
[Elbe, Magdeburg]

Tseitin or not Tseitin?

The Impact of CNF Transformations on Feature-Model Analyses

MCW@SAT 2023 (ASE 2022) — July 4 — Alghero, Italy

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University of Magdeburg[1], Ulm[2]

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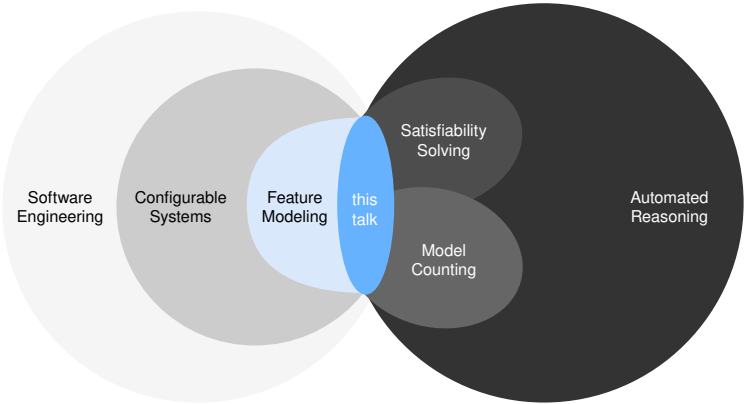
Software Engineering Meets Automated Reasoning



Implementing Configurable Software Systems

A Configurable Graph

```
class Node {
  #ifdef LABELED
    std::string label;
  #endif
  #ifdef COLORED
    std::string color;
  #endif
};

class Edge {
  #ifdef DIRECTED
    Node from, to;
  #elif UNDIRECTED && HYPER
    std::set<Node> nodes;
  #endif
};
```

Product Line Implementation
(here: C++ with C preprocessor)

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Product Line Implementation
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Configuration

A Labeled Directed Graph

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class Node {
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  Node from, to;
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Product Implementation

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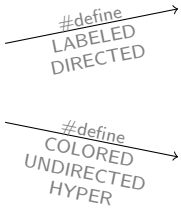


Configuration

A Labeled Directed Graph

```
class Node {
  std::string label;
};

class Edge {
  Node from, to;
};
```

A Colored Undirected Hypergraph

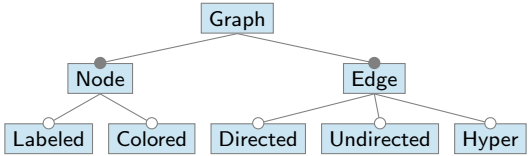
```
class Node {
  std::string color;
};

class Edge {
  std::set<Node> nodes;
};
```

Product Implementation

Modeling Features and their Dependencies

Feature Models

- tree models **features**
- cross-tree **constraints** model dependencies
- solver-based **analyses** can be used to understand the configuration space better



$\neg(Directed \wedge Undirected)$ **feature conflict**

$Hyper \rightarrow Undirected$ **missing implementation**

$Directed \nleftrightarrow (Undirected \wedge Hyper)$ **well-defined #ifdef**

Modeling Features and their Dependencies

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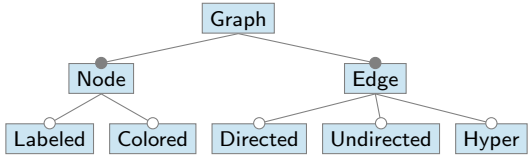


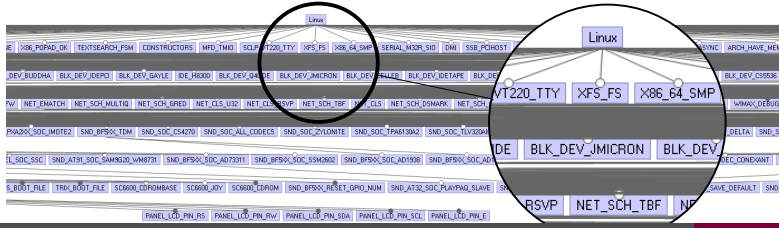
$\neg(\mathit{Directed} \wedge \mathit{Undirected})$ **feature conflict**

$\mathit{Hyper} \rightarrow \mathit{Undirected}$ **missing implementation**

$\mathit{Directed} \nleftrightarrow (\mathit{Undirected} \wedge \mathit{Hyper})$ **well-defined #ifdef**

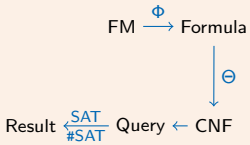
The Linux Kernel

- $>$ 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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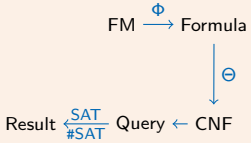
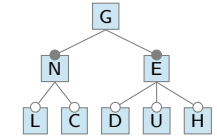


