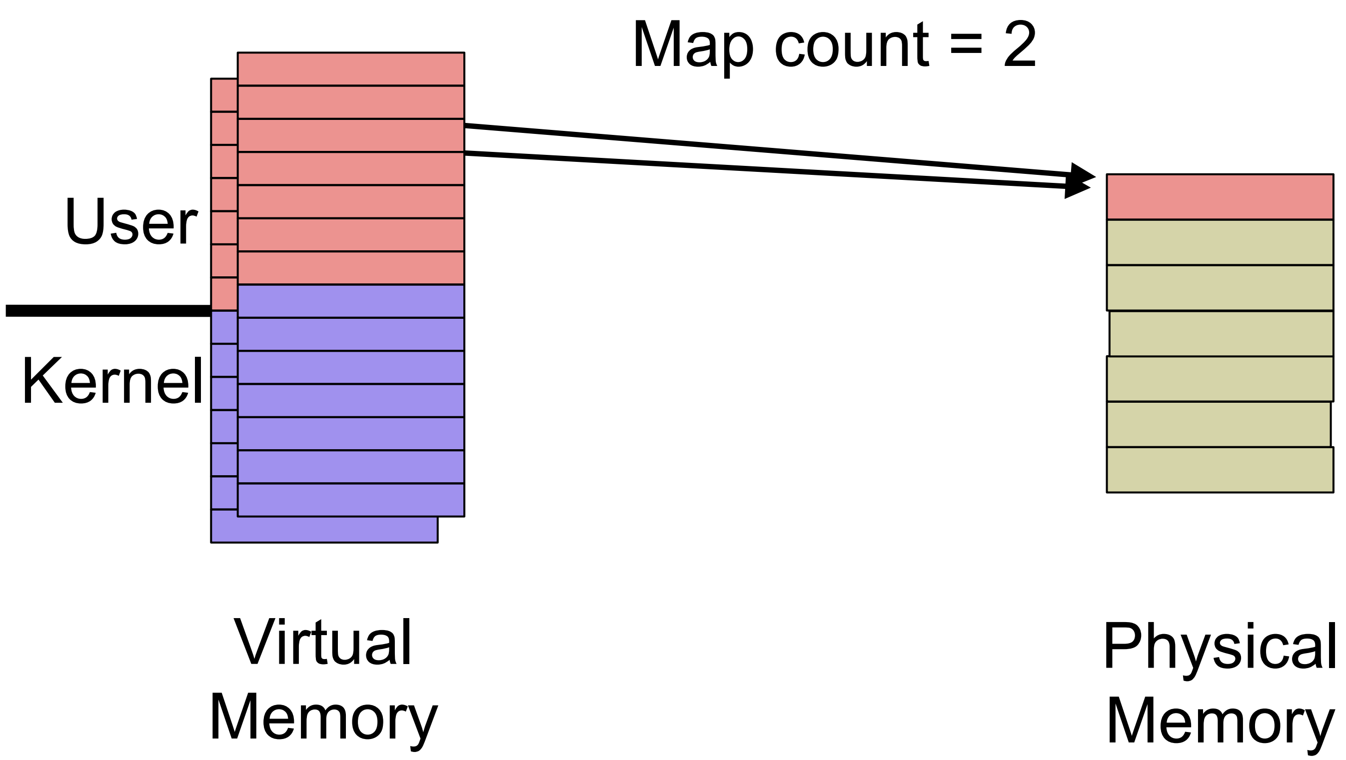

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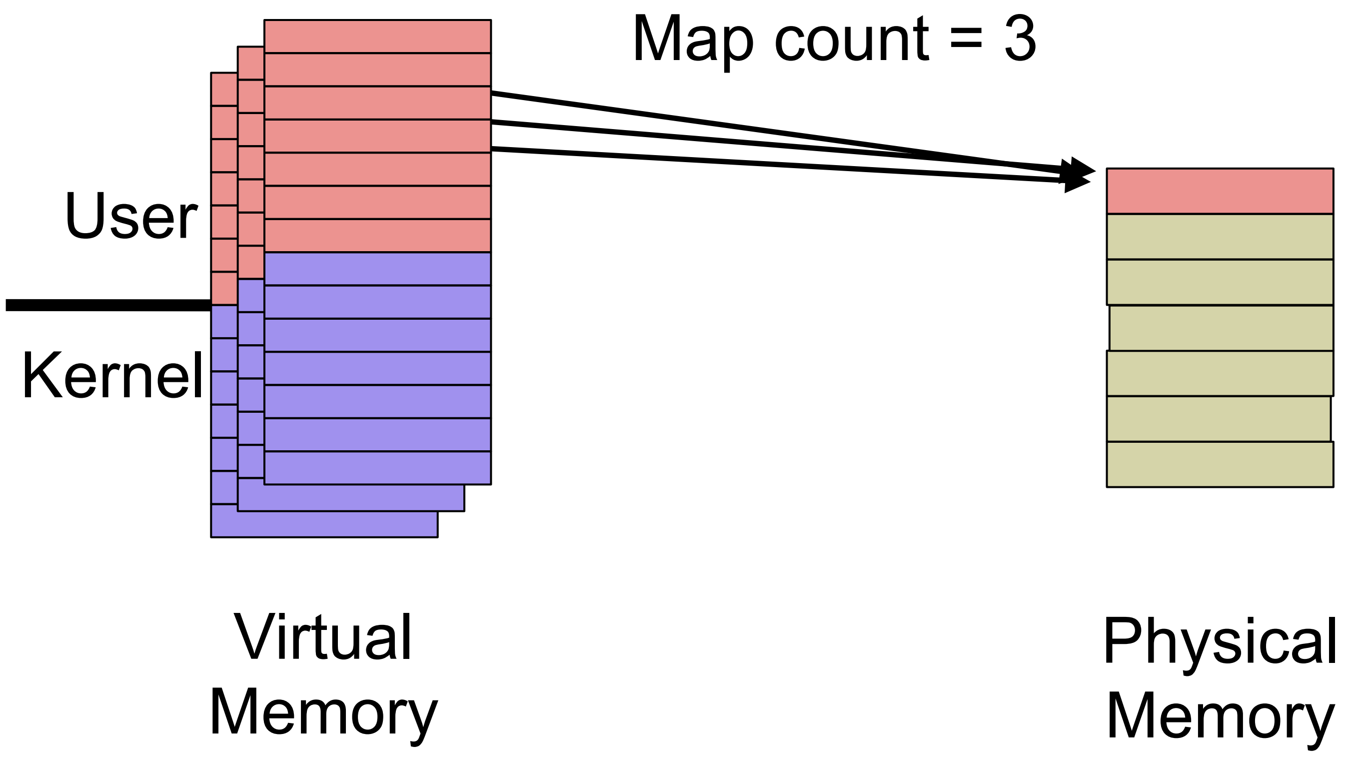

