Sisyphus:
Mostly Automated Proof Repair for Verified Libraries

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Pictured: OCaml programmer fixing a broken Coq proof

Let’s write a program!

Let’s write a *verified* program!

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Q: Convert a sequence to an array.

OCaml's `'a Seq.t` datatype

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type 'a t    = unit -> 'a node
and  'a node = Nil
             | Cons of 'a * (unit -> 'a node)
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A *thunked* tail

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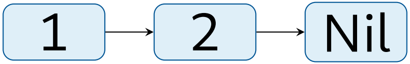

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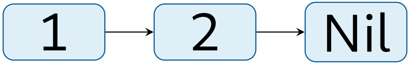

```
fun () -> Cons (1, fun () -> Cons (2, fun () -> Nil))
```

Let’s write a verified program!

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Let’s write
some code!

```
let to_array s =
```

```
let to_array s =
  match s () with
```

```
let to_array s =
  match s () with
  | Nil ->
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```
let to_array s =
  match s () with
  | Nil -> [| |]
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```
let to_array s =
  match s () with
  | Nil -> [| |]
  | Cons (h, _) ->
```

```
let to_array s =
  match s () with
  | Nil -> [| |]
  | Cons (h, _) ->
    let sz = length s in
```

```
let to_array s =
  match s () with
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    let sz = length s in
    let a = make sz h in
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let to_array s =
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Let’s write a verified program!

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$$\exists a,\ \{a \mapsto \mathsf{Array}\ \ell\}$$

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“a” **points-to** an array

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Using CFML2 verification library

Charguéraud (2023)

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Qed.

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Conclusion:

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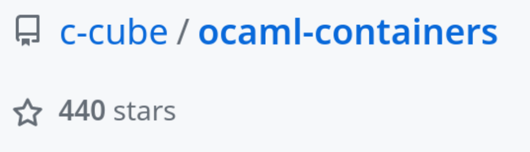
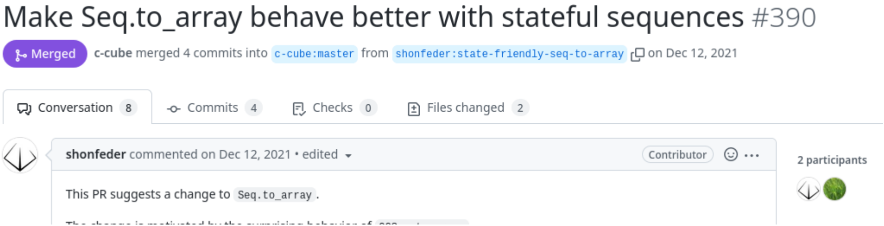


c-cube / **ocaml-containers**

440 stars

A problem arises…



Make Seq.to_array behave better with stateful sequences #390

c-cube merged 4 commits into `c-cube:master` from `shonfeder:state-friendly-seq-to-array` on Dec 12, 2021

shonfeder commented on Dec 12, 2021 • edited

This PR suggests a change to `Seq.to_array`.

The change is motivated by the surprising behavior of

Old

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New

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let to_array s =
  let sz, ls = fold_left
    (fun (i, acc) x ->
      (i+1, x::acc))
    (0, []) l in
  match ls with
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Completely different implementation…

…proof must be redone.

Writing verified code is hard...

Maintaining

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Proof Repair

Maintaining ~~Writing~~ verified code is hard...

Proof Repair

Ringer (2021)

Maintaining

~~Writing~~ verified code is hard...

...can we make it easier?

Maintaining ~~Writing~~ verified code is hard…

…can we make it easier?

Yes!

This Work

Sisyphus

Mostly automated *proof-repair* for OCaml programs

Outline

1. Motivation

2. Key Challenges & Solutions

3. Evaluation

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How to generate a proof script?

Observation: proofs are syntax-directed

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How to fill in holes?

Key challenges for proof repair

① *Generating* candidate invariants

② *Choosing* valid invariants

Key challenges for proof repair

1. *Generating* candidate invariants
2. *Choosing* valid invariants

How to generate invariants?

How to generate invariants?

Use the old program and proofs!

Generating candidate invariants

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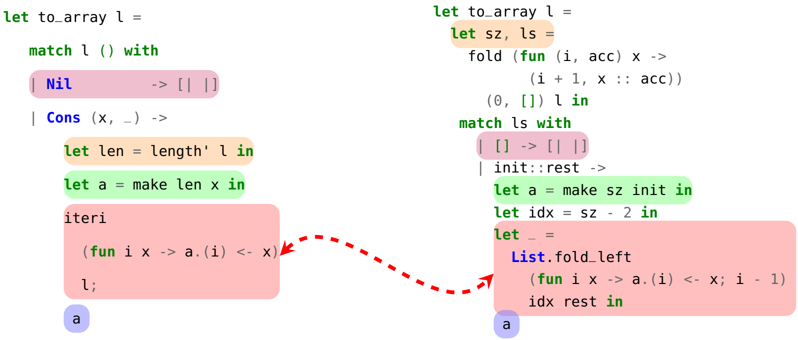
Generating candidate invariants



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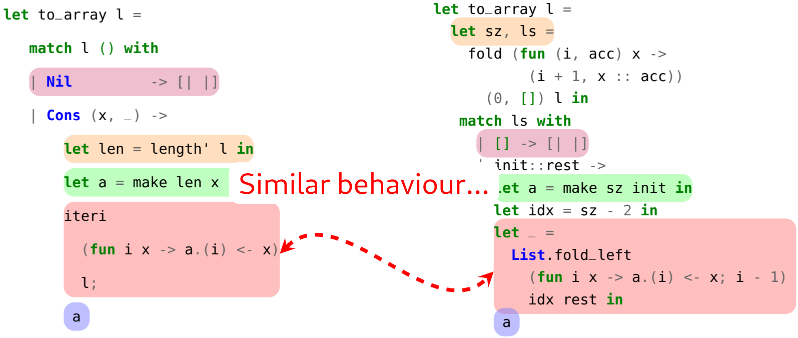
Generating candidate invariants



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Generating candidate invariants

Q: How to discover these similarities automatically?

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Generating candidate invariants

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A: Instrumentation based dynamic analysis

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Generating candidate invariants

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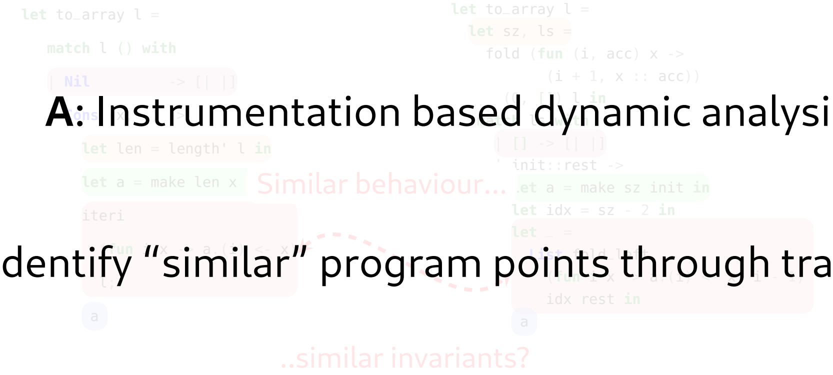

A: Instrumentation based dynamic analysis

Identify “similar” program points through traces.

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Seq.of_list [1; 2; 3]

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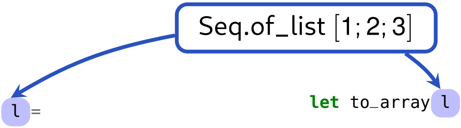

Seq.of_list [1; 2; 3]

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   | Cons (x, _) ->
       let len = length' l in
       let a = make len x in
       iteri
         (fun i x -> a.(i) <- x)
         l;
       a
```

