Fast Synthesis of Fast Collections

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Data structures are everywhere

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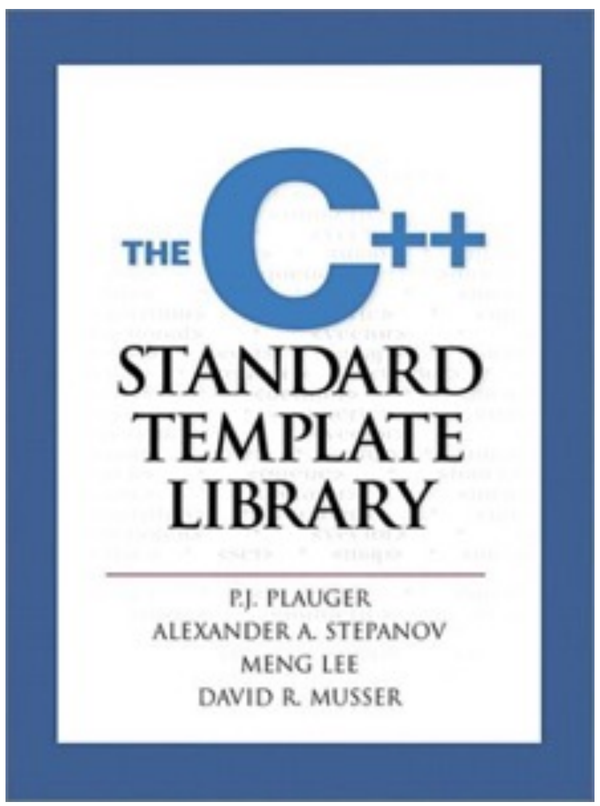

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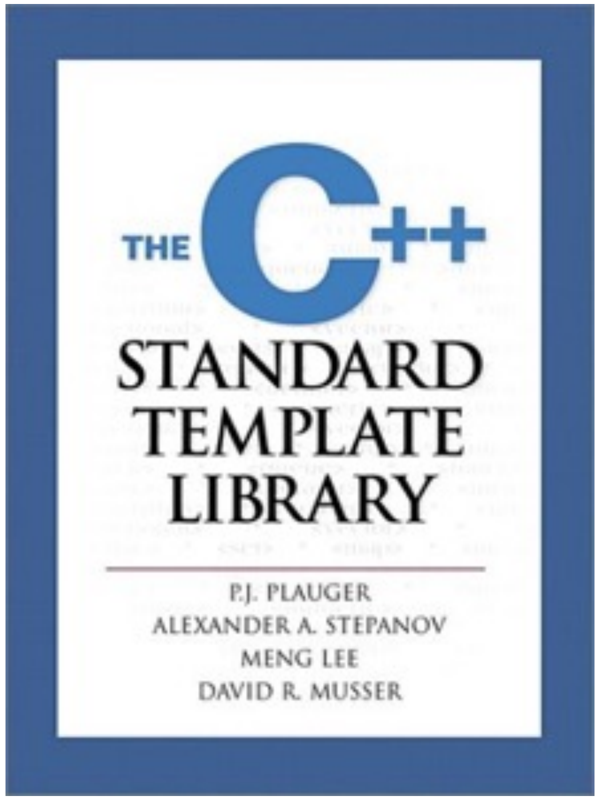

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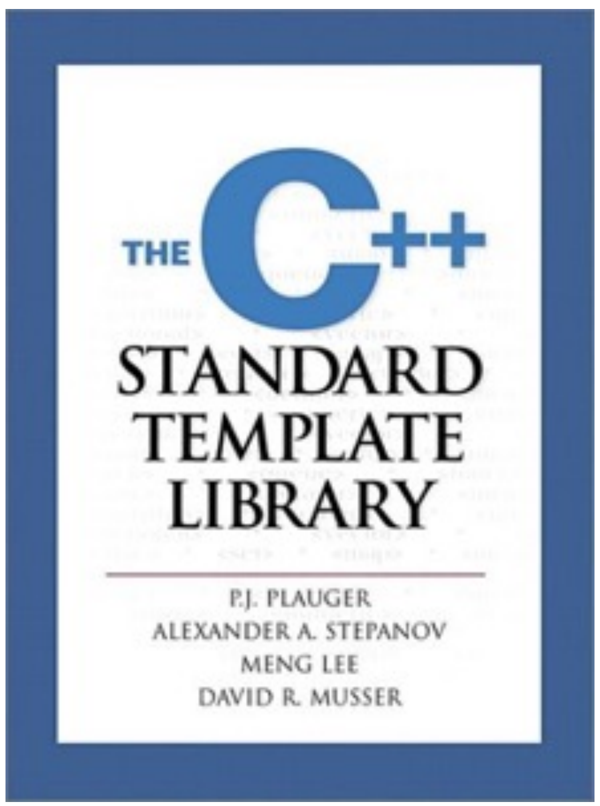


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The Collections Framework

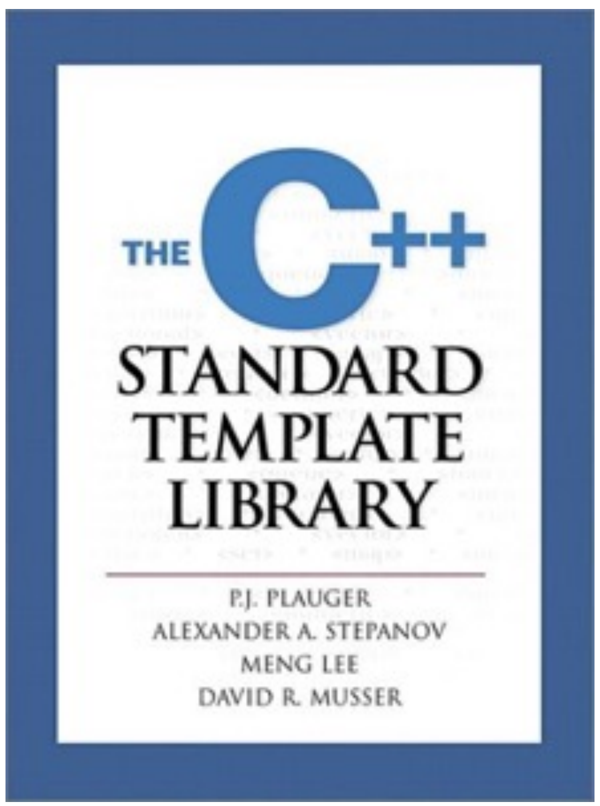
The collections framework is a unified architecture for representin
increasing performance. It enables interoperability among unrelate


8.3. collections — Container datatypes

Source code: Lib/collections/__init__.py

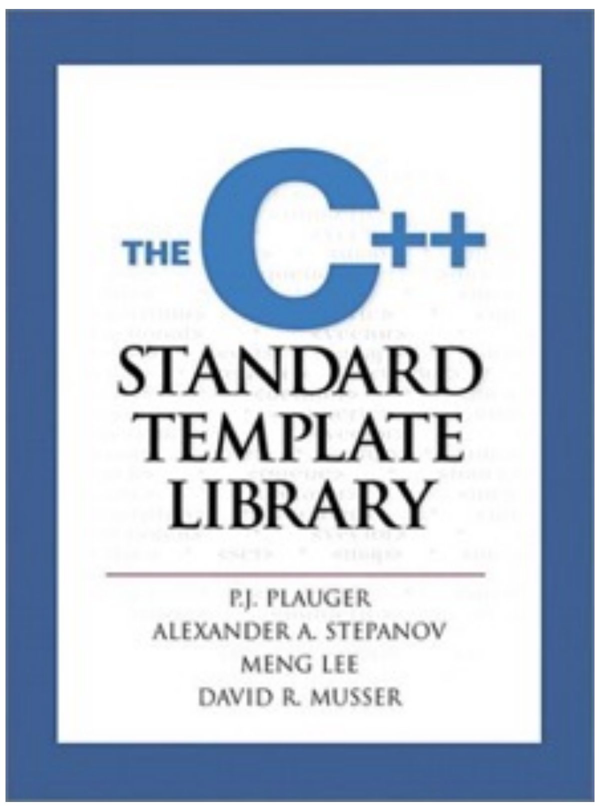
This module implements specialized container datatypes prov
to Python's general purpose built-in containers, dict, list, se

Data structures are everywhere



Lists, maps, and sets solve many problems

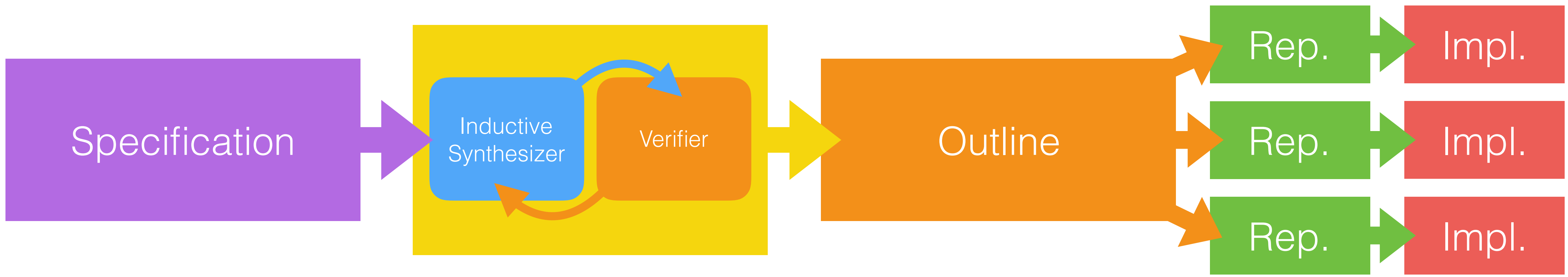
Data structures are everywhere



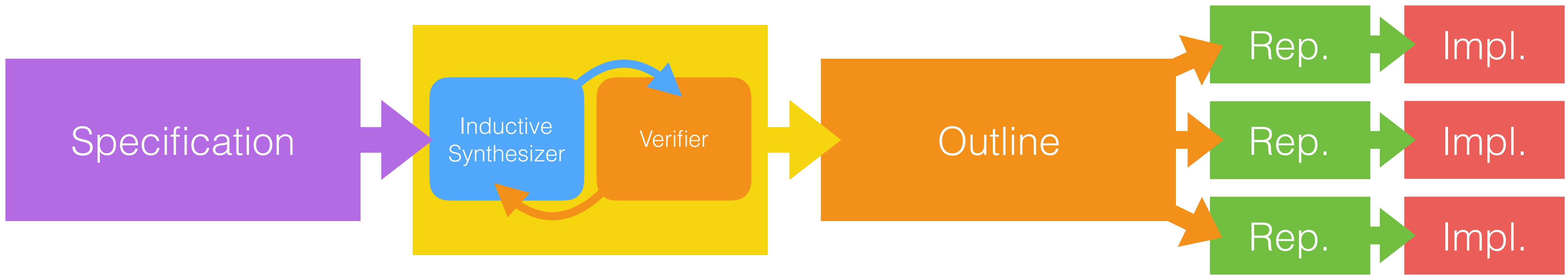
Lists, maps, and sets solve many problems

What if I need a custom data structure?

Cozy synthesizes collections

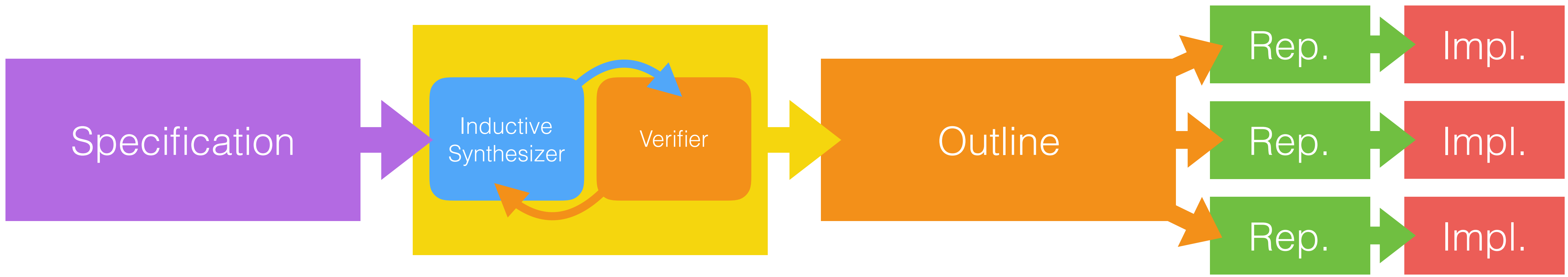


Cozy synthesizes collections



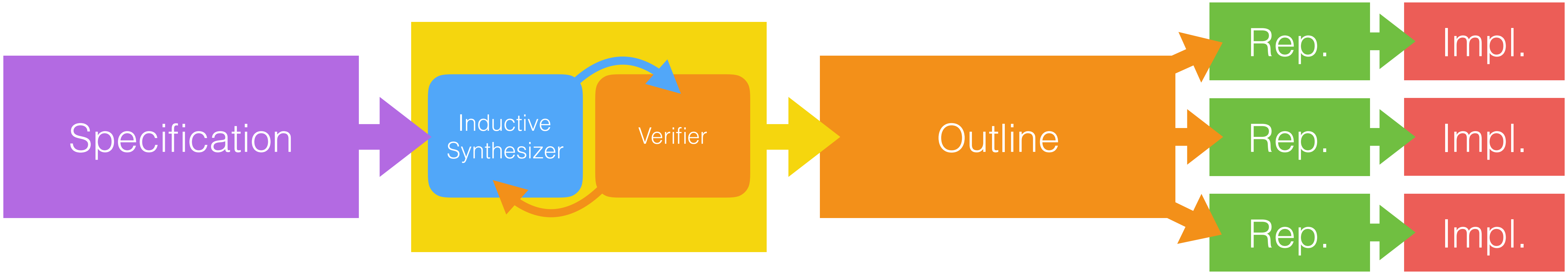
- Correct by construction

Cozy synthesizes collections



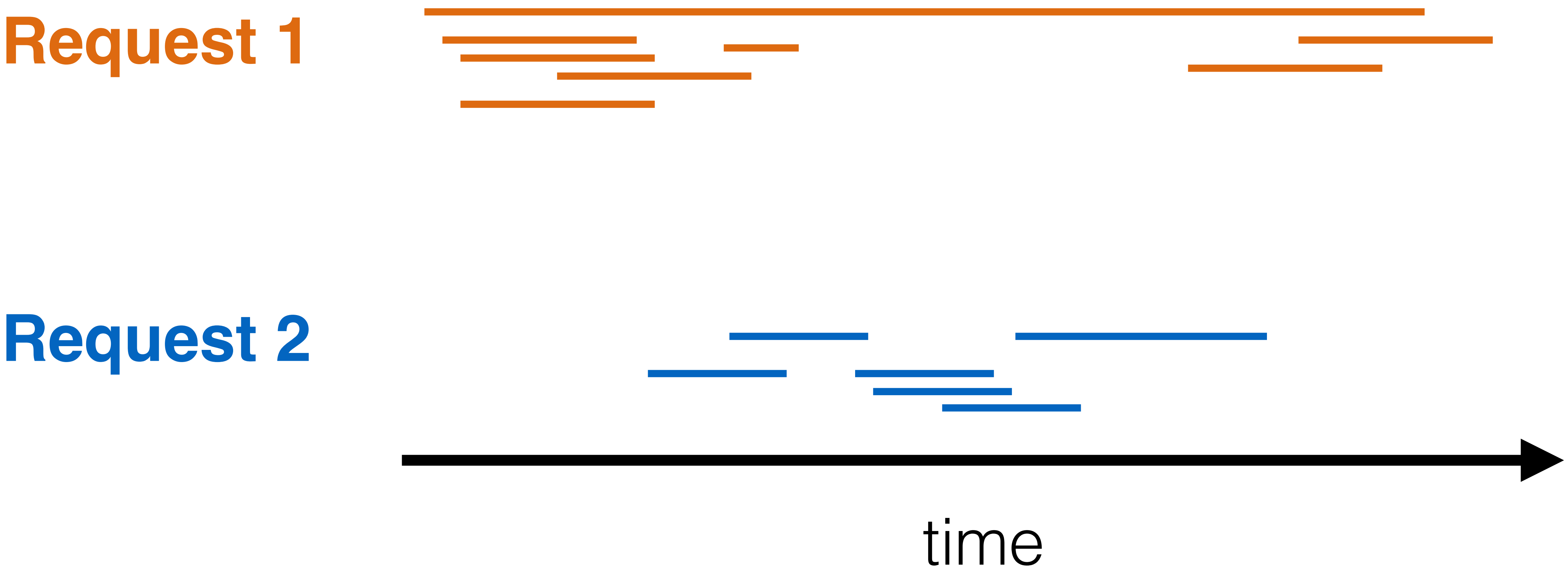
- Correct by construction
- Specifications orders-of-magnitude shorter than implementations, synthesized in < 90 seconds

