

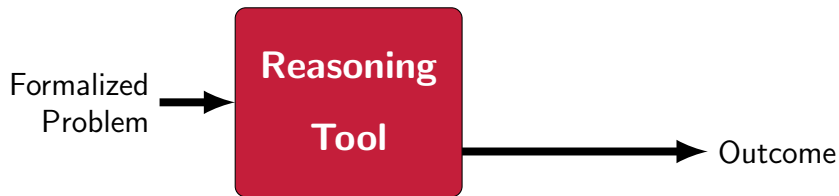
Certified Knowledge Compilation with Application to Verified Model Counting

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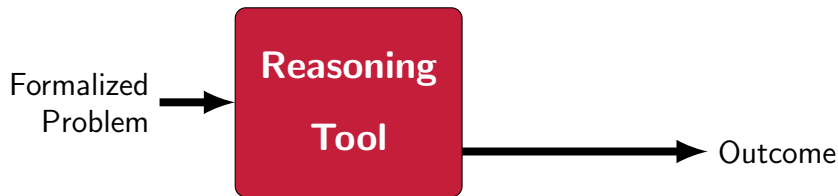
**Carnegie
Mellon
University**

SAT, 2023

Motivation: Automated Reasoning Programs



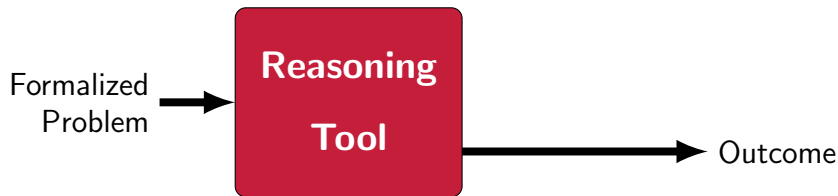
Motivation: Automated Reasoning Programs



Standard Tools

- ▶ Lingering doubt about whether result can be trusted
- ▶ If find bug in tool, must rerun all prior verifications

Motivation: Automated Reasoning Programs



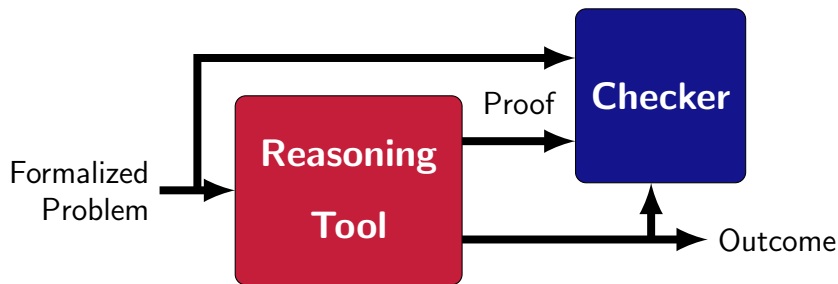
Standard Tools

- ▶ Lingering doubt about whether result can be trusted
- ▶ If find bug in tool, must rerun all prior verifications

Formally Verified Tools

- ▶ Hard to develop
- ▶ Hard to make scalable

Proof-Generating Automated Reasoning Programs



Proof-Generating Tools

- ▶ Verify individual executions, not entire program
- ▶ Can have bugs in tool but still trust result
- ▶ Can we trust the checker?

Ideal: formally verified

Model Counting

Formula ϕ	Models $\mathcal{M}(\phi)$
$[\bar{x}_1 \vee x_3 \vee \bar{x}_4] \wedge$	
$[\bar{x}_1 \vee \bar{x}_3 \vee x_4] \wedge$	$\{\bar{x}_1, \bar{x}_2, \bar{x}_3, \bar{x}_4\} \quad \{\bar{x}_1, \bar{x}_2, x_3, x_4\}$
$[x_1 \vee x_3 \vee \bar{x}_4] \wedge$	$\{\bar{x}_1, x_2, x_3, x_4\} \quad \{x_1, \bar{x}_2, x_3, x_4\}$
$[x_1 \vee \bar{x}_3 \vee x_4] \wedge$	$\{\bar{x}_1, x_2, \bar{x}_3, \bar{x}_4\} \quad \{x_1, \bar{x}_2, \bar{x}_3, \bar{x}_4\}$
$[\bar{x}_1 \vee \bar{x}_2]$	

