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

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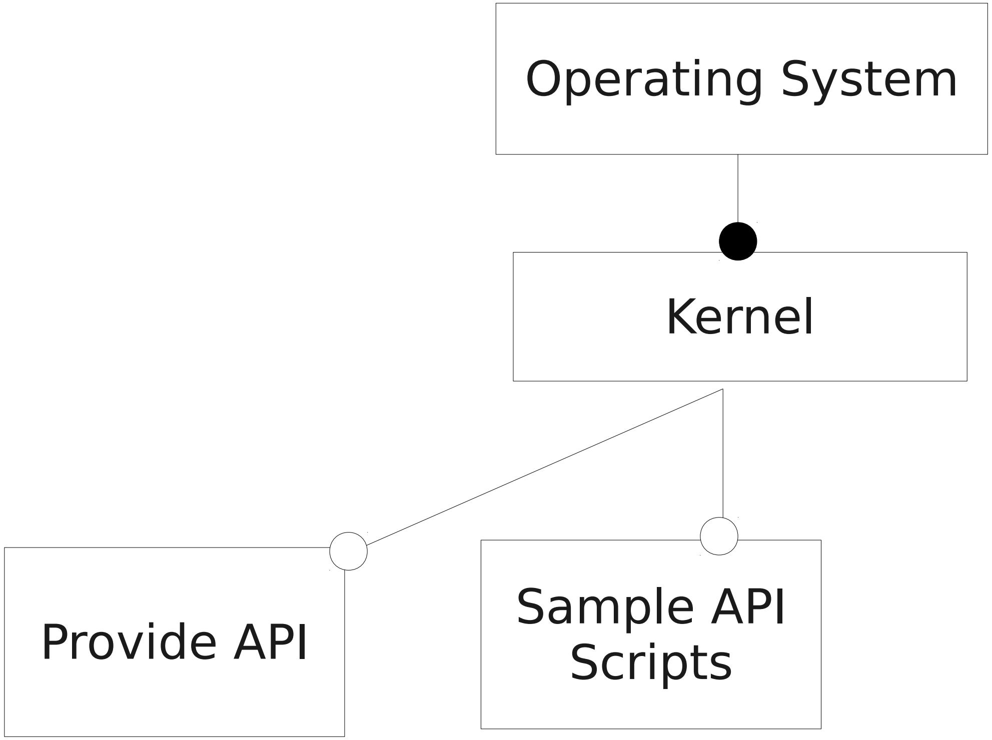
Contents

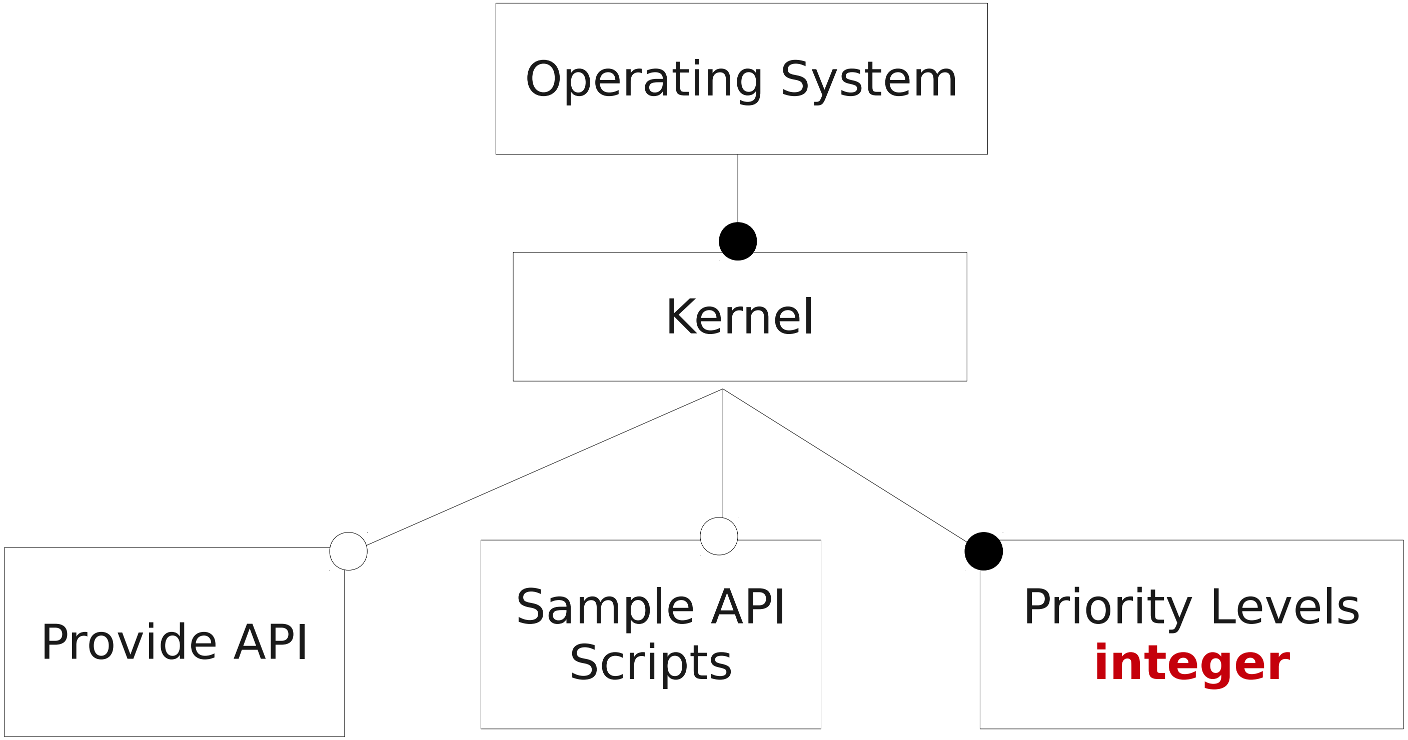
- Non-Boolean FMs
- Motivation
- eCos
- Results
  - Non-linear arithmetic constraints
- Conclusions

