Testing

Fast Track to Haskell

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Well-Typed
The Haskell Consultants

What is testing about?

- Gain confidence in the correctness of your program.
- Show that common cases work correctly.
- Show that corner cases work correctly.

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- Show that corner cases work correctly.
- Testing cannot prove the absence of bugs.
- Exception: Exhaustive testing.

Correctness

- When is a program correct?

Correctness

- When is a program correct?
- What is a specification?
- How to establish a relation between the specification and the implementation?
- What about bugs in the specification?

Testing versus types

Do types free us from the need to test?

Testing versus types

Do types free us from the need to test?

In general, no.

- There are limits to what the type system can express.
- While Haskell's type system is quite expressive, expressing advanced invariants of programs in the types is often a lot of work.
- There's usually a natural balance between compile-time type checking and run-time properties that should be tested.
- However, the presence of types means that we can concentrate on testing the interesting properties.

Testing in Haskell

There are a quite a number of tools and libraries.

Some noteworthy examples:

- HUnit – a classic unit testing library;
- QuickCheck – type-driven testing with random test case generation;
- smallcheck – a variant of QuickCheck supporting exhaustive testing of “small” test cases;
- test-framework – integrating different testing libraries into a common framework and Cabal packages;
- hspec and doctest – integrating testing with documentation.

Making a choice

We obviously don’t have time to look at them all, so we focus on one rather remarkable library:

QuickCheck

Type-driven testing with random test case generation.

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QuickCheck

Type-driven testing with random test case generation.

QuickCheck shares with other Haskell testing libraries the feature that tests are themselves Haskell programs, and as such they are type checked.

History of QuickCheck

- Developed in 2000 by Koen Claessen and John Hughes.
- Copied to other programming languages: Common Lisp, Scheme, Erlang, Python, Ruby, SML, Clean, Java, Scala, F#.
- Erlang version is sold by a company, QuviQ, founded by the authors of QuickCheck.

Example: specifying and testing sorting

A first version of the code

An attempt at insertion sort in Haskell:

$$
\begin{array}{l}
\mathsf{sort} :: [\mathsf{Int}] \to [\mathsf{Int}] \\
\mathsf{sort}\ [\,] \qquad\quad = [\,] \\
\mathsf{sort}\ (\mathsf{x} : \mathsf{xs}) = \mathsf{insert}\ \mathsf{x}\ \mathsf{xs}
\end{array}
$$

$$
\begin{array}{lll}
\multicolumn{3}{l}{\mathsf{insert} :: \mathsf{Int} \to [\mathsf{Int}] \to [\mathsf{Int}]} \\
\mathsf{insert}\ \mathsf{x}\ [\,] & & = [\mathsf{x}] \\
\mathsf{insert}\ \mathsf{x}\ (\mathsf{y} : \mathsf{ys}) & \mid \mathsf{x} \leqslant \mathsf{y} & = \mathsf{x} : \mathsf{ys} \\
 & \mid \mathsf{otherwise} & = \mathsf{y} : \mathsf{insert}\ \mathsf{x}\ \mathsf{ys}
\end{array}
$$

(This is an example – if you spot errors immediately, ignore them for now . . .)

Well-Typed

How to specify sorting?

A good specification is

- as precise as necessary,
- no more precise than necessary.

How to specify sorting?

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- no more precise than necessary.

If we want to specify sorting, we should give a specification that distinguishes sorting from all other operations, but does not force us to use a particular sorting algorithm.

