Mondrix: Memory Isolation for Linux using Mondriaan Memory Protection

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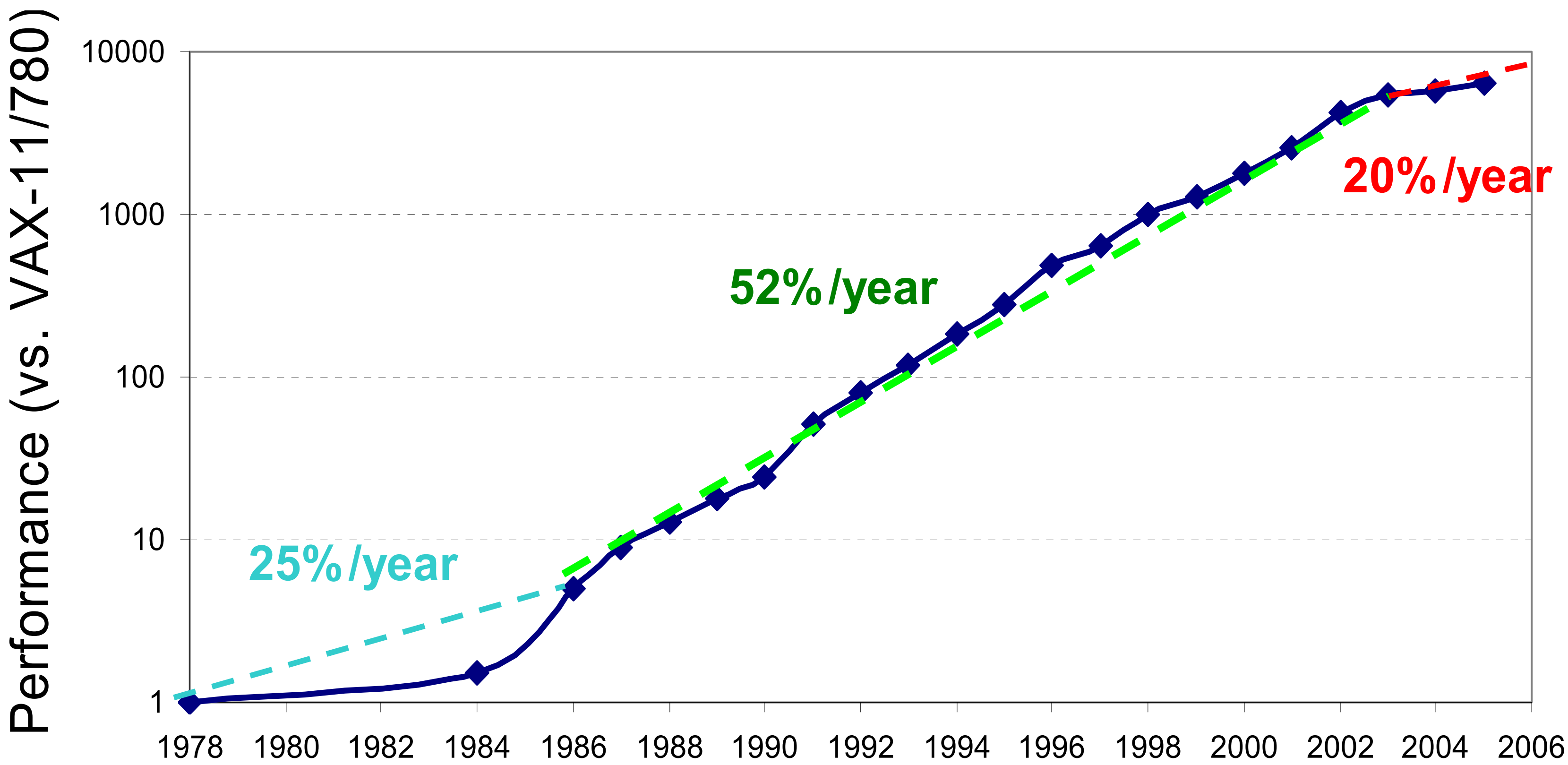
Uniprocessor Performance Not Scaling

