Signature Inference for Functional Property Discovery

or: How never to come up with tests manually anymore(*)

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Long term vision: A future in which ...

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Software works

Long term vision: A future in which ...

Software works because is cheaper to make software that works

Long term vision: A future in which ...

Software works because is cheaper to make software that works, even in the short term.

Long term goal:

We never come up with tests manually.

Motivation

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Writing correct software is hard for humans.

Idea

Motivation

Make machines do it!

Idea

Motivation

I will write the code myself, and get the machine to prove that it is correct.

Idea

Motivation

I will write the code myself, and get the machine to test that it works.

Making machines test that my code works

```
sort
    [4, 1, 6]
        ==
            [1, 4, 6]
```

Making machines test that my code works

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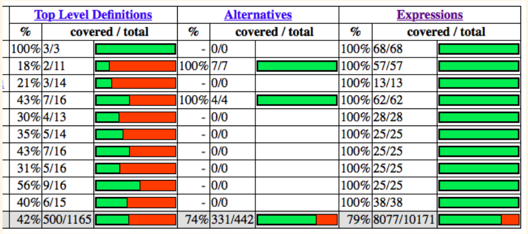

Top Level Definitions			Alternatives			Expressions		
%	covered / total		%	covered / total		%	covered / total	
100%	3/3	🟩	-	0/0		100%	68/68	🟩
18%	2/11	🟩🟥	100%	7/7	🟩	100%	57/57	🟩
21%	3/14	🟩🟥	-	0/0		100%	13/13	🟩
43%	7/16	🟩🟥	100%	4/4	🟩	100%	62/62	🟩
30%	4/13	🟩🟥	-	0/0		100%	28/28	🟩
35%	5/14	🟩🟥	-	0/0		100%	25/25	🟩
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42%	500/1165	🟩🟥	74%	331/442	🟩🟥	79%	8077/10171	🟩🟥

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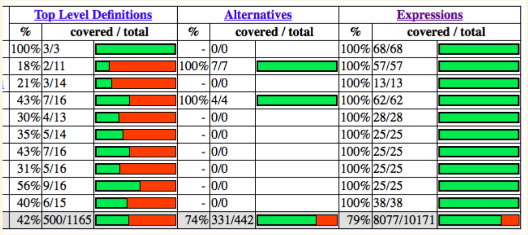

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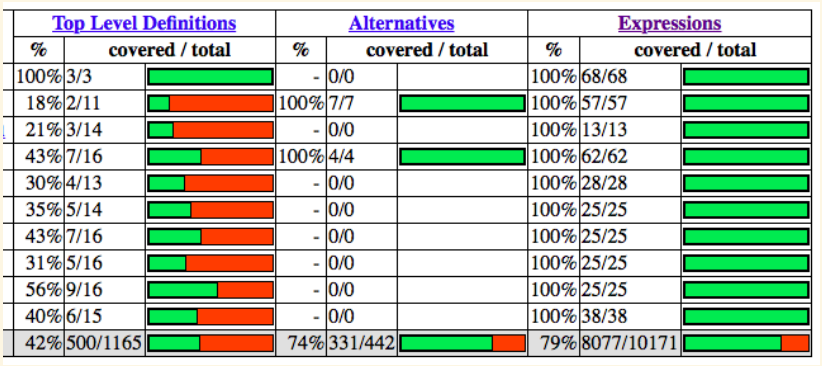
Fixing the coverage problem



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Property testing

```
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  arbitrary
    $ \ls ->
      isSorted (sort ls)
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Fixing the cost problem

Property Discovery

```
forAll
  arbitrary
    $ \ls ->
      sort ls == ls
```

Property Discovery with QuickSpec

Example code

```haskell
module MySort where

mySort :: Ord a => [a] -> [a]
mySort [] = []
mySort (x:xs) = insert (mySort xs)
  where
    insert [] = [x]
    insert (y:ys)
        | x <= y = x : y : ys
        | otherwise = y : insert ys

myIsSorted :: Ord a => [a] -> Bool
myIsSorted [] = True
myIsSorted [_] = True
myIsSorted (x:y:ls) = x <= y && myIsSorted (y : ls)
```

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Property discovery using QuickSpec

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== Signature ==
      True :: Bool
      (<=) :: Ord a => a -> a -> Bool
       (:) :: a -> [a] -> [a]
    mySort :: Ord a => [a] -> [a]
myIsSorted :: Ord a => [a] -> Bool
```

