Program Verification in Elixir

Master's Degree in Formal Methods and Computer Engineering

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  - Verification conditions discharged by the Z3 theorem prover
  - Compiled also to other programming languages

The Elixir programming language

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- A functional programming language that runs on the Erlang Virtual Machine

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- A functional programming language that runs on the Erlang Virtual Machine
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- Main current verification approaches:
  - Dialyzer (static)
  - Property-based testing (dynamic)
  - Both of them show the presence of errors rather than their absence

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Provide a system similar to Dafny but specialized for Elixir and implemented in Elixir itself

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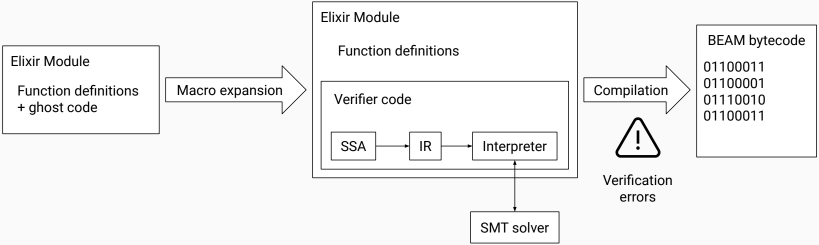
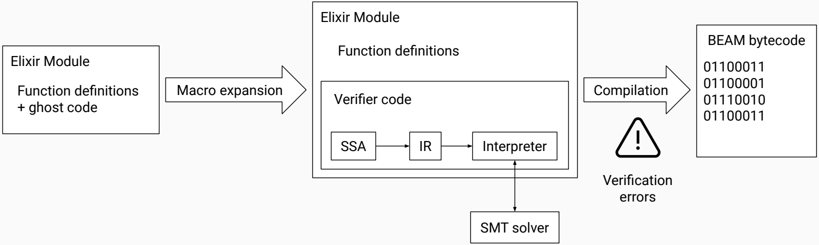


`https://github.com/adrianen-ucm/verixir-project`

Our aim

Provide a system similar to Dafny but specialized for Elixir and implemented in Elixir itself



`https://github.com/adrianen-ucm/verixir-project`

Scope: only a subset of sequential Elixir for the moment, and partial verification (i.e. not verifying termination)

A valid Elixir program

```
result =
  if selector === 1 do
    1
  else
    false
  end

result =
  if selector === 1 do
    result + 1
  else
    not result
  end
```

Plan

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1. SMT solver integration in Elixir

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2. L0, a low level language close to the SMT solver

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4. L2, a high level language that models Elixir + verification annotations

SMT Solver Integration in Elixir

Elixir SMT-LIB binding

We have developed an SMT-LIB (an SMT standard) binding for Elixir with the following features:

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Elixir SMT-LIB binding

We have developed an SMT-LIB (an SMT standard) binding for Elixir with the following features:

- A DSL for a subset of SMT-LIB
- Different SMT solvers that implement SMT-LIB can be easily integrated
- Out-of-the-box support for Z3

Elixir SMT-LIB binding example

```elixir
import SmtLib

with_local_conn do
  declare_const x: Int,
                y: Int

  assert !(
      (:x + 3 <= :y + 3) ~> (:x <= :y)
    )

  check_sat
end
```

The L0 language

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- The lowest level language of our verification stack

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- The lowest level language of our verification stack
- Close to the SMT solver
- Restricted SMT-LIB + control flow + failure

L0 expressions syntax

$$
\begin{array}{rcl}
\textbf{Exp}^0 \ni \epsilon & ::= & \textbf{skip} \\
& \mid & \textbf{fail} \\
& \mid & \epsilon_1 ; \epsilon_2 \\
& \mid & \textbf{local } \epsilon \\
& \mid & \textbf{add } \varphi \\
& \mid & \textbf{declare } x \\
& \mid & \textbf{when-unsat } \epsilon_1 \textbf{ do } \epsilon_2 \textbf{ else } \epsilon_3
\end{array}
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& | & \textbf{when-unsat } \epsilon_1 \textbf{ do } \epsilon_2 \textbf{ else } \epsilon_3
\end{array}
$$

where $x \in V$ is a variable name and $\varphi \in \mathbb{F}$ is a formula with many-sorted terms $t \in \mathbb{T}$

L0 Elixir example

```
eval conn do
  declare_const :x

  when_unsat add :x != :x do
    skip # Does not reach fail
  else
    fail
  end
end
```

L0 Elixir example

```elixir
eval conn do
  declare_const :x

  when_unsat add :x == :x do
    skip
  else
    fail # Reaches fail
  end
end
```

