# Safe User-Level Sharing of Memory-Mapped Resources

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# The University of Rochester

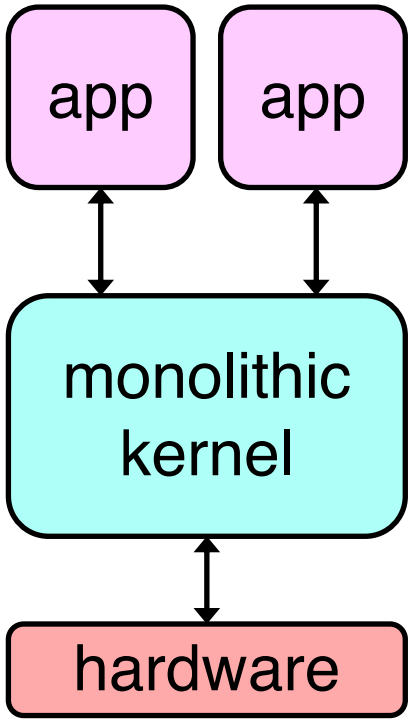

- Small private research university
- 6800 undergraduates
- 5000 graduate students
- Set on the Genesee River in Western New York State, near the south shore of Lake Ontario
- 250km by road from Toronto; 590km from New York City

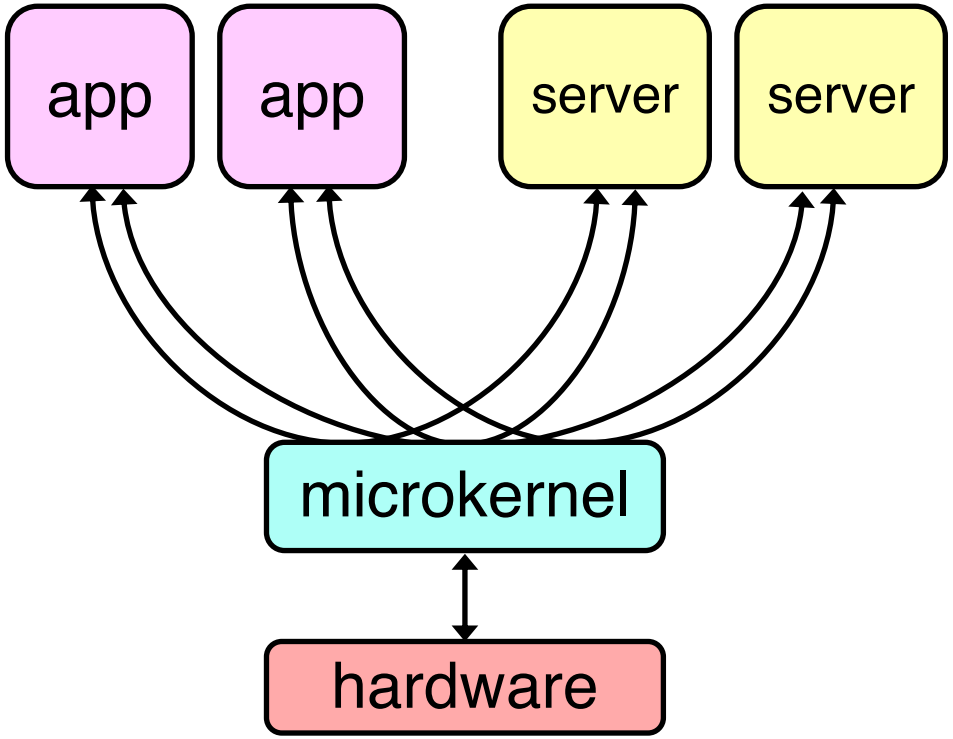

# The Computer Science Dept.

- Founded in 1974
- 20 tenure-track faculty; 70 Ph.D. students
- Specializing in AI, theory, HCI, and parallel and distributed systems
- Among the best small departments in the US

# A Bit of OS History

- Monolithic kernels
  - All OS functionality in a single large kernel — long the dominant approach
  - Fast, but hard to understand / modify / customize / secure
- Microkernels
  - Increase modularity, for easy update / customization; bug containment
  - Export functionality into servers; communicate via the kernel
- Exokernels / library OSes / kernel-bypass IO
  - Export functionality into *library* for faster access
  - Kernel involved only on setup; app subsequently touches hardware directly


app
app
monolithic kernel
hardware


app
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server
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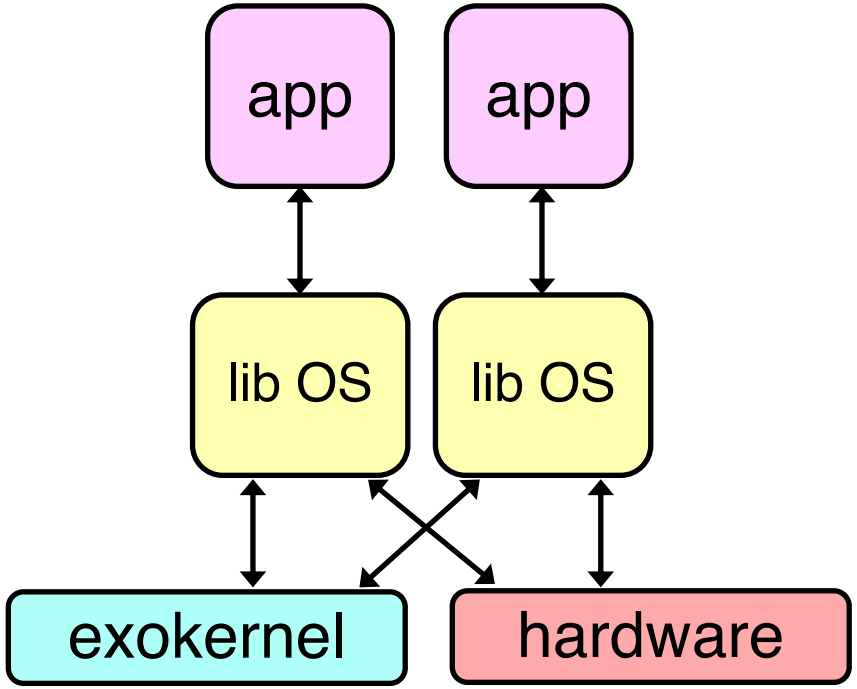
microkernel
hardware


