# Fast Synthesis of Fast Collections

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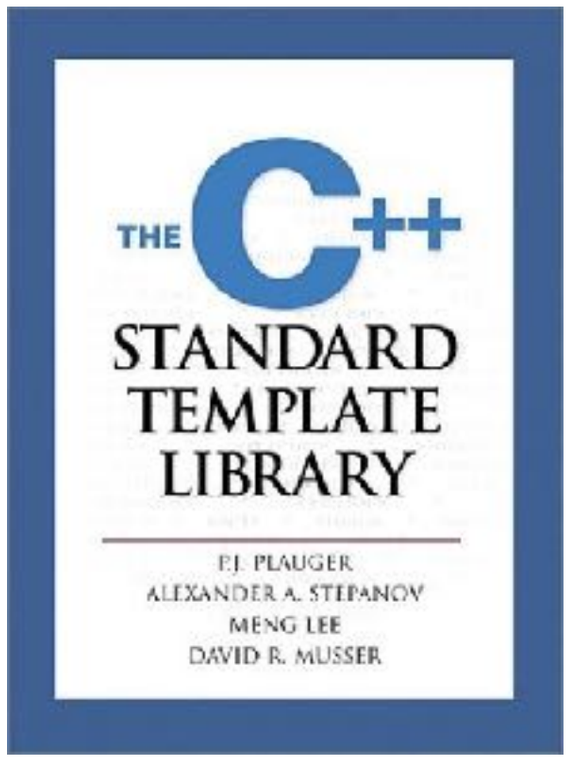
# Data structures are everywhere