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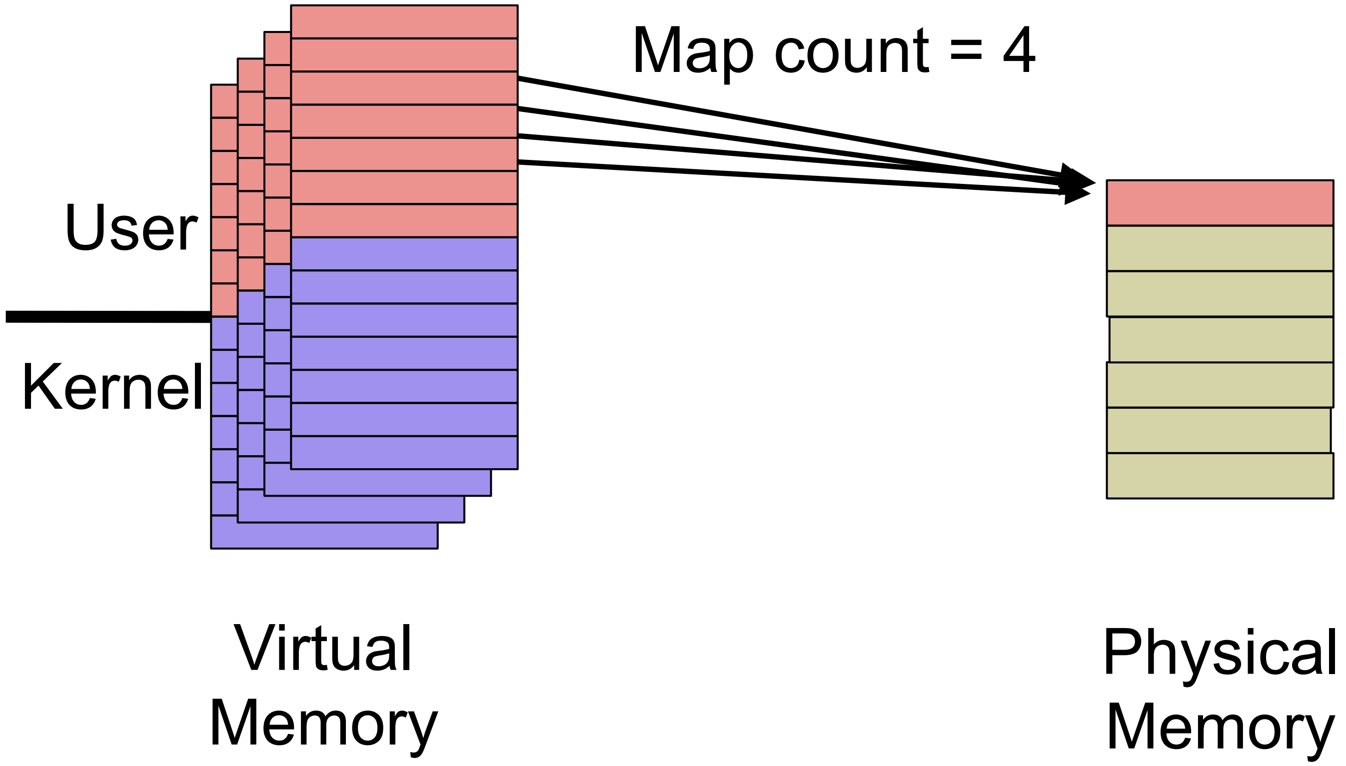

