SMT: Past, Present & Future

Clark Barrett
New York University

Leonardo de Moura
Microsoft Research

Silvio Ranise
FBK Trento

Aaron Stump
The University of Iowa

Cesare Tinelli
The University of Iowa

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Clark Barrett

Leo de Moura

Silvio Ranise

Aron Stump

Cesare Tinelli

Many Thanks to

- The HVC Award Committee
- All of our students and collaborators
- Our colleagues in the SMT community

Formal Verification and Logic

- Formal verification requires checking the satisfiability of formulas in some symbolic logic

- Often, the logic is propositional

  $\neg p \wedge (q \vee r) \Rightarrow s, \quad \Box p \Rightarrow \Diamond s, \quad qUr \wedge Gq$

- In many cases, it is first-order

  $(p(x) \wedge x > 3) \Rightarrow y + x = 2, \quad f(x,a) = g(y)$

Satisfiability Modulo Theories

- In the first-order case, we are not interested in satisfiability in arbitrary models
- But in those that fix the interpretation of certain predicate and function symbols
  (=, <, +, 3, cons, cdr, read, write, …)
- We are interested in satisfiability modulo a certain theory of these symbols (SMT)

Satisfiability Modulo Theories

$$b + 2 = c \ \ and \ \ f(read(write(a,b,3), c\text{-}2) \neq f(c\text{-}b+1)$$

Satisfiability Modulo Theories

$$\boxed{b + 2 = c} \text{ and } f(read(write(a,b\boxed{,3}), \boxed{c\text{-}2}) \neq f\boxed{(c\text{-}b+1})$$

Arithmetic

Satisfiability Modulo Theories

$$b + 2 = c \;\; and \;\; f(\boxed{read}(\boxed{write}(a,b,3), c\text{-}2) \neq f(c\text{-}b+1)$$

Array Theory

Satisfiability Modulo Theories

$$b + 2 = c \;\; and \;\; \boxed{f}(read(write(a,b,3), c\text{-}2) \neq \boxed{f}(c\text{-}b+1)$$

Uninterpreted Functions

Satisfiability Modulo Theories

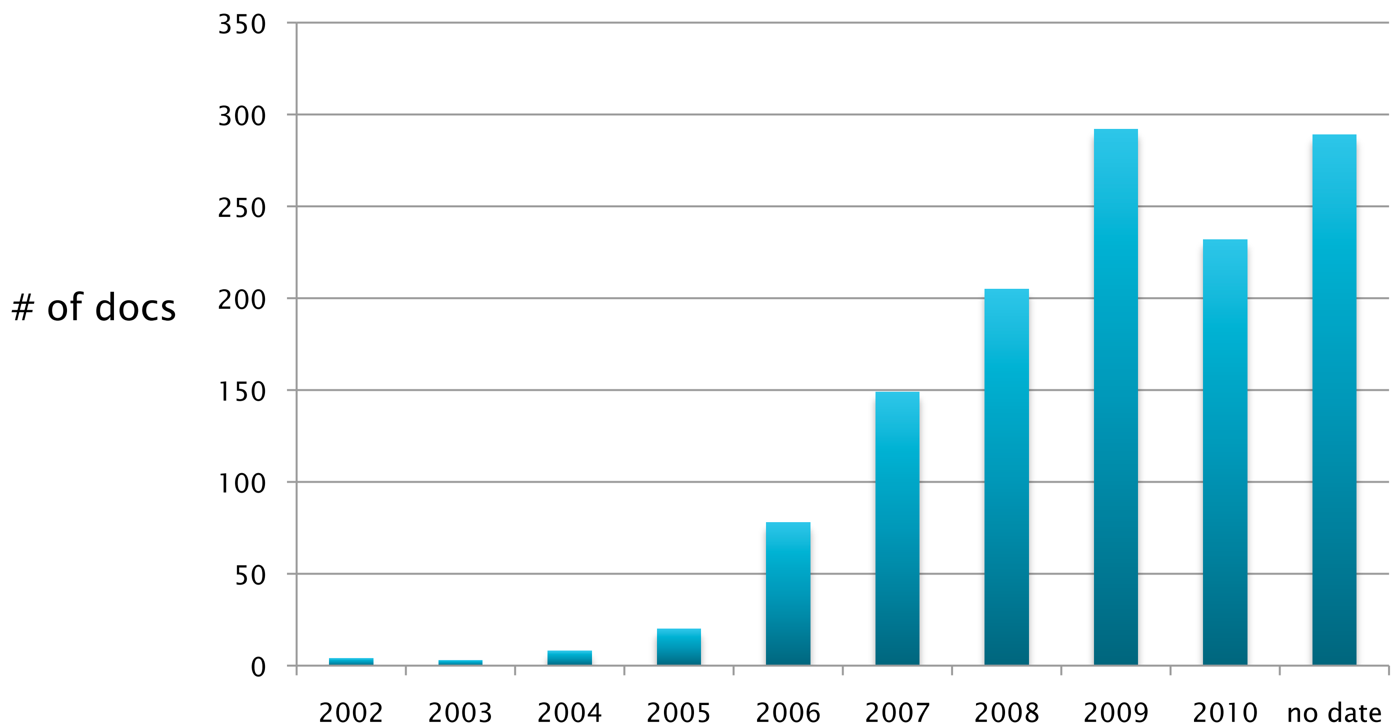
- **Problem:** traditional deduction techniques for FOL are inadequate for SMT:
  - some theories are not finitely axiomatizable
  - general FOL calculi are not efficient enough
- **Fact:** the satisfiability of sets of literals is decidable, efficiently, in several theories
- **Catch:** checking the satisfiability of qffs is at least as hard as in the propositional case