Cozy synthesizes collections



- Correct by construction
- Specifications orders-of-magnitude shorter than implementations, synthesized in < 90 seconds
- Equivalent performance to human-written code

Myria Analytics Storage



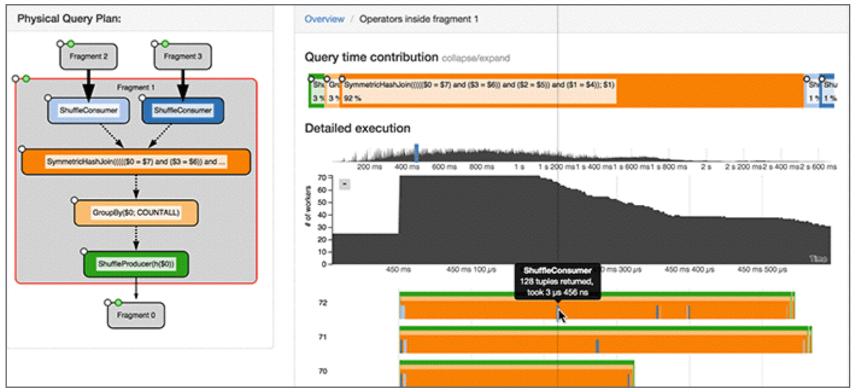
Myria Analytics Storage

Request 1

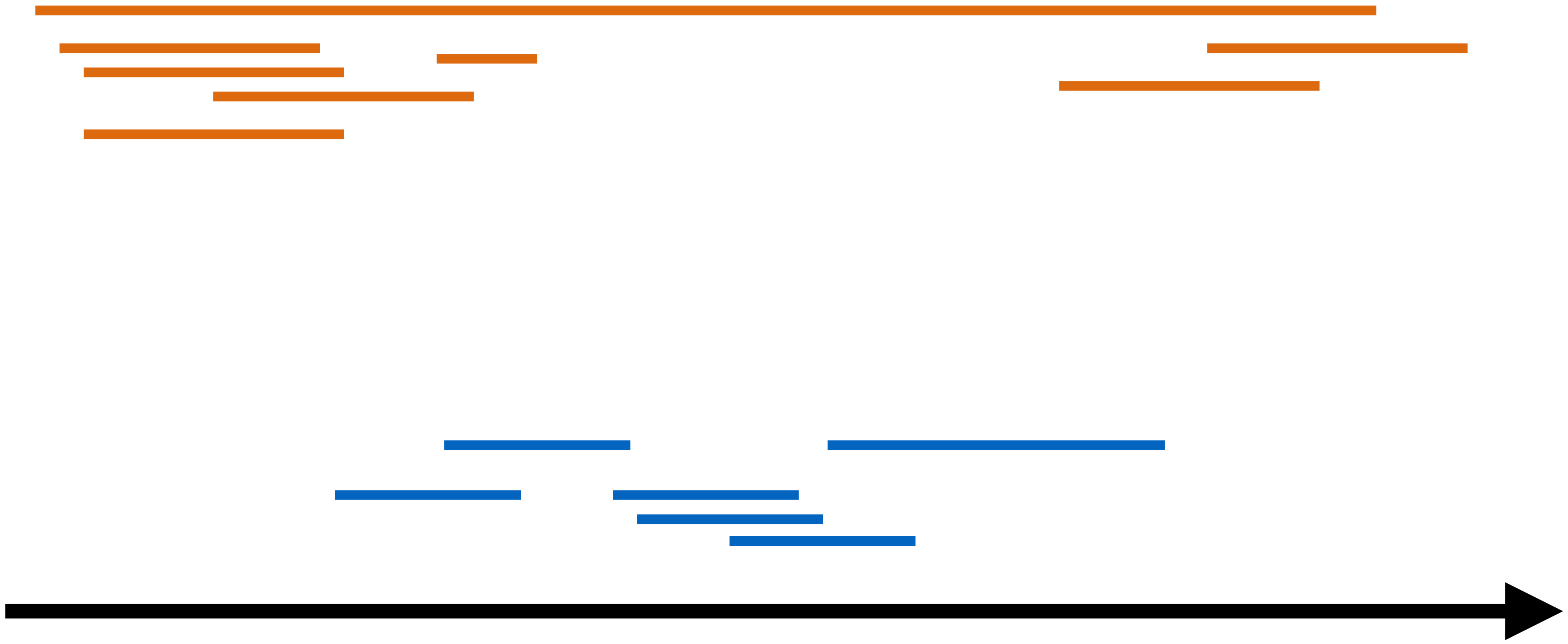
Request 2

time

Myria Analytics Storage



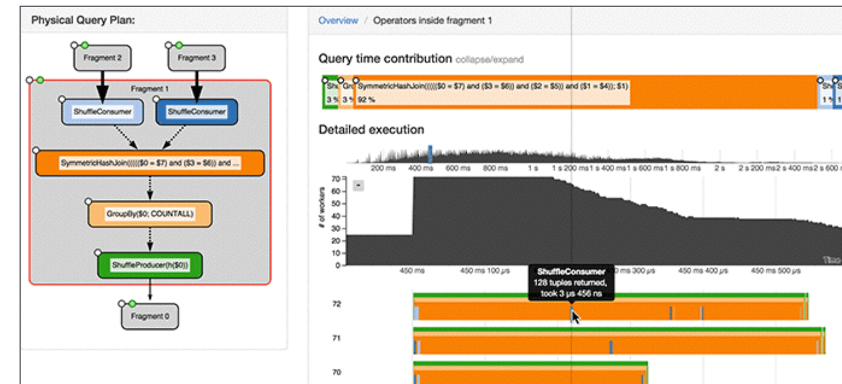
Request 1

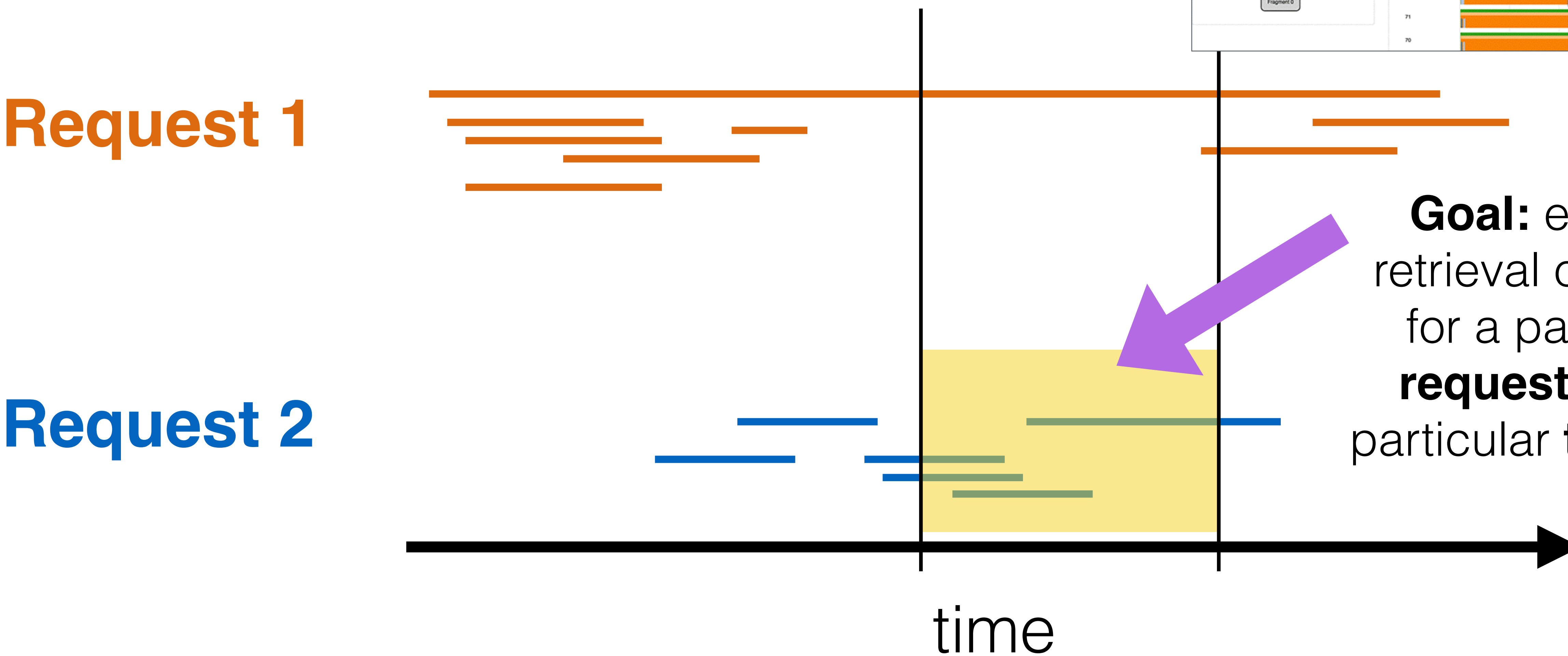


Request 2

time

Myria Analytics Storage





Goal: efficient retrieval of entries for a particular **request ID** in a particular **timespan**

Myria Analytics Storage

```
class AnalyticsLog {

    void log(Entry e)

    Iterator<Entry> getEntries(
        int   queryId,
        int   subqueryId,
        int   fragmentId,
        long  start,
        long  end)

}
```

Myria Analytics Storage

Insert an entry into
the data structure

```
class AnalyticsLog {

    void log(Entry e)

    Iterator<Entry> getEntries(
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}
```

Myria Analytics Storage

Insert an entry into the data structure

Retrieve entries

```
class AnalyticsLog {

    void log(Entry e)

    Iterator<Entry> getEntries(
        int   queryId,
        int   subqueryId,
        int   fragmentId,
        long  start,
        long  end)

}
```

Myria Analytics Storage

Specification:

```
Entry has:
   queryId    : Int,
   subqueryId : Int,
   fragmentId : Int,
   start, end : Long,
   …


getEntries: all e where
   e.queryId = queryId and
   e.subqueryId = subqueryId and
   e.fragmentId = fragmentId and
   e.end >= start and
   e.start <= end
```

```
class AnalyticsLog {

     void log(Entry e)

     Iterator<Entry> getEntries(
          int    queryId,
          int    subqueryId,
          int    fragmentId,
          long   start,
          long   end)

}
```

Cozy synthesizes collections

Specification:

```
Entry has:
    field1 : Type1,
    field2 : Type2,
    …



retrieveA: all e where
    condition

retrieveB: all e where
    condition
```


```
class Structure {

    void add(Entry e)
    void remove(Entry e)
    void update(Entry e, …)

    Iterator<Entry> retrieveA(…)
    Iterator<Entry> retrieveB(…)

}
```

Trivial Solution

```
retrieve: all e where
    P(e, input)
```

Trivial Solution

retrieve: all e where
    P(e, input)

```
List<Entry> data;

Iterator<Entry> retrieve(input) {
    for e in data:
        if P(e, input):
            yield e
}
```

Trivial Solution

```
retrieve: all e where
    P(e, input)
```

```
List<Entry> data;

Iterator<Entry> re
    for e in data:
        if P(e, input):
            yield e
}
```

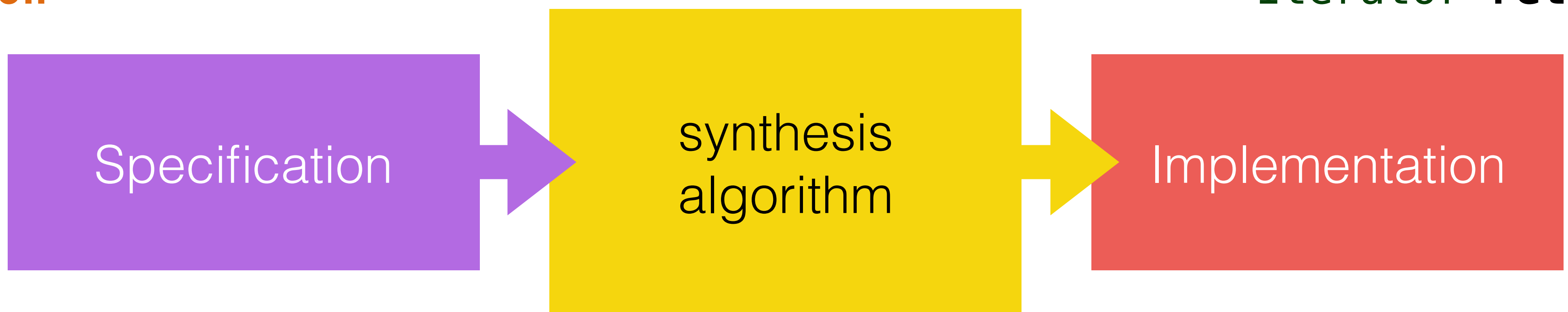
There has to be a better way!

```
Entry has:
   field1, field2, …
retrieveA: all e where
   condition
retrieveB: all e where
   condition
```

Intractable

```
void add(Entry e)
void remove(Entry e)
void update(Entry e, …)

Iterator retrieveA(…)
Iterator retrieveB(…)
```



In the quest for a good solution, the search space of “all possible programs” is simply too large