A Feature Model *FM*



$\neg(D \wedge U)$

$H \rightarrow U$

$D \nleftrightarrow (U \wedge H)$

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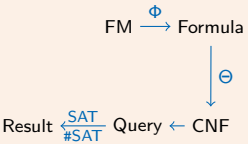

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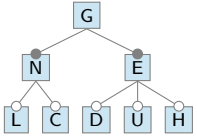


$\neg(D \wedge U)$
$H \rightarrow U$
$D \nleftrightarrow (U \wedge H)$

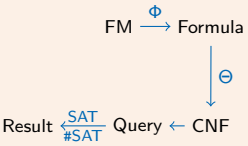
$\xrightarrow{\Phi}$

As a Formula $\Phi(FM)$

$$
\begin{aligned}
& G \\
\wedge\ & (N \leftrightarrow G) \wedge (E \leftrightarrow G) \\
\wedge\ & ((L \vee C) \rightarrow N) \\
\wedge\ & ((D \vee U \vee H) \rightarrow E) \\
\wedge\ & \neg(D \wedge U) \wedge (H \rightarrow U) \\
\wedge\ & (D \nleftrightarrow (U \wedge H))
\end{aligned}
$$

Analyzing Feature Models with SAT and #SAT Solvers

Feature-Model Analysis



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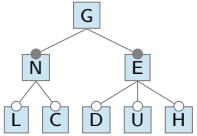

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&\wedge\ \neg(D \wedge U) \wedge (H \rightarrow U) \\
&\wedge\ (D \not\leftrightarrow (U \wedge H))
\end{aligned}
$$

$\downarrow \Theta$

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\}, \\
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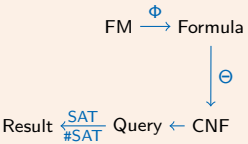
Analyzing Feature Models with SAT and #SAT Solvers

Feature-Model Analysis



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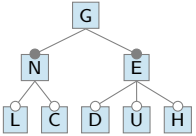

Φ →

As a Formula Φ(*FM*)

$$
\begin{aligned}
&G \\
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\end{aligned}
$$

↓ Θ

As a CNF Θ(Φ(*FM*))

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\begin{aligned}
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&\ \{\{D, U\}, \{D, H\}, \{\neg D, \neg U, \neg H\}\}\}
\end{aligned}
$$

←

Core Feature *F*?

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

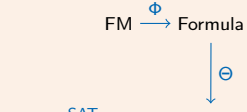
←

Core Features

$\{G, N, E\}$

Analyzing Feature Models with SAT and #SAT Solvers

Feature-Model Analysis



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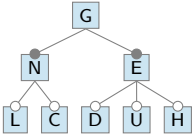

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\end{aligned}
$$

←

Core Feature *F*?

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

←

Products in *FM*?

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

←

Feature Model Cardinality

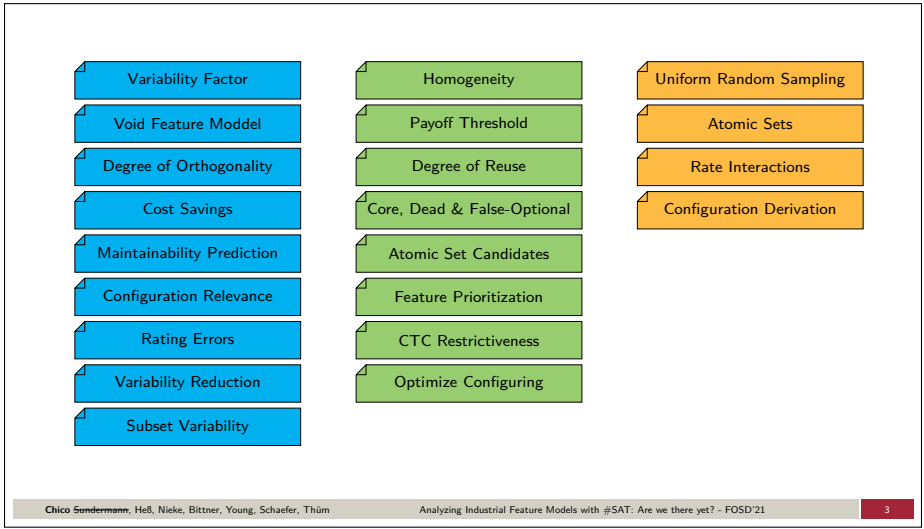
8

←

Core Features

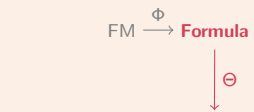
$\{G, N, E\}$

Feature Modeling Meets Model Counting



Often Overlooked: Conjunctive Normal Form (CNF)

Feature-Model Analysis



From Formula ...

$$
\begin{aligned}
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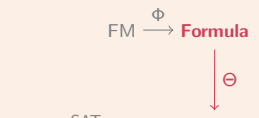
Often Overlooked: Conjunctive Normal Form (CNF)

