Tactics and Metaprogramming

An introduction to Meta-F*

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F* PoP Up Seminar
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This Talk

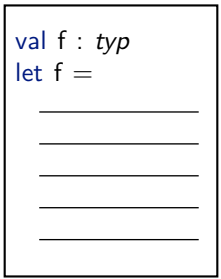
- High-level presentation + some live examples at the end.
- No way we cover everything today.
- See new chapter (in construction) in $\mathbf{F}^\star$ tutorial.

Main uses of Meta-F*

- Simplifying/proving assertions: assert φ by τ
- Metaprogramming, in various flavors.
- Solving implicit arguments (typeclasses).
- Program transformations (e.g. for efficient extraction).

Proving

Auto-active Verification



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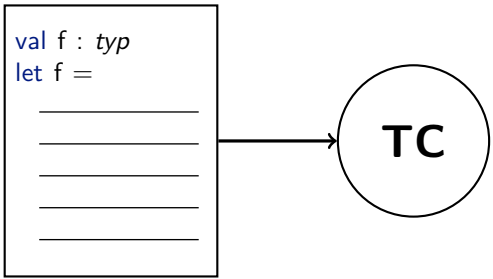

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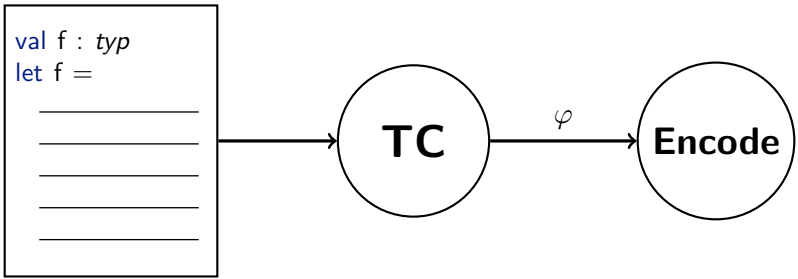

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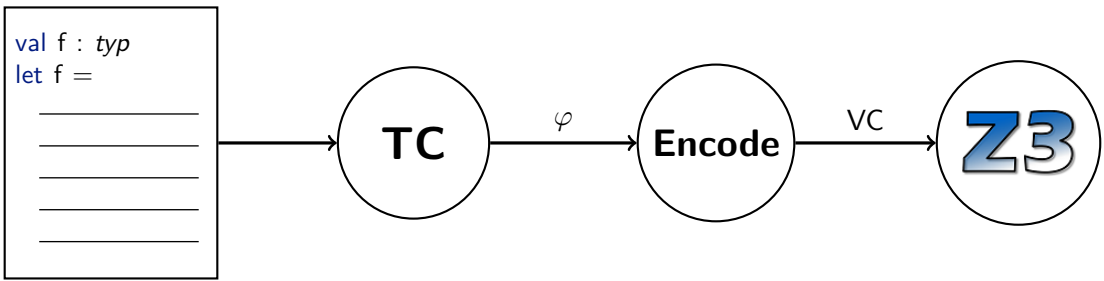

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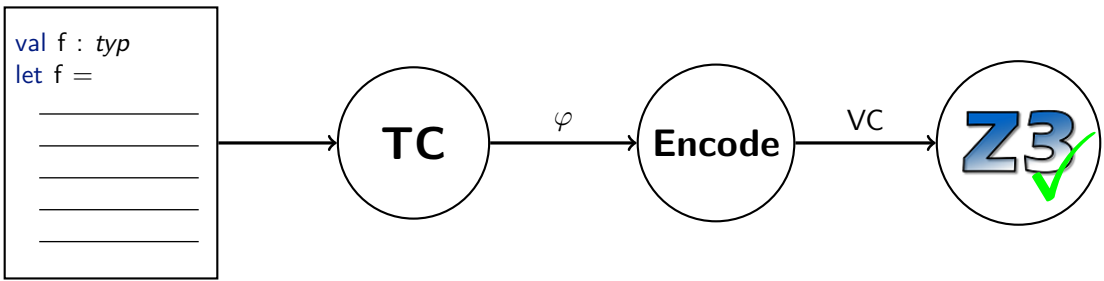