Intermediate Representation for Verification

The L1 language

The L1 language

- IR for Verification

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The L1 language

- IR for Verification
- It models dynamically typed Elixir expressions
- Statements for writing verification annotations (ghost code)

L1 expressions syntax

$$
\begin{array}{rcl}
\mathbf{Exp}^1 \ni e & ::= & c \\
& \mid & x \\
& \mid & e_1 \ \mathbf{and} \ e_2 \\
& \mid & e_1 \ \mathbf{or} \ e_2 \\
& \mid & [] \\
& \mid & [e_1 \mid e_2] \\
& \mid & \{e_1, \ldots, e_n\} \\
& \mid & f(e_1, \ldots, e_n)
\end{array}
$$

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\end{array}
$$

where c is a constant literal of a simple type, currently integer or boolean, and $f \in \Sigma^1$ a function name

L1 statements syntax

$$
\begin{array}{rcl}
\textbf{Stm} \ni S & ::= & \textbf{skip} \\
& | & \textbf{block } S \\
& | & \textbf{havoc } x \\
& | & S_1 ; S_2 \\
& | & \textbf{assume } e \\
& | & \textbf{assert } e \\
& | & \textbf{unfold } f(e_1, \ldots, e_n)
\end{array}
$$

Built-in SMT-LIB declarations

Prelude to represent L1 expressions in the underlying many-sorted logic (all of them have sort *Term* and can be associated to a *Type*):

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```
(declare-sort Term 0)
(declare-sort Type 0)
...
(declare-const int Type)
(declare-const bool Type)
(assert (distinct int bool))
...
(declare-fun type (Term) Type)
(define-fun is_integer ((x Term)) Bool
  (= (type x) int)
)
...
```

Built-in L1 specifications

Built-in **sets** of pair/postconditions for functions to model their behavior in Elixir

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$\{\textit{is-integer}(x) \wedge \textit{is-integer}(y)\}$

x + y

$\{$

$\quad \textit{is-integer}(\widehat{+}(x, y)) \wedge$

$\quad \textit{integer-value}(\widehat{+}(x, y)) = \textit{integer-value}(x) + \textit{integer-value}(y)$

$\}$

Built-in L1 specifications

Built-in **sets** of pair/postconditions for functions to model their behavior in Elixir

$$
\begin{array}{l}
\{\textit{is-integer}(x) \wedge \textit{is-integer}(y)\} \\
x \texttt{ + } y \\
\{ \\
\quad \textit{is-integer}(\widehat{+}(x, y)) \wedge \\
\quad \textit{integer-value}(\widehat{+}(x, y)) = \textit{integer-value}(x) + \textit{integer-value}(y) \\
\}
\end{array}
$$

There could be more for other types (e.g. float)

Translation from L1 into L0

$$
\begin{aligned}
\mathit{trExp}\ \_\ [\![\_]\!] : &\quad \mathbf{Exp}^0 \times \mathbf{Exp}^1 \rightarrow \mathbf{Exp}^0 \times \mathbb{T} \\
\mathit{trStm}\ [\![\_]\!] : &\quad \mathbf{Stm} \rightarrow \mathbf{Exp}^0
\end{aligned}
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- ϵ is an L0 expression that models the semantics of e
- t is a term in the underlying logic to refer to the result of e
- γ models known facts by the time e is evaluated

Translation of L1 lists

$$
\begin{aligned}
&\mathit{trExp}\ \_\ [\![[]]\!] \equiv (\mathbf{skip}, \mathit{nil}) \\
&\mathit{trExp}\ \gamma\ [\![[e_1 \mid e_2]]\!] \equiv (\epsilon_1; \epsilon_2; \epsilon, t) \\
&\qquad \mathbf{where}\ (\epsilon_1, t_1) = \mathit{trExp}\ \gamma\ [\![e_1]\!] \\
&\qquad\qquad\quad (\epsilon_2, t_2) = \mathit{trExp}\ \gamma\ [\![e_2]\!] \\
&\qquad\qquad\quad t = \mathit{cons}(t_1, t_2) \\
&\qquad\qquad\quad \epsilon = \begin{bmatrix} \mathbf{add}\ \mathit{is\text{-}nonempty\text{-}list}(t); \\ \mathbf{add}\ \mathit{hd}(t) = t_1; \\ \mathbf{add}\ \mathit{tl}(t) = t_2 \end{bmatrix}
\end{aligned}
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t = \mathit{cons}(t_1, t_2) \\
\epsilon = \left[\begin{array}{l}
\mathbf{add}\ \mathit{is\text{-}nonempty\text{-}list}(t); \\
\mathbf{add}\ \mathit{hd}(t) = t_1; \\
\mathbf{add}\ \mathit{tl}(t) = t_2
\end{array} \right]
\end{array}
\end{array}
$$

Remember: the constants and functions involved in the result of the translation must be defined in the SMT prelude. For example:

```
(declare-const nil Term)
(declare-fun cons (Term Term) Term)
```

L1 Elixir example

```
import Boogiex

with_local_env do
  assert (false or 2) === 2
  assert elem({1, 2, 3}, 0) === 1
  assert true or true + true

  havoc x
  assert x === x
  assert not (x !== x)
end
```

Elixir Code Verification

The L2 language

The L2 language

- The highest level language of our verification stack

The L2 language

- The highest level language of our verification stack
- A subset of Elixir + ghost verification annotations

L2 expressions syntax

$$
\begin{array}{rcl}
\mathbf{Exp}^2 \ni E & ::= & e \\
& \mid & P = E \\
& \mid & \mathbf{empty} \\
& \mid & E_1; E_2 \\
& \mid & \mathbf{case}\ E\ \mathbf{do} \\
& & \quad P_1\ \mathbf{when}\ f_1 \rightarrow E_1 \\
& & \quad \vdots \\
& & \quad P_n\ \mathbf{when}\ f_n \rightarrow E_n \\
& & \mathbf{end} \\
& \mid & \mathbf{ghost\ do}\ S\ \mathbf{end}
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& & \quad P_n\ \mathbf{when}\ f_n \to E_n \\
& & \mathbf{end} \\
& | & \mathbf{ghost\ do}\ S\ \mathbf{end}
\end{array}
$$

where $e, f_1, \ldots, f_n \in \mathbf{Exp}^1$ and $P, P_1, \ldots P_n$ are patterns:

$$\mathbf{Pat} \ni P ::= c \mid x \mid [\,] \mid [P_1 \mid P_2] \mid \{P_1, \ldots, P_n\}$$

Translation from L2 into L1

$$\mathit{trEXP}\ [\![\_]\!] : \mathbf{Exp}^2 \rightarrow [\mathbf{Stm} \times \mathbf{Exp}^1]$$
$$\mathit{trMatch}\ [\![\_]\!]\ [\![\_]\!] : \mathbf{Exp}^1 \times \mathbf{Pat} \rightarrow \mathbf{Exp}^1$$

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$trEXP\ [\![E]\!]$ generates a sequence of pairs (S, e) where

- S is an L1 statement that models the semantics of E
- e is an L1 expression that represents the result to which E is evaluated
- Each pair corresponds to an execution path

Translation of L2 pattern matching expressions

$$
\begin{aligned}
& \mathit{trEXP}\ [\![P = E]\!] = [(S_1; S_1', e_1), \ldots, (S_n; S_n', e_n)] \\
& \qquad \textbf{where} \quad [(S_1, e_1), \ldots, (S_n, e_n)] = \mathit{trEXP}\ [\![E]\!] \\
& \qquad\qquad\qquad \{y_1, \ldots, y_m\} = \mathit{vars}(P) \\
& \qquad\qquad\qquad \forall i \in \{1..n\} : S_i' = \begin{pmatrix} \textbf{assert}\ \mathit{trMatch}\ [\![e_i]\!]\ [\![P]\!]; \\ \textbf{havoc}\ y_1; \\ \vdots \\ \textbf{havoc}\ y_m; \\ \textbf{assume}\ e_i \ \texttt{===}\ P \end{pmatrix}
\end{aligned}
$$

Verifying user-defined functions

A single clause of a function with arity n:

$$def \equiv (\{p\} \quad (P_1, \ldots, P_n)\ B \quad \{q\})$$

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Clauses of a function f with arity n:

$$Defs(f/n) = (def_1, \ldots, def_k)$$

Verifying user-defined functions

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3. Translate into the corresponding execution paths in our IR
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Note: our formalization does not address currently the verification of user-defined function invocations (i.e. their specifications and body unfolding), but our implementation does it by automatically generating ghost code

L2 Elixir example

Live demo

Conclusions

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    - Extend the Elixir subset to verify (e.g. pin operator and higher-order)

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- Future work may address concurrent code and total verification
- Also, we have left several improvements on the way:
  - More of the SMT-LIB standard and support for other SMT solvers
  - Extend our IR to model more Elixir value types and built-in functions
  - Extend the Elixir subset to verify (e.g. pin operator and higher-order)
  - The current implementation is in an early proof of concept stage

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