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Entry has:
   field1, field2, …
retrieveA: all e where
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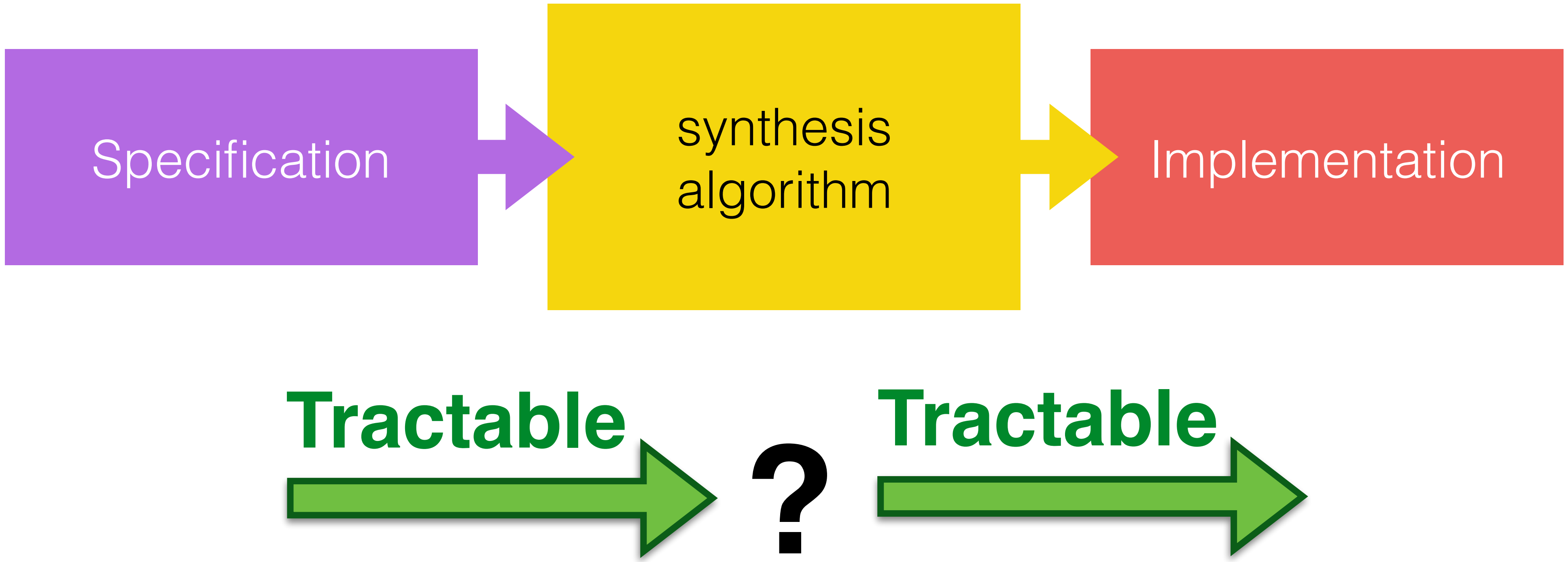
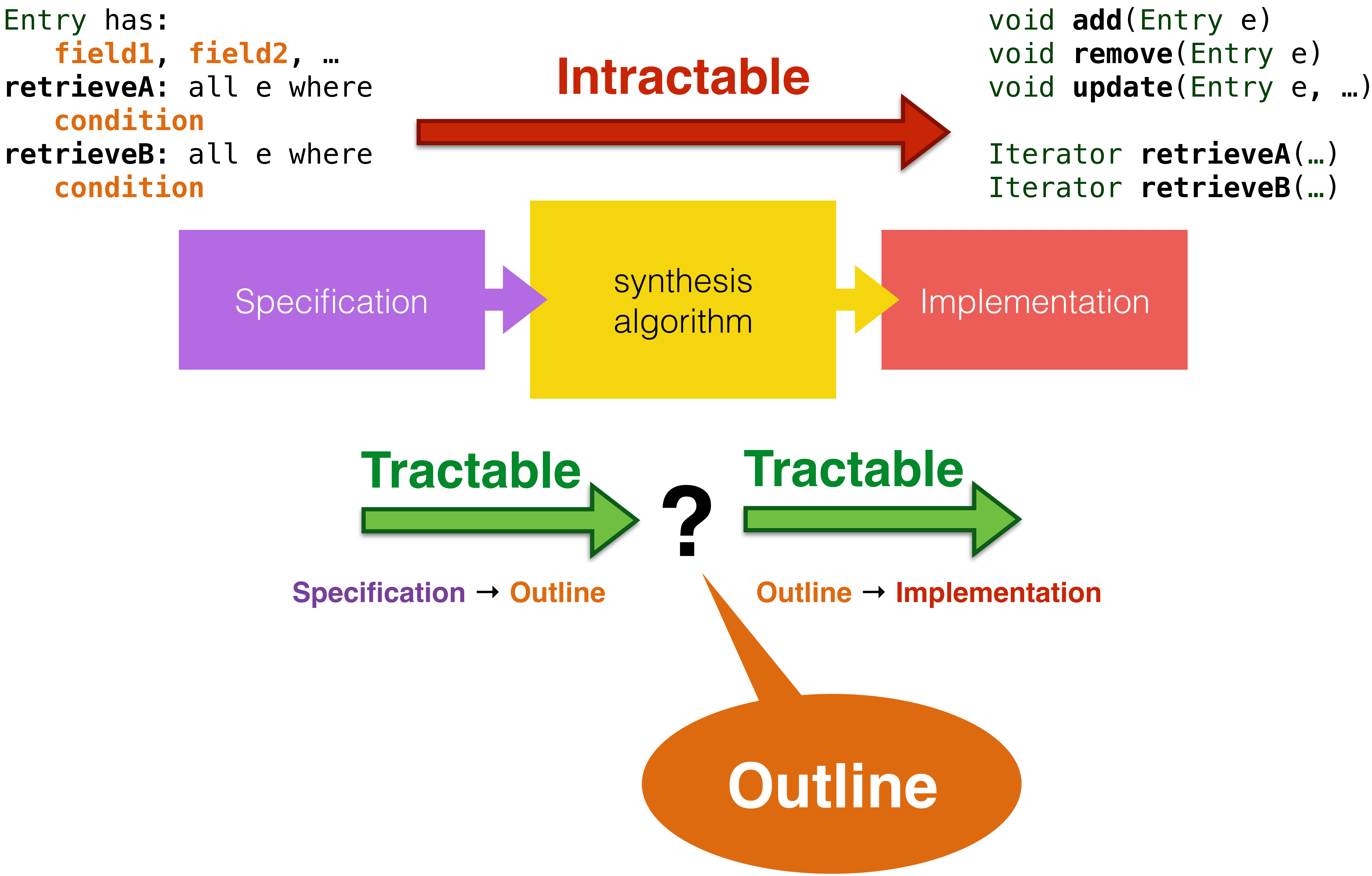


In the quest for a good solution, the search space of “all possible programs” is simply too large



Entry has:
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retrieveA: all e where
condition
retrieveB: all e where
condition
Intractable
void add(Entry e)
void remove(Entry e)
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Iterator retrieveA(…)
Iterator retrieveB(…)
Specification
synthesis algorithm
Implementation
Tractable
?
Tractable
Specification → Outline
Outline → Implementation
Outline

```
Entry has:
   field1, field2, …
retrieveA: all e where
   condition
retrieveB: all e where
   condition
```

Intractable

```
void add(Entry e)
void remove(Entry e)
void update(Entry e, …)

Iterator retrieveA(…)
Iterator retrieveB(…)
```

Specification → synthesis algorithm → Implementation

Tractable ? **Tractable**

Specification → Outline   **Outline → Implementation**

specific enough to describe
asymptotic performance

general enough to encode
a data structure succinctly

Outline

Outlines

Plans for retrieving entries

Outlines

Plans for retrieving entries

- **All** ( )

Outlines

Plans for retrieving entries

- **All** ( )
- **HashLookup** (outline, field = var)

Outlines

Plans for retrieving entries

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- **HashLookup** (outline, field = var)
- **BinarySearch** (outline, field > var)

Outlines

Plans for retrieving entries

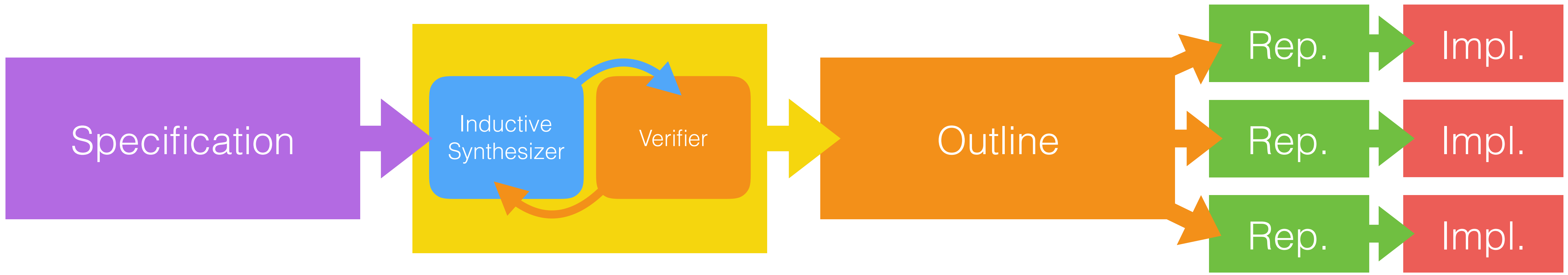
- **All** ( )
- **HashLookup** (outline, field = var)
- **BinarySearch** (outline, field > var)
- **Concat** (outline_1, outline_2)

Outlines

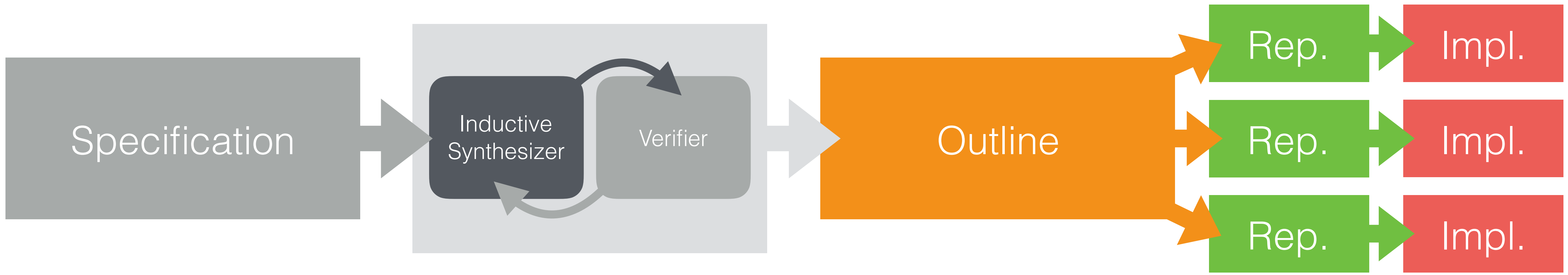
Plans for retrieving entries

- **All** ( )
- **HashLookup** (outline, field = var)
- **BinarySearch** (outline, field > var)
- **Concat** ($outline_1$, $outline_2$)
- **Filter** (outline, predicate)

Outlines → Implementations



Outlines → Implementations



Outlines → Implementations

HashLookup (
  All(),
  e.queryId = q)

```
class Structure {

    Iterator<Entry> retrieve(q) { … }

}
```

Outlines → Implementations

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HashLookup (
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```
class Structure {
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    Iterator<Entry> retrieve(q) { … }
}
```

Outlines → Implementations

```
HashLookup (
    data,
    e.queryId = q )
```

```
class Structure {

    HMap<K,V> data;

    Iterator<Entry>
    retrieve(q) { … }

}
```

Outlines → Implementations

HashLookup (
  data,
  e.queryId = q)

```
class Structure {
    HMap<K,V> data;
    Iterator<Entry>
    retrieve(q) { … }
}
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Outlines → Implementations

HashLookup (
  data,
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    retrieve(q) { … }
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```

Outlines → Implementations

HashLookup (
  `data`,
  $\boxed{\text{e.queryId} = \text{q}}$)

```
class Structure {

    HMap<int,V> data;

    Iterator<Entry>
    retrieve(q) { … }

}
```

Outlines → Implementations

HashLookup (
 data,
 e.queryId = q)

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class Structure {
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Outlines → Implementations

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Outlines → Implementations

HashLookup (
  data,
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class Structure {
    HMap<int,V> data;
    Iterator<Entry>
    retrieve(q) { … }
}
```

```
V = ArrayList<Entry>
```

Outlines → Implementations

HashLookup (
  data,
  e.queryId = q)

```
class Structure {
    HMap<int,V> data;
    Iterator<Entry>
    retrieve(q) { … }
}
```

`V = ArrayList<Entry>`   `V = LinkedList<Entry>`

Outlines → Implementations

HashLookup (
  data,
  e.queryId = q)

```
class Structure {
    HMap<int,V> data;
    Iterator<Entry>
    retrieve(q) { … }
}
```

Outlines → Implementations

HashLookup (
  data,
  e.queryId = q)

```
class Structure {

    HMap<int,V> data;

    Iterator<Entry>
    retrieve(q)
    {
      v = data.get(q);
      return v.iterator();
    }
```

Outlines → Implementations

add, remove, update

HashLookup (
 data,
 e.queryId = q)

```
class Structur
  HMap<int,V> data;
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  {
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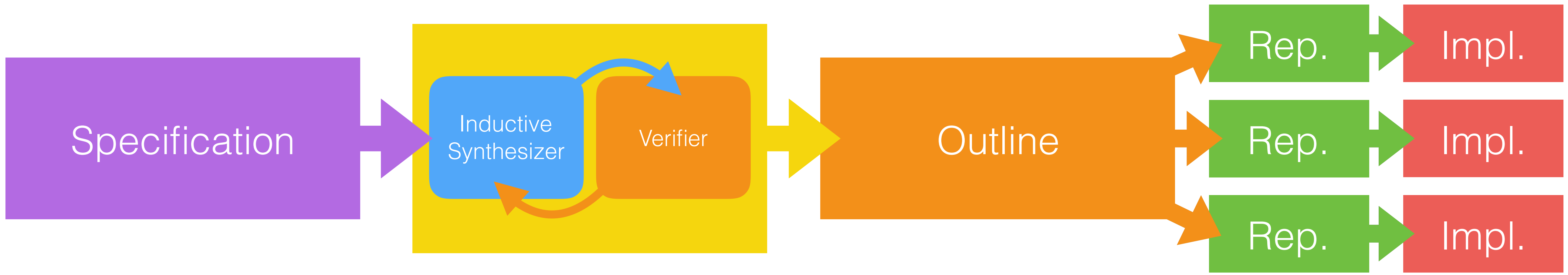
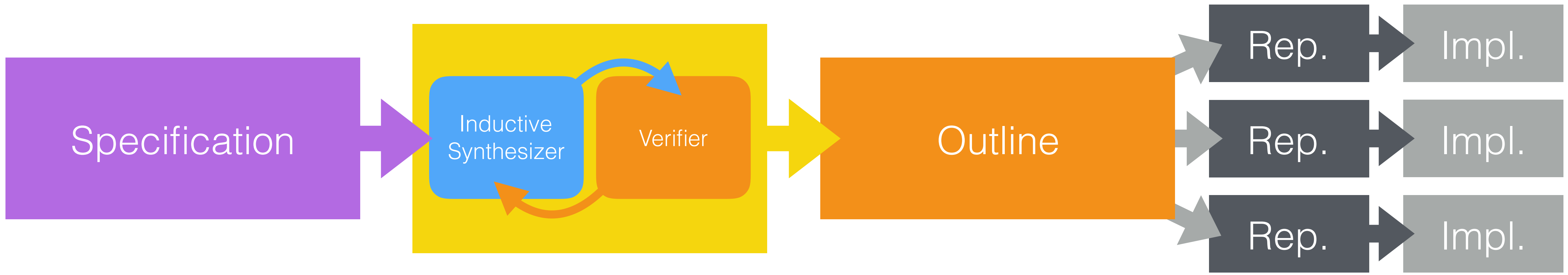
Specification → Outline