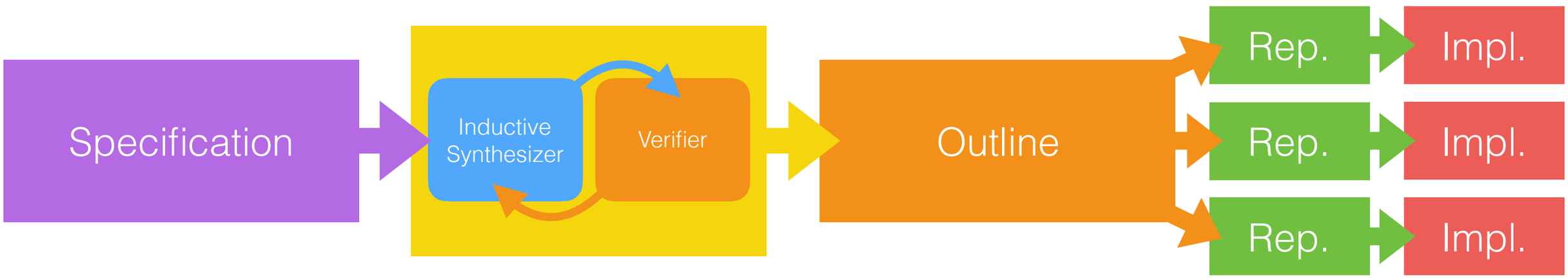





Lists, maps, and sets solve many problems

**What if I need a custom data structure?**

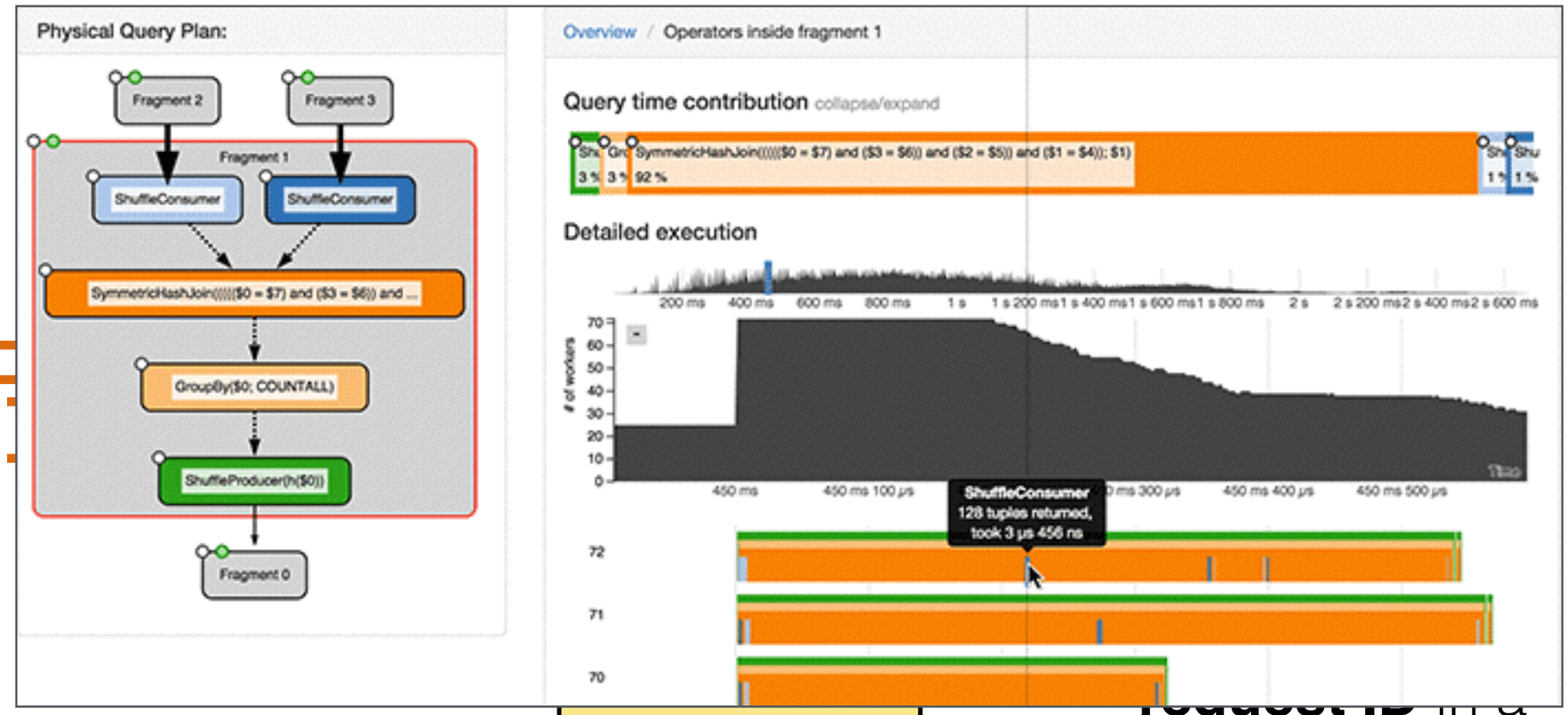
# Cozy synthesizes collections




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

# Myria Analytics Storage

**Request 1**



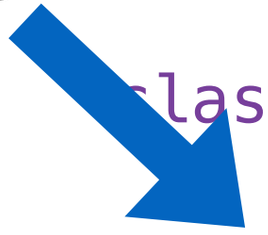

**Request 2**

**request ID** in a particular **timespan**

time

# Myria Analytics Storage

Insert an entry into
the data structure

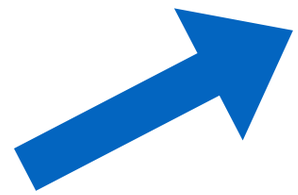


```
class AnalyticsLog {

    void log(Entry e)

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

}
```



Retrieve entries

# 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)**

```
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(…)
```


**Tractable** → ? → **Tractable**

**Specification** → **Outline** → **Implementation**

**specific** enough to describe asymptotic performance

**general** enough to encode a data structure succinctly

"In the quest for a good solution, the search space of possible … is simply te…"

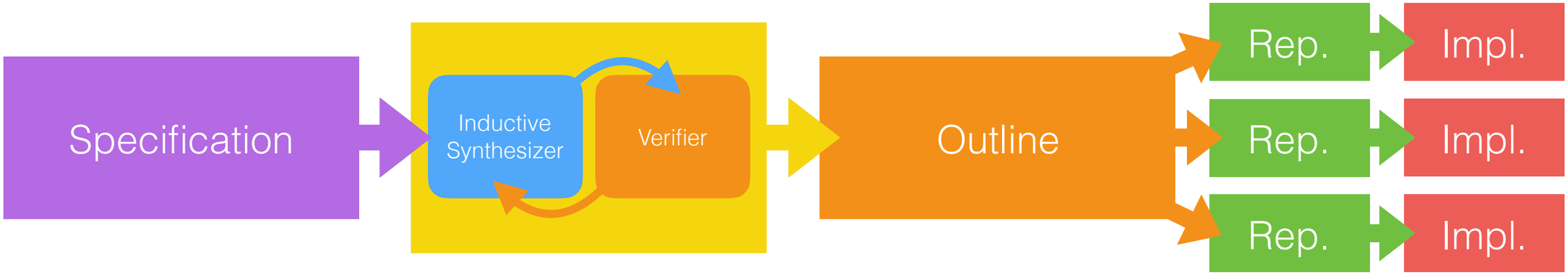
**Outline**

# 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

**HashLookup** (

**All**(),

e.queryId = q )

```
class Structure {

  T data;

  Iterator<Entry>
  retrieve(q) { … }

}
```