app
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exokernel
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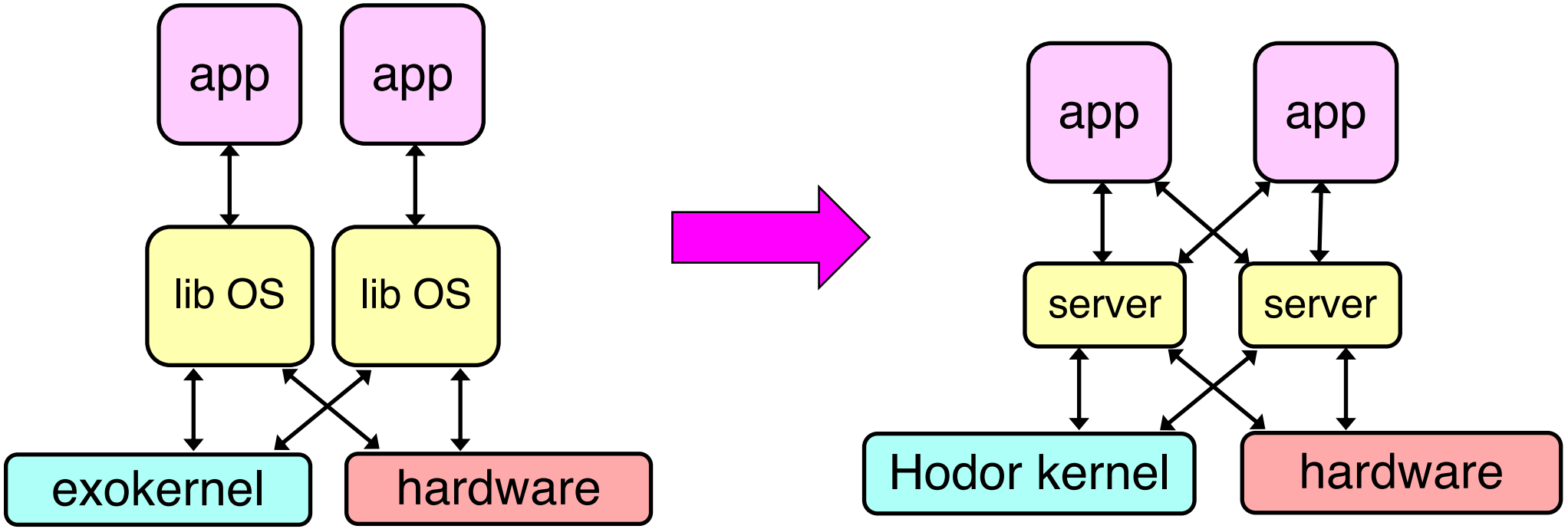
app
app
lib OS
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exokernel
hardware
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server
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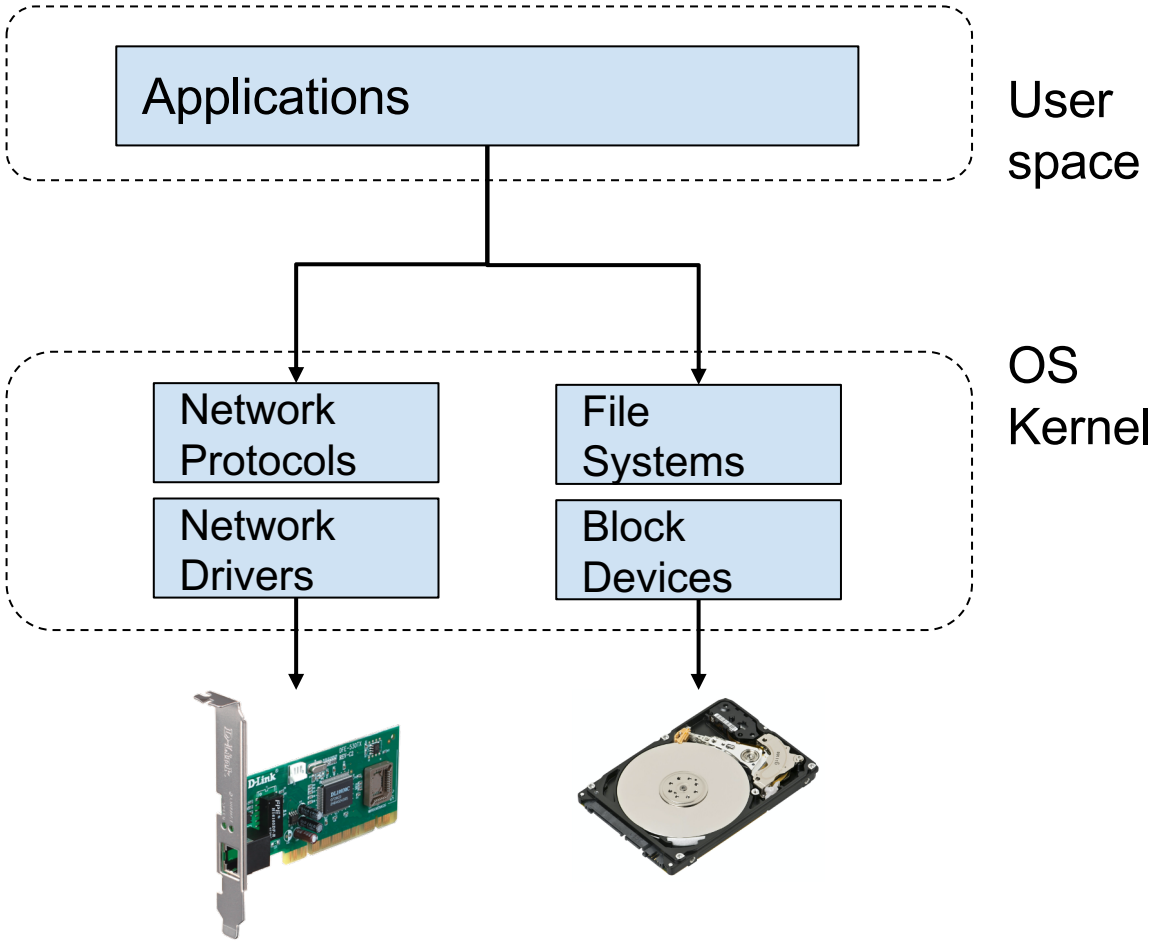
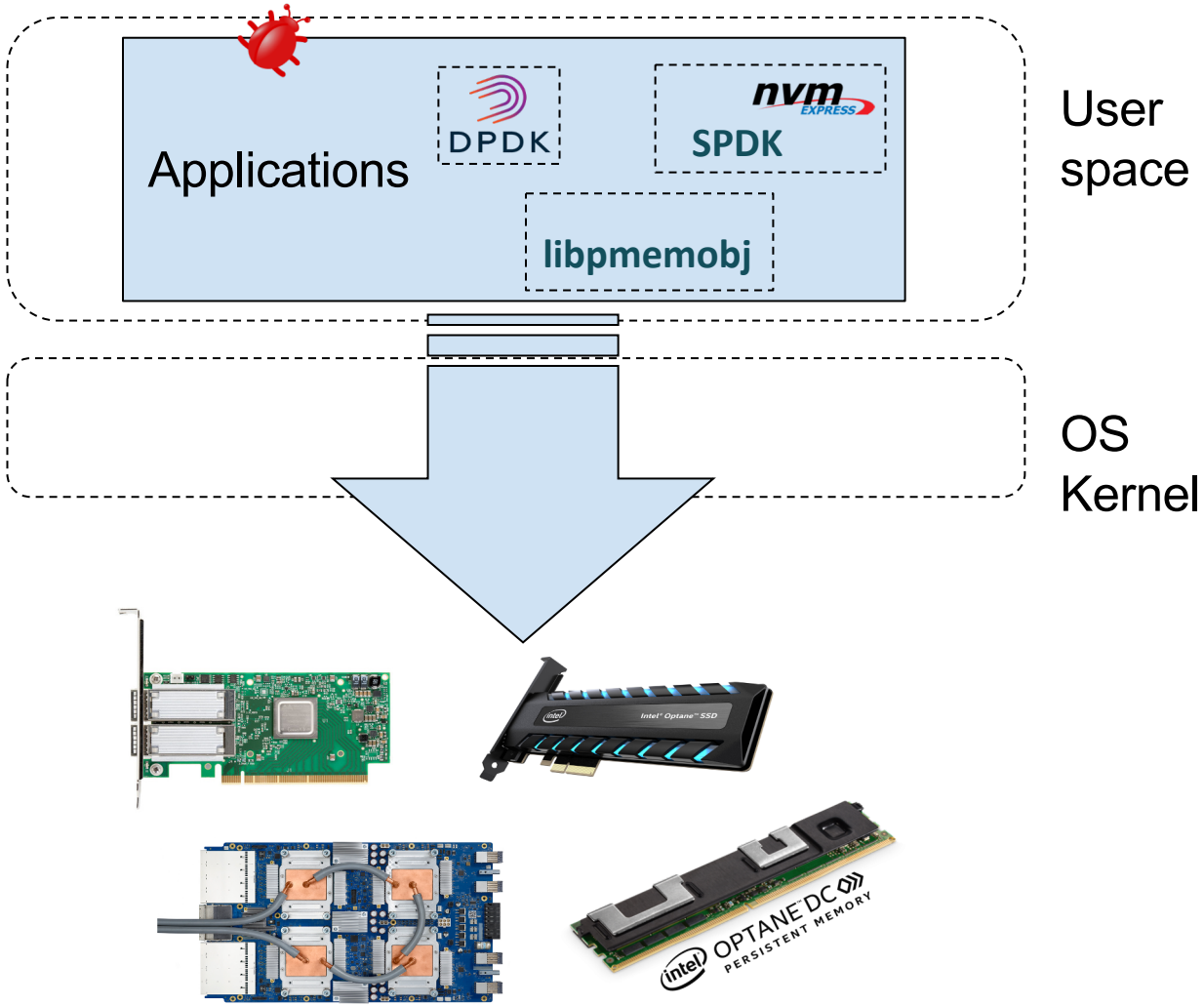
# Kernel I/O

