

VeriMAP

A Tool for Verifying Programs
through Transformations

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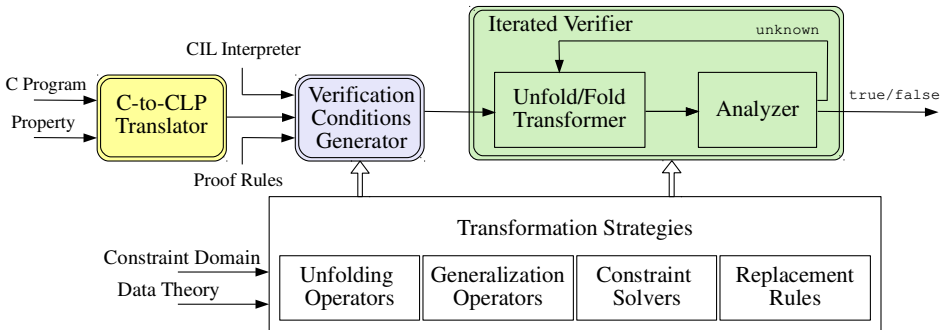
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What is VeriMAP?

- a tool for the verification of **safety properties** of C programs manipulating integers and integer arrays
- based on **Constraint Logic Programs (CLP)** as a **metalanguage** for representing:
 - the operational semantics of the C language
 - the proof rules for safety
 - the C program to be verified
 - the safety property to be checked
- *satisfiability preserving* **transformations of CLP programs** for:
 - generating Verification Conditions
 - checking their satisfiability

Tool Architecture



Available at <http://map.uniroma2.it/VeriMAP/>

Verification of Safety Properties

Given the specification $\{\varphi_{init}\} CProg \{\psi\}$, define $\varphi_{error} \equiv \neg\psi$

```
int x, y, n;  
while(x<n) {  
    x=x+1;  
    y=y+2;  
}
```

Initial and error properties

$\varphi_{init}(x,y,n) \equiv x=0 \wedge y=0 \wedge n \geq 0$

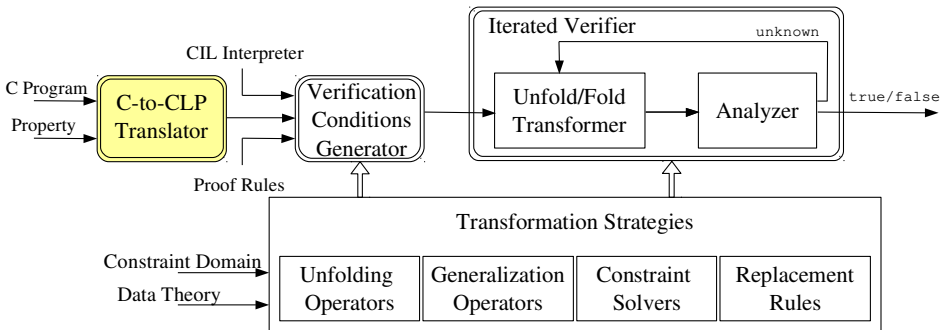
$\varphi_{error}(x,y,n) \equiv y > 2x$

A program is **incorrect** w.r.t. φ_{init} and φ_{error} iff from an initial configuration satisfying φ_{init} it is possible to reach a final configuration satisfying φ_{error} .

Step 1: C-to-CLP - Translating C programs into CLP

Construct the CLP encoding of

- the C Program $CProg$ as a set of facts at (Label, Command)
- the Property $\langle \varphi_{init}, \varphi_{error} \rangle$ as constrained facts



C-to-CLP translator

- First the C program is preprocessed using CIL.
 - while's and for's are translated into equivalent commands that use if-else's and goto's.
- Then, for each program command, C-to-CLP generates a CLP fact of the form $\text{at}(L, C)$, where C and L represent the command and its label.

```
1.  $l_0$  : if (x<n) goto  $l_1$ ;  
           else goto  $l_h$ ;  
2.  $l_1$  : x=x+1;  
3.  $l_2$  : y=y+2;  
4.  $l_3$  : goto  $l_0$ ;  
5.  $l_h$  : halt;
```

```
1. at(10,ite(less(x,n),l1,lh)).  
2. at(l1,asgn(x,expr(plus(x,1)),l2)).  
3. at(l2,asgn(y,expr(plus(y,2)),l3)).  
4. at(l3,goto(10)).  
5. at(lh,halt).
```