Property discovery using QuickSpec

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== Laws ==
  1. y <= y = True
  2. y <= True = True
  3. True <= x = x
  4. myIsSorted (mySort xs) = True
  5. mySort (mySort xs) = mySort xs
  6. xs <= mySort xs = myIsSorted xs
  7. mySort xs <= xs = True
  8. myIsSorted (y : (y : xs)) = myIsSorted (y : xs)
  9. mySort (y : mySort xs) = mySort (y : xs)
```

Property discovery using QuickSpec

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== Signature ==
      True :: Bool
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QuickSpec Code

```haskell
{-# LANGUAGE ScopedTypeVariables #-}
{-# LANGUAGE ConstraintKinds #-}
{-# LANGUAGE RankNTypes #-}
{-# LANGUAGE FlexibleContexts #-}

module MySortQuickSpec where

import Control.Monad
import MySort
import QuickSpec

main :: IO ()
main =
    void $
    quickSpec
        signature
        { constants =
              [ constant "True" (True :: Bool)
              , constant "<=" (mkDict (<=) :: Dict (Ord A) -> A -> A -> Bool)
              , constant ":" ((:) :: A -> [A] -> [A])
              , constant "mySort" (mkDict mySort :: Dict (Ord A) -> [A] -> [A])
              , constant
                    "myIsSorted"
                    (mkDict myIsSorted :: Dict (Ord A) -> [A] -> Bool)
              ]
        }

mkDict ::
       (c =>
            a)
    -> Dict c
    -> a
mkDict x Dict = x
```

Problems with QuickSpec: Monomorphisation

Only for monomorphic functions

```
constant "<"
  (mkDict (<) :: Dict (Ord A) -> A -> A -> Bool)
```

Problems with QuickSpec: Code

Programmer has to write code for all functions of interest
15 lines of subject code.
33 lines of QuickSpec code.

Problems with QuickSpec: Speed

Dumb version of the QuickSpec approach:

1. Generate all possible terms
2. Generate all possible equations (tuples) of terms
3. Type check them to make sure the equation makes sense
4. Check that the input can be generated and the output compared for equality
5. Run QuickCheck to see if the equation holds

Pause slide with a joke

```
strictId :: a -> a
strictId !x = x
```

Property Discovery with EasySpec

Step 1: Automation

Signatures

```
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              ]
        }

mkDict ::
       (c =>
             a)
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mkDict x Dict = x
```

A QuickSpec Signature

```
data Signature =
  Signature {
    constants           :: [Constant],
    instances           :: [[Instance]],
    [...]
    background          :: [Prop],
    [...]
  }

quickSpec :: Signature -> IO Signature
```

Automatic Monomorphisation

```
filter :: (a -> Bool) -> [a] -> [a]
```

becomes

```
filter :: (A -> Bool) -> [A] -> [A]
```

Automatic Monomorphisation

```
filter :: (a -> Bool) -> [a] -> [a]
```

becomes

```
filter :: (A -> Bool) -> [A] -> [A]
```

```
sort :: Ord a => [a] -> [a]
```

becomes

```
sort :: Dict (Ord A) -> [A] -> [A]
```

Signature Expression Generation

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Signature Expression Generation

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sort :: Ord a => [a] -> [a]

sort :: Dict (Ord A) => [A] -> [A]

constant "sort"
  (mkDict sort :: Dict (Ord A) -> [A] -> [A])

signature { constants = [...] }
```

Current situation

```
$ cat Reverse.hs
{-# LANGUAGE NoImplicitPrelude #-}

module Reverse where

import Data.List (reverse, sort)
```

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```
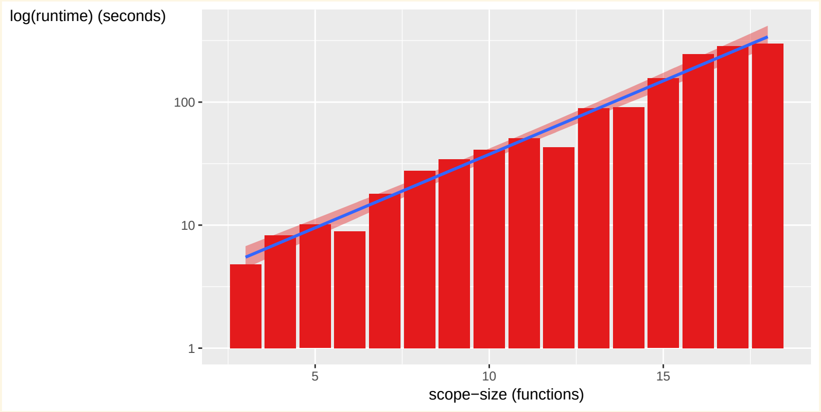

```
$ easyspec discover Reverse.hs
    reverse (reverse xs) = xs
    sort (reverse xs) = sort xs
```