- Enables sharing
- Provides guarantees
  - Fairness
  - Recovery
  - Security
- All without needing to trust



# Kernel-bypass I/O

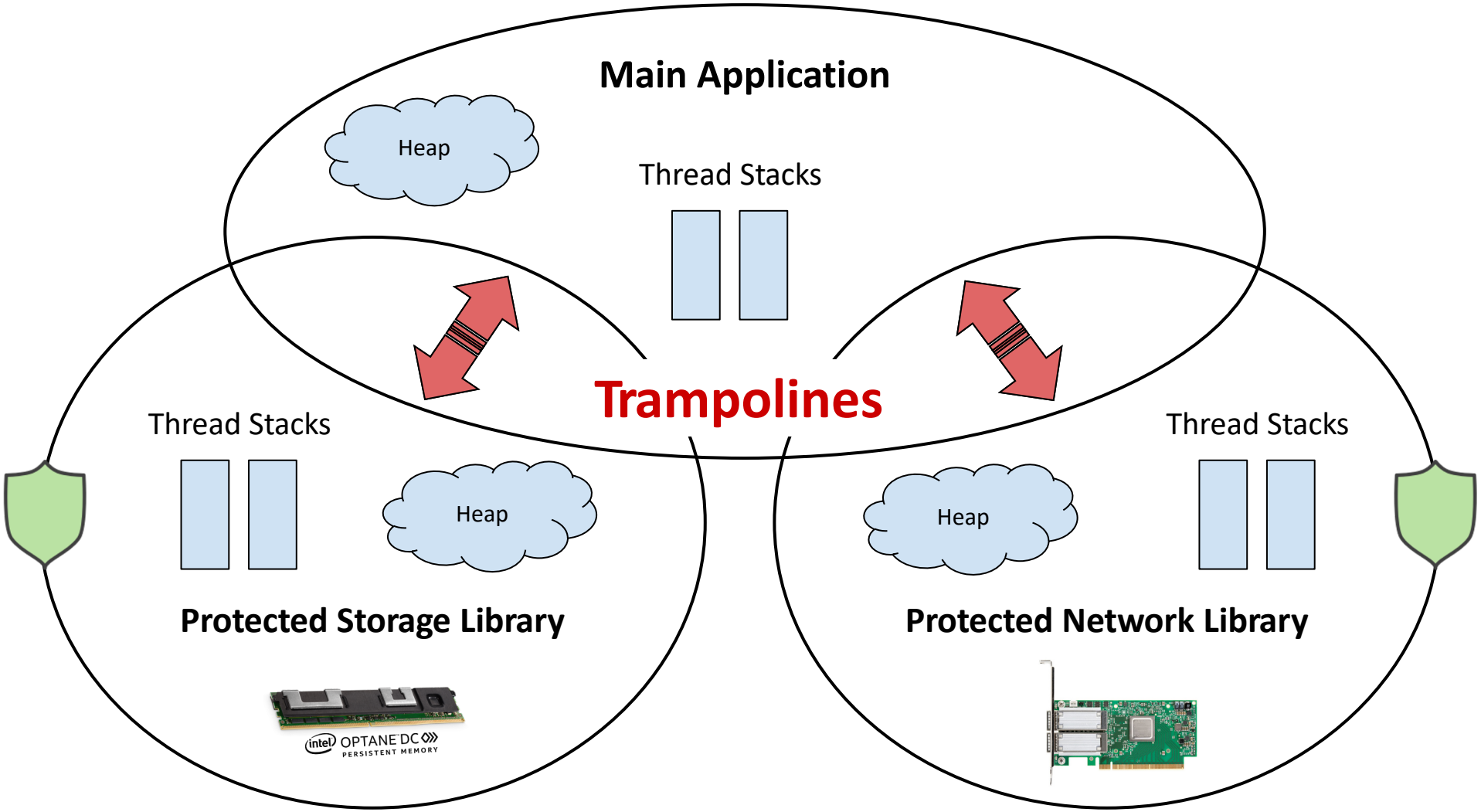
- Pros:
  - Lower latency
  - Rapid development
  - Specialization
- Cons:
  - No guarantees (e.g., of fairness)
  - Hard to multiplex



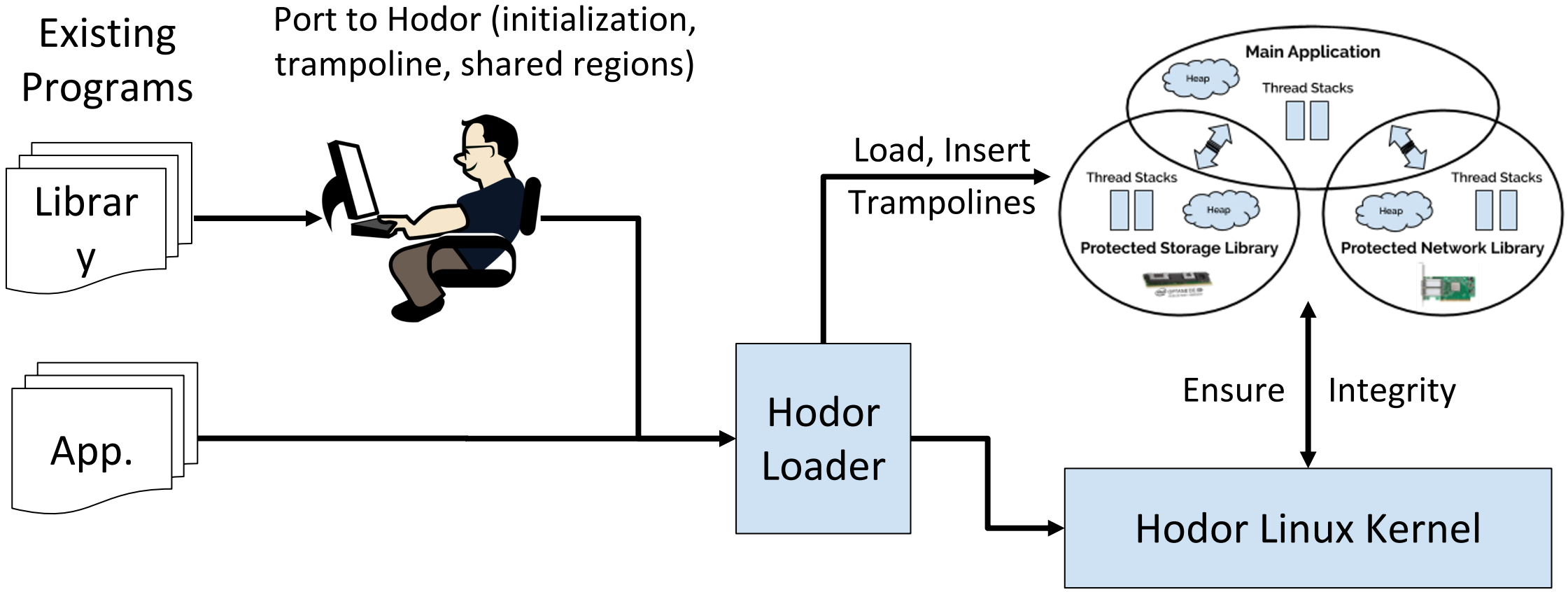
# Overview

- Motivation
- Design of Hodor
- Fast Memory Isolation
- IO Performance
- Cross-Application Sharing
- Conclusion

