The Linux Kernel's Attack Surface (and how we can reduce it)

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> If you don’t have a dog, your neighbor can’t poison it.

Sergey Nikitin, *If You Don’t Have an Aunt* (Russian song)

The Linux kernel: All you (n)ever wanted

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RDS protocol

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Perf events

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Perf events

/proc/pid/mem

The Linux kernel: All you (n)ever wanted

RDS protocol

Perf events

/proc/pid/mem

Berkley Packet Filter (BPF)

The Linux kernel: All you (n)ever wanted

RDS protocol
CVE-2010-3904

Perf events
CVE-2013-2094

/proc/pid/mem
CVE-2012-0056

BPF
CVE-2010-4158

How popular are those features?

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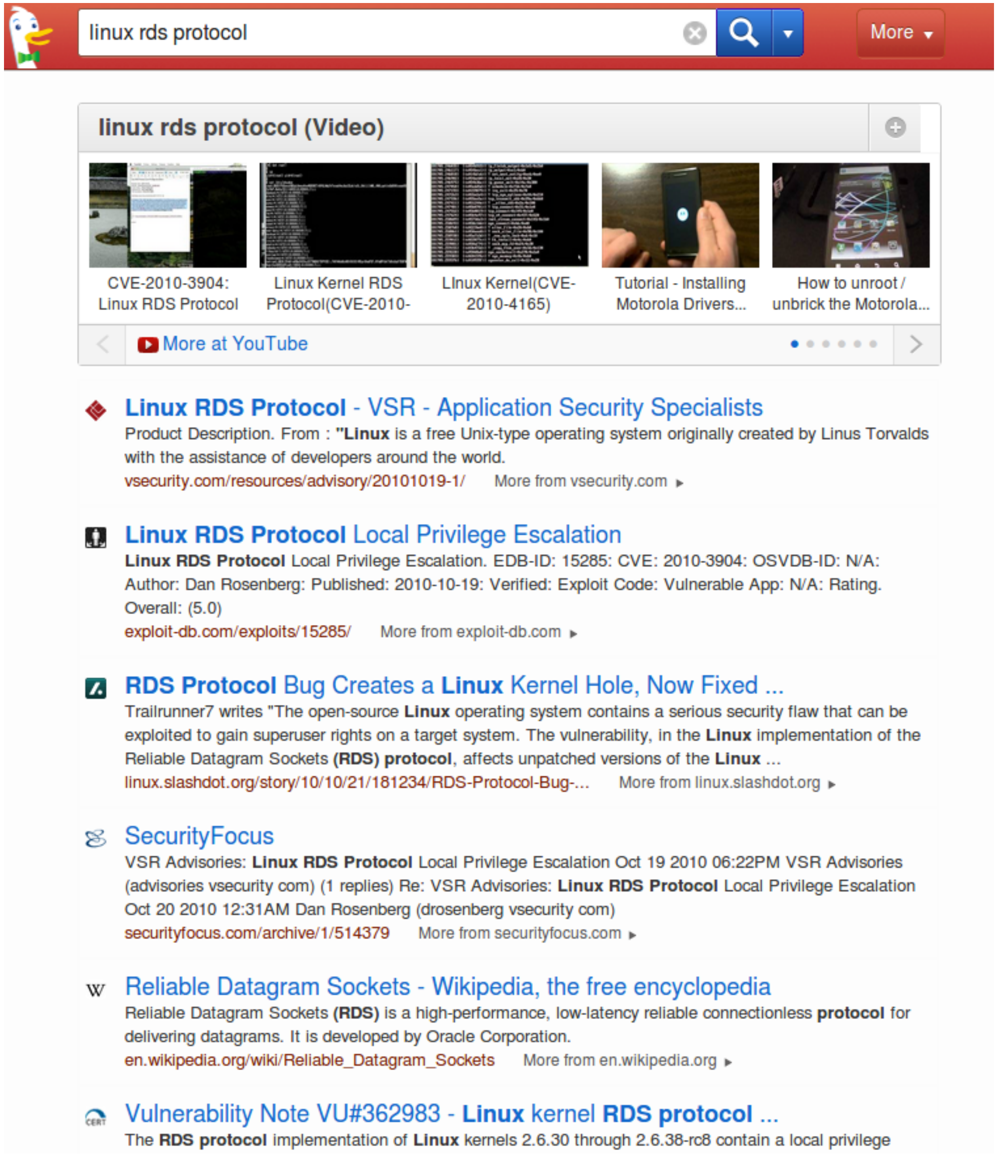

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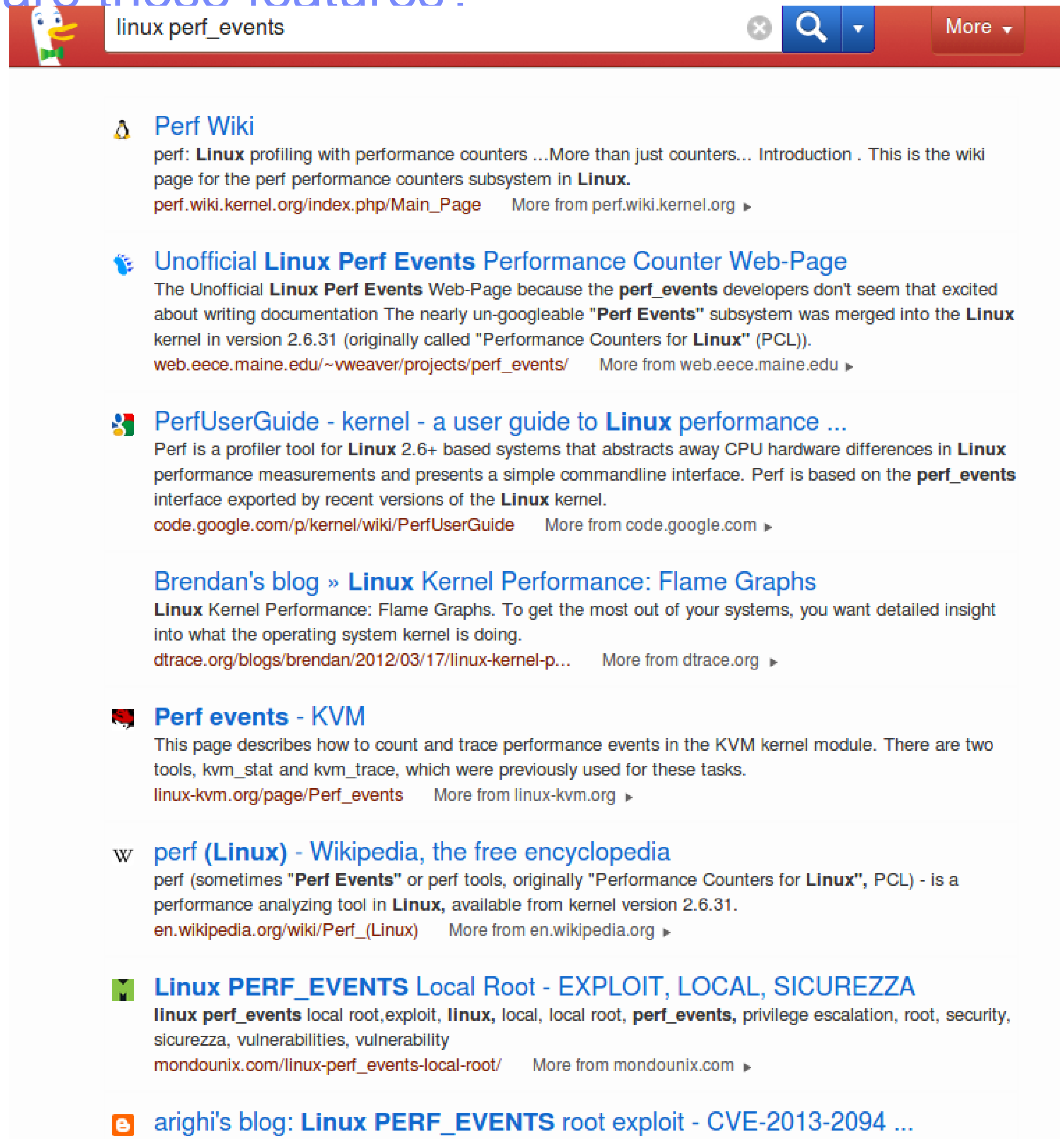

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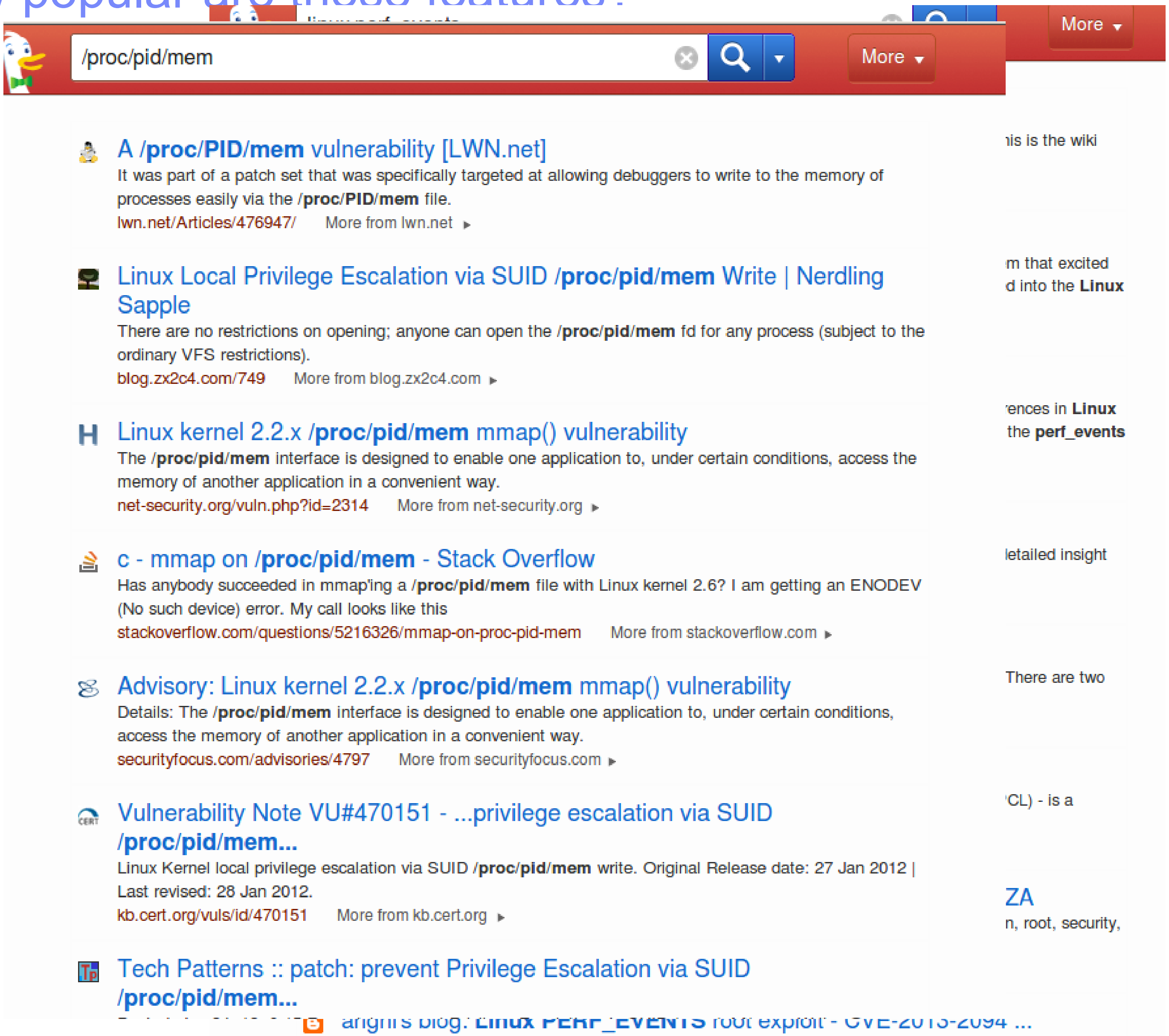

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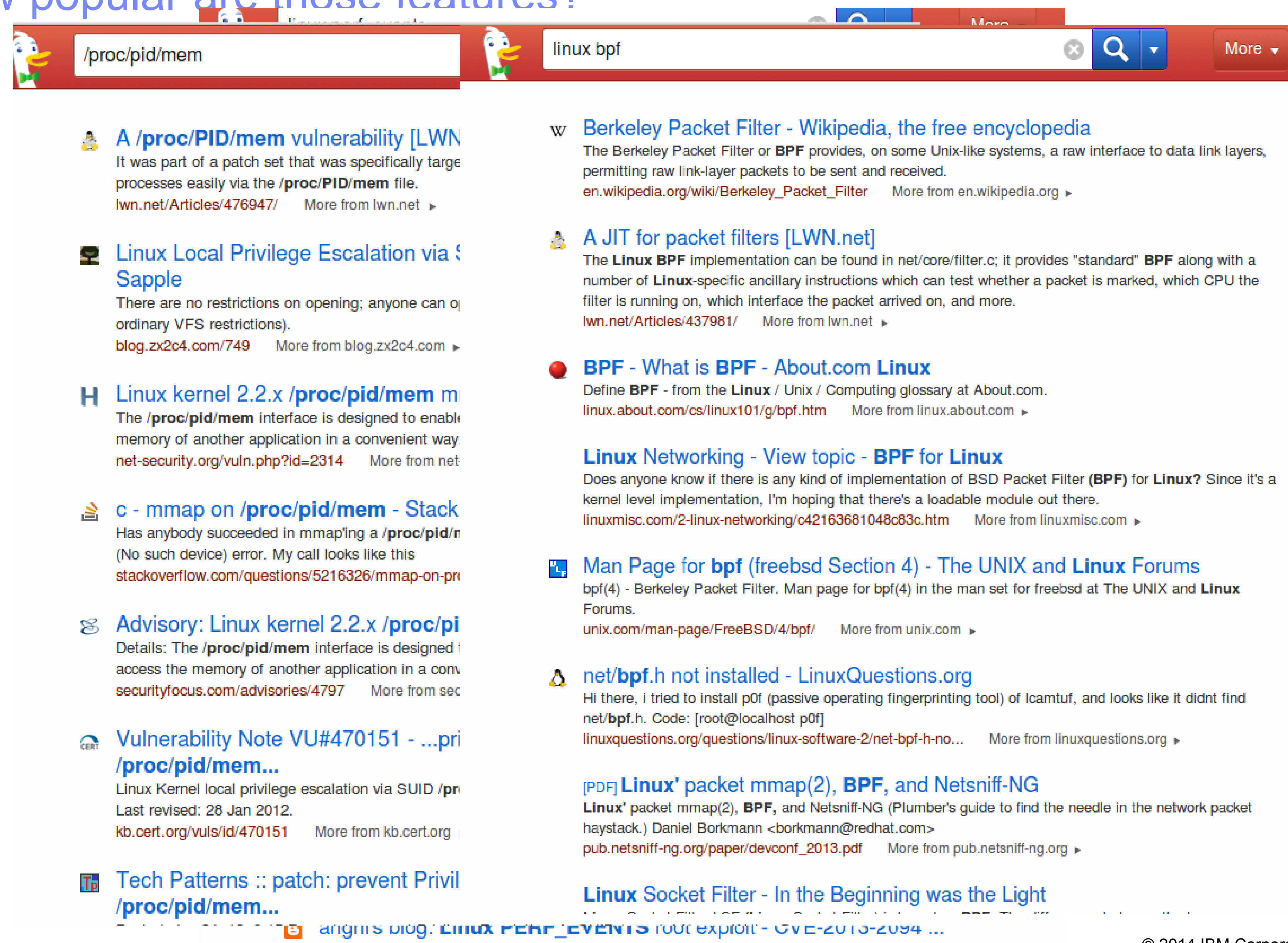

How popular are those features?

Large attack surface for no reason?

Research questions (1/2)

Q1: Is it possible to precisely define the kernel attack surface? How can it be measured?

Research questions (2/2)

Q2: Can we develop kernel protection mechanisms whose attack surface reduction is quantifiable? To what extent can these mechanisms be applied to Linux in practice?

This talk

P1: Kernel Attack Surface Quantification (NDSS'13)

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P2: Compile-time Kernel Tailoring (HotDep'13, NDSS'13)

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P2: Compile-time Kernel Tailoring (HotDep'13, NDSS'13)

P3: Run-time Kernel Trimming (Eurosec'11, DIMVA'14, CCS'14)

Measuring
Kernel Attack Surface

- [NDSS'13] Anil Kurmus, Reinhard Tartler, Daniela Dorneanu, Bernhard Heinloth, Valentin Rothberg, Andreas Ruprecht, Wolfgang Schröder-Preikschat, Daniel Lohmann and Rüdiger Kapitza. "**Attack Surface Metrics and Automated Compile-Time OS Kernel Tailoring.**" In: Proceedings of the 20th Network and Distributed System Security Symposium. 2013.

  https://www.ibr.cs.tu-bs.de/users/kurmus/papers/kurmus-ndss13.pdf

- [DIMVA'14] Anil Kurmus, Sergej Dechand, and Ruediger Kapitza. "**Quantifiable Run-time Kernel Attack Surface Reduction**". In: Proceedings of the 10th International Conference on Detection of Intrusions and Malware, and Vulnerability Assessment (DIMVA’14). 2014.

  https://www.ibr.cs.tu-bs.de/users/kurmus/papers/kurmus-dimva14.pdf

Existing approaches and limitations

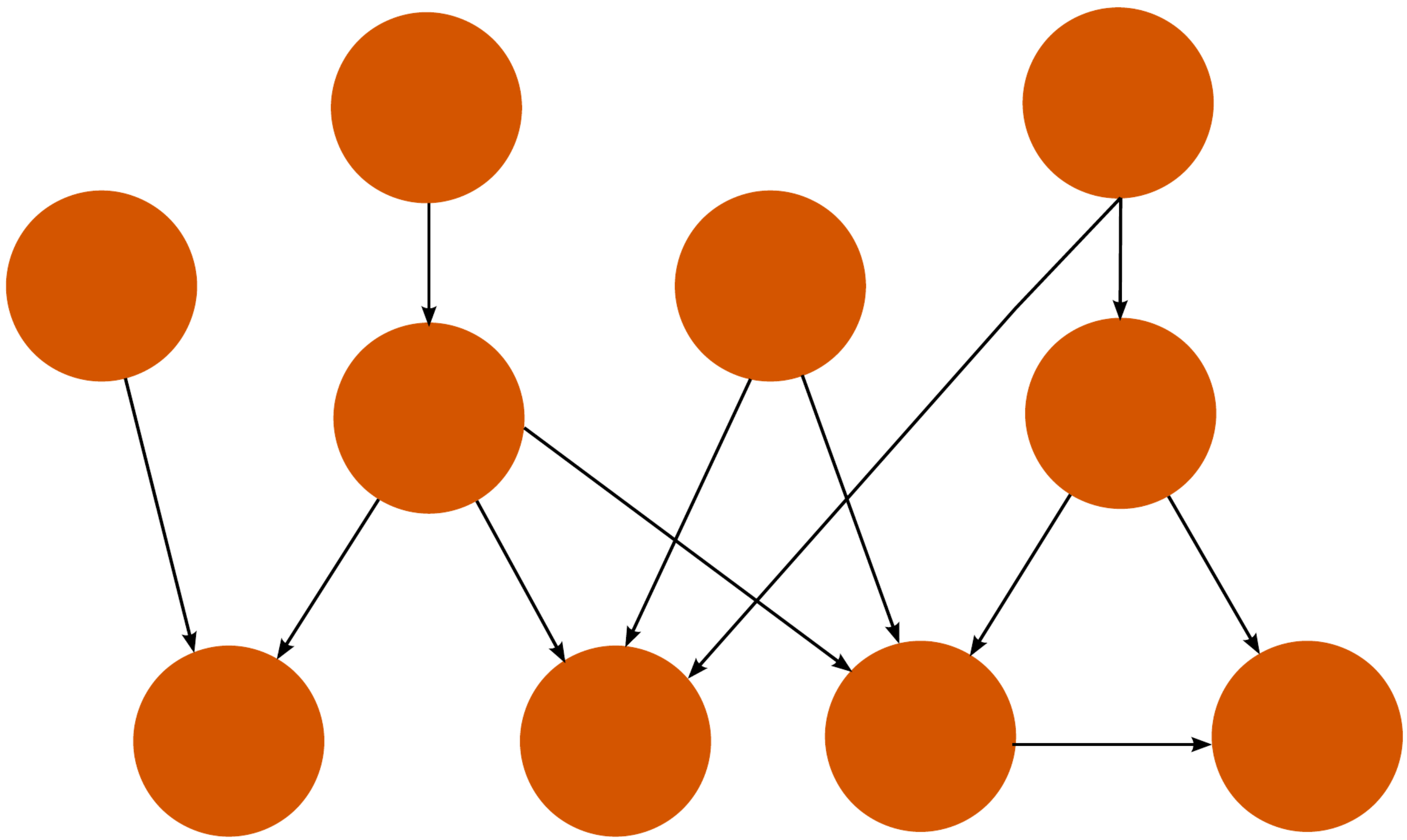
- Typically in OS research: measure TCB size in source lines of code.
  - Fiasco 15K SLOC; Minix 3 4K SLOC; Flicker 250 SLOC
  - Linux 3.0 10M SLOC;
- However:
  - Source files that are not compiled? Configuration-dependent code?
  - Loadable kernel modules (LKMs)? On-demand loadable kernel modules?
  - Code that is not reachable from the system call interface? Initialization code?
  - Code that is only reachable by privileged processes?

General Idea

- Attack surface ~= attacker-reachable code
  - Idea: use reachability over kernel call graph
  - Assumptions on the attacker and kernel? (**security model**)

- Measurements: code quality metrics
  - SLOCs, CVEs, ...

