[Jahrtausendturm Magdeburg]

Tseitin or not Tseitin?

The Impact of CNF Transformations on Feature-Model Analyses

SE 2023 (ASE 2022) — February 22–24 — Paderborn

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University of Magdeburg[1], Ulm[2]

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;
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};
```

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

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LABELED
DIRECTED

Configuration

A Labeled Directed Graph

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Product Implementation

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

#define LABELED DIRECTED

#define COLORED UNDIRECTED HYPER

Configuration

A Labeled Directed Graph

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

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  Node from, to;
};
```

A Colored Undirected Hypergraph

```
class Node {
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};

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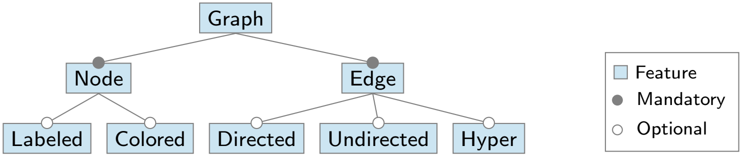

Product Implementation

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



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

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

$\mathit{Directed} \not\leftrightarrow (\mathit{Undirected} \land \mathit{Hyper})$ **well-defined #ifdef**

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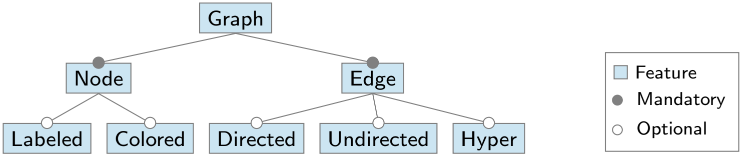

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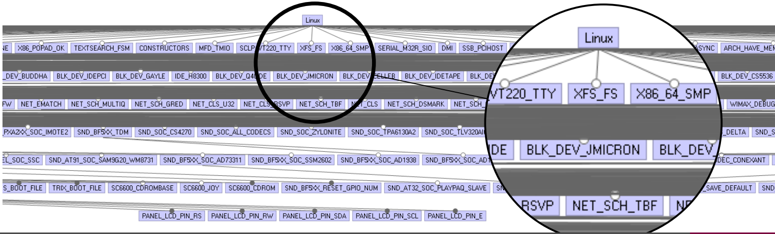
$\mathit{Directed} \not\leftrightarrow (\mathit{Undirected} \wedge \mathit{Hyper})$	**well-defined #ifdef**

The Linux Kernel

- $>$ 12000 features [2016]
- $>10^{5000}$ products [2016]
- 114 dead features [2013]
- 151 reverse dependency bugs [2019]



Analyzing Feature Models with SAT and #SAT Solvers

Feature-Model Analysis

$$
\begin{tikzcd}
 & & \text{FM} \arrow[r, "\Phi"] & \text{Formula} \arrow[d, "\Theta"] \\
\text{Result} & \text{Query} \arrow[l, "\text{SAT}"', "\text{\#SAT}"] & & \text{CNF} \arrow[ll]
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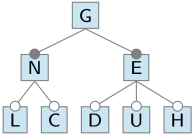
A Feature Model *FM*



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

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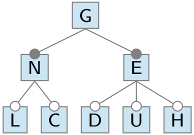

$\neg(D \land U)$

$H \rightarrow U$

$D \nleftrightarrow (U \land H)$

$\xrightarrow{\Phi}$

As a Formula $\Phi(FM)$

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

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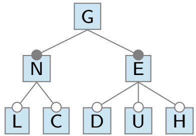

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$\downarrow \Theta$

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

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

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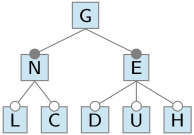

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$\leftarrow$

Core Feature F?

