ML as a Tactic Language, Again

A look at Meta-$\mathrm{F}^\star$

The $\mathrm{F}^\star$ team

ML Workshop 2018

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A look at Meta-$\mathrm{F}^\star$

The $\mathrm{F}^\star$ team

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What's this $\mathrm{F}^\star$ thing?

A dependently-typed, effectful, functional programming language

- ML-like: higher-order, polymorphic, strict, safe
- Very expressive specs over effectful terms
- Proof-irrelevant logic: refinements and WP-calculus
- SMT backend (Z3)

An example

```
let incr (r:ref int) = r := !r + 1
let f () =
    let r = alloc 1 in
    incr r;
    let v = !r in
    assert (v == 2)
```

An example

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```

```
st_wp a = (state → a → prop) → state → prop
```

```
val alloc : #a:Type → x:a → ST (ref a) (λ p h → ∀r. r ∉h ⟹ p (alloc_heap r x h) r)
val (!) : #a:Type → r:ref a → ST a (λ p h → h ∈p ∧ p h h.[r])
val (:=) : #a:Type → r:ref a → v:a → ST unit (λ p h → h ∈p ∧ p (upd h r v) ())
```

```
∀(p: st_post_h heap unit)
  (h: heap).
  (∀ (h1: heap). auto_squash (p a h1)) ⟹
  (∀ (a: mref int (trivial_preorder int))
      (h1: heap).
      fresh a h h1 ∧ modifies empty h h1 ∧
      sel h1 a == 1 ⟹
      (∀ (return_val: int).
          return_val == sel h1 a + 1 ⟹
          trivial_preorder int (sel h1 a) return_val ∧
              (h1: _: heap
                {trivial_preorder int (sel h1 a) return_val})
            .
              trivial_preorder int (sel h1 a) return_val ∧
              contains h1 a ∧
              modifies (singleton (addr_of a))
                h1
                h1 ∧ equal_dom h1 h1 ∧
              sel h1 a == return_val ⟹
              sel h1 a == 2 ∧
                  sel h1 a == 2 ⟹ p pure_result h1))
```

Doing proofs

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- User writes program
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- $\mathrm{F}^\star$ queries the SMT solver

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```
val lemma_mod_spec: a:int → p:pos → Lemma (a / p = (a - (a % p)) / p)
```

Doing proofs

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All user input happens before VC generation: *auto-active verification*
What does the user do when then solver fails?

```
val lemma_mod_spec: a:int → p:pos → Lemma (a / p = (a - (a % p)) / p)
let lemma_mod_spec a p = ()
```

Doing proofs

What's the modus operandi?

- User writes program
- $\mathrm{F}^\star$ computes VC
- $\mathrm{F}^\star$ queries the SMT solver

All user input happens before VC generation: *auto-active verification*

What does the user do when then solver fails?

```
val lemma_mod_spec: a:int → p:pos → Lemma (a / p = (a - (a % p)) / p)
let lemma_mod_spec a p =
    lemma_div_mod a p;
    assert (a = p * (a / p) + a % p);
    assert (a % p = a - p * (a / p));
    assert (a - (a % p) = p * (a / p));
    lemma_mod_plus 0 (a / p) p;
    assert ((p * (a / p)) % p = 0);
    lemma_div_exact (p * (a / p)) p
```

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- User writes program
- $\mathrm{F}^\star$ computes VC
- Custom tactics apply
- $\mathrm{F}^\star$ *maybe* queries the SMT solver

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Some proofs are just out of the solver's scope
And the programmer's sanity scope...
Tactics engine: tweak proof obligations before SMT, *interactive*[1] verification

- User writes program
- $\mathrm{F}^\star$ + custom tactics compute VC
- $\mathrm{F}^\star$ *maybe* queries the SMT solver

[1] WIP

The entrypoints

Proving:

... assert φ by τ ...

Catching entire VCs:

let e : C by τ = ...

Metaprogramming terms:

... (_ by τ) ...

Metaprogramming top-level definitions:

%splice τ

The entrypoints

Proving:

... assert φ by τ ... $\quad \Gamma \vdash \_ : \text{squash } \tau$

Catching entire VCs:

let e : C by τ = ... $\quad \Gamma \vdash \_ : \text{squash VC}$

Metaprogramming terms:

... (_ by τ) ... $\quad \Gamma \vdash \_ : \text{ty}$

Metaprogramming top-level definitions:

%splice τ $\quad \cdot \vdash \_ : \text{list def}$

Slapping a tactic on an assertion

```
let f x y z =
    ...
    assert (g x y == h z)
    ...
```

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```
let f x y z =
    ...
    assert (g x y == h z)
        by (compute ();
            canon_semiring int_cr;
            trefl ());
    ...
```

Metaprogramming: generating terms

Beyond proving, Meta-$\mathrm{F}^\star$ 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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%splice (mk_printer (`t1))
```

```
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
```

Control flow

```
val f : n:int → Pure int (requires ⊤) (ensures (λ n' → n' > n))
let f (n:int) =
    if n > 0
    then begin
         assert (n + n > n) by τ;
         n + n
         end
    else 1 - n
```

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Context in the proofstate contains hypothesis that `n > 0`.

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Context in the proofstate contains hypothesis that $n > 0$.