Obtaining the attack surface: an example



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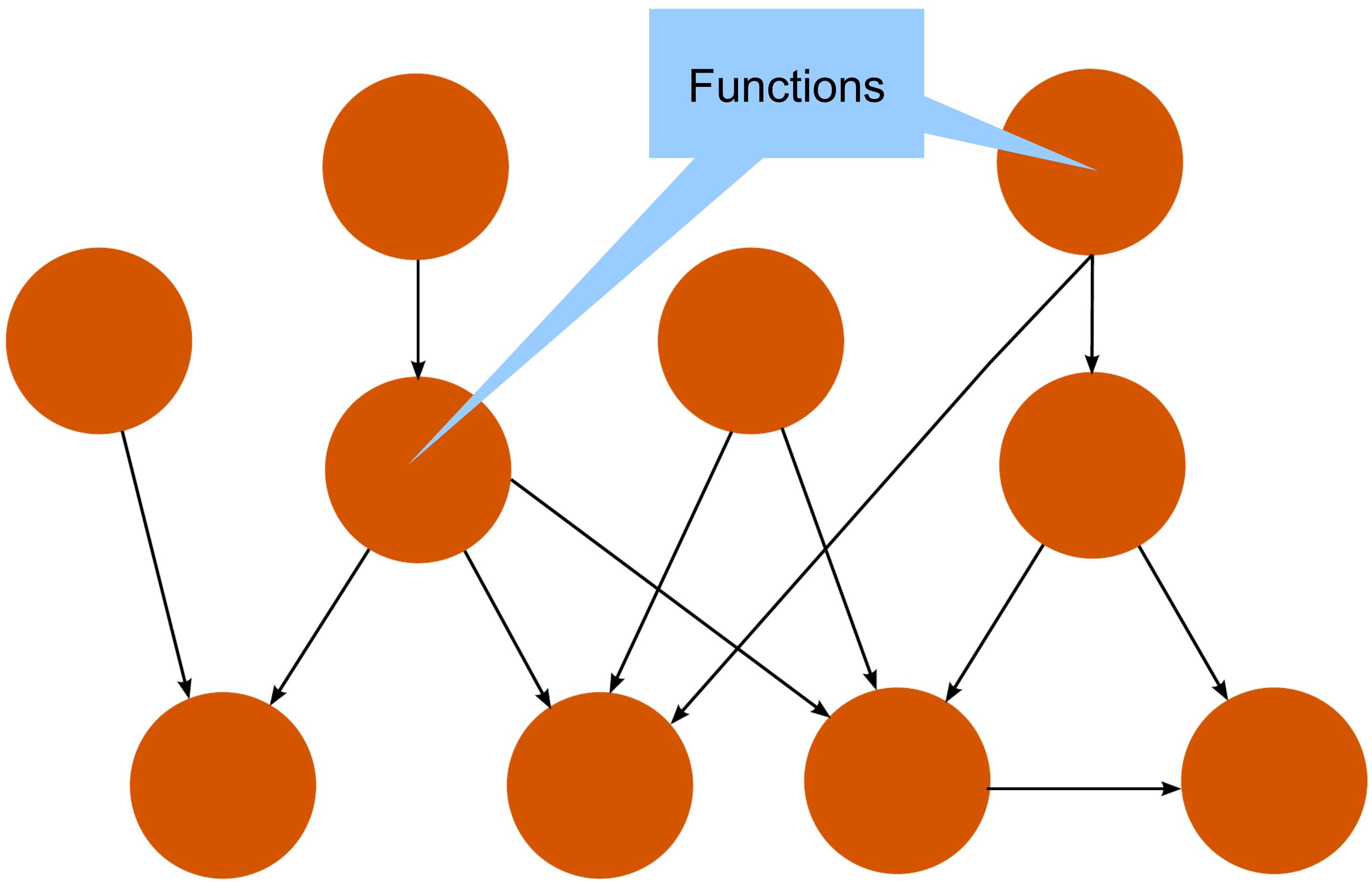

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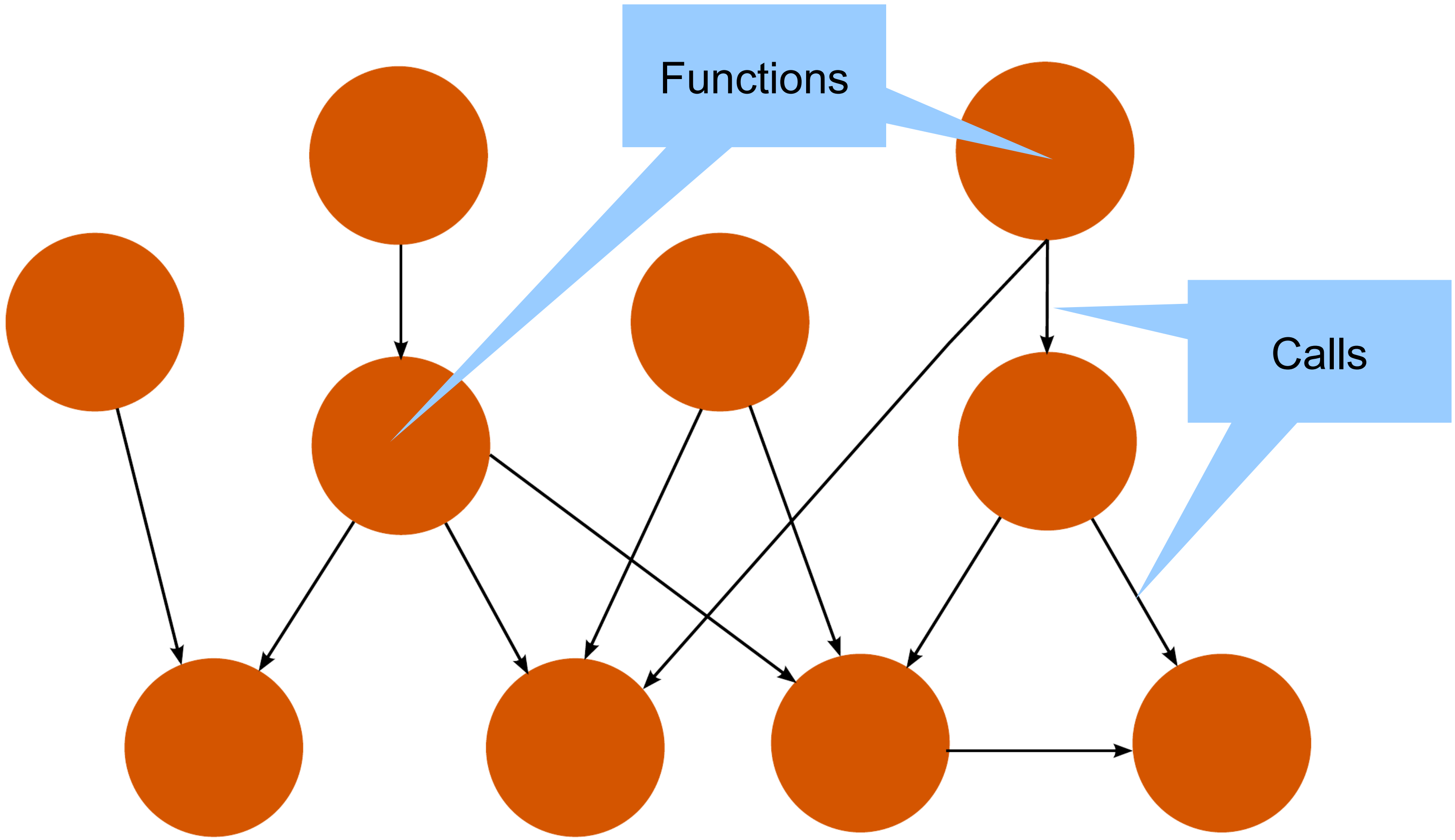

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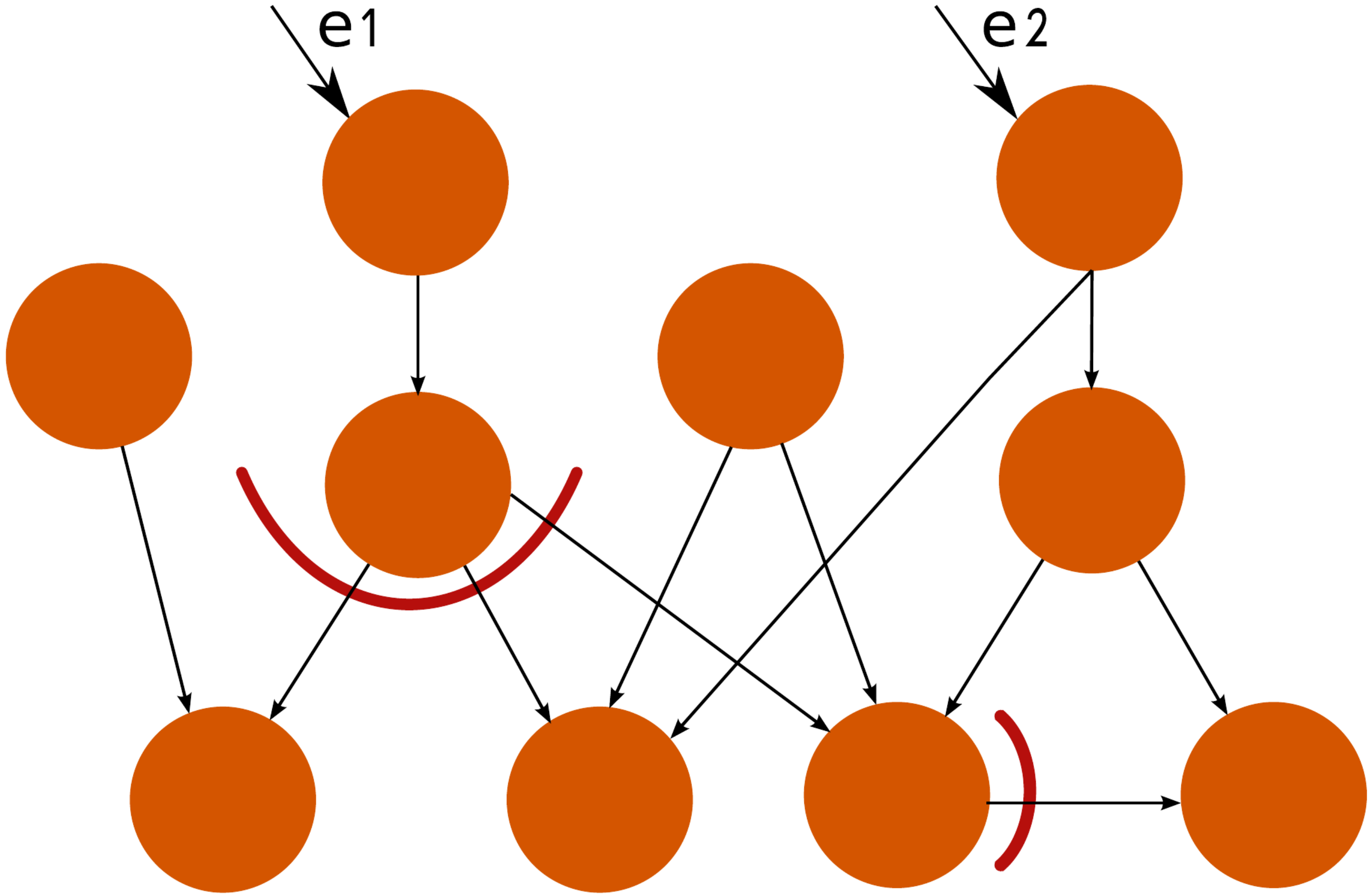

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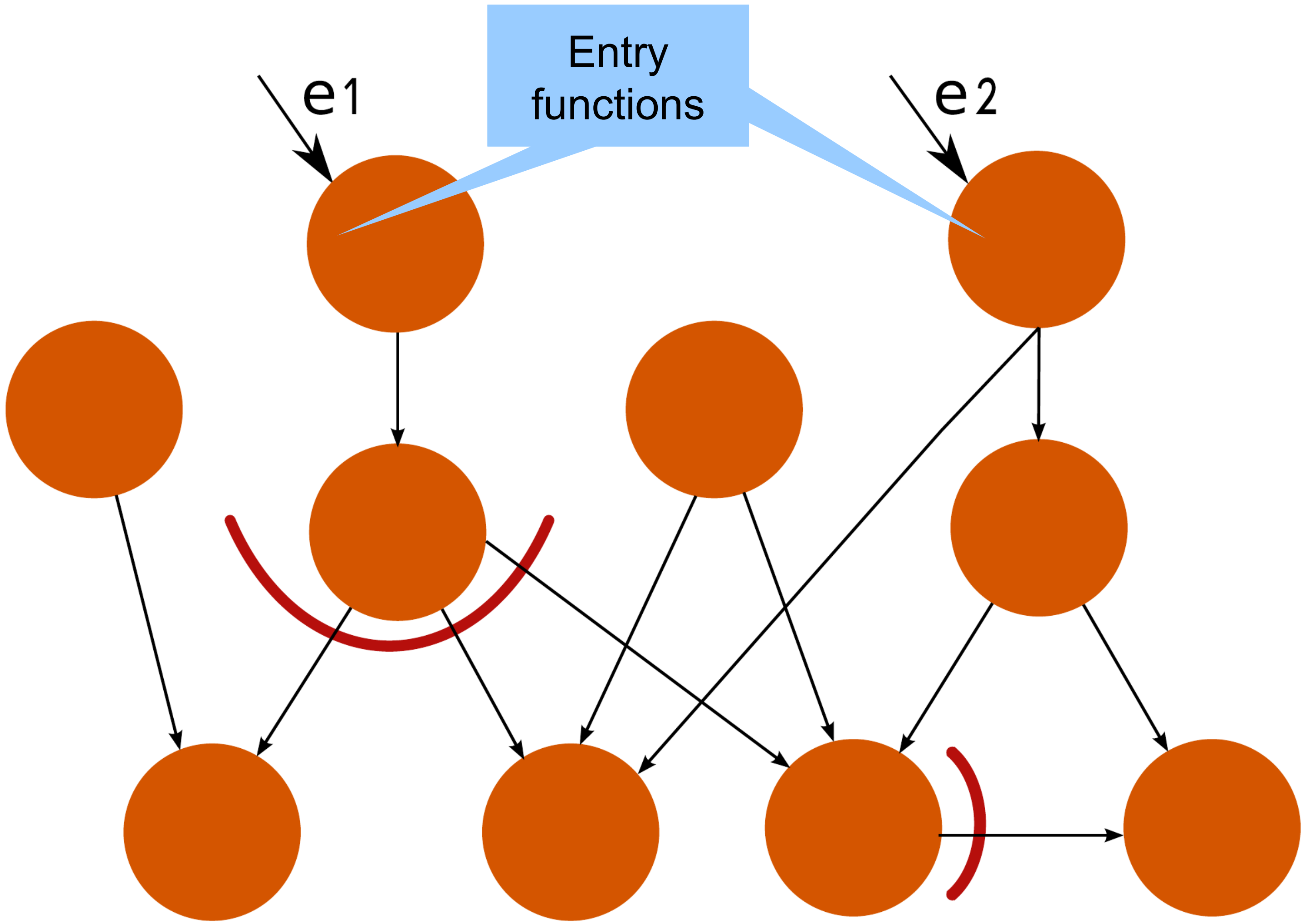

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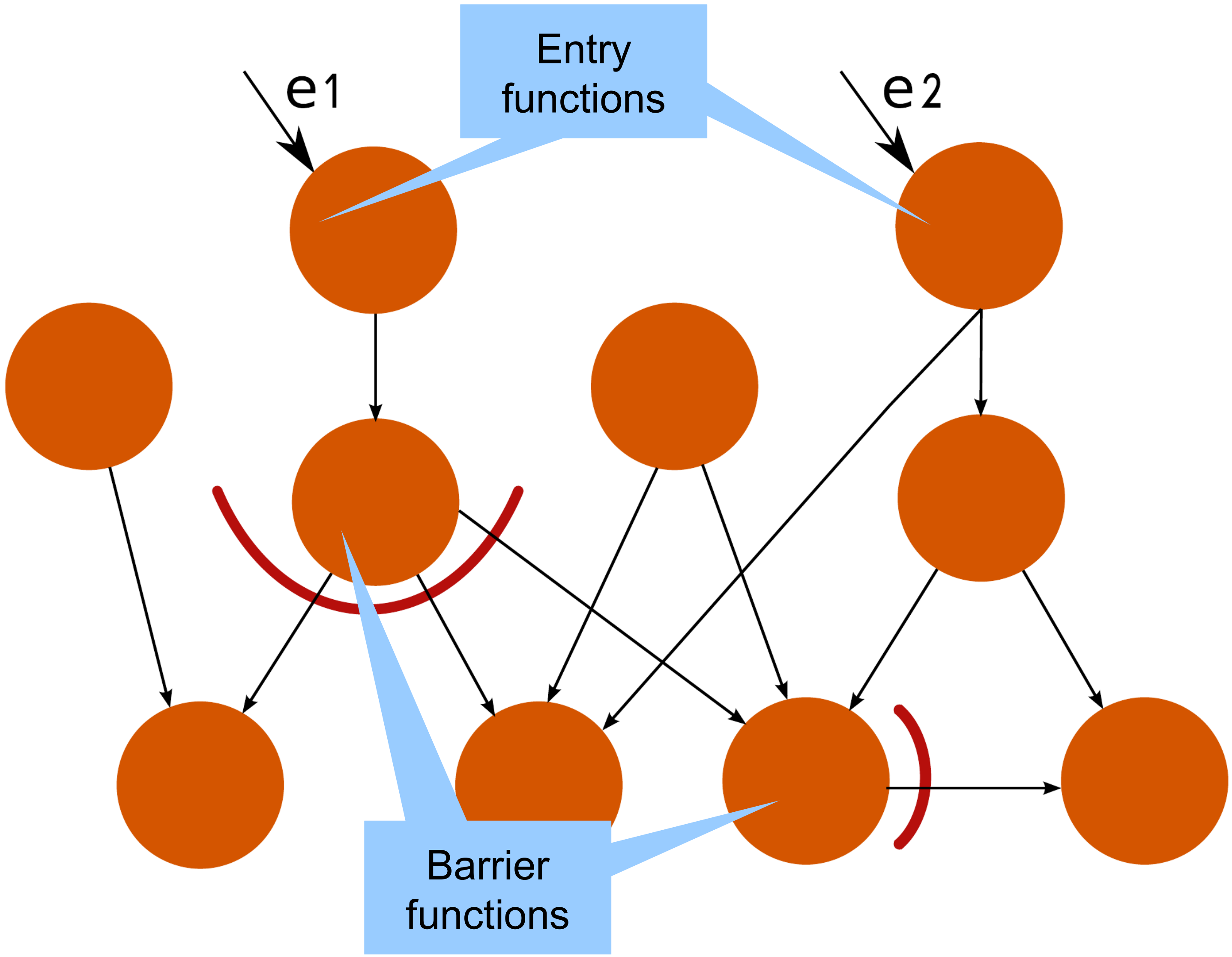

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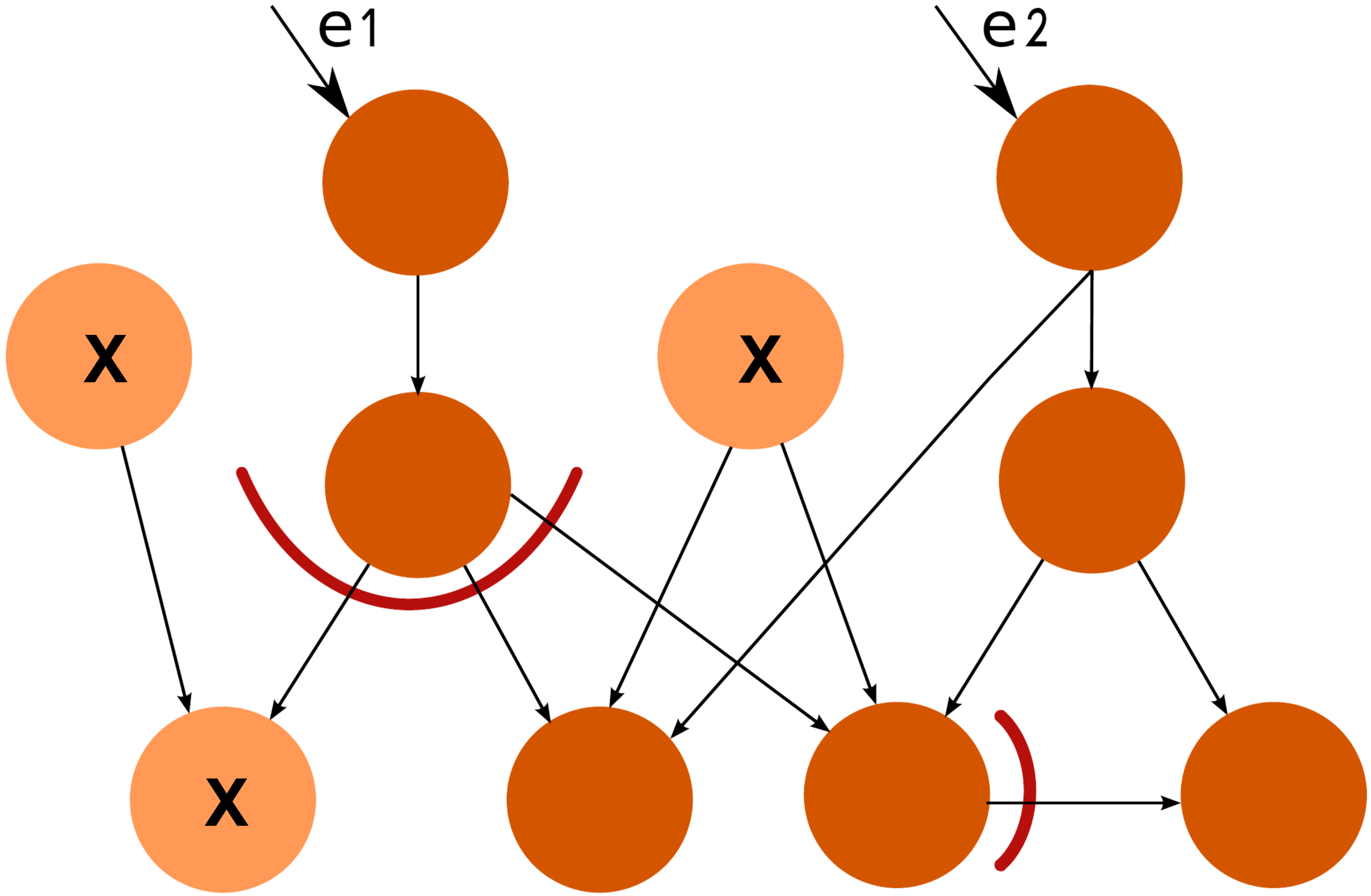

