Identification of Feature Interactions Through Combinatorial Interaction Analysis

FOSD 2023 | **Sabrina Böhm**, S. Krieter, T. Heß, T. Thüm, M. Lochau | March 27–31, 2023

Software Engineering
Programming Languages

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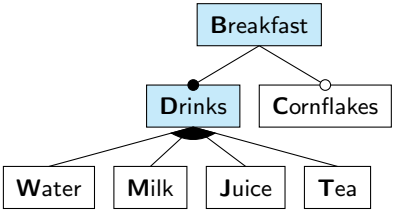
Feature Interactions

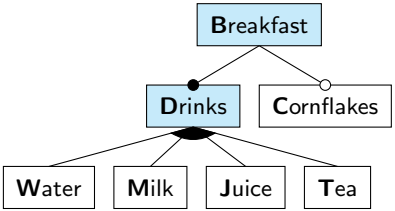



```
1  void main(){
2      // ...
3      #ifdef Milk
4      addMilk();
5      #endif
6
7      #ifdef Cornflakes
8      addCornflakes();
9      #endif
10 }
```

Cornflakes $\Rightarrow$ **M**ilk

$$c_{fail} = \{M, J, T\}$$

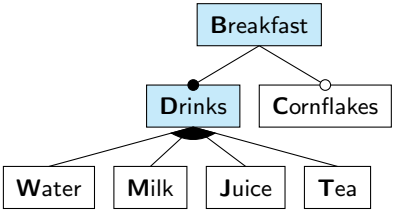
t-wise Feature Interactions: $t = 1$



$$W \quad \neg W$$
$$M \quad \neg M$$
$$J \quad \neg J$$
$$T \quad \neg T$$
$$C \quad \neg C$$

Cornflakes $\Rightarrow$ **M**ilk

t-wise Feature Interactions: $t = 2$

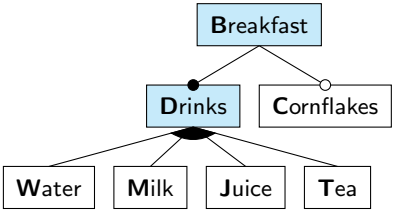


Cornflakes $\Rightarrow$ **M**ilk

$W \wedge M$	$W \wedge \neg M$	$\neg W \wedge M$	$\neg W \wedge \neg M$
$W \wedge J$	$W \wedge \neg J$	$\neg W \wedge J$	$\neg W \wedge \neg J$
$W \wedge T$	$W \wedge \neg T$	$\neg W \wedge T$	$\neg W \wedge \neg T$
$W \wedge C$	$W \wedge \neg C$	$\neg W \wedge C$	$\neg W \wedge \neg C$
$M \wedge J$	$M \wedge \neg J$	$\neg M \wedge J$	$\neg M \wedge \neg J$
$M \wedge T$	$M \wedge \neg T$	$\neg M \wedge T$	$\neg M \wedge \neg T$
$M \wedge C$	$M \wedge \neg C$		$\neg M \wedge \neg C$
$J \wedge T$	$J \wedge \neg T$	$\neg J \wedge T$	$\neg J \wedge \neg T$
$J \wedge C$	$J \wedge \neg C$	$\neg J \wedge C$	$\neg J \wedge \neg C$
$T \wedge C$	$T \wedge \neg C$	$\neg T \wedge C$	$\neg T \wedge \neg C$

or higher-order interaction size $t = 3$: $W \wedge M \wedge J$ ...

