Privbox: Faster System Calls Through Sandboxed Privileged Execution

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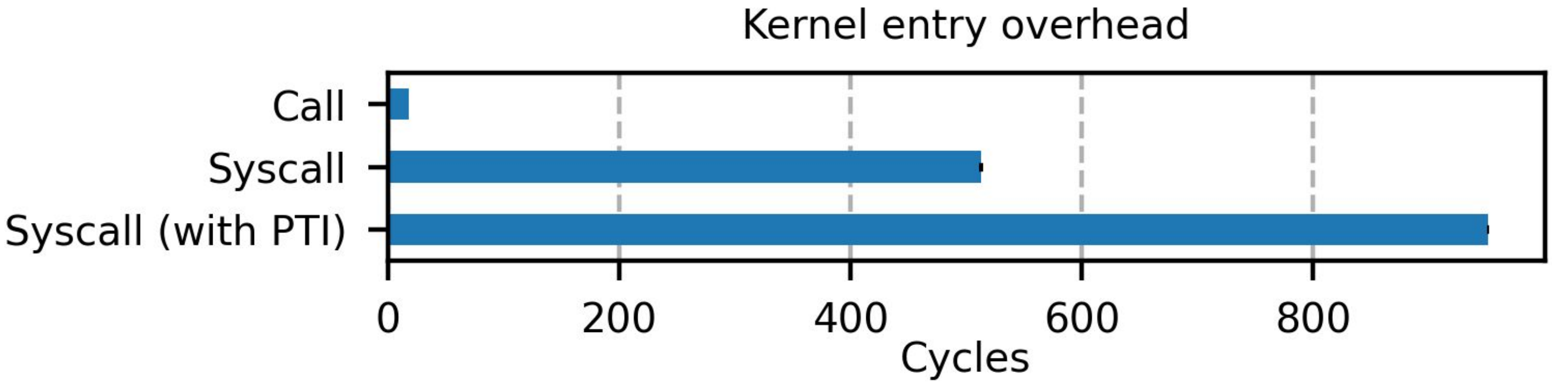
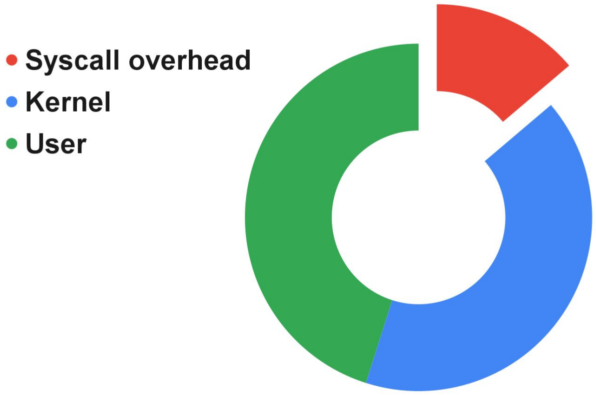
System Calls

- Main interface for requesting operating system services
- Semantically similar to simple function call (i.e. prepare parameters, invoke, receive result)
- Unlike function call, involves many more steps and is much slower!
  - E.g. hardware: privilege level change
- Spectre/Meltdown mitigations (e.g. PTI) make things even worse



System Call Overhead

- Particularly bad for system call heavy workloads
  - Recall: almost all I/O operations eventually translate to a system call
  - System call heavy = I/O heavy
- Back-of-the-envelope: Redis
  - 200k requests / second (single threaded, w/o pipelining)
  - At least 2 system calls per request (recv + send)
  - ~900 cycles per system call
  - ✗ **Over 13% of a core running at 2.6GHz**



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- **Batching (*preadv/…*):** perform less round-trips to kernel by doing several operations each entry:
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- **Kernel bypass (*DPDK, SPDK*):** map whole device into process memory:
  - ✗ No high-level abstractions from kernel (files, sockets)
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➢ **All of the above require software re-architecture!**

Privbox

- New mechanism for system call intensive workloads that allows **system calls with less overhead**
- **Privbox** achieves this by allowing user programs to load and execute system call heavy code under a new **semi-privileged** (almost kernel-like) **but sandboxed** execution mode

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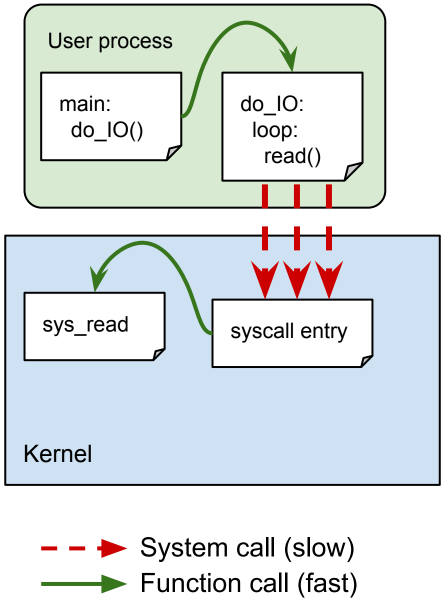
Advantages:

