Konfigurierbare Systemsoftware (KSS)

VL 6 – Variability Management in the Large: The VAMOS/CADOS Approach

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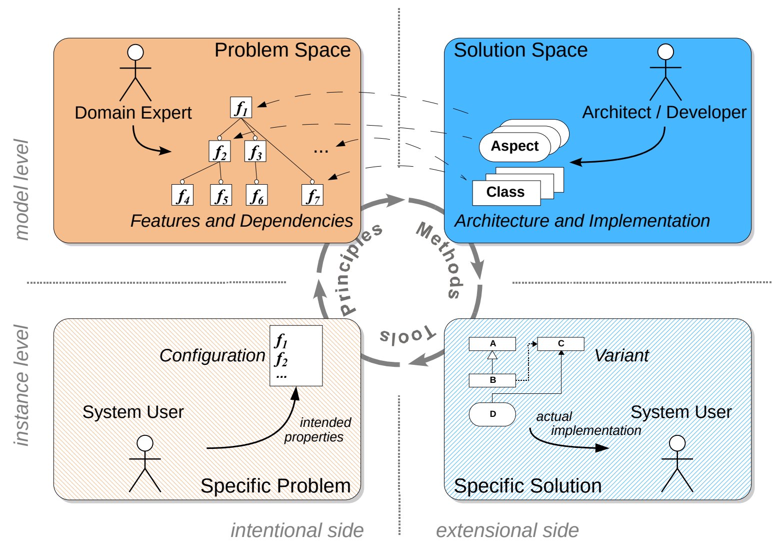
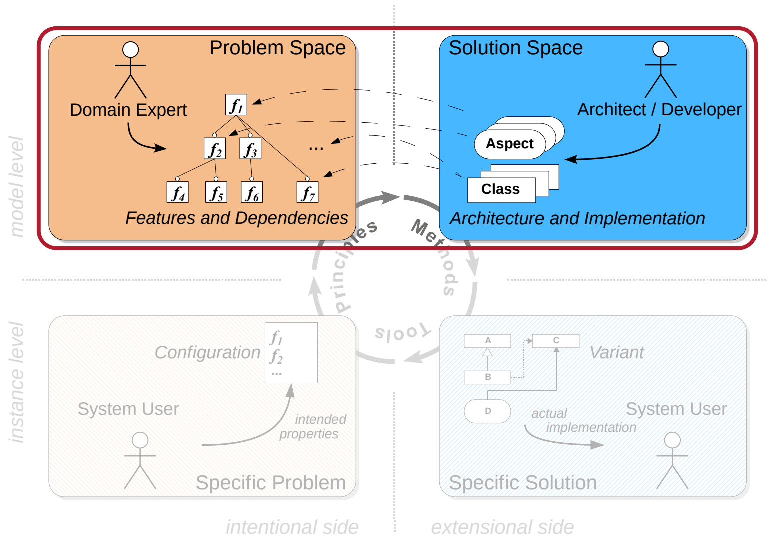
About this Lecture



About this Lecture



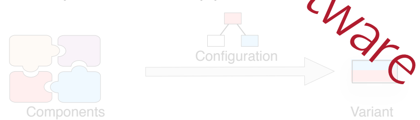
Implementation Techniques: Classification

↪ ??