Feature-Model Analysis



Conjunctive Normal Form

- **conjunction** $\wedge$ of **disjunctions** $\vee$ of **literals** X, $\neg X$
- here: a set of **clauses**, which are sets of literals
- used by almost all solvers

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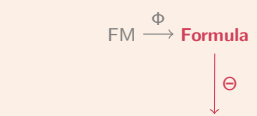

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\end{aligned}
$$

$\downarrow \Theta$

Our Goal: Raise Awareness for CNF Transformations [ASE'22]

- how to **transform** feature-model formulas **into CNF**?
  $\Rightarrow$ describe and classify CNF transformations
- does this **impact** the work of **practitioners and researchers**?
  $\Rightarrow$ evaluate efficiency and correctness on feature models

... to CNF

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

CNF Transformations

Distributive $\Theta = D$

apply laws of logic (**De Morgan's laws** and **distributivity**)

$$D \not\leftrightarrow (U \wedge H)$$
$$\xrightarrow{D} (D \vee (U \wedge H)) \wedge (\neg D \vee \neg (U \wedge H))$$
$$\xrightarrow{D} \{\{D, U\}, \{D, H\}, \{\neg D, \neg U, \neg H\}\}$$

✓ **equivalence**
SAT ✓, $\#SAT = 4$

✓ easy to implement

✗ **exponential** complexity

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Tseitin $\Theta = T$ ['83]

abbreviate a subformula ϕ with an auxiliary variable $x_\phi \leftrightarrow \phi$

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$$\xrightarrow{D} \{\{D, x\}, \{\neg D, \neg x\}, \{\neg x, U\}, \{\neg x, H\}, \{\neg U, \neg H, x\}\}$$

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✗ take care of new variables

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✓ **quasi-equivalence**
SAT ✓, $\#SAT = 4$
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Plaisted-Greenbaum $\Theta = PG$ ['86]

abbreviate a subformula ϕ with an auxiliary variable $x_\phi \rightarrow \phi$

$$D \not\Leftrightarrow (U \wedge H)$$
$$\xrightarrow{PG} (D \not\Leftrightarrow x) \wedge x \rightarrow (U \wedge H)$$
$$\xrightarrow{D} \{\{D, x\}, \{\neg D, \neg x\}, \{\neg x, U\}, \{\neg x, H\}\}$$

✓ **equi-assignability** SAT ✓
✓ **linear** complexity $< T$
✗ **equi-countability** $\#SAT = 5$

Evaluation

Research Questions

RQ 1 **efficiency** of CNF transformations?

RQ 2 CNF transformation → **efficiency** of analyses?

RQ 3 CNF transformation → **correctness** of analyses?

Evaluation

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Experimental Setup

- 22 configurable software systems
- 3 CNF transformation tools
- 23 SAT and #SAT solvers

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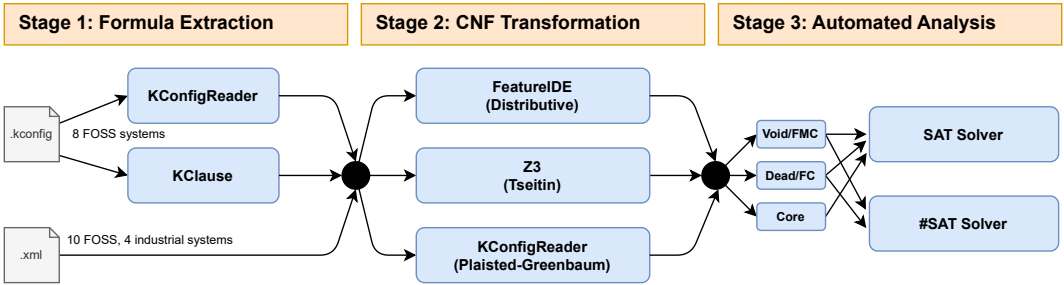
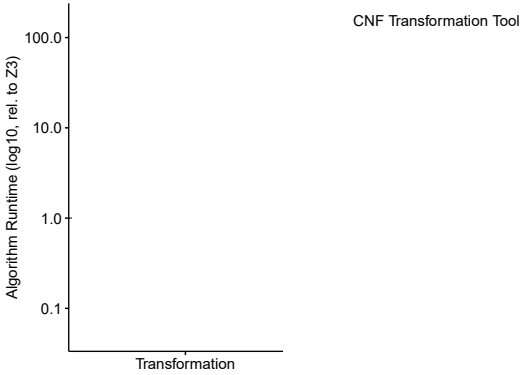


Efficiency of CNF Transformations (RQ 1) and Analyses (RQ 2)