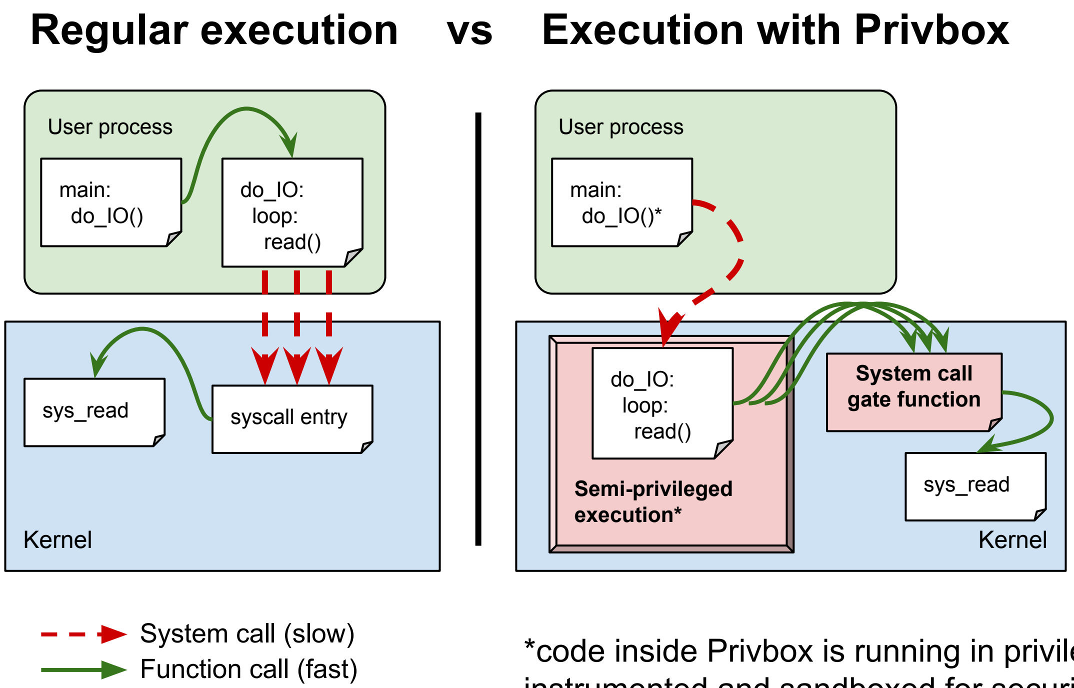
- ✓ 2.2x less system call overhead
- ✓ System call retain familiar and synchronous semantics
- ✓ Does not require software re-architecture or major source code changes
  - ➢ Example: Memcached:
    - ✓ Ported to use Privbox in under one hour and 70 LOC

Privbox Mechanism

Regular execution



Privbox Mechanism



*code inside Privbox is running in privileged CPU mode, but instrumented and sandboxed for security

Semi-Privileged Execution Mode (SPEM)

- New execution mode for user processes
  - Based on Kernel-mode Linux
- Used during Privboxed code invocation

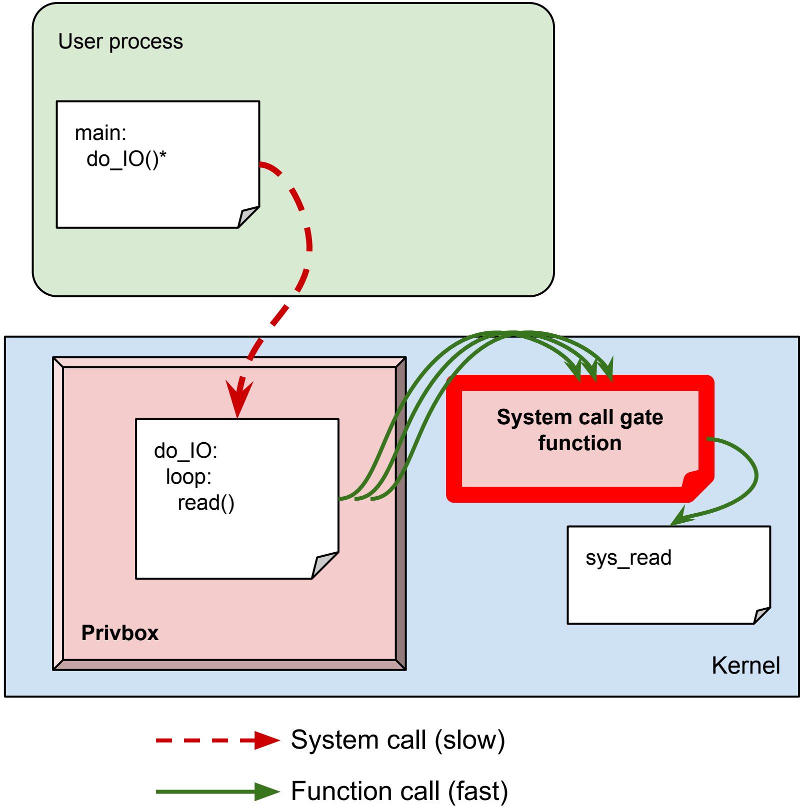
Details:

- Runs under privileged CPU mode (e.g. ring 0)
- Allows system calls through system call gate function
- Identical to regular processes from all other perspectives
  - Same permission checks, scheduling, etc

	Regular	SPEM
Subject to permissions checks	✓	✓
Preemptible	✓	✓
Can block	✓	✓
...	✓	✓

