A Robust Approach for Variability Extraction from the Linux Build System

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ABSTRACT

With more than 11,000 optional and alternative features, the Linux kernel is a highly configurable piece of software. Linux is generally perceived as a textbook example for preprocessor-based product derivation, but more than 65 percent of all features are actually handled by the build system. Hence, variability-aware static analysis tools have to take the build system into account.

However, extracting variability information from the build system is difficult due to the declarative and turing-complete MAKE language. Existing approaches based on text processing do not cover this challenges and tend to be tailored to a specific Linux version and architecture. This renders them practically unusable as a basis for variability-aware tool support – Linux is a moving target!

We describe a *robust* approach for extracting implementation variability from the Linux build system. Instead of extracting the variability information by a text-based analysis of all build scripts, our approach exploits the build system itself to produce this information. As our results show, our approach is robust and works for all versions and architectures from the (git-)history of Linux.

Categories and Subject Descriptors

D.4.7 [**Operating Systems**]: Organization and Design; D.2.9 [**Management**]: Software configuration management

General Terms

Design, Experimentation, Management

Keywords

Configurability, Maintenance, Linux, Build Systems, Kbuild, Static Analysis, VAMOS

1. INTRODUCTION

System-software product lines usually employ compile-time configuration as a simple and widely used technique for tailoring with respect to a broad range of supported hardware architectures and application domains. A prominent example is the Linux kernel.

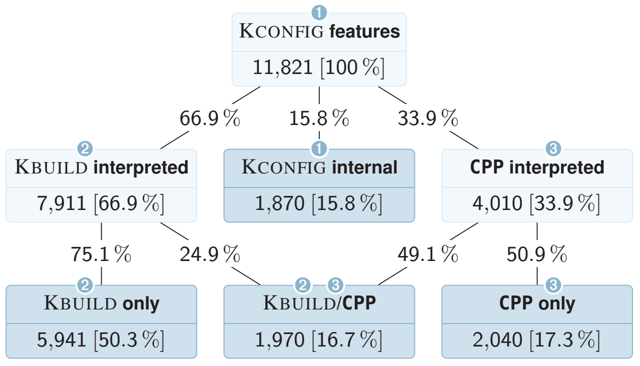

Figure 1: Statistic how the features, declared in KCONFIG, are referenced by source-code and Makefiles in Linux v3.2

The Linux KCONFIG feature model provides more than 11,000 configurable features in Linux v3.2. The thereby described *intended* variability is implemented by 28,000 source files containing 84,000 `#ifdef`-blocks.

In previous work, we could show that intended and actually implemented variability (i.e., the KCONFIG feature model and the variability points in the code) do not necessarily match. However, many configurability-related defects, such as dead `#ifdef`-code, and bugs, can be found upfront by better tool support [29]. This eventually has led to (accepted) fixes for twenty new bugs and the removal of 5,000 superfluous lines of `#ifdef`-code in Linux v2.6.36. However, these numbers are just the tip of an iceberg. The lesson to be learned from this is: Variability has to be understood, analyzed, and tested as a system property in its own respect. For a system-software product line at the size of Linux, this requires profound and robust tool support.

1.1 The Role of the Build System

A crucial building block for variability-aware static checking tools are reliable extractors that transform the *actually implemented* variability from their various sources into a formal model. Existing studies (including our own) have mostly focused on the C Preprocessor (CPP) as a means to implement features in Linux [13, 14, 25, 28, 29]; however, in Linux, variability is mostly implemented in a more coarse-grained manner (Figure 1): Only a third (33.9%) of all features do affect the work of the CPP, that is, have an effect on the sub-file level. On the other hand, two third (66.9%) of all features are referenced in the build system (KBUILD). These features have an effect on the selection of whole files into the build process. Hence, we need robust tools to extract the implementation variability from the Linux build system.

1.2 Related Work in a Nutshell

Approaches to extract implementation variability from KBUILD have previously been published by Berger et al. [4] and Nadi and Holt [18]. A common characteristic of both approaches is that they rely on *text processing* of makefiles, that is, they employ parsing (Berger et al.) or clever regular expressions (Nadi and Holt) to extract the presence implications for Linux source files from the build scripts. However, the underlying MAKE language is a declarative and turing-complete language; its advanced features, such as the `$(eval)`, `$(shell)`, or `$(wildcard)` functions, make it notoriously difficult to analyze. If these features are used, a text-processing–based approach quickly hits its limits, since the enclosed fragments may be for instance arbitrary shell command.

Even worse from a practical point of view is, however, that the existing approaches are brittle with respect to evolutionary changes in the KBUILD system itself: To achieve good results, they have to provide explicit support for many corner cases of KBUILD analysis, which effectively tailors them for a specific Linux version and architecture. While this might be perfectly acceptable if the goal is to analyze a certain Linux version, it renders them as practically unusable as a basis for general variability-aware tool support – Linux is a moving target.

1.3 About this Paper

The contribution of this paper is a *robust* approach for extracting implementation variability from the Linux KBUILD system. Instead of text processing, our approach exploits the build system itself to produce this information. Thereby, our approach is not only simple to implement, but also robust with respect to evolutionary changes and the usage of advanced MAKE features. Our evaluation results show that our approach works for all versions and architectures from the (git-)history of Linux and reliably extracts presence conditions for more than 93% percent of all source code files. In two applications, we show that the presented implementation significantly improves our previous results on configuration defects [29] and configuration coverage (CC) [28].

The context of this work is the VAMOS [1] project, funded by the German Research Council (DFG). The goal is to provide practical tools for analysis and management of variability in system software. So far the produced tool hav produced over 100 patches that have been integrated into the Linux mainline kernel.

The remainder of this paper is structured as following: In Section 2, we introduce the background and technical context and analyze the challenges in build-system analysis. This is followed by the description of the basics of our approach in Section 3. Then, we analyze the results in Section 4, followed by two applications in Section 5. After discussing the results in Section 6 and an overview over further related work in Section 7, the paper concludes with Section 8.