```
Goal 1/1
n: int
p: pure_post int
...
uu____: squash (n > 0 == true)
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
squash (n + n > n)
```

Extracting sub-VCs

abstract with_tactic (τ : unit $\to$ Tac unit) (φ : prop) : prop = φ

assert φ by τ : Pure unit (requires (with_tactic $\tau\,\varphi$)) (ensures (λ _ $\to \varphi$)))

- In a positive position: with_tactic $\tau\,\varphi \rightsquigarrow \top$, run τ on φ and prove resulting goals too

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$$\frac{\Gamma \vDash C[\top] \quad \Gamma' \vDash \varphi}{\Gamma \vDash C[\varphi]}$$

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- In a negative position: with_tactic $\tau\,\varphi \rightsquigarrow \varphi$

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$$\frac{\Gamma_1 \vdash ?_1 : t_1 \quad \Gamma_2 \vdash ?_2 : t_2 \quad \ldots \quad \Gamma_n \vdash ?_n : t_n}{\Gamma_0 \vdash ?_0 : t_0}\ R$$

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- The proofstate is transformed by primitives, which implement typing rules in backwards style
- Essentially scripting typing derivations instead of term syntax

What are metaprograms?

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- Use $\mathrm{F}^\star$'s effect extension machinery to make new effect: TAC
  - Representation: proofstate $\rightarrow$ either error (a $*$ proofstate)
  - Completely standard and user-defined...
  - ... except for the assumed primitives

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```
type error = exn * proofstate (* error and proofstate at the time of failure *)
type result a = | Success : a → proofstate → result a | Failed : error → result a
let tac a = proofstate → Dv (result a) (* Dv: possibly diverging *)
let t_return (x:α) = λps → Success x ps
let t_bind (m:tac α) (f:α → tac β) : tac β=
            λps → match m ps with | Success x ps' → f x ps' | Error e → Error e

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 $\mathrm{F}^\star$

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 $\mathrm{F}^\star$

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 $\mathrm{F}^\star$

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 $\mathrm{F}^\star$

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;
    ...
```

Customizing implicit arguments

Meta-$\mathrm{F}^\star$ 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)

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

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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))
```

Putting it together: Typeclasses

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module FStar.Typeclasses
val mk_class : name → Tac unit (* creates method toplevels *)
val tcresolve : unit → Tac unit (* resolves dictionaries *)
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  eq : a → a → bool;
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%splice (mk_class "MyMod.deq")

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

instance eq_int : deq int = { eq = (λ x y → x = y); eq_ok = easy }
```

A peek at tcresolve

```
let rec tcresolve' (seen:list term) (fuel:int) : Tac unit =
  if fuel ≤ 0 then
      fail "out of fuel";
  let g = cur_goal () in
  if FStar.List.Tot.Base.existsb (term_eq g) seen then
      fail "loop";
  let seen = g :: seen in
    local seen fuel `or_else` global seen fuel
and local (seen:list term) (fuel:int) () : Tac unit =
  let bs = binders_of_env (cur_env ()) in
  first (λ b → trywith seen fuel (pack (Tv_Var (bv_of_binder b)))) bs
and global (seen:list term) (fuel:int) () : Tac unit =
  let cands = lookup_attr (`tcinstance) (cur_env ()) in
  first (λ fv → trywith seen fuel (pack (Tv_FVar fv))) cands
and trywith (seen:list term) (fuel:int) (t:term) : Tac unit =
  (λ () → apply t) `seq` (λ () → tcresolve' seen (fuel - 1))

let tcresolve () : Tac unit = tcresolve' [] 16
```

