Konfigurierbare Systemsoftware (KSS)

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

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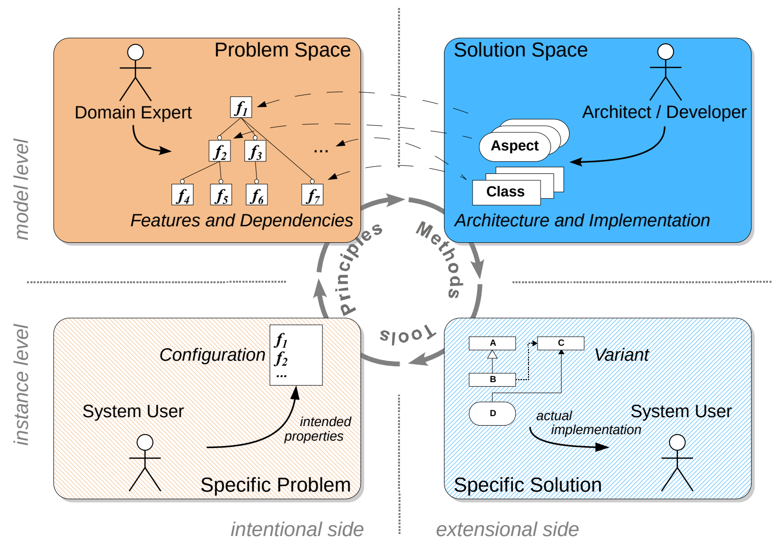
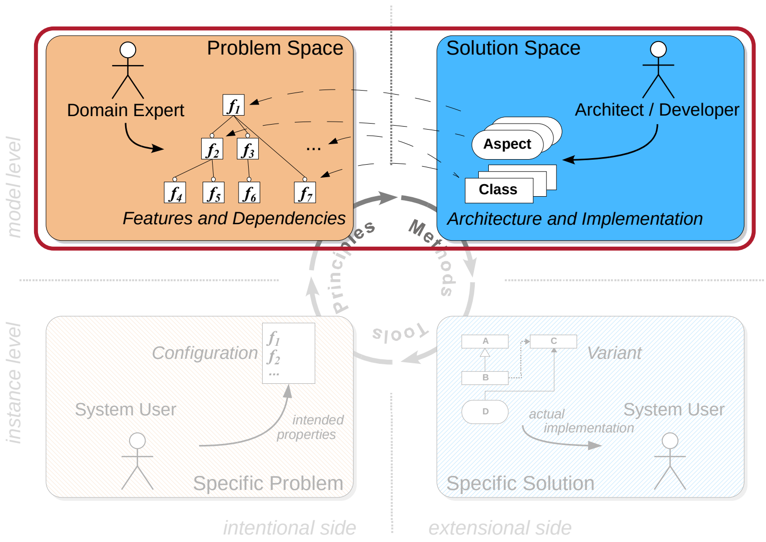
About this Lecture



About this Lecture



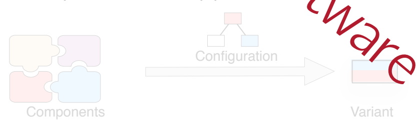
Implementation Techniques: Classification ↪ ??

Real-world software uses them all!