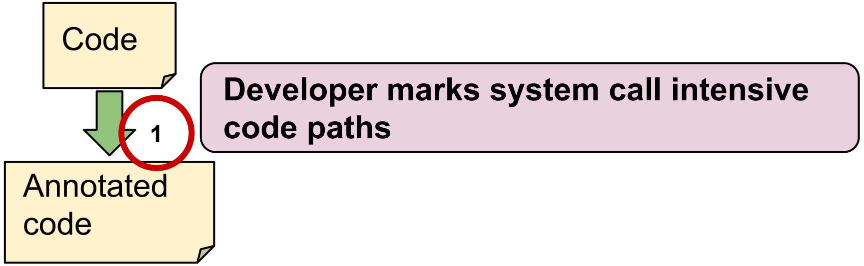
System Call Gate Function

- Function in kernel memory
- Similar to syscall instruction handler
  - ✓ But with less steps
- Same semantics
- Reach kernel code through function calls
  - ✓ No need to change privilege level



Flow

1. Developer marks code intended for Privbox



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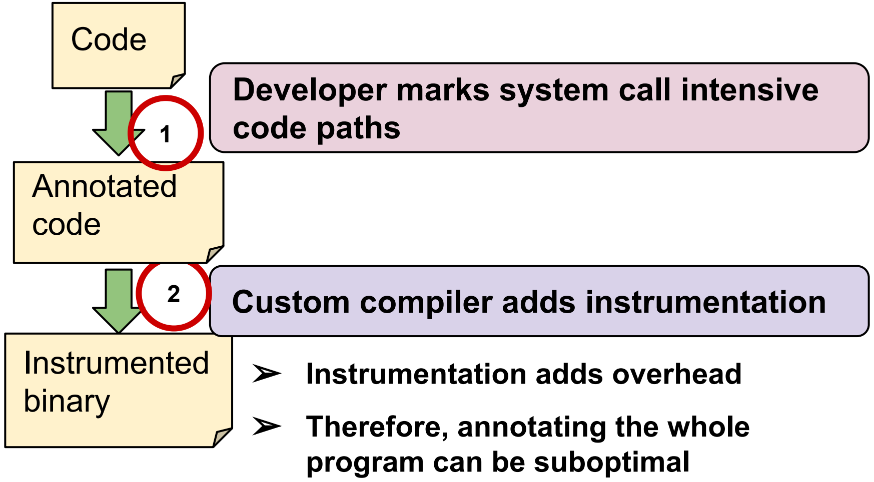

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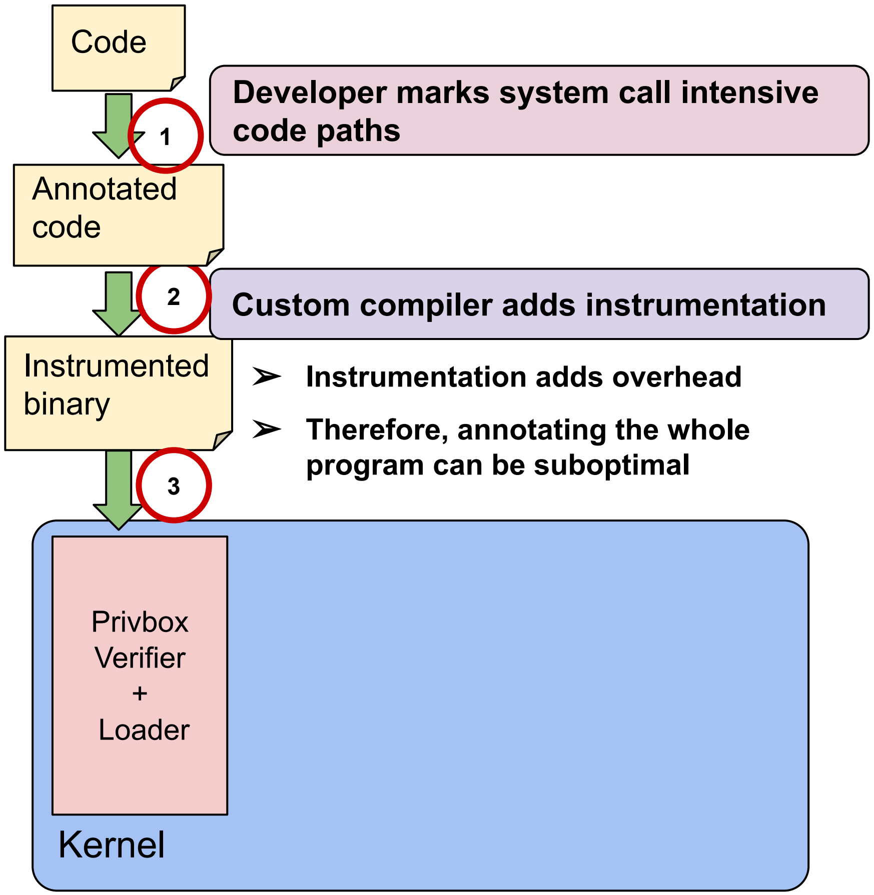

