Embracing monotonicity in

Danel Ahman @ INRIA Paris

based on a joint POPL 2018 paper with

Cătălin Hriţcu and Kenji Maillard @ INRIA Paris
Cédric Fournet, Aseem Rastogi, and Nikhil Swamy @ MSR

Software Science Departmental Seminar, TUT
February 12, 2018

and embracing monotonicity (in it)

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Outline

* F* overview
* Monotonic state by example
* Key ideas behind our general extension to Hoare-style logics
* Accommodating monotonic state in F*
* Some examples of monotonic state at work
* Glimpse of meta-theory and correctness results
* More examples of monotonic state at work (see our paper)
* Monadic reification and reflection (see our 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; tactics and metaprogramming (WIP)
- **Application-driven** development
  - Project Everest [project-everest.github.io]
  - miTLS, HACL*, Vale, ...
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module Talk
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// Dependent (inductive) types

type vector 'a : nat -> Type =
  | Nil : vector 'a 0
  | Cons : #n:nat -> 'a -> vector 'a n -> vector 'a (n + 1)
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// Dependently typed (recursive, total) functions

val append : #a:Type -> #n:nat -> #m:nat -> vector a n -> vector a m -> Tot (vector a (n + m))
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// Refinement types

let in_range_index (min:nat) (max:nat) = i:nat{min <= i /\ i <= max}

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

type is_prefix_of (#a:Type) (#n:nat) (#m:nat) (xs:vector a n) (zs:vector a m{n <= m}) : Type0 =
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// Extrinsic reasoning (using separate lemmas)

val lemma : #a:Type -> #n:nat -> #m:nat -> xs:vector a n -> ys:vector a m -> Lemma (requires (True))
                                                                                  (ensures  (xs `is_prefix_of` (append xs ys)))
let rec lemma #a #n #m xs ys =
  match xs with
  | Nil -> ()
  | Cons x xs' -> lemma xs' ys
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// Intrinsic reasoning (making lemmas part of definitions, e.g., using Hoare-style pre- and postconditions)

val take : #a:Type -> n:nat -> #m:nat -> zs:vector a m -> Pure (vector a n) (requires (n <= m))
                                                                           (ensures  (fun xs -> xs `is_prefix_of` zs))
let rec take #a n #m zs =
  if n > 0 then match zs with
                | Cons z zs' -> let n':nat = n - 1 in Cons z (take n' zs')
           else Nil
```

```
// Heaps, ML-style typed references, and Hoare logic

open FStar.Heap
open FStar.ST
```

```
let rec program n =
  let r = alloc 0 in
  sum_loop 1 n r;
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and sum_loop i n r =
  if i < n then (r := !r + i; sum_loop (i + 1) n r)
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val sum : i:nat -> n:nat{i <= n} -> Tot nat (decreases (n - i))

let rec sum i n =
  if i < n then i + sum (i + 1) n
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val program : n:nat -> ST (ref nat) (requires (fun h0 -> 1 <= n))
                                    (ensures  (fun h0 r h1 -> fresh r h0 h1 /\
                                                            modifies (Set.empty) h0 h1 /\
                                                            sel h1 r = sum 1 n))
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val sum_plus_lemma : i:nat -> n:nat -> Lemma (requires  (i <= n))
                                             (ensures   (sum i (n + 1) = sum i n + (n + 1)))
                                             (decreases (n - i))
                                             [SMTPat (sum i n)]
let rec sum_plus_lemma i n =
  if i < n then sum_plus_lemma (i + 1) n
           else ()

val program : n:nat -> ST (ref nat) (requires (fun h0 -> 1 <= n))
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F* – not just a pure programming language

- `Tot`, `Lemma`, `Pure`, ... are just some **effects** amongst many
  - `Tot t`
  - `Lemma (requires pre`$_{\texttt{Lemma}}$`) (ensures post`$_{\texttt{Lemma}}$`)`
  - `Pure t (requires pre`$_{\texttt{Pure}}$`) (ensures post`$_{\texttt{Pure}}$`)`
  - `Div t (requires pre`$_{\texttt{Div}}$`) (ensures post`$_{\texttt{Div}}$`)`
  - `Exc t (requires pre`$_{\texttt{Exc}}$`) (ensures post`$_{\texttt{Exc}}$`)`
  - `ST t (requires pre`$_{\texttt{ST}}$`) (ensures post`$_{\texttt{ST}}$`)`
  - ...
- **Monad morphs.** $\texttt{Pure} \rightsquigarrow \{\texttt{Div}, \texttt{Exc}, \texttt{ST}\}$; $\texttt{Exc} \rightsquigarrow \texttt{STExc}$; ...
- Systematically derived from **WP-calculi** [POPL 2017]

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Monotonicity in program verification

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

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

- 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 $\texttt{w}$

- 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, we will see how monotonicity gives us
  - 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`]
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Key ideas behind our general framework

- Based on **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

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

  - a stateful predicate `p` is **stable** (wrt. `rel`) when

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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**
  - a means to **recall** the validity of `p` s′ in any future state s′
- Provides a **unifying account** of the existing *ad hoc* uses in F*

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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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- Provides a **unifying account** of the existing *ad hoc* uses in F*

Key ideas behind our general framework

- Based on **monotonic programs** and **stable predicates**
  - per verification task, we **choose a preorder** `rel` on states
    - set inclusion, heap inclusion, increasing counter values, ...
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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

