[Herrenkrug-Eisenbahnbrücke Magdeburg]

Advanced Topics in Feature-Model Analysis

Thesis Topics and Software Projects

April 4, 2024

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OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

1. Introduction

About Me

Short CV

- **2020**: M.Sc. Computer Science in Magdeburg
- **since 2021**: PhD student in Magdeburg
  supervised by Gunter Saake (Magdeburg) and Thomas Thüm (Ulm)

Research Interests

- Feature-Model Extraction, Transformation, and Analysis
- Satisfiability Solving, Formal Methods, Applied Category Theory

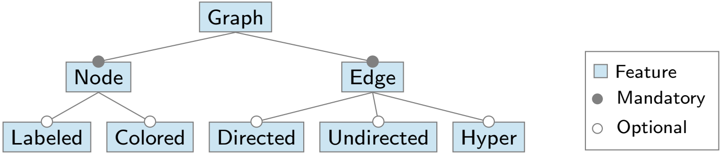
- **P**: Software Project
- **B**: Bachelor Thesis
- **M**: Master Thesis

Contact me:
`kuiter@ovgu.de`

Modeling Features and their Dependencies

Feature Models

- tree models **features**
- cross-tree **constraints** model dependencies
- solver-based **analyses** for investigating the configuration space



$$\neg(\mathit{Directed} \land \mathit{Undirected})$$

$$\mathit{Hyper} \rightarrow \mathit{Undirected}$$

$$\mathit{Directed} \not\leftrightarrow (\mathit{Undirected} \land \mathit{Hyper})$$

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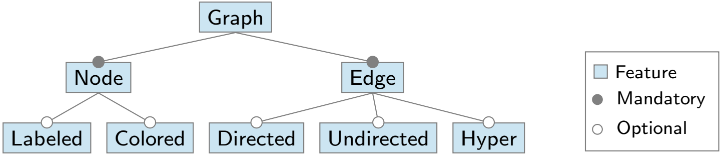


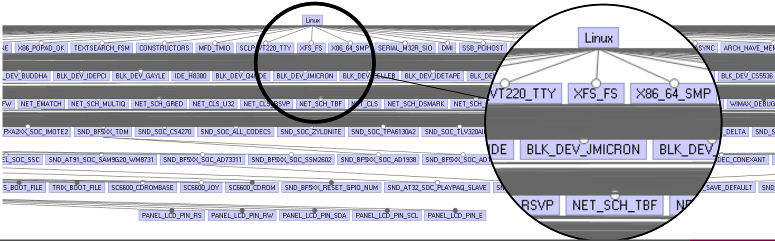
$$\neg(Directed \wedge Undirected)$$

$$Hyper \rightarrow Undirected$$

$$Directed \not\leftrightarrow (Undirected \wedge Hyper)$$

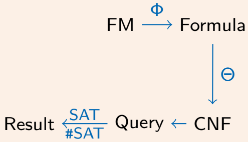
The Linux Kernel

- $>$ 13000 features [2018]
- $>$ 10^{700} products [2007]
- 114 dead features [2013]
- 151 reverse dependency bugs [2019]



Analyzing Feature Models with SAT and #SAT Solvers

Feature-Model Analysis



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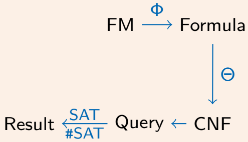
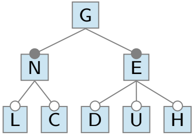


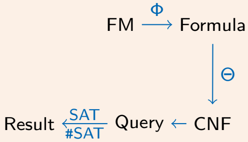
A Feature Model *FM*



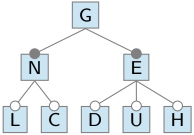
$$\neg(D \wedge U)$$
$$H \rightarrow U$$
$$D \not\leftrightarrow (U \wedge H)$$