# Outlines → Implementations

```
class Structure {
```

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

```
  T data;

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

# Outlines → Implementations

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

```
class Structure {
  HMap<K,V> data;

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

# Outlines → Implementations

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

**HashLookup**(
data,
e.queryId = 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 )

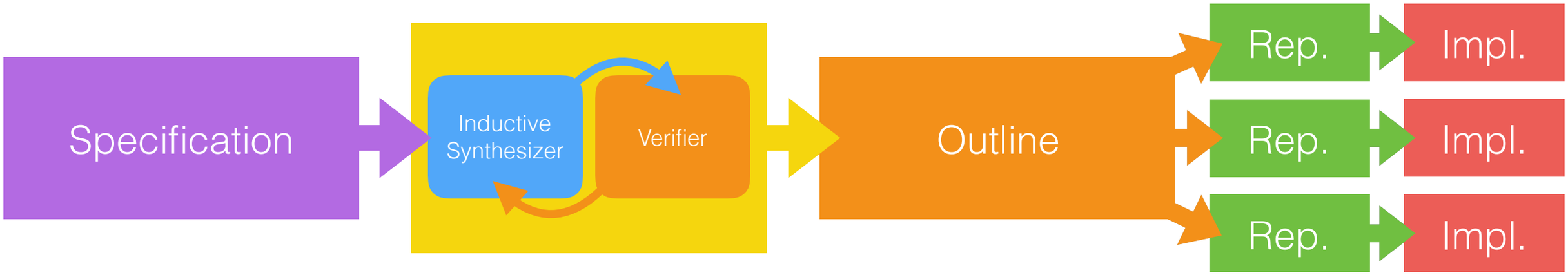
```
class Structur
```

**add, remove, update**

```
HMap<int,V> data;

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

# Specification → Outline

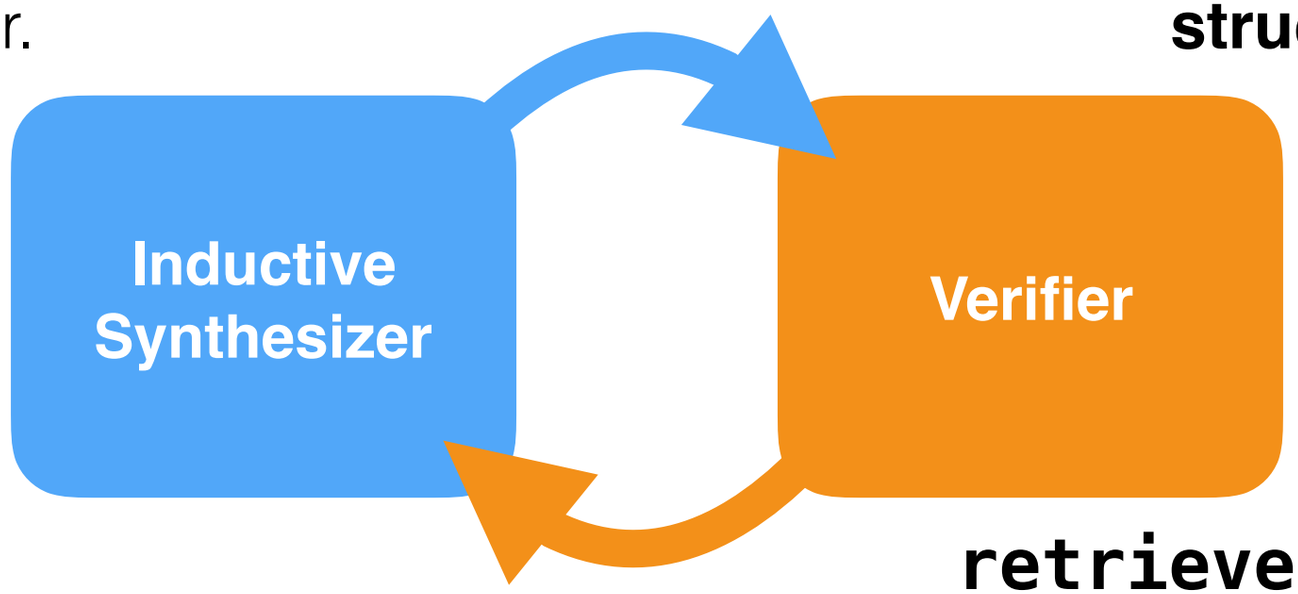


