Today's Topic

Testing of programs

- Specification-based
- Tool-supported
- Automatically

Questions

How can we gain (sufficient) confidence that...

- our programs are *sound*,
- other people's programs are *sound*?

Answers

- Verification
  - Formal soundness proof (soundness of the specification, soundness of the implementation)
  - High confidence, high effort
- Testing
  - Variants: *systematically* vs. *ad hoc*
  - Controllable effort, undefined quality statement

    Remember:
    "*Testing can only show the presence of errors, not their absence*" (Dijkstra)

On the other hand...

Observation

Testing is...

- often amazingly successful in disclosing errors

Requirements

Reporting on...

- What has been tested?
- How thoroughly, how comprehensively has been tested?
- How was *success* defined?

Additionally desirable...

- Reproducibility of tests
- Repeated testing after program modifications

Preconditions

Indispensable...

- Specification of the meaning of the program
  - *Informally* (commentary in the program, in a separate documentation)
    $\leadsto$ ...often ambiguous, open to interpretation
  - *Formally*
    $\leadsto$ ...precise semantics, unique

In the following

Specification-based, tool-supported testing in Haskell

- QuickCheck (a *combinator library*)
  - defines a *formal specification language*
    $\leadsto$ ...allows property definition inside the (Haskell) source code
  - defines a *test data generator language*
    $\leadsto$ ...allows a simple and concise description of a large number of tests
  - allows automatic testing of all properties specified in a module, including failure reports
  - allows tests to be repeated at will

Note

Specification- and test data generator language are...

- Examples of so-called *domain-specific embedded languages*
  $\leadsto$ ...special strength of functional programming
- implemented as a *combinator library* in Haskell
  $\leadsto$ ...allows to make use of the full expressiveness of Haskell when defining properties and test data generators
- Part of the standard Haskell-distribution (both GHC and Hugs) (see module `QuickCheck`)
  $\leadsto$ ...ensures simple and direct usability

Reference

The following presentation is based on...

- Koen Claessen, John Hughes. *Specification-based Testing with QuickCheck*. In Jeremy Gibbons, Oege de Moor (Eds.), *The Fun of Programming*. Palgrave MacMillan, 2003.

For implementation details and applications...

- Koen Claessen, John Hughes. *QuickCheck: A Lightweight Tool for Random Testing of Haskell Programs*. In Proceedings of the ACM SIGPLAN 2000 International Conference on Functional Programming (ICFP 2000), 268 - 279, 2000.
- Koen Claessen, John Hughes. *Testing Monadic Code with QuickCheck*. In Proceedings ACM SIGPLAN 2002 Haskell Workshop, 65 - 77, 2002.

Property Definition w/ QuickCheck 1

In the most basic case properties are defined as predicates, i.e., Boolean valued functions.

Example 1

Inside the program:

```
prop_PlusAssociative :: Integer -> Integer -> Integer -> Bool
prop_PlusAssociative x y z = (x+y)+z == x+(y+z)
```

In Hugs:

```
Main>quickCheck prop_PlusAssociative
OK, passed 100 tests
```

Note:

- Type specification for `prop_PlusAssociative` is required because of the overloading of + (otherwise error message)
- Type specification allows a type-specific generation of test data

Property Definition w/ QuickCheck 2

Example 2

In the program:

```
prop_PlusAssociative :: Float -> Float -> Float -> Bool
prop_PlusAssociative x y z = (x+y)+z == x+(y+z)
```

In Hugs (falsifiable for type `Float`; think e.g. of rounding errors):

```
Main>quickCheck prop_PlusAssociative
Falsifiable, after 13 tests:
1.0
-5.16667
-3.71429
```

Note:

The error report contains:

- Number of tests successfully passed

More Complex Property Definitions w/ QuickCheck 1(3)

Consider as the property to be checked:
...to insert in a sorted list
(we suppose that a function `insert` and a predicate `ordered` are given)

The straightforward property definition, however,

```
prop_InsertOrdered x xs = ordered (insert x xs)
```

...is falsifiable.

