Test Data Generators

Repeating Instructions

```
doTwice io =
  do a <- io
     b <- io
     return (a,b)
dont io =
    return ()
```

An instruction to compute the given result

```
Main> doTwice (print "hello”)
"hello"
"hello"
((),())
Main> dont (print "hello”)
```

Writing instructions and *obeying* them are two different things!

Why Distinguish Instructions?

- *Functions* always give the same result for the same arguments
- *Instructions* can behave differently on different occasions
- Confusing them (as in most programming languages) is a major source of bugs
  - This concept a major breakthrough in programming languages in the 1990s
  - How would you write **`doTwice`** in C?

Monads = Instructions

- What is the type of doTwice?

```
Main> :i doTwice
doTwice :: Monad a => a b -> a (b,b)
```

Even the *kind of instructions* can vary! Different kinds of instructions, depending on who obeys them.

Whatever kind of result argument produces, we get a pair of them

IO means operating system.

QuickCheck Instructions

- QuickCheck can perform random testing with values of any type which is in class Arbitrary
- For any type *a* in Arbitrary there is a random value generator, **Gen a**
- **Gen** is a Monad – so things of type **Gen a** are another kind of “instruction”

IO vs Gen

$\underbrace{\text{IO A}}$

- Instructions to build a value of type A by interacting with the operating system
- Run by the ghc runtime system

$\underbrace{\text{Gen A}}$

- Instructions to create a random value of type A
- Run by the QuickCheck library functions to perform random tests

Instructions for Test Data Generation

- Generate *different* test data every time
  - Hence need ”instructions to generate an *a*”
  - Instructions to QuickCheck, not the OS
  - **Gen a ≠ IO a**
- Generating data of different types?

```
QuickCheck> :i Arbitrary
-- type class
class Arbitrary a where
  arbitrary :: Gen a
  ...
```

Sampling

To inspect generators QuickCheck provides

sample :: Gen a -> IO ()

```
Sample> sample (arbitrary :: Gen Integer)
1
0
-5
14
-3
```

Say which type we want to generate

Prints (fairly small) test data QuickCheck might generate

Sampling Booleans

```
Sample> sample (arbitrary :: Gen Bool)
True
False
True
True
True
```

- Note: the definition of sample is not important here – it is just a way for QuickCheck users to “inspect” something of type Gen a.

Sampling Doubles

```
Sample> sample (arbitrary :: Gen Double)
-5.75
-1.75
2.1666666666667
1.0
-9.25
```

Sampling Lists

```
Sample> sample (arbitrary :: Gen [Integer])
[-15,-12,7,-13,6,-6,-2,4]
[3,-2,0,-2,1]
[]
[-11,14,2,8,-10,-8,-7,-12,-13,14,15,15,11,7]
[-4,10,18,8,14]
```

Writing Generators

- We build generators in the same way we build other instructions (like IO): using exiting generators, **return** and **do**:

```
Sample> sample (return True)
True
True
True
True
True
```

Writing Generators

- Write instructions using **do** and return:

```
Main> sample (doTwice (arbitrary :: Gen Integer))
(12,-6)
(5,5)
(-1,-9)
(4,2)
(13,-6)
```

It' s important that the instructions are followed *twice*, to generate two *different* values.

Writing Generators

- Write instructions using **do** and return:

```
Main> sample evenInteger
-32
-6
0
4
0
```

```
evenInteger :: Gen Integer
evenInteger =
  do n <- arbitrary
     return (2*n)
```

Generation Library

- QuickCheck provides *many* functions for constructing generators

```
Main> sample (choose (1,10) :: Gen Integer)
6
7
10
6
10
```

Generation Library

- QuickCheck provides *many* functions for constructing generators

```
Main> sample (oneof [return 1, return 10])
1
1
10
1
1
```

```
oneof :: [Gen a] -> Gen a
```

Generating a Suit

```
data Suit = Spades | Hearts | Diamonds | Clubs
    deriving (Show,Eq)
```

```
Main> sample rSuit
Spades
Hearts
Diamonds
Diamonds
Clubs
```

```
rSuit :: Gen Suit
rSuit = oneof [return Spades,
               return Hearts,
               return Diamonds,
               return Clubs]
```

QuickCheck chooses one set of instructions from the list

Generating a Suit

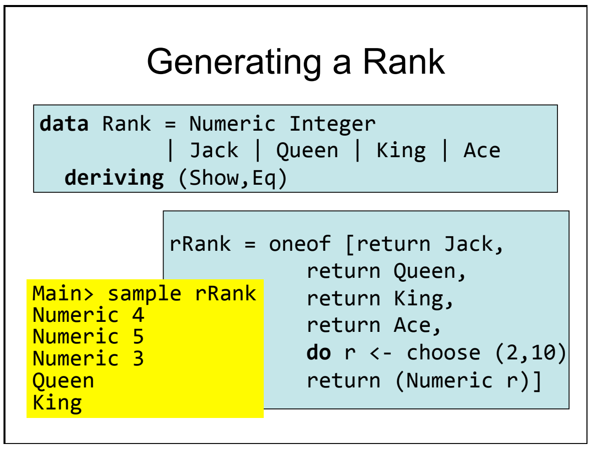
```
data Suit = Spades | Hearts | Diamonds | Clubs
    deriving (Show,Eq)
```