# Protected Library



# Hodor


Existing Programs
Port to Hodor (initialization, trampoline, shared regions)
Librar y
App.
Load, Insert Trampolines
Hodor Loader
Main Application
Heap
Thread Stacks
Thread Stacks
Heap
Protected Storage Library
Thread Stacks
Heap
Protected Network Library
Ensure
Integrity
Hodor Linux Kernel

# Overview

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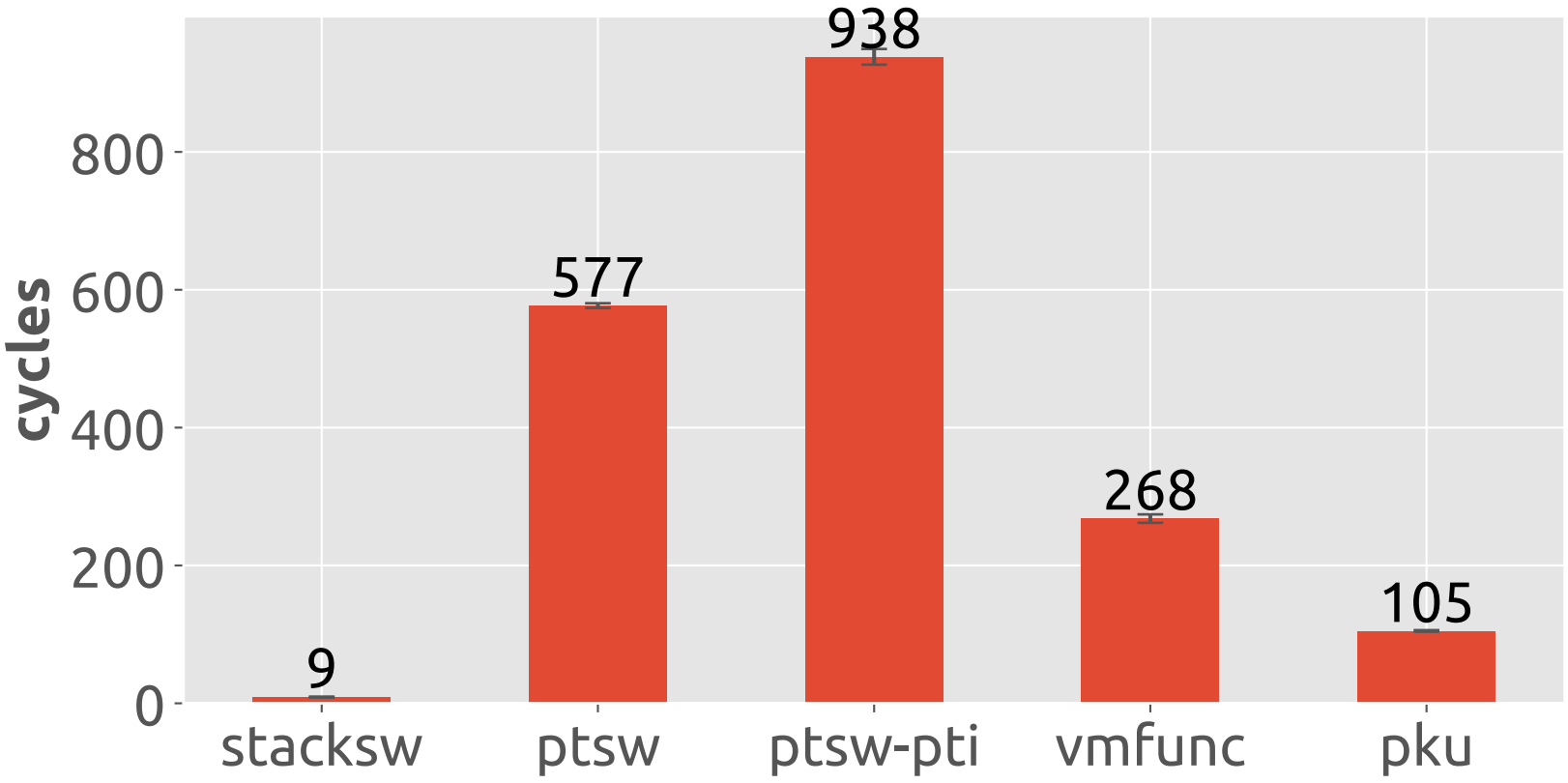
# Possible isolation strategies

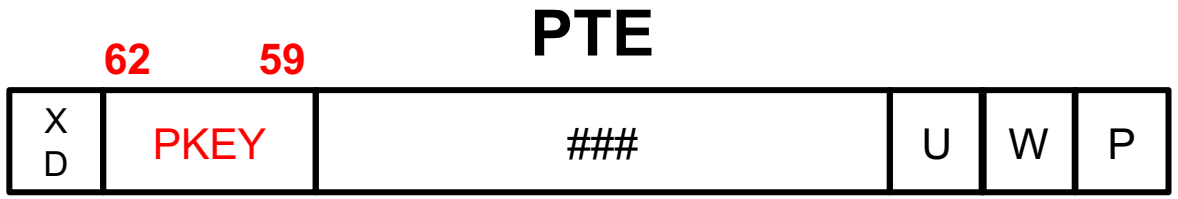
- Separate address spaces
  - » Conventional hardware; high switching overhead
- Software fault isolation (SFI — a.k.a. sandboxing)
  - » Trusted compiler; no special hardware; high overhead throughout app
- Virtualization (as in Dune [Belay OSDI 2012])
  - » Hardware enforced; single protected domain; high switching overhead; additional overhead from VMEXITs and 2-level paging
- VMFUNC on recent Intel machines
  - » Multiple protection domains in one VM guest; low switching overhead; but still the overhead of VMEXITs and 2-level paging
- ★ User-space protection keys [Hedayati ATC 2019; Vahldiek-Oberwagner Sec 2019]