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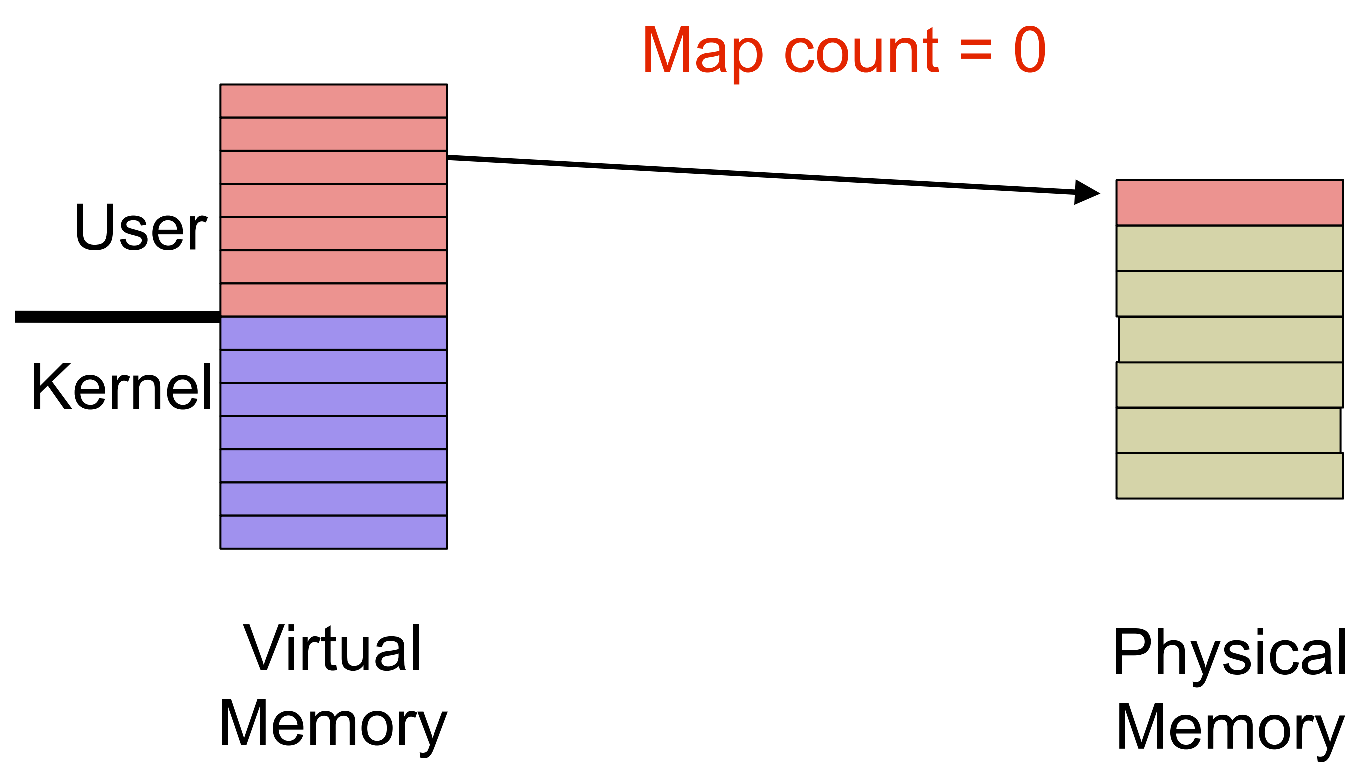

