Electrolysis

Simple Verification of Rust Programs via Functional Purification

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OPLSS 2016

Outline

Why Rust

Simple Verification via Functional Purification

Verifying `std::[T]::binary_search`

Further Intricacies
- Associated Types
- Returning &mut

Why Rust? (What is Rust?)

Rust is a new systems programming language sponsored by Mozilla Research

- multi-paradigm with an ML-like syntax
- pursues "the trifecta: safety, concurrency, and speed"
  - speed through zero-cost abstractions and manual memory management
  - memory safety through tracking reference lifetimes in the type system
  - safe concurrency through forbidding shared mutable references

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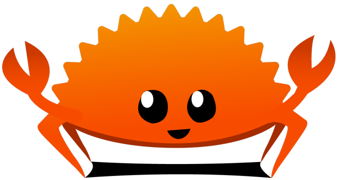

Why Rust: Because It's Almost Pure Already

- turn destructive updates into functional ones

```
p.x += 1;                let p = Point { x = p.x + 1, ..p };
```

- turn `&mut` parameters into input+output parameters

```
let x = f(&mut p);       let (x, p) = f(p);
```

Simple Verification via Functional Purification

1. make Rust program purely functional
2. transpile it into expression language of a theorem prover (Lean)
3. prove correctness of the Lean definition

Simple Verification via Functional Purification

1. make Rust program purely functional
2. transpile it into expression language of a theorem prover (Lean)
   - run `rustc` up to CFG generation
   - sort definitions topologically by dependencies
   - extract loops (SCCs) from CFG and put them into loop combinator
   - resolve static/dynamic trait calls

   Things Rust fortunately does not have:
   - exceptions
   - subtyping
3. prove correctness of the Lean definition

Verifying `std::[T]::binary_search`: Input

```rust
impl<T> [T] {
    fn binary_search_by<'a, F>(&'a self, mut f: F) -> Result<usize, usize>
        where F: FnMut(&'a T) -> Ordering
    {
        let mut base = 0usize;
        let mut s = self;

        loop {
            let (head, tail) = s.split_at(s.len() >> 1);
            if tail.is_empty() {
                return Err(base)
            }
            match f(&tail[0]) {
                Less => {
                    base += head.len() + 1;
                    s = &tail[1..];
                }
                Greater => s = head,
                Equal => return Ok(base + head.len()),
            }
        }
    }

    fn binary_search(&self, x: &T) -> Result<usize, usize> where T: Ord {
        self.binary_search_by(|p| p.cmp(x))
    }
}
```

- high-level implementation working with subslices instead of explicit indicing
- transitively uses
  - 5 traits
  - 6 structs and enums
  - 7 functions

Verifying std::[T]::binary_search: Output

```
section
  parameters {F : Type₁} {T : Type₁}
  parameters [«ops.FnMut F (T)» : ops.FnMut F (T) (cmp.Ordering)]
  parameters (selfₐ : (slice T)) (fₐ : F)

  definition «[T] as core.slice.SliceExt».binary_search_by.loop_4 (state__ : F × usize × (slice T))
  ↪     : sem (sum (F × usize × (slice T)) ((result.Result usize usize))) :=
  ...

  definition «[T] as core.slice.SliceExt».binary_search_by : sem ((result.Result usize usize)) :=
  let' self ← (selfₐ);
  let' f ← (fₐ);
  let' base ← ((0 : nat));
  let' t1 ← (self);
  let' s ← (t1);
  loop («[T] as core.slice.SliceExt».binary_search_by.loop_4) (f, base, s)
end

...

structure cmp.Ord [class] (Self : Type₁)  extends cmp.Eq Self, cmp.PartialOrd Self Self :=
(cmp : Self → Self → sem ((cmp.Ordering)))

definition «[T] as core.slice.SliceExt».binary_search {T : Type₁} [«cmp.Ord T» : cmp.Ord T] (selfₐ :
  ↪     (slice T)) (xₐ : T) : sem ((result.Result usize usize)) :=
let' self ← (selfₐ);
let' x ← (xₐ);
let' t0 ← (self);
let' t2 ← (x);
let' t1 ← ((λ upvarsₐ pₐ, let' p ← (pₐ);
let' t0 ← (p);
let' t1 ← ((upvarsₐ));
dostep «$tmp» ← @cmp.Ord.cmp _ «cmp.Ord T» (t0) (t1);
let' ret ← «$tmp»;
return ret) (t2));
dostep «$tmp» ← @«[T] as core.slice.SliceExt».binary_search_by _ _ fn (t0) (t1);
let' ret ← «$tmp»;
return (ret)
```