2. VARIABILITY IN LINUX

The scattered nature of variability and variability implementation in Linux makes holistic reasoning challenging. In practice, the analysis of the different models, languages and representations of variability requires very specialized and sophisticated extraction tools. A solid understanding of how the Linux build system KBUILD and the configuration tool KCONFIG play together is instrumental to correctly relate variability implementations from different extraction tools. This subsection analyzes the mechanics of KBUILD and identifies the challenges for an automated extraction of variability.

[1] **V**ariability **M**anagement in **O**perating **S**ystems

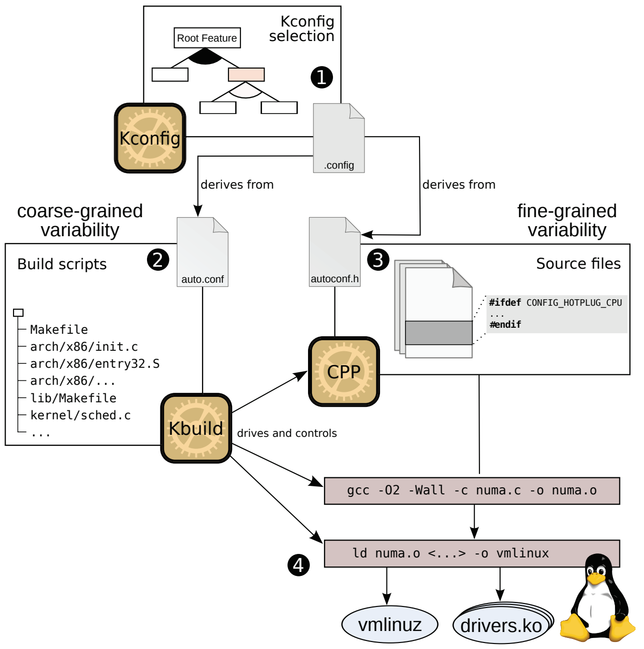

Figure 2: Overview of the technical realization of software variability in Linux. The coarse-grained varibility implemented in makefile dominates fine-grained varibility in `CPP` code.

2.1 Levels of Variability

In a nutshell, static configurability is specified and implemented in Linux top-down on three major levels, for which Figure 1 illustrates their quantitative relevance:

❶ The configuration system (KCONFIG) defines the available features and their constraints (*intended variability*) and provides an interface to specify and manage a concrete (product) **configuration**.

❷ The build system (KBUILD) implements *coarse-grained variability* in the code by inclusion and exclusion of complete translation units in the build process. The produced **build products** include object files, the bootable kernel image and loadable kernel modules (LKMs).

❸ The `CPP` implements *fine-grained variability* by inclusion or exclusion of `#ifdef`-blocks within the files selected by KBUILD.

Figure 2 describes the Linux toolchain that drives the compilation process. At the top, the Linux feature model defines the (intentional) **product line variability** [16, 20]. Here, the user selects a concrete product configuration with the KCONFIG tool and saves his selection to a file named `.config`. The Linux build system KBUILD transforms the thereby encoded feature selection into two further representations: An `auto.conf` file in MAKE-syntax and an `autoconf.h` file in `CPP` syntax (Figure 3). Technically, these representations control the (extensional) **software variability** [16, 27] in makefiles and C source code during the compilation process.

For the `CPP` representation, an additional normalization step is applied for tristate features: Many features, especially device drivers, can be configured as *compiled into kernel*, *compiled as loadable kernel module* or *disabled*. To ease the use in `#ifdef` statements, KCONFIG maps this to boolean flags by inserting an additional `CPP` variable with the `_MODULE`, suffix into `autoconf.h` for each tristate feature (Figure 3).

(a) KCONFIG output: .config

```
SMP=n
PM=y
APM=m
```

(b) MAKE representation: auto.conf

```
CONFIG_SMP    := n
CONFIG_PM     := y
CONFIG_APM    := m
```

(c) CPP representation: autoconf.h

```
#undef  CONFIG_SMP
#define CONFIG_PM           1
#undef  CONFIG_APM
#define CONFIG_APM_MODULE   1
```

Figure 3: Representation of a feature selection

In Step ❷, the MAKE representation of the current feature selection is then used by KBUILD to implement the coarse-grained variability on a per-file basis. All thereby included translation units are passed to the compiler, which in turn uses the CPP representation during preprocessing (Step ❸) to implement the *fine-grained* configurability. The invocation of the compiler and linker is, however, controlled by KBUILD,[2] which again uses the MAKE representation of the current feature selection to construct compiler and linker options used in Step ❹ for creating the build goals: The `vmlinuz` kernel image and the library of loadable driver objects.

2.2 Variability Implementation in Kbuild

As detailed in the previous section, KBUILD gets a file `auto.conf` that describes all selected features and their values in MAKE syntax. KBUILD then resolves which file implements what feature, determines the set of translation units that are relevant for a given configuration selection, and invokes the compiler for each translation unit with potentially configuration-dependent settings and compilation flags. Internally, KBUILD employs GNU MAKE [26] to control the actual build process; in Linux v3.2 the mapping from features to translation units is encoded in 1,568 makefiles that are spread across the source tree. However, Linux makefiles look quite different from typical text-book makefiles as they employ KBUILD-specific idioms to implement Linux-specific (variability) requirements, such as [11]:

- **Optional features:** Many features, such as drivers, are present (or absent) by deciding about the inclusion of their respective implementation files.
- **Tristate features:** Linux allows most drivers to be compiled either statically into the kernel or as LKM.
- **Loose coupling:** The decision about what set of files is used for a given configuration can be specified at various levels of granularity (such as disabling a complete subsystem by not descending a subdirectory).

In the following, we provide further details on these idioms, as they are relevant for this paper.