# Specification → Outline

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

CEGIS

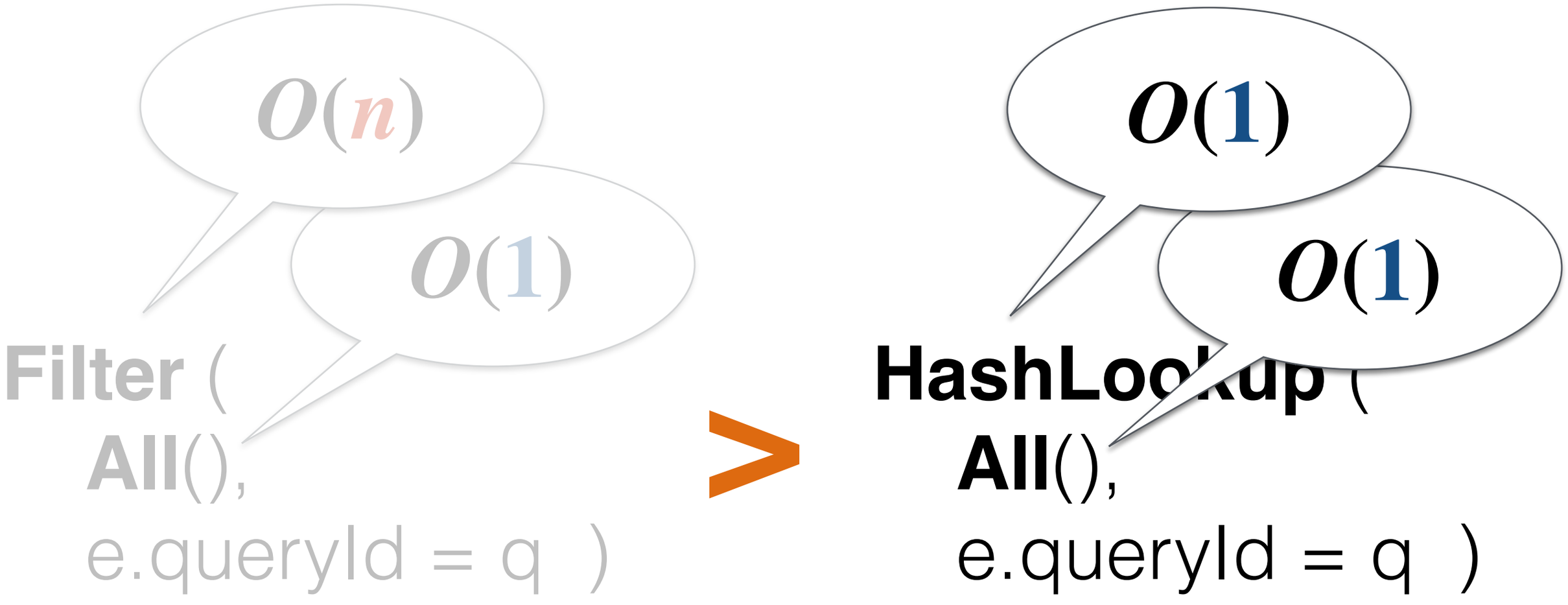
Must ensure the outline is correct for **all possible inputs** and **all possible data structure states.**



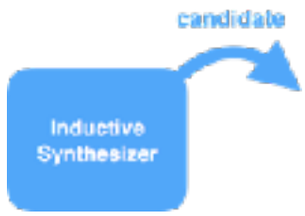

```
retrieve: all e where
    e.queryId = q and …
```

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

# Cost Model




**Cozy prefers outlines with lower cost**




# Inductive S

Enum

size 1

size 2

Concat(**HashLookup(…)**,…)
vs
Concat(**Filter(…)**,…)

All

HashLookup(All, x=

Filter(All, x=y)

BinarySearch(All, x>y)

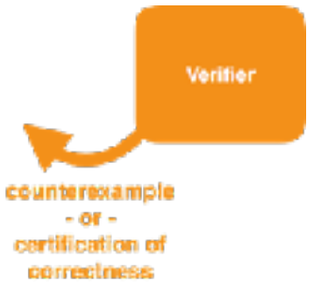
HashLookup(
HashLookup(…), a=b)

Filter(
HashLookup(…), p=q)

Filter(
BinarySearch(…), x<y)

…

…




# Outline Verification

**Specification:**

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

