Konfigurierbare Systemsoftware (KSS)

VL 5 – Variability Management in the Large: The VAMOS Approach

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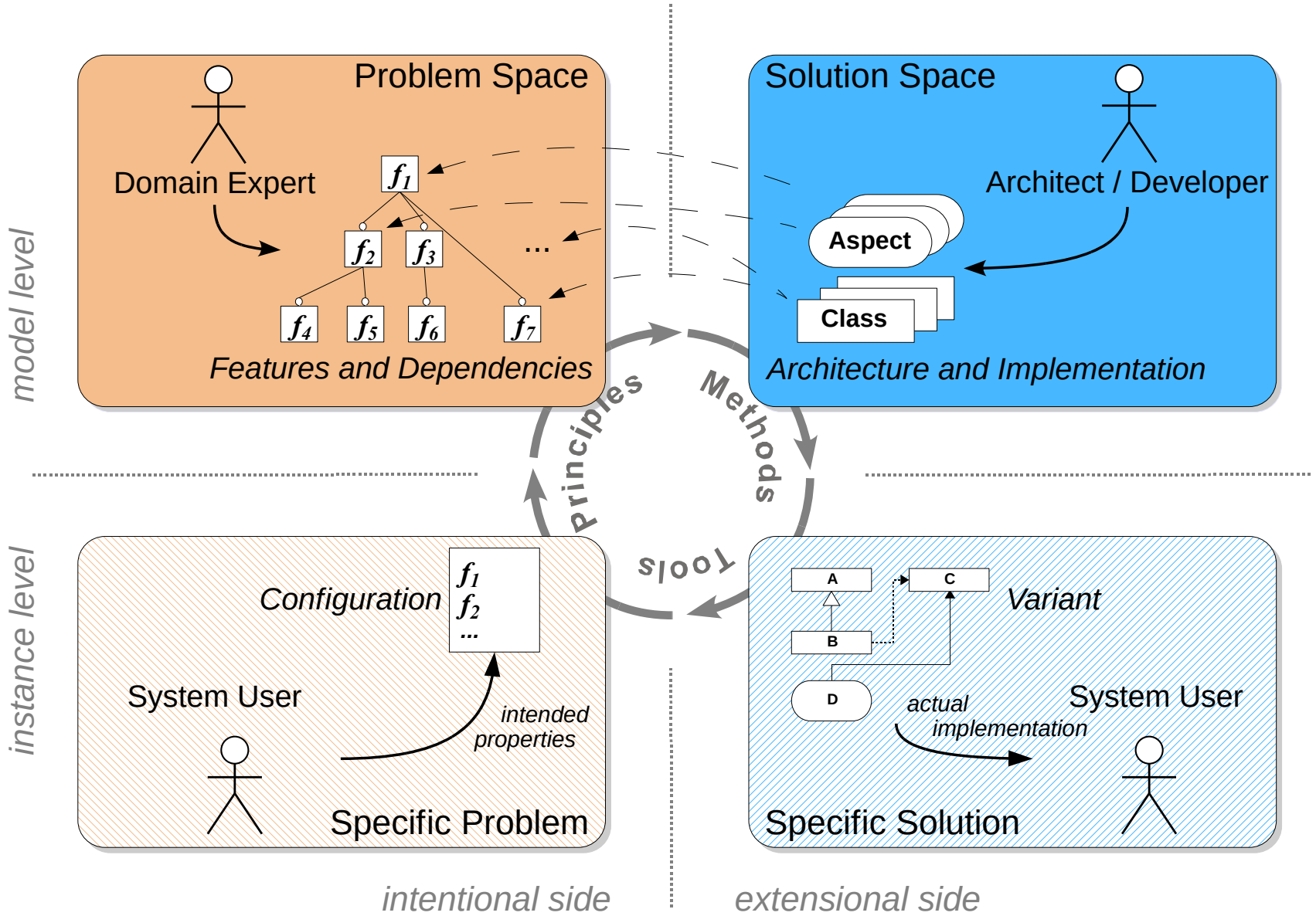
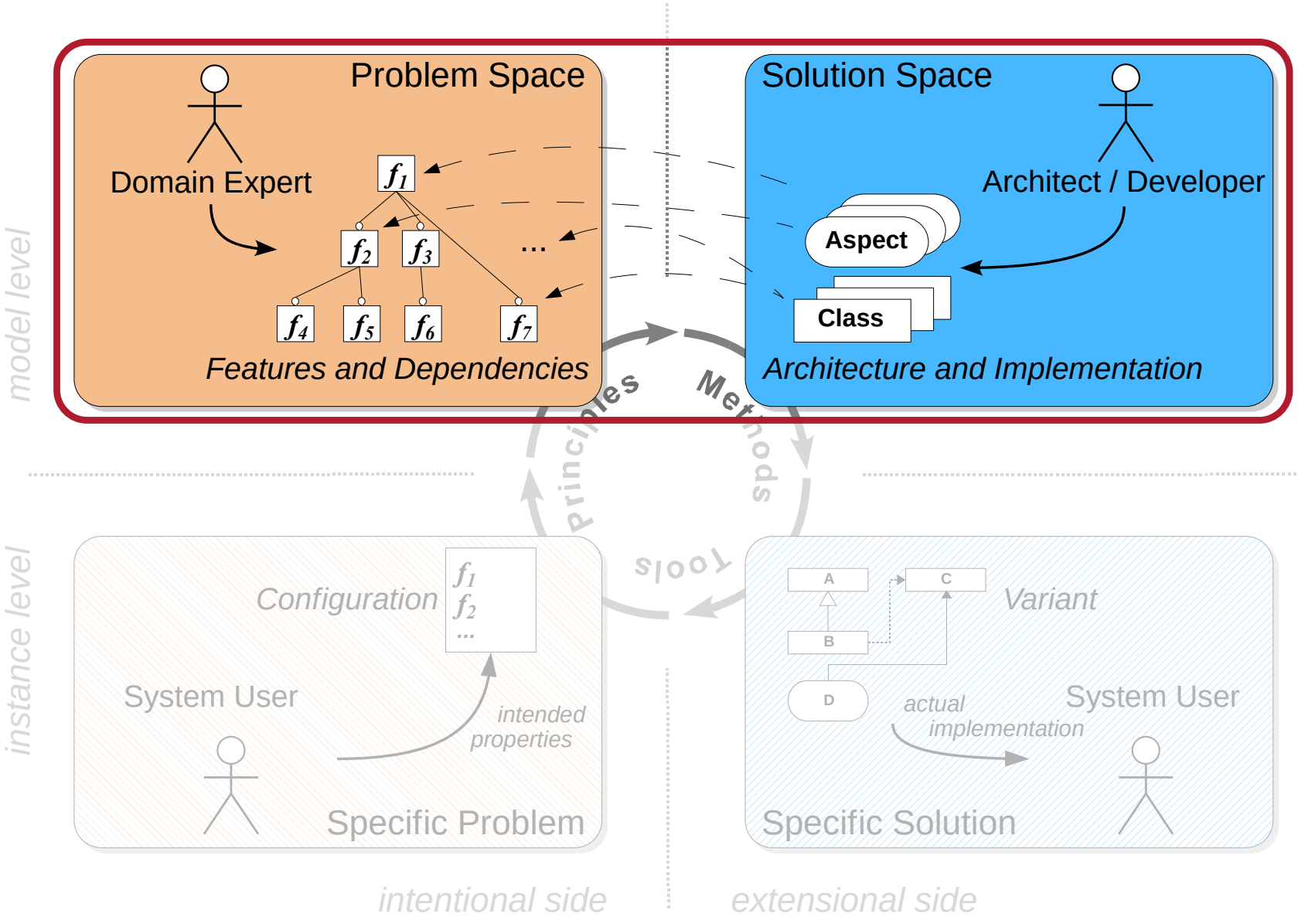
http://www4.informatik.uni-erlangen.de/Lehre/SS14/V_KSS

About this Lecture



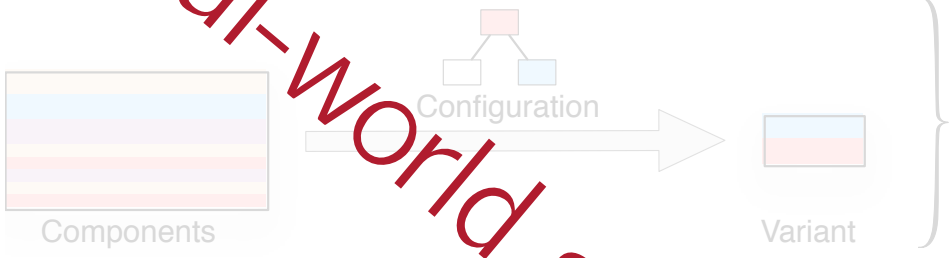
About this Lecture



Implementation Techniques: Classification

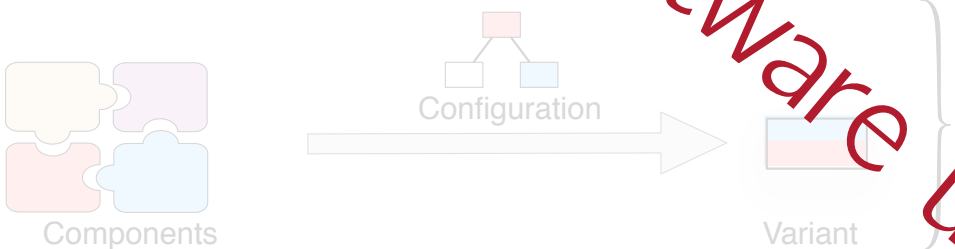
↪ ??

- Decompositional Approaches



  - Text-based filtering (untyped)
  - Preprocessors

- Compositional Approaches



  - Language-based composition mechanisms (typed)
  - OOP, AOP, Templates

- Generative Approaches

  - Metamodel-based generation of components (typed)
  - MDD, C++ TMP, generators

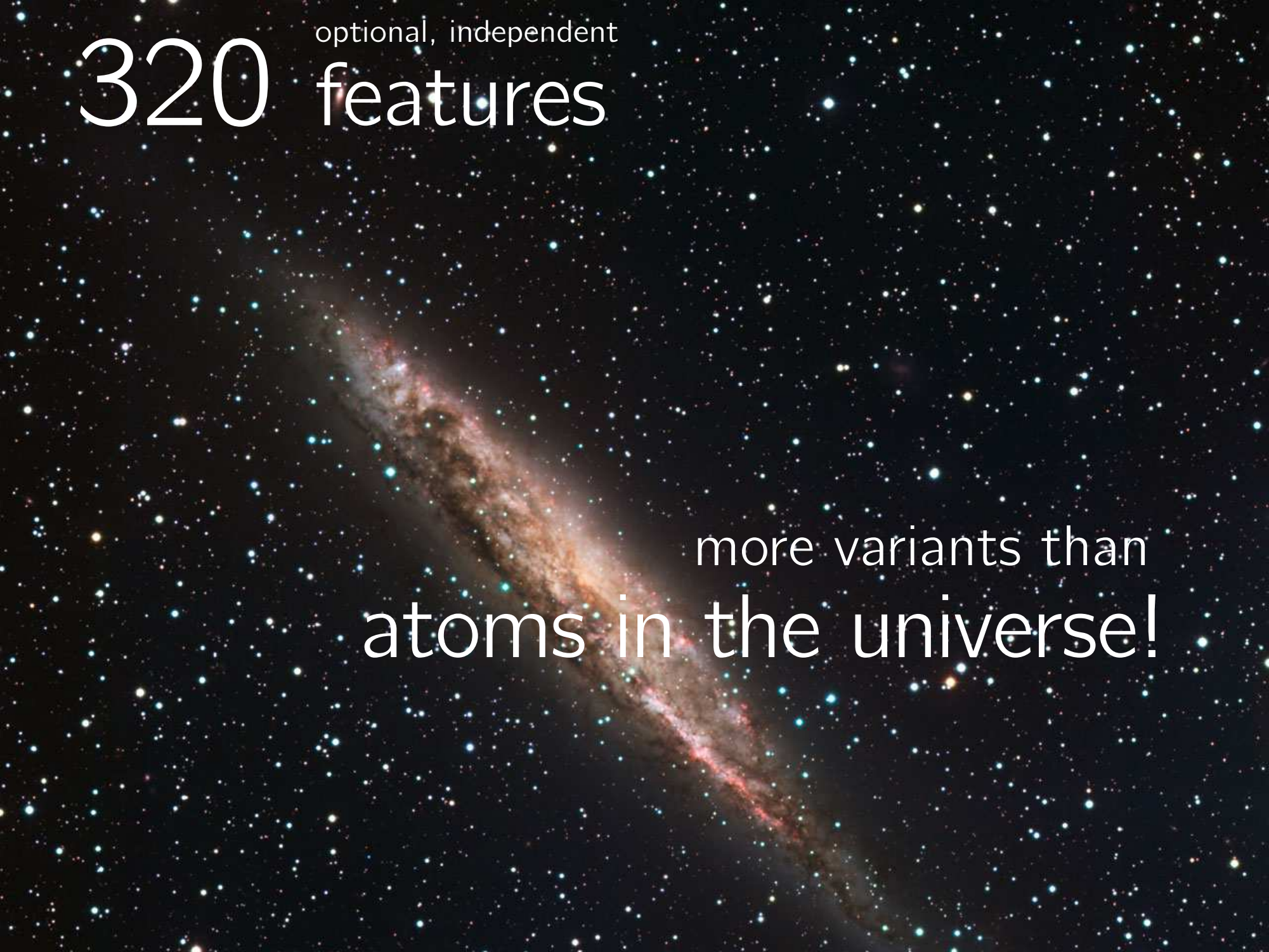
Real-world software uses them all!

