Copilot : Traceability and Verification of a Low Level Automatically Generated C Source Code

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1. Preliminaries
   - Copilot language
   - ACSL
   - Copilot toolchain

2. Working on the backend

3. Conclusion

Copilot language

Copilot is an *EDSL* (embedded domain specific language), embedded in *Haskell* and used for writing *runtime monitors* for hard real-time, distributed, reactive systems written in C.

A Copilot program, can either be :

- compiled to C using two back-ends : SBV, ATOM
- interpreted
- analyzed using static analysis tools (CBMC, Kind)

Copilot syntax

A program is a list of streams that can be either external or internal which are defined by mutually recursive stream equations.

Each stream has a type which can be `Bool`, `Int8`, `Int16`, `Int32`, `Int64`, `Word8`, `Word16`, `Word32`, `Word64`, `Float`, `Double`.

```
x :: Stream Word16
x = 0
-- x = {0, 0, 0, ...}
y :: Stream Bool
y = x `mod` 2 == 0
-- y = {T, T, ...}
nats :: Stream Word64
nats = [0] ++ (1 + nats)
-- nats = {0,1,2, ..., 2^64-1, 0, 1, ..}
```

Operators

Each operator and constant has been lifted to Streams (working pointwise).

Two temporal operations working on Streams :

- $++$: which prepends a finite list to a Stream

```
(++) :: [a] -> Stream a -> Stream a
```

- drop : which drops a finite number of elements at the beginning of a Stream

```
drop :: Int -> Stream a -> Stream a
```

Casts and unsafe casts are also provided :

```
cast :: (Typed a, Typed b) => Stream a -> Stream b
unsafeCast :: (Typed a, Typed b) => Stream a -> Stream b
```

Examples

Fibonacci sequence :

```
fib :: Stream Word64
fib = [1,1] ++ (fib + drop 1 fib)
-- fib = {1,1,2,3,5,8,13,...,
--        12200160415121876738,
--   /!\  1293530146158671551,...}
```

Interaction

Sensors :

- Sample external variables.

  ```
  extern :: Typed a => String -> Maybe [a] -> Stream a
  ```

  Example :

  ```
  unsigned long long int x;
  ```

  ```
  x :: Stream Word64
  x = extern "x" (Just [0,0..])

  x2 = externW64 "x" Nothing
  ```

Interaction

Sensors :

- Sample external variables.
- Sample external arrays.

```
externArray :: (Typed a, Typed b, Integral a) =>
String -> Stream a -> Int -> Maybe [[a]] -> Stream b
```

Example :

```
unsigned long long int tab[1000];
```

```
-- nat = [0] ++ (nats + 1)
x :: Stream Word64
x = externArray "tab" nats 1000 Nothing

x2 = externArrayW64 "tab" nats 1000 Nothing
```

Interaction

Sensors :

- Sample external variables.
- Sample external arrays.
- Sample external functions.

```
externFun :: Typed a =>
String -> [FunArg] -> Maybe [a] -> Stream a
```

Example :

```
double sin(double a); //from math.h

x :: Stream Double
x = externDouble "x" Nothing

sinx = externFun "sin" [arg x] Nothing
```

Interaction

Sensors :

- Sample external variables.
- Sample external arrays.
- Sample external functions.

Interaction

Actuators :

- Triggers :

```
trigger ::
  String -> Stream Bool -> [TriggerArg] -> Spec
```

- Observers :

```
observer :: Typed a => String -> Stream a -> Spec
```

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ACSL syntax

ACSL is a specification language for C programs. Those contracts are written according to the following example :

```
/*@ requires true
assigns \nothing
ensures \result >= x && \result >= y;
ensures \result == x || \result == y;
*/
int max (int x, int y) { return (x > y) ? x : y; }
```

Floyd-Hoare logic

A Floyd-Hoare triple is :
$\{P\}$ *prog* $\{Q\}$

- *prog* is a program fragment
- P and Q are logical assertions over program variables
- P is the precondition
- Q the postcondition

$\{P\}$ *prog* $\{Q\}$ holds iff

- P holds before the execution of *prog*
- Q holds after the execution of *prog*[1]

[1] Unless *prog* does not terminate or encounters an error.

Floyd-Hoare logic

Here is an example of a proof tree of a program[2]:

$$\dfrac{\dfrac{\dfrac{}{\{true\}\ I \leftarrow I-1\ \ \{true\}}}{\{I \neq 0\}\ I \leftarrow I-1\ \ \{true\}}}{\dfrac{\{true\}\ \texttt{while}\ I \neq 0\ \texttt{do}\ I \leftarrow I-1\ \ \{true \wedge \neg(I \neq 0)\}}{\{true\}\ \texttt{while}\ I \neq 0\ \texttt{do}\ I \leftarrow I-1\ \ \{I = 0\}}}$$

[2] A. Miné, *Semantics and application to program verification : Axiomatic semantics*, 2015.