Native execution

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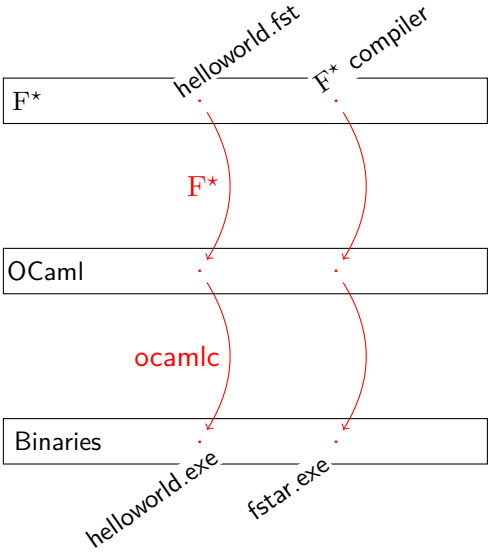
- By default, metaprograms are evaluated in $\mathrm{F}^\star$'s normalizer. Primitives are evaluated by calling into compiler internals.
- As an alternative, we can reuse $\mathrm{F}^\star$'s extraction mechanism to compile metaprograms as OCaml code.
- This code can then be compiled into dynamic objects and loaded

Compilation



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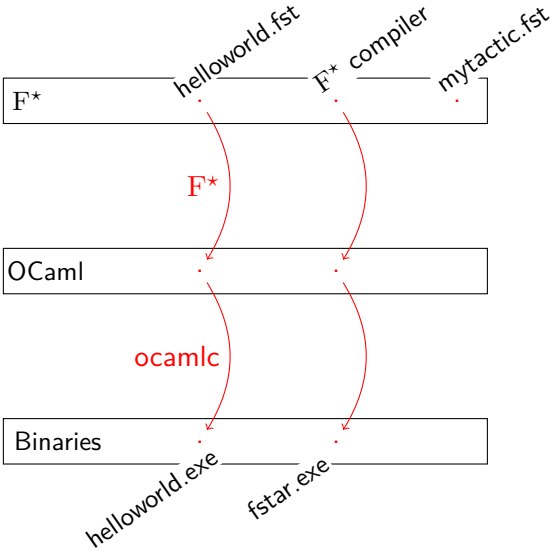

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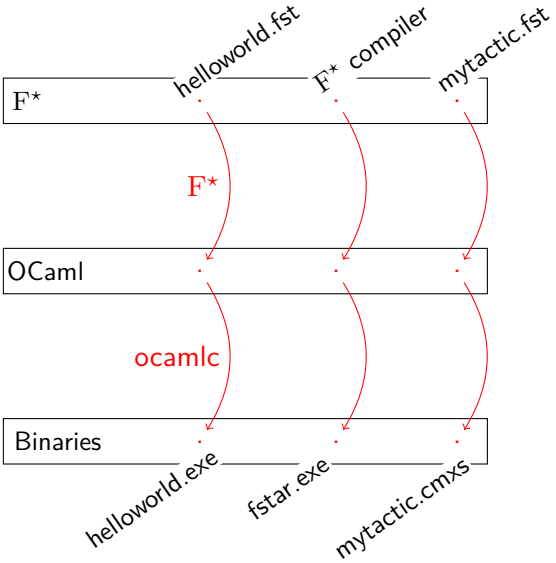
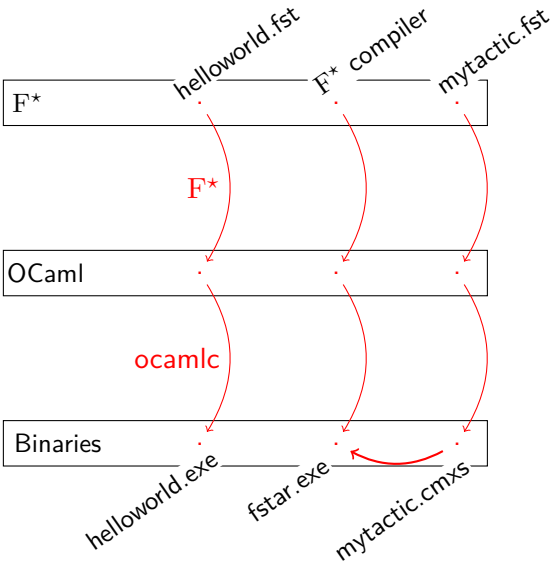


- Extract the user tactic and compile it into a dynamic object

Compilation



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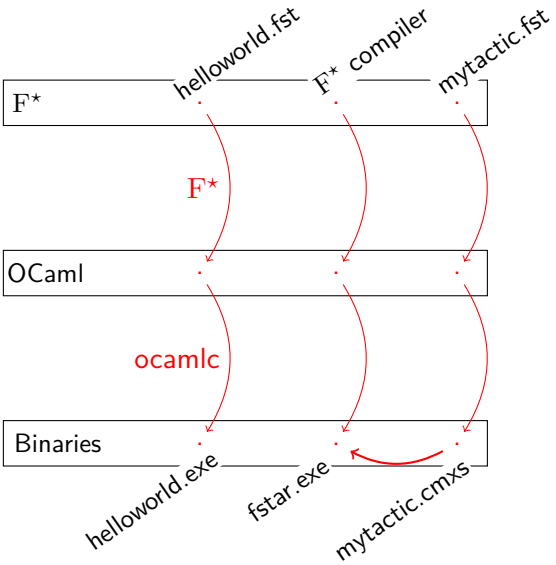