3

[|1; 1; 1|]

[|1; 2; 3|]

```
let to_array l =
  let sz, ls =
    fold (fun (i, acc) x ->
           (i + 1, x :: acc))
      (0, []) l in
   match ls with
     | [] -> [| |]
     | init::rest ->
       let a = make sz init in
       let idx = sz - 2 in
       let _ =
         List.fold_left
           (fun i x -> a.(i) <- x; i - 1)
           idx rest in
       a
```

3

Seq.of_list [1; 2; 3]

```
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3

[|1; 1; 1|]

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           (fun i x -> a.(i) <- x; i - 1)
           idx rest in

       a
```

3

[|3; 3; 3|]

Seq.of_list [1; 2; 3]

```
let to_array l =
   match l () with
   | Nil         -> [| |]
   | Cons (x, _) ->
       let len = length' l in
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         l;
       a
```

3

[|1; 1; 1|]

[|1; 2; 3|]

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           idx rest in
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```

3

[|3; 3; 3|]

Seq.of_list [1; 2; 3]

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let to_array l =

   match l () with

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       a
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3

[|1; 1; 1|]

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3

[|3; 3; 3|]

Seq.of_list [1; 2; 3]

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3

[|1; 1; 1|]

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       a
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3

[|3; 3; 3|]

[|1; 2; 3|]

Seq.of_list [1; 2; 3]

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3

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```

3

[|3; 3; 3|]

[|1; 2; 3|]

Seq.of_list [1; 2; 3]

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3

[|3; 3; 3|]

[|1; 2; 3|]

Seq.of_list [1; 2; 3]

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[|1; 1; 1|]

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3

[|3; 3; 3|]

[|1; 2; 3|]

Seq.of_list [1; 2; 3]

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       let idx = sz - 2 in
       let _ =
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           (fun i x -> a.(i) <- x; i - 1)
           idx rest in
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3

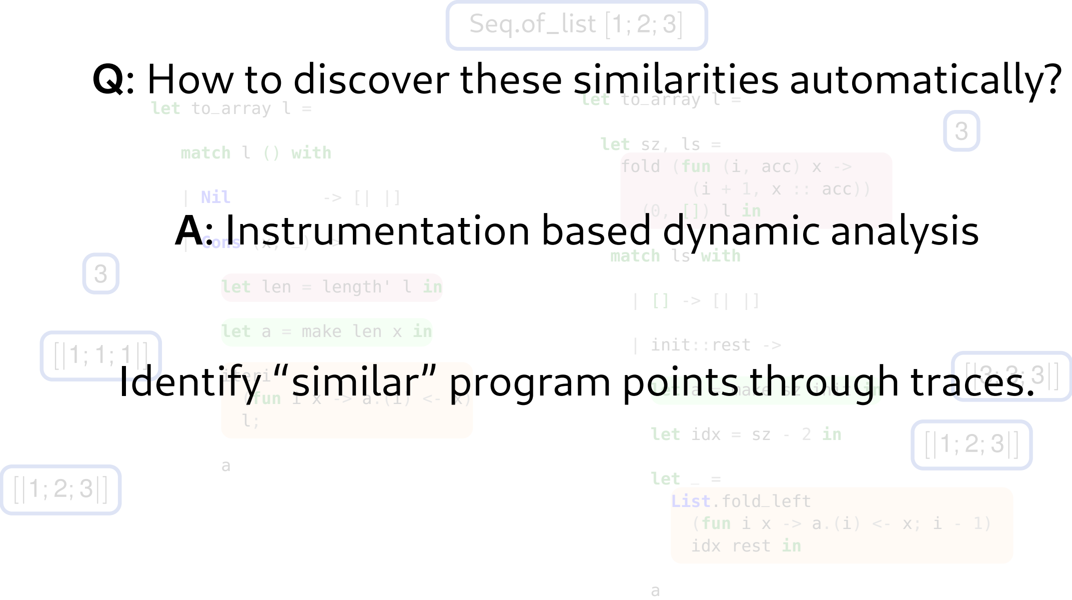
[|3; 3; 3|]

[|1; 2; 3|]

Q: How to discover these similarities automatically?

A: Instrumentation based dynamic analysis

Identify "similar" program points through traces.