- Also facts for the initial and error properties are generated:

```
phiInit(cf(..., [(x,X), (y,Y), (n,N)])) :- X=0, Y=0, N>=0.  
phiError(cf(..., [(x,X), (y,Y), (n,N)])) :- Y>2*X.
```

The CLP interpreter *Int*

Proof rules for safety

```
incorrect :- initial(X), phiInit(X), reach(X).  
reach(X) :- tr(X,Y), reach(Y).  
reach(X) :- final(X), phiError(X).
```

Operational semantics of the programming language

```
tr(cf(Lab1, Cmd1), cf(Lab2, Cmd2)) :- ...
```

e.g., operational semantics of the conditional command

<pre>L: if(Expr) { L1: ... } else L2: ... }</pre>	<pre>tr(cf(cmd(L, ite(Expr, L1, L2)), S), cf(C, S)) :- beval(Expr, S), <i>expression is true</i> at(L1, C). <i>next command</i> tr(cf(cmd(L, ite(Expr, L1, L2)), S), cf(C, S)) :- beval(not(Expr), S), <i>expression is false</i> at(L2, C). <i>next command</i></pre>
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Correctness of Encoding:

$CProg$ is *correct* iff $incorrect \notin M(Int)$ (the least model of *Int*)

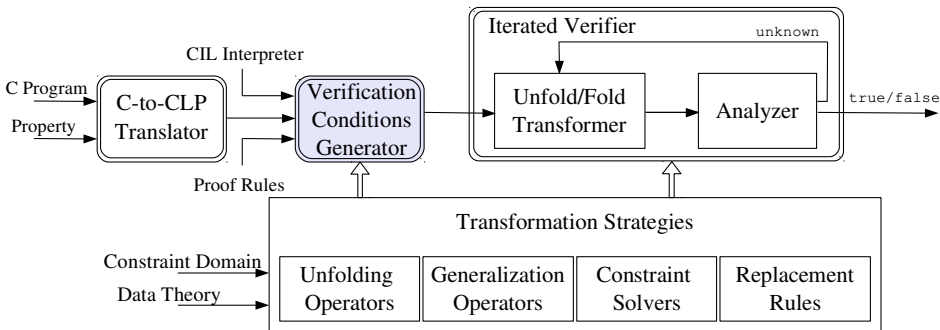
Step 2: Generating Verification Conditions

Generate the Verification Conditions (VCs) by **specializing** the CLP interpreter *Int* (CIL Interpreter + Proof Rules) w.r.t. the CLP encoding of the C program *CProg* .

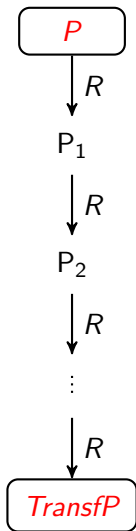
All references to

- *tr* (operational semantics of the C language)
- *at* (encoding of the C program *CProg*)

are removed.



Rule-based Program Transformation



- transformation **rules**:

$R \in \{ \text{Definition, Unfolding, Folding, Clause Removal, Constraint Replacement} \}$

- the transformation rules

change the **syntax** of a program
preserve its **least model semantics**.

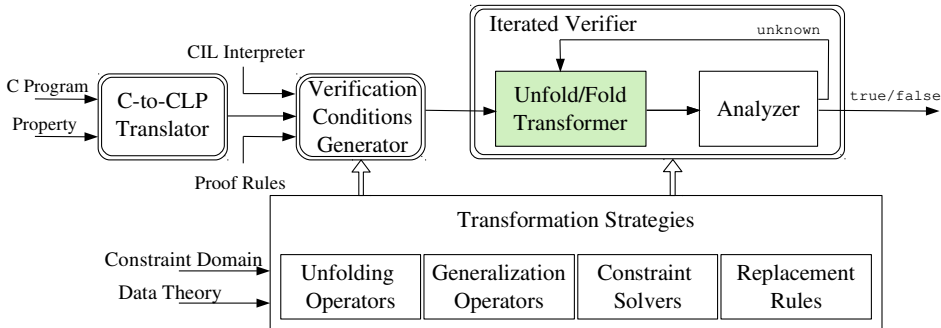
incorrect $\in M(P)$ iff **incorrect** $\in M(\text{Transf}P)$

- the rules are guided by a **strategy**.