A first approximation

Certainly, sorting a list should not change its length.

```
sortPreservesLength :: [Int] → Bool
sortPreservesLength xs = length xs == length (sort xs)
```

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```
sortPreservesLength :: [Int] → Bool
sortPreservesLength xs = length xs == length (sort xs)
```

We can test by invoking the function `quickCheck`:

```
⟩ quickCheck sortPreservesLength
*** Failed! Falsifiable (after 4 tests and 2 shrinks):
[0, 0]
```

Correcting the bug

$$
\begin{aligned}
&\mathsf{sort} :: [\mathsf{Int}] \to [\mathsf{Int}] \\
&\mathsf{sort}\ [\,] \qquad\quad = [\,] \\
&\mathsf{sort}\ (x : xs) = \mathsf{insert}\ x\ xs
\end{aligned}
$$

$$
\begin{aligned}
&\mathsf{insert} :: \mathsf{Int} \to [\mathsf{Int}] \to [\mathsf{Int}] \\
&\mathsf{insert}\ x\ [\,] \qquad\qquad\qquad\qquad\quad = [x] \\
&\mathsf{insert}\ x\ (y : ys) \mid x \leqslant y \qquad\ \ = x : ys \\
&\qquad\qquad\qquad\quad \mid \mathsf{otherwise} = y : \mathsf{insert}\ x\ ys
\end{aligned}
$$

Correcting the bug

$$
\begin{array}{l}
\mathsf{sort} :: [\mathsf{Int}] \to [\mathsf{Int}] \\
\mathsf{sort}\ [\,] \qquad\quad = [\,] \\
\mathsf{sort}\ (\mathsf{x} : \mathsf{xs}) = \mathsf{insert}\ \mathsf{x}\ \mathsf{xs}
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\mathsf{insert}\ \mathsf{x}\ [\,] & & = [\mathsf{x}] \\
\mathsf{insert}\ \mathsf{x}\ (\mathsf{y} : \mathsf{ys}) & \mid \mathsf{x} \leqslant \mathsf{y} & = \mathsf{x} : \boxed{\mathsf{y} :}\ \mathsf{ys} \\
 & \mid \mathsf{otherwise} & = \mathsf{y} : \mathsf{insert}\ \mathsf{x}\ \mathsf{ys}
\end{array}
$$

A new attempt

```
〉 quickCheck sortPreservesLength
+++ OK, passed 100 tests.
```

Looks better. But have we tested enough?

Properties are first-class objects

Note that we can define our own testing-inspired abstractions:

```
(f `preserves` p) x = p x == p (f x)
sortPreservesLength = sort `preserves` length
```

Is sorting the only list function preserving length?

Properties are first-class objects

Note that we can define our own testing-inspired abstractions:

```
(f `preserves` p) x = p x == p (f x)
sortPreservesLength = sort `preserves` length
```

Is sorting the only list function preserving length?

```
idPreservesLength = id `preserves` length
```

```
⟩ quickCheck idPreservesLength
+++ OK, passed 100 tests.
```

Clearly, the identity function does not sort the list.

When is a list sorted?

$$
\begin{aligned}
&\mathsf{sorted} :: [\mathsf{Int}] \to \mathsf{Bool} \\
&\mathsf{sorted}\ [\,] && = \mathsf{True} \\
&\mathsf{sorted}\ (\mathsf{x} : \mathsf{xs}) && = \ \ldots
\end{aligned}
$$

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&\mathsf{sorted} :: [\mathsf{Int}] \to \mathsf{Bool} \\
&\mathsf{sorted}\ [\,] &&= \mathsf{True} \\
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\end{aligned}
$$

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\begin{aligned}
&\mathsf{sorted} :: [\mathsf{Int}] \to \mathsf{Bool} \\
&\mathsf{sorted}\ [\,] &&= \mathsf{True} \\
&\mathsf{sorted}\ (\mathsf{x} : \boxed{[\,]}) &&= \ \ldots \\
&\mathsf{sorted}\ (\mathsf{x} : \boxed{\mathsf{y} : \mathsf{ys}}) &&= \ \ldots
\end{aligned}
$$

When is a list sorted?

$$
\begin{aligned}
&\mathsf{sorted} :: [\mathsf{Int}] \to \mathsf{Bool}\\
&\mathsf{sorted}\ [\,] \qquad\qquad\;\; = \mathsf{True}\\
&\mathsf{sorted}\ (\mathsf{x} : [\,]) \qquad = \mathsf{True}\\
&\mathsf{sorted}\ (\mathsf{x} : \mathsf{y} : \mathsf{ys}) = \ \ldots
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When is a list sorted?

$$
\begin{aligned}
&\mathsf{sorted} :: [\mathsf{Int}] \rightarrow \mathsf{Bool}\\
&\mathsf{sorted}\ [\,] && = \mathsf{True}\\
&\mathsf{sorted}\ (\mathsf{x} : [\,]) && = \mathsf{True}\\
&\mathsf{sorted}\ (\mathsf{x} : \mathsf{y} : \mathsf{ys}) && = \mathsf{x} < \mathsf{y}\ \&\&\ \mathsf{sorted}\ (\mathsf{y} : \mathsf{ys})
\end{aligned}
$$

Testing again

$$\text{sortEnsuresSorted} :: [\text{Int}] \to \text{Bool}$$
$$\text{sortEnsuresSorted xs} = \text{sorted (sort xs)}$$

Testing again