- Decompositional Approaches

  - Text-based filtering (untyped)
  - Preprocessors

- Compositional Approaches



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

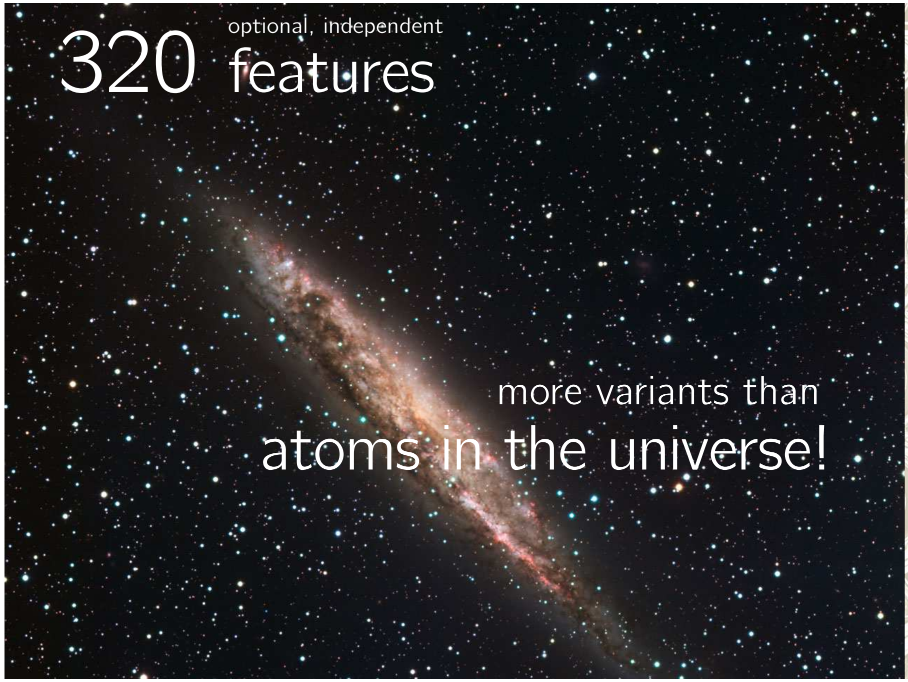
- Generative Approaches

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

Agenda

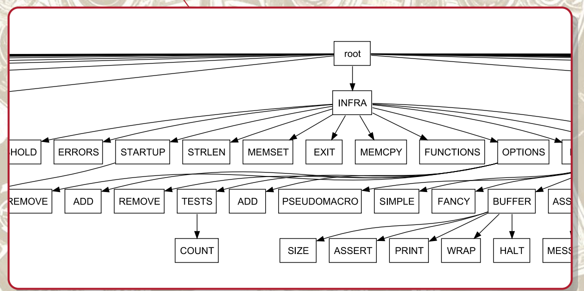
33 optional, independent features

one individual variant
for each human being



Typical Configurable Operating Systems...

ecos
1,250 features



Typical Configurable Operating Systems...