Definitions

- ▶ Input variables x_1, x_2, \dots, x_n
- ▶ **Assignment:** $\alpha = \{\ell_1, \ell_2, \dots, \ell_n\}$ with each $\ell_i \in \{x_i, \bar{x}_i\}$
- ▶ **Models:** $\mathcal{M}(\phi)$ is set of satisfying assignments for formula ϕ

Model Counting

Formula ϕ	Models $\mathcal{M}(\phi)$
$[\bar{x}_1 \vee x_3 \vee \bar{x}_4] \wedge$	
$[\bar{x}_1 \vee \bar{x}_3 \vee x_4] \wedge$	$\{\bar{x}_1, \bar{x}_2, \bar{x}_3, \bar{x}_4\} \quad \{\bar{x}_1, \bar{x}_2, x_3, x_4\}$
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$[\bar{x}_1 \vee \bar{x}_2]$	

Definitions

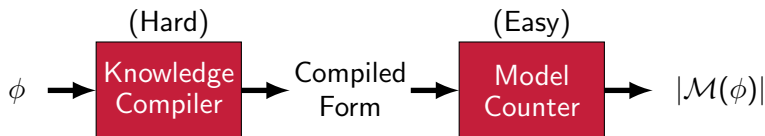
- ▶ Input variables x_1, x_2, \dots, x_n
- ▶ **Assignment**: $\alpha = \{\ell_1, \ell_2, \dots, \ell_n\}$ with each $\ell_i \in \{x_i, \bar{x}_i\}$
- ▶ **Models**: $\mathcal{M}(\phi)$ is set of satisfying assignments for formula ϕ

Model Counting Problem

- ▶ Given formula ϕ , compute $|\mathcal{M}(\phi)|$
- ▶ Challenging: $\#SAT$ more difficult than SAT

Knowledge Compilation

- ▶ Darwiche [DarMar-2002]

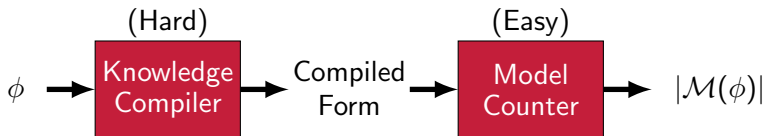


Convert CNF formula into more tractable representation

- ▶ Potentially exponential size
- ▶ Model counting polynomial in size of representation

Knowledge Compilation

- ▶ Darwiche [DarMar-2002]



Convert CNF formula into more tractable representation

- ▶ Potentially exponential size
- ▶ Model counting polynomial in size of representation

Concerns:

- ▶ Is the compiled form logically equivalent to the input formula?
- ▶ Is the counting computed correctly?

(Weighted) Model Counting

- ▶ Assign weight $w(x_i)$ to each input variable x_i
 - $0.0 < w(x_i) < 1.0$
- ▶ Define $w(\bar{x}_i) = 1 - w(x_i)$
 - Write as $\sim w(x_i)$
- ▶ Weighted count $\Delta(\phi, w)$ of formula ϕ :

$$\Delta(\phi, w) = \sum_{\alpha \in \mathcal{M}(\phi)} \prod_{\ell_i \in \alpha} w(\ell_i)$$

Standard Model Counting

- ▶ $w(x_i) = w(\bar{x}_i) = 1/2$ for all i
- ▶ $\Delta(\phi, w)$ gives **density** of function
 - Fraction of assignments that satisfy ϕ
- ▶ Scale by 2^n to get model count

Partitioned-Operation Formulas

Allowed Operations

- ▶ **Product:** $\phi_1 \wedge^p \phi_2$, where $\mathcal{D}(\phi_1) \cap \mathcal{D}(\phi_2) = \emptyset$
 - $\mathcal{D}(\phi)$: Set of variables occurring in ϕ
- ▶ **Sum:** $\phi_1 \vee^p \phi_2$, where $\mathcal{M}(\phi_1) \cap \mathcal{M}(\phi_2) = \emptyset$
- ▶ **Negation:** $\neg\phi$