It is too strong/naive (note that `xs` is not supposed to be sorted).

More Complex Property Definitions w/ QuickCheck 2(3)

Remedy:

```
prop_InsertOrdered :: Integer -> [Integer] -> Property
prop_InsertOrdered x xs = ordered xs ==> ordered (insert x xs)
```

Note:

- `ordered xs ==>`: Adding a *precondition*

  ⇝ Test data, which do not match the precondition, are dropped

- `==>`: ...is not a Boolean operator; it is an operator, which affects the selection of test data

  ⇝ Property definitions, which rely on such operators, always have the type `Property`

More Complex Property Definitions w/ QuickCheck 3(3)

Another option supported by QuickCheck:

- Direct quantification over sorted lists

```
prop_InsertOrdered :: Integer -> Property
prop_InsertOrdered x =
        forAll orderedLists $ \xs -> ordered (insert x xs)
```

Also more sophisticated properties could be specified:

- Refining the specification such that the result list coincides with the argument list (except of the inserted element)

The Operator $

See Standard Prelude:

```
($) :: (a -> b) -> a -> b
f $ x = f x
```

Note

- The operator $ is Haskell's infix function application
- It is useful to avoid the usage of parentheses:

  Example: `f (g x)` can be written as `f $ g x`

An Extended Example

...abstract data type for (first-in-first-out) *queues.*

Simple (yet inefficient) implementation, which serves as *abstract model* – as *reference model* of a queue:

```
type Queue a = [a]
empty        = []
add x q      = q ++ [x]     -- inefficient!
isEmpty q    = null q
front (x:q)  = x
remove (x:q) = q
```

A More Efficient Implementation

...the implementation of interest. Its basic idea:

- Split the list into two portions (list front and list back)
- Back of the list in reverse order

⇝ This ensures: Efficient access to list front and list back

```
type QueueI a   = ([a],[a])
emptyI          = ([],[])
addI x (f,b)    = (f,x:b)
isEmptyI (f,b)  = null f
frontI (x:f,b)  = x
removeI (x:f,b) = flipQ (f,b)
  where
    flipQ ([],b) = (reverse b, [])
    flipQ q      = q
```


In the following

Think of

- `Queue` and
- `QueueI`

in terms of

- *specification* and
- *implementation*

We now want to check/test if operations of the implementation (`QueueI`) behave properly according to the operations of the specification (`Queue`)...

List Representations and Represented Abstract Lists: The Relation

...by means of a *retrieve* function:

```
retrieve :: QueueI Integer -> [Integer]
retrieve (f,b) = f ++ reverse b
```

The function `retrieve`...

- transforms the (usually many) representations of an abstract list as values of `QueueI` into the underlying abstract list as values of `Queue`

The understanding of `QueueI` and `Queue` as lists on integers allows us to drop type specifications in the definitions of properties defined next...

Soundness Properties for Functions on QueueI

...by means of `retrieve` we can check, if

- the results of applying the efficient functions on `QueueI` coincide with those of the abstract functions on `Queue`

Soundness Properties: 1st Try 1(3)

Apparently, the following properties are expected to hold:

```
prop_empty     = retrieve emptyI == empty
prop_add x q   = retrieve (addI x q) == add x (retrieve q)
prop_isEmpty q = isEmptyI q == isEmpty (retrieve q)
prop_front q   = frontI q == front (retrieve q)
prop_remove q  = retrieve (removeI q) == remove (retrieve q)
```

However, this is not true...

Soundness Properties: 1st Try 2(3)

E.g., testing `prop_isEmpty` using `QuickCheck` yields:

```
Main>quickCheck prop_isEmpty
Falsifiable, after 4 tests:
([],[-1])
```

Problem:

- The specification of `isEmpty` implicitly assumes that the following *invariant* holds:
  - The front of the list is only empty, if the back of the list is empty, too

Soundness Properties: 1st Try 3(3)

In fact:

- `prop_isEmpty`, `prop_front`, and `prop_remove` are falsifiable because of this!
- The implementations of `isEmptyI`, `frontI`, and `removeI` implicitly assume that the front of a queue will only be empty if the back also is.