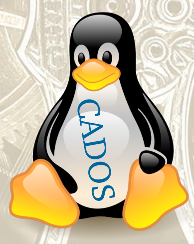
eCos

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

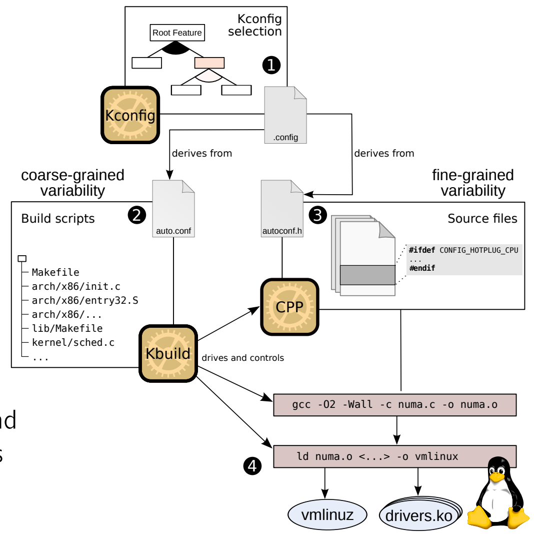


12,000 features

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



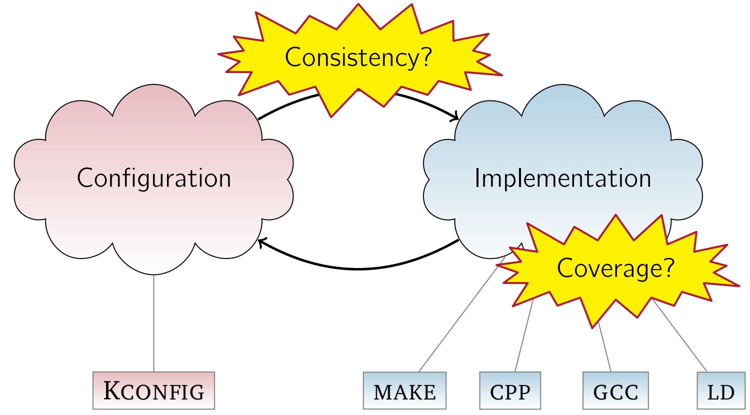
Dominancy and Hierarchy of Variability

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, ...		

$\left.\begin{matrix} l_0 \\ l_1 \\ l_2 \\ l_3 \end{matrix}\right\}$ KCONFIG controlled Variability

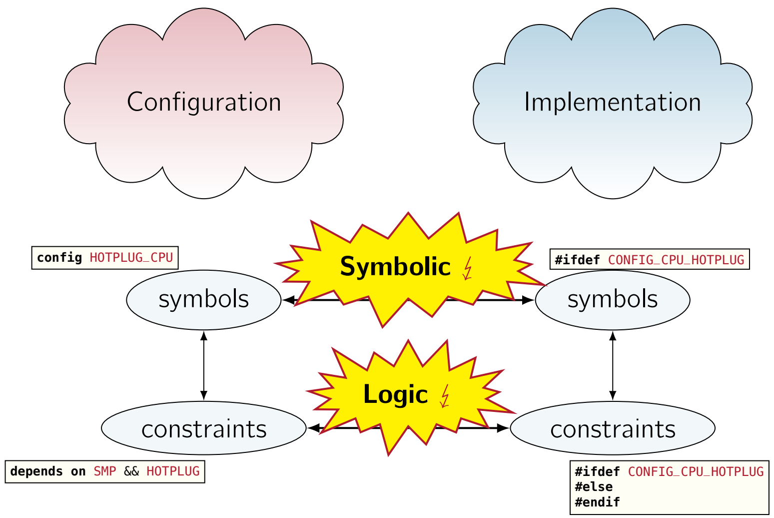
Challenges with Implemented Variability



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

Agenda

Problem Analysis: Configuration Consistency



Problem Analysis: Symbolic Inconsistency [11]