- 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

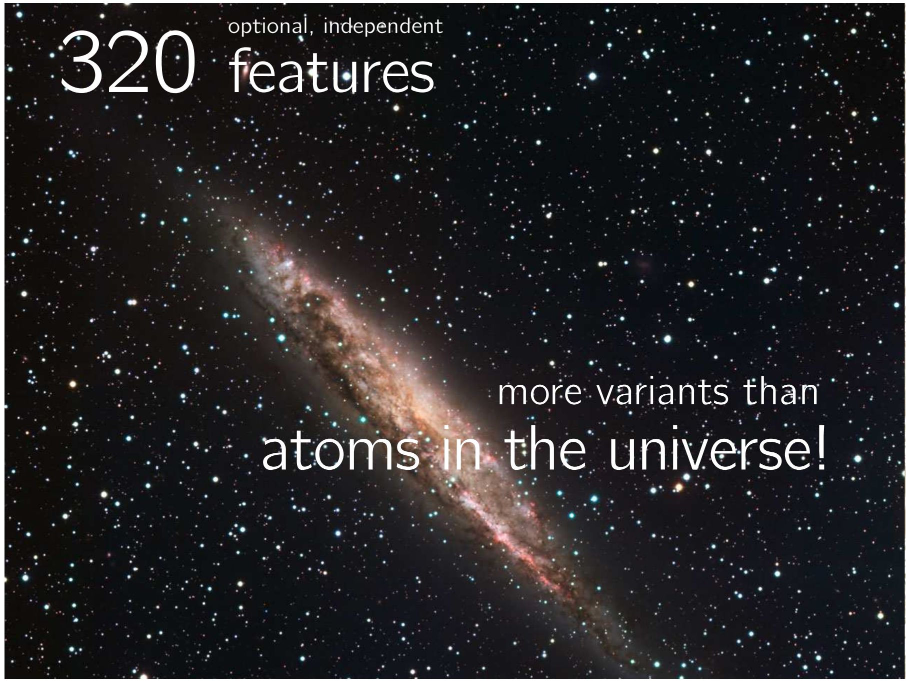
Real-world software uses them all!

Agenda

33 optional, independent features

one individual variant

for each human being



320 optional, independent features

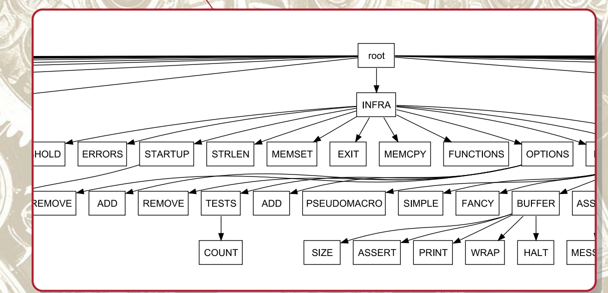
more variants than

atoms in the universe!

Typical Configurable Operating Systems...

ecos

1,250 features



Typical Configurable Operating Systems…

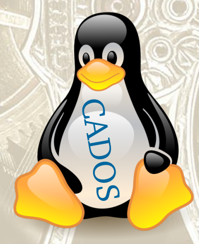
eCos

1,250 features

Challenges: ↦ **VAMOS/CADOS***

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

* VAriability Management in Operating Systems
Configurability-Aware Development of Operating Systems

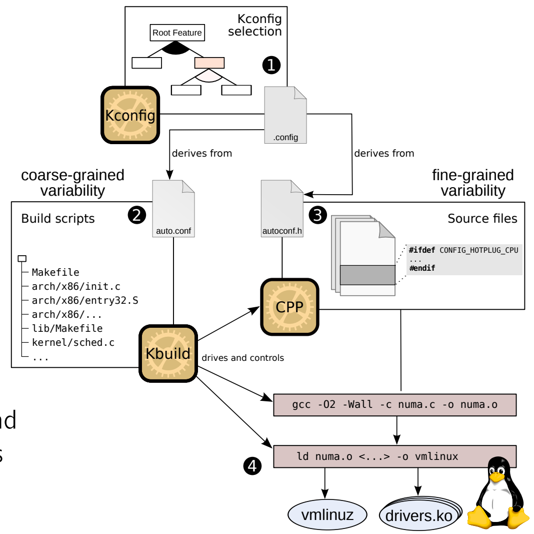


12,000 features

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



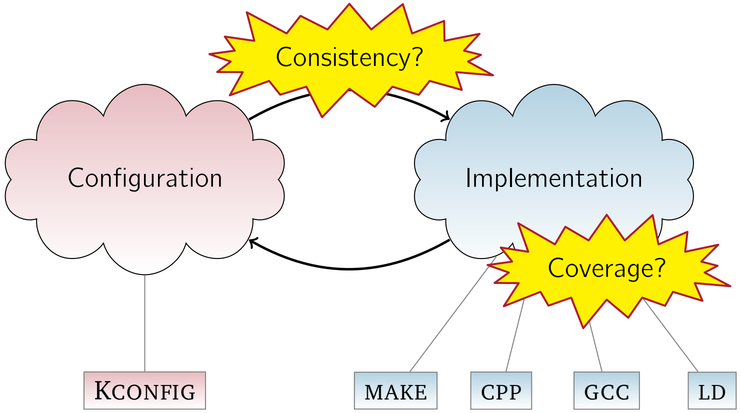
Dominancy and Hierarchy of Variability

Linux V3.2

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	→ `if(CONFIG_SMP) ...`	
l_4: Link time: LD	→ branches in linker scripts	
l_5: Run time: INSMOD, MODPROBE, …		