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

$\leftarrow$

Core Features

$$\{G, N, E\}$$

Analyzing Feature Models with SAT and #SAT Solvers

Feature-Model Analysis

$$\begin{array}{ccccc} & & \text{FM} & \xrightarrow{\Phi} & \text{Formula} \\ & & & & \downarrow \Theta \\ \text{Result} & \xleftarrow[\#SAT]{SAT} & \text{Query} & \leftarrow & \text{CNF} \end{array}$$

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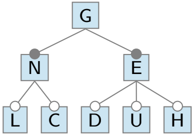

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Core Feature *F*?

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

$\leftarrow$

Core Features

$\{G, N, E\}$

$\leftarrow$

Products in *FM*?

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

$\leftarrow$

Feature Model Cardinality

8

Often Overlooked: Conjunctive Normal Form (CNF)

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From Formula . . .

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. . . to CNF

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Often Overlooked: Conjunctive Normal Form (CNF)

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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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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

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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✓ **quasi-equivalence**
SAT ✓, $\#SAT = 4$

✓ **linear** complexity

✗ take care of new variables

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- ✗ take care of new variables

Plaisted-Greenbaum $\Theta = PG$ ['86]

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

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

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

Evaluation

Research Questions

RQ 1 **efficiency** of CNF transformations?

RQ 2 CNF transformation $\rightarrow$ **efficiency** of analyses?

RQ 3 CNF transformation $\rightarrow$ **correctness** of analyses?

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

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Experimental Setup

- 22 configurable software systems
- 3 CNF transformation tools
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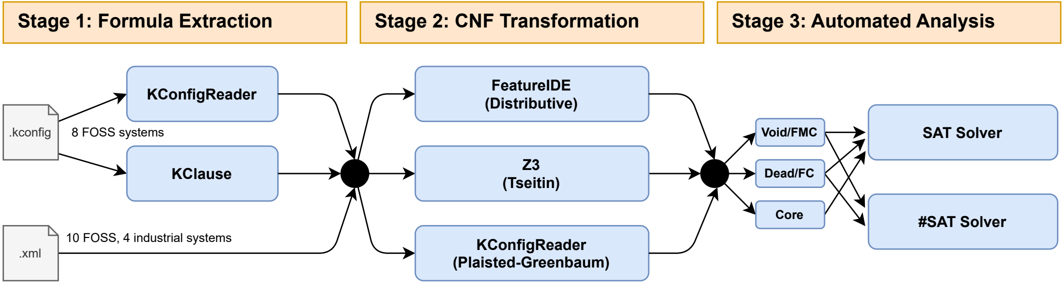
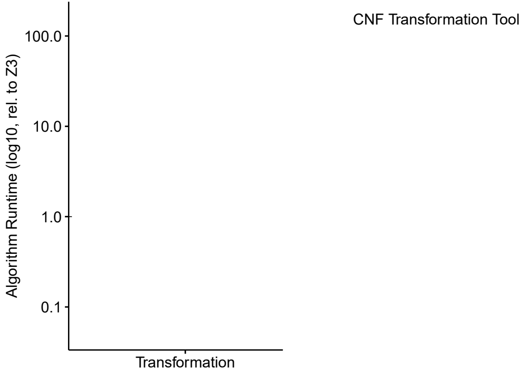


Efficiency of CNF Transformations (RQ 1) and Analyses (RQ 2)



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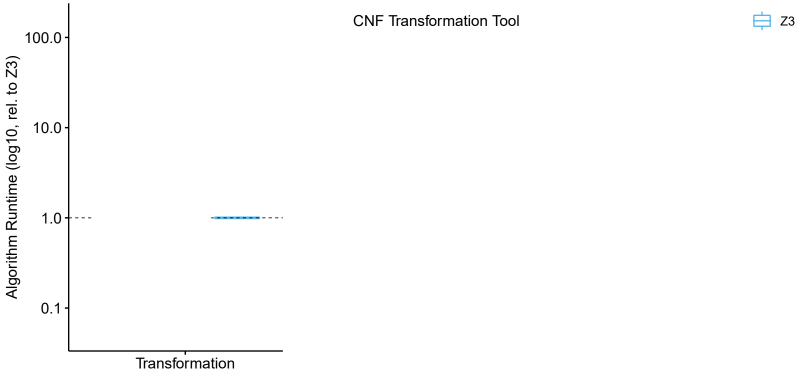

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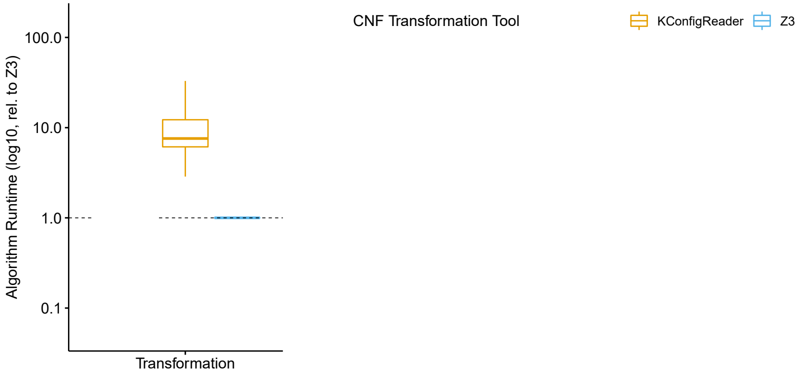

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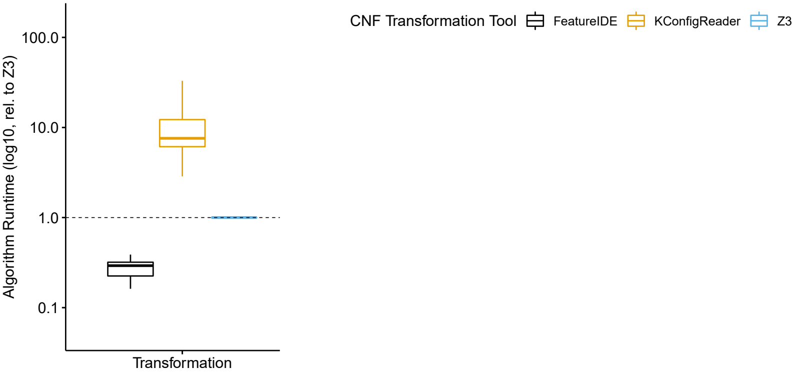

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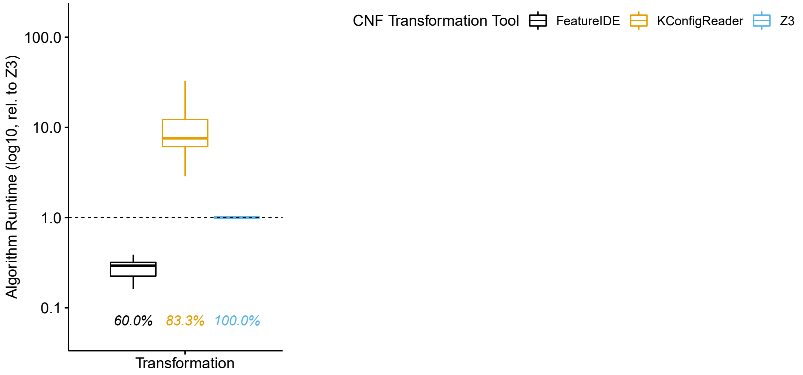
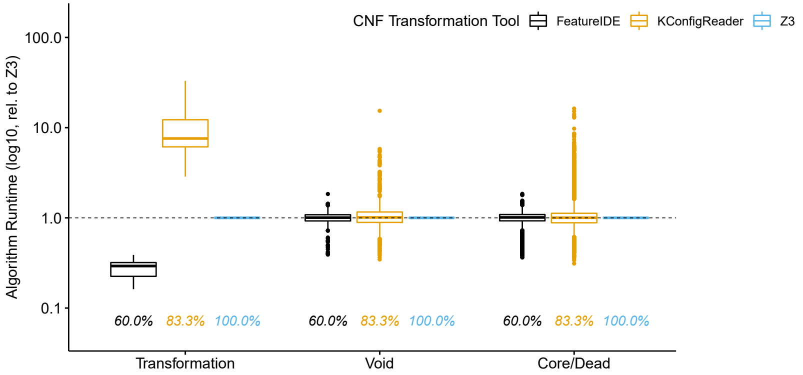


RQ 1: *D* **often fails**, tools **differ significantly**

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

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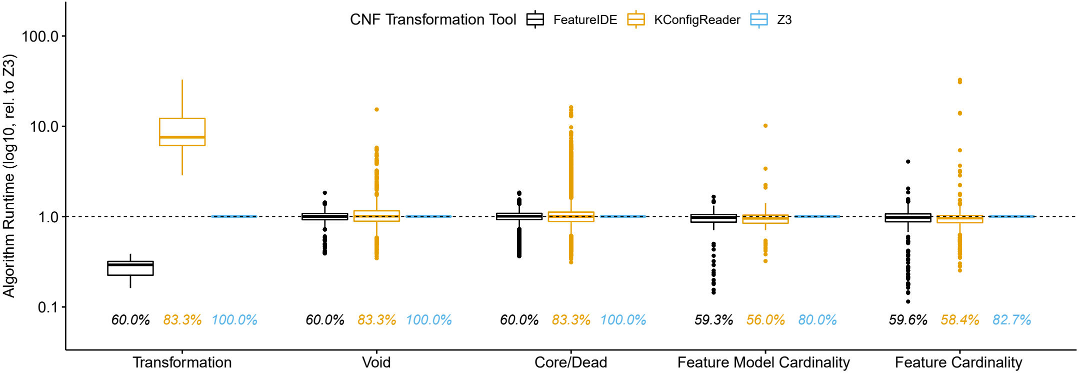

RQ 1: *D* **often fails**,
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RQ 2 (SAT): almost all calls succeed,
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RQ 2 (#SAT): 81.6% of calls succeed,
solve time varies by factor 0.11–32.7

Correctness of #SAT-Based Analyses (RQ 3)

How Many Valid Configurations in BusyBox 1.35.0?

FeatureIDE (Distributive) says:

47842046044873008384 13517649496919484532 17980737275928522342 35800557238486733859 78971326945465595845 72908124465341304467 84732350200161989505 38440744692509401678 99136000000000000000 000000000

Tseitin (Z3) says:

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KConfigReader (Plaisted-Greenbaum) says:

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

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RQ 3

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

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47842046044873008384 13517649496919484532 17980737275928522342 35800557238486733859 78971326945465595845 72908124465341304467 84732350200161989505 38440744692509401678 99136000000000000000 000000000

Tseitin (Z3) says:

47842046044873008384 13517649496919484532 17980737275928522342 35800557238486733859 78971326945465595845 72908124465341304467 84732350200161989505 38440744692509401678 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 ≈ 3 (median)
- incorrect by factor $\approx 10^{77}$ (worst)

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

Conclusion

The Impact of CNF Transformations on Feature-Model Analyses

Distributive	Tseitin	Plaisted-Greenbaum
apply laws of logic	abbreviate ϕ with $x_\phi \leftrightarrow \phi$	abbreviate ϕ with $x_\phi \rightarrow \phi$
✓ **equivalence**	✓ **quasi-equivalence**	✓ **equi-assignability**
✓ easy to implement	✓ **linear** complexity	✓ **linear** complexity
× **exponential** complexity	× take care of new variables	× **equi-countability**

FeatureIDE	Z3	KConfigReader
often fails on large models	succeeds correctly on all models	often incorrect for #SAT calls

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

Tseitin or not Tseitin?

