SteelCore & Steel: An Extensible Concurrent Separation Logic for Effectful Dependent Programs

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Thanks to **Aymeric Fromherz**

Verifying Concurrent Programs

- Lots of recent work on using Concurrent Separation Logic (CSL) for verification

$$\textsc{Write}\quad \{r \mapsto \_\}\ r := v\ \{r \mapsto v\}$$

$$\textsc{Frame}\quad \frac{\{P\}\ c\ \{Q\}}{\{P * F\}\ c\ \{Q * F\}}$$

$$\textsc{Par}\quad \frac{\forall i. \{P_i\}\ c_i\ \{Q_i\}}{\{P_0 * P_1\}\ c_0 || c_1\ \{Q_0 * Q_1\}}$$

Verifying Concurrent Programs

- Lots of recent work on using Concurrent Separation Logic (CSL) for verification
  - Iris: Comprehensive, expressive logic. But applies to deeply embedded, simply-typed languages

```
Definition swap : val := λ: "x" "y",
  let: "tmp" := !"x" in
  "x" <- !"y";;
  "y" <- "tmp".
```

```
Lemma swap_spec x y v1 v2 :
  {{{ x ↦ v1 ∗ y ↦ v2 }}} swap #x #y {{{ RET #(); x ↦ v2 ∗ y ↦ v1 }}}.
```

```
Proof.
  iIntros (Φ) "[Hx Hy] Post".
  unfold swap.
  wp_lam. wp_let.
  wp_load. wp_let.
  wp_load. wp_store.
  wp_store.
  iApply "Post".
  iSplitL "Hx".
  - iApply "Hx".
  - iApply "Hy".
Qed.
```

Verifying Concurrent Programs

How to get a CSL for a dependently-typed language? Through a shallow embedding?

```
let swap (r0 r1:ref a)
  : ST unit
    (requires r0 ↦ v0 ∗ r1 ↦ v1)
    (ensures λ_ → r0 ↦ v1 ∗ r1 ↦ v0)
  = let v0 = !r0 in
    r0 := !r1;
    r1 := v0
```

Challenges

- How to reflect the effect of concurrency in the language?
- How to support partial correctness?
- How to enable dynamically allocated invariants?

Steel: A Concurrent Separation Logic (CSL) for F*

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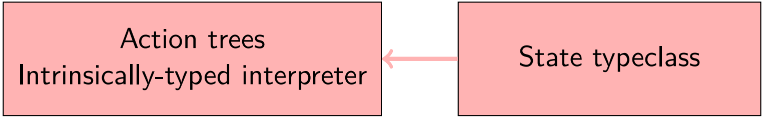

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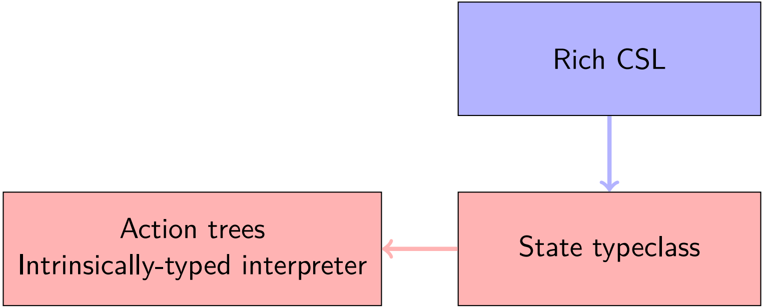

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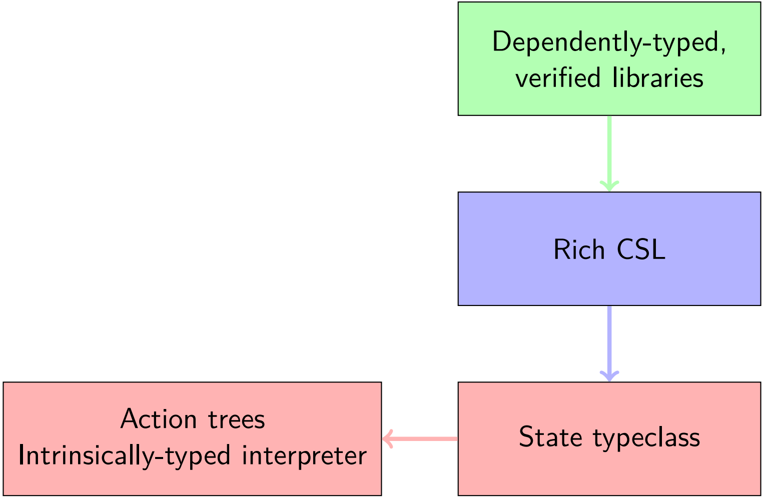