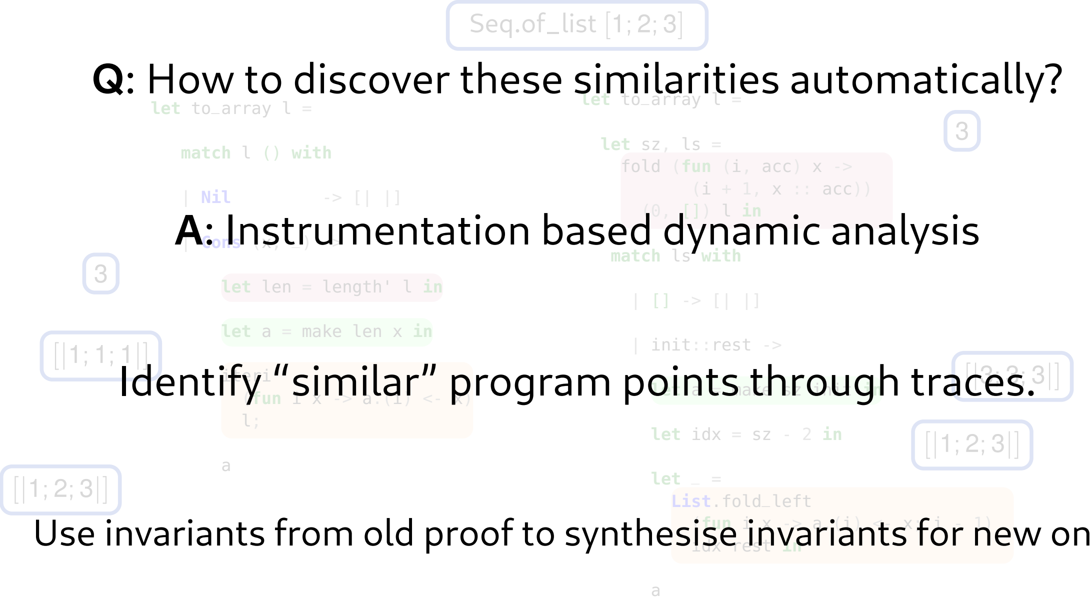


Q: How to discover these similarities automatically?

A: Instrumentation based dynamic analysis

Identify “similar” program points through traces.

Use invariants from old proof to synthesise invariants for new one.



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```

Old Invariant:

$$a \mapsto \texttt{Array}(t \mathbin{+\!\!+} \mathit{drop}\ (\mathit{length}\ t)\ (\mathit{make}\ (\mathit{length}\ \ell)\ h))$$

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New Invariant:

Old Invariant:

$$a \mapsto \texttt{Array}(t \mathbin{++} \mathit{drop}\ (\mathit{length}\ t)\ (\mathit{make}\ (\mathit{length}\ \ell)\ h))$$

New Invariant:

```
(fun acc t => a ↦
   Array (repeat (acc + 1) init ++
          drop (acc + 1) ℓ))
```

(1)

Old Invariant:

$$a \mapsto \texttt{Array}(t \mathbin{+\!\!+} drop\ (length\ t)\ (make\ (length\ \ell)\ h))$$

New Invariant:

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(fun acc t => a ↦
   Array (repeat (acc + 1) init ++        • • •
          drop (acc + 1) ℓ))
```

(1)

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```

(1)

• • •

```
(fun acc t => a ↦
   Array ([] ++ drop 0
    (repeat (length t) init)))
```

(n)

Key challenges for proof repair

① *Generating* candidate invariants

② *Choosing* valid invariants

Key challenges for proof repair

1. *Generating* candidate invariants

2. *Choosing* valid invariants

Choosing an Invariant

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```
...
xlet idx.
xapp (fold_left_spec idx rest
(fun acc t =>
  (??)  )).
...
```

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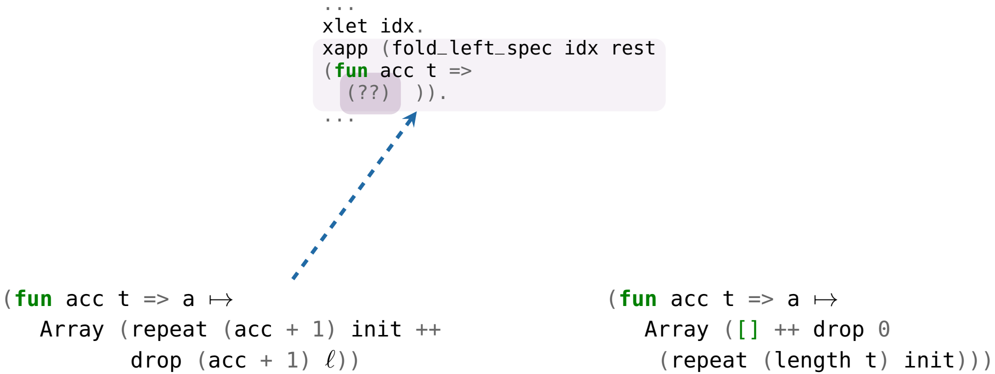
Choosing an Invariant



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Choosing an Invariant

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Which one?

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(fun acc t => a ↦
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```
...
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Validate using SMT?

Which one?

```
(fun acc t => a ↦
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Choosing an Invariant

```
...
xlet idx.
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  (??)  )).
...
```

Validate using SMT?

Which one?

Too slow!

```
(fun acc t => a ↦
   Array (repeat (acc + 1) init ++
          drop (acc + 1) ℓ))
```

```
(fun acc t => a ↦
   Array ([] ++ drop 0
    (repeat (length t) init)))
```

Choosing an Invariant

```
...
xlet idx.
xapp (fold_left_spec idx rest
(fun acc t =>
  (??)  )).
...
```

If only we could *test*...

Which one?

```
(fun acc t => a ↦
   Array (repeat (acc + 1) init ++
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```
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Choosing an Invariant

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xlet idx.
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Depends on
logical parameters!

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Choosing an Invariant

```
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Choosing an Invariant

```
...
xlet idx.
xapp (fold_left_spec idx rest
(fun acc t =>
  (??)  )).
...
```

Verified Fold Left

```
let fold_left f acc ls    =

  match ls with
  | [] ->

    acc
  | h :: tl ->

    let acc' = f acc h in

    fold_left f acc' tl
```

Verified Fold Left

```
let fold_left f acc ls t =

  match ls with
  | [] ->

    acc
  | h :: tl ->

    let acc' = f acc h in

    fold_left f acc' tl
```

Verified Fold Left

```
let fold_left f acc ls t l =

  match ls with
  | [] ->

    acc
  | h :: tl ->

    let acc' = f acc h in

    fold_left f acc' tl
```

Verified Fold Left

```
let fold_left f acc ls t I =
  {I acc t}
  match ls with
  | [] ->

    acc
  | h :: tl ->

    let acc' = f acc h in

    fold_left f acc' tl
```

Verified Fold Left

```
let fold_left f acc ls t l =
  {l  acc  t}
  match ls with
  | [] ->
    {l  acc  t}
    acc
  | h :: tl ->

    let acc' = f acc h in

    fold_left f acc' tl
```

Verified Fold Left

```
let fold_left f acc ls t l =
  {l  acc  t}
  match ls with
  | [] ->
    {l  acc  t}
    acc
  | h :: tl ->
    {l  acc  t}
    let acc' = f acc h in

    fold_left f acc' tl
```

Verified Fold Left

```
let fold_left f acc ls t l =
  {l acc t}
  match ls with
  | [] ->
    {l acc t}
    acc
  | h :: tl ->
    {l acc t}
    let acc' = f acc h in
    {l acc' (t ++ [h])}
    fold_left f acc' tl
```

Verified Fold Left