Potential Interactions $t = 2$

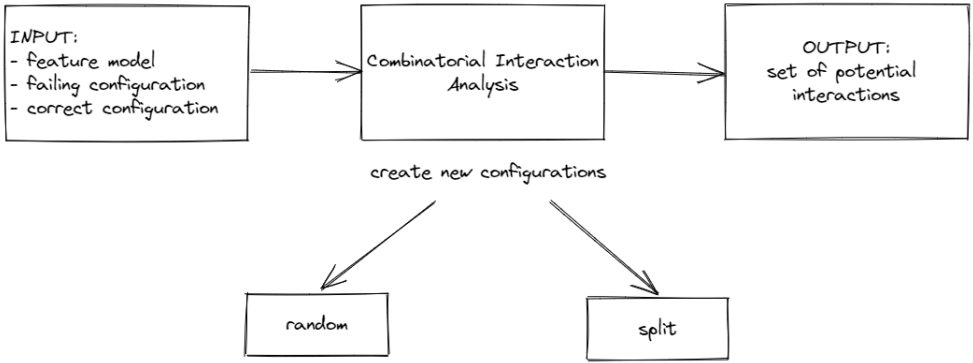


Cornflakes $\Rightarrow$ **M**ilk

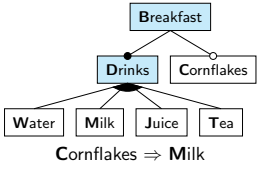
$c_{fail} = \{M, J, T\}$

$W \wedge M$	$W \wedge \neg M$	$\neg W \wedge M$	$\neg W \wedge \neg M$
$W \wedge J$	$W \wedge \neg J$	$\neg W \wedge J$	$\neg W \wedge \neg J$
$W \wedge T$	$W \wedge \neg T$	$\neg W \wedge T$	$\neg W \wedge \neg T$
$W \wedge C$	$W \wedge \neg C$	$\neg W \wedge C$	$\neg W \wedge \neg C$
$M \wedge J$	$M \wedge \neg J$	$\neg M \wedge J$	$\neg M \wedge \neg J$
$M \wedge T$	$M \wedge \neg T$	$\neg M \wedge T$	$\neg M \wedge \neg T$
$M \wedge C$	$M \wedge \neg C$		$\neg M \wedge \neg C$
$J \wedge T$	$J \wedge \neg T$	$\neg J \wedge T$	$\neg J \wedge \neg T$
$J \wedge C$	$J \wedge \neg C$	$\neg J \wedge C$	$\neg J \wedge \neg C$
$T \wedge C$	$T \wedge \neg C$	$\neg T \wedge C$	$\neg T \wedge \neg C$

Procedure


INPUT:
- feature model
- failing configuration
- correct configuration
Combinatorial Interaction Analysis
OUTPUT:
set of potential interactions
create new configurations
random
split

Split Approach $t = 2$



$$c_{fail} = \{M, J, T\} \qquad c_{corr} = \{W\}$$

$\neg W \wedge M$	$\neg W \wedge J$	$\neg W \wedge T$	$\neg W \wedge \neg C$	$M \wedge J$
$M \wedge T$	$M \wedge \neg C$	$J \wedge T$	$J \wedge \neg C$	$T \wedge \neg C$

configuration $c_1 : \{J, T\}$ ✓

$\neg W \wedge M$	$\neg W \wedge J$	$\neg W \wedge T$	$\neg W \wedge \neg C$	$M \wedge J$
$M \wedge T$	$M \wedge \neg C$	$J \wedge T$	$J \wedge \neg C$	$T \wedge \neg C$

$\neg W \wedge M$ $\quad$ $M \wedge J$

$M \wedge T$ $\quad$ $M \wedge \neg C$

configuration $c_2 : \{W, M, T\}$ ↯

$\neg W \wedge M$ $\quad$ $M \wedge J$

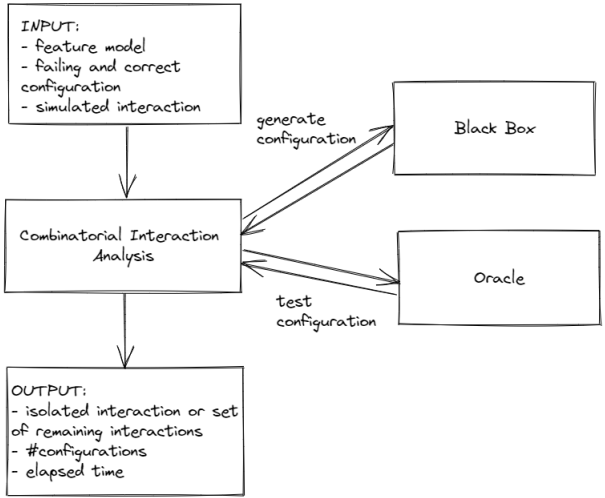
$M \wedge T$ $\quad$ $M \wedge \neg C$

configuration $c_3 : \{M\}$ ↯

$M \wedge T$ $\quad$ $M \wedge \neg C$

Output: isolated feature interaction $M \wedge \neg C$ with three new configurations

