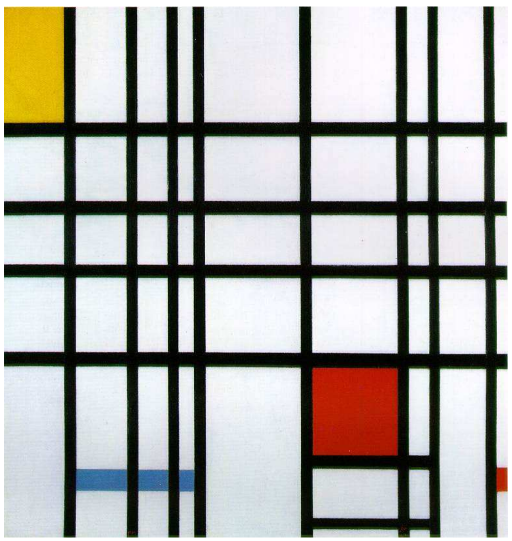
Hardware Works, Software Doesn't: Enforcing Modularity with Mondriaan Memory Protection



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HW Works, SW Doesn't — Negative

- Hardware has a bozo cousin named Software.

Hardware

Software

HW Works, SW Doesn't — Positive

- Hardware cooperates with software. Each has their strengths.

Hardware

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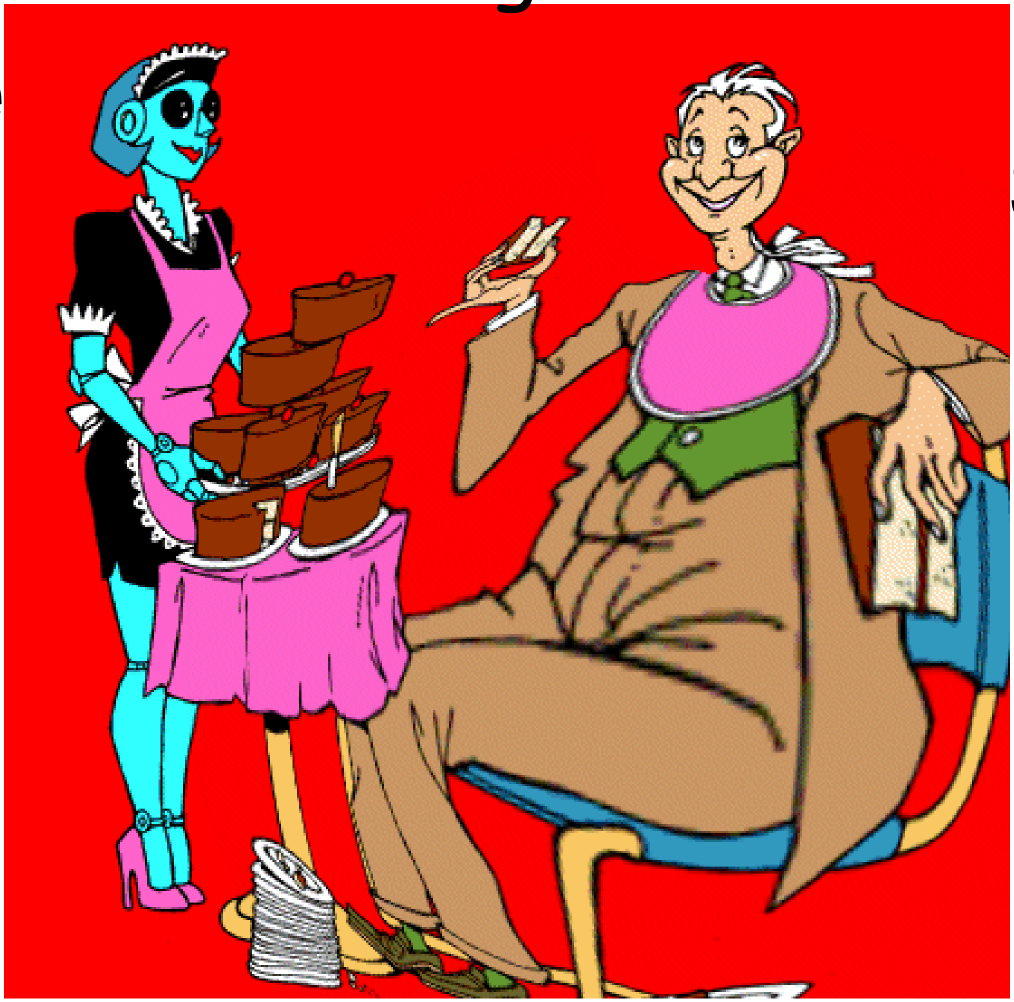
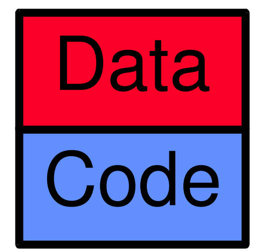
Hardware