Non-Boolean FMs



Sample API Scripts ⇒ Provide API

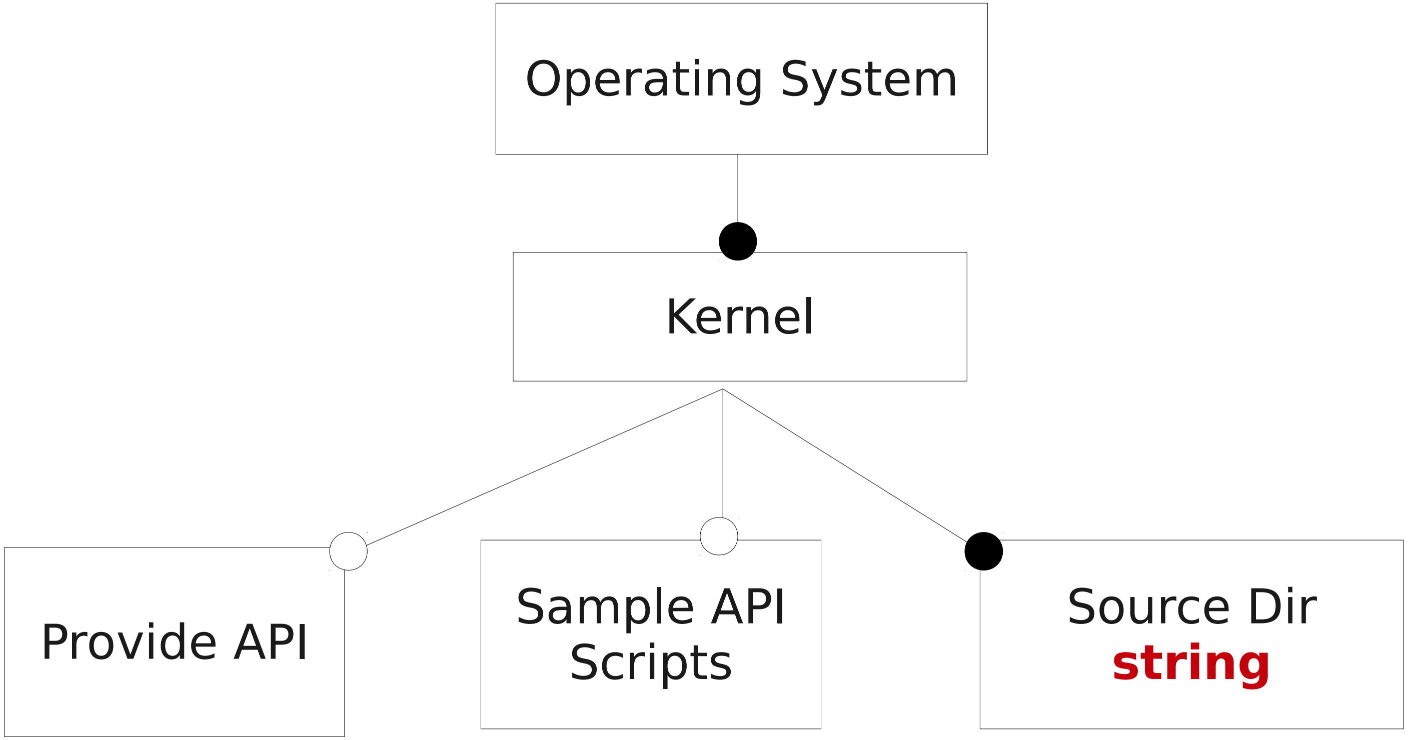
Non-Boolean FMs



Sample API Scripts ⇒ Provide API

Priority Levels ≥ 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?

Motivation

The Goal:

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

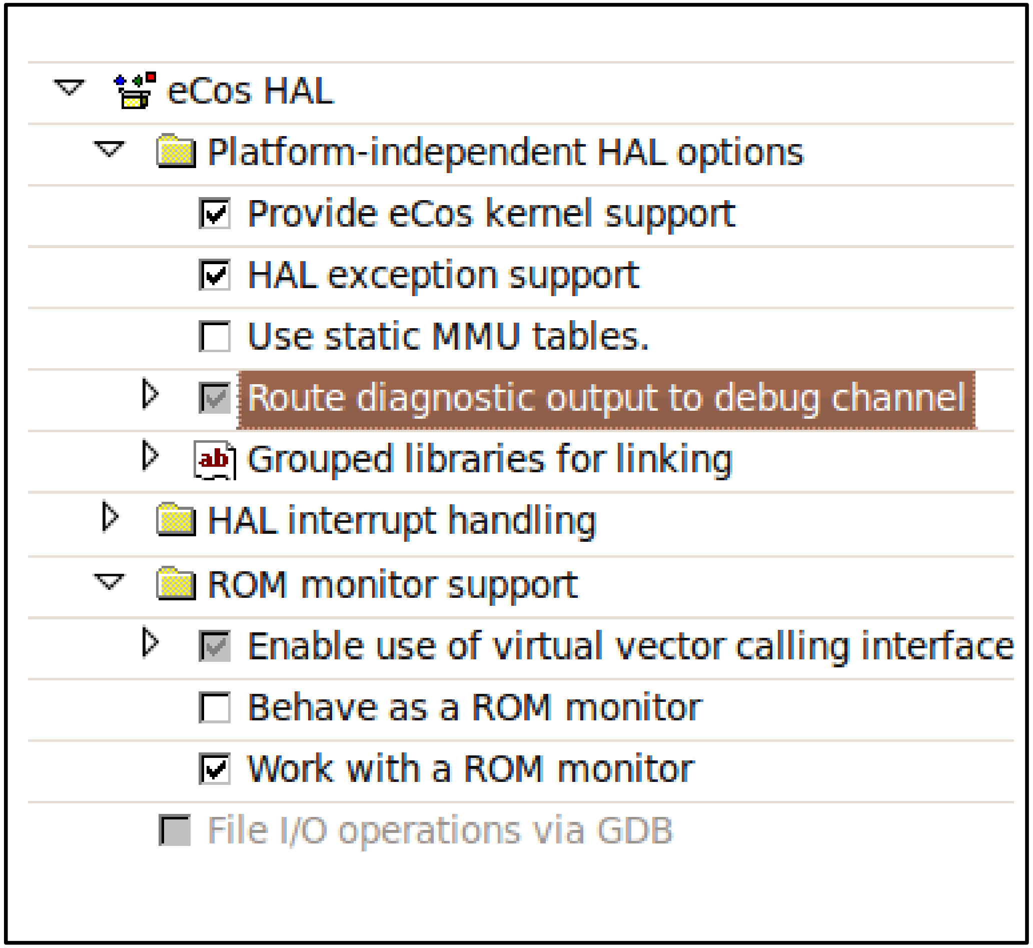
Subject of the study

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

- Non-Boolean Feature Model
- Publicly Available

eCos

116 Architectures



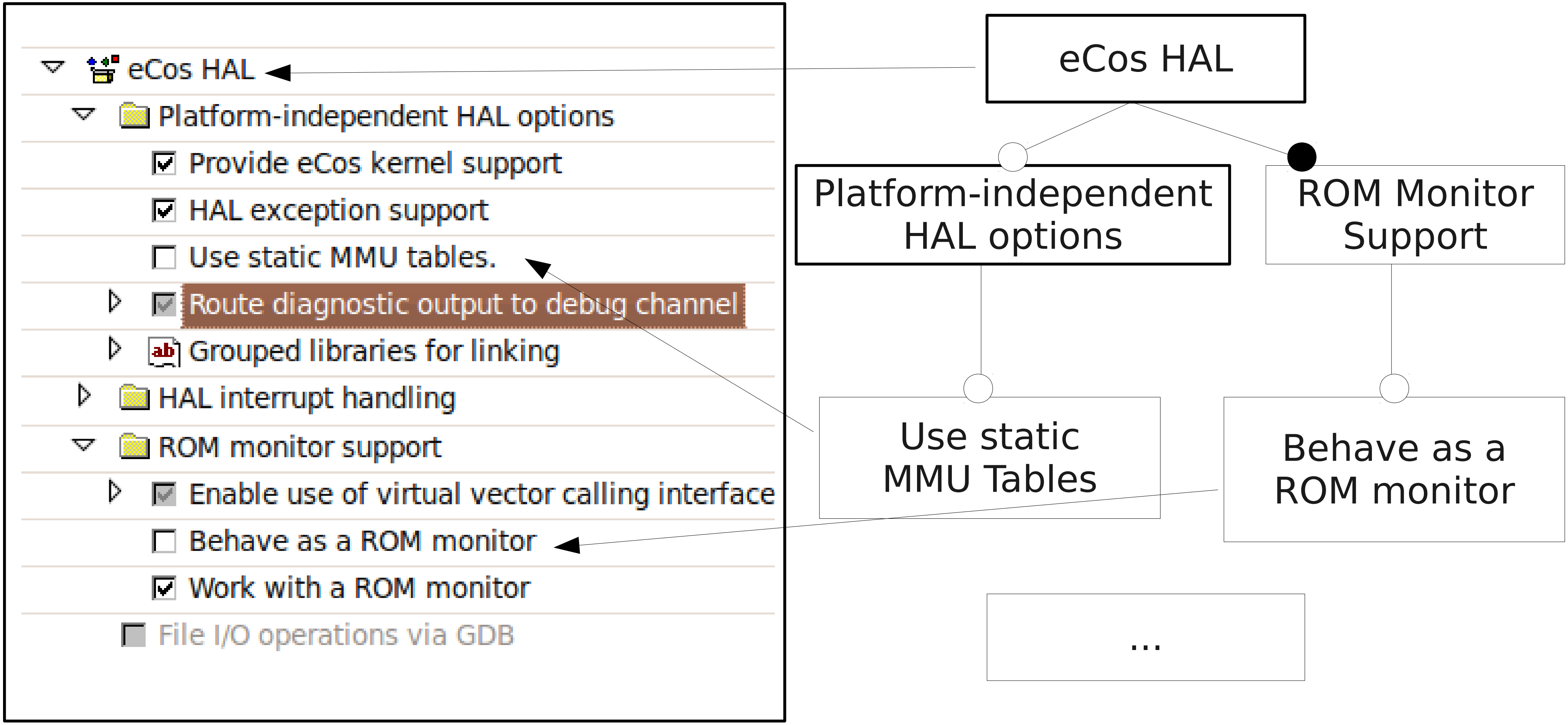
- ▽ eCos HAL
  - ▽ Platform-independent HAL options
    - ☑ Provide eCos kernel support
    - ☑ HAL exception support
    - □ Use static MMU tables.
    - ▷ ☑ Route diagnostic output to debug channel
    - ▷ Grouped libraries for linking
  - ▷ HAL interrupt handling
  - ▽ ROM monitor support
    - ▷ ☑ Enable use of virtual vector calling interface
    - □ Behave as a ROM monitor
    - ☑ Work with a ROM monitor
  - □ File I/O operations via GDB

Configuration done using the Configurator

eCos

116 Architectures

Each is a Feature Model



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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

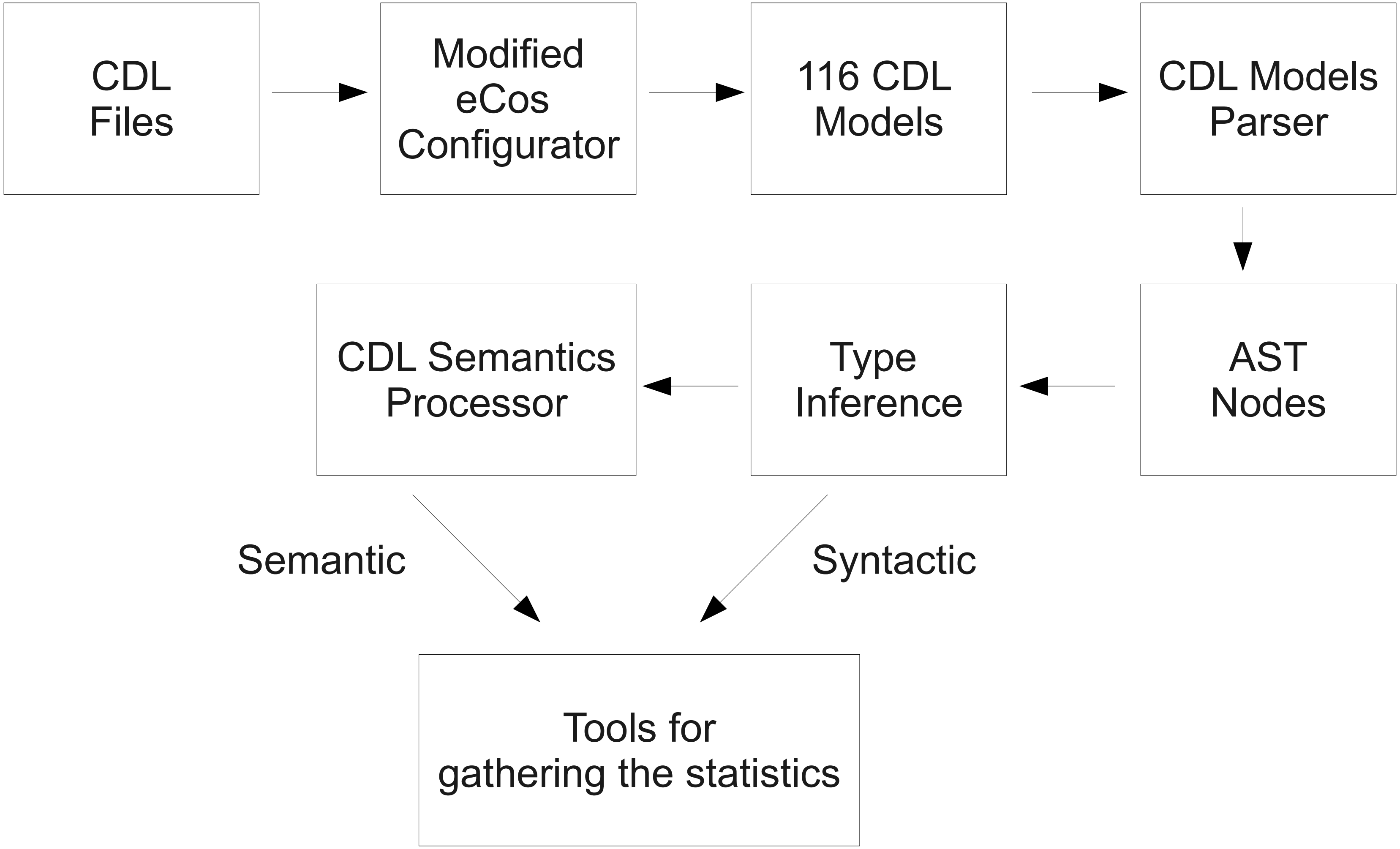
- **Models as created by eCos developers**

