

Embracing monotonicity in



Danel Ahman @ INRIA Paris

based on a joint POPL 2018 paper with

Cătălin Hrițcu 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
- Monotonicity (monotonic state) in programming and verification
- Key ideas behind our general extension to Hoare-style logics
- Accommodating monotonic state in F*
- Some examples of monotonic state at work
- Glimpse of the 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* 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
 - tactics and metaprogramming (WIP)
 - a **semi-automated verifier** of imperative programs
 - Dafny, Why3, FramaC, ...
 - Z3-based SMT-automation (for discharging VCs)
- F*'s development is driven by **Project Everest**
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// Dependent types, recursive functions, and type inference

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type vector 'a : nat -> Type =  
  | Nil : vector 'a 0  
  | Cons : #n:nat -> 'a -> vector 'a n -> vector 'a (n + 1)
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let rec concat #a #n #m (xs:vector a n) (ys:vector a m) : Tot (vector a (n + m)) =
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```
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  | Cons #n x xs' -> Cons x (concat xs' ys)
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// Refinement types

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let in_range_index min max : Type = i:nat{min <= i /\ i <= max}  
  
let rec lkp #a #n (xs:vector a n) (i:in_range_index 1 n) : Tot a =  
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// First-class predicates (for which Type0 behaves like (classical) Prop)

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type is_prefix_of #a #n #m (xs:vector a n) (zs:vector a m{n <= m}) : Type0 =  
  forall (i:nat) . (1 <= i /\ i <= n) ==> lkp xs i == lkp zs i
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// Extrinsic reasoning (using separate lemmas)

```
let rec lemma #a #n #m (xs:vector a n) (ys:vector a m) : Lemma (xs `is_prefix_of` (concat 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 pre- and postconditions)

```
let rec take #a n #m (zs:vector a m) : Pure (vector a n) (requires (n <= m)  
  (ensures (fun xs -> xs `is_prefix_of` 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 program : n:nat -> ST (ref nat) (requires (fun h0 -> 1 <= n))
                                   (ensures (fun _ r h1 -> sel h1 r = sum 1 n))
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val sum : i:nat -> n:nat{i <= n} -> GTot nat (decreases (n - i))
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let rec sum i n =
  if i < n then i + sum (i + 1) n
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val sum_loop : i:nat -> n:nat -> r:ref nat -> ST unit (requires (fun h0 -> (1 <= i ∧ i <= 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)]
```

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let rec sum_plus_lemma i 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 $\text{pre}_{\text{Lemma}}$) (ensures $\text{post}_{\text{Lemma}}$)
 - Pure t (requires pre_{Pure}) (ensures $\text{post}_{\text{Pure}}$)
 - Div t (requires pre_{Div}) (ensures post_{Div})
 - Exc t (requires pre_{Exc}) (ensures post_{Exc})
 - ST t (requires pre_{ST}) (ensures post_{ST})
 - ...
- **Monad morphs.** $\text{Pure} \rightsquigarrow \{\text{Div}, \text{Exc}, \text{ST}\}; \text{Exc} \rightsquigarrow \text{STExc}; \dots$
- Systematically derived from **WP-calculi**

[POPL 2017]

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Monotonicity in program verification

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

`insert v; complex_procedure(); assert (v ∈ get())`

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

$\{\lambda s. v \in s\}$ `complex_procedure()` $\{\lambda s. v \in s\}$

- likely that we have to **carry** $\lambda s. v \in s$ **through** the proof of `c_p`
- does not guarantee** that $\lambda s. v \in s$ holds at every point in `c_p`
- sensitive** to proving that `c_p` maintains $\lambda s. w \in s$ for some w
- However, if `c_p` **never removes**, then $\lambda s. v \in s$ is **stable**, and we would like the program logic to give us $v \in \text{get}()$ “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 $r:\text{ref } a$
 - 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
$$\forall s e' s'. (e, s) \rightsquigarrow^* (e', s') \implies \text{rel } s s'$$
 - a stateful predicate p is **stable** (wrt. rel) when
$$\forall s s'. p \ s \wedge \text{rel } s s' \implies p \ s'$$
- **Our solution:** extend Hoare-style program logics (e.g., F^*) with
 - i) a means to **witness** the validity of $p \ s$ in some state s
 - ii) a means for turning a p into a **state-independent proposition**
 - iii) 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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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

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

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

$$\forall s s'. p \ s \wedge \text{rel } s s' \implies p \ s'$$

- **Our solution:** extend Hoare-style program logics (e.g., F^*) with
 - i) a means to **witness** the validity of $p \ s$ in some state s
 - ii) 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**

$ST \#state\ t\ (\text{requires } pre)\ (\text{ensures } post)$

where

$pre : state \rightarrow Type$ $post : state \rightarrow t \rightarrow state \rightarrow Type$

- ST is an abstract pre-postcondition refinement of

$st\ t \stackrel{\text{def}}{=} state \rightarrow t * state$

- The global state **actions** have types

$get : unit \rightarrow ST\ state\ (\text{requires } (\lambda _ . \top))\ (\text{ensures } (\lambda s_0\ s\ s_1 . s_0 = s = s_1))$

$put : s : state \rightarrow ST\ unit\ (\text{requires } (\lambda _ . \top))\ (\text{ensures } (\lambda _ _ s_1 . s_1 = s))$

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New: Monotonic global state in F^*

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`MST #state #rel t (requires pre) (ensures post)`

- The `get` action is typed as in ST

`get : unit → MST state (requires (λ_.T))
(ensures (λ s0 s s1 . s0 = s = s1))`

- To ensure **monotonicity**, the `put` action gets a precondition

`put : s:state → MST unit (requires (λ s0 . rel s0 s))
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- So intuitively, MST is an **abstract** pre-postcondition refinement of

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New: Recalling a Witness

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

$\text{witnessed} : (\text{state} \rightarrow \text{Type}) \rightarrow \text{Type}$

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

$\text{wk} : p, q : (\text{state} \rightarrow \text{Type}) \rightarrow \text{Lemma} (\text{requires } (\forall s. p\ s \implies q\ s))$
 $(\text{ensures } (\text{witnessed } p \implies \text{witnessed } q))$

- Intuitively, think of it as a **necessity modality**

$$\begin{aligned} \llbracket \text{witnessed } p \rrbracket(s) &\stackrel{\text{def}}{=} p \text{ 'stable_from' } s \\ &\stackrel{\text{def}}{=} \forall s'. \text{rel } s\ s' \implies \llbracket p\ s' \rrbracket(s) \end{aligned}$$

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- But, wait a minute ...
- ... Hoare-style logics are essentially **world/state-indexed**, so
- we include a **stateful introduction rule** for witnessed

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witness : p:(state  $\rightarrow$  Type0)  
          $\rightarrow$  MST unit (requires ( $\lambda s_0. p$  'stable_from'  $s_0$ ))  
                   (ensures ( $\lambda s_0 - s_1. s_0 = s_1 \wedge$  witnessed  $p$ )))
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The motivating example revisited

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