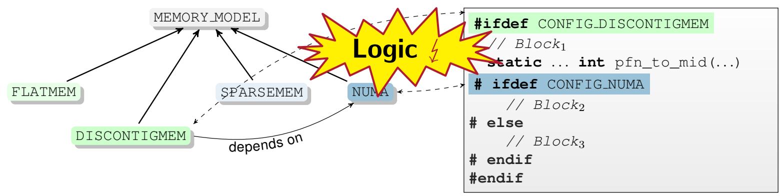
```
config HOTPLUG_CPU
    bool "Support for hot-pluggable CPUs"
    depends on SMP && HOTPLUG
    ---help---
```

```
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 ϟ

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**

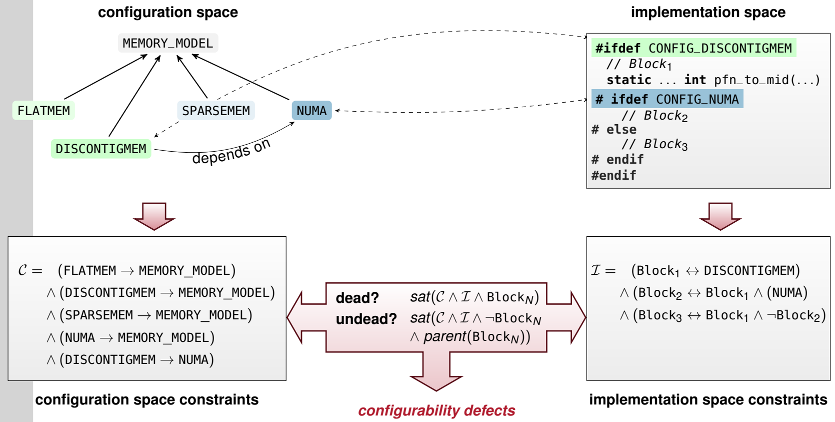
  } **configurability defects**

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

Result:
Code cleanup

Solution Approach: Consistency Validation

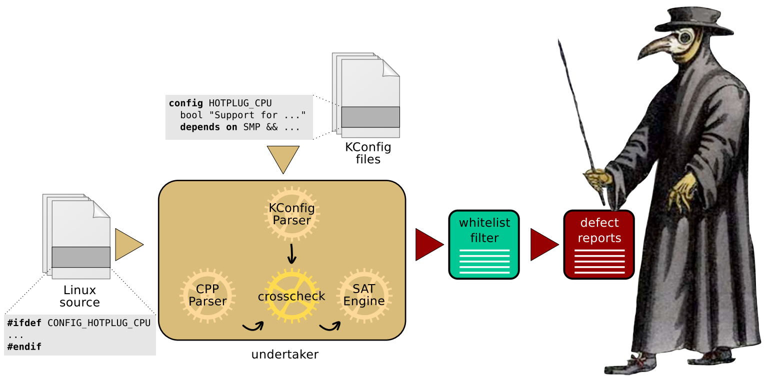
Problem and solution space are analyzed for configuration points:



⇒ and transformed into propositional formulas

Implementation: The UNDERTAKER [11]

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



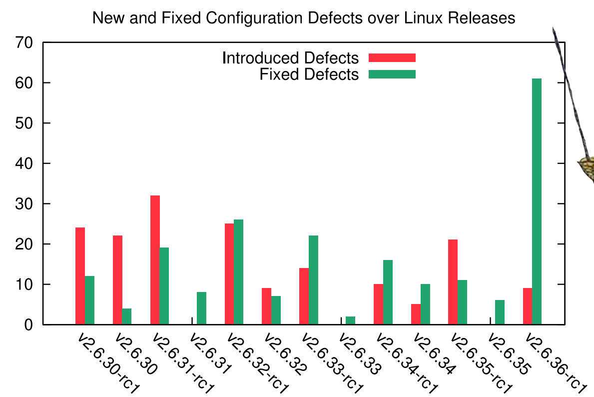
Implementation: The UNDERTAKER [11]