Flow

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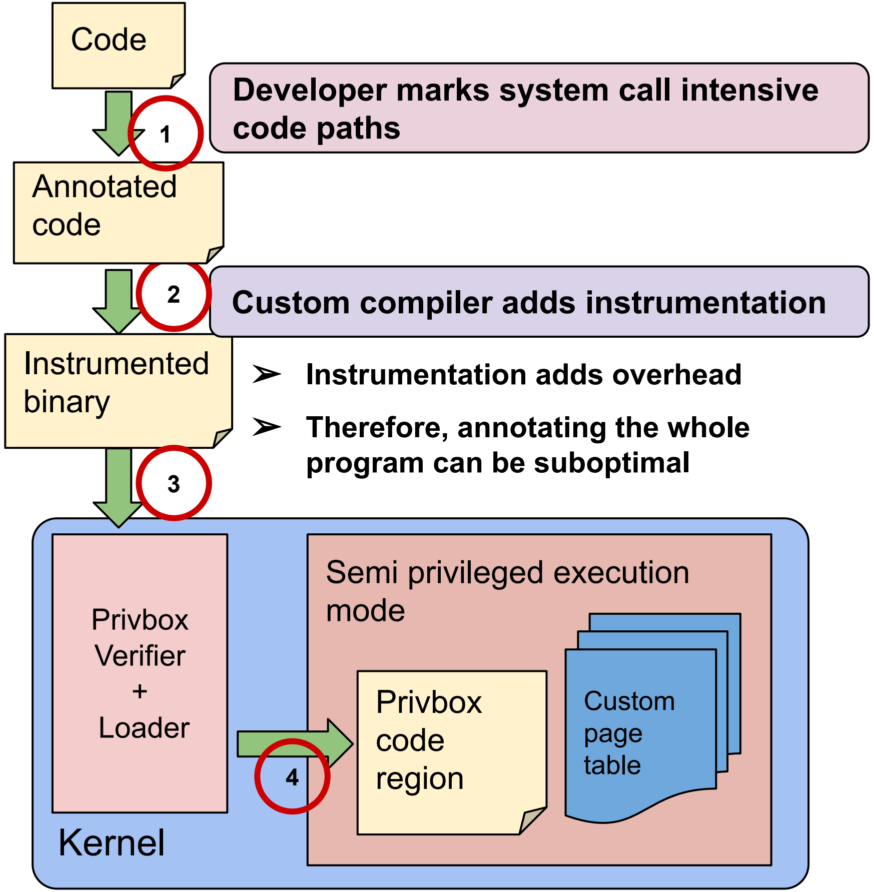
2. Developer compiles code with a custom compiler that introduces instrumentation
3. Program loads instrumented code into a Privbox environment
4. Program can invoke loaded code through a special system call that transfers control to invoked code under Semi-Privileged Execution mode



