Boolector: An Efficient SMT Solver for Bit-Vectors and Arrays

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Satisfiability Modulo Theories (SMT)

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- Generalization of the Boolean Satisfiability Problem (SAT)
- Satisfiability with respect to background theories
- Software and Hardware verification
- SMT Solvers
  - Boolector, Z3, CVC3, STP, Barcelogic, MathSAT, Spear, OpenSMT, ...
- Theories
  - Decidable fragments of first-order logic (typically quantifier-free)
    - Theory of bit-vectors and extensional theory of arrays

Boolector: Schematic Overview

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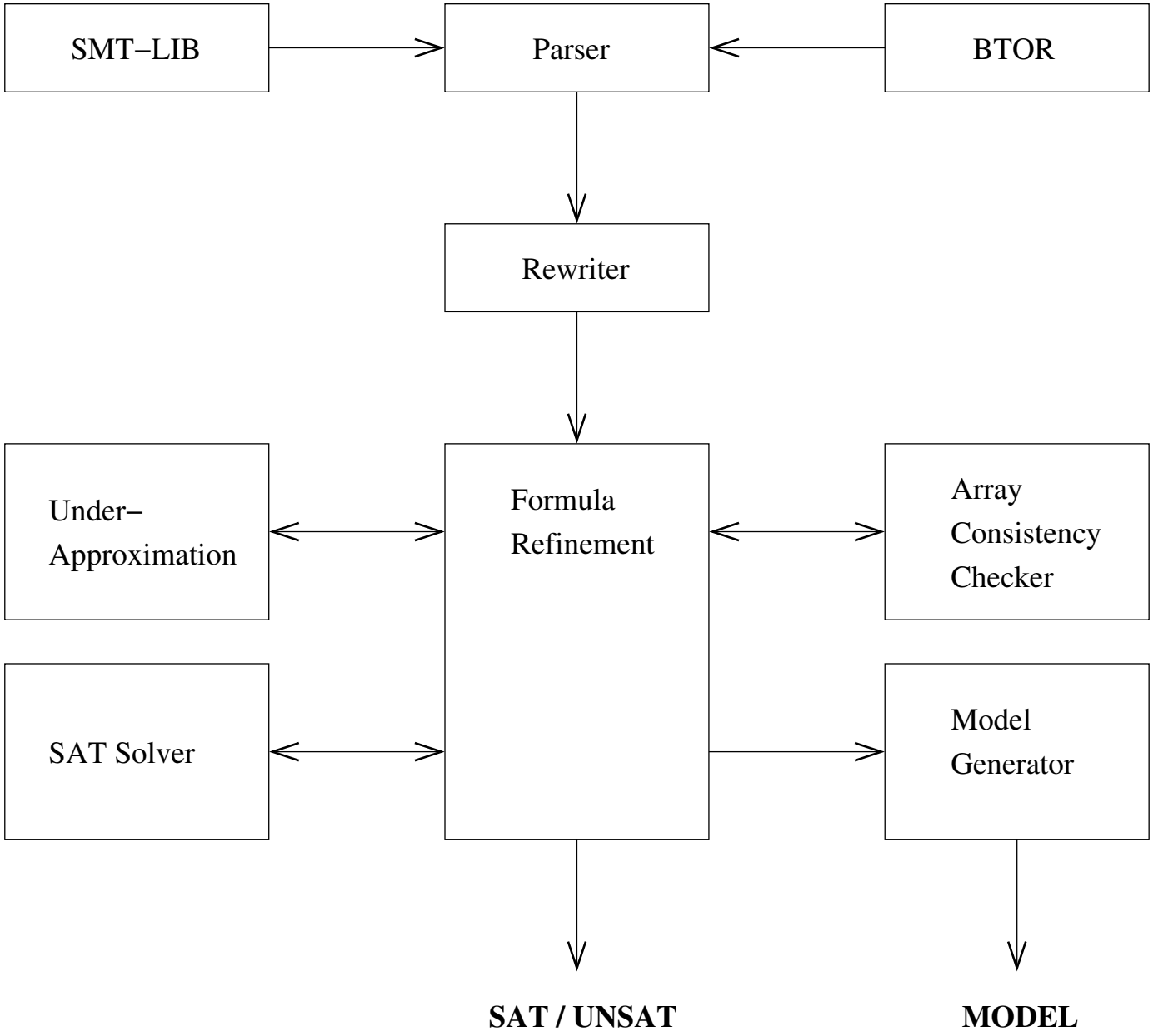