Weighted Count of Partitioned Formula

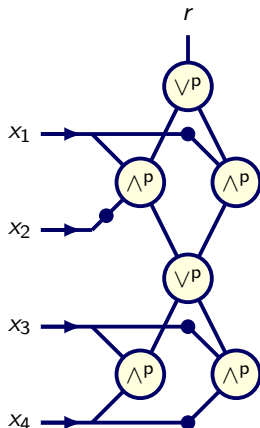
$$\Delta(\phi_1 \wedge^p \phi_2, w) = \Delta(\phi_1, w) \times \Delta(\phi_2, w)$$

$$\Delta(\phi_1 \vee^p \phi_2, w) = \Delta(\phi_1, w) + \Delta(\phi_2, w)$$

$$\Delta(\neg\phi, w) = \sim \Delta(\phi, w)$$

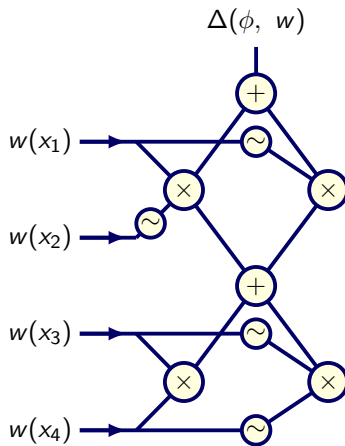
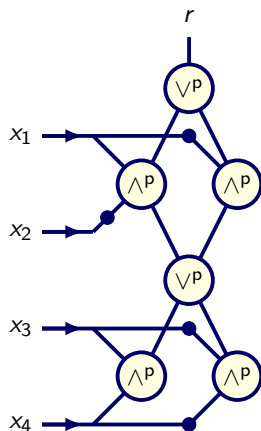
Partitioned-Operation Graph (POG)

Formula ϕ	
$[\bar{x}_1 \vee x_3 \vee \bar{x}_4]$	\wedge
$[\bar{x}_1 \vee \bar{x}_3 \vee x_4]$	\wedge
$[x_1 \vee x_3 \vee \bar{x}_4]$	\wedge
$[x_1 \vee \bar{x}_3 \vee x_4]$	\wedge
$[\bar{x}_1 \vee \bar{x}_2]$	



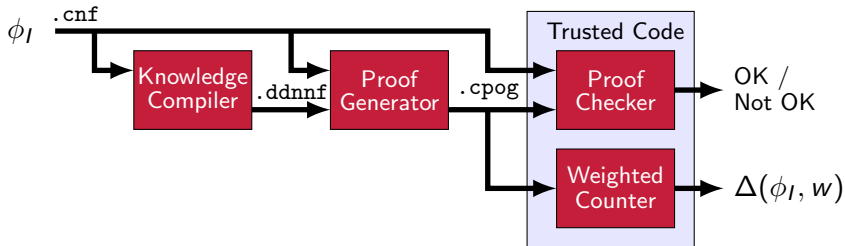
- ▶ Directed graph representation of partitioned-operation formula
- ▶ Each edge can be negative or positive

Weighted Count of POG



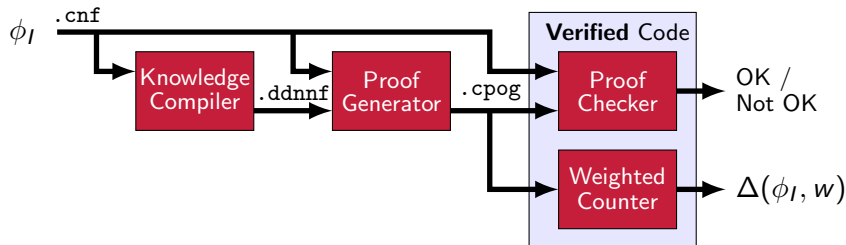
- Evaluation: Number of operations linear in graph size

Certifying Toolchain



- ▶ **Knowledge Compiler** (D4 [LagMar-2017]): Convert CNF into representation using only partitioned operations
- ▶ **Proof Generator**: Generate file combining POG definition + equivalence proof
- ▶ **Proof Checker**: Validate proof file
- ▶ **Weighted Counter**: Compute standard or weighted model count

Verifying the Trusted Code



Using the Lean 4 theorem prover [DemUlr-2021]

- ▶ Soundness of proof system
 - Helped us identify unsoundness in our prototype proof rules
- ▶ Verified proof checker
 - Around $6\times$ slower than one implemented in C
- ▶ Verified weighted counter

Formally Verified Theorems

Theorem (Proof framework and checker correctness)

If the CPOG proof checker has assembled POG P starting from input formula ϕ_I , and the final check succeeds, then ϕ_I is logically equivalent to the formula ϕ_P represented by P .

Theorem (Correctness of efficient weighted counter)

For any POG P , the weighted counter executed on P with weights w returns $\Delta(\phi_P, w)$.