Analyzing Feature Models with SAT and #SAT Solvers

Feature-Model Analysis



A Feature Model FM



$$\neg(D \land U)$$
$$H \rightarrow U$$
$$D \not\leftrightarrow (U \land H)$$

$\xrightarrow{\Phi}$

As a Formula $\Phi(FM)$

$$\begin{aligned} & G \\ \land\ & (N \leftrightarrow G) \land (E \leftrightarrow G) \\ \land\ & ((L \lor C) \rightarrow N) \\ \land\ & ((D \lor U \lor H) \rightarrow E) \\ \land\ & \neg(D \land U) \land (H \rightarrow U) \\ \land\ & (D \not\leftrightarrow (U \land H)) \end{aligned}$$

Analyzing Feature Models with SAT and #SAT Solvers

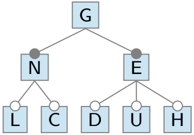
Feature-Model Analysis

$$\text{FM} \xrightarrow{\Phi} \text{Formula}$$

$$\downarrow \Theta$$

$$\text{Result} \xleftarrow[\#\text{SAT}]{\text{SAT}} \text{Query} \leftarrow \text{CNF}$$

A Feature Model *FM*



$\neg(D \wedge U)$

$H \rightarrow U$

$D \not\leftrightarrow (U \wedge H)$

$\xrightarrow{\Phi}$

As a Formula $\Phi(FM)$

$$\begin{aligned} & G \\ \wedge\ & (N \leftrightarrow G) \wedge (E \leftrightarrow G) \\ \wedge\ & ((L \vee C) \rightarrow N) \\ \wedge\ & ((D \vee U \vee H) \rightarrow E) \\ \wedge\ & \neg(D \wedge U) \wedge (H \rightarrow U) \\ \wedge\ & (D \not\leftrightarrow (U \wedge H)) \end{aligned}$$

$\downarrow \Theta$

As a CNF $\Theta(\Phi(FM))$

$$\begin{aligned} \{ & \{G\}, \{\neg N, G\}, \{N, \neg G\}, \\ & \{\neg E, G\}, \{E, \neg G\}, \{\neg L, N\}, \\ & \{\neg C, N\}, \{\neg D, E\}, \{\neg U, E\}, \\ & \{\neg H, E\}, \{\neg D, \neg U\}, \{\neg H, U\}, \\ & \{\{D, U\}, \{D, H\}, \{\neg D, \neg U, \neg H\}\}\} \end{aligned}$$

Analyzing Feature Models with SAT and #SAT Solvers

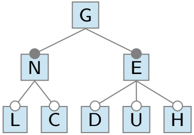
Feature-Model Analysis

FM $\xrightarrow{\Phi}$ Formula

$\downarrow \Theta$

Result $\xleftarrow[\#SAT]{SAT}$ Query $\leftarrow$ CNF

A Feature Model *FM*



$\neg(D \wedge U)$
$H \rightarrow U$
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$\xrightarrow{\Phi}$

As a Formula $\Phi(FM)$

$$
\begin{aligned}
& G \\
\wedge\ & (N \leftrightarrow G) \wedge (E \leftrightarrow G) \\
\wedge\ & ((L \vee C) \rightarrow N) \\
\wedge\ & ((D \vee U \vee H) \rightarrow E) \\
\wedge\ & \neg(D \wedge U) \wedge (H \rightarrow U) \\
\wedge\ & (D \not\leftrightarrow (U \wedge H))
\end{aligned}
$$

$\downarrow \Theta$

As a CNF $\Theta(\Phi(FM))$

$$
\begin{aligned}
\{ & \{G\}, \{\neg N, G\}, \{N, \neg G\}, \\
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\end{aligned}
$$

$\leftarrow$

Core Feature *F*?

