Alt-Ergo

An SMT Solver for Software Verification

Mohamed Iguernelala — OCamlPro SAS

About ...

About the Spearker

Who am I?

- Mohamed Iguernelala
- Senior R&D engineer at OCamlPro SAS
- Research associate in the VALS team, LRI

My Research topics

- Satisfiability Modulo Theories (SMT)
- Combining rewriting and SMT techniques
- Designing and combining decision procedures for SMT

Formerly, I was a PhD student in the VALS team

Maintainer of the Alt-Ergo SMT solver at OCamlPro

About OCamlPro

Help companies to use OCaml in industrial projects ...

Developments on demand in OCaml

Developments to promote the use of OCaml

- OPAM package manager
- the Typerex toolbox (IDE, memory/GC profilers, libs, ...)

Code analysis and optimization

- analysis of OCaml code
- introduction of new optimization passes in OCaml compiler
- tools for numerical calculus (Scilab, Modelica)

Formal methods

- maintenance and improvement of Alt-Ergo

The Origins of Alt-Ergo ...

History of Alt-Ergo

Preliminary work by Sylvain Conchon in 2002 on decision procedures and their combination :

- Combining Shostak theories
- Generic framework for combining decision procedures à la Nelson-Oppen

SMT solvers at that time :

- Simplify (DEC/Compaq/HP)
- SVC, CVC (Stanford)
- ICS (SRI)
- UCLID (Berkeley)

History of Alt-Ergo : Motivations

Deductive program verification plateforms at that time

- ESC/Java (DEC/Compaq/HP)
- Why/Caduceus/Krakatoa (LRI)

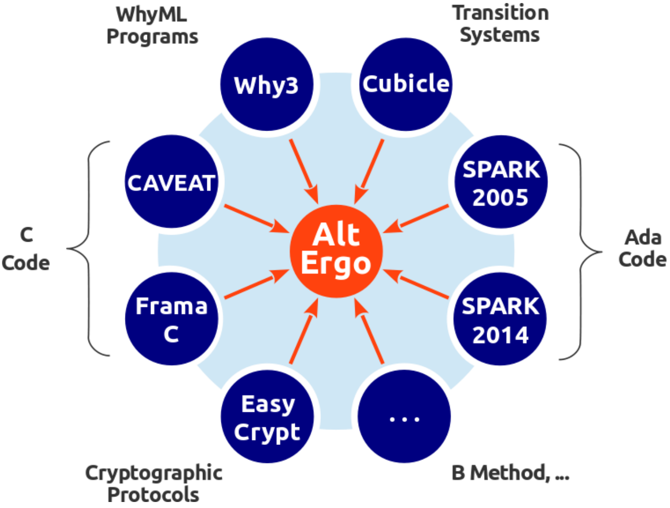
Main motivations :

- An automatic theorem prover for Why
- Polymorphic first-order logic with built-in theories (free equality, linear arithmetic) similar to Why's syntax
- Certification (in Coq)

History of Alt-Ergo : First Release in 2006

70's :	Stanford Pascal Verifier (Nelson-Oppen combination)
1984 :	Shostak algorithm
1992 :	Simplify
1995 :	SVC
2001 :	ICS
2002 :	CVC, UCLID
2004 :	CVC Lite
2005 :	Barcelogic, MathSAT
2005 :	Yices
2006 :	CVC3, Alt-Ergo
2007 :	Z3, MathSAT4
2008 :	Boolector, OpenSMT, Beaver,Yices2
2009 :	STP, VeriT
2010 :	MathSAT5, SONOLAR
2011 :	STP2, SMTInterpol
2012 :	CVC4

Tools Using Alt-Ergo Today



SPARK 2014, EasyCrypt and Atelier-B use it via Why3

Alt-Ergo : Contributors

Project leaders :

- Sylvain Conchon
- Evelyne Contejean

PhD students :

- Stéphane Lescuyer (reflexive Coq tactic)
- Mohamed Igernelala (AC, arithmetic, SAT)
- Claire Dross (quantifiers, user-defined axiomatic theories)

Post-docs, interns, engineers :

- François Bobot (arithmetic, case-split analysis)
- Denis Cousineau (prototype of a lightweight Coq traces)
- Johannes Kanig (Coq traces)
- Alain Mebsout (altgr-ergo, DO-178C)
- Cody Roux (prototype of a floating-point theory)

Alt-Ergo @ OCamlPro ...