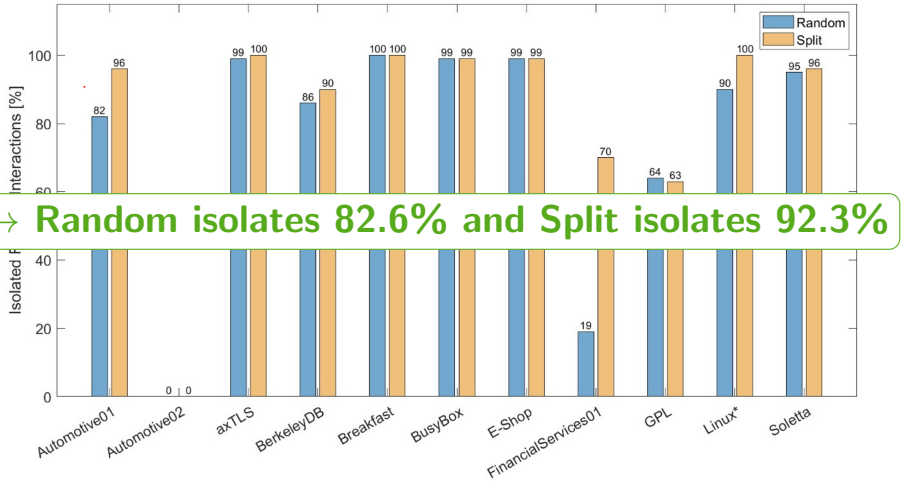
Experiment Design



Feature Models

Feature Model	#Features	#Constraints	#Products	#PairwisePotInts
Automotive01	2,513	2,833	$5.28 \cdot 10^{210}$	1,358,776
Automotive02	18,616	1,369	$1.78 \cdot 10^{1534}$	-
axTLS	153	14	$2.78 \cdot 10^{21}$	4,186
BerkeleyDB	76	20	$4.08 \cdot 10^{9}$	1,326
Breakfast	7	1	23	10
BusyBox	854	123	$2.06 \cdot 10^{201}$	129,795
E-Shop	326	21	$2.26 \cdot 10^{49}$	22,155
FinancialServices01	771	1,080	$9.75 \cdot 10^{13}$	204,480
GPL	38	16	156	210
Linux	6,467	3,545	$\sim 10^{3200}$	15,896,341
Soletta	114	214	$9.29 \cdot 10^{19}$	3,240

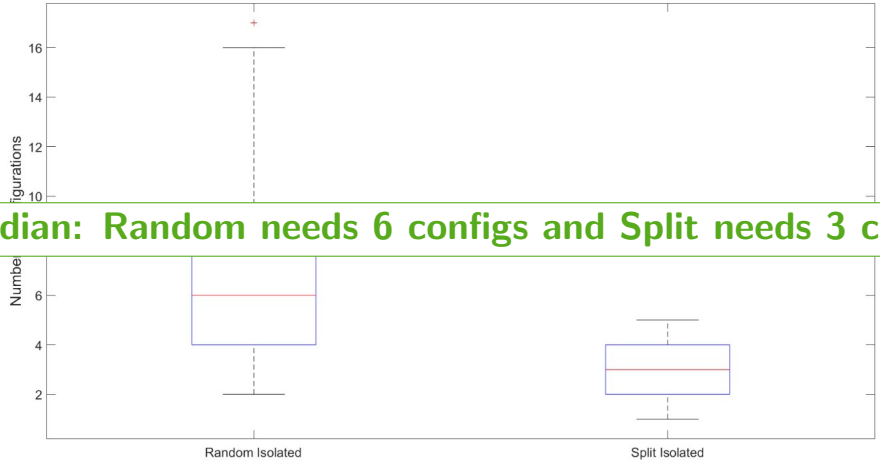
RQ1: How effective can we isolate the feature interaction that leads to the failing configuration?



→ **Random isolates 82.6% and Split isolates 92.3%**

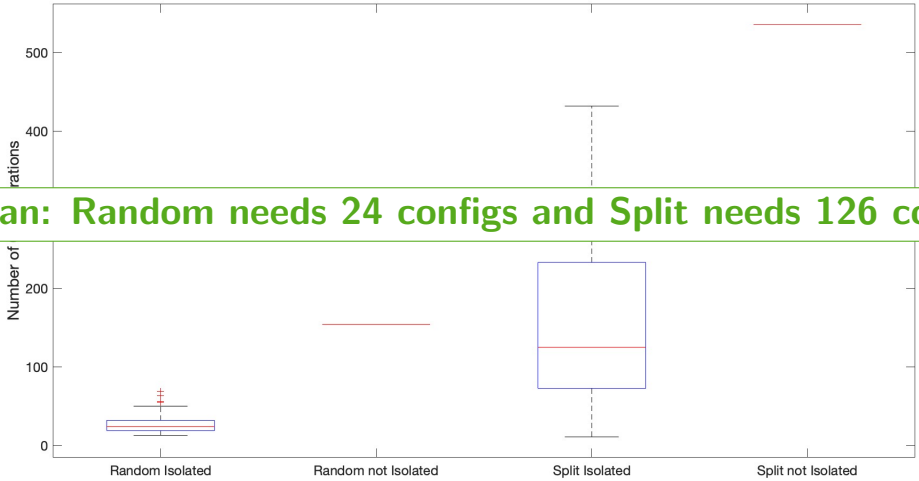
*Only 26 out of 100 experiments have been completed for the split algorithm.

RQ2: How many configurations are needed to isolate the feature interaction? - **Breakfast**



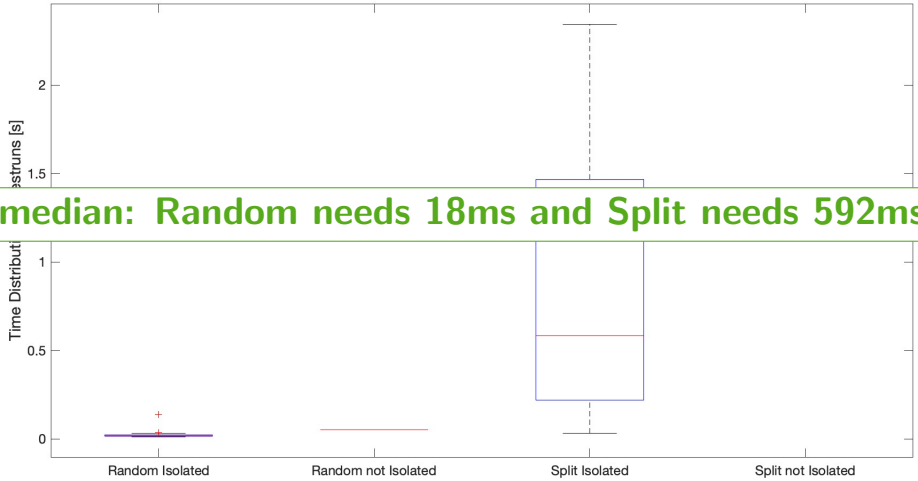
→ **median: Random needs 6 configs and Split needs 3 configs**