Pause slide with a joke

```haskell
safePerformIO :: IO a -> IO a
safePerformIO ioa = ioa >>= return
```

Automated, but still slow



Definitions

Definitions: Property

Example:

```
reverse (reverse ls) = ls
```

Short for:

```
(\ls -> reverse (reverse ls)) = (\ls -> ls)
```

In general:

```
(f :: A -> B) = (g :: A -> B)
for some A and B with
instance Arbitrary A
instance Eq B
```

Definitions: Size of property

Example:

```
xs <= mySort xs = myIsSorted xs
```

Definitions: Size of property

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Size: 4

Definitions: Size of property

Example:

```
    xs <= mySort xs = myIsSorted xs
```

Size: 4

In general: It's complicated

Definitions: Property of a function

Functions:

```
f = (* 2)
g = (* 3)
z = 0
```

Properties of `f`:

```
f (g x) = g (f x)
f z = z
```

Not properties of `f`:

```
g z = z
```

Definitions: Relevant function

Functions:

```
f = (* 2)
g = (* 3)
z = 0
h = id
```

Properties:

```
f (g x) = g (f x)
f z = z
g z = z
h x = x
```

`g` and `z` are relevant to `f` but `h` is not.

relevant property = property of focus function

Definitions: Scope

Scope: Functions in scope

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Size of scope: Number of functions in scope

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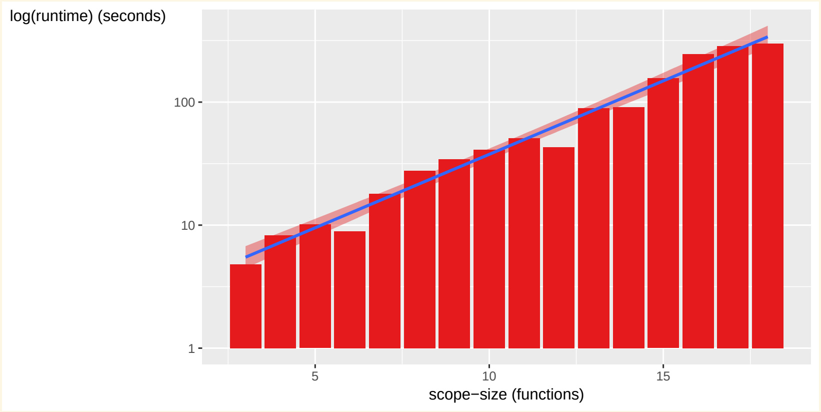
Size of signature: Number of functions in signature

Automated, but still slow



Why is this slow?

1. Maximum size of the discovered properties

Why is this slow?

1. Maximum size of the discovered properties
2. Size of the signature

Idea

Critical insight

We are not interested in the entire codebase.

We are interested in a relatively small amount of code.

Reducing the size of the signature

```
inferSignature
  :: [Function] -- Focus functions
  -> [Function] -- Functions in scope
  -> [Function] -- Chosen functions
```

Full background and empty background

```
inferFullBackground _ scope = scope

inferEmptyBackground focus _ = focus
```

Full background and empty background

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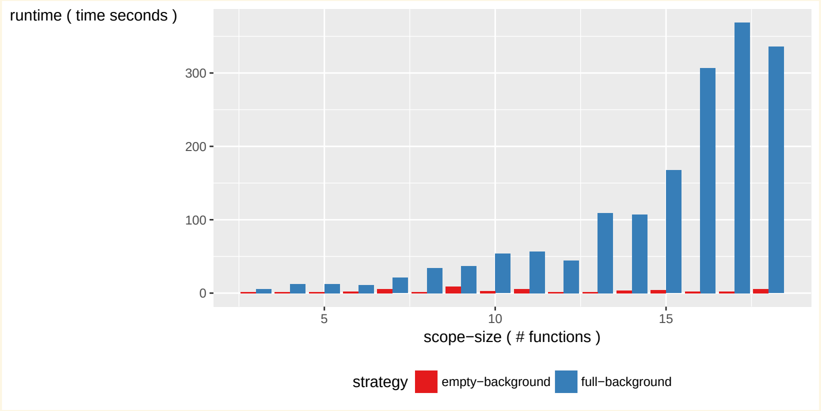