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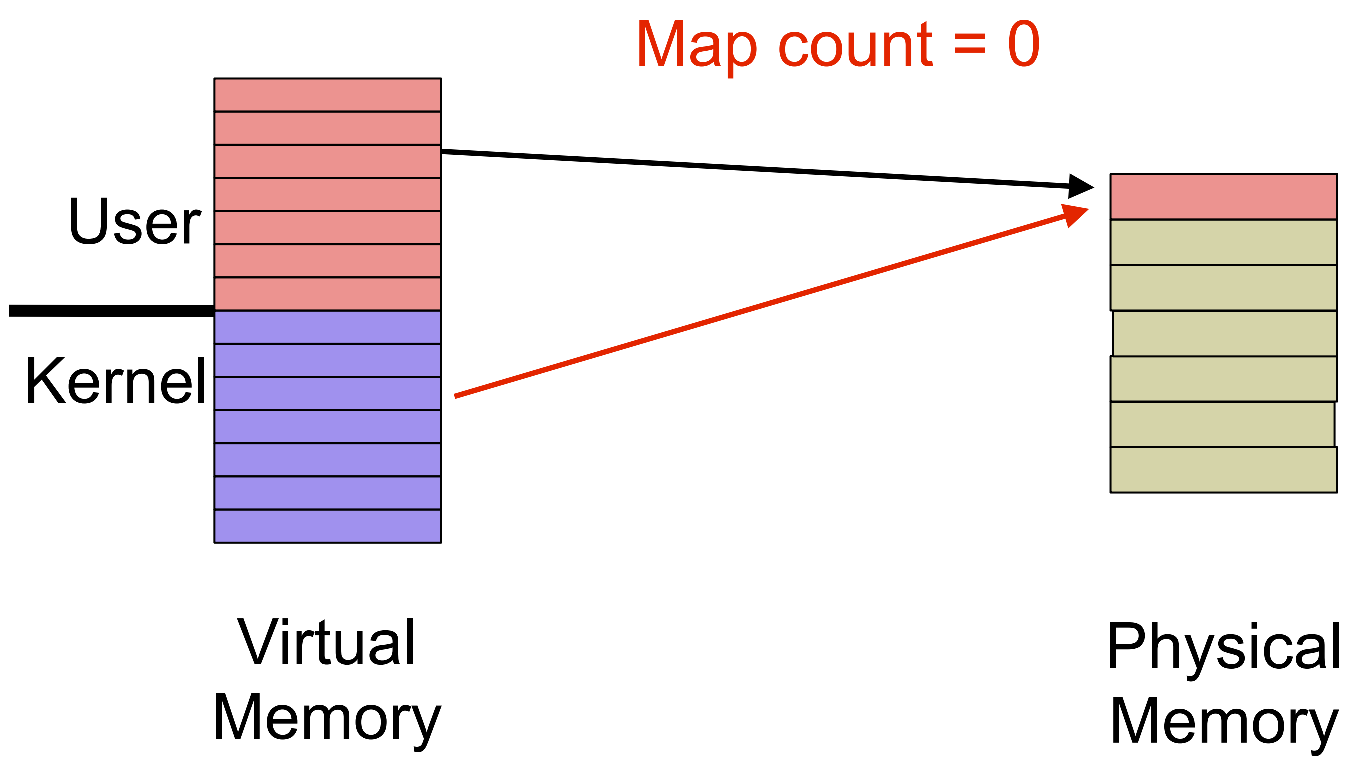