```
let fold_left f acc ls t l =
  {l  acc  t}
  match ls with
  | [] ->
    {l  acc  t}
    acc
  | h :: tl ->
    {l  acc  t}
    let acc' = f acc h in
    {l  acc'  (t ++ [h])}
    fold_left f acc' tl
    {l  acc''  (t ++ [h] ++ tl)}
```

Verified Fold Left

```
let fold_left f acc ls t I =
  {I  acc  t}
  match ls with
  | [] ->
    {I  acc  t}
    acc
  | h :: tl ->
    {I  acc  t}
    let acc' = f acc h in
    {I  acc'  (t ++ [h])}
    fold_left f acc' tl
    {I  acc''  (t ++ [h] ++ tl)}
```

Describes **exactly** how *I* is maintained

Verified Fold Left

```
let fold_left f acc ls t l =
  {l  acc  t}
  match ls with
  | [] ->
    {l  acc  t}
    acc
  | h :: tl ->
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    let acc' = f acc h in
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    fold_left f acc' tl
    {l  acc''  (t ++ [h] ++ tl)}
```

Verified Fold Left

```
let fold_left f acc ls t I =
  assert {I  acc  t}
  match ls with
  | [] ->
    assert {I  acc  t}
    acc
  | h :: tl ->
    assert {I  acc  t}
    let acc' = f acc h in
    assert {I  acc'  (t ++ [h])}
    fold_left f acc' tl
    assert {I  acc''  (t ++ [h] ++ tl)}
```

Verified Fold Left

```
let fold_left f acc ls t l =
  assert {I acc t}
  match ls with
  | [] ->
    assert {I acc t}
    ac
    h
    assert {I acc t}
    let acc' = f acc h in
    assert {I acc' (t ++ [h])}
    fold_left f acc' tl
    assert {I acc'' (t ++ [h] ++ tl)}
```

Proof-Driven Testing

Proof-Driven Testing

`fold_left_spec`

Proof-Driven Testing

$$\texttt{fold\_left\_spec}\ ?l\ \ f\ \ 2\ \ [2; 1]$$

Proof-Driven Testing

Instantiate with concrete arguments..

$\texttt{fold\_left\_spec}\ ?l\ \boxed{f\ \ 2\ \ [2;1]}$

Proof-Driven Testing

Instantiate with concrete arguments..

`fold_left_spec` $?l\ f\ 2\ [2; 1]$

Proof-Driven Testing

Instantiate with concrete arguments..

`fold_left_spec` $?l \; f \; 2 \; [2;1]$

...with existentials for proof arguments

Proof-Driven Testing

`fold_left_spec` $?l \ f \ 2 \ [2; 1]$

Proof-Driven Testing

`fold_left_spec` $?l\ \ f\ \ 2\ \ [2; 1]$

Proof-Driven Testing

`fold_left_spec` $?l\ \ f\ \ 2\ \ [2;1]$

reduce proof term

↓

Proof-Driven Testing

```
let fold_left f acc ls $t$ =
  $\{I \ \ acc \ \ t\}$
  match ls with
  | [] ->
    $\{I \ \ acc \ \ t\}$
    acc
  | h :: tl ->
    $\{I \ \ acc \ \ t\}$
    let acc' = f acc h in
    $\{I \ \ acc' \ \ (t ++ [h])\}$
    fold_left f acc' tl
    $\{I \ \ acc'' \ \ (t ++ [h] ++ tl)\}$
```

Proof-Driven Testing

```
let fold_left f acc ls t =
  {I 2 []}
  match ls with
  | [] ->
    {I 2 []}
    acc
  | 2 :: [1] ->
    {I 2 []}
    let acc' = f 2 2 in
    {I acc' [2]}
    fold_left f acc' tl
    {I acc'' [2, 1]}
```

Proof-Driven Testing

`fold_left_spec` $?l\ f\ 2\ [2;1]$

|

reduce proof term

↓

`(* ...reduced proof term... *)`

Proof-Driven Testing

`fold_left_spec` $?l\ f\ 2\ [2;1]$

reduce proof term

↓

`(* ...reduced proof term... *)`

custom proof extraction

↓

Proof-Driven Testing

```
let fold_left f acc ls =
  {l 2 []}
  match ls with
  | [] ->
    {l 2 []}
    acc
  | 2 :: [1] ->
    {l 2 []}
    let acc' = f 2 2 in
    {l acc' [2]}
    fold_left f acc' tl
    {l acc'' [2, 1]}
```

Proof-Driven Testing

```
assert (/ len []);
let acc = f len 2 in
assert (/ acc [2]);
let acc = f acc 1 in
assert (/ acc [2; 1]);
()
```

Proof-Driven Testing

```
assert (I len []);
let acc = f len 2 in
assert (I acc [2]);
let acc = f acc 1 in
assert (I acc [2; 1]);
()
```

Simulates concrete run of `List.fold_left`

Proof-Driven Testing

Instantiate I with embedding of candidate invariant...

```
assert (I len []);
let acc = f len 2 in
assert (I acc [2]);
let acc = f acc 1 in
assert (I acc [2; 1]);
()
```

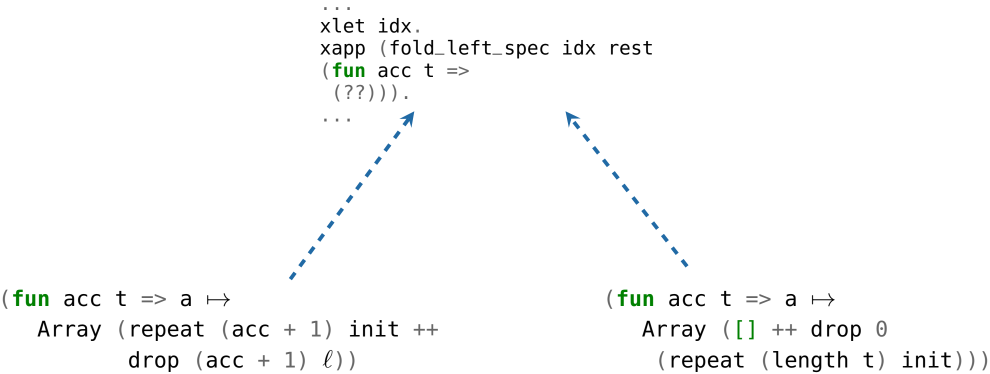
Proof-Driven Testing

Instantiate I with embedding of candidate invariant...