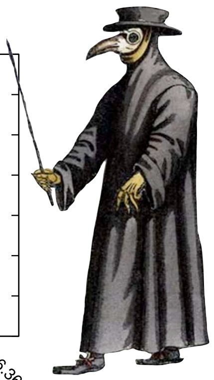
Job: Find (and eventually bury) dead `#ifdef`-code!

- 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?*

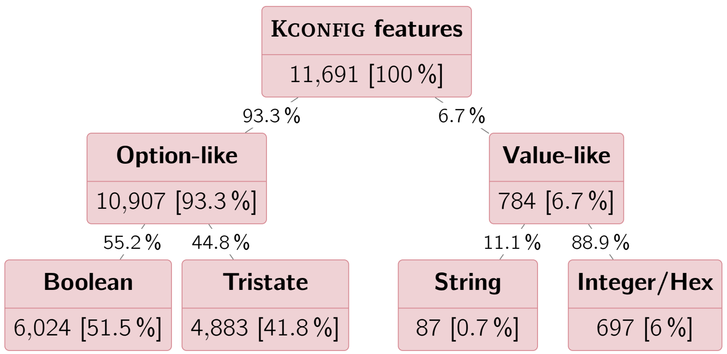
Agenda

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

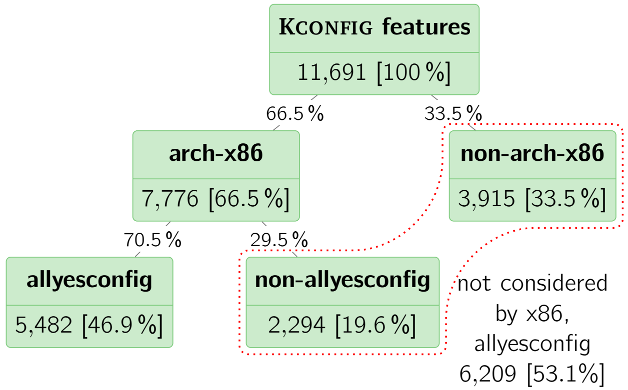
1. Most variability is expressed by boolean (or tristate) switches



⇒ Almost all features in Linux are option-like

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

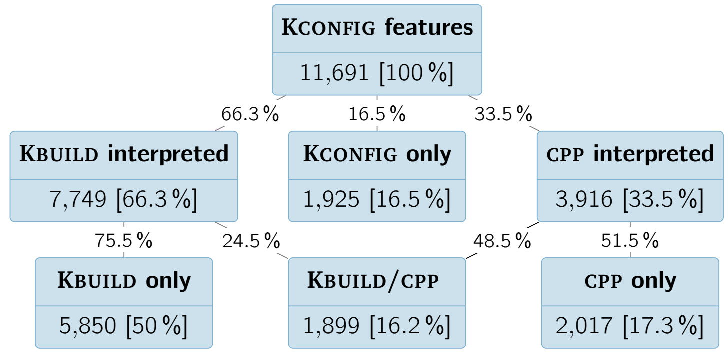
❷ arch-x86 is the largest and allyesconfig selects most features



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

Linux v3.1: Distribution by Granularity

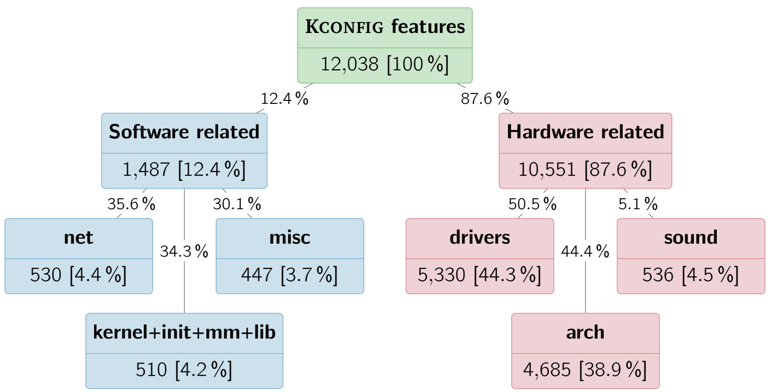
❸ Variability is mostly implemented with the CPP



⇒ KBUILD implements more than two thirds of all variation points