Porting Programs to Privbox

```
do_IO(...) {
  for (...) { ...}
  return result;
}

main(...) {
  …
  do_IO(...);
  …
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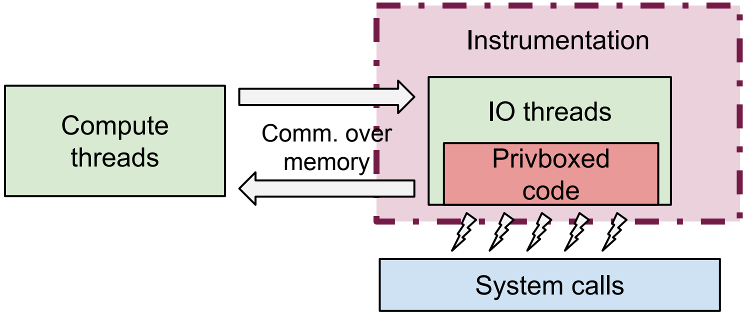
Application with Privbox

✓ Minimal code changes
✓ Well suited for I/O threaded workloads



Safety Requirements

Problem:

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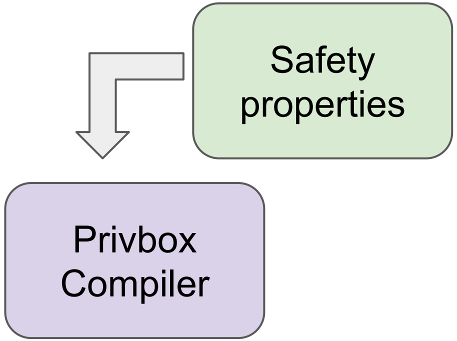
High-level safety objective: no new access through Privbox

Sandbox imposes following properties on loaded code:

1. No privileged instructions
2. No kernel memory accesses
3. No branching to unverified code

Compilation and Verification

- Safety of Privbox relies on verification of loaded code
- Inspired by Native Client work
- **Privbox Compiler:**
  - Transforms potentially unsafe instructions into equivalent but verifiably safe instruction sequences



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- **Privbox Compiler:**
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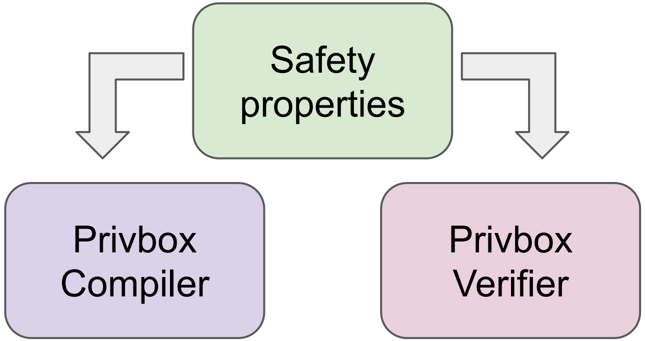
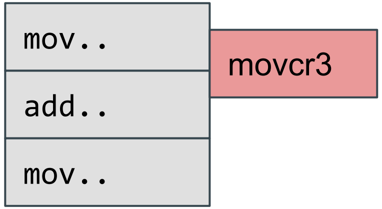
- **Privbox Verifier:**
  - Triggered each time code is loaded into Privbox
  - Disassemble loaded code
  - Reject if code violates safety requirements



Verification



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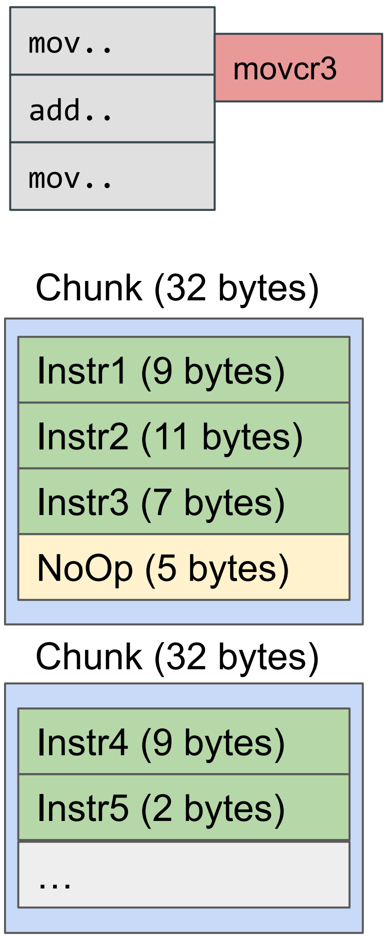

Verification

- **Challenge:**
  - Variable length instructions hamper the ability to disassemble code
- **Code chunk**:
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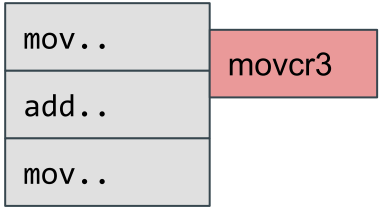
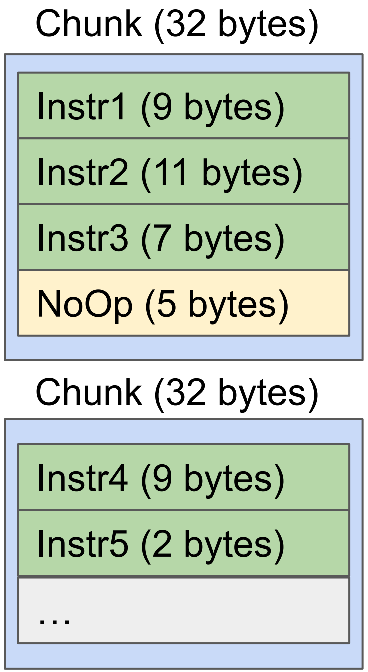
- **Solution**:
  - Pack code into *code chunks*
  - Restrict branching to chunk-aligned addresses





Privileged Instructions

- Trivial:
  - Check during disassembly
  - Reject if present

No priv. instructions	✓
No kernel access	N/A
No branching outside sandbox	N/A

Load/Store Instructions

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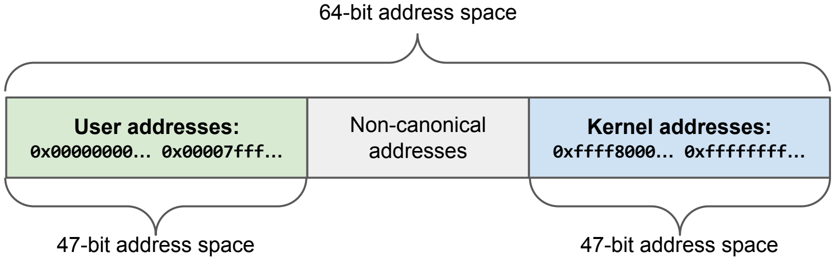
- Effective address of memory operand may be known only at run time
- **Safety requirement:**
  - No kernel memory access
- **Sanitation:**
  - Mask most significant bit of memory operand
  - `addr => addr & ~(1<<63)`
  - … no longer a kernel address

No priv. instructions	**N/A**
No kernel access	**✓**
No branching outside sandbox	**N/A**



Memory load:

```
%dest = mov disp(%base, scale, %index)
```

⇩

```
%tmp1 = lea disp(%base, scale, %index)
%tmp2 = btr $63, %tmp1
%dest = mov (%tmp2)
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  - Mask MSB and clear lowest bits
  - `addr => addr & ~(1<<63) & ~31`
  - ... non-kernel address and chunk-aligned.

