A Study of non-Boolean Constraints in Variability Models of an Embedded Operating System

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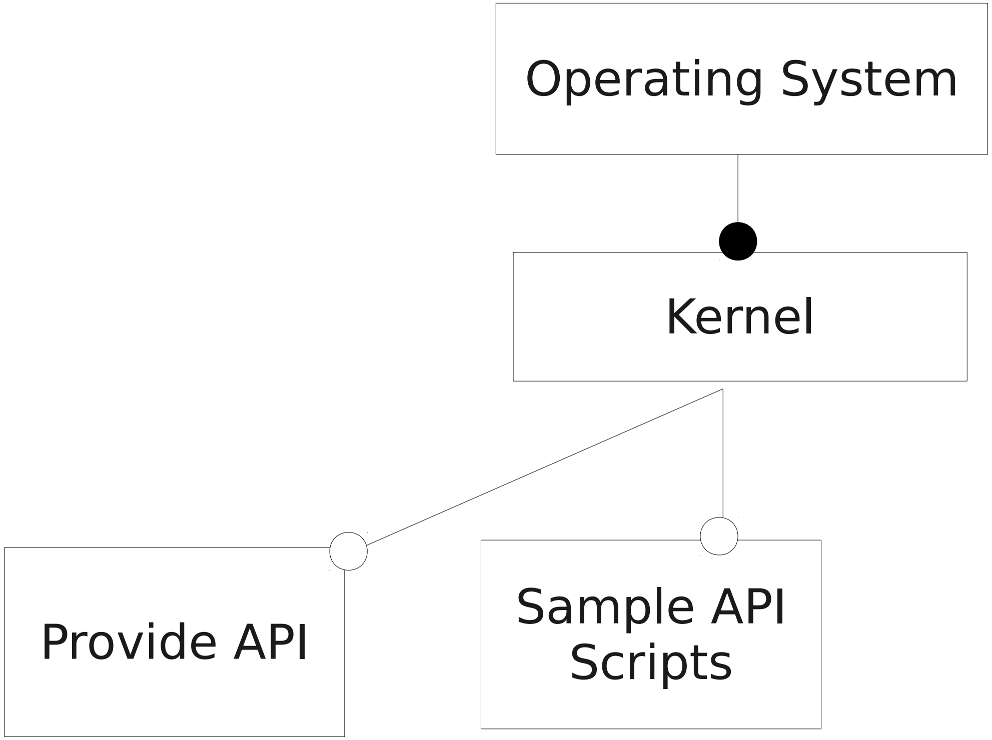
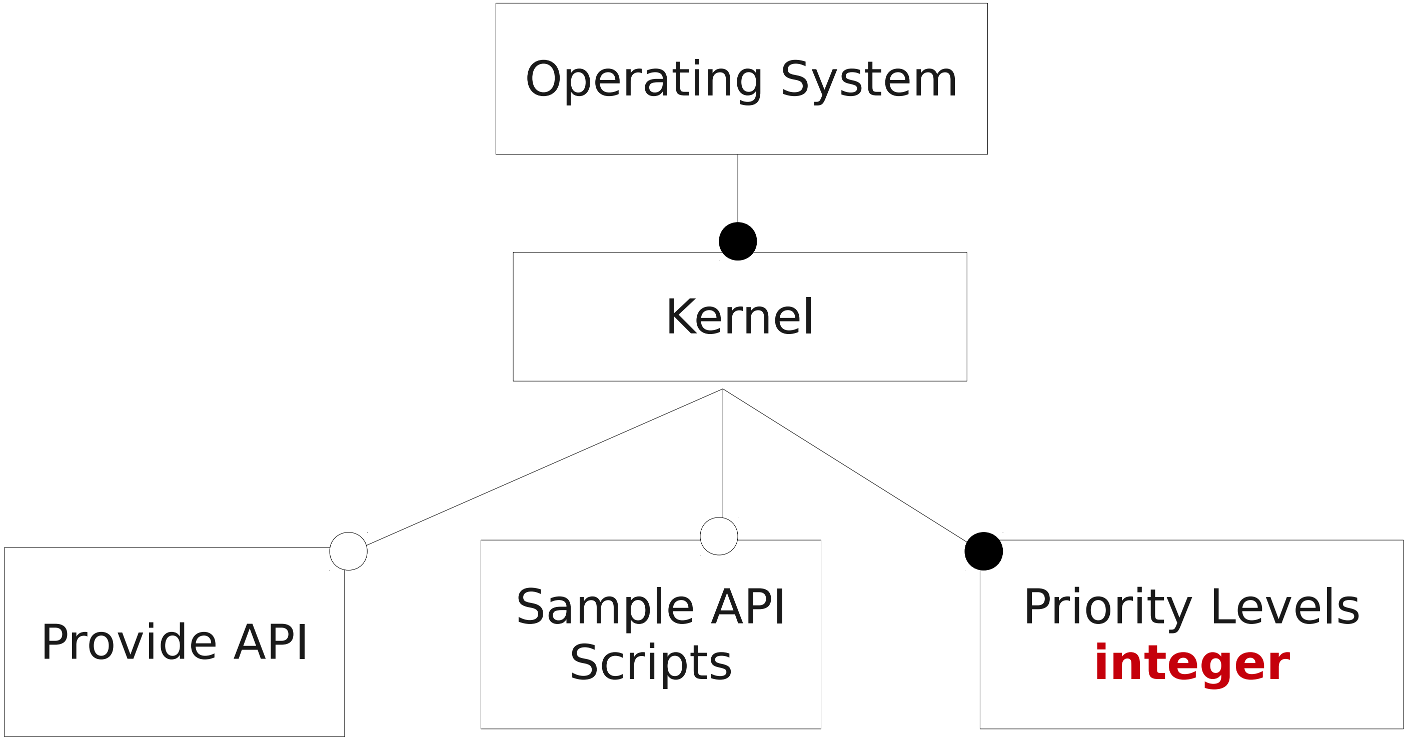
Non-Boolean FMs