2.2.1 Optional and Tristate Features

In all makefile fragments, we can find two variables that collect selected and unselected object files: The make variable `obj-y` contains the list of all files that are to be statically compiled into the kernel. Similarly, the variable `obj-m` collects all object files that will be compiled as LKM. Object files in the make variable `obj-n` are not considered for compilation. The suffixes {`y,m,n`} are added by the expansion of variables from `auto.conf` (Figure 3).[3] This pattern for managing variability with KBUILD is best illustrated by a concrete example:

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

In line 1, the target `fork.o` is unconditionally added to the list `obj-y`, which instructs KBUILD to compile and link the file directly into the kernel. In line 2, the variable `CONFIG_SMP`, which is taken from the KCONFIG selection, controls the compilation of the target `spinlock.o`. The variable derives from the feature `SMP`, which is declared as `boolean`. Therefore, `spinlock.o` cannot be compiled as LKM. When the feature selection from Figure 3 (b) is applied, `CONFIG_SMP` has the value `n`, `spinlock.o` is added to `obj-n` and therefore not compiled. In line 3 the file `apm.o` is handled in a similar way to `spinlock.o`. Because the enabling feature `APM` is declared as *tristate*, it might take value `m`. With the feature selection from Figure 3 (b), `APM` has the value `m`, therefore `apm.o` is added to `obj-m` and compiled as LKM.

Note that instead of mentioning the source files, the makefile rules reference only the resulting build products. The mapping to source files is implemented by *implicit rules* (for details, cf. [26, Chapter 10]). This mapping has to be considered for any kind of makefile variability analysis.

2.2.2 Loose Coupling

Programmers specify in KBUILD makefiles the conditions that lead to the inclusion of source files in the compilation process. As shown above, this commonly happens by mentioning the respective build products in the special targets `obj-y` and `obj-m`. This works for the majority of cases, where a feature is implemented by a single implementation file. However, in order to control complete subsystems, which generally consist of several implementation files, the programmer can also include subdirectories:

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

This line adds the subdirectory `power` conditionally, depending on the selection of the feature `PM` (power management). For each listed subdirectory, its containing Makefile is evaluated during the build process. This allows a more coarse-grained control of source file compilation with KCONFIG configuration options. As we will show later in this paper, the inclusion of most source files in Linux is controlled by enabling a single configuration option.

2.3 Challenges in Build-System Analysis

While the selection process described in Section 2.2 is conceptually simple, an automated analysis is challenging because of engineering reasons. Since KBUILD is implemented with the MAKE tool, the kernel developer has many possibilities to express constraints. Not only is MAKE a full-blown programming language that supports a wide range of operations, including string modifications, conditionals, and meta-programming, it also allows the execution of arbitrary further programs ("shell escapes"). The Linux coding guidelines do not pose any restrictions on what MAKE features should be used

[2]The exact mechanisms are fairly technical and have already been discussed elsewhere (e.g., [11, 17]).

[3]The idea of this pattern dates back to 1997 and was proposed by Micheal Elizabeth Castain under the working title "Dancing Makefiles" (`https://lkml.org/lkml/1997/1/29/1`). It was globally integrated into the kernel makefiles by Linus Torvalds shortly before the release of Linux v2.4.

in KBUILD. This subsection presents a few selected examples of constructs that are present in the build system of Linux and are far more expressive than the standard constructs.

The following example is taken from `arch/x86/kvm/Makefile` and uses the function `addprefix`:

```
obj-$(CONFIG_KVM_ASYNC_PF)  += \
  $(addprefix ../../../virt/kvm/, async_pf.o)
```

The `addprefix` function takes an arbitrary amount of arguments, prepends its first argument to the remaining ones, and returns them. In this case using `addprefix` is not really necessary, because there is only one additional argument and the whole expression is equal to `../../../virt/kvm/async_pf.o`. Nevertheless, this case requires special handling with a text-processing–based approach.

In KBUILD, programmers also use generative programming techniques and loop constructs, like in this excerpt taken from `arch/ia64/kernel/Makefile`:

```
ASM_PARAVIRT_OBJS = ivt.o entry.o fsys.o
define paravirtualized_native
AFLAGS_$(1) += -D__IA64_ASM_PARAVIRTUALIZED_NATIVE
[...]
extra-y += pvchk-$(1)
endef
$(foreach obj,$(ASM_PARAVIRT_OBJS),$(eval $(call
     paravirtualized_native,$(obj))))
```

Here, a list of implementation files (`ivt.S`, `entry.S` and `fsys.S`) not only need to be included, but also require special compilation flags. In this example, the macro `paravirtualized_native` is evaluated for all three implementation files by the MAKE tool at compilation-time. Again, for a text-processing–based approach, this corner case is challenging to implement in a general manner.

Even worse is the `shell` function, which makes it possible to spawn an arbitrary external program to let it control (parts of) the compilation process.

The text-processing–based approaches [4, 18] both fail on the examples shown above. Luckily – and this comes to their rescue – these MAKE language features are currently not used very frequently in KBUILD. However, they *are* used[4] and their usage is not discouraged by Linux coding guidelines. On the longer term, this implies a danger regarding the robustness of text processing as a means to extract variability information from the Linux build system. In the following, we therefore devise a pragmatic approach that, conceptually and practically, is robust with respect to these challenges.

3. EXPERIMENTAL PROBING FOR BUILD-SYSTEM VARIABILITY

In order to enable variability analyses, such as consistency checks with the KCONFIG feature model [29] or variability aware static analysis with existing tools [28], the results of the variability extractors may require a normalization step. Literature proposes propositional formulas as lingua franca for combining the different sources of variability (e.g., [4, 13, 15, 18]). Similar to [4, 18] , we extract propositional formulas that model the behavior of KBUILD, similar as we did in previous work for the CPP [24].

The set of files that KBUILD produces during the compilation process depends on selection of features done by KCONFIG. The basic idea of our approach is to (partially) execute KBUILD with different feature selections and observe the behavioral changes. This allows to correlate variability points in the feature model with the produced build products.

[4]In Linux v3.2, we count for `shell`: 127, `foreach`: 16, `eval`: 3, and `addprefix`: 88 occurrences.

The presence implication of a source file is determined by the feature selections that include the file in the compilation process. Therefore, in order to extract the presence implication for a specific source file, all feature selections that enable this file need to be recorded. Our approach exploits this observation and determines for each file all selections that include the file during the compilation process.

Instead of parsing the makefile, our approach is based on "clever probing": Basically, we "ask" the build system for each feature which files it *would* built. The basic idea is to investigate a feature selection S_{base}, which uses the set F_{base} during the compilation process. Now we add one additional feature f_1 to it. The new feature selection $S_1 := S_{\text{base}} + \{f_1\}$ now compiles the set of files F_1. For every file that is in F_1 but not in F_{base} we have found a feature selection that enables this particular file.