Software

Software is Growing, Becoming Modular

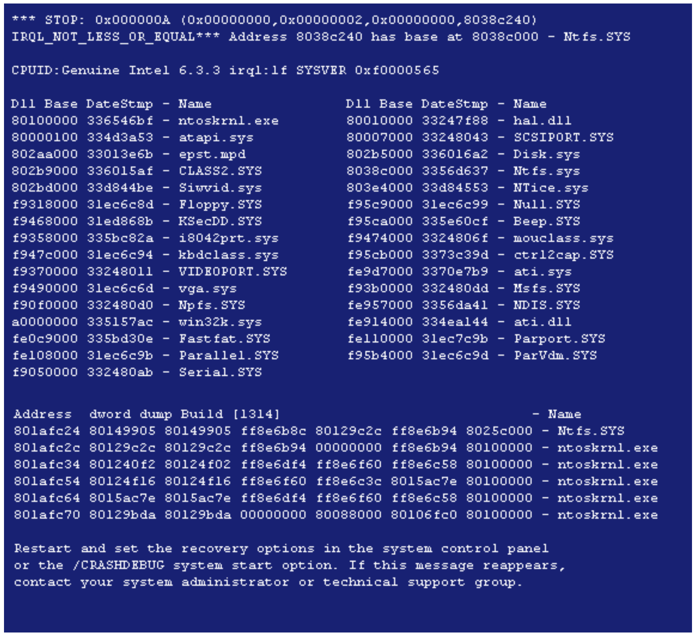
- Software complexity growing quickly.
  - Faster processors, larger memories allow more complicated software.
  - Linux kernel growing 200,000 lines/yr.
- Debian Linux supports 253 different kernel modules.
  - A module is code + data, possibly loaded at runtime, to provide functionality.



- Modules have narrow interfaces.
  - Not usually as narrow as an API, some internals are exposed.
  - Enforced by programming convention.

Modular Software is Failing

- Big, complex software fails too often.
  - Device drivers are a big problem.
- Big, complex software is hard to maintain.
  - Dependencies are tough to track.



Safe Languages (More SW) Not Answer

- Safe languages are slow and use lots of memory.
  - Restricts implementation to a single language.
  - Ignores a large installed base of code.
  - Can require analysis that is difficult to scale.
- Safe language compiler and run-time system is hard to verify.
  - Especially as more performance is demanded from safe language.
- Doing it all in SW as dumb as doing it all in HW.

Both Hardware and Software Needed

- Modules have narrow, but irregular interfaces.
  - HW should enforce SW convention without getting in the way.
- Module execution is finely interleaved.
  - Protection hardware should be efficient and support a general programming model.
- New hardware is needed to support software to make fast, robust systems.

