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Version: Accepted Version

Proceedings Paper:

https://doi.org/10.1145/3122955.3122961
Speculate: Discovering Conditional Equations and Inequalities about Black-Box Functions by Reasoning from Test Results

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Abstract

This paper presents Speculate, a tool that automatically conjectures laws involving conditional equations and inequalities about Haskell functions. Speculate enumerates expressions involving a given collection of Haskell functions, testing to separate those expressions into apparent equivalence classes. Expressions in the same equivalence class are used to conjecture equations. Representative expressions of different equivalence classes are used to conjecture conditional equations and inequalities. Speculate uses lightweight equational reasoning based on term rewriting to discard redundant laws and to avoid needless testing. Several applications demonstrate the effectiveness of Speculate.

CCS Concepts

•Software and its engineering →Software testing and debugging; •Theory of computation →Program specifications;

Keywords

formal specification, property-based testing, Haskell.

ACM Reference format:


DOI: 10.1145/3122955.3122961

1 Introduction

Writing formal specifications for programs is hard, but nevertheless useful. Formally specifying a program can contribute to understanding, documentation, and regression testing using a tool like QuickCheck [6].

This paper presents a new tool called Speculate. Given a collection of Haskell functions and values bound to monomorphic types, Speculate automatically conjectures a specification containing equations and inequalities involving those functions. Both equations and inequalities may be conditional. In these respects we extend previous work by other researchers on discovering unconditional equations [8, 22]. As Speculate is based on testing, its results are speculative.

Speculate enumerates expressions by combining free variables, functions and values provided by the user (§3). It evaluates these expressions for automatically generated test cases to partition the

Expressions into apparent equivalence classes. It conjectures equations between expressions in the same equivalence class. Then, it conjectures conditional equations (⇒) and inequalities (≤) from representatives of different equivalence classes (§4). Speculate uses lightweight equational reasoning to discard redundant equations and to avoid needless testing. Speculate is implemented in Haskell.

Example 1.1. When provided with the integer values 0 and 1, the functions id and abs, and the addition operator (+), Speculate first discovers and prints the following apparent equations:

\[
\begin{align*}
\text{id} \ x &= x \\
\text{x} + 0 &= x \\
\text{abs} \ (\text{abs} \ x) &= \text{abs} \ x \\
\text{x} + y &= y + x \\
\text{abs} \ (\text{x} + \text{y}) &= \text{abs} \ x + \text{abs} \ x \\
\text{abs} \ (\text{x} + \text{abs} \ x) &= \text{x} + \text{abs} \ x \\
\text{abs} \ 1 + \text{abs} \ x &= 1 + \text{abs} \ x \\
\text{x} + \text{y} &= \text{x} + \text{abs} \ y \\
\text{abs} \ (\text{x} + 1) &= 1 + \text{abs} \ x
\end{align*}
\]

Similar equational laws are found by the existing tool QuickSpec [8, 22]. But Speculate goes on to print the following apparent inequalities:

\[
\begin{align*}
\text{x} \leq \text{abs} \ x \\
0 \leq \text{abs} \ x \\
x \leq x + 1 \\
x \leq x + \text{abs} \ y \\
x \leq \text{abs} \ (x + x) \\
x \leq 1 + \text{abs} \ x \\
0 \leq x + \text{abs} \ x \\
x + y \leq x + \text{abs} \ y \\
\text{abs} \ (x + 1) \leq 1 + \text{abs} \ x
\end{align*}
\]

Finally, it prints these apparent conditional laws:

\[
\begin{align*}
\text{x} \leq \text{y} \Rightarrow \text{x} \leq \text{abs} \ y \\
\text{abs} \ x \leq \text{y} \Rightarrow \text{x} \leq \text{y} \\
\text{abs} \ x < \text{y} \Rightarrow \text{x} < \text{y} \\
x \leq 0 \Rightarrow \text{x} \leq \text{abs} \ y \\
\text{abs} \ x \leq \text{y} \Rightarrow 0 \leq \text{y} \\
\text{abs} \ x < \text{y} \Rightarrow 1 \leq \text{y} \\
x = 1 \Rightarrow 1 \leq \text{abs} \ x \\
x < 0 \Rightarrow 1 \leq \text{abs} \ x \\
y \leq x \Rightarrow \text{abs} \ (x + \text{abs} \ y) \geq x + \text{abs} \ y \\
x \leq 0 \Rightarrow x + \text{abs} \ x = 0 \\
\text{abs} \ x \leq \text{y} \Rightarrow \text{abs} \ (x + y) \geq x + y \\
\text{abs} \ y \leq \text{abs} \ (x + y) \Rightarrow x + y
\end{align*}
\]

The total execution time for Speculate to generate all the above laws is about 3 seconds. Speculate is implemented as a library, and the total application-specific source code required for this example is less than 10 lines.
import Test.Speculate

main :: IO ()
main = speculate args
  ( constants =
    [ constant "+" ((+) :: Int -> Int -> Int),
    constant "id" (id :: Int -> Int),
    constant "abs" (abs :: Int -> Int),
    background, constant "0" (0 :: Int),
    constant "1" (1 :: Int),
    constant "<=" ((<=) :: Int -> Int -> Bool),
    constant "<" ((<) :: Int -> Int -> Bool) ]
  )

Figure 1. Program used to obtain the results in §1.

3. How Speculate is Used
Speculate is used as a library (by "import Test.Speculate").

1.1 Contributions.
The main contributions of this paper are:
1. methods using automated black-box testing and equational reasoning to
discover apparent conditional equations and inequalities between functional expressions;
2. the design of the Speculate tool, which implements these
methods in Haskell and for Haskell functions;
3. a selection of small case-studies, investigating the effectiveness
of Speculate.

1.2 Road-map.
The paper is organized as follows: §2 defines expressions, expres-
sion size and a complexity ordering on expressions; §3 describes
how to use Speculate; §4 describes how Speculate works internally;
§5 presents example applications and results; §6 discusses related
work; §7 draws conclusions and suggests future work.

2. Definitions
Expressions and their sizes
All expressions formed by Speculate
have monomorphic types. Expressions, and their sizes, are:

Constants constant data-value and function symbols of size 1, e.g.,
• 0 :: Int,
• 'a' :: Char,
• (+) :: Int -> Int -> Int

Variables variable symbols, also of size 1, such as
• x :: Int,
• f :: Int -> Int;

Applications type-correct applications of functional expressions
to one or more argument expressions, including partial applications,
such as
• id y :: Int of size 2,
• (1+) :: Int -> Int of size 2,
• x + (y + 0) :: Int of size 5.
The size of an application is the number of constant and variable
symbols it contains.