Related Work: CD4

CD4: Certifying D4 [CapLagMar-2021]

- ▶ Modified version of D4
 - ▶ Generates annotated output + clausal proof in DRAT format
 - ▶ Verify with checker + DRAT-TRIM [HeuHunWet-2013]
- ▶ Experiments: Scales very well

Limitations:

- ▶ Proof framework tied closely to compiler implementation
- ▶ No formal proof of soundness
 - Found exploitable weakness

Related Work: MICE

MICE: Proof framework for top-down model counters

[FicHecRol-2022]

- ▶ Modify model counter or generate proof from D4 output
- ▶ Generates series of proof obligations
- ▶ Experiments: Scaling problems when many shared subgraphs

Limitations:

- ▶ Only verifies standard model counting
- ▶ Proof framework based on specific class of model counters
- ▶ No formal proof of soundness
- ▶ No verified checker

Importance of Formal Verification

Claim:

Any proof framework that has not been mechanically verified is unsound

- ▶ Borne out by our own experience

CPOG File: Declaration + Proof

Clausal Representation of POG θ_P

- ▶ Tseitin encoding of POG operations
 - Extension variable u for each operation node \mathbf{u}
 - Node \mathbf{u} with k children characterized by $k + 1$ defining clauses
- ▶ Each child indicated by literal
 - Positive or negated argument
 - Input variable or result from other operation
- ▶ Unit clause $[r]$ for root node \mathbf{r}

Proof Steps

- ▶ Sequence of clause additions and deletions

CPOG Proof Objective

$$\phi_I(X) \iff \exists! Z \theta_P(X, Z)$$

- ▶ ϕ_I : Input formula
- ▶ θ_P : POG formula
 - Defining clauses for POG
 - Unit clause $[r]$ for root literal
- ▶ Z : extension variables for the POG operations
- ▶ For any assignment α to X :
 - Defining clauses induce unique extension α^* to $X \cup Z$
 - α satisfies ϕ_I if and only if $\alpha^*(r) = 1$

Proof Methodology

- ▶ Transform ϕ_I to θ_P
 - Via sequence of equivalence-preserving proof steps

CPOG Example: Formula

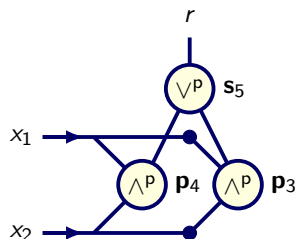
- ▶ Encode formula $x_1 \leftrightarrow x_2$.
- ▶ CNF representation:

$$[x_1 \vee \bar{x}_2] \wedge [\bar{x}_1 \vee x_2]$$

Clause Database

ID	Literals	Explanation
1	1 -2	Input
2	-1 2	Input

CPOG Example: POG Declaration



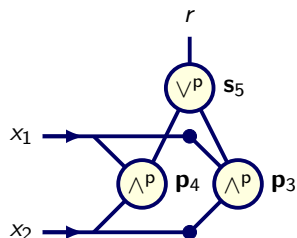
CPOG Declarations

3 p 3 -1 -2 0

Clause Database

ID	Literals	Explanation
1	1 -2	Input
2	-1 2	Input
3	3 1 2	p_3
4	-3 -1	
5	-3 -2	

CPOG Example: POG Declaration



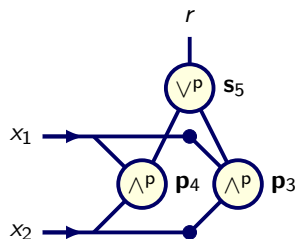
CPOG Declarations

3	p	3	-1	-2	0
6	p	4	1	2	0

Clause Database

ID	Literals	Explanation
1	1 -2	Input
2	-1 2	Input
3	3 1 2	p₃
4	-3 -1	
5	-3 -2	
6	4 -1 -2	p₄
7	-4 1	
8	-4 2	

CPOG Example: POG Declaration



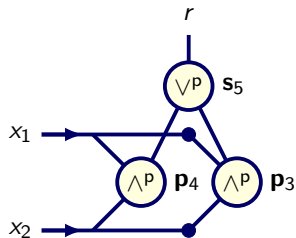
CPOG Declarations

3	p	3	-1	-2	0		
6	p	4	1	2	0		
9	s	5	3	4	4	7	0

Clause Database

ID	Literals	Explanation
1	1 -2	Input
2	-1 2	Input
3	3 1 2	p₃
4	-3 -1	
5	-3 -2	
6	4 -1 -2	p₄
7	-4 1	
8	-4 2	
9	-5 3 4	s₅
10	5 -3	
11	5 -4	

CPOG Example: POG Declaration



CPOG Declarations

9 s 5 3 4 4 7 0

- Sum declaration must justify mutual exclusion
- Resolving clauses 4 and 7 gives $\bar{p}_3 \vee \bar{p}_4$.