3.1 Subdirectories

As discussed in Section 2.2.2, not necessarily all subdirectories in the Linux source tree are traversed at compilation time. Subdirectories are therefore not only used to organize files for the programmer, but also for implementing build-system variability. We address this in our approach by treating subdirectories that appear in the file sets F_{n+1} in a special way: For each subdirectory we determine the condition under which the compilation process traverses it. If the condition is non-trivial, then it is taken as precondition (the "base expression") to all presence condition of its included files. After processing all files in the file set F_n, each of the included subdirectories is processed recursively.

3.2 From Feature Selections to File Sets

Our approach relies on the following primitive operation to find the file set and all considered subdirectories that are associated to a feature selection:

$$\textit{list} : \text{Selection} \longmapsto (\text{FileSet},\ \text{SubDirs}) \qquad (1)$$

This primitive is essential for any build system that implements variability. There are several options how this can be implemented for a given build system. As a last resort, the mapping could be extracted from build traces of a real build process [cf. 2]. However, in order to avoid unnecessary compilation steps, an efficient extraction of this mapping is essential.

For KBUILD, our implementation traverses the source tree in the same way the regular compilation process. Hereby, MAKE collects all selected files and the visited subdirectories into lists (technically MAKE variables), which are used internally to drive the compilation. We make use of these implementation internals and therefore exploit the built-in KBUILD functionality to ensure an accurate operation of the *list* primitive. The full implementation is available for download from the VAMOS website [30].

As an additional optimization, our implementation ignores logical constraints that stem from KCONFIG declarations, which allows us to reduce the number of necessary probing steps. This optimization would not have been possible to implement using build traces, which (successfully) compiles and links only valid configurations.

3.3 Base Selection and Added Features

The algorithm starts with the empty selection $S_\emptyset$ as starting point for the recursion, which serves as base point for the file set and subdirectory differences. The empty selection contains no selected feature at all; it is therefore not a valid configuration according to the KCONFIG model. This base file set only includes files that are included in every configuration. One example of such a file is kernel/fork.c, which is essential for the process creation and therefore needed in every configuration.

$$(F_{\text{base}}, D_{\text{base}}) = list(S_\emptyset) \tag{2}$$

The files F_{base} selected by $S_\emptyset$ are unconditionally compiled into the kernel. In Linux v3.2 arch-x86, our implementation detects 334 such unconditional files. $S_\emptyset$ also selects the subdirectories D_{base}, which are the starting point for the build system during the source tree traversal. The presented approach uses F_{base} and D_{base} in the same manner as starting point.

In the process of adding single features to the base selection, it is necessary to know which variables have to be considered. We exploit the fact that the Linux source tree is organized hierarchically: Each conditional subdirectory carries, in addition to the base selection, a base directory d_{base}. All features referenced in the makefile of a base directory are added to the list of features to probe.

$$features\_in\_dir : \text{Directory} \longmapsto \text{FeatureSet} \tag{3}$$

For KBUILD, the *features_in_dir* function is straight-forward to implement with regular expressions that extract all referenced variables in the Makefile that start with CONFIG_. This is also some sort of text processing, but in contrast to the competing approaches [4, 18], we just extract the feature identifiers and not their (context-dependent) semantics. Therefore, the *features_in_dir* function also detects referential KCONFIG $\leftrightarrow$ KBUILD defects, similar as described by Nadi and Holt in [18]. By excluding undeclared configuration variables from the FeatureSet, we reduce the number of necessary probing steps.

3.4 Build-System Probing

```
1:  function KBUILDPROBE
2:      vDirs ← empty set                              ▷ set of visited dirs
3:      filePC ← empty map [ File → list [ Selection ]]
4:      $(F_{base}, D_{base}) = list(S_\emptyset)$
5:      for all $d_{base}$ in $D_{base}$ do
6:          KBuildProbeRecursion($d_{base}$, $S_\emptyset$, $F_{base}$)
7:      end for
8:      for all (file, selections) in filePC do
9:          toPC(file, selections)
10:     end for
11: end function
```

Figure 4: Starting-Point for the Build-System Probing

Figure 4 shows the recursion step over the source tree for probing the file presence implications. The recursion is done only once for each directory. In line 2, a set of already visited directories is initialized. The resulting selections for each file is stored in filePC, which holds a list of selections for each file (line 3). For each directory that is considered by the empty selection $S_\emptyset$, we start the recursion in line 6 to dig into the source tree beginning at the directory. After all file sets have been calculated, the presence implications for all source files are calculated by the helper function *toPC* in line 9.

In Figure 5, the recursion step, which is executed for every subdirectory that may be considered by KBUILD, is shown. The function *KBuildProbeRecursion* takes three arguments: The first argument d_{base} is the directory this function call should focus on. S_{base} contains the features that are necessary to visit d_{base} in the first place. The third argument is the file set associated with S_{base}. Our implementation avoids unnecessary recalculation of F_{base} by caching the result.

```
1:  function KBUILDPROBERECURSION($d_{base}$, $S_{base}$, $F_{base}$)
2:      if $d_{base} \in$ vDirs then                      ▷ already visited
3:          return
4:      end if
5:      vDirs ← vDirs ∪ {$d_{base}$}                       ▷ mark as visited
6:      features ← $features\_in\_dir(d_{base})$
7:      for all $f$ in features do
8:          $S_{new} \leftarrow S_{base} \cup \{f\}$              ▷ add one feature
9:          $(F_{new}, D_{new}) \leftarrow list(S_{new})$
10:         for all file in $(F_{new} - F_{base})$ do
11:             filePC[file].append($S_{new}$)           ▷ new files found
12:         end for
13:         for all dir in $(D_{new} - D_{base})$ do
14:             KBuildProbeRecursion(dir, $S_{new}$, $F_{new}$)
15:         end for
16:     end for
17: end function
```

Figure 5: Recursion step in the Build-System Probing.