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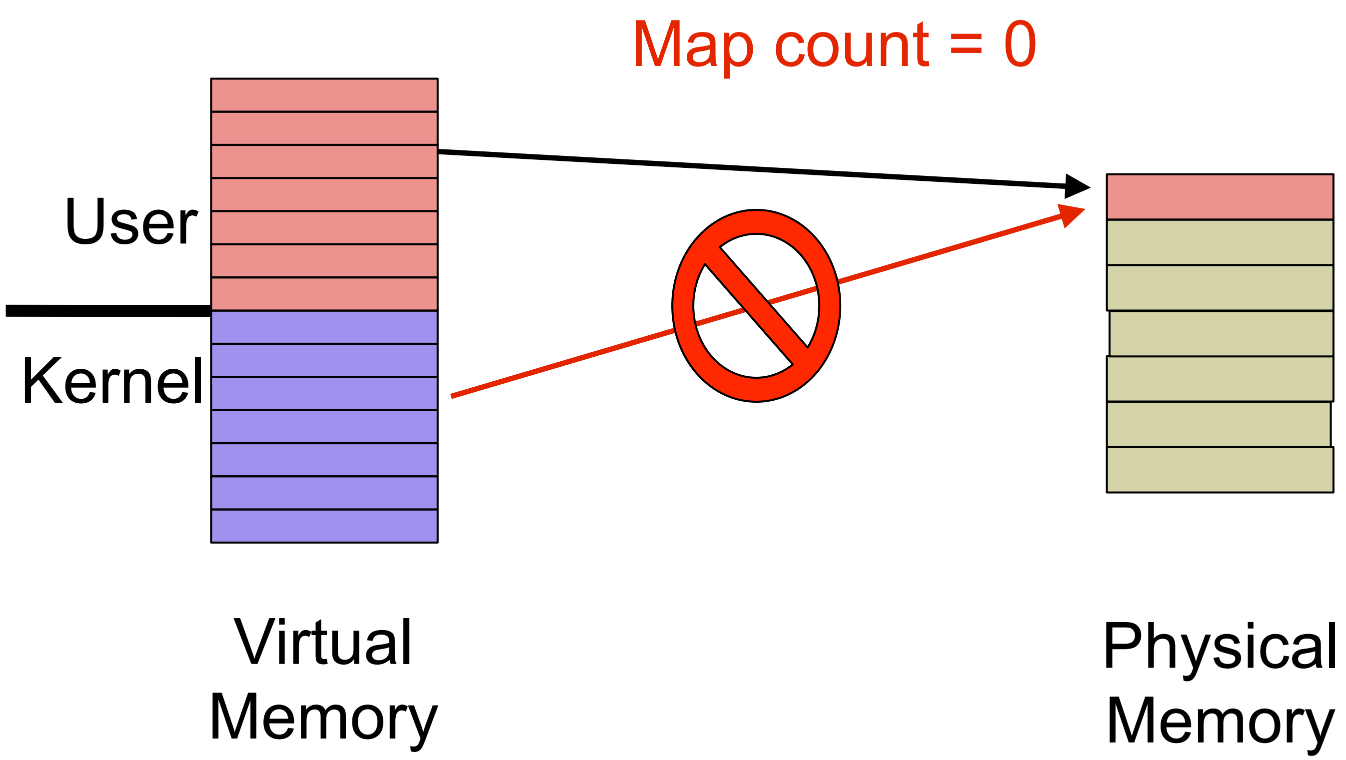