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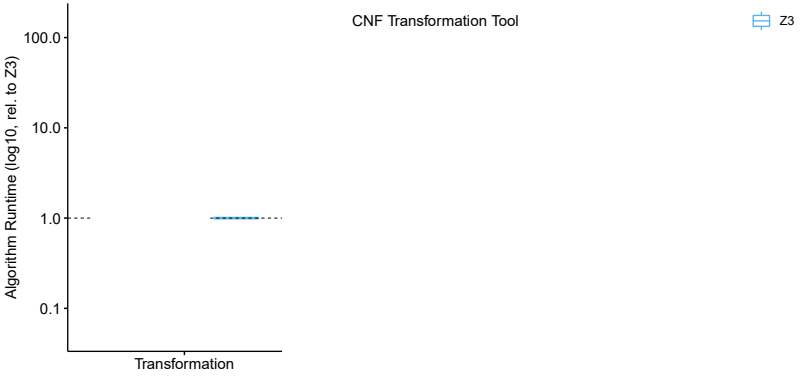

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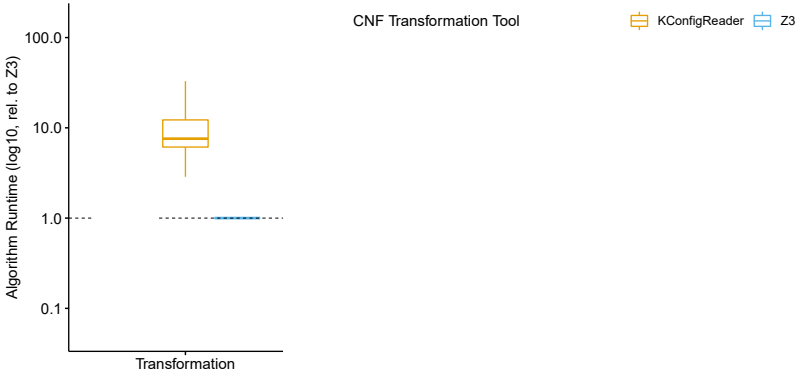

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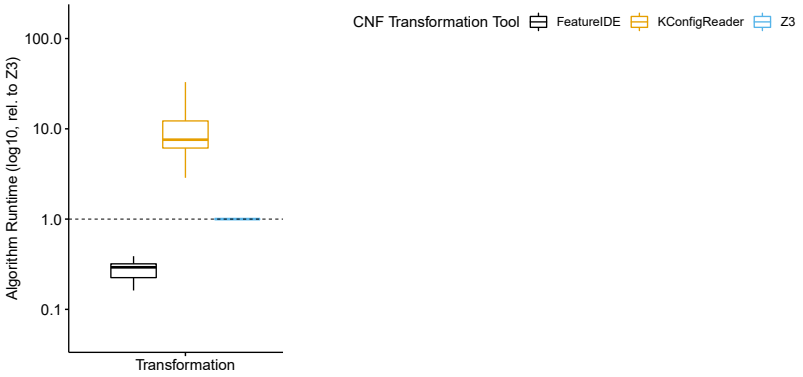

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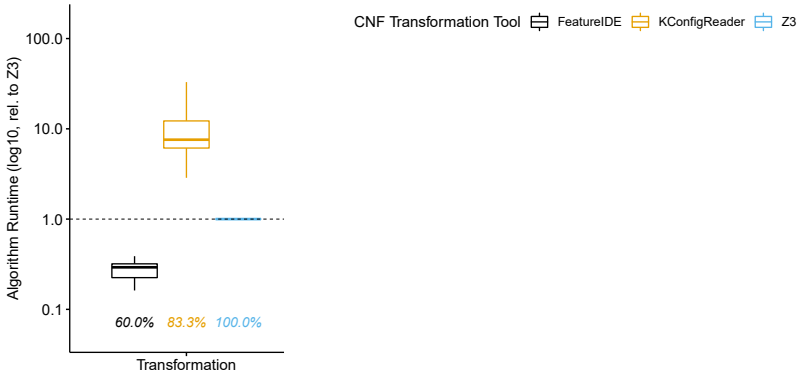
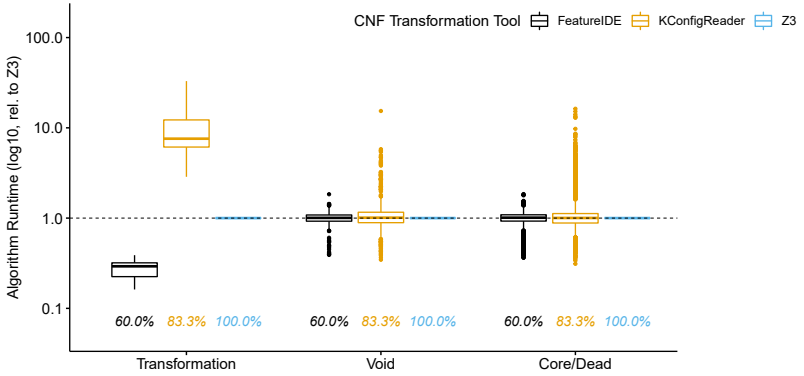