Alternative definition:

Quiz: define `elements` using `oneof`

```
rSuit :: Gen Suit
rSuit = elements [Spades,
                  Hearts,
                  Diamonds,
                  Clubs]
```

QuickCheck chooses one of the elements from the list

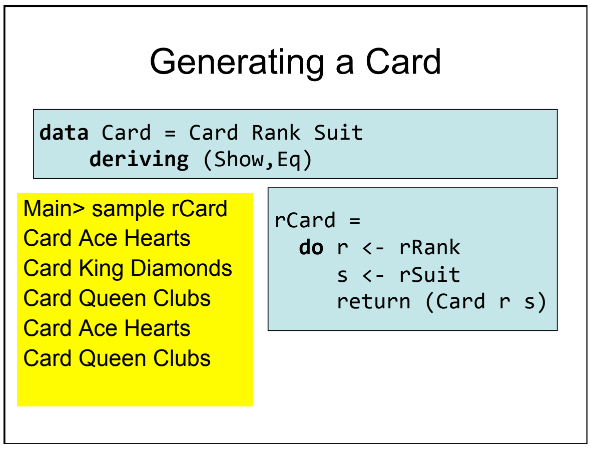


Generating a Rank

```
data Rank = Numeric Integer
          | Jack | Queen | King | Ace
  deriving (Show,Eq)
```

```
rRank = oneof [return Jack,
               return Queen,
               return King,
               return Ace,
               do r <- choose (2,10)
               return (Numeric r)]
```

```
Main> sample rRank
Numeric 4
Numeric 5
Numeric 3
Queen
King
```

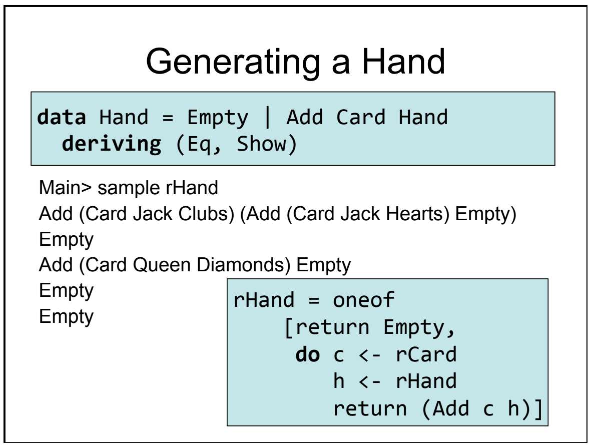


Generating a Card

```
data Card = Card Rank Suit
    deriving (Show,Eq)
```

```
Main> sample rCard
Card Ace Hearts
Card King Diamonds
Card Queen Clubs
Card Ace Hearts
Card Queen Clubs
```

```
rCard =
  do r <- rRank
     s <- rSuit
     return (Card r s)
```

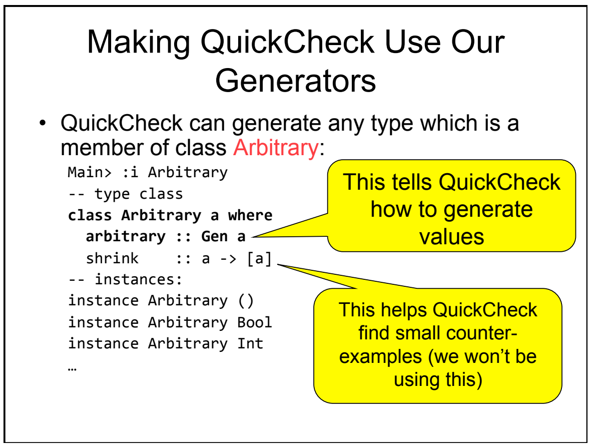


Generating a Hand

```
data Hand = Empty | Add Card Hand
  deriving (Eq, Show)
```

```
Main> sample rHand
Add (Card Jack Clubs) (Add (Card Jack Hearts) Empty)
Empty
Add (Card Queen Diamonds) Empty
Empty
Empty
```

```
rHand = oneof
    [return Empty,
     do c <- rCard
        h <- rHand
        return (Add c h)]
```

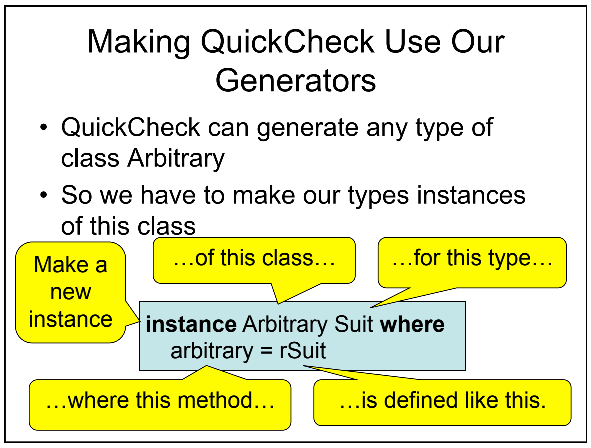


Making QuickCheck Use Our Generators

- QuickCheck can generate any type which is a member of class Arbitrary:

```
Main> :i Arbitrary
-- type class
class Arbitrary a where
  arbitrary :: Gen a
  shrink    :: a -> [a]
-- instances:
instance Arbitrary ()
instance Arbitrary Bool
instance Arbitrary Int
…
```