$SAT(\Theta(\Phi(FM)) \wedge \neg F)$

$\leftarrow$

Core Features

$\{G, N, E\}$

Analyzing Feature Models with SAT and #SAT Solvers

Feature-Model Analysis

FM $\xrightarrow{\Phi}$ Formula

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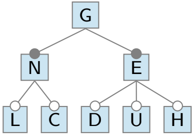
Result $\xleftarrow[\#SAT]{SAT}$ Query $\leftarrow$ CNF

A Feature Model FM



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$\xrightarrow{\Phi}$

As a Formula $\Phi(FM)$

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$\downarrow \Theta$

As a CNF $\Theta(\Phi(FM))$

$$\{\{G\}, \{\neg N, G\}, \{N, \neg G\}, \{\neg E, G\}, \{E, \neg G\}, \{\neg L, N\}, \{\neg C, N\}, \{\neg D, E\}, \{\neg U, E\}, \{\neg H, E\}, \{\neg D, \neg U\}, \{\neg H, U\}, \{\{D, U\}, \{D, H\}, \{\neg D, \neg U, \neg H\}\}\}$$

$\leftarrow$

Core Feature F?

$SAT(\Theta(\Phi(FM)) \wedge \neg F)$

$\leftarrow$

Core Features

$\{G, N, E\}$

$\leftarrow$

Products in FM?

$\#SAT(\Theta(\Phi(FM)))$

$\leftarrow$

Feature Model Cardinality

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2. Thesis Topics

Extracting Feature Hierarchies for KConfig-Based Feature Models (B/M)

Problem

- feature-model extractors for KConfig mostly ignore the **feature hierarchy**
- tooling for extracting hierarchies is now defunct, identification of **feature parents** in Kconfig is yet under-researched

```
namespace Root

features
    Root
        optional
            UNWINDER_ORC
            UNWINDER_FRAME_POINTER
            UNWINDER_GUESS
            X86_64
            IO_DELAY_0X80
            IO_DELAY_0XED
            IO_DELAY_UDELAY
            IO_DELAY_NONE
            BRANCH_PROFILE_NONE
            PROFILE_ANNOTATED_BRANCHES
```

Extracting Feature Hierarchies for KConfig-Based Feature Models (B/M)

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```

Goal

- extract a feature hierarchy from KConfig specifications + evaluate accuracy
- and/or: reverse-engineer hierarchy from formula + compare with KConfig hierarchy

Requirements

- interested in research
- adjusting KConfig parser written in C
- adjust or implement a tool for reverse-engineering
- c.f. Yaman 2023, Yaman et al. 2024

Feature-Model Analysis with SAT Solvers: A Journey Through Time (B/M) [assigned]

Problem

- feature models grow more complex over time
- automated reasoning tools (e.g., SAT solvers) get more efficient over time
- **but**: which development is faster? can SAT solvers actually keep up?

[Photo: Laurent Simon]

Feature-Model Analysis with SAT Solvers: A Journey Through Time (B/M) [assigned]

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- feature models grow more complex over time
- automated reasoning tools (e.g., SAT solvers) get more efficient over time
- **but**: which development is faster? can SAT solvers actually keep up?

[Photo: Laurent Simon]

Goal

- collect best SAT solvers of the last 20 years
- collect feature models from the last 20 years
- run selected feature-model analyses with solver from year **X** on model of year **X**
- evaluate evolution of SAT solving performance (cf. Moore's law)
- see time travel challenge

Requirements

- interested in research
- methodology design, reading literature
- challenges: data availability and formats

Minimizing CNFs to Isolate Solver Bugs (B/M)

Problem

- CNFs of real-world feature models sometimes uncover **bugs** even in production-grade (#)SAT and SMT solvers
- e.g., in countAntom, sharpSAT/dSharp, Z3, clausy, FeatJAR
- during development and maintenance of such solvers, reducing problematic CNFs to a **minimum non-working example** can facilitate finding the causes of bugs, reporting them, and preventing future regressions
- however, this process is currently a manual task and time-consuming

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- however, this process is currently a manual task and time-consuming