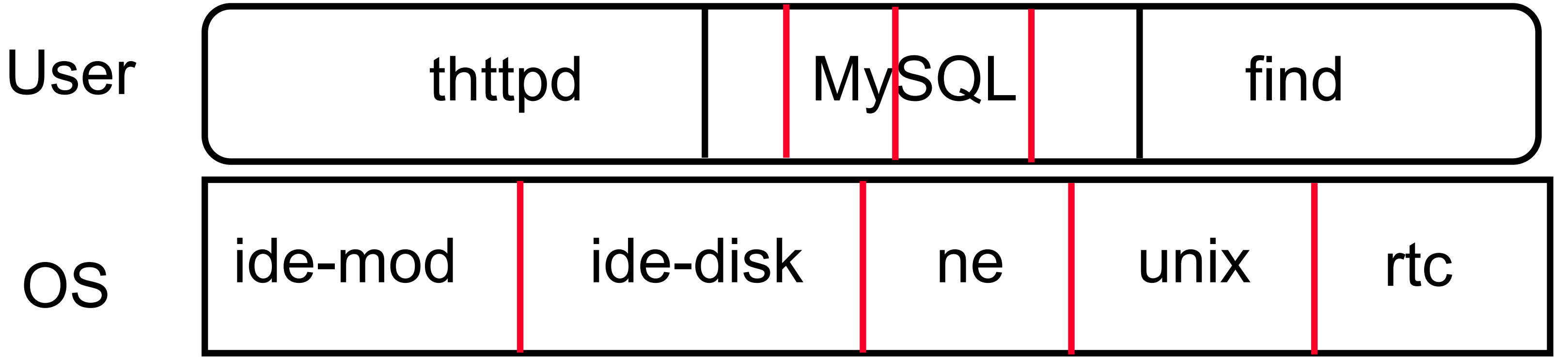
- OS can help HW designers keep their job



Graph by Dave Patterson

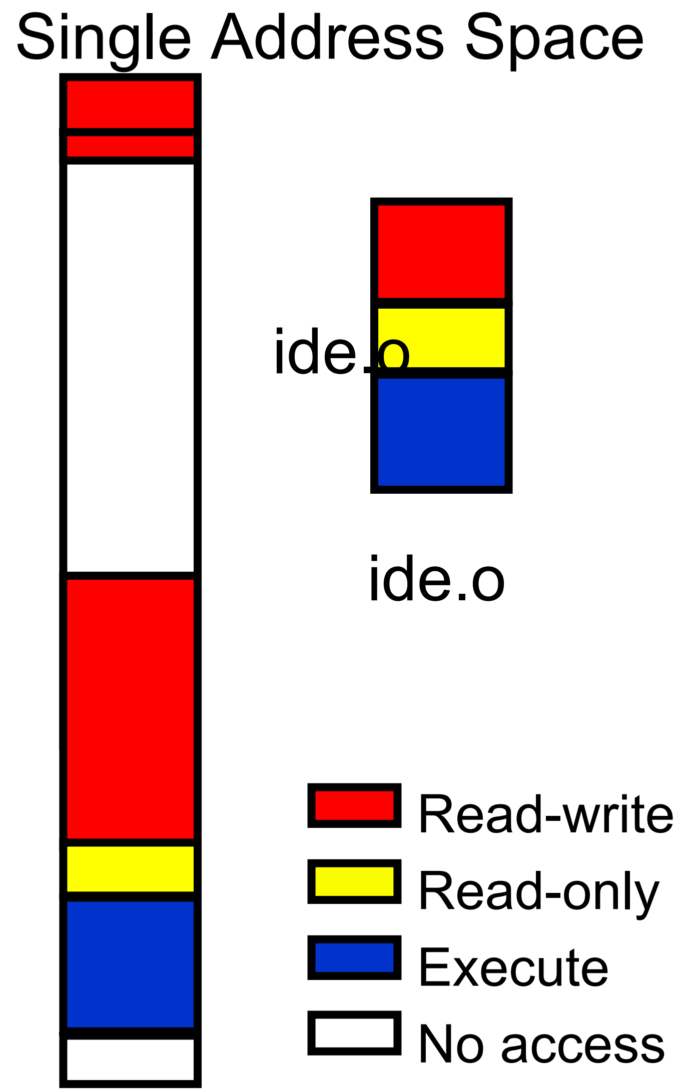
Lightweight HW Protection Domains

- Divisions within address space
  - Backwards compatible with binaries, OS, ISA
  - Linear addressing – one datum per address
- HW complexity about same as TLB
- Switching protection contexts faster than addressing contexts
  - Protection check off load critical path
  - No pipeline flush on cross-domain call