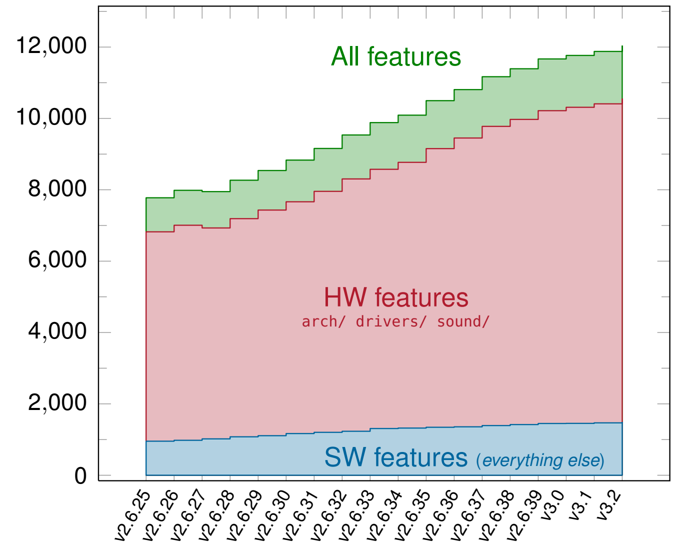
Linux v3.2: Distribution by HW/SW

❹ The Linux *kernel* is highly configurable

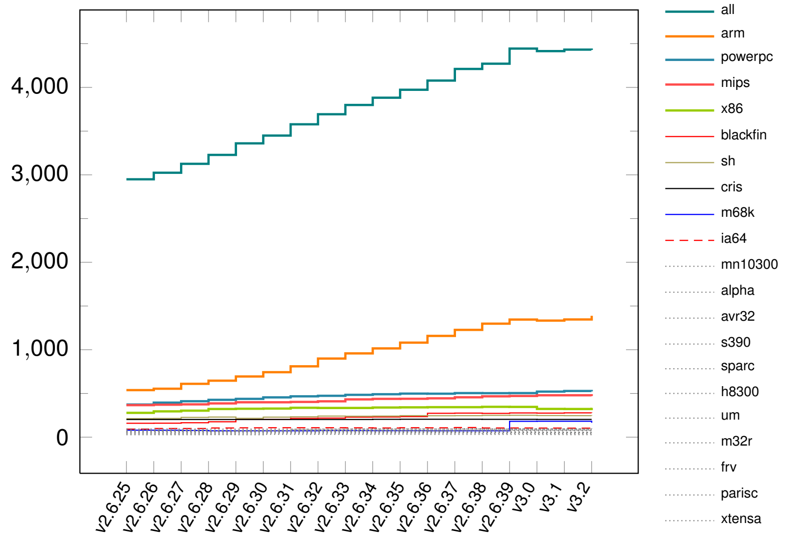


⇒ Software features account for only twelve percent of all variation points

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

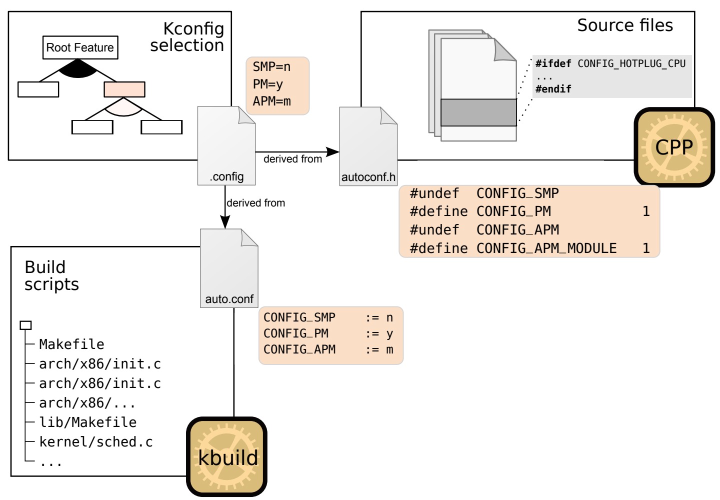
Challenges: Variability Extraction from the Build System

- 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, 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

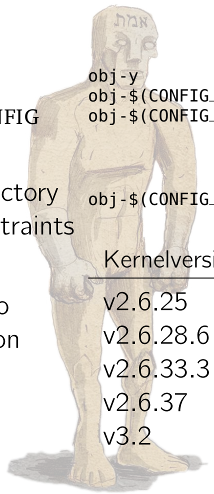
Linux Build Process Revisited



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

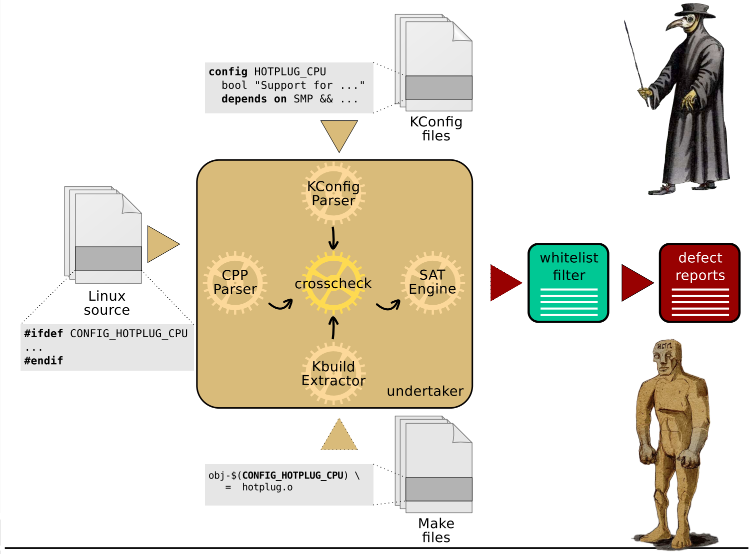
```
obj-y              += fork.o
obj-$(CONFIG_SMP)  += spinlock.o
obj-$(CONFIG_APM)  += apm.o

