CHC-COMP 2018

Arie Gurfinkel

Philipp Ruemmer, Grigory Fedyukovich, Adrien Champion

1st Competition on Solving Constrained Horn Clauses

CHC-COMP: CHC Solving Competition

First edition on July 13, 2018 at HVCS@FLOC

Constrained Horn Clauses (CHC) is a fragment of First Order Logic (FOL) that is sufficiently expressive to describe many verification, inference, and synthesis problems including inductive invariant inference, model checking of safety properties, inference of procedure summaries, regression verification, and sequential equivalence. The CHC competition (CHC-COMP) will compare state-of-the-art tools for CHC solving with respect to performance and effectiveness on a set of publicly available benchmarks. The winners among participating solvers are recognized by measuring the number of correctly solved benchmarks as well as the runtime.

Web: https://chc-comp.github.io/

Gitter: https://gitter.im/chc-comp/Lobby

GitHub: https://github.com/chc-comp

Format: https://chc-comp.github.io/2018/format.html

Constrained Horn Clauses (CHC)

A Constrained Horn Clause (CHC) is a FOL formula of the form

$$\forall V \cdot (\varphi \wedge p_1[X_1] \wedge \cdots \wedge p_n[X_n] \rightarrow h[X]$$

where

- $\mathcal{T}$ is a background theory (e.g., Linear Arithmetic, Arrays, Bit-Vectors, or combinations of the above)
- φ is a constraint in the background theory $\mathcal{T}$
- p_1, …, p_n, h are n-ary predicates
- p_i[X] is an application of a predicate to first-order terms

CHC Satisfiability

A $\mathcal{T}$-**model** of a set of a CHCs Π is an extension of the model M of $\mathcal{T}$ with a first-order interpretation of each predicate p_i that makes all clauses in Π true in M

A set of clauses is **satisfiable** if and only if it has a model

- This is the usual FOL satisfiability

A $\mathcal{T}$**-solution** of a set of CHCs Π is a substitution σ from predicates p_i to $\mathcal{T}$-formulas such that $\Pi\sigma$ is $\mathcal{T}$-valid

In the context of program verification

- a program satisfies a property iff corresponding CHCs are satisfiable
- solutions are inductive invariants
- refutation proofs are counterexample traces

Format


```
benchmark ::=
        logic
        fun_decl+
        (assert chc_assert)*
        (assert chc_query)
        (check-sat)

logic ::= (set-logic HORN)
fun_decl ::= (declare-fun symbol ( sort* ) Bool)
```

chc_assert ::= ;; a well-formed first-order sentence of the form

| (forall (var_decl+) (=> chc_tail chc_head))

| chc_head

Format 2/2

```
var_decl ::= (symbol sort)
chc_head ::=
        | (u_predicate var*) , where all variables are
DISTINCT
chc_tail ::=
       | (u_predicate var*)
       | i_formula
       | (and (u_predicate var*)+ i_formula*)
chc_query ::= ;; a well-formed first-order sentence of the form
       | (forall ( var_decl+ ) (=> chc_tail false)

u_predicate ::= uninterperted predicate (i.e., Boolean function)
i_formula ::= an SMT-LIB formula over variables, and
              interpreted functions and predicates
```

Example

```
(set-logic HORN)
(declare-fun Inv (Int) Bool)
;; fact
(assert (forall ((x Int)) (=> (= x 0) (Inv x))))
;; chc
(assert (forall ((x Int) (y Int))
        (=> (and (Inv x) (<= x 10) (= y (+ x 1))) (Inv y))))
;; query
(assert (forall ((x Int))
              (=> (and (Inv x) (> x 15)) false)))
(check-sat)
```

Benchmark Selection

chc-comp.github.io as collection for CHC benchmarks

- Collected from participants
- Generated with SeaHorn from SV-COMP Device Driver problems

Converted to competition format using format script (Adriene)

- https://github.com/chc-comp/scripts

Out of successfully formatted benchmarks selected

- 339 CHC-LINEAR(LIA)
- 132 CHC-LINEAR(LRA)
- Random selection, favoring hard-for-spacer benchmarks

Benchmarks released after competition:

- https://github.com/chc-comp/chc-comp18-benchmarks

Participants

Eldarica	Philipp Rümmer
Hoice	Adriene Champion
PECOS	John Gallagher
TransfHORNer	Fabio Fioravanti
Ultimate TreeAutomizer	Alexander Nutz
Ultimate Unihorn Automizer	Alexander Nutz