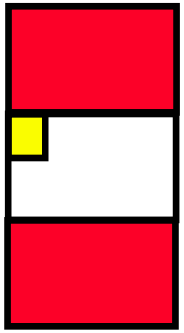
Problems With Modern Modules

- Modules in a single address space
  - + Simple
  - + Inter-module calls are fast
  - + Data sharing is easy (no marshalling)
- – No isolation
  - – Bugs lead to bad memory accesses
  - – One bad access crashes system



Current Hardware Broken

- Page based memory protection
  - Came with virtual memory, not designed for protection
  - A reasonable design point, but not for safe modules
  - Modules are not clean abstractions

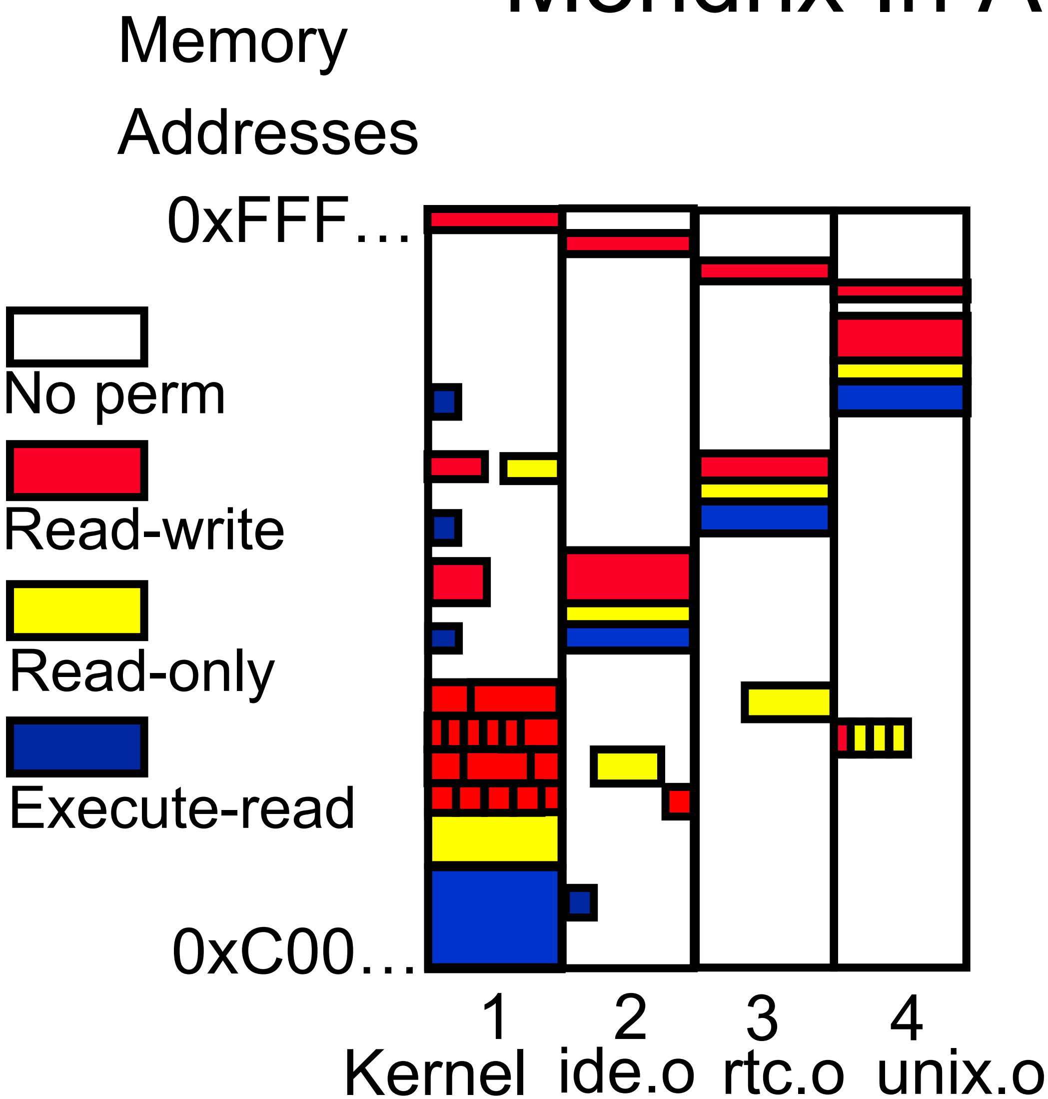


- Hardware capabilities have problems
  - Different programming model
  - Revocation difficult [System/38, M-machine]
  - Tagged pointers complicate machine
- x86 segment facilities are broken capabilities
  - HW that does not nourish SW

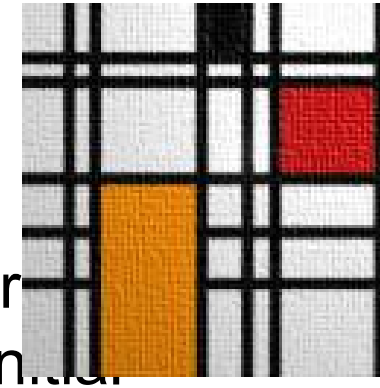
Mondriaan + Linux = Mondrix

- Each kernel module in different protection domain to increase memory isolation
  - Failure indicated before data corruption