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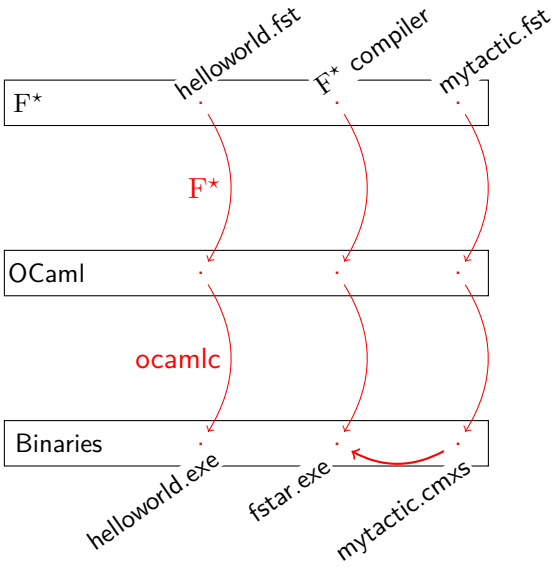

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- Not metaprogram specific *at all*

Coming back to this:

```
let tcresolve () = ...
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Fast and Safe extensions to $\mathrm{F}^\star$

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[@plugin] let tcresolve () = ...
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- Significant efficiency gains
- tcresolve outside of the TCB

Summary

- Provides both automation and a “manual mode” to users
- Using an effect for metaprograms increases reuse
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- Improve user experience, REPL
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Thank you!

TRACE @ …Star.Tactics.Derived.fst(165,12-165,13) Fri Sep 7 10:49:00 2018

Goal 1/1

p: pos
n r h r0 r1 h0 _h1 _h2 s1 d0 d1 d2 h1 h2 hh: ℤ
p: pure_post unit
uu___: squash ($r_1 \geq 0 \wedge n > 0 \wedge 4 \times (n \times n) == p + 5 \wedge r == r_1 \times n + r_0 \wedge$
$h == h_2 \times (n \times n) + h_1 \times n + h_0 \wedge s_1 == r_1 + r_1 / 4 \wedge r_1 \,\%\, 4 == 0 \wedge d_0 == h_0 \times r_0 + h_1 \times s_1 \wedge$
$d_1 == h_0 \times r_1 + h_1 \times r_0 + h_2 \times s_1 \wedge d_2 == h_2 \times r_0 \wedge hh == d_2 \times (n \times n) + d_1 \times n + d_0 \wedge$
(∀ (pure_result: unit). $h \times r \,\%\, p == hh \,\%\, p \implies$ p pure_result))

pure_result: unit
uu___: squash $(((h_2 \times r_0) \times (n \times n) + (h_0 \times ((r_1 / 4) \times 4) + h_1 \times r_0 + h_2 \times (5 \times (r_1 / 4))) \times n +$
$(h_0 \times r_0 + h_1 \times (5 \times (r_1 / 4))) +$
$((h_2 \times n + h_1) \times (r_1 / 4)) \times p) \,\%$
$p =$
$((h_2 \times r_0) \times (n \times n) + (h_0 \times ((r_1 / 4) \times 4) + h_1 \times r_0 + h_2 \times (5 \times (r_1 / 4))) \times n +$
$(h_0 \times r_0 + h_1 \times (5 \times (r_1 / 4)))) \,\%$
$p)$

$$\begin{aligned}
&\text{squash } (4 \times (h_2 \times (n \times (n \times (n \times (r_1 / 4))))) + h_2 \times (n \times (n \times r_0)) + \\
&(4 \times (n \times (n \times (h_1 \times (r_1 / 4)))) + n \times (h_1 \times r_0)) + \\
&(4 \times (n \times (h_0 \times (r_1 / 4))) + h_0 \times r_0) == \\
&h_2 \times (n \times (n \times r_0)) + (4 \times (n \times (h_0 \times (r_1 / 4))) + n \times (h_1 \times r_0) + 5 \times (h_2 \times (n \times (r_1 / 4)))) + \\
&(h_0 \times r_0 + 5 \times (h_1 \times (r_1 / 4))) + \\
&(4 \times (h_2 \times (n \times (n \times (n \times (r_1 / 4)))))) + -5 \times (h_2 \times (n \times (r_1 / 4))) + \\
&(4 \times (n \times (n \times (h_1 \times (r_1 / 4))))) + -5 \times (h_1 \times (r_1 / 4)))))
\end{aligned}$$

(*?u3948*) _