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%)

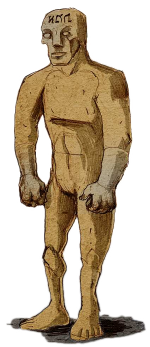
Case Study: Configuration Consistency ↪ 5–17



Case Study: Configuration Consistency ↪ 5–17

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!**

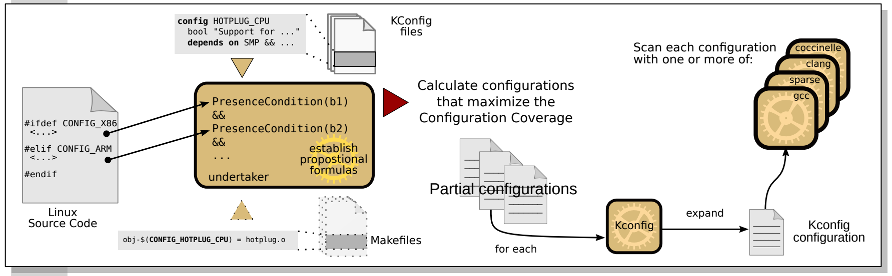
Make sure that the submitted code...

> “ *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 ... ce
  - *Stat*

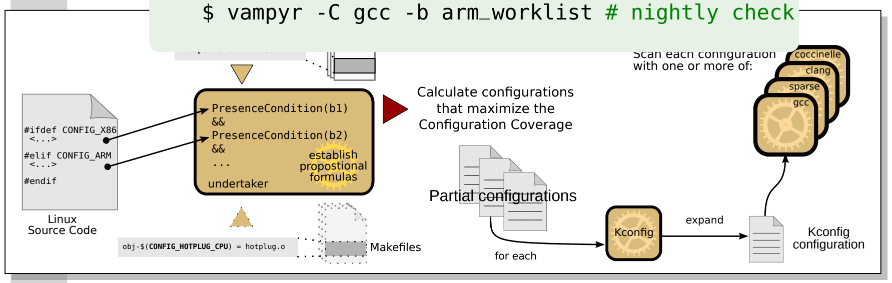
⇒ Create

- 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 [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

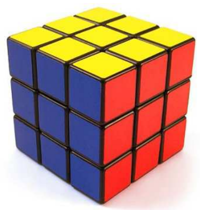
- Increased CC compared to `allyesconfig` from **60%** to **84%**
- **199 (+64%)** additional issues reported by GCC
- **91** reported issues have to be considered as **serious bugs**
- **7** patches submitted – all got immediately accepted

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.