KCONFIG controlled Variability (l_0–l_3)

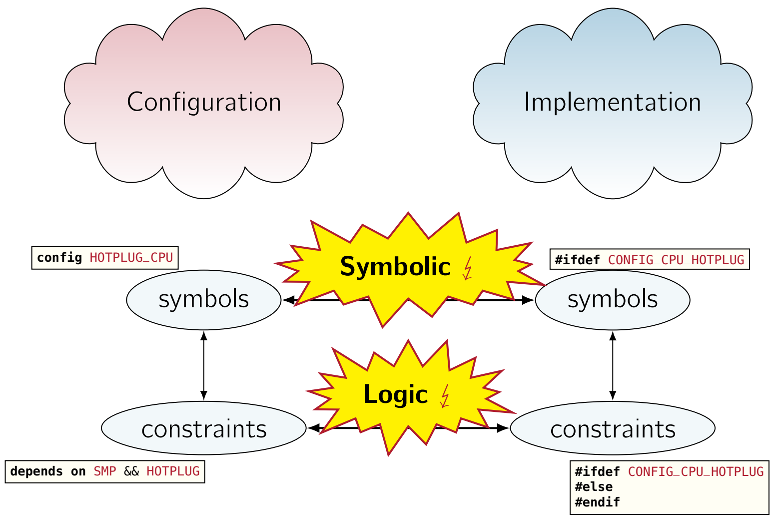
Challenges with Implemented Variability



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

Agenda

Problem Analysis: Configuration Consistency



Problem Analysis: Symbolic Inconsistency [11]

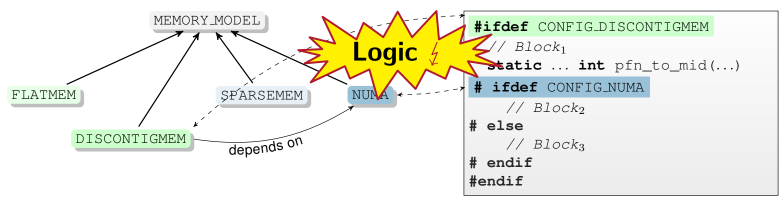
```
config HOTPLUG_CPU
    bool "Support for hot-pluggable CPUs"
    depends on SMP && HOTPLUG
    ---help---
```

```
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;
  }
```

Symbolic ↯

Result:
Fix for a critical bug

Problem Analysis: Logic Inconsistency [11]



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

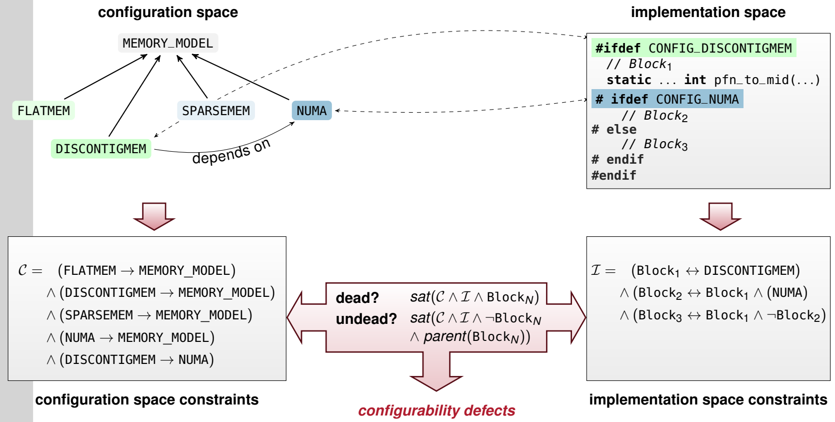
  } **configurability defects**

⇝ Linux contains **superfluous** `#ifdef` Blocks!