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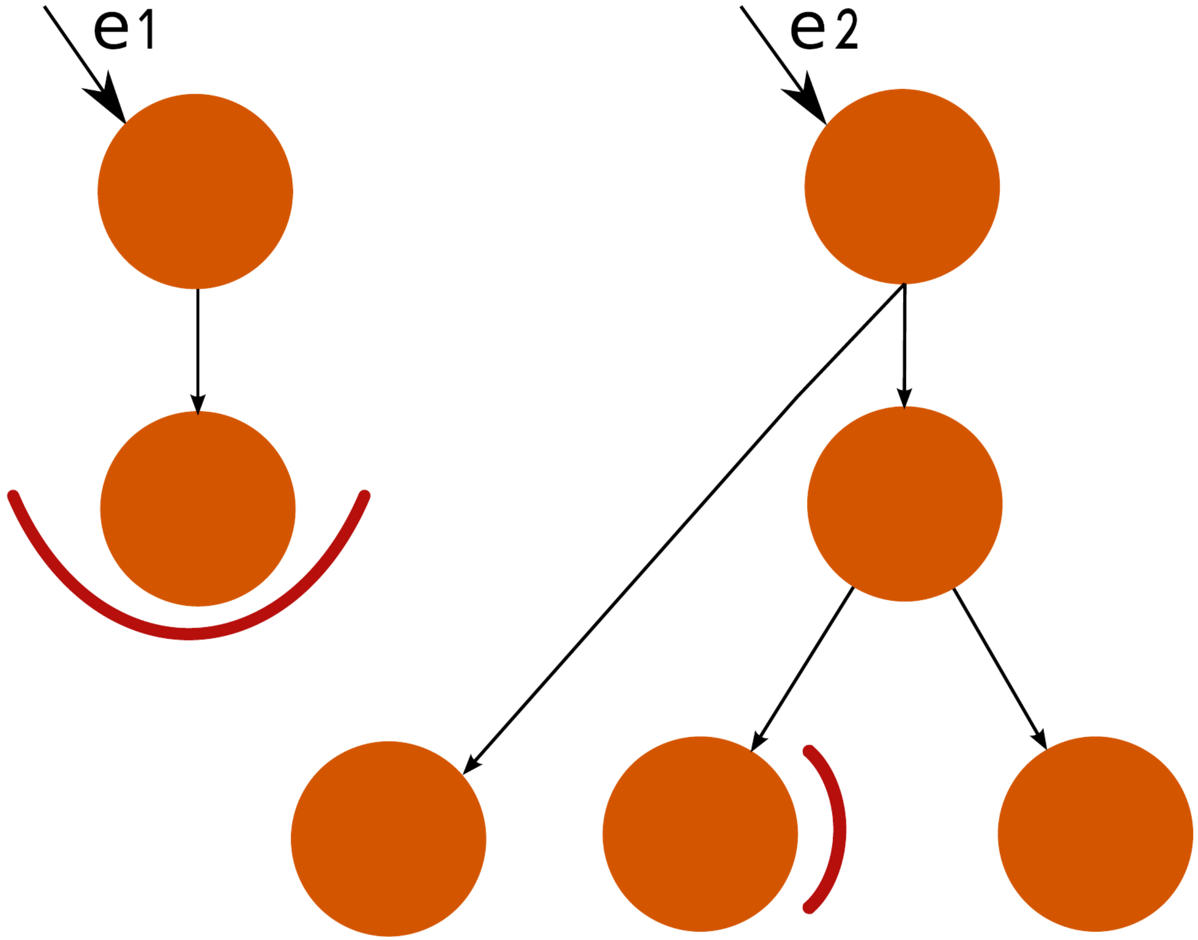
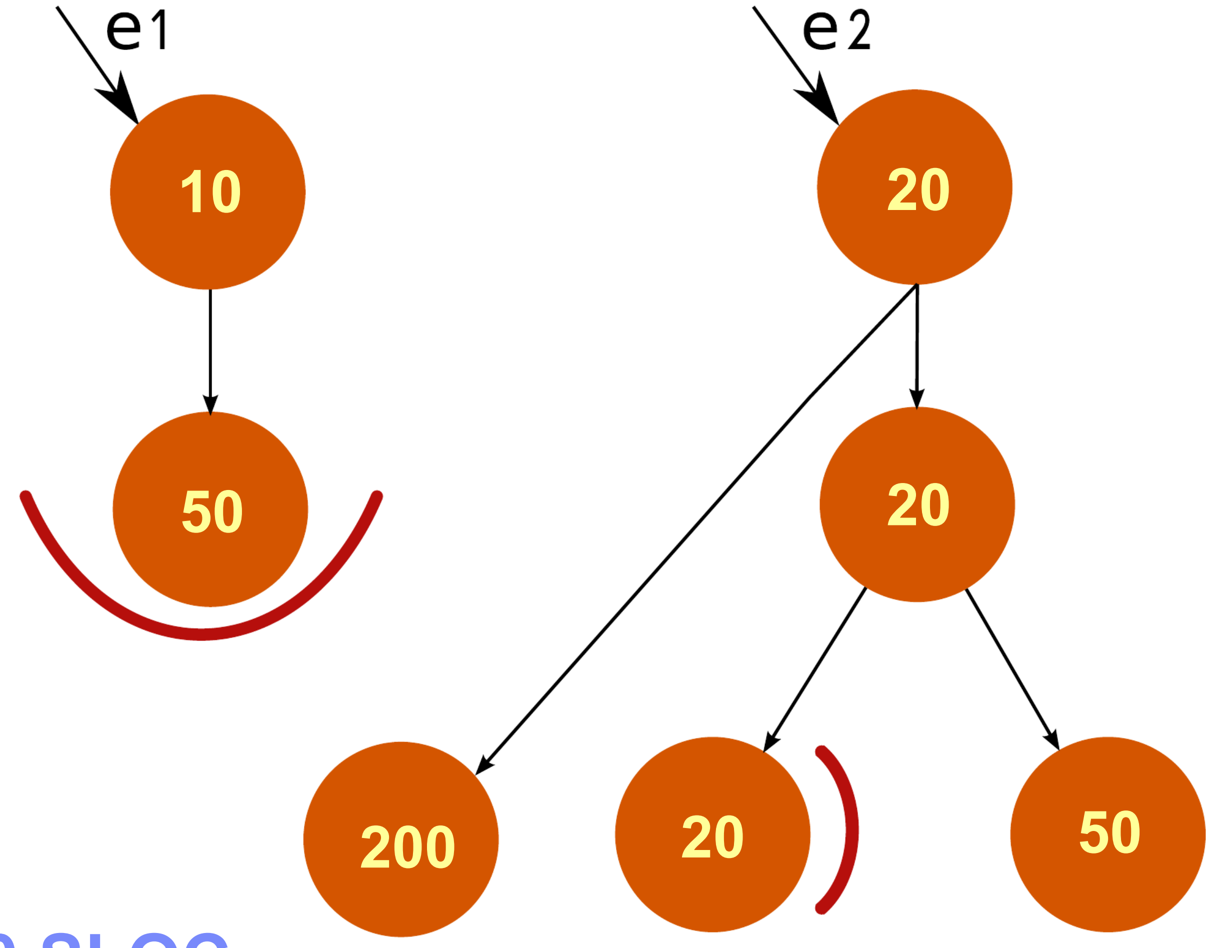
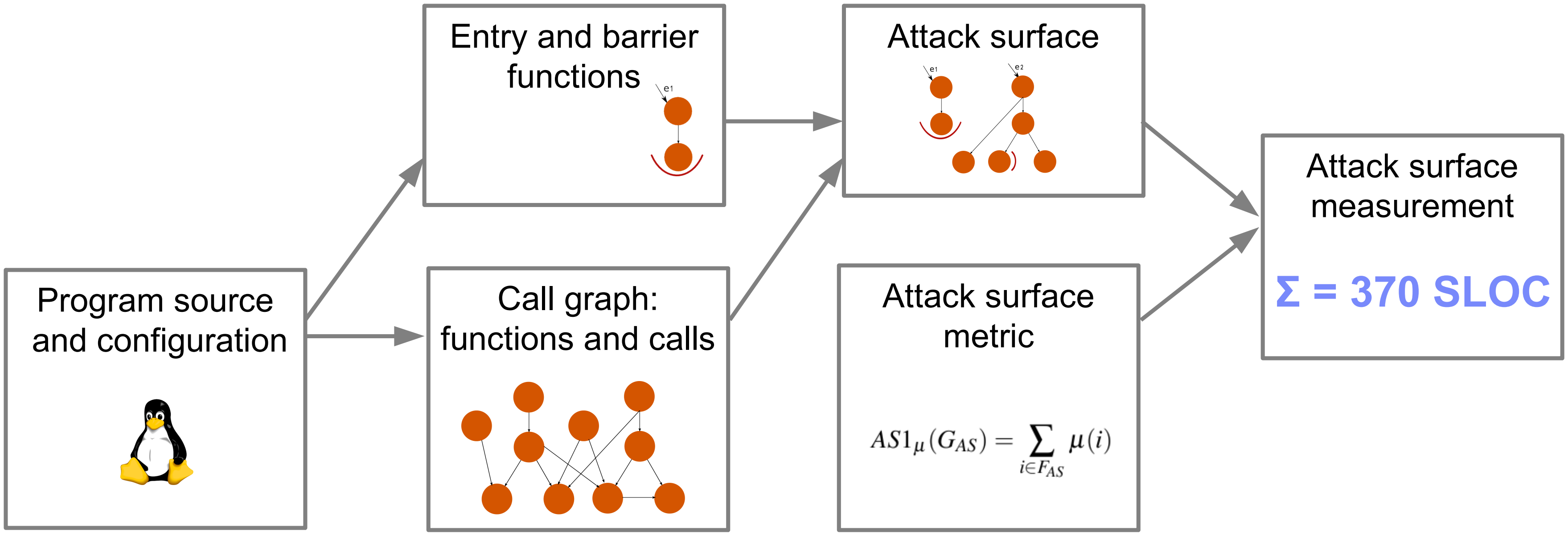


Attack surface measurement: AS1 with SLOC metric



Σ = 370 SLOC

Attack surface measurements: summary



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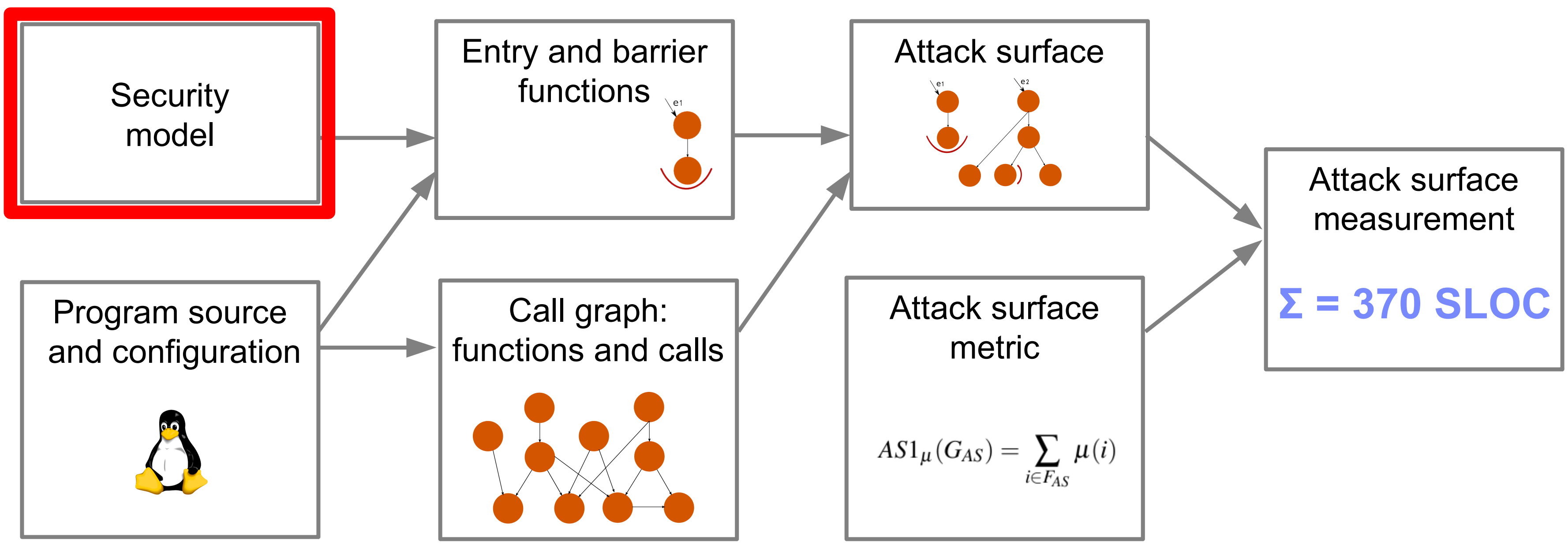
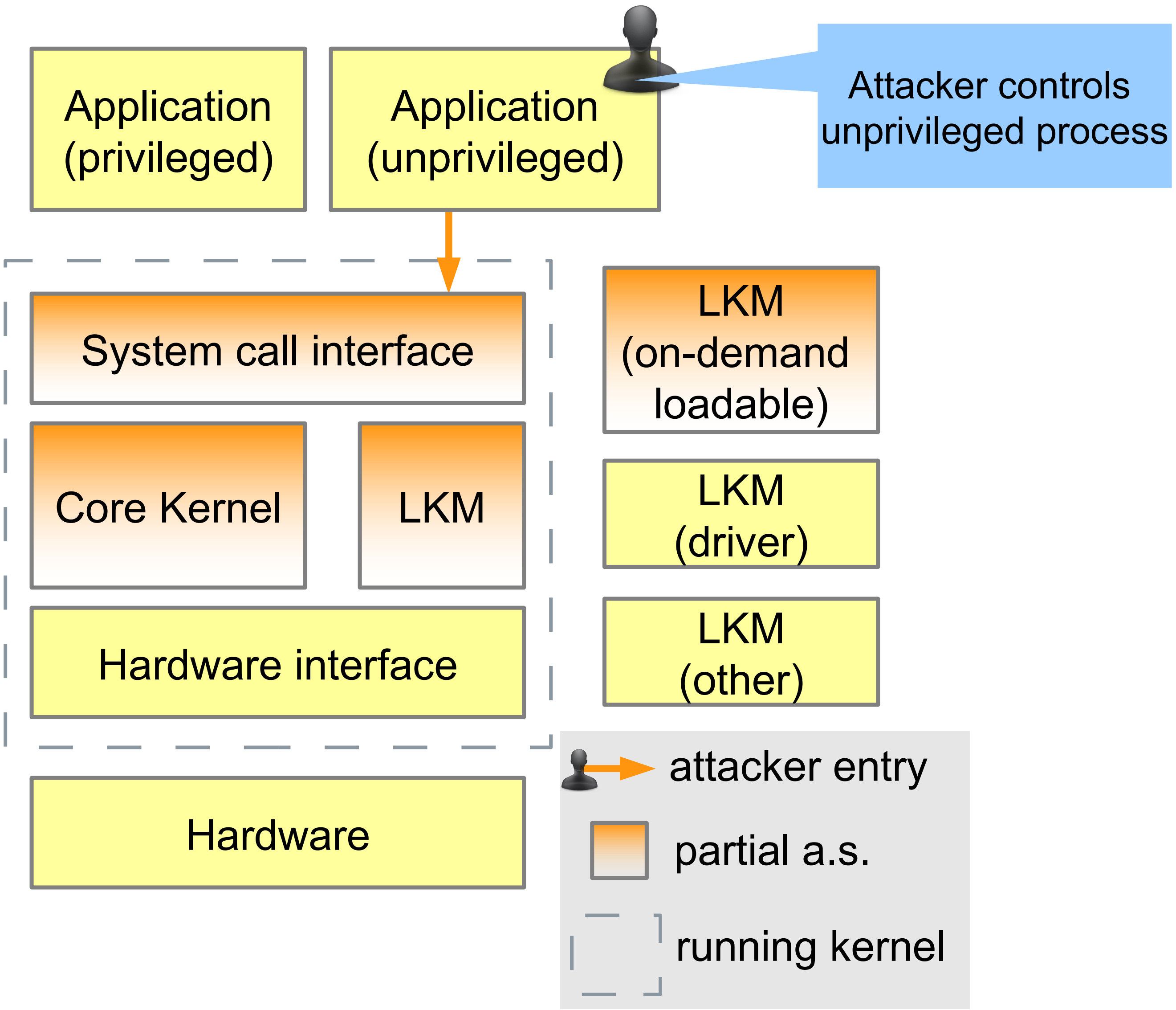


What security model?

IsolSec Linux Kernel Security Model



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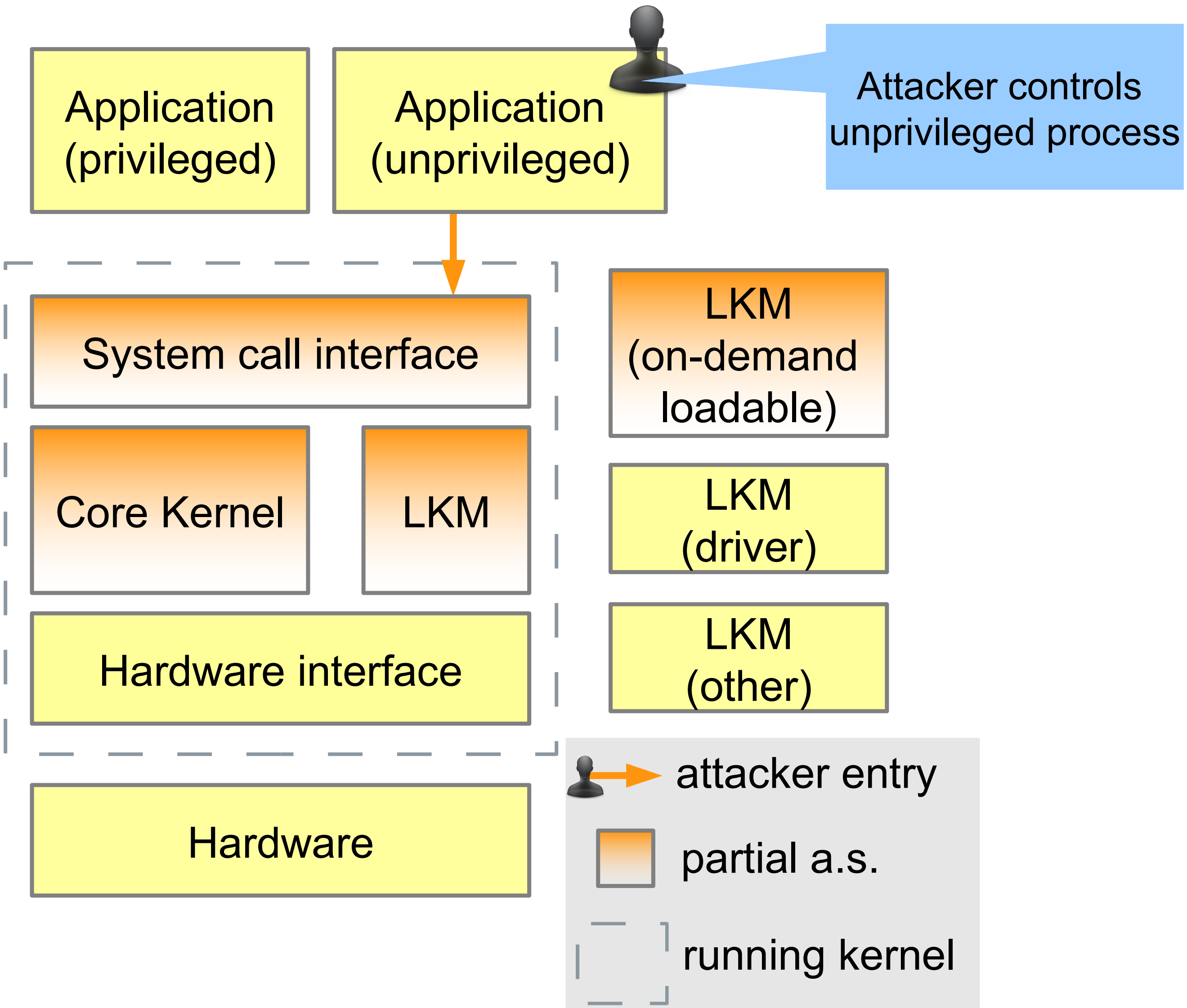

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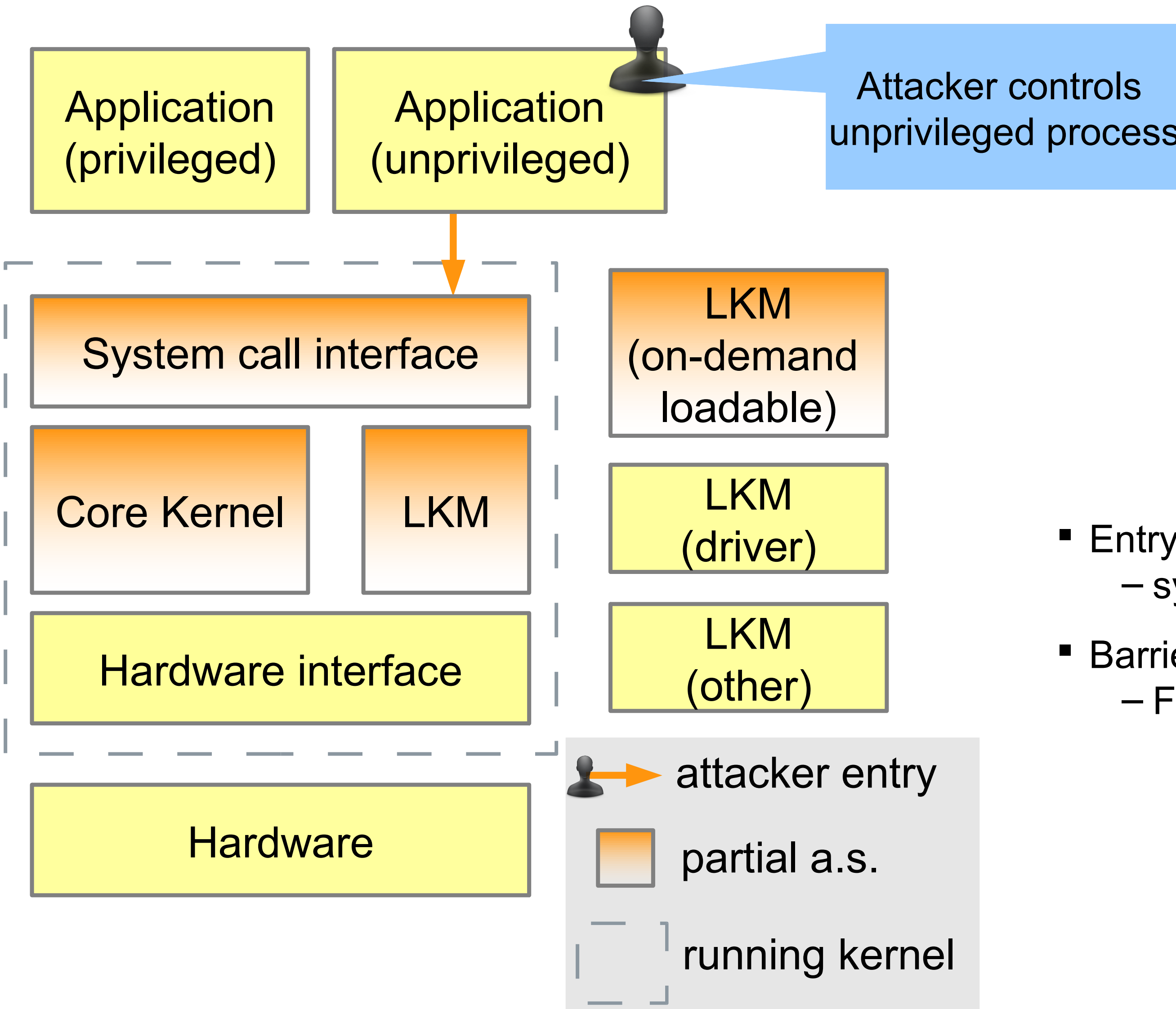
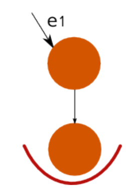