Rewriting Engine

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- Goal is to simplify Formula as soon and as much as possible
- Basic level 1 rewrite rules, e.g. $a \wedge \neg a \Leftrightarrow \bot$
  - Locally applied during formula construction
- Level 2 rewrite rules perform global substitutions
  - Topological sorting allows substitutions in one pass
  - Static analysis techniques
- Level 3 rewrite rules perform arithmetic normalization
- Rules of quadratic worst-case complexity bounded in recursion depth

- Replace reads in ϕ by fresh abstraction variables to obtain $\bar{\phi}$
- Let SAT solver "guess" solution
  - If SAT solver cannot find a solution, ϕ is unsat
- Explicitly check if model is consistent with theory
- If check succeeds, ϕ is sat
- If check fails
  - Add lemma to refine formula
  - Let SAT solver "guess" a new solution

- Axiom of extensionality
  - $a = b \quad \Leftrightarrow \quad \forall i\,(read(a,i) = read(b,i))$
- Replace array equality $a = b$ by boolean abstraction variable $\alpha(a = b)$
- For each array equality $a = b$ add $a \neq b \;\Rightarrow\; \exists\lambda(read(a,\lambda) \neq read(b,\lambda))$
  - Guarantees that there exists a witness for inequality
- If underlying decision procedure assigns $\alpha(a = b)$ to $\top$
  - Explicitly check if model is consistent with extensional theory

- Propagation-based approach
- Annotate each array node with its set of reads ρ
- Propagate reads according to array axioms until fix-point is reached
- Handling extensionality
  - For each $\alpha(a = b)$ where $\sigma(\alpha(a = b)) = \top$
    - add every read $\in \rho(a)$ to $\rho(b)$ and vice versa.
- Finally, check read congruence on all arrays

Supported Under-Approximation Techniques (1/4)

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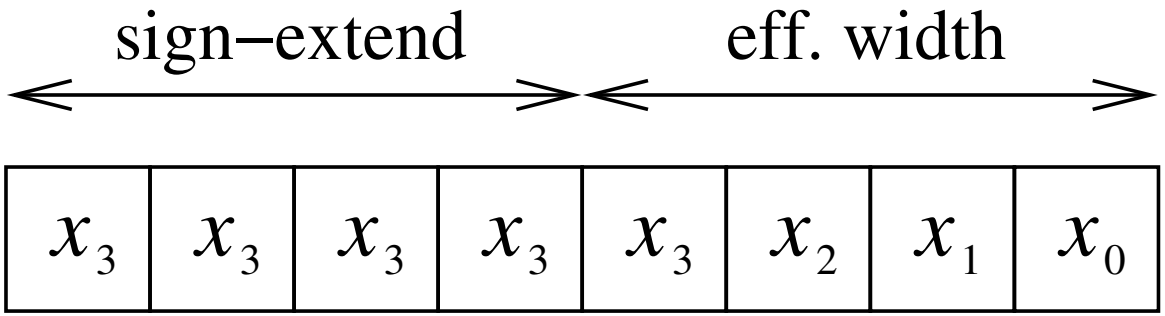
- Sign-Extension of BV variables
  - Let the n least significant bits be variable
  - We call n the effective bit-width
  - Sign-extend the n^{th} bit
  - Appropriate in software verification with two's complement semantics



Supported Under-Approximation Techniques (2/4)