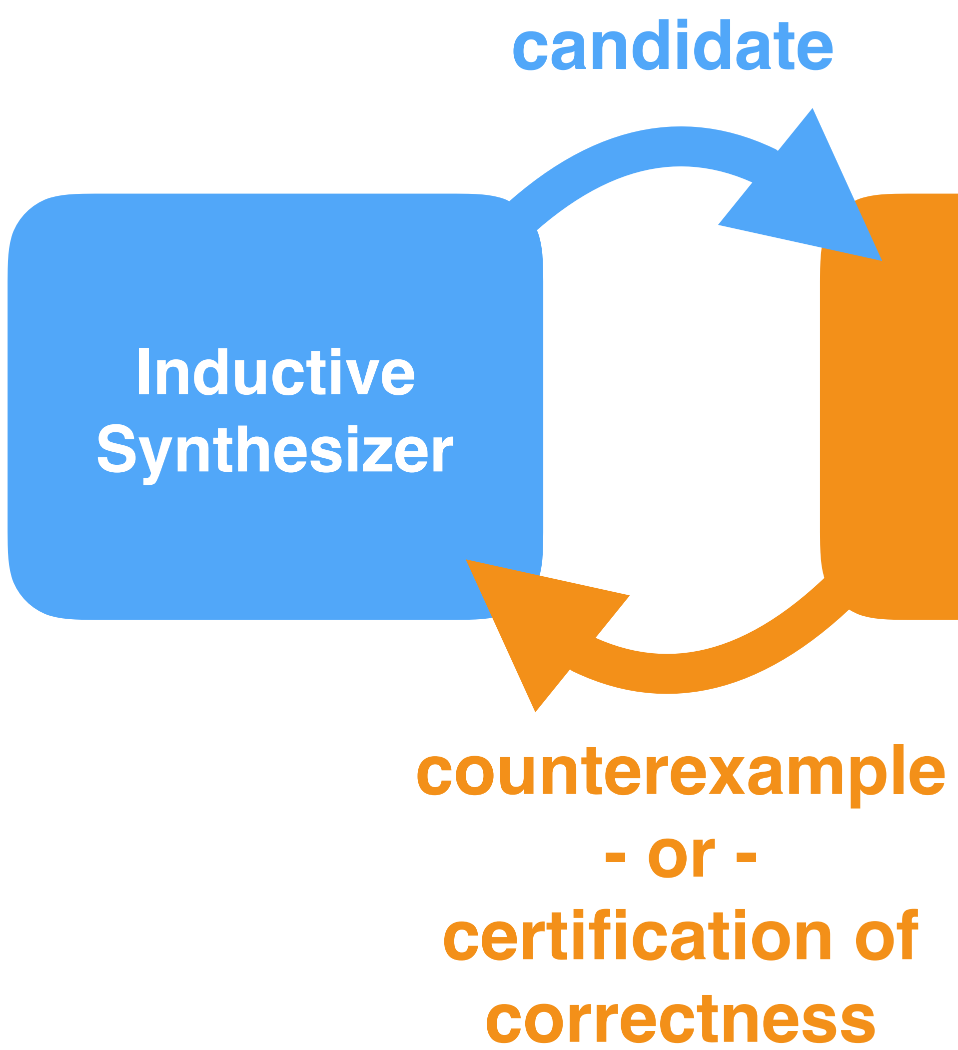


Specification → Outline



Specification → Outline

CEGIS

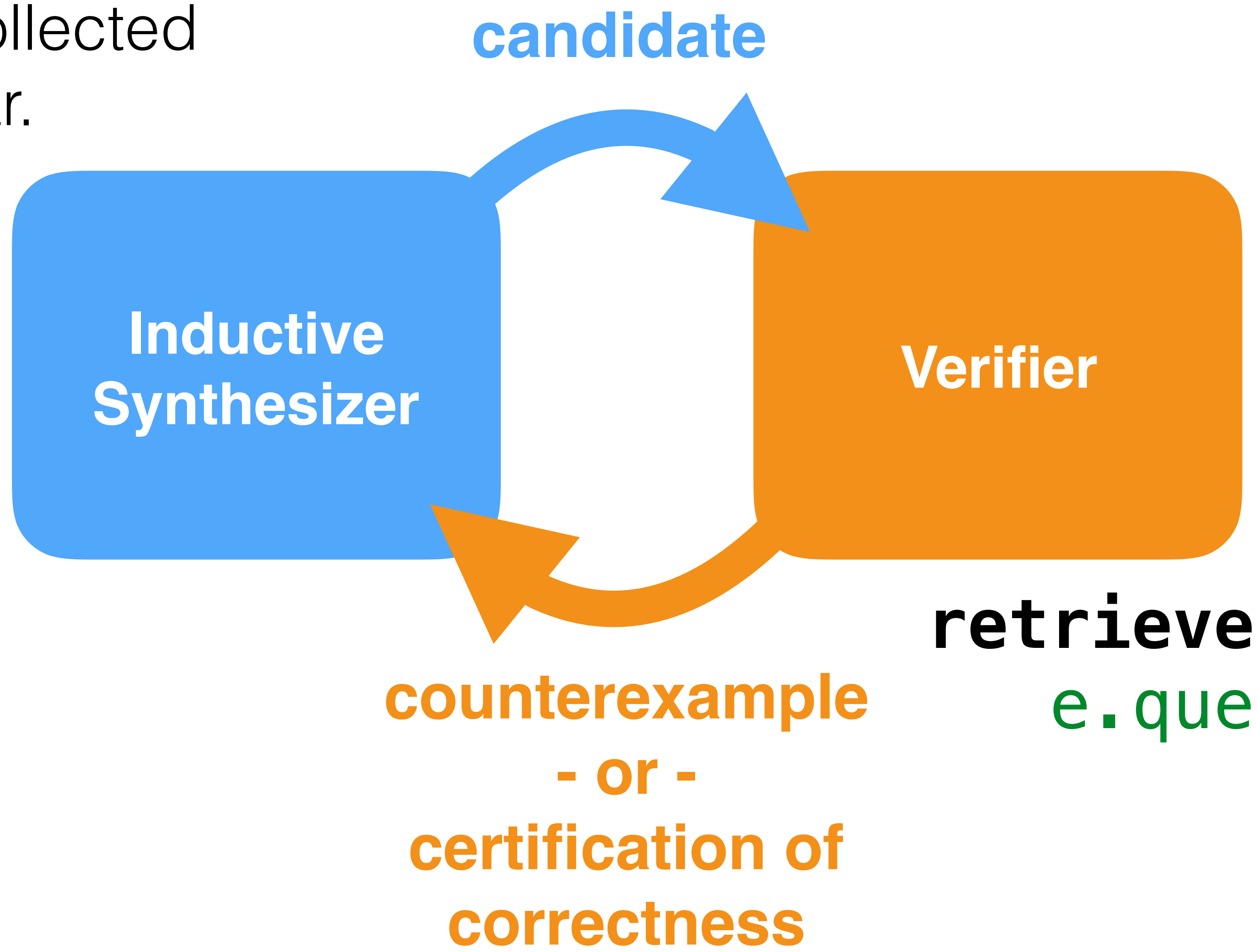



```
retrieve: all e where
   e.queryId = q and …
```

Specification → Outline

Remembers all examples; only reasons about examples collected thus far.

CEGIS




```
retrieve: all e where
    e.queryId = q and …
```

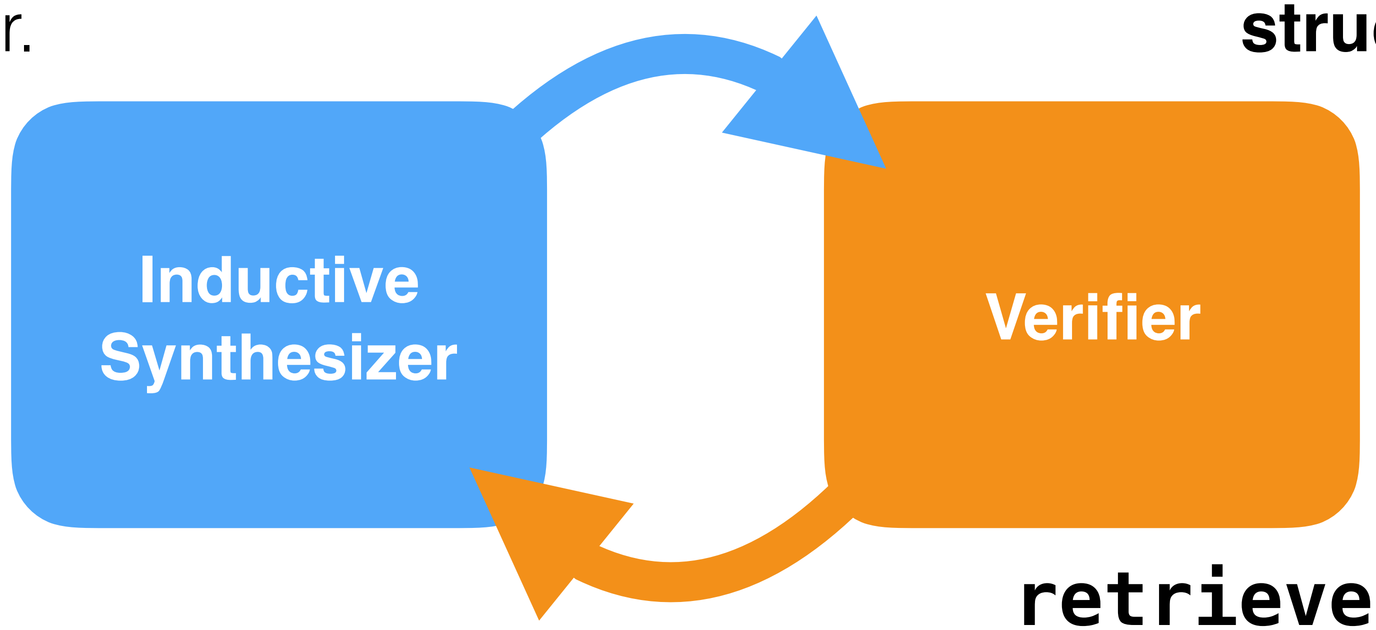
Specification → Outline

Remembers all examples; only reasons about examples collected thus far.

CEGIS

Must ensure the outline is correct for **all possible inputs** and **all possible data structure states.**

candidate



counterexample
- or -
certification of correctness

```
retrieve: all e where
    e.queryId = q and …
```

$$\forall I\ \forall S,\ out = \{\ e \mid e \in S \land P(I, e)\ \}$$

Cost Model

Filter (
    All(),
    e.queryId = q)

HashLookup (
    All(),
    e.queryId = q)

Cost Model

$O(1)$

Filter (
All(),
e.queryId = q)

HashLookup (
All(),
e.queryId = q)

Cost Model

$O(n)$

$O(1)$

Filter (
    All(),
    e.queryId = q)

HashLookup (
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Cost Model

$O(n)$

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Filter (
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Cost Model

$O(n)$

$O(1)$

Filter (
  All(),
  e.queryId = q)

$O(1)$

$O(1)$

HashLookup (
  All(),
  e.queryId = q)

Cost Model

$O(n)$

$O(1)$

Filter (
  All(),
  e.queryId = q)

>

$O(1)$

$O(1)$

HashLookup (
  All(),
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Cost Model

$O(n)$ $O(1)$

Filter (
 All(),
 e.queryId = q)

>

$O(1)$ $O(1)$

HashLookup (
 All(),
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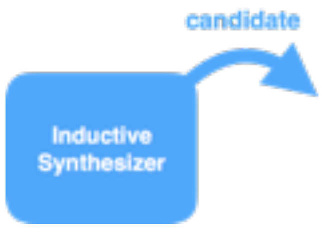
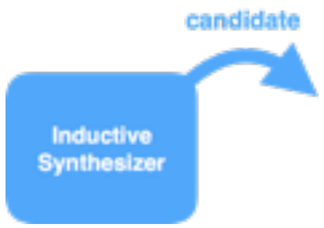
Cozy prefers outlines with lower cost