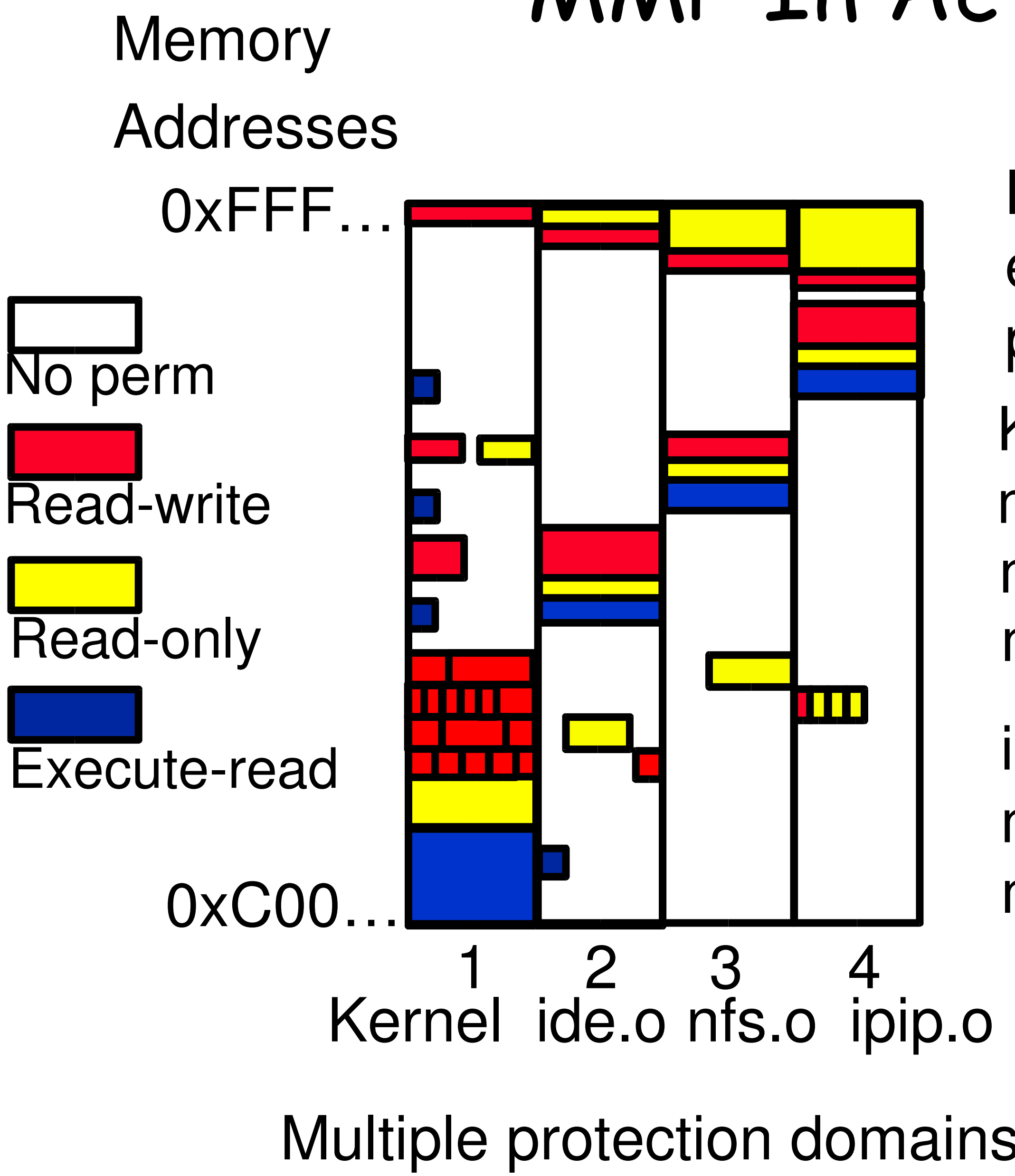
Current Hardware Broken

- Page based memory protection.
  - A reasonable design point, but we need more.
- Capabilities have problems.
  - Revocation difficult [System/38, M-machine].
  - Tagged pointers complicate machine.
  - Requires new instructions.
  - Different protection values for different domains via shared capability is hard.
- x86 segment facilities are broken capabilities.
  - HW that does not nourish SW.

Mondriaan Memory Protection

- Efficient word-level protection HW.
  - <0.7% space overhead, <0.6% extra memory references for coarse-grained use.
  - <9% space overhead, <8% extra memory references for fine-grained use. [Witchel ASPLOS '02]
- Compatible with conventional ISAs and binaries.
  - HW can change, if it's backwards compatible.
  - Let's put those transistors to good use.
- [Engler '01] studied linux kernel bugs.
  - Page protection can catch 45% (e.g., null).
  - Fine-grained protection could catch 64% (e.g., range checking).

MMP In Action



Kernel loader establishes initial permission regions

Kernel calls
mprotect(buf0, RO, 2);
mprotect(buf1, RW, 2);
mprotect(printk, EX, 2);

ide.o calls
mprotect(req_q, RW, 1);
mprotect(mod_init, EX, 1);

How Much Work to Use MMP?

- Do nothing.
  - Your application will still work.
- Change the malloc library (any dynamic lib).
  - You can add electric fences.
- Change the dynamic loader.
  - You can have module isolation.
- Add vmware/dynamo-like runtime system.
  - Many possibilities for fine-grained sharing.
- Change the program source.
  - You can have and control fine-grained sharing.