This silent assumption has to be made explicit as *invariant*...

Soundness Properties: 2nd Try 1(2)

We define the following invariant:

```
invariant :: QueueI Integer -> Bool
invariant (f,b) = not (null f) || null b
```

...and add them to all property definitions:

```
prop_empty     = retrieve emptyI == empty
prop_add x q   = invariant q ==>
                    retrieve (addI x q) == add x (retrieve q)
prop_isEmpty q = invariant q ==>
                    isEmptyI q == isEmpty (retrieve q)
prop_front q   = invariant q ==>
                    frontI q == front (retrieve q)
prop_remove q  = invariant q ==>
                    retrieve (removeI q) == remove (retrieve q)
```

Soundness Properties: 2nd Try 2(2)

Now, testing `prop_isEmpty` using `QuickCheck` yields:

```
Main>quickCheck prop_isEmpty
OK, passed 100 tests
```

However, testing `prop_front` still fails:

```
Main>quickCheck prop_front
Program error: front ([],[])
```

Problem:

- `frontI` (as well as `removeI`) may only be applied to non-empty lists. So far, this is not taken into account.

Remedy:

- Add `not (isEmptyI q)` to the preconditions of the relevant properties

Soundness Properties: Corrected Version

We obtain:

```
prop_empty      = retrieve emptyI == empty
prop_add x q    = invariant q ==>
                    retrieve (addI x q) == add x (retrieve q)
prop_isEmpty q = invariant q ==>
                    isEmptyI q == isEmpty (retrieve q)
prop_front q    = invariant q && not (isEmptyI q) ==>
                    frontI q == front (retrieve q)
prop_remove q   = invariant q && not (isEmptyI q) ==>
                    retrieve (removeI q) == remove (retrieve q)
```

Now

- All properties pass the test successfully!

Soundness Properties: Still to be Done

We still need to check:

- Operations producing queues do only produce queues, which satisfy this invariant.

Since so far we only tested:

- Operations on queues behave correctly on representations of queues which satisfy the invariant

```
invariant (f,b) = not (null f) || null b
```


Soundness Properties: Towards This

The formulation of appropriate properties for functions producing queues:

```
prop_inv_empty    = invariant emptyI
prop_inv_add x q  = invariant q ==> invariant (addI x q)
prop_inv_remove q = invariant q && not (isEmptyI q) ==>
                        invariant (removeI q)
```

Soundness Properties: Still to be Done

Testing by means of `QuickCheck` yields:

```
Main>quickCheck prop_inv_add
Falsifiable, after 0 tests:
0
([],[])
```

Problem:

- The invariant must hold
  - not only after applying `removeI`,
  - but also after applying `addI` to the empty list; adding to the back of a queue breaks the invariant in this case.

Soundness Properties: Done Now!

To this end:

- Adjust the function `addI` as follows:

```
addI x (f,b) = flipQ(f,x:b)  -- instead of: addI x (f,b) = (f,x:b)
```

with `flipQ` defined previously.

Now

- All properties pass the test successfully!

Observation

In the course of developing this example it turned out:

- Testing disclosed (only) one bug in the implementation (this was in function `addI`)
- *But*: Several missing preconditions and a missing invariant in the original definitions of properties were found and added

Both is typical, and valuable:

- The additional conditions and invariants are now explicitly given in the program text
- They add to understanding the program and are valuable as documentation, both for the program developer and for future users (think of program maintaining!)

Algebraic Specifications

...(often a desired) alternative to the abstract model

An algebraic specification...