Agenda

33 optional, independent features

one individual variant

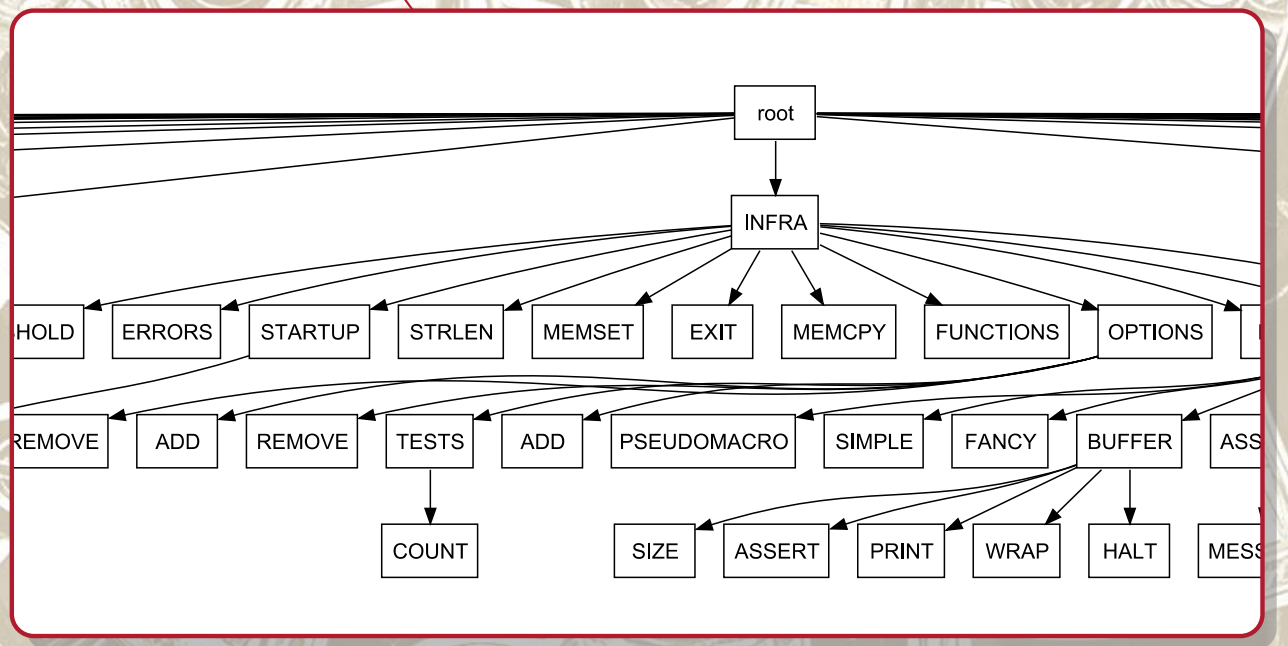
for each human being


320
optional, independent
features
more variants than
atoms in the universe!

Typical Configurable Operating Systems...

eCos

1,250 features



Typical Configurable Operating Systems...

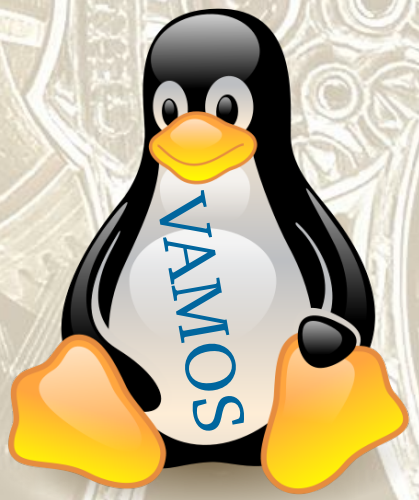
eCos

1,250 features

Challenges: $\mapsto$ VAMOS*

- How to maintain this?
- How to test this?
- Why so many features anyway?

* VAriability Management in Operating Systems

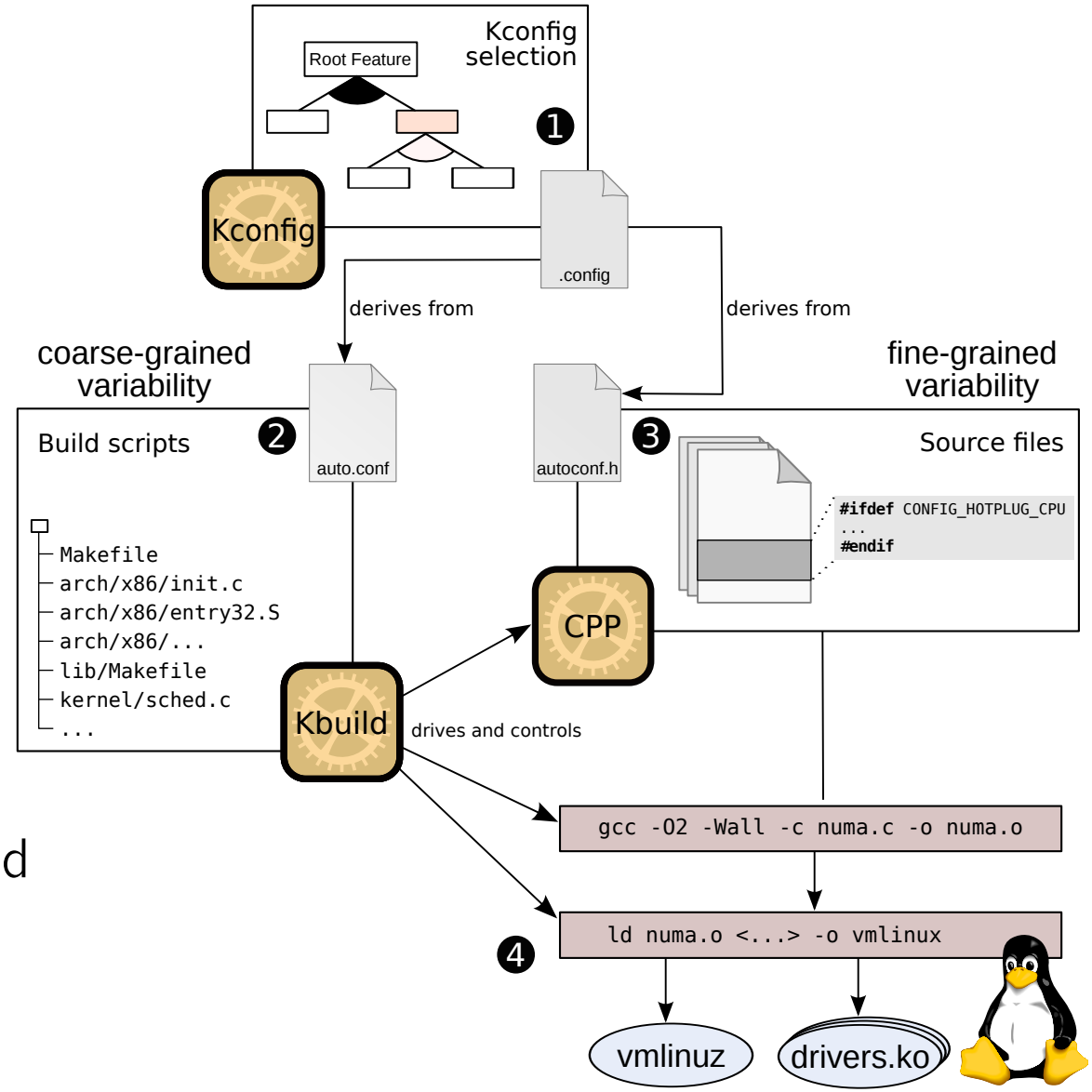


12,000 features

Agenda

The Linux Configuration and Generation Process

1. Configuration with an KCONFIG frontend
2. Compilation of a subset of files
3. Selection of a subset of CPP Blocks
4. Linking of the kernel and loadable kernel modules



Dominancy and Hierarchy of Variability

l_0: Feature Modeling — 12,000 features

l_1: Coarse-grained: KBUILD — 31,000 source files

l_2: Fine-grained: CPP — 89,000 `#ifdef` blocks

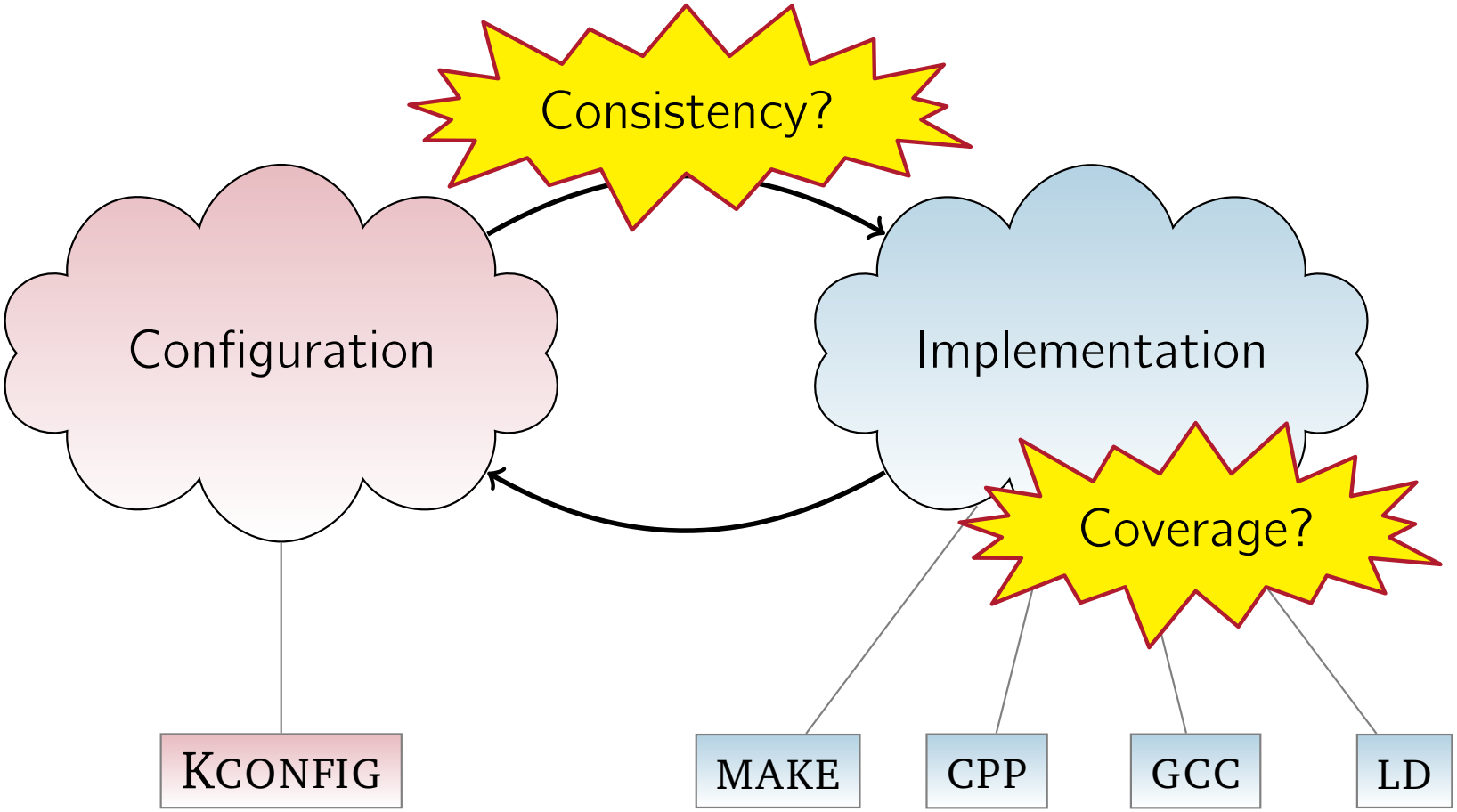
l_3: Language-level: GCC — $\rightarrow$ `if(CONFIG_SMP) ...`

l_4: Link time: LD — $\rightarrow$ branches in linker scripts

l_5: Run time: INSMOD, MODPROBE, ...

KCONFIG controlled Variability

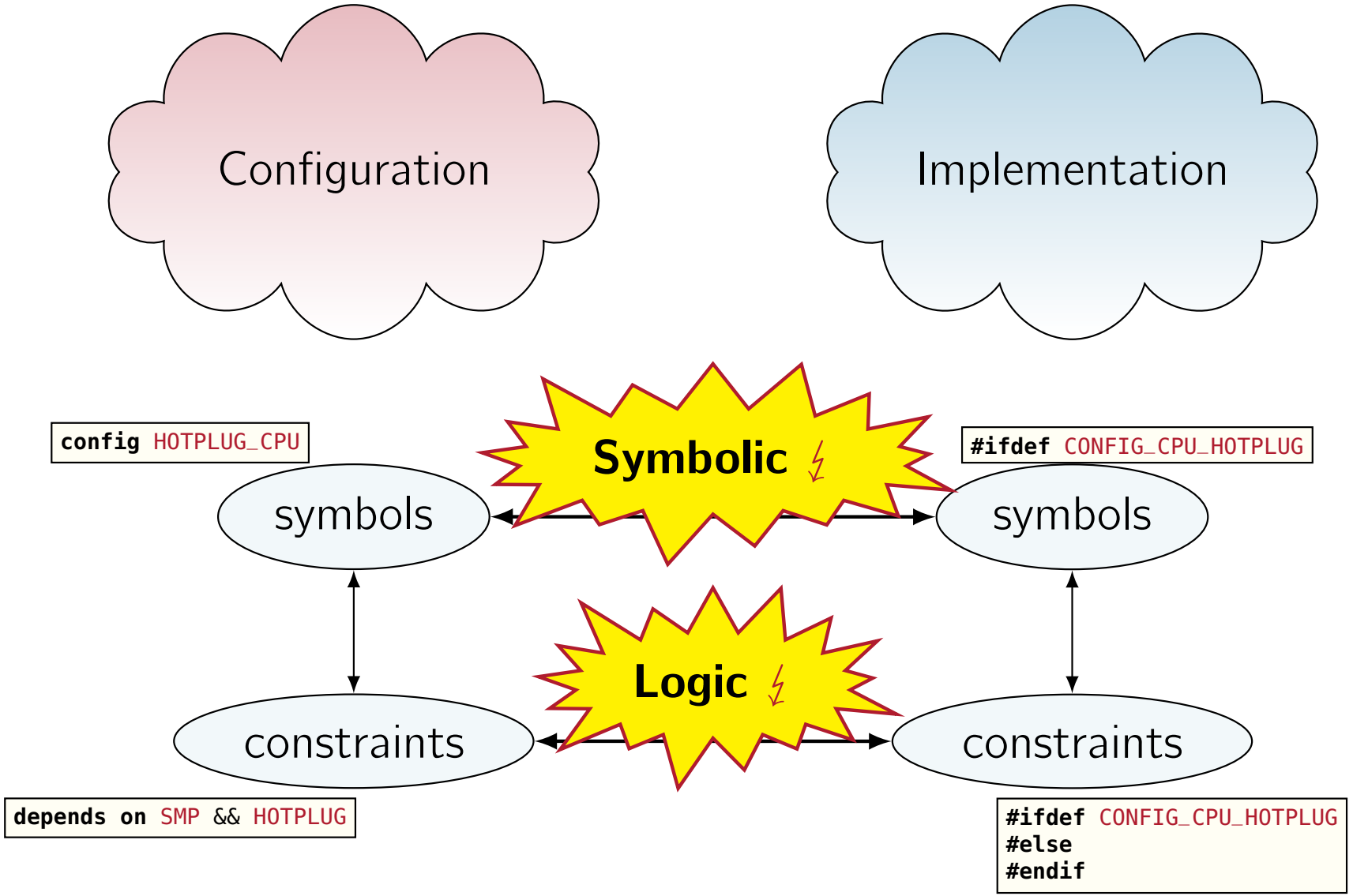
Challenges with Implemented Variability



- Central declaration of configurability: KCONFIG
- Distributed implementation of configurability: MAKE, CPP, GCC, LD