To avoid an explosive increase in the search-space, we do not in-
clude other forms of Haskell expression such as lambda expressions
or case expressions.

A complexity ordering on expressions
When there is redundant
between laws, Speculate has to decide which to keep and
which to discard. As a general rule, it keeps the simplest laws. It
also presents final sets of laws in order of increasing complexity.

An expression e1 is strictly simpler than another expression e2, if
the first of the following conditions to distinguish between them is:
1. e1 is smaller in size than e2,
e.g.: x + y < x + (y + z);
2. or, e1 has more distinct variables than e2,
e.g.: x + y < x + x;
3. or, e1 has more variable occurrences than e2,
e.g.: x + x < 1 + x;
4. or, e1 has fewer distinct constants than e2,
e.g.: 1 + 1 < 0 + 1;
5. or, e1 precedes e2 lexicographically,
e.g.: x + y < y + z.
A similar ordering is used in QuickSpec [8, 22].
4 How Speculate Works

In summary, Speculate works by enumerating expressions and evaluating test instances of them. In order for that to work effectively, Speculate uses equational reasoning (§4.1). Speculate determines, in the following order, apparent:

1. equations and equivalence classes of expressions (§4.2);
2. inequalities (§4.3);
3. conditional equations (§4.4).

To encapsulate values of different types, Speculate uses the Data.Dynamic module [1] provided with GHC [23] and declares a type to encode Haskell expressions.

4.1 Equational Reasoning based on Term Rewriting

Following QuickSpec [22], Speculate performs basic equational reasoning based on unfailing Knuth-Bendix Completion [3, 13]. The aims are to prune the search space avoiding needless testing, and to filter redundant laws so that the output is more useful to the user.

Completion The Knuth-Bendix Completion procedure takes a set of equations and produces a confluent term rewriting system [2, 13]: a set of rewrite rules that can be used to simplify, or normalize, expressions. To check if two expressions are equal, we can check if their normal forms are the same. The completion procedure has two problems: failure in the presence of unorientable equations and possible non-termination. Speculate solves these problems similarly to QuickSpec as detailed in the following paragraphs.

Unorientable equations To deal with unorientable equations, we use the technique of unfailing completion [3] which allows unorientable equations to be kept in a separate set from rules. Checking for equivalence using normalization is still sound, but incomplete (the fact that two expressions are equivalent may be undetected). We can use unorientable equations to improve the check for equivalence between expressions $e_1$ and $e_2$: first normalize both $e_1$ and $e_2$; then take the equivalence closure using the set of unorientable equations; finally, if one of the expressions in the closure of $e_1$ is equivalent to one of the expressions in the closure of $e_2$ then they are equivalent. To ensure termination, we impose a configurable bound on the number of closure applications.

Non-termination To deal with non-termination of the completion procedure, we impose a limit on the size of generated rules, discarding any rules where the left-hand size is bigger than the maximum expression size we are exploring.

4.2 Equations and Equivalence Classes of Expressions

Speculate finds equations in a similar way to QuickSpec 2 [22]. As QuickSpec 2 has many features, like support for polymorphism, use of external theorem provers for reasoning and several configuration options, we chose to reimplement a core variant before extending it with support for conditional equations and inequalities. Differences to QuickSpec are highlighted in §6.

This section summarizes how Speculate finds equations.

State Speculate processes each expression in turn, transforming a state. Speculate keeps track of:

- a theory (§4.1) based on equations discovered so far;
- a set of equivalence classes of all expressions considered so far, and for each of them a smallest representative.

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Table 1.

<table>
<thead>
<tr>
<th>equivalence classes</th>
<th>equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>repr.</td>
</tr>
<tr>
<td>Int</td>
<td>x</td>
</tr>
<tr>
<td>Int</td>
<td>1</td>
</tr>
<tr>
<td>Int</td>
<td>1</td>
</tr>
<tr>
<td>Int</td>
<td>1</td>
</tr>
<tr>
<td>Int</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.

<table>
<thead>
<tr>
<th>equivalence classes</th>
<th>equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>repr.</td>
</tr>
<tr>
<td>Int</td>
<td>1</td>
</tr>
<tr>
<td>Int</td>
<td>1</td>
</tr>
<tr>
<td>Int</td>
<td>1</td>
</tr>
<tr>
<td>Int</td>
<td>1</td>
</tr>
</tbody>
</table>

Considering an expression Speculate considers an expression $E$ by trying to find an equivalence-class representative $R$ that is equivalent to $E$:

- If expression $E$ is found equivalent to $R$ using equational reasoning, then $E$ is discarded. The equations already tell us that $E = R$.
- If expression $E$ is found equivalent to $R$ using testing, then the new equation $E = R$ is inserted into the theory and $E$ is inserted into $R$’s equivalence class.

Initialization The algorithm starts by considering single-symbol expressions in the signature and one free variable for each type. After this initialization, Speculate knows all equivalence classes between expressions of size 1.

Example 1.1 (revisited). Table 1 shows the equivalence classes after initialization for the example from §1 with 0, 1, id, abs and (+) in the signature. As yet there are no equations.

Generating and considering expressions Speculate generates expressions in size order until the size limit is reached. Expressions are constructed from type-correct applications of equivalence-class representatives.

Example 1.1 (revisited). Using the size 1 representatives in Table 1, Speculate generates all candidate expressions of size 2: id x, id 0, id 1, abs x, abs 0, abs 1, (x+), (0+), (1+). Then, it considers all those expressions to arrive at the equations and equivalence classes shown in Table 2.
### Table 3. Equivalence classes and equations after considering all expressions of size 3.

<table>
<thead>
<tr>
<th>equivalence classes</th>
<th>equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>repr.</td>
</tr>
<tr>
<td>Int</td>
<td>x</td>
</tr>
<tr>
<td>Int</td>
<td>0</td>
</tr>
<tr>
<td>Int</td>
<td>1</td>
</tr>
<tr>
<td>Int</td>
<td>abs x</td>
</tr>
<tr>
<td>Int</td>
<td>x + 1</td>
</tr>
<tr>
<td>Int</td>
<td>x + x</td>
</tr>
</tbody>
</table>

The process of considering expressions is repeated with expressions of further sizes. Table 3 shows equivalence classes after considering all expressions of size 3.