RQ 1: D **often fails**, tools **differ significantly**

Efficiency of CNF Transformations (RQ 1) and Analyses (RQ 2)



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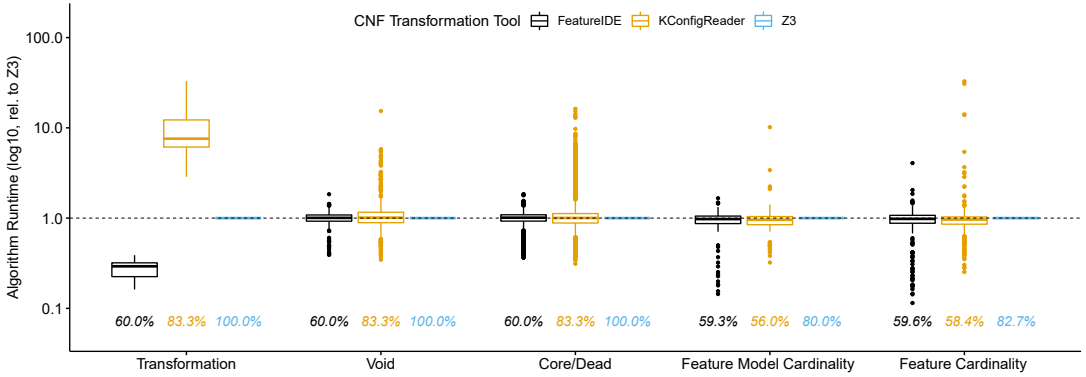
RQ 2 (SAT): almost all calls succeed, **solve time varies** by factor 0.31–16.27

Efficiency of CNF Transformations (RQ 1) and Analyses (RQ 2)



RQ 1: *D* **often fails**, tools **differ significantly**

RQ 2 (SAT): almost all calls succeed, **solve time varies** by factor 0.31–16.27

RQ 2 (#SAT): 81.6% of calls succeed, **solve time varies** by factor 0.11–32.7

Correctness of #SAT-Based Analyses (RQ 3)

How Many Valid Configurations in BusyBox 1.35.0?

FeatureIDE (Distributive) says:

4784204604487300838413517649496919484532179807372759285223423580055723848673385978971326945465595845729081244653413044678473235020016198950538440744692509401678991360000000000000000000000000

Tseitin (Z3) says:

4784204604487300838413517649496919484532179807372759285223423580055723848673385978971326945465595845729081244653413044678473235020016198950538440744692509401678991360000000000000000000000000

KConfigReader (Plaisted-Greenbaum) says:

1575135744671846821390135565599655459622677965648288591932216373689376057491458888085034207835407579838471914912986177301713184427402667443446803879599396016337818607616000000000000000000000000 **0 ⇒ off by factor 3.292**

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4784204604873008384 13517649496919484532 17980737275928522342 35800557238486733859
78971326945465595845 72908124465341304467 84732350200161989505 38440744692509401678
99136000000000000000 000000000

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4784204604873008384 13517649496919484532 17980737275928522342 35800557238486733859
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99136000000000000000 000000000

KConfigReader (Plaisted-Greenbaum) says:

15751357446718468213 90135655996554596226 77965648288591932216 37368937605749145888
80850342078354075798 38471914912986177301 71318442740266744344 68038795993960163378
18607616000000000000 000000000 **0 $\Rightarrow$ off by factor 3.292**

RQ 3

- with PG, $\approx$ 70% of #SAT calls return **incorrect results**
- incorrect by factor $\approx$ 3 (median)
- incorrect by factor $\approx 10^{77}$ (worst)

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RQ 3

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Our Recommendations

RQ 1 D for small, T for large models

RQ 2 largely depends on the model
$\Rightarrow$ future work

RQ 3 do not use PG for #SAT

Perspective: Model Counting Meets Feature Modeling?

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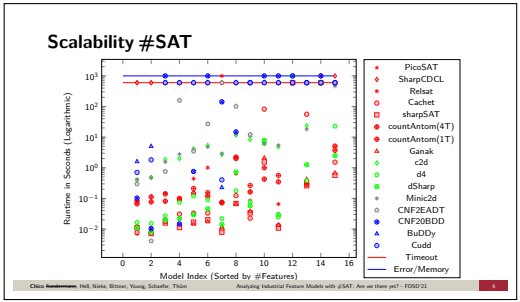
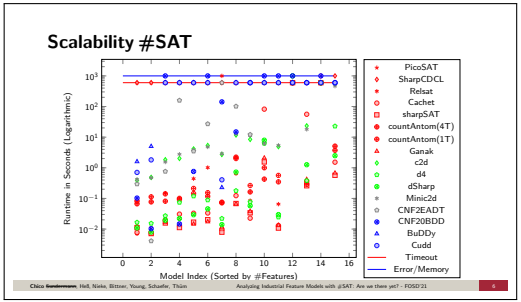
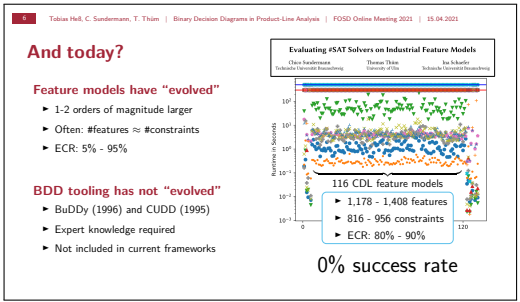