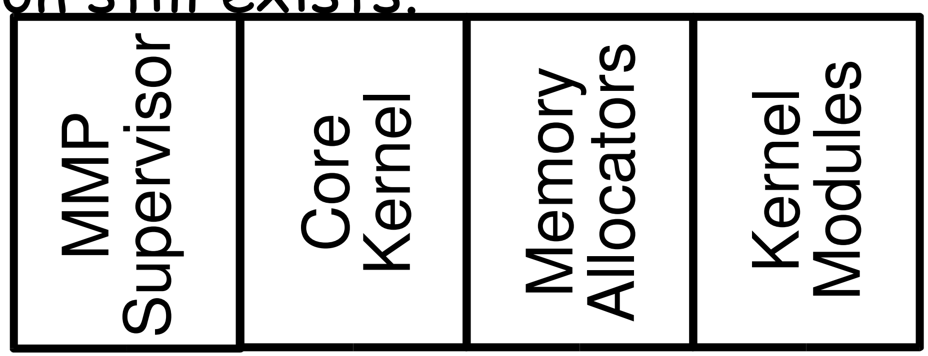
Trusted Computing Base of MMP

- MMP hardware checks every load, store and instruction fetch.
- MMP memory supervisor (software) writes the permissions tables read by the hardware.
  - Provides additional functionality and semantic guarantees.

MMP TCB smaller than safe language.

Memory Supervisor

- One protection domain (PD) to rule them all.
  - Writes MMP tables for other domains.
  - Handles memory protection faults.
  - Provides basic memory management for domain creation.
  - Enforces some memory use policies.
- Memory supervisor is part of kernel.
  - User/kernel distinction still exists.



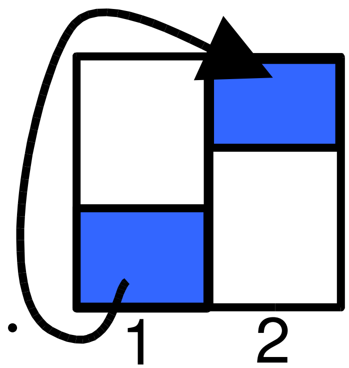
Kernel Protection Domains (PD-IDs) 0 1 2,..,N N+1,…

Memory Supervisor API

- Create and destroy protection domains.
  - `mmp_alloc_PD(user/kernel);`
  - `mmp_free_PD(recursive);`
- Allocate and free memory.
  - `mmp_alloc(n_bytes);`
  - `mmp_free(ptr);`
- Set permissions on memory (global PD-ID supported).
  - `mmp_set_perm(ptr, len, perm, PD-ID);`
- Control memory ownership.
  - `mmp_mem_chown(ptr, length, PD-ID);`

