"Sections are types, linking is policy"

Intra-Process Memory Protection for Applications on ARM and x86: Leveraging the ELF ABI

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Outline

- Why and how to use ELF ABI for policy
- Our design of an ELF-backed intra-memory ACLs
  - Linux x86 prototype
  - ARM prototype
- Case studies:
  - ICS protocol proxy
  - OpenSSH policy

Motivation

- File-level policies (e.g., SELinux) fail to capture what happens **inside** a process (cf. Heartbleed, etc.)
- CFI, DFI, SFI, etc. are good *mitigations*, but they aren't policy: they don't describe **intended** operation of code
- **ELF ABI** has plenty of structure to encode intent of a process' parts: libraries, code & data sections
  - Already supported by the GCC toolchain!
  - Policy is easy to create, intuitive for C/C++ programmers

Policy vs mitigations

- Both aim to block unintended execution (exploits)
- Mitigations attempt to **derive** intent
  - E.g., no calls into middles of functions, no returns to non-call sites, etc.
- Policy attempts to **express** intent explicitly
  - E.g., no execution from data areas, no syscalls beyond a whitelist, no access to files not properly marked
- Policy should be **relevant** & **concise** (or else it's ignored)

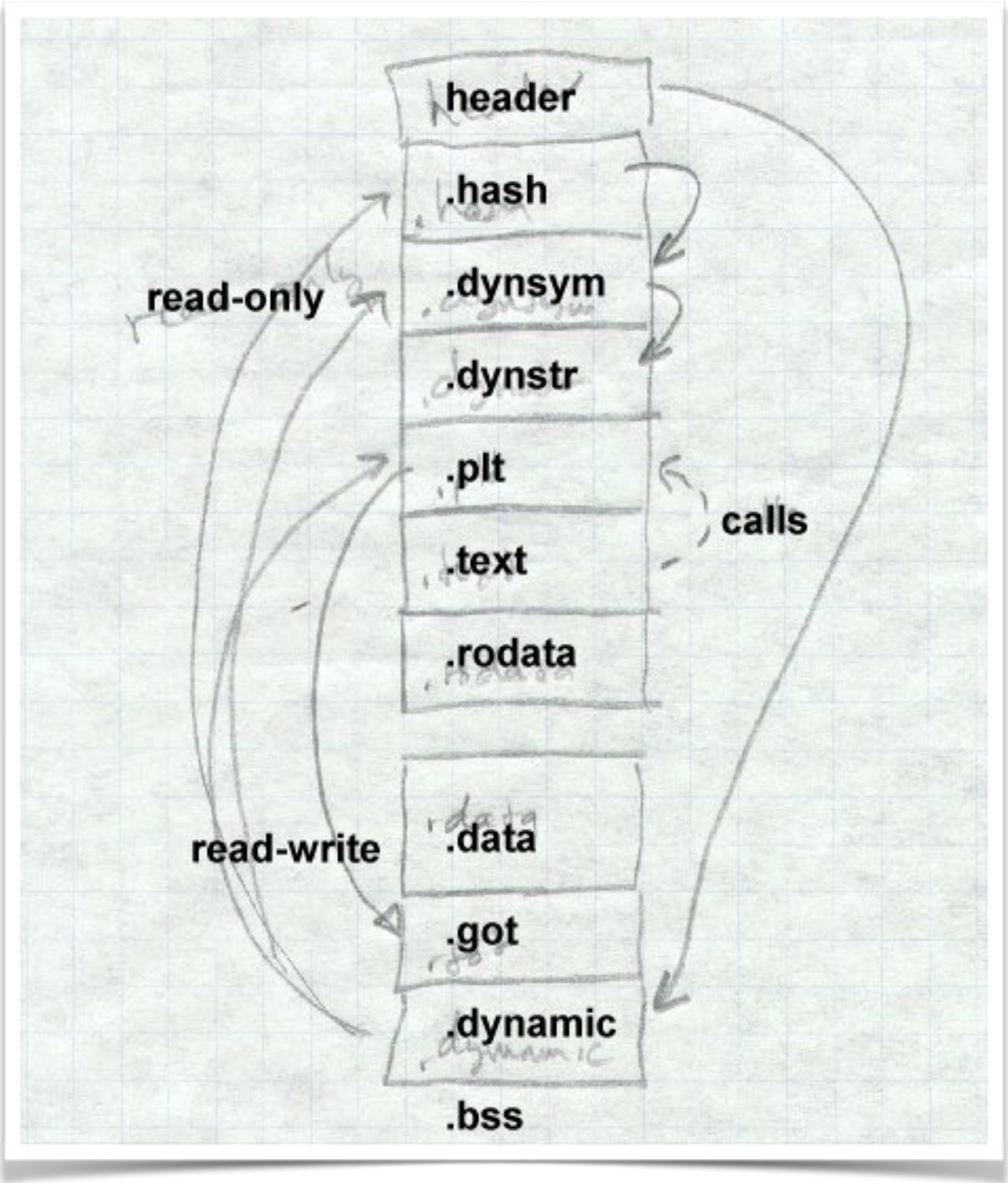
Policy wish list

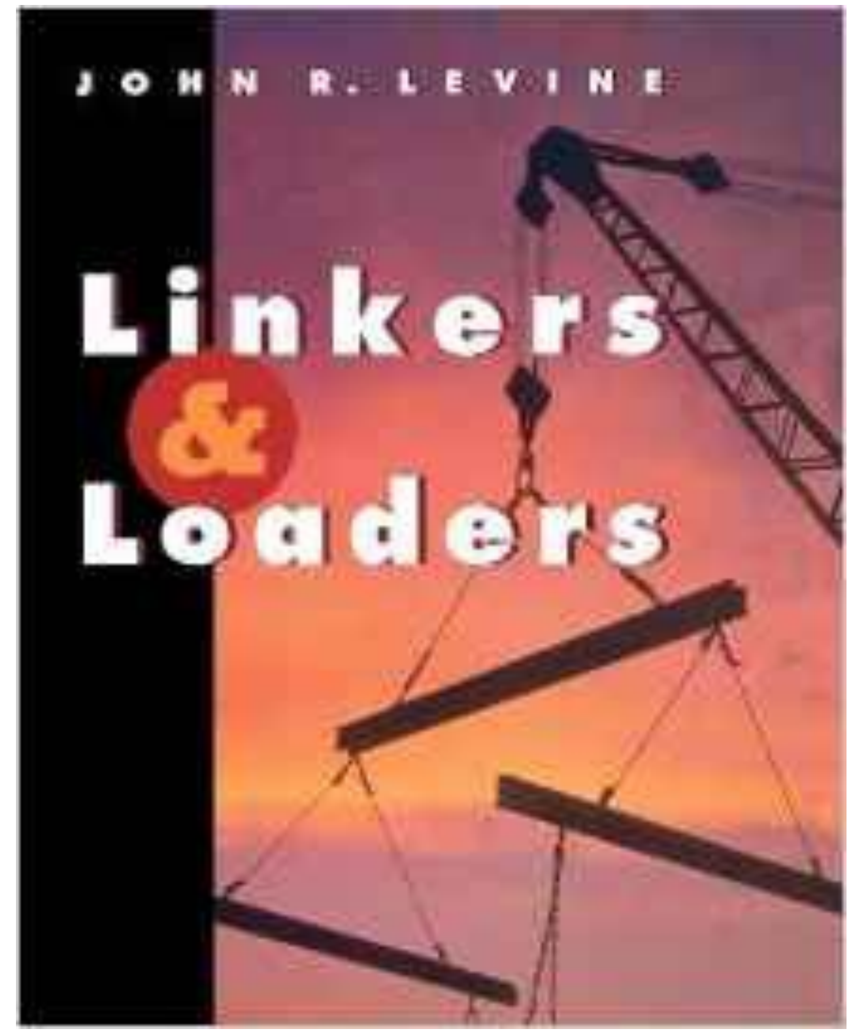
- Relevance: describe what matters
  - E.g.: SELinux is a "bag of permissions" on file ops. Can't describe order of ops, number of ops, memory accesses, any **parts** or **internals** of a process
- Brevity: describe only what matters
  - E.g.: SELinux makes you describe **all** file ops; you need tools to **compute** allowed data flows

What matters?

- Composition: a process is no longer "a program"; it's also many different **components** & libraries, all in one space, but with very different purposes & intents
- Order of things: a process has **phases**, which have different purposes & intents
- Exclusive relationships: pieces of code and data have **exclusive relationships** by function & intent
  - "This is *my* data, only *I* should be using it"

An inspiration: ELF RTLD

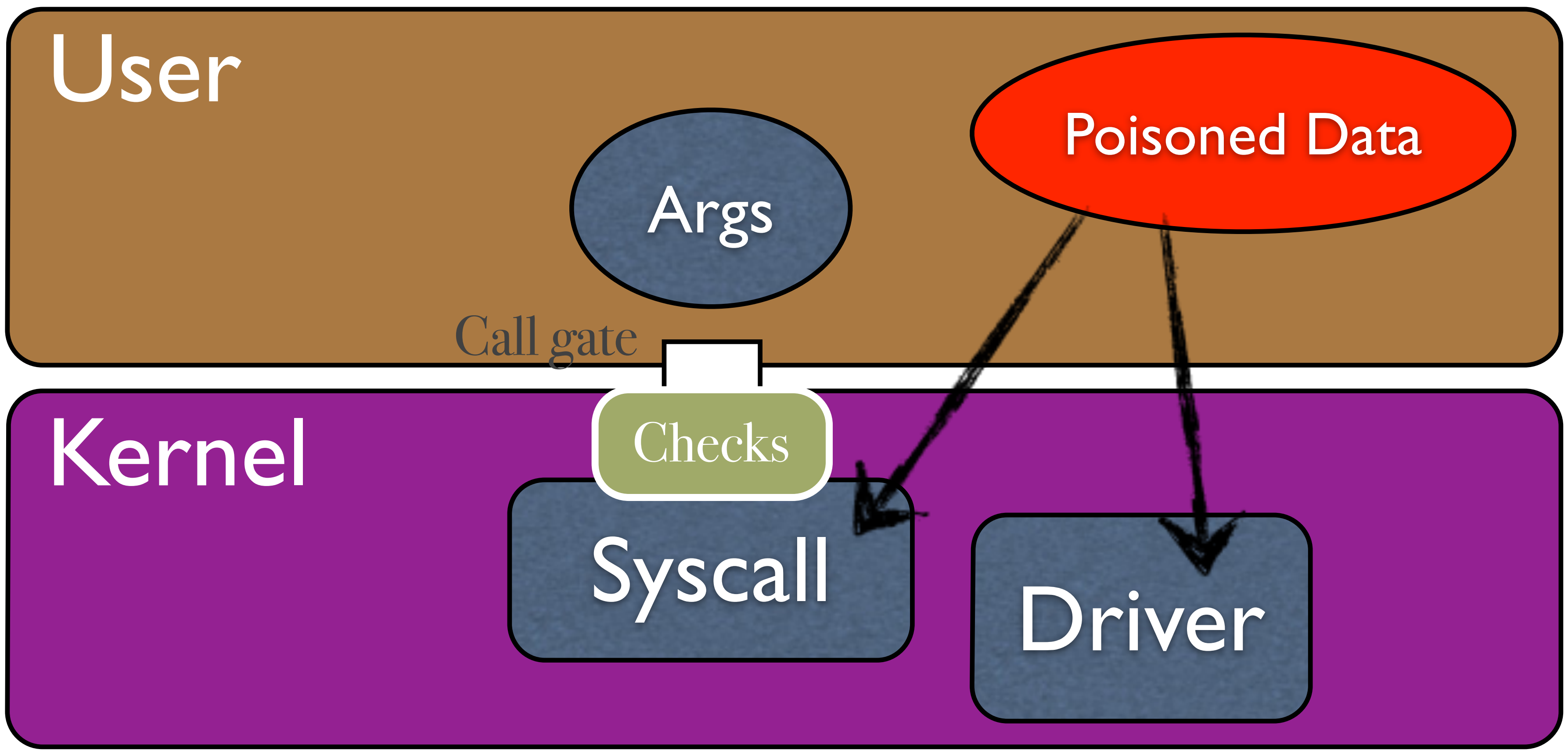




John Levine,
"Linkers & loaders"