```
sortEnsuresSorted :: [Int] → Bool
sortEnsuresSorted xs = sorted (sort xs)
```

Or:

```
(f `ensures` p) x = p (f x)
sortEnsuresSorted = sort `ensures` sorted
```

Testing again

```
sortEnsuresSorted :: [Int] → Bool
sortEnsuresSorted xs = sorted (sort xs)
```

Or:

```
(f `ensures` p) x = p (f x)
sortEnsuresSorted = sort `ensures` sorted
```

```
⟩ quickCheck sortEnsuresSorted
*** Failed! Falsifiable (after 4 tests and 1 shrink):
[1, 1]
⟩ sort [1, 1]
[1, 1]
```

But this is correct. So what went wrong?

Specifications can have bugs, too!

$\rangle$ sorted $[2, 2, 4]$
False

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False

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\begin{aligned}
&\text{sorted} :: [\text{Int}] \to \text{Bool} \\
&\text{sorted } [\,] && = \text{True} \\
&\text{sorted } (x : [\,]) && = \text{True} \\
&\text{sorted } (x : y : ys) && = x < y \;\&\&\; \text{sorted } (y : ys)
\end{aligned}
$$

Specifications can have bugs, too!

$\rangle$ sorted $[2, 2, 4]$
False

$$
\begin{aligned}
&\text{sorted} :: [\text{Int}] \to \text{Bool} \\
&\text{sorted}\ [\,] = \text{True} \\
&\text{sorted}\ (x : [\,]) = \text{True} \\
&\text{sorted}\ (x : y : ys) = x \boxed{\leqslant} y\ \&\&\ \text{sorted}\ (y : ys)
\end{aligned}
$$

Well-Typed

Another attempt

$\rangle$ quickCheck sortEnsuresSorted
*** Failed! Falsifiable (after 5 tests and 4 shrinks):
$[0, 0, -1]$

There still seems to be a bug.

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```
⟩ quickCheck sortEnsuresSorted
*** Failed! Falsifiable (after 5 tests and 4 shrinks):
[0, 0, -1]
```

There still seems to be a bug.

```
⟩ sort [0, 0, -1]
[0, 0, -1]
```

Correcting again

$$
\begin{array}{l}
\mathsf{sort} :: [\mathsf{Int}] \to [\mathsf{Int}] \\
\mathsf{sort}\ [\,] \qquad\quad = [\,] \\
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$$

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\begin{array}{llll}
\multicolumn{4}{l}{\mathsf{insert} :: \mathsf{Int} \to [\mathsf{Int}] \to [\mathsf{Int}]} \\
\mathsf{insert}\ \mathsf{x}\ [\,] & & = & [\mathsf{x}] \\
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 & \mid \mathsf{otherwise} & = & \mathsf{y} : \mathsf{insert}\ \mathsf{x}\ \mathsf{ys}
\end{array}
$$