RQ2: How many configurations are needed to isolate the feature interaction? - **BbusyBox**



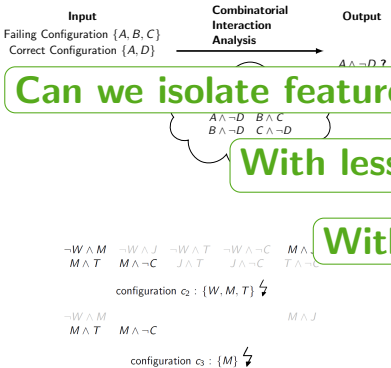
→ **median: Random needs 24 configs and Split needs 126 configs**

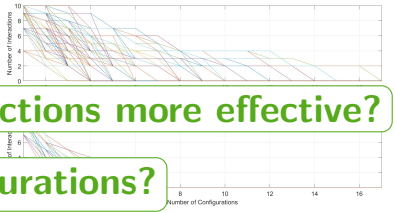
RQ3: How long does it take to isolate the feature interaction that leads to the failing configuration? - **BusyBox**



→ **median: Random needs 18ms and Split needs 592ms**

Conclusion & Future Work

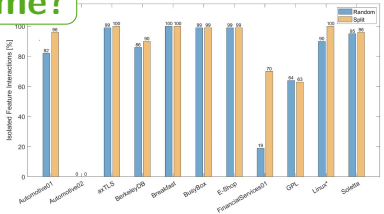




Can we isolate feature interactions more effective?

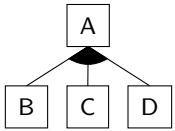
With less configurations?

With less time?



Identification of Feature Interactions Through Combinatorial Interaction Analysis

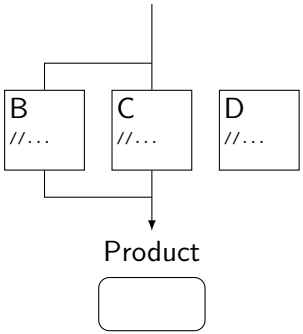
Problem Space



Configuration

$\{A, B, C\}$

Solution Space



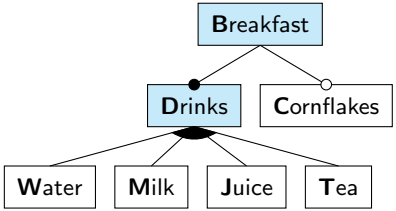
Assumptions

A1: The feature model has at least one valid configuration that contains the feature interaction.

A2: The feature model has at least one valid configuration that does not contain the feature interaction.

A3: There is exactly one feature interaction in our system and the occurring fault is exactly reproducible.

t-wise Feature Interaction Coverage: $t = 1$



Cornflakes $\Rightarrow$ Milk

W	$\neg W$
M	$\neg M$
J	$\neg J$
T	$\neg T$
C	$\neg C$

Input: configuration c : {M,J,T}

c_1 : {M,C} ✓

c_2 : {W,J,T} ✓

$M \wedge \neg C$

t-wise Feature Interaction Coverage: $t = 2$

Configuration 1: $\{M, J, T, C\}$
Configuration 2: $\{W\}$
Configuration 3: $\{M, J, T\}$
Configuration 4: $\{M, C\}$
Configuration 5: $\{J\}$
Configuration 6: $\{T\}$