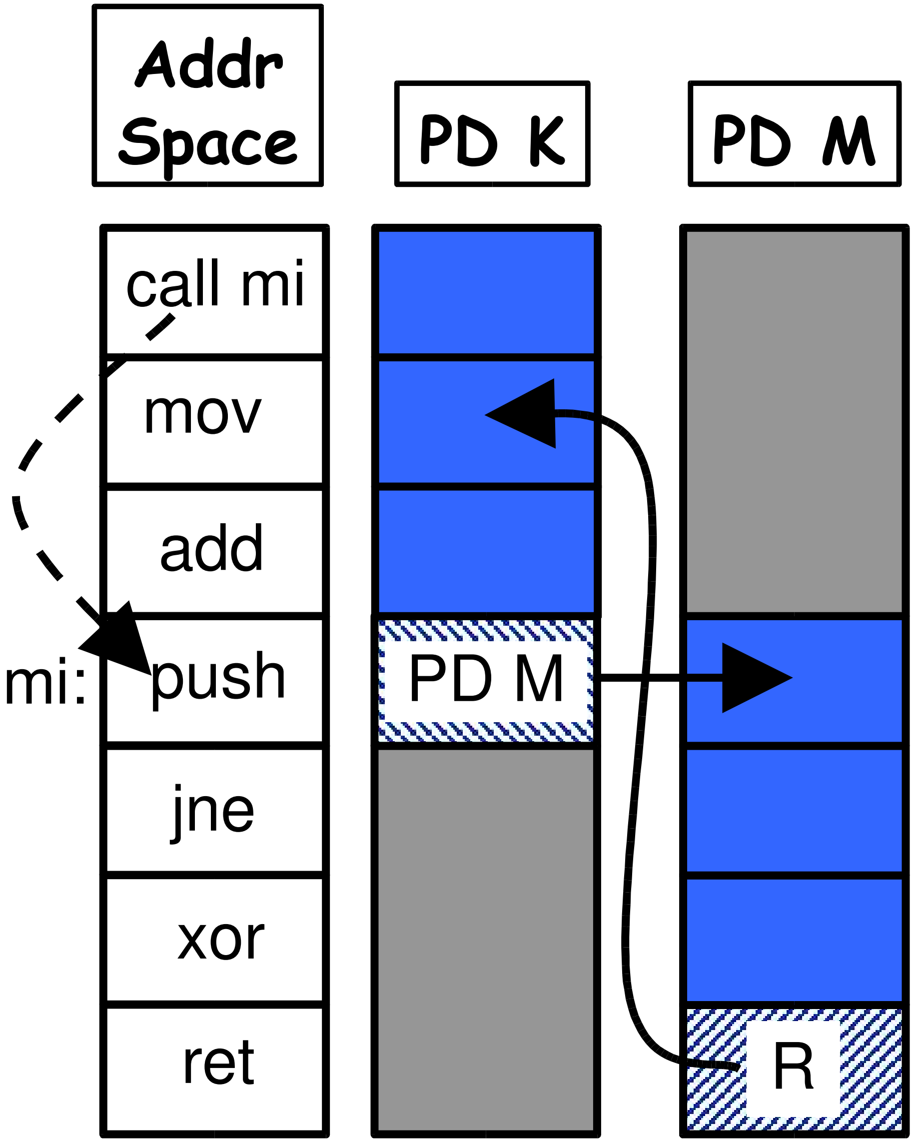
Managing Data

- Heap data is owned by PD.
  - Permissions managed with supervisor API.
  - E.g., `mmp_set_perm(&buf, 256, read-only, consumer_PD-ID);`
- Code is owned by PD.
  - Execute permission used within a PD.
  - Call gates are used for cross-domain calls, which cross protection domain boundaries.



- Stack is difficult to do fast.

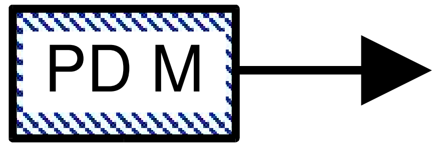
Call and Return Gates



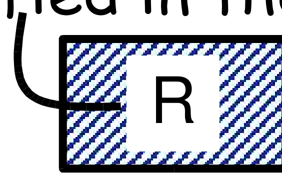
- Procedure entry is call gate, exit is return gate.
- Call gate data stored in permissions table.
- Return gate returns & restores original PD.

Architectural Support for Gates

- Architecture uses protected storage, the cross-domain call stack, to implement gates.
- On call gate execution:



  - Save current PD-ID and return address on cross-domain call stack.
  - Transfer control to PD specified in the gate.



- On return gate execution:
  - Check instruction RA = RA on top of cross-domain call stack, and fault if they are different.
  - Transfer control to RA in PD specified by popping cross-domain call stack.

Are Gate Semantics Useful?

- Returns are paired with calls.
  - Works for callbacks.
  - Works for closures.
  - Works for most implementations of exceptions (not setjmp/longjmp).
- Maybe need a call-only gate.
  - To support continuations and more exception models.
  - Allow cross-domain call stack to be paged out.

Stack Headache

- Threads cross PDs, and multiple threads allowed in one PD.
  - So no single PD can own the stack.
- MMP for stack permissions work, but it is slow.
  - Can copy stack parameters on entry/exit.
  - Can add more hardware to make it efficient.
  - Can exploit stack usage properties.
    - How prevalent are writes to stack parameters?

Finding Modularity in the OS

- Let MMP enforce module boundaries already present in software.
- Defining proper trust relations between modules is a huge task.
  - Not one I want to do by hand.
- Can we get 90% of the benefit from 5% of the effort?