Sample API Scripts ⇒ Provide API

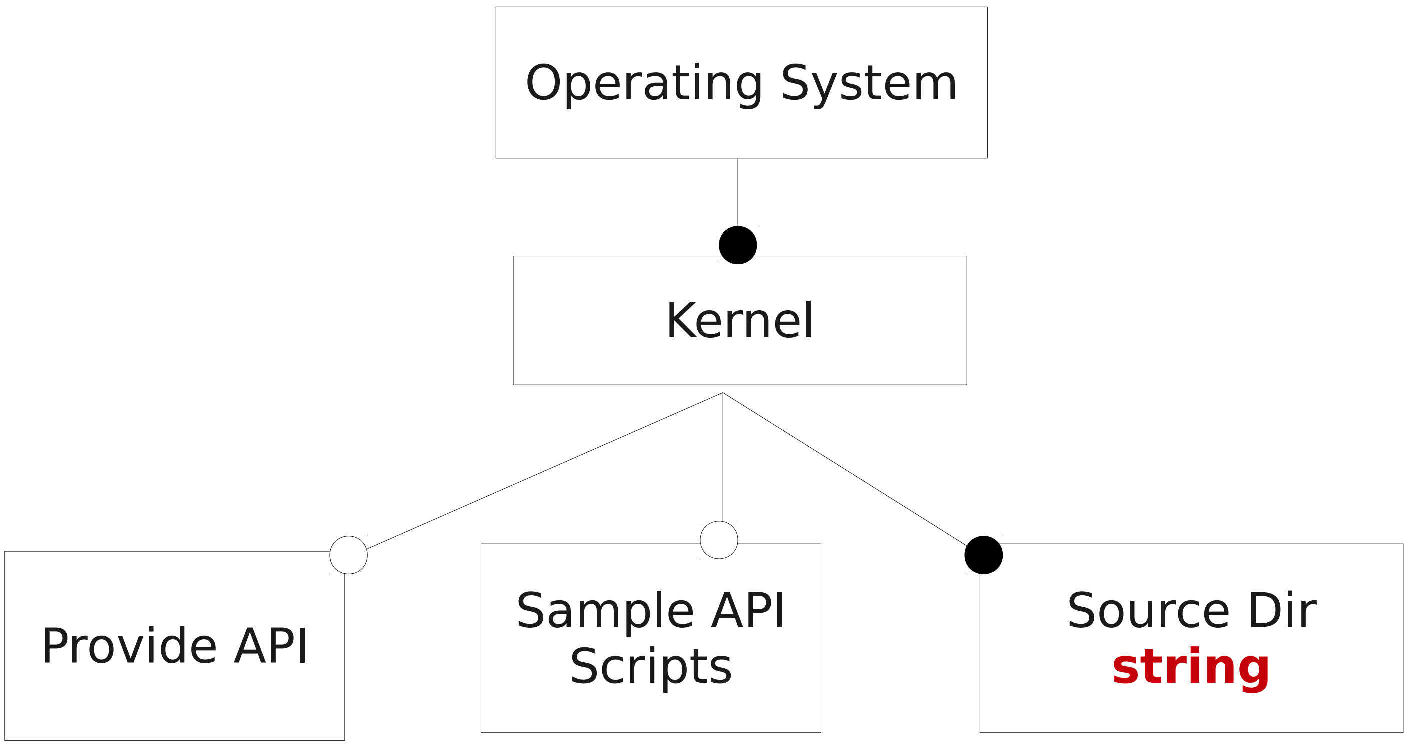
Non-Boolean FMs



Sample API Scripts $\Rightarrow$ Provide API

Priority Levels $\geq$ 1 $\&\&$ Priority Levels $<$ 32

Non-Boolean FMs



Sample API Scripts ⇒ Provide API

(Source Dir) . contains(“src”)

Sample non-Boolean constraint

API_SCRIPTS && LEVELS ≤ 32 &&

(BLOCK_SIZE ***** BLOCK_COUNT **+** SWAP_SIZE ≤ MEM_SIZE) &&

BASE_LIB **contains** (LINUX **?** ".so" **:** ".dll") &&

SRC_DIR **contains** ("src")

⇒ ENABLE_API

Non-Boolean FMs

Contain constraints with:

- Arithmetic, Relational and String operations
- Integer, Float, String, Boolean operands

SAT checking is hard

- Boolean Constraints — NP Complete
- Integer, String and Float — undecidable in general

Motivation

The Goal:

What constraints are used in practice?

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What constraints are used in practice?

Why is that important?

Motivation

We need efficient reasoning to:

- Better support configuration guidance
- Do model analyses – dead features detection
- List valid configurations

Motivation

However:

- Constraints are hard to solve, potentially undecidable
- Can we use existing tools to reason over them?

Motivation

Benchmark for tool developers

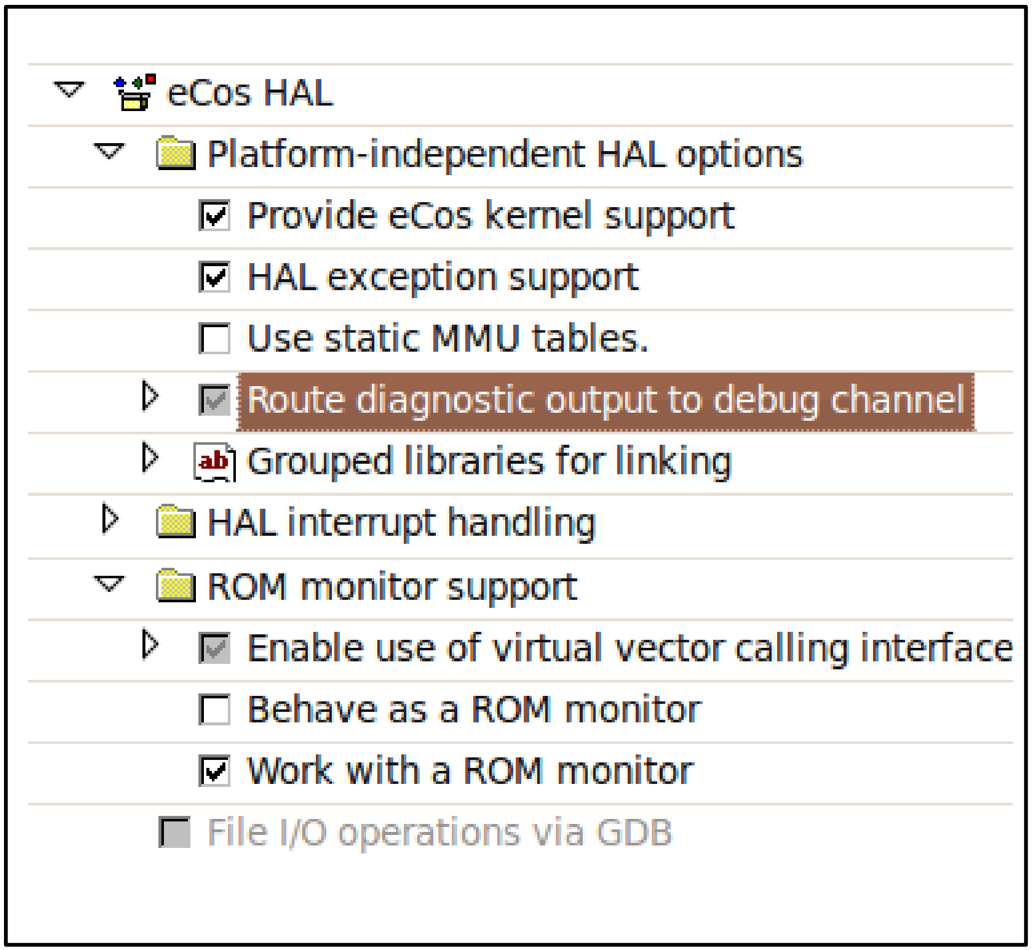
- Add support for new constraints
- Optimize existing tools