Sources of SMT Success

The current success of SMT derives from

1. A long line of old and new efficient decision procedures for many theories
2. Spectacular advances in SAT solving
3. Smart new ways of combining 1 and 2
4. A substantial standardization effort
5. A large set of applications waiting in the wings

An Explosion of Interest in SMT



- 2002: birth year of the term SMT
- Google Scholar entries per year for "SMT Satisfiability Modulo Theories" in Engineering, CS and Math

Where are SMT solvers now used?

- processor verification
- equivalence checking
- (un)bounded model checking
- predicate abstraction
- static analysis
- symbolic execution
- automated test case generation
- extended static checking
- scheduling and optimization
- …

SMT just at Microsoft

- The Spec# Programming System
- HAVOC
- ForμLa
- Hyper-V Microsoft Virtualization
- F7
- Terminator T-2
- VCC
- SLAM
- Yogi
- NModel
- Vigilante
- SpecExplorer
- Pex
- SAGE

SMT Prehistory [late '70s to '80s]

- Pioneers:
  - R. Boyer, J Moore, G. Nelson, D. Oppen, R. Shostak
- Influential results:
  - N&O congruence closure procedure
  - N&O combination method
  - Shostak combination method
- Influential systems:
  - Nqthm prover [Boyer & Moore]
  - Simplify [Nelson et al.]

SMT Beginnings [late 1990s]

- Game changer:
  - Advances in SAT
  - Very fast solvers (Chaff, Berkmin, …)
- Main new ideas:
  - "eager" encodings of SMT problems into SAT
    [Bryant, Velev, Strichman, Lahiri, Seisha,…, –'02]
  - "lazy" encodings into SAT + decision procedures
    [Armando et al.'00, Audemard et al.'02, Ruess & de Moura'02, Barrett et al.'02]

State of the art on SMT in 2002

- Many different solvers
  - based on different variants of FOL
  - working with different theories
  - dealing with different classes of formulas
  - having different interfaces and input formats
- Solver's theory unclear
- Arduous to assess the relative merits of techniques or solvers
- Each solver good on its own benchmarks
- Difficult even to a evaluate a single solver

FroCoS 2002: a call for arms

- G. Nelson gives invited talk on Simplify's work
- Excitement about the promise of the field
- Unhappiness about lack of standard benchmarks
- Chair A. Armando calls for the creation of a common library of benchmarks
- SR and CT agree to lead the initiative
- Several participants promise assistance and contributions