Full background and empty background

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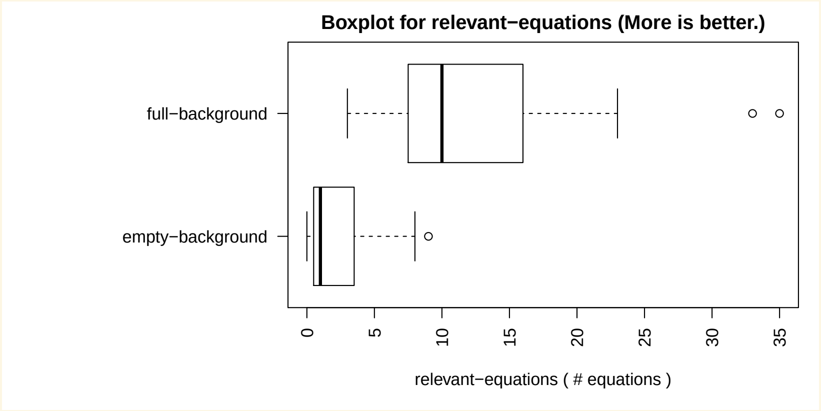
```



Pause slide with a joke

```
safeCoerce :: a ~ b => a -> b
safeCoerce x = x
```

Syntactic similarity: Name

```
inferSyntacticSimilarityName [focus] scope
    = take 5 $ sortOn
      (\sf ->
        hammingDistance
          (name focus) (name sf))
      scope
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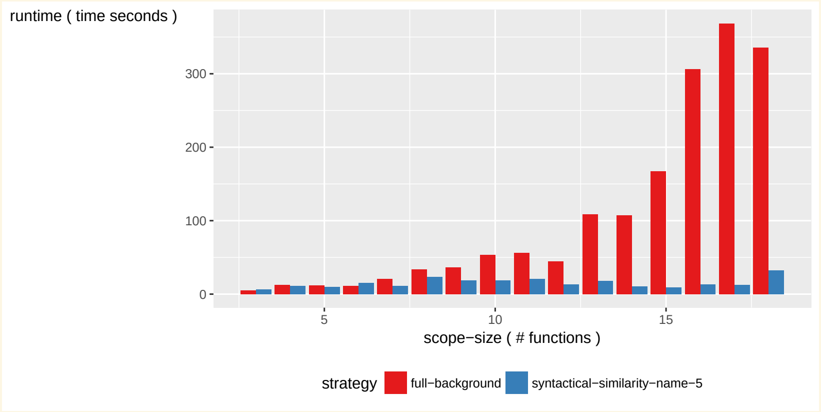

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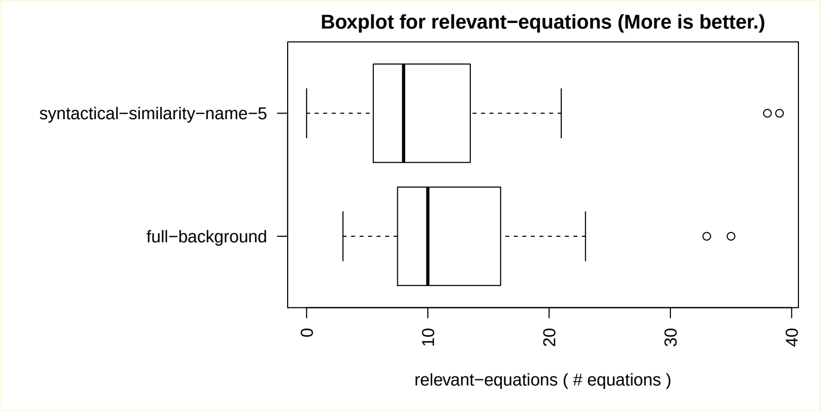

Syntactic similarity: Implementation

```
inferSyntacticSimilaritySymbols i [focus] scope
    = take i $ sortOn
      (\sf ->
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          (symbols focus) (symbols sf))
      scope
```

Syntactic similarity: Implementation

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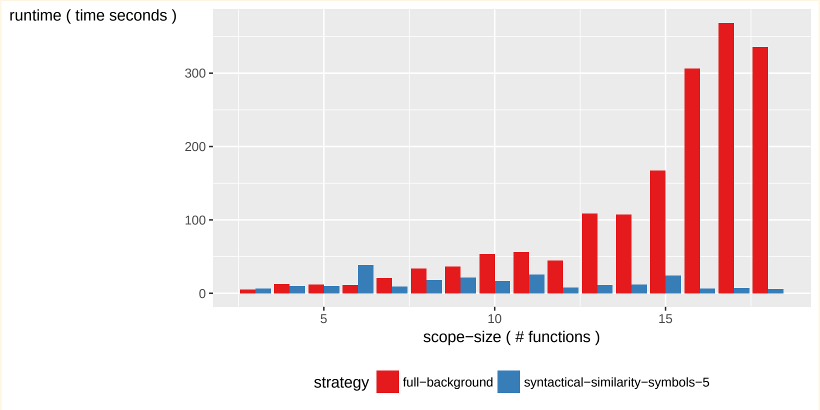