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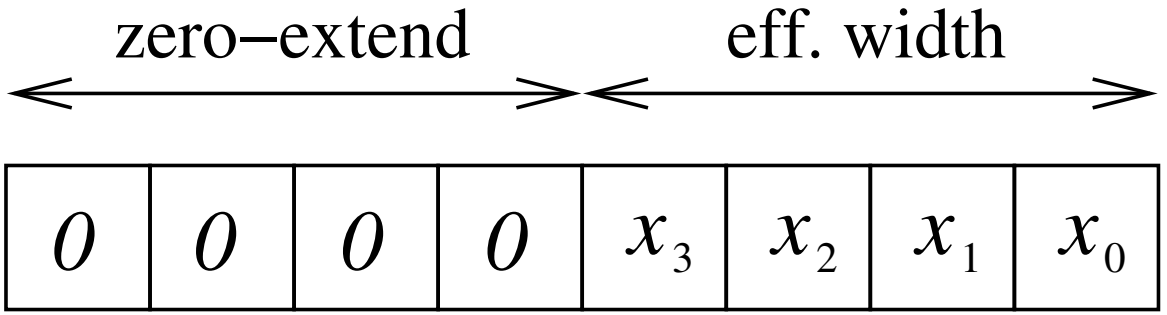
- Zero-Extension (Unsigned-Extension) of BV variables
  - Let the n least significant bits be variable
  - Set remaining bits to zero
  - Appropriate in verification with unsigned semantics
    - May speed up decision procedure more than sign-extension



Supported Under-Approximation Techniques (3/4)

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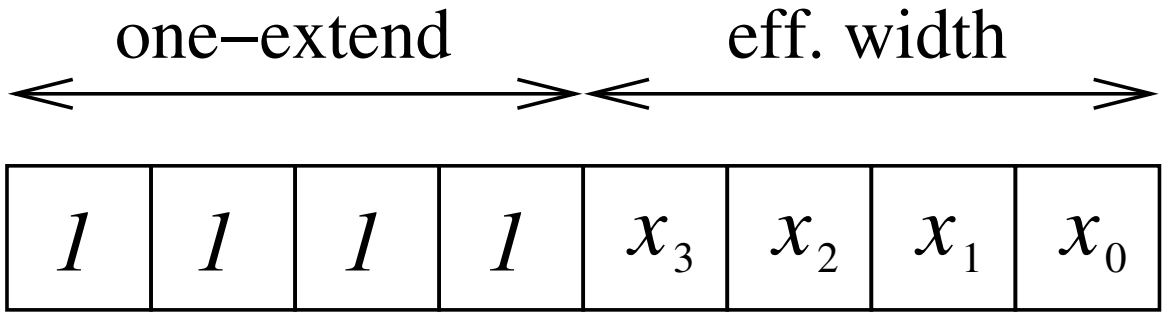
- One-Extension of BV variables
  - Let the n least significant bits be variable
  - Set remaining bits to one
  - Beneficial in context of negative numbers
    - May speed up decision procedure more than sign-extension



Supported Under-Approximation Techniques (4/4)

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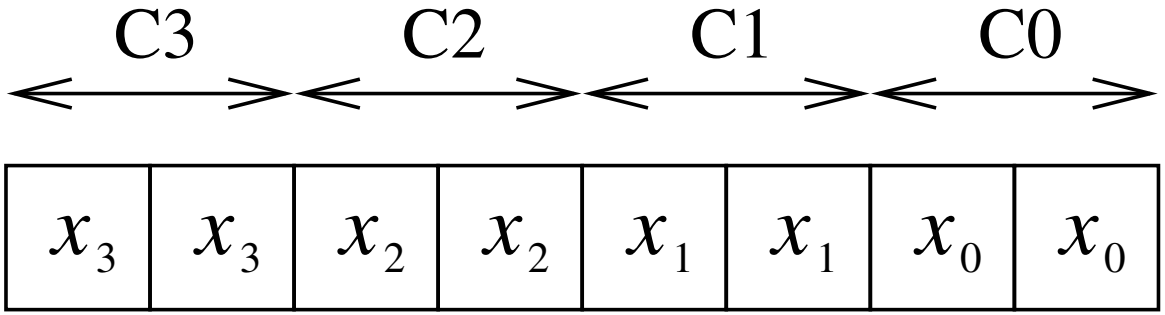
- Equivalence class splitting of BV variables
  - Split bit-vector into n equivalence classes
  - Refinement variants
    - Either refine overall class splitting
    - Or find out which classes to refine



Early Unsat Termination [BrummayerBiere09]