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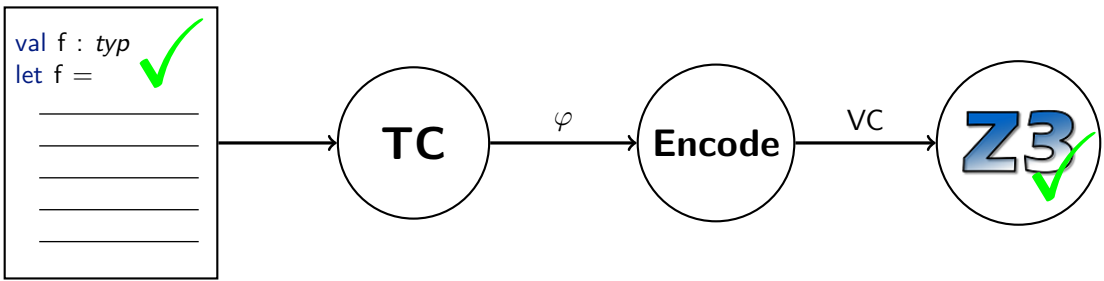

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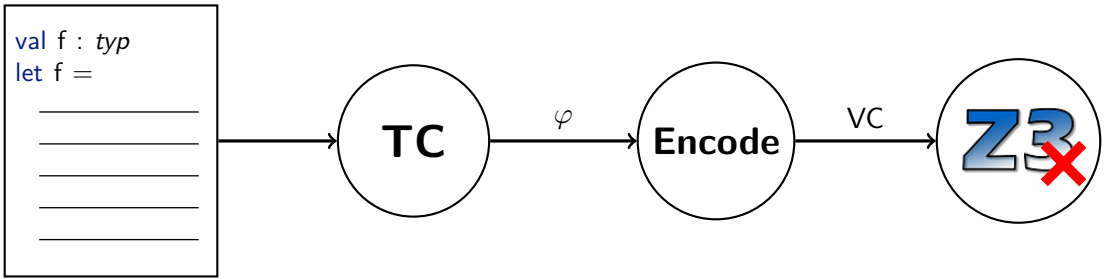

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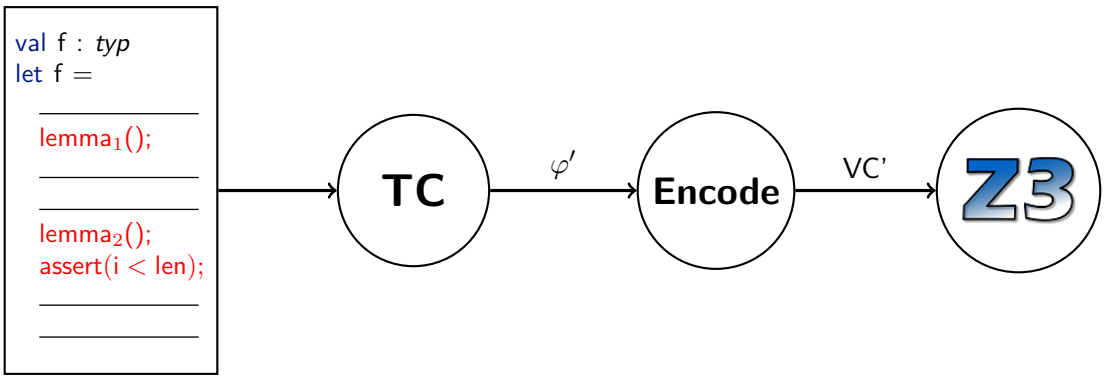