This tells QuickCheck how to generate values
This helps QuickCheck find small counter-examples (we won't be using this)

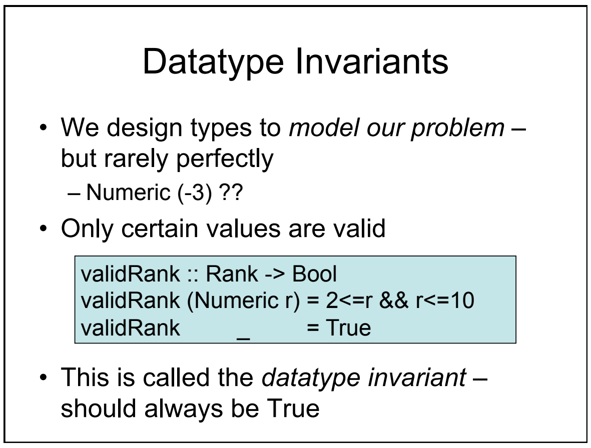


Making QuickCheck Use Our Generators

- QuickCheck can generate any type of class Arbitrary
- So we have to make our types instances of this class

```
instance Arbitrary Suit where
  arbitrary = rSuit
```

Make a new instance
…of this class…
…for this type…
…where this method…
…is defined like this.



Datatype Invariants

- We design types to *model our problem* – but rarely perfectly
  - Numeric (-3) ??
- Only certain values are valid

```
validRank :: Rank -> Bool
validRank (Numeric r) = 2<=r && r<=10
validRank     _       = True
```

- This is called the *datatype invariant* – should always be True

Testing Datatype Invariants

- Generators should only produce values satisfying the datatype invariant:

```
prop_Rank r = validRank r
```

- Stating the datatype invariant helps us understand the program, avoid bugs
- Testing it helps uncover errors in test data generators!

Testing-code needs testing too!

Test Data Distribution

- We don't *see* the test cases when quickCheck succeeds
- Important to know what kind of test data is being used

```
prop_Rank r = collect r (validRank r)
```

This property *means* the same as validRank r, but when tested, collects the values of r

Distribution of Ranks

```
Main> quickCheck prop_Rank
OK, passed 100 tests.
26% King.
25% Queen.
19% Jack.
17% Ace.
7% Numeric 9.
2% Numeric 7.
1% Numeric 8.
1% Numeric 6.
1% Numeric 5.
1% Numeric 2.
```

We see a summary, showing *how often* each value occured

Face cards occur much more frequently than numeric cards!

Fixing the Generator

```
rRank = frequency
  [(1,return Jack),
   (1,return Queen),
   (1,return King),
   (1,return Ace),
   (9, do r <- choose (2,10)
          return (Numeric r))]
```

Each alternative is paired with a *weight* determining how often it is chosen.

Choose number cards 9x as often.

Distribution of Hands

- Collecting each hand generated produces too much data—hard to understand
- Collect a summary instead—say the number of cards in a hand

```
numCards :: Hand -> Integer
numCards Empty = 0
numCards (Add _ h) = 1 + numCards h
```

Distribution of Hands

```
prop_Hand h = collect (numCards h) True
```

```
Main> quickCheck prop_Hand
OK, passed 100 tests.
53% 0.
25% 1.
9% 2.
5% 3.
4% 4.
2% 9.
2% 5.
```

Nearly 80% have no more than one card!

Fixing the Generator

```
rHand = frequency [(1,return Empty),
                   (4, do c <- rCard
                          h <- rHand
                          return (Add c h))]
```

- Returning Empty 20% of the time gives average hands of 5 cards

```
Main> quickCheck prop_Hand
OK, passed 100 tests.
22% 0.
13% 2.
13% 1.
12% 5.
12% 3.
6% 4.
4% 9.
4% 8.
…
```

Datatype Invariant?

```
prop_Hand h = collect (numCards h) True
```

We're not testing any particular property of Hands

- Are there properties that every hand should have?

Testing Algorithms

Testing insert

- insert x xs—inserts x at the right place in an ordered list

```
Main> insert 3 [1..5]
[1,2,3,3,4,5]
```

- The result should always be ordered

```
prop_insert :: Integer -> [Integer] -> Bool
prop_insert x xs = ordered (insert x xs)
```

Testing insert

```
Main> quickCheck prop_insert
Falsifiable, after 2 tests:
3
[0,1,-1]
```

Of course, the result won't be ordered unless the input is

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

Testing succeeds, but…

Testing insert

- Let's observe the test data…

```
prop_insert :: Integer -> [Integer] -> Property
prop_insert x xs =
    collect (length xs) $
    ordered xs ==> ordered (insert x xs)
```

```
Main> quickCheck prop_insert