  - Failures localized, damage bounded
- Mondriaan Memory Protection (MMP) makes legacy software memory safe
  - Verify HW design by building software (OS)
- ASPLOS ’02, the MMP permission table
  - Nine months
- SOSP ’05, Linux support + MMP redesign
  - Two years

Mondrix In Action



Multiple protection domains



Kernel loader establishes initial permission regions

Kernel calls

```
mprotect(buf0, RO, 2)
mprotect(buf1, RW, 2)
mprotect(kfree, EX, 2)
```

ide.o calls

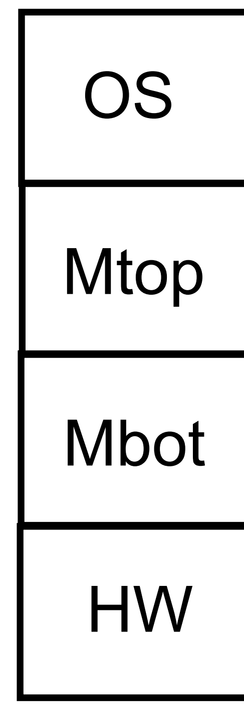
```
mprotect(req_q,RW,1)
mprotect(mod_init,EX,1)
```

Challenges for Mondrix

- Memory supervisor
  - Manage permissions, enforce sharing policy
- Memory allocators
  - Keep semantics of **`kfree`** even with memory sharing
- Cross-domain calling (lightweight, local RPC)
  - e.g., kernel calls **`start_recv`** in network driver
- Group domains
  - Permissions for groups of memory locations whose members change with time
- Device drivers (disk and net)
- Evaluation (safety and performance)