```
assert (I len []);
let acc = f len 2 in
assert (I acc [2]);
let acc = f acc 1 in
assert (I acc [2; 1]);
()
```

...prune candidate if assertion raised.

Testing Candidate Invariants



```
...
xlet idx.
xapp (fold_left_spec idx rest
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 (??))).
...
```

```
(fun acc t => a ↦
   Array (repeat (acc + 1) init ++
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```

```
(fun acc t => a ↦
   Array ([] ++ drop 0
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```
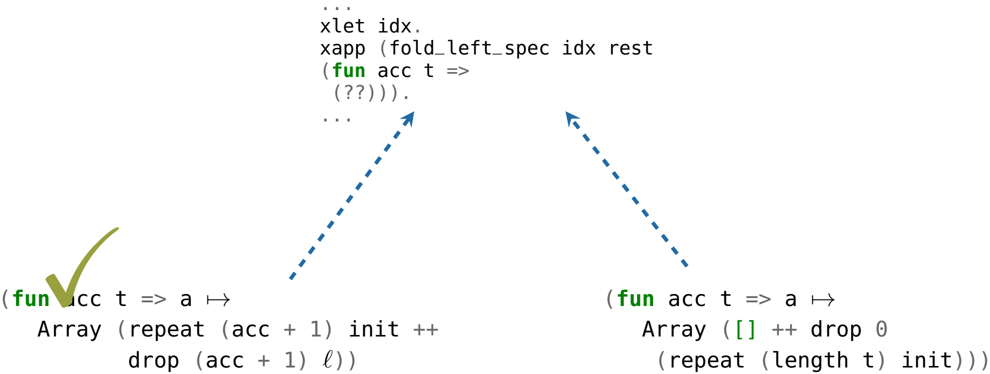

Testing Candidate Invariants



```
...
xlet idx.
xapp (fold_left_spec idx rest
(fun acc t =>
 (??))).
...
```

✓

```
(fun acc t => a ↦
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```
(fun acc t => a ↦
   Array ([] ++ drop 0
    (repeat (length t) init)))
```

Testing Candidate Invariants

```
...
xlet idx.
xapp (fold_left_spec idx rest
(fun acc t =>
 (??))).
...
```

✓

```
(fun acc t => a ↦
   Array (repeat (acc + 1) init ++
          drop (acc + 1) ℓ))
```

✗