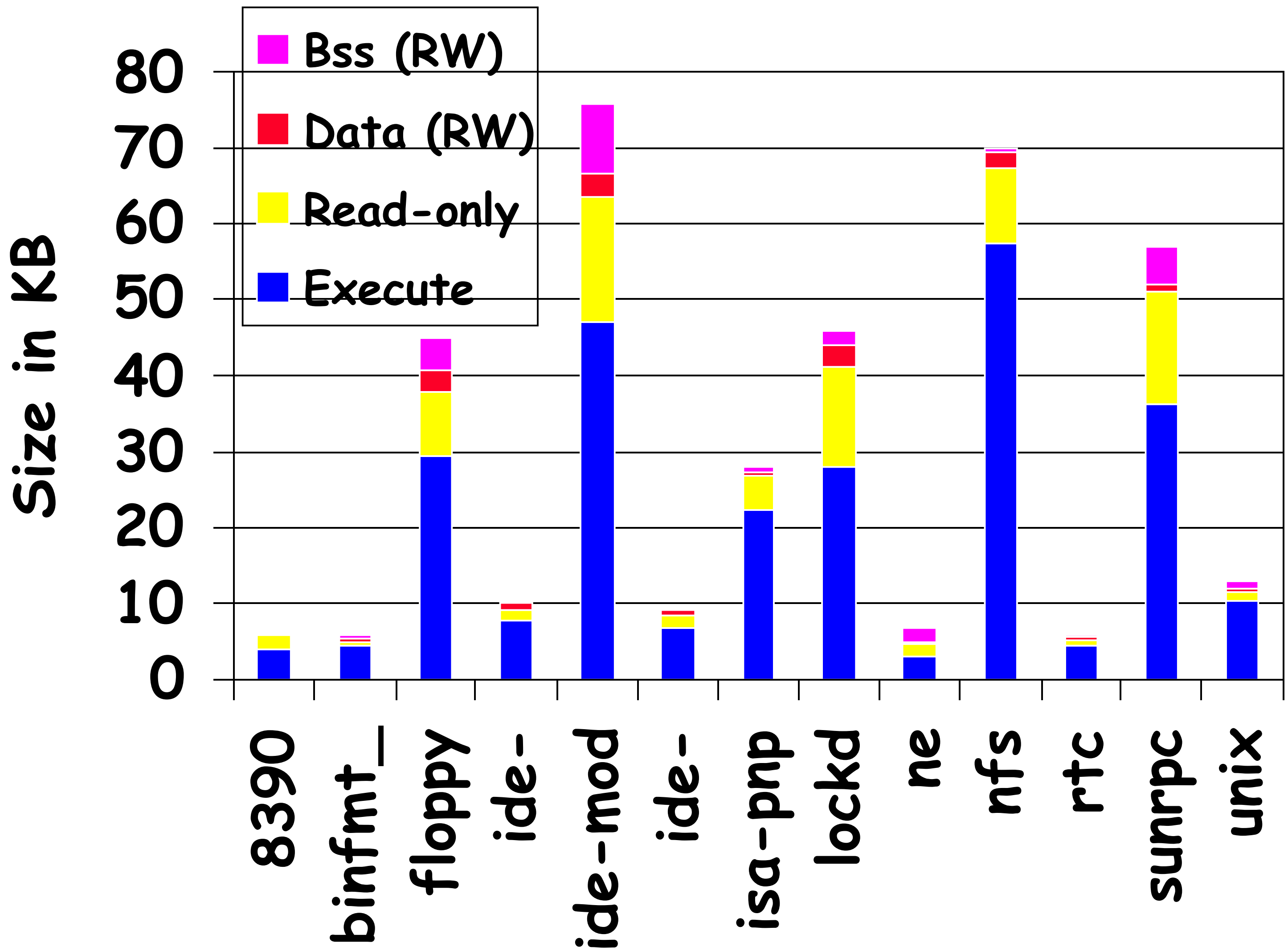
Using Symbol Information

- Symbol import/export gives information about trust relations.
  - Module that imports "printk" symbol will need permission to call printk.
- Data imports are trickier than code imports.
  - E.g., code can follow a pointer out of a structure imported via symbol name.
  - Do array names name the array or just one entry?