Memory Supervisor

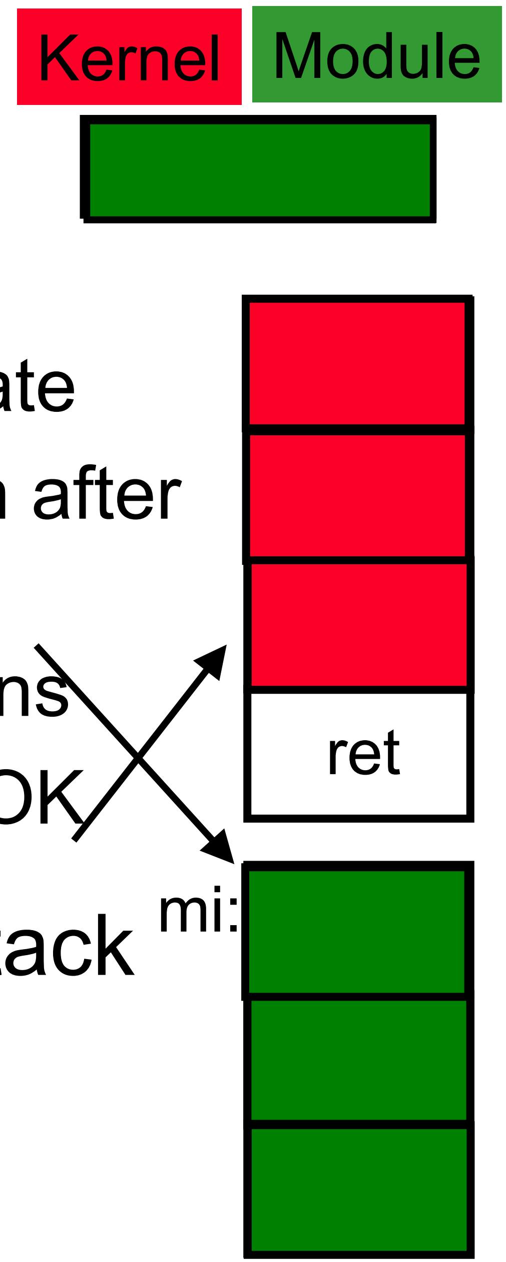
- Kernel subsystem to manage memory permissions (Mtop). Not trust kernel.
  - Exports device independent protection API
    - **`mprot_export(ptr,len,prot,domain-ID)`**
  - Tracks memory owned by each domain
  - Enforces memory isolation policy
    - Non-owner can not increase permissions
    - Regulates domains joining a group domain
- Writes protection tables (Mbot)
  - All-powerful. Small.



Memory Allocation

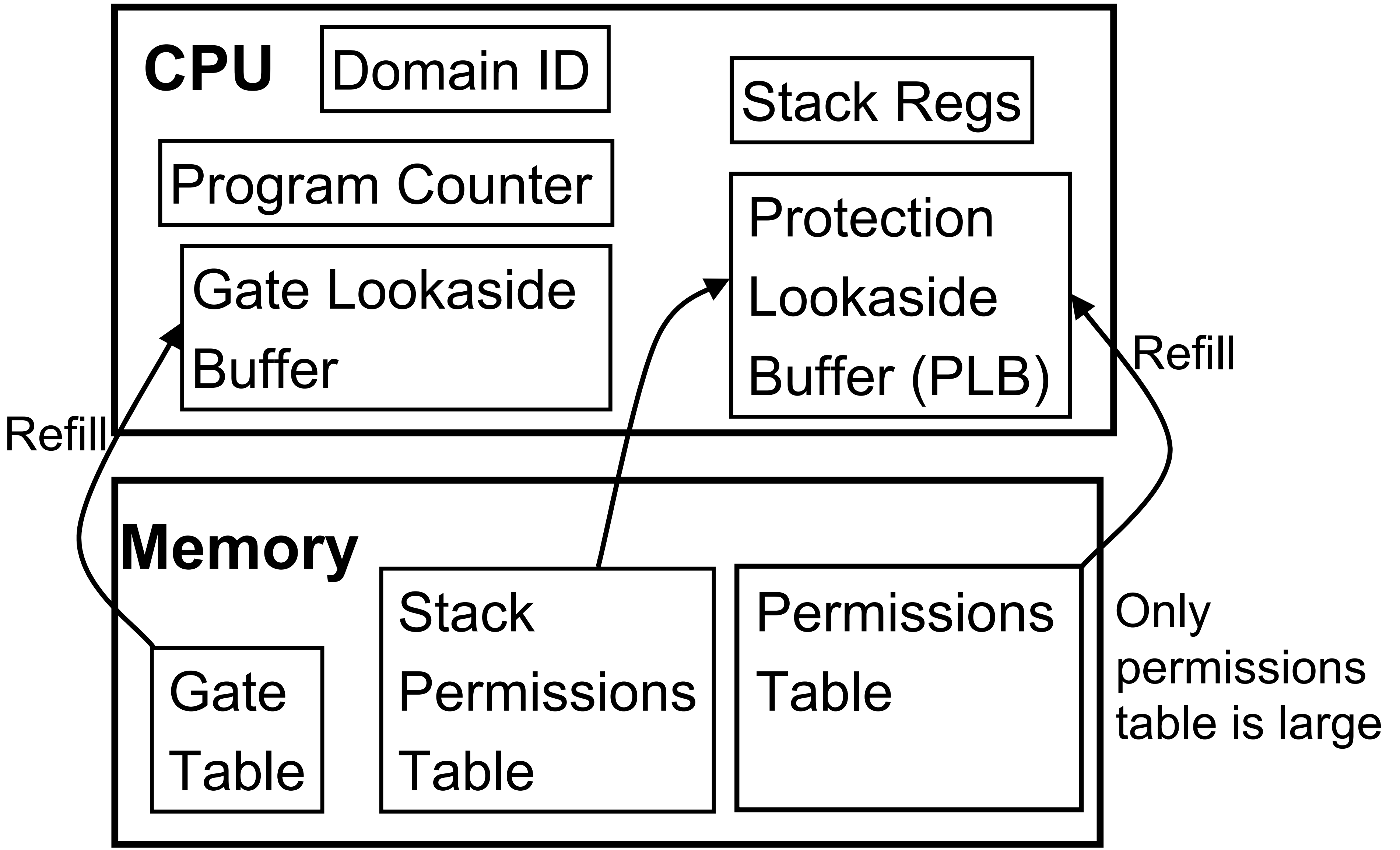
- Memory allocators kept out of supervisor
  - Allocator finds block of proper length
  - Supervisor grants permissions
- Supervisor tracks sharing relationships
  - **`kfree`** applies to all domains & groups
  - No modifications to kernel to track sharing
- Slab allocator made MMP aware
  - Allows some writes to uninitialized memory