Agenda

Problem Analysis: Configuration Consistency



Problem Analysis: Symbolic Inconsistency [10]

```
config HOTPLUG_CPU
    bool "Support for hot-pluggable CPUs"
    depends on SMP && HOTPLUG
    ---help---
```

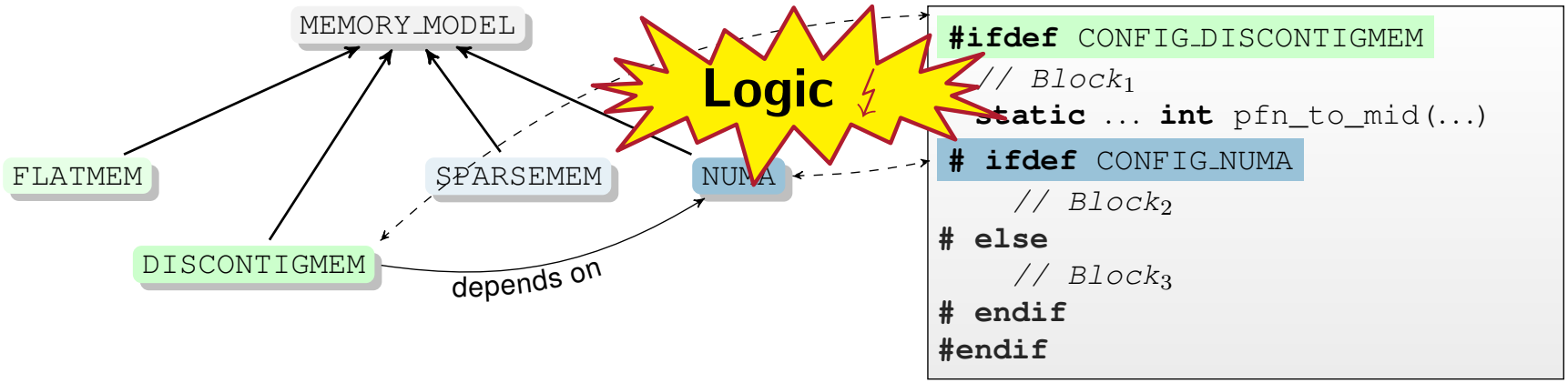
```
static int
  hotplug_cfd(struct notifier_block *nfb, unsigned long action, void *hcpu)
  {
    // [...]
          switch (action) {
          case CPU_UP_PREPARE:
          case CPU_UP_PREPARE_FROZEN:
      // [...]
#ifdef CONFIG_CPU_HOTPLUG
          case CPU_UP_CANCELED:
          case CPU_UP_CANCELED_FROZEN:

          case CPU_DEAD:
          case CPU_DEAD_FROZEN:
                  free_cpumask_var(cfd->cpumask);
                  break;
#endif
          };
          return NOTIFY_OK;
  }
```

Result:

Fix for a critical bug

Problem Analysis: Logic Inconsistency [10]



- Feature `DISCONTIGMEM` **implies** feature `NUMA`
- Inner blocks are not actually configuration-dependent
  - $Block_2$ is **always** selected $\mapsto$ **undead**
  - $Block_3$ is **never** selected $\mapsto$ **dead**

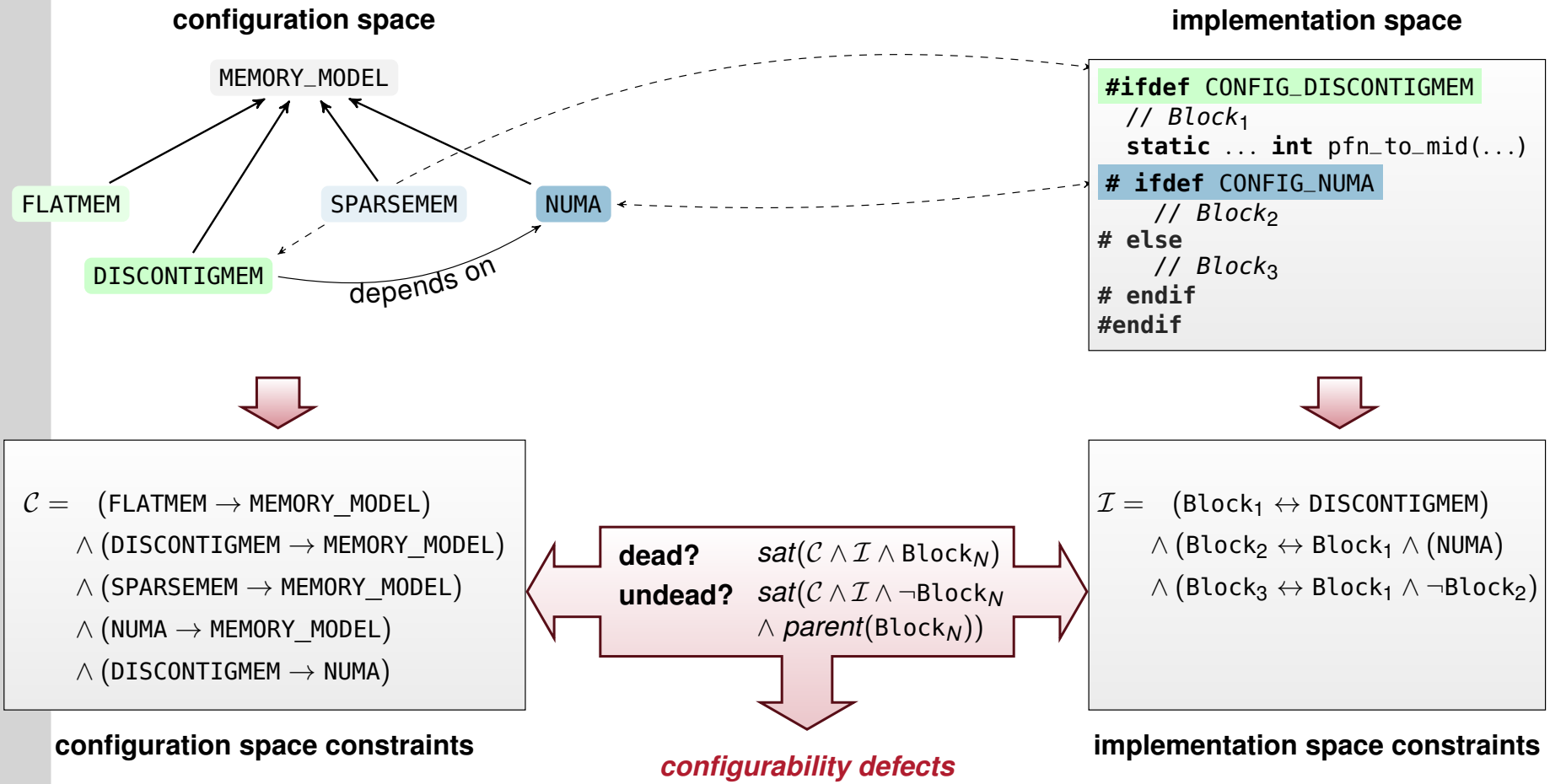
} **configurability defects**

$\rightsquigarrow$ Linux contains **superfluous** `#ifdef` Blocks!

Result:
Code cleanup

Solution Approach: Consistency Validation

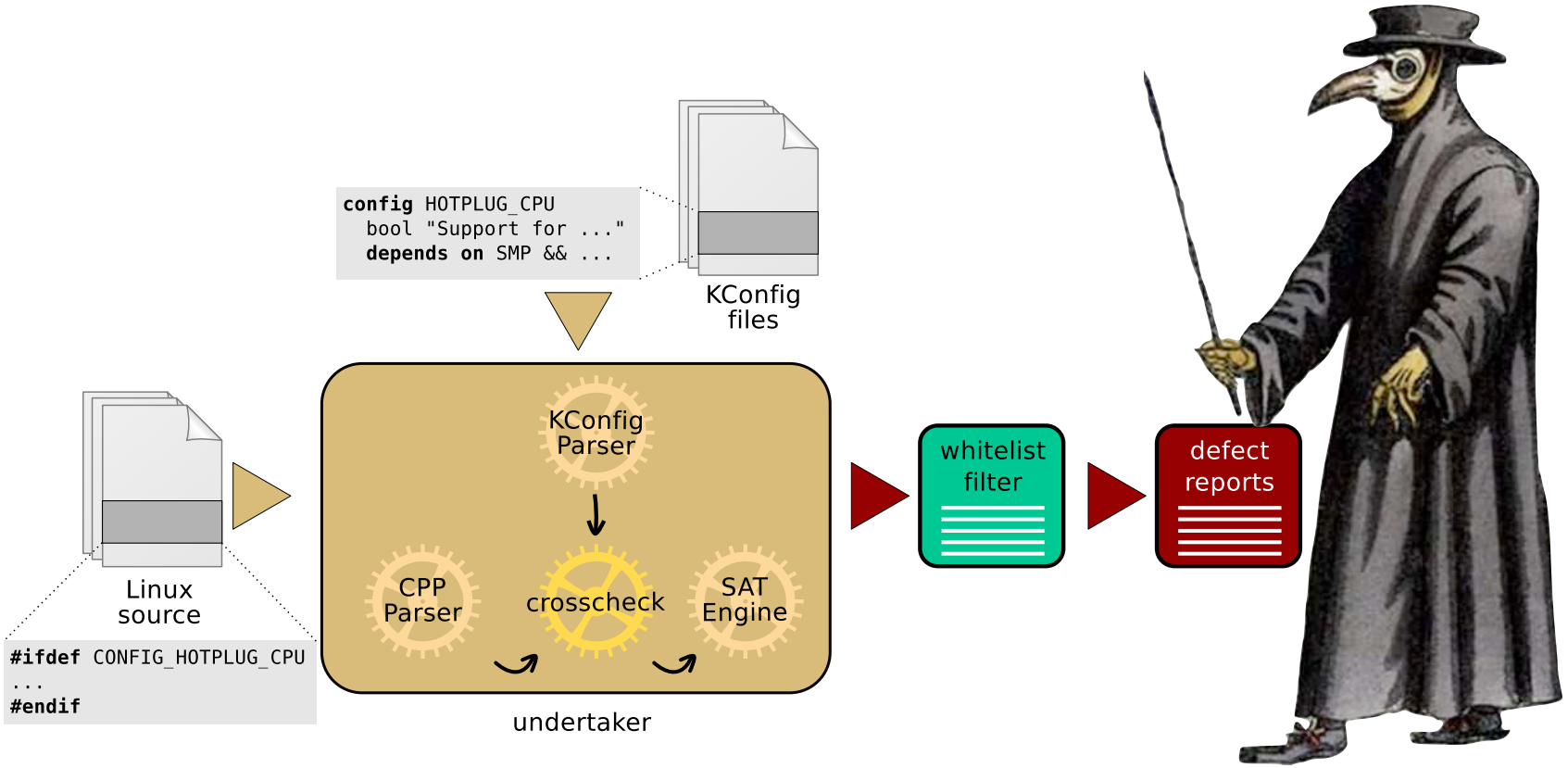
Problem and solution space are analyzed for configuration points:



⇒ and transformed into propositional formulas

Implementation: The UNDERTAKER [10]

Job: Find (and eventually bury) dead `#ifdef`-code!