Inductive Synthesis

Enumerative search

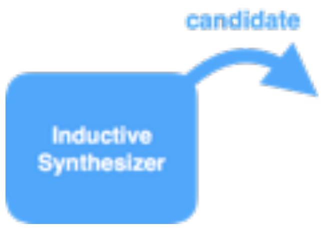


Inductive Synthesis

Enumerative search

size 1

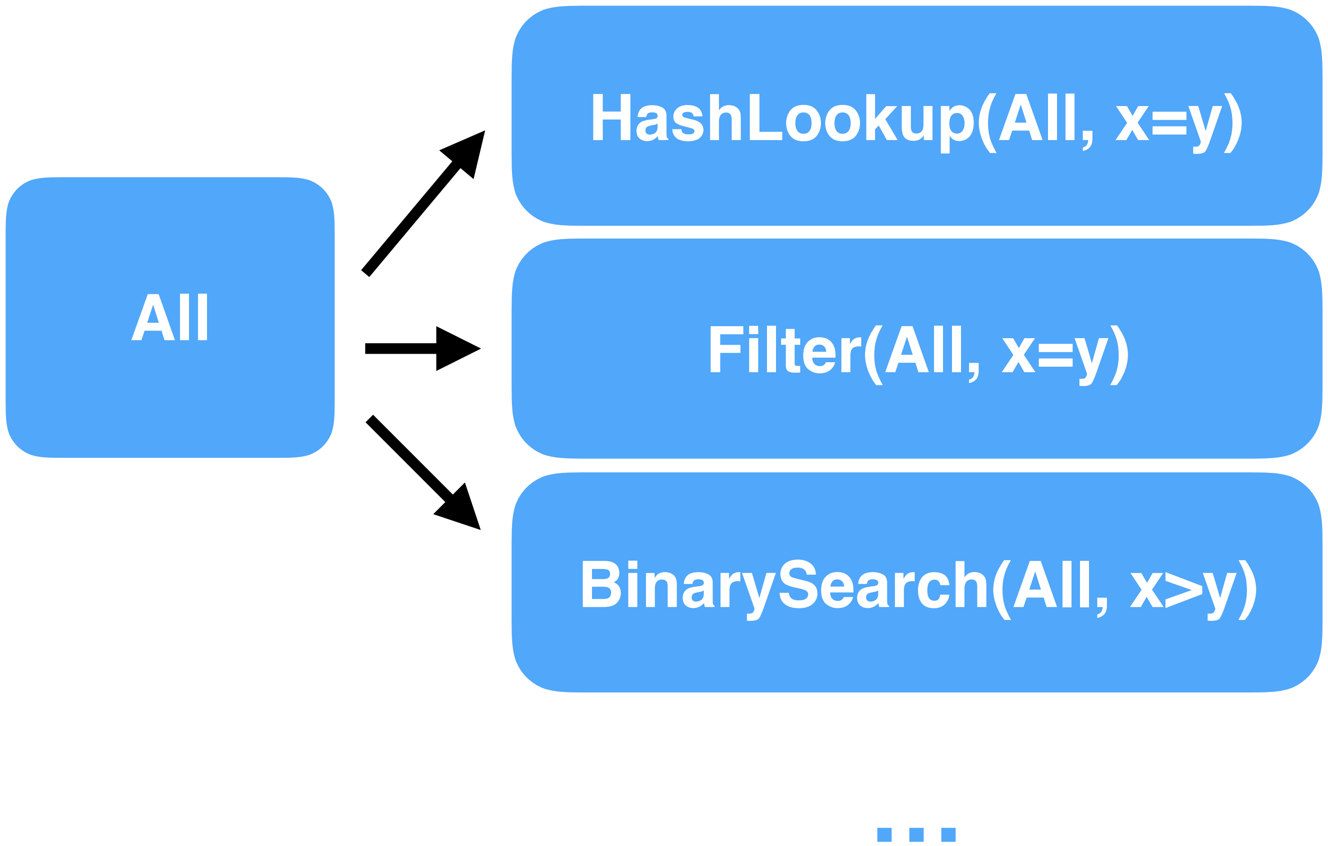
All

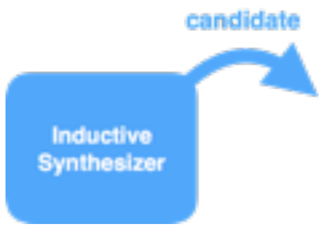


Inductive Synthesis

Enumerative search

size 1 size 2

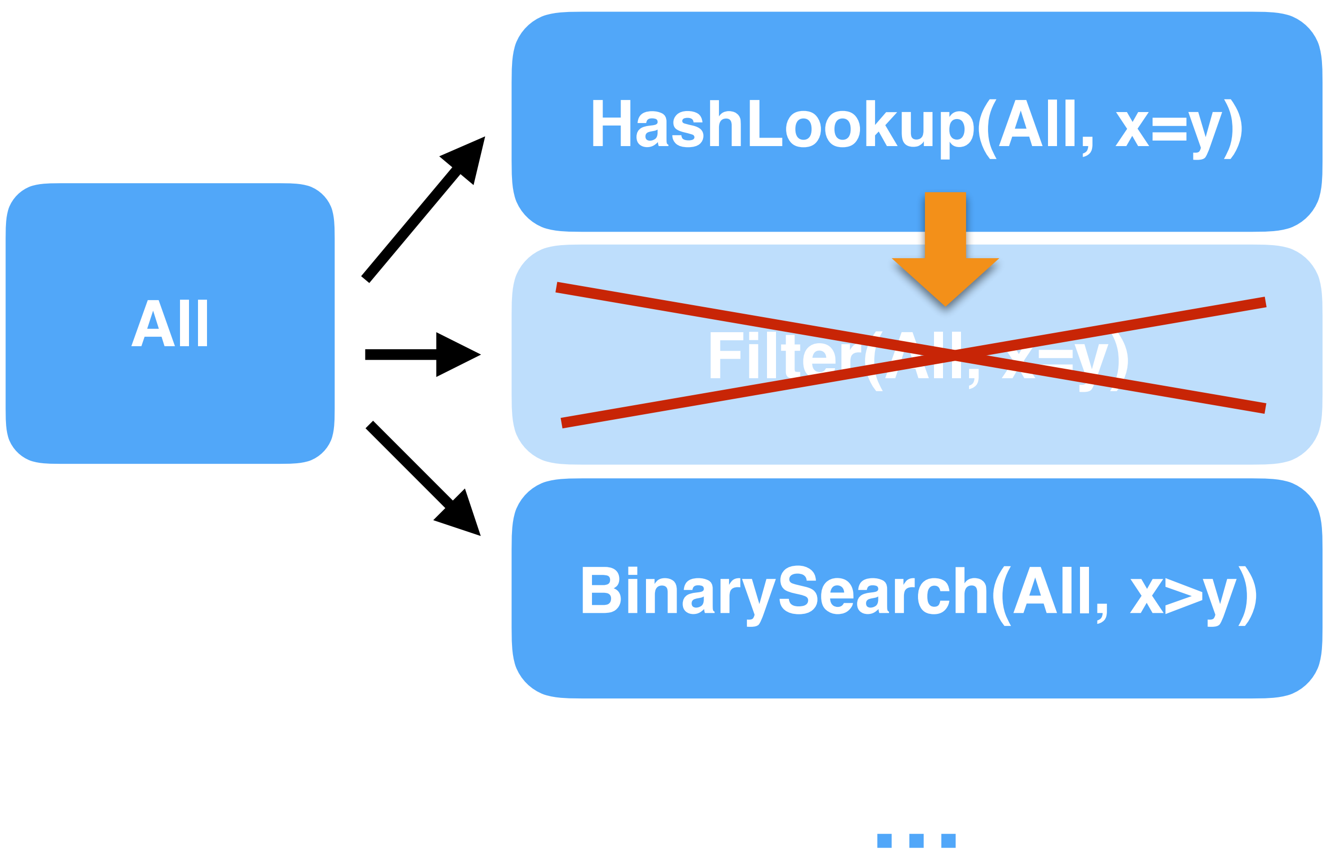


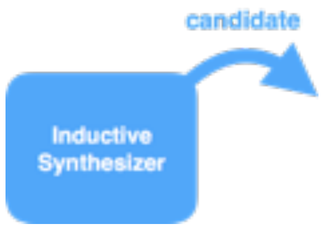


Inductive Synthesis

Enumerative search

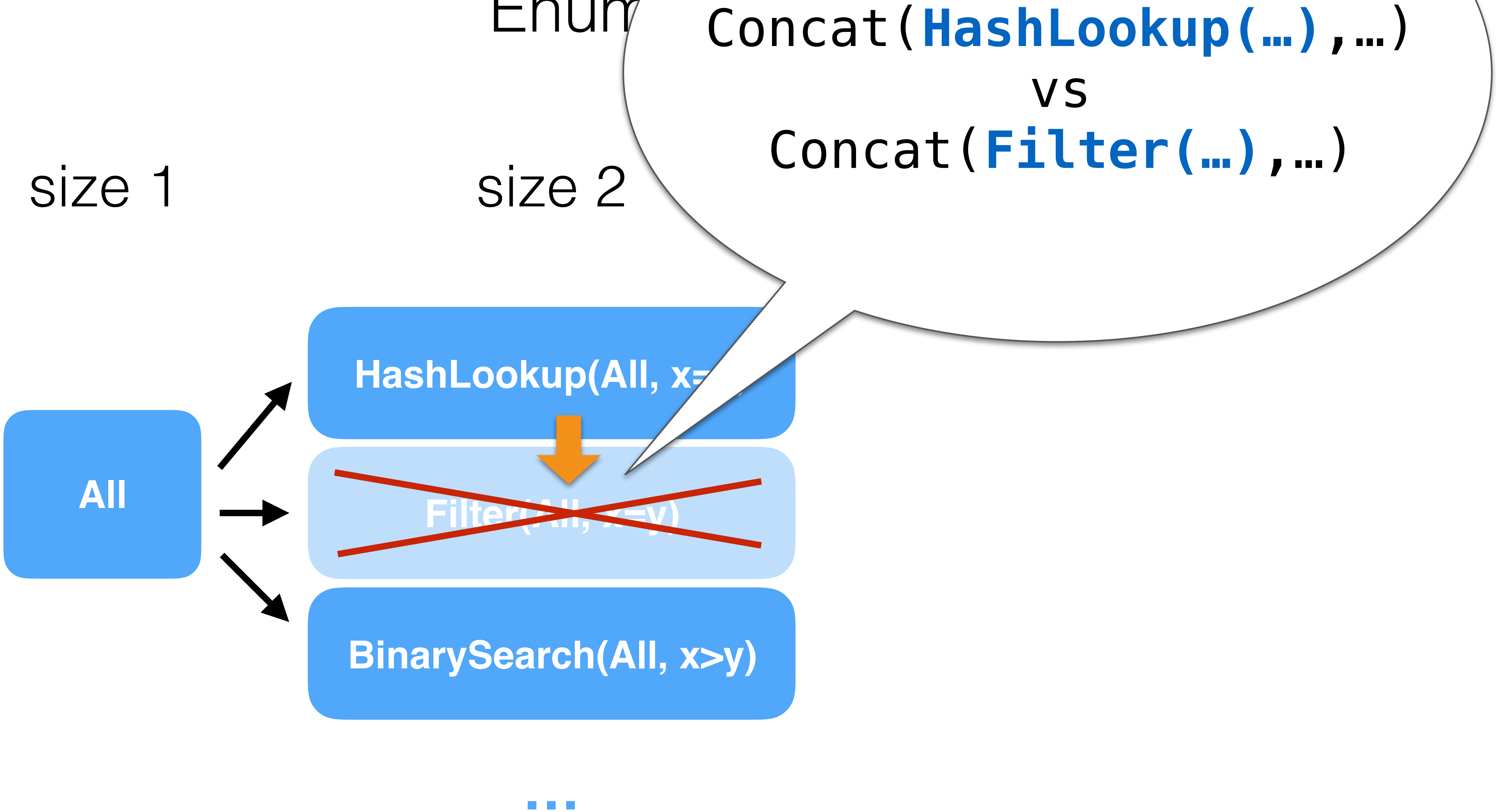
size 1 size 2

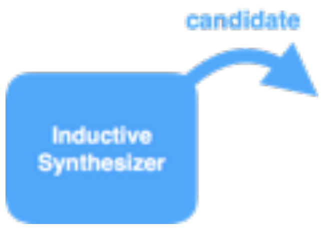




Inductive

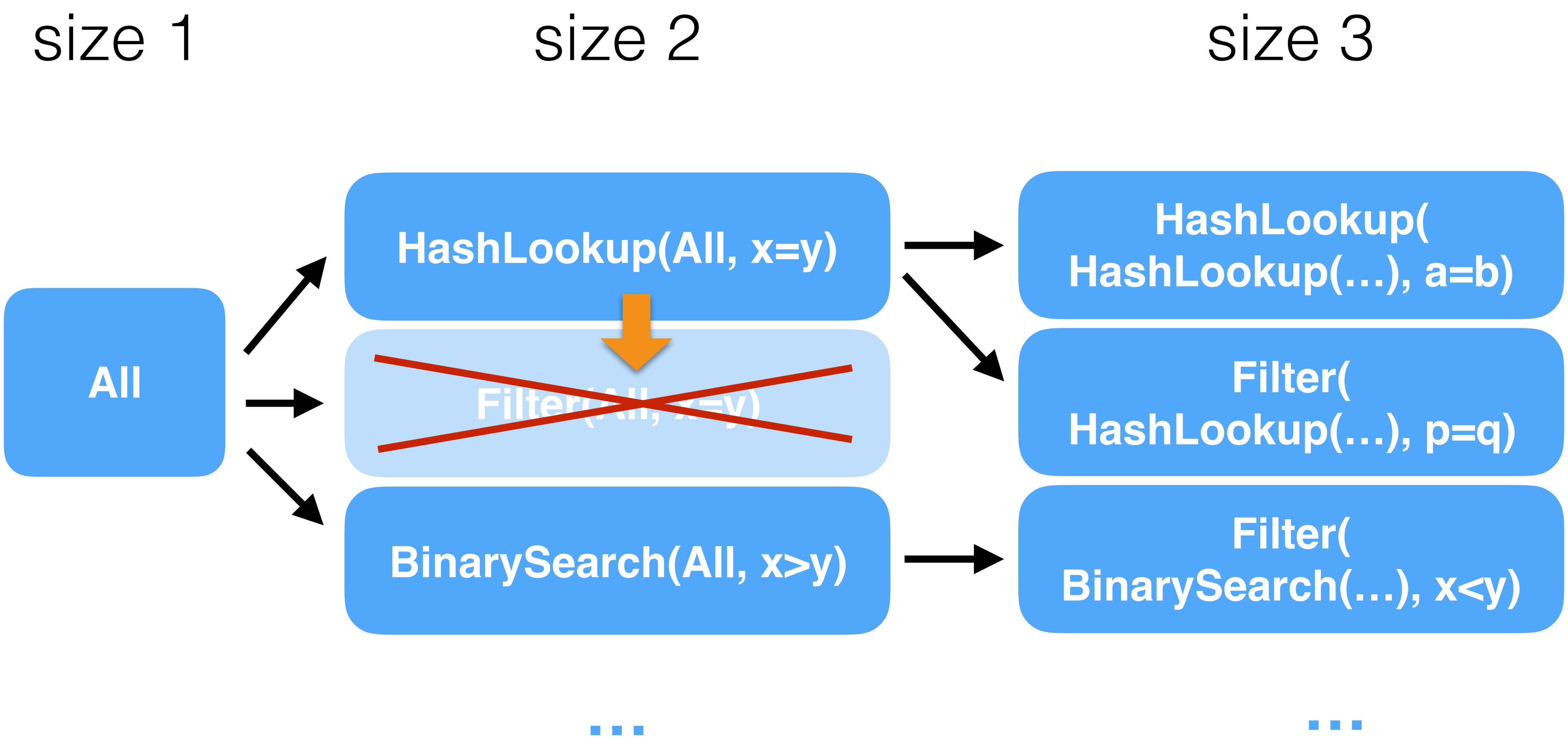
Enum

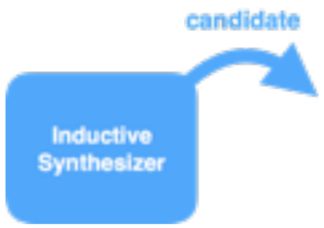




Inductive Synthesis

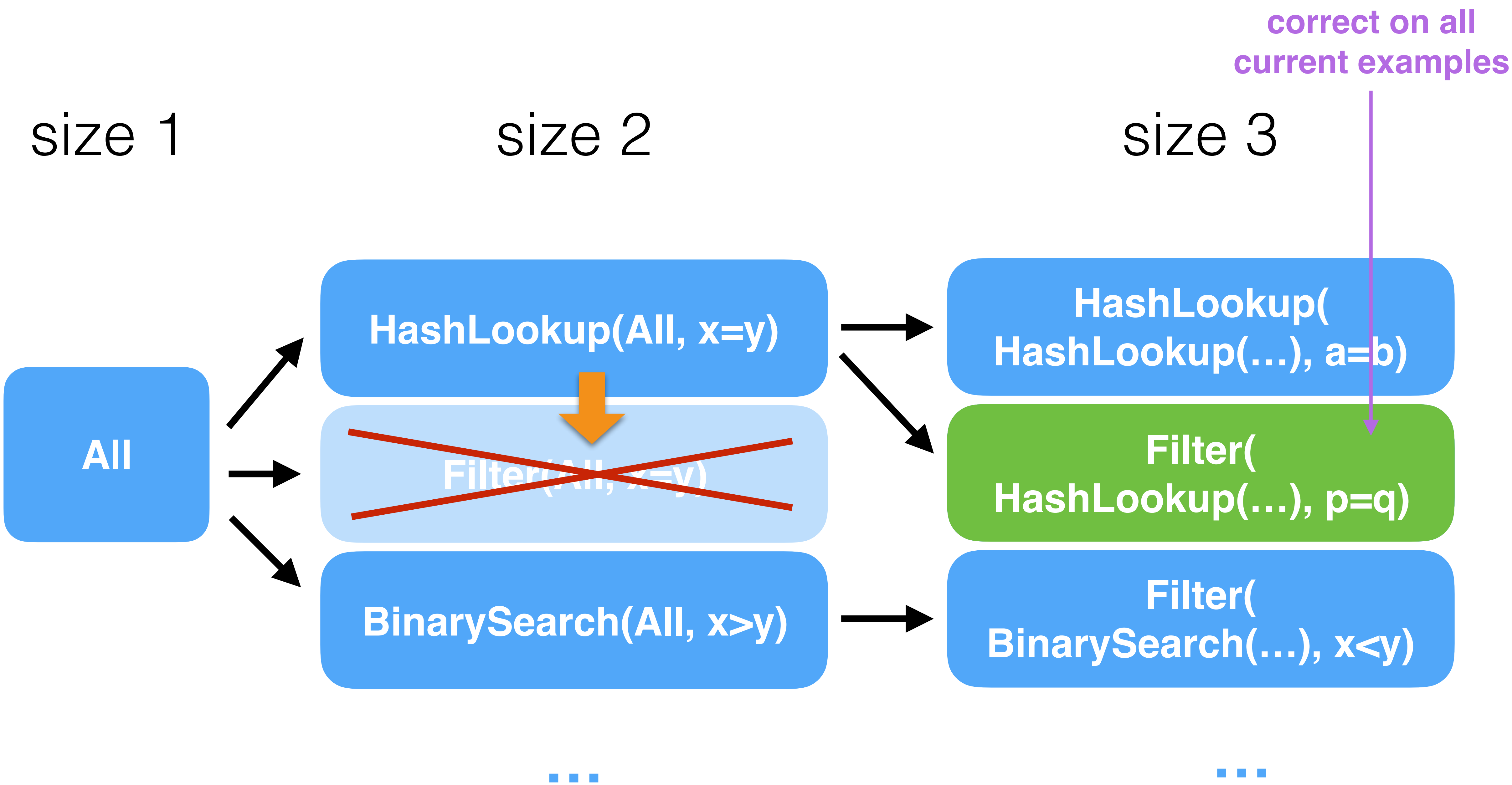
Enumerative search

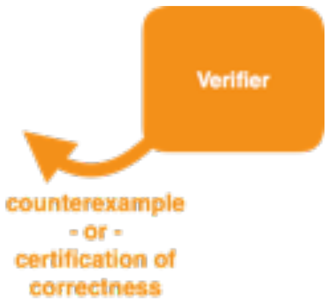




Inductive Synthesis

Enumerative search





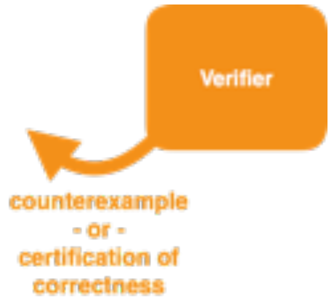
Outline Verification

Specification:

```
Entry has:
   queryId : Int,
   subqueryId : Int,
   …
```

P

```
retrieve: all e where
   e.queryId = q and …
```



Outline Verification

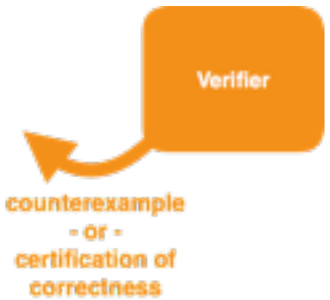
Specification:

$\{ e \mid e \in S \wedge P(I, e) \}$

```
   subquer Id : Int,
   …
```

P

```
retrieve: all e where
   e.queryId = q and …
```



Outline Verification

Specification:

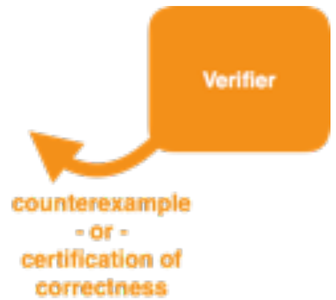
$\{\, e \mid e \in S \wedge P(I, e) \,\}$

```
subque   Id : Int,
…
```

P

```
retrieve: all e where
   e.queryId = q and …
```

HashLookup(
All(),
e.queryId = q)



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representative predicate Q

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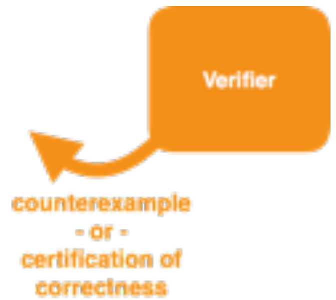

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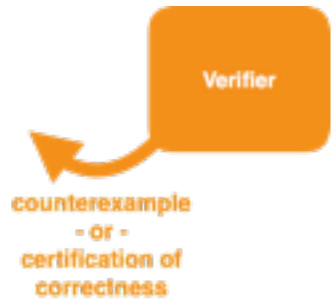

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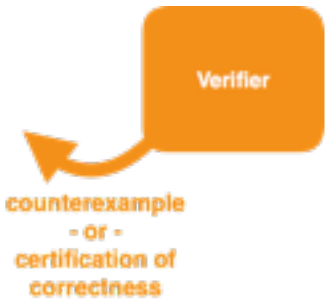

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yes **if and only if** for all I, e:

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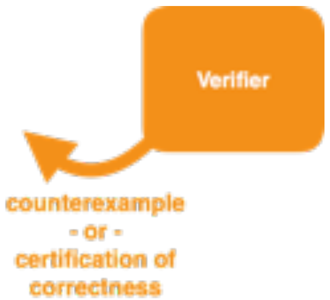