Result: Code cleanup

Solution Approach: Consistency Validation

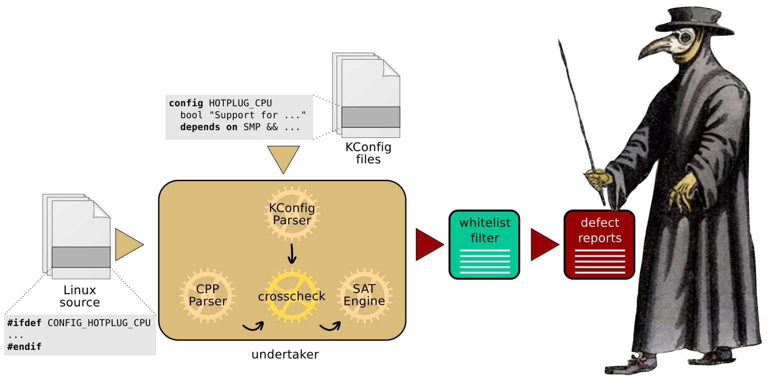
Problem and solution space are analyzed for configuration points:



⇒ and transformed into propositional formulas

Implementation: The UNDERTAKER [11]

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



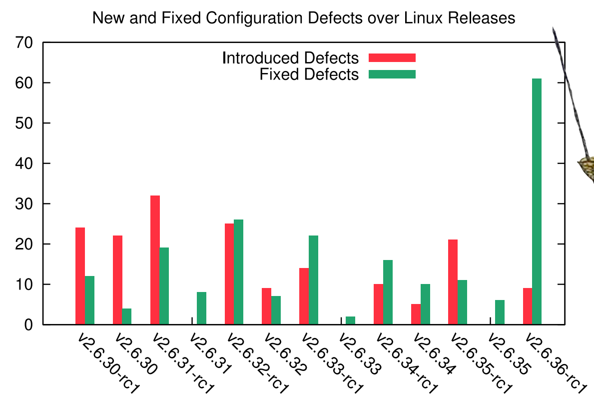
Implementation: The UNDERTAKER [11]

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 [11]

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



How good is this, *really?*

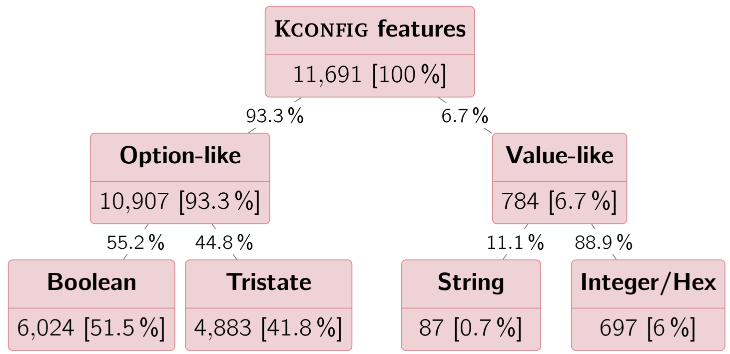
Agenda

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

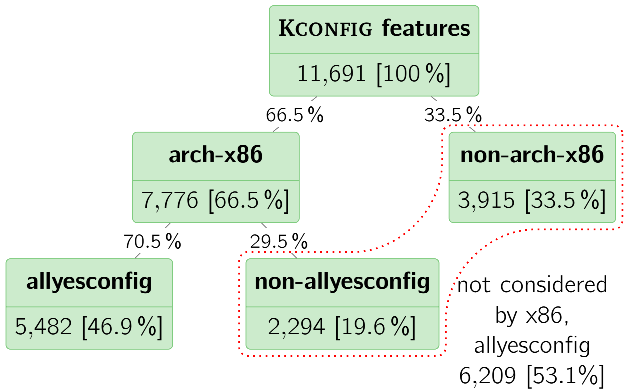
1. Most variability is expressed by boolean (or tristate) switches