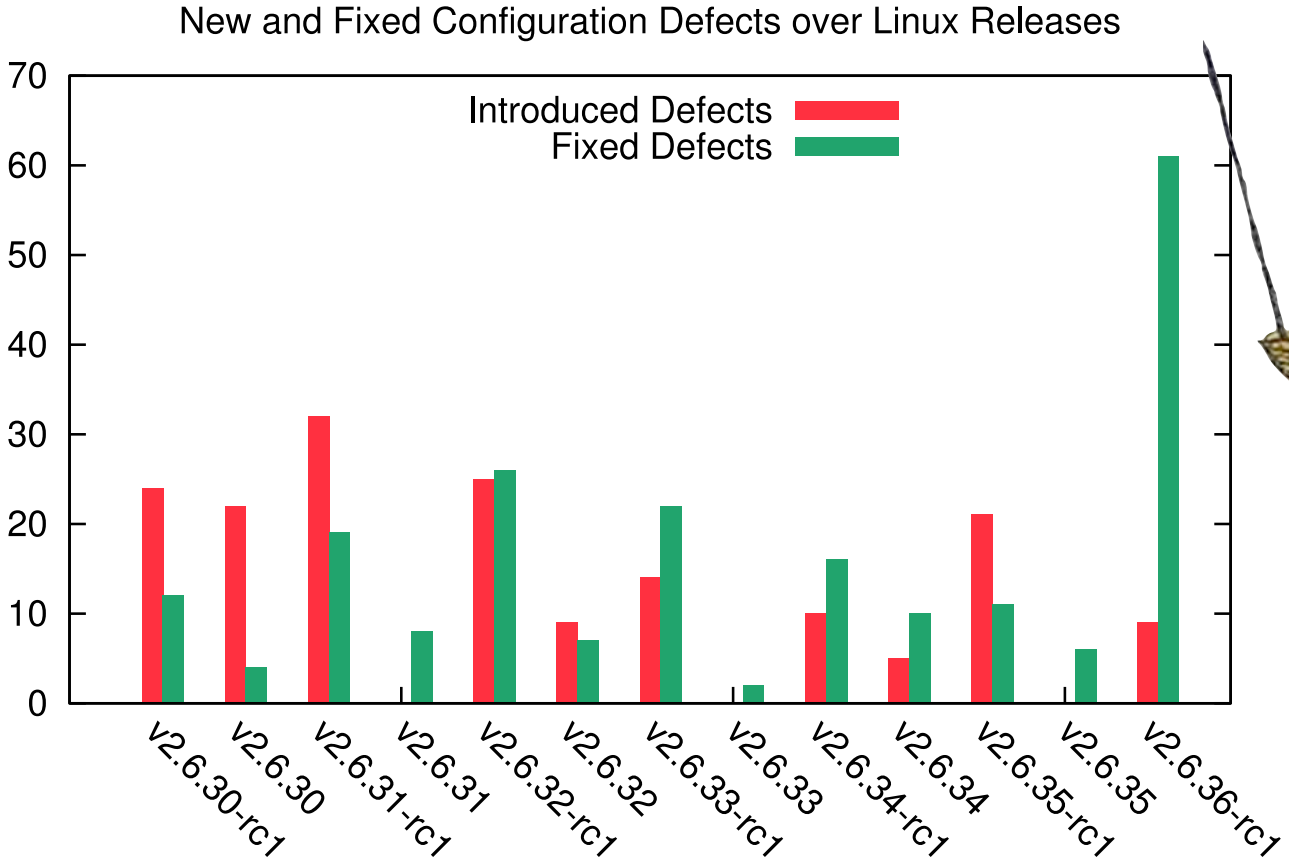
Implementation: The UNDERTAKER [10]

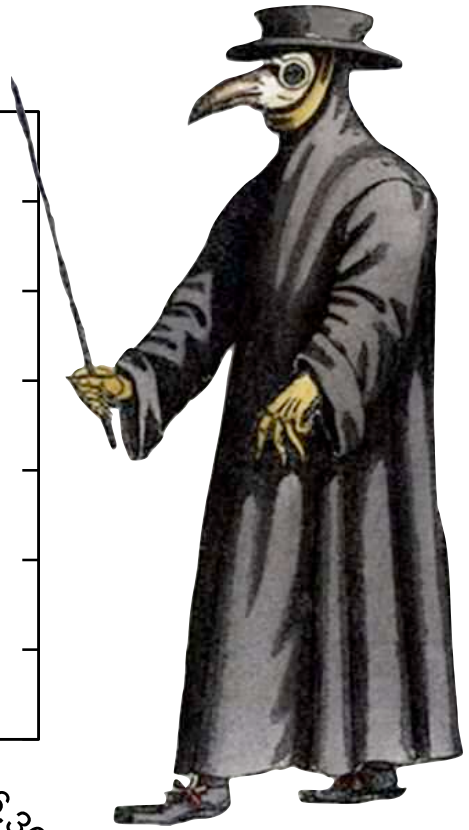
Job: Find (and eventually bury) dead `#ifdef`-code!

- We have found **1776** configurability defects in Linux v2.6.35
- Submitted **123** patches for **364** defects
- **20** are confirmed **new bugs** (affecting binary code)
- Cleaned up **5129** lines of cruft code

Implementation: The UNDERTAKER [10]

Job: Find (and eventually bury) dead `#ifdef`-code!





How good is this, *really?*

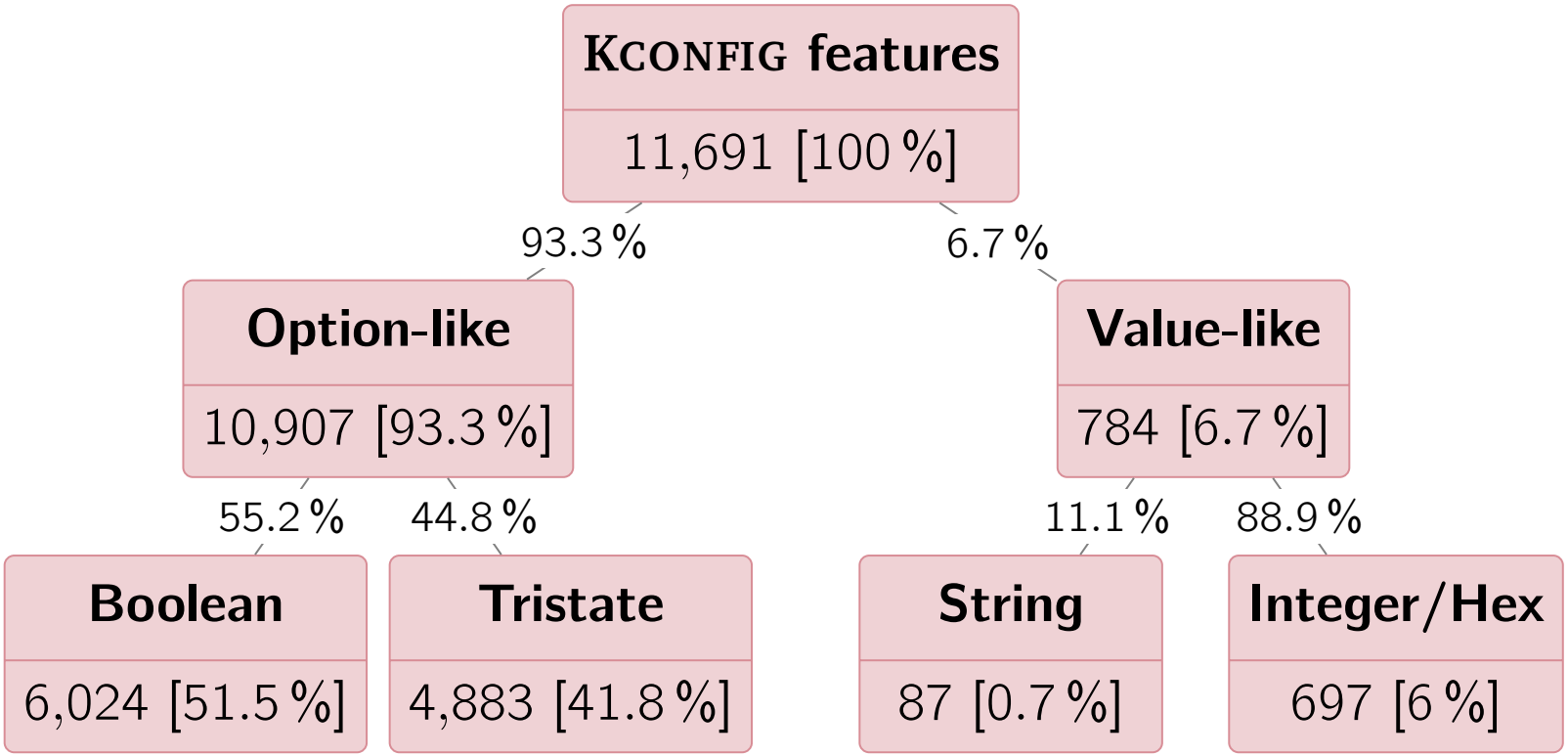
Agenda

Common Beliefs About Variability in Linux

1. Most variability is expressed by boolean (or tristate) switches.
2. arch-x86 is the largest and allyesconfig selects most features.
3. Variability is mostly implemented with the CPP.
4. The Linux *kernel* is highly configurable.

Linux v3.1: Feature Distribution by Type

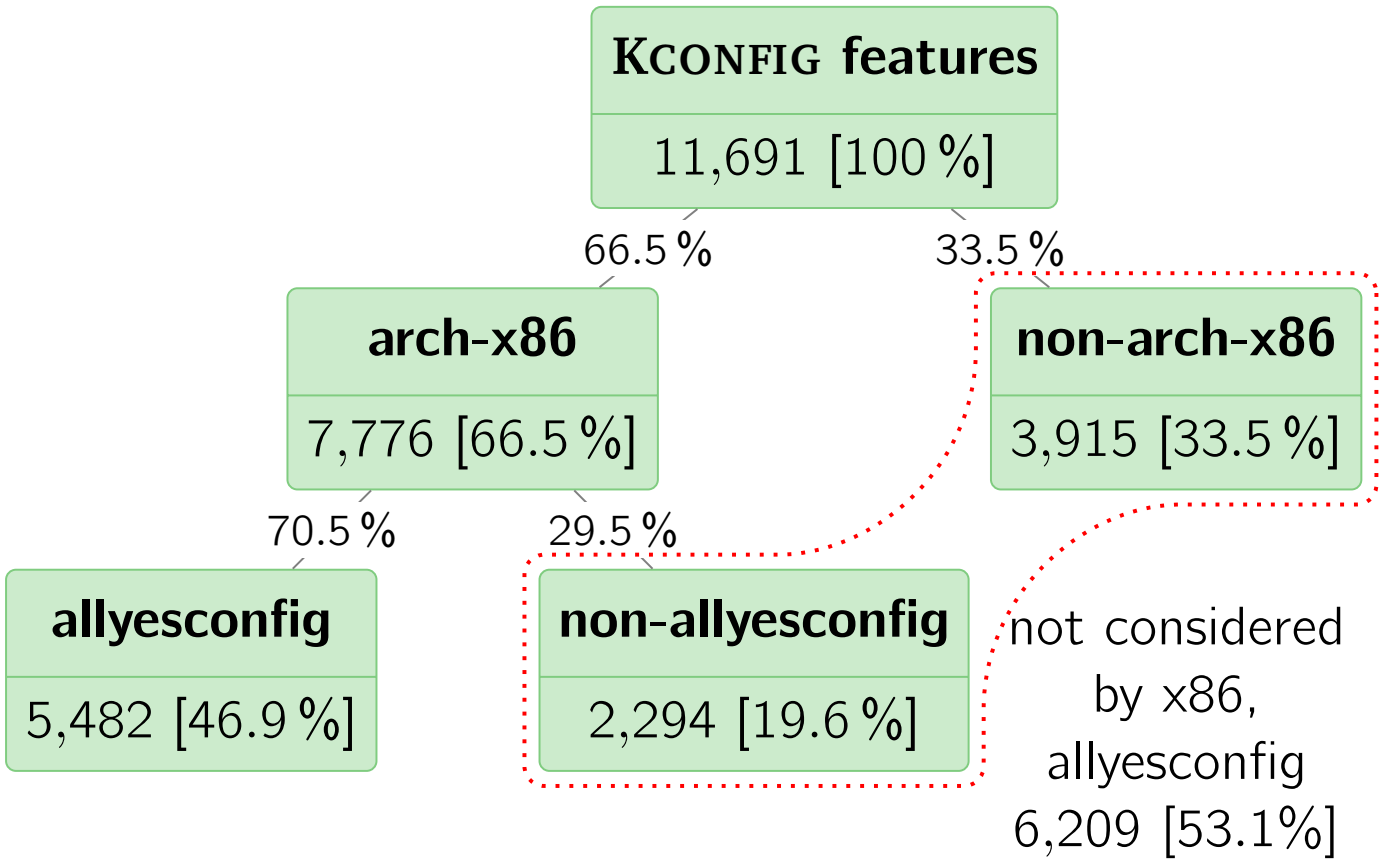
❶ Most variability is expressed by boolean (or tristate) switches



⇒ Almost all features in Linux are option-like

Linux v3.1: Coverage of arch-x86 / allyesconfig

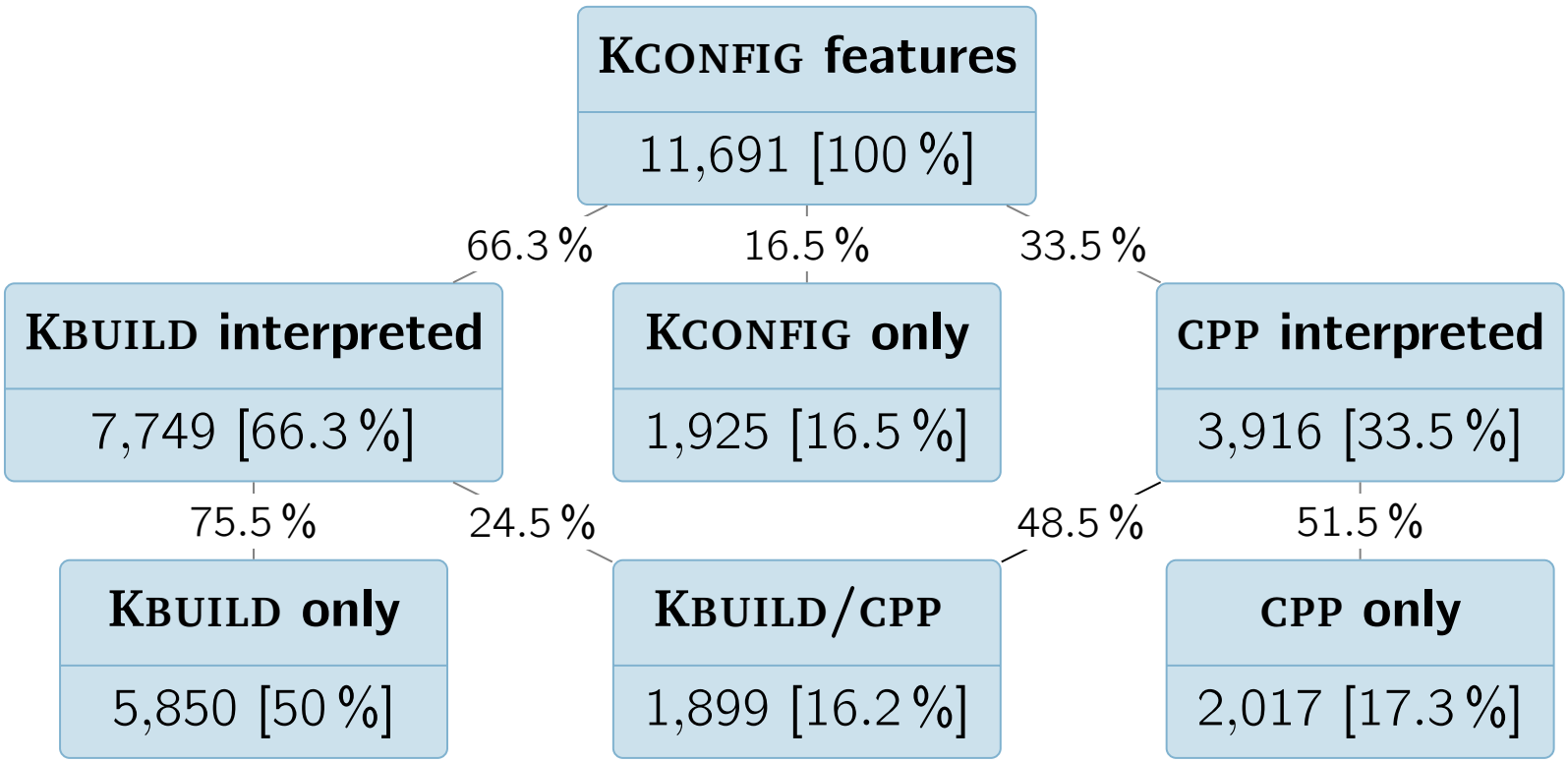
❷ arch-x86 is the largest and allyesconfig selects most features



