Embracing monotonicity in F*

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joint work with

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ICE-TCS Seminar

January 29, 2018

Outline

- F*
- Monotonic state by example
- Key ideas behind our general framework
- Accommodating monotonic state in F*
- Some examples of monotonic state at work
- More examples of monotonic state at work (see POPL'18 paper)
- Monadic reification and reflection (if time permits, or see paper)
- Meta-theory and correctness results (see POPL'18 paper)

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F* [fstar-lang.org]

- **F*** is
  - a **functional programming language**
    - ML, OCaml, F#, Haskell, ...
    - extracted to OCaml or F#; subset compiled to efficient C code
  - an **interactive proof assistant**
    - Agda, Coq, Lean, Isabelle/HOL, ...
    - interactive modes for Emacs and Atom
  - a **semi-automated verifier** of imperative programs
    - Dafny, Why3, FramaC, ...
    - Z3-based SMT automation
- **Application-driven** development
  - Project Everest [project-everest.github.io]
  - Microsoft Research (US, UK, India), INRIA (Paris), ...
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F* – programming language/proof assistant

```
module Talk

// Inductive types

type vector 'a : nat -> Type =
  | Nil : vector 'a 0
  | Cons : #n:nat -> 'a -> vector 'a n -> vector 'a (n + 1)

// Dependently typed recursive functions

val append : #a:Type -> #n:nat -> #m:nat -> vector a n -> vector a m -> Tot (vector a (n + m))
let rec append #a #n #m xs ys =
  match xs with
  | Nil -> ys
  | Cons #n x xs -> Cons x (append xs ys)

// Refinement types (nat is defined as z:int{z >= 0})

val lkp : #a:Type -> #n:nat -> vector a n -> i:nat{0 < i /\ i <= n} -> a
let rec lkp #a #n xs i =
  match xs with
  | Cons x xs -> if i = n then x else lkp xs i

// First-class predicates (for which Type0 behaves like (classical) Prop)

type prefix_of (#a:Type) (#n:nat) (#m:nat{n <= m}) (xs:vector a n) (zs:vector a m) : Type0 =
  forall (i:nat) . (0 < i /\ i <= n) ==> lkp xs i == lkp zs i

// Extrinsic reasoning (using separate lemmas)

val theorem : #a:Type -> #n:nat -> #m:nat -> xs:vector a n -> ys:vector a m -> Lemma (prefix_of xs (append xs ys))
let theorem #a #n #m xs ys =
  match xs with
  | Nil -> ()
  | Cons x xs -> admit () // need to call an appropriate lemma here

// Intrinsic reasoning (using pre- and postconditions)

val append' : #a:Type -> #n:nat -> #m:nat -> xs:vector a n -> vector a m -> Pure (vector a (n + m)) (requires (True))
                                                                                                    (ensures  (fun zs -> prefix_of xs zs))
```

F* – not just a pure programming language

- Tot, Pure, ... are just some **effects** amongst many
  - Tot t
  - Pure t (requires pre) (ensures post)
  - Lemma (requires pre) (ensures post)
  - Div t (requires pre) (ensures post)
  - Exc t (requires $\mathtt{pre}_{\mathtt{Exc}}$) (ensures $\mathtt{post}_{\mathtt{Exc}}$)
  - ST t (requires $\mathtt{pre}_{\mathtt{ST}}$) (ensures $\mathtt{post}_{\mathtt{ST}}$)
  - ...
- Some connected by **monad morphisms**
- Most derived from **WP-calculi** (see our POPL'17 paper)

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(Global state +) monotonicity is really useful!

Its essence can be captured very neatly!

Monotonicity in verification

- Consider a program operating on **set-valued state**

$$\texttt{insert v; complex\_procedure(); } \texttt{assert } (\texttt{v} \in \texttt{get()})$$

- To prove the assertion (say, in a Floyd-Hoare style logic), we could prove that the code maintains a **stateful invariant**

$$\{\lambda\, \texttt{s}\,.\, \texttt{v} \in \texttt{s}\}\ \texttt{complex\_procedure()}\ \{\lambda\, \texttt{s}\,.\, \texttt{v} \in \texttt{s}\}$$

  - likely that we have to **carry** $\lambda\, \texttt{s}\,.\, \texttt{v} \in \texttt{s}$ **through** the proof of c_p
    - **does not guarantee** that $\lambda\, \texttt{s}\,.\, \texttt{v} \in \texttt{s}$ holds at every point in c_p
    - **sensitive** to proving that c_p maintains $\lambda\, \texttt{s}\,.\, \texttt{w} \in \texttt{s}$ for some other w

- However, if c_p **never removes**, then $\lambda\, \texttt{s}\,.\, \texttt{v} \in \texttt{s}$ is **stable**, and we would like the program logic to give us $\texttt{v} \in \texttt{get()}$ "**for free**"

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Monotonicity in programming

- **Programming** also relies on **monotonicity**,
  even if you don't realise it!