- Entry functions:
  - system calls
- Barrier functions:
  - Functions calling `capable()`



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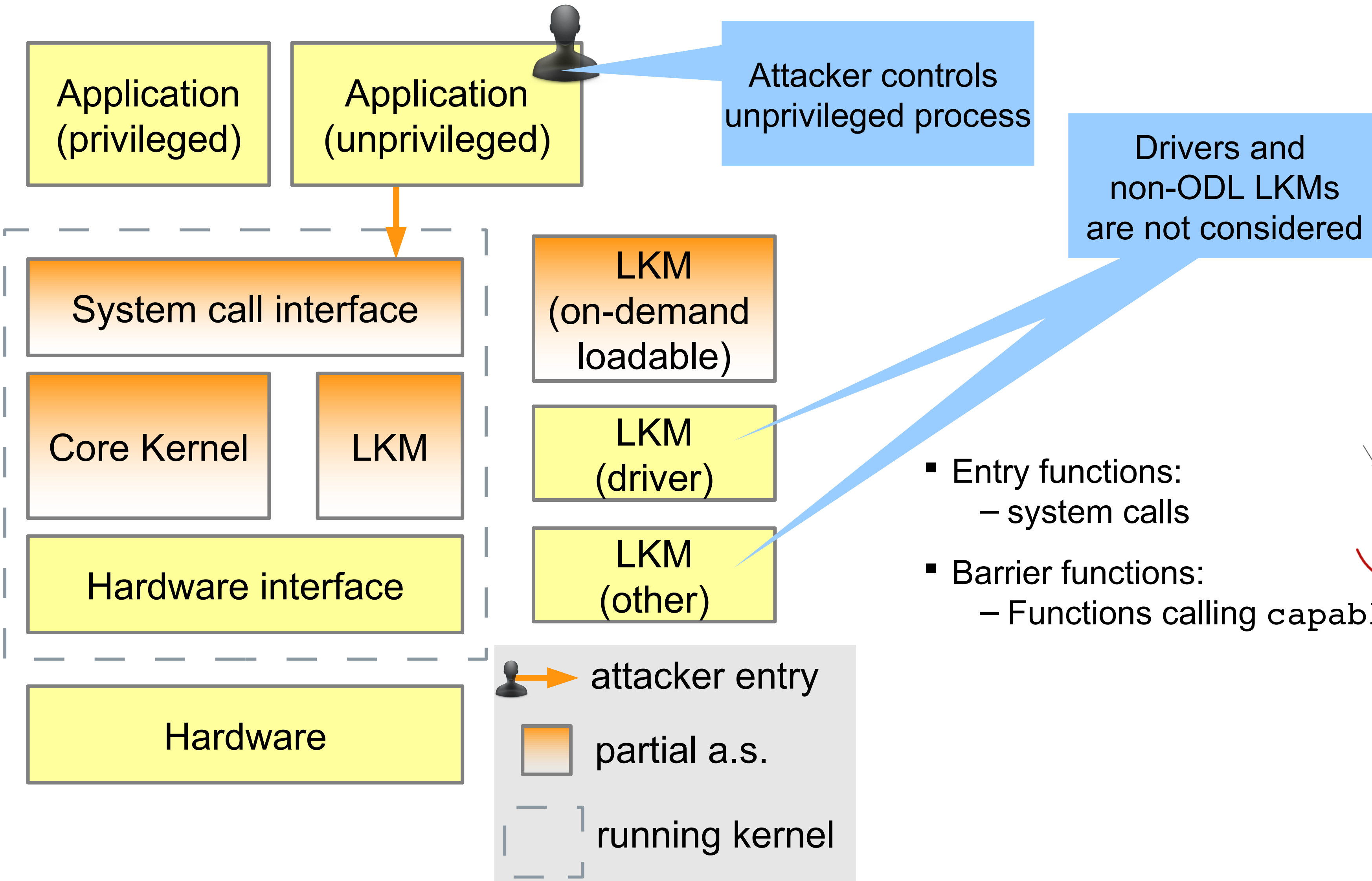

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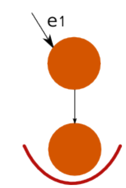

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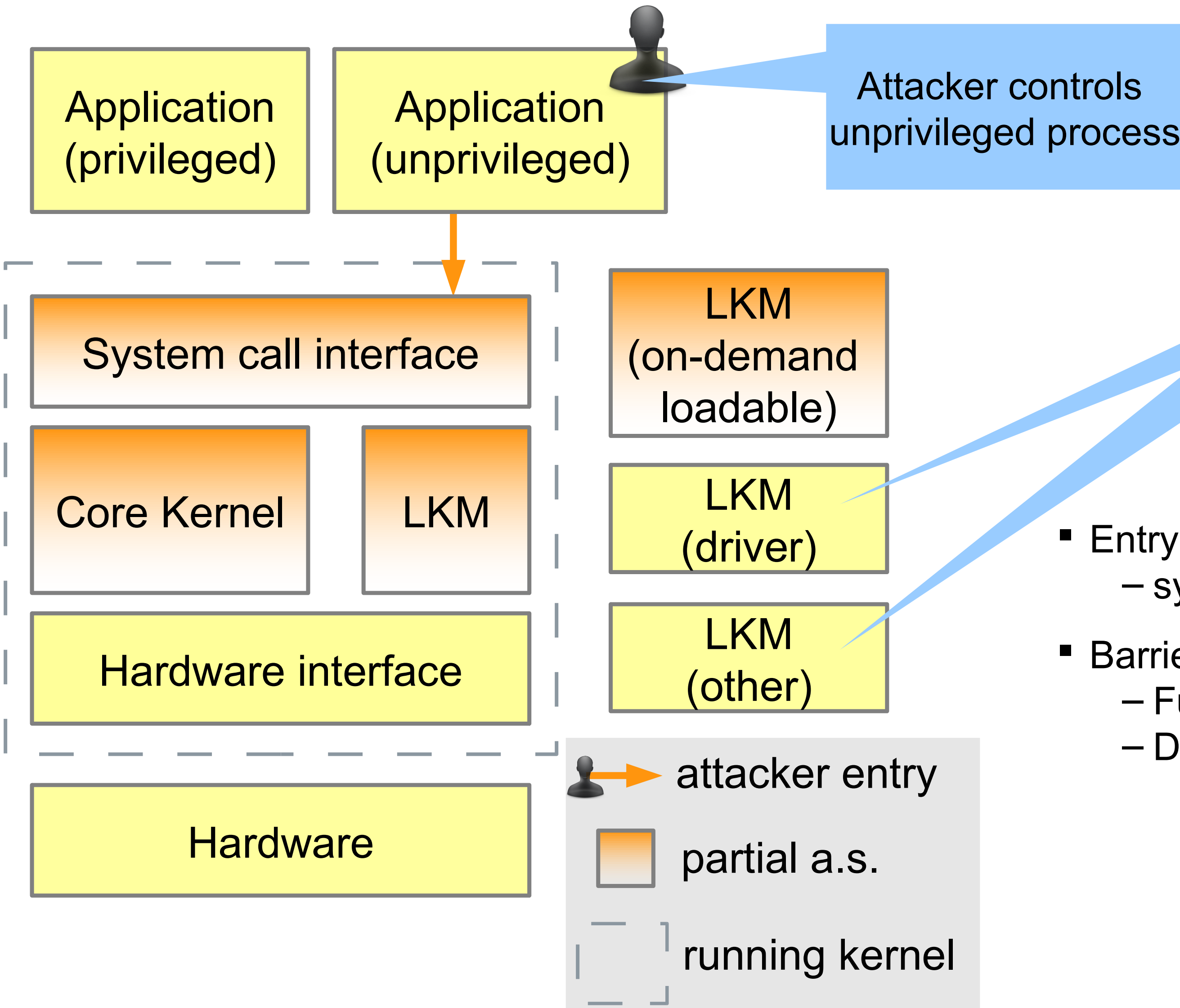
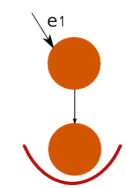


Drivers and non-ODL LKMs are not considered

- Entry functions:
  - system calls
- Barrier functions:
  - Functions calling `capable()`
  - Drivers and “other” LKMs



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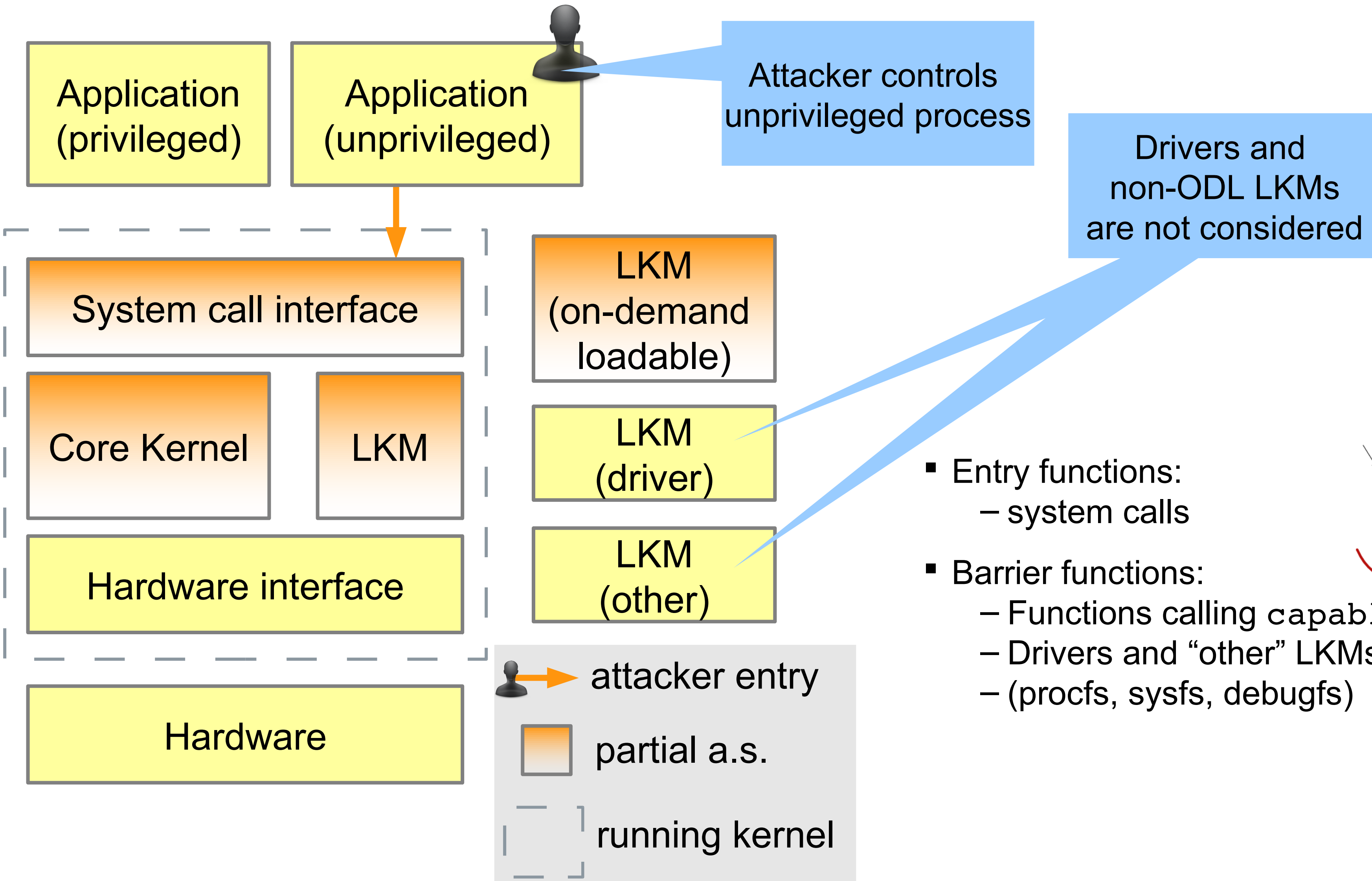

- Entry functions:
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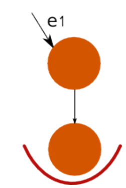
  - Drivers and “other” LKMs
  - (procfs, sysfs, debugfs)



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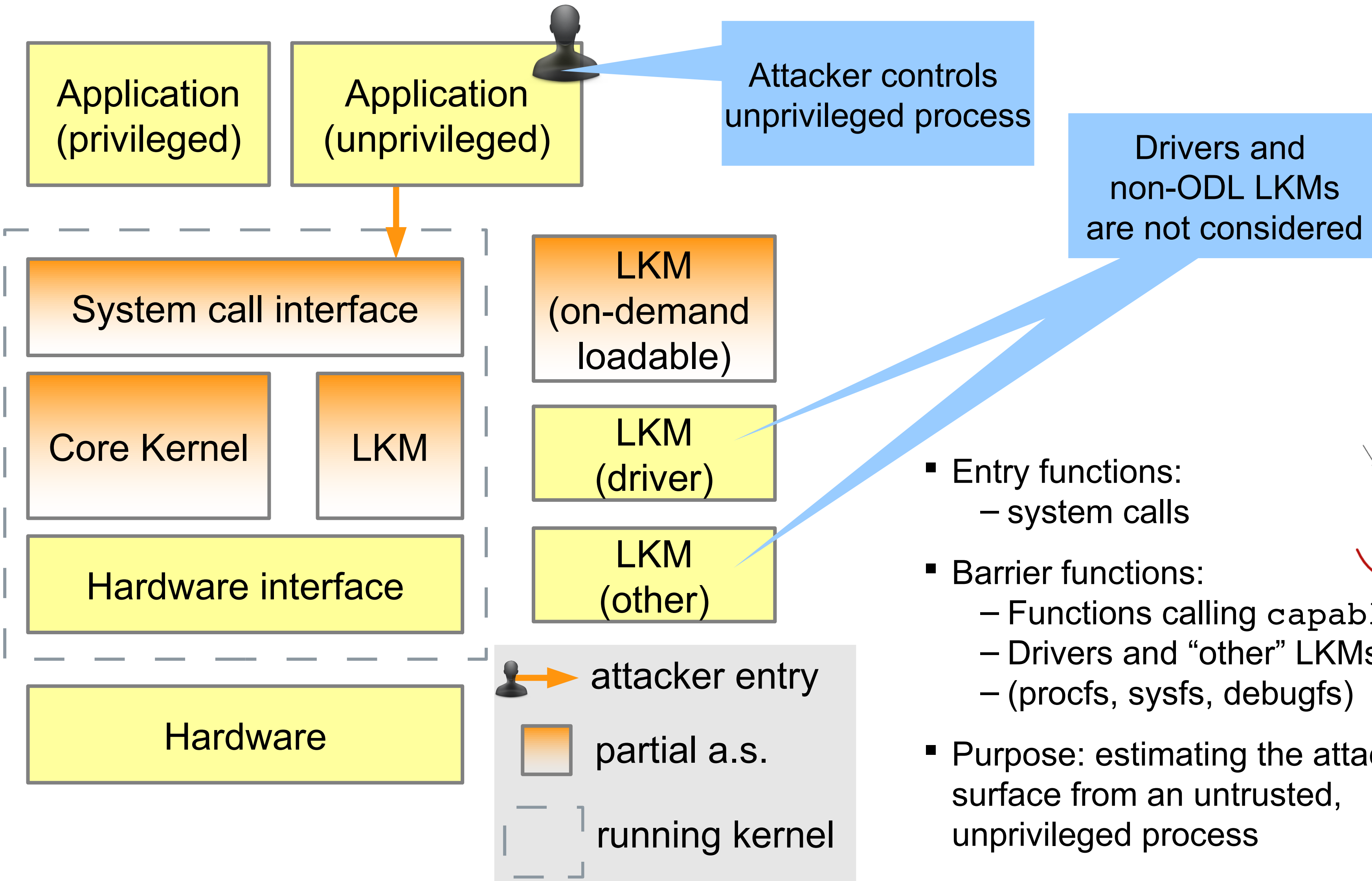
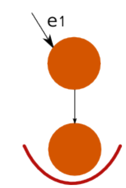
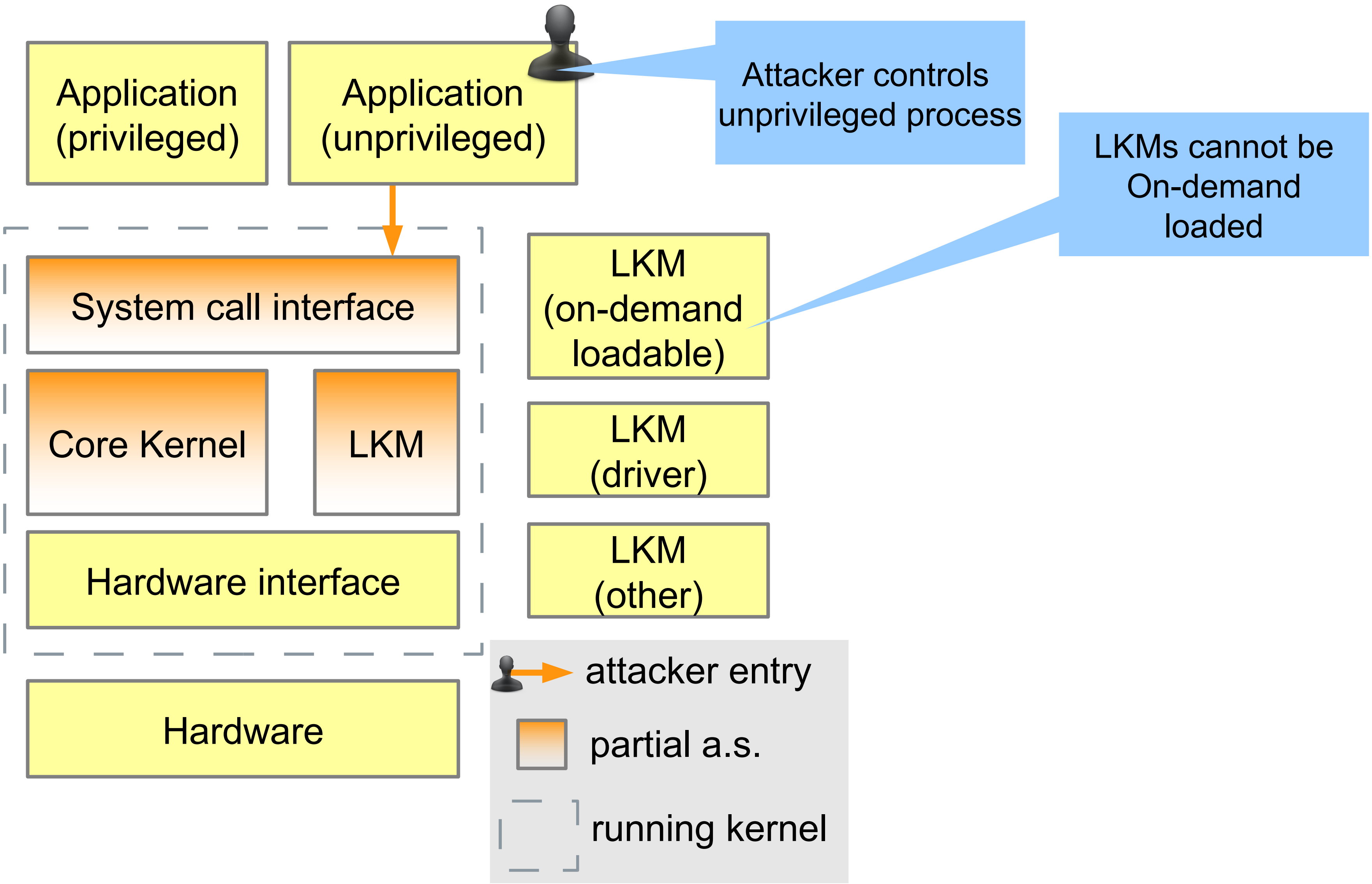


