Extracting from F* to C: a progress report

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F* [5] is a language in the tradition of ML equipped with dependent types, monadic effects, refinement types and a weakest precondition calculus. Together, these features enable the F* programmer to prove functional correctness using a combination of automation via SMT solving and manual program proofs.

In the context of the greater Everest project [4], we are using F* to prove, build and deploy miTLS [1], a verified, *efficient* implementation of the Transport Layer Security (TLS) 1.3 protocol.

While the current extraction to OCaml may seem sufficient for most use-cases, our ambition is to see our provably-secure code execute in the "real world"; that is, servers (such as Apache, Nginx or IIS) and browsers (such as Chrome, Firefox or Edge). In that context, extracting to OCaml is not an option. The first reason is performance: switching to the OCaml value representation at ABI boundaries, and GC pauses are a hard sell for performance-conscious browser vendors. Second the target audience will most likely not be familiar with OCaml. Thus, for social and technical reasons, our aim is to extract to C or C++.

This extended abstract presents our work in progress. We are currently focusing our efforts on proving the memory safety and functional correctness of Elliptic Curve Cryptography (ECC) primitives, and on extracting this code to C. ECC primitives are a good candidate: the upcoming TLS-1.3 standard makes a significant move towards using ECC in the main ciphersuites. Additionally, crypto routines are extremely performance sensitive and extracting verified implementations to anything other than native code is generally considered unacceptable. As such, we program ECC primitives in a first-order fragment of F*, closely following existing C implementations of those primitives, and after verification extract the code back to C.

The original C code has a straightforward memory management strategy, and only uses stack-based allocation. The ECC primitives are thus written against an F* library that models stacks, and models pushing and popping a new stack frame; suitable pre- and post-conditions ensure that no memory errors can occur. Once this is done, we prove functional correctness of the code (i.e. the math is correct), still using the automation and proving facilities of F* [6]. Finally, knowing that the F* code has been proven memory safe, we can translate the it back to C, thus obtaining a fully verified C implementation of elliptic curves.

1. Modeling stack-based allocation

Consider the following sample program that exercises our stack library.

```
open FStar.Int32
open FStar.HyperStack (* for :=, ! and alloc *)

let incr (): STL unit =
  with_frame (fun () ->
    let y = alloc 1ul in
    y := !y + 1ul;
  )
```

Since the original program is shown to perform proper stack-based memory management, the extraction facility need not worry about lifetimes, and can safely translate the original program into the following C code.

```
void incr() {
  int32_t y = 1;
  y = y + 1;
}
```

Extraction is sound because:

- the definition of the `STL` effect guarantees that the caller's stack is preserved, that is, the function neither `push`es more than it `pop`s, nor allocates within its caller's stack;
- no integer operation overflows thanks to the `FStar.Int32.+` operator (this would be undefined C behavior);
- the `alloc` operation tags `y` as living within the current stack frame;
- the `:=` and `!` operations operate on a stack reference `y` whose frame (the current one) is still alive.

The stacked memory is modeled on top of hyperheaps [5]. A hyperheap divides memory into nested sub-trees; any function whose effect modifies a given sub-tree can be shown (by virtue of the memory model) to leave any *disjoint* sub-tree untouched. In short, hyperheaps provide framing guarantees. Each sub-tree is assigned a region-id (`rid`), and a hyperheap maps an `rid` to a `heap`.

A stack of regions is a specific hyperheap that has a list-like structure, starting at the `root` down to the `tip`, that is, the top-most stack frame. The `is_tip` predicate guarantees the list-like shape.

```
module HH = FStar.HyperHeap

type mem =
| HS: h:HH.t{Map.contains h HH.root /\ HH.map_invariant h}
     -> tip:HH.rid{is_tip tip h} -> mem

val push_frame: unit -> ST unit
  (requires (fun m -> True))
  (ensures (fun (m0:mem) _ (m1:mem) ->
    not (Map.contains m0.h m1.tip)
    /\ HH.parent m1.tip = m0.tip
    /\ m1.h = Map.upd m0.h m1.tip Heap.emp))

val (!) #a:Type -> r:sref a -> STL a
  (requires (fun m -> is_above r.id m.tip))
  (ensures (fun s0 v s1 -> s1=s0 /\ v=HyperStack.sel s0 r))
```

The `push_frame` combinator allocates a new `tip`, that is, allocates a new stack frame, which is initially empty. The `(!)` combinator requires that the stack reference `r` live in a region whose `id` is equal to, or above, the `id` of the topmost stack frame. It ensures that that the memory remains unchanged, and it returns the value found at address `r`. Other combinators are modeled in a similar manner.