Lines 2 to 5 ensure that each directory is only visited once and the recursion terminates in finite steps. The function *features_in_dir* is called in line 6 to determine all features that are used in the directory's makefile. These features will be probed together with the base selection against this Makefile. A new feature selection S_{new} is created (line 8) as an extention to S_{base} for each of these features. For this feature selection, all considered files and subdirectories are collected by a call to *list* in line 9. The difference between the new file set and the old file set are all files that are additionally enabled by the current feature. The feature selection is added in line 11 to all additionally enabled files. Similar to this, we recurse into the file system hierarchy for each newly detected directory in line 14. The newly detected directory is used as base directory and S_{new}, with the associated file set, as base selection. The conversion from the feature selections to the presence implications for a file is straightforward:

$$toPC(\text{File}, \text{Selection}) = \text{File} \rightarrow \bigvee_{S \in \text{Sels}} \left(\bigwedge_{f \in S} f \right) \tag{4}$$

Each selection is a conjunction of the set features that must be enabled in order satisfy the developer-specified KBUILD constraint to compile the file. Multiple selections occur when there are multiple rules that require the source file to be compiled. In case of multiple selections, all selections are disjuncted, because any of these disjunction leads to the inclusion of the file in the compilation process.

The resulting propositional formula can by simplified, for instance by removing selections that are a full subset of another selection.

4. EVALUATION

In the following, we evaluate our approach and compare it to the existing approaches. We start with a general description and compare the three respective implementations, which is followed by analyses regarding run time, robustness and coverage.

4.1 Implementation Overview

The GOLEM tool

We have implemented the algorithms from Section 3 into the GOLEM tool which is part of our VAMOS [30] toolchain [28, 29]. The implementation encompasses about 1,000 lines of Python code.

The KBUILD specific probing primitives are implemented in two additional "front-end" makefiles (about 120 lines of MAKE code), so that not a single line in Linux had to be changed for the analysis. The tools are freely available on the project website.

KBUILDMINER

KBUILDMINER by Berger and She [3] has been presented on a poster at SPLC '10 [5] and is further detailed in a technical report [4]: A fuzzy parser transforms KBUILD makefiles into an abstract syntax tree (AST), which is then transformed into presence conditions. The implementation consists of about 1,400 lines of Scala code and 450 lines of Java code. The tool, as well as a result set for Linux v2.6.33.3, have been downloaded from [3]. Because this tool requires manual modification of existing makefiles (the technical report states that for Linux v2.6.28.6, 28 makefiles were adapted manually [4]), it is not easily possible to apply it to arbitrary versions of Linux.

The UNDERTAKER Extension by Nadi

Nadi and Holt [18] have implemented their KBUILD extractor independently from us. Similar to our GOLEM tool, this extractor calculates logical constraints that our UNDERTAKER tool [29] can use directly. Their implementation employs pattern matching in Linux makefiles to identify variability in KBUILD. It consists of about 750 lines of Java code. While not (yet) publicly available, the authors have kindly provided us with the version that has been used in [18].

4.2 Runtime

All parsing-based approaches are (persumably) much faster than the GOLEM implementation presented in this paper. For KBUILDMINER [4], no run-time data is available. The parser by Nadi and Holt [18] processes a architecture in under 30 seconds. The current GOLEM implemenation takes approximately 90 minutes per architecture. The obvious bottleneck is the run-time and the amount of probing steps, which have been described in Figure 4. For Linux v3.2 `arch-x86`, the *list* operation takes about a second (depending on the selected features and filesystem cache state) and was executed 7,073 times.

However, the *list* function does neither modify the analyzed source tree, nor exhibit other side effects. We therefore see a great potential in improving the performance by running several probing steps in parallel. For practical applications, the large runtime overhead has little big impact on the usability of the approach, because for many applications, such as the applications in Section 5, the variability extraction has to be done only once per version and architecture.

4.3 Robustness

As Linux is a moving target, variability identification and extraction approaches need to be both conceptually as well as implementation-wise robust. In order to evaluate the property of robustness for future versions of Linux, we test on a wide-ranged number of Linux versions have been retrieved from the git history. We choose five Linux releases with one year distance that cover 4 years of the Linux development (2008-2012). In order to keep the results for the various implementations comparable, we refrain from analyzing earlier versions than Linux v2.6.25, because the `arch-x86` architecture was introduced in v2.6.24 by merging the 32bit and 64bit variants, which were previously maintained separately. Table 1 summarizes the results of this analysis.

In general we found it challenging to apply the parsing-based approaches to Linux versions for which they have not been tailored to.

Table 1: Direct quantitative comparsion over Linux versions over the last 5 years. The Kernel versions are roughly equidistant over the time and include all version for which dataset are available for KBUILDMINER and the Nadi Parser.

All source files for v2.6.25 (w/o `#included` files)	6,826	(127)
Files hit by KBUILDMINER	*data not available*	
Files hit by GOLEM	6,274	(93.7%)
Files hit by Nadi parser	*tool crashes*	
All source files for v2.6.28.6 (w/o `#included` files)	7,665	(153)
Files hit by KBUILDMINER	7,243	(96.4%)
Files hit by GOLEM tool	7,032	(93.6%)
Files hit by Nadi parser	*tool crashes*	
All source files for v2.6.33.3 (w/o `#included` files)	9,827	(261)
Files hit by KBUILDMINER	9,090	(95%)
Files hit by GOLEM	9,079	(94.9%)
Files hit by Nadi parser	7,154	(74.8%)
All source files for v2.6.37 (w/o `#included` files)	10,958	(292)
Files hit by KBUILDMINER	*data not available*	
Files hit by GOLEM	10,145	(95.1%)
Files hit by Nadi parser	7,916	(74.2%)
All source files for v3.2 (w/o `#included` files)	11,862	(276)
Files hit by KBUILDMINER	*data not available*	
Files hit by GOLEM	11,050	(95.4%)
Files hit by Nadi parser	8,592	(74.2%)

For the fuzzy-parsing approach presented by Berger et al. [4], there are only data sets for Linux version v2.6.28.6 [4] and v2.6.33.3 [3] available. For all other versions we were unable to produce any results, because of the necessary (but undocumented) changes of the Linux makefiles. These modifications include the disabling parts of `arch/x86/Makefile` in a way that break a regular compilation. The technical report leaves it open what effects these changes have on the extracted logical constraints.