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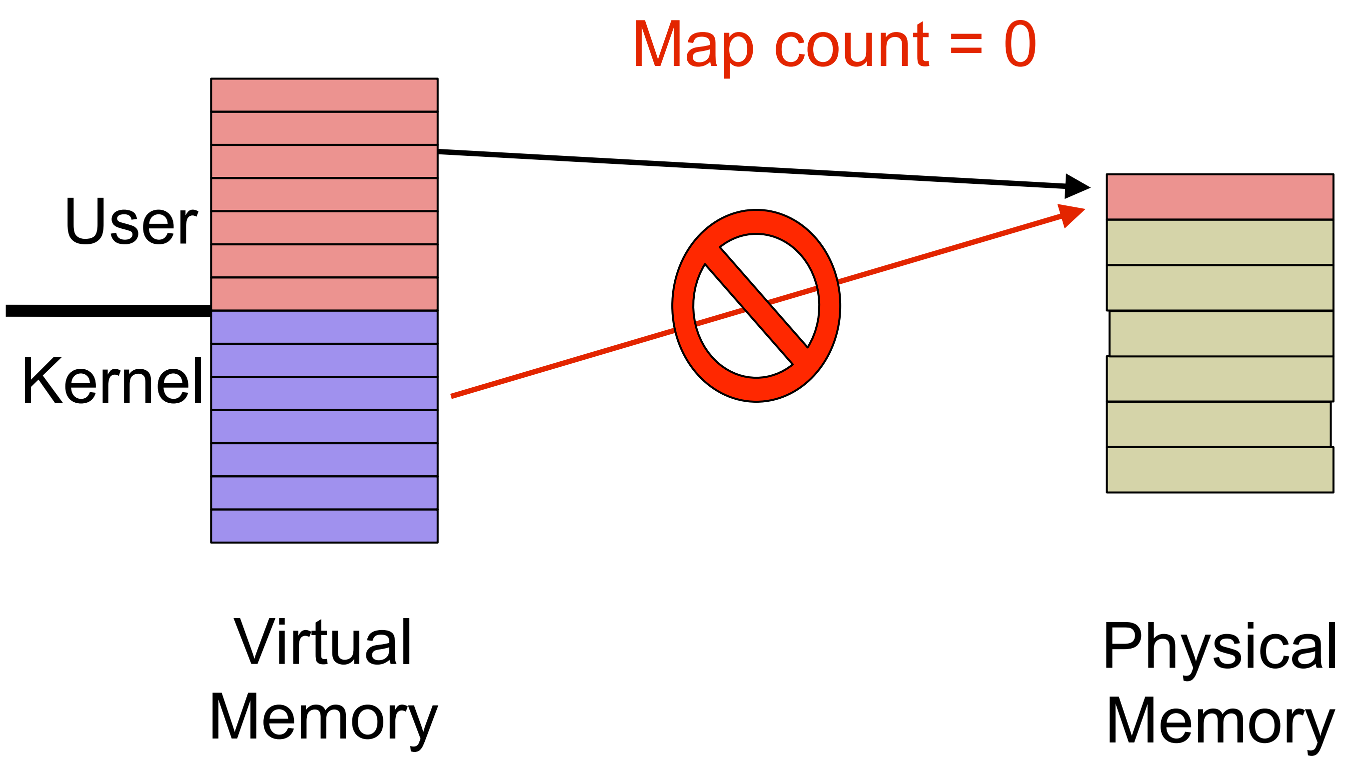