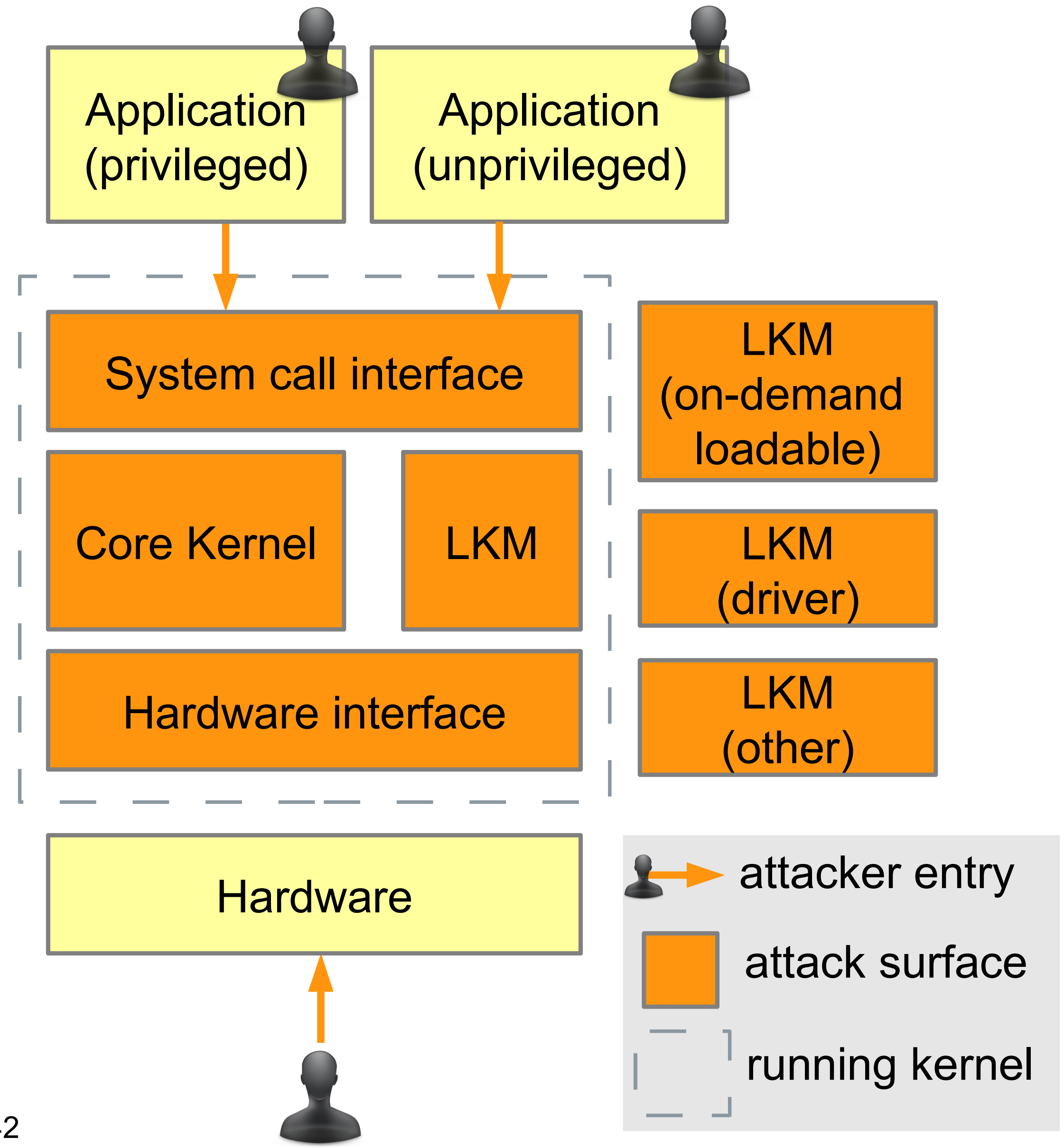
- Entry functions:
  - system calls
- Barrier functions:
  - Functions calling `capable()`
  - Drivers and “other” LKMs
  - (procfs, sysfs, debugfs)
- Purpose: estimating the attack surface from an untrusted, unprivileged process



StaticSec Linux Kernel Security Model



GenSec Linux Kernel Security Model



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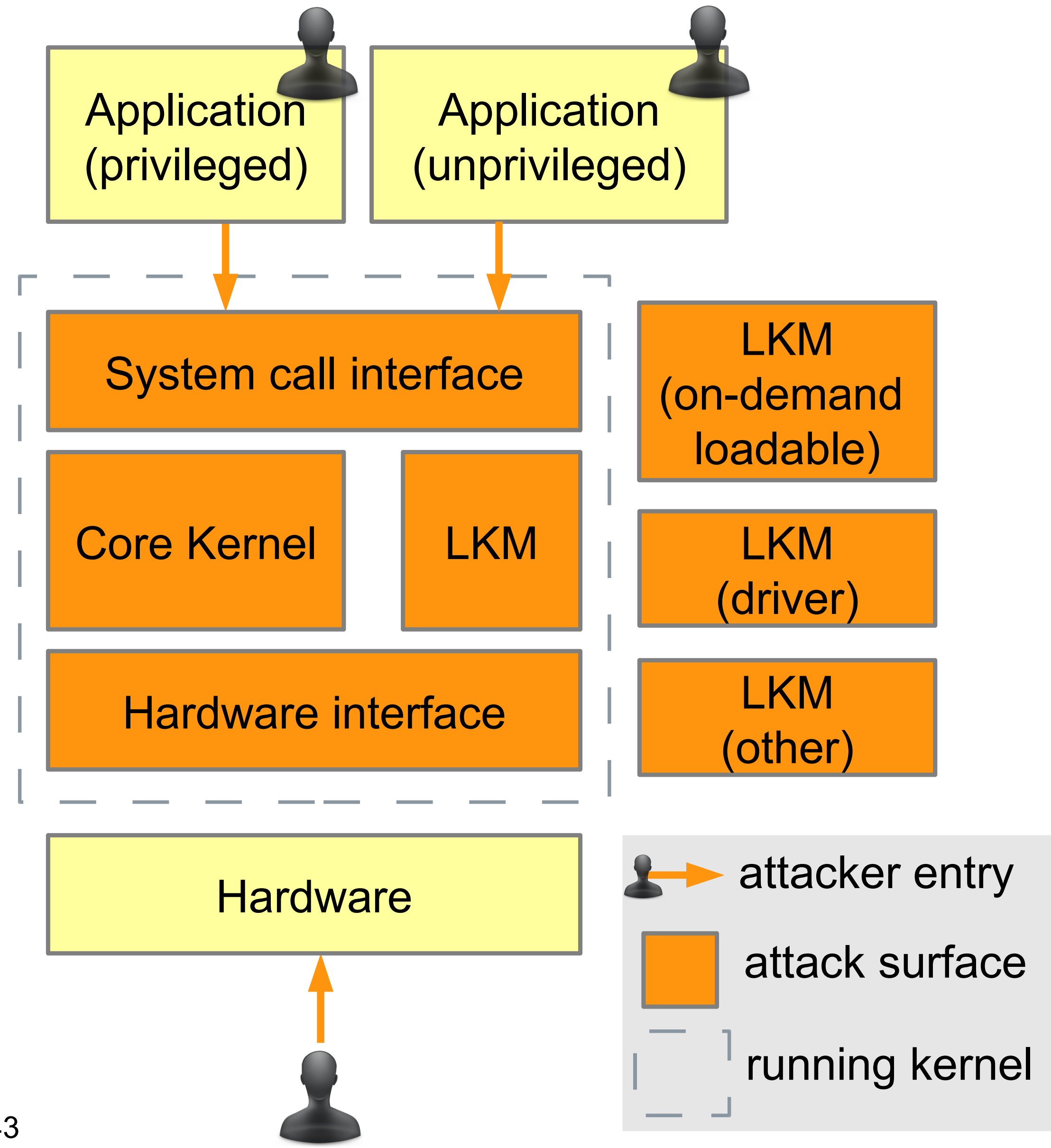
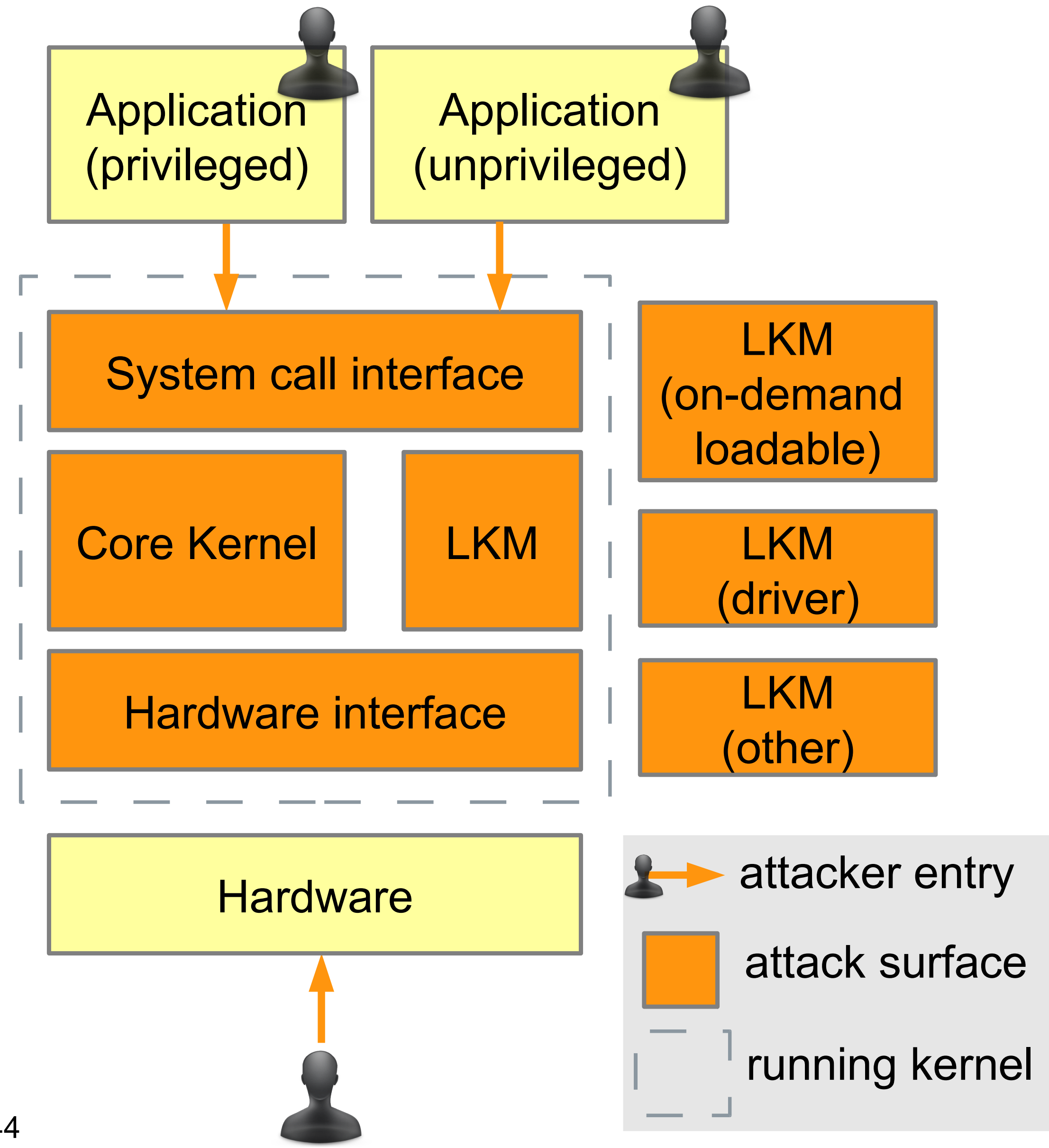


- Entry functions:
  - all
- Barrier functions:
  - none

GenSec Linux Kernel Security Model



- Entry functions:
  - all
- Barrier functions:
  - none
- Overestimates attack surface
  - attacker is privileged?
  - not all LKMs can be loaded
- Purpose:
  - upper bound
  - TCB point of view

Compile-time Kernel Tailoring

- [NDSS'13] Anil Kurmus, Reinhard Tartler, Daniela Dorneanu, Bernhard Heinloth, Valentin Rothberg, Andreas Ruprecht, Wolfgang Schröder-Preikschat, Daniel Lohmann and Rüdiger Kapitza. "**Attack Surface Metrics and Automated Compile-Time OS Kernel Tailoring.**" In: Proceedings of the 20th Network and Distributed System Security Symposium. 2013.

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Making the kernel smaller

~ 5000 features
(ubuntu 12.04)

~ 500 features
(realistic use case)

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(realistic use case)

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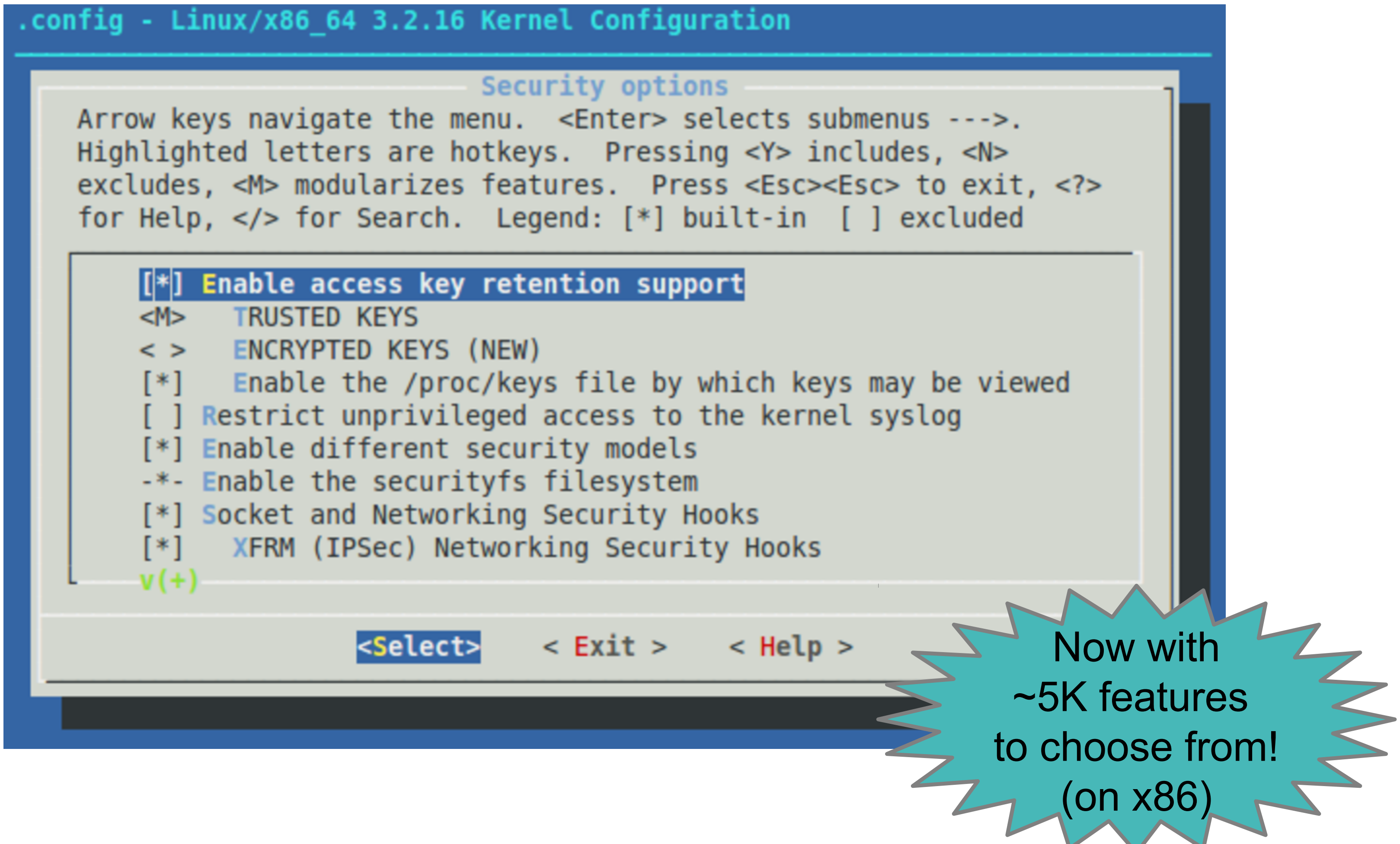
(ubuntu 12.04)

Remove unnecessary features from the kernel by leveraging built-in configurability

Make (menuconfig) your way to a smaller kernel



Don't take my word for it

[RFC] Simplifying kernel configuration for distro issues

87 messages

Linus Torvalds <torvalds@linux-foundation.org> Fri, Jul 13, 2012 at 10:37 PM
To: Dave Jones <davej@redhat.com>, Greg Kroah-Hartman <greg@kroah.com>, Ubuntu Kernel Team <kernel-team@lists.ubuntu.com>, Debian Kernel Team <debian-kernel@lists.debian.org>, OpenSUSE Kernel Team <opensuse-kernel@opensuse.org>
Cc: Linux Kernel Mailing List <linux-kernel@vger.kernel.org>

So this has long been one of my pet configuration peeves: as a user I am perfectly happy answering the questions about what kinds of hardware I want the kernel to support (I kind of know that), but many of the "support infrastructure" questions are very opaque, and I have no idea which of the them any particular distribution actually depends on.

And it tends to change over time. For example, F14 (iirc) started using TMPFS and TMPFS_POSIX_ACL/XATTR for /dev. And starting in F16, the initrd setup requires DEVTMPFS and DEVTMPFS_MOUNT. There's been several times when I started with my old minimal config, and the resulting kernel would boot, but something wouldn't quite work right, and it can be very subtle indeed.

Similarly, the distro ends up having very particular requirements for exactly *which* security models it uses and needs, and they tend to change over time. And now with systemd, CGROUPS suddenly aren't just esoteric things that no normal person would want to use, but are used for basic infrastructure. And I remember being surprised by OpenSUSE suddenly needing the RAW table support for netfilter, because it had a NOTRACK rule or something.

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Automatic Kernel-Configuration Tailoring

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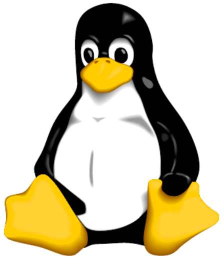
Distribution kernel
and use case



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Tailored kernel

Automatic Kernel-Configuration Tailoring

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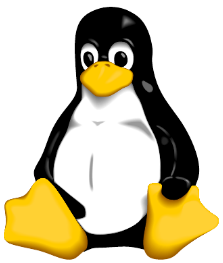
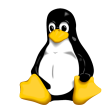
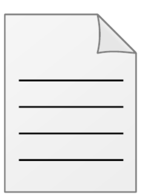


Tailored kernel





run workload
and collect **trace**

```
Makefile
arch/x86/init.c:59
arch/x86/entry32.S:14
arch/x86/...
lib/Makefile
kernel/sched.c:723
...
```

correlate to
source line locations
and **#ifdefs**

```
B00 <-> CONFIG_X86
&&
B1 <-> CONFIG_NUMA
&&
B2 <-> ! B1
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...
```

correlate to **features**
and take into account
feature dependencies

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CONFIG_X86=y
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solve formula
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Automatic Kernel-Configuration Tailoring

Distribution kernel
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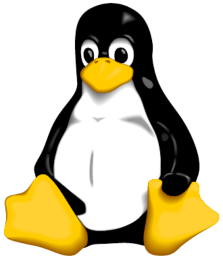

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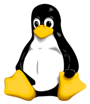

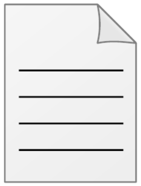

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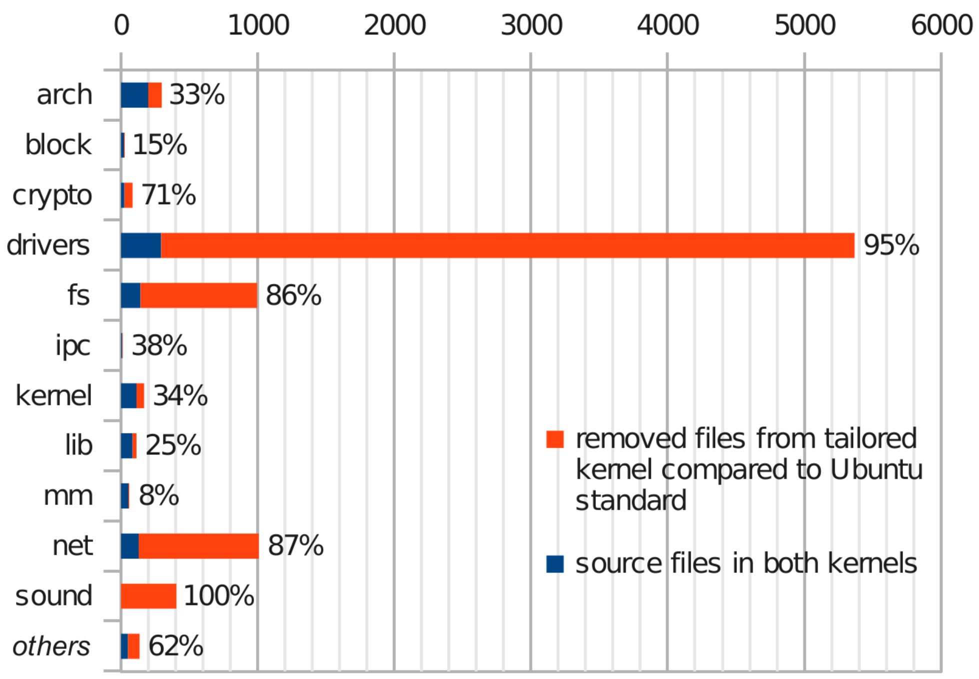
Resulting kernel



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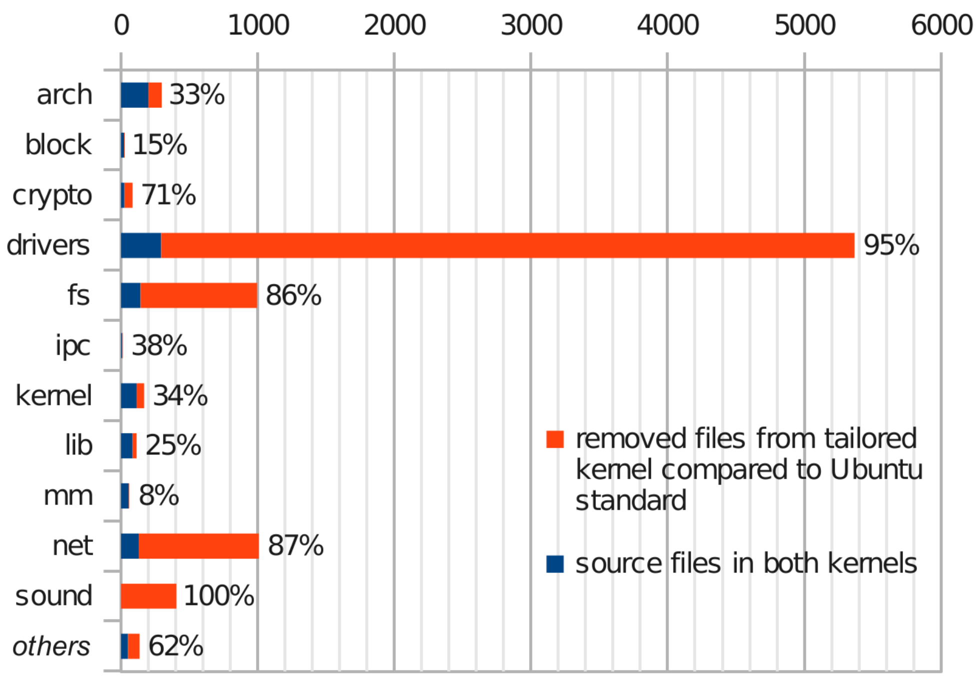