- provides equational constraints the operations ought to satisfy

Algebraic Specifications

For the example of queues, for instance, as follows:

```
prop_isEmpty q      = invariant q ==> isEmptyI q == (q == emptyI)
prop_front_empty x  = frontI (addI x emptyI) == x
prop_front_add x q  = invariant q && not (isEmptyI q) ==>
                          frontI (addI x q) == frontI q
prop_remove_empty x = removeI (addI x emptyI) == emptyI
prop_remove_add x q = invariant q && not (isEmptyI q) ==>
                          removeI (addI x q) == addI x (removeI q)
```


Algebraic Specifications

Testing using `QuickCheck` yields:

```
Main>quickCheck prop_remove_add
Falsifiable, after 1 tests:
0
([1],[0])
```

Problem:

- Left hand side yields: `([0,0],[])`
- Right hand side yields: `([0],[0])`
- Equivalent but not equal!

Algebraic Specifications

Solution:

- Consider instead of “equal” now “equivalent”

```
q 'equiv' q' = invariant q && invariant q' &&
               retrieve q == retrieve q'
```

Then replacing of

```
prop_remove_add x q = invariant q && not (isEmptyI q) ==>
                      removeI (addI x q) == addI x (removeI q)
```

by

```
prop_remove_add x q = invariant q && not (isEmptyI q) ==>
                      removeI (addI x q) 'equiv' addI x (removeI q)
```

yields the desired result: the test passes successfully.

Algebraic Specifications

Similar to the previous setting, we have to check:

- All operations producing queues yield results, which are equivalent, if the arguments are.

Considering the operation `addI`, for instance, this can be done by:

```
prop_add_equiv q q' x = q 'equiv' q' ==> addI x q 'equiv' addI x q'
```

Algebraic Specifications

Though mathematically sound, the definition of `prop_add_equiv` is inappropriate for fully automatic testing.

We might observe:

```
Main>quickCheck prop_add_equiv Arguments exhausted after 58 tests.
```

Problem and background:

- `QuickCheck` generates lists `q` und `q'` randomly.
- Most of the pairs of lists will not be equivalent, and hence be discarded for the actual test.
- `QuickCheck` generates a maximum number of candidate arguments only (default: 1.000), and then stops, possibly before the number of 100 test cases is met.

Enhancing Usability

...of QuickCheck by providing support for

- Quantification over subsets
  - by means of *filters*
  - by means of *generators* (type-based, weighted, size controlled,...)
- ...
- test case monitoring

In the following:

⇝ ...illustrating this support in terms of examples!

Quantifications over Subsets

For `QuickCheck` holds:

- By default, parameters are quantified over values of the appropriate type

Often, however, it is desired:

- A quantification over subsets of these values

Quantifications over Subsets

`QuickCheck` offers several options for this purpose:

- Representation of subsets in terms of *Boolean functions*, which act as a filter for test cases
  - Adequate, if many elements of the underlying set are members of the relevant subset, too.
  - Inadequate, if only a few elements of the underlying set are members of the relevant subset.
- Representation of subsets in terms of *generators*
  - A generator of type `Gen a` yields a random sequence of values of type `a`.
  - The property `forall set p` successively checks `p` on randomly generated elements of `set`.

Support by QuickCheck

For the effective usage of generators `QuickCheck` supports:

- different variants for the specification of relations such as `equiv`
  - As a Boolean function
    - simple to check equivalency of two values (but difficult to generate values which are equivalent).
  - As a function from a set of values to another set of equivalent values (generator!)
    - simple to generate equivalent values (but difficult to check equivalency of two values).

Generators

The generator variant for `equiv`:

```
equivQ :: QueueI a -> Gen(QueueI a)
equivQ q = do k <- choose (0,0 'max' (n-1))
              return (take (n-k) els, reverse (drop (n-k) els))
 where
   els = retrieve q
   n   = length els
```

Note:

- Definition of `choose` will be given later

Generators

This allows us to check that

- generated elements are related, i.e., equivalent

To this end check:

```
prop_EquivQ q = invariant q ==>
   forAll (equivQ q) $ \q' -> q 'equiv' q'
```

Note:

- $ means function application. Using $ allows the omission of parentheses, see the λ expression in the example.
- The property which is dual to `prop_EquivQ`, i.e., that all related elements can be generated, cannot be checked by testing.