Subject of the study

E*mbedded* ***C****onfigurable*
O*perating* ***S****ystem*

- Non-Boolean Feature Model
- Publicly Available

116 Architectures

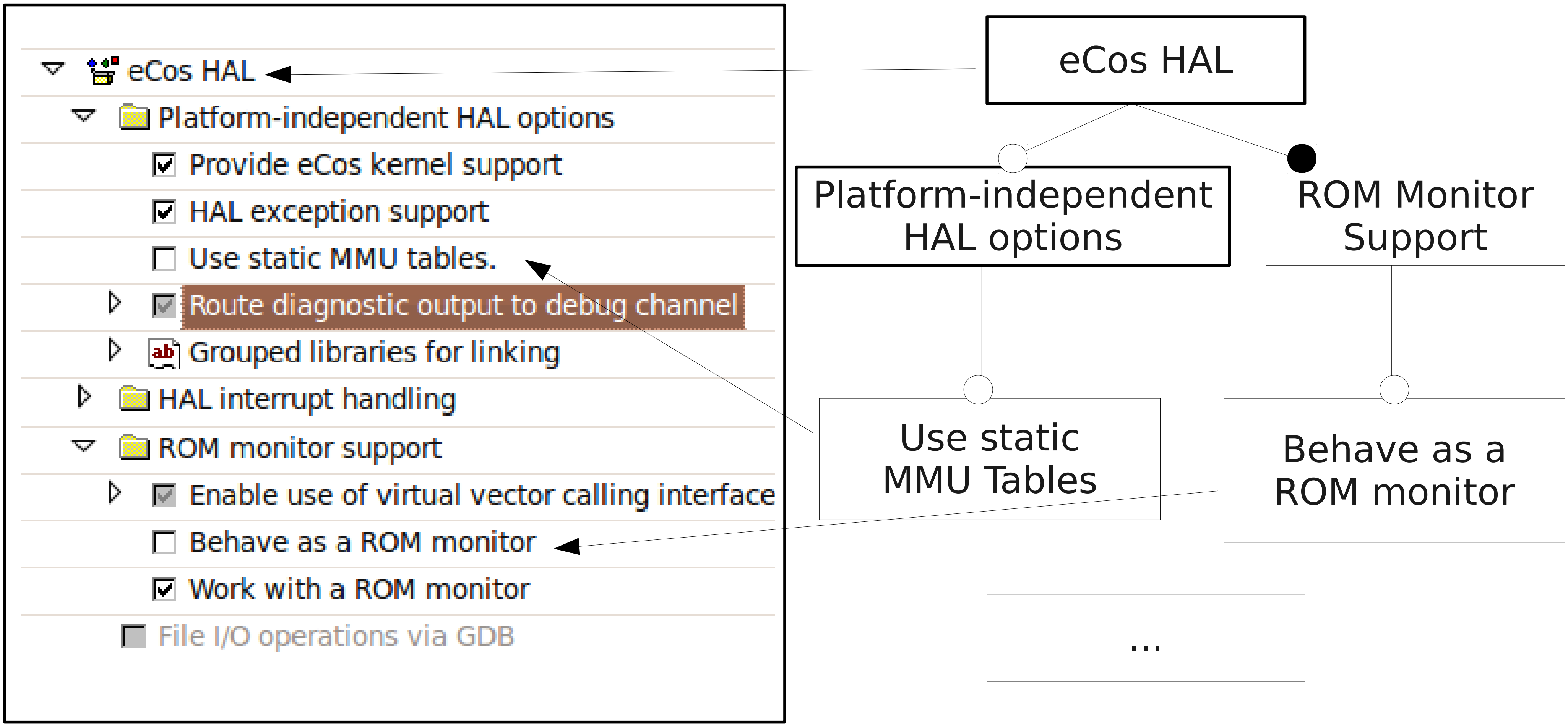


Configuration done using the Configurator

eCos

116 Architectures

Each is a Feature Model



Configuration done using the Configurator

CDL

Domain-specific variability language provided by eCos

```
...

cdl_option CYGNUM_KERNEL_SCHED_BITMAP_SIZE {
  display "Bitmap size"

  requires CYGNUM_KERNEL_SCHED_PRIORITIES > 2

  flavor data
}
...
```

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Analyzing eCos

Different aspects for analyses.

Analyzing eCos

Different aspects for analyses.

Syntactic

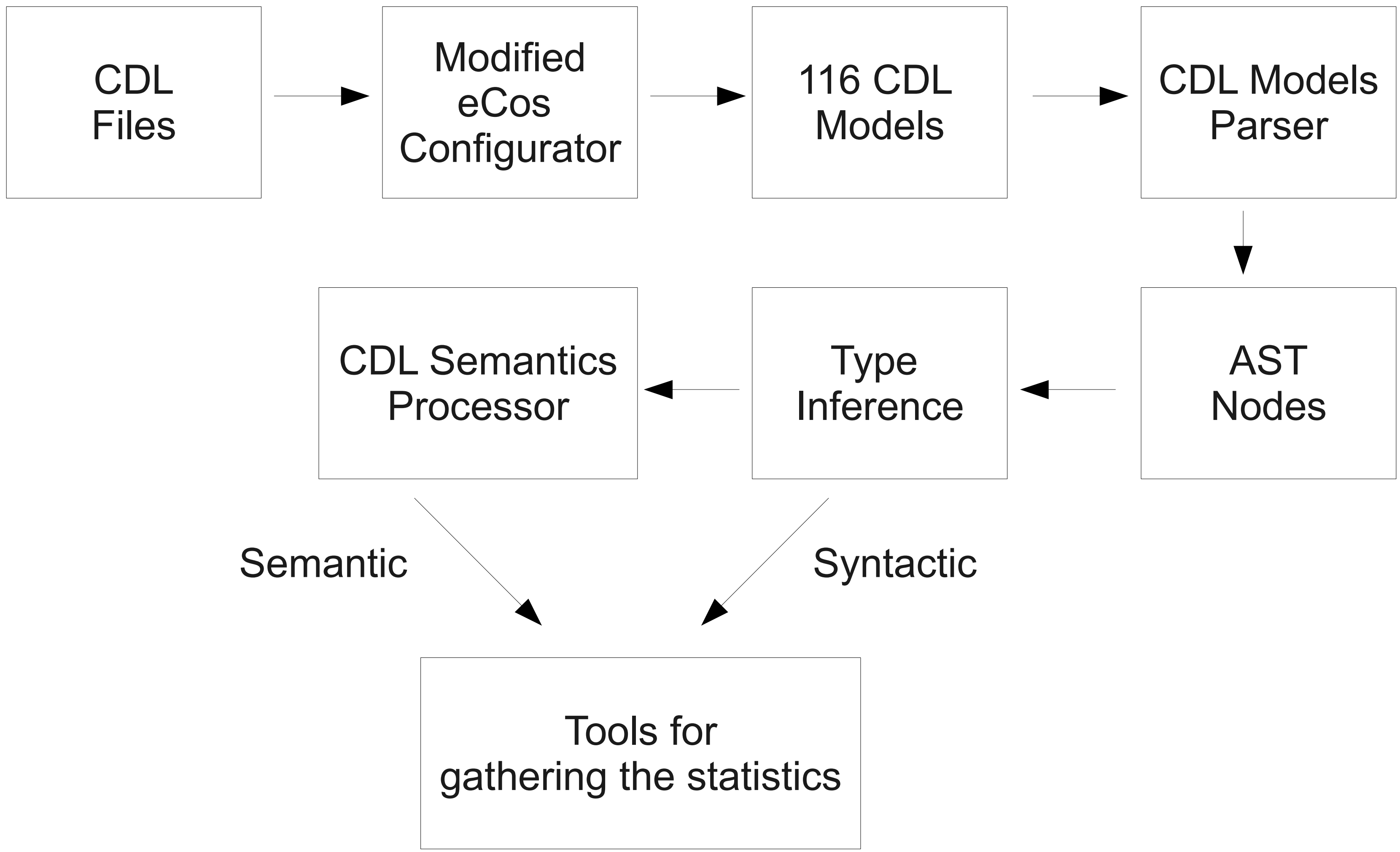
- **Models as created by eCos developers**