- BID9686
  - Missing error check on **mremap**
  - MMU mappings not cleared

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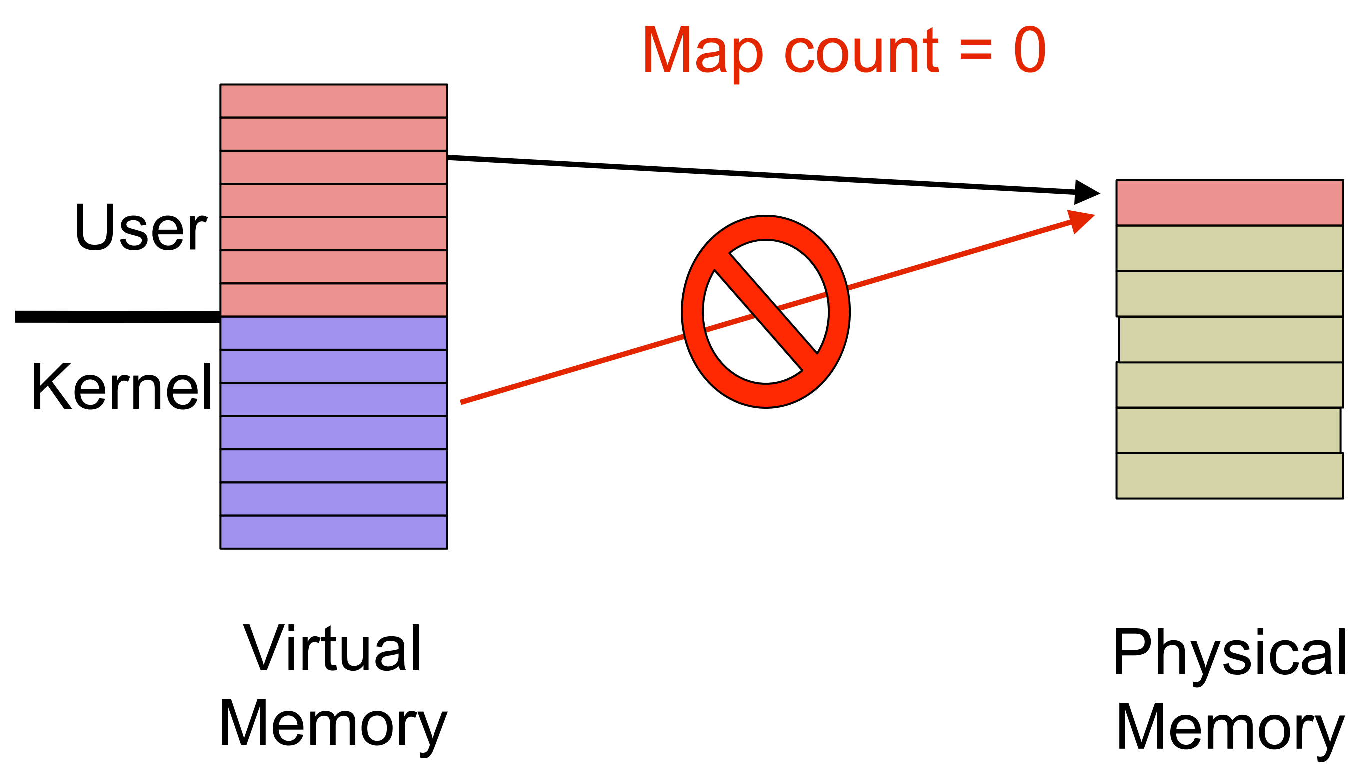

- BID9686
  - Missing error check on **mremap**
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Both bugs were detected by SVA-OS, not SVA

Error Injection

- Modification of Processor State
- Double mapping of a type-safe memory object
- Modify metadata of SVA with incorrect bounds

Error Injection

- Modification of Processor State

  SVA: control flow changed

  SVA-OS: Caught as an invalid integer to pointer cast
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- Double mapping of a type-safe memory object