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



CDL Files

Modified eCos Configurator

116 CDL Models

CDL Models Parser

AST Nodes

Type Inference

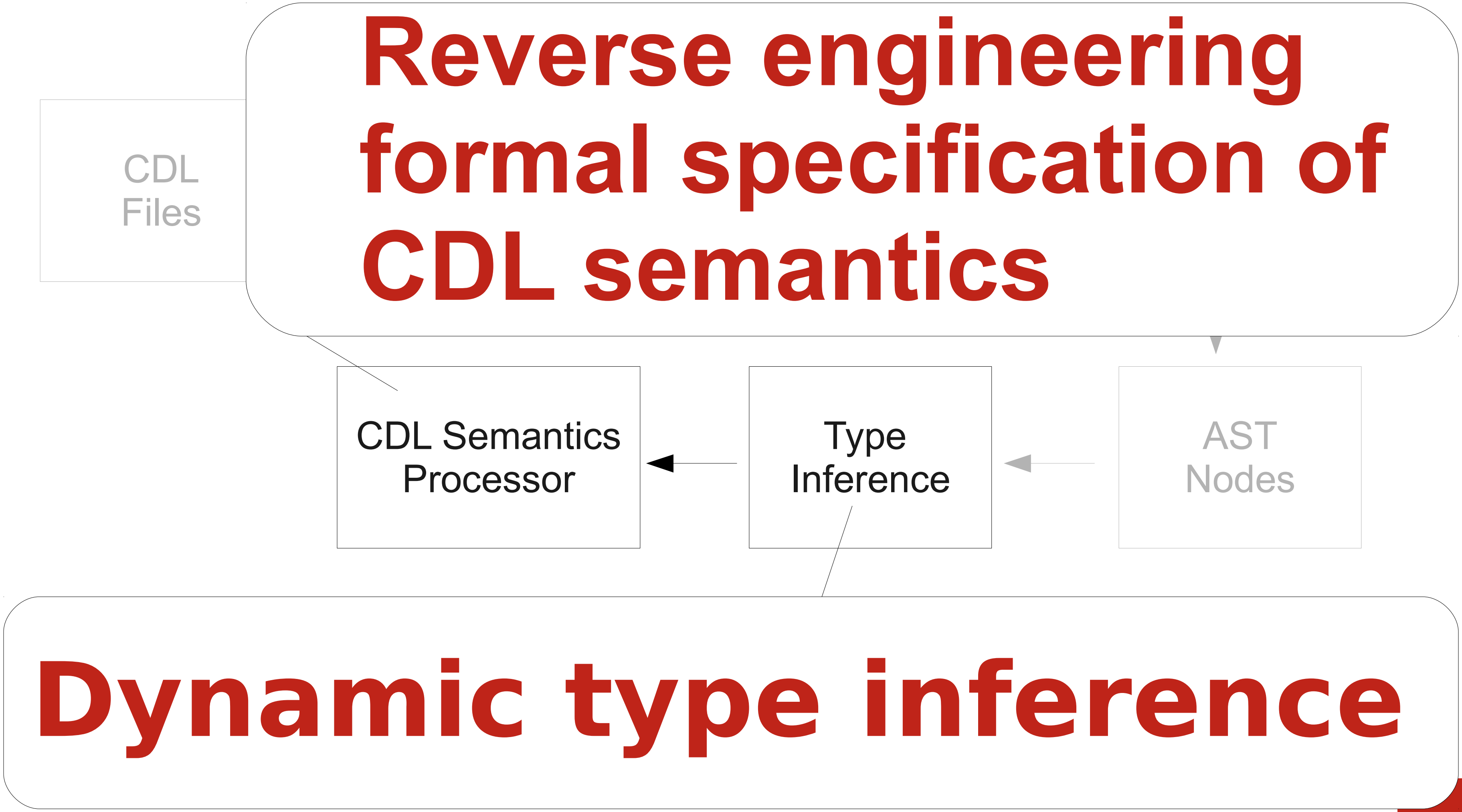
CDL Semantics Processor

Semantic

Syntactic

Tools for gathering the statistics

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

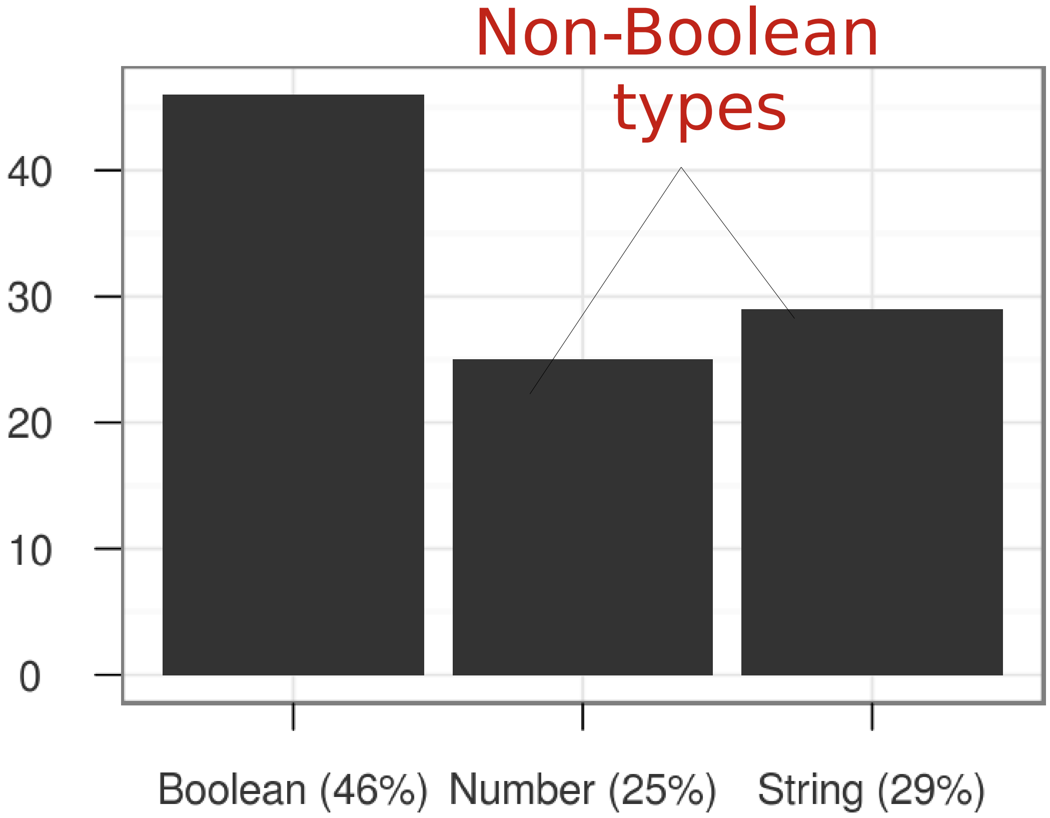


Figure: feature types - median value

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

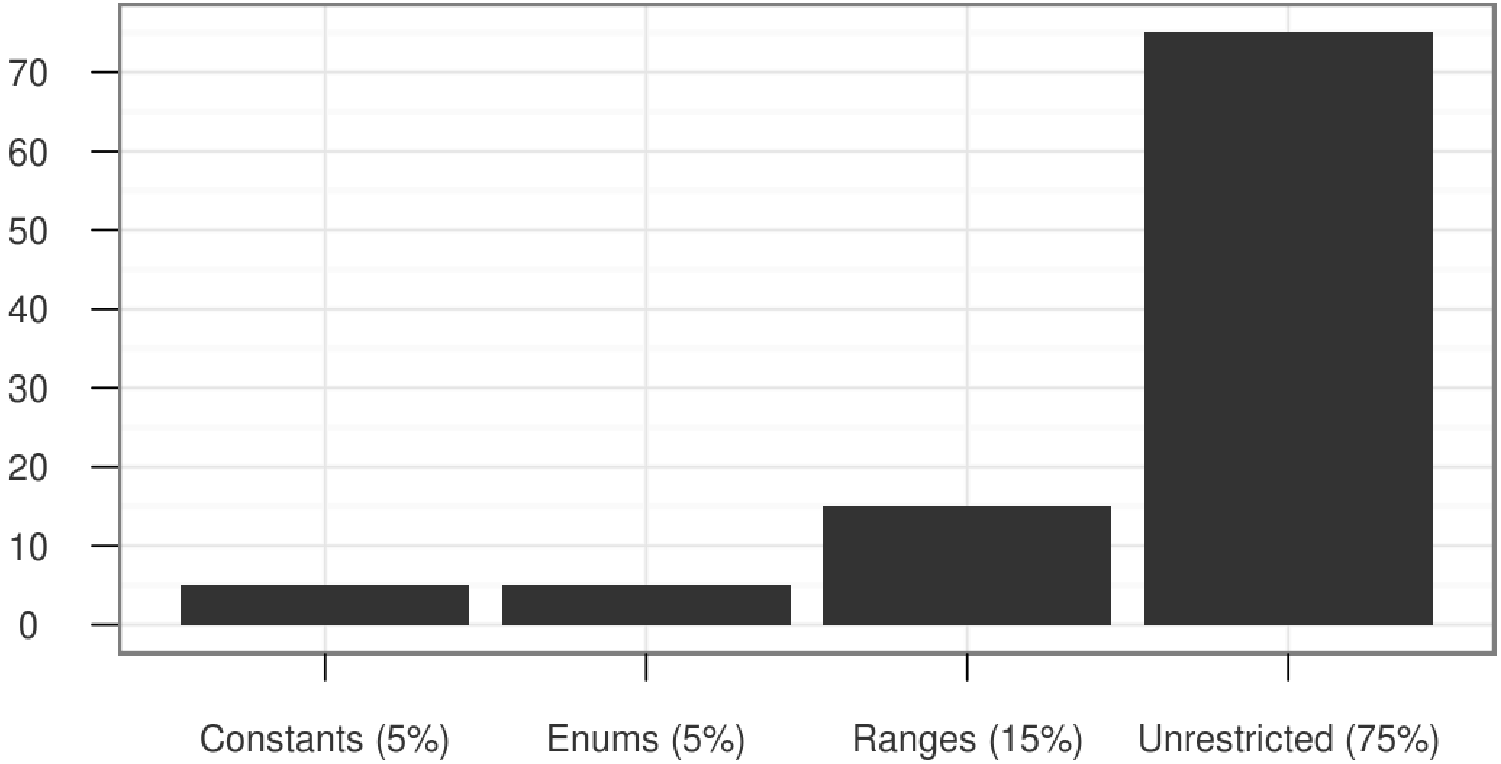