Floyd-Hoare logic

The Floyd-Hoare logic does not take into account program termination:

$$\dfrac{\dfrac{\dfrac{}{\{true\}\ I \leftarrow I\ \ \{true\}}}{\{I \neq 0\}\ I \leftarrow I\ \ \{true\}}}{\dfrac{\{true\}\ \texttt{while}\ I \neq 0\ \texttt{do}\ I \leftarrow I\ \ \{true \wedge \neg(I \neq 0)\}}{\{true\}\ \texttt{while}\ I \neq 0\ \texttt{do}\ I \leftarrow I\ \{I = 0\}}}$$

Floyd-Hoare logic

Or even safety against runtime errors (we speak about partial correctness):

$$\dfrac{\dfrac{\dfrac{}{\{true\}\ \textbf{fail}\ \ \{true\}}}{\{I \neq 0\}\ \textbf{fail}\ \ \{true\}}}{\dfrac{\{true\}\ \texttt{while}\ I \neq 0\ \texttt{do}\ \textbf{fail}\ \ \{true \wedge \neg(I \neq 0)\}}{\{true\}\ \texttt{while}\ I \neq 0\ \texttt{do}\ \textbf{fail}\ \{I = 0\}}}$$

More generally, any property is true after fail :

$$\dfrac{}{\{P\}\ \textbf{fail}\ \{Q\}}$$

Floyd-Hoare logic

It is nevertheless possible to prove total correctness by the following proof tree (ranking functions have to be provided):

$$\frac{\{P\}\ prog\ \{Q\} \qquad [P]\ prog\ [true]}{[P]\ prog\ [Q]}$$

Dijkstra's Weakest Liberal Precondition

We define the weakest liberal precondition : $wlp(prog, Q)$ which is defined as the most general condition such that $\{wlp(prog, Q)\}\ prog\ \{Q\}$ holds.

We can automate the computation of the precondition by induction on the syntax.

- $wlp(skip, P) = P$
- $wlp(fail, P) = true$
- $wlp(s; t, P) = wlp(s, wlp(t, P))$
- $wlp(X \leftarrow e, P) = P[e/X]$
- $wlp(\texttt{if } e \texttt{ then } s \texttt{ else } t, P) = (e \Rightarrow wlp(s, P)) \wedge (\neg e \Rightarrow wlp(t, P))$

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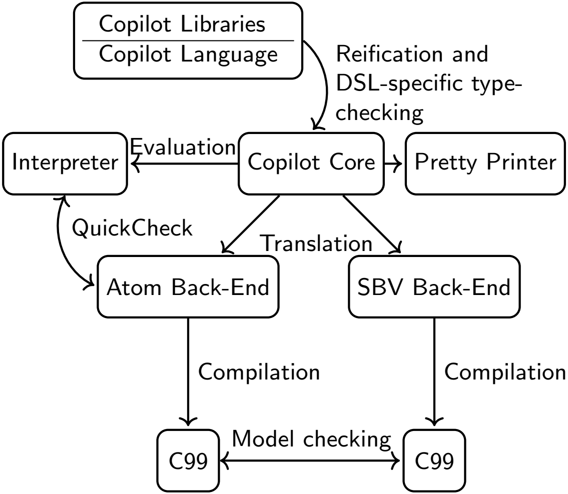

Figure: The Copilot toolchain[3]

[3] L. Pike, N. Wegmann, S. Niller, and A. Goodloe, *Experience report: A do-it-yourself high-assurance compiler*, 2012.