An inspiration: PaX/Grsec UDEREF

- UDEREF guards code from accessing the data it wasn't meant to access
- "Privilege Rings" are too about code/data relationships

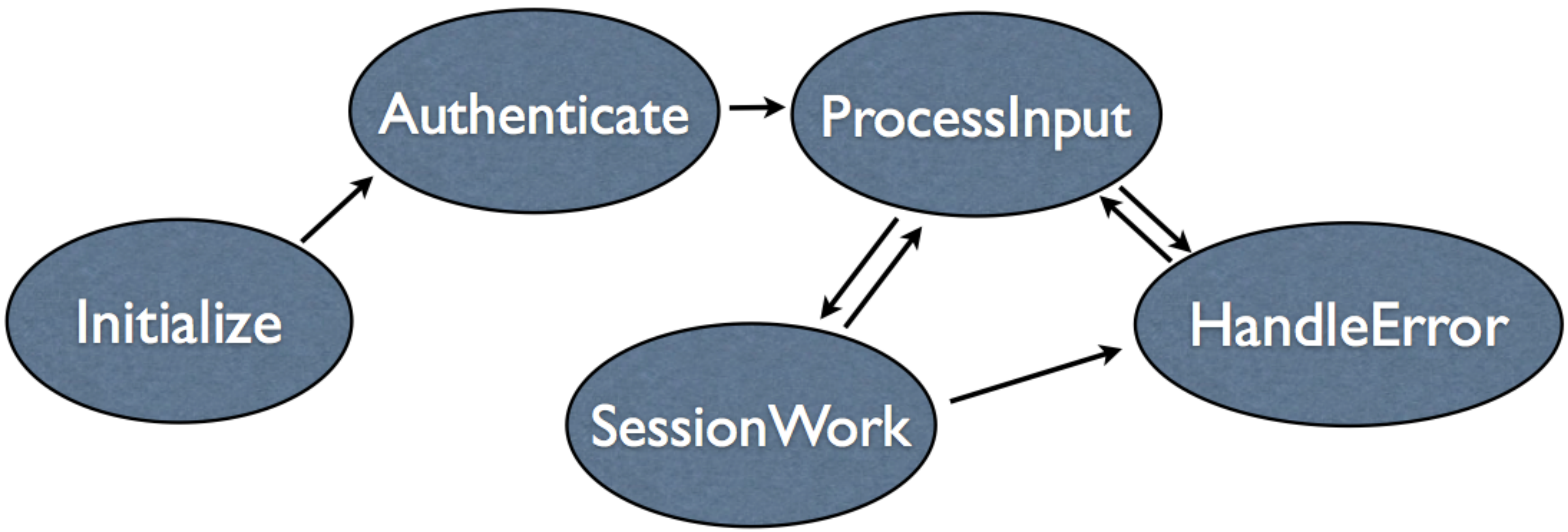


"Some thoughts on security after ten years of qmail", D.J. Bernstein, 2007

- Used process isolation as security boundaries
  - Split functionality into many per-process pieces
- Enforced **explicit data flow** via process isolation
- Avoided in-process parsing
- Least privilege was a distraction, but **isolation** worked

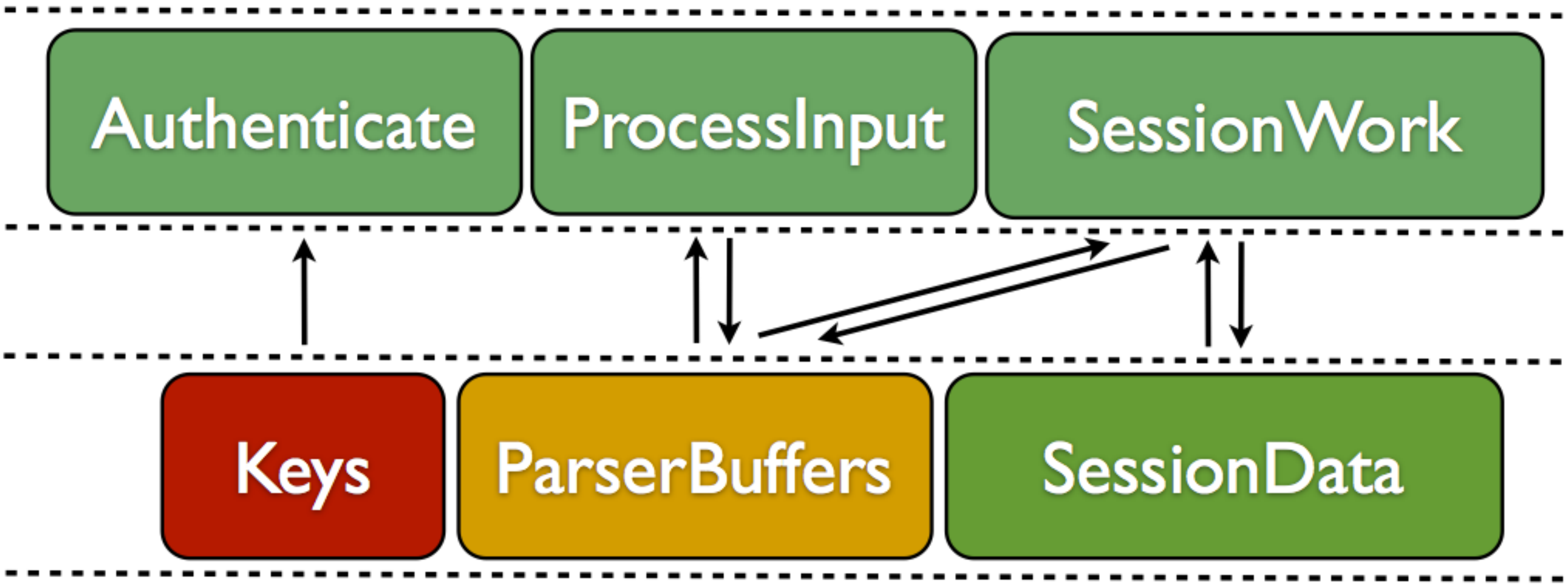
http://cr.yp.to/qmail/qmailsec-20071101.pdf

Process phases



- "Phase" ~ code unit ~ EIP range ~ memory section

Access relationships are key to programmer intent



- Unit semantics ~ Explicit data flows (cf. *qmail*)

Intent-level semantics

- "*The **gostak distims** the **doshes***"

  -- Andrew Ingraham, 1903

  - Non-dictionary words, English grammar
  - Semantics == relationships between terms
- **Relationships** between code & data sections reflect their **intent**, often uniquely

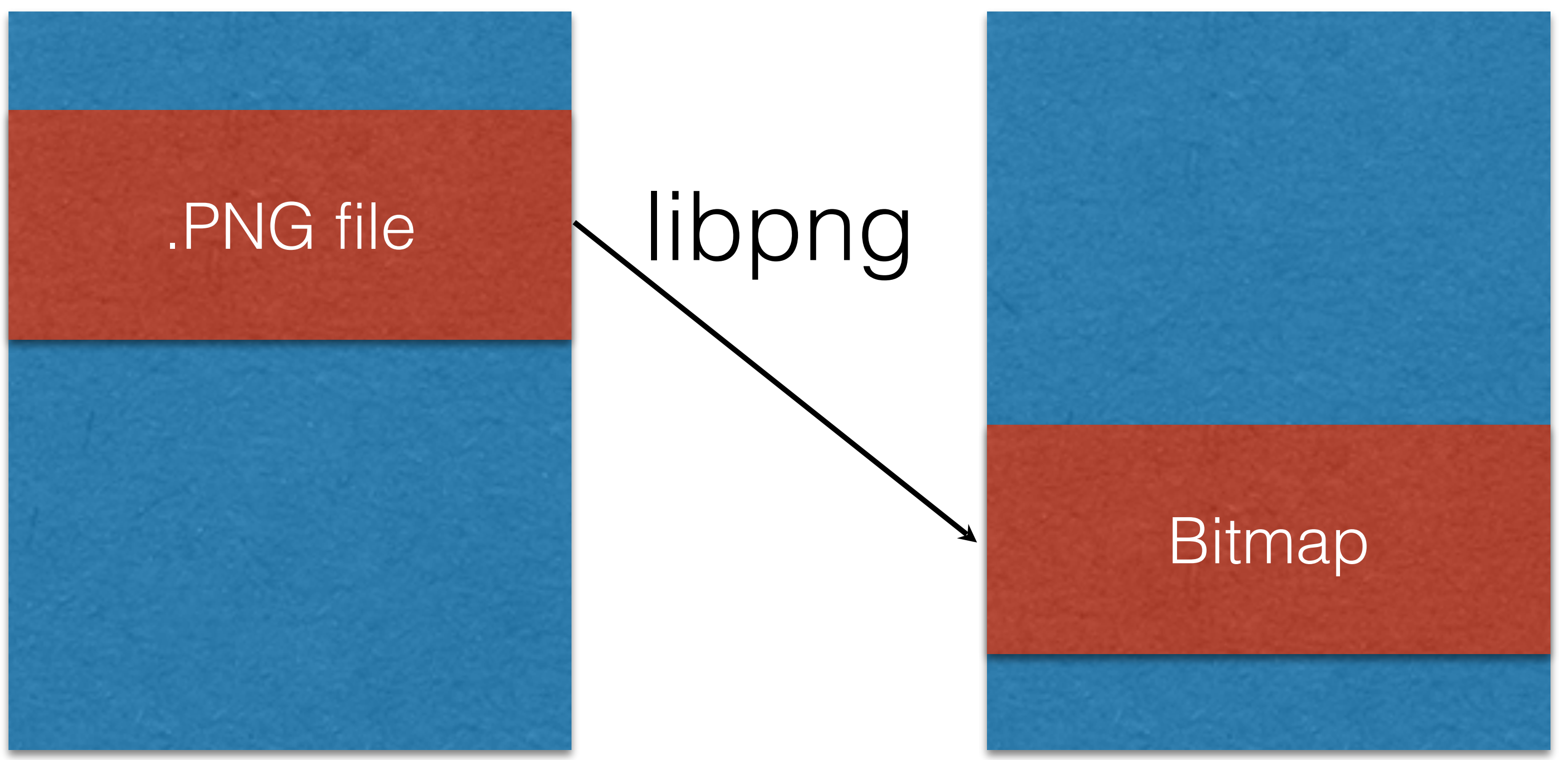
"Sections are types, linking is policy"

- The idea of a *type* is "objects with common operations"
  - Methods of a class in OOP, typeclasses in FP, etc.
- For data sections, their dedicated code sections are their operations
  - It's dual: data accessed by code tells much about code
- Linkers collect similar sections into contiguous pieces
  - **Linker maps** are the closest we have to intent descriptions of binary objects in process space!