```
subque   Id : Int,
…
```

$P$

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

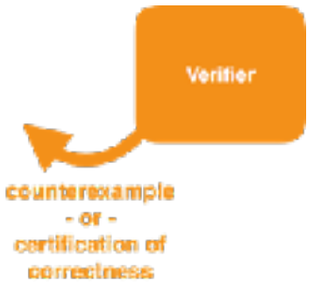
**Hashl**

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

e.qu

**representative predicate $Q$**

e.queryId = q




# Outline Verification

$$\{\, e \mid e \in S \wedge P(I, e) \,\} \stackrel{?}{=} \{\, e \mid e \in S \wedge Q(I, e) \,\}$$

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

$$P(I, e) = Q(I, e)$$

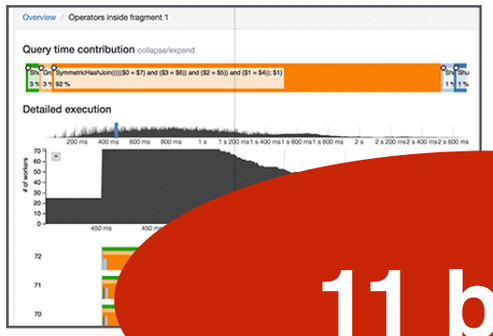
**equivalence can be checked with an SMT solver**

# Evaluation

- Improve correctness 
- Save programmer effort 
- Match performance 

# Case studies

- **Myria:** analytics



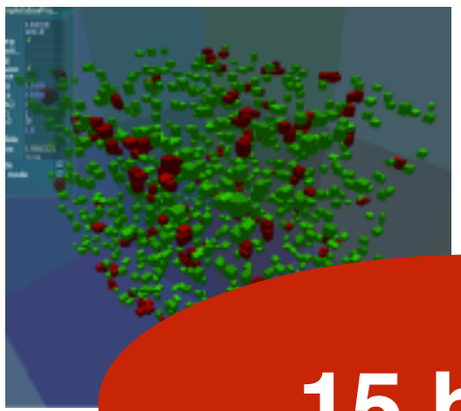

Analytics data indexed by
n and by

**11 bugs**

- **ZTopo:** tile cache

Tracks map tiles in a least-recently-used cache

- **Bullet:** volume tree



Stores axis-aligned bounding boxes for fast collision detection

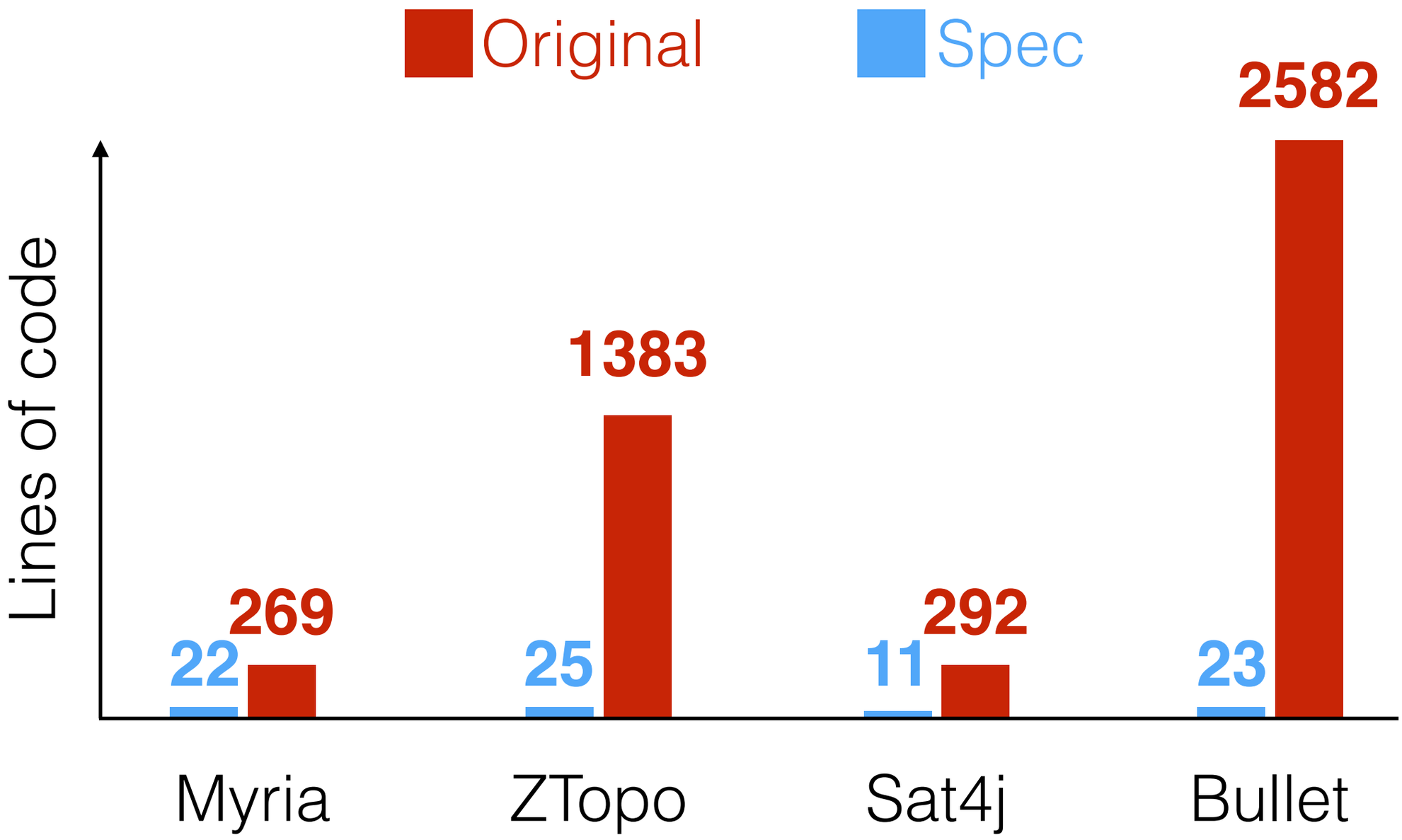
**15 bugs**

- **Sat4j:** variable metadata