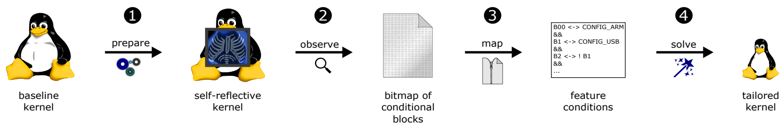
Automatic Tailoring: Approach

Main idea: "measure" needed features

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

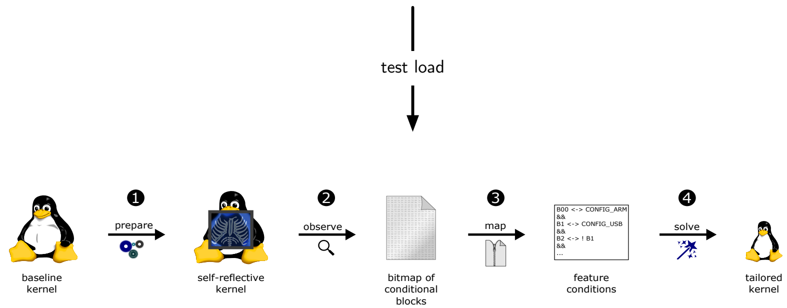
Automatic Tailoring: Approach

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



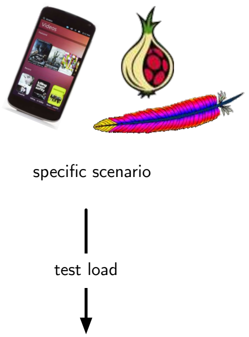
Automatic Tailoring: Approach

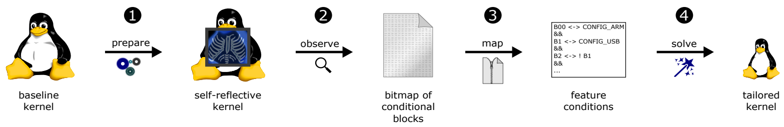
1. Prepare feature tracing
   - enable ftrace, or
   - patch source with flipper
2. Run test load, observe
   - trace invoked kernel code
   - address ↦ `#ifdef` block



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
3. Map to partial config
   - blocks ↦ dependend blocks
   - blocks ↦ features





Automatic Tailoring: Approach

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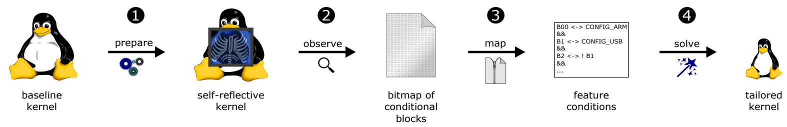
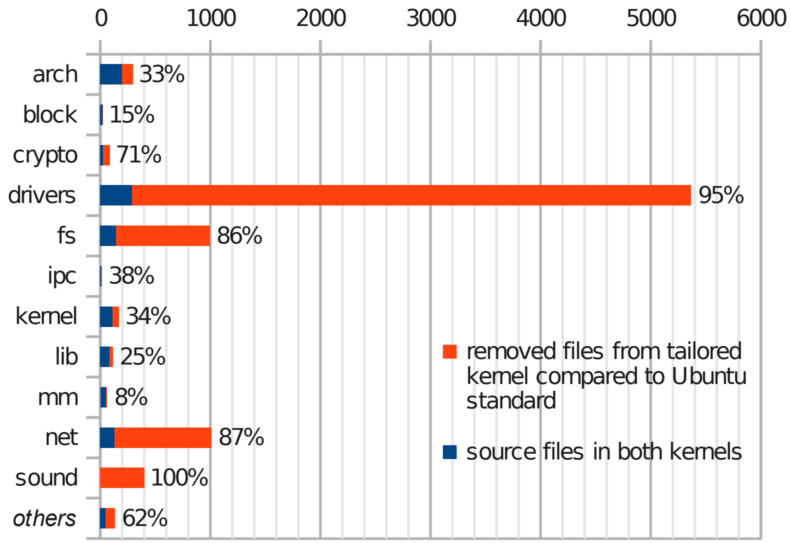
2. Run test load, observe
   - trace invoked kernel code
   - address ↦ `#ifdef` block
3. Map to partial config
   - blocks ↦ dependend blocks
   - blocks ↦ features
4. Expand to full config
   - apply white/black list
   - resolve constraints



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 entires 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 $\rightsquigarrow$ 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/CADOS
  - 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`.

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