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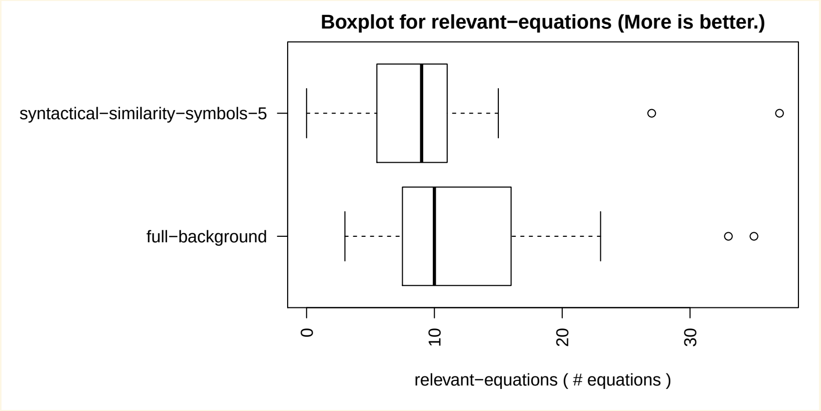

Syntactic similarity: Type

```haskell
inferSyntacticSimilarityType i [focus] scope
    = take i $ sortOn
      (\sf ->
        hammingDistance
          (getTypeParts focus) (getTypeParts sf))
      scope
```

Syntactic similarity: Type

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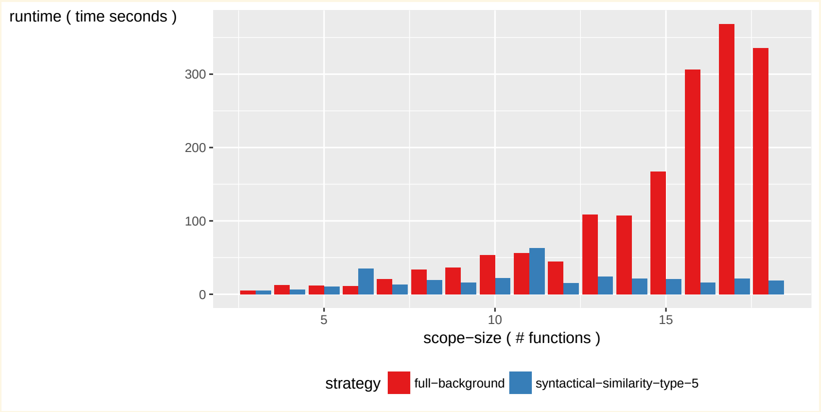

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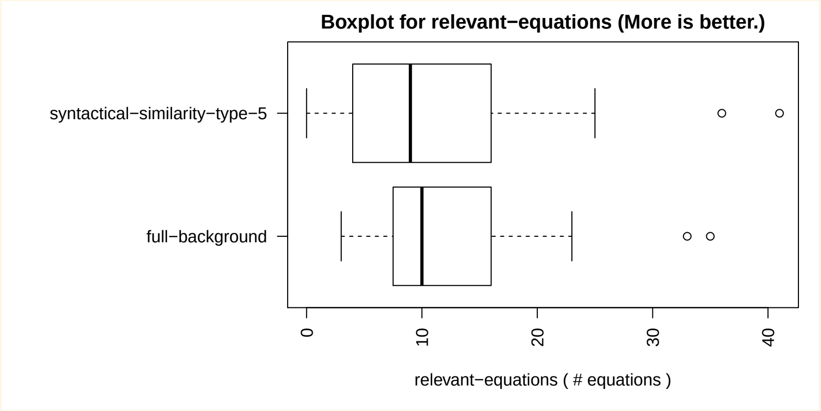
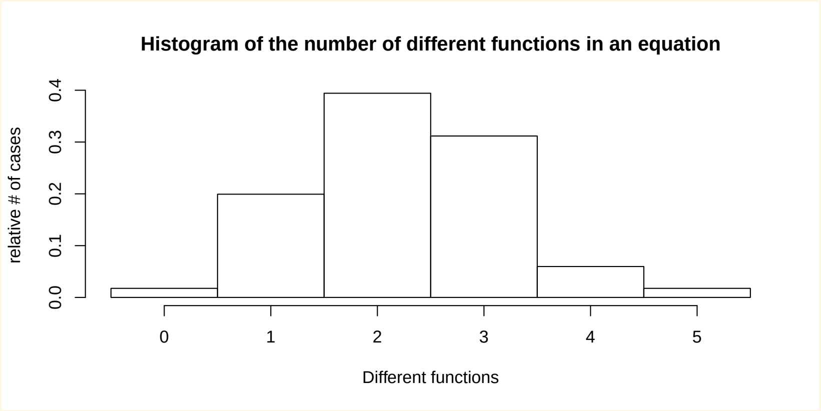