**Multiple variables** The algorithm described so far is only able to discover laws involving one distinct variable of each type. Following QuickSpec, dealing with multiple variables is based on the following observation and its contrapositive:

- **Multi** ⇒ **Single** For a several-variables-per-type equation to be true, its one-variable-per-type instance should be true as well, for example:
  \[ \forall x \ y \ z. (x + y) + z = x + (y + z) \Rightarrow \forall x. (x + x) + x = x + (x + x) \]
  - **Single** ⇒ ¬ **Multi** If a one-variable-per-type equation is false, all its several-variable-per-type generalizations are false as well, for example:
  \[ \exists x. (x + x) + x \neq x + (x + x) \Rightarrow \exists x \ y. (x + y) + z \neq x + (y + z) \]

So, we only test a multi-variable equation when its single variable instance is true.

**Example 1.1 (revisited).** When exploring expressions of size 5, Speculate finds that
\[(x + x) + x == x + (x + x)\]
then proceeds to test all its generalizations to find that
\[(x + y) + z == x + (y + z) \]

**Finding commutativity** After processing expressions of size 3 we might expect to have found commutativity of addition (+). However, it is not found by the algorithm just described. To find commutativity and other similar laws, we must also consider generalizations of a representative expression equated with itself. For example, \[x + y == y + x\] is a generalization of \[x + x == x + x\].

**Expressions with several variables per type** Speculate has to find classes of expressions with several variables per type before searching for inequalities (§4.3) and conditional equations (§4.4). For each representative expression with at most one variable per type, Speculate considers its possible generalizations up to \(n\) variables, merging expressions into the same equivalence class if either of the following is true:
- 1. they normalize to the same expression using the theory;
- 2. they test equal.

### Table 4. How the number of expressions and classes increases with the size limit (for example 1.1).

<table>
<thead>
<tr>
<th>size limit</th>
<th>max. 2 variables</th>
<th>max. 3 variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#-exprs.</td>
<td>#-classes</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>12</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>44</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>172</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>748</td>
<td>36</td>
</tr>
<tr>
<td>6</td>
<td>3436</td>
<td>72</td>
</tr>
<tr>
<td>7</td>
<td>16492</td>
<td>114</td>
</tr>
</tbody>
</table>

**Summary** So far, we have unconditional equations and equivalence classes of expressions.

### 4.3 Inequalities between Class Representatives

**A naive approach** To find inequalities (\(<\) and \(\leq\)), a naïve approach enumerates all possible expressions and computes all \(\leq\) relations. But it blows up as the size limit increases.

**Example 1.1 (revisited).** With a limit of 7 symbols, we would have to check over a quarter of a billion pairs of expressions (16492 × 16492, see Table 4). Using the default number of tests, 500, we would perform over one hundred billion evaluations. Even if we waited for that computation to complete, we would still have the problem of filtering redundant laws.

**A slightly less naive approach** If we instead insert \(\text{True}\) and \(\leq\) in the background signature, then generate equations, inequalities will appear in the output as:
\[(\text{LHS} \leq \text{RHS}) \Rightarrow \text{True}\]

In this way, no explicit support for inequalities is needed. For QuickSpec to discover the law \((x + y \leq \text{abs } x + \text{abs } y) \Rightarrow \text{True}\) it is enough to set it to explore expressions up to size 9. In about 28s, QuickSpec will print this law along with 125 other laws (see Table 9). The algorithm described in the rest of this section is faster, discovering an equivalent law in about 1s among only 43 other laws. See §6 for further comparison with QuickSpec.

**A better approach** The actual method used in Speculate is based on two observations:
1. the number of non-functional equivalence classes is far smaller than the number of expressions (Table 4);
2. we already have all equivalence classes and their smallest representatives as a by-product of finding unconditional equations.

So, Speculate finds inequalities in three steps:
1. list all pairs of class representatives;
2. test to select pairs that are related by \(\leq\);
3. discard redundant inequalities.

**Example 1.1 (revisited).** Here are the inequalities found by listing and selecting pairs related by \(\leq\) before discarding redundant inequalities:
1. \(0 \leq 1\)
2. \(x \leq \text{abs } x\)
3. \(y \leq \text{abs } y\)
4. \(0 \leq \text{abs } x\)
5. \(0 \leq \text{abs } y\)
6. \(x \leq x + 1\)
7. \(y \leq y + 1\)
8. \(0 \leq 1 + 1\)
9. \(1 \leq 1 + 1\)
Examples of redundancy include: inequalities 2 and 3 are equivalent; inequalities 4 and 5 are equivalent; inequality 8 is implied by inequalities 1 and 9.

**Discarding redundant inequalities.** To discard redundant inequalities, Speculate uses the complexity order defined in §2. This is done in three steps, described in the following three paragraphs.

1. **Instances** Speculate discards more complex inequalities that are instances of simpler inequalities.

**Example 1.1 (revisited).** The following 4 inequalities are discarded

3. \( y \leq \text{abs} \ y \) (implied by 2. \( x \leq \text{abs} \ x \))
4. \( 0 \leq \text{abs} \ y \) (implied by 4. \( 0 \leq \text{abs} \ x \))
5. \( y \leq y + 1 \) (implied by 6. \( x \leq x + 1 \))
6. \( 1 \leq 1 + 1 \) (implied by 6. \( x \leq x + 1 \))

...to arrive at

1. \( 0 \leq 1 \) 6. \( x \leq x + 1 \)
2. \( x \leq \text{abs} \ x \) 8. \( 0 \leq 1 + 1 \)
4. \( 0 \leq \text{abs} \ x \)

2. **Consequences of transitivity** Speculate discards consequences of transitivity \( e_1 \leq e_2 \land e_2 \leq e_3 \Rightarrow e_1 \leq e_3 \) when both antecedents \( (e_1 \leq e_2 \text{ and } e_2 \leq e_3) \) are either simpler than the consequence \( (e_1 \leq e_3) \), or instances of inequalities simpler than the consequence.

**Example 1.1 (revisited).** The inequality \( 0 \leq 1 + 1 \) is discarded as it is a consequence of \( 0 \leq 1 \) and \( x \leq x + 1 \).

3. **Instances modulo equivalence closure** For all pairs of inequalities \( I_1 \) and \( I_2 \) where \( I_1 \) is simpler than \( I_2 \), if any of the expressions in the bounded equivalence closure (§4.1) of \( I_2 \) is an instance of any of the expressions in the bounded equivalence closure of \( I_1 \), Speculate discards \( I_2 \).