- Consider ML-style typed **references** `r:ref a`
  - `r` is a **proof of existence** of an `a`-typed value in the heap

- Correctness relies on **monotonicity**!
  1) Allocation **stores** an `a`-typed value in the heap
  2) Writes **don't change type** and there is **no deallocation**
  3) So, given a ref. `r`, it is **guaranteed to point** to an `a`-typed value

- Baked into the memory models of most languages
- We derive them from **global state + general monotonicity**

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Monotonicity is really useful!

- In this talk
  - our **motivating example** and **monotonic counters**
  - **typed references** (`ref t`) and **untyped references** (`uref`)
  - more flexibility with **monotonic references** (`mref t rel`)
- See our POPL 2018 paper for more
  - temporarily **violating monotonicity** via snapshots
  - two substantial case studies in F*
    - a **secure file-transfer** application
    - Ariadne **state continuity** protocol [Strackx, Piessens 2016]
  - pointers to other works in F* relying on monotonicity for
    - sophisticated **region-based memory models** [`fstar-lang.org`]
    - **crypto** and **TLS verification** [`project-everest.github.io`]

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Key ideas behind our general framework

- We make use of **monotonic programs** and **stable predicates**
  - per verification task, we **choose a preorder** `rel` on states
    - set inclusion, heap inclusion, increasing counter values, ...
  - a stateful program e is **monotonic** (wrt. `rel`) when

$$\forall\, s\, e'\, s'.\ (e, s) \rightsquigarrow^* (e', s') \implies \mathtt{rel}\ s\ s'$$

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- **Our solution:** extend Hoare-style program logics (e.g., F*) with
  - a means to **witness** the validity of `p` s in some state s
  - a means for turning a `p` into a **state-independent proposition**
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Recap: Ordinary global state in F*

- F* supports Hoare-style reasoning about state via the **comp. type**

$$\mathtt{ST}_{\mathtt{state}}\ \mathtt{t}\ (\mathtt{requires}\ \mathtt{pre})\ (\mathtt{ensures}\ \mathtt{post})$$

  where

$$\mathtt{pre} : \mathtt{state} \to \mathrm{Type} \qquad \mathtt{post} : \mathtt{state} \to \mathtt{t} \to \mathtt{state} \to \mathrm{Type}$$

- ST is an abstract pre-postcondition refinement of

$$\mathtt{st}\ \mathtt{t} \stackrel{\mathrm{def}}{=} \mathtt{state} \to \mathtt{t} * \mathtt{state}$$

- The global state **actions** have types

$$\mathtt{get} : \mathtt{unit} \to \mathtt{ST}\ \mathtt{state}\ (\mathtt{requires}\ (\lambda\,\_\,.\top))\ (\mathtt{ensures}\ (\lambda\,\mathtt{s}_0\ \mathtt{s}\ \mathtt{s}_1\,.\,\mathtt{s}_0 = \mathtt{s} = \mathtt{s}_1))$$

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New: Monotonic global state in F*

- We capture monotonic state with a new **computational type**

$$\mathtt{MST}_{\mathtt{state},\mathtt{rel}}\ \mathtt{t}\ (\mathtt{requires}\ \mathtt{pre})\ (\mathtt{ensures}\ \mathtt{post})$$

- The **get** action is typed as in ST

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- We capture monotonic state with a new **computational type**

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- We extend F* with a **logical capability**

$$\texttt{witnessed} : (\texttt{state} \to \texttt{Type}) \to \texttt{Type}$$

together with a **weakening principle** (**functoriality**)

$$\texttt{wk} : \texttt{p,q}{:}(\texttt{state} \to \texttt{Type}) \to \texttt{Lemma}\ (\texttt{requires}\ (\forall\, \texttt{s}\,.\,\texttt{p s} \implies \texttt{q s}))$$
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- Intuitively, think of it as a **necessity modality**

$$[\![\texttt{witnessed p}]\!](\texttt{s}) \stackrel{\text{def}}{=} \forall\, \texttt{s}'\,.\,\texttt{rel s s}' \implies [\![\texttt{p s}']\!](\texttt{s})$$

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- we include a **stateful introduction rule** for witnessed

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\texttt{witness} : & p{:}(\texttt{state} \rightarrow \texttt{Type}_0) \\
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Outline

- Monotonic state by example
- Key ideas behind our general framework
- Accommodating monotonic state in F*
- Some examples of monotonic state at work
- More examples of monotonic state at work (see POPL'18 paper)
- Monadic reification and reflection (if time permits, or see paper)
- Meta-theory and correctness results (see POPL'18 paper)

The motivating example revisited

- Recall the program operating on the **set-valued state**

$$\mathtt{insert}\ \mathtt{v};\ \mathtt{complex\_procedure}();\ \mathtt{assert}\ (\mathtt{v} \in \mathtt{get}())$$