Semantic

- Configuration setting used by code generator
- **The behavior of the Configurator**
  - Richer semantics, for interactive support
  - E.g., is a feature active in the GUI or not

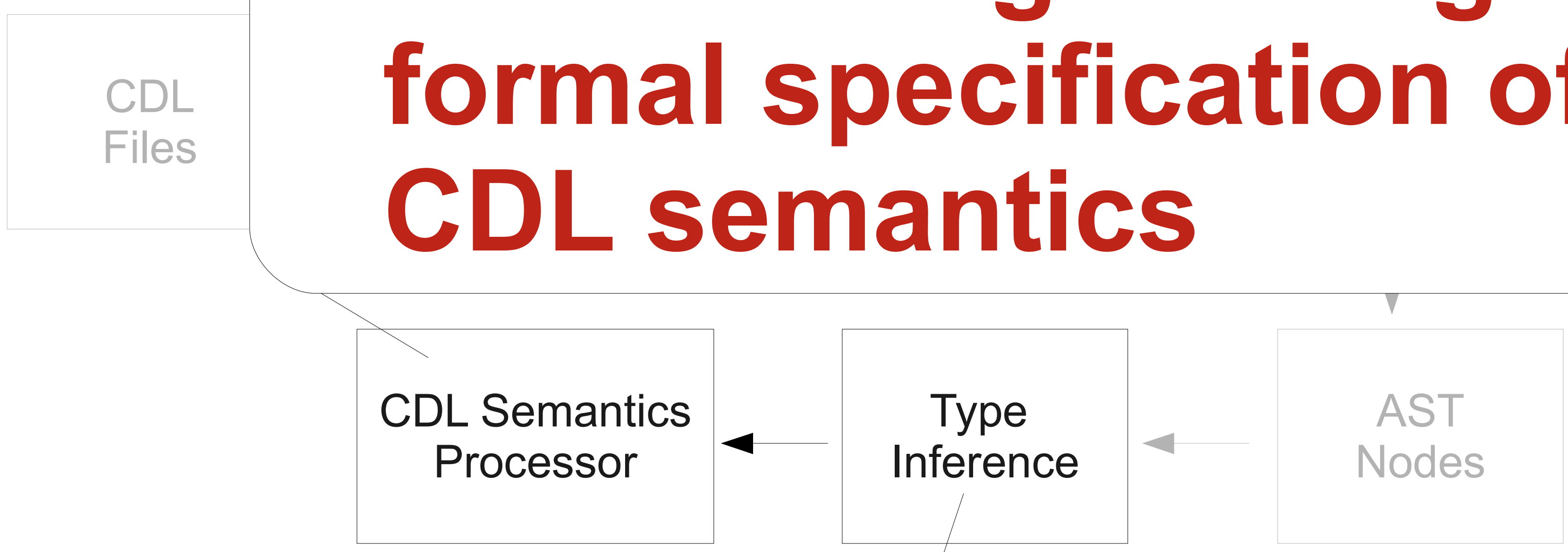
Methodology

The Toolchain



Methodology

Reverse engineering formal specification of CDL semantics



Dynamic type inference

The Results

Summary statistics (min, max, med)
over 116 eCos models

1. Feature Types Proportions

eCos has 3 types of features

- Number (Integer and Float)
- String
- Boolean

Why?

- Many non-Boolean features can not be ignored

1. Feature Types Proportions

Total # of features:

1230 Median
1312 Maximum
1159 Minimum

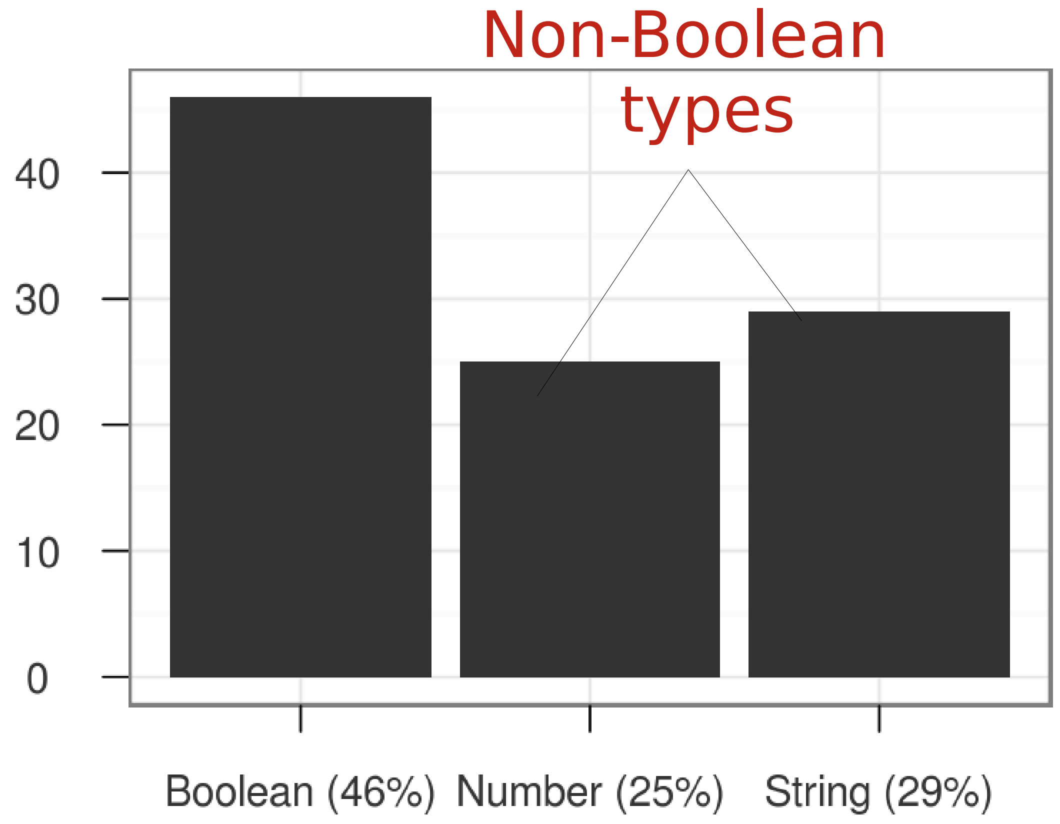


Figure: feature types - median value

2. Restriction on non-Boolean types

Static constraints effectively specifying types (sets of values)