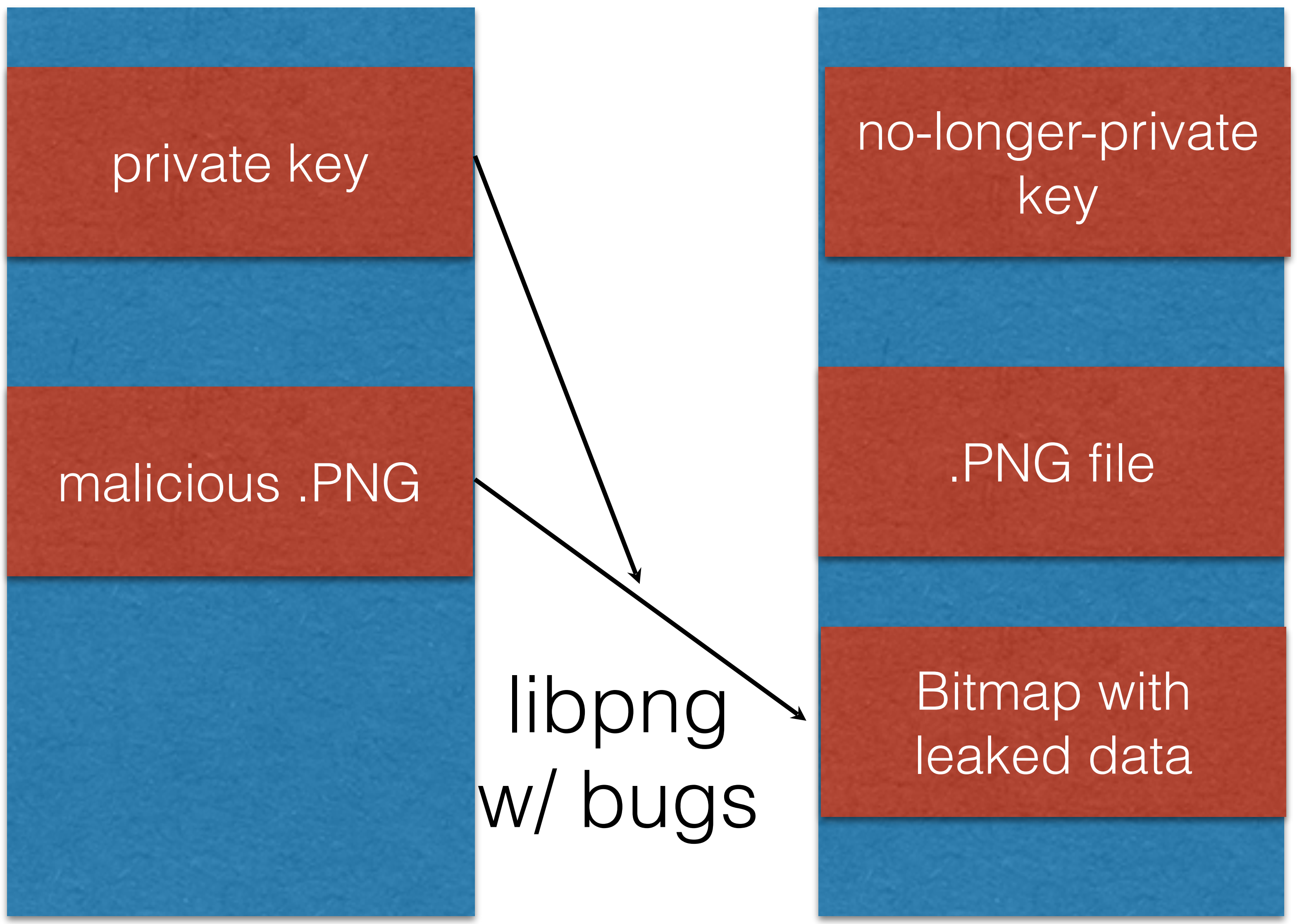
Motivating Example

Example policies

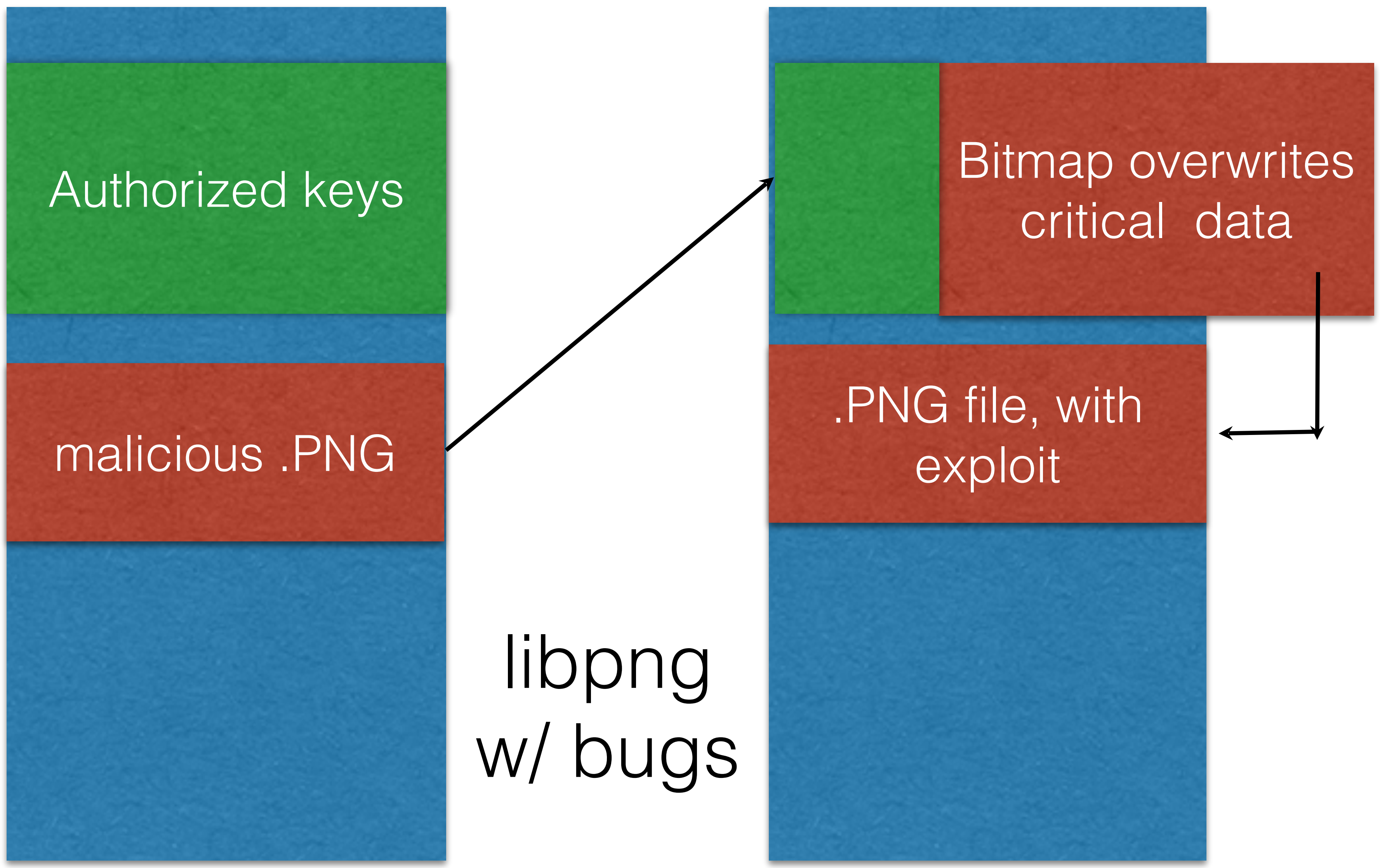
- Web application decompresses a PNG file
- Mental model