Hors Concours

spacer	Arie Gurfinkel
rebus	unnamed solver not entered in the competition

Hoice [Champion et al., 2018]

ICE-based Refinement Type Discovery for Higher-Order Functional Programs

Adrien Champion[1], Tomoya Chiba[1],
Naoki Kobayashi[1], Ryosuke Sato[2]

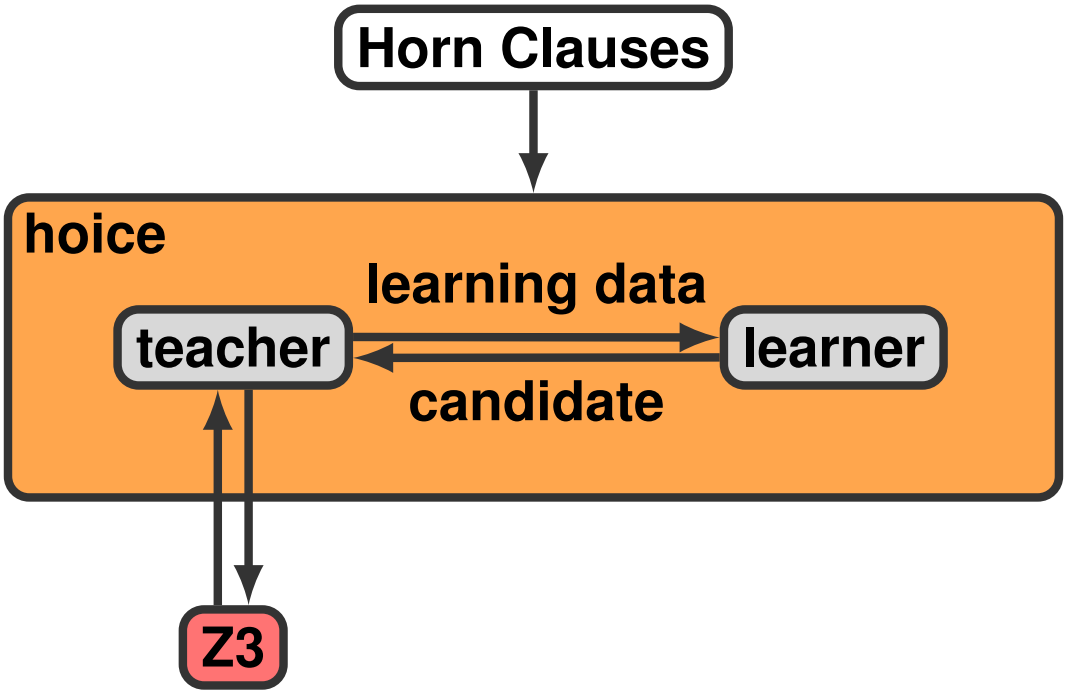
[1] The University of Tokyo
[2] Kyushu University

`https://github.com/hopv/hoice`

- machine-learning-based Horn clause solver: generalized ICE framework [Garg et al., 2014]
- context: higher-order program verification
- supports `Int`, `Real`, and `Array`
- support for datatypes coming soon

Hoice [Champion et al., 2018]

- learner produces candidates for the predicates
- teacher checks each clause is respected
- $\Rightarrow$ each check is a quantifier-free (non-Horn) formula
- using Z3 [de Moura and Bjørner, 2008] (separate process)



TransfHORNer

E. De Angelis [(1)], F. Fioravanti [(1)],
A. Pettorossi [(2)], M. Proietti [(3)]

(1) DEC, University ”G. d’Annunzio” of Chieti-Pescara, Italy
(2) DICII, University of Rome Tor Vergata, Rome, Italy
(3) CNR-IASI, Rome, Italy

HCVS 2018 **Oxford – July 13, 2018**

TransfHORNer distinctive features

Apply satisfiability-preserving CHC transformations (Unfold/Define/Fold)

Discover invariants and try to increase the effectiveness of backend CHC solvers

Convert from SMT-LIB format to Prolog format;
Try to transform non-linear recursive CHCs into linear-recursive CHCs;
if linearization successful **then** { run* Z3 (Spacer and PDR); (requires conversion to SMT-LIB)
if sat / unsat **then** exit; }
while (true) **do**
Propagate* constraints and discover invariants (using widening with convex-hull);
if Propagate timed-out **then** use simpler widening for Propagate
else { run* Z3 (Spacer and PDR);
if sat / unsat **then** exit; }
if CHCs are linear-recursive **then** change direction (backward/forward) of Propagate;