  SVA: Subsequent store succeeds

  SVA-OS: Second mapping caught by MMU checks

- Modify metadata of SVA with incorrect bounds

Error Injection

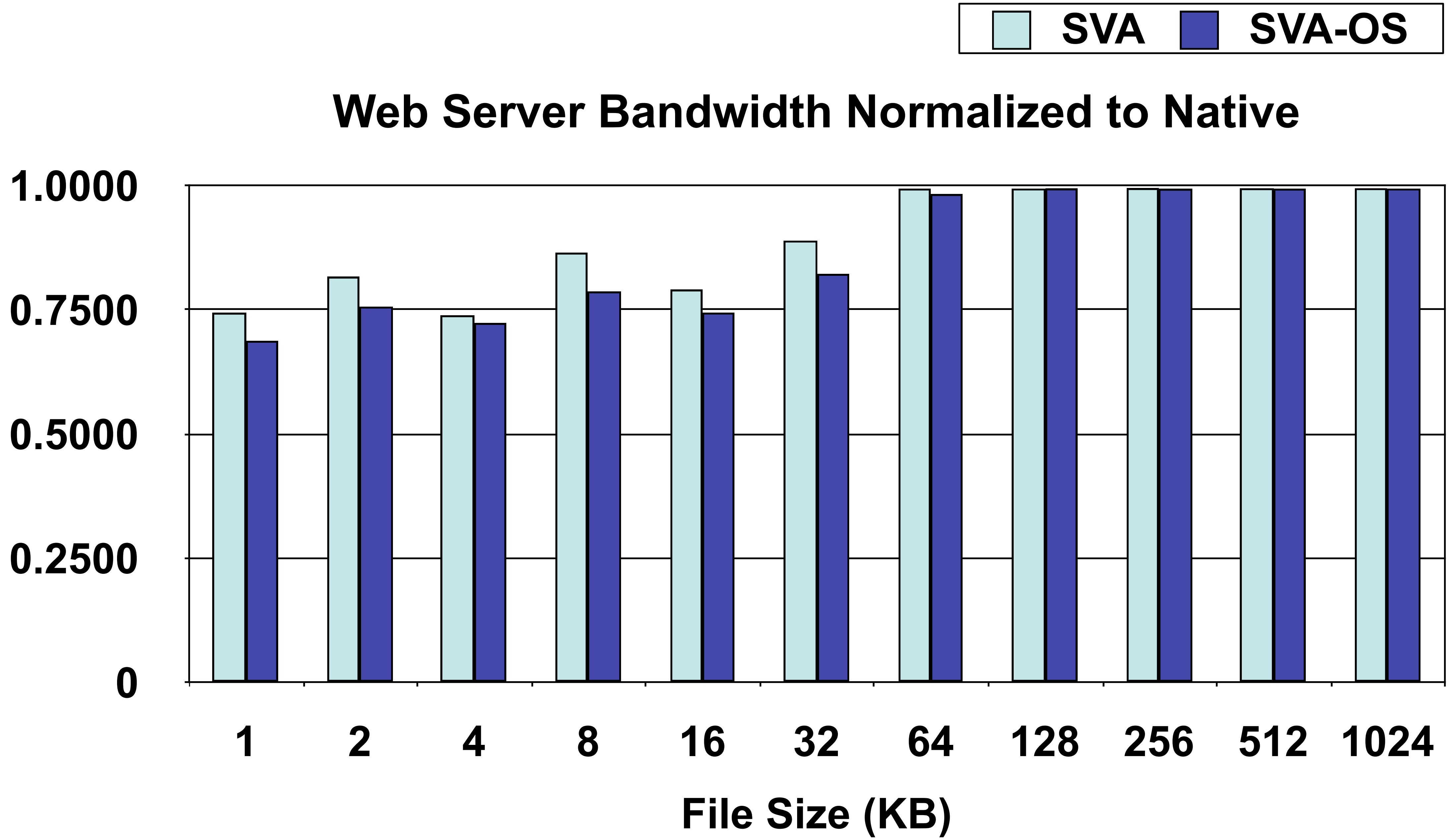
- Modification of Processor State
  - ***SVA: control flow changed***
  - ***SVA-OS: Caught as an invalid integer to pointer cast***
- Double mapping of a type-safe memory object
  - ***SVA: Subsequent store succeeds***
  - ***SVA-OS: Second mapping caught by MMU checks***
- Modify metadata of SVA with incorrect bounds
  - ***SVA: Memory safety guarantees disabled***
  - ***SVA-OS:Access to SVA memory caught by MMU checks***

E1000E Bug on Linux 2.6

- cmpxchg on dangling pointer
  - Instruction thought it was code memory
  - Unpredictable behavior on I/O memory
  - **Network card damaged**
- With SVA-OS
  - No I/O memory mapped on code page
  - Load/Store checks on I/O memory

Web Server Bandwidth: thttpd

- Athlon 2100+, 1GB of RAM, 1Gb/s network
- Higher is better
- Micro-benchmark overheads in paper



User-Application Benchmarks

- Negligible overhead on user-space applications

Benchmark	i386 (s)	SVA (s)	SVA-OS (s)	% Increase (i386 to SVA-OS)
bzip2	18.7	18.3	18.0	0.0%
lame	133.3	132.0	126.0	-0.1%
perl	22.3	22.3	22.3	0.0%

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Future Work

- Improve Static Analysis
  - Reduce run-time checks
- Additional Security Properties
  - Information flow control
- Apply to other systems
  - Type-safe language OS, e.g. Singularity
  - JVMs, hypervisors

Contributions

- Identified memory-safety violations from low-level software/hardware operations
- *First system* to provide comprehensive safety guarantees for such operations
  - Leaves control under OS
  - Incurs little run-time overhead above SVA

Questions?

See what we do at http://sva.cs.uiuc.edu