The parsing approach presented by Nadi and Holt [18] does not require any modifications to existing Makefiles. We were able to produce presence implications for two additional versions. Unfortunately, the tool crashes with an endless recursion and a stack overflow on Linux v2.6.28.6 and earlier, so that no logical constraints could be obtained.

The presented approach and implementation in this article produces presence implications on all selected versions without requiring any source code modification or version specific adaptations. Also, the extraction process for the 22 other architectures in Linux v3.2 did not require any further modification.

As shown in this section, both parsing-based approaches have difficulties to achieve a robust operation on a wide range of versions. Since the Linux build system is still in active development and difficulties like those described in Section 2.3 may appear with every new version, every new introduced MAKE idiom requires manual (and thus error-prone) additional engineering in order to keep up with the Linux development. In contrast to to that, our approach works in a robust manner with stable results for each version without any further adaptations.

4.4 Coverage

This subsection compares the results of the three KBUILD variability extractors quantitatively. We do this by analyzing for how many source files the respective approach produces a logical formula as metric for their coverage in the Linux v2.6.33.3 source tree for `arch-x86`. We choose this source tree because it is the most recent version of Linux for which results of all tools are available.

For that version, KBUILD handles a total of 9,827 source files. As pointed out by Nadi and Holt [17], 276 of these source files (2.8%) are referenced by `#include`-statements in other implementation

Table 2: Configuration Defect Analysis Results with Linux v3.2

Configuration Defects without file constraints	
Code defects	1835
Referential defects	415
Logical defects	83
Total:	Σ 2333
Configuration Defects with file constraints	
Code defects	1835
Referential defects	439
Logical defects	299
Total:	Σ 2573

source files rather than KBUILD rules in KBUILD.

The UNDERTAKER extension by Nadi and Holt [18] approach identifies presence implications for 7,154 out of all source files (74.8%). For 2,412 source files, no logical implication was found. A quick analysis of the data indicates that deficiencies in the mapping from build products to source files (cf. Section 2.2.1) are part of the problem for this relatively high number.

An analysis of the data provided for KBUILDMINER [3] on the tool's website for `arch-x86` shows that the tool produces presence implications for 9,090 out of all source files (95%) on Linux v2.6.33.3, `arch-x86`. This data is consistent to the technical report [4], which states a coverage of 94 percent on Linux v2.6.28.6, `arch-x86`.

The current implementation of our GOLEM tool calculates presence implications for 9,079 out of the 9,566 source files on Linux v2.6.33.3 (94.9%) on `arch-x86`.

5. APPLICATIONS

As part of the VAMOS project [30], we aim at providing (Linux) developers tool support for managing and maintaining variability. This goal includes finding configuration defects [29] and making existing tools for static analysis variability-aware [28]. The remainder of this section demonstrates the improvements of considering the build system in these tools.

5.1 Configuration Defect Analysis

In earlier work [29], we have discussed and analyzed configuration-derived defects in the variability implementation on an earlier version of Linux v2.6.35. Such defects are inconsistencies in the variability implementation, such as `#ifdef` blocks that either cannot be selected under any configuration selection (a *dead* block), or there is provably no configuration that deselects a `CPP` block (an *undead* block). Our UNDERTAKER tool creates for each `#ifdef` block a set of propositional formulas and checks their satisfiability with a SAT Checker. The first formula includes only the constraints that are found in the structure of the `CPP` statements [cf. 24]. If this formula is unsatisfiable, then the block is classified as a *code defect*. If it is satisfiable, logical constraints that derive from the KCONFIG feature model are added as further conjunctions to the formula. If the enriched formula is unsatisfiable, the UNDERTAKER tool classifies the `CPP` block as a *logical defect*. This formula may (still) contain configuration variables that are not declared in the configuration model for this architecture (e.g., `CONFIG_ARM` is not present on `arch-x86`, etc.). The third formula therefore adds contraints to set such absent variables to false, and checks for satisfiability again. If this enriched formula is now unsatisfiable, then the UNDERTAKER tool classifies the `CPP` block as *referential defect*.

For this kind of analysis, our tools, which (now) include the extracted variability from KBUILD, do not only need to be robust regarding the Linux version, but also the analyzed architecture. A more detailed explanation of this experiment can be found in [29]. That work has yielded 1,776 configurability issues, for which 123 patches has been proposed (49 merged, 8 accepted, 15 acknowledged), which in total have fixed 364 of these issues (among them 20 confirmed new bugs).

Table 3: CC-Analysis Results with Linux v3.2, `arch-x86`

Analyzed files	10,383
Number of variation points (files + `#ifdef` blocks)	25,369
1. Comparison with 'allyesconfig'	
Number of compiler (tool) invocations	10,383
Rate of skipped invocations	18.5%
Configuration Coverage	67.2%
2. Expansion without file constraints	
Number of partial configurations	14,169
Rate of skipped tool invocations (partial configurations)	83.6%
Configuration Coverage	37.4%
3. Expansion with file constraints	
Number of partial configurations	12,388
Rate of skipped tool invocations (partial configurations)	18.2%
Configuration Coverage	78.6%

Table 2 compares the impact of the inclusion of the extracted source file constraints by our GOLEM tool on the results produced by the approach as presented in [29]. In this experiment, source file constraints from all 23 architectures in Linux v3.2 have been used to enrich the variability models. Every defect is tested against each architecture individually (where applicable) and classified as such.

In this work, we define as **variation point** every `CPP` block and source file that KCONFIG allows to include or exclude in the resulting build products. This simplifaction is valid, because the coarse-grained selection of source files by MAKE could also be implemented by `CPP` by introducing additional `#ifdef` blocks that contain the whole file.

We did not find any *dead* source files, that is, files that will never be compiled due to the constraints from KBUILD. We can therefore confirm that the contributions of Nadi and Holt [18] have fixed all these "dead files". Nevertheless, by considering KBUILD-derived constraints, the UNDERTAKER tool detects 216 additional (+260.2%) logical defects in `#ifdef`-blocks. The number of configuration defects increases by 10.3 percent. This shows that the source-file constraints have an considerable improvement on the results.