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Indirect function call:

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call disp(%base, scale, %index)
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⇩

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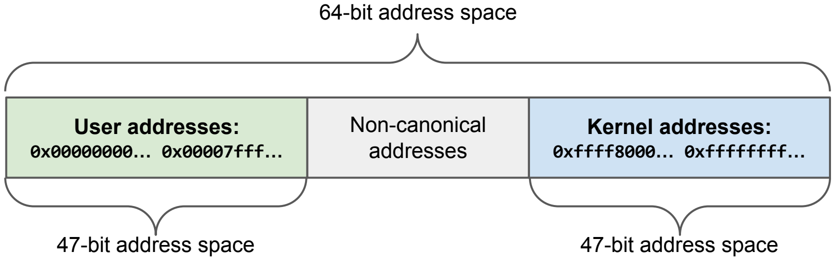

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  - ✗ **Can still branch to aligned user address!**

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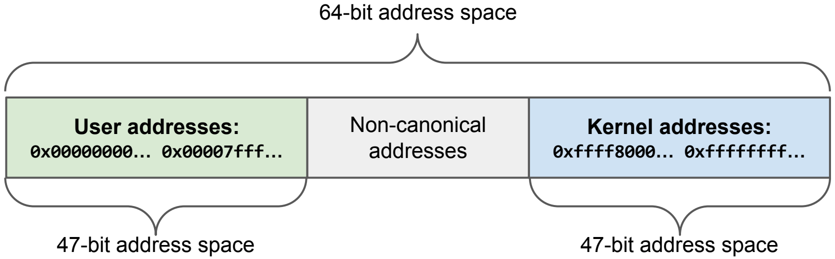

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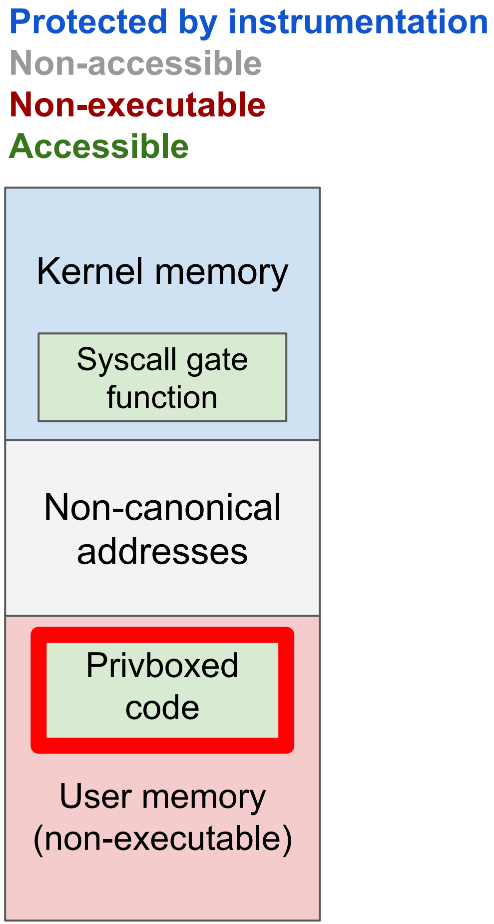

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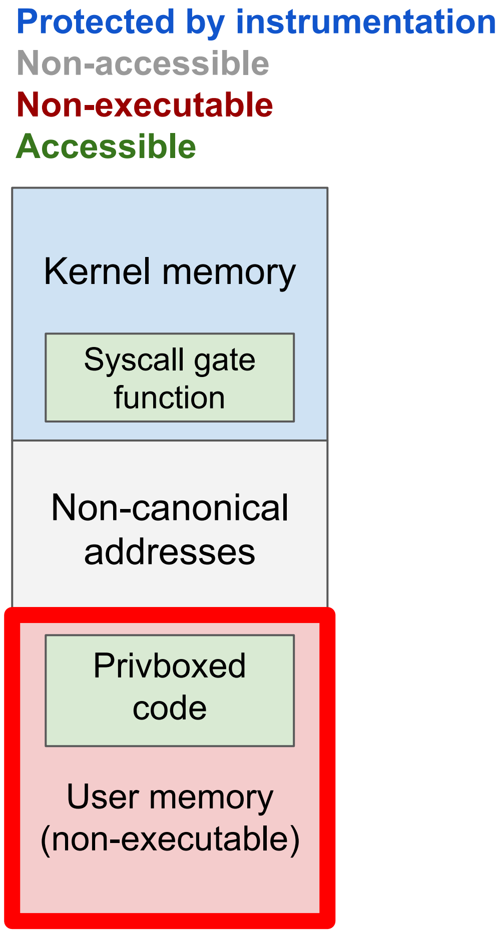

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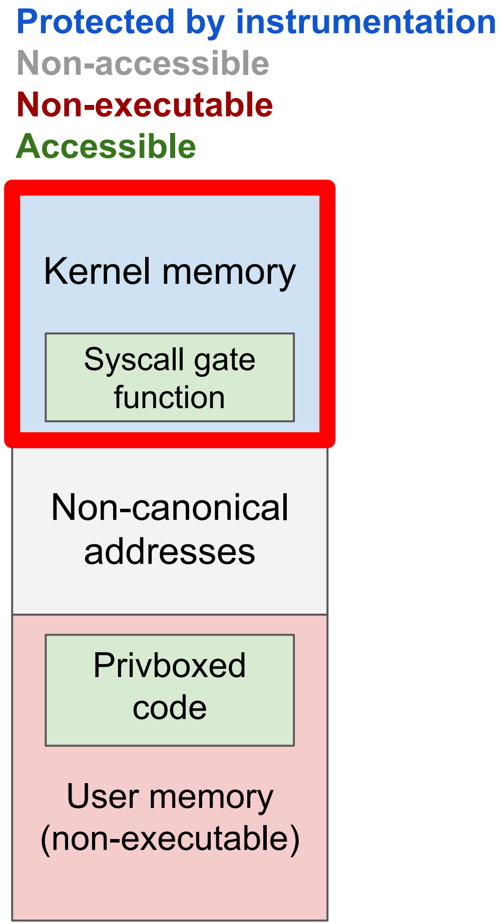
3. **Kernel memory** is mapped and accessible
    - Enables direct branching to syscall gate function!
    - Undesired kernel accesses blocked by instrumentation