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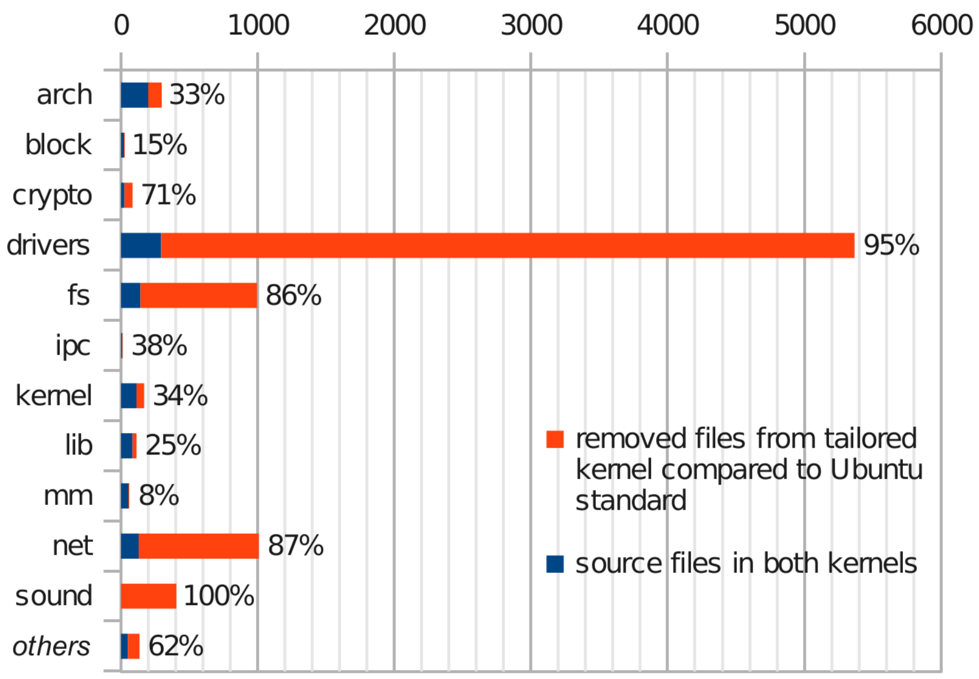
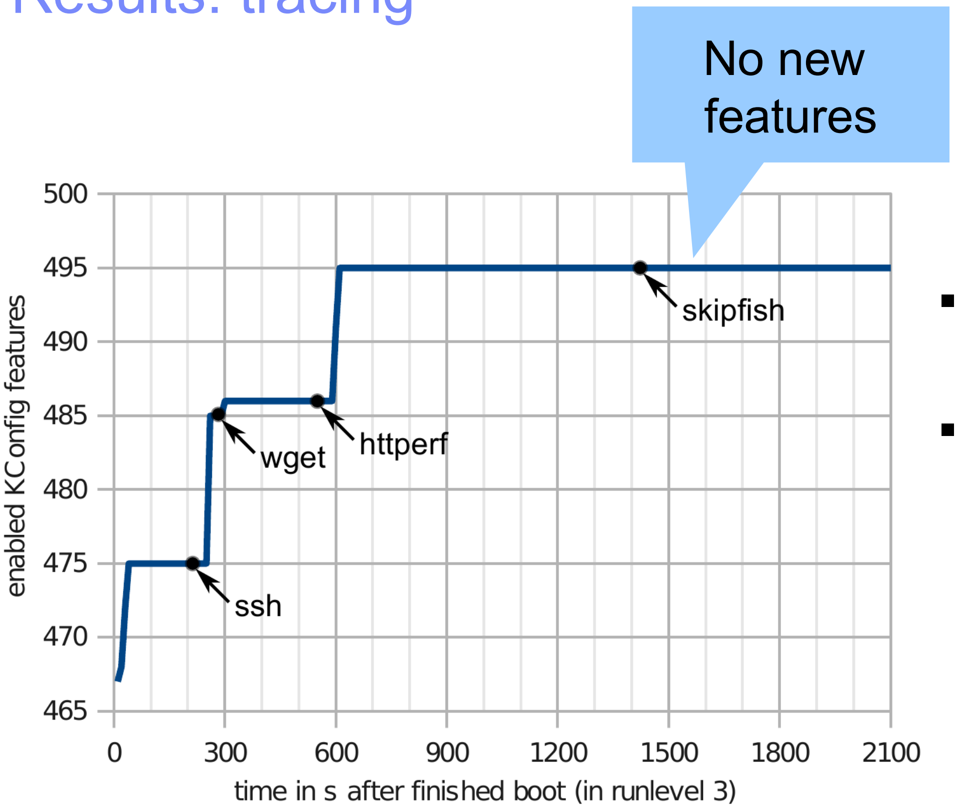


- How much **attack surface reduction**?

Selected results of the evaluation

- Typical server use case: LAMP

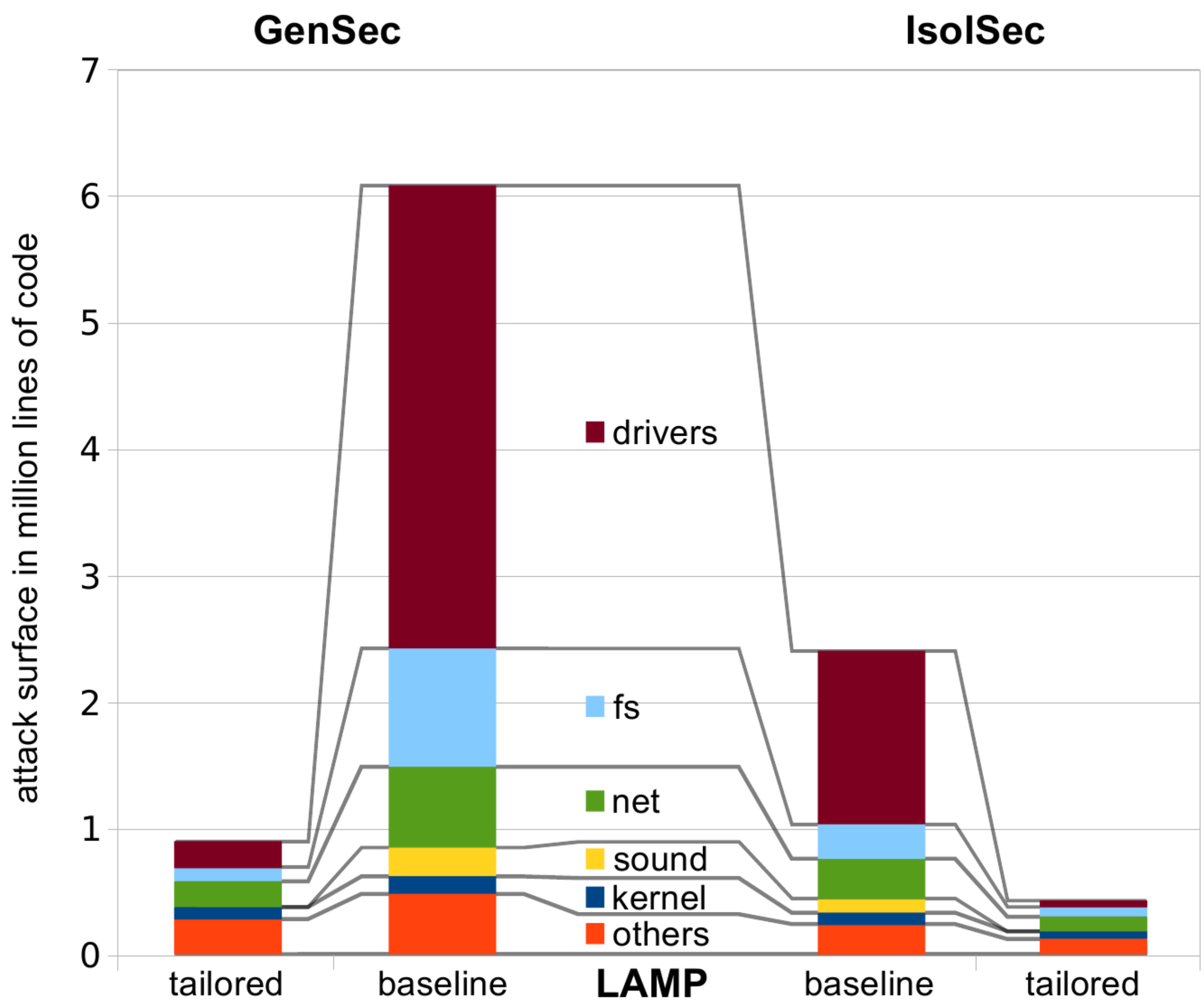
Results: tracing



- Httperf benchmark triggers new features
  – Stabilizes at 495 features
- Skipfish: high coverage of the web application
  – Goes beyond real-world workload

Tracing at "feature-granularity" converges quickly

Results: attack surface reduction



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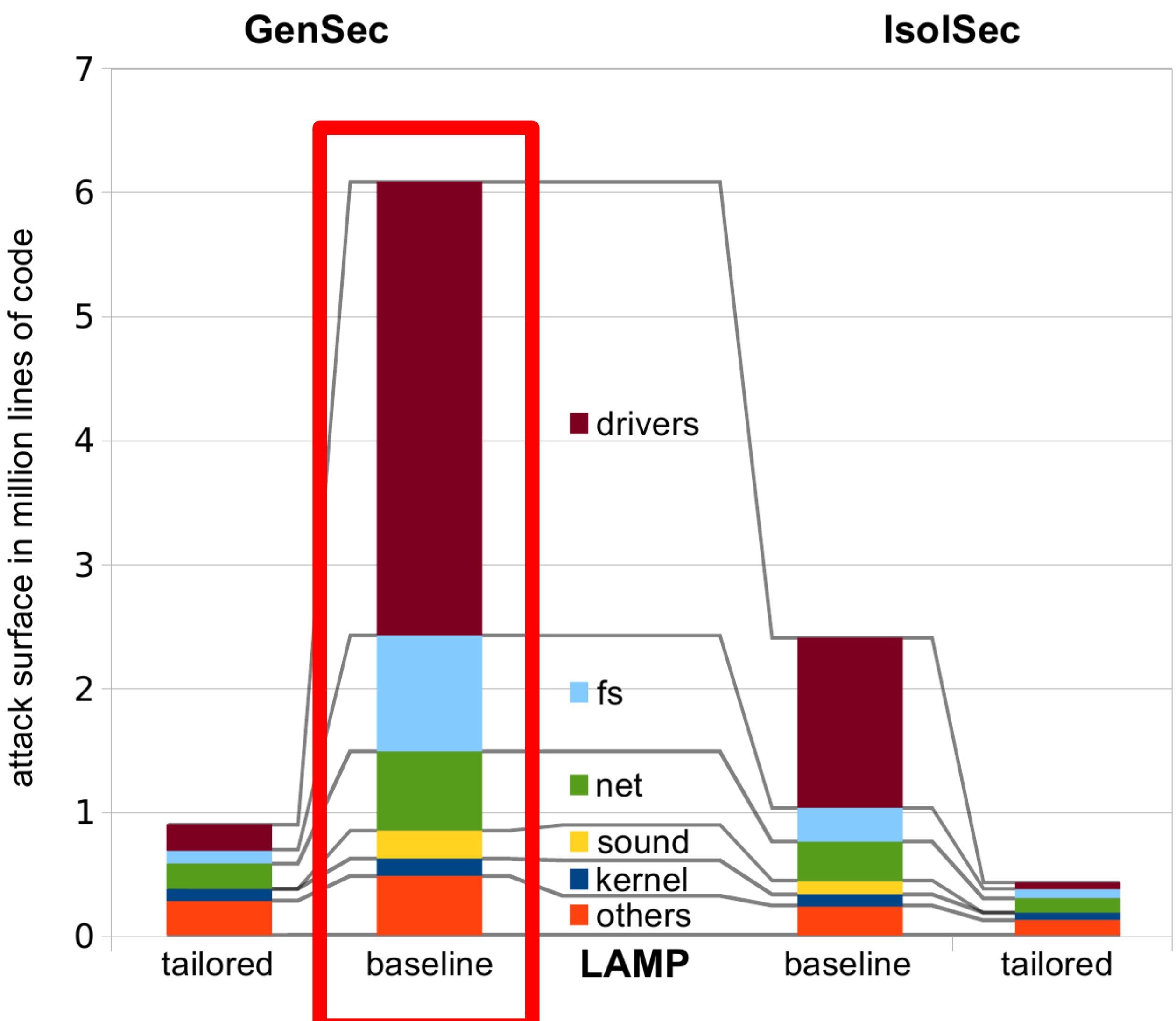

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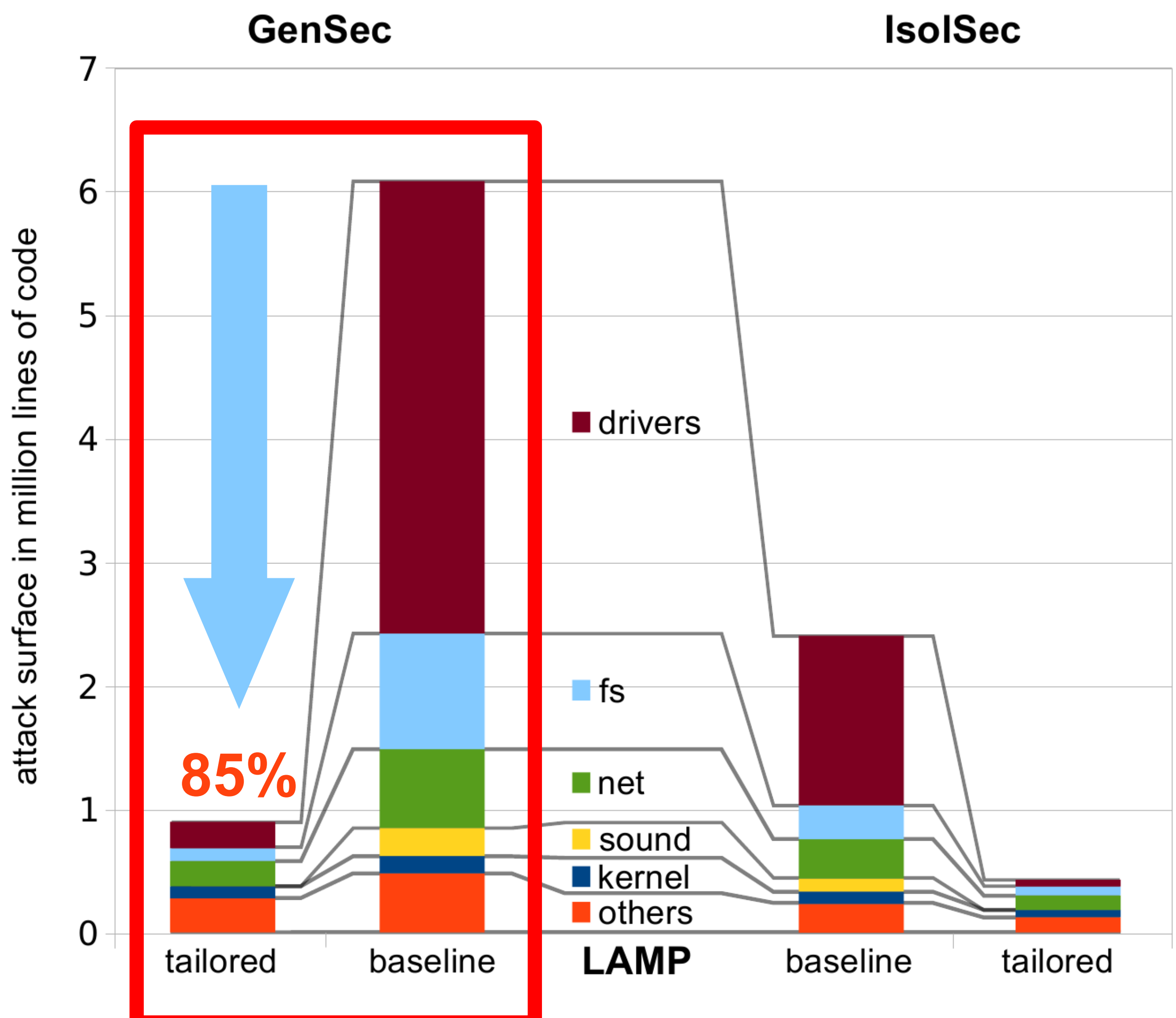
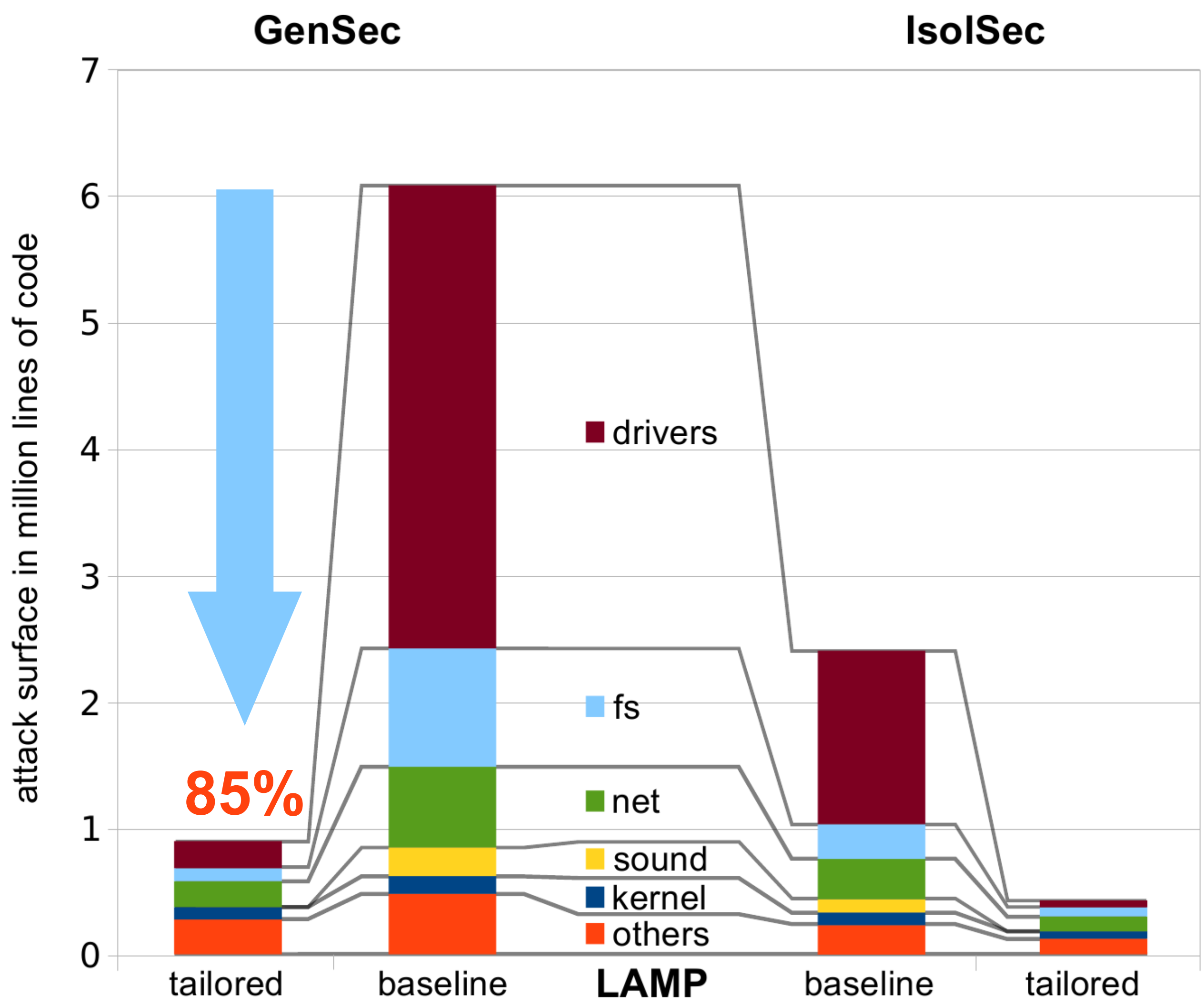
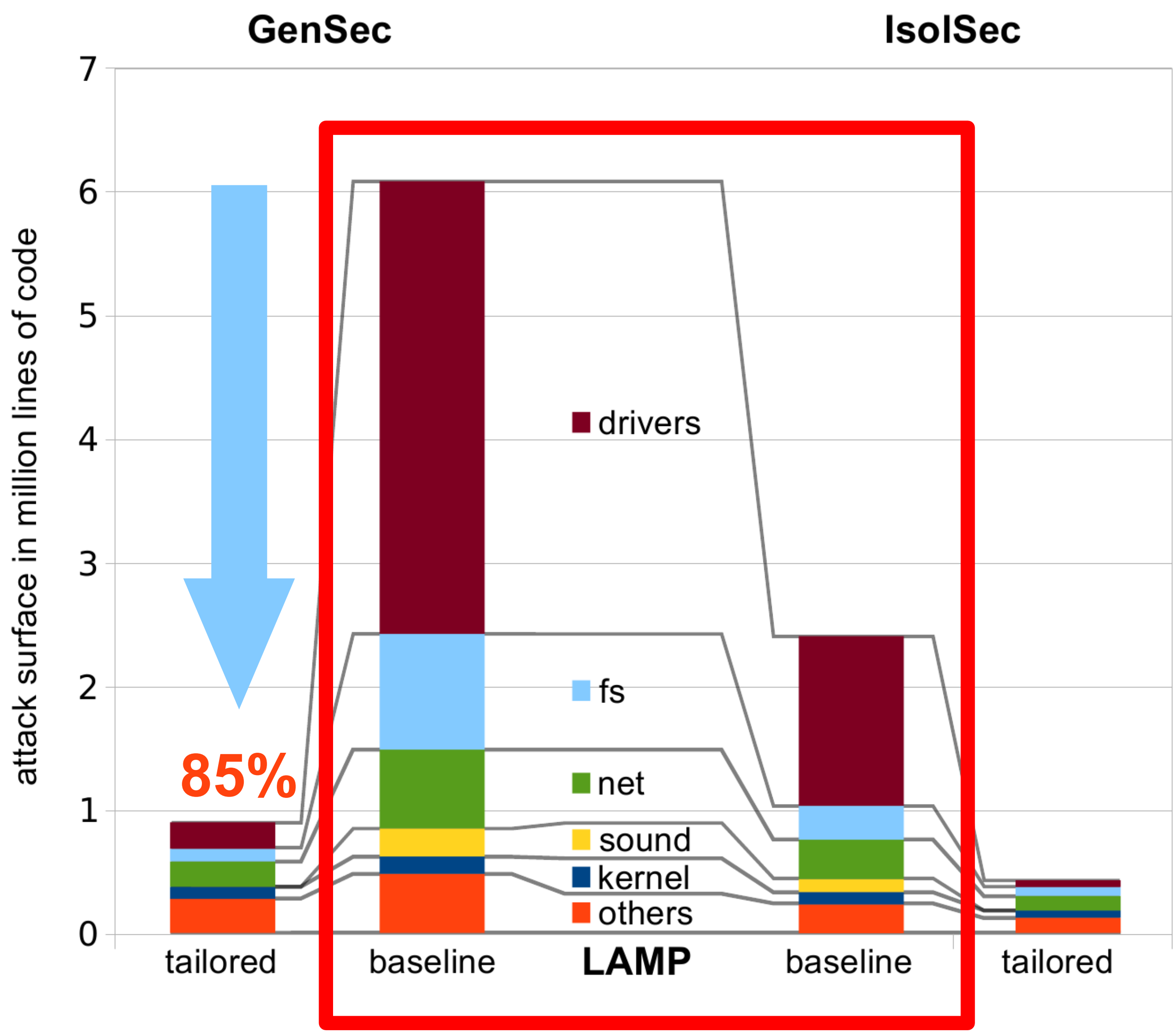