⇒ Almost all features in Linux are option-like

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

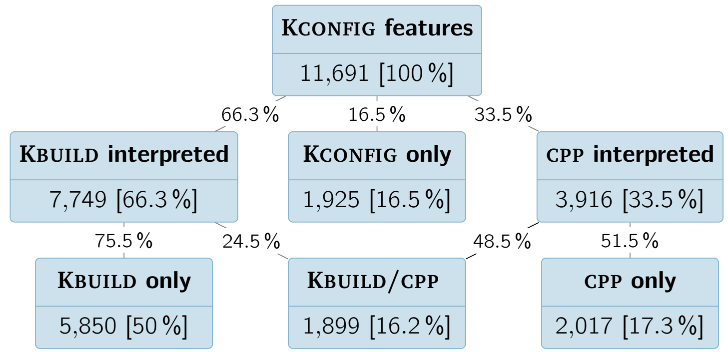
❷ arch-x86 is the largest and allyesconfig selects most features



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

Linux v3.1: Distribution by Granularity

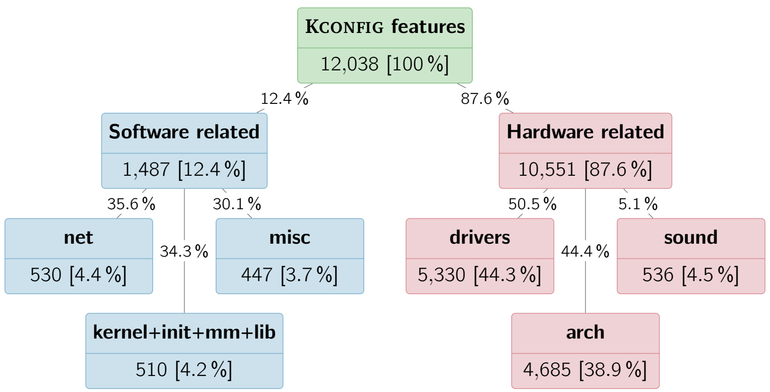
❸ Variability is mostly implemented with the CPP