- Ranges – 1 to 7
- Constants – “ROM”
- Enumerations – {1, 2, 3}
- Unrestricted – just string or integer

2. Restriction on non-Boolean types

Advantages:

- Model simplification
- Shrinking the domain
- Replace constants occurrences with the value
- Enumerations are “easier” than integers

2. Restriction on non-Boolean types

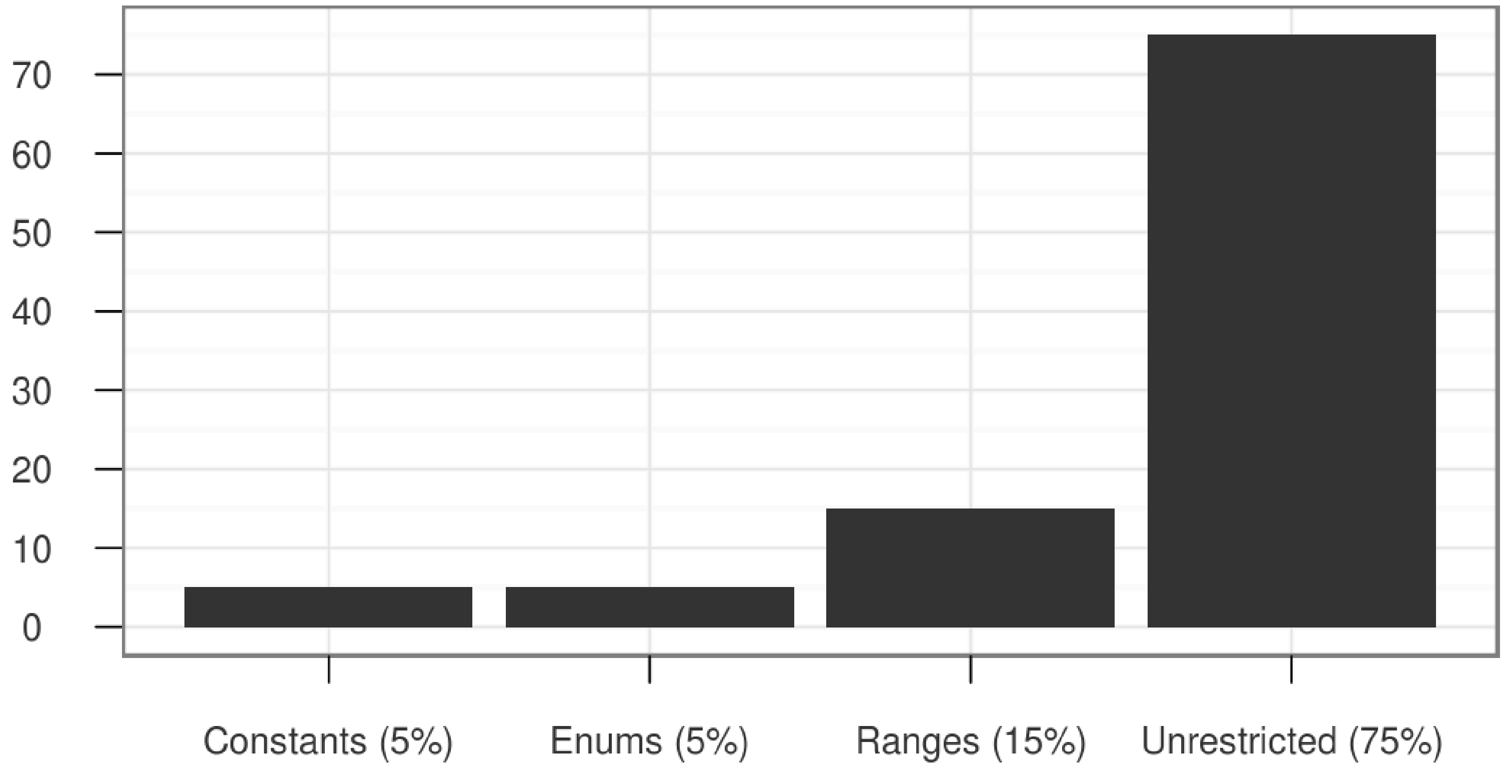


Figure: restrictions - median value

3. The Constraints (Syntactic level)

Constraints classification:

- Purely Boolean
  - Boolean operators and features
  - A && B, A || B

- Purely non-Boolean
  - Non-Boolean operators and features
  - A + 10 == C

- Mixed
  - B && (A + 10 == C)

3. The Constraints (Syntactic level)

We want to do efficient analysis over the constraints

- We want to better understand the hardness of the Real World constraints
- Purely Boolean – SAT solving

3. The Constraints (Syntactic level)

Number of constraints:

1015 Median
1269 Maximum
916 Minimum

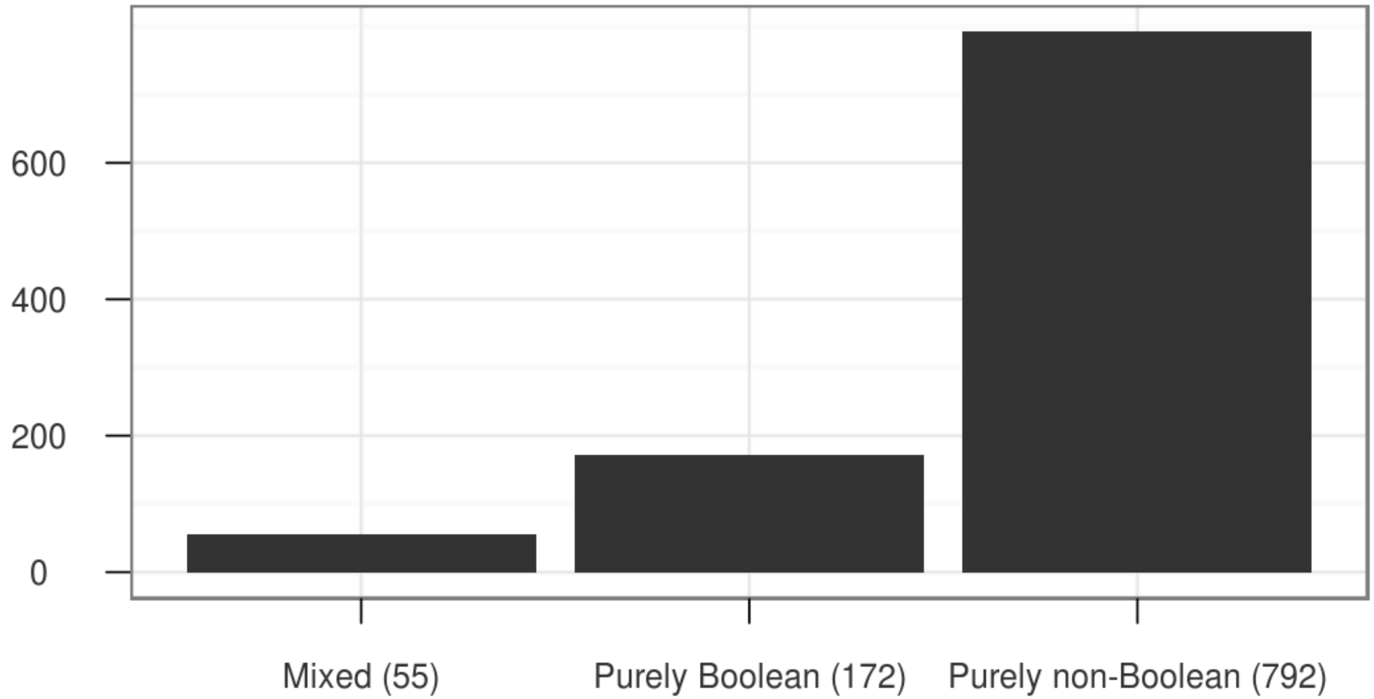


Figure: No. of constraints - median value

4. Semantic Constraints

Capturing the configurator behavior

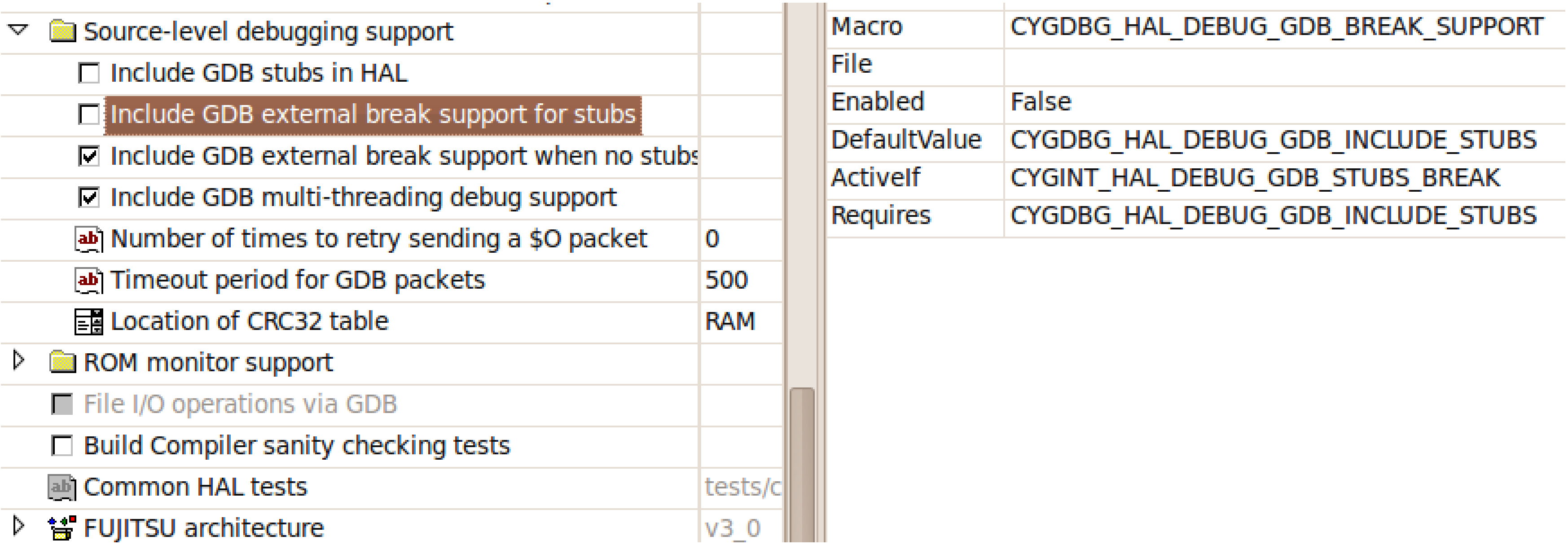


Figure: The configurator

4. Semantic Constraints

Capturing the configurator behavior