Cross-Domain Calling



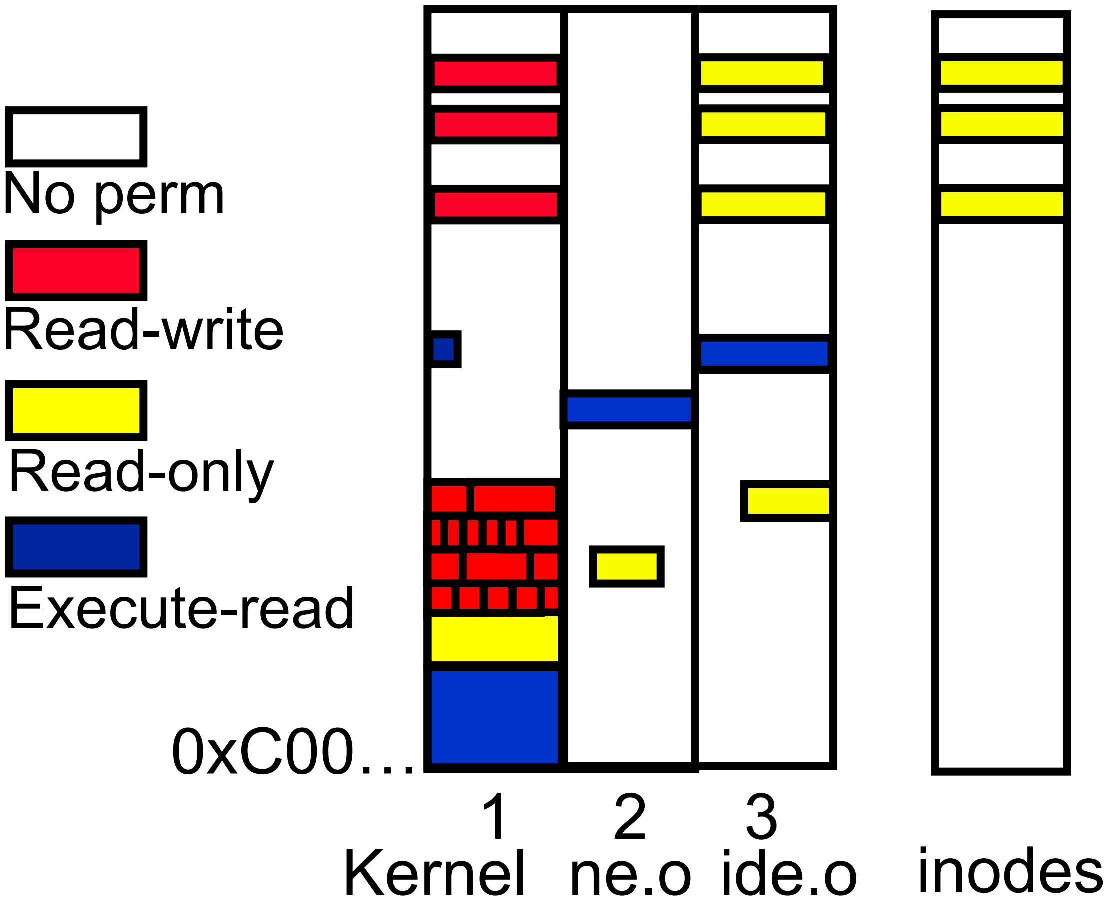
- Mondrix guarantees: push
  - Module only entered at switch gate
  - Return gate returns to instruction after call, to calling domain ret
  - “Marshalling” = Giving permissions
  - Stack allocated parameters are OK
- HW writes cross-domain call stack