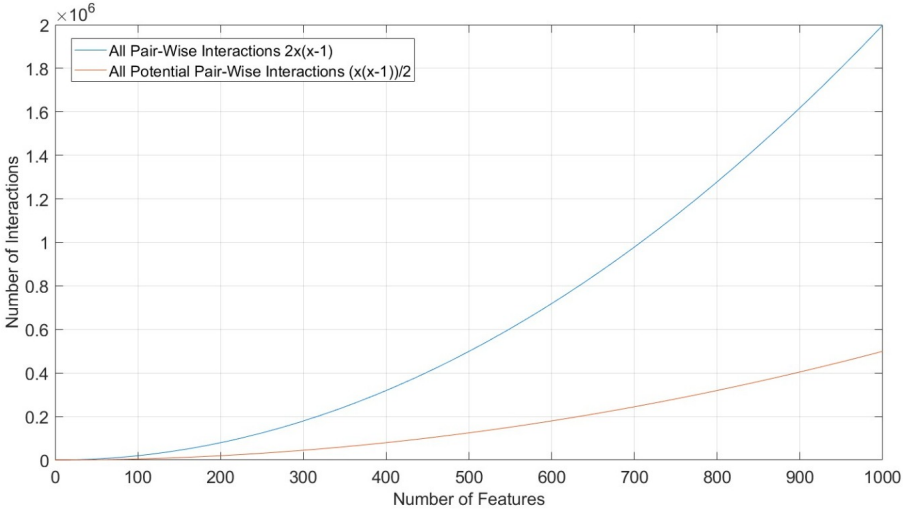
$W \wedge M$	$W \wedge \neg M$	$\neg W \wedge M$	$\neg W \wedge \neg M$
$W \wedge J$	$W \wedge \neg J$	$\neg W \wedge J$	$\neg W \wedge \neg J$
$W \wedge T$	$W \wedge \neg T$	$\neg W \wedge T$	$\neg W \wedge \neg T$
$W \wedge C$	$W \wedge \neg C$	$\neg W \wedge C$	$\neg W \wedge \neg C$
$M \wedge J$	$M \wedge \neg J$	$\neg M \wedge J$	$\neg M \wedge \neg J$
$M \wedge T$	$M \wedge \neg T$	$\neg M \wedge T$	$\neg M \wedge \neg T$
$M \wedge C$	$M \wedge \neg C$		$\neg M \wedge \neg C$
$J \wedge T$	$J \wedge \neg T$	$\neg J \wedge T$	$\neg J \wedge \neg T$
$J \wedge C$	$J \wedge \neg C$	$\neg J \wedge C$	$\neg J \wedge \neg C$
$T \wedge C$	$T \wedge \neg C$	$\neg T \wedge C$	$\neg T \wedge \neg C$

t-wise Feature Interactions: $t = 3$

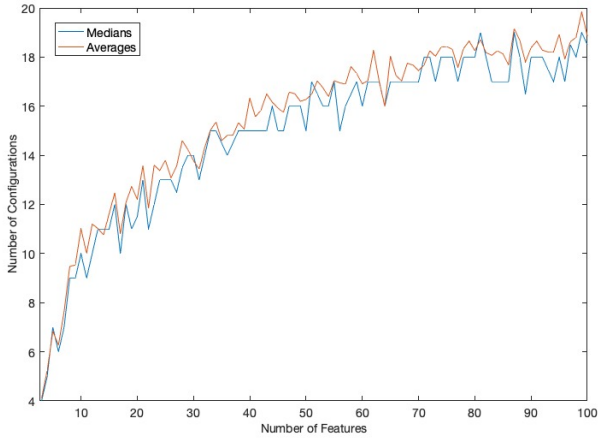
$$
\begin{array}{ccccc}
W & \wedge & M & \wedge & J \\
\neg W & \wedge & M & \wedge & J \\
W & \wedge & \neg M & \wedge & J \\
W & \wedge & M & \wedge & \neg J \\
\neg W & \wedge & \neg M & \wedge & J \\
\neg W & \wedge & M & \wedge & \neg J \\
W & \wedge & \neg M & \wedge & \neg J \\
\neg W & \wedge & \neg M & \wedge & \neg J
\end{array}
$$

- $\binom{n}{t} = \frac{n!}{t!(n-t)!}$
- $t = 2 : \binom{n}{2} = \frac{n(n-1)}{2}$
- e.g. : $n = 5$ $t = 3 : \binom{5}{3} = \frac{5!}{3!(5-3)!} = 10 \rightarrow$ each contains 8 interactions $\rightarrow$ 80

Potential Interactions

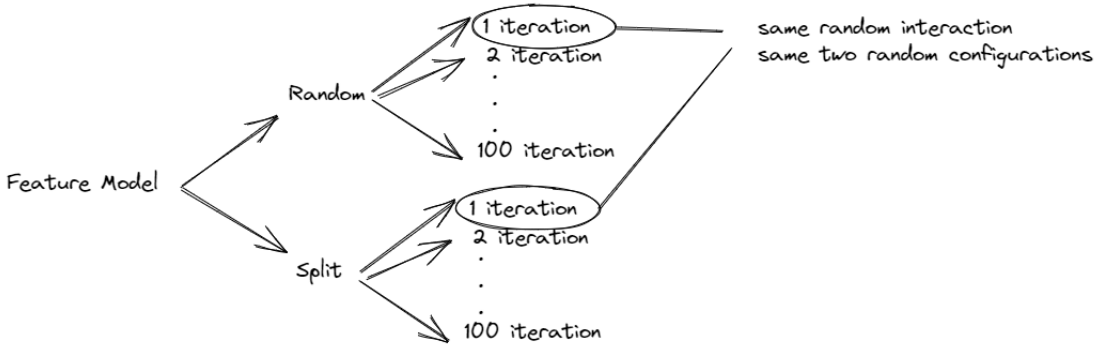


Maximum Number of Configurations Approximation

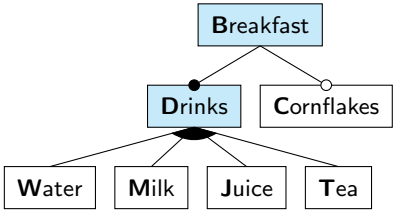


$$\text{maxConfig} = 2 \cdot \mathit{round}(3 \cdot \mathit{log}_2(\mathit{numberOfFeatures})) + 100$$