4.4 Conditional Equations between Class Representatives

In this section, we detail how conditional equations are generated based on the equational theory (§4.2), class representatives (§4.2) and inequalities (§4.3) between boolean values.

**A digraph of candidate conditions** There is a connection between conditional laws and inequalities. Using the standard definition of boolean \( \leq \) we could define:

\[
(\Rightarrow) = (\leq)
\]

We already have information about \( \leq \) from the previous step (§4.3). We can build a digraph of boolean expressions ordered by implication as shown in Figure 2. We include \texttt{False} and \texttt{True}.

**Discovering conditional laws** For each pair of representatives \( e_1 \) and \( e_2 \) from different equivalence classes, we search for the weakest conditions under which each of them holds. Instead of searching through all possible conditions from class representatives we use the digraph of conditions to prune the search space. We make a fresh copy of the digraph and repeat the following until there are no unmarked nodes:

1. pick an arbitrary unmarked node with condition \( c \);
2. check \( c \Rightarrow e_1 = e_2 \) by evaluating it for a set number of test cases;
3. if all tests pass then mark \( c \) as visited and remove all nodes from which \( c \) can be reached as these are for stronger conditions than \( c \).
4. if any test fails remove \( c \) and all nodes reachable from it as these are for weaker conditions than \( c \).

The remaining nodes are the weakest conditions for which \( e_1 = e_2 \). The algorithm is sound modulo testing.

**Example 1.1 (revisited).** Suppose we are trying to find the weakest condition for which \( x + \text{abs} \ x = 0 \) holds. We may start by considering \( 1 < x \Rightarrow x + \text{abs} \ x = 0 \) for which tests fail: the node for \( 1 < x \) and all five nodes reachable from it are removed from the graph, yielding the first graph in Figure 3. We may then consider \( x \leq 0 \), for which all tests succeed: we mark it as visited and remove three other nodes from which it can be reached, yielding the second graph in Figure 3. Fast-forwarding to the end, we are left with a single node: the condition \( x \leq 0 \) is the weakest condition for \( x + \text{abs} \ x = 0 \) to hold.
Filtering redundant conditional laws  In brief, we discard a conditional equation \( c_1 \Rightarrow e_1 = e_2 \) if we also have a conditional equation \( c_0 \Rightarrow e_1 = e_2 \) and either \( c_1 = c_0 \) according to the theory (§4.2), or \( c_1 \Rightarrow c_0 \) according to the implication digraph.

5 Example Applications and Results

In this section, we use Speculate:

- to find laws about simple functions on lists (§5.1);
- to find a complete implementation of insertion sort (§5.2);
- to find ordering properties of binary-tree functions (§5.3);
- to find ordering properties of digraph functions (§5.4);
- to find an almost complete axiomatisation for regular-expression equivalence (§5.5).

Then, in §5.6 we give a summary of performance results for all these applications.

We emphasize what is new compared with QuickSpec [8, 22]. So we often omit details of reported unconditional equations where QuickSpec produces similar results. In §6 we shall summarise differences with QuickSpec, including some reasons why the tools may give slightly different sets of unconditional equations.

Sometimes, for the sake of space, we discuss only a selection of inequalities and conditional equations, but always note where others are also generated.

5.1 Finding properties of basic functions on lists

Given the value [], the operators (:) and (++), and the functions head and tail, all with \texttt{Int} as element type, Speculate first reports the following equations:

\[
\begin{align*}
\text{xs} &+ [] = \text{xs} \\
[] &+ \text{xs} = \text{xs} \\
(\text{xs} + \text{ys}) &+ \text{zs} = \text{xs} + (\text{ys} + \text{zs}) \\
(\text{x}:\text{xs}) &+ \text{ys} = \text{x}:(\text{xs} + \text{ys}) \\
\text{head} (\text{x}:\text{xs}) &= \text{x} \\
\text{tail} (\text{x}:\text{xs}) &= \text{xs}
\end{align*}
\]

Exactly the same laws are found by QuickSpec [8, 22].

Lexicographic ordering  But Speculate goes on to print the following inequalities, assuming the default lexicographical ordering Haskell derives for lists.

\[
\begin{align*}
[] &\leq \text{xs} \\
\text{xs} &\leq \text{xs} + \text{ys} \\
\text{xs} &\leq \text{head} \text{xs}:\text{tail} \text{xs} \\
\text{xs} + \text{ys} &\leq \text{xs} + (\text{ys} + \text{zs})
\end{align*}
\]

The law \( \text{x} \leq \text{head} \text{x}:\text{tail} \text{x} \) may seem strange, but it is correct, even when \( \text{x} = []. \) As (:) is non-strict:

\[
\begin{align*}
[] &\leq \text{head} []:\text{tail} [] \\
[] &\leq \bot:\bot
\end{align*}
\]

Subsequence ordering  Speculate allows the user to request inequalities based on orderings other than an \texttt{Ord} instance. For example, if we provide as an \texttt{Args} field (§3)

\[
\text{instances} = 
\begin{align*}
[ \text{ordWith} \text{\{isSubsequenceOf :: [Int]->[Int]->[Bool]\}} ]
\end{align*}
\]

then Speculate uses \text{isSubsequenceOf} (from \texttt{Data.List}) as \( \leq \) for lists of \texttt{Ints}, and reports the following inequalities:

\[
\begin{align*}
[] &\leq \text{xs} \\
\text{x} &\leq \text{x}:\text{xs} \\
\text{x} &\leq \text{x} + \text{ys} \\
\text{x} &\leq \text{ys} + \text{xs} \\
\text{x} &\leq \text{tail} (\text{x} + \text{xs}) \\
\text{[x]} &\leq \text{x}:\text{xs} \\
\text{x} &\leq \text{head} \text{x}:\text{tail} \text{x} \\
\text{x}:\text{xs} &\leq \text{x}:(\text{y}:\text{xs}) \\
\text{x} + \text{ys} &\leq \text{x} + (\text{ys} + \text{zs}) \\
\text{x} + \text{ys} &\leq \text{x} + (\text{zs} + \text{ys}) \\
\text{x}:\text{xs} &\leq \text{x}:(\text{xs} + \text{ys}) \\
\text{x}:\text{xs} &\leq \text{x}:(\text{ys} + \text{xs}) \\
\text{x} + \text{ys} &\leq \text{x} + (\text{x}:\text{ys}) \\
\text{[x,y]} &\leq \text{x}:(\text{y}:\text{xs}) \\
\text{x} + \text{[x]} &\leq \text{x} + (\text{x}:\text{ys})
\end{align*}
\]