Generators

This allows:

- Reformulating the property that `addI` maps equivalent queues to equivalent queues

```
prop_add_equiv q x = invariant q ==>
   forAll (equivQ q) $ \q' -> addI x q 'equiv' addI x q'
```

Remark:

- Other properties analogously

Next: How to define generators...

Defining Generators

...is simplified because of the monadic type of `Gen`.

It holds:

- `return a` always yields (generates) `a` and represents the singleton set {`a`}
- `do` {`x <- s; e`} can be considered the (generated) set {`e` | `x` ∈ `s`}

Defining Generators

The fundamental function to make a choice:

```
choose :: Random a => (a,a) -> Gen a
```

Remark:

- The function `choose` generates "randomly" an element of the specified domain
- `choose (1,n)` represents the set {`1...n`}

Applying choose

Using `choose` we can define `equivQ` (as seen above):

```
equivQ :: QueueI a -> Gen(QueueI a)
equivQ q = do k <- choose (0,0 'max' (n-1))
              return (take (n-k) els, reverse (drop (n-k) els))
 where
   els = retrieve q
   n   = length els
```

- Generates a random queue containing the same elements as `q`
- The number of elements in the remainder of the list will be chosen such that it is properly smaller than the total number of elements of the list (supposed the total number is different from 0)

Type-based Generators

...by means of the overloaded generator `arbitrary`, e.g. for the generation of arguments of properties:

Example:

```
prop_max_le x y = x <= x 'max' y
```

is equivalent to

```
prop_max_le = forAll arbitrary $ \x -> forAll arbitrary $ \y ->
   x <= x 'max' y
```

Type-based Generators

Another example:

The set $\{y \mid y \geq x\}$ can be generated by

```
atLeast x = do diff <- arbitrary
               return (x + abs diff)
```

because of the equality

$$\{y \mid y \geq x\} = \{x + abs\ d \mid d \in \mathbb{Z}\}$$

that holds for numerical types.

Note: Similar definitions for other types are possible.

Selection

...between several generators can be achieved by means of a generator `oneof`, which can be thought of as set union.

Example: Constructing a sorted list

```
orderedLists = do x <- arbitrary
                  listsFrom x
   where
      listsFrom x = oneof [return [], do y <- atLeast x
                                         liftM (x:) (listsFrom y)]
```

Underlying intuition:

- A sorted list is either empty or the addition of a new head element to a sorted list of larger elements

Weighted Selection

- The `oneof` combinator picks with equal probability one of the alternatives
- This often has an unduly impact on the test case generation (in the previous example the empty set will be selected too often)
- *Remedy*: A weight function `frequency`, which assigns different weights to the alternatives

```
frequency :: [(Int,Gen a)] -> Gen a
```

Application:

```
listsFrom x = frequency [(1,return []),
                         (4,do y <- atLeast x
                               liftM (x:) (listsFrom y)) ]
```

- A `QuickCheck` generator corresponds to a probability distribution over a set, not the set itself
- The impact of the above assignment of weights is that on average the length of generated lists is 4

The Class Arbitrary

If non-standard generators such as `orderedLists` are used frequently, it is advisable to make this type an instance of `Arbitrary`:

```
newtype OrderedList a = OL [a]

instance (Num a, Arbitrary a) => Arbitrary(OrderedList a) where
  arbitrary = liftM OL orderedLists
```

Together with the re-definition of `insert` as

```
insert :: Ord a => a -> OrderedList a -> OrderedList a
```

arguments generated for it will automatically be ordered.