Figure: restrictions - median value

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

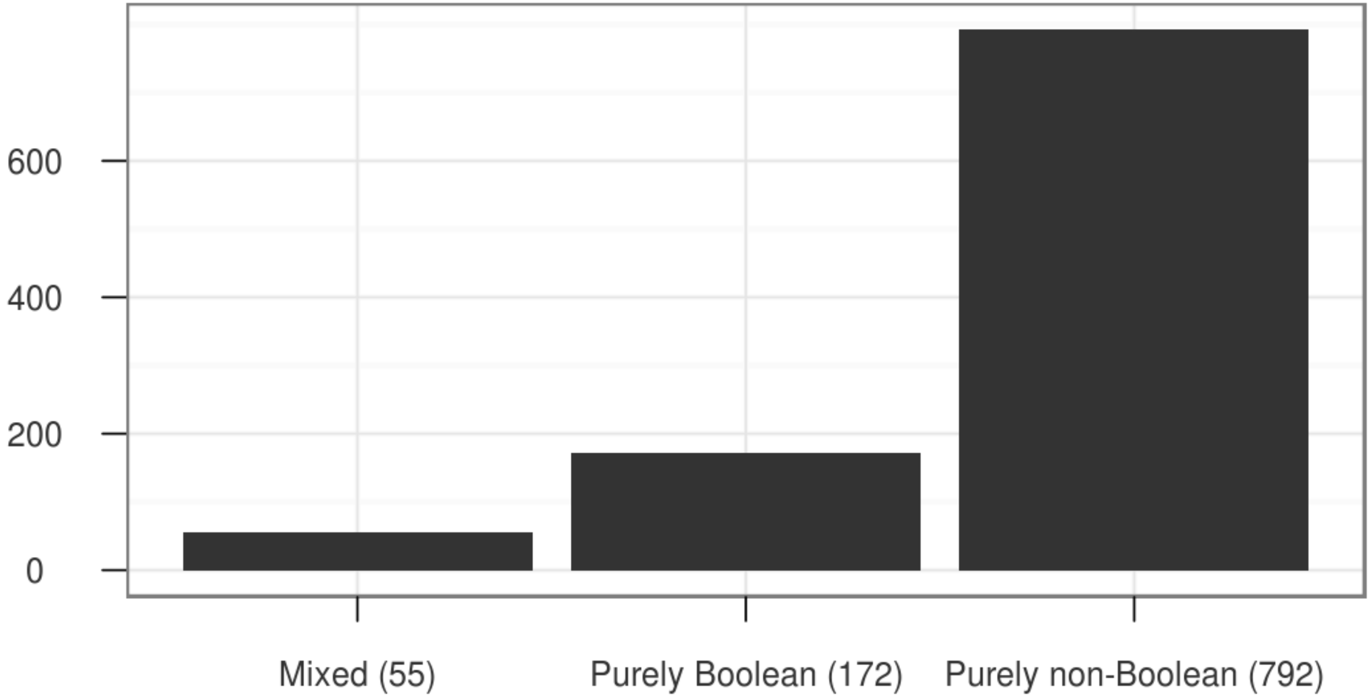
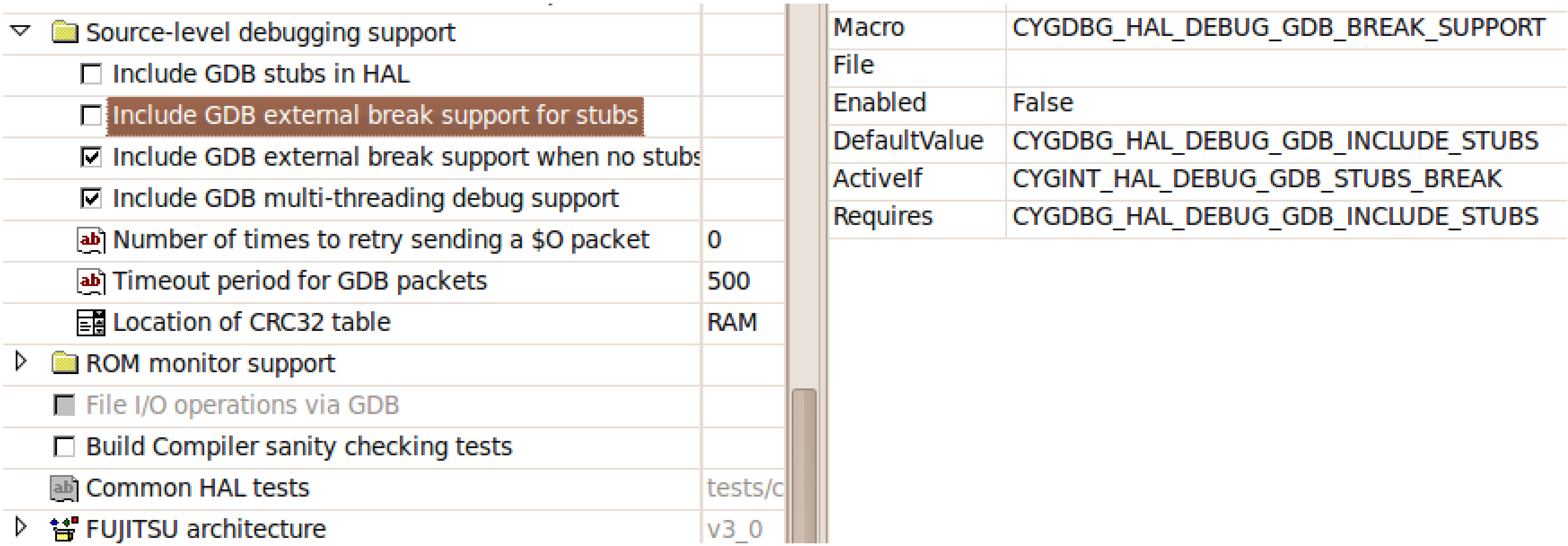


Figure: No. of constraints - median value

4. Semantic Constraints

Capturing the configurator behavior



▽ Source-level debugging support	
□ Include GDB stubs in HAL	
□ Include GDB external break support for stubs	
☑ Include GDB external break support when no stubs	
☑ Include GDB multi-threading debug support	
Number of times to retry sending a $O packet	0