What Can OCamlPro Do For Alt-Ergo

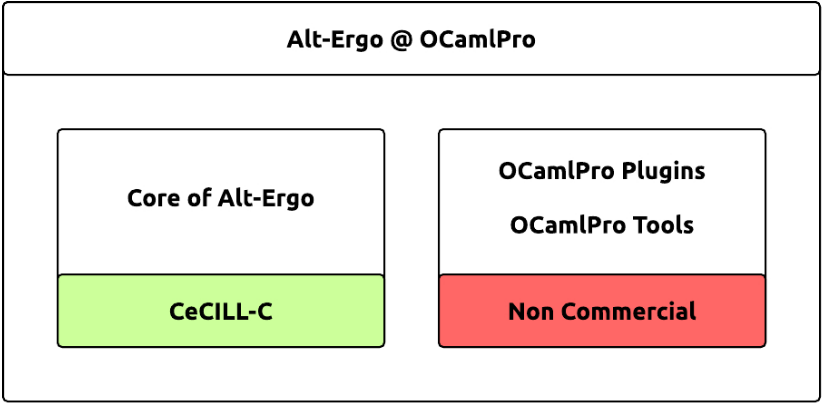
at OCamlPro

- Better reactivity for bugs fixes
- Improving performances and expressiveness, even if there are no research challenges
- Commercial support and services on demand

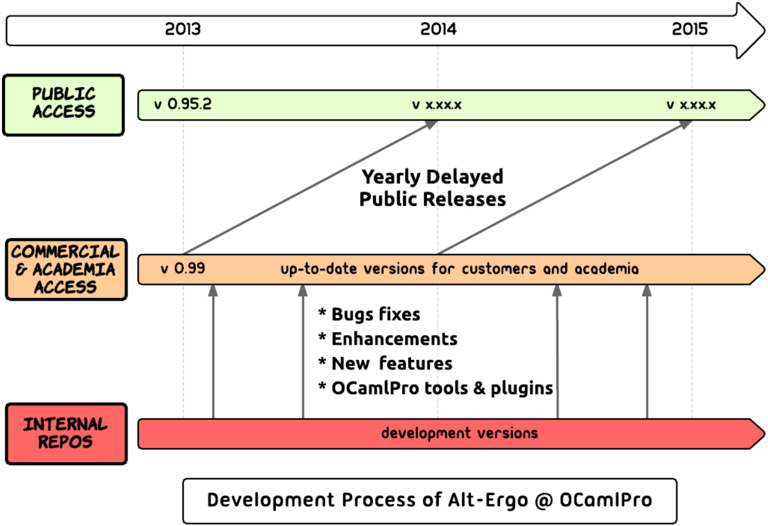
in collaboration with the VALS team

- Exploring research/theoretical aspects such as designing new decision procedures and their combination

Alt-Ergo @ OCamlPro : Code Base



Alt-Ergo @ OCamlPro : Devel & Release Processes

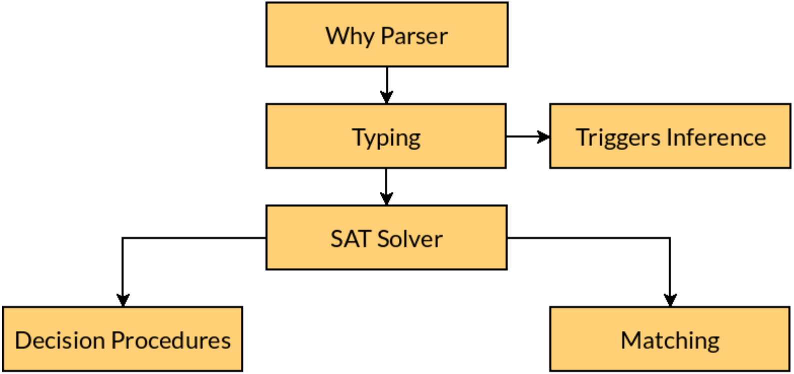


Releases Since September 2013

Septembre 2013	public release 0.95.2
Octobre 2013	private release 0.99
Juillet 2014	Try Alt-Ergo 0.99
Decembre 2014	public release 0.99.1
Decembre 2014	private release 1.00-beta
January 2015	private release 1.00
January 2015	Try Alt-Ergo 1.00

Under the Hood ...