Conclusion

The Impact of CNF Transformations on Feature-Model Analyses

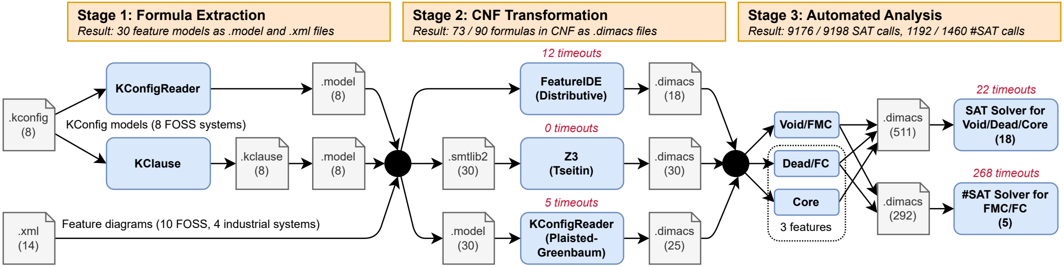
Distributive	Tseitin	Plaisted-Greenbaum
apply laws of logic	abbreviate ϕ with $x_\phi \leftrightarrow \phi$	abbreviate ϕ with $x_\phi \rightarrow \phi$
✓ **equivalence** ✓ easy to implement ✗ **exponential** complexity	✓ **quasi-equivalence** ✓ **linear** complexity ✗ take care of new variables	✓ **equi-assignability** ✓ **linear** complexity ✗ **equi-countability**

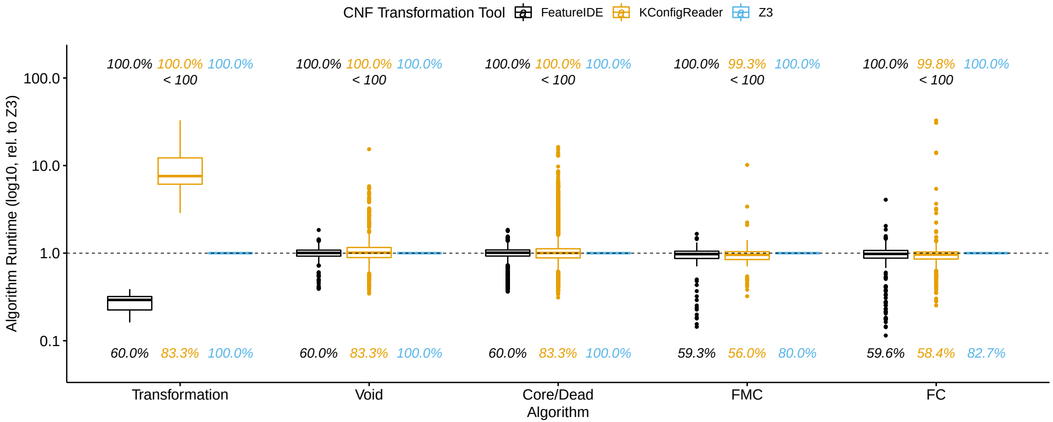
FeatureIDE	Z3	KConfigReader
often fails on large models	succeeds correctly on all models	often incorrect for #SAT calls

Tseitin or not Tseitin? $\Rightarrow$ Yes!

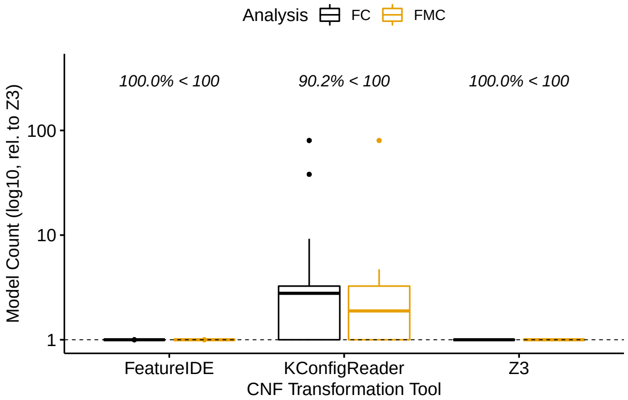
find out more:

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)
KConfigReader
KClause
KConfig models (8 FOSS systems)
.model (8)
.kclause (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