Correcting again

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\begin{aligned}
&\mathsf{sort} :: [\mathsf{Int}] \to [\mathsf{Int}]\\
&\mathsf{sort}\ [\,] = [\,]\\
&\mathsf{sort}\ (\mathsf{x} : \mathsf{xs}) = \mathsf{insert}\ \mathsf{x}\ (\boxed{\mathsf{sort}\ \mathsf{xs}})
\end{aligned}
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&\qquad\qquad\qquad\quad \mid \mathsf{otherwise} = \mathsf{y} : \mathsf{insert}\ \mathsf{x}\ \mathsf{ys}
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&\mathsf{insert}\ \mathsf{x}\ (\mathsf{y} : \mathsf{ys})\ |\ \mathsf{x} \leqslant \mathsf{y} \qquad\ \ = \mathsf{x} : \mathsf{y} : \mathsf{ys}\\
&\qquad\qquad\qquad\qquad\ |\ \mathsf{otherwise} = \mathsf{y} : \mathsf{insert}\ \mathsf{x}\ \mathsf{ys}
\end{aligned}
$$

⟩ quickCheck sortEnsuresSorted
+++ OK, passed 100 tests.

Are we done yet?

Is sorting specified completely by saying that

- sorting preserves the length of the input list,
- the resulting list is sorted?

No, not quite

```
evilNoSort :: [Int] → [Int]
evilNoSort xs = replicate (length xs) 0
```

This function fulfills both specifications, but still does not sort.

We need to make the relation between the input and output lists precise: both should contain the same elements – or one should be a permutation of the other.

Specifying sorting

```
f `permutes` xs    = f xs `elem` permutations xs
sortPermutes xs = sort `permutes` xs
```

Our sorting function fulfills this specification, but `evilNoSort` does not.

How QuickCheck works

How to use QuickCheck

To use QuickCheck in your program:

```
import Test.QuickCheck    -- from package QuickCheck
```

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Define properties.

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```
import Test.QuickCheck    -- from package QuickCheck
```

Define properties.

Then call `quickCheck` to test the properties.

```
quickCheck :: Testable prop ⇒ prop → IO ()
```

Well-Typed

The type of quickCheck

The type of quickCheck is an overloaded type:

$$\text{quickCheck} :: \text{Testable prop} \Rightarrow \text{prop} \rightarrow \text{IO} \ ()$$

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$$\text{quickCheck} :: \boxed{\text{Testable prop} \Rightarrow} \text{prop} \rightarrow \text{IO} \; ()$$

- The argument of quickCheck is a property of type prop.
- The only restriction on the type prop is that it is in the Testable type class.

Well-Typed

The type of quickCheck

The type of quickCheck is an overloaded type:

$$\text{quickCheck} :: \text{Testable prop} \Rightarrow \text{prop} \rightarrow \boxed{\text{IO ()}}$$

- The argument of quickCheck is a property of type prop.
- The only restriction on the type prop is that it is in the Testable type class.
- When executed, quickCheck prints the results of the test to the screen – hence the IO () result type.

Which properties are Testable?

So far, all our properties have been of type $[\mathsf{Int}] \to \mathsf{Bool}$:

$$\begin{aligned}
&\mathsf{sortPreservesLength} :: [\mathsf{Int}] \to \mathsf{Bool}\\
&\mathsf{sortEnsuresSorted} :: [\mathsf{Int}] \to \mathsf{Bool}\\
&\mathsf{sortPermutes} :: [\mathsf{Int}] \to \mathsf{Bool}
\end{aligned}$$

When used on such properties, QuickCheck generates random integer lists and verifies that the result is True.

- If the result is True for 100 cases, this success is reported in a message.
- If the result is False for a case, the test case triggering the result is printed.

Other forms of properties

All these properties can be tested with `quickCheck`:

```
appendLength :: [a] → [a] → Bool
appendLength xs ys = length xs + length ys == length (xs ++ ys)

plusIsCommutative :: Int → Int → Bool
plusIsCommutative m n = m + n == n + m

takeDrop :: Int → [Int] → Bool
takeDrop n xs = take n xs ++ drop n xs == xs

dropTwice :: Int → Int → [Int] → Bool
dropTwice m n xs = drop m (drop n xs) == drop (m + n) xs
```

Other forms of properties (contd.)