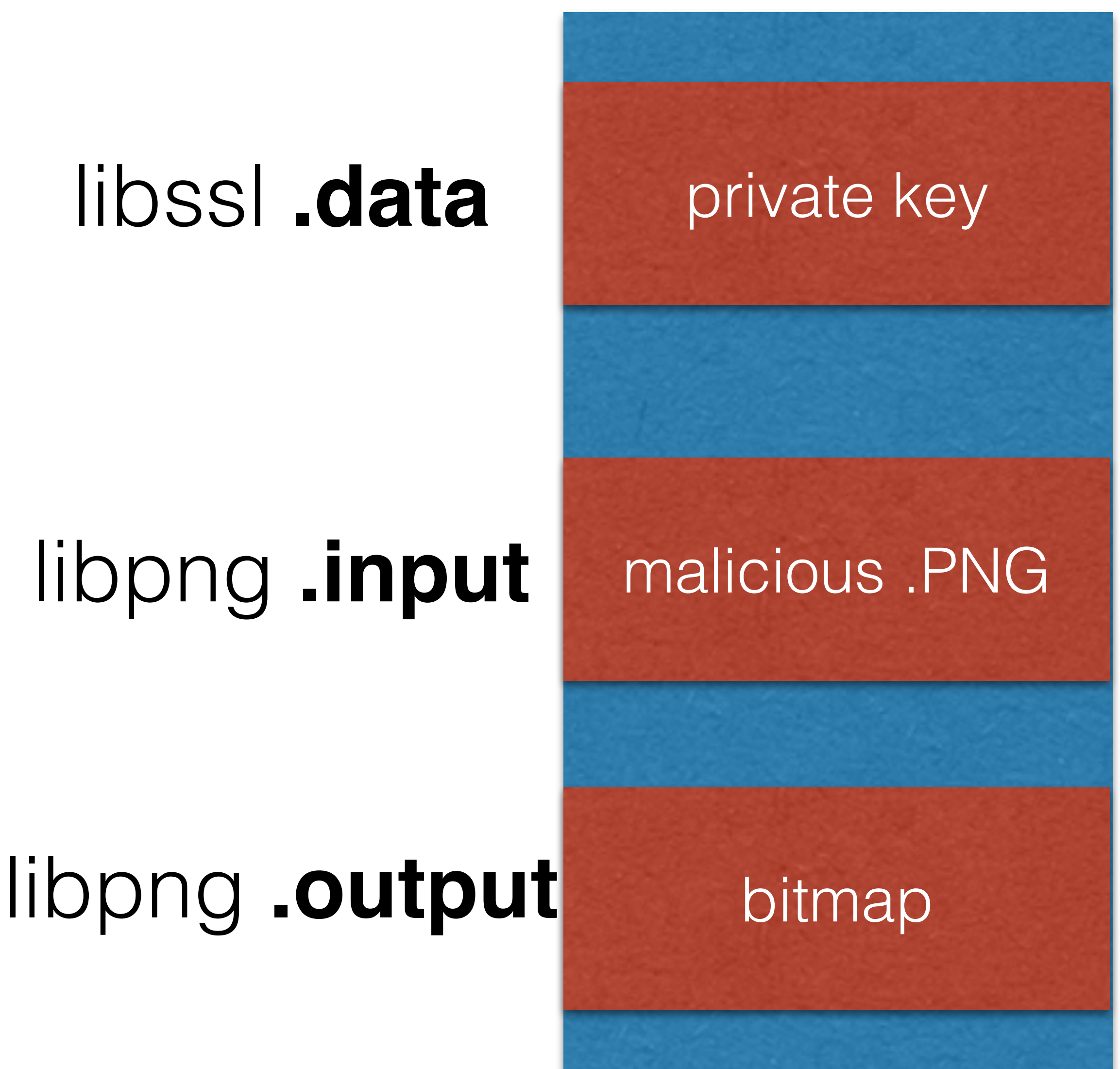
What attackers see



Or

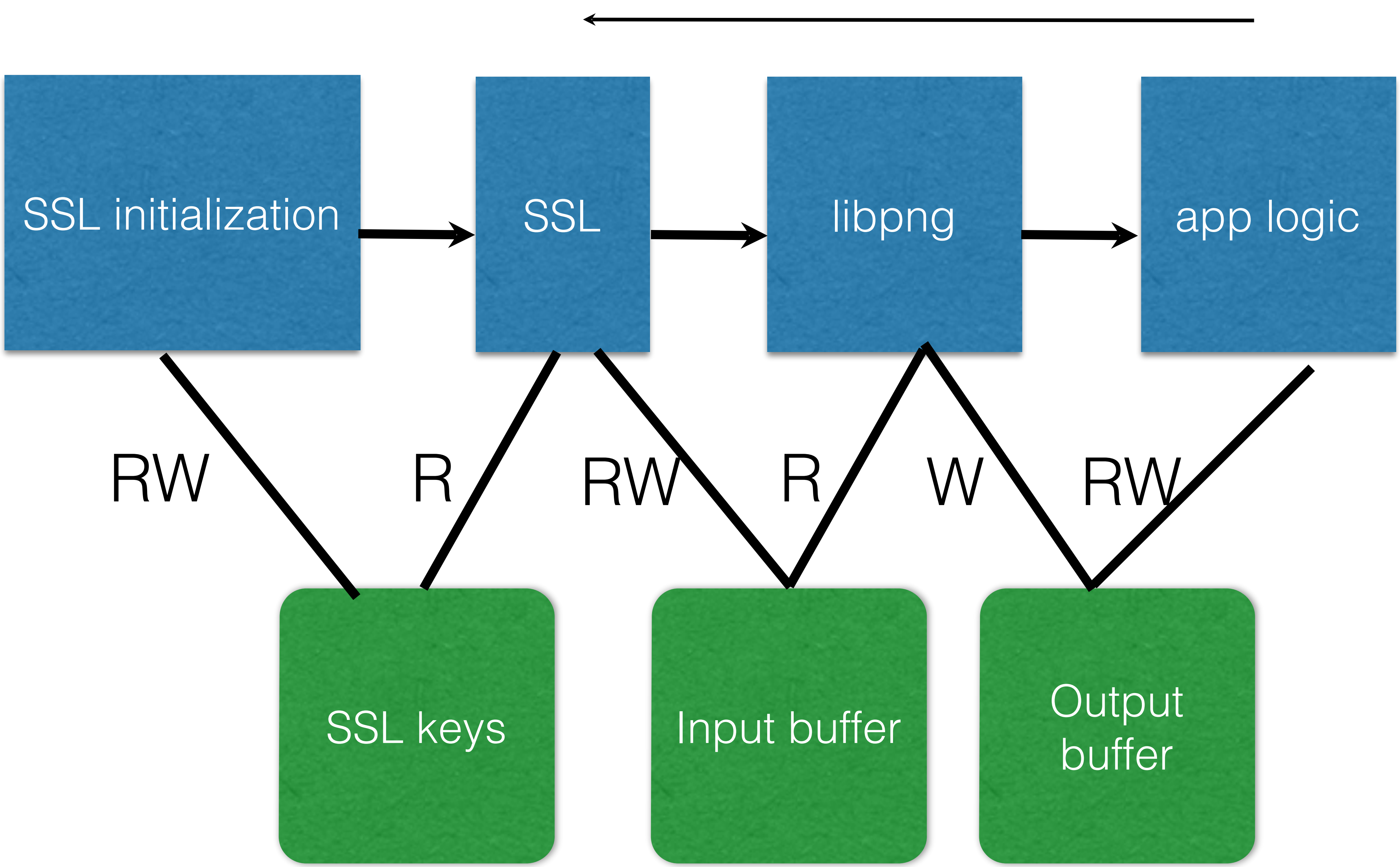

Authorized keys
malicious .PNG
Bitmap overwrites critical data
.PNG file, with exploit
libpng w/ bugs

Mapping it into the ABI



- Easy to introduce new sections
- Each code segment can get different permissions
- Only libssl.text can access libssl.data
- libpng.text can only access libpng.input and libpng.output
- And libpng.input can only be read by libpng.

Back to our example



Enforcing

- Modern OS loaders **discard** section information
- New architecture:
  - '**Unforgetful** loader' preserves section identity after loading
  - Enforcement scheme for **intent-level semantics**
  - Better tools to capture semantics in ABI

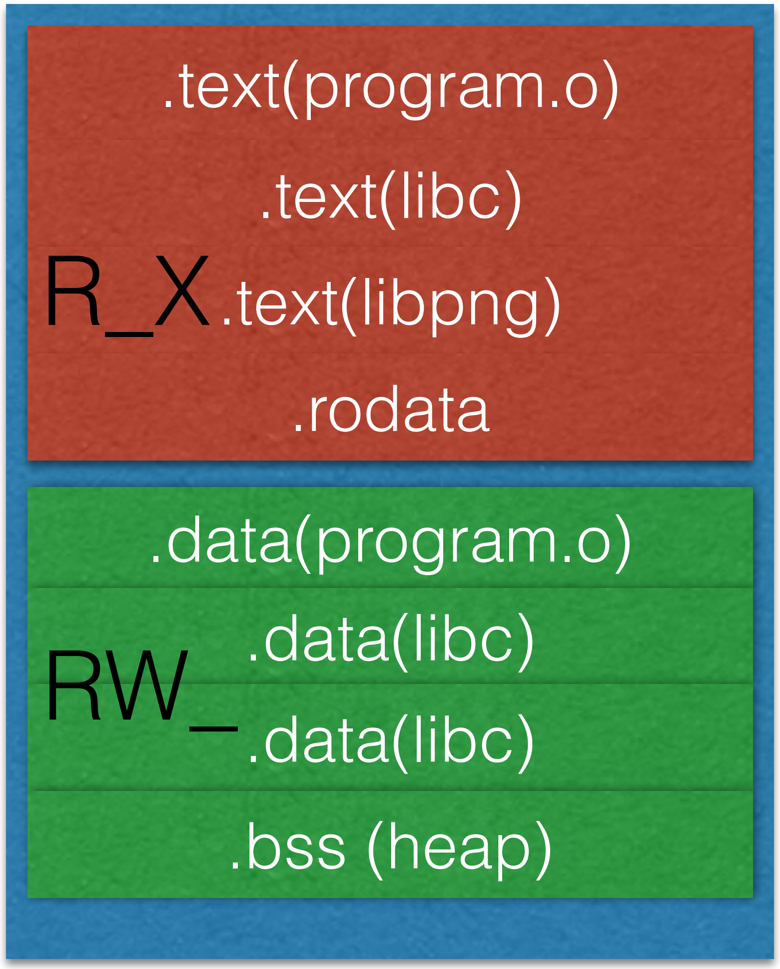
ELF sections

ELF consists of sections:

- Code
- Data (RW/RO)
- GOT/PLT jump tables for dynamic linking
- Metadata: Symbols, ...
- Can be controlled from C:
  __section__(section_name)
- Flexible mechanism
- ~30 sections in typical file

Sections turn into segments

Linker combines sections & groups them into segments:



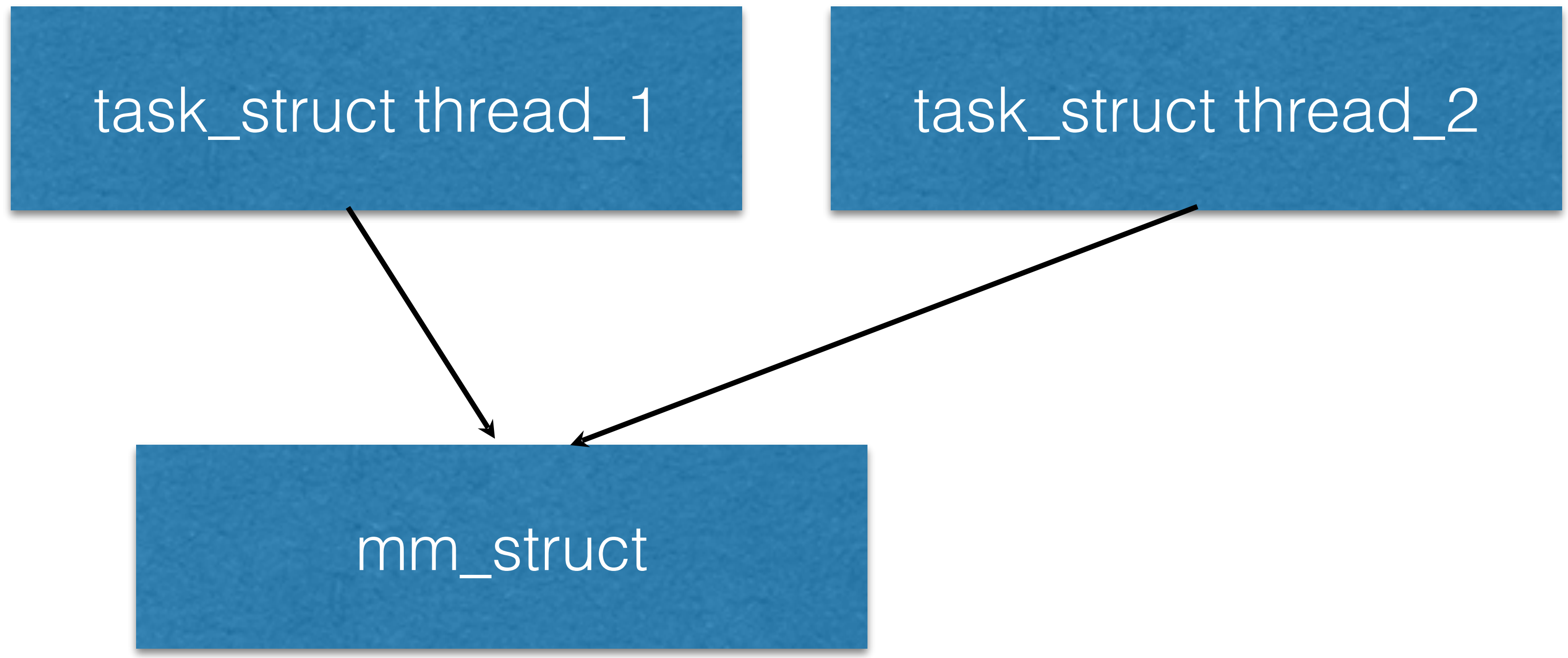
Only RWX bits enforced

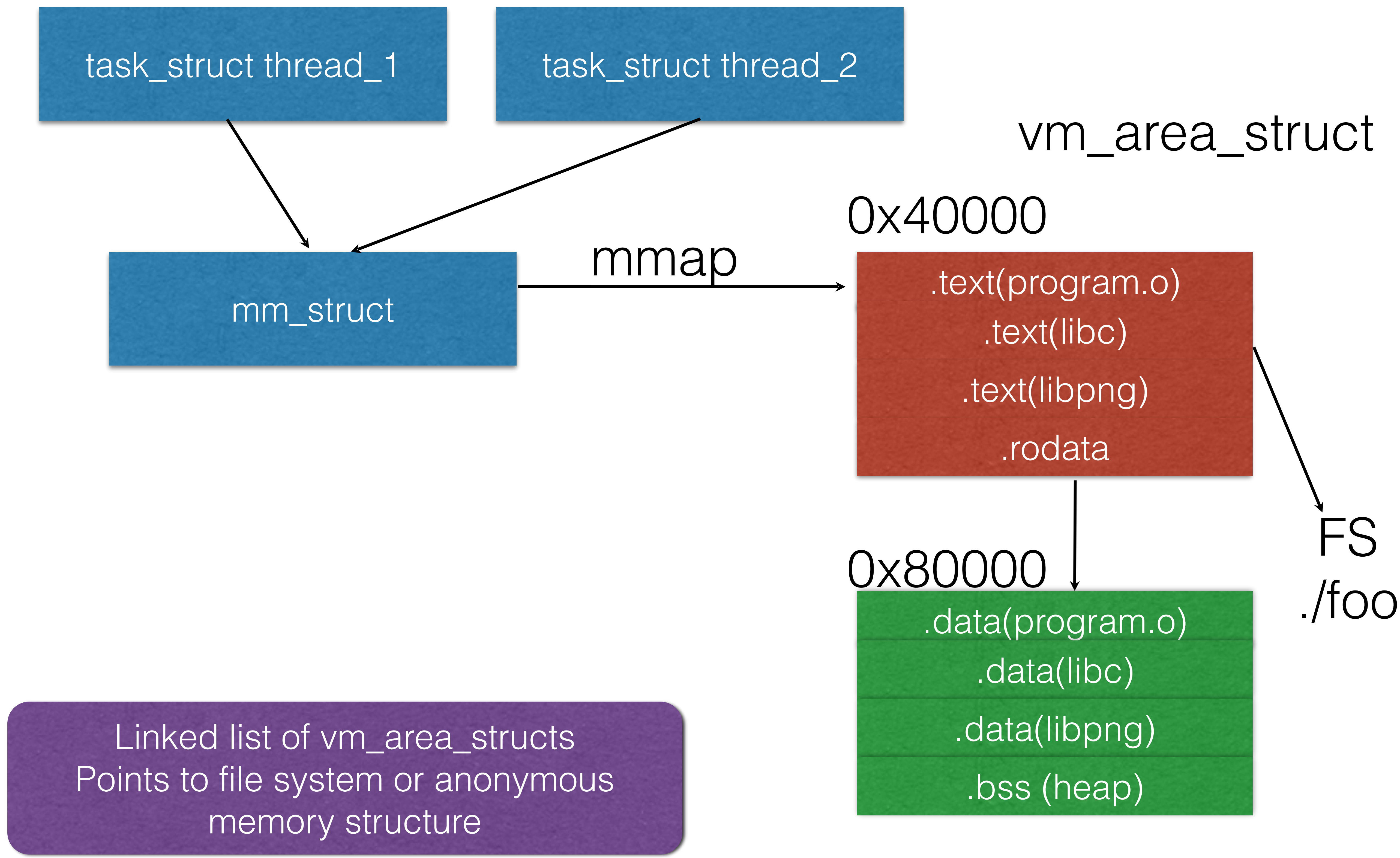
Two loaders

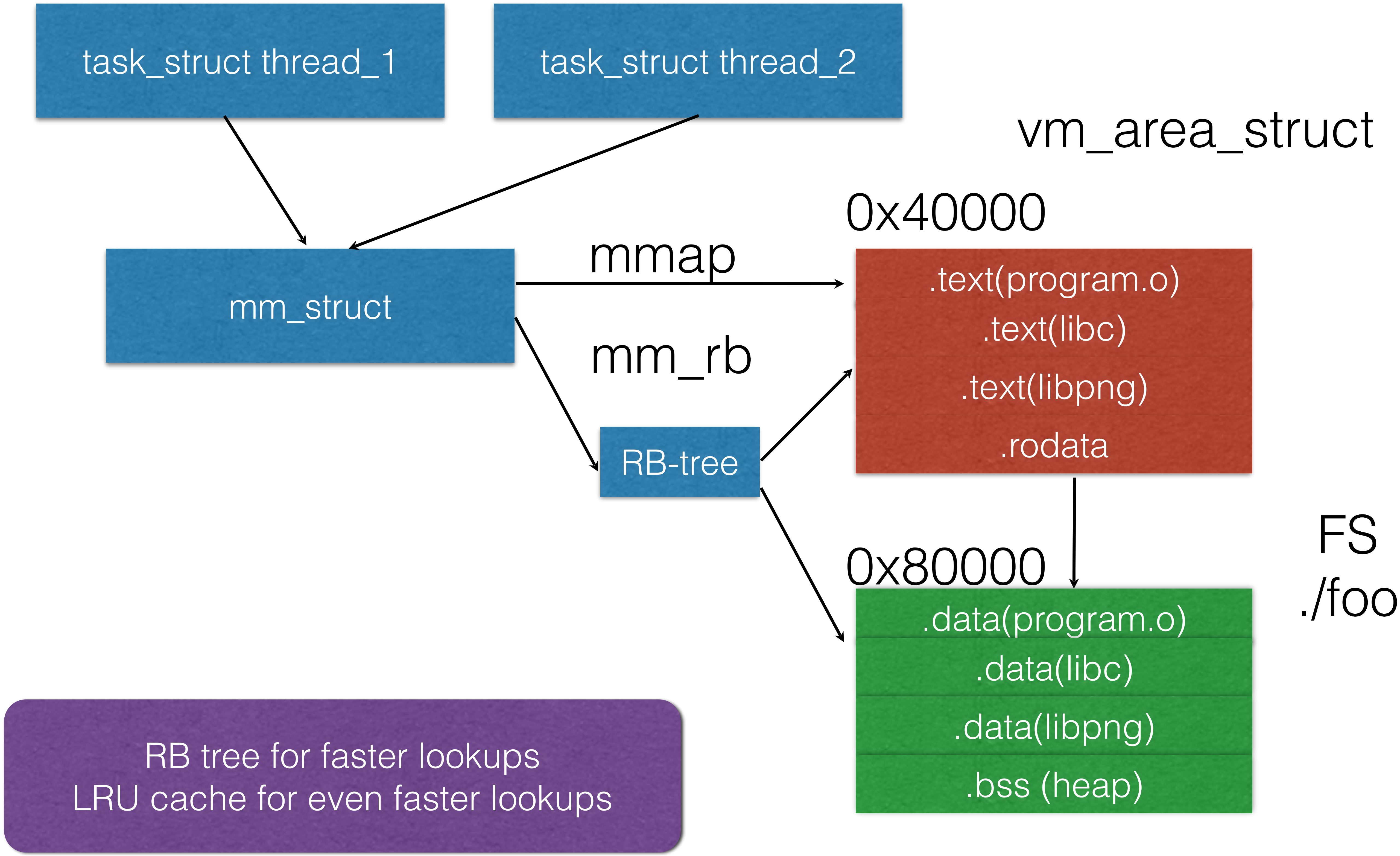
- Static linking:
  - kernel (binfmt_elf.{c,ko}) reads segments
  - calls mmap() for each segment
  - jumps to entry point
- Dynamic linking
  - Kernel loads ld.so (as in the above)
  - ld.so parses ELF file again (bugs happen here)
  - ld.so opens shared libraries, mmaps and maintains .PLT/.GOT tables
- One mmap() call per segment

What the kernel does:

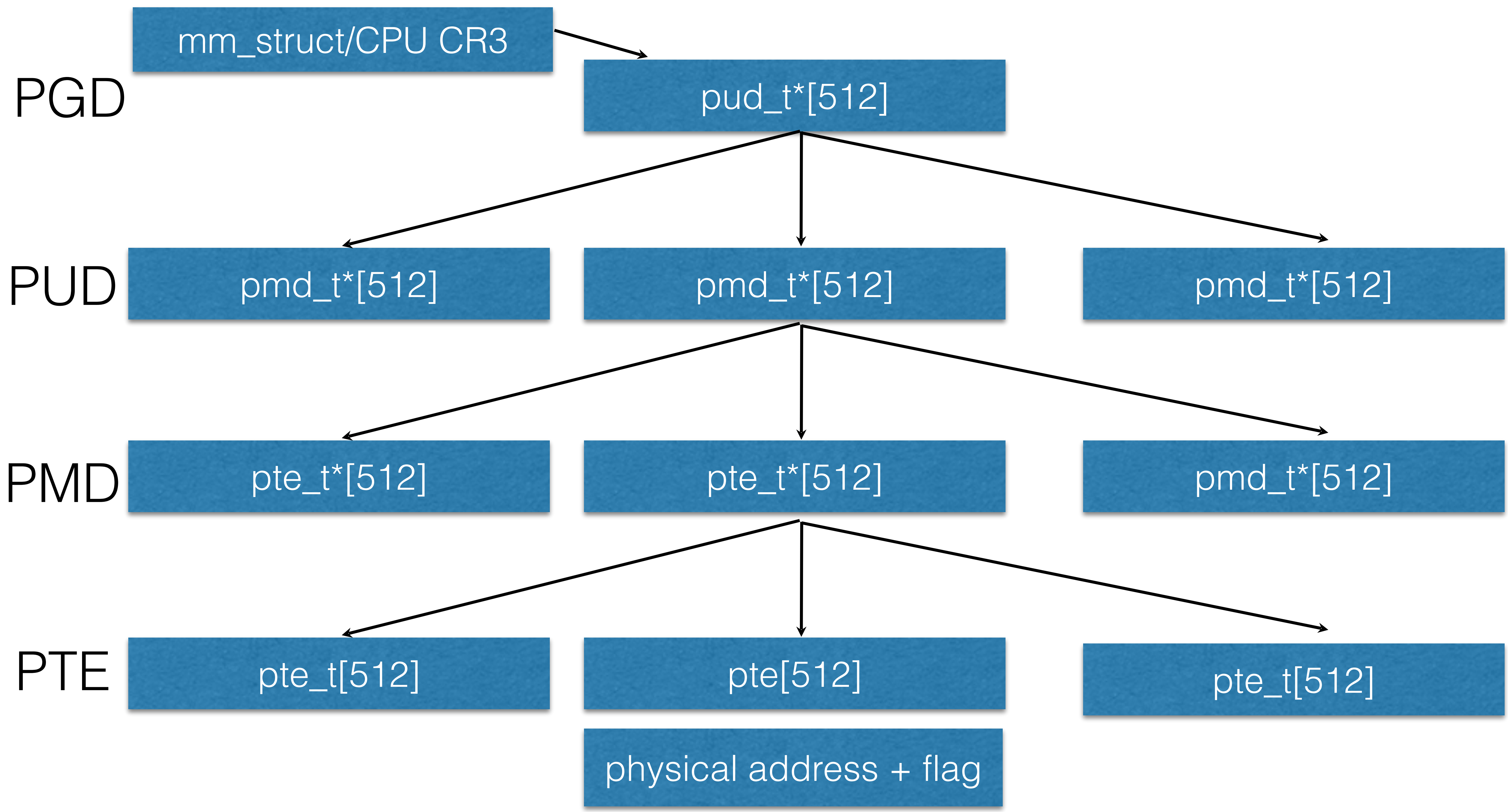
- Kernel:
  - task_struct for each thread
    - registers, execution context => state
    - pid, uid, capabilities => identity of the process
  - mm_struct for address space


task_struct thread_1
task_struct thread_2
mm_struct


task_struct thread_1
task_struct thread_2
vm_area_struct
0x40000
mm_struct
mmap
.text(program.o)
.text(libc)
.text(libpng)
.rodata
FS
./foo
0x80000
.data(program.o)
.data(libc)
.data(libpng)
.bss (heap)
Linked list of vm_area_structs
Points to file system or anonymous
memory structure


task_struct thread_1
task_struct thread_2
vm_area_struct
0x40000
mmap
mm_struct
mm_rb
.text(program.o)
.text(libc)
.text(libpng)
.rodata
RB-tree
FS
./foo
0x80000
.data(program.o)
.data(libc)
.data(libpng)
.bss (heap)
RB tree for faster lookups
LRU cache for even faster lookups

What the CPU sees



All three structures have to be kept in sync

Caching

- Walking these structures on every memory access would be prohibitively slow
- TLBs cache every level of this hierarchy
- Originally invalidated on reload
- **Tagged** TLBs (PCID on intel). ELFbac also had the first PCID patch for linux. Transparent on AMD

Caches enforce policy!

- NX bit is seen as a mere mitigation
- Actually it is **policy** that express **intent**
- First implementations of NX used cache state (split TLB) meant for performance to add semantics
- ELFbac does the same with TLBs and PCID

It's all about caching

- Each VM system layer is a **cache**
- And performs checks
  - Checks get semantically less expressive as you get closer to hardware
- ELFbac adds another layer of per-phase **caching**
- Allows us to enforce a semantically rich **policy**

Example: Page faults

- If the page table lookup fails, CPU calls the kernel
- Kernel looks for the vm_area_struct (rb_tree)
- **Check:** If not present, SIGSEGV
- Fill in page table, with **added semantics**
    - Swap-in
    - Copy-on-write
    - Grow stacks

ELFbac execution model

- Old **n-1 relationship**:
  - task_struct(n threads) <-> mm_struct(1 process)
- New **n-m relationship:**
  - task_struct(n threads) <-> mm_struct(m ELFbac states)
- A lot of kernel code would have to change to update m copies

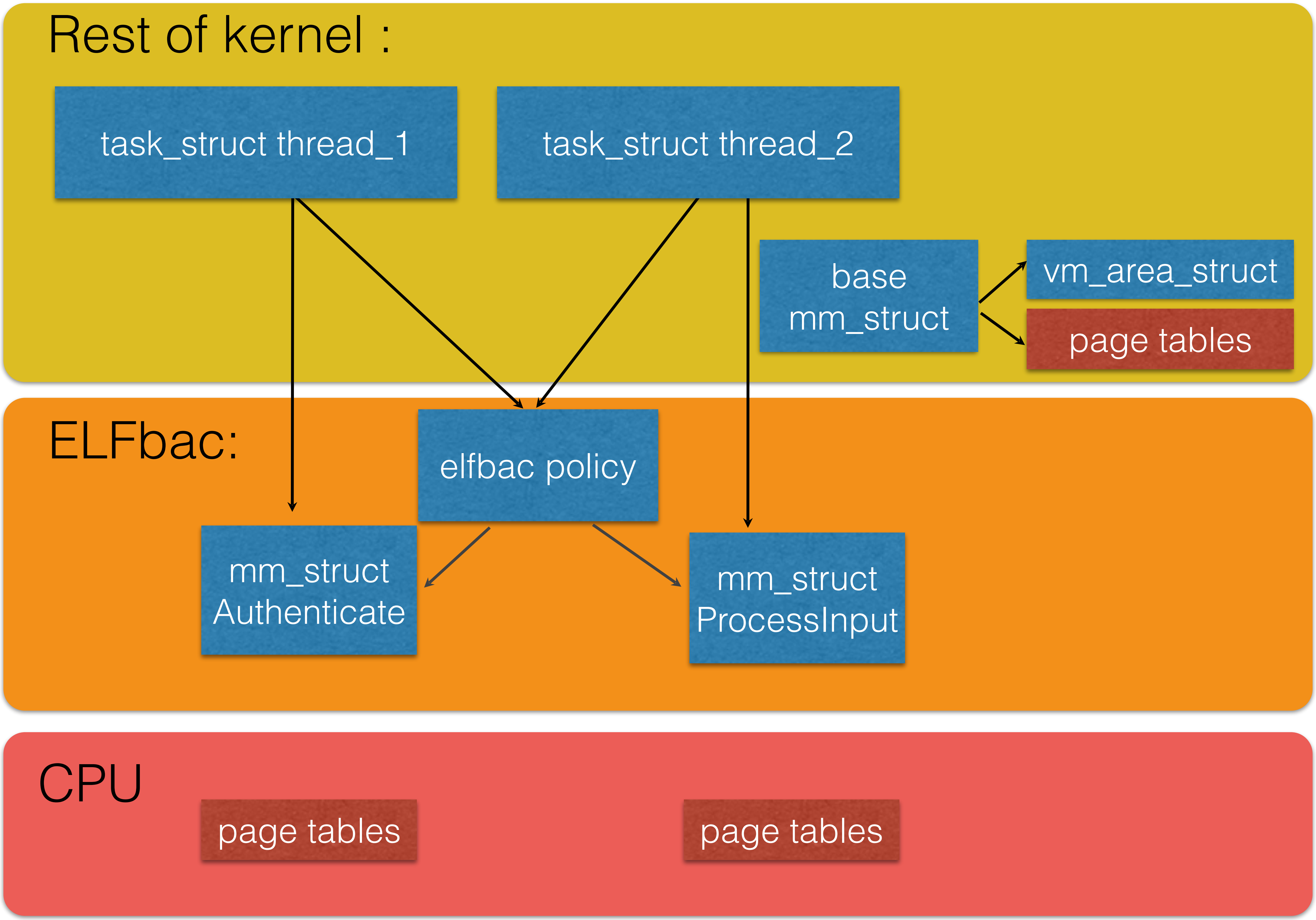
Caching as a solution

- ElfBAC states are **subsets** of the base address space
  - Base address space still represented by mm
- Squint enough, and a subset is like a **cache**
- Only need **invalidation** instead of mutation
- Caches already have to be invalidated (TLB)
- Linux: mm_notifier plug-in API(virtualization)

ELFbac page fault handler

- If the access would fault on the base page tables
  - Fall back to the old page fault handler
- Look up the address in ELFbac policy
  - Move process to new phase if necessary
  - Otherwise copy page table entry to allow future accesses

What each part sees:

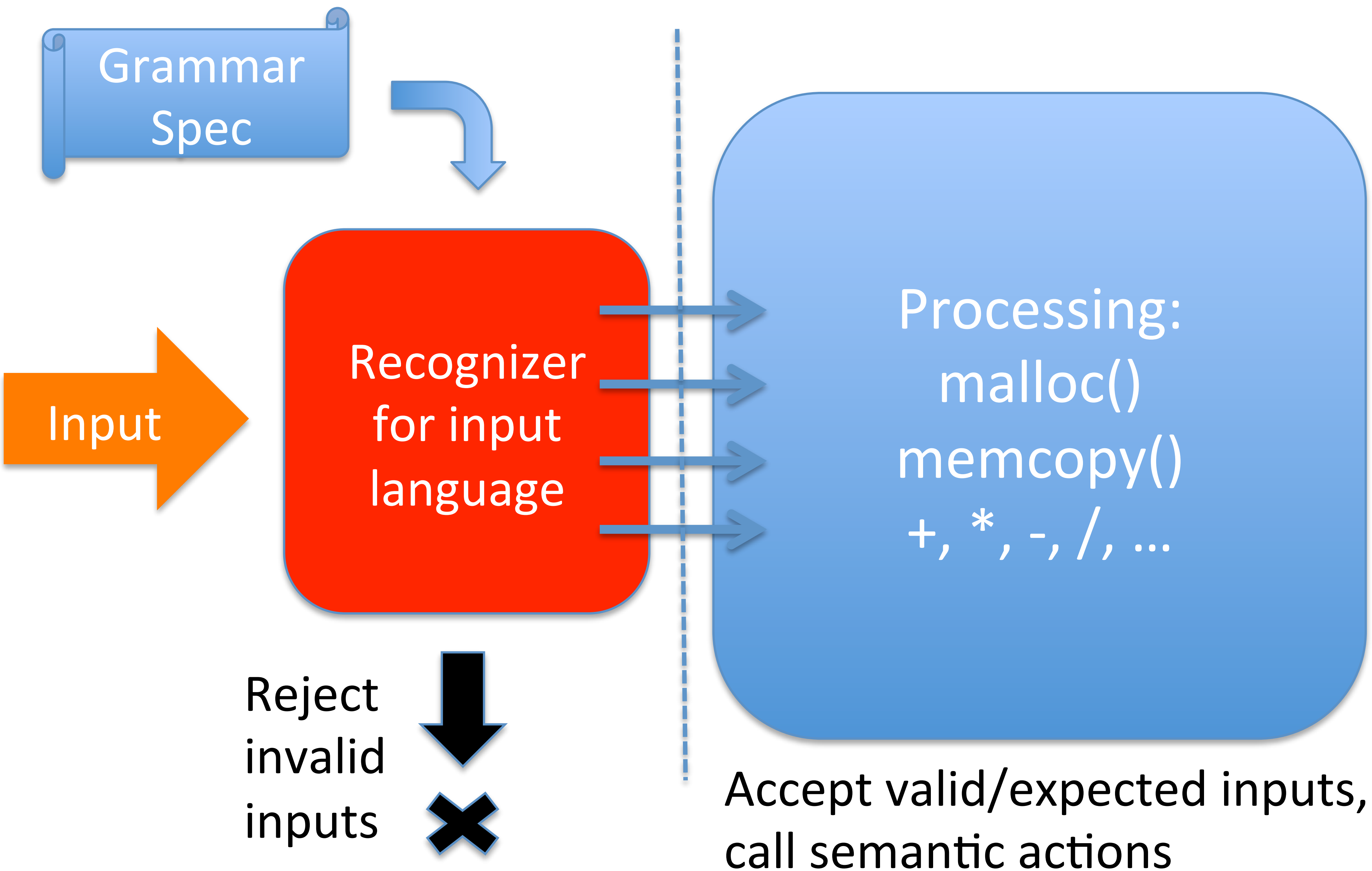


Porting to embedded ARM

- Focused on compartmentalizing ELF binaries under **static** linking
  - Dynamic linking case supportable by creating an ELFbac-aware ld.so, left to future work
- Policies generated from a JSON descriptor file
  - tool produces both the linker script and the binary policy
- Binary policy is packed into a special segment, loaded by the kernel during ELF loading time
- Modifications to the page fault handler enforce the policy at runtime, verifying memory accesses and state transitions
- ARM ASIDs (tagged TLB) reduce overhead between state transitions

Case Studies

Basic example: isolating a parser



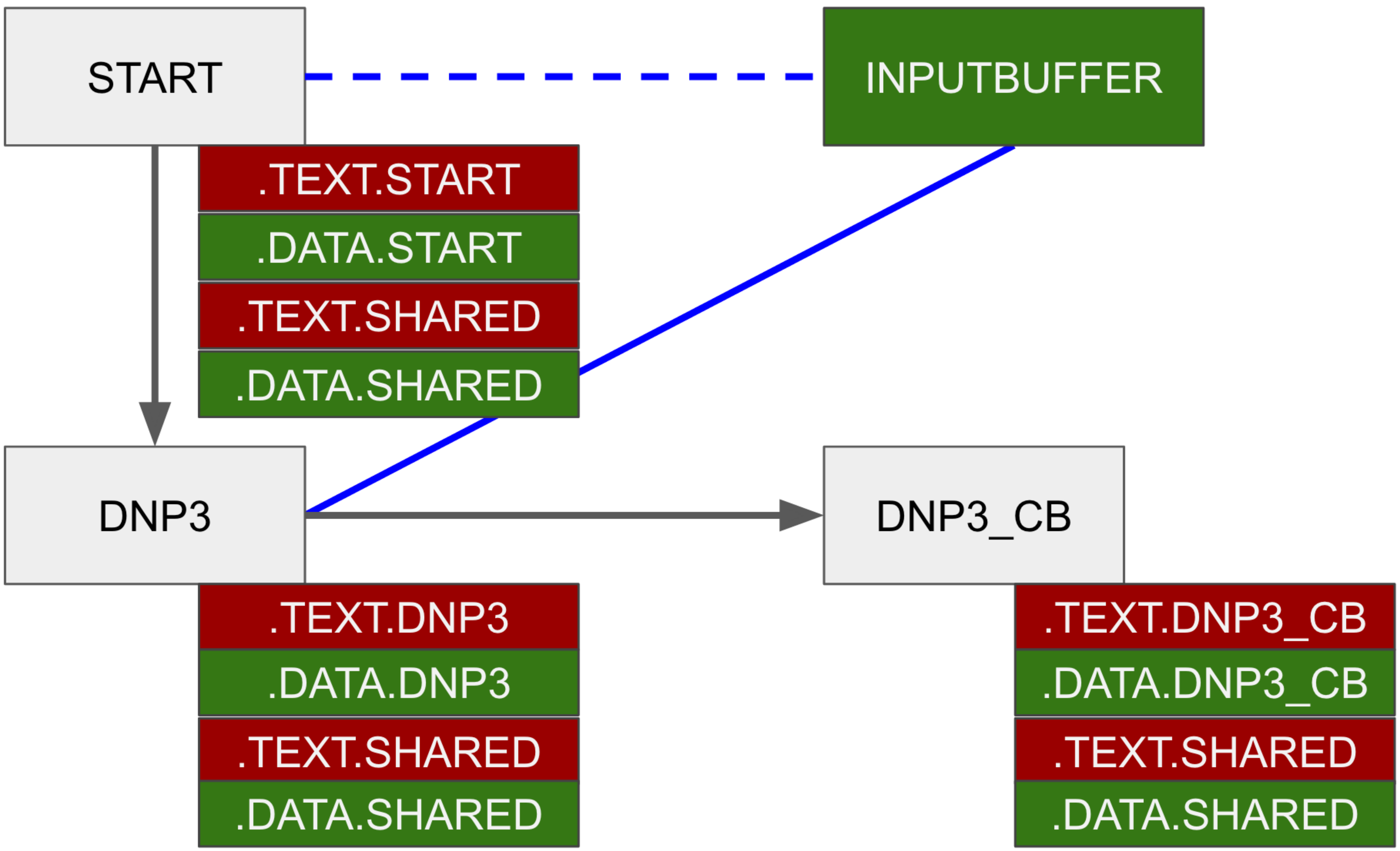
ELFbac for SCADA/ICS

- DNP3 is a complex ICS protocol; prone to parser errors
  - S4x14: "Robus Master Serial Killer", Crain & Sistrunk
- Only a small subset of the protocol is used on any single device. Whitelisting this syntax is natural.
  - A filtering proxy is a DNP3 device's best friend
  - "Exhaustive syntactic inspection": ***langsec.org/dnp3/***
- ELFbac policy: isolate the parser from the rest of the app

Parser isolation

- Raw data is (likely) poison; parsing code is the riskiest part of the app & its only defense
- Parser must be separated from the rest of the code
  - No other section touches raw input
  - Parser touches no memory outside of its output area, where it outputs checked, well-typed objects
- *Input* => Parser => *Well-typed data* => Processing code

ICS proxy policy at a glance



Our ARM target

UC-8100 Series

Communication-centric RISC computing platform

- ARMv7 Cortex-A8 300/600/1000 MHz processor
- Dual auto-sensing 10/100 Mbps Ethernet ports
- SD socket for storage expansion and OS installation
- Rich programmable LEDs and a programmable button for easy installation and maintenance
- Mini PCIe socket for cellular module
- Debian ARM 7 open platform
- Cybersecurity

c UL us LISTED

ELFbac & Grsec/PaX for ARM

- We worked with the Grsecurity to integrate ELFbac on ARM with **Grsecurity for ICS** hardening:
  - Cohesive set of protections for ICS systems on ARM
    - PAX_KERNEXEC, PAX_UDEREF, PAX_USERCOPY, PAX_CONSTIFY, PAX_PAGEEXEC, PAX_ASLR, and PAX_MPROTECT
  - Available from ***https://grsecurity.net/ics.php***
- ELFbac + Grsecurity ICS tested with our DNP3 proxy on a common industrial computer Moxa UC-8100, ARM v7 (Cortex-A8)

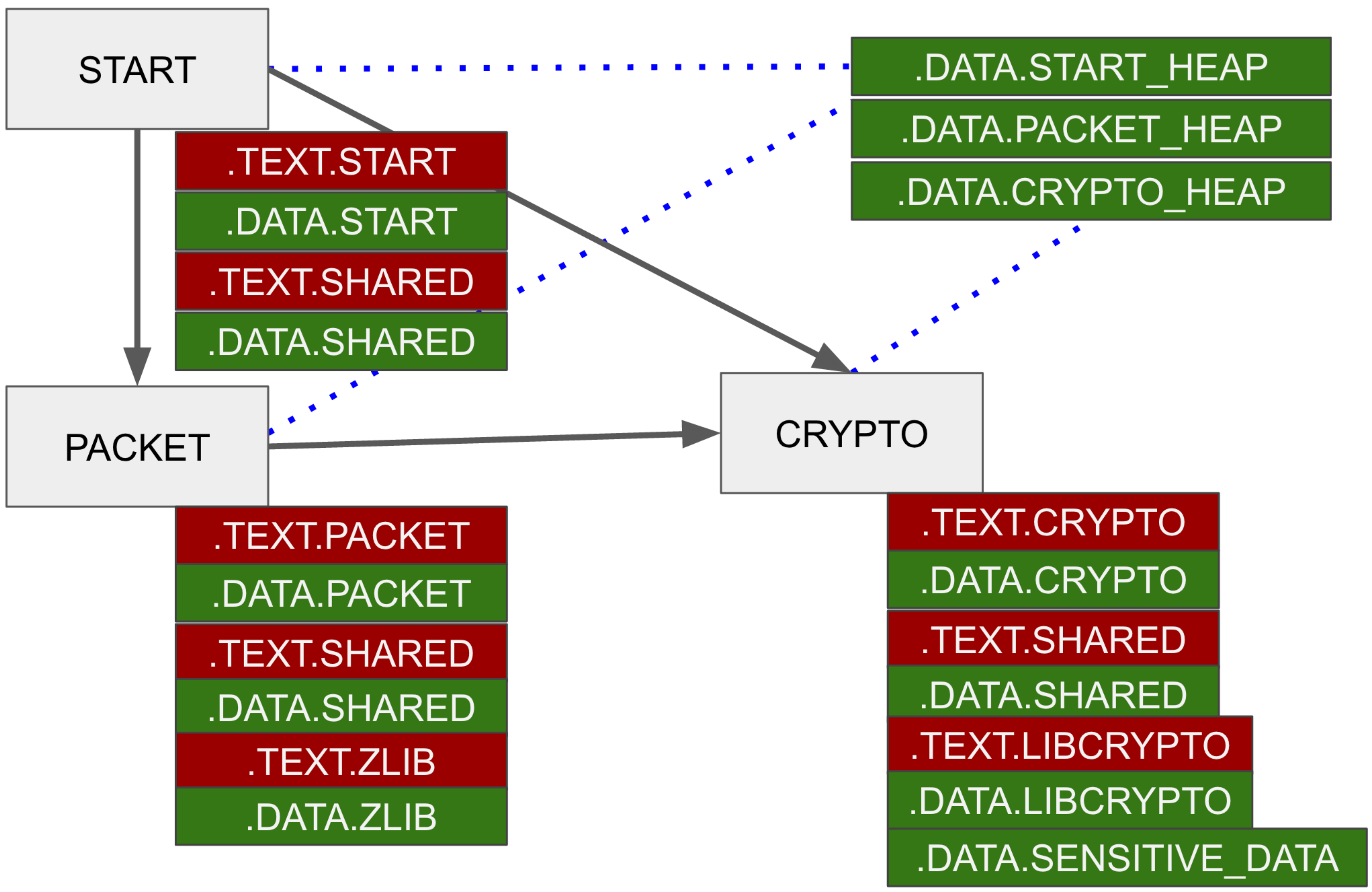
OpenSSH policy

- OpenSSH attacked via crafted inputs
  - GOBBLES pre-auth RCE 2002 -- CVE-2016-077{7,8}
- OpenSSH introduced the original **privilege drop** as a **policy** primitive
  - "If the process asks for a privileged op after *this point*, it's no longer trustworthy; kill it"
- But access to (a) non-raw data for a parser (b) raw data beyond the parser is **also** privilege!