Automatically checking given orderings  Before starting to compute conjectures, Speculate checks by testing that the requested inequality ordering is reflexive and antisymmetric with respect to \( (\Rightarrow) \), and transitive. If not, it refuses to go further. For example, if we set \( (/=) \) as an ordering function for the type \texttt{[Int]}. Speculate reports:

Error: \( (\leq) :: [\text{Int}] \rightarrow [\text{Int}] \rightarrow \text{Bool} \)

is not an ordering (not reflexive, not antisymmetric, not transitive)

5.2 Sorting and Inserting: deducing their implementation

With [], and (:) in the background signature, and functions insert and sort from \texttt{Data.List} in the foreground, Speculate first reports 7 equations. QuickSpec produces a different but similar set of 7 equations. Both QuickSpec and Speculate find the base case of insert and the recursive case of insertion sort:

\[
\text{insert} \text{x} [] = [\text{x}] \\
\text{sort} (\text{x}:\text{xs}) = \text{insert} \text{x} (\text{sort} \text{xs})
\]

By default, Speculate hides laws with no variables. If we switch on the option to reveal them, Speculate also reports the base case for sort:

\[
\text{sort} [] = []
\]

If we also include \( \leq \) and \( < \) for the element type in the background, Speculate reports the two conditional recursive cases

\[
\begin{align*}
\text{x} &\leq \text{y} \Rightarrow \text{insert} \text{x} (\text{y}:\text{xs}) = \text{x}:(\text{y}:\text{xs}) \\
\text{x} &< \text{y} \Rightarrow \text{insert} \text{y} (\text{x}:\text{xs}) = \text{x}:(\text{insert} \text{y} \text{xs})
\end{align*}
\]

completing a full implementation of insertion sort synthesised from results of black-box testing.

5.3 Binary search trees

In this section, we apply Speculate to functions on binary search trees, with the following datatype.

\[
\text{data} \ BT \ a = \text{Null} \mid \text{Fork} (BT \ a) \ a (BT \ a)
\]

We declare two search trees equivalent if they contain the same elements. Also, tree \( a \) is less than or equal to tree \( b \) if all elements of tree \( a \) are present in tree \( b \).
We find that insertion and deletion of an element \( x \) are idempotent, and that they appropriately determine the outcomes of subsequent membership tests.

### Inequalities

Speculate then reports 11 inequalities. The first three are:

\[
\text{Null} \leq t \\
t \leq \text{insert } x \ t \\
d \text{insert } x \ t \leq t
\]

That is: the least tree is an empty tree; inserting elements makes trees larger; deleting elements makes trees smaller.

Another group of five inequalities are about combinations of some pair of the functions \text{insert} and \text{delete} and \text{isIn}:

\[
\text{delete } x \ t \leq \text{delete } x \ (\text{insert } y \ t) \\
\text{insert } x \ (\text{delete } y \ t) \leq \text{insert } x \ t \\
\text{delete } x \ (\text{insert } y \ t) \leq \text{insert } y \ (\text{delete } x \ t) \\
\text{isIn } x \ t \implies \text{isIn } x \ (\text{insert } y \ t) \\
\text{isIn } x \ (\text{delete } x \ t) \implies \text{isIn } x \ t
\]

### Conditional equation

Speculate also reports this conditional equation:

\[
x \neq y \implies \\
\text{insert } y \ (\text{delete } x \ t) \leq \text{delete } x \ (\text{insert } y \ t)
\]

Applied to distinct elements, \text{insert} and \text{delete} commute.

### 5.4 Digraphs

In this section, we apply Speculate to a directed-graph library based on the following adjacency-list datatype:

```haskell
data Digraph a = D [(a,[a])]  
```

where values of the parametric type \( a \) are identified with nodes of the digraph.

With \text{elem} and \[] in the background, we apply Speculate to the following functions:

```haskell
empty :: Digraph a 
addNode :: Ord a => a -> Digraph a -> Digraph a 
addEdge :: Ord a => a -> a -> Digraph a -> Digraph a 
preds :: Ord a => a -> Digraph a -> [a] 
succs :: Ord a => a -> Digraph a -> [a] 
isNode :: Ord a => a -> Digraph a -> Bool 
```

We declare the \text{Listable} instance

```haskell
instance Listable a => Listable (RE a) where  
tiers = cons0 Empty  
\ |
\ | cons0 None `ofWeight` 1  
\ | cons1 Lit  
\ | cons1 Star  
\ | cons2 (:)  
```

The \text{subgraph} \( ns \) function extracts the subgraph of its argument with nodes restricted to those listed in \( ns \).

We define an ordering on digraphs as follows.

```haskell
instance Ord a => Ord (Digraph a) where 
g1 <= g2 = all (`elem` nodes g2) (nodes g1) 
\&\& all (`elem` edges g2) (edges g1)
```

The ordering relationship holds if all nodes and edges of \( g1 \) are also present in \( g2 \).

### Equations

Speculate reports 15 equations. For example, they include these commutativity rules about \text{addNode} and \text{subgraph}:

\[
\text{addNode } x \ (\text{addNode } y \ a) = \text{addNode } y \ (\text{addNode } x \ a) \\
\text{subgraph } xs \ (\text{subgraph } ys \ a) = \text{subgraph } ys \ (\text{subgraph } xs \ a)
\]

### Conditional Equations

Of the two reported conditional equations, the most interesting is:

\[
\text{elem } x \ xs \implies \text{subgraph } xs \ (\text{addNode } x \ a) \\
\quad = \text{addNode } x \ (\text{subgraph } xs \ a)
\]

Indeed, \text{addNode} \( x \) and \text{subgraph} \( xs \) commute when \( x \) is an element of \( xs \).

### Inequalities

Speculate reports a dozen inequalities. These five are general laws about the relative extent of graphs.

\[
\text{empty } \leq a \\
\quad a \leq \text{addNode } x \ a \\
\quad \text{subgraph } xs \ a \leq a \\
\quad a \leq \text{addEdge } x \ y \ a \\
\quad \text{addNode } x \ a \leq \text{addEdge } x \ y \ a
\]

Other inequalities involve \text{empty} or give simple rules about \text{isNode}, \text{isEdge} and \text{isPath}. They are all correct, but we omit them to save space.

### 5.5 Regular Expressions

In this section, we use Speculate to conjecture properties about regular expressions. As we shall see, this is a much more demanding example. We shall reach the limits of what we can do with Speculate.