```
⟩ quickCheck takeDrop
+++ OK, passed 100 tests.
⟩ quickCheck dropTwice
*** Failed! Falsifiable (after 2 tests and 1 shrink):
1
−1
[0]
⟩ drop (−1) [0]
[0]
⟩ drop 1 (drop (−1) [0])
[]
⟩ drop (1 + (−1)) [0]
[0]
```

Other forms of properties (contd.)

```
〉 quickCheck takeDrop
+++ OK, passed 100 tests.
〉 quickCheck dropTwice
*** Failed! Falsifiable (after 2 tests and 1 shrink):
1
−1
[0]
〉 drop (−1) [0]
[0]
〉 drop 1 (drop (−1) [0])
[]
〉 drop (1 + (−1)) [0]
[0]
```

Nullary properties

A property without arguments is also possible:

```
lengthEmpty :: Bool
lengthEmpty = length [] == 0

wrong :: Bool
wrong = False

⟩ quickCheck lengthEmpty
+++ OK, passed 100 tests.

⟩ quickCheck wrong
*** Failed! Falsifiable (after 1 test):
```

Nullary properties

A property without arguments is also possible:

```
lengthEmpty :: Bool
lengthEmpty = length [ ] == 0

wrong :: Bool
wrong = False

〉quickCheck lengthEmpty
+++ OK, passed 100 tests.

〉quickCheck wrong
*** Failed! Falsifiable (after 1 test):
```

No random test cases are involved for nullary properties.

QuickCheck subsumes unit tests.

Properties

Recall the type of quickCheck:

$$\text{quickCheck} :: \text{Testable prop} \Rightarrow \text{prop} \rightarrow \text{IO ()}$$

We can now say more about when types are in Testable:

- testable properties usually are functions (with arbitrarily many arguments) resulting in a Bool

Properties

Recall the type of quickCheck:

$$\text{quickCheck} :: \text{Testable prop} \Rightarrow \text{prop} \rightarrow \text{IO} ()$$

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Are arbitrary argument types admissible?

Properties

Recall the type of quickCheck:

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We can now say more about when types are in Testable:

- testable properties usually are functions (with arbitrarily many arguments) resulting in a Bool

Are arbitrary argument types admissible?

No – QuickCheck has to know how to produce random test cases of such types.

Properties (contd.)

We can express the idea in Haskell using the type class language.

```
class Testable prop where
  property :: prop → Property
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A `Bool` is testable:

```
instance Testable Bool where
  ...
```

Properties (contd.)

We can express the idea in Haskell using the type class language.

```haskell
class Testable prop where
  property :: prop → Property
```

A `Bool` is testable:

```haskell
instance Testable Bool where
  ...
```

If a type is testable, we can add another function argument, as long as we know how to generate and print test cases:

```haskell
instance (Arbitrary a, Show a, Testable b) ⇒
          Testable (a → b) where
  ...
```

Analyzing the test data

Obtaining information about the test data

Question

Why is it important to know what data we actually test on?

Obtaining information about the test data

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Why is it important to know what data we actually test on?

A simple way is to use

$$\text{verboseCheck} :: \text{Testable prop} \Rightarrow \text{prop} \rightarrow \text{IO } ()$$

rather than

$$\text{quickCheck} :: \text{Testable prop} \Rightarrow \text{prop} \rightarrow \text{IO } ()$$

Observations about QuickCheck test data

- First test cases seem to be rather small.
- Test cases seem to increase in size over time.
- Duplicate test cases occur.

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- First test cases seem to be rather small.
- Test cases seem to increase in size over time.
- Duplicate test cases occur.

Often, `verboseCheck` is too much. We want to get information on the distribution of test cases according to a certain property.