⇒ KBUILD implements more than two thirds of all variation points

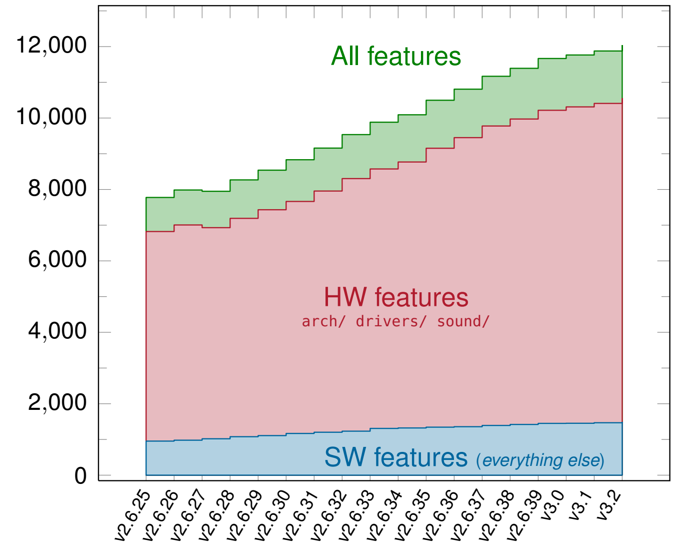
Linux v3.2: Distribution by HW/SW

❹ The Linux *kernel* is highly configurable

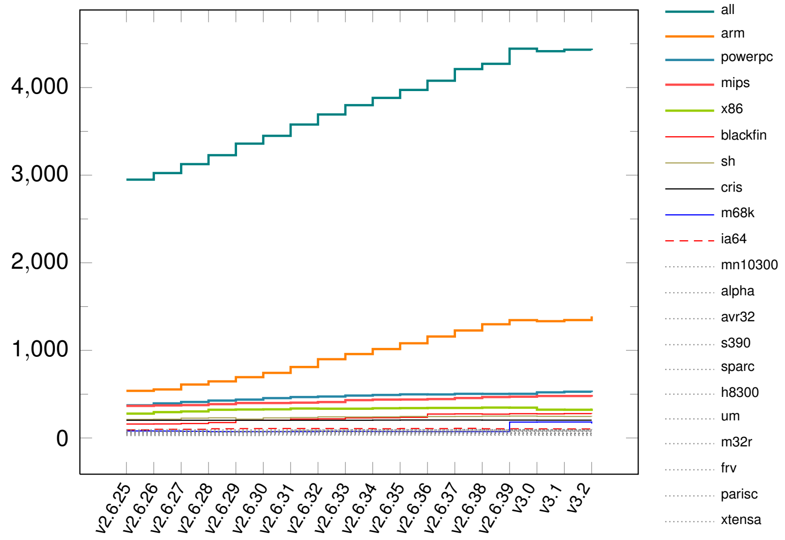


⇒ Software features account for only twelve percent of all variation points

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

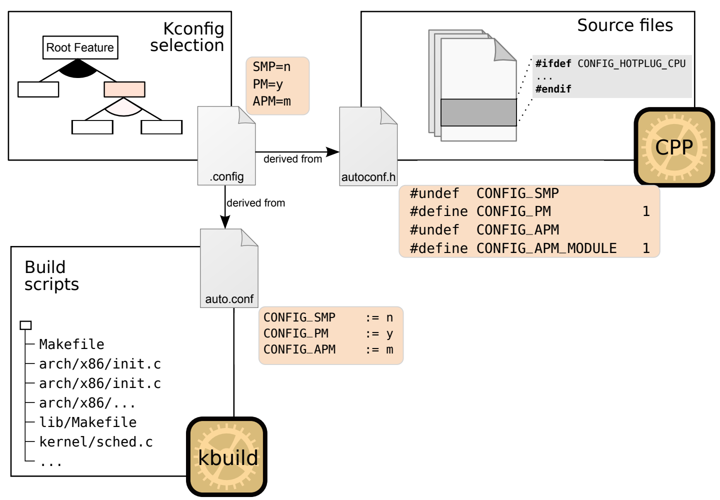
Challenges: Variability Extraction from the Build System

- Variability extraction ↦ which file is selected by which feature?
- Usual approach for variability extraction [7, 11] (KCONFIG, CPP, ...):

  source → parse & transform → *propositional formula*

- 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, and Wasowski [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