⇒ `arch-x86/allyesconfig` is not nearly a full configuration

Linux v3.1: Distribution by Granularity

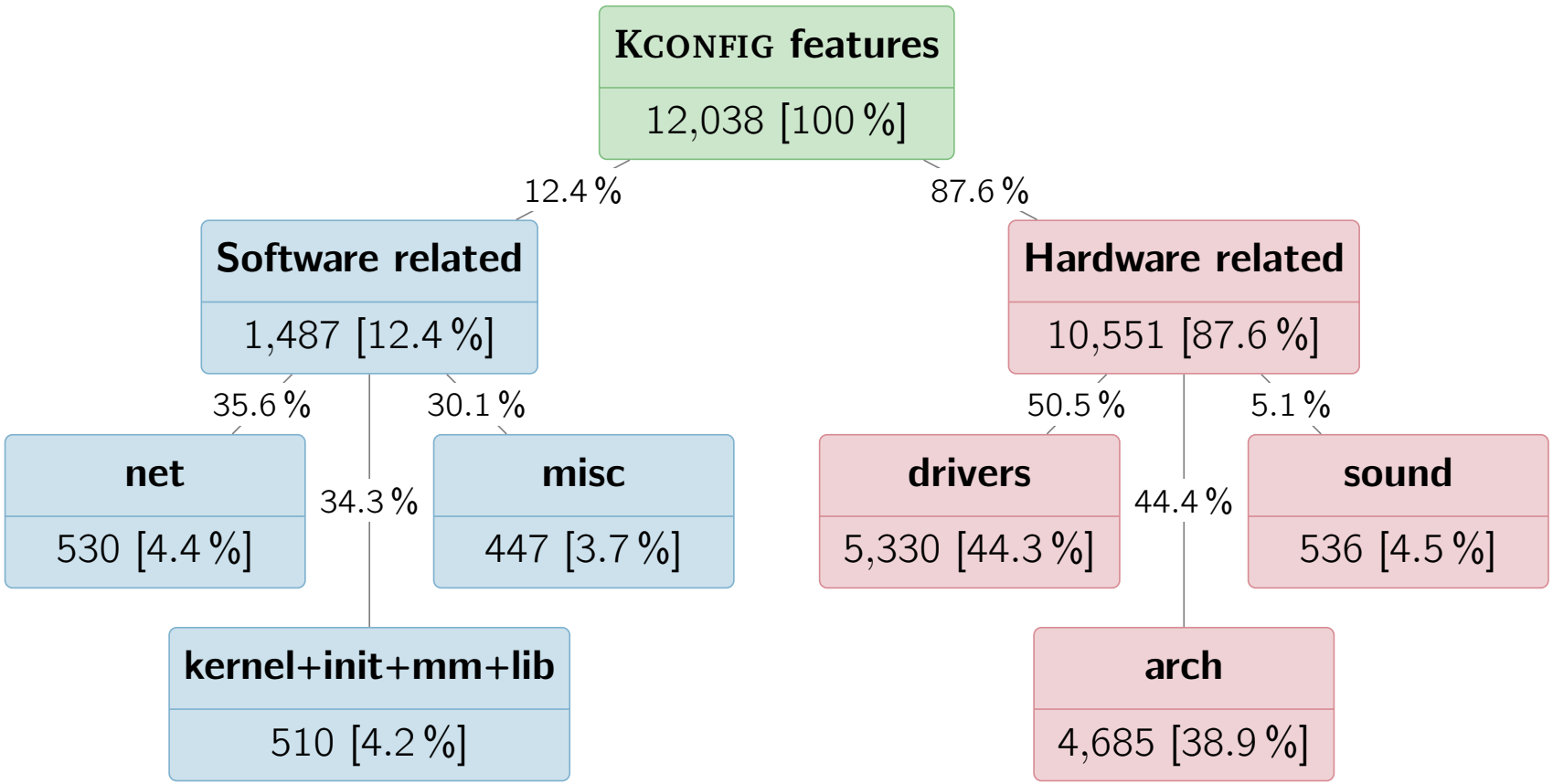
❸ Variability is mostly implemented with the CPP



⇒ KBUILD implements more than two thirds of all variation points

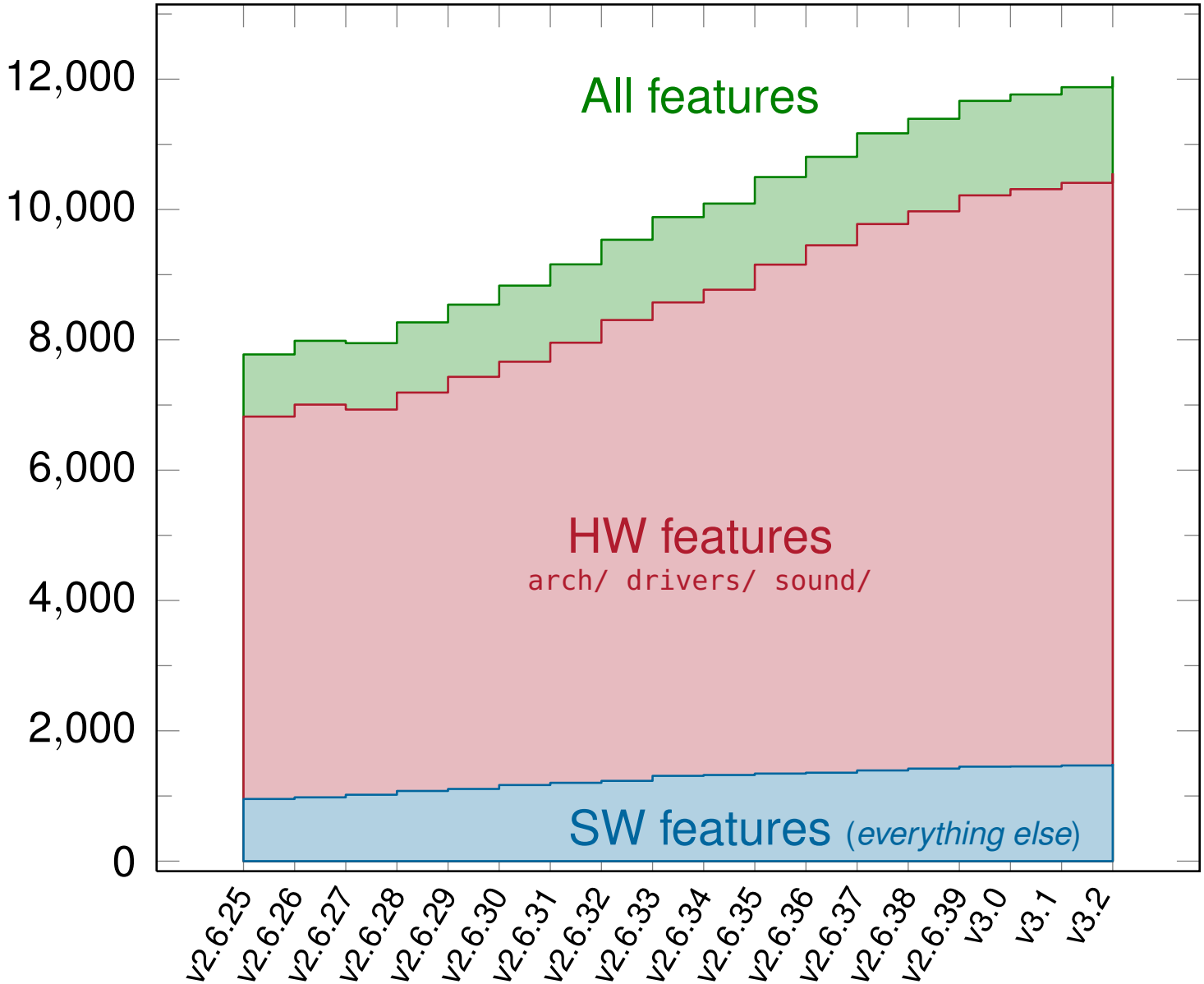
Linux v3.2: Distribution by HW/SW

❹ The Linux *kernel* is highly configurable

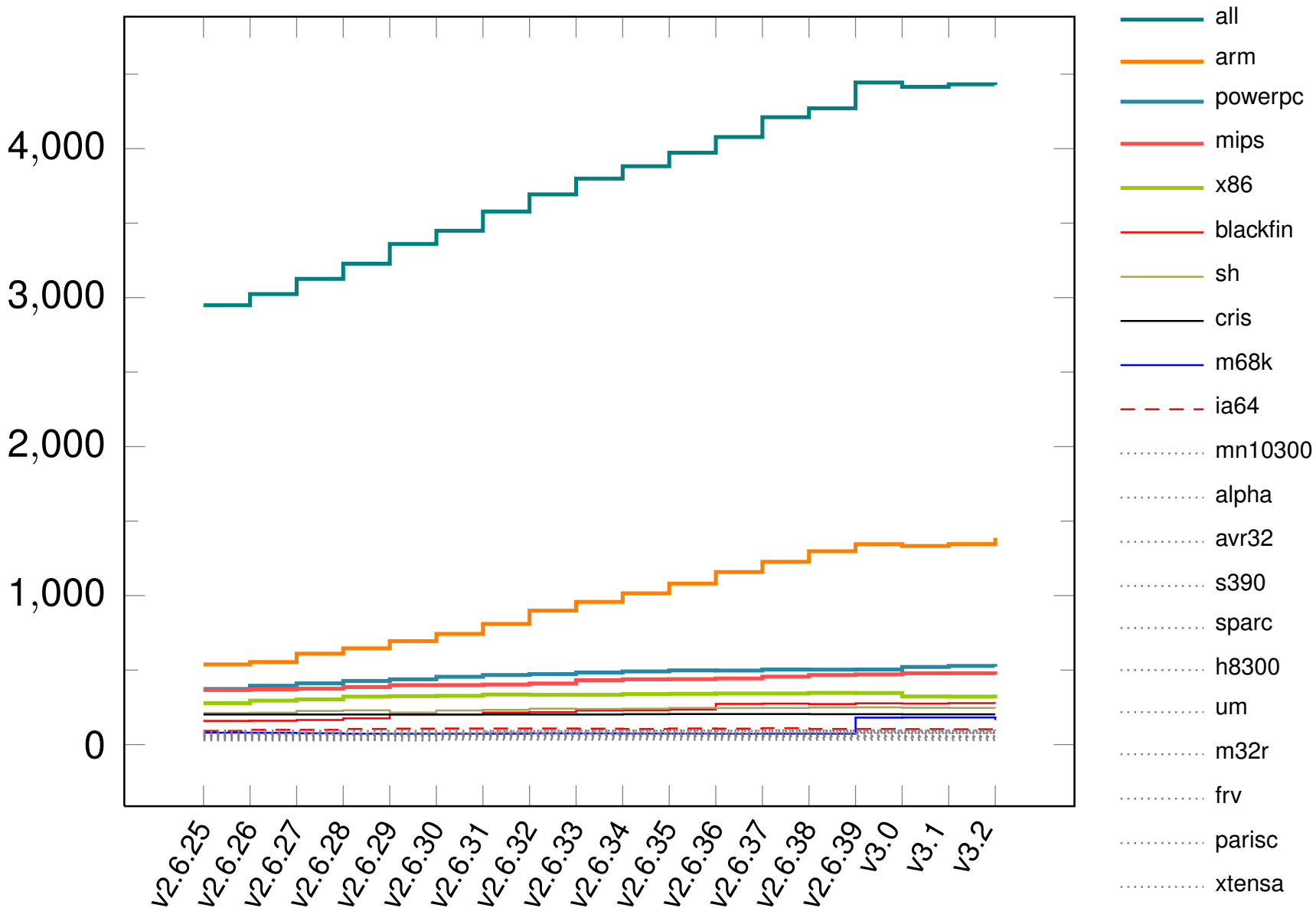


⇒ Software features account for
only twelve percent of all variation points

Linux Feature Growth over Time (#Features, 2007–2012)



Linux Feature Growth over Time (#Features in arch, 2007–2012)



Results: Where Have all the Features Gone?