The function collect

$$\mathsf{collect} :: (\mathsf{Testable}\ \mathsf{prop}, \mathsf{Show}\ \mathsf{a}) \Rightarrow \mathsf{a} \rightarrow \mathsf{prop} \rightarrow \mathsf{Property}$$

The function collect gathers statistics about test cases. This information is displayed when a test passes:

The function collect

$$\text{collect} :: (\text{Testable prop}, \text{Show a}) \Rightarrow \text{a} \to \text{prop} \to \text{Property}$$

The function collect gathers statistics about test cases. This information is displayed when a test passes:

```
〉 let sPL = sortPreservesLength
〉 quickCheck (λxs → collect (null xs) (sPL xs))
+++ OK, passed 100 tests:
97%  False .
  3%  True .
```

The function collect (contd.)

```
〉 quickCheck (λxs → collect (length xs `div` 10) (sPL xs))
+++ OK, passed 100 tests:
29% 0
23% 1
14% 2
11% 3
 7% 4
 6% 5
 4% 9
 4% 6
 2% 7
```

Well-Typed

The type Property

Recall the type of collect:

$$\text{collect} :: (\text{Testable prop}, \text{Show a}) \Rightarrow \text{a} \rightarrow \text{prop} \rightarrow \text{Property}$$

The type Property is QuickCheck-specific. It holds more structural information about a property than a plain Bool ever could.

```
instance Testable Property where ...
```

Like Bool, a Property is testable, so for us, not much changes.

Conditions in properties

Implications

The function insert preserves an ordered list.

```
implies :: Bool → Bool → Bool
implies x y = not x || y
```

A problematic property

```
insertPreservesOrdered :: Int → [Int] → Bool
insertPreservesOrdered x xs =
  sorted xs `implies` sorted (insert x xs)
```

Can you imagine why?

Implications (contd.)

```
⟩ quickCheck insertPreservesOrdered
+++ OK, passed 100 tests.
```

Implications (contd.)

```
⟩ quickCheck insertPreservesOrdered
+++ OK, passed 100 tests.
```

But:

```
⟩ let iPO = insertPreservesOrdered
⟩ quickCheck (λx xs → collect (sorted xs) (iPO x xs))
+++ OK, passed 100 tests:
88% False
12% True
```

For 88 test cases, `insert` has not actually been relevant for the result.

Implications (contd.)

The solution is to use the QuickCheck implication operator:

$$(\Longrightarrow) :: (\text{Testable prop}) \Rightarrow \text{Bool} \to \text{prop} \to \text{Property}$$

We see Property again – this type allows us to encode not only True or False, but also to reject the test case.

$$\begin{array}{l} \text{iPO} :: \text{Int} \to [\text{Int}] \to \text{Property} \\ \text{iPO x xs} = \text{sorted xs} \Longrightarrow \text{sorted (insert x xs)} \end{array}$$

Now, lists that are not sorted are discarded and do not contribute towards the goal of 100 test cases.

Implications (contd.)

We can now easily run into a new problem:

```
⟩ quickCheck (λx xs → collect (sorted xs) (iPO x xs))
*** Gave up! Passed only 41 tests (100% True ).
```

The chance that a random list is sorted is extremely small.

QuickCheck will give up after a while if too few test cases pass the precondition.

Custom generators

Generators

- Generators belong to an abstract data type Gen.
- We can define our own generators using another domain-specific language. The default generators for datatypes are specified by defining instances of class Arbitrary:

```
class Arbitrary a where
  arbitrary :: Gen a
  ...
```

Generators

- Generators belong to an abstract data type `Gen`.
- We can define our own generators using another domain-specific language. The default generators for datatypes are specified by defining instances of class `Arbitrary`:

```
class Arbitrary a where
  arbitrary :: Gen a
  ...
```

Think of a `Gen a` as an abstract set of information on how to produce values of type `a` randomly.

Running generators

QuickCheck has internal functions to extract random values from generators.

For end users, two debugging functions are offered:

$$
\begin{aligned}
&\mathsf{sample} \;\; :: \mathsf{Show}\ a \Rightarrow \mathsf{Gen}\ a \rightarrow \mathsf{IO}\ () \\
&\mathsf{sample'} :: \mathsf{Show}\ a \Rightarrow \mathsf{Gen}\ a \rightarrow \mathsf{IO}\ [a]
\end{aligned}
$$

These produce a number of random values generated by the given Gen a, and print them in the case of sample, or return them in the case of sample′.