Compiling to d-DNNFs [Chico Sundermann]

works on most models (but not Linux/Automotive)
15 software systems, 130 models (some industrial)

Perspective: Model Counting Meets Feature Modeling?





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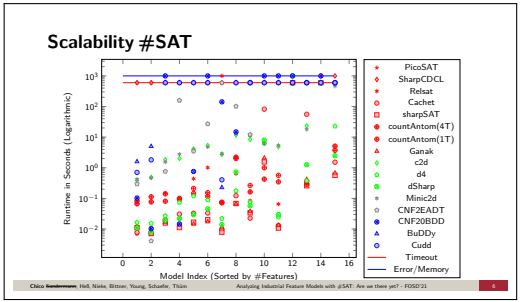

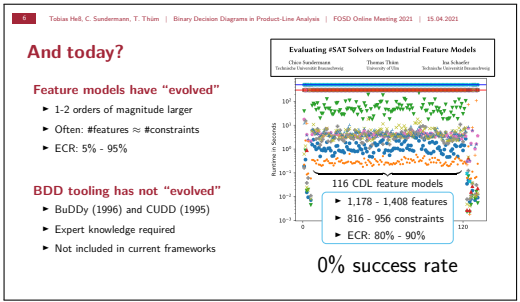

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our opinion: feature models are interesting, diverse, and potentially hard problem instances for benchmarking (#)SAT and knowledge compilation. maybe they could contribute to the SAT and MC competition as well?

Perspective: How Hard can Linux be, Really?

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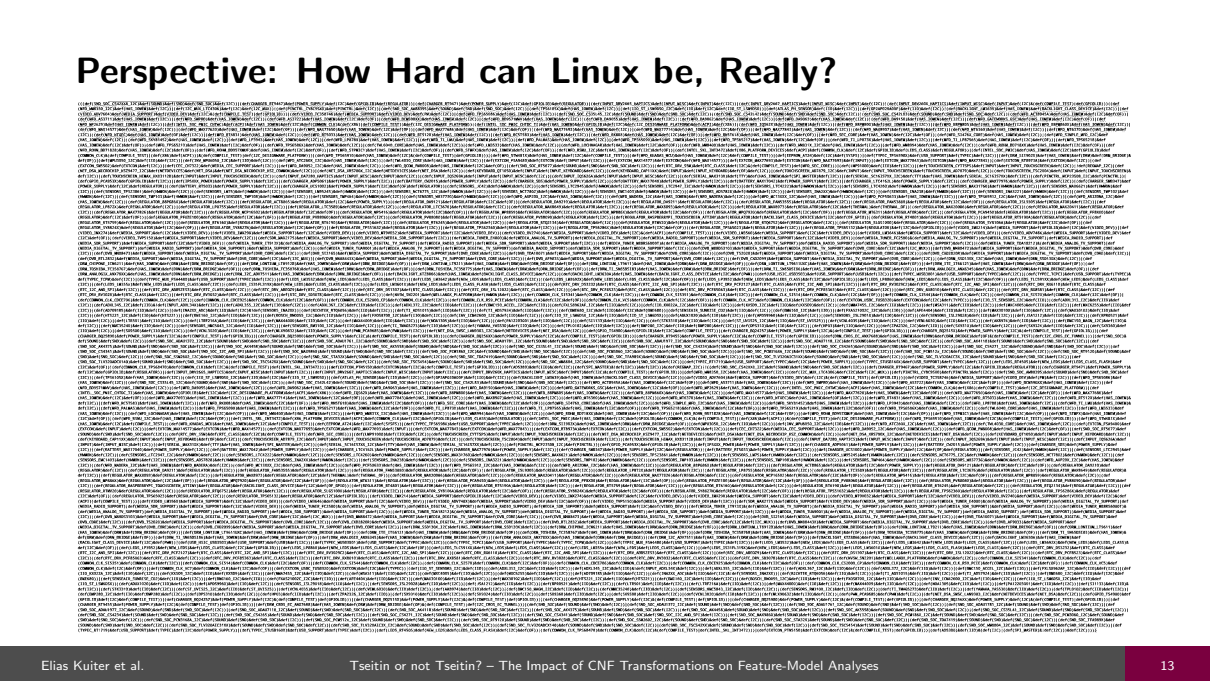
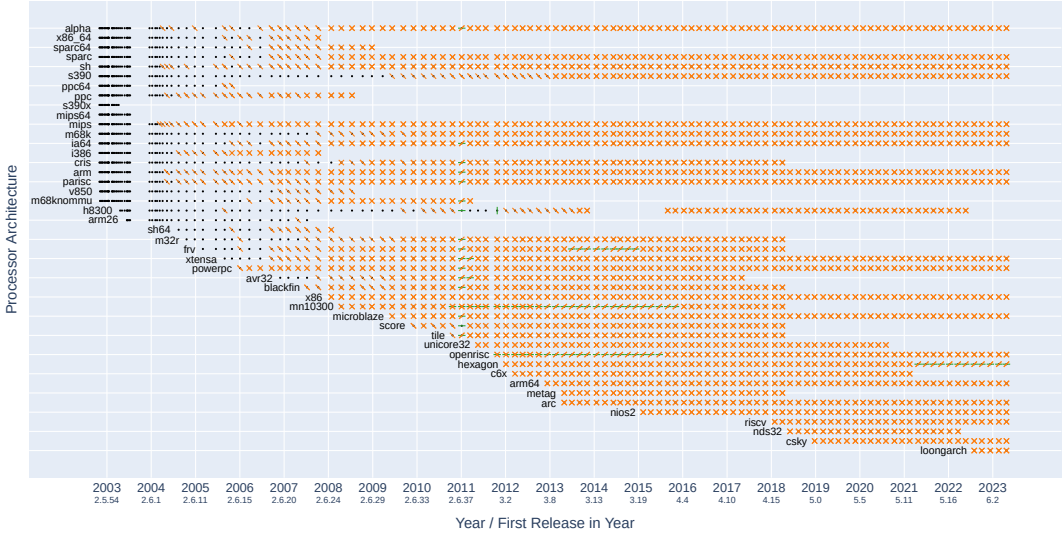


