Electrolysis

Simple Verification of Rust Programs via Functional Purification

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OPLSS 2016

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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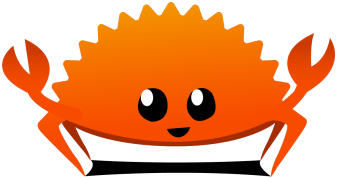

Why Rust: Because It's Almost Pure Already

- turn destructive updates into functional ones

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

- references: save value instead of pointer, write back at end of lifetime

```
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 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
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) :=
...
```

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`