(*) with time limit

Related work

- Verification of C programs with integers and arrays (PEPM13, VMCAI14, SCP14,…)
- VeriMAP (TACAS14) https://fmlab.unich.it/VeriMAP/
- Semantics-based VC generation for C programs (PPDP15, SCP17)
- Relational program verification (SAS16, TPLP18)
- Verification of BPMN business processes (LOPSTR16, RULEML+RR17)
- Satisfiability checking of CHCs with inductively defined data structures (lists, trees, ...) without induction

ICLP 2018 on Saturday, July 14th 3 PM

PECOS: Partial evaluation and Constraint Specialisation

Developed by John P. Gallagher, Bishoksan Kafle and José F. Morales (Roskilde, IMDEA, Melbourne). Based partly on previous experiments with RAHFT (Kafle, Gallagher & Morales, CAV'2016).
Oriented towards pure LRA Horn clauses (challenging to modify for mixed Boolean/numeric constraints). Iteratively performs the following transformations.

- *Constraint specialisation* (PEPM'2015, Sci. Comput. Program. 2017) for invariant discovery. Backwards/forwards propagation, convex polyhedral global analysis with query-answer (magic-set) transformation.
- *Partial evaluation* of the computation trees for *false*. Achieves control-flow refinement and predicate specialisation. Employs a property-based finite abstract domain. Described in PEPM'1993, ICLP'2018, WST'2018.

Prototype software on github.com/jpgallagher/pecos. Implemented in Ciao Prolog with interfaces to PPL and Yices.

Ultimate TreeAutomizer

Tree Automizer = Trace Abstraction + Tree Automata

Trace Abstraction (Automizer) approach:

Program is correct iff each error trace (word) is infeasible.

Tree Automizer approach:

Set of CHCs is sat iff the constraints in each derivation of `false` (tree) are unsat.

Under the hood:

- Ultimate Automata Library
- SMTInterpol

Contributors:
Daniel Dietsch, Alexander Nutz, Mostafa M. Mohamed, Daniel Tischner, Jochen Hoenicke, Matthias Heizmann, Andreas Podelski

Ultimate Unihorn Automizer

Input: Set of constrained Horn clauses Φ

Approach:

- Construct (possibly recursive) program P_Φ such that:
  P_Φ is safe iff Φ is sat
- Apply off-the-shelf program verifier

Under the hood:

- Program verifier: Ultimate Automizer
- Predicate providers: Newton-style interpolation, SMTInterpol
- SMT Solvers: CVC4, MathSAT5, SMTInterpol, Z3
- Ultimate Automata Library

Contributors:
Daniel Dietsch, Matthias Heizmann, Jochen Hoenicke, Alexander Nutz, Andreas Podelski

The ELDARICA Horn Solver

Hossein Hojjat[1] Philipp Rümmer [2]

[1]Rochester Institute of Technology
[2]Uppsala University

HCVS 2018: 5th Workshop on Horn Clauses for Verification and Synthesis
13 July 2018