General Architecture (Alt-Ergo 1.00)



Input Language : Similar to (Old) Why's Syntax

```
(* this is a comment *)

type 'a list (* abstract parametric type *)

logic nil: 'a list (* function symbol of arity 0 *)
logic cons: 'a, 'a list -> 'a list
logic length: 'a list -> int

(* implicit quantification over a type variable 'a *)
axiom a1: length(nil) = 0

axiom a2:
  forall x:'a. forall l:'a list.
  length(cons(x,l)) = 1 + length(l)

goal g: forall x:'a. length(cons(x,nil)) = 1
```

Frontend

Typing : à la ML, with prenex polymorphism

Triggers inference :

- Compute triggers ("guards") that will be used to generate ground instances from universally quantified formulas

Example

```
axiom a2:
  forall x:'a. forall l:'a list.
    length(cons(x,l)) = 1 + length(l)
```

- The type variable 'a is implicitly universally quantified
- Possible "good" triggers are $cons(x, l)$ and $length(cons(x, l))$. They cover all variables and type variables

No additional pre-processing steps in Alt-Ergo's frontend !

SAT Solver(s)

A "default" DPLL solver, coded in a functional style :

- Efficient in the context of deductive program verification
- No "clauses learning" when backjumping
- BCP modulo theories
- Lazy CNF conversion
- Generated instances in a branch of the SAT are ignored when looking for a model in another branch

A CDCL solver inspired by minisat, coded in an imperative style :

- Efficient when a complex propositional reasoning is needed
- Clauses learning when backjumping
- All the instances generated during the matching process are kept in the SAT's environment

Matching

Generates ground “consequences” from universally quantified formulas

Works by Matching techniques :

- if a universally quantified formula $\forall x.F(x)$ is “guarded“ by a trigger $g(h(x))$
- if some ground term $g(h(a))$ is present in decision procedures' environment
- then, add the instance $F(a)$ to the SAT solver's context

Matching Modulo

The Matching process is done :

(1) modulo the equalities that are true when matching :

- the trigger $g(h(x))$ "matches" the term $g(c)$ modulo the equality $c = h(b)$.
- the resulting substitution is $\{x \mapsto b\}$

(2) modulo the theory of records :

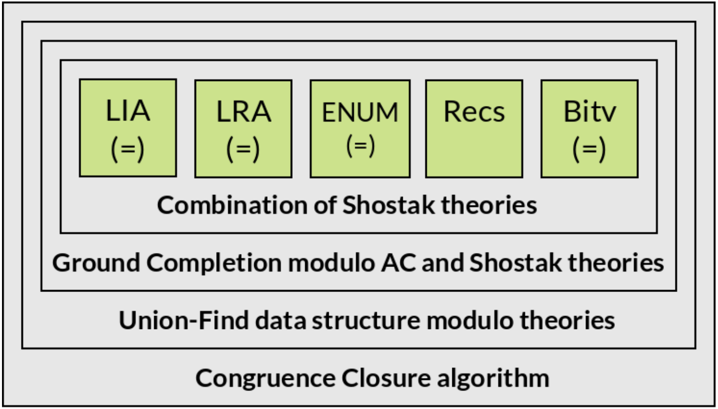
- the trigger $\{\mathit{field}_1 = x \; ; \; \mathit{field}_2 = y\}$ "matches" any ground terms r in decision procedures' context of the same type.
- the resulting substitution is : $\{x \mapsto r.\mathit{field}_1 \; ; \; y \mapsto r.\mathit{field}_2\}$

Decision Procedures : Supported Theories

- The free theory of equality with uninterpreted symbols
- Linear arithmetic over integers and rationals
- Non-linear arithmetic
- Polymorphic functional arrays
- Enumerated datatypes
- Record datatypes
- Associative and commutative (AC) symbols
- Fixed-size bit-vectors with concatenation and extraction

Decision Procedures : Combination Architecture (1/3)

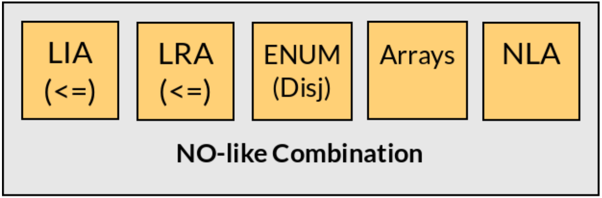
Convex equational theories



- Produces a union-find data structure modulo theories

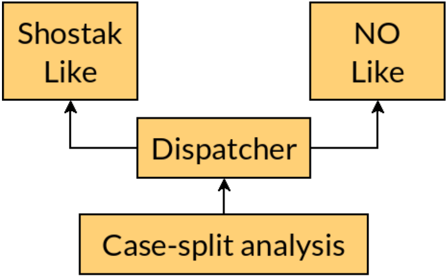
Decision Procedures : Combination Architecture (2/3)