Other things we tried

1. Similarity using a different metric: edit distance
2. Unions of the previous strategies

Breakthrough



Idea

We can run QuickSpec more than once!

Inferred Signature

```
type SignatureInferenceStrategy
    = [Function] -> [Function] -> InferredSignature
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Combine the results of multiple runs:

```
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User previous results as background properties:

```
type InferredSignature = Forest Signature
```

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Combine the results of multiple runs:

```
type InferredSignature = [Signature]
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User previous results as background properties:

```
type InferredSignature = Forest Signature
```

Share previous runs:

```
type InferredSignature = DAG Signature
```

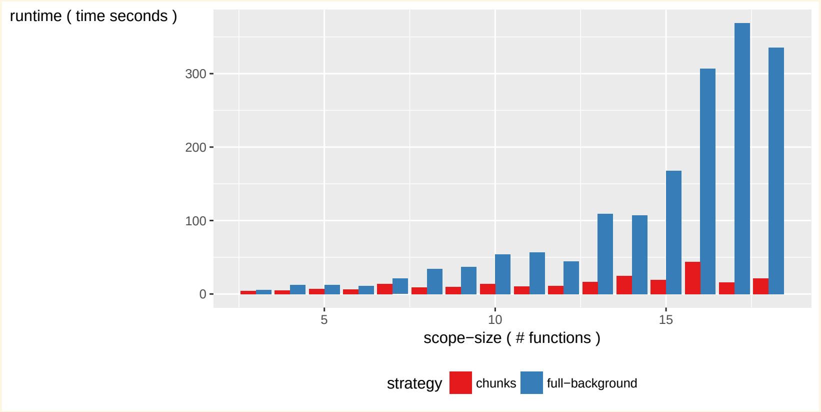
Chunks

```
chunks :: SignatureInferenceStrategy
```

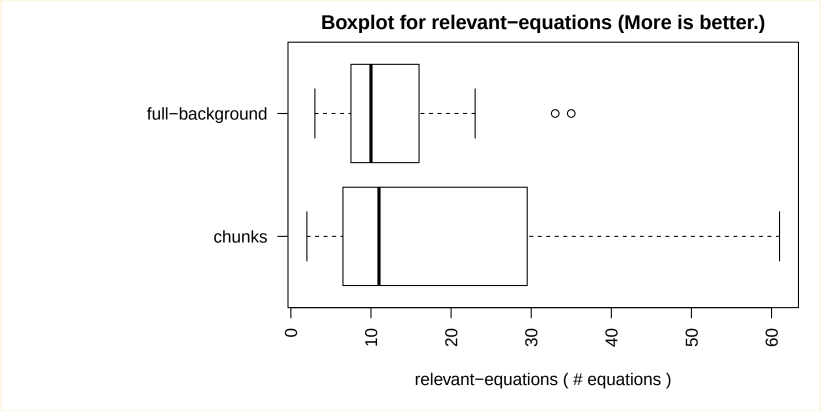
```
> chunks
>     [sort :: Ord a => [a] -> [a]]
>     [reverse :: [a] -> [a], id :: a -> a]