Experiments



Example Interaction Not Found



Cornflakes $\Rightarrow$ **M**ilk

Cornflakes $\Rightarrow$ **W**ater

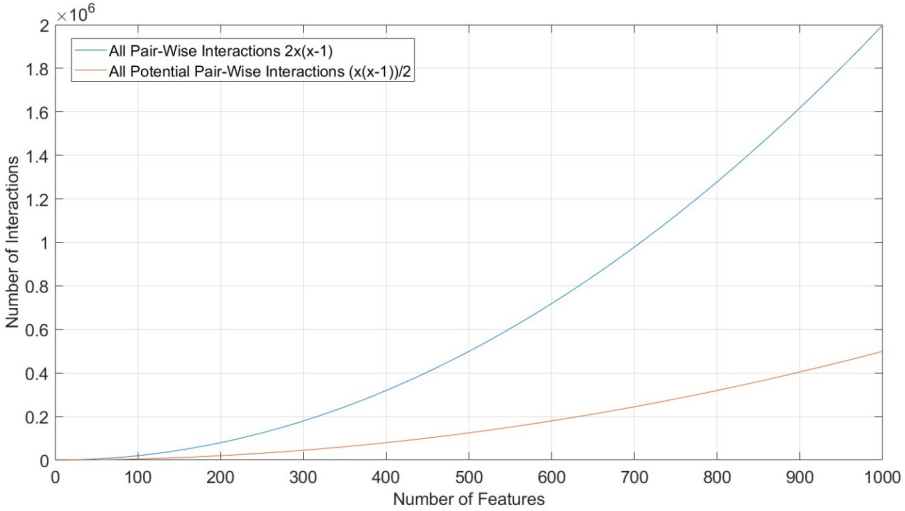
Remaining Potential Interactions

$C \wedge M$

$C \wedge W$

$c = \{C, ?\}$

Curves

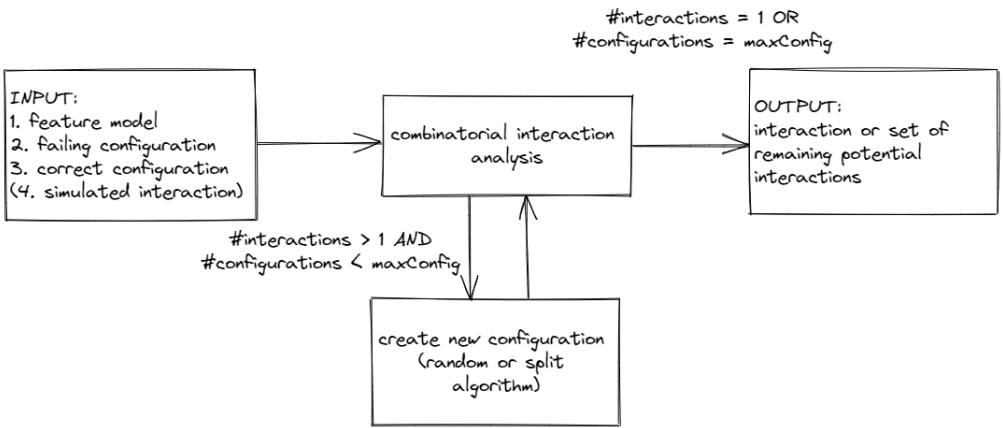

×10^6
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
All Pair-Wise Interactions 2x(x-1)
All Potential Pair-Wise Interactions (x(x-1))/2
Number of Interactions
0
100
200
300
400
500
600
700
800
900
1000
Number of Features

Occurred Feature-Interaction Bugs by Abal et al.*

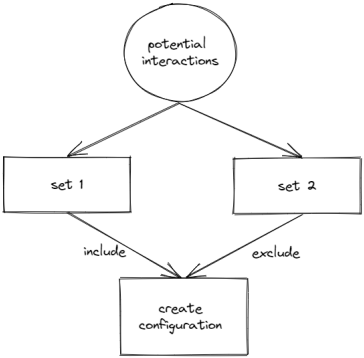
	Interaction	L	M	B	A	$\sum$
some selected	A	5	6	3	7	21
	$A \wedge B$	10	3	3	5	21
	$A \wedge B \wedge C$	5	-	1	-	6
	$A \wedge B \wedge C \wedge D \wedge E$	1	-	-	-	1
some-selected-one-deselected	$\neg A$	3	1	6	10	20
	$A \wedge \neg B$	13	3	4	-	20
	$A \wedge B \wedge \neg C$	3	-	1	-	4
	$A \wedge B \wedge C \wedge D \wedge \neg E$	1	-	-	-	1
other configurations	$\neg A \wedge \neg B$	1	-	-	-	1
	$A \wedge \neg B \wedge \neg C$	-	1	-	-	2
	$A \wedge \neg B \wedge \neg C \wedge \neg D \wedge \neg E$	1	-	-	1	2