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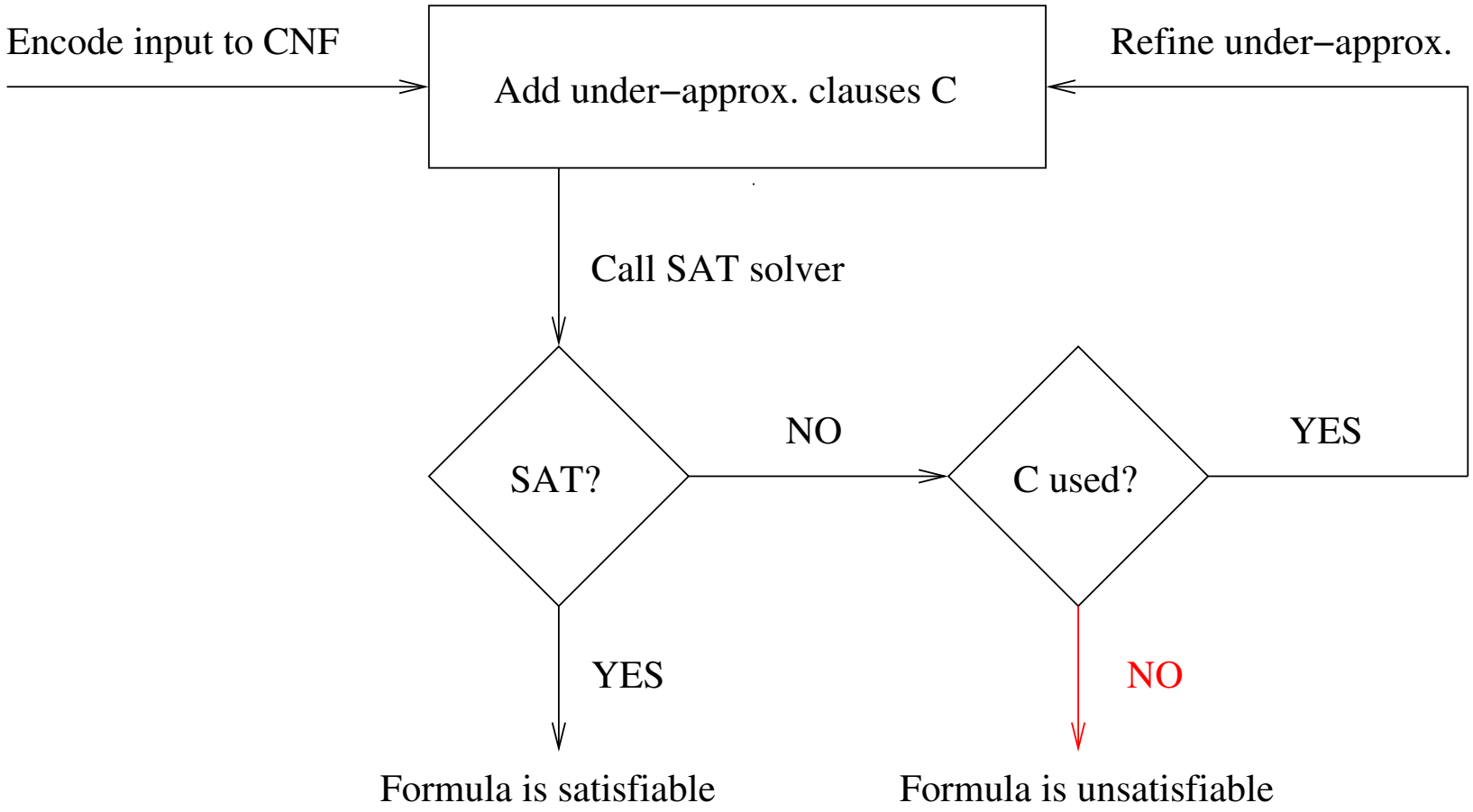

Combining Over- and Under-Approximation [BrummayerBiere09]