Clause Database

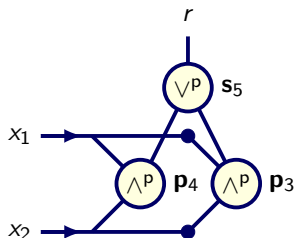
ID	Literals	Explanation
1	1 -2	Input
2	-1 2	Input
3	3 1 2	p_3
4	-3 -1	
5	-3 -2	
6	4 -1 -2	p_4
7	-4 1	
8	-4 2	
9	-5 3 4	s_5
10	5 -3	
11	5 -4	

CPOG Proof Structure: Forward Implication

$$\phi_I(X) \implies \exists! Z \theta_P(X, Z)$$

- ▶ Add clauses by reverse unit propagation (RUP)
- ▶ Terminating with unit clause $[r]$
- ▶ Any assignment satisfying ϕ_I (when extended) causes the POG to evaluate to true

CPOG Example: Forward Implication



CPOG Assertions

12	a	-2	5	0	11	1	6	0
13	a	5		0	10	12	2	3

- ▶ Must give justifying RUP sequences
- ▶ Finish with unit clause asserting root literal

1	1	-2			Input
2	-1	2			Input
3	3	1	2		p₃
4	-3	-1			
5	-3	-2			
6	4	-1	-2		p₄
7	-4	1			
8	-4	2			
9	-5	3	4		s₅
10	5	-3			
11	5	-4			
12	-2	5			Root literal
13	5				

Forward Proof Generation Methods

Monolithic

- ▶ Single call to proof-generating SAT solver
- ▶ Experimentally: Scales to POGs with $\sim 10^6$ defining clauses

Structural

- ▶ Top-down recursion on POG structure
- ▶ Avoid exponential expansion by defining and applying lemmas
 - Can express within CPOG structure
- ▶ Experimentally: Scales to POGs with $\sim 10^8$ defining clauses

CPOG Proof Structure: Reverse Implication

Reverse Implication Proof

$$\exists! Z \theta_P(X, Z) \implies \phi_I(X)$$

- ▶ Delete clauses by RUP
 - Deleted clause implied by remaining ones
- ▶ Only clausal representation of POG θ_P remains at end

CPOG Example: Reverse Implication

CPOG Deletions

d 12 11 1 6 0

- All deletions must give justifying RUP sequence

1	1	-2		Input
2	-1	2		Input
3	3	1	2	p₃
4	-3	-1		
5	-3	-2		
6	4	-1	-2	p₄
7	-4	1		
8	-4	2		
9	-5	3	4	s₅
10	5	-3		
11	5	-4		
12				<i>Deleted</i>
13	5			Root literal

CPOG Example: Reverse Implication

CPOG Deletions

d	12	11	1	6	0
---	----	----	---	---	---

d	1	13	5	7	9	0
---	---	----	---	---	---	---

- All deletions must give justifying RUP sequence

1					<i>Deleted</i>
2	-1	2			Input
3	3	1	2		p₃
4	-3	-1			
5	-3	-2			
6	4	-1	-2		p₄
7	-4	1			
8	-4	2			
9	-5	3	4		s₅
10	5	-3			
11	5	-4			
12					<i>Deleted</i>
13	5				Root literal

CPOG Example: Reverse Implication

CPOG Deletions

d	12	11	1	6		0
d	1	13	5	7	9	0
d	2	13	4	8	9	0

- All deletions must give justifying RUP sequence

1					<i>Deleted</i>
2					<i>Deleted</i>
3	3	1	2		p₃
4	-3	-1			
5	-3	-2			
6	4	-1	-2		p₄
7	-4	1			
8	-4	2			
9	-5	3	4		s₅
10	5	-3			
11	5	-4			
12					<i>Deleted</i>
13	5				Root literal