Timeout period for GDB packets	500
Location of CRC32 table	RAM
▷ ROM monitor support	
File I/O operations via GDB	
□ Build Compiler sanity checking tests	
Common HAL tests	tests/c
▷ FUJITSU architecture	v3_0

Macro	CYGDBG_HAL_DEBUG_GDB_BREAK_SUPPORT
File	
Enabled	False
DefaultValue	CYGDBG_HAL_DEBUG_GDB_INCLUDE_STUBS
ActiveIf	CYGINT_HAL_DEBUG_GDB_STUBS_BREAK
Requires	CYGDBG_HAL_DEBUG_GDB_INCLUDE_STUBS

Figure: The configurator

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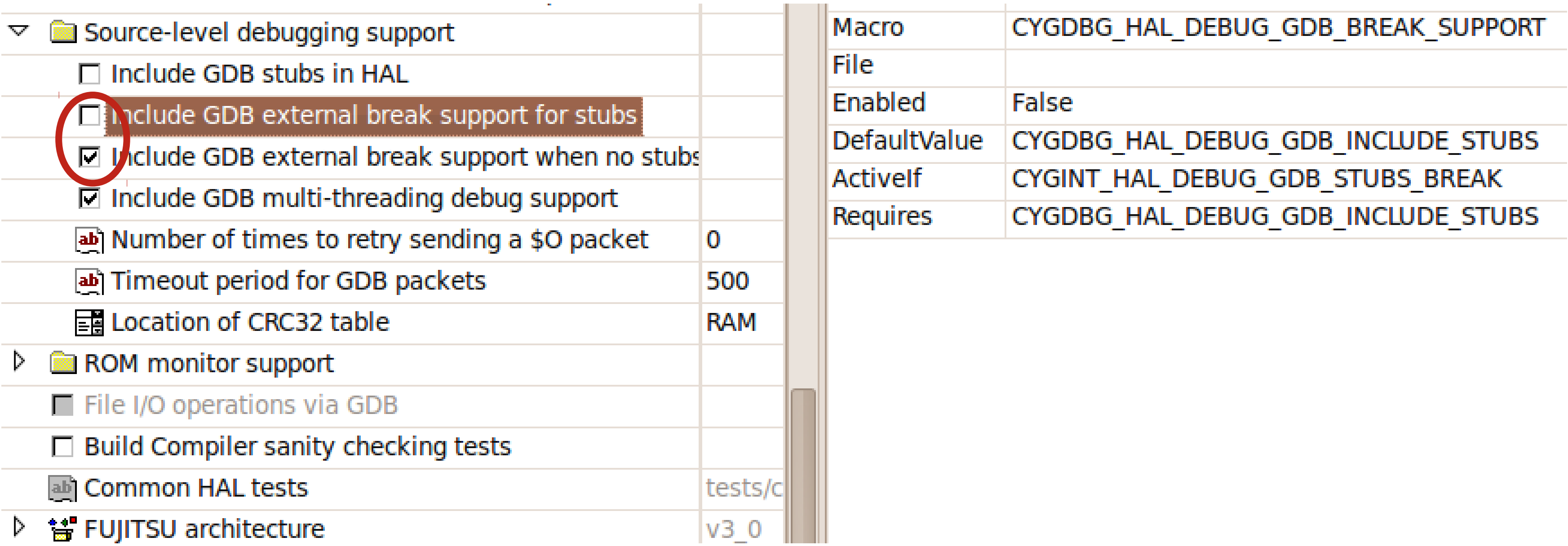