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equivalence can be checked with an SMT solver

Evaluation

Evaluation

- Improve correctness

Evaluation

- Improve correctness
- Save programmer effort

Evaluation

- Improve correctness
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- Match performance

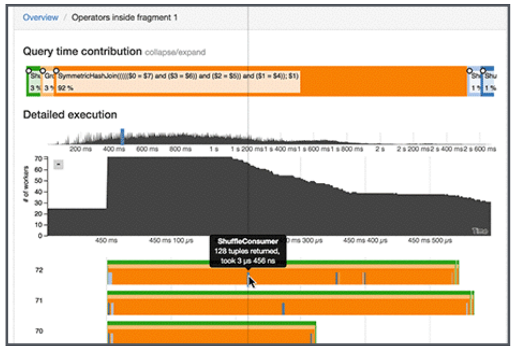
Evaluation

- Improve correctness ✓
- Save programmer effort ✓
- Match performance ✓

Case studies

Case studies

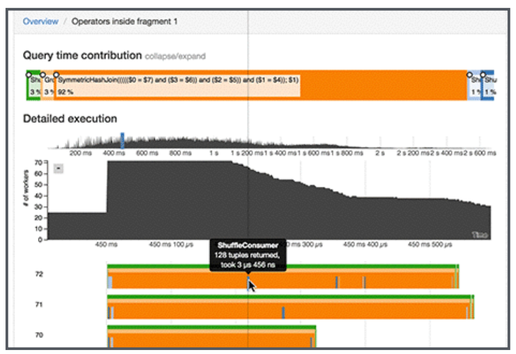
- **Myria:** analytics



Analytics data indexed by timespan and by request ID

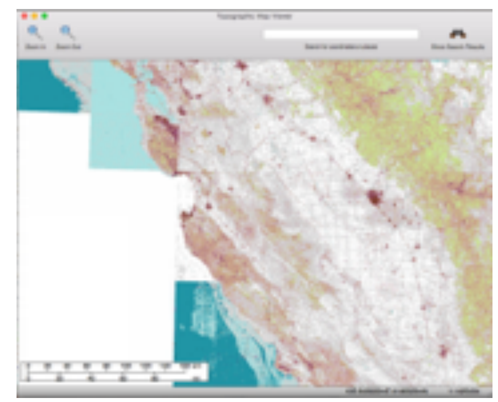
Case studies

- **Myria:** analytics



Analytics data indexed by timespan and by request ID

- **ZTopo:** tile cache



Tracks map tiles in a least-recently-used cache

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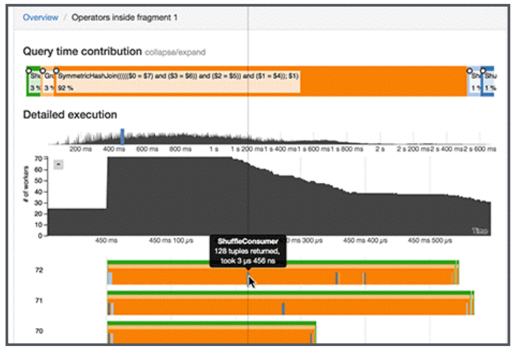

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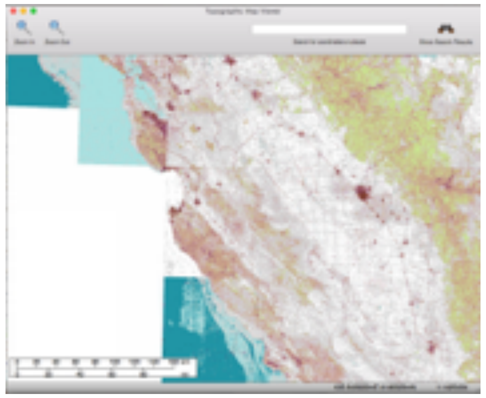

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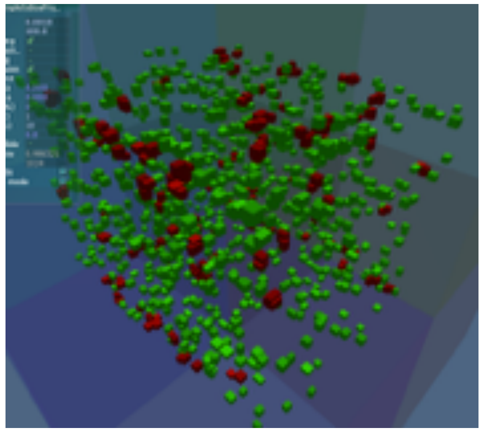
- **Bullet:** volume tree



Stores axis-aligned bounding boxes for fast collision detection

Case studies

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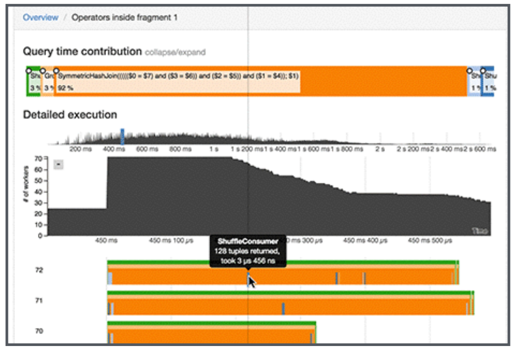

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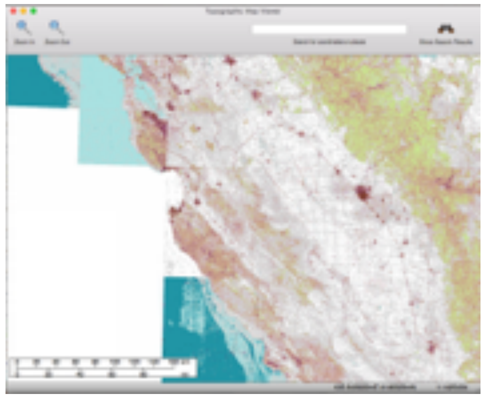

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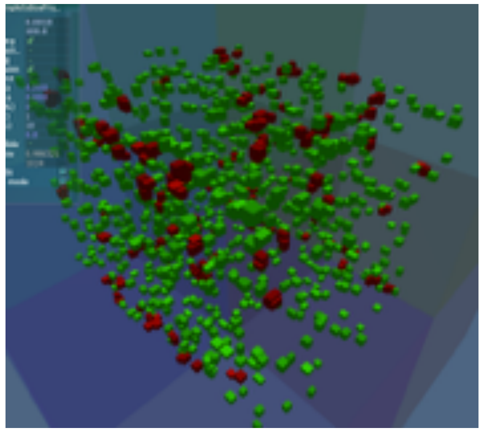

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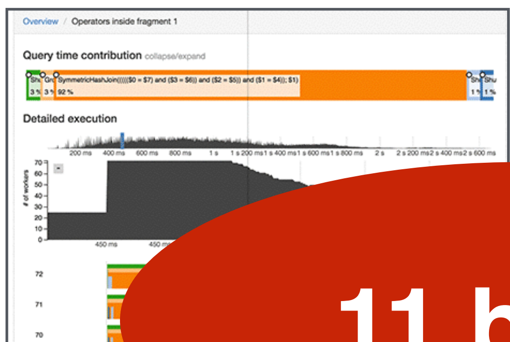
- **Sat4j:** variable metadata

Tracks information about each variable in the formula

Case studies

- **Myria:** analytics



Analytics data indexed by n and by

11 bugs

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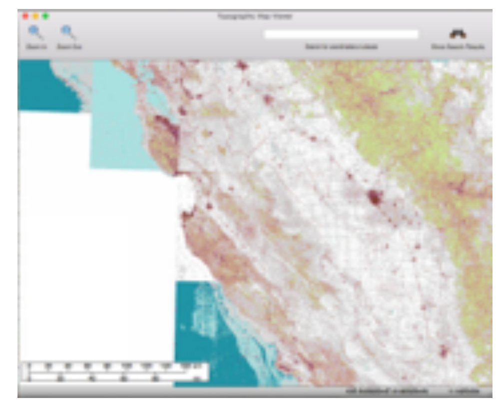

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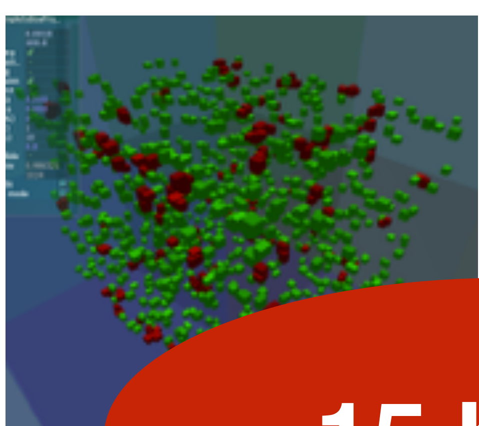