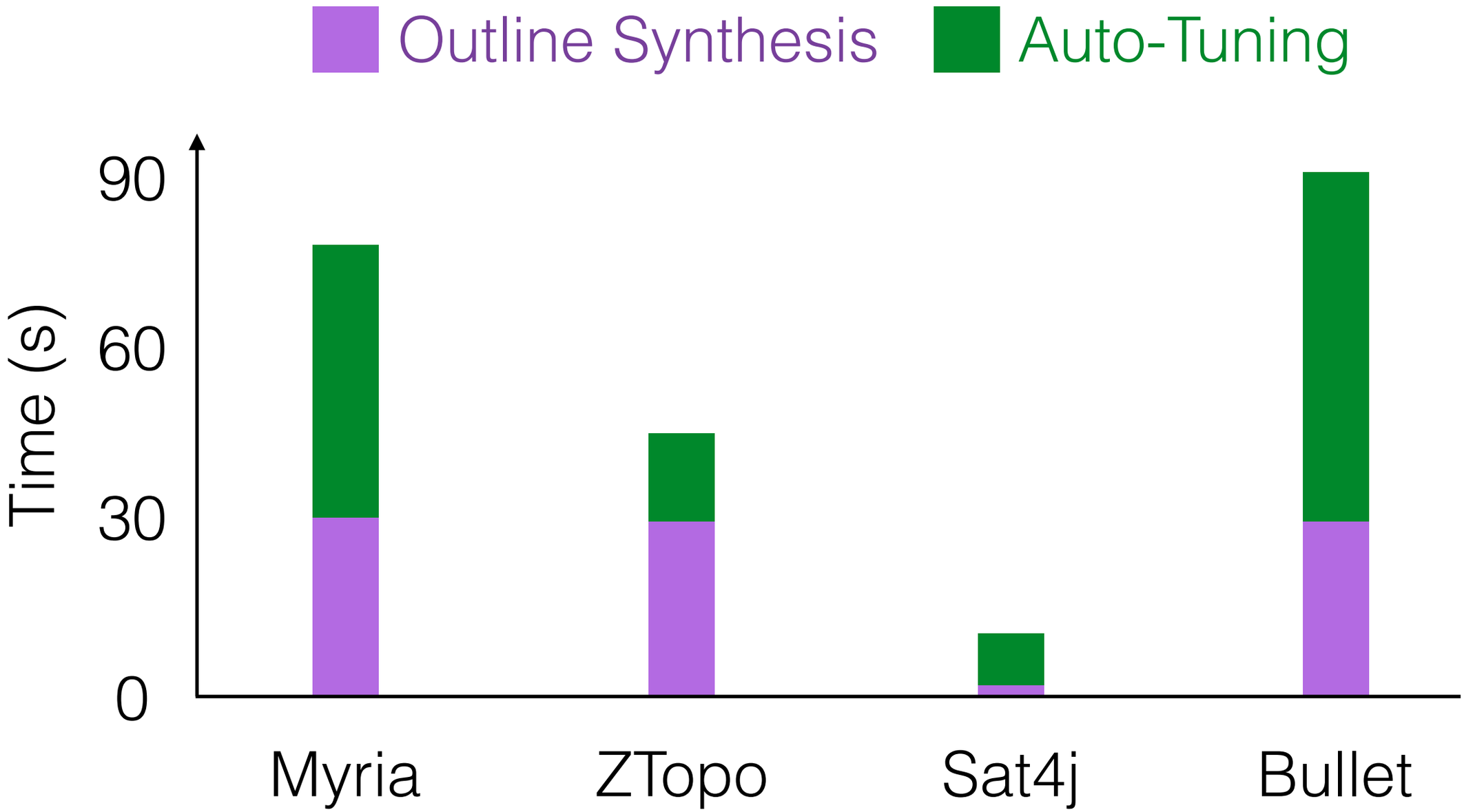

Tracks information about each variable in the formula

**7 bugs**

# Specifications vs. Implementations



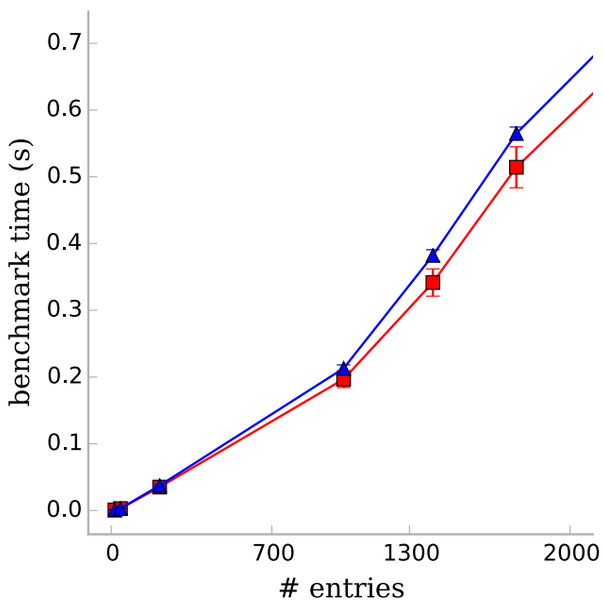
# Synthesis Time



# Performance

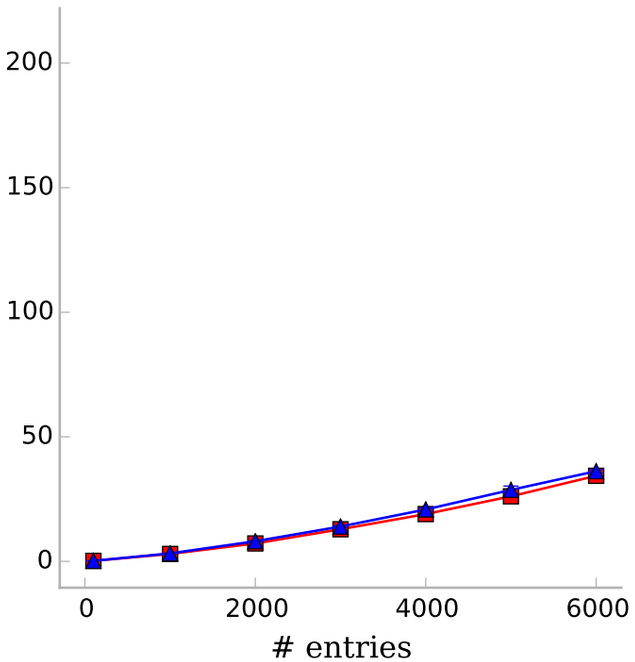
Original Synthesized

Data structures are nearly identical



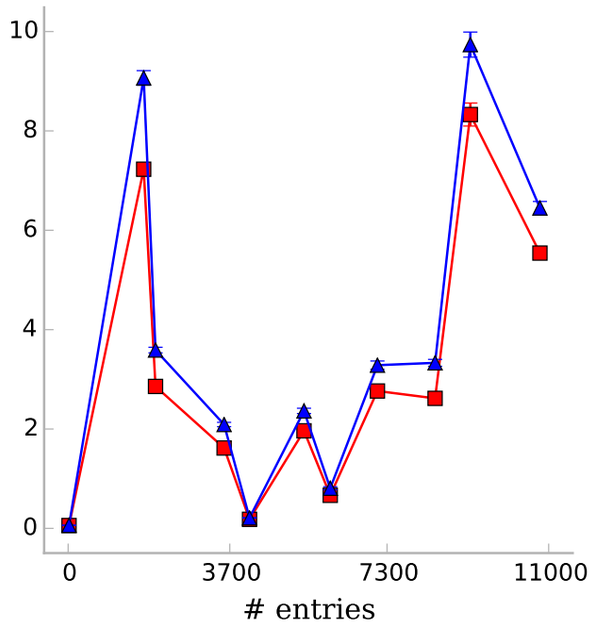

**ZTopo**

Binary search tree vs. space partitioning tree



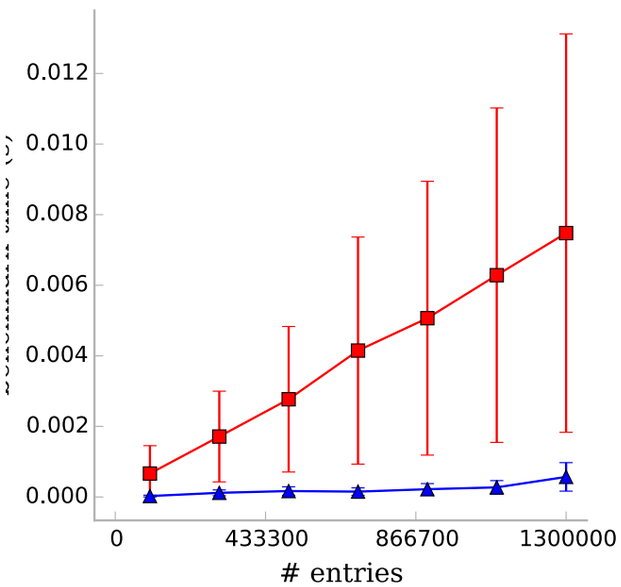