Semi-Privileged Access Prevention (SPAP)

- **Observation:** Majority of overhead comes from load/store instrumentation
- **Solution**: we propose a new, SMAP/SMEP-like, hardware extension
    - Mechanism:
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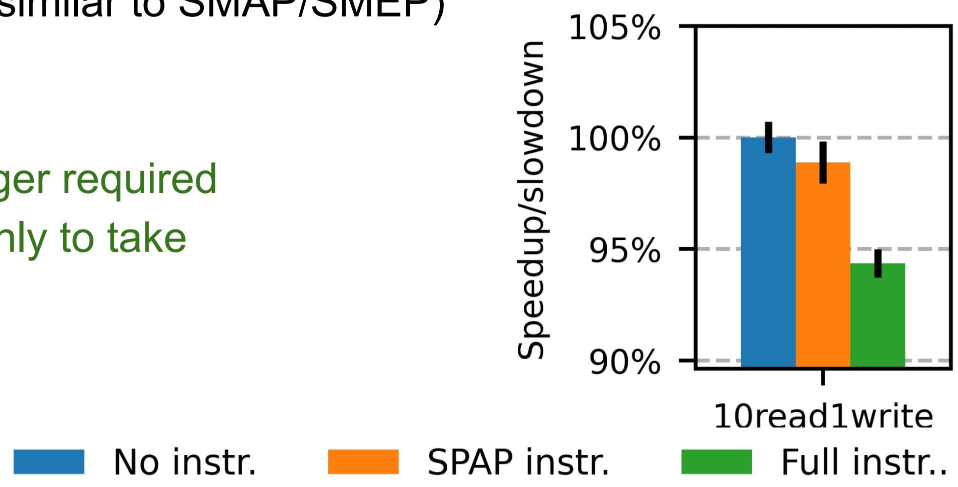
- **Outcome**:

✓ Load/store instrumentation no longer required

✓ Branching instrumentation need only to take care of alignment

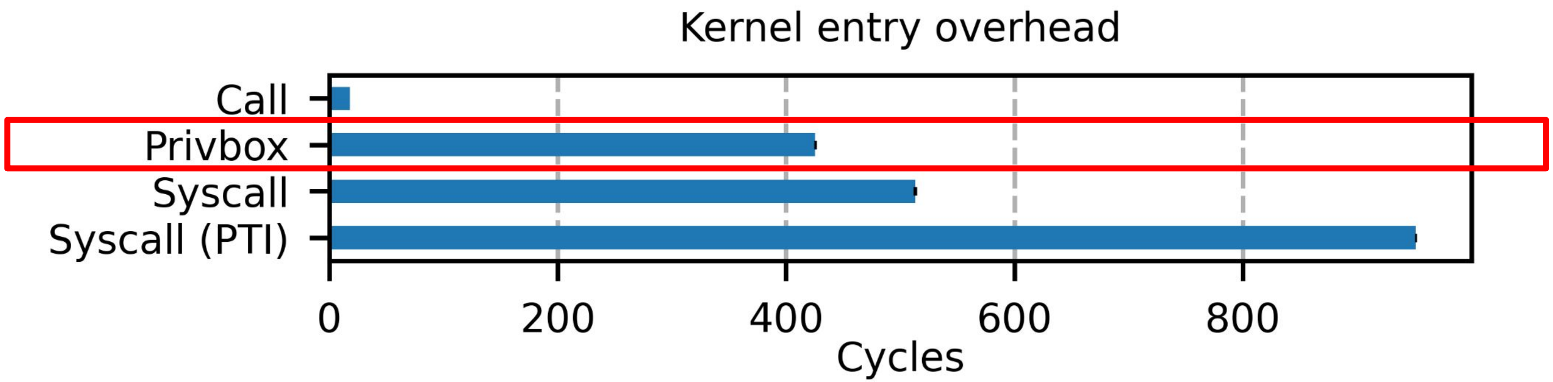


Evaluation: Entry Overheads

Benchmark: measurement of system call entry/exit overhead (on x86)

Results:

✓ Privbox is **2.2x** faster than regular system call on system with PTI

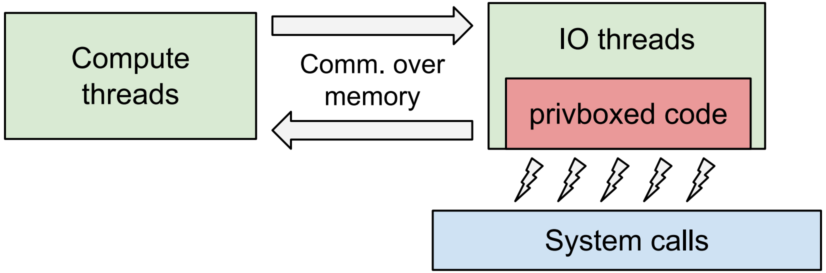


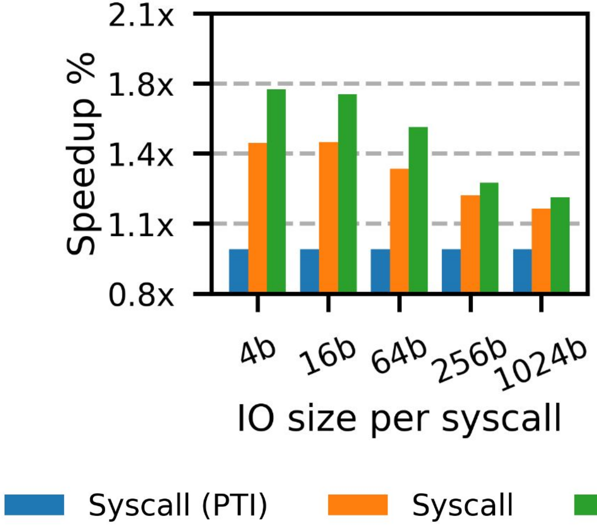
Evaluation: I/O Threaded Workloads

Benchmark: server with I/O isolated to dedicated threads

Results:

✓ Up to **72%** speedup for scenarios where I/O is the bottleneck (on kernels with PTI)





Evaluation: Real-world Workloads

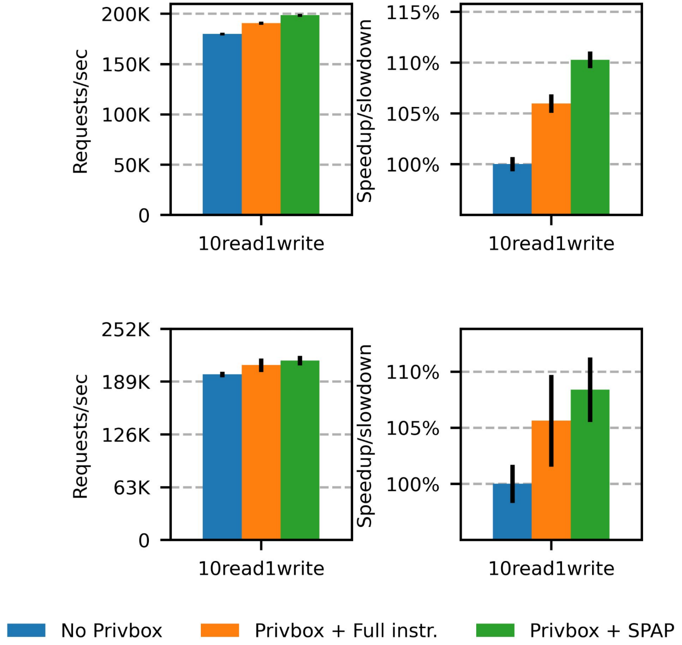
redis

- **Benchmark**: redis-bench / memtier_benchmark
- **Results**:
  - ✓ Up to **7.6%** speedup on hardware that requires PTI
  - ✓ Up to **11%** speedup if hardware supported SPAP

memcached

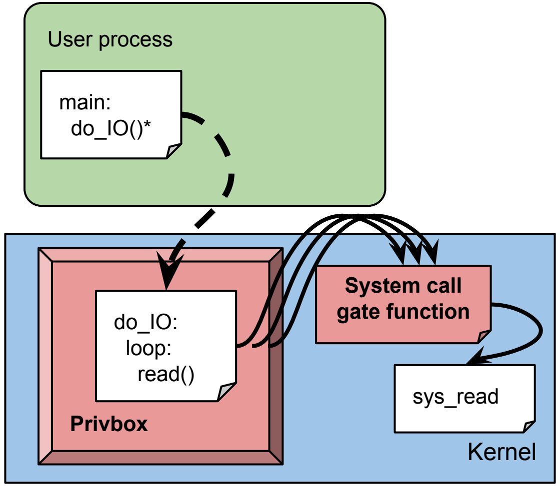
- **Benchmark**: memtier_benchmark
- **Results**:
  - ✓ Up to **5.5%** speedup on hardware that requires PTI
  - ✓ Up to **8.4%** speedup if hardware supported SPAP

Note: Lower bounds, whole processes instrumented



Conclusion

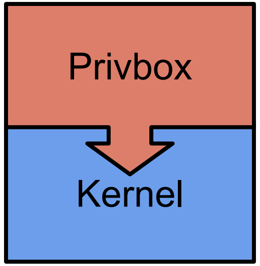
- ✓ **Privbox:** faster system calls with familiar semantics
- ✓ No need to re-architect software
- ✓ 2.2x times faster system call entry/exit
- ✓ Up to 72% speedup for IO-threaded workloads
- ✓ Lower bound of 7% speedup for workloads like Redis/Memcached
- ✓ Github: https://github.com/privbox



Privbox vs eBPF

Privbox:

- Safety guarantees:
  - Memory accesses
- Scope:
  - Full programs
- Execution model:
  - Runs like regular process
  - Uses system call as needed



eBPF:

- Safety guarantees:
  - Memory safety
  - Termination
- Scope:
  - Callback functions, small programs
- Execution model:
  - Invoked by kernel on events
  - Can invoke only specific helpers