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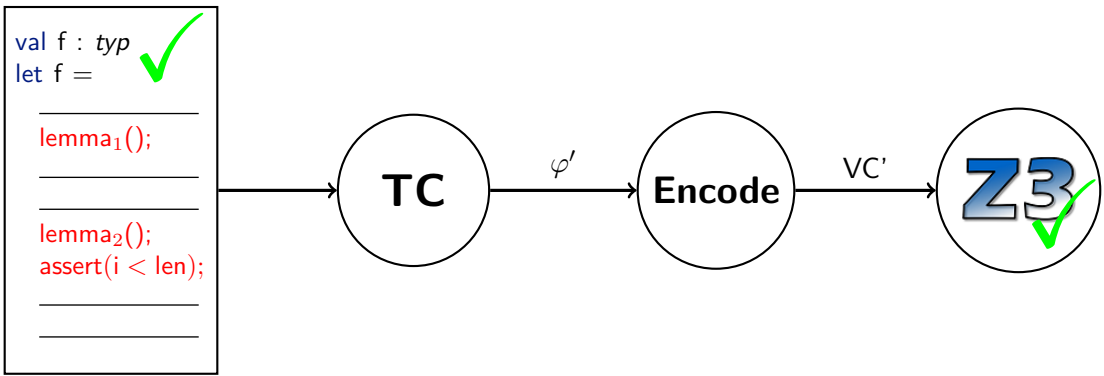

Proofs by SMT

Z3 fleshes out many proofs easily. Normally, the "key insights" are all that is needed.

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val mod_add_both (a:int) (b:int) (x:int) (n:pos) : Lemma
    (requires a % n == b % n)
    (ensures (a + x) % n == (b + x) % n)
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let mod_add_both (a:int) (b:int) (x:int) (n:pos) =
  lemma_div_mod a n;
  lemma_div_mod b n;
  lemma_div_mod (a + x) n;
  lemma_div_mod (b + x) n;
  let xx = (b + x) / n - (a + x) / n - b / n + a / n in
  distributivity_sub_left ((b + x) / n) ((a + x) / n) n;
  distributivity_sub_left ((b + x) / n - (a + x) / n) (b / n) n;
  distributivity_add_left ((b + x) / n - (a + x) / n - b / n) (a / n) n;
  lt_multiple_is_equal ((a + x) % n) ((b + x) % n) xx n
```

When SMT *really* doesn't cut it

```
let lemma_poly_multiply (n p r h r0 r1 h0 h1 h2 s1 d0 d1 d2 hh : int)
  : Lemma
    (requires p > 0 ∧ r1 ≥ 0 ∧ n > 0 ∧ 4 * (n * n) == p + 5 ∧ r == r1 * n + r0 ∧
              h == h2 * (n * n) + h1 * n + h0 ∧ s1 == r1 + (r1 / 4) ∧ r1 % 4 == 0 ∧
              d0 == h0 * r0 + h1 * s1 ∧ d1 == h0 * r1 + h1 * r0 + h2 * s1 ∧
              d2 == h2 * r0 ∧ hh == d2 * (n * n) + d1 * n + d0)
    (ensures (h * r) % p == hh % p)
  =
  let r1_4 = r1 / 4 in
  let h_r_expand = (h2 * (n * n) + h1 * n + h0) * ((r1_4 * 4) * n + r0) in
  let hh_expand = (h2 * r0) * (n * n) + (h0 * (r1_4 * 4) + h1 * r0 + h2 * (5 * r1_4)) * n
                  + (h0 * r0 + h1 * (5 * r1_4)) in
  let b = ((h2 * n + h1) * r1_4) in
  modulo_addition_lemma hh_expand p b;
  assert (h_r_expand == hh_expand + b * (n * n * 4 + (- 5)))
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              d0 == h0 * r0 + h1 * s1 ∧ d1 == h0 * r1 + [illegible] + h2 * s[illegible]
              d2 == h2 * r0 ∧ hh == d2 * (n * n) + d1 * n [illegible]
    (ensures (h * r) % p == hh % p)
  =
  let r1_4 = r1 / 4 in
  let h_r_expand = (h2 * (n * n) + h1 * n + h0) * ((r1_4 * 4) [illegible] 0)
  let hh_expand = (h2 * r0) * (n * n) + (h0 * (r1_4 * 4) + [illegible] + h2 * ([illegible] 4)) * n
                  + (h0 * r0 + h1 * (5 * r1_4)) in
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- Arithmetic canonicalization (nlarith)
- Simplification via rewrites, normalization
- Case splitting
- Proof environment manipulation (e.g. fact pruning)