Measuring OS Modularity

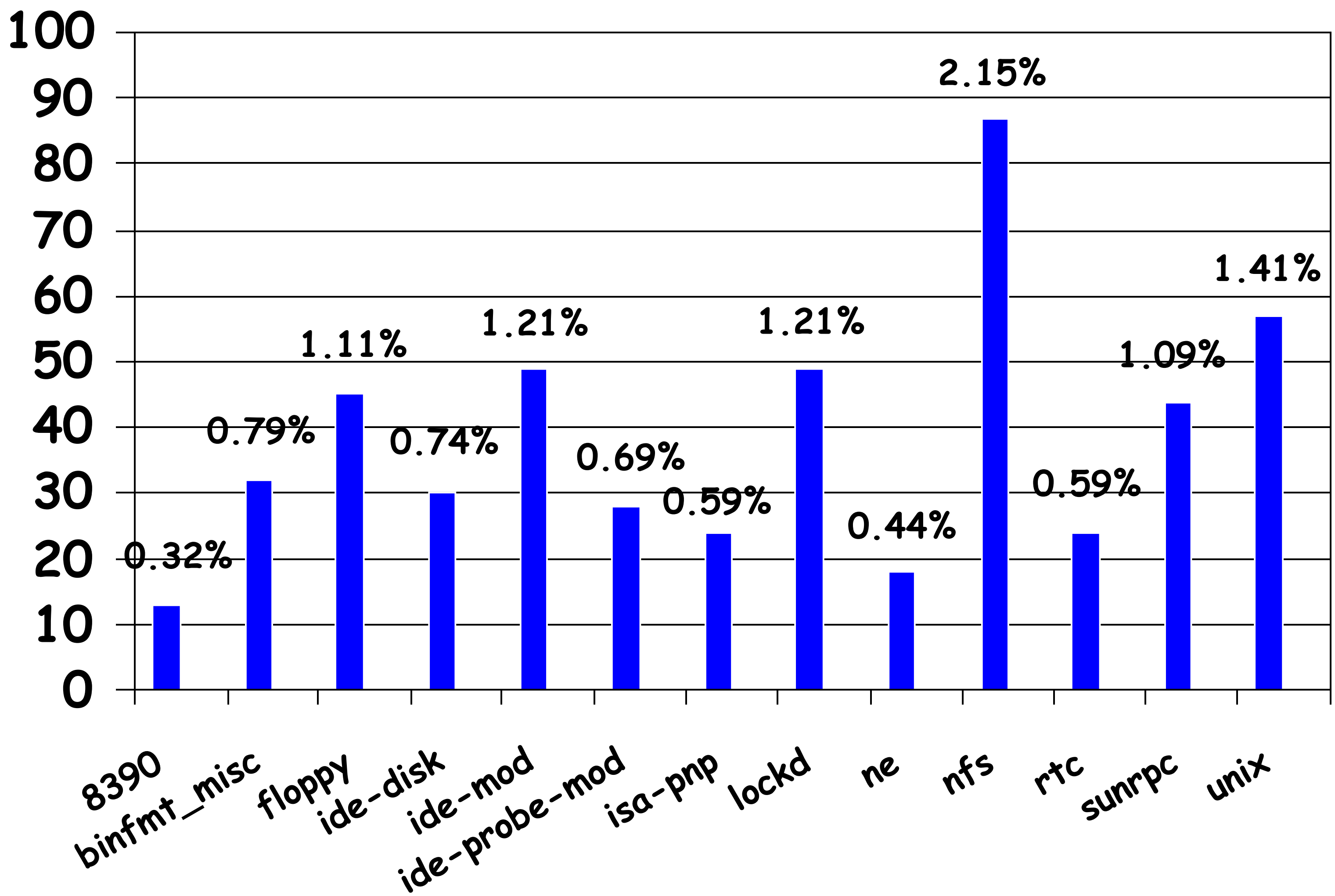
- Is module interface narrow?
  - Yes, according to symbol information.
  - Measured the static data dependence between modules and the kernel.
- How often are module boundaries crossed?
  - Often, at least in the boot.
  - Measured dynamic calling pattern.