# Cost of an empty library call

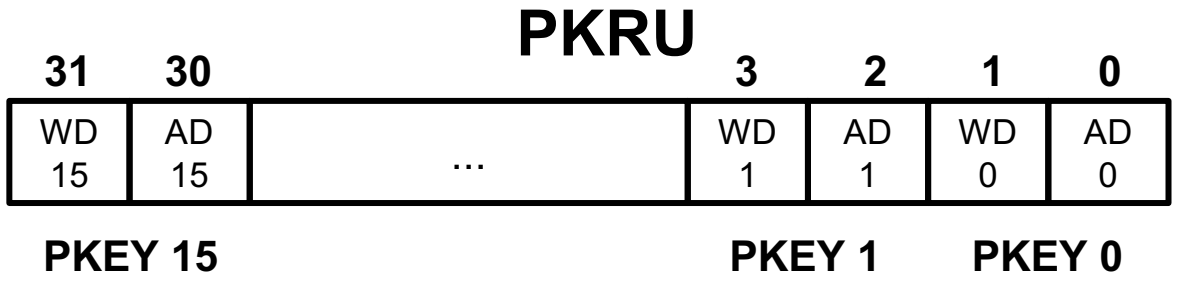


# Preferred strategy: Intel PKU

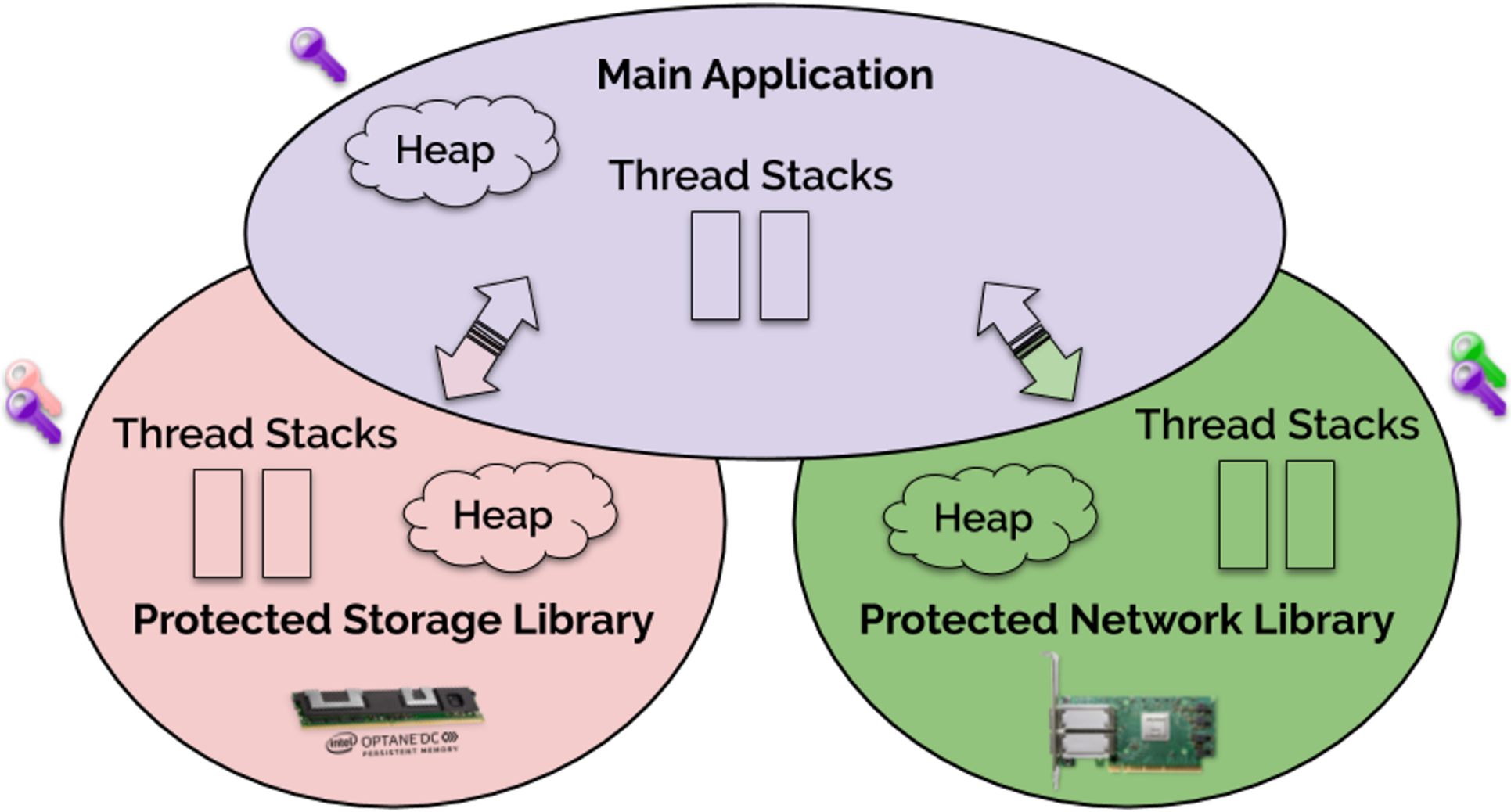
- Protection Keys for User-Space (a.k.a. MPK)
- Introduced in Skylake-SP




- 32-bit PKRU register (Access/Write Disable)
- WRPKRU/RDPKRU



# Hodor: Memory Isolation



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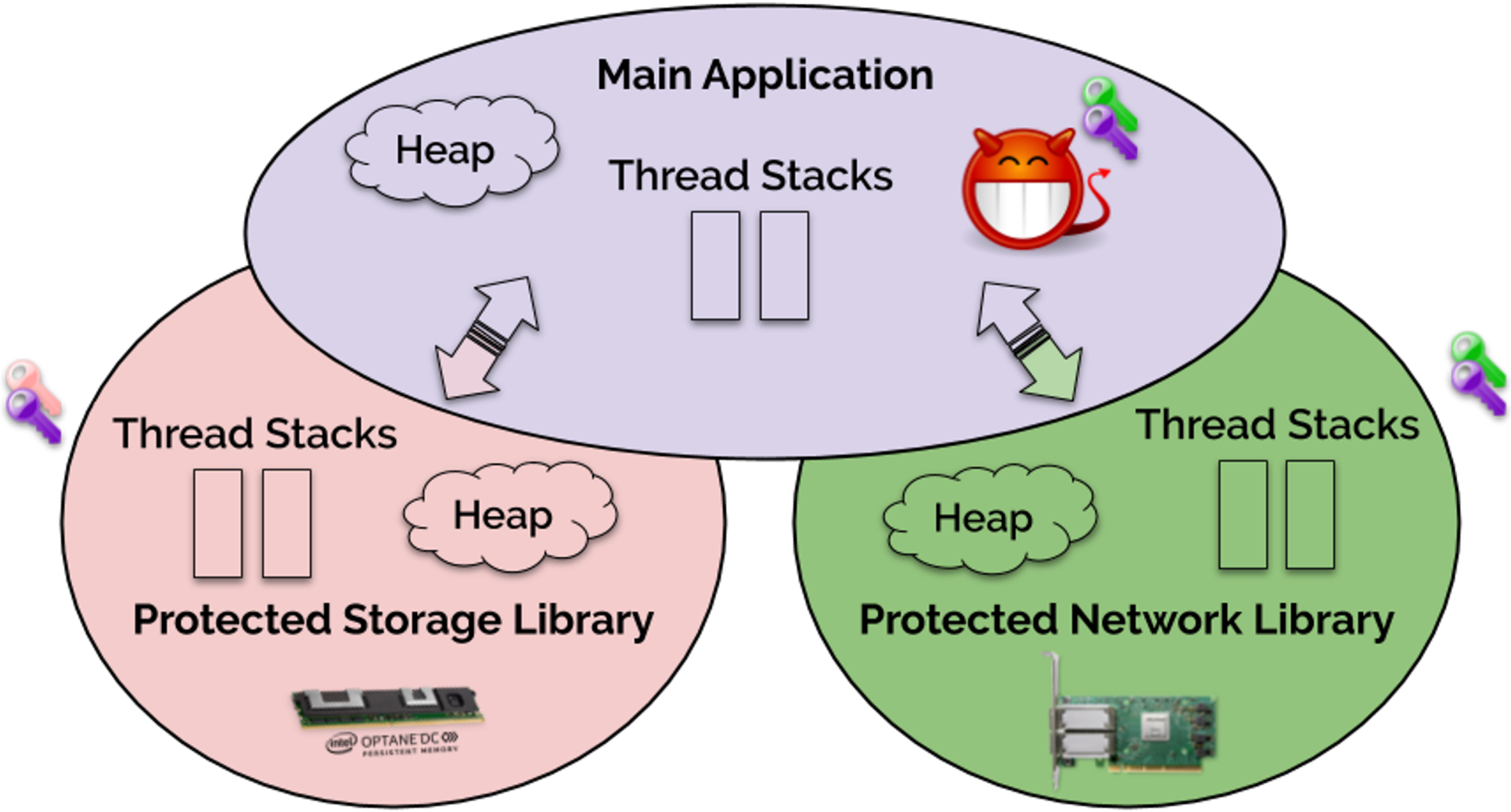


# Hodor: Vetting `WRPKRUs`

- Inspect executable regions
  - » Load (by Hodor loader)
  - » W⟶X change (by Hodor kernel at run-time)
- Look for WRPKRU (0f 01 ef) instances