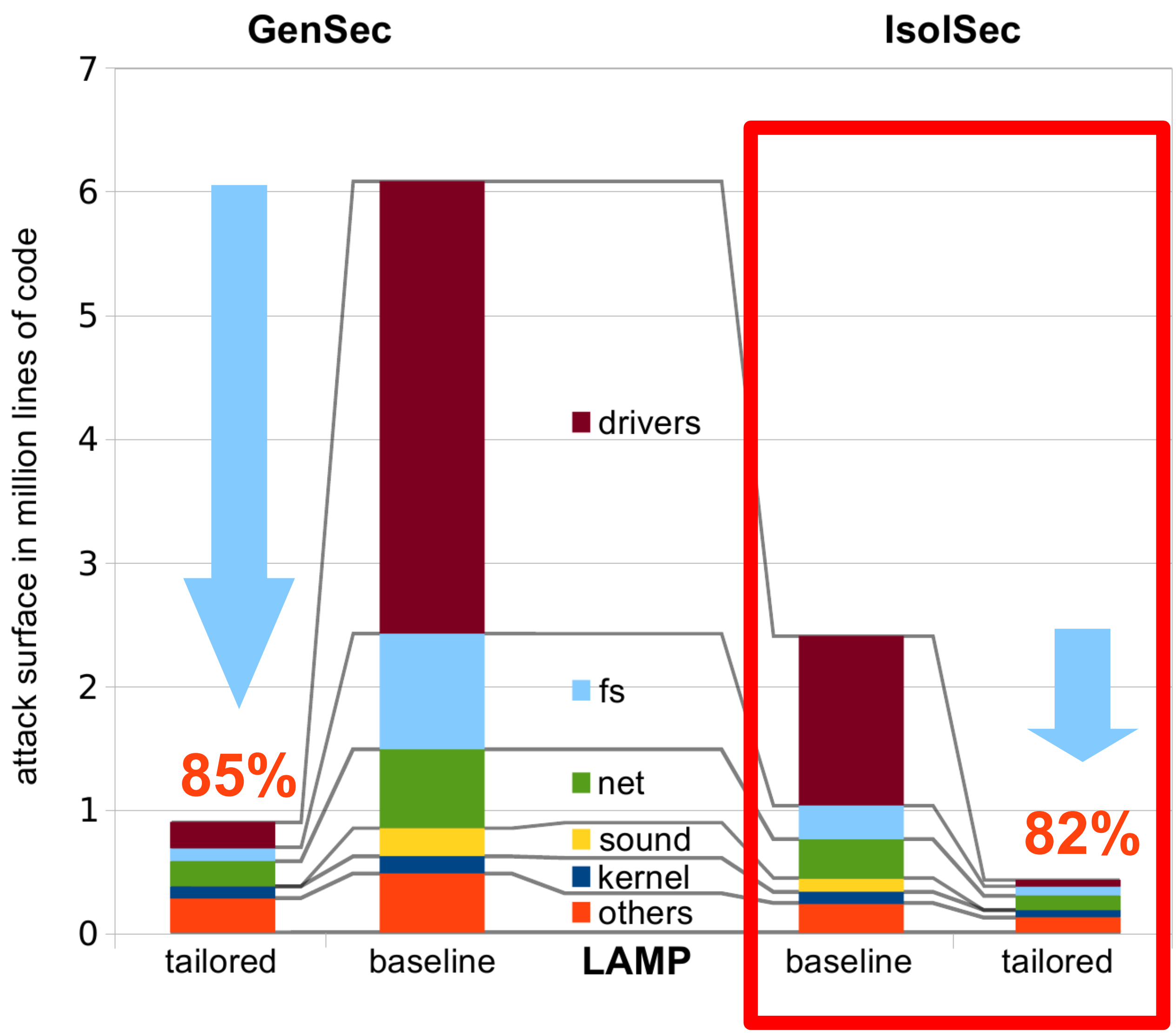
Results: attack surface reduction



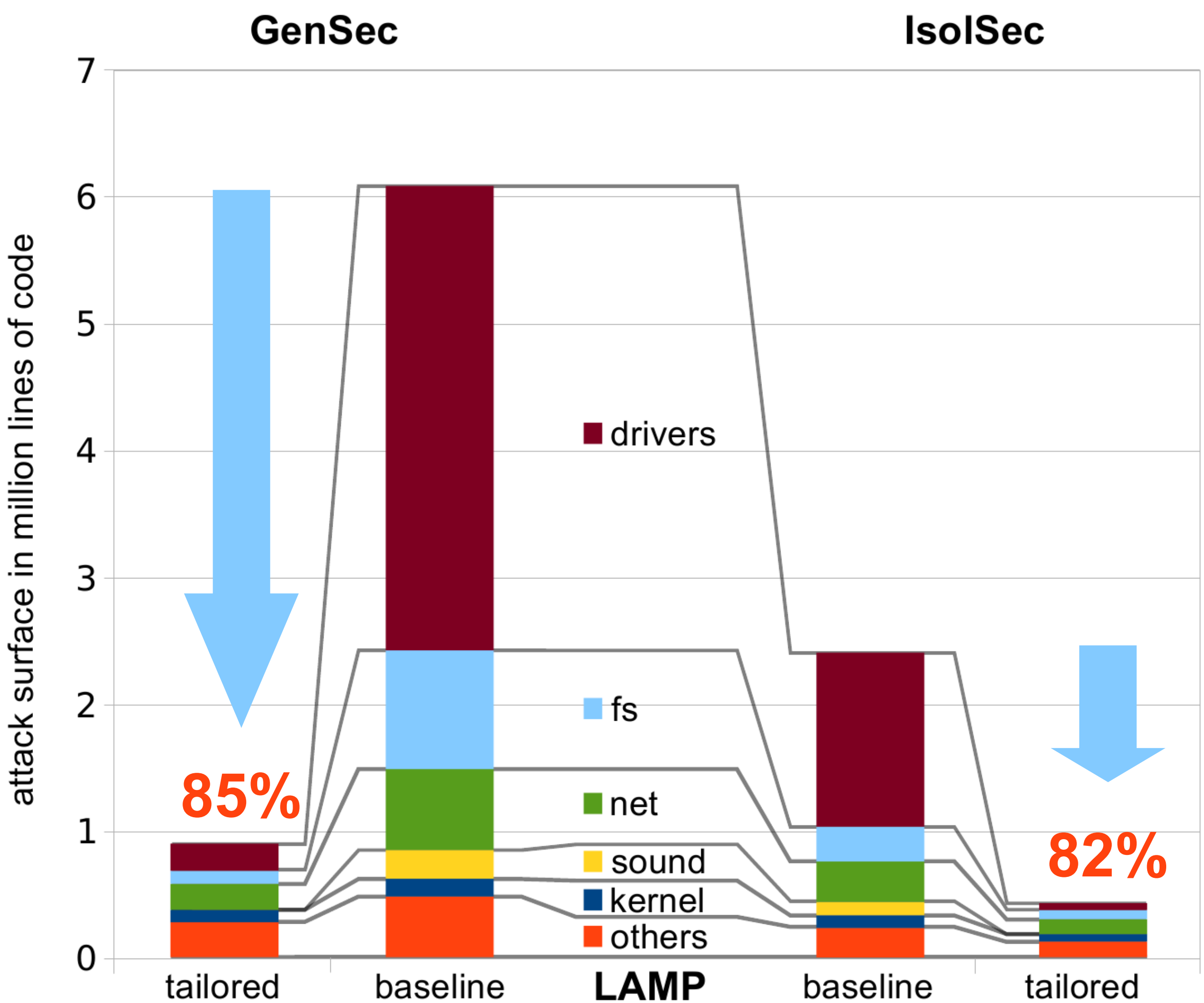
Results: attack surface reduction



Results: attack surface reduction



Results: attack surface reduction



Run-time Kernel Trimming

- [DIMVA'14] Anil Kurmus, Sergej Dechand, and Ruediger Kapitza. "**Quantifiable Run-time Kernel Attack Surface Reduction**". In: Proceedings of the 10th International Conference on Detection of Intrusions and Malware, and Vulnerability Assessment (DIMVA’14). 2014.

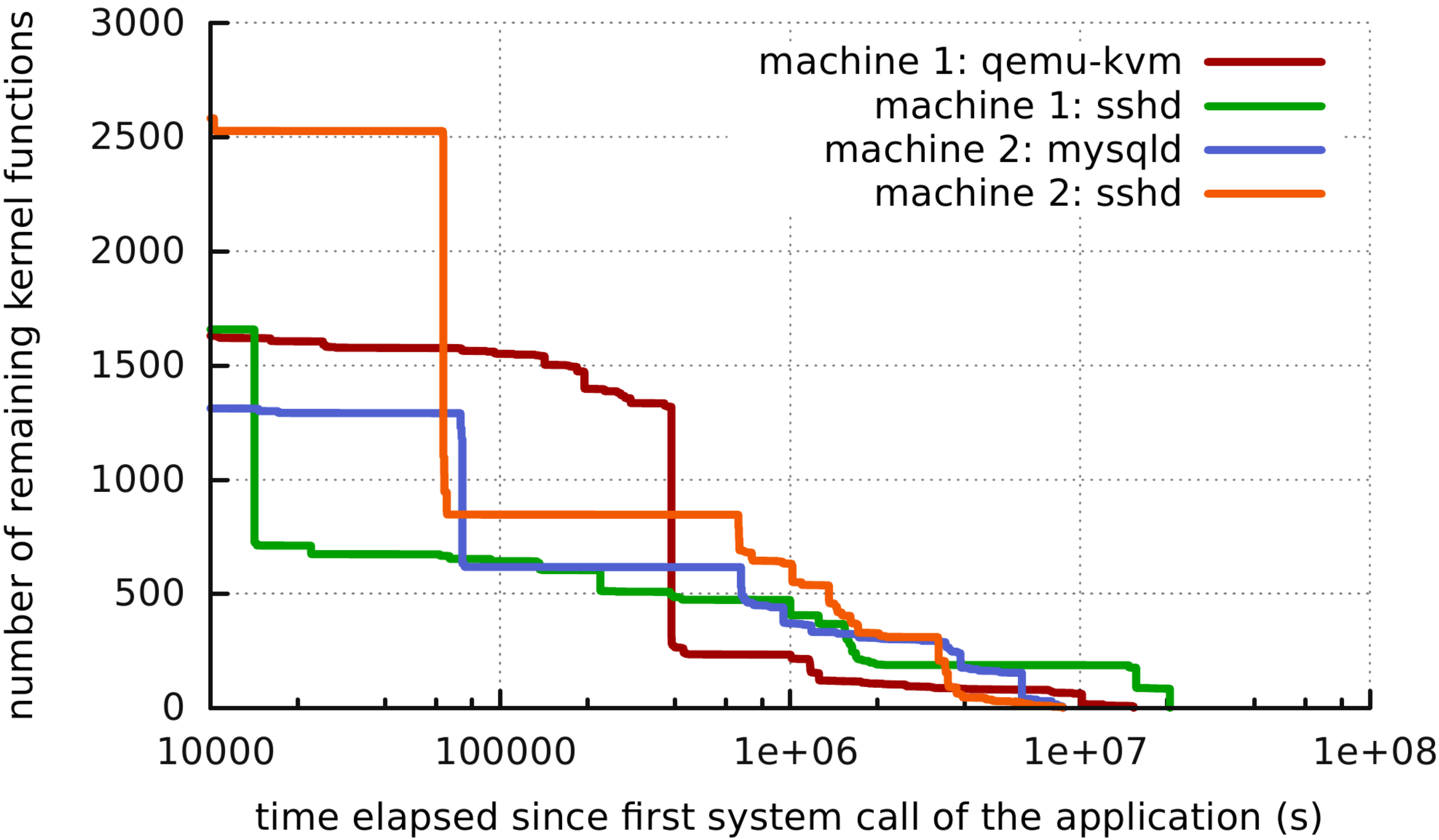
  https://www.ibr.cs.tu-bs.de/users/kurmus/papers/kurmus-dimva14.pdf

- [CCS'14] Anil Kurmus, and Robby Zippel. "**A Tale of Two Kernels: Towards Ending Kernel Hardening Wars with Split Kernel**". In: Proceedings of the 2014 ACM Conference on Computer and Communications Security (accepted for publication). 2014.

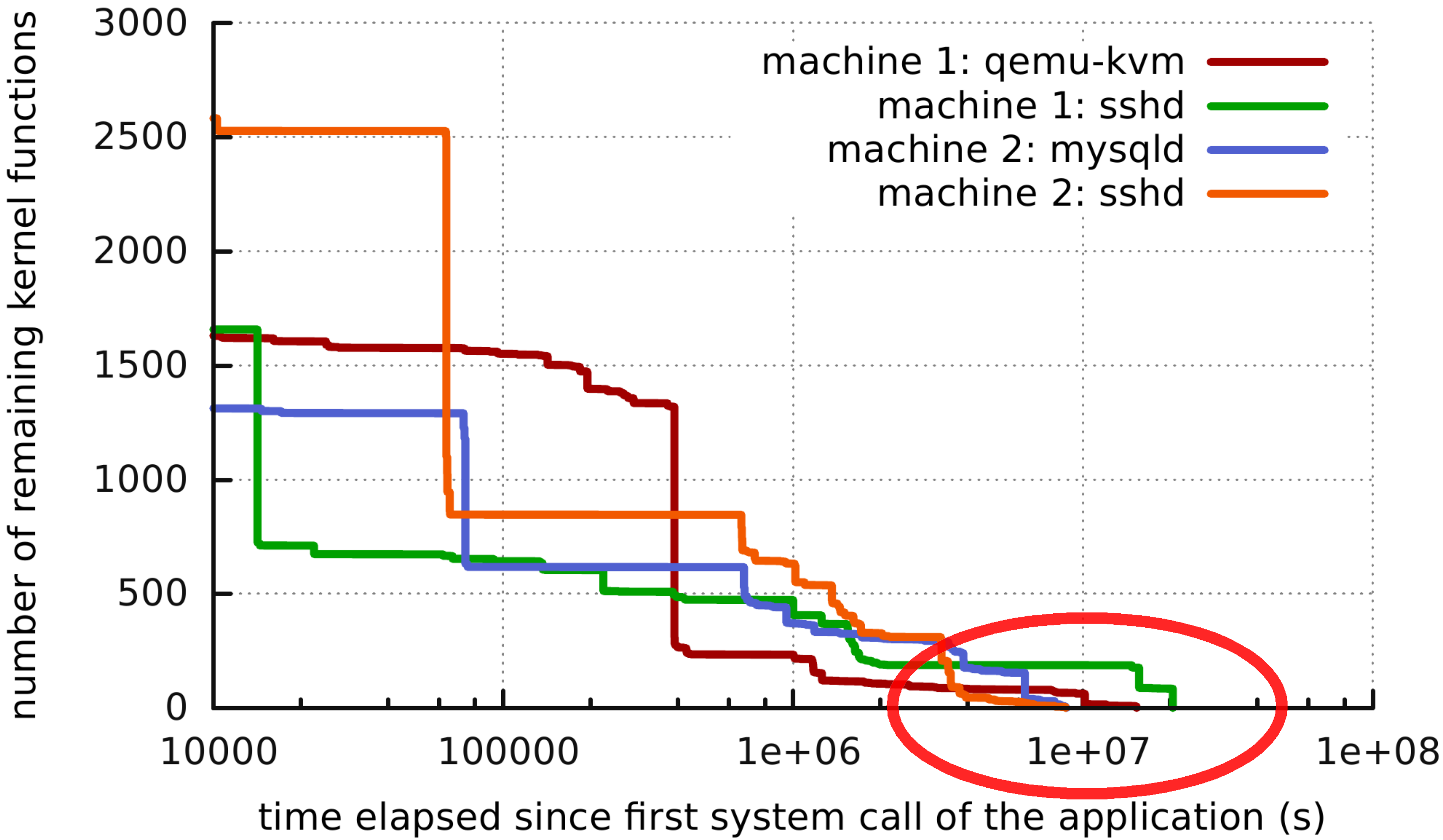
Same idea, more attack surface reduction!

- The promises of run-time attack surface reduction:
- **More granular**
  - E.g., function-level instead of configuration-level
- **Application-specific**
  - Different application may exercise different kernel functionality
- Challenges:
  - **Performance overhead** of run-time instrumentation
  - **False positives**