1 Preliminaries

2 Working on the backend
- Hand-written ACSL
- ACSL generation

3 Conclusion

Hand written ACSL

```
import Copilot.Language.Reify
import Copilot.Language
import qualified Copilot.Compile.SBV as S

logic :: Stream Bool
logic = [True, False] ++ logic && drop 1 logic

spec :: Spec
spec = do
observer "obs1" logic

main = do
interpret 10 spec
reify spec >>= S.compile S.defaultParams --SBV Backend
```

```
/*@
requires ptr_2 < 0x0078;
requires \valid(queue_2 + (0..0x02U-1));
assigns \nothing;
ensures \result == ( queue_2[ptr_2 % 0x02U]
                && queue_2[(ptr_2 + 0x01U) % 0x02U]);
*/
SBool update_state_2(const SBool *queue_2
                    , const SWord16 ptr_2)
{
  const SWord16 s2 = ptr_2;
  const SWord16 s4 = (0x02U == 0)?s2:(s2%0x02U);
  const SBool   s5 = queue_2[s4];
  const SWord16 s7 = s2 + 0x0001U;
  const SWord16 s8 = (0x02U == 0)?s7:(s7%0x02U);
  const SBool   s9 = queue_2[s8];
  const SBool   s10 = s5 && s9;

  return s10;
}
```

```
frama-c -wp -wp-out .  -wp-prover PROVER

[wp] Proved goals:   19 / 19
Qed:             18  (4ms-4ms)
cvc4:             1  (150ms-150ms)

[wp] Proved goals:   19 / 19
Qed:             18  (4ms-4ms)
cvc3:             1  (90ms-90ms)

[wp] Proved goals:   19 / 19
Qed:             18  (4ms-8ms)
Alt-Ergo:         1  (3.5s-3.5s) (248)

[wp] Proved goals:   19 / 19
Qed:             18  (4ms-4ms)
z3:               1  (20ms-20ms)
```

Bitwise version :

```
/*@
requires ptr_2 < 0x0078;
requires \valid(queue_2 + (0..0x02U-1));
assigns \nothing;
ensures \result == ( queue_2[ptr_2 % 0x02U]
& queue_2[(ptr_2 + 0x01U) % 0x02U]);
*/
SBool update_state_2(const SBool *queue_2
, const SWord16 ptr_2)
{
const SWord16 s2 = ptr_2;
const SWord16 s4 = (0x02U == 0)?s2:(s2%0x02U);
const SBool   s5 = queue_2[s4];
const SWord16 s7 = s2 + 0x0001U;
const SWord16 s8 = (0x02U == 0)?s7:(s7%0x02U);
const SBool   s9 = queue_2[s8];
const SBool   s10 = s5 & s9;

return s10;
}
```

```
frama-c -wp -wp-out .  -wp-prover PROVER

[wp] Proved goals:   15 / 16
Qed:              15  (4ms-4ms)
cvc4:              0  (interrupted: 1)

[wp] Proved goals:   15 / 16
Qed:              15  (4ms-4ms)
cvc3:              0  (unknown: 1)

[wp] Proved goals:   15 / 16
Qed:              15  (4ms-4ms)
Alt-Ergo:          0  (interrupted: 1)

[wp] Proved goals:   15 / 16
Qed:              15  (4ms-4ms)
z3:                0  (interrupted: 1)
----> Timeout after 30 seconds
```

Unsafe version :

```
/*@
requires \valid(queue_2 + (0..0x02U-1));
assigns \nothing;
ensures \result == ( queue_2[ptr_2 % 0x02U]
&& queue_2[(ptr_2 + 0x01U) % 0x02U]);
*/
SBool update_state_2(const SBool *queue_2
, const SWord16 ptr_2)
{
const SWord16 s2 = ptr_2;
const SWord16 s4 = (0x02U == 0)?s2:(s2%0x02U);
const SBool   s5 = queue_2[s4];
const SWord16 s7 = s2 + 0x0001U;
const SWord16 s8 = (0x02U == 0)?s7:(s7%0x02U);
const SBool   s9 = queue_2[s8];
const SBool   s10 = s5 && s9;

return s10;
}
```

```
frama-c -wp -wp-out .  -wp-prover PROVER

[wp] Proved goals:   18 / 19
Qed:               18  (4ms-4ms)
cvc4:               0  (interrupted: 1)

[wp] Proved goals:   18 / 19
Qed:               18  (4ms-4ms)
Alt-Ergo:           0  (interrupted: 1)

[wp] Proved goals:   18 / 19
Qed:               18  (4ms-4ms)
z3:                 0  (unknown: 1)
----> NO TIMEOUT : unsafe
```

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ACSL generation

The easiest way to do it is by induction on the syntax, when compiling the expression. Here is how the function ppACSL is constructed :

- `Const type value` $\rightarrow$ *show* `value`
- `Drop type i id` $\rightarrow$ *queue_*`id`[*ptr_*`id` + `i` *mod* (*length* `id`)]
- `ExternVar t name b` $\rightarrow$ *ext_*`name`
- `Var type name` $\rightarrow$ `name`
- `Op2 op e1 e2` $\rightarrow$ (*ppACSL* `e1`) *show* `op` (*ppACSL* `e2`)
- `Label t s e` $\rightarrow$ *ppACSL* `e`

ACSL generation

Nevertheless, some hacks :

- Let bindings have been deprecated.
- Abs are converted to $\backslash a \rightarrow \mathit{sign}\ a \times a$
- Sign to $\backslash x \rightarrow ((x > 0)\ ?\ 1 : ((x < 0) ? -1 : 0))$
- Mux where branches have type Bool to $\mathit{Mux}\ e1\ e2\ e3 = (e2 \wedge e1) \vee (e3 \wedge \neg e1)$
- No bitwise operator are supported.