Perspective: How Hard can Linux be, Really? [SharpSAT-td+Arjun, d4]



Conclusion

The Impact of CNF Transformations on Feature-Model Analyses

Distributive

apply laws of logic

- ✓ **equivalence**
- ✓ easy to implement
- ✗ **exponential** complexity

Tseitin

abbreviate ϕ with $x_\phi \leftrightarrow \phi$

- ✓ **quasi-equivalence**
- ✓ **linear** complexity
- ✗ take care of new variables

Plaisted-Greenbaum

abbreviate ϕ with $x_\phi \rightarrow \phi$

- ✓ **equi-assignability**
- ✓ **linear** complexity
- ✗ **equi-countability**

FeatureIDE

often fails on large models

Z3

succeeds correctly on all models

KConfigReader

often incorrect for #SAT calls

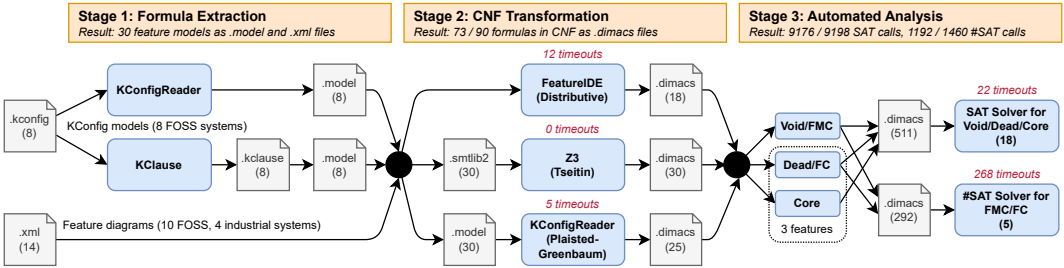
Compiling to **d-DNNFs**

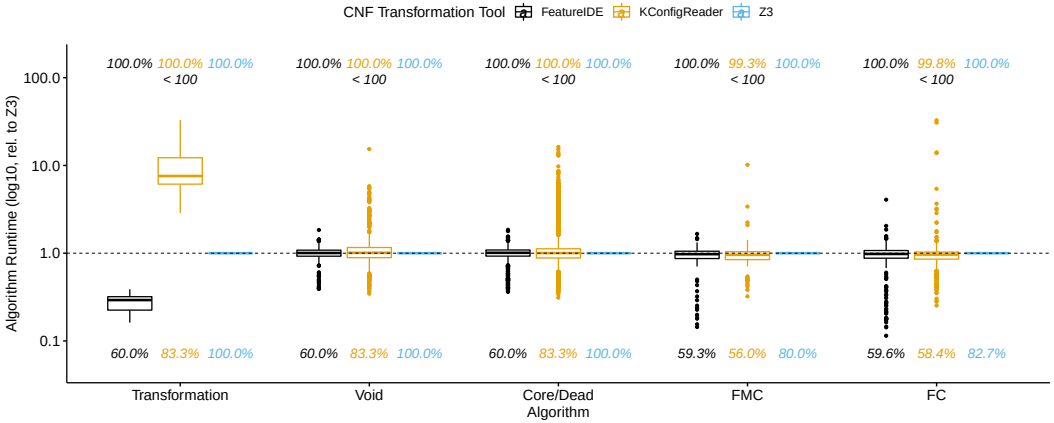
Compiling to **BDDs**

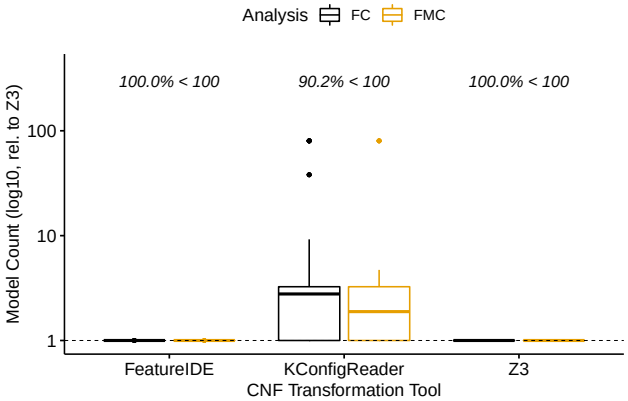
Counting **Linux** is hard

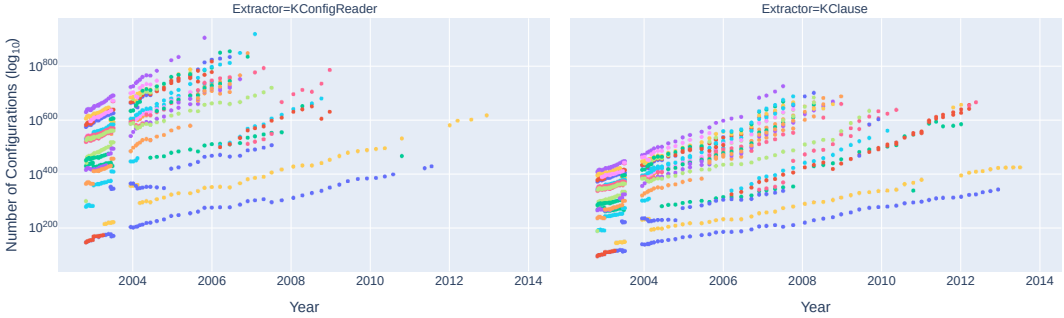
find out more:

github.com/ekuiter/tseitin-or-not-tseitin


Stage 1: Formula Extraction
Result: 30 feature models as .model and .xml files
Stage 2: CNF Transformation
Result: 73 / 90 formulas in CNF as .dimacs files
Stage 3: Automated Analysis
Result: 9176 / 9198 SAT calls, 1192 / 1460 #SAT calls