[sort, reverse]
        |
        v
     -> [sort]
     |
     |
[sort, id]
```

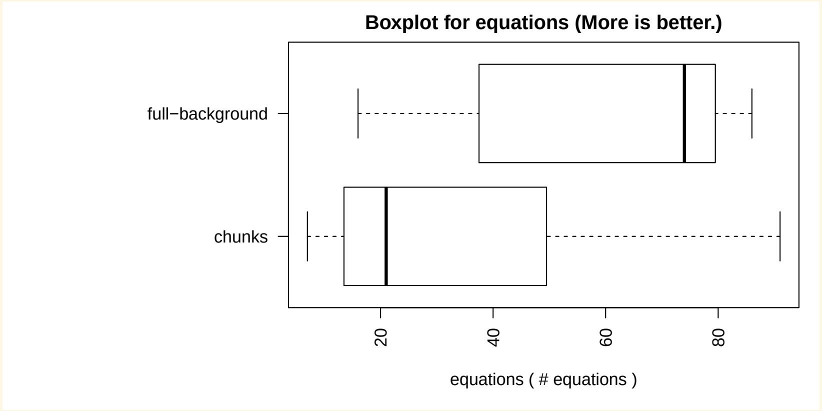
The runtime of chunks



The outcome of chunks: Relevant equations



Why does chunks find more relevant equations?



Why does chunks find more relevant equations?

Scope:

```
i = (+ 1)
j = (+ 2)
k = (+ 3)
l = (+ 4)
m = (+ 5)
n = (+ 6)
o = (+ 7)
p = (+ 8)
q = (+ 9)
r = (+ 10)
```

Why does chunks find more relevant equations?

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Full background:

```
i (i x) = j x
i (j x) = k x
i (k x) = l x
i (l x) = m x
i (m x) = n x
i (n x) = o x
i (o x) = p x
i (p x) = q x
i (q x) = r x
```

Relevant to r:

```
i (q x) = r x
```

Why does chunks find more relevant equations?

Scope:

```
i = (+ 1)
j = (+ 2)
k = (+ 3)
l = (+ 4)
m = (+ 5)
n = (+ 6)
o = (+ 7)
p = (+ 8)
q = (+ 9)
r = (+ 10)
```

Full background:

```
i (i x) = j x
i (j x) = k x
i (k x) = l x
i (l x) = m x
i (m x) = n x
i (n x) = o x
i (o x) = p x
i (p x) = q x
i (q x) = r x
```

Relevant to r:

```
i (q x) = r x
```

Chunks for r:

```
q (i x) = r x
q (q x) = p (r x)
q (q (q x)) = o (r (r x))
q (q (q (q (q x)))) = m (r (r (r (r x))))
q (q (q (q (q (q x))))) = l (r (r (r (r (r x)))))
```

All relevant

Inferred Signature

```
type SignatureInferenceStrategy
    = [Function] -> [Function] -> InferredSignature
```

```
type InferredSignature =
    DAG ([(Signature, [Equation])] -> Signature)
```

Inferred Signature

```
type SignatureInferenceStrategy
    = [Function] -> [Function] -> InferM ()

data InferM a where
    InferPure :: a -> InferM a
    InferFmap :: (a -> b) -> InferM a -> InferM b
    InferApp :: InferM (a -> b) -> InferM a -> InferM b
    InferBind :: InferM a -> (a -> InferM b) -> InferM b

    InferFrom
        :: [EasyNamedExp]
        -> [OptiToken]
        -> InferM (OptiToken, [EasyEq])
```

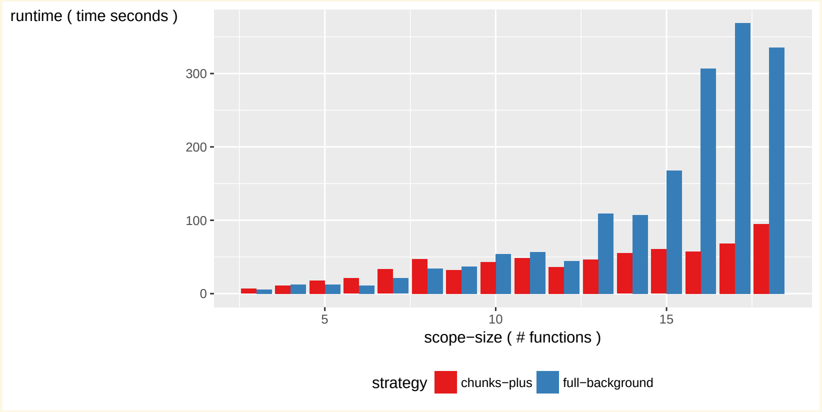
Chunks Plus