FroCoS 2002 aftermath

- R&T soon realize that a common library would need to develop a standard:
  1. background logic
  2. catalog of rigorously defined theories
  3. specification of relevant fragments of these theories
  4. concrete syntax for benchmarks

- This becomes the blueprint for the SMT-LIB initiative

The SMT-LIB Initiative

International effort supported by several research groups worldwide

The SMT-LIB Initiative

- Goals:
  - Collect a large on-line library of SMT benchmarks
  - Promote the adoption of common languages and interfaces for SMT solvers
- Sister initiatives:
  - SMT-COMP, solver competition
  - SMT-EXEC, solver execution service
- Funding:
  - NSF, SRC, Intel, Microsoft, U. of Iowa

The SMT-LIB Initiative today

- 94,000+ benchmarks in online repository
- 22 logics
- SMT-LIB format (V. 1.2) adopted by all major SMT solvers (12+)
- Version 2, major new version, of SMT-LIB format and library released in 2010
- SMT-COMP'10 run with Version 2.0

SMT-LIB Format

Three main components:

1. Theory declarations, semi-formal specifications of background theories of interest (e.g., integers, reals, arrays, bit vectors, . . .)
2. Logic declarations, semi-formal specifications of fragments of (combinations of) background theories (e.g., quantifier-free linear real arithmetic, integer difference constraints, . . .)
3. Benchmarks, formulas to be checked for satisfiability (previously), or scripts (now)

SMT-LIB Repository

Three main components:

1. Catalog of theory declarations
2. Catalog of logic declarations
3. Library of benchmarks

www.smt-lib.org

SMT-LIB 2 format highlights

- Command language
  - Allows more sophisticated interaction with solvers
  - Stack-based, tell-and-ask execution model
  - Benchmarks are command scripts
- Concrete syntax
  - Sublanguage of Common Lisp S-expressions
  - Few syntactic categories
- Powerful underlying logic
  - Many-sorted FOL with (pseudo-)parametric sorts
  - Function symbol overloading

SMT-LIB chronology

SMT-LIB chronology

Aug 2002: Initial website, SMT-LIB is born

Sep-Dec 2002: Email discussion on SMT-LIB standard led by SR, CT

- initial feedback by A. Armando, CB, G. Nelson, H. Ruess, N. Shankar, AS

Oct 2002: A few external subsites, with benchmarks in different formats

- by SR, O. Strichman, AS

SMT-LIB chronology

Jul 2003: White paper on SMT-LIB standard
- drafted and circulated by SR, CT

Aug 2003: First PDPAR workshop, with panel on SMT-LIB standard
- organized by SR, CT
- panelists: CB, G. Nelson, R. Sebastiani, G. Sutcliffe, AS

Jul 2004: Version 1 of SMT-LIB standard
- written and released by SR, CT

SMT-LIB chronology

Jul 2004: SMT-LIB panel at PDPAR

- Call for a solver competition by A. Armando
- CB, LdM, AS agree to organize SMT-COMP in 2005

Aug 2004-Oct 2004 Several rounds of discussion on SMT-COMP'05

- by CB, LdM, SR, AS, CT
- major feedback from A. Armando and A. Cimatti

SMT-LIB chronology

Sep 2004–Apr 2005 Lots of work by all on

- refining the SMT-LIB format, into Version 1.1
- defining an initial set of theories and logics
- collecting existing benchmarks in other formats
- translating them into the SMT-LIB format
- producing some utility tools for the community

Apr 2005: First version of SMT-LIB repository

- 11 logics
- 1,350 benchmarks

SMT-LIB chronology

Jul 2005 First SMT-COMP

- organized by CB, LdM, AS
- 12 solvers, 7 divisions

Jul 2005: PDPAR

- chaired by A. Cimatti, A. Armando
- E. Singerman calls for SMT solvers to support bit vectors