```
insert v; complex_procedure(); assert (v ∈ get())
```

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

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insert v; witness ( $\lambda s. v \in s$ ); c_p(); recall ( $\lambda s. v \in s$ ); assert (v ∈ get())
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- for **any other** `w`, wrapping

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`create 0; incr(); witness ($\lambda c. c > 0$); c_p(); recall ($\lambda c. c > 0$)`

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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 { ∀ r . ctr ≤ r ⇒ h r = Unused } → heap
```

where

```
type cell =
```

```
| Unused : cell
```

```
| Used : a : Type → v : a → cell
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- Next, we define a **preorder** on heaps (**heap inclusion**)

```
let heap_inclusion (H h0 _) (H h1 _) =
```

```
  ∀ r . match h0 r , h1 r with
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    | Unused , _ → ⊤
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ML-style typed references (local state)

- As a result, we can define a new **ML-style local state effect**

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

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

```
abstract type ref a = r:N{witnessed ( $\lambda h. \text{contains } h \text{ } r \text{ } a$ )}
```

where

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

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

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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 ! (r:ref a) : MLST a (req. (\top)) (ens. (...)) = ...`
 - recall that the given ref. is in the heap
 - get the current heap
 - select the given reference from the heap
- `let := (r:ref a) (v:a) : MLST unit ... = ...`
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 - get the current heap
 - update the heap with the given value at the given ref.
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 - **get** the current heap
 - **update** the heap with the given value at the given ref.
 - **put** the updated heap back

ML-style typed references (local state)

- Finally, we define **MLST**'s **actions** using **MST**'s actions
 - **let alloc** ($\#a:\text{Type}$) ($v:a$) : **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 !** ($r:\text{ref a}$) : **MLST** a (**req.** (\top)) (**ens.** (...)) = ...
 - **recall** that the given ref. is in the heap
 - **get** the current heap
 - **select** the given reference from the heap
 - **let :=** ($r:\text{ref a}$) ($v:a$) : **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
$$\text{Used} : a:\text{Type} \rightarrow v:a \rightarrow \text{t:tag} \rightarrow \text{cell}$$

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

- actions corresponding to urefs have **weaker types** than for refs

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- `mrefs` provide **more flexibility** with ref.-wise monotonicity

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

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Outline

- * F^* overview
- Monotonicity (monotonic state) in programming and verification
- Key ideas behind our general extension to Hoare-style logics
- Accommodating monotonic state in F^*
- Some examples of monotonic state at work
- Glimpse of the 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

- Using an **instrumented operational semantics**, where

$$(\text{witness } p, s, W) \rightsquigarrow (\text{return } (), s, W \cup \{p\})$$
$$(\text{recall } p, s, W) \rightsquigarrow (\text{return } (), s, W)$$

- **Strong normalisation** via type-erasure and TT-lifting
- **Logical consistency** of pre-post cond. logic via cut elimination
- Hoare-style **total correctness** via SN, progress, and preservation

if $\vdash e : \text{MST } t$ *pre post* and

$\vdash (s, W) \text{ wf}$ and witnessed $W \vdash$ *pre* s

then $(e, s, W) \rightsquigarrow^* (\text{return } v, s', W')$ and $\vdash v : t$ and

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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 the **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.