Eldarica Overview

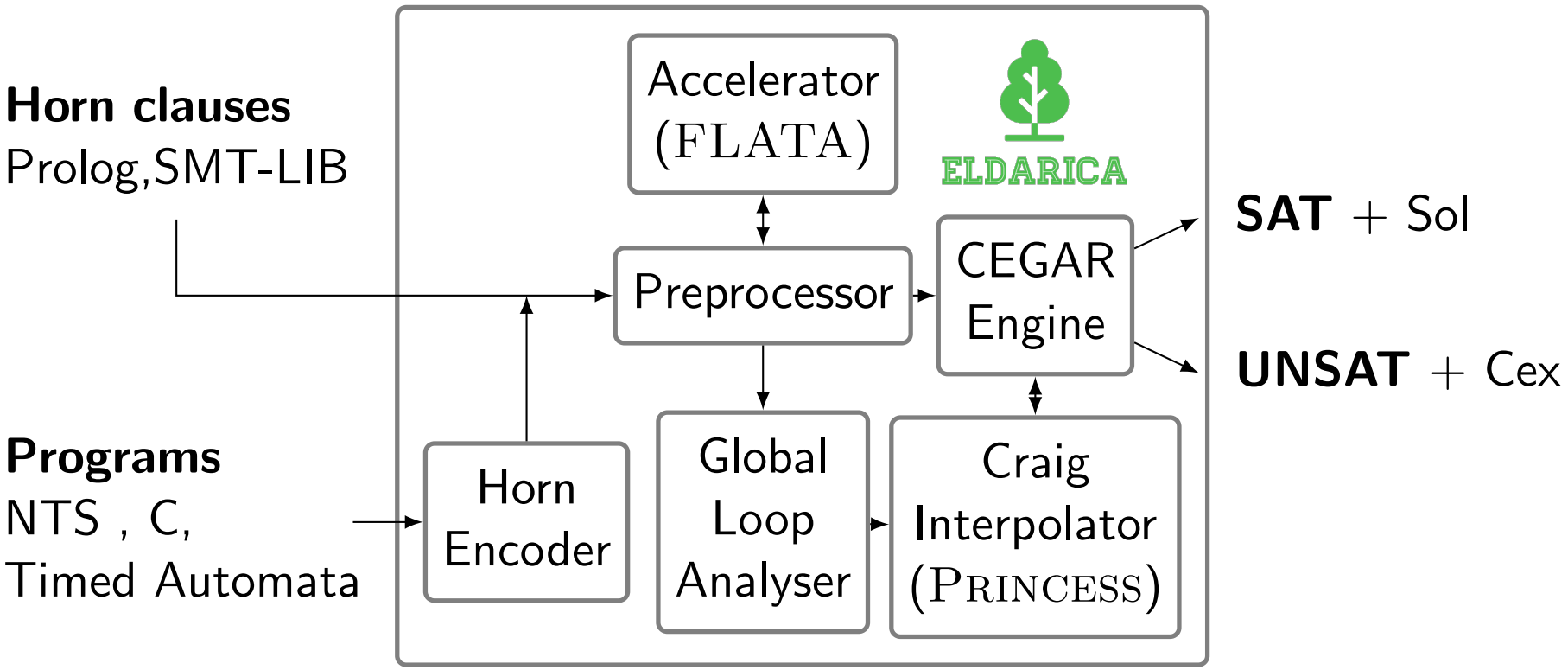
- Horn solver developed since 2011
- Open-source, implemented in Scala, running in JVM

- **Input formats:**
  SMT-LIB, Prolog, C, timed automata
- **Theories:**
  LIA, NIA, arrays, algebraic data-types, bit-vectors

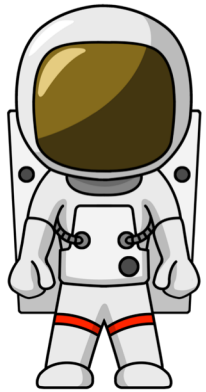
- Scala/Java API
- Support for linear + non-linear clauses

- `https://github.com/uuverifiers/eldarica`

ELDARICA Architecture



Spacer: Solving SMT-constrained CHC



Spacer: a solver for SMT-constrained Horn Clauses

- now the default (and only) CHC solver in Z3
  - https://github.com/Z3Prover/z3
  - dev branch at https://github.com/agurfinkel/z3

Supported SMT-Theories

- Linear Real and Integer Arithmetic
- Quantifier-free theory of arrays
- *Universally quantified theory of arrays + arithmetic (work in progress)*
- Best-effort support for many other SMT-theories
  - data-structures, bit-vectors, non-linear arithmetic

Support for Non-Linear CHC

- for procedure summaries in inter-procedural verification conditions
- for compositional reasoning: abstraction, assume-guarantee, thread modular, etc.