**glibc-devel-static-2.27-alt9.x86_64**

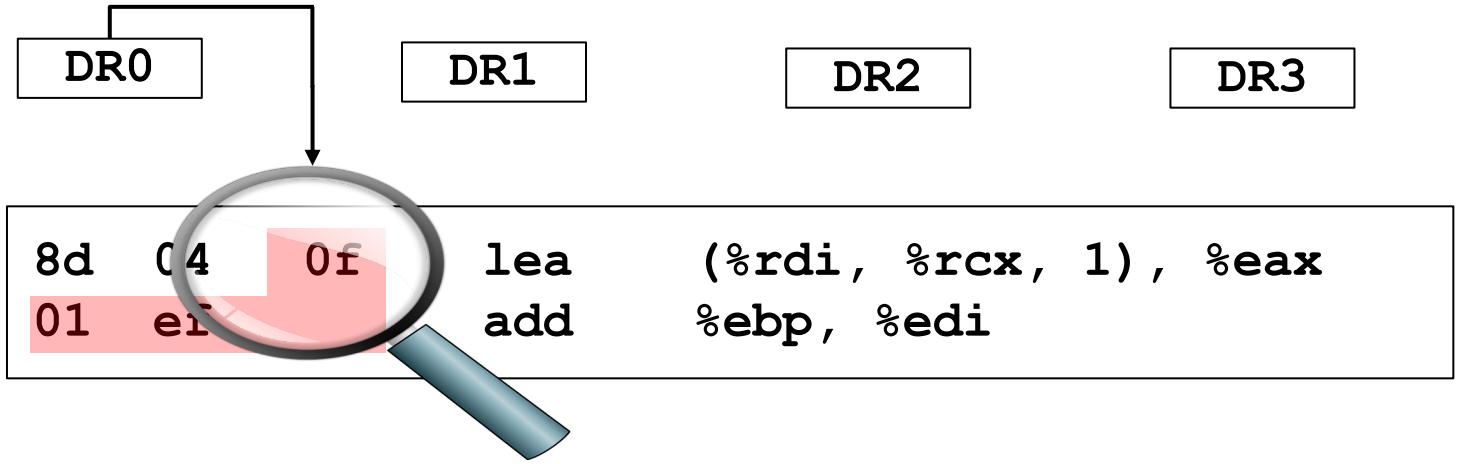
```
f7 d2          not     %edx
21 d0          and     %edx,%eax
44 89 c2       mov     %r8d,%edx
09 f0          or      %esi,%eax
0f 01 ef       wrpkru
31 c0          xor     %eax,%eax
```

**blender-2.79b-7.fc29.x86_64**

```
8d  04   0f     lea     (%rdi, %rcx, 1), %eax
01  ef          add     %ebp, %edi
```

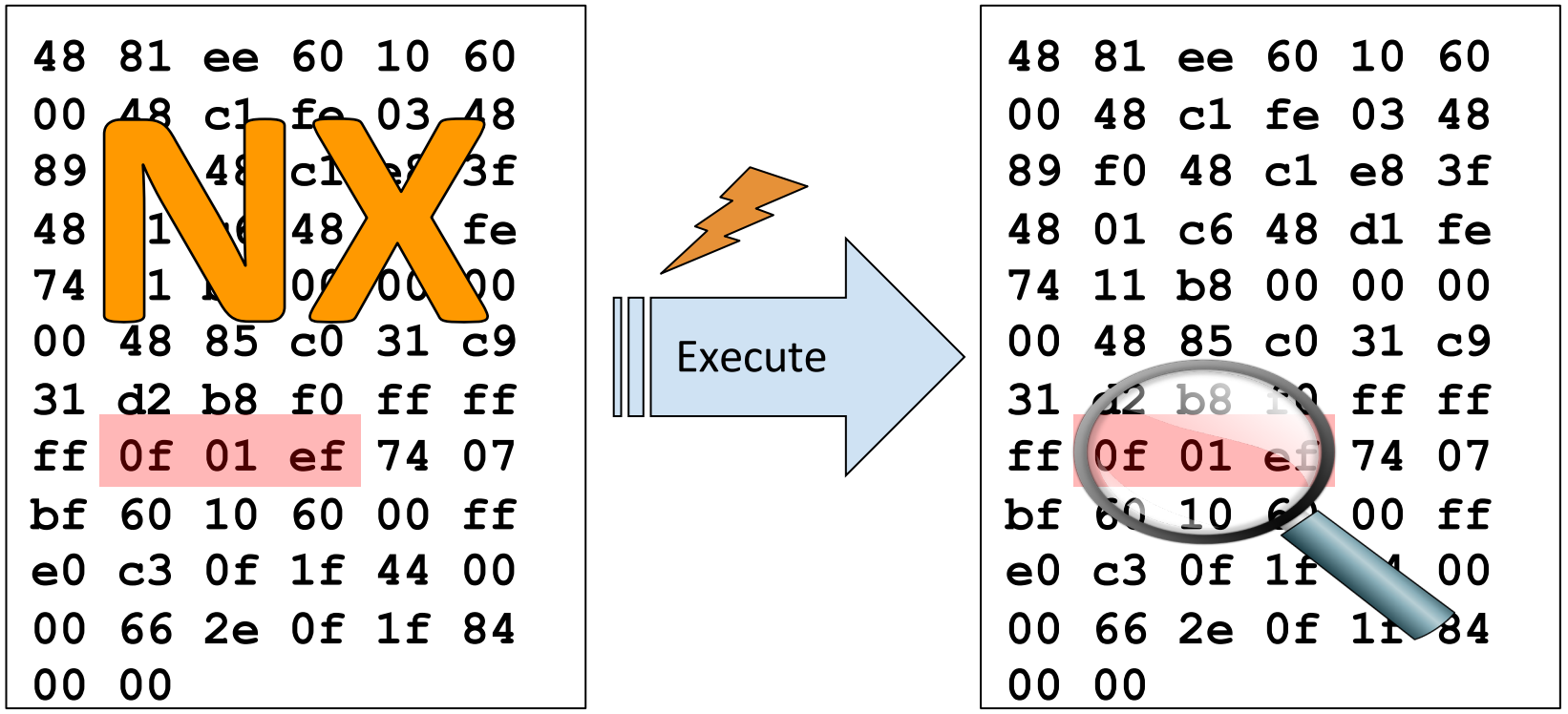
# Hodor: Vetting `WRPKRUs`

- Hardware watchpoints
  - » DR# registers point to the beginning of illegal byte sequence
  - » No spurious traps when correctly aligned execution runs past an implicit instance



# Hodor: Illegal `WRPKRUs`

- Limited hardware watchpoints
  - » Only 4 on Intel Processors
  - » HW watchpoints as cache for illegal sequences

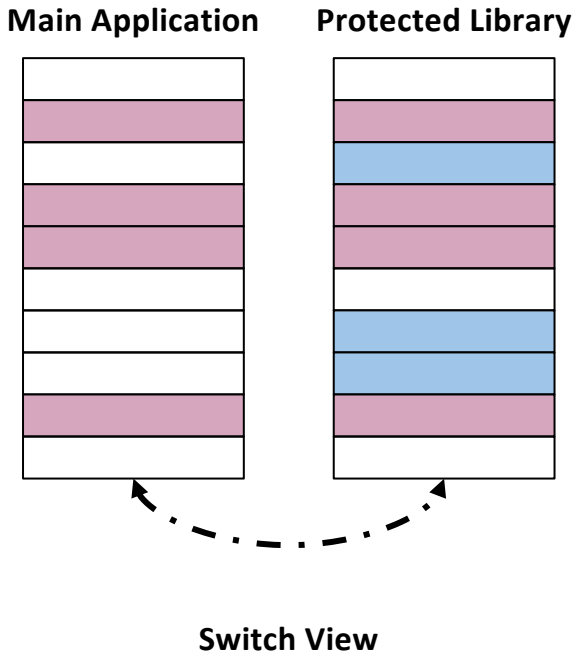


# Hodor: Vetting `WRPKRU`s

- Vetting cost
  - » Implicit instances incur no run-time overhead
  - » Explicit instances should use pkey_set()
  - » No measurable overhead as long as:
    - – #hot illegal seq. fewer than #hw watchpoints
- How often?
  - » 58,273 rpm packages on Fedora 29 (108K executables)
  - » Only 123 binaries with one or more illegal byte sequences
    - – Only 2 (less than 0.02%) with more than 4