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- Arithmetic canonicalization (nlarith)
- Simplification via rewrites, normalization
- Case splitting
- Proof environment manipulation (e.g. fact pruning)
- Fully automating proofs also possible

Tackling individual assertions

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  let b = ((h2 * n + h1) * r1_4) in
  modulo_addition_lemma hh_expand p b;
  assert (h_r_expand == hh_expand + b * (n * n * 4 + (- 5))) by (canon_semiring int_cr)
```

Splitting assertions

VC will not contain the obligation,
instead we get a *goal* for it

$$
\begin{aligned}
&\forall \mathsf{n\ p\ r}\ \ldots, \\
&\varphi_1 \Longrightarrow \psi_1 \wedge \\
&\qquad \varphi_2 \Longrightarrow \psi_2 \wedge \\
&\qquad\qquad \ldots \Longrightarrow \mathsf{L} = \mathsf{R} \wedge \\
&\qquad\qquad\qquad \mathsf{L} = \mathsf{R} \Longrightarrow \ldots
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... $\Longrightarrow$ ~~L = R~~ $\wedge$
L = R $\Longrightarrow$ ...

Goal 1/1
n : int
p : int
r : int
...
H0 : φ_1
H1 : φ_2
...

L = R

- Can switch between part of a VC (formula) and a goal (type-theoretic hole)

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```
type error = exn * proofstate (* error and proofstate at the time of failure *)
let tac a = proofstate → Dv ((a & proofstate) 'either' error) (* Dv: possibly diverging *)
let t_return (x:α) = ...
let t_bind (m:tac α) (f:α → tac β) : tac β= ...

new_effect { TAC with repr = tac ; return = t_return ; bind = t_bind }

sub_effect DIV ⇝TAC = ...          sub_effect EXN ⇝TAC = ...
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- No put operation, can only modify proofstate via primitives:

  exact, apply, intro, tc, raise, catch, ...

TAC is a first-class citizen of F*

Metaprograms are written as any other kind of program:

```
let mytac () : Tac unit =
    let h1 = implies_intro () in
    rewrite h1;
    apply_lemma (`mylem);
    ...
```

TAC is a first-class citizen of F*

Higher-order combinators too:

```
let rec repeat (t : unit → Tac α) : Tac (list α) =
    match catch t with
    | Inl _ → []
    | Inr x → x :: repeat t

let repeat1 (t : unit → Tac α) : Tac (list α) = t () :: repeat t
```

TAC is a first-class citizen of F*

Use exceptions:

```
exception NotAForall

let forall_intro () : Tac binder =
    let g = cur_goal () in
    match term_as_formula g with
    | Forall _ _ → begin apply_lemma (`fa_intro_lem); intro () end
    | _ → raise NotAForall

let t () =
    try forall_intro () with
    | NotAForall → ()
    | e → raise e
```

TAC is a first-class citizen of F*

Call into existing pure, diverging, and exception-raising code:

```
let f (seen:list term) : Tac unit =
    let g = cur_goal () in
    if FStar.List.Tot.Base.existsb (term_eq g) seen then
      raise Loop;
    ...
```

Metaprogramming

Metaprogramming: generating terms

Beyond proving, Meta-**F*** enables constructing terms and top-level definitions

```
let one = _ by (exact (`1))
let one_plus_two = _ by (apply (`(+)); exact (`1); exact (`2))
```

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let one = _ by (exact (`1))
let one_plus_two = _ by (apply (`(+)); exact (`1); exact (`2))

let fib (i:nat) = if i < 2 then exact (`1)
                  else begin
                    apply (`(+));
                    fib (i - 1);
                    fib (i - 2)
                  end

let t = _ by (fib 8)
```