5.2 Configuration Coverage

This subsection investigates the effects of the extracted source-file constraints on the configuration coverage (CC) [28]: We define CC as the fraction of selected variation points (`#ifdef`-blocks and source files as defined in Section 2.1) divided by all possible variation points. However, one has to be careful with calculating the "possible" variation points on a specific architecture, because architecture-specific drivers or `#ifdef` blocks that test for a specific other architecture must not be counted. In order to get a fair comparison, we use our UNDERTAKER tool to detect such unselectable variation points in the 11,862 source files considered by KBUILD on `arch-x86` and exclude them from all results in this subsection.

We calculate a set of configurations which, when combined (i.e., compile each configuration individually), maximize the CC. This allows "traditional" tools for static analysis to uncover additional defects that are hidden in seldomly selected `#ifdef`-blocks. Table 3 summarizes the results. Since the analyzed source files only reference a subset of all available KCONFIG features, the produced configuration are "incomplete" in the sense that they define only referenced features. Such a *partial configuration* sets only variation points from the extracted software variability [27] of a given source file. The remaining, unreferenced features need to be set in a way that they do not conflict in order to obtain a concrete product configuration, upon which traditional tools for static analysis can be employed. We use the KCONFIG tool to *expand* such partial to *full* configurations.

For comparison purposes, we first calculate the CC for the KCONFIG provided configuration preset `allyesconfig`. Interestingly, `allyesconfig` is way off from a "full" configuration, as 1,917 (18.5%) of all source files for `arch-x86` are **not** compiled. This, and the fact that every file with `#else` and `#elif` statements require more than one configuration to select all lines of code, account for the missing 32.8% CC.

In previous work [28], we have calculated partial configurations on all source files, and applied the KCONFIG infrastructure to expand each partial configuration to a full configuration. In this work, we consider both, KCONFIG-controlled `#ifdef` blocks (i.e., `#ifdef` blocks with a logical expression that contains at least one reference to a variable that starts with `CONFIG_`), as well as the inclusion of a source file into the compilation process, as a variation point. Therefore, the numbers of the calculated CC are hard to compare to those in our previous work [28].

Table 3 shows that the number of calculated configurations is not much higher than the number of analyzed source files (about 19.3% more configurations than source files). This number is surprisingly low because most files in Linux do not contain `#ifdef` blocks, but are controlled by at most a single MAKE variable (cf. Section 2.2). This means the majority of files in Linux require only a single configuration to achieve full CC.

For each partial configuration, we check if the respective expanded configuration would actually let KBUILD include the file in the build process. Because of uncovered source file constraints in the GOLEM implementation and incompleteness of our KCONFIG variability model, this is not always the case. We do not count variation points of a partial configuration that does not include its corresponding file, because this configuration does not practically cover any variation point.

When calculating the CC without considering source file constraints (the second experiment in Table 3), we notice a coverage of only 9,492 out of 25,369 (37.4%) possible variation points. The reason for this alarmingly low rate is that 11,844 out of 14,169 (83.6%) variation points have not been considered, because the calculated configuration did not compile the source file for which it has been calculated.

When calculating the CC with considering the file constraints (the third experiment in Table 3), we observe a CC of 19,938 out of 25,369 (78.6%) variation points. The reason for this improvement is that the rate of skipped configurations decreases dramatically to 16.4 percent. This number is still considerable. Since each skipped configuration provably contains skipped variation points, we expect that additional engineering (cf. Section 6.1) will considerably increase the CC even further. Additionally, a first analysis of the calculated partial configurations shows that the quality of the expansion process still leaves room for improvement: In many expanded configurations, we observe omitted and wrongly set features. Improving the expansion process would therefore improve the achieved CC as well.

Because of the skipped partial configurations and the deficiencies in the expansion process, the improvement of the calculated CC has to be seen as lower bound that can be greatly improved by more precise MAKE and KCONFIG models, and better expansion of partial configurations. We are currently working on improving these results.

6. DISCUSSION

As demonstrated by the two applications in the previous section, the implementation of our approach greatly assists variability-aware analyses. This subsection discusses the limitations and in what way the results can be transferred to other systems.

6.1 Benefits and Limitations of the Approach

Compared to parsing-based approaches for extracting variability from the build system [e.g., 4, 13, 18] our approach of build-system probing exhibits a number of unique characteristics. While existing parsing-based approaches suffer from technical implementation challenges that require manual (and error-prone) engineering for the many corner-cases, our approach handles complicated makefile constructions as presented in Section 2.3 and shell escapes (i.e., invocation of external tools in the build system) error-free. It is also much harder, as presented in Section 4.3, for a parsing based approach to keep pace with the Linux development, whereas our approach works predictably for a wide range of Linux versions and architectures.

However, we also make a number assumptions on the build system, which may impact the results of our approach:

1. We exploit the observation that the file presence implications in KBUILD correspond to the hierarchical organiztion of directories along subsystems. If a feature is a prequisite for enabling files in a subdirectories, then this constraint applies for each file in that directory.

2. We assume that in a subdirectory, each file is only dependant on single features and not by a conjunction of two or more features.

3. In KBUILD, a feature always selects additional sources files for compilation. In no case the selection of a feature causes a source file to be removed from compilation process. This is a rather uncommon feature for MAKE based systems but more commonly found in systems that employ delta-oriented programming (DOP) [22].

As shown in Section 4, the current implementation produces presence implications for 95.4% of all source files in Linux on `arch-x86`. An investigation of the remaining 4.6% source files reveales that the majority of files violate assumption #2. The violation of this assumption is best explained with an example:

```
my-obj-$(CONFIG_FB_MATROX_G)  += matroxfb_crtc2.o
obj-$(CONFIG_FB_MATROX)       += $(my-obj-y)
```

Here the the file `matroxfb_crtc2.o` is only built if both features `FB_MATROX_G` and `FB_MATROX` are enabled at the same time. The helper function *features_in_dir* fails to detect that those two features have a connection. Therefore both features are tested independently and the build product `matroxfb_crtc2.o` does not show up in the output of *list*.