ACSL generation

Still some problems with frama-c :

- No global invariant : we have to split the dereferencing of the pointer into a black box that only do this.
- No math functions (such as sin, cos, exp, log, ...) : we have to do the same.

WP vs VA

How effective value analysis is ?

- Global invariants supported
- No lemma supported
- Safe ... for only one iteration of the main loop
- Does not really go well with external variables
- Requires access to all C source files of the project to say anything about one contract.

(Very bad) solution : unroll the infinite loop !

```
frama-c -val -main testing -slevel 10000000 *.h *.c
```

(Better) solution : forget about value analysis for the monitor.

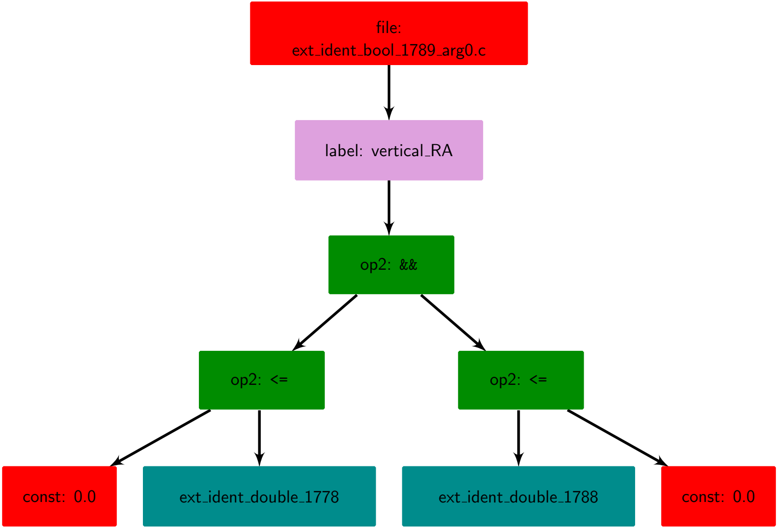
Other changes

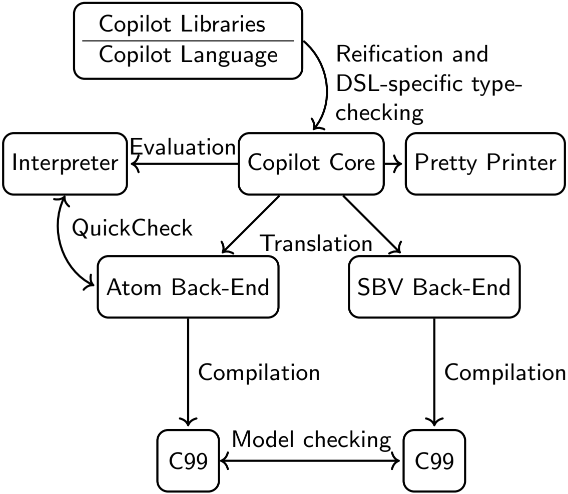
- Added m4 preprocessing
- Added CompCert for compiling the C source file generated
- Deprecated ATOM
- Added a dot graph generation for each source file.

Dot File: "ext_ident_bool_1789_arg0.c"

```
/*@
assigns \nothing;
ensures \result ==
      ((((((0.0) <= (ext_ident_double_1778)))
      && (((ext_ident_double_1788) <= (0.0))))));
*/
SBool ext_ident_bool_1789_arg0
(const SDouble ext_ident_double_1778,
const SDouble ext_ident_double_1788)
{
  const SDouble s0 = ext_ident_double_1778;
  const SDouble s14 = ext_ident_double_1788;
  const SBool   s25 = 0.0 <= s0;
  const SBool   s26 = s14 <= 0.0;
  const SBool   s27 = s25 && s26;
  const SBool   s28 = s27 /* vertical_RA */;
  return s28;
}
```

Dot File: "ext_ident_bool_1789_arg0.c"




Copilot Libraries
Copilot Language
Reification and DSL-specific type-checking
Interpreter
Evaluation
Copilot Core
Pretty Printer
QuickCheck
Translation
Atom Back-End
SBV Back-End
Compilation
Compilation
C99
Model checking
C99

Questions

Questions ?