Controlling the Size of Generated Test Data

- Often wise for type-based test data generation
- Explicitly supported by `QuickCheck`

Generators that depend on the size can be defined by:

```
sized :: (Int -> Gen a) -> Gen a  -- For defining size aware gen.

sized $ \n -> do len <- choose (0,n) -- Application of sized
                 vector len          -- in the Def. of the default
                                     -- list generator

vector n = sequence [arbitrary | i <- [1..n]] -- generates random list
                                              -- of length n

resize :: Int -> Gen a -> Gen a -- for controlling the size of
                                -- generated values

sized $ \n -> resize (round (sqrt (fromInt n))) arbitrary
        -- Application of resize
```


Generators for User-defined Types

Test data generators for...

- *predefined ("built-in") types* of Haskell
  - are provided by `QuickCheck`
  - for *user-defined types*, this is not possible
- *user-defined types*
  - have to be provided by the user in terms of defining a suitable instance of class `Arbitrary`
  - require usually, especially in case of recursive types, to control the size of generated test cases

Example: Binary Trees

Consider type `Tree`:

```
data Tree a = Leaf | Branch (Tree a) a (Tree a)
```

The following definition of the test-case generator is apparent:

```
instance Arbitrary a => Arbitrary (Tree a) where
  arbitrary =
     frequency [(1,return Leaf),
                (3,liftM3 Branch arbitrary arbitrary arbitrary)]
```


Example: Binary Trees

Note:

- The assignment of weights (1 vs. 3) has been done in order to avoid the generation of all too many trivial trees of size 1
- *Problem*: The likelihood that a generator comes up with a *finite* tree, is only one third

  $\leadsto$ this is because termination is possible only, if all subtrees generated are finite. With increasing breadth of the trees, the requirement of always selecting the "terminating" branch has to satisfied at ever more places simultaneously

Example: Binary Trees

Remedy:

- Usage of the parameter `size` in order to ensure
  - termination and
  - "reasonable" size

  of the trees generated

Example: Binary Trees

Implementation:

```
instance Arbitrary a => Arbitrary (Tree a) where
   arbitrary = sized arbTree

arbTree 0 = return Leaf
arbTree n | n>0 =
   frequency [(1,return Leaf),
              (3,liftM3 Branch shrub arbitrary shrub)]
     where
       shrub = arbTree (n 'div' 2)
```

Note: `shrub` is a generator for small(er) trees.

Example: Binary Trees

Remark:

- `shrub` is a *generator* for "small" trees
- `shrub` is not bounded to a special tree; the two occurrences of `shrub` will usually generate different trees
- Since the size limit for subtrees is halved, the total size is bounded by the parameter `size`
- Defining generators for recursive types must usually be handled specifically as in this example

Test-Data Monitoring / Test Coverage

In practice, it is meaningful...

- to monitor the test cases generated
- in order to obtain a hint on the quality and the coverage of test cases of a `QuickCheck` run

For this purpose `QuickCheck` provides...

- an array of monitoring possibilities

Test-Data Monitoring / Test Coverage

Why is test-data monitoring meaningful?

Reconsider the example of inserting into a sorted list:

```
prop_InsertOrdered :: Integer -> [Integer] -> Property
prop_InsertOrdered x xs = ordered xs ==> ordered (insert x xs)
```


Test-Data Monitoring / Test Coverage

QuickCheck performs the check of prop_InsertOrdered such that...

- lists are generated randomly
- each generated list will be checked, if it is sorted (used test case) or not (discarded test case)

Obviously, it holds...

- the likelihood that a randomly generated list is sorted is the higher the shorter the list is

This introduces the danger that...

- the property prop_InsertOrdered is mostly tested with lists of length one or two
- even a successful test is not meaningful

Test-Data Monitoring / Test Coverage

For monitoring QuickCheck provides a...

- combinator trivial, where the meaning of "trivial" is user-definable

Example:

```
prop_InsertOrdered :: Integer -> [Integer] -> Property
prop_InsertOrdered x xs = ordered xs ==>
      trivial (length xs <= 2) $ ordered (insert x xs)
```

with

```
Main>quickCheck prop_InsertOrdered
OK, passed 100 tests (91% trivial)
```


Test-Data Monitoring / Test Coverage

Observation:

- 91% are too many trivial test cases in order to ensure that the total test is meaningful
- The operator ==> should be used with care in test-case generators

Remedy:

- User-defined generators

  $\leadsto$ as in the example of prop_InsertOrdered on slide 14

Test-Data Monitoring / Test Coverage

The combinator `trivial` is...