**Bullet**

Small overhead; performance dominated by other factors




**Sat4j**

Original implementation has worst-case linear time

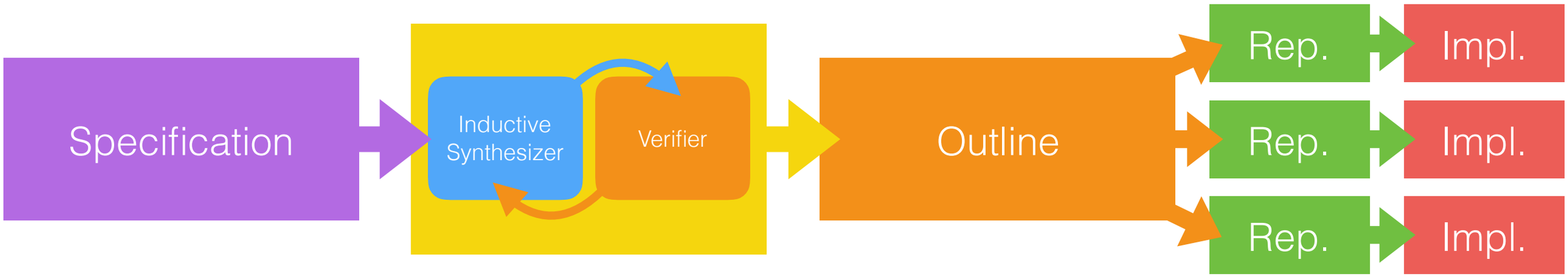



**Myria**

# Related Work

- J. Earley: "**High level iterators and a method for automatically designing data structure representation**" (1974)
    - Hard-coded rewrite rules
- S. Agrawal et al: "**Automated selection of materialized views and indexes in sql databases**" (2000)
    - 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