Non convex or non equational theories



- This part has access to the union-find data structure constructed so far
- Case-split analysis over finite domains is needed for completeness

Decision Procedures : Combination Architecture (3/3)



- The case-split module maintains two environments
  - real theory env
  - real theory env + guesses (for values over finite domains)
- All components are implemented in a pure functional style, which facilitates backtracking

Decision Procedures : Theoretical Foundations

- CC(X) : Semantical Combination of Congruence Closure with Solvable Theories.
- AC(X) : Canonized Rewriting and Ground AC Completion Modulo Shostak Theories
- A Simplex-based extension of Fourier-Motzkin for solving linear integer arithmetic
- A Collaborative Framework for Non-Linear Integer Arithmetic Reasoning in Alt-Ergo
- Combining Shostak Theories (Work In Progress)

More on `alt-ergo.lri.fr`

Current Funding / R&D Projects ...

OCamlPro / BWare (2012 — 2016)

Extend Atelier-B with state-of-the-art automatic solvers

- We did a lot of optimizations in different parts of Alt-Ergo to make it scale on B proof obligations
- We developed profiling tools to monitor the solver and quickly detect the parts that need improvements
- We identified some theoretical challenges on which we are currently working

OCamlPro / SOPRANO (2014 — 2018)

Explore new combination schemes and tackle hard theories

- Integrate floating-point arithmetic in Alt-Ergo
- Extend the theory of bit-vectors (bitwise operators, conversion from/to bounded integers, ...)
- Generate models when formulas are satisfiable

Performances of Alt-Ergo 1.00 ...

Quick Comparison Between Different Versions

	public release 0.95.2	public release 0.99.1	private release 1.00
Proved valid	15980	16334	17638
Proved valid (%)	84,01 %	85,77 %	92,62 %
Required time (seconds)	10831	10504	9767
Average speed (formulas / second)	1,47	1,55	1,81

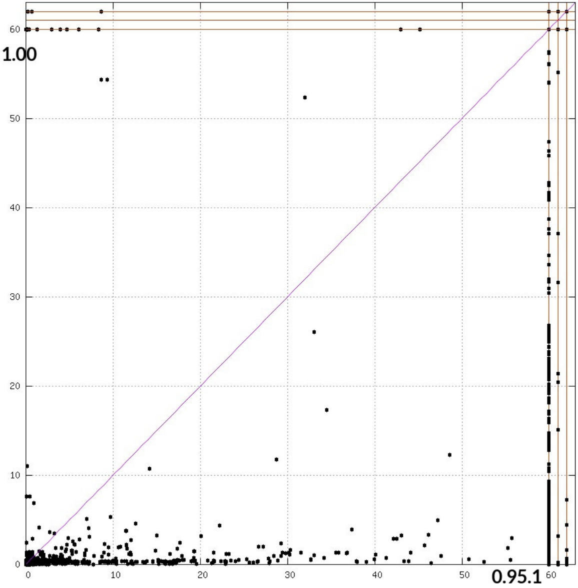
- timeout = 60 seconds, benchmark of 19044 formulas
- some formulas are known to be invalid
- some formulas need inductive reasoning

Zoom on BWare Benchmarks (1/2)

	before the project started (v. 0.95.1)	private release 1.00	1.00 + dedicated options
Proved valid	5696	10287	10422
Proved valid (%)	53,73 %	97,03 %	98,30 %
Required time (seconds)	4081	5578	3045
Average speed (formulas / second)	1,40	1,84	3,43

- timeout = 60 seconds, benchmark of 10602 formulas
- success rate of Atelier-B's automatic prover = 86 %
- remaining formulas (14%) proved interactively
- dedicated options : no E-Matching, one trigger per axiom (default value is 2)

Zoom on BWare Benchmarks (2/2)



Main Changes in Version 1.00 (w.r.t. 0.99.x)

- 20 bugs fixes
- Two new OCamlPro plugins (profiling and linear integer arithmetic inequalities)
- A lot of improvements in different data structures
- Improvements/rewriting/simplification of many components and algorithms
- Enhancement of SAT and instantiation heuristics
- ...

More on `http://www.ocamlpro.com/blog/index.html`