Goal

- identify fault oracles (e.g., solver crashes), review reduction strategies (e.g., removing clauses one-by-one, bisection, backtracking to avoid a local minimum)
- implement a (semi-)automatic tool that repeatedly reduces clauses and literals in a faulty CNF until it is minimal
- evaluate performance and compare with global minimum (e.g., obtained manually)

Requirements

- interested in research, cf. Böhm et al. 2024
- algorithm design, reading literature
- challenge: generative effects, local minima

3. Software Projects

torte: Towards Fully Automated Feature-Model Experiments (P)

What is torte? 🍰 [github.com/ekuiter/torte]

- a declarative workbench for **reproducible** feature-model analysis experiments
- can extract, transform, and analyze feature models in a **fully automated** fashion
- draft, execute distribute, and adapt experiments (without clone-and-own)

A Simple Experiment: Counting BusyBox

```
experiment-subjects() {
    add-busybox-kconfig-history --from 1_36_0 --to 1_36_1
}
experiment-stages() {
    clone-systems
    extract-kconfig-models
    transform-models-into-dimacs
    solve-model-count --timeout 10
}
```

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}
```

Goal

fix problems and implement new features from roadmap (issue #1)
⇒ enabling new use cases for torte

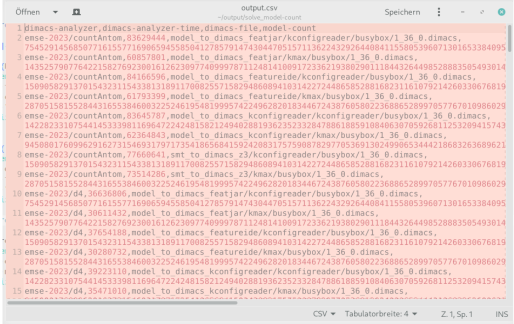
Requirements

- experience with Bash programming
- some experience with Docker
- willing to write clean code in Bash :-)

A Dashboard for Evolving Variability in Open-Source Systems (P)

Problem

- torte fully automates feature-model analysis
- can be used to analyze latest Linux kernel
- **but**: no user-friendly frontend exists yet



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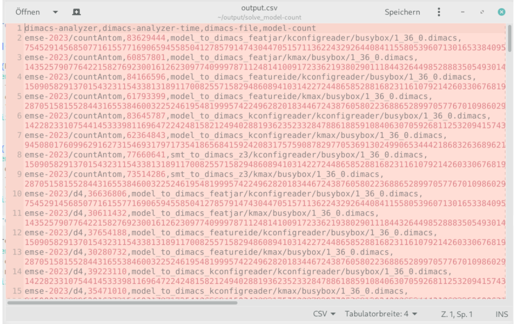

Goal

- develop a web frontend for torte
- find appropriate visualizations

$\Rightarrow$ quick visualization of current state of variability

Requirements

- experience with frontend development (e.g., HTML/CSS, React/Vue/Dash, ...)
- no backend experience needed (assuming a static CSV file over AJAX)

On-Demand Extraction of KConfig-Based Feature Models (P)

Problem

- torte fully automates feature-model analysis
- can be used to analyze latest Linux kernel
- **but**: replication packages are huge and not up-to-date, on-demand extraction is missing

model_to_xml_featureide	179,8 GB
kconfig	83,8 GB
kconfigreader	47,5 GB
kmax	36,3 GB
model_to_smt_z3	29,3 GB
dimacs	27,4 GB
backbone-dimacs	20,7 GB
model_to_uvl_featureide	10,8 GB

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Goal

- develop a server backend for torte
- design an appropriate job architecture
- strengthen against RCE

$\Rightarrow$ quick "self-help" for common extraction needs

Requirements

- experience with backend development (e.g., Docker, job processing, PHP/Node.js, . . .)
- willing to write a simple HTML frontend

Interested?

Contact me: `kuiter@ovgu.de`

/ekuiter/🎅

/ekuiter/🍰