Stores axis-aligned bounding boxes for fast collision detection

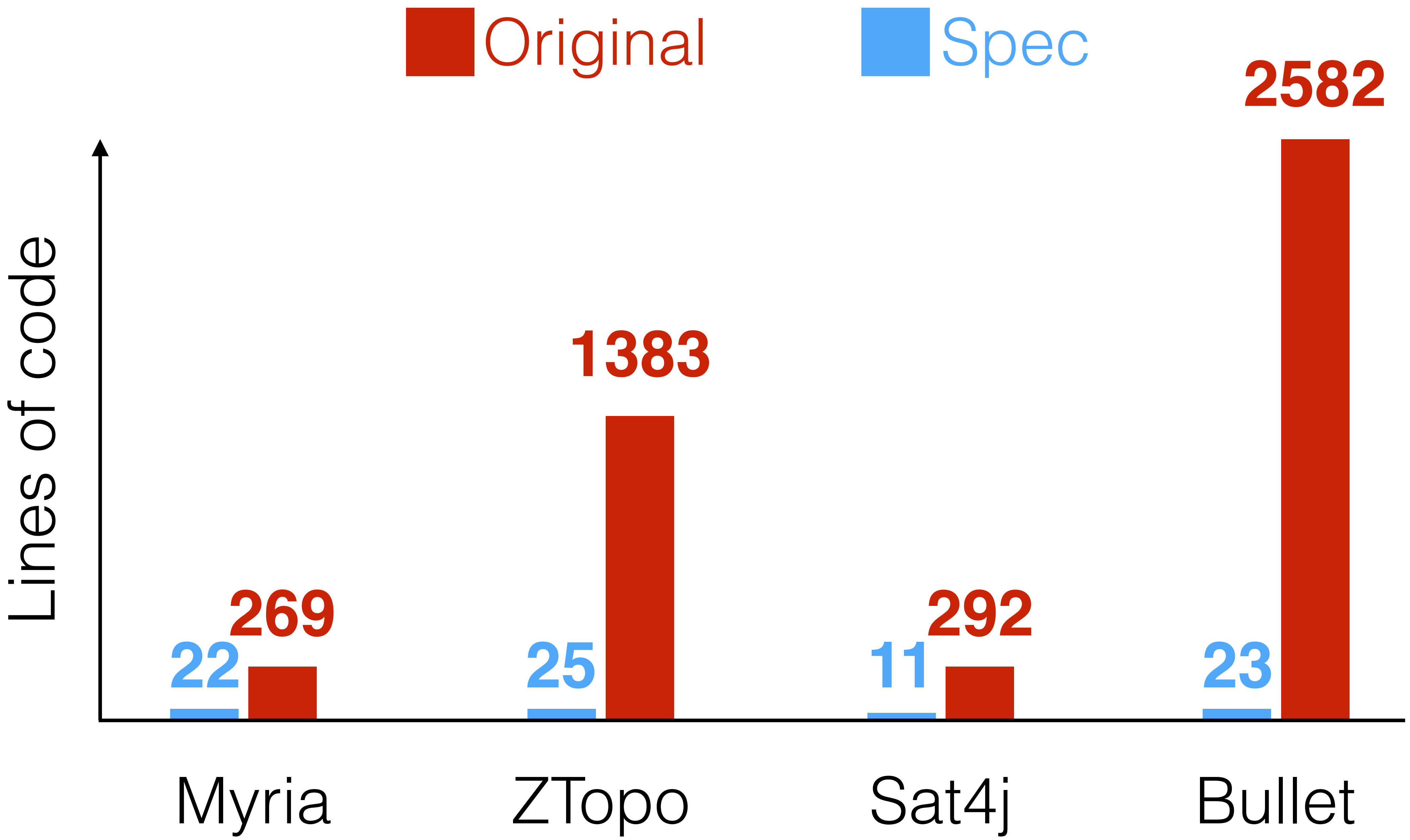
15 bugs

- **Sat4j:** variable metadata

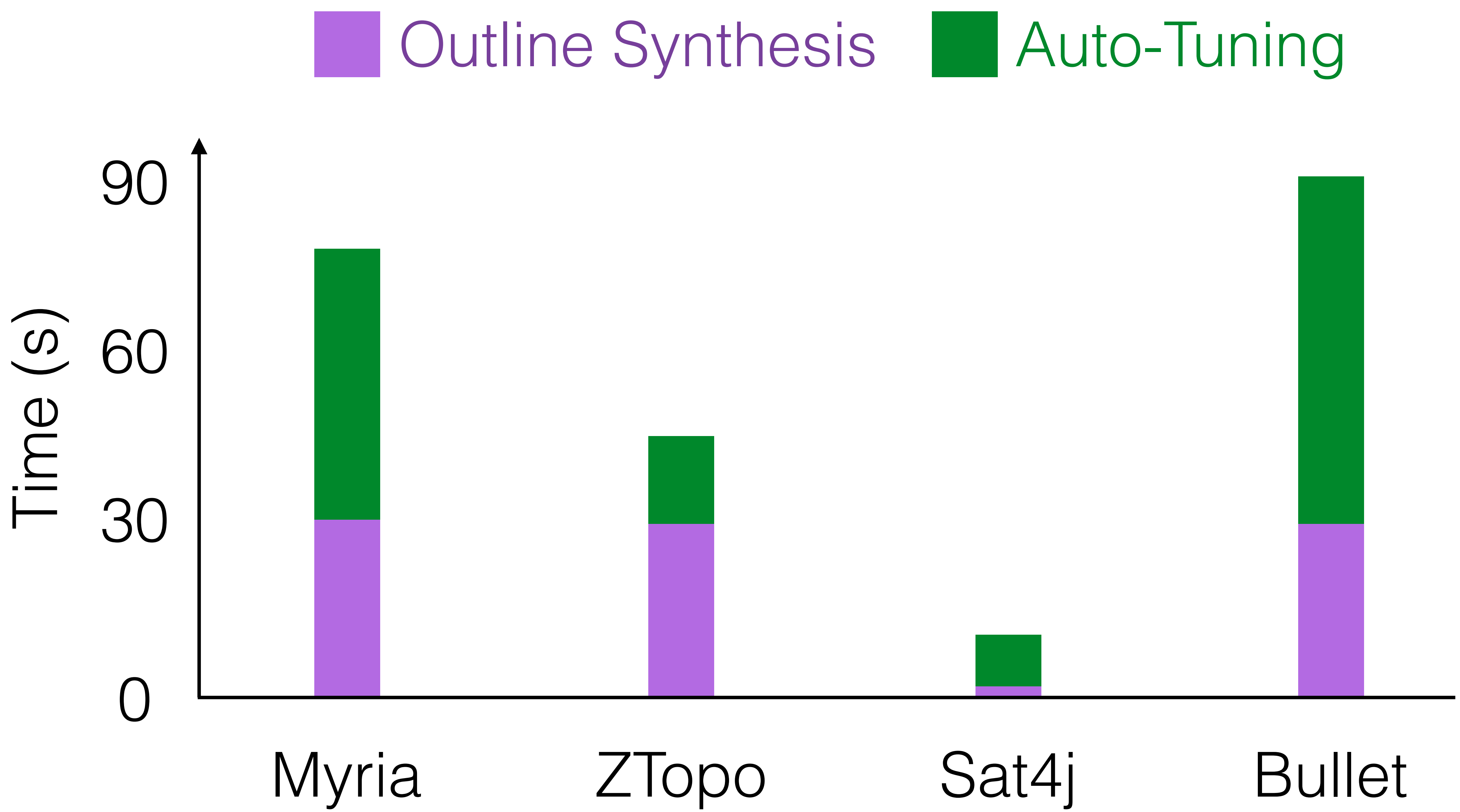
Tracks information about each variable in the formula

7 bugs

Specifications vs. Implementations



Synthesis Time



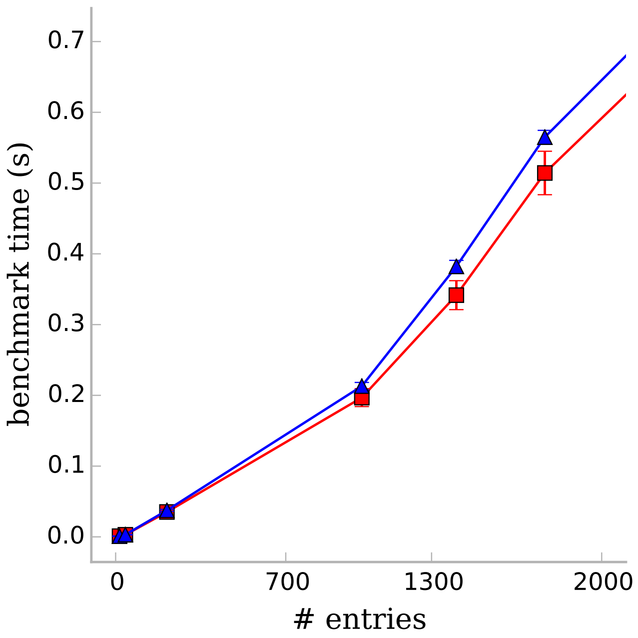
Performance

Original Synthesized

Performance

Original   Synthesized

Data structures are
nearly identical



ZTopo

Performance

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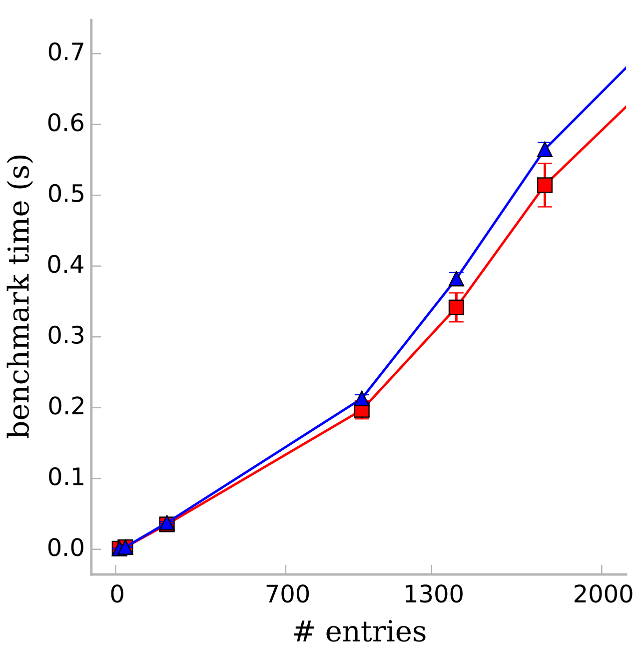
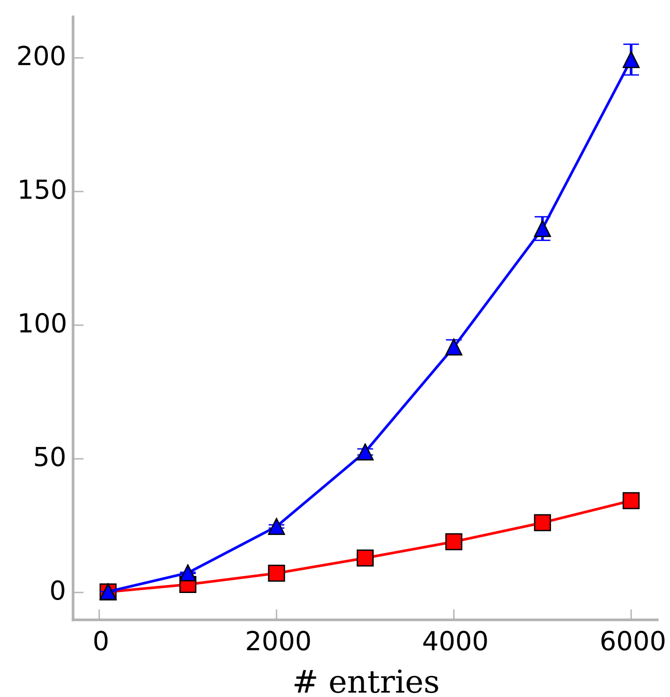
Data structures are nearly identical

Binary search tree vs. space partitioning tree





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Bullet

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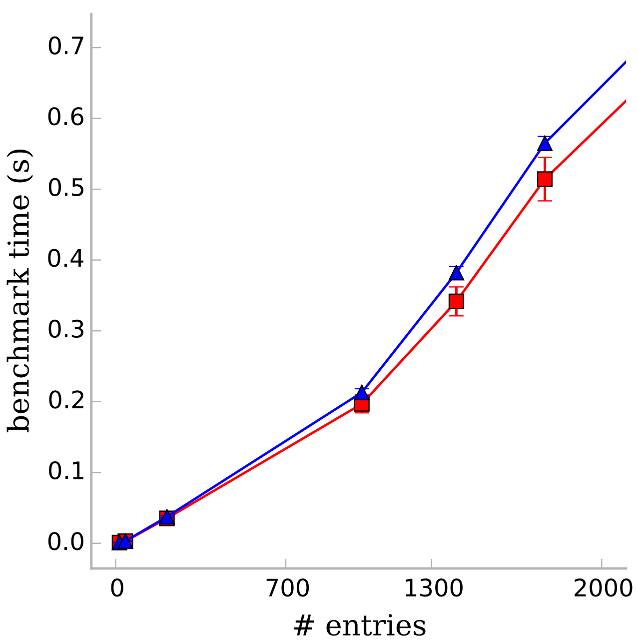

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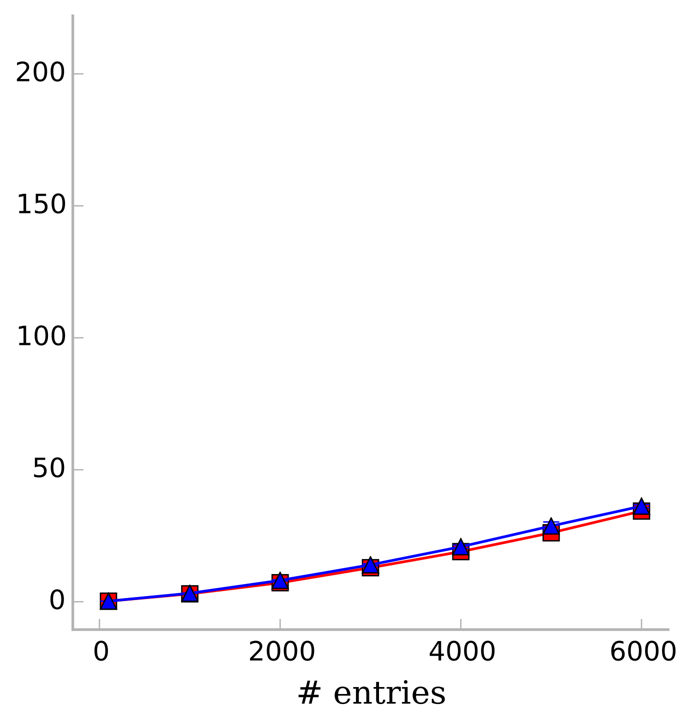

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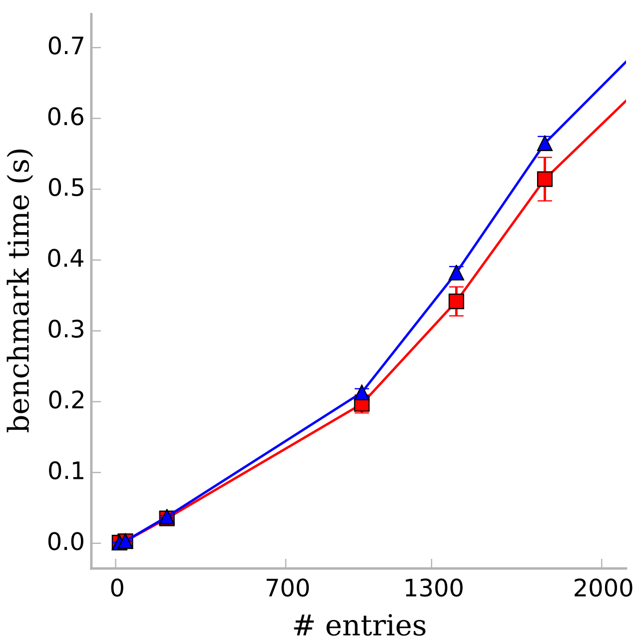