We declare the following datatype \text{RE} \( a \) with a parametric type \( a \) for the alphabet.

```haskell
data RE a = Empty  
| None  
| Lit a  
| Star (RE a)  
| RE a :+: RE a  
| RE a :: RE a
```

We declare the \text{Listable} instance

```haskell
instance Listable a => Listable (RE a) where  
tiers = cons0 Empty  
\ |
\ | cons0 None `ofWeight` 1  
\ | cons1 Lit  
\ | cons1 Star  
\ | cons2 (:)  
```
We declare a three-symbol alphabet, also with a `Listable` instance:

```haskell
newtype Symbol = Symbol Char deriving (Eq, Ord, Show)

instance Listable Symbol where
  tiers = cons$ (Symbol 'a')
  \ cons$ (Symbol 'b') 'ofWeight' 1
  \ cons$ (Symbol 'c') 'ofWeight' 2
```

The `ofWeight` applications make these constructions appear less frequently in the test value enumeration.

**Testing equivalence by matching**  We wish to define equivalence of REs by equality of string-matching outcomes. To do so, we define a function to translate the RE representation into the string format used by an existing library for matching.

```haskell
translate :: (a -> Char) -> RE a -> String
```

The library exports (=) where s =~ e if s matches e. Using `translate` and `=`, we define:

```haskell
match :: (a -> Char) -> [a] -> RE a -> Bool
match f xs r = map f xs =~ translate f r
```

So, for example:

```haskell
> match id "aa" (Star (Lit 'a')) :: Lit 'b'
False
> match id "aa" (Star (Lit 'a')) :: Star (Lit 'b'))
True
```

With `match` defined, we can now implement approximate equivalence and ordering of regular expressions based on a limited number of membership tests:

```haskell
  testMatches :: (Listable a, Show a, Charable a, Ord a) => RE a -> [Bool]
  testMatches = map (\ e -> match toChar e r)
    $ take 120 list

  testMatches :: RE Symbol -> RE Symbol -> Bool
  r /= s = testMatches r == testMatches s
  r <= s =
    and $ zipWith (<=) (testMatches r) (testMatches s)
```

**Failing first attempts**  In our first attempts using this approach, execution times were excessive. Even after caching up to ten million `testMatches` results, a 30-minute run produced some wrong equations due to insufficient testing! Our solution was **down-sizing**.

**Starting small**  We reconfigure Speculate to produce equations only up to size 3. After a couple of minutes, it prints:

1.  r :+ r == r
2.  Star (Star r) == Star r
3.  r :+: None == r
4.  r :. Empty == r
5.  r :. None == None
6.  Empty :. r == r
7.  None :. r == None
8.  r :+ s == s :+ r
All these are sensible and correct laws about regular expressions. So now we declare `canonicalRE` as follows:

```haskell
canonicalRE :: (Eq a, Ord a) => RE a -> Bool
```

```haskell
canonicalRE (r ++ s) | r >= s = False -- by 1&8
```

```haskell
canonicalRE (r ++ None) = False -- by 3&8
```

```haskell
canonicalRE (r ++ Empty) = False -- by 4
```

```haskell
canonicalRE (r ++ r) = False -- by 5
```

```haskell
canonicalRE (Empty ++ r) = False -- by 6
```

```haskell
canonicalRE (None ++ r) = False -- by 7
```

```haskell
canonicalRE _ = True
```
and use it to refine our `Listable` instance by adding `suchThat` `canonicalRE`.

### Equations of size 4

With the updated `Listable` instance, Speculate considers a greater range of candidate equations with the same number of tests. Configured to produce equations up to size 4, it prints the following new laws:

```haskell
r ++ Star r == Star r
```

```haskell
Star r ++ r == r ++ Star r
```

```haskell
Star (r ++ Empty) == Star r
```

```haskell
Empty ++ Star r == Star r
```

Now we repeat the process, further refining `canonicalRE`, and so the `Listable` instance, on the basis of these conjectured laws.

### Equations of size 5 and 6

We reduce the number of tests to 200 and again repeat the process for sizes 5 and 6. Speculate prints seven equations of size 5 and nine of size 6 — including axioms 5, 9 and K10 from Table 5.

### Inequalities and equations of size 7

Configured to explore equations and inequalities of size 7, Speculate finds the distributive laws 7 and 8 from Table 5. At last, Speculate finds all the common laws from all three axiomatisations of regular expressions. It also finds the following degenerate cases of Kozen’s conditional inequalities — crucial ingredients in his complete axiomatisation:

```haskell
r ++ (s ++ s) <= s => r ++ Star s <= s
```

```haskell
r ++ (s ++ s) <= s => r ++ (r ++ s) <= s
```

### Summary

This case study was “a stretch”. We wanted to see how far we could get with Speculate. With patience, we can get very close to a complete axiom system, but with the current version of Speculate it is just out of reach.

### 5.6 Performance Summary

Performance results are summarized in Table 6. Leaving aside the regular-expression application, Speculate takes up to a few seconds to consider expressions for up to size 5. Our tool and examples were compiled using `ghc -O2` (version 8.0.1) under Linux. The platform was a PC with a 2.2Ghz 4-core processor and 8GB of RAM.

### 6 Related Work

**QuickSpec** The QuickSpec tool [8, 20–22] discovers equational specifications automatically. Our technique is an extension that allows production of conditional equations and inequalities. QuickSpec inspired us to start working on Speculate. Table 7 shows a summary of differences between QuickSpec 1, QuickSpec 2 and Speculate.

In principle QuickSpec can generate conditional equations, but only with conditions restricted to applications of a set of declared predicates. Consider the following example from [22]. When asked to generate laws about `zip` and `++`, both QuickSpec and Speculate produce the following equations:

```haskell
zip xs (ys ++ zs) == zip xs ys
zip (xs ++ ys) ys == zip xs ys
```

These laws are valid but they have conditional generalizations:

```haskell
length xs == length ys =>
```

```haskell
zip xs (ys ++ zs) == zip xs ys
```

```haskell
length xs == length ys =>
```

```haskell
zip (xs ++ zs) ys == zip xs ys
```

In Speculate, it is enough to have `length` and length among the background constants to obtain the more general laws.