Verifying std::[T]::binary_search: Proof

```
/- fn binary_search(&self, x: &T) -> Result<usize, usize> where T: Ord

Binary search a sorted slice for a given element.

If the value is found then Ok is returned, containing the index of the matching element;
if the value is not found then Err is returned, containing the index where a matching element could
be inserted while maintaining sorted order.-/
inductive binary_search_res : Result usize usize → Prop :=
| found     : Πi, nth self i = some needle → binary_search_res (Result.Ok i)
| not_found : Πi, needle ∉ self → sorted le (insert_at self i needle) →
  binary_search_res (Result.Err i)

...

theorem binary_search.spec :
  ∃₀f ∈ 𝒪(λp, log₂ p.1 * p.2) [at ∞ × ∞],
  ∀(self : slice T) (needle : T), sorted le self → sem.terminates_with_in
    (binary_search_res self needle)
    (f (length self, Ord'.cmp_max_cost needle self))
    (binary_search self needle) :=
...
```

Associated Types

```
pub trait Add<RHS=Self> {
    type Output;
    fn add(self, rhs: RHS) -> Self::Output;
}

impl Add for u32 {
    type Output = u32;
    fn add(self, rhs: u32) -> u32 { self + rhs }
}

...

fn add3<T : Add>(a: T, b: T, c: T::Output) -> <T::Output as Add>::Output
    where T::Output: Add {
    a + b + c
}

fn add3_<T : Add<Output=T>>(a: T, b: T, c: T) -> T { a + b + c }
```

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fn add3_<T : Add<Output=T>>(a: T, b: T, c: T) -> T { a + b + c }
```

```
structure ops.Add [class] (Self : Type₁) (RHS : Type₁) (Output : Type₁) :=
(add : Self → RHS → sem (Output))

definition «u32 as core.ops.Add».add (selfₐ : u32) (otherₐ : u32) : sem (u32) := ...

definition «u32 as core.ops.Add» [instance] := ⦃
  ops.Add u32 u32 u32,
  add := «u32 as core.ops.Add».add
⦄

...

definition add3 {T : Type₁} (Output : Type₁) [«core.ops.Add T T» : core.ops.Add T T Output] (Output :
  ↪    Type₁) [«core.ops.Add Output Output» : core.ops.Add Output Output Output] (aₐ : T) (bₐ : T)
  ↪    (cₐ : Output) : sem (Output) := ...

definition add3_ {T : Type₁} [«core.ops.Add T T» : core.ops.Add T T T] (aₐ : T) (bₐ : T) (cₐ : T) :
  ↪    sem (T) := ...
```

Returning &mut

```
impl<T> [T] {
    unsafe fn get_unchecked_mut(&mut self, index: usize) -> &mut T {
        &mut *self.as_mut_ptr().offset(index as isize)
    }
}
```

```
structure lens (Outer Inner : Type₁) :=
(get : Outer → sem Inner)
(set : Outer → Inner → sem Outer)

definition lens.index [constructor] (Inner : Type₁) (index : ℕ) : lens (list Inner) Inner :=
⦃lens,
  get := λ self, sem.lift_opt (list.nth self index),
  set := λ self, sem.lift_opt  list.update self index⦄

...

definition «[T]».get_unchecked_mut {T : Type₁} (self : slice T) (index : usize) :
  sem (lens (slice T) T × slice T) :=
return (lens.index _ index, self)
```

Conclusion and Future Work

- a tool for verifying real-world Rust code
- correctness proof of a central stdlib algorithm

- next step: find a new algorithm to verify!
- possible enhancement: different monad stacks for e.g. complexity analysis, global side effects, ...
- maybe allow some restricted forms of unsafe code

`github.com/Kha/electrolysis`