Building new generators

QuickCheck includes a library for the construction of new generators:

$$
\begin{array}{ll}
\mathsf{choose} & :: \mathsf{Random\ a} \Rightarrow (\mathsf{a}, \mathsf{a}) \rightarrow \mathsf{Gen\ a} \\
\mathsf{oneof} & :: [\mathsf{Gen\ a}] \rightarrow \mathsf{Gen\ a} \\
\mathsf{frequency} & :: [(\mathsf{Int}, \mathsf{Gen\ a})] \rightarrow \mathsf{Gen\ a} \\
\mathsf{elements} & :: [\mathsf{a}] \rightarrow \mathsf{Gen\ a} \\
\mathsf{sized} & :: (\mathsf{Int} \rightarrow \mathsf{Gen\ a}) \rightarrow \mathsf{Gen\ a}
\end{array}
$$

Simple generators

For enumeration types, defining generators is easy:

```
instance Arbitrary Bool where
  arbitrary = elements [False, True]
instance Arbitrary Dir where
  arbitrary = elements [North, East, South, West]
```

Generating numbers

A simple possibility:

```
instance Arbitrary Int where
  arbitrary = choose (− 20, 20)
```

Better:

```
instance Arbitrary Int where
  arbitrary = sized (λn → choose (− n, n))
```

QuickCheck automatically increases the size gradually, up to the configured maximum value.

How to generate sorted lists

Idea: Adapt the default generator for lists.

The following function turns a list of integers into a sorted list of integers:

$$
\begin{aligned}
&\mathsf{mkSorted} :: [\mathsf{Int}] \to [\mathsf{Int}] \\
&\mathsf{mkSorted}\ [\,] &&= [\,] \\
&\mathsf{mkSorted}\ [\mathsf{x}] &&= [\mathsf{x}] \\
&\mathsf{mkSorted}\ (\mathsf{x} : \mathsf{y} : \mathsf{ys}) &&= \mathsf{x} : \mathsf{mkSorted}\ (\mathsf{x} + \mathsf{abs}\ \mathsf{y} : \mathsf{ys})
\end{aligned}
$$

How to generate sorted lists

Idea: Adapt the default generator for lists.

The following function turns a list of integers into a sorted list of integers:

$$
\begin{aligned}
&\mathrm{mkSorted} :: [\mathrm{Int}] \to [\mathrm{Int}] \\
&\mathrm{mkSorted}\ [\,] \qquad\qquad = [\,] \\
&\mathrm{mkSorted}\ [x] \qquad\quad\ = [x] \\
&\mathrm{mkSorted}\ (x : y : ys) = x : \mathrm{mkSorted}\ (x + \mathrm{abs}\ y : ys)
\end{aligned}
$$

Example

$\rangle$ $\mathrm{mkSorted}\ [1, 3, -4, 0, 2]$
$[1, 4, 8, 8, 10]$

How to generate sorted lists (contd.)

The original generator can be adapted as follows:

```
genSorted :: Gen [Int]
genSorted = fmap mkSorted arbitrary
```

Yes, `Gen` is an instance of `Functor`!

Using a custom generator

There is another function to construct properties provided by QuickCheck:

$$\mathsf{forAll} :: (\mathsf{Show}\ \mathsf{a}, \mathsf{Testable}\ \mathsf{b}) \Rightarrow \mathsf{Gen}\ \mathsf{a} \rightarrow (\mathsf{a} \rightarrow \mathsf{b}) \rightarrow \mathsf{Property}$$

This is how we use it:

$$\begin{array}{l}\mathsf{iPO} :: \mathsf{Int} \rightarrow \mathsf{Property} \\ \mathsf{iPO}\ \mathsf{x} = \mathsf{forAll}\ \mathsf{genSorted} \\ \quad (\lambda \mathsf{xs} \rightarrow \mathsf{sorted}\ \mathsf{xs} \Longrightarrow \mathsf{sorted}\ (\mathsf{insert}\ \mathsf{x}\ \mathsf{xs}))\end{array}$$