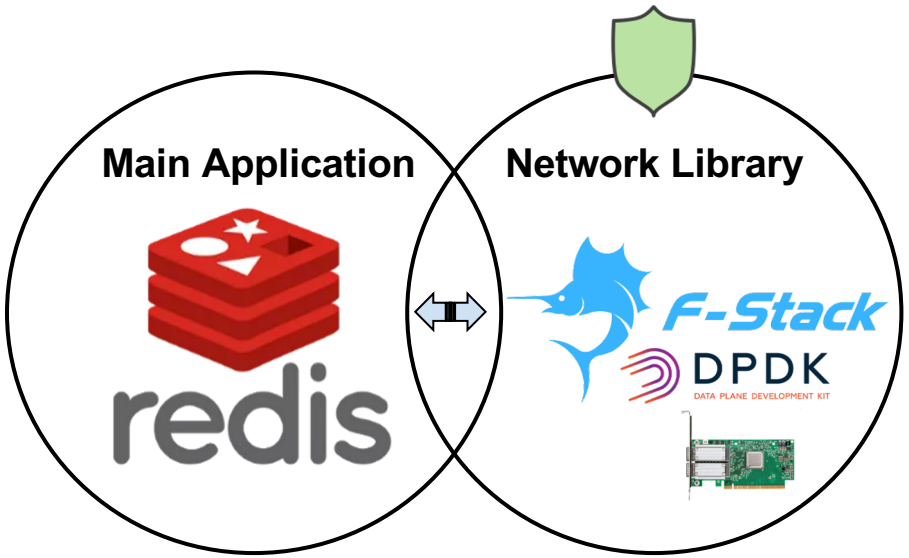
# Alternative Memory Isolation

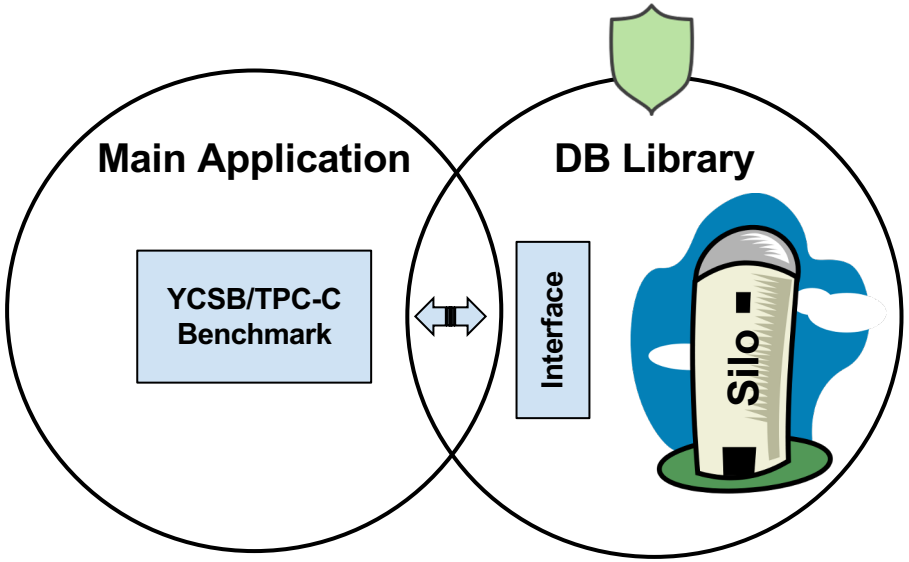
- Per-Domain Page-Table
  - » Each mapping the view of a domain
  - » Switch using system calls
- Per-Domain Extended Page-Table
  - » Requires running virtualized (in Intel VMX)
  - » Switch using VMFUNC w/o causing VMEXIT



# Evaluation: Applications

- Redis (kernel-bypass network TCP/IP stack)
- Silo (in-memory database)
- DPDK (kernel-bypass packet processing) -- in the ATC paper



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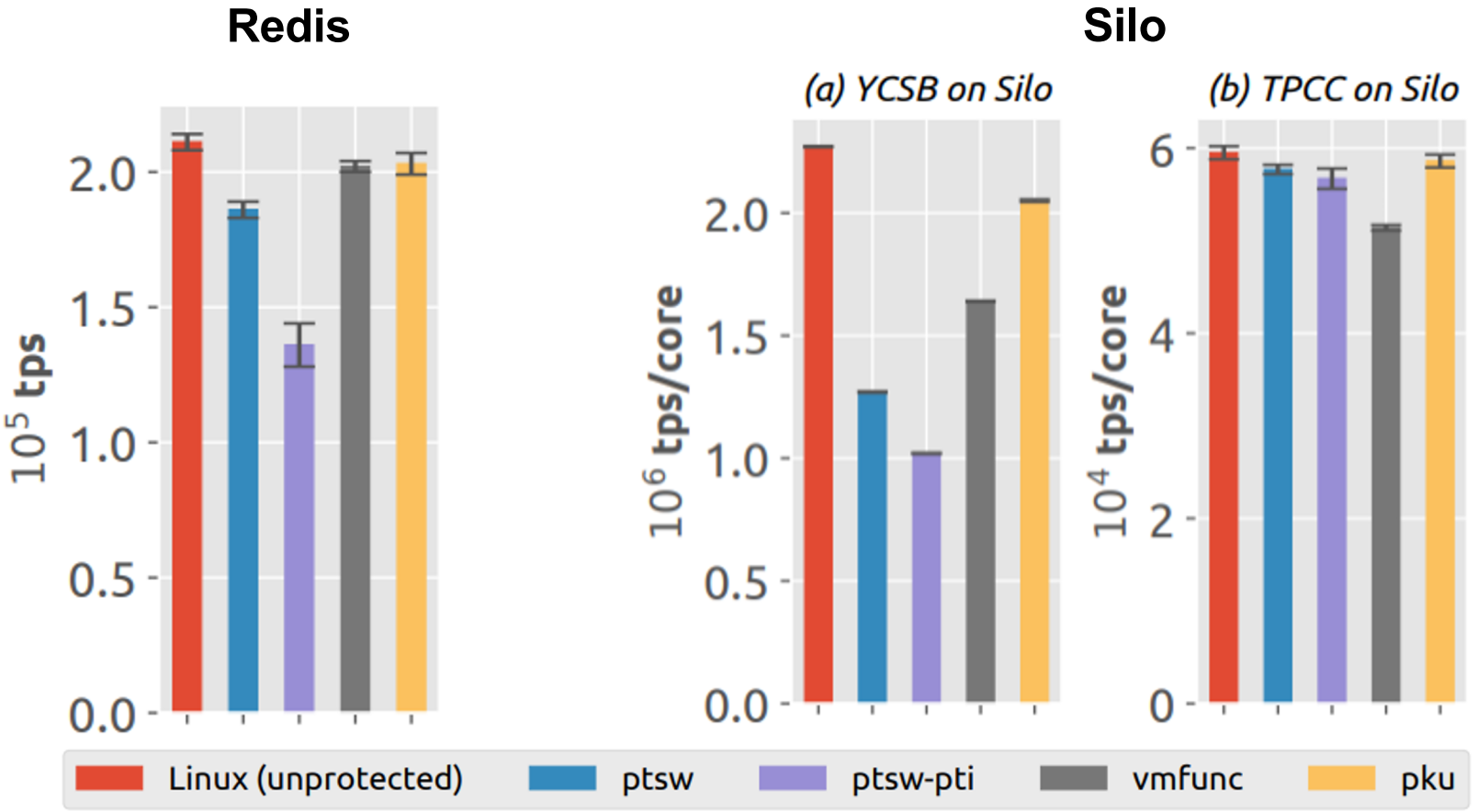
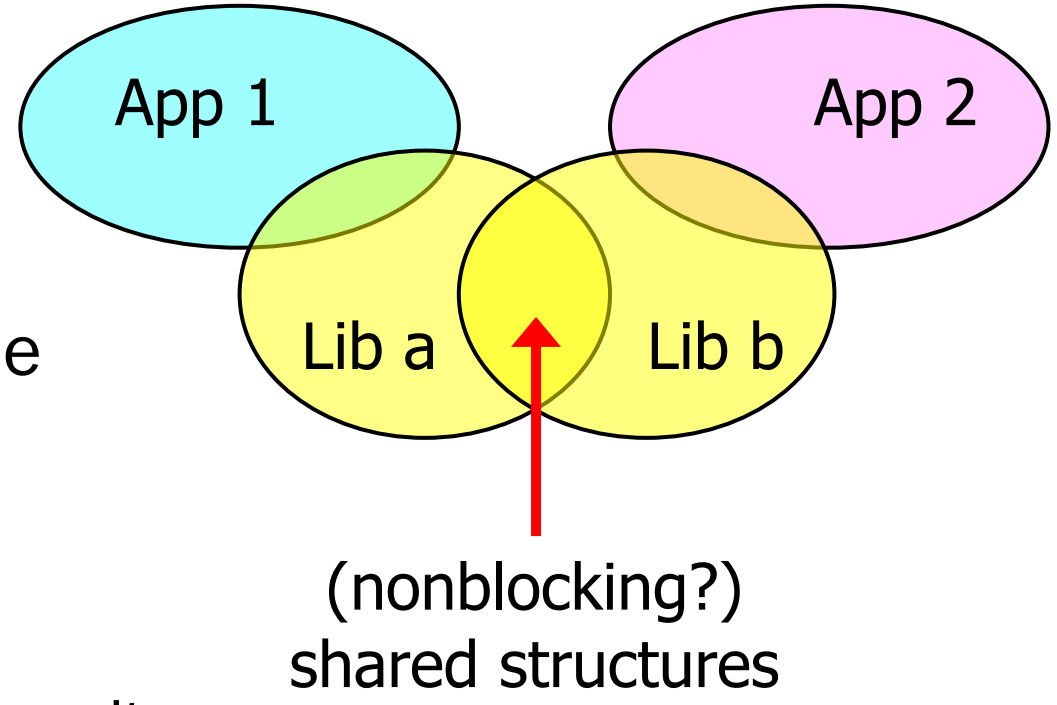