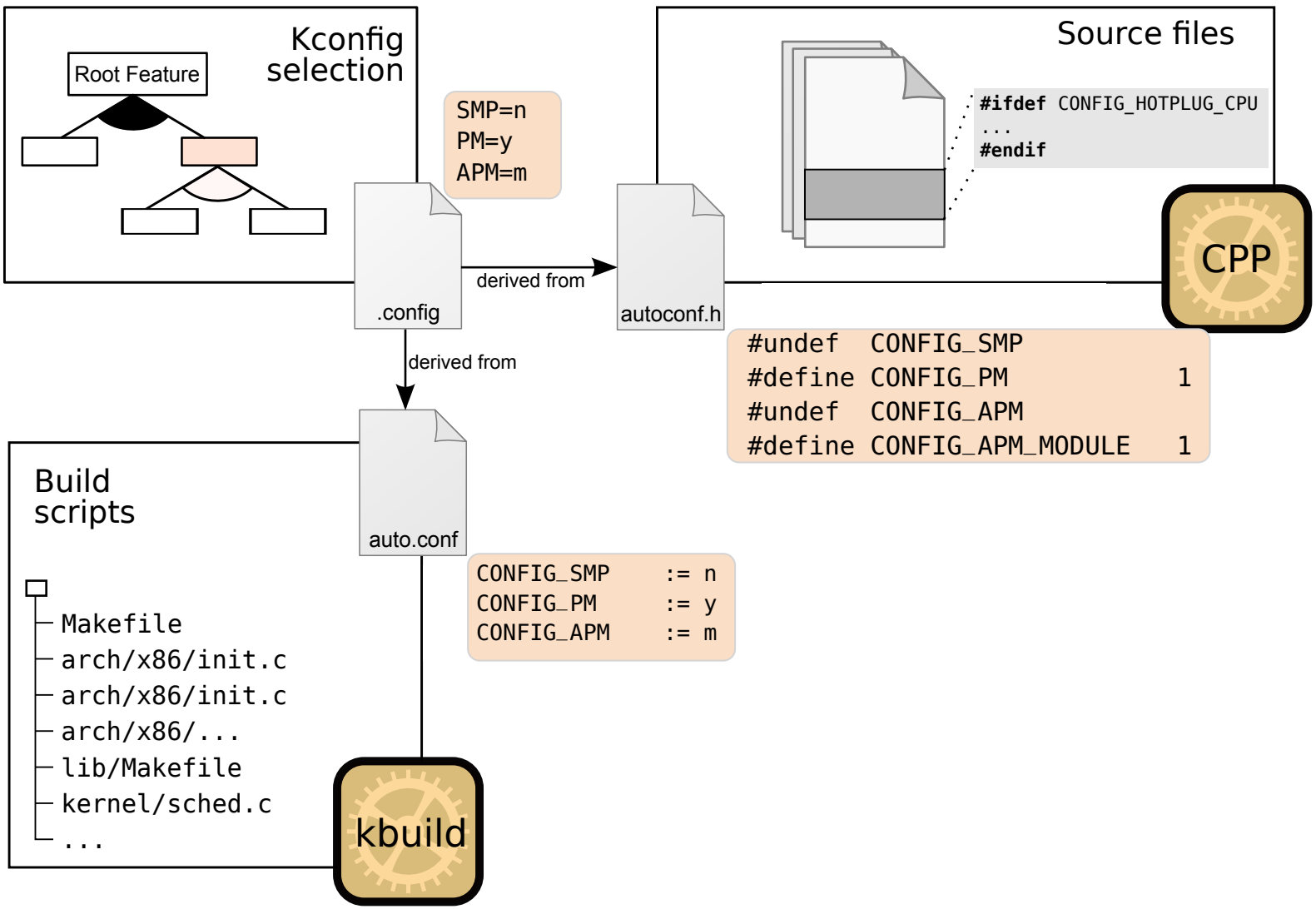
1. Most variability is expressed by boolean (or tristate) switches ✔
   - more than 93 percent of all features are option-like
     ⇝ it is acceptable for tools to ignore value-type features
2. arch-x86 is the largest and allyesconfig selects most features ✘
   - more than 53 percent are not covered by this configuration
     ⇝ other parts of Linux are probably less tested and error-prone!
3. Variability is mostly implemented with the CPP ✘
   - more than 66 percent of all features are handled by the build system, only 17 percent are handled by CPP only
     ⇝ variability extraction from KBUILD is necessary
4. The Linux *kernel* is highly configurable ✘
   - only 12 percent of all features configure software only
   - variability is mostly induced by advances in hardware
     ⇝ complexity will increase further

Challenges: Variability Extraction from the Build System

- Variability extraction $\mapsto$ which file is selected by which feature?
- Usual approach for variability extraction [6, 10] (KCONFIG, CPP, ...):

- Parsing does not work well for MAKE-languages
  - declarative and Turing-complete languages
  - special features, like `shell`, `foreach`, `eval`, `addprefix`, ...
- Linux's KBUILD is built on top of (GNU) MAKE
  - nevertheless, researchers have tried parsing to extract variability
    - KBUILDMINER by Berger, She, Czarnecki, et al. [1]
    - Nadi parser by Nadi and Holt [5]
  - resulting tools are too brittle at best
    - work for a (few) Linux version(s) only
    - each usage of a special feature requires manual tailoring

Linux Build Process Revisited



Variability Extraction from KBUILD with GOLEM [2]

Basic idea: Systematic probing and inferring of implications

SPLC '12: Dietrich, et al. [2]

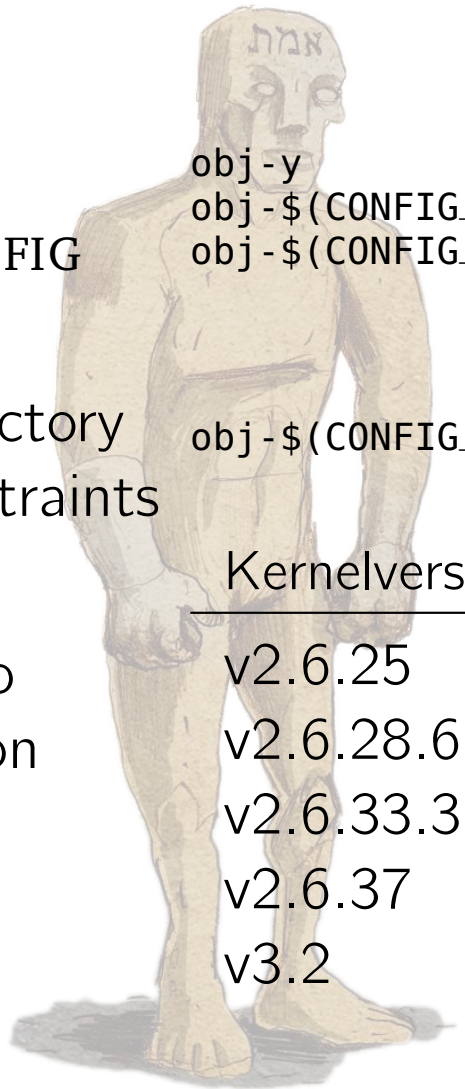
- *Dancing Makefiles*
- Identification of KCONFIG references
- Recursion into subdirectory while considering constraints

```
obj-y                += fork.o
obj-$(CONFIG_SMP)    += spinlock.o
obj-$(CONFIG_APM)    += apm.o


obj-$(CONFIG_PM)     += power/
```

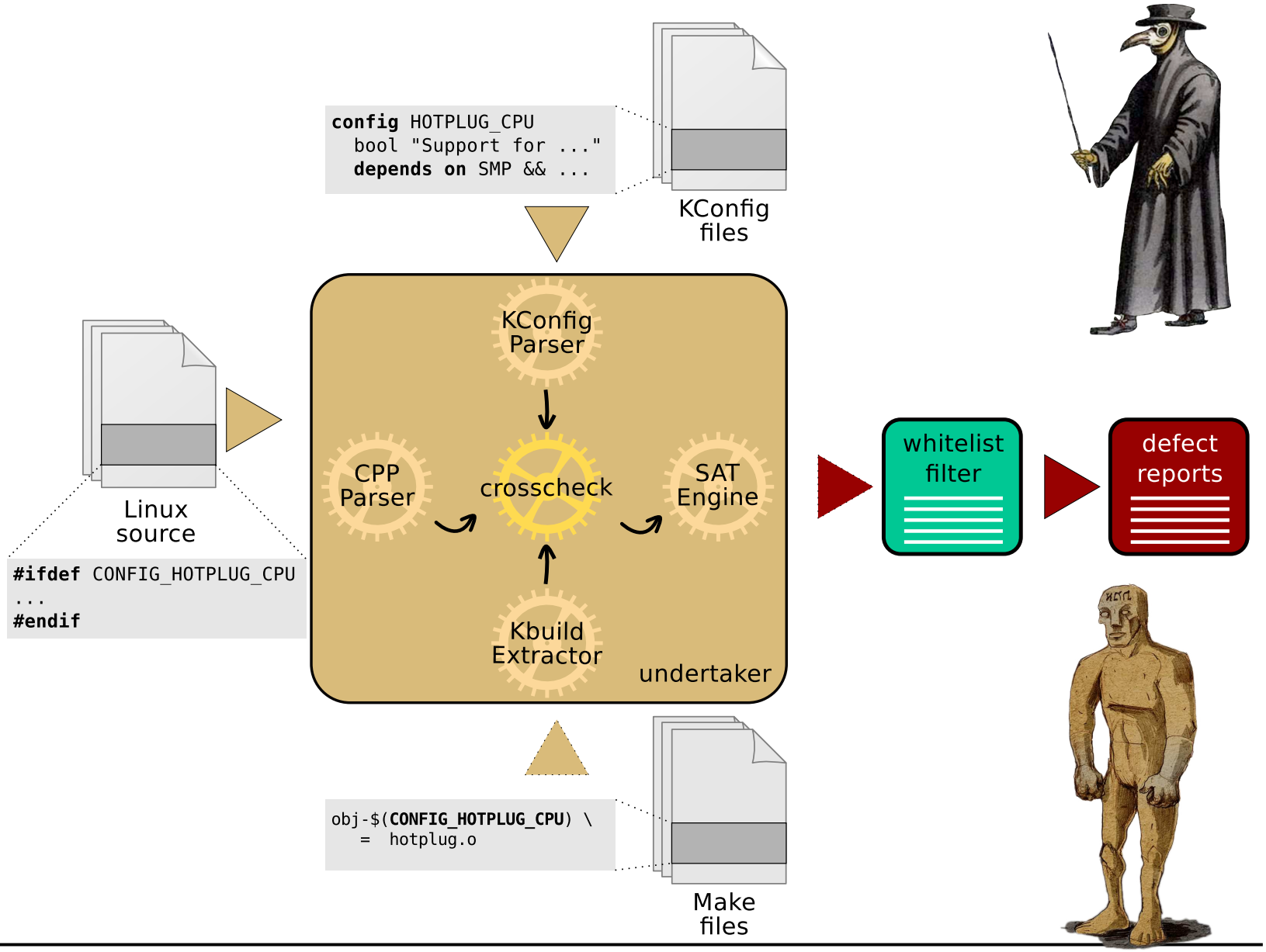
- Robust with respect to architecture and version

⇒ no adaptations on or for KBUILD!



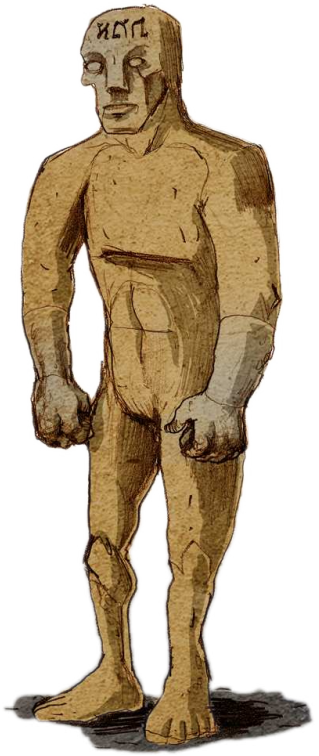
Kernelversion	found inferences	
v2.6.25	6,274	(93.7%)
v2.6.28.6	7,032	(93.6%)
v2.6.33.3	9,079	(94.9%)
v2.6.37	10,145	(95.1%)
v3.2	11,050	(95.4%)

Case Study: Configuration Consistency



Configuration defects in Linux v3.2:

Without KBUILD *constraints*	
Code defects	1835
Referential defects	415
Logical defects	83
Sum:	**Σ 2333**
With KBUILD *constraints*	
Code defects	1835
Referential defects	439
Logical defects	299
Sum:	**Σ 2573**



Result: +10%

Implementation Space Coverage

Issue: Decompositional Implementation of Variability

```
#ifdef CONFIG_NUMA
  Block1
#else
  Block2
#endif
```

Developer has to derive at least two configurations to ensure that the every line of code **even compiles!**

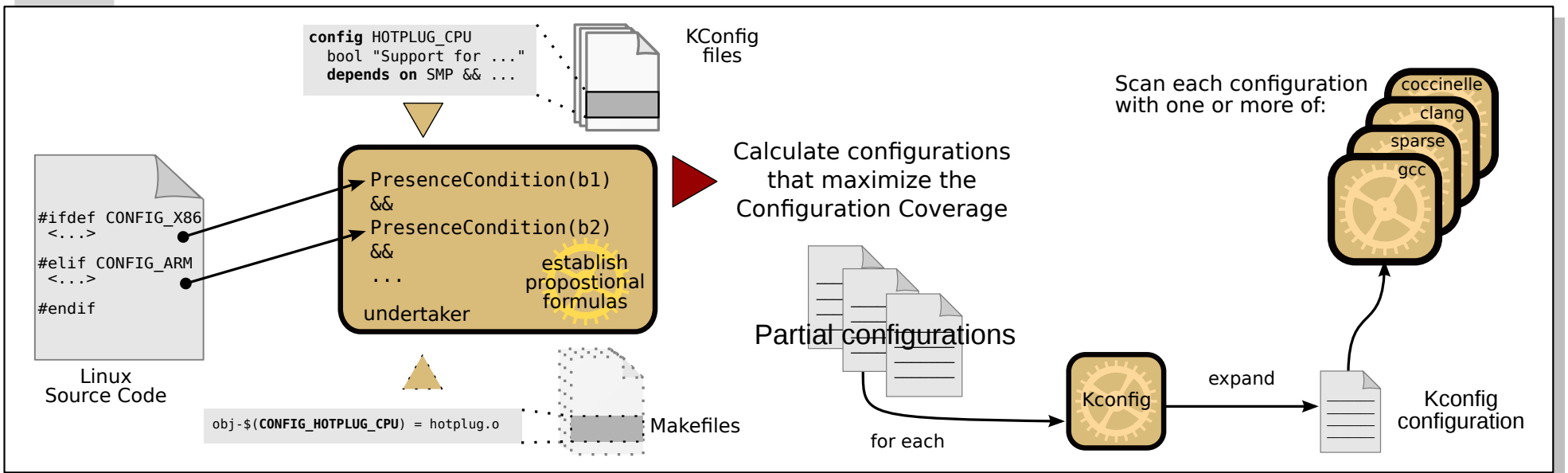
Make sure that the submitted code. . .