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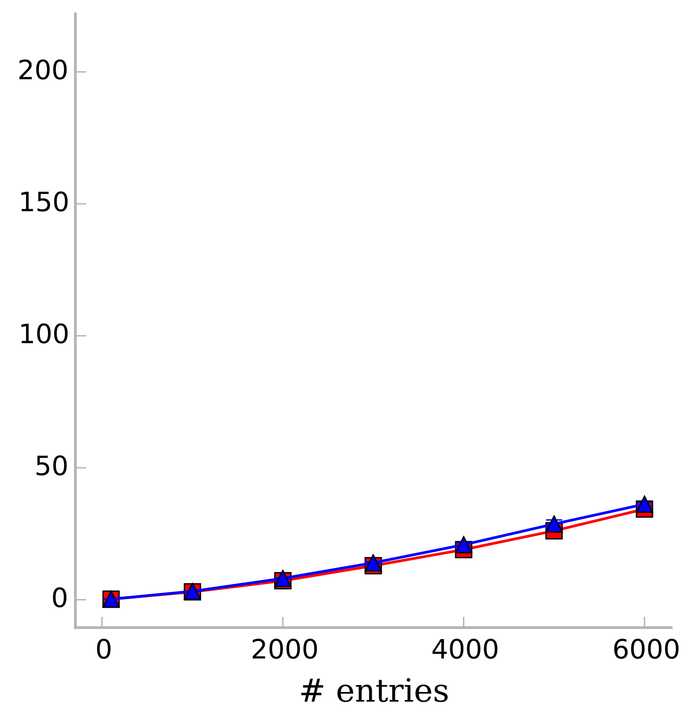
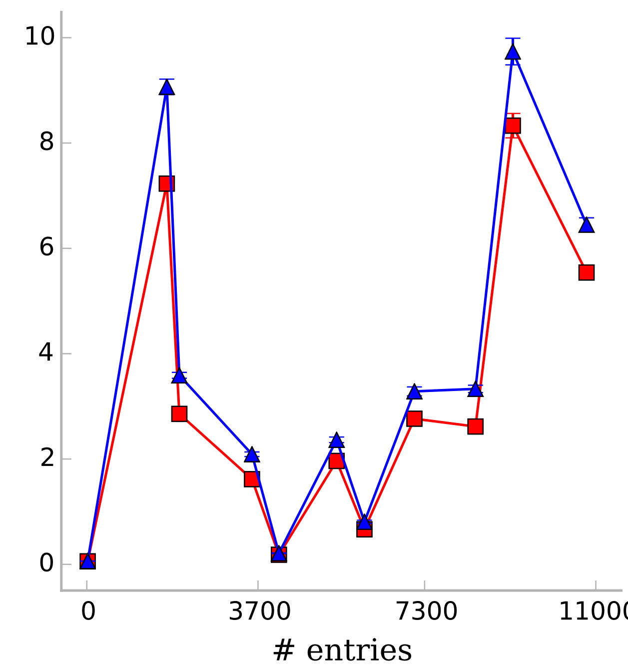


Bullet

Small overhead; performance dominated by other factors



Sat4j

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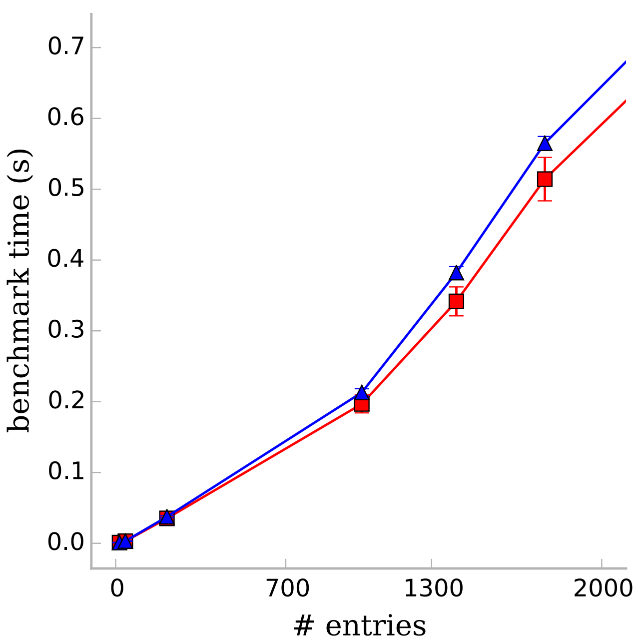

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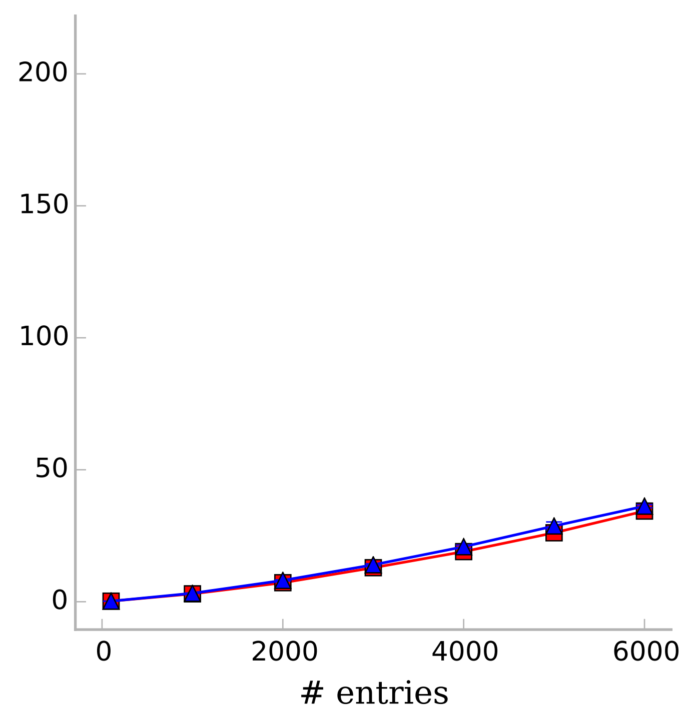

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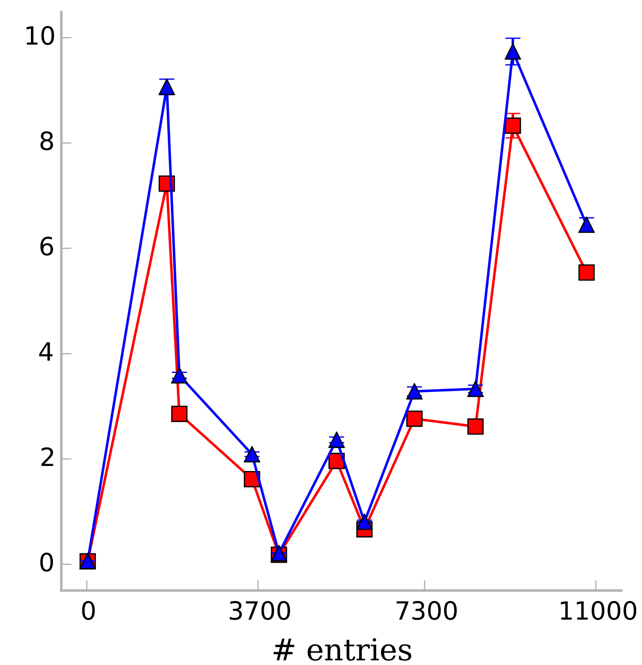
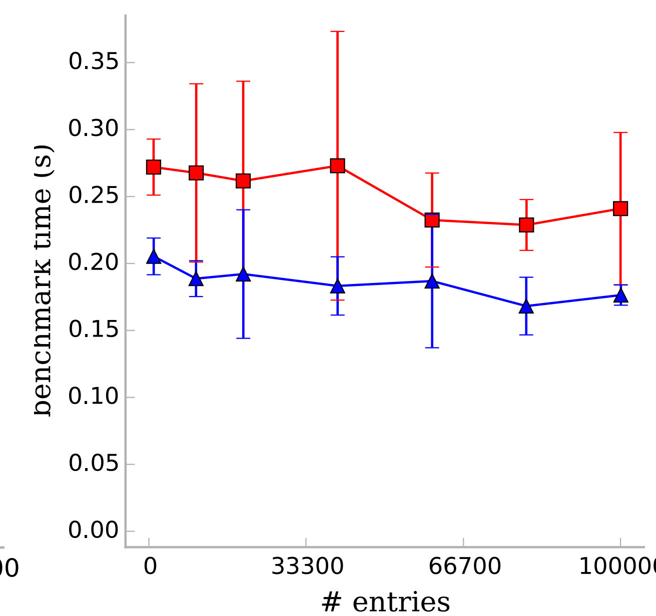


Sat4j

Original implementation has worst-case linear time



Myria

Performance

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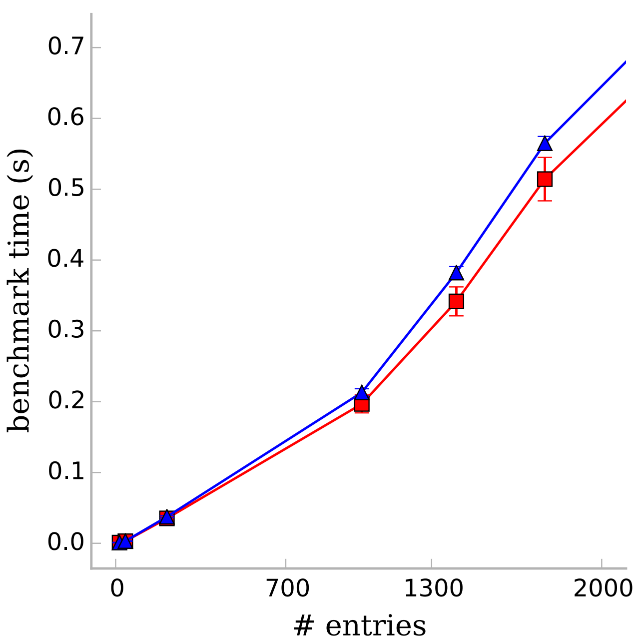

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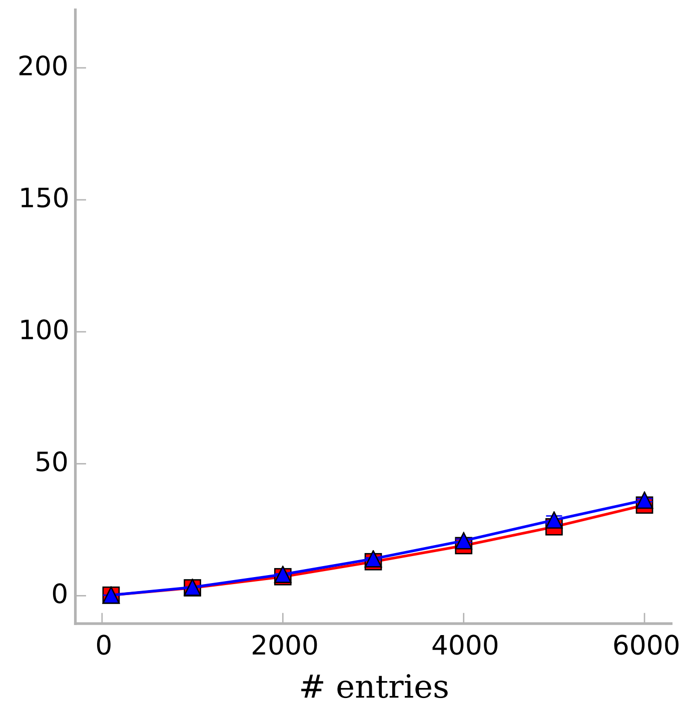

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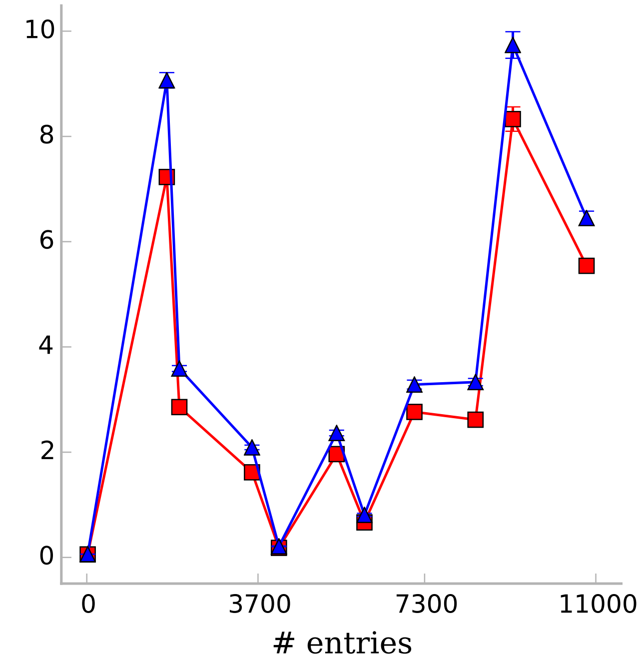

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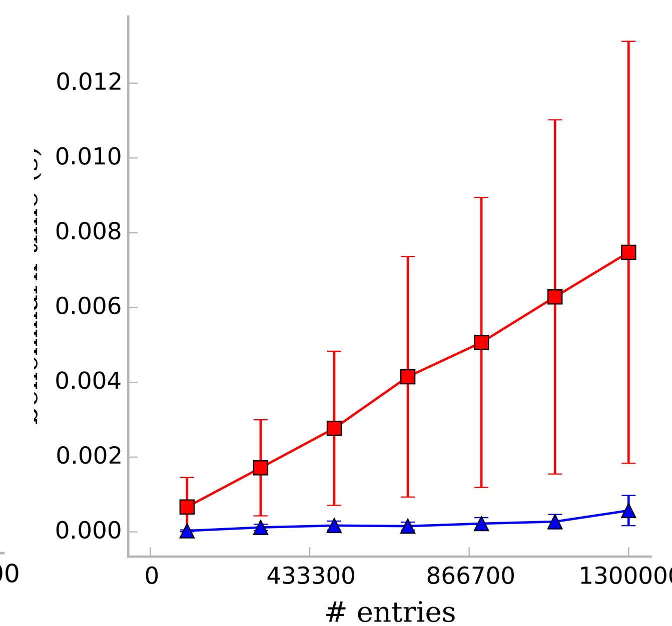

Myria

Related Work

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    - Hard-coded rewrite rules

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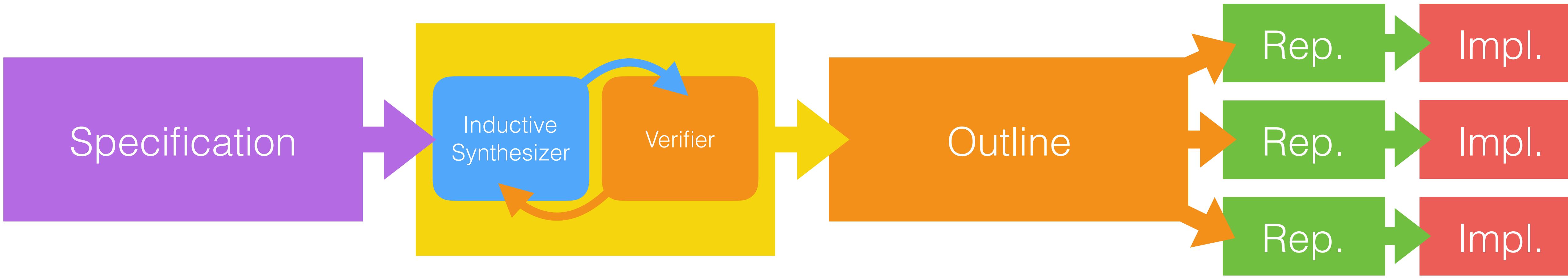
  - Enumerate possible views & indexes based on query syntax and use the planner to decide which ones to keep
- P. Hawkins et al: "**Data representation synthesis**" (2011)
  - Enumerate representations and use a planner to implement retrieval operations; conjunctions of equalities only

http://cozy.uwplse.org



- Implementation outlines make the problem tractable
- Synthesis completes < 90 seconds
- Cozy generates correct code, and matches handwritten implementation performance

Special thanks to:


Michael Ernst


Emina Torlak

also Haoming Liu & Daniel Perelman