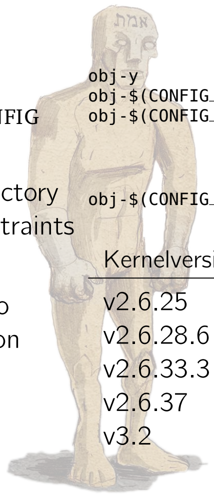
Linux Build Process Revisited



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

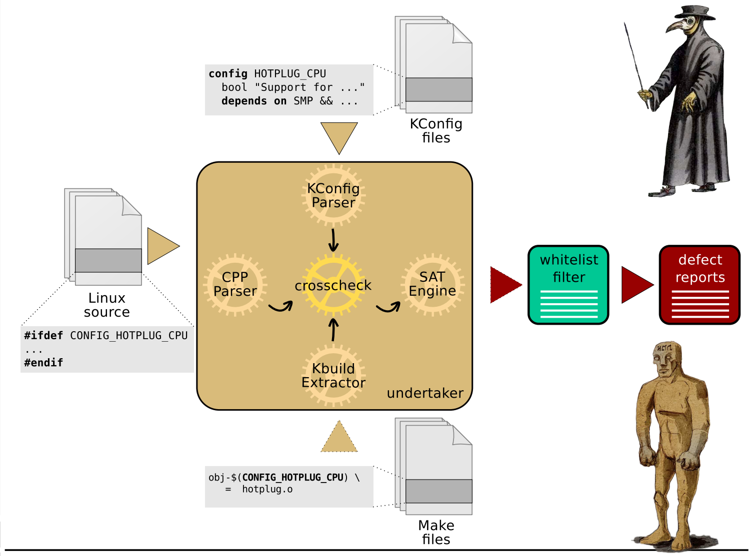
```
obj-y              += fork.o
obj-$(CONFIG_SMP)  += spinlock.o
obj-$(CONFIG_APM)  += apm.o

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%)

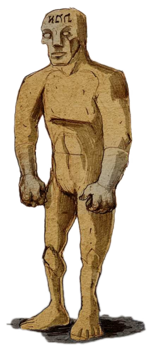
Case Study: Configuration Consistency ↪ 6–17



Case Study: Configuration Consistency ↪ 6–17

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...

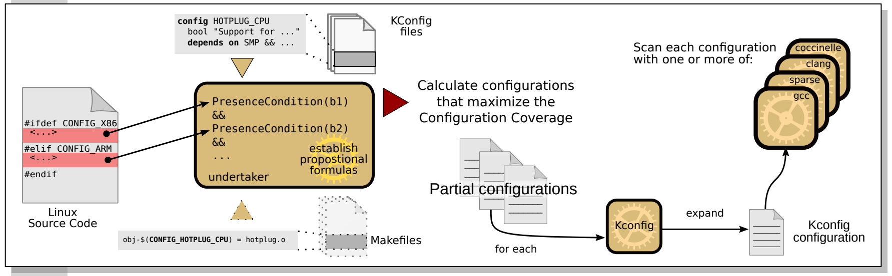
“ *8. has been carefully reviewed with respect to relevant KCONFIG combinations.* ***This is very hard to get right with testing – brain-power pays off here.*** ”

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
  - Every configuration-conditional part should be covered at least once
  - *Statement coverage*

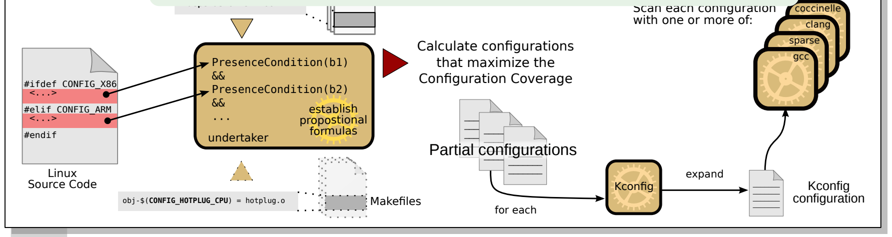
⇒ Create a set of configurations and scan each individually

- 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 [8]

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

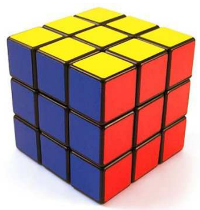
- Increased CC compared to `allyesconfig` from **60%** to **84%**
- **199 (+64%)** additional issues reported by GCC
- **91** reported issues have to be considered as **serious bugs**
- **7** patches submitted – all got immediately accepted

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.

Automatic Tailoring: Approach

baseline kernel

specific scenario

tailored kernel

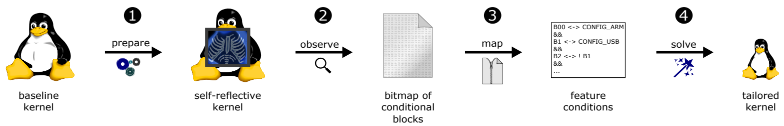
Main idea: "measure" needed features

- Start with standard distribution kernel
- Run use-case–specific test load ➠ "observe" needed functionality
- Derive configuration for tailored kernel

Automatic Tailoring: Approach

1. Prepare feature tracing
   - enable ftrace, or
   - patch source with flipper

specific scenario

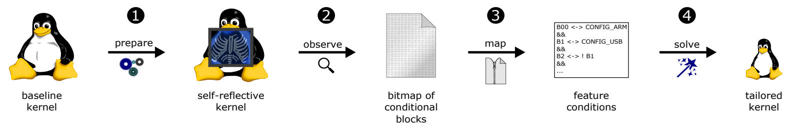


Automatic Tailoring: Approach

1. Prepare feature tracing
   - enable ftrace, or
   - patch source with flipper
2. Run test load, observe
   - trace invoked kernel code
   - address ↦ `#ifdef` block

specific scenario

test load



Automatic Tailoring: Approach

1. Prepare feature tracing
   - enable ftrace, or