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  - □ Include GDB stubs in HAL
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  - ☑ Include GDB external break support when no stubs
  - ☑ Include GDB multi-threading debug support
  - Number of times to retry sending a $O packet — 0
  - Timeout period for GDB packets — 500
  - Location of CRC32 table — RAM
- ROM monitor support
- □ File I/O operations via GDB
- □ Build Compiler sanity checking tests
- Common HAL tests — tests/c
- FUJITSU architecture — v3_0

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Figure: Enabling features

4. Semantic Constraints

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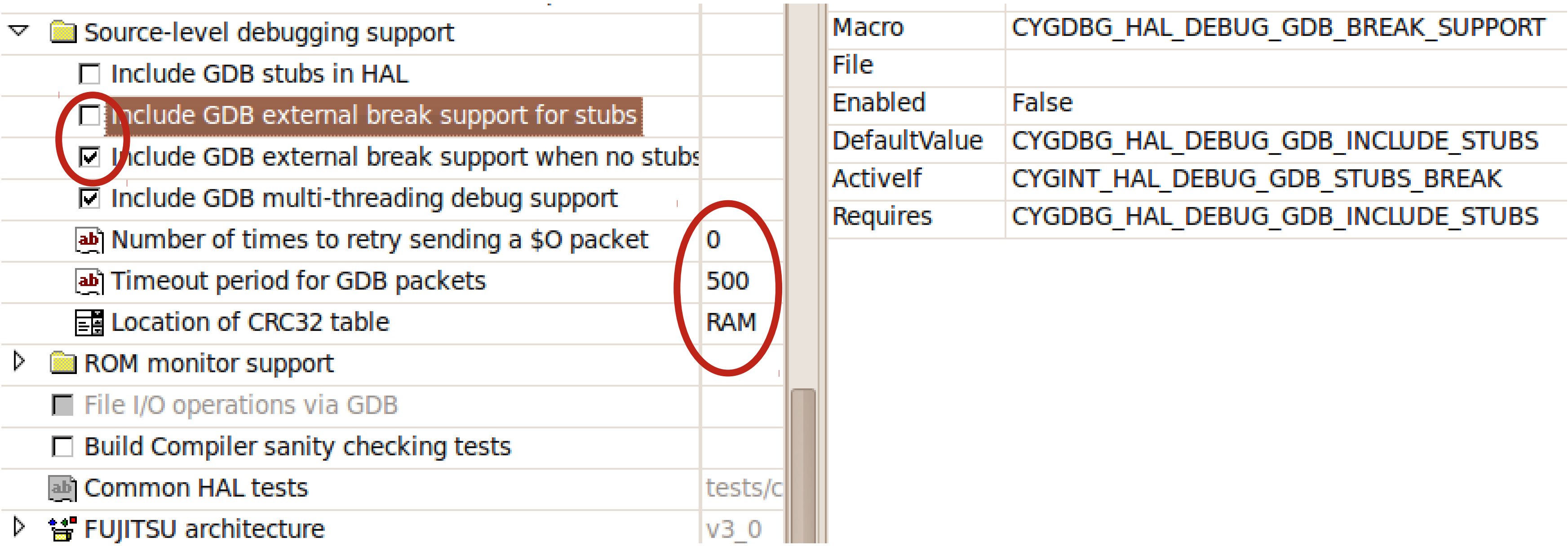