**ptsw**: page table switching
**vmfunc**: EPT switching

**ptsw-pti**: page table switching w/ KPTI
**pku**: using memory protection keys

# Cross-application sharing

- The network stack in Redis was used by one application at a time, as was the Silo database
- Sharing the network stack would enable system-wide QoS guarantees; sharing an in-core database is also appealing — Memcached as an example
- Threads of different applications can fail independently
  - » Ideal use case for nonblocking structures, as originally envisioned by the theory community

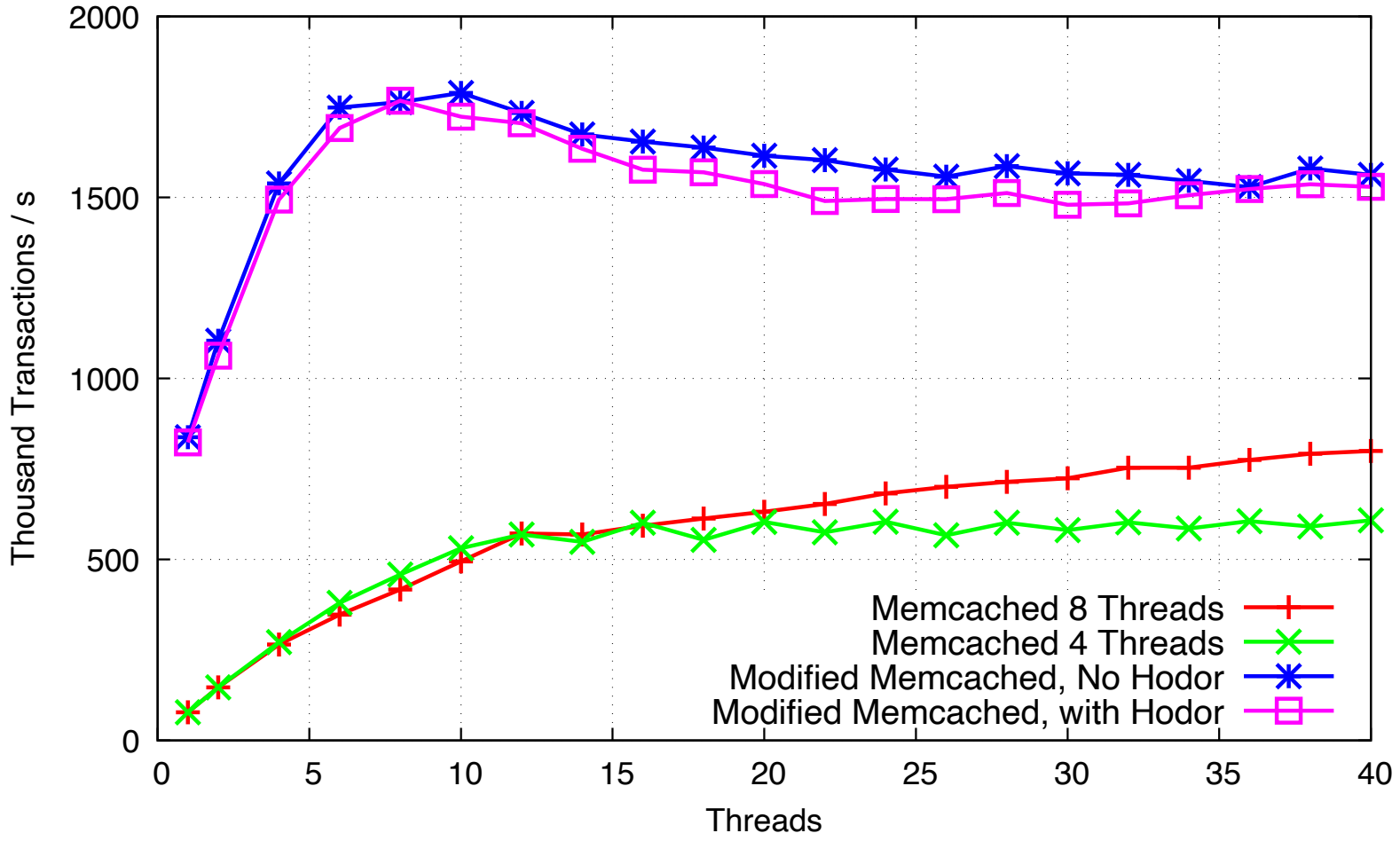


# Memcached

- Widely used in datacenters and smaller operations
  - » Typically accessed over a network, but also within a single machine, where socket overhead seems wasteful
  - » Typically used to cache disk contents, but also standalone
- Converted to work with Hodor
  - » Replaced “slab” allocator with Ralloc [Cai ISMM 2020]
  - » Elided network code
  - » Added trampolines and persistence labels
  - » Rely on Hodor to complete execution of library calls on process crash

# Memcached results

- Original 26KLoC; added ~600; removed ~6.8K (5.2k network; 1.6K alloc)
- Latency of individual ops improved by 11–56x; throughput by ~2x



# Caveats

- Protected libraries must be written with care
  - » Cannot fail in library code: must be bulletproof
  - » Must finish all ops in bounded time (kernel has limited patience)
  - » Cannot trust user data: must validate before using
  - » Cannot trust data not to change: must copy in before validating
  - » Cannot trust user locations: must copy out after dropping locks
- These are the same set of rules required for kernel code

# Conclusion

Introduced *protected libraries.* Showed that:

- Intel PKU can safely be used for isolation, retaining high performance
  - 90–98% of unprotected throughput
- Libraries can enforce global OS policy
- Mutually untrusting applications can share a protected library
  - Perform “server” operations using their own threads, without IPC
  - memcached as an example
- Appealing alternative to microkernels: low-cost modularity
  - Lots of future work!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