In the future, we intend to cover these cases by employing some simple heuristics (e.g., with data from the KCONFIG model) in the helper function *features_in_dir* to probe for more than a single configuration variable at the same time without increasing the number of necessary probing steps excessively. We expect this to improve the resulting logical constraints both the quantitatively and qualitatively even further.

Depending on how the extracted build-system constraints are employed, the higher runtime, compared to other approaches, might be a limitation of the approach. However many applications require the KBUILD constraints to be calculated exactly once and reuse them in analyses that take much longer compared to the extraction process. This applies to both applications that have been presented in Section 5.

6.2 Generalizability

In contrast to the parsing-based approaches, which rely heavily the idiomatic style in which KBUILD makes use of the MAKE language, we avoid this dependency by treating the build system as a black box. Only two primitives, *list* and *features_in_dir*, have to be reimplemented for other build systems. This thin connection to the internal structures is the main reason for the robustness of the probing based approach with respect to the presented application on a wide range of Linux versions and architectures.

In order to show the portability of our approach, we have implemented the necessary adaptations for two further software projects: The build system of BUSYBOX [7], a toolbox of UNIX-tools for embedded systems, and the build system of FIASCO [12], a L4-like micro kernel. Both ports took less than 100 additional lines of code and were straight-forward to implement. We are convinced that the assumptions made on KBUILD in Section 6.1 also apply to other build systems.

6.3 Comparison of the Calculated Source File Constraints

For a qualitative evaluation of the extracted presence implications, we compare the output of our GOLEM tool to the results of Berger et al. [4] and Nadi and Holt [18]. For all the files that have a presence implication in our model, the presence implication from the other models is checked for semantic equivalence by using a SAT Checker.

$$\phi_{M_1}(f) \leftrightarrow \phi_{M_2}(f) \qquad f \in files(M_1) \cap files(M_2)$$

This equivalence check is done by instrumenting the SAT checker to prove that the bi-implication of the presence implications is a tautology and therefore have always the same implication. We use this check to compare the GOLEM model to the models of Nadi and Holt and Berger et al.

For the much smaller model of Nadi and Holt, 15 percent of the 7,082 common files have an equivalent presence implication and 81.9 percent have a presence implication that implies the GOLEM presence implication. We conclude that this model is mostly subsumed by the GOLEM model.

The comparison of the GOLEM model with the model from Berger et al. shows that out of 8,885 common files, 99.6 percent fulfill this bi-implication. This pratical equivalence shows that both tools are similarly mature.

7. RELATED WORK

The analysis of variability in Linux is a hot topic in the Software Engineering (SWE) and Software Product Line (SPL) community. Zengler and Küchlin [31] show an attempt to derive formal semantics of KCONFIG. She et al. [23] reverse-engineer the KCONFIG variability declaration in order to reconstruct a feature model. In [10] we have shown and quantified that the fine-grained variability implementation by CPP is dominated by a more coarse-grained management in KBUILD. We therefore think that KBUILD variability extractors, such as KBUILDMINER [3], the Nadi parser [18] or the GOLEM tool presented in this article, are a necessary complement for holistic variability analysis.

Berger et al. [6] investigate the configuration languages and tools KCONFIG and configuration description language (CDL). While the work shows that variability-management tools are employed successfully in open-source operating systems, it covers only the feature specification and modeling.

Adams et al. [2] demonstrate that analysis, visualization and in essence, re-engineering of the Linux build system is feasible. Their framework Makao [1] infers modularity in KBUILD by analyzing build traces. However, the amount of variation points that we identify in KBUILD with this article indicates that the full re-engineering of build-system variability remains an unsolved problem.

Kästner et al. [13] propose a technique coined "variability aware parsing", which essentially integrates the CPP variability into tools for variability aware type-checking. Mainly because of implementation challenges, TypeChef focuses on `arch-x86` and requires assistance in form of additional constraints by tools like KBUILD-MINER [3]. Even with this, the approach is restricted to CPP based variability—the build-system–derived variability remains out of scope.

Palix et al. [19] try to reproduce a ten year old analysis on Linux by Chou et al. [8] in order to investigate the evolutionary development of Linux across the last decade. As the old experiment misses to state the exact configuration that was used, the environment could only be approximated. Hereby, the paper indirectly discusses CC in the sense that the selected configuration can (and does) affect the results of static analysis tools considerably. We take this anecdote as call for further integration of configuration consistency checks and CC into static analysis tools.

Inside the software verification community, Post and Sinz [21] introduce a technique coined "configuration lifting", which translates the variability expressed in KCONFIG, KBUILD and CPP into C source code. The generated C files encode the variability of the original source, the makefiles, and the feature model, and is verified with the CBMC tool by Clarke, Kroening, and Lerda [9]. While "configuration lifting" has similar goals, it remains unclear if that approach scales to the size of Linux.

8. SUMMARY AND CONCLUSION

To cope with a broad range of application and hardware settings, system software has to be highly configurable. Linux v3.2, as a prominent example, offers 11,000 configurable features. The implementation of this huge amount of static variability is implemented by `#ifdef`-blocks in the source code, but especially by the Linux make system. From the maintenance point of view, this imposes big challenges, as the feature model and the configurability that is *actually* implemented in the code have to be kept in sync. This calls for tool support.

A major hurdle for acceptance by the Linux developers is that such tools have to work reliably on the latest development version of Linux. Robustness against evolutionary changes in Linux, which includes both C code and the build system, is a strong requirement. In this paper, we have presented such a robust approach for extracting variability from the Linux build system that extracts logical constraints for 95.4% of all source files in Linux v3.2 on the `x86` architecture. Unlike existing approaches, our approach does not try to analyze the makefiles, but exploits the build system itself to infer the effects of selected features on the set of compiled files. Instead of manual and error-prone engineering that tailors the variability extractor to a specific version or architecture of Linux, our approach requires only two basic and straightforward to implement primitives. This thin interface to the build system allows a straight-forward to implement adaptation of the approach to other software projects, which has been demonstrated for BUSYBOX [7] and FIASCO [12].

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