Jan-May 2006: work on defining an SMT-LIB theory of bit vectors

- by SR, CT, with major feedback from CB, LdM, AS

SMT-LIB chronology

Jan-May 2006: Thousands of contributed benchmarks translated and added to SMT-LIB by CB, LdM

Aug 2006: Version 1.2 of SMT-LIB format released by SR, CT

Aug 2006: SMT-COMP organized by CB, LdM, AS

- 11 divisions, including one on bit vectors
- 42,100 benchmarks
- 12 solvers (4 new)

SMT-LIB chronology

Jun 2007: SMT-EXEC cluster set up by AS

Jul 2007: PDPAR workshop renamed SMT
- chaired by S. Krstic, A. Oliveras
- SMT-LIB panel discusses commands and parametric type extensions to format

Jul 2007: SMT-COMP runs on SMT-EXEC cluster
- organized by CB, M. Deters, A. Oliveras, AS
- live results with a fancy interface by M. Deters
- 55,400 benchmarks from 12 divisions
- 9 solvers (4 new)

SMT-LIB chronology

Jan 2008: CB, AS, CT create 3 workgroups

- each on a major improvement to SMT-LIB format

Jan 2008: SMT-EXEC open to public use

Jul 2008: SMT workshop chaired by CB, LdM

- record attendance (75)

Jul 2008: SMT-COMP

- organized by CB, M. Deters, A. Oliveras, AS
- 70K benchmarks from 12 divisions
- 13 solvers

SMT-LIB chronology

May 2009: SMT workshop gets Steering Committee and bylaws

- bylaws edited by CT with input from past PC chairs

Jul 2009: Web-based query facility for SMT-LIB repository

- by M. Deters, with inputs from CB, CT

Aug 2009: Draft of Version 2 of SMT-LIB format posted to the community

- produced by 3 workgroups led by CB, AS, CT, resp.

SMT-LIB chronology

Aug 2009: SMT'09 largest workshop at IJCAR

- 60 registrants
- chaired by B. Dudertre, O. Strichman

Mar 2010: SMT-LIB Version 2 document officially released by CB, AS, CT

May 2010: SMT-LIB benchmarks (90K+) ported to Version 2 by CB, C. Conway, M. Deters

SMT-LIB chronology

July 2010: SMT'10 largest workshop at FLoC

- chaired by A. Gupta & D. Kroening
- 65 registrants

July 2010: SMT-COMP uses SMT-LIB 2

- organized by CB, M. Deters, A. Oliveras, AS
- 94K benchmarks in 18 divisions
- 10 solvers

Oct 2010: HVC 2010 Award!

SMT-LIB immediate future

- Fresh blood in SMT-COMP
  - 2011,12 by R. Bruttomesso, M. Deters, A. Griggio
- SMT-LIB tutorial, by D. Cok
- Formalization contributions by the community
  - a theory of floating point arithmetic, by P. Ruemmer, T. Wahl, et al.
  - several theories of container data structures, by P. Ruemmer, CT, et al.

    (lists with length, finite maps, finite sets with cardinality)
  - a theory of character strings, by V. Ganesh et al.

SMT-LIB Future

- Benchmarks with more complex scripts
- An expanded command language
- An extension of the format with algebraic data type declarations
- A common standard for SMT proofs
  - based on an extension of LF, by AS, CT
- More logics

SMT Future

- Bit vector solvers dynamically combining algebraic reasoning and reduction to SAT
- Novel FP arithmetic solvers
- Non-linear integer/real arithmetic solvers

SMT Future

- Proof-production
  - proofs of unsatisfiable queries

- Interpolation
  - interpolants of unsat queries $F \wedge G$

- Projections
  - given $F(\mathbf{x},\mathbf{y})$, producing a (suitable over approxim.) of $\exists \mathbf{x}\, F(\mathbf{x},\mathbf{y})$

SMT Future

- Quantifiers, quantifiers, quantifiers
  - needed in some proof obligations
  - used to formalize non-built-in theory symbols
- Inductive reasoning on functions over algebraic data types

Thank you!