- instance of a more general combinator `classify`

```
trivial p = classify p "trivial"
```


Test-Data Monitoring / Test Coverage

Multiple application of `classify` allows an even more refined test-case monitoring:

```
prop_InsertOrdered x xs = ordered xs =>
   classify (null xs) "empty lists" $
      classify (length xs == 1) "unit lists" $
         ordered (insert x xs)
```

This yields:

```
Main>quickCheck prop_InsertOrdered
OK, passed 100 tests.
42% unit lists.
40% empty lists.
```


Test-Data Monitoring / Test Coverage

Going beyond, the combinator `collect` allows to keep track on all test cases:

```
prop_InsertOrdered x xs = ordered xs =>
   collect (length xs) $ ordered (insert x xs)
```

This yields a histogram of values:

```
Main>quickCheck prop_InsertOrdered
OK, passed 100 tests.
46% 0.
34% 1.
15% 2.
5% 3.
```


Notes on the Implementation of Quick-Check 1(2)

```
class Testable a where
  property :: a -> Property

newtype Property = Prop (Gen Result)

instance Testable Bool where
  property b = Prop (return (resultBool b))

instance (Arbitrary a, Show a, Testable b) =>
                          Testable (a->b) where
  property f = forAll arbitrary f

instance Testable Property where
  property p = p

quickCheck :: Testable a => a -> IO ()
```

Notes on the Implementation of QuickCheck 2(2)

QuickCheck: In total about 300 lines of code.

For further details check out:

- Koen Claessen, John Hughes. *QuickCheck: A Lightweight Tool for Random Testing of Haskell Programs*. In Proceedings of the ACM SIGPLAN 2000 International Conference on Functional Programming (ICFP 2000), 268 - 279, 2000.

Conclusions 1(3)

Generally, it holds:

- Formalizing specifications is meaningful (even without a subsequent formal proof of soundness)

Experience shows:

- Specifications provided are often (initially) faulty themselves

Conclusions 2(3)

`QuickCheck` is an effective tool...

- to disclose bugs in
  - programs and
  - specifications

  with little effort.
- to reduce
  - test costs
  - while simultaneously testing more thoroughly

Conclusions 3(3)

Investigations of Richard Hamlet in...

Richard Hamlet. *Random Testing*. In J. Marciniak (Ed.), Encyclopedia of Software Engineering, Wiley, 970-978, 1994

suggest that

- a high number of test cases yields meaningful results even in the case of *random testing*

In principle, it holds:

- The generation of random test cases is "cheap"

Hence, there are many reasons advising...

- the routine usage of a tool like `QuickCheck`!

Further Reading

- Colin Runciman, Matthew Naylor, and Fredrik Lindblad. *SmallCheck and Lazy SmallCheck*. In Proceedings ACM SIGPLAN 2008 Haskell Workshop, 37 - 48, 2008.

  [Freely available from `http://hackage.haskell.org`]

- Jan Christiansen, Sebastian Fischer. *Easycheck – Test Data for Free*. In Proceedings of the 9th International Symposium on Functional and Logic Programming (FLPS 2008), LNCS 4989, 322 - 336, 2008.

- Koen Claessen, Colin Runciman, Olaf Chitil, John Hughes, M. Wallace. *Testing and Tracing Lazy Functional Programs Using QuickCheck and Hat*. In Proceedings 4th International School on Advanced Functional Programming (AFP 2002), LNCS 2638, 59 - 99, 2002.

Next course meeting...

- Thursday, April 14, 2011, lecture time: 4.15 p.m. to 5.45 p.m., lecture room on the ground floor of the building Argentinierstr. 8