```
(fun acc t => a ↦
   Array ([] ++ drop 0
    (repeat (length t) init)))
```

Proof-Driven Testing

Proofs are proofs

Proofs are programs

Proofs are tests

Proof are *programs*…

Proof-Driven Testing

Proof are *programs*...

but, what do they *compute*?

Proof-Driven Testing

Proofs are proofs

Proofs are programs

Proofs are tests

Proof are *programs*...

but, what do they *compute*?

Curry Howard: They establish logical facts.

Proof-Driven Testing

Proofs are proofs

Proofs are programs

Proofs are tests

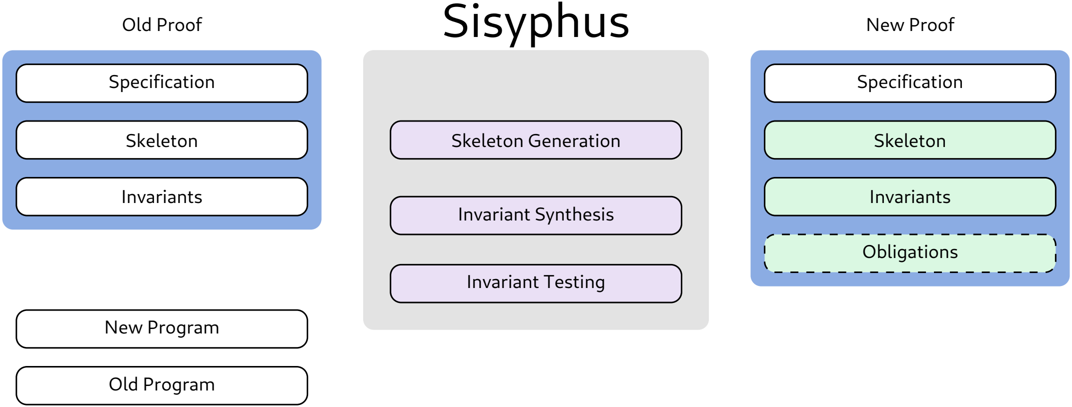
Proof are *programs*...

but, what do they *compute*?

Curry Howard: They establish logical facts.

PDT: HO-proofs describe tests!

Sisyphus



Old Proof

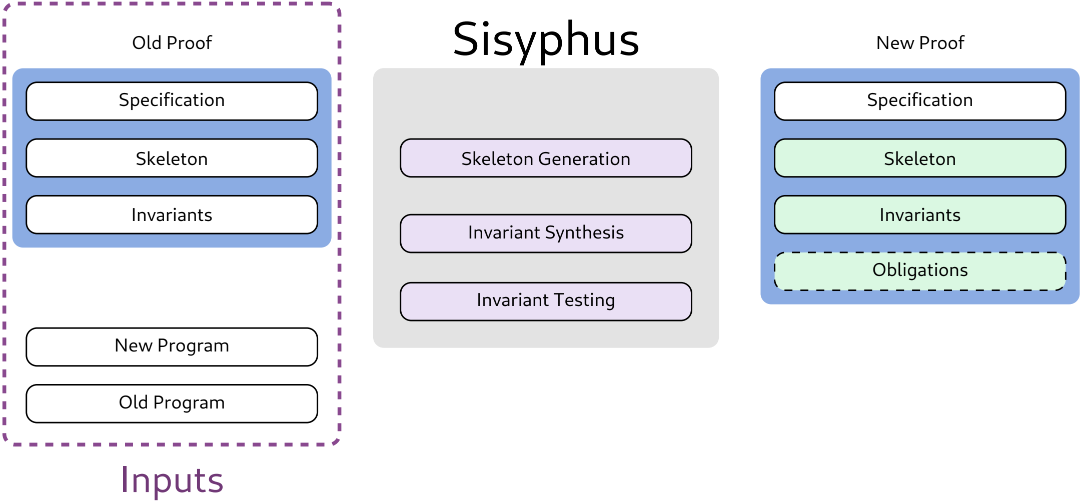
- Specification
- Skeleton
- Invariants

- New Program
- Old Program

- Skeleton Generation
- Invariant Synthesis
- Invariant Testing

New Proof

- Specification
- Skeleton
- Invariants
- Obligations



Old Proof

Specification

Skeleton

Invariants

New Program

Old Program

Inputs

Sisyphus

Skeleton Generation

Invariant Synthesis

Invariant Testing

New Proof

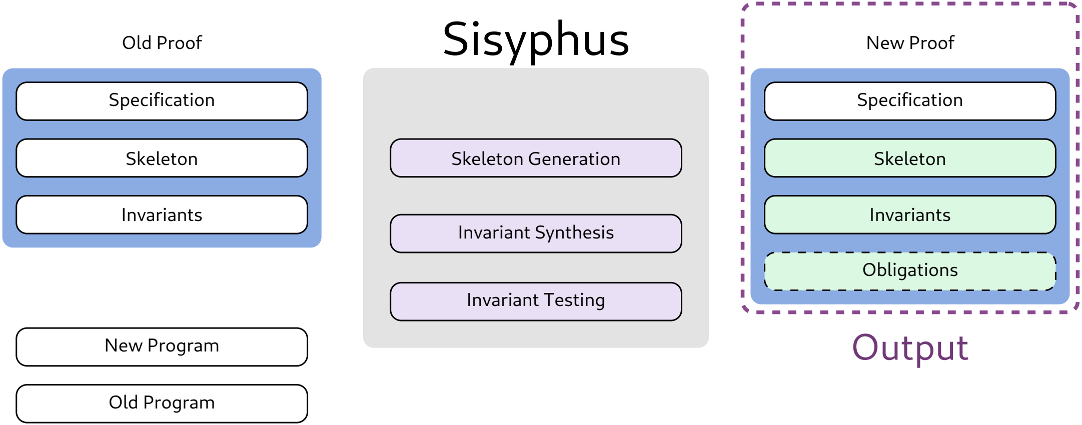
Specification

Skeleton

Invariants

Obligations

Sisyphus



Old Proof

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New Program

Old Program

Skeleton Generation

Invariant Synthesis

Invariant Testing

New Proof

- Specification
- Skeleton
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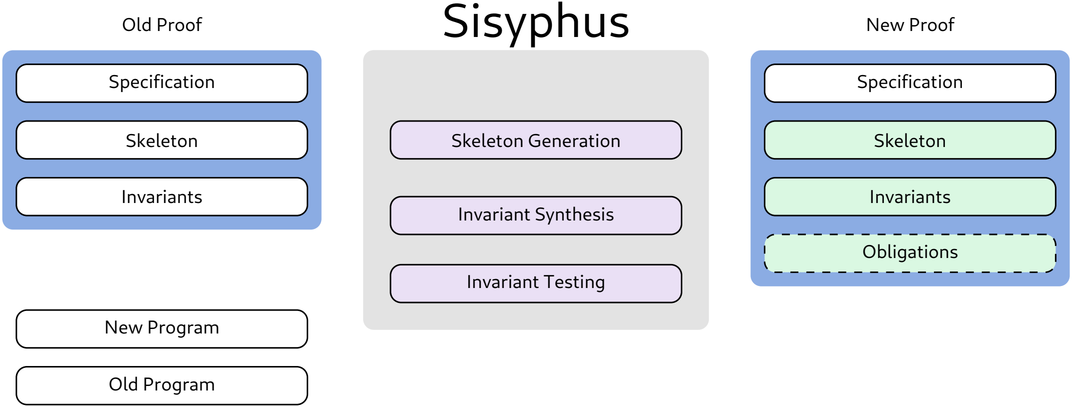
Output

Sisyphus



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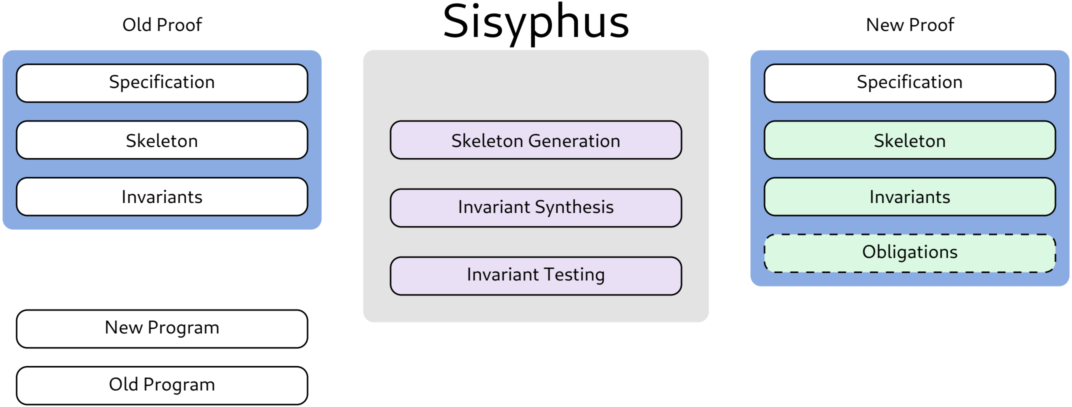

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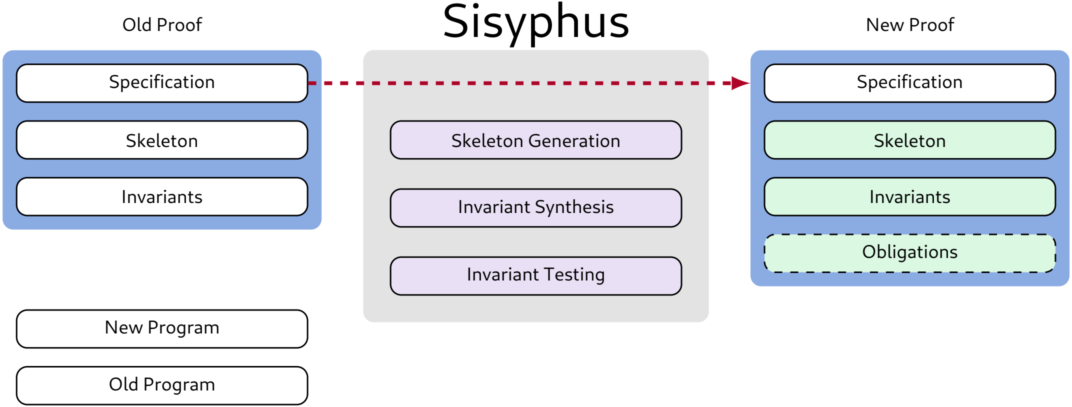

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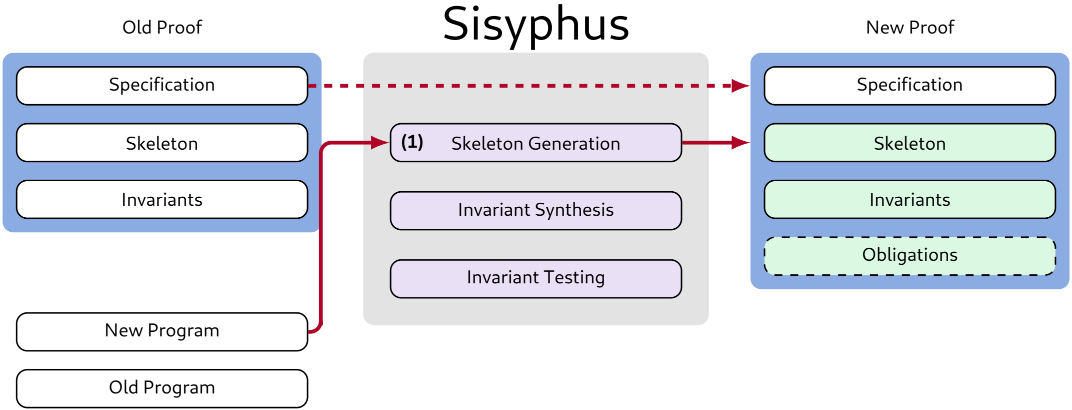

Sisyphus

Old Proof

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Old Program

(1) Skeleton Generation

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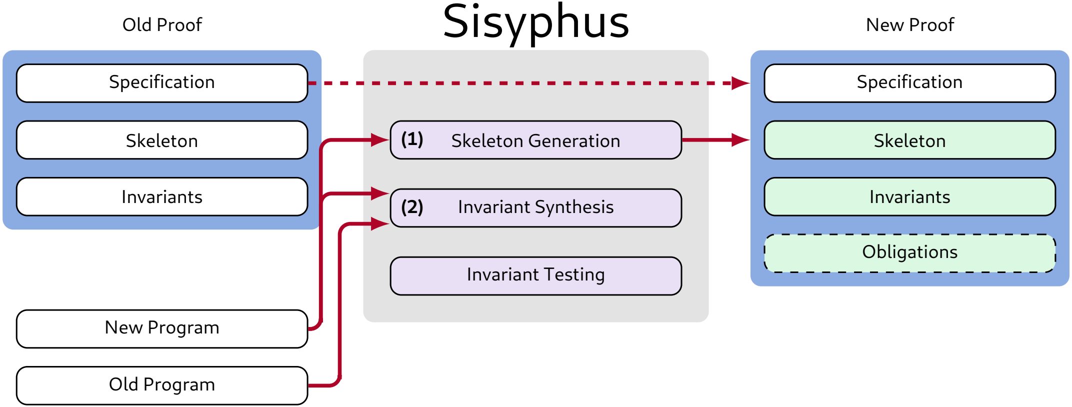

Old Proof

Specification

Skeleton

Invariants

New Program

Old Program

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(2) Invariant Synthesis

Invariant Testing

New Proof

Specification

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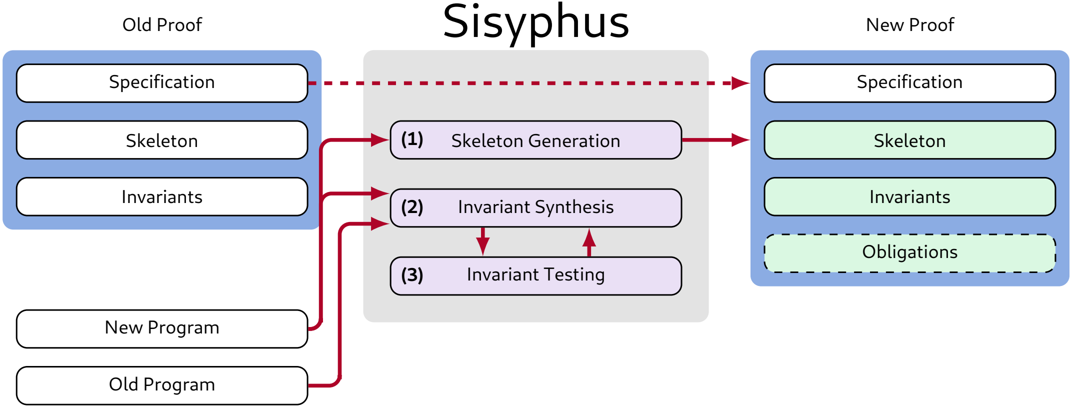

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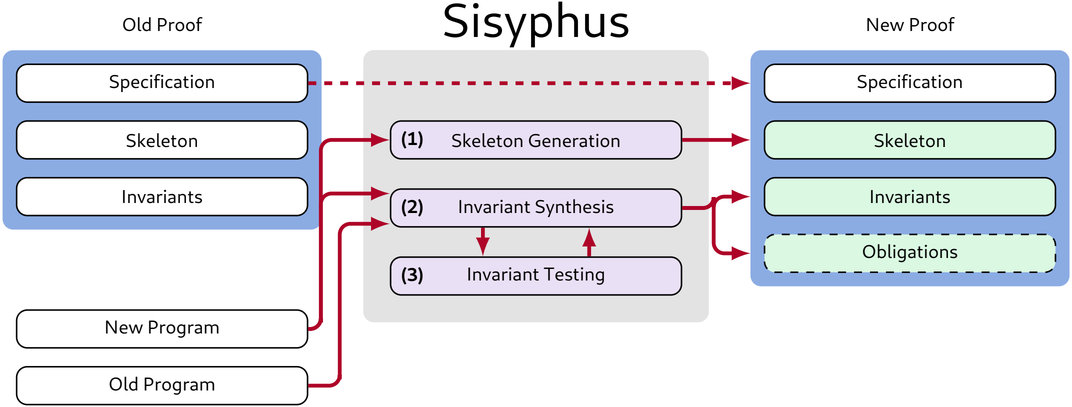