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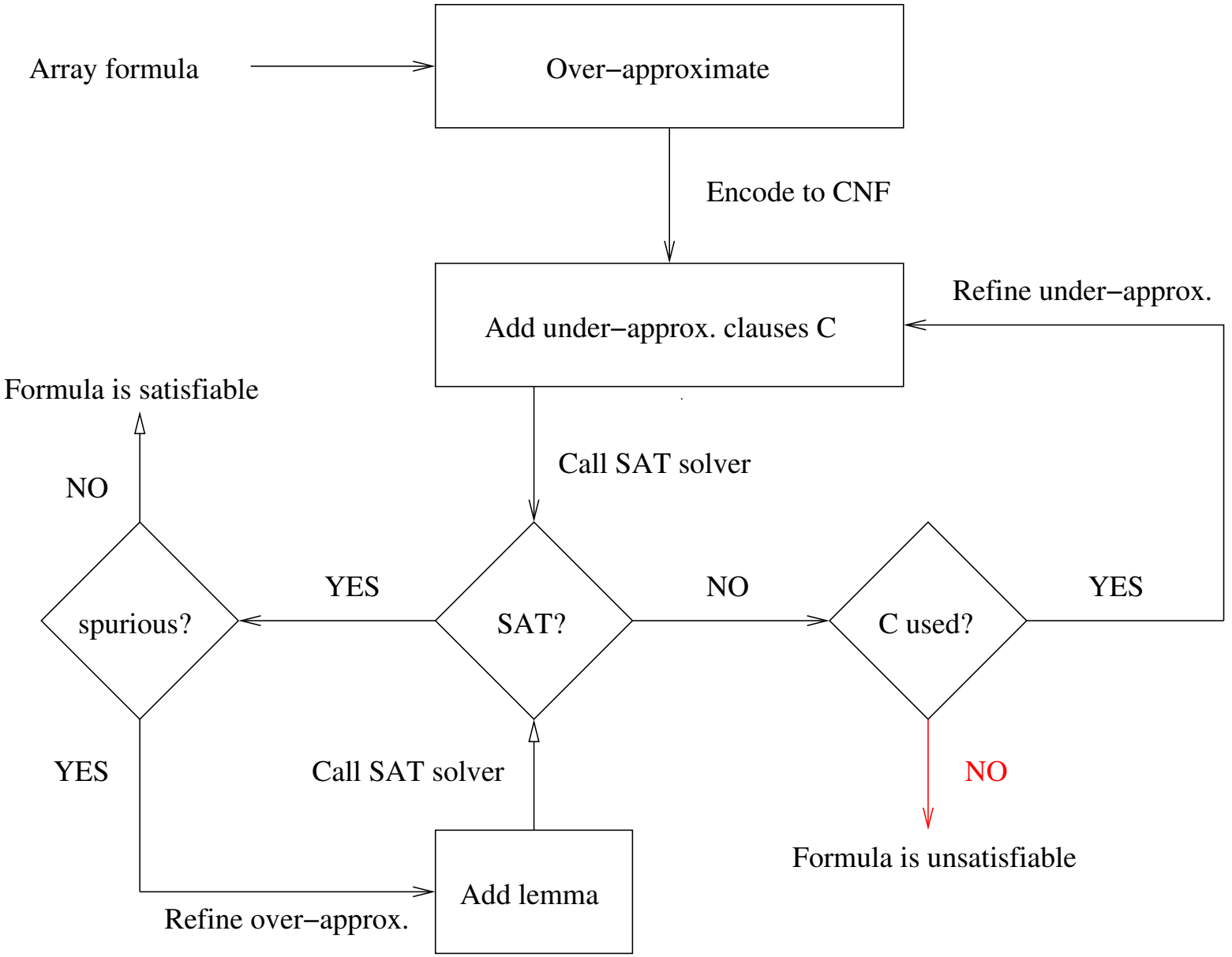

Additional Features

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- Word-level model checking [BrummayerBiereLonsing08]
  - BTOR Format provides ”next“ operator for registers and memories
  - Boolector can be used as bounded model checker
    - Searching witnesses, k-induction with and without simple paths
- Rich C API
- Model Generation
  - Bit-vector and array variables
  - Consistent assignments for terms and formulas in ϕ
- Pretty Printer: Conversion between SMT-LIB 1.2 and BTOR format

Conclusion

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- Rewriting Engine
- Over-approximation techniques for arrays
- Under-approximation techniques for bit-vector variables and reads
- Combining over-approximation and under-approximation
- Additional features
- Boolector 1.0 available for research
  - http://fmv.jku.at/boolector