2. Relating F* and C*

We formalize a subset of F* in which effects are represented à la Haskell, that is, as fully functional transformations that take state as an input parameter and return an updated state as an output. This is our reference semantics; the reduction rules only mention expressions. In that context the state effect `ST` is generic; we instantiate it with `HS` (hyperstacks) and define monadic actions `push_frame`, `pop_frame`, `!`, `(:=)` and `alloc`.

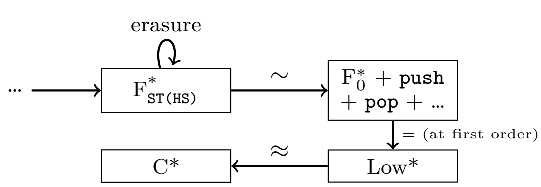
At the end of the pipeline is C*, a well-behaved subset of C: this is the target of our extraction. C* is designed to be as faithful as possible to the C semantics (as in Compcert's Clight). To that effect, memory is represented as blocks; pointers are made up of a block identifier along with an offset.

Our goal, naturally, is to relate the semantics of the original F* program to the extracted C* program. We proceed as follows.

First, we define an erasure procedure that removes computationally-irrelevant code (e.g. calls to lemmas). The erasure procedure is modeled after Coq's and also inserts casts as needed. We also perform a few other transformations, such as A-normal form, enforcing the evaluation order of impure arguments, removing nested let-bindings, etc. We prove that the erasure is a bisimulation and preserves the dynamic semantics.

Next, we define F^*_0, a loosely typed version of F* with a primitive semantics for state; that is, the reduction rules are now of the form (H, e), where H is the (imperative, effectful) hyperstack. We show the dynamic semantics of F* and F^*_0 are equivalent through the use of a logical relation.

Finally, we define a first-order subset of F^*_0 called Low* and show that the compilation of Low* to C* is a bisimulation.



If the original program is well-typed in F*, and if it is in the subset we know how to translate (i.e. uses stack-based allocation), then we obtain two end-to-end results:

- **safety**: the resulting C* program will not get stuck;
- **preservation of semantics**: the extracted C* program refines the original Low* program.

We reuse a proof strategy in the style of Compcert [2] that relates Low* and C* through the use of a bisimulation. More precisely, we prove that C* is a refinement of Low*; that is, for every step a C* program may take, it corresponds to a legitimate Low* reduction sequence, hereby justifying that we have generated a faithful extraction.

Following the Compcert style, we first prove the opposite direction, that is, Low* is a refinement of C*. Based on the fact that C* is deterministic, we get the main theorems above.

3. Implementation and conclusion

F* was equipped last summer with a proper extraction mechanism in the style of Coq [3] that targets both OCaml and F#. This extraction mechanism performs the transformations mentioned earlier, with the exception of A-normal form transformation, and inner let-binding lifting.

At this stage, the the AST is handed off to an external tool dubbed KreMLin. KreMLin performs the rest of the transformations and deals with other mundane matters, such as avoiding name collisions.

Our ambition for KreMLin is manyfold. First, the immediate goal is to extend its input language to handle more ML-like constructs, such as data types and pairs. Sum types can be translated using the classic "tagged `union`" scheme; records and pairs can be translated using `struct`s. F* does not have mutable record fields; we can thus pass the latter structs by value, which means no proof obligations for the F* programmer.

Second, we hope that the KreMLin tool can prove useful to other languages. Should anyone want to mimic our stack formalization in, say, Coq, then the effort required to hook onto the existing tool and get a C backend for free should be minimal.

Finally, we naturally want to mechanically prove the soundness of the translation. We hope to perform this task using F* itself.

References

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