.kconfig (8)
KConfig models (8 FOSS systems)
KConfigReader
KClause
.kclause (8)
.model (8)
.model (8)
.xml (14)
Feature diagrams (10 FOSS, 4 industrial systems)
.smtlib2 (30)
.model (30)
12 timeouts
FeatureIDE (Distributive)
0 timeouts
Z3 (Tseitin)
5 timeouts
KConfigReader (Plaisted-Greenbaum)
.dimacs (18)
.dimacs (30)
.dimacs (25)
Void/FMC
Dead/FC
Core
3 features
.dimacs (511)
.dimacs (292)
22 timeouts
SAT Solver for Void/Dead/Core (18)
268 timeouts
#SAT Solver for FMC/FC (5)


CNF Transformation Tool
FeatureIDE
KConfigReader
Z3
Algorithm Runtime (log10, rel. to Z3)
100.0
10.0
1.0
0.1
100.0% 100.0% 100.0%
< 100
100.0% 100.0% 100.0%
< 100
100.0% 100.0% 100.0%
< 100
100.0% 99.3% 100.0%
< 100
100.0% 99.8% 100.0%
< 100
60.0% 83.3% 100.0%
60.0% 83.3% 100.0%
60.0% 83.3% 100.0%
59.3% 56.0% 80.0%
59.6% 58.4% 82.7%
Transformation
Void
Core/Dead
FMC
FC
Algorithm


Analysis
FC
FMC
100.0% < 100
90.2% < 100
100.0% < 100
Model Count (log10, rel. to Z3)
100
10
1
FeatureIDE
KConfigReader
Z3
CNF Transformation Tool


Extractor=KConfigReader
Extractor=KClause
Number of Configurations ($\log_{10}$)
10^{800}
10^{600}
10^{400}
10^{200}
2004
2006
2008
2010
2012
2014
Year