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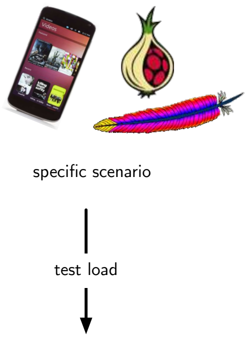
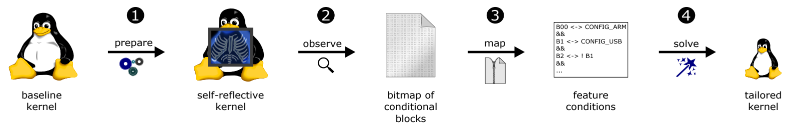
2. Run test load, observe
   - trace invoked kernel code
   - address ↦ `#ifdef` block
3. Map to partial config
   - blocks ↦ dependend blocks
   - blocks ↦ features





Automatic Tailoring: Approach

1. Prepare feature tracing
   - enable ftrace, or
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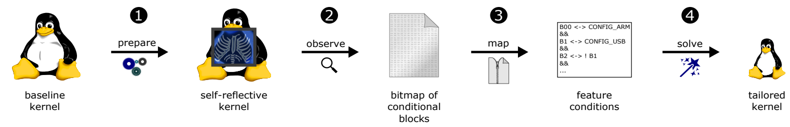
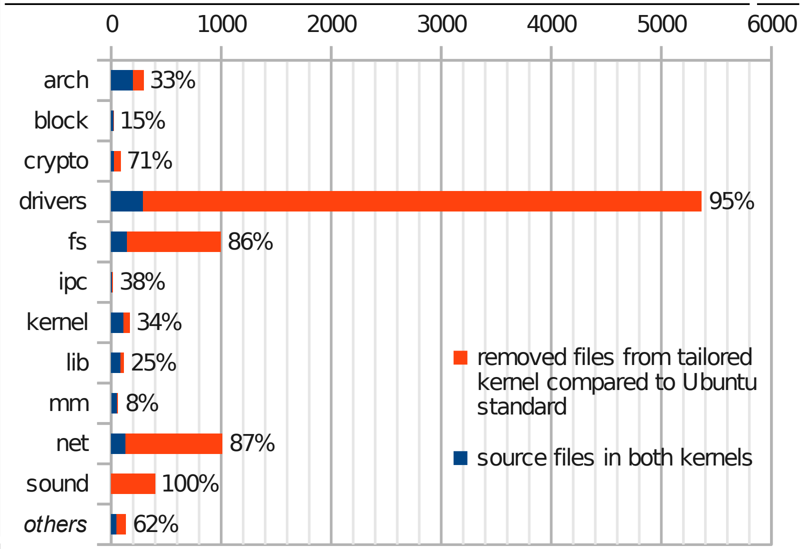
2. Run test load, observe
   - trace invoked kernel code
   - address ↦ `#ifdef` block
3. Map to partial config
   - blocks ↦ dependend blocks
   - blocks ↦ features
4. Expand to full config
   - apply white/black list
   - resolve constraints



Automatic Tailoring: Results [4, 6, 9]

- x86-based server/workstation systems (LAMP, Desktop with NFS)
  - 90% fewer features, 9 entries on white list (out of 495–555)
  - 90% less executable code
  - 10% fewer functions with CVE entries
- ARM-based low-cost appliances (raspBMC, Google Coder, Onionπ)
  - 70% fewer features, 14 entires on white list (out of 471–497)
  - 75% less executable code
- ARM-based high-end ASIC (Nexus 4 with Ubuntu Phone)
  - 30% fewer features, 14 entries on white list (out of 850)
  - 25% less executable code

Evaluation: Reduction for LAMP



Results: Automatic Tailoring [9]

HotDep '12: Tartler, Kurmus, Ruprecht, Heinloth, Rothberg et al. [9]

- 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 ⇝ CFG analysis
  - At runtime: Block illegal invocations.

Summary

- Real-world system software offers thousands of features
  - eCos: 1,250 features } mostly induced by hardware!
  - Linux: 12,000 features
  - 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 ↦ VAMOS/CADOS
  - already found thousands and fixed hundreds of defects and bugs
  - more to come!

Referenzen

[1] Thorsten Berger, Steven She, Krzysztof Czarnecki, and Andrzej Wasowski. *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, and Daniel Lohmann. "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, and Daniel Lohmann. "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.

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