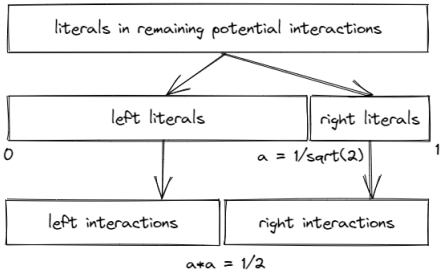
* "Variability Bugs in Highly Configurable Systems: A Qualitative Analysis" - TOSEM 2018

Procedure

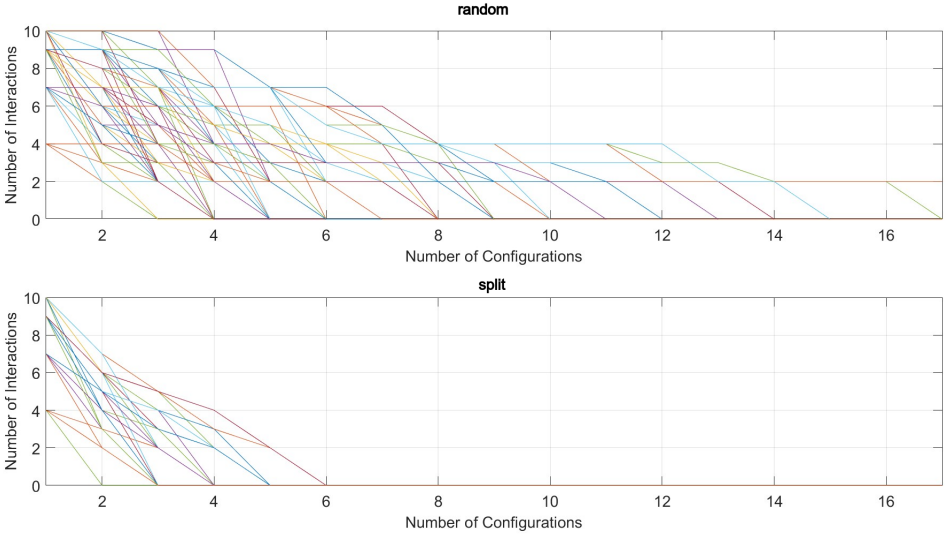

#interactions = 1 OR
#configurations = maxConfig
INPUT:
1. feature model
2. failing configuration
3. correct configuration
(4. simulated interaction)
combinatorial interaction analysis
OUTPUT:
interaction or set of remaining potential interactions
#interactions > 1 AND
#configurations < maxConfig
create new configuration (random or split algorithm)

Split Algorithm

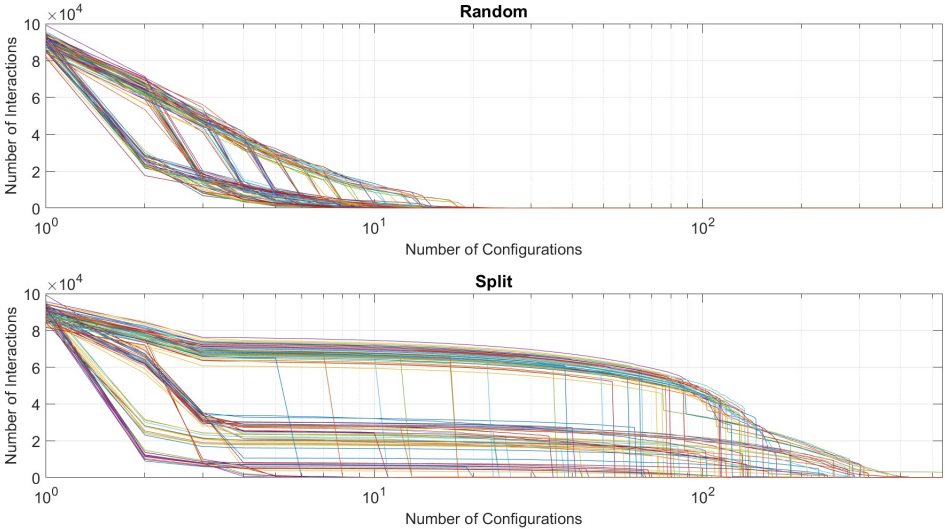




RQ2: How many configurations are needed to isolate the feature interaction? - **Breakfast**