Step 3: Transforming the VCs

Transform the VCs by propagating either

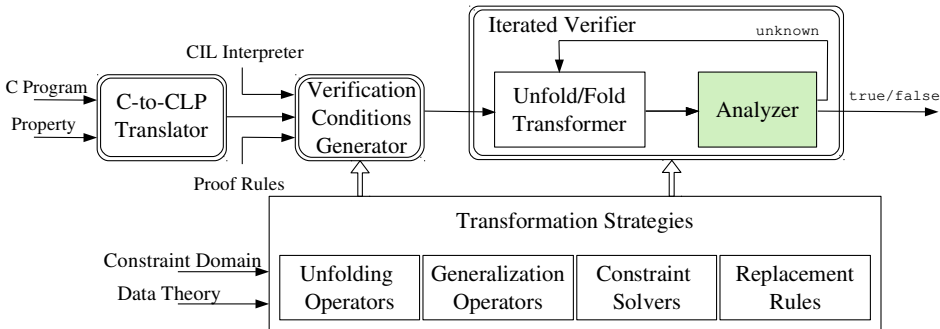
- the constraint encoded by `phiInit` (φ_{init}) or
- the constraint encoded by `phiError` (φ_{error})



Step 4: Checking satisfiability of the VCs

Analyze the CLP program representing the transformed VCs

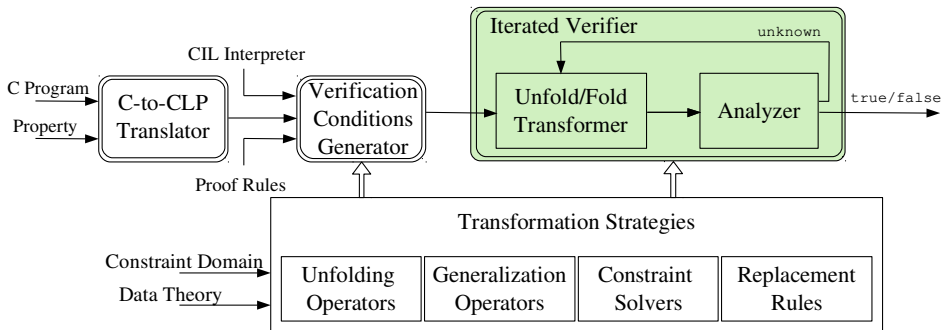
- *CProg* **correct** if no constrained facts appear in the VCs.
- *CProg* **incorrect** if the fact **incorrect**. appears in the VCs.



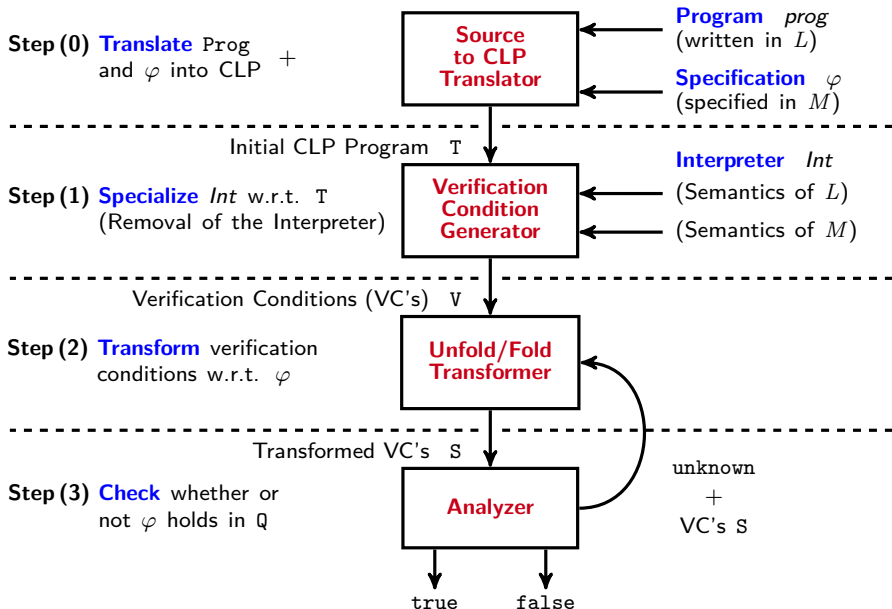
Precision achieved by iteration:

- reverse the direction of the state-space exploration
- transform and analyze

(i.e., alternate the propagation of φ_{init} and φ_{error})



Verification Framework



Experimental Evaluation - Integer Programs

216 examples taken from: DAGGER, TRACER, InvGen, and TACAS 2013 Software Verification Competition.