Size of Kernel Modules



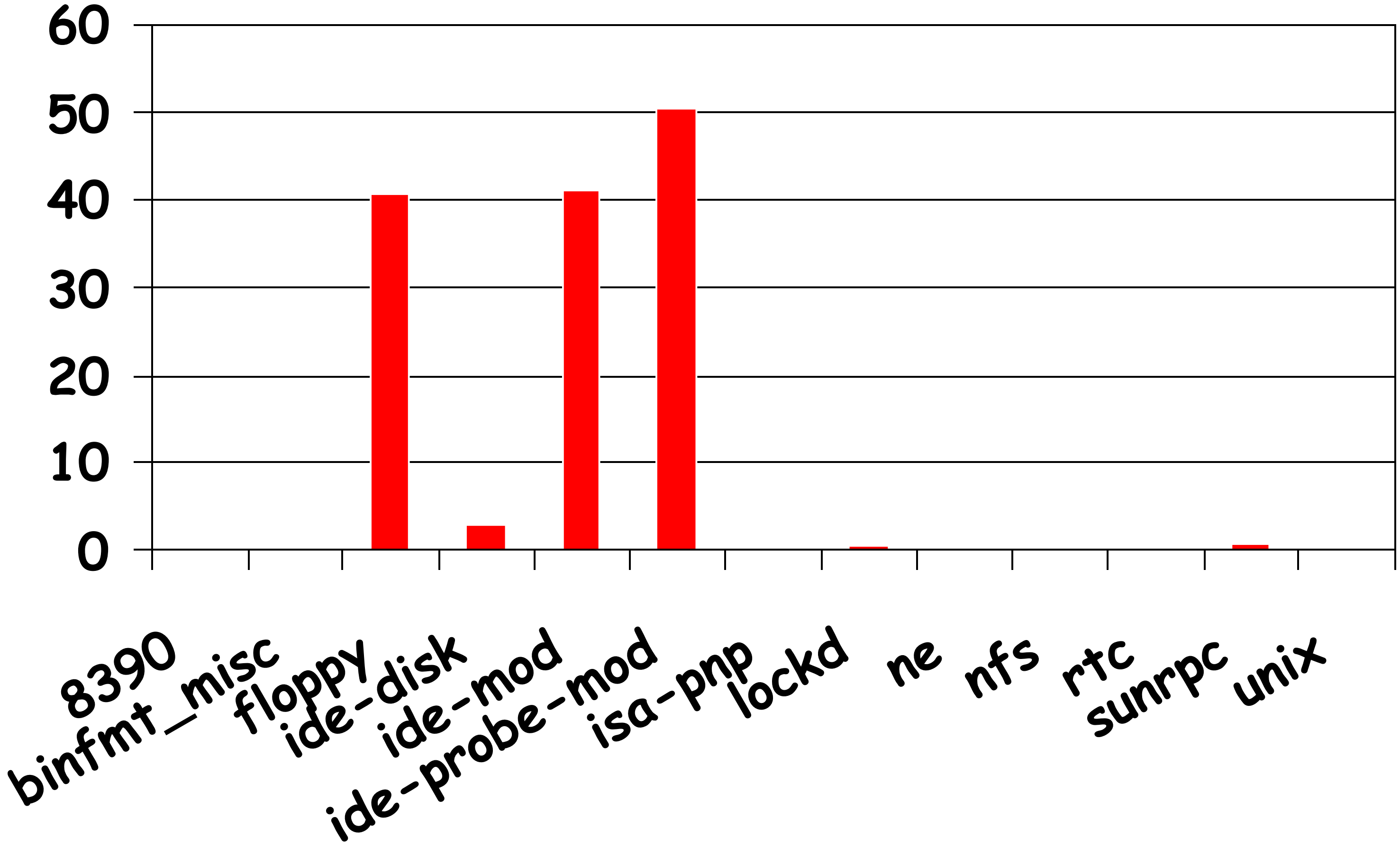
- Modules are small and mostly code.

Number of Imported Call Gates



- 4,031 named entry points in kernel.

Size of Imported Data (KB)



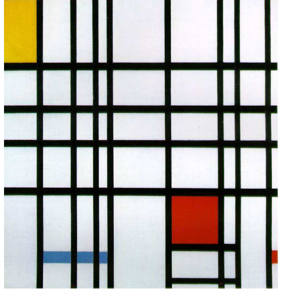
- Kernel has 551KB of static data.
- Block devices import arrays of structures.

Measuring Cross-Domain Calls

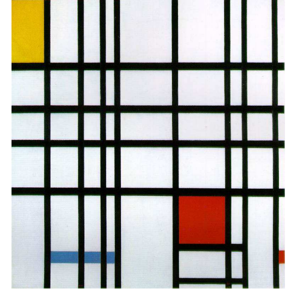
- Instrumented bochs simulator to gather data about module interactions in Debian Linux 2.4.19.
  - Enforce module boundaries: deal with module loader, deal with module version strings in text section, etc.
- 284,822 protection domain switches in the billion instruction boot.
  - 3,353 instructions between domain switch.
  - 97.5% switches to IDE disc driver.
- This is fine-grained interleaving.

Additional Applications

- Once you have fine-grained protection, exciting possibilities for system design become possible.
- Eliminate memory copying from syscalls.
- Provide specialized kernel entry points.
- Enable optimistic compiler optimizations.
- Implement C++ const.



Conclusion



- Hardware should help make software more reliable.
  - Without getting in the way of the software programming model.
- MMP enables fast, robust, and extensible software systems.
  - Previously it was pick two out of three.