QuickSpec can only discover these more general laws given quite explicit directions. By providing `length` in the background and setting the following in QuickSpec’s predicates field:

```haskell
predicates = [
    predicate (undefined :: Proxy "eqLen") eqLen ]
```

where

```haskell
eqLen :: [Int] -> [Int] -> Bool
eqLen xs ys = length xs == length ys
```

QuickSpec is able to find the more general laws in the form:

```haskell
eqLen xs ys => zip xs (ys ++ zs) == zip xs ys
```

```haskell
eqLen xs ys => zip (xs ++ zs) ys == zip xs ys
```

With regards to how laws are reported, we made a different design choice to QuickSpec. QuickSpec reports laws as soon as they are discovered, so the user sees progress as QuickSpec runs. Speculate only reports laws after running the completion procedure, so later laws can be used to discard earlier ones. Speculate also, by default, does not report variable-free laws like `sort [] == []`.

QuickSpec has support for polymorphism: if an equation is discovered for a polymorphic version of a function it can be used as a pruning rule for all its monomorphic instances. Speculate does not yet support that polymorphism; it requires monomorphic instances.

To double-check Speculate’s reimplementations of the basic equation generation machinery in QuickSpec: (1) we compared Speculate output with QuickSpec output to check if there was any missing equation, and (2) we compared performance of the two tools. This comparison is summarized in Table 8. QuickSpec 2 is a little bit faster than Speculate — early profiling indicates that we were not as smart as the QuickSpec authors when implementing our term rewriting and completion engine.

Table 9 presents needed size limits and times to generate some inequalities and conditional laws for QuickSpec 2 and Speculate. Results in tables 8 and 9 are based on QuickSpec 1 version 0.9.6 and on QuickSpec 2 development version from 11 May 2017 with git commit hash 3c66e018. At the time of writing, developers are working on improving support for conditional laws in QuickSpec.
Table 6. Summary of Performance Results: figures are mean values across all runs; size limit = maximum number of expression size; #-tests = maximum number of test-cases for any property; time = rounded elapsed time and space = peak memory residency (both from GNU time).

<table>
<thead>
<tr>
<th>Example</th>
<th>configured size limit for maximum resources</th>
<th>number of reported</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>eqs. ineqs. cond. eqs. #-vars #-tests time space eqs. ineqs. cond. eqs.</td>
<td></td>
</tr>
<tr>
<td>(+) and abs</td>
<td>5 4 4 2 500 3s 7MB 23 17 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 5 5 2 500 23s 7MB 23 44 4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 5 3 3 500 2m 37s 8MB 43 44 24</td>
<td></td>
</tr>
<tr>
<td>List (§5.1)</td>
<td>5 4 – 3 500 &lt; 1s 7MB 6 6 –</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 6 – 3 500 31s 9MB 7 30 –</td>
<td></td>
</tr>
<tr>
<td>Insert Sort</td>
<td>5 – 3 2 500 &lt; 1s 7MB 11 – 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 – 5 3 500 5s 8MB 16 – 8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 – 6 3 500 1m 27s 12MB 12 – 12</td>
<td></td>
</tr>
<tr>
<td>Binary Trees</td>
<td>5 4 4 2 500 &lt; 1s 7MB 16 4 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 5 5 3 500 14s 7MB 16 22 5</td>
<td></td>
</tr>
<tr>
<td>Digraphs (§5.4)</td>
<td>5 4 4 2 500 1s 8MB 15 12 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 5 5 3 500 1m 52s 10MB 27 30 34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 5 5 3 6000 2m 22s 23MB 25 30 17</td>
<td></td>
</tr>
<tr>
<td>Regexes (§5.5)</td>
<td>3 – – – 500 1m 30s &lt; 6GB 8 – –</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 – – – 400 9m 11s &lt; 6GB 12 – –</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 – – – 200 17m 13s &lt; 6GB 19 – –</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 – – – 200 1h 26m 32s 6GB 28 – –</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7 7 – 2 200 2d 22h 30m 10s 6GB 130 699 –</td>
<td></td>
</tr>
</tbody>
</table>

Table 7. Speculate contrasted with QuickSpec 1 and QuickSpec 2.

<table>
<thead>
<tr>
<th>Testing Strategy</th>
<th>QuickSpec 1</th>
<th>QuickSpec 2</th>
<th>Speculate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct discovery of equations</td>
<td>yes (QuickCheck)</td>
<td>yes (QuickCheck)</td>
<td>yes (LeanCheck)</td>
</tr>
<tr>
<td>Direct discovery of inequalities</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Direct discovery of conditional equations</td>
<td>no</td>
<td>restricted</td>
<td>yes</td>
</tr>
<tr>
<td>Reported equations</td>
<td>as discovered</td>
<td>as discovered</td>
<td>after completion</td>
</tr>
<tr>
<td>Constant laws (laws with no variables)</td>
<td>yes</td>
<td>yes</td>
<td>hidden by default</td>
</tr>
<tr>
<td>How search is bounded</td>
<td>depth-bounded</td>
<td>size-bounded</td>
<td>size-bounded</td>
</tr>
<tr>
<td>Support for pruning by external theorem provers</td>
<td>no</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Performance (see Table 8)</td>
<td>slowest</td>
<td>fastest</td>
<td>median</td>
</tr>
</tbody>
</table>

Table 8. Timings and equation counts when generating unconditional equations using Speculate, QuickSpec 1 and QuickSpec 2. In QS1, expressions are primarily explored up to a certain depth [8], so, for a fair comparison, we have introduced a depth limit in QS2 and Speculate.

<table>
<thead>
<tr>
<th>Example</th>
<th>size</th>
<th>depth</th>
<th>max. #-tests</th>
<th>Runtime in seconds</th>
<th>#-reported equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+) and abs</td>
<td>500</td>
<td>4</td>
<td>4</td>
<td>4s &lt; 1s</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>4</td>
<td>500</td>
<td>7s &lt; 1s</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>0, 1, +, × (Int)</td>
<td>500</td>
<td>95s 3s 6s 9 13 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>List (§5.1)</td>
<td>500</td>
<td>4</td>
<td>252</td>
<td>&lt; 1s &lt; 1s</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>4</td>
<td>10m 31s 1s  &lt; 1s</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>7</td>
<td></td>
<td></td>
<td>7</td>
</tr>
</tbody>
</table>
Table 9. Needed size limits and times to generate some inequalities and conditional laws for QuickSpec 2 and Speculate. Speculate is able to find some laws much faster as they appear when exploring a smaller size.