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Figure: Providing the data

3. Semantic Constraints

Capturing the configurator behavior

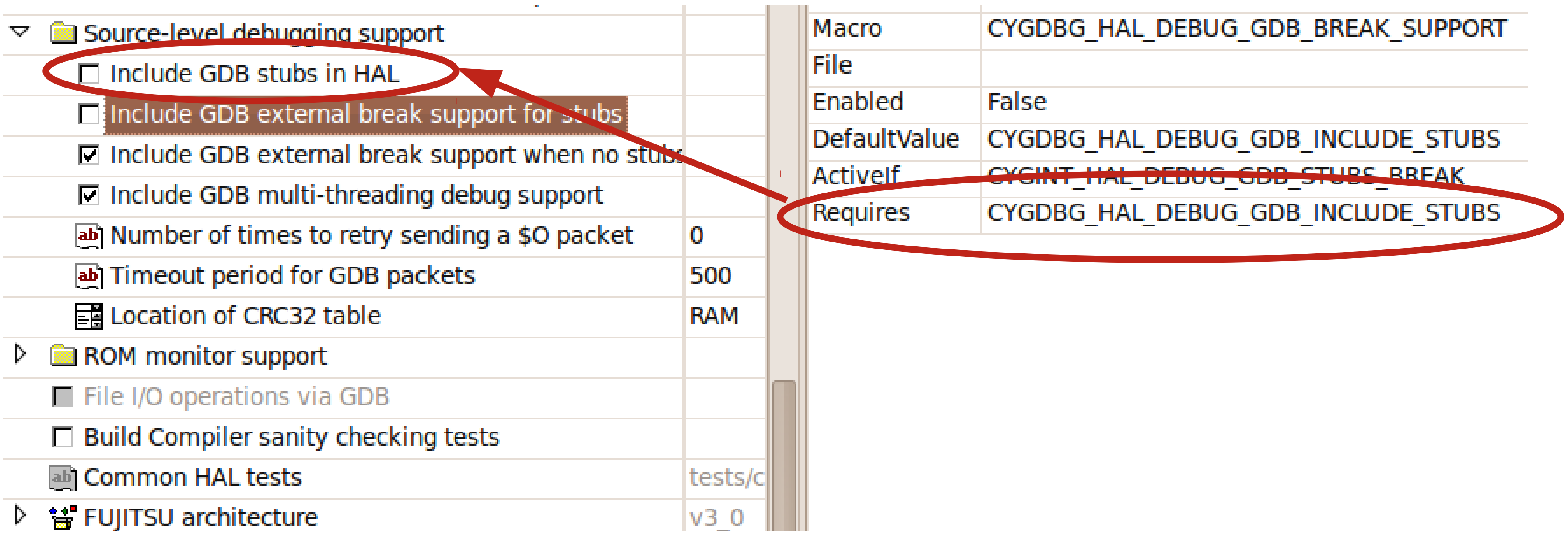

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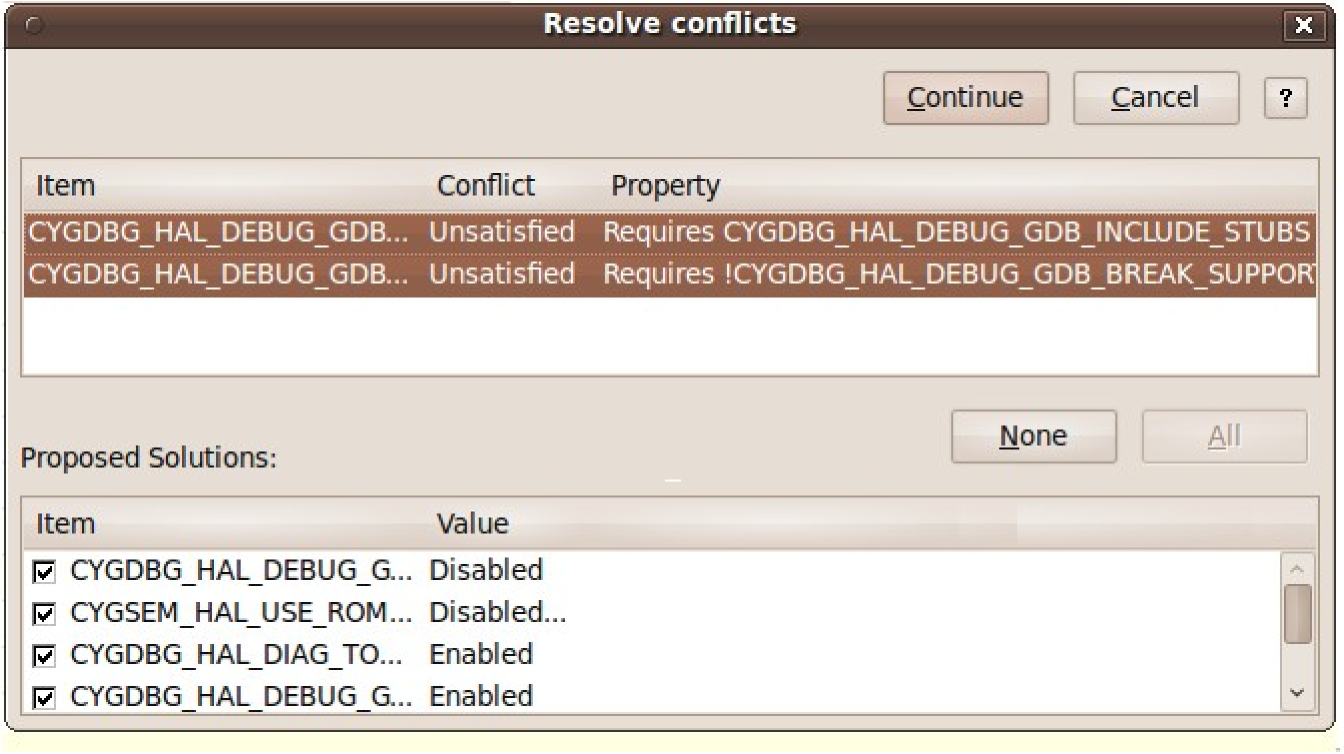
Figure: A constraint

4. Semantic Constraints

Capturing the configurator behavior



Item	Conflict	Property
CYGDBG_HAL_DEBUG_GDB...	Unsatisfied	Requires CYGDBG_HAL_DEBUG_GDB_INCLUDE_STUBS
CYGDBG_HAL_DEBUG_GDB...	Unsatisfied	Requires !CYGDBG_HAL_DEBUG_GDB_BREAK_SUPPOR

Proposed Solutions:

Item	Value
☑ CYGDBG_HAL_DEBUG_G...	Disabled
☑ CYGSEM_HAL_USE_ROM...	Disabled...
☑ CYGDBG_HAL_DIAG_TO...	Enabled
☑ CYGDBG_HAL_DEBUG_G...	Enabled

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

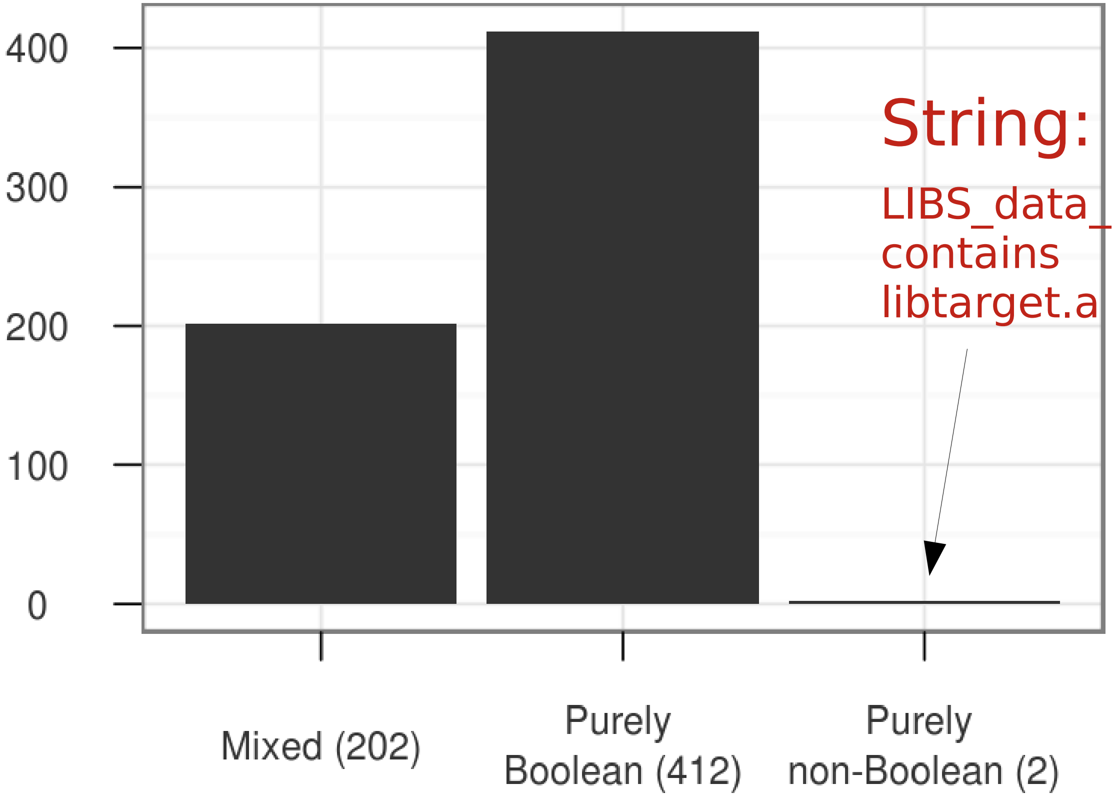
Semantic constraints classification:

- 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



String:
LIBS_data_var contains libtarget.a

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	≥ ≤	b, max. occurrences = 2
aXY / Z	≥ ≤	b, max. occurrences = 2
aXY / PZ	≤	b, max. occurrences = 1
aXYZ/(α+β)PQ	≥ ≤	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?