Spacer Contributors

Arie Gurfinkel
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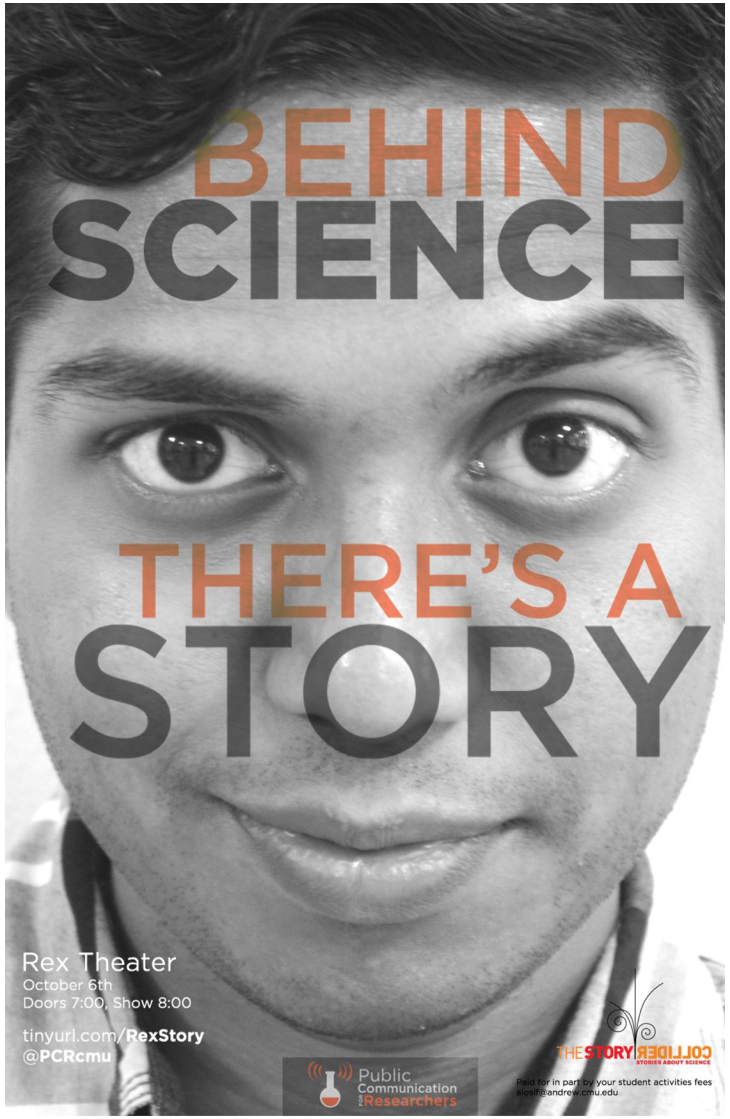
Nikolaj Bjorner
(Krystof Hoder)
Yakir Vizel
Bernhard Gleiss
Matteo Marescotti



Competition Setup

StarExec cluster environment

Dedicated Queue of 20 nodes

2 jobs per node

64GB per job (more than promised)

900s timeout enforced by runsolver

About 12 hours for one complete run of all tools and categories

Detailed results (and benchmarks) will be publicly available on StarExec

Results: LRA

solver	cnt	ok	sat	uns	fld	to	mo	time	real	space	uniq
rebus	132	96	82	14	36	36	0	42838	42842	59	15
spacer	132	82	73	9	50	50	0	54070	54032	93	3
tree-aut	132	25	24	1	107	107	0	101241	92580	7488	0
eldarica	132	20	18	2	112	77	0	72526	35825	2120	0
TransfHORNer	*132*	*15*	*2*	*13*	*117*	*105*	*1*	*103490*	*103619*	*1294*	*2*
uni-aut	132	9	9	0	123	90	0	82877	70345	7536	0
hoice	132	1	0	1	131	131	0	118793	118459	31	0
pecos	132	0	0	0	132	57	1	54743	54811	893	0

cnt – number of benchmarks

ok – solved

sat – solved sat

uns – solved unsat

fld – failed

to – timeout

mo -- memory out

time – sum of time

real – sum of wall

Space – sum of mem

uniq – unique solved

front-end issues

Results: LIA

solver	cnt	ok	sat	uns	fld	to	mo	time	real	space	uniq
spacer	339	225	153	72	114	112	1	122323	122337	509	56
rebus	339	185	139	46	154	154	0	147539	147553	182	12
hoice	339	107	75	32	232	231	0	219810	217971	93	2
eldarica	339	105	97	8	234	234	0	216152	133402	5856	5
TransfHORNer	*339*	*99*	*63*	*36*	*240*	*160*	*8*	*196339*	*196471*	*1642*	*0*
pecos	339	61	61	0	278	152	1	171955	173970	3819	3
tree-aut	339	53	34	19	286	247	0	241323	220198	19234	0
uni-aut	339	51	43	8	288	211	0	199278	140978	19378	0

Big Thanks to

Discussion

CHC-COMP 2019

- Dates, format, co-location, tracks

Ranking

- Should we decide on 1st three places ?

Non-Linear CHC as a category?

Benchmark storage

- Github is limited to 1-2GB per repo

Benchmark selection / availability

Common conversion / simplification utilities