MMP Hardware



Group Protection Domains

- Domains need permission on group of related memory objects.



- Group domain virtual until a regular domain joins.
- Supervisor regulates membership

Disk and Network Device Drivers

- Disk driver (EIDE)
  - Permission granted before device read/write
  - Permission revoked after device read/write
  - DMA supported
- Network driver (NE2000)
  - Permissions tightly controlled
  - Read-write to 32 of 144 bytes of **`sk_buff`**
    - Device driver does not write kernel pointers
  - Device does not support DMA

Net Driver Example

```
mprot_export(&skb, PROT_RW,sr_pd);

dev->start_recv(skb, dev); // XD

mprot_export(&skb,PROT_NONE,sr_pd)
```

- Kernel loader modifications
  - `start_recv` becomes cross-domain call
- Also add module memory sharing policy
  - Permission grant/revoke explicit

Evaluation Methodolgy

- Turned x86 into x86 with MMP
  - Instrumented SimICS & bochs machine simulator
  - Complete system simulation, including BIOS
  - 4,000 lines of hardware model of MMP
- Turned Linux into Mondrix
  - 4,000 lines of memory supervisor top
  - 1,720 lines of memory supervisor bottom
  - 2,000 lines of kernel changes
    - Modified allocators, tough but only done once
    - Modified disk & network code easier

Fault Injection Experiments

- Ext2 file system, RIO/Nooks fault injector

Symptom	# runs	MMP catch
None	157	4 (2.5%)
Hang	23	9 (39%)
Panic	20	18 (90%)

- Mondrix prevented 3 of 5 cases where filesystem became corrupt (lost data)
  - MMP detected problems before propagation
  - 2 of 3 errors detected outside device driver