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

- $\mathtt{ST}$ is an abstract pre-postcondition refinement of

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

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

$$\texttt{MST}\ \texttt{\#state}\ \texttt{\#rel}\ \texttt{t}\ (\texttt{requires}\ \texttt{pre})\ (\texttt{ensures}\ \texttt{post})$$

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New: Recalling a Witness

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

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

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

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

$$\begin{aligned} [\![\texttt{witnessed p}]\!](\texttt{s}) &\stackrel{\text{def}}{=} \texttt{p}\ \text{`}\texttt{stable\_from}\text{`}\ \texttt{s} \\ &\stackrel{\text{def}}{=} \forall\, \texttt{s}'\,.\,\texttt{rel s s}' \implies [\![\texttt{p s}']\!](\texttt{s}) \end{aligned}$$

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- … Hoare-style logics are essentially **world/state-indexed**, so

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

$$\begin{array}{lll} \texttt{witness} & : & \texttt{p}{:}(\texttt{state} \to \texttt{Type}_0) \\ & & \to \texttt{MST unit } (\texttt{requires } (\lambda\, \texttt{s}_0\,.\, \texttt{p `stable\_from` s}_0)) \\ & & \qquad\qquad (\texttt{ensures } (\lambda\, \texttt{s}_0\, \_\, \texttt{s}_1\,.\, \texttt{s}_0 = \texttt{s}_1 \wedge \texttt{witnessed p})) \end{array}$$

- and a **stateful elimination rule** for `witnessed`

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The motivating example revisited

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

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

  - We pick **set inclusion** $\subseteq$ as our preorder `rel` on states
  - We **prove the assertion** by inserting a `witness` and `recall`

$$\texttt{insert v};\ \texttt{witness}\ (\lambda\, \mathrm{s}\,.\, \mathrm{v} \in \mathrm{s});\ \mathrm{c\_p}();\ \texttt{recall}\ (\lambda\, \mathrm{s}\,.\, \mathrm{v} \in \mathrm{s});\ \texttt{assert}\ (\mathrm{v} \in \mathrm{get}())$$

  - For **any other** `w`, wrapping

$$\texttt{insert w};\ [\ \ ];\ \texttt{assert}\ (\mathrm{w} \in \mathrm{get}())$$

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

$$\texttt{insert w};\ \texttt{witness}\ (\lambda\, \mathrm{s}\,.\, \mathrm{w} \in \mathrm{s});\ [\ \ ];\ \texttt{recall}\ (\lambda\, \mathrm{s}\,.\, \mathrm{w} \in \mathrm{s});\ \texttt{assert}\ (\mathrm{w} \in \mathrm{get}())$$

- **Monotonic counters** are analogous, by picking $\mathbb{N}$ and $\leq$, e.g.,

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

The motivating example revisited

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

  `insert v; complex_procedure(); assert` $(\mathtt{v} \in \mathtt{get}())$

  - We pick **set inclusion** $\subseteq$ as our preorder `rel` on states
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  - For **any other** `w`, wrapping

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ML-style typed references (local state)

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

$$\texttt{type heap} =$$
$$\quad | \ \texttt{H} : \texttt{h}{:}(\mathbb{N} \to \texttt{cell}) \to \texttt{ctr}{:}\mathbb{N}\{\forall\, \texttt{n}\,.\, \texttt{ctr} \le \texttt{n} \implies \texttt{h n} = \texttt{Unused}\} \to \texttt{heap}$$

  where

$$\texttt{type cell} =$$
$$\quad | \ \texttt{Unused} : \texttt{cell}$$
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- As a result, we can define new **local state effect**

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

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

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

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let contains (H h _) id a =
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- Finally, we define `MLST`'s **actions** using `MST`'s actions
  - `let alloc (#a:Type) (v:a) : MLST (ref a) ... = ...`
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Adding untyped and monotonic references

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

    where

    $$| \ \texttt{Used} : \mathrm{a{:}Type} \to \mathrm{v{:}a} \to \mathrm{t{:}}\texttt{tag} \to \texttt{cell}$$

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Outline

* F* overview
- Monotonic state by example
- Key ideas behind our general extension to Hoare-style logics
- Accommodating monotonic state in F*
- Some examples of monotonic state at work
- Glimpse of meta-theory and correctness results
- More examples of monotonic state at work (see our paper)
- Monadic reification and reflection (see our paper)

Glimpse of meta-theory

- A small **dependently typed λ-calculus** with `Tot` and `MST` effects
- **Logical consistency** shown via cut elimination
- Using an **instrumented operational semantics**, where

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- Hoare-style **total correctness** via SN, progress, and preservation

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Conclusion

- Monotonicity
  - can be distilled into a **simple** and **general** framework
  - is **useful** for **programming** (refs.) and **verification** (Prj. Everest)

- See our POPL 2018 paper for
  - further **examples** and **case studies**
  - details of **meta-theory** for `MST`
  - first steps towards **monadic reification** for `MST` (rel. reasoning)

- Ongoing: taking the **modality** aspect of `witnessed` seriously
  - to remove instrumentation from op. sem., and
  - to improve support for monadic reification

Thank you for your attention!

Questions?

D. Ahman, C. Fournet, C. Hrițcu, K. Maillard, A. Rastogi, N. Swamy.

Recalling a Witness: Foundations and Applications of Monotonic State

Proc. ACM Program. Lang., volume 2, issue POPL, article 65, 2018.