> “ ***8.*** *has been carefully reviewed with respect to relevant* KConfig *combinations.* ***This is very hard to get right with testing – brain-power pays off here.*** ”
>
> Linux kernel patch submission checklist (`Documentation/SubmitChecklist`)

The VAMPYR Driver for Static Checkers

- **Goal:** Maximize configuration coverage of *existing* tools
  - Every configuration-conditional part should be covered at least once
  - *Statement coverage*

⇒ Create a set of configurations and scan each individually



The VAMPYR Driver for Static Checkers

- **Goal:** Maximize configuration coverage of *existing* tools
  - Ever… …ce
  - *Stat…*

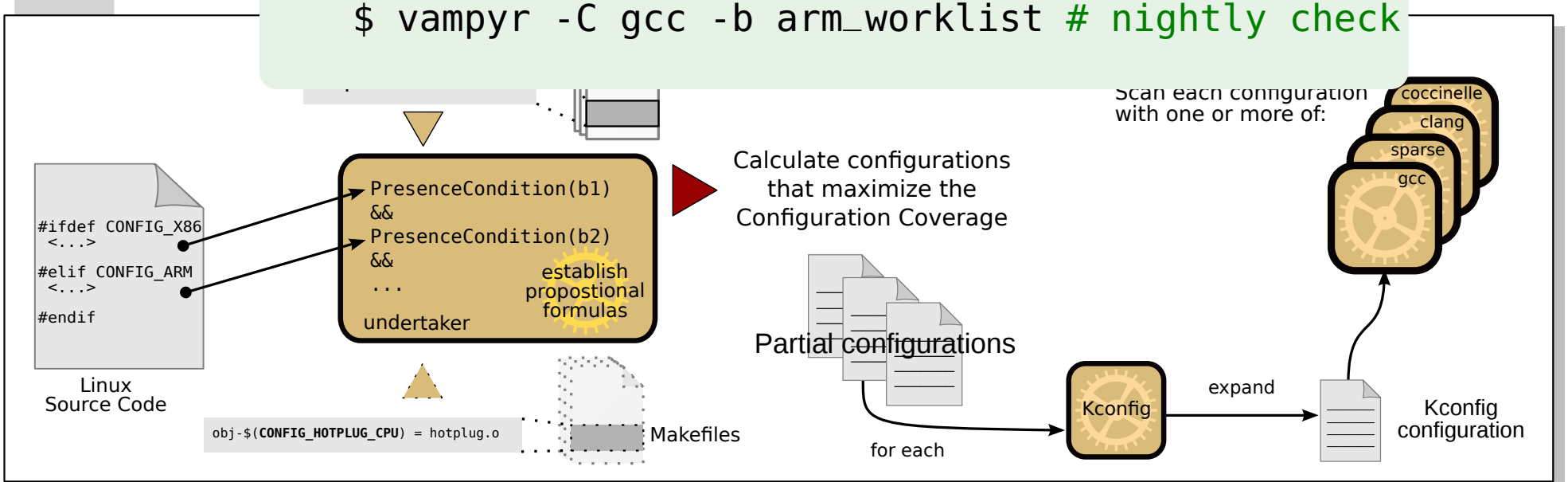
⇒ Create…

- Cover each conditional block affected by patch:

```
$ git am bugfix.diff              # Apply patch
$ vampyr -C gcc --commit HEAD     # Examine
```

- Cover *each* conditional block on arch-arm:

```
$ vampyr -C gcc -b arm_worklist # nightly check
```



Results with GCC as Static Checker

USENIX '14 [7]

Software Project	allyesconf CC_N	VAMPYR CC_N	Overhead: increase of GCC Invocations	GCC #warnings VAMPYR (allyesconfig)	GCC #errors VAMPYR (allyesconfig)	Σ Issues	#ifdef blocks per reported issue (bpi)	**Result**: increase of GCC messages
Linux/x86	78.6%	88.4%	21.5%	201 (176)	1 (0)	202	110	26 (+15%)
hardware	76.8%	86.5%	21.0%	180 (155)	1 (0)	181	82	26 (+17%)
software	82.7%	92.4%	22.7%	21 (21)	0 (0)	21	351	0 (+0%)
Linux/arm	59.9%	84.4%	22.7%	417 (294)	92 (15)	508	46	199 (+64%)
hardware	51.2%	80.1%	23.7%	380 (262)	92 (15)	471	34	194 (+70%)
software	83.6%	96.3%	19.5%	37 (32)	0 (0)	37	192	5 (+16%)
Linux/mips	54.5%	90.9%	22.0%	220 (157)	29 (1)	249	85	91 (+58%)
hardware	42.1%	88.2%	21.5%	174 (121)	17 (1)	191	72	69 (+57%)
software	79.8%	96.3%	23.2%	46 (36)	12 (0)	58	128	22 (+61%)
L4/FIASCO	99.1%	99.8%	see text	20 (5)	1 (0)	21	see text	16 (+320%)
Busybox	74.2%	97.3%	60.3%	44 (35)	0 (0)	44	72	9 (+26%)

Example: arch-arm

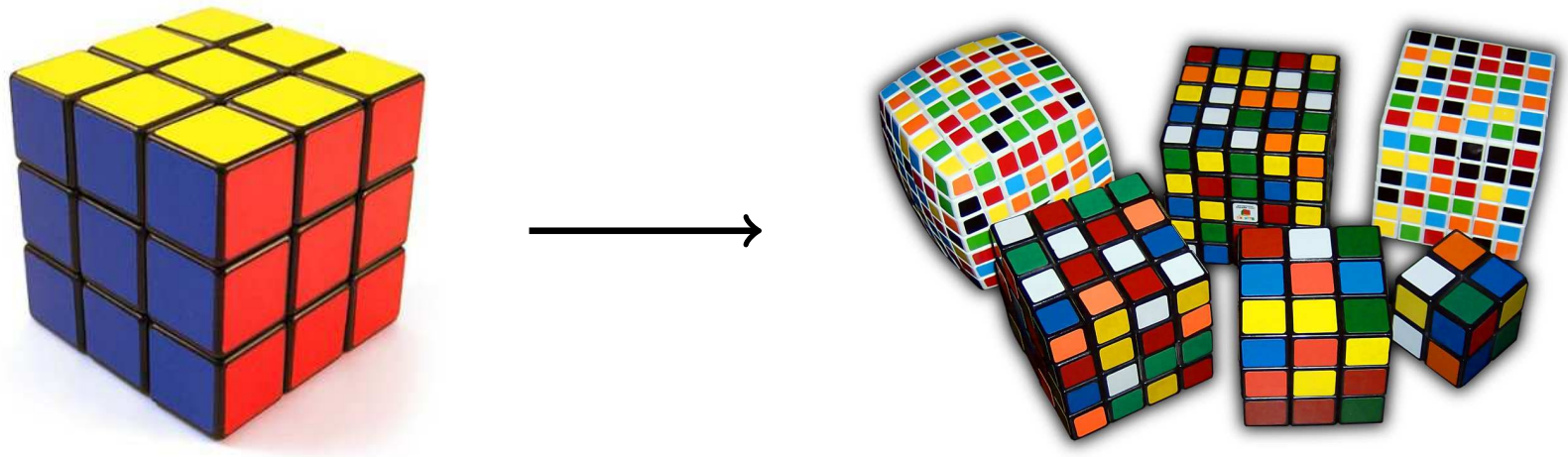
- Increased CC compared to `allyesconfig` from **60%** to **84%**
- **199 (+64%)** additional issues reported by GCC
- **91** reported issues have to be considered as **serious bugs**
- **7** patches submitted – all got immediately accepted

Just by letting **the compiler** see *all* the code!

Agenda

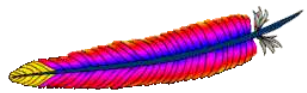
Idea: Automated Tailoring of Linux

- Distribution kernels today come with a maximum configuration
- As side-effect, this maximizes the attack surface!
- Each use-case needs its specific, ideal configuration



→ Automatically derive an ideal configuration for a given use case.

Approach



Specific Scenario

automatically derive

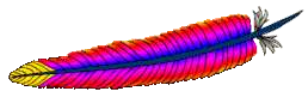
CONFIG_X86=y
CONFIG_SCSI=n
[. . .]

Tailored Configuration

observe

FTRACE

Approach



Specific Scenario

automatically derive

```
CONFIG_X86=y
CONFIG_SCSI=n
[...]
```

Tailored Configuration

employ SAT checker

φ

```
0x8043566 -- kern/sched.c:80
0x80452d8 -- drivers/scsi.c:4302
[...5000 more locations]
```