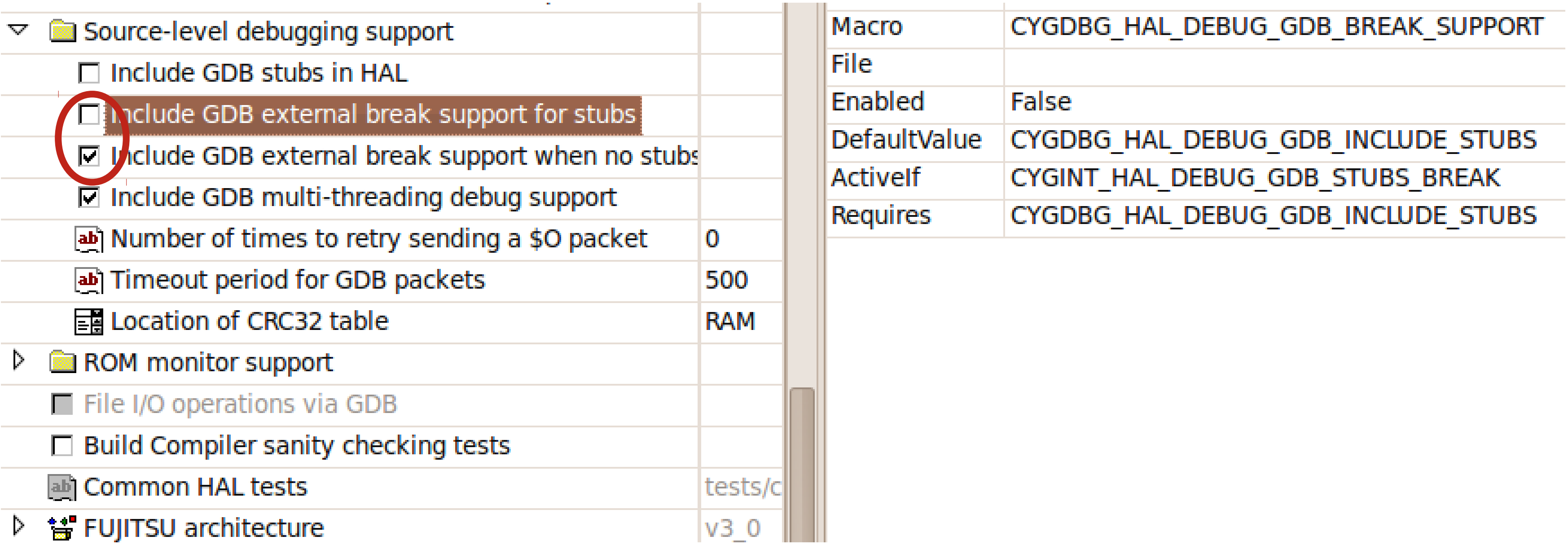


Figure: Enabling features

4. Semantic Constraints

Capturing the configurator behavior

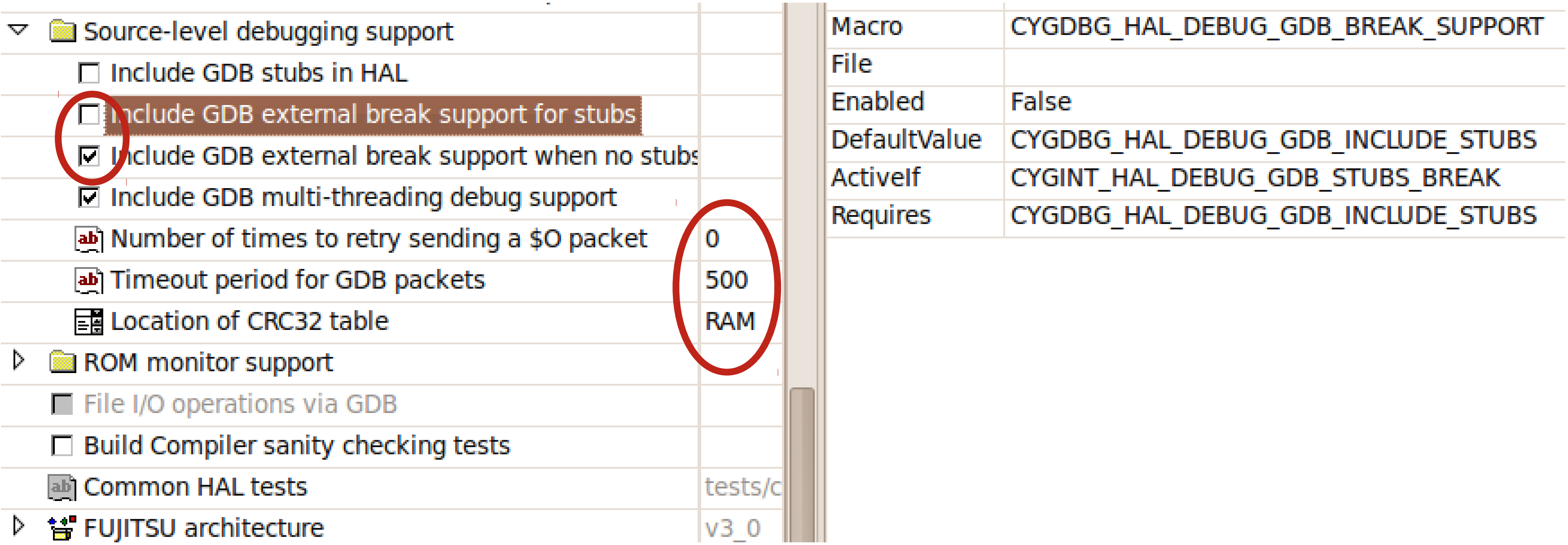


Figure: Providing the data

3. Semantic Constraints

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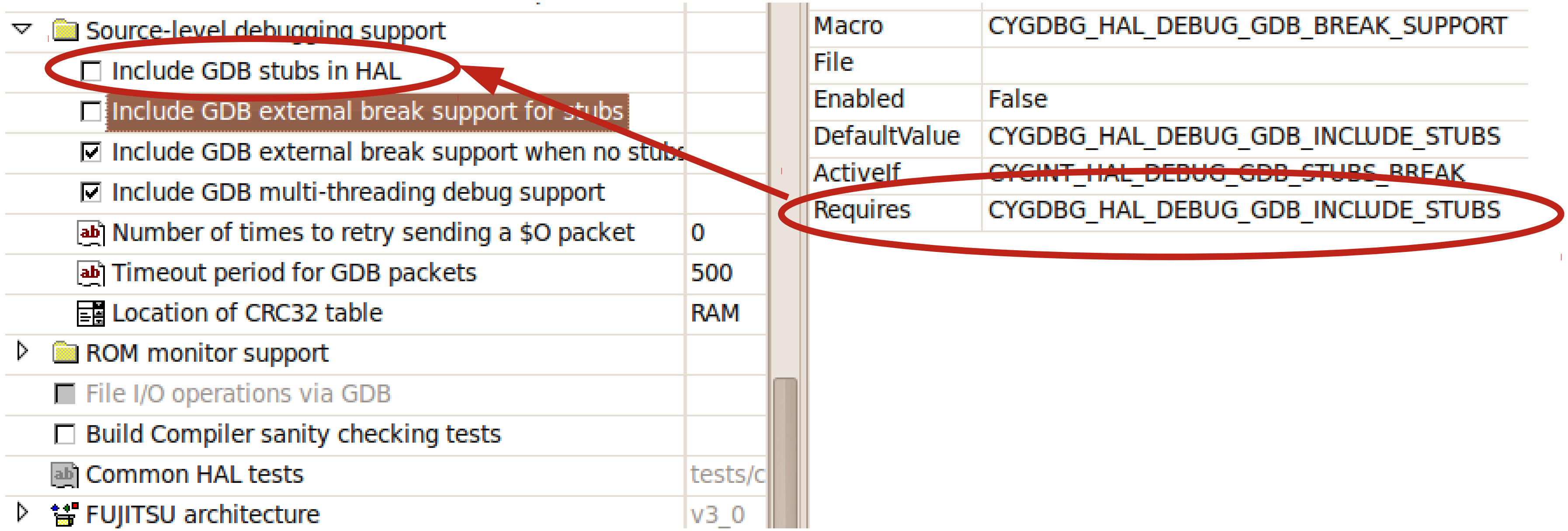