Encoding Computations through Effectful Indexed Action Trees

```
type state = {mem: Type;
              slprop:Type; equals; emp; star;
              interp: slprop → mem → prop}
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```
type state = {mem: Type;
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type ctree (st:state) : a:Type → pre:st.slprop → post:(a → st.slprop) → Type =
  | Ret : y:a → ctree st a (post y) post
  | Act : action a pre post' → (x:a → Dv (ctree st b (post' x) post)) → ctree st a pre post
  | Par : ctree st unit p q → ctree st unit p' q' → ctree st a (q ‘st.star‘ q') post → ctree st a (
```

Proving Soundness of the Semantics

- We propose an intrinsically-typed definitional interpreter
- Atomic actions are non-deterministically interleaved
- The type of the interpreter states its soundness

```
val run (e:ctree st a p q) : NST a
  (requires λm → st.interp p m)
  (ensures λm0 y m1 → st.interp (q y) m1)
```

Instantiating the Program Logic

- **Memory:** Map from abstract addresses to typed references

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- **Memory:** Map from abstract addresses to typed references
- Standard SL connectives: $\star$, $-\!\!*$, $\wedge$, $\vee$, $\exists$, $\forall$
- Partial Commutative Monoid (PCM)-indexed pts_to assertion
- Invariants

Invariants in Steel

```
let inv_name = nat
val (⇝) (i:inv_name) (p:slprop) : prop
let ival (p:slprop) = i:inv_name{i ⇝p}
```

Invariants in Steel

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let inv_name = nat
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val new_invariant (p:slprop) : Steel (ival p) p emp
```

Using Invariants

Atomic commands

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```
val with_invariant (i:ival p) (f:unit → SteelAtomic a g (p ⋆ q) (λ y → p ⋆ r y))
  : SteelAtomic a g q r
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Atomic commands

- Atomic actions
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- New effect: SteelAtomic a (...) is_ghost p q

```
val with_invariant (i:ival p) (f:unit → SteelAtomic a (i ⊎ u) g (p ⋆ q) (λ y → p ⋆ r y))
  : SteelAtomic a u g q r
```

Stacking Abstractions in Steel

module Steel.Effect
module Steel.Effect.Atomic

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module Steel.Effect
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module Steel.ForkJoin
module Steel.Channels

Steel Example: Channel Types

```
val chan (p:prot) : Type
val sender #p (c:chan p) (cur:prot) : slprop
val receiver #p (c:chan p) (cur:prot) : slprop
```

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val chan (p:prot) : Type
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val receiver #p (c:chan p) (cur:prot) : slprop

val send #p (#cur:prot{more cur}) (c:chan p) (x:msg_t cur)
  : Steel unit (sender c cur) (λ _ → sender c (step cur x))
```

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val chan (p:prot) : Type
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val send #p (#cur:prot{more cur}) (c:chan p) (x:msg_t cur)
  : Steel unit (sender c cur) (λ _ → sender c (step cur x))

val recv ... : Steel (msg_t cur) (receiver c cur) (λ x → receiver c (step cur x))
```

Steel Example: PingPong Protocol

```
let pingpong : prot =
  x ← Protocol.send int;
  y ← Protocol.recv (y:int{y > x});
  Protocol.done
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let pingpong : prot =
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let client (c:chan pingpong) =
  send c 17;
  let y = recv c in
  assert (y > 17);
  return ()
```

Conclusion

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- A PCM-based memory model
- Concurrency reasoning through dynamically allocated invariants
- 28 kLoC in F*, and a growing stack of verified libraries

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Also in the paper

- Implicit Dynamic Frames
- Monotonicity and Preorders for References
- More libraries: Lock-coupling Lists, Counters with local state, ...

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