Testing

The Practice of Haskell Programming

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Well-Typed

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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?

This lecture

QuickCheck, an automated testing library/tool for Haskell

Features:

- Describe properties as Haskell programs.
- Random test case generation.
- Test case generators can be adapted.

History

- 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:

```
sort :: [Int] → [Int]
sort []       = []
sort (x : xs) = insert x xs

insert :: Int → [Int] → [Int]
insert x []                   = [x]
insert x (y : ys) | x ⩽ y     = x : ys
                  | otherwise = y : insert x ys
```

How to specify sorting?

A good specification is

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

How to specify sorting?

A good specification is

- as precise as necessary,
- 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)
```

We can test by invoking the function `quickCheck`:

```
〉 quickCheck sortPreservesLength
```

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

Correcting the bug

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

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

Correcting the bug

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

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

A new attempt

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

Looks better. But have we tested enough?

Properties are first-class objects

```haskell
(f `preserves` p) x = p x == p (f x)
sortPreservesLength = sort `preserves` 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?

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

When is a list sorted?

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

When is a list sorted?

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

When is a list sorted?

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&\mathsf{sorted}\ (x : y : ys) &&= \ \ldots
\end{aligned}
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When is a list sorted?

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

Testing again

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

Testing again

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

Or:

$$(f\ \text{`}\mathit{ensures}\text{`}\ p)\ x = p\ (f\ x)$$
$$\mathit{sortEnsuresSorted} = \mathit{sort}\ \text{`}\mathit{ensures}\text{`}\ \mathit{sorted}$$

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!

```
〉 sorted [2, 2, 4]
False
```

Specifications can have bugs, too!

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

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

Specifications can have bugs, too!

```
〉sorted [2, 2, 4]
False
```

```
sorted :: [Int] → Bool
sorted []           = True
sorted (x : [])     = True
sorted (x : y : ys) = x ⩽ y && sorted (y : ys)
```

Another attempt

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

There still seems to be a bug.

Another attempt

```
⟩ 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

```
sort :: [Int] → [Int]
sort []       = []
sort (x : xs) = insert x xs

insert :: Int → [Int] → [Int]
insert x []                        = [x]
insert x (y : ys) | x ⩽ y          = x : y : ys
                  | otherwise      = y : insert x ys
```

Correcting again

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&\mathrm{insert}\ x\ (y : ys)\ \mid x \leqslant y = x : y : ys\\
&\qquad\qquad\qquad\quad \mid \mathrm{otherwise} = y : \mathrm{insert}\ x\ 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 now fulfills the specification.

How QuickCheck works

How to use QuickCheck

To use QuickCheck in your program:

```
import Test.QuickCheck
```

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Define properties.

How to use QuickCheck

To use QuickCheck in your program:

```haskell
import Test.QuickCheck
```

Define properties.

Then call `quickCheck` to test the properties.

```haskell
quickCheck :: Testable prop => prop -> IO ()
```

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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- The argument of `quickCheck` is a property of type `prop`.

The type of `quickCheck`

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

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- The only restriction on the type `prop` is that it is in the `Testable` **type class**.

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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 $[\mathrm{Int}] \rightarrow \mathrm{Bool}$:

```
sortPreservesLength :: [Int] → Bool
sortEnsuresSorted   :: [Int] → Bool
sortPermutes        :: [Int] → Bool
```

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`:

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

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`:

```
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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
```

Properties – contd.

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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.

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

A Bool is testable:

```
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:

```
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

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

rather than

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

Observations about random test data

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

Observations about random test data

- First test case are 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`

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

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

The function `collect`

```
collect :: (Testable prop, Show a) ⇒ a → prop → 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
```

The type `Property`

Recall the type of `collect`:

```
collect :: (Testable prop, Show a) ⇒ a → prop → Property
```

The type `Property` is QuickCheck-specific. It holds a 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:

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

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

$$\mathsf{iPO} :: \mathsf{Int} \to [\mathsf{Int}] \to \mathsf{Property}$$
$$\mathsf{iPO\ x\ xs} = \mathsf{sorted\ xs} \Longrightarrow \mathsf{sorted\ (insert\ x\ xs)}$$

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:

$\rangle$ quickCheck (λx xs $\rightarrow$ 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
  ...
```

Building new generators

QuickCheck includes a library for the construction of new generators:

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

Quickly testing generators:

$$
\mathsf{sample} \quad :: \mathsf{Show}\ a \Rightarrow \mathsf{Gen}\ a \rightarrow \mathsf{IO}\ ()
$$

Simple generators

```haskell
instance Arbitrary Bool where
  arbitrary = chooose (False, True)

instance (Arbitrary a, Arbitrary b) ⇒ Arbitrary (a, b) where
  arbitrary = do
                x ← arbitrary
                y ← arbitrary
                return (x, y)

data Dir = North | East | South | West
instance Arbitrary Dir where
  arbitrary = elements [North, East, South, West]
```

Generating numbers

A simple possibility:

$$\textbf{instance}\ \text{Arbitrary Int}\ \textbf{where}$$
$$\quad \text{arbitrary} = \text{chooose}\ (-\ 20, 20)$$

Better:

$$\textbf{instance}\ \text{Arbitrary Int}\ \textbf{where}$$
$$\quad \text{arbitrary} = \text{sized}\ (\lambda \text{n} \rightarrow \text{chooose}\ (-\ \text{n}, \text{n}))$$

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:

```
mkSorted :: [Int] → [Int]
mkSorted []           = []
mkSorted [x]          = [x]
mkSorted (x : y : ys) = x : mkSorted (x + abs y : ys)
```

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:

```
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```

Example

```
〉 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 = do
              xs ← arbitrary
              return (mkSorted xs)
```

Using a custom generator

There is another function to construct properties provided by QuickCheck:

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

This is how we use it:

```
iPO :: Int → Property
iPO x = forAll genSorted
  (λxs → sorted xs ==> sorted (insert x xs))
```

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There is another function to construct properties provided by QuickCheck:

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

This is how we use it:

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

And it works:

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

Summary

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.

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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Reachable code can be classified further:

- **covered code**: code that is actually executed during a number of program executions (for instance, tests)
- **uncovered code**: code that is not executed during testing

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- **uncovered code**: code that is not executed during testing

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.

More on testing

- QuickCheck can subsume unit tests, but QuickCheck is less suitable for testing `IO`-based code.
- There is a more classic unit test library for Haskell called **HUnit**.
- For small domains, exhaustive testing becomes a real option. The libraries **smallcheck** and **lazysmallcheck** migrate the ideas of QuickCheck to systematic exhaustive testing.
- Test suites can be integrated into Cabal packages.
- Tests can be integrated with Haddock documentation using **doctest**.