Embracing monotonicity in F*

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joint work with

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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, ...
    - 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 type families

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

// Dependently typed recursive total 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   x:t{phi x}

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

// Type-theoretic predicates

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

// Extrinsic reasoning

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

// Intrinsic reasoning

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**
- All derived from respective **WP-calculi** (see our POPL'17 paper)

(Global state +) monotonicity is really useful!

Its essence can be captured very neatly!

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Monotonicity in verification

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

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

- 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 $\texttt{w}$

- 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
  - 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

- 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

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

  - 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
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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

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

- 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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- **Refs.** and **local state** are defined in F* using **monotonicity**

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

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- So intuitively, MST is an **abstract** pre-postcondition refinement of

$$\mathtt{mst}\ \mathtt{t} \stackrel{\text{def}}{=} \mathtt{s}_0{:}\mathtt{state} \to \mathtt{t} * \mathtt{s}_1{:}\mathtt{state}\{\mathtt{rel}\ \mathtt{s}_0\ \mathtt{s}_1\}$$

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New: Recalling a Witness

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

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

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

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

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

- As usual, for natural deduction, need **world-indexed sequents**
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- … Hoare-style logics are essentially **world/state-indexed**, so

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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**

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

- 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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ML-style typed references (local state)

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

  $\mathtt{type\ heap} =$

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

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

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ML-style typed references (local state)

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

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

- 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

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

ML-style typed references (local state)

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

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Adding untyped and monotonic references

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

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Conclusion

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

- See our POPL 2018 paper for
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  - **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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Appendix: Mon. reification and reflection

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

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

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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