		VeriMAP	ARMC	HSF(C)	TRACER
1	<i>correct answers</i>	185	138	160	103
2	safe problems	154	112	138	85
3	unsafe problems	31	26	22	18
4	<i>incorrect answers</i>	0	9	4	14
5	false alarms	0	8	3	14
6	missed bugs	0	1	1	0
7	<i>errors</i>	0	18	0	22
8	<i>timed-out problems</i>	31	51	52	77
<hr/>					
9	<i>total time</i>	10717.34	15788.21	15770.33	23259.19
10	<i>average time</i>	57.93	114.41	98.56	225.82

- ARMC [Podelski, Rybalchenko PADL 2007]
- HSF(C) [Grebenshchikov et al. TACAS 2012]
- TRACER [Jaffar, Murali, Navas, Santosa CAV 2012]

Array constraints

- $\text{read}(a, i, v)$
the i -th element of array a is v
- $\text{write}(a, i, v, b)$
array b is equal to array a except that its i -th element is v
- $\text{dim}(a, n)$
the dimension of a is n

Theory of Arrays

Array congruence

$$(AC) \quad I = J, \text{ read}(A, I, U), \text{ read}(A, J, V) \rightarrow U = V$$

Read-over-Write

$$(RoW1) \quad I = J, \text{ write}(A, I, U, B), \text{ read}(B, J, V) \rightarrow U = V$$

$$(RoW2) \quad I \neq J, \text{ write}(A, I, U, B), \text{ read}(B, J, V) \rightarrow \text{read}(A, J, V)$$

Experimental evaluation - Array Programs

Program	$Gen_{W,I,\mathbb{M}}$	$Gen_{H,V,\subseteq}$	$Gen_{H,V,\mathbb{M}}$	$Gen_{H,I,\subseteq}$	$Gen_{H,I,\mathbb{M}}$
bubblesort-inner	0.9	<i>unknown</i>	<i>unknown</i>	<i>unknown</i>	1.52
copy-partial	<i>unknown</i>	<i>unknown</i>	3.52	3.51	3.54
copy-reverse	<i>unknown</i>	<i>unknown</i>	5.25	<i>unknown</i>	5.23
copy	<i>unknown</i>	<i>unknown</i>	5.00	4.88	4.90
find-first-non-null	0.14	0.66	0.64	0.28	0.27
find	1.04	6.53	2.35	2.33	2.29
first-not-null	0.11	0.22	0.22	0.22	0.22
init-backward	<i>unknown</i>	1.04	1.04	1.03	1.04
init-non-constant	<i>unknown</i>	2.51	2.51	2.47	2.47
init-partial	<i>unknown</i>	0.9	0.89	0.9	0.89
init-sequence	<i>unknown</i>	4.38	4.33	4.41	4.29
init	<i>unknown</i>	1.00	0.97	0.98	0.98
insertionsort-inner	0.58	2.41	2.4	2.38	2.37
max	<i>unknown</i>	<i>unknown</i>	0.8	0.81	0.82
partition	0.84	1.77	1.78	1.76	1.76
rearrange-in-situ	<i>unknown</i>	<i>unknown</i>	3.06	3.01	3.03
selectionsort-inner	<i>unknown</i>	<i>time-out</i>	<i>unknown</i>	2.84	2.83
verified	6	10	15	15	17
total time	3.61	21.42	34.76	31.81	38.45
average time	0.60	2.14	2.31	2.12	2.26

Ongoing and Future Work

VeriMAP is an **instance** of a general transformation-based **Verification Framework**, which is **parametric** w.r.t.

- the **language** of the programs to be verified, and
- the **logic** of the property to be checked.

Experimenting with:

- other properties (e.g., CTL)
- integration with other tools and techniques (e.g., CEGAR)

Extending the interpreter to deal with:

- dynamic data structures (e.g., heaps)
- recursive functions (e.g., big step semantics)
- other programming language features (e.g., concurrency)
- an assertion specification language

Thank you!

<http://map.uniroma2.it/VeriMAP/>