<table>
<thead>
<tr>
<th>Example</th>
<th>Target Law</th>
<th>Needed size limit</th>
<th>Needed max #-tests</th>
<th>Runtime</th>
<th># reported laws</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+) and abs ($)</td>
<td>$x &lt;= abs x$</td>
<td>QS2 Spl.</td>
<td>QS2 Spl.</td>
<td>QS2 Spl.</td>
<td>QS2 Spl.</td>
</tr>
<tr>
<td></td>
<td>$x &lt;= abs (x + x)$</td>
<td>4</td>
<td>2</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>$x + y &lt;= x + abs y$</td>
<td>6</td>
<td>4</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>$x + y &lt;= abs x + abs y$</td>
<td>8</td>
<td>4</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td></td>
<td>$(or x + y &lt;= abs x + y)$</td>
<td>9</td>
<td>5</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Binary Trees ($)</td>
<td>$isIn x t ==&gt; isIn x (insert y t)$</td>
<td>9</td>
<td>5</td>
<td>2000</td>
<td>500</td>
</tr>
<tr>
<td>Regexes ($)</td>
<td>$F + GE \leq G \Rightarrow E'F \leq G$</td>
<td>14</td>
<td>7</td>
<td>(open research problem)</td>
<td></td>
</tr>
</tbody>
</table>

7 Conclusions and Future Work

Conclusions In summary, we have presented a tool that, given a collection of Haskell functions, conjectures a specification involving apparent inequalities and conditional equations. This specification can contribute to understanding, documentation and properties for regression tests. As set out in §3 and §4, Speculate enumerates, tests expressions and reasons from test results to produce its conjectures. We have demonstrated in §5 Speculate’s applicability to a range of small examples, and we have briefly compared in §6 some of the results obtained with related results from other tools.

Value of reported laws The conjectured equations and inequalities reported by Speculate are surprisingly accurate in practice, despite their inherent uncertainty in principle. These conjectures provide helpful insights into the behaviour of functions. For the sorting example in §5.2, we were even able to synthesise a complete implementation. When Speculate finds an apparent but incorrect law, increasing the number of tests per law is a simple and effective solution (§5.4). The special treatment of inequalities and conditional equations makes possible the generation of laws previously unreachable by a tool such as QuickSpec [8, 22].

Ease of use Arguably, a tool is easier to use if it requires less work from the programmer. As we illustrated in §3, writing a minimal program to apply Speculate takes only a few lines of code. The speculative function parses command-line arguments to allow easy configuration of test parameters. If only standard Haskell datatypes are involved, no extra Listable instances are needed. If user-defined data types can be freely enumerated without a constraining data invariant, instances can be automatically derived.

However, often we do need to restrict enumeration by a data invariant, and a crude application of a filtering predicate may be too costly, with huge numbers of discarded values. Effective use of Speculate may require careful programming of custom Listable instances, even if suitable definitions can be very concise. The Speculate library does not currently incorporate methods to derive enumerators of values satisfying given preconditions [5, 15].

Future Work We note a few avenues for further investigation that could lead to improved versions of Speculate or similar tools.

Improve performance when generating inequalities The algorithm to generate equations is partly based on the observation that, for an equation to be true, its one-variable-per-type instance must
be true. So, Speculate initially considers one-variable-per-type equations, generalizing them to their several-variable versions only if they are found true ($\S 4.2$). The same applies to inequalities: for $x + y \leq x + \text{abs } y$ to be true $x + x \leq x + \text{abs } x$ must be true. Speculate does not yet exploit this and does some unnecessary testing.

**Parallelism** As a way to improve performance, particularly when dealing with costly test functions such as in the regular expressions example ($\S 5.5$), we could parallelise parts of Speculate. For example, divide the testing of laws among multiple processors.

**Automated generation of efficient Listable instances** Right now, to use Speculate, Listable instances have to be explicitly declared. Speculate could take the constructors of a type in its constants list ($\S 3$) and automatically construct a generator for values of that type. This generator could be improved as new equations are discovered. If for a given type constructor Cons, we discover that $\text{Cons } x y \equiv \text{Cons } y x$, in further tests, we would only apply Cons to ordered $x$ and $y$. This is what we did manually in our regular-expressions example ($\S 5.5$).

**Improve filtering of redundant inequalities and conditions** Although Speculate already filters out a lot of redundant inequalities and conditional equations, there is still room for improvement. Recall these laws from Example 1.1:

1. $x \equiv 1 \Rightarrow 1 \equiv \text{abs } x$
2. $\text{abs } x \equiv y \Rightarrow \text{abs } (x + y) \equiv x + y$
3. $\text{abs } y \equiv x \Rightarrow \text{abs } (x + y) \equiv x + y$

By interpreting the condition as a variable assignment, the first law is an instance of $1 \equiv \text{abs } 1$. The other two laws are equivalent by the commutativity of addition ($\cdot$).

**Special treatment of conjunctions and disjunctions** Although not explored much in the examples in this paper, conjunctions ($\&$) and disjunctions ($|$) can often occur as conditions of properties [$17$]. In the current version of Speculate, logical operators are treated as regular functions. In future versions we could treat them specially, exploiting their properties of commutativity and associativity to reduce the search space.

**Checking that given equivalences are congruences** In $\S 5.1$, we mention that before running any tests, Speculate checks whether given equality ($\equiv$) functions are equivalences (reflexive, symmetric and transitive). Speculate also assumes, but does not check, that given $\equiv$ functions are congruences: in any expression $e$, suppose we replace a subexpression $s$ by $s'$, where $s \equiv s'$, to obtain $e'$ as the whole: then we require $e \equiv e'$. Future versions of Speculate should check for congruence.

**Detecting and using equivalences and orderings** In the current version of Speculate, the user has to say which equivalence ($\equiv$) and ordering ($\leq$) functions to use. Or, in the case of standard types, the user has to explicitly provide functions to override the standard ones. The algorithm to compute equations can work with any function that is a congruent equivalence. Similarly, the algorithm to compute inequalities, can work with any function that is an ordering. Speculate could detect any given functions that have these properties and autonomously search for laws based on them.

### Availability

Speculate is freely available with a BSD3-style license from:

- [https://hackage.haskell.org/package/speculate](https://hackage.haskell.org/package/speculate)
- [https://github.com/rudymatela/speculate](https://github.com/rudymatela/speculate)

This paper describes Speculate as of version 0.2.5.

### Acknowledgements

We thank Nick Smallbone for hospitality and many interesting discussions about QuickSpec; Maximilian Algehed for helping with running one of QuickSpec’s examples; Ivaylo Hristakiev for discovering a bug in our term unification algorithm; and anonymous reviewers for their comments on earlier drafts.

Rudy Braquehais is supported by CAPES, Ministry of Education of Brazil (Grant BEX 9980-13-0).

### References