Proof Result

Initial Clause Database: ϕ_I

ID	Literals	Explanation
1	1 -2	Input
2	-1 2	Input

Final Clause Database: θ_P

ID	Literals	Explanation
3	3 1 2	\mathbf{p}_3
4	-3 -1	
5	-3 -2	
6	4 -1 -2	\mathbf{p}_4
7	-4 1	
8	-4 2	
9	-5 3 4	\mathbf{s}_5
10	5 -3	
11	5 -4	
13	5	Root literal

- Transformed input formula ϕ_I into POG formula θ_P
 - Via equivalence-preserving proof steps

CPOG Checking Requirements

- ▶ Partitioned product: $\mathcal{D}(\phi_1) \cap \mathcal{D}(\phi_2) = \emptyset$
 - Syntactic check of dependencies
- ▶ Partitioned sum: $\mathcal{M}(\phi_1) \cap \mathcal{M}(\phi_2) = \emptyset$
 - Check of mutual-exclusion RUP sequence
- ▶ Clause addition and deletion
 - Check of RUP sequence

Experimental Evaluation

Benchmark Problems:

- ▶ 180 unique formulas from 2022 unweighted and weighted model counting competitions

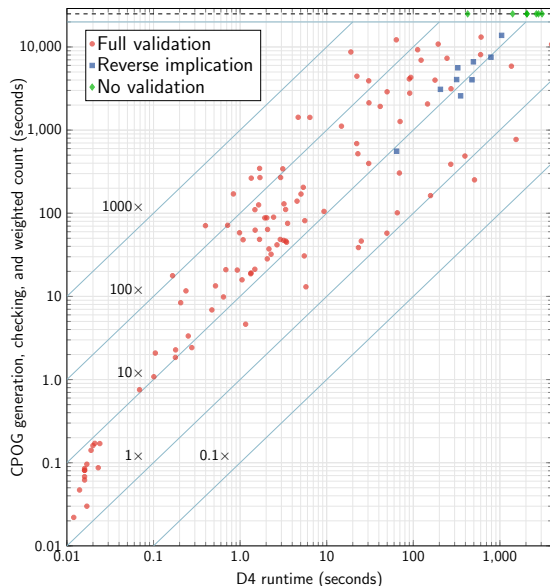
D4 Execution

- ▶ Time limit of 4000 seconds
- ▶ Completed 124 problems
- ▶ Converted to POGs ranging from 304 to 2,761,457,765 defining clauses

Running our toolchain

- ▶ Limited CPOG generation to 10,000 seconds
- ▶ Full proofs for 108 problems
- ▶ Reverse implication proofs for 9 more
- ▶ No proofs of 7

Experimental Results: Toolchain Runtime



Ratios

Min

0.5×

Harmonic mean

5.9×

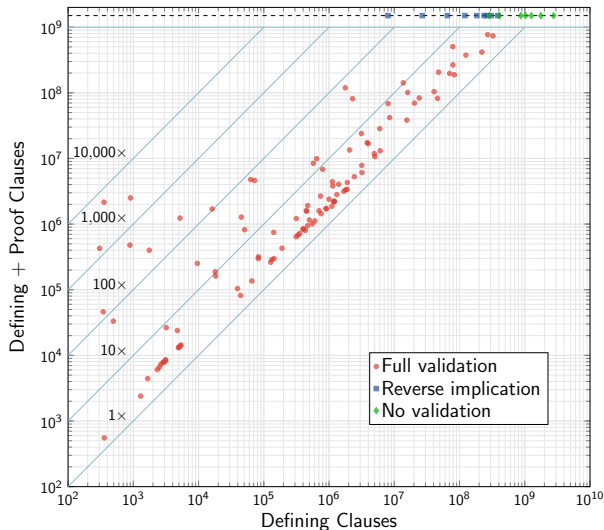
Median

16.4×

Max

465.8×

Experimental Results: CPOG Sizes



Ratios

Min

1.5x

Harmonic mean

3.1x

Median

2.7x

Max

6073.0x

Final Thoughts

Observations

- ▶ Toolchain can handle all but largest outputs from D4
- ▶ Framework is very general
 - E.g., can generate, prove, and apply lemmas without any extensions
 - Not tied to particular compilation method

Future Work

- ▶ Improve speed and capacity of toolchain
- ▶ Handle outputs from other knowledge compilers
- ▶ Certification of other automated reasoning tools

Supplementary Information

Code

<https://github.com/rebryant/cpog>

Documentation

<https://doi.org/10.5281/zenodo.7966174>

- ▶ Worked example
- ▶ More details on algorithms
- ▶ More details on formal verification
- ▶ Lots of experimental results

References

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