```
chunksPlus :: SignatureInferenceStrategy
```

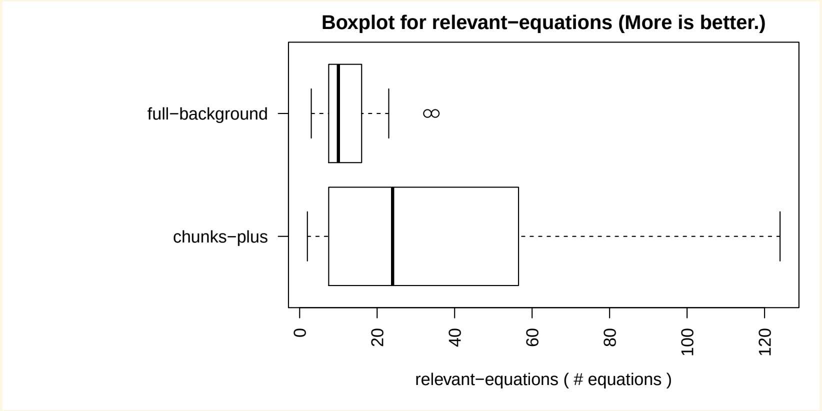
```
> chunksPlus
>     [sort :: Ord a => [a] -> [a]]
>     [reverse :: [a] -> [a], id :: a -> a]

                      ->  [sort, reverse]
                     /            |
                    /             v
[sort, reverse, id]             -> [sort]
                    \          |
                     \         |
                      ->  [sort, id]
```

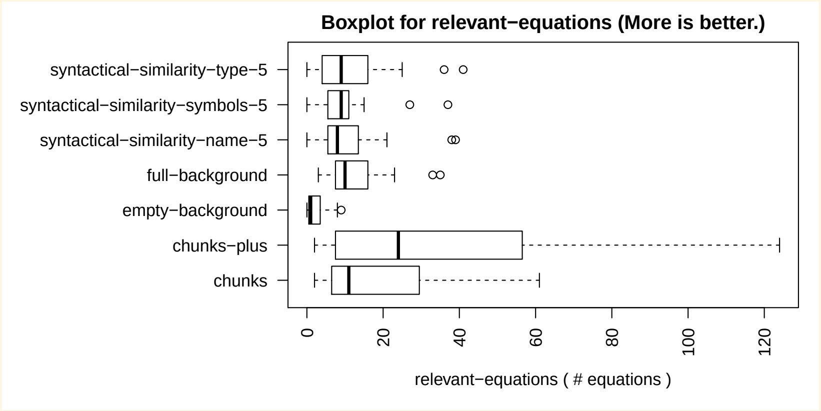
The runtime of chunks plus



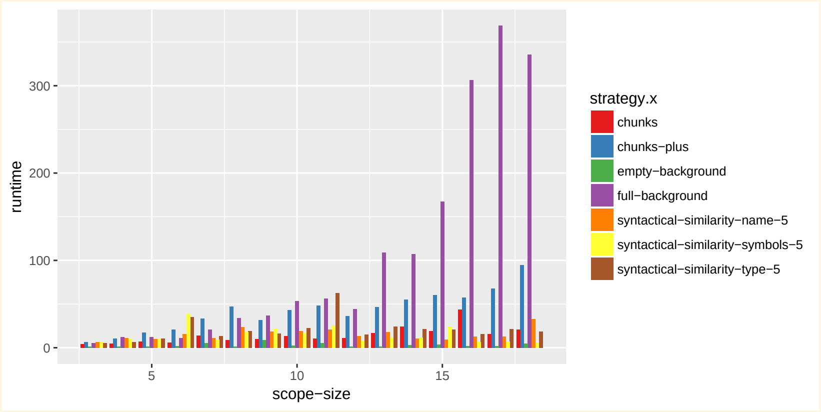
The outcome of chunks plus: Relevant equations



All strategies



All strategies



Neat

```
$ time stack exec easyspec \
      -- discover MySort.hs MySort.mySort

xs <= mySort xs = myIsSorted xs
mySort xs <= xs = True
myIsSorted (mySort xs) = True
mySort (mySort xs) = mySort xs

3.61s user 1.14s system 193% cpu 2.450 total
```

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1. Only works for functions in scope of which the type is in scope too.

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All technical problems, not theoretical problems!

Further Research

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1. Can we go faster?
2. Which constants do we choose for built in types?
3. Can we apply this to effectful code?
4. Relative importance of equations

Call to action

Proofs of concept:

`https://github.com/nick8325/quickcheck`
`https://github.com/nick8325/quickspec`

`https://github.com/NorfairKing/easyspec`

Now we need to make it production ready!

About Me

Student at ETH
This is my master thesis
Wrote Haskell in open source
Taught Haskell at ETH
Wrote Haskell in industry
Looking for a job!

`https://cs-syd.eu/`
`https://cs-syd.eu/cv`
`https://github.com/NorfairKing`