Figure: A constraint

4. Semantic Constraints

Capturing the configurator behavior

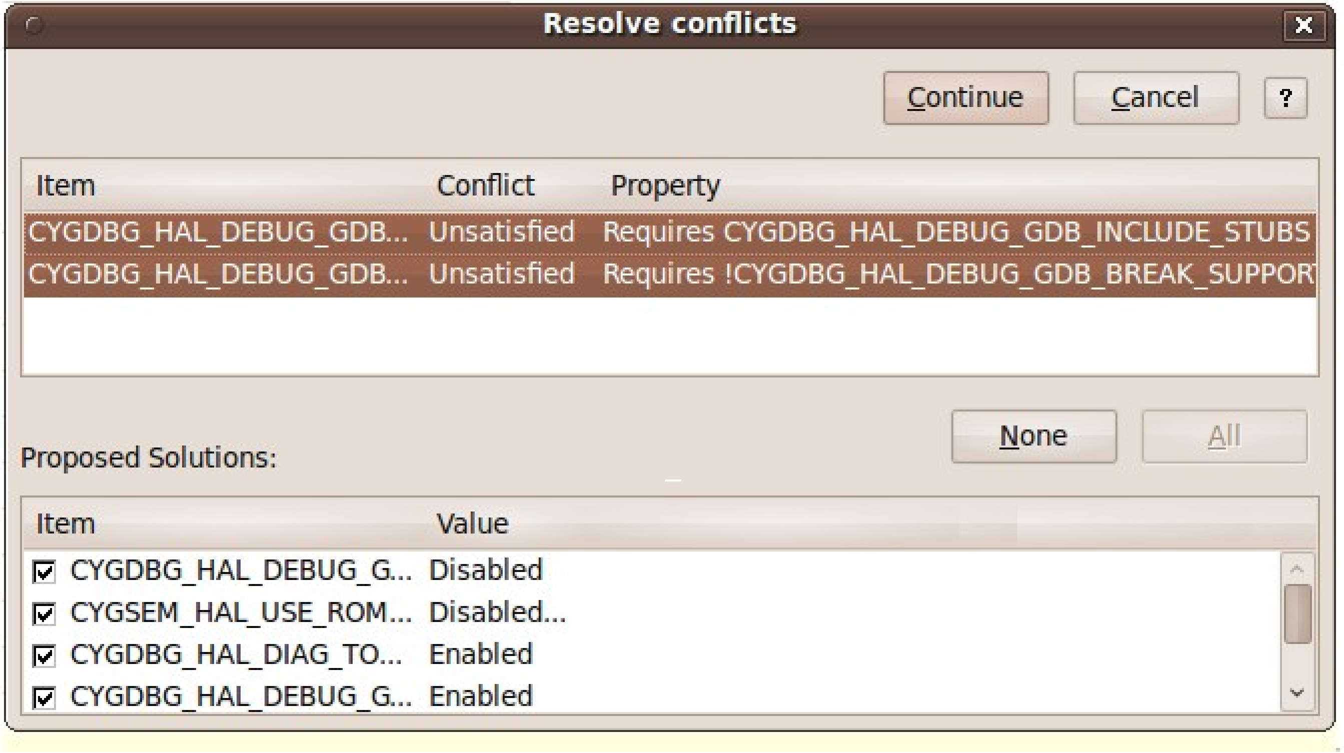

Figure: Conflict

4. Semantic Constraints

Capturing the configurator behavior

We transform the model:

- Enable state variables – enabled_var
- Data variables – data_var
- Constraints mapping the conflicts

4. Semantic Constraints

Semantic constraints classification:

- Purely Boolean
  - Enabled state variables
  - Boolean operators
- Purely non-Boolean
  - Data state variables
  - non-Boolean operators – relational, string, arithmetic
- Mixed

4. Semantic Constraints

Number of constraints:
616 Median
686 Maximum
593 Minimum

Median number of variables:
420 Data
521 Enabled

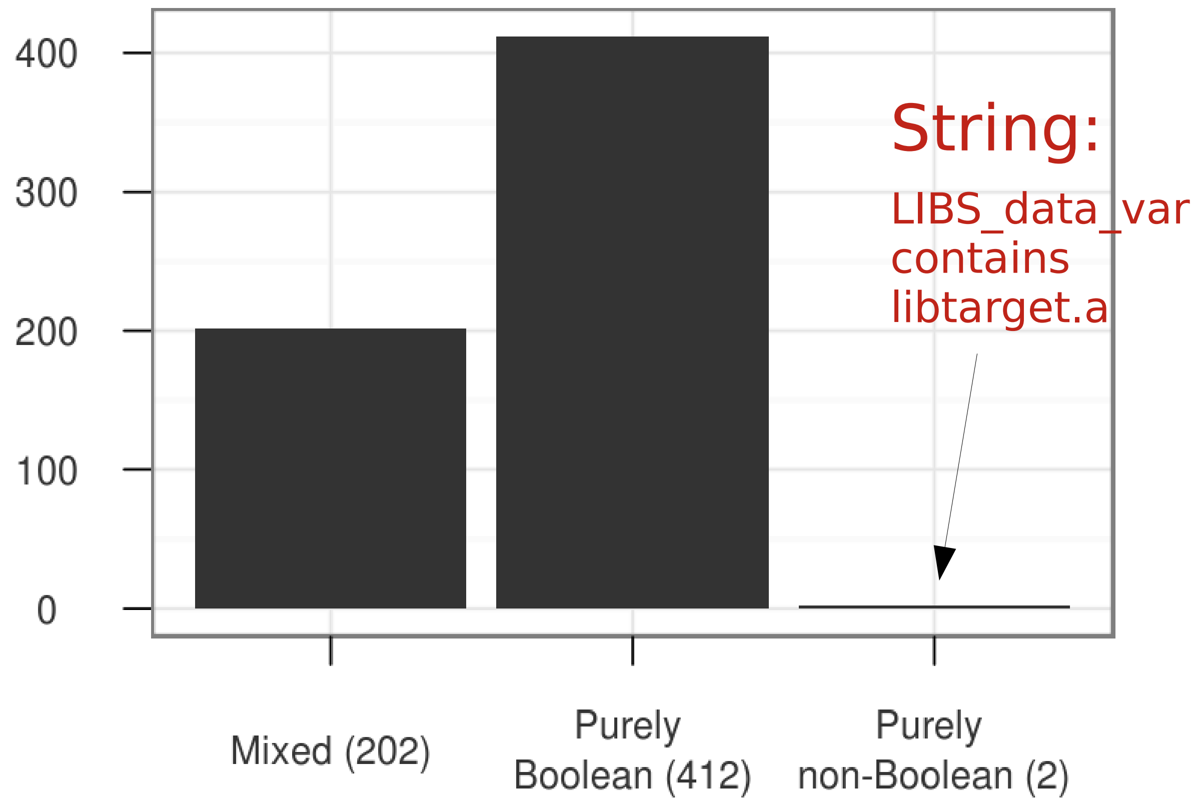

Figure: Number of occurrences median value

5. Semantic Expansion - Patterns

Sample eCos pattern:

```
(1 ≤
 (
  ((
   (RTC_NUMERATOR_data *
    (((OSC_MAIN data * PLL_MULTIPLIER_data) / PLL_DIVIDER_data)/2)
   )
   /(TIMER_TC_enabled ? 32 : 16)
   )/RTC_DENOMINATOR_data)/ 1000000000
 )
)
```

5. Semantic Expansion - Patterns

Patterns:

aXY	$\geq$ $\leq$	b, max. occurrences = 2
aXY / Z	$\geq$ $\leq$	b, max. occurrences = 2
aXY / PZ	$\leq$	b, max. occurrences = 1
aXYZ/(α+β)PQ	$\geq$ $\leq$	b, max. occurrences = 2

More details in the paper

- Boolean, number and string operator occurrence frequency at semantic and syntactic
- Explanation of the semantics
- All 116 models as Clafer models are available @ http://gsd.uwaterloo.ca/FOSD11

Conclusions

- Studied 116 real-world non-Boolean FM
- ~50% of features are non-Boolean (numbers and strings)
- ~70% of constraints are non-Boolean
- Some constraints are complex (e.g. non-linear)
- Provided 116 models as a benchmark for tool builders

- Such non-Boolean models are likely to occur in embedded systems

Future:

- Provide reasoning techniques that work on these constraints

Thank you!

Questions?