Metaprogramming: generating terms

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```
noeq type t1 =
    | A : int → string → t1
    | B : t1 → int → t1
    | C : t1
    | D : string → t1
    | E : t1 → t1

%splice (mk_printer (`t1))
```

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```
let t1_print = λv →
  let rec ff_rec v_inner =
    (match v_inner with
      | A a1 a2 →
        concat "" [ "(";
                    concat "  " ["A"; print_int a1; print_string a2];
                    ")" ]
      | B a1 a2 → concat ""
                    ["("; concat "  " ["B"; ff_rec a1; print_int a2]; ")"]
      | C → "C"
      | ...
  in ff_rec v
```

Customizing implicit arguments

Meta-$\mathbf{F}^\star$ can also be used to provide strategies for resolution of implicits.

```
let diag (x:int) (#[same_as x] y : int) : int * int = (x, y)
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let diag (x:int) (#[same_as x] y : int) : int * int = (x, y)

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```
let diag (x:int) (#[same_as x] y : int) : int * int = (x, y)

let _ = assert (diag 42 == (42, 42))

let _ = assert (diag 42 #21 == (42, 21))
```

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(* val eq : #a:Type → (#[tcresolve] d : deq a) → (a → a → bool) *)
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[@tcinstance] let eq_int : deq int = { eq = (λ x y → x = y); eq_ok = easy }
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instance eq_int : deq int = { eq = (λ x y →x = y); eq_ok = easy }
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Canonicalization

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  (a@a)@(b@(c@d)) = ((a@(a@([]@b)))@c)@d

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- Say we a complex goal involving list concatenation.
  (a@a)@(b@(c@d)) = ((a@(a@([]@b)))@c)@d
- We can already apply lemmas repeatedly to solve it, but that's not much better.

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- First idea: write automation to inspect the goal and apply the lemma as needed.
- This works, but is very slow due to the constant use of the typechecker/unifier.

Proof-by-reflection: 1 minute pitch

- Obtain an AST of the expression.

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type atom = list α
type expr =
  | App : expr → expr → expr
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denote (App a' (App b' c'))
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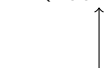
```



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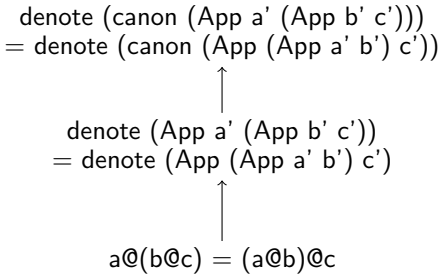

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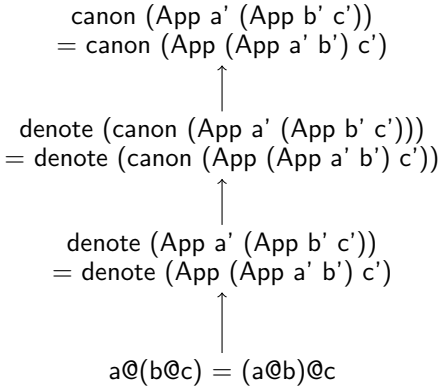

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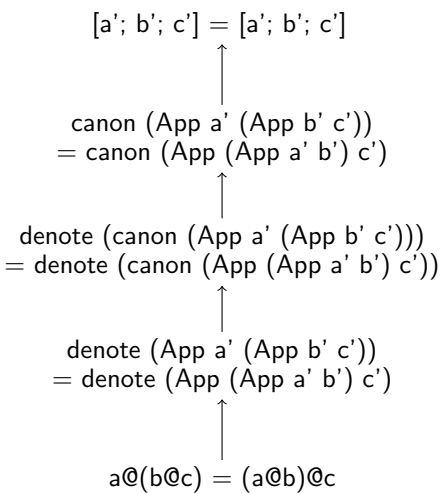

Summary

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- Also check out `examples/` and `tests/`

Other topics:

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Demo!