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Obligations

Outline

1. Motivation
2. Key Challenges & Solutions
3. Evaluation

Outline

1. Motivation
2. Key Challenges & Solutions
3. Evaluation

Pragmatic Concerns

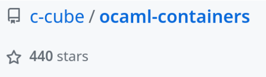
① Is Sisyphus effective at repairing proofs?

② Does Sisyphus repair proofs in reasonable time?

Benchmark Programs

- 14 OCaml programs and their changes
- 10 from real-world OCaml codebases
- ...such as `containers` or Jane Street's `core`

Benchmark Programs


c-cube / **ocaml-containers**

☆ 440 stars

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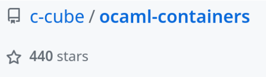
Benchmark Programs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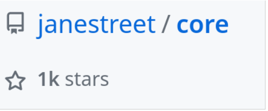
janestreet / **core**

☆ 1k stars

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Benchmark Programs

Example	Data Structure	Refactoring
Seq to array	Array, Seq	IterOrd, DataStr
Make rev list†	Ref	Mutable/Pure
Tree to array†	Array, Tree	IterOrd, DataStr
Array exists	Array	Mutable/Pure
Array find mapi	Array, Ref	Pure/Mutable
Array is sorted	Array	Pure/Mutable
Array findi	Array	Pure/Mutable
Array of rev list	Array	DataStr
Array foldi	Array	Pure/Mutable
Array partition	Array	DataStr
Stack filter‡	Stack	DataStr
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Sll partition‡	SLL	Mutable/Pure, IterOrd
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Benchmark Programs

Array

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Benchmark Programs

Array

Seq

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Benchmark Programs

Array

Stack

Seq

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SLL

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Benchmark Programs

Array

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Tree

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Benchmark Programs

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Benchmark Programs

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Seq

Iteration Order

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Benchmark Programs

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Iteration Order

Pure to Mutable

Benchmark Programs

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Pure to Mutable

Mutable to Pure