Identify in Source Code

establish

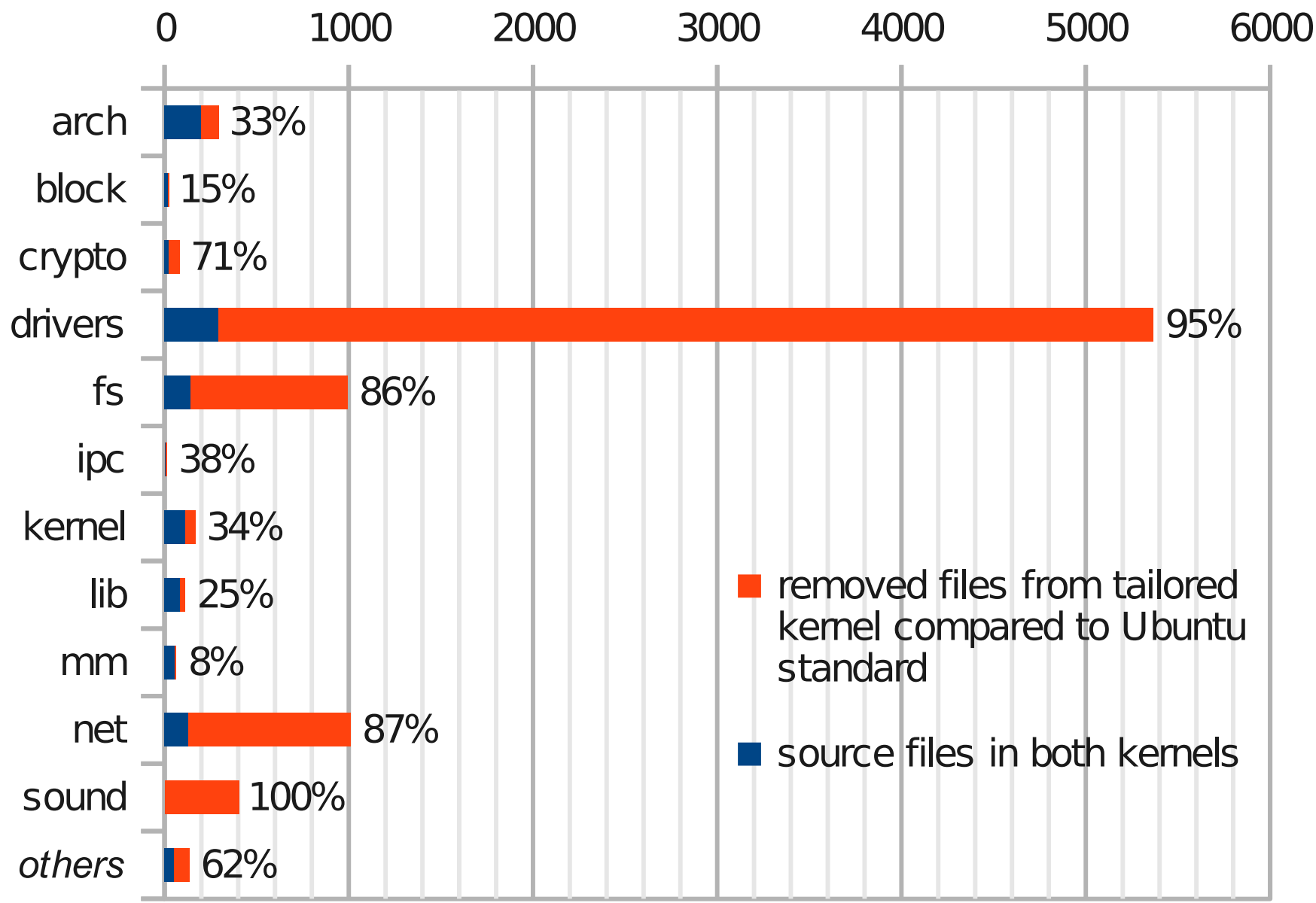
Holistic Variability Model

Evaluation

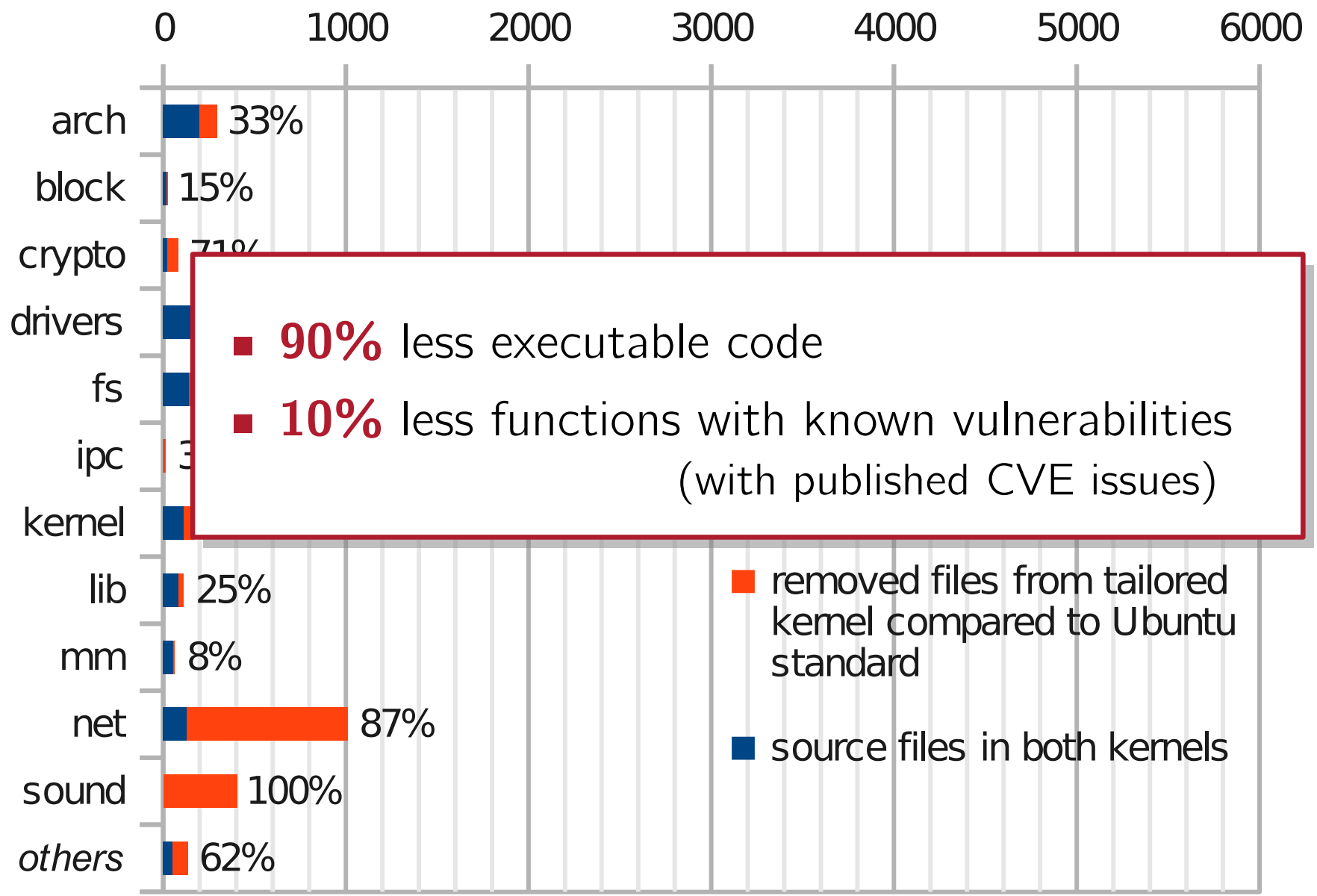
- Ubuntu 12.04 with Linux 3.2 kernel; two use cases
  - Web server setup with Apache, MySQL, PHP (LAMP)
  - Workstation setup with NFS (Desktop)
- Trace time: 15 min, running defined workload
  - LAMP: Google Skipfish $\leadsto$ 5377 unique kernel functions
  - Desktop: iozone, bonnie++ $\leadsto$ 6933 unique kernel functions
- Black and whitelist for manual tailoring
  - **Blacklist:** `CONFIG_FTRACE`
  - **Whitelist:** `CONFIG_UNIX, CONFIG_PACKET, CONFIG_DEVTMPFS, CONFIG_DEVTMPFS_MOUNT, CONFIG_ATA_PIIX, CONFIG_SATA_AHCI, CONFIG_ATA_GENERIC, CONFIG_DRM_I915_KMS, CONFIG_BLK_DEV_INITRD`

	Baseline	Tailored LAMP	Tailored Workstation/NFS
Kernel size in Bytes	9,933,860	4,228,235 (44%)	4,792,508 (48%)
LKM total size in Bytes	62,987,539	2,139,642 (3%)	2,648,034 (4%)
Options set to 'y'	1,537	452 (29%)	492 (32%)
Options set to 'm'	3,142	43 (1%)	63 (2%)
Compiled source files	8,670	1,121 (13%)	1,423 (16%)

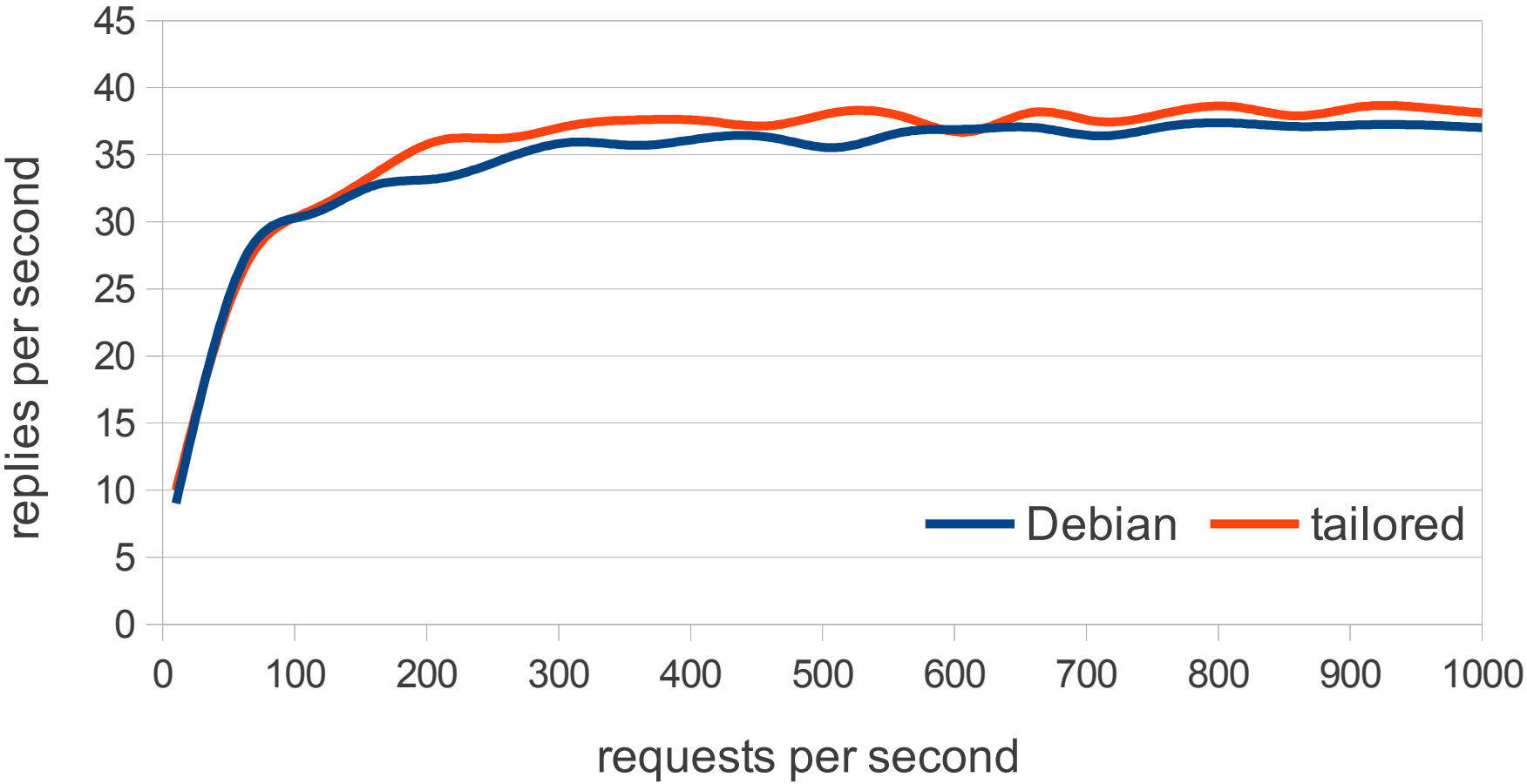
Evaluation: Reduction for LAMP



Evaluation: Reduction for LAMP



Evaluation: Performance Impact for LAMP



No observable performance impact

Results: Automatic Tailoring [8]

HotDep '12: Tartler, Kurmus, Ruprecht, Heinloth, Rothberg et al. [8]

- TCB is significantly smaller
- Easy to use: process is fully automated
- If necessary, the tailoring can guided with whitelists and blacklists
- Going further: Dynamic ASR [4]
  - Even if present: Who is allowed to call what $\leadsto$ CFG analysis
  - At runtime: Block illegal invocations.

Summary

- Real-world system software offers thousands of features
  - eCos: 1,250 features
  - Linux: 12,000 features

  } mostly induced by hardware!
  - central declaration (ecosConfig, KCONFIG)
  - distributed, multi-paradigm implementation (MAKE, CPP, GCC, ...)
- This imposes great challenges for management and maintenance
  - how to ensure configurability consistency?
  - how to ensure configuration coverage?
  - how to keep pace with the constant feature increase?
- A strong call for adequate tool support $\mapsto$ VAMOS
  - already found thousands and fixed hundreds of defects and bugs
  - more to come!

Referenzen

[1] Thorsten Berger, Steven She, Krzysztof Czarnecki, et al. *Feature-to-Code Mapping in Two Large Product Lines*. Tech. rep. University of Leipzig (Germany), University of Waterloo (Canada), IT University of Copenhagen (Denmark), 2010.

[2] Christian Dietrich, Reinhard Tartler, Wolfgang Schröder-Preikschat, et al. "A Robust Approach for Variability Extraction from the Linux Build System". In: *Proceedings of the 16th Software Product Line Conference (SPLC '12)*. (Salvador, Brazil, Sept. 2–7, 2012). Ed. by Eduardo Santana de Almeida, Christa Schwanninger, and David Benavides. New York, NY, USA: ACM Press, 2012, pp. 21–30. ISBN: 978-1-4503-1094-9. DOI: `10.1145/2362536.2362544`.

[3] Christian Dietrich, Reinhard Tartler, Wolfgang Schröder-Preikschat, et al. "Understanding Linux Feature Distribution". In: *Proceedings of the 2nd AOSD Workshop on Modularity in Systems Software (AOSD-MISS '12)*. (Potsdam, Germany, Mar. 27, 2012). Ed. by Christoph Borchert, Michael Haupt, and Daniel Lohmann. New York, NY, USA: ACM Press, 2012. ISBN: 978-1-4503-1217-2. DOI: `10.1145/2162024.2162030`.

[4] Anil Kurmus, Reinhard Tartler, Daniela Dorneanu, et al. "Attack Surface Metrics and Automated Compile-Time OS Kernel Tailoring". In: *Proceedings of the 20th Network and Distributed Systems Security Symposium*. (San Diego, CA, USA, Feb. 24–27, 2013). The Internet Society, 2013. URL: `http://www.internetsociety.org/sites/default/files/03_2_0.pdf`.

Referenzen (Cont'd)

[5] Sarah Nadi and Richard C. Holt. "Mining Kbuild to Detect Variability Anomalies in Linux". In: *Proceedings of the 16th European Conference on Software Maintenance and Reengineering (CSMR '12)*. (Szeged, Hungary, Mar. 27–30, 2012). Ed. by Tom Mens, Yiannis Kanellopoulos, and Andreas Winter. Washington, DC, USA: IEEE Computer Society Press, 2012. ISBN: 978-1-4673-0984-4. DOI: 10.1109/CSMR.2012.21.

[6] Julio Sincero, Reinhard Tartler, Daniel Lohmann, et al. "Efficient Extraction and Analysis of Preprocessor-Based Variability". In: *Proceedings of the 9th International Conference on Generative Programming and Component Engineering (GPCE '10)*. (Eindhoven, The Netherlands). Ed. by Eelco Visser and Jaakko Järvi. New York, NY, USA: ACM Press, 2010, pp. 33–42. ISBN: 978-1-4503-0154-1. DOI: 10.1145/1868294.1868300.

[7] Reinhard Tartler, Christian Dietrich, Julio Sincero, et al. "Static Analysis of Variability in System Software: The 90,000 #ifdefs Issue". In: *Proceedings of the 2014 USENIX Annual Technical Conference (USENIX '14)*. To appear. Philadelphia, PA, USA: USENIX Association, 2014.

[8] Reinhard Tartler, Anil Kurmus, Bernard Heinloth, et al. "Automatic OS Kernel TCB Reduction by Leveraging Compile-Time Configurability". In: *Proceedings of the 8th International Workshop on Hot Topics in System Dependability (HotDep '12)*. (Los Angeles, CA, USA). Berkeley, CA, USA: USENIX Association, 2012, pp. 1–6.

Referenzen (Cont'd)

[9] Reinhard Tartler, Daniel Lohmann, Christian Dietrich, et al. "Configuration Coverage in the Analysis of Large-Scale System Software". In: *ACM SIGOPS Operating Systems Review* 45.3 (Jan. 2012), pp. 10–14. ISSN: 0163-5980. DOI: 10.1145/2094091.2094095.

[10] Reinhard Tartler, Daniel Lohmann, Julio Sincero, et al. "Feature Consistency in Compile-Time-Configurable System Software: Facing the Linux 10,000 Feature Problem". In: *Proceedings of the ACM SIGOPS/EuroSys European Conference on Computer Systems 2011 (EuroSys '11)*. (Salzburg, Austria). Ed. by Christoph M. Kirsch and Gernot Heiser. New York, NY, USA: ACM Press, Apr. 2011, pp. 47–60. ISBN: 978-1-4503-0634-8. DOI: 10.1145/1966445.1966451.