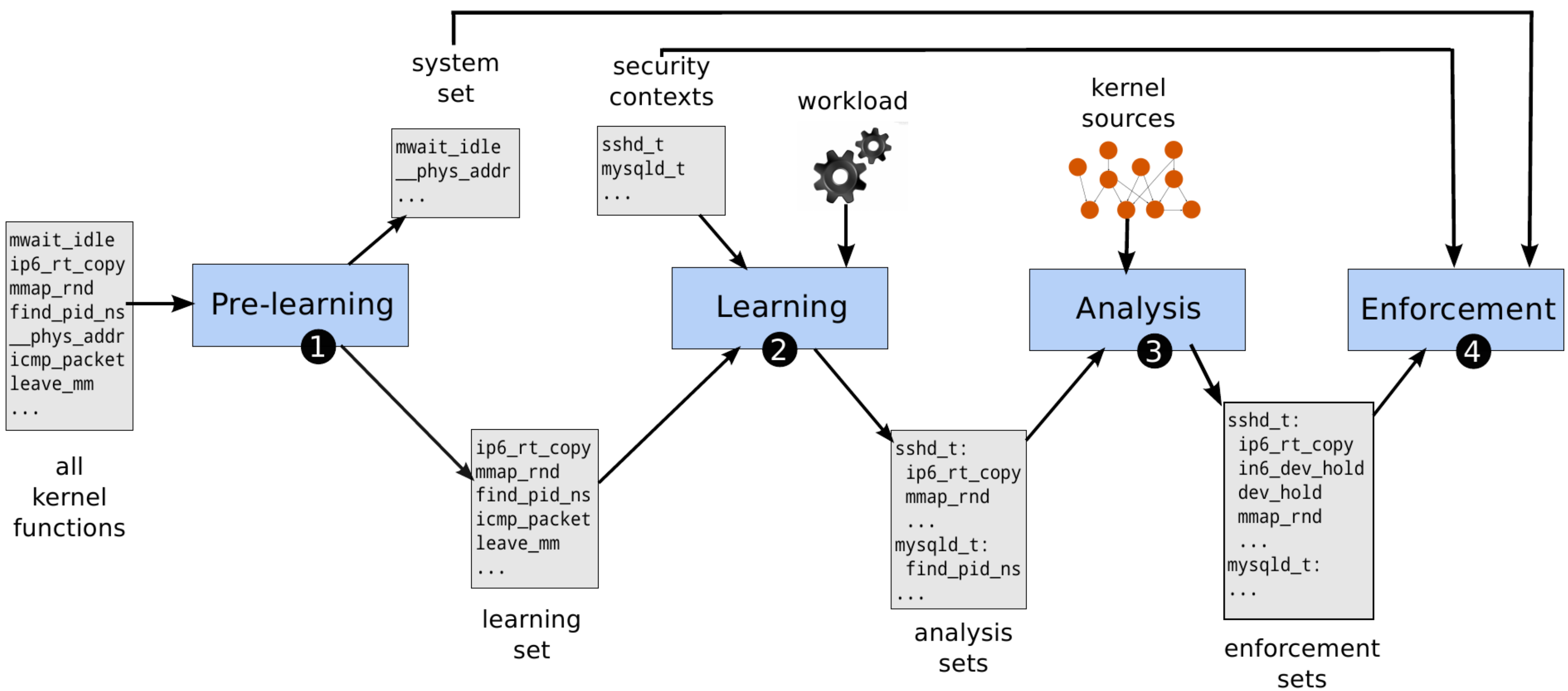
The false positive challenge



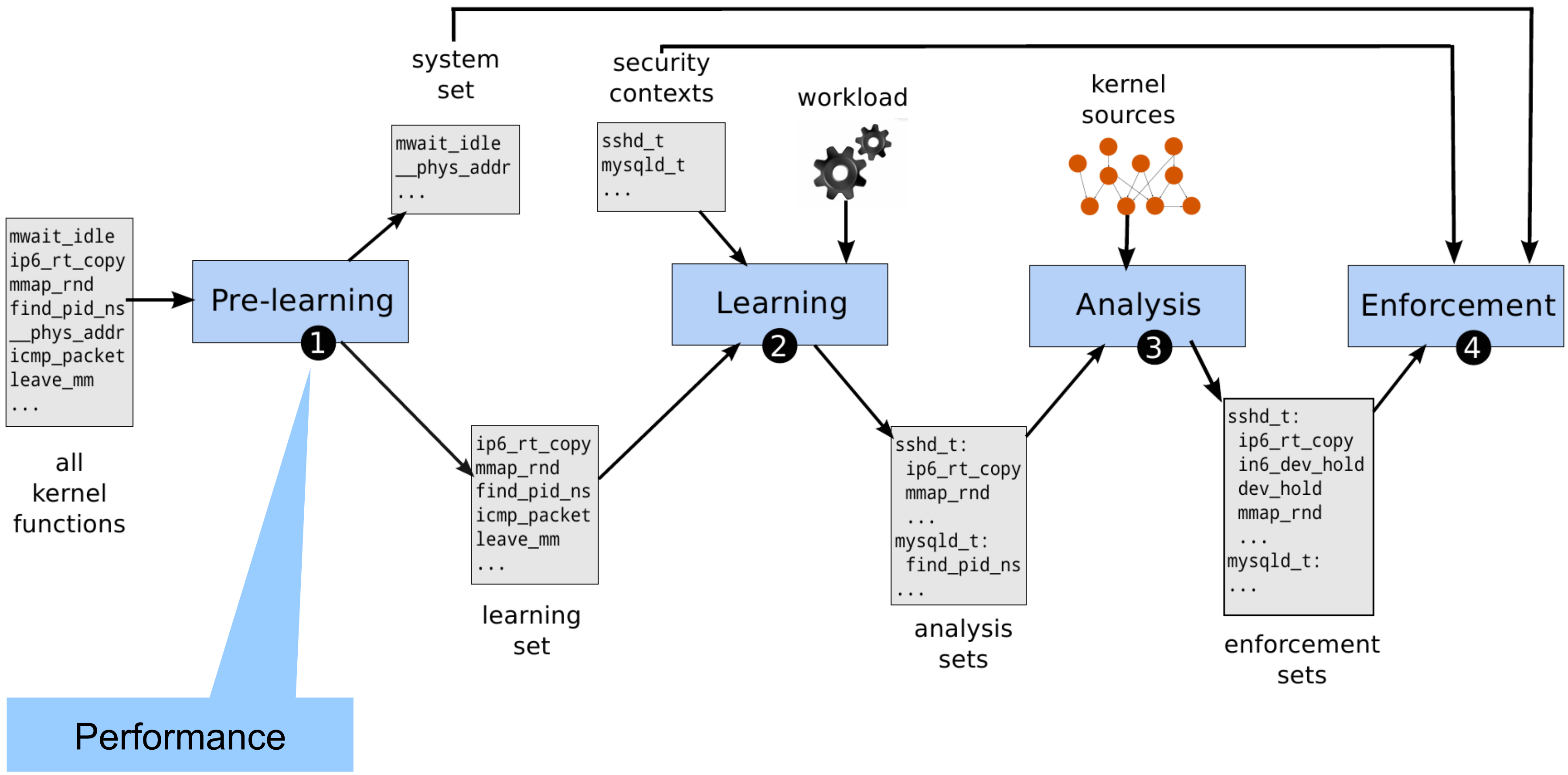
The false positive challenge



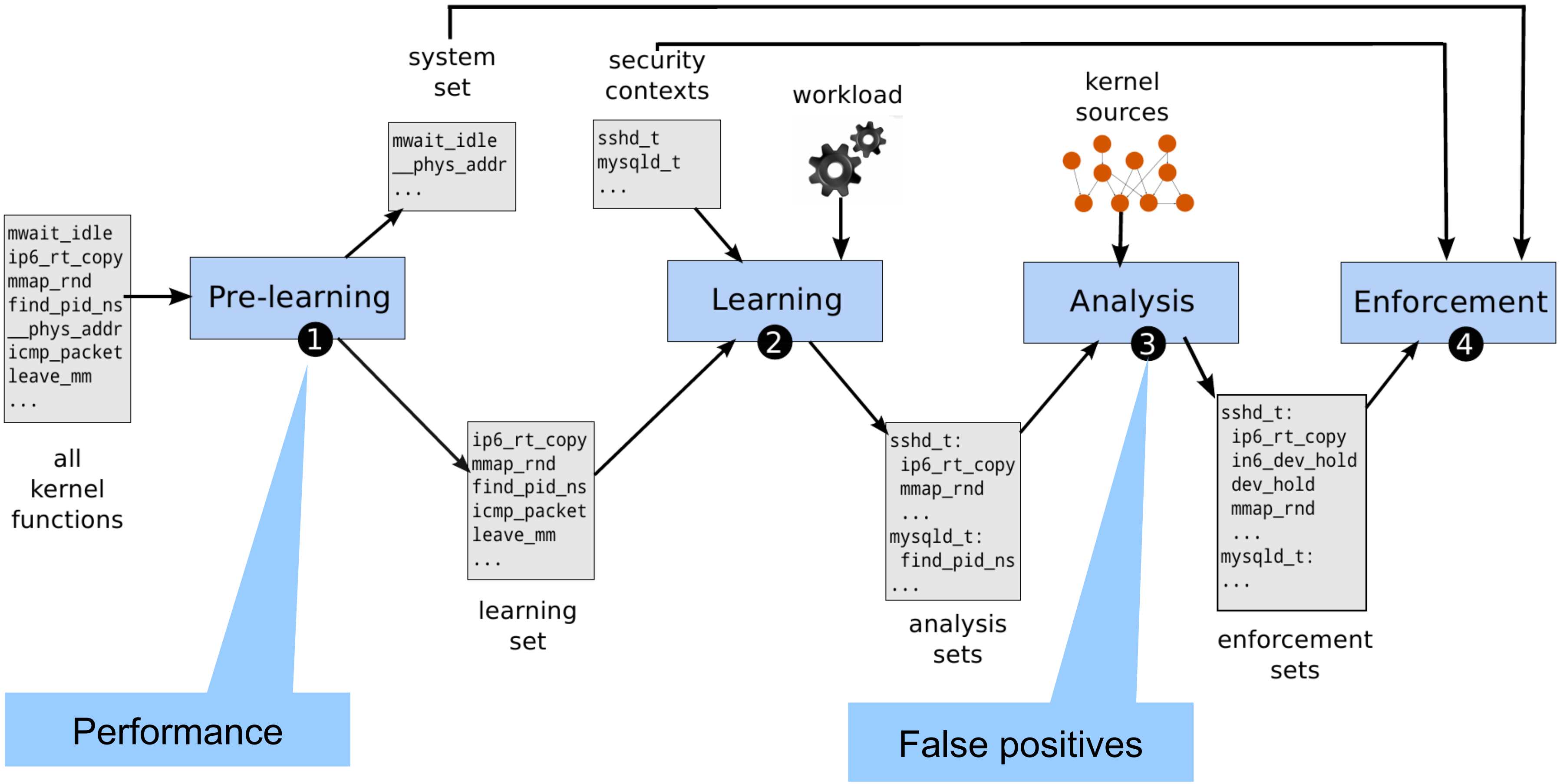
Run-time kernel attack surface reduction



Run-time kernel attack surface reduction



Run-time kernel attack surface reduction



Phase 1: Pre-learning

- Heuristic approach to improve performance
- Functions hit with frequency above a (dynamically computed) threshold are ignored
- Example:

```
ext4_fsblk_t ext4_mb_new_blocks(...)
{
  ...
    while (ar->len && ext4_claim_free_blocks(sbi,
          ar->len)) {
      /* let others to free the space */
      yield();
      ar->len = ar->len >> 1;
    }
  ...
}
```

→ **Pre-learning reduces performance overhead**

Phase 3: Analysis

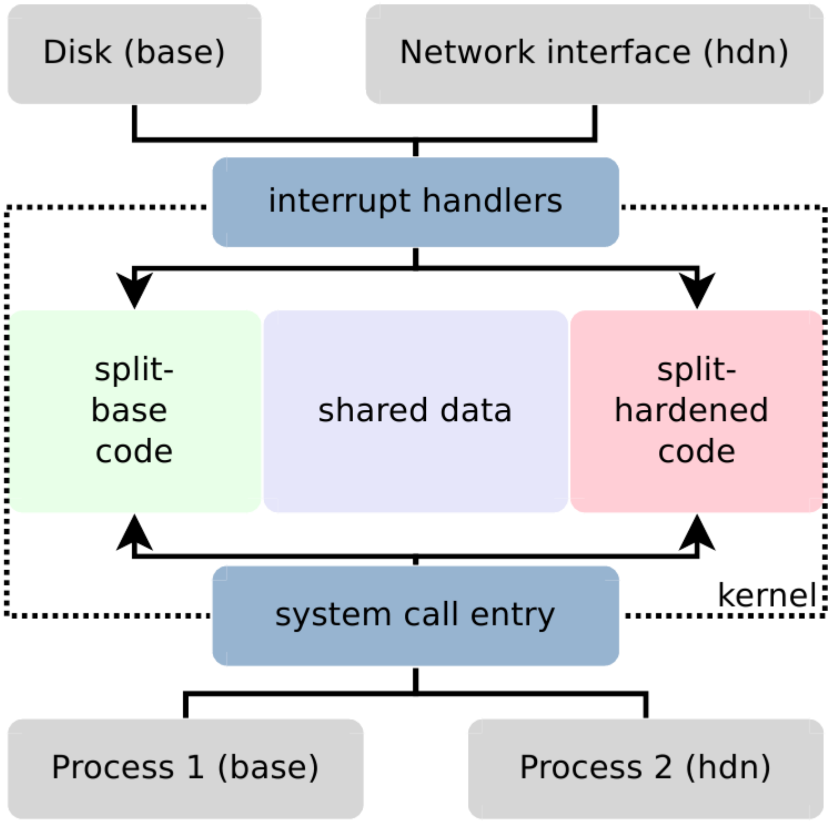
- Group functions together to reduce false positives
- 4 different modes
  - No grouping
  - File grouping
  - Directory grouping
  - Cluster grouping

Phase 4: Enforcement

- Can't terminate process
  - False positives
  - Shared kernel state
- Two choices:
  - Logging (IDS)
  - Hardened mode enforcement via split kernel [CCS'14]

Split Kernel overview

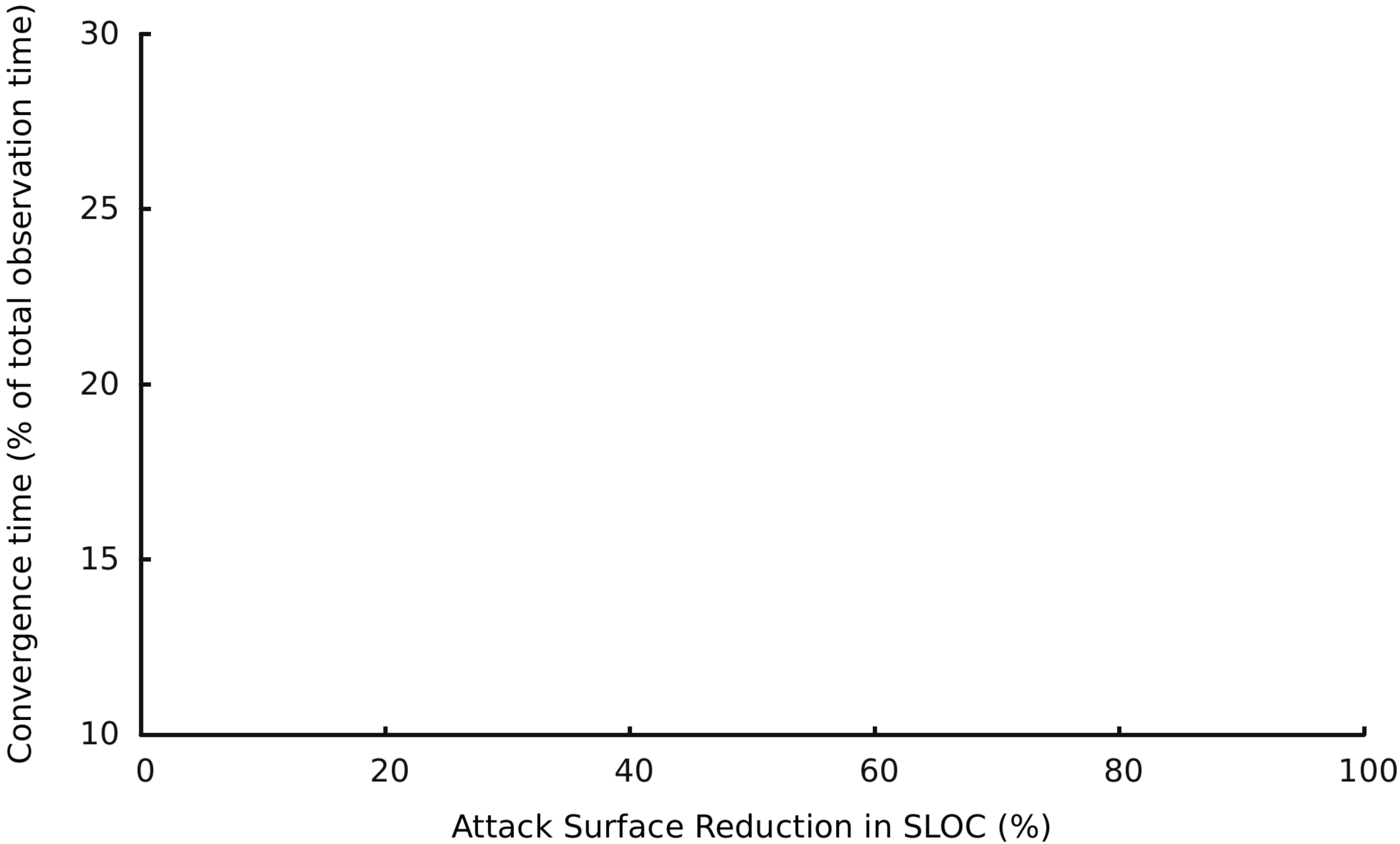
- Build kernel with and without hardening
- Chose at run-time whether to run in hardened mode
- Performance impact of hardening greatly reduced



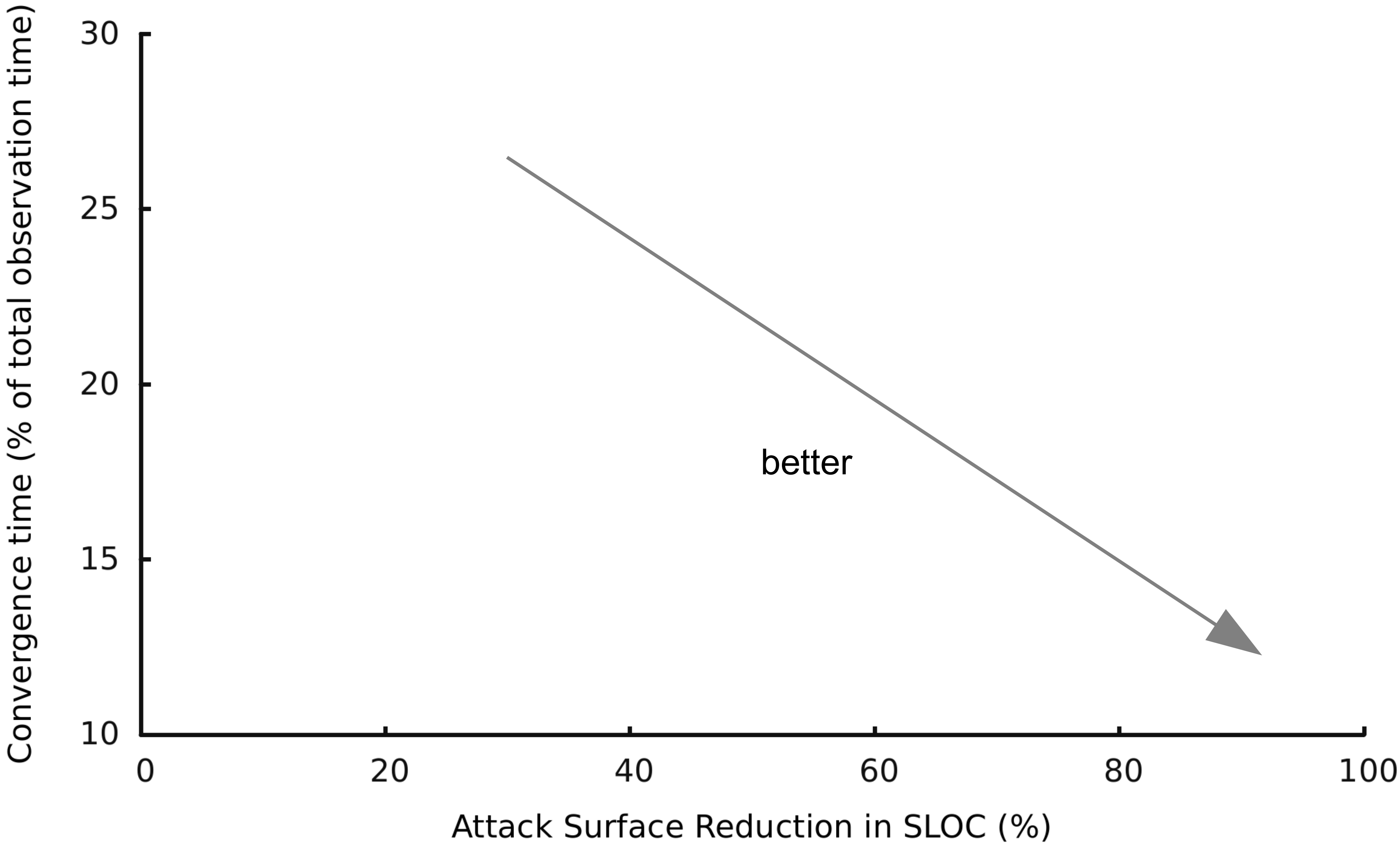
Selected results of the evaluation

- Real-world workload on RHEL 6 development server
  – Total observation time: 403 days

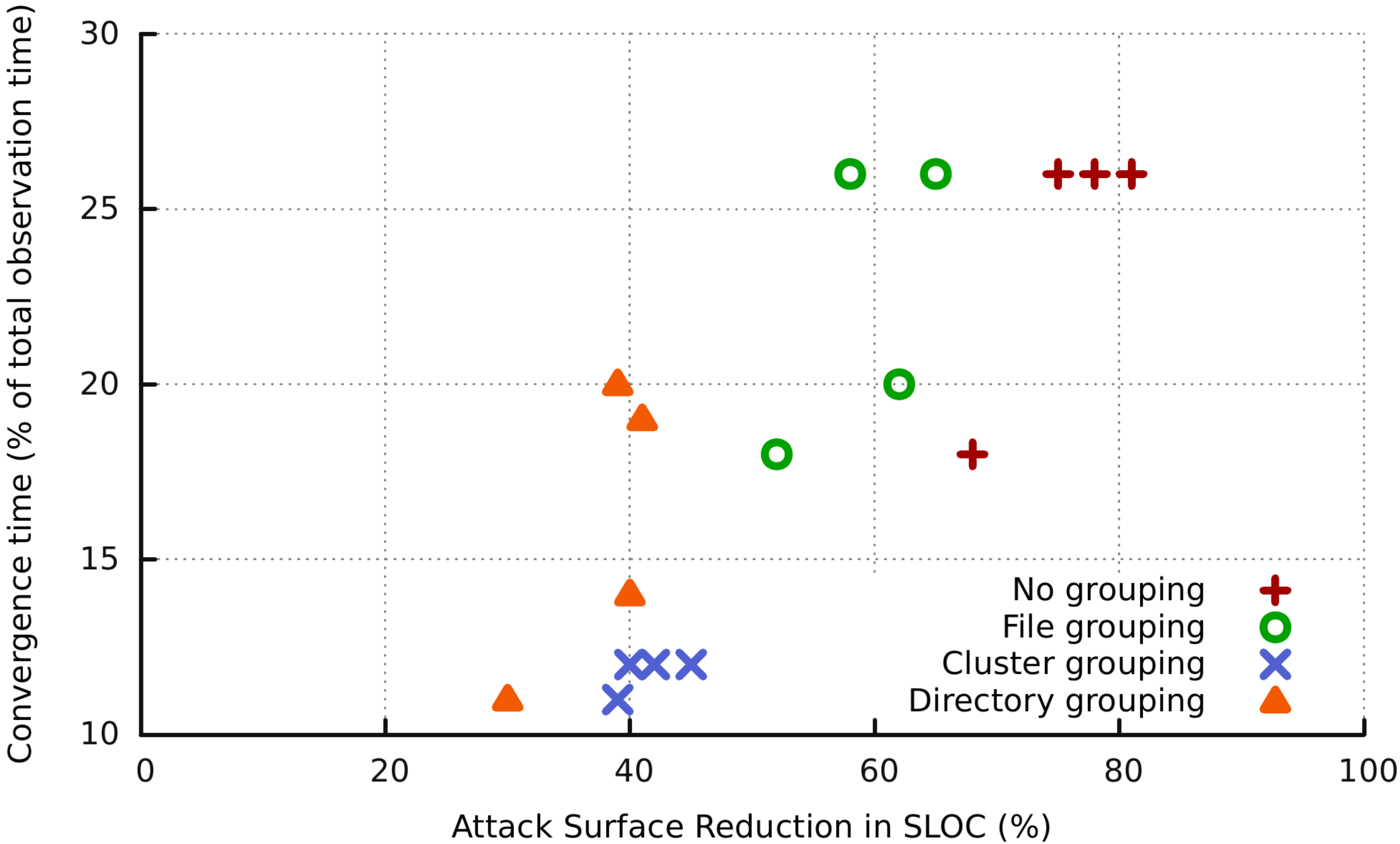
Attack surface reduction vs. convergence rate



Attack surface reduction vs. convergence rate



Attack surface reduction vs. convergence rate



Conclusion

Conclusion

- The kernel attack surface can be quantified
- This can be used to evaluate the effectiveness of kernel attack surface reduction
- Kernel attack surface reduction is effective in preventing kernel exploits:
  - Compile-time Tailoring
    - Prevents 285 out of 485 CVEs.
    - For well-defined use cases (e.g., embedded systems)
  - Run-time Trimming
    - Prevents up to 184 out of 262 CVEs.
    - More flexible, higher ASR but slower convergence rate
- Both mechanism aim to be practical
  - no significant overhead
  - non-intrusive

References

- [Eurosec'11] Anil Kurmus, Alessandro Sorniotti, and Ruediger Kapitza. "**Attack Surface Reduction For Commodity OS Kernels**". In: Proceedings of the Fourth European Workshop on System Security. 2011.
- [NDSS'13] Anil Kurmus, Reinhard Tartler, Daniela Dorneanu, Bernhard Heinloth, Valentin Rothberg, Andreas Ruprecht, Wolfgang Schröder-Preikschat, Daniel Lohmann and Rüdiger Kapitza. "**Attack Surface Metrics and Automated Compile-Time OS Kernel Tailoring.**" In: Proceedings of the 20th Network and Distributed System Security Symposium. 2013.
- [DIMVA'14] Anil Kurmus, Sergej Dechand, and Ruediger Kapitza. "**Quantifiable Run-time Kernel Attack Surface Reduction**". In: Proceedings of the 10th International Conference on Detection of Intrusions and Malware, and Vulnerability Assessment (DIMVA’14). 2014.
- [CCS'14] Anil Kurmus, and Robby Zippel. "**A Tale of Two Kernels: Towards Ending Kernel Hardening Wars with Split Kernel**". In: Proceedings of the 2014 ACM Conference on Computer and Communications Security (accepted for publication). 2014.