  - We pick **set inclusion** $\subseteq$ as our preorder `rel` on states
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$$\mathtt{insert}\ \mathtt{v};\ \mathtt{witness}\ (\lambda\, \mathtt{s}\, .\, \mathtt{v} \in \mathtt{s});\ \mathtt{c\_p}();\ \mathtt{recall}\ (\lambda\, \mathtt{s}\, .\, \mathtt{v} \in \mathtt{s});\ \mathtt{assert}\ (\mathtt{v} \in \mathtt{get}())$$

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    around the program is handled **similarly easily** by

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$$\mathtt{create}\ 0;\ \mathtt{incr}();\ \mathtt{witness}\ (\lambda\, \mathtt{c}\, .\, \mathtt{c} > 0);\ \mathtt{c\_p}();\ \mathtt{recall}\ (\lambda\, \mathtt{c}\, .\, \mathtt{c} > 0)$$

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ML-style typed references (local state)

- First, we define a type of **heaps** as a finite map

```
type heap =
  | H : h:(ℕ → cell) → ctr:ℕ{∀ n . ctr ≤ n ⟹ h n = Unused} → heap
```

where

```
type cell =
  | Unused : cell
  | Used : a:Type → v:a → cell
```

- Next, we define a **preorder** on heaps (**heap inclusion**)

```
let heap_inclusion (H h0 _) (H h1 _) = ∀ id . match h0 id , h1 id with
  | Used a _ , Used b _  →  a = b
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- As a result, we can define new **local state effect**

$$\texttt{MLST t pre post} \stackrel{\text{def}}{=} \texttt{MST}_{\texttt{heap},\texttt{heap\_inclusion}}\ \texttt{t pre post}$$

- Next, we define the type of **references** using monotonicity

$$\texttt{abstract type ref a} = \texttt{id}{:}\mathbb{N}\{\texttt{witnessed}\ (\lambda\,\texttt{h}\,.\,\texttt{contains h id a})\}$$

where

```
let contains (H h _) id a =
  match h id with
    | Used b _ → a = b
    | Unused → ⊥
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- Important: `contains` is **stable** wrt. `heap_inclusion`

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$$\texttt{MLST t pre post} \stackrel{\text{def}}{=} \texttt{MST}_{\texttt{heap},\texttt{heap\_inclusion}} \texttt{ t pre post}$$

- Next, we define the type of **references** using monotonicity

$$\texttt{abstract type ref a} = \texttt{id}{:}\mathbb{N}\{\texttt{witnessed}\ (\lambda\,\texttt{h}\,.\,\texttt{contains h id a})\}$$

  where

```
let contains (H h _) id a =
  match h id with
    | Used b _ → a = b
    | Unused → ⊥
```

- Important: `contains` is **stable** wrt. `heap_inclusion`

ML-style typed references (local state)

- Finally, we define `MLST`'s **actions** using `MST`'s actions
  - `let alloc` (a:Type) (v:a) : `MLST (ref a) ... = ...`
    - **get** the current heap
    - **create** a fresh ref., and **add** it to the heap
    - **put** the updated heap back
    - **witness** that the created ref. is in the heap
  - `let read` (r:ref a) : `MLST t ... = ...`
    - **recall** that the given ref. is in the heap
    - **get** the current heap
    - **select** the given reference from the heap
  - `let write` (r:ref a) (v:a) : `MLST unit ... = ...`
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Adding untyped and monotonic references

- **Untyped references** (`uref`) with strong updates
  - Used `heap` cells are extended with **tags**

    where

    $$\mid\ \mathtt{Used} : \mathrm{a{:}Type} \to \mathrm{v{:}a} \to \mathrm{t{:}tag} \to \mathtt{cell}$$

    $$\mathtt{type\ tag}\ =\ \mathtt{Typed} : \mathtt{tag}\ \mid\ \mathtt{Untyped} : \mathtt{tag}$$

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- Further, all three can be extended with **manually managed** refs.

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  - is **useful** for **programming** (refs.) and **verification** (Prj. Everest)

- See our POPL 2018 paper for
  - further **examples** and **case studies**
  - **meta-theory** and **correctness results** for `MST`
    - based on an instrumented operational semantics

$$(\texttt{witness}\ x.\varphi\,,\, s\,,\, W) \rightsquigarrow (\texttt{return}\ ()\,,\, s\,,\, W \cup \{x.\varphi\})$$

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- In F* every **abstract** ST **computation**

$$\mathtt{e} : \mathtt{ST}\ \mathtt{t}\ (\mathtt{requires}\ \mathtt{pre})\ (\mathtt{ensures}\ \mathtt{post})$$

can be **reified** into its **underlying** Pure **representation**

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and vice versa using **reflection** (see our POPL 2017 paper)

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  - indexing $\mathtt{MST}_{\mathtt{state},\mathtt{rel},\mathtt{b}}$ with a **boolean flag** `b` (reifiable?), and
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  so if `b = true` then `witness` and `recall` are **logically no-ops.**

- This **works** but leads to **duplication** of pre- and postconditions!

- Instead, ongoing work is taking (hybrid) **modal logic** seriously

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