ELFbac for OpenSSH

- Policies for both the OpenSSH **client** and **server**
  - Isolate portions of OpenSSH responsible for crypto/key management from those responsible for processing & parsing packets
  - Create separate sections for sensitive data blobs, allowing for finer-grained access control
  - Control access to libraries used by OpenSSH based on **where** used
- Prevent direct leaking of sensitive data like private keys from, e.g., ***CVE-2016-0777*** (roaming vuln)
- Separate heaps for dynamic allocations, with specific access permissions across process phase boundaries

OpenSSH policy at a glance



Application design considerations

- "Separating concerns" is good engineering, but has limited security pay-offs
  - All concerns still live in the **same address space**
- Keeping separate heaps in a process has limited returns
  - Proximity obstacles to overflows/massaging, but still the same address space, accessible by all code
  - Mitigation, not policy
- With ELFbac, keeping marked, separating heaps becomes policy: clear **intent**, enforced w.r.t. code units

ELFbac is a design style

- "Who cares? That's not how code gets written"
- Availability of enforcement mechanisms reshapes programming practice
  - C++ took over the world by making contracts (e.g., encapsulation) enforceable (weakly, at compile time)
  - Non-enforceable designs are harder to adopt & check
- **Only enforceable separation matters**

Performance & TODOs

Performance overheads (x86)

- NGINX benchmarked with a policy isolating **all** libraries from the main process:
  - Best case: around ~5% (AMD Opteron Piledriver)
    - worst case: ~30% on some Intel platforms
  - Too many state transitions on the hot path
  - Policy must be adapted to the application structure
- Average ~15% when running on KVM
  - KVM already incurs performance costs
  - KVM optimizes virtual memory handling

Drawbacks and TODOs

- Significant performance tuning still outstanding
- Implement an ELFbac-aware malloc
- Integration with system call policy mechanisms (e.g. Capsicum)
- Provide rich policies for many standard libraries
    - ELFbac is not a mitigation, it's a way to design policies and resilient applications

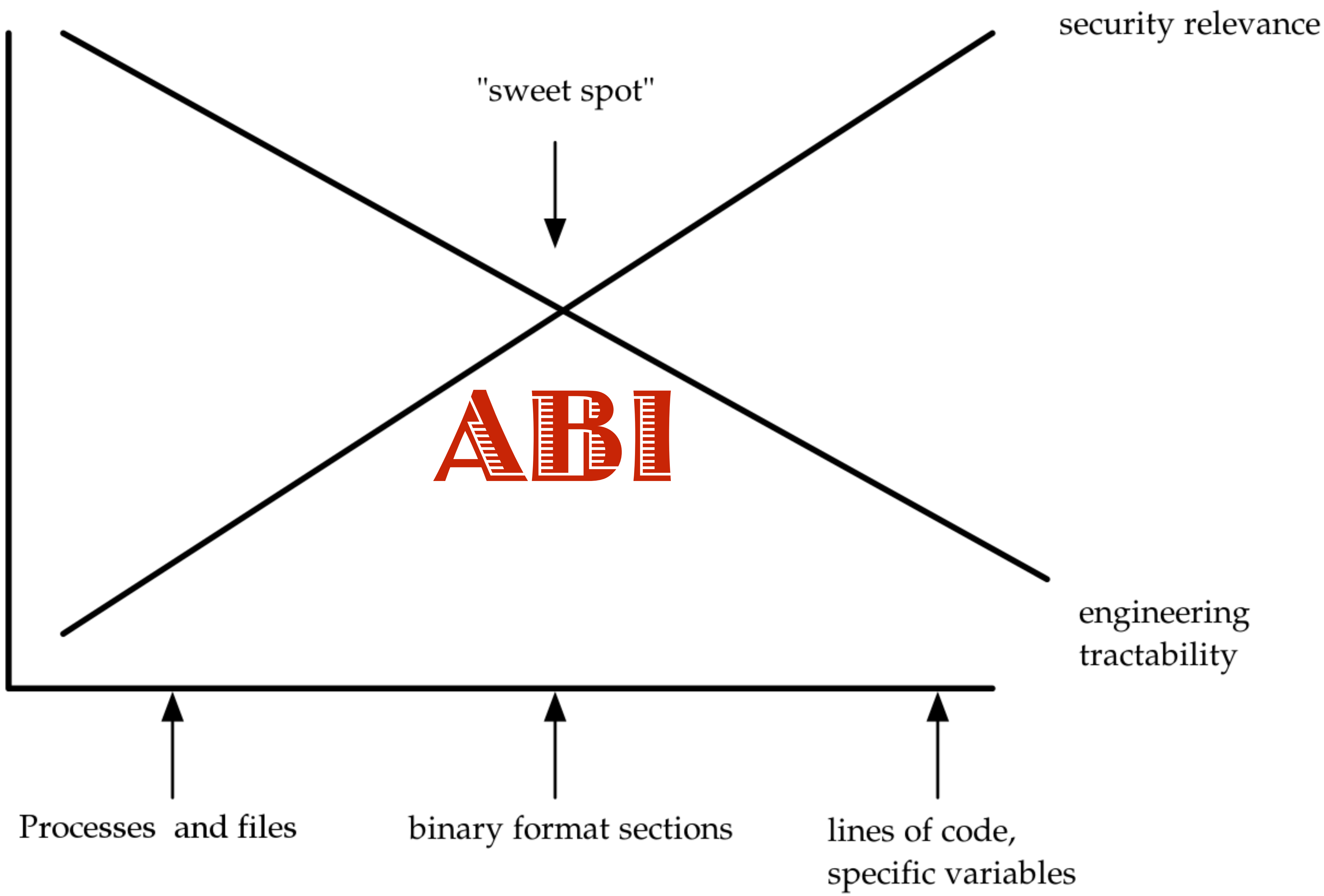
Binary Rewriting Tools

- Store policy in the ELF file
- Loader sends it to the kernel with a new syscall
- Adding a policy requires binary rewriting
  - Made our own tool: ***Mithril***, currently only implemented for ELF
- Translates binaries into a *canonical form* that is less context-dependent and can be easily modified
- Tested on the **entire** Debian x86_64 archive, producing a bootable system
  - ~25GB of packages

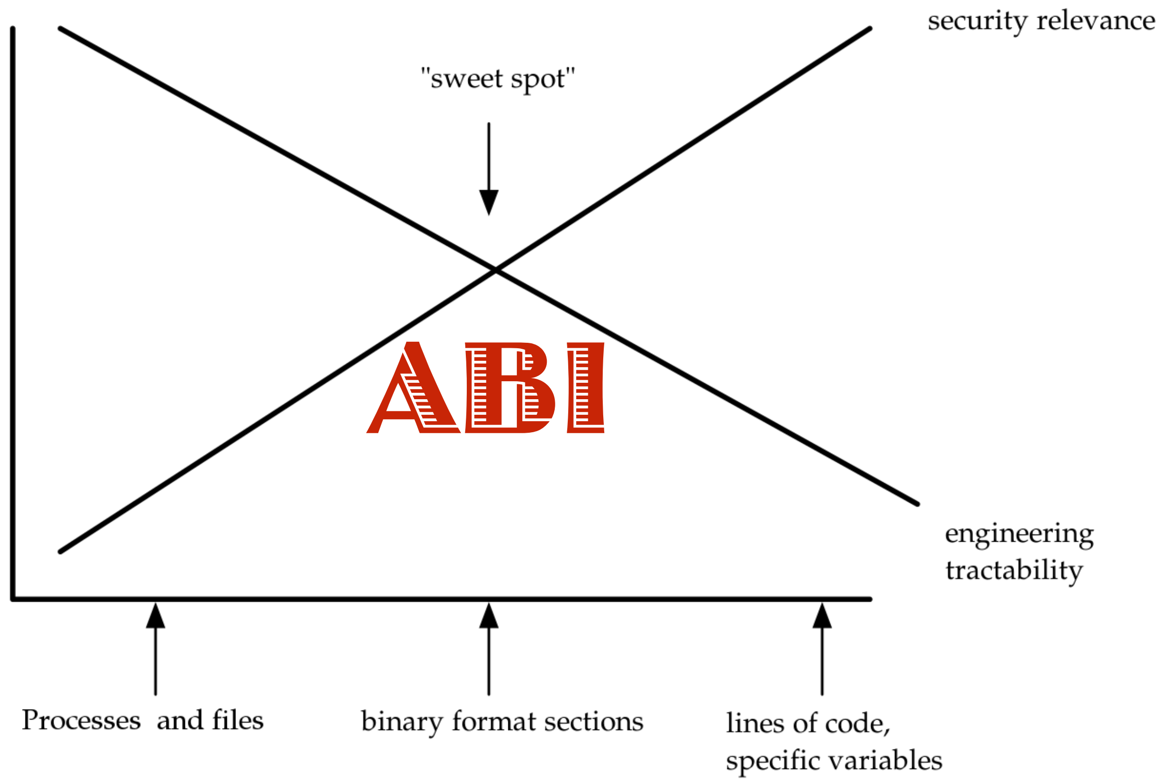
Takeaway

- Per-process bags of permission are no longer a suitable basis for policy
- Instead, ABI-level memory objects at process runtime are the sweet spot for security policy
- Modern ABIs provide enough granularity to capture programmers intent w.r.t. code and data units
  - Intent-level semantics compatible with ABI, standard build/binary tool chains

Policy Granularity: ABI is the Sweet Spot



Thank you



- *http://elfbac.org/*
- *https://github.com/sergeybratus/elfbac-arm/*