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Benchmark Programs

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RQ1: Effectiveness of proof repair

Name	# Admits / # Obligations	Time (old)	Time (new)
Seq to array	3 / 5	2hrs	17m
Make rev list	0 / 2	10m	-
Tree to array	2 / 4	5hrs	18m
Array exists	2 / 4	30m	12m
Array find mapi	2 / 5	1.5hrs	12m
Array is sorted	2 / 5	4hrs	2m
Array findi	3 / 7	1.5hrs	9m
Array of rev list	2 / 3	1hr	3m
Array foldi	0 / 1	15m	-
Array partition	3 / 3	2.5hrs	5m
Stack filter	3 / 3	1.5hrs	11m
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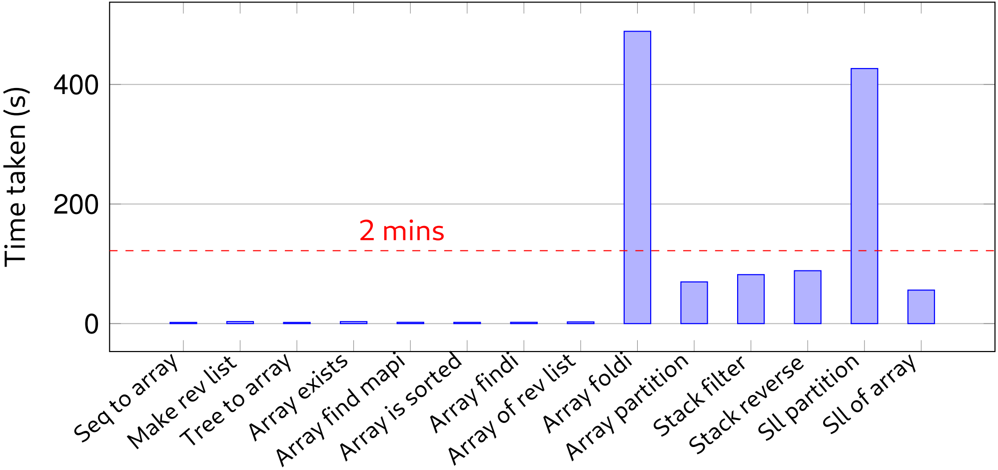
RQ2: Efficiency of proof repair



RQ2: Efficiency of proof repair

Example	Time (s)				Total (s)
	Generation	Extraction	Testing	Remaining	
seq_to_array	28.57	1.95	20.36	5.28	58
make_rev_list	$\leq 10ms$	3.36	$\leq 10ms$	11.95	15
tree_to_array	6.75	1.95	2.98	13.32	25
array_exists	$\leq 10ms$	3.30	$\leq 10ms$	13.23	17
array_find_mapi	$\leq 10ms$	2.13	$\leq 10ms$	13.95	17
array_is_sorted	$\leq 10ms$	2.04	$\leq 10ms$	15.38	18
array_findi	$\leq 10ms$	2.13	$\leq 10ms$	19.07	22
array_of_rev_list	1.72	2.82	0.96	15.62	21
array_foldi	$\leq 10ms$	488.89	$\leq 10ms$	15.00	504
array_partition	3.51	69.73	2.62	17.53	95
stack_filter	$\leq 10ms$	81.88	$\leq 10ms$	21.53	104
stack_reverse	$\leq 10ms$	88.42	$\leq 10ms$	16.94	105
sll_partition	$\leq 10ms$	426.62	$\leq 10ms$	16.43	443
sll_of_array	0.02	55.98	0.01	13.33	69

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To Take Away

1. Building blocks for *new proof* found in *old proof*

2. *Picking* a correct invariant is hard!

3. A new take on Curry-Howard: *Proof-Driven Testing*

To Take Away

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Thanks!

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Thanks!

Backup Slides

RQ3: Failure Modes

- Repair assumes components from old proof are sufficient for new one.
- Quality of repair degrades when this fails to hold.

e.g. `array_partition`'s pure obligations required fact

$$\texttt{filter}\, p\, (\texttt{filter}\, p\, \ell) = \texttt{filter}\, p\, \ell$$

not present in original proof.

RQ3: Failure Modes

```
let to_array s =
  let batches = (* .. *) in
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RQ3: Failure Modes

Invariant requires *flattening* operation...

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...not present in old proof.