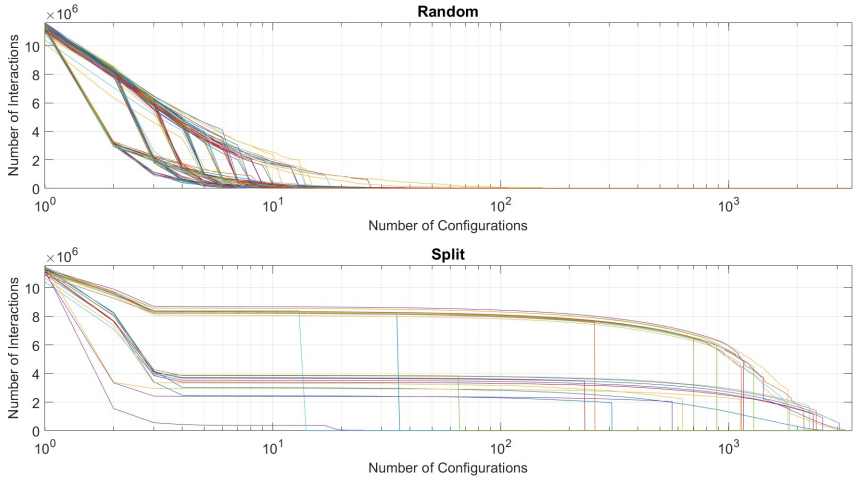
RQ2: How many configurations are needed to isolate the feature interaction? - **BusyBox**



RQ2

Model	Max	Min	*all*		*isolated*		*not isolated*	
			Avg	Med	Avg	Med	Avg	Med
Automotive01 - random	164	16	70.6	47	50.1	40	164	164
Automotive01 - split	1,348	16	512.7	522.5	493.6	475	970.5	866.5
Automotive02 - random	-	-	-	-	-	-	-	-
Automotive02 - split	-	-	-	-	-	-	-	-
BerkeleyDB - random	134	7	44.6	22.5	30	20	134	134
BerkeleyDB - split	51	4	23.5	21	23.3	21	24.6	23.5
Breakfast - random	17	2	6.7	6	6.7	6	-	-
Breakfast - split	5	1	3.1	3	3.1	3	-	-
BusyBox - random	154	13	28.3	24	27	24	154	154
BusyBox - split	536	11	155.3	126.5	151.5	125	536	536
axTLS - random	140	8	22.3	17	21.1	17	140	140
axTLS - split	69	8	31.9	31.5	31.9	31.5	-	-
E-Shop - random	146	10	30.1	23.5	28.9	23	146	146
E-Shop - split	149	9	65	61.5	64.5	61	109	109
FinancialServices01 - random	156	9	139.6	156	69.8	74	156	156
FinancialServices01 - split	326	14	142.5	141	127.8	112.5	176.9	175.5
GPL - random	126	4	58.3	27	20.1	14.5	126	126
GPL - split	13	2	8.5	8	8.6	9	8.2	8
Linux - random	174	20	67.7	52	66.5	57	174	174
Linux - split	3,472	24	1,699.9	1,555.5	1,699.9	1,555.5	-	-
Soletta - random	138	6	27.7	19	21.9	18	138	138
Soletta - split	73	7	33.2	32.5	32.4	31	53	54

Linux - Reduced Interaction per Configuration



RQ3 Computation Time in Seconds

Model	Max	Min	*all*		*isolated*		*not isolated*	
			Avg	Med	Avg	Med	Avg	Med
Automotive01 - random	0.499	0.107	0.2043	0.181	0.1831	0.167	0.3007	0.2795
Automotive01 - split	482.31	0.329	25.5978	21.663	25.203	21.492	35.072	27.6105
Automotive02 - random	-	-	-	-	-	-	-	-
Automotive02 - split	-	-	-	-	-	-	-	-
axTLS - random	0.037	0.001	0.0038	0.003	0.0036	0.003	0.022	0.022
axTLS - split	0.125	0.003	0.0149	0.012	0.0149	0.012	-	-
BerkeleyDB - random	0.031	0.001	0.0052	0.003	0.0038	0.002	0.0138	0.012
BerkeleyDB - split	0.056	0.001	0.0094	0.007	0.009	0.0065	0.0129	0.01
Breakfast - random	0.016	0	0.0011	0.001	0.0011	0.001	-	-
Breakfast - split	0.022	0.001	0.0018	0.001	0.0018	0.001	-	-
BusyBox - random	0.137	0.011	0.0204	0.018	0.02	0.018	0.052	0.052
BusyBox - split	2.343	0.031	0.848	0.592	0.8441	0.584	1.228	1.228
E-Shop - random	0.074	0.003	0.0081	0.007	0.0079	0.007	0.021	0.021
E-Shop - split	0.202	0.006	0.0815	0.0815	0.0807	0.081	0.169	0.169
FinancialServices01 - random	0.353	0.015	0.0794	0.08	0.0572	0.041	0.0846	0.082
FinancialServices01 - split	8.895	0.076	1.383	0.8685	0.7514	0.617	2.8568	2.529
GPL - random	0.029	0	0.0062	0.003	0.0026	0.002	0.0126	0.012
GPL - split	0.053	0.001	0.0046	0.004	0.0044	0.003	0.005	0.004
Linux - random	12.402	1.432	2.2355	1.933	2.418	1.878	2.656	2.656
Linux - split	3,069.227	5.956	1,378.0113	1,560.199	1,378.0113	1,560.199	-	-
Soletta - random	0.047	0.001	0.0048	0.003	0.0042	0.003	0.0164	0.015
Soletta - split	0.101	0.003	0.0151	0.014	0.0149	0.0135	0.0188	0.0175