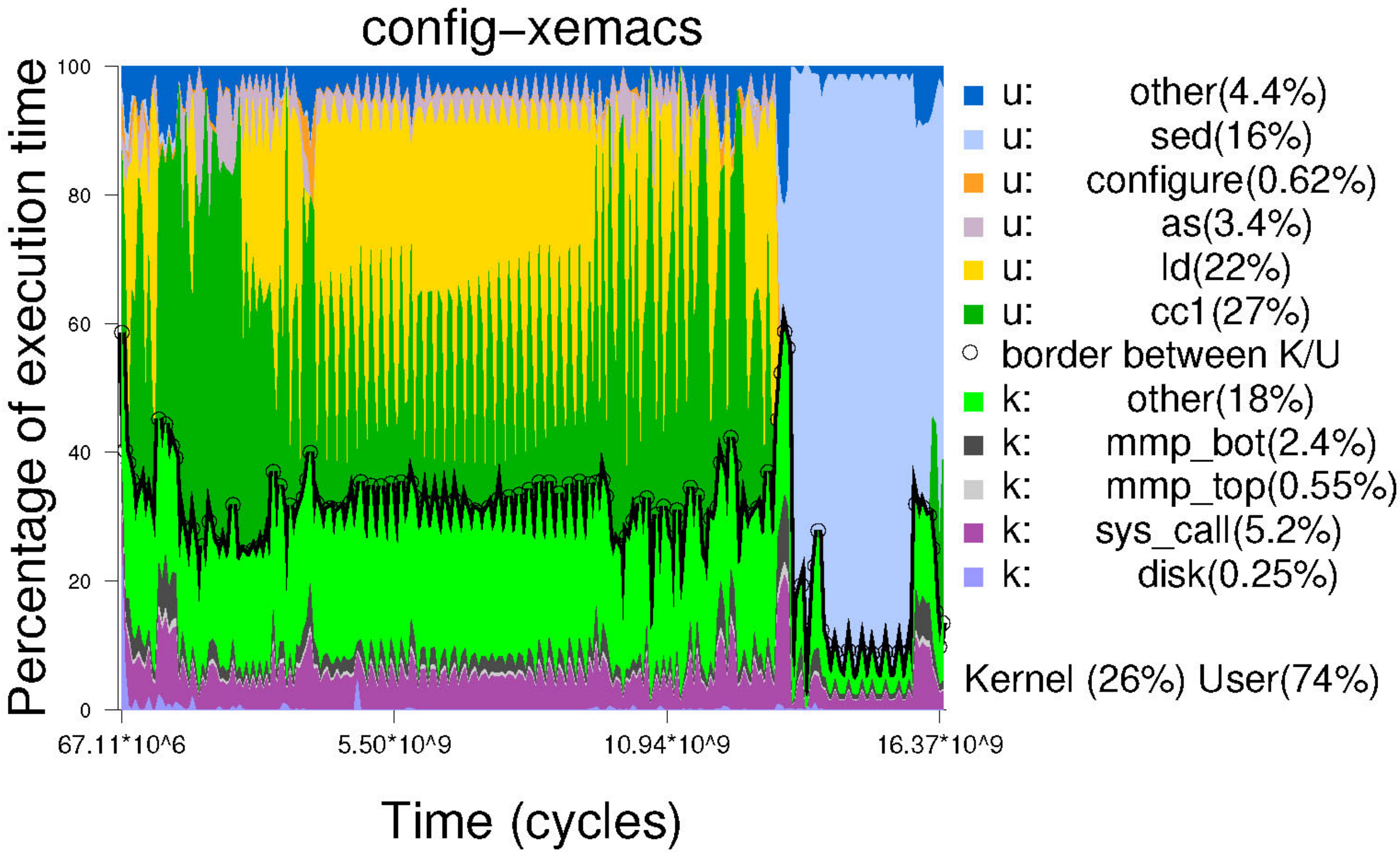
Workloads

- ./configure for xemacs-21.4.14
  - Launches many processes, creates many temporary files
- thttpd
  - Web server with cgi scripts
- find /usr –print | xargs grep kangaroo
- MySQL – client test subset 150 test transactions

Performance Model

- 1 instruction per cycle
- 16KB 4-way L1 I & D cache
- 2MB 8-way associative unified L2 cache
- 4 GHz processor, 50ns memory
- L1 miss = 16 cycles, L2 miss 200 cycles
- Slowdown = Total time of Mondrix workload/Total time of Linux workload

config-xemacs



Performance

Benchmark	Slow	Cyc*10^9	Mbot	Mtop	Kern
conf-xemacs	4.4%	16.5	2.4%	0.7%	1.3%
thttpd	14.8%	0.23	9.3%	2.0%	3.7%
find	3.3%	14.3	1.3%	1.2%	0.8%
MySQL	9.6%	0.21	4.0%	3.3%	2.3%

Benchmark	Mem	XD	Cy/XD	PLB
conf-xemacs	10.2%	0.3%	1,286	0.8%
thttpd	1.1%	0.8%	939	3.8%
find	7.8%	0.2%	846	0.4%
MySQL	1.6%	0.7%	664	1.7%

Performance, Protection, Programming

- Incremental performance cost for incremental isolation
- Loader only (~0.1%)
  - Gates, inaccessible words between strings
- Memory allocation package (~1.0%)
  - Guard words
  - Fault on accessing uninitialized data
- Module-specific policies (~10%)

Related Work

- Safe device drivers with Nooks [Swift '04]
- Asbestos [Efstathopoulos '05] event processes
  - Isolating user state perfect task for MMP
- Failure oblivious software [Rinard '04]
  - MMP optimizes out some memory checks
- Useful to implement safe languages?
  - Unmanaged pieces/unsafe extensions
  - Reduce trusted computing base

Conclusion

- Mondrix demonstrates that legacy software can be made safe (efficiently)
- MMP enables fast, robust, and extensible software systems
  - Previously it was pick two out of three
- OS should demand more of HW

Thanks to the PC, and I hope SOSP ’07 accepts ~20%