Well-Typed

Using a custom generator

There is another function to construct properties provided by QuickCheck:

$$\mathsf{forAll} :: (\mathsf{Show}\ a, \mathsf{Testable}\ b) \Rightarrow \mathsf{Gen}\ a \to (a \to b) \to \mathsf{Property}$$

This is how we use it:

$$\begin{array}{l} \mathsf{iPO} :: \mathsf{Int} \to \mathsf{Property} \\ \mathsf{iPO}\ x = \mathsf{forAll}\ \mathsf{genSorted} \\ \quad (\lambda xs \to \mathsf{sorted}\ xs \Longrightarrow \mathsf{sorted}\ (\mathsf{insert}\ x\ xs)) \end{array}$$

And it works:

$\rangle$ quickCheck iPO
+++ OK, passed 100 tests.

Modifiers

The module `Test.QuickCheck.Modifiers` defines a number of **newtype** wrappers:

```
newtype Positive a      = Positive a
newtype NonNegative a   = NonNegative a
newtype NonZero a       = NonZero a
newtype NonEmptyList a  = NonEmpty [a]
newtype OrderedList a   = Ordered [a]
```

These types have different `Arbitrary` instances than their underlying types, implementing a number of frequently required additional invariants.

Using modifiers

So, instead of hand-writing our own generator for sorted lists, we could have used:

```
iPO :: Int → OrderedList [Int] → Bool
iPO x (Ordered xs) = sorted (insert x xs)
```

Using modifiers

So, instead of hand-writing our own generator for sorted lists, we could have used:

$$\mathsf{iPO} :: \mathsf{Int} \to \mathsf{OrderedList}\ [\mathsf{Int}] \to \mathsf{Bool}$$
$$\mathsf{iPO}\ \mathsf{x}\ (\mathsf{Ordered}\ \mathsf{xs}) = \mathsf{sorted}\ (\mathsf{insert}\ \mathsf{x}\ \mathsf{xs})$$

The **newtype** wrapper technique for non-standard class instances is also applicable for your own generators, and also applicable in completely different situations.

GHCi pitfall

All lists are sorted?

```
⟩ quickCheck sorted
+++ OK, passed 100 tests.
```

GHCi pitfall

All lists are sorted?

$\rangle$ quickCheck sorted
+++ OK, passed 100 tests.

Use type signatures in GHCi to make sure a sensible type is used!

$\rangle$ quickCheck (ordered :: [Int] $\rightarrow$ Bool)
*** Failed! Falsifiable (after 3 tests and 2 shrinks):
$[0, -1]$

Lessons

QuickCheck is a great tool:

- A domain-specific language for writing properties.
- Test data is generated automatically and randomly.
- Another domain-specific language to write custom generators.
- You should use it.
- The `smallcheck` and `HUnit` libraries are also worth checking out.

However, keep in mind that writing good tests still requires training, and that tests can have bugs, too.

Haskell Program Coverage

Reachable uncovered code

Program code can be classified:

- unreachable code: code that simply is not used by the program, usually library code
- reachable code: code that can in principle be executed by the program

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Uncovered code is untested code – it could be executed, and it could do anything!

Introducing HPC

- HPC (Haskell Program Coverage) is a tool – integrated into GHC – that can identify uncovered code.
- Using HPC is extremely simple:
  - Compile your program with the flag `-fhpc`.
  - Run your program, possibly multiple times.
  - Run `hpc report` for a short coverage summary.
  - Run `hpc markup` to generate an annotated HTML version of your source code.

What HPC does

- HPC can present your program source code in a color-coded fashion.
- Yellow code is uncovered code.
- Uncovered code is discovered down to the level of subexpressions! (Most tools for imperative language only give you line-based coverage analyis.)
- HPC also analyzes boolean expressions:
  - Boolean expressions that have always been True are displayed in green.
  - Boolean expressions that have always been False are displayed in red.

QuickCheck and HPC

QuickCheck and HPC interact well!

- Use HPC to discover code that is not covered by your tests.
- Define new test properties such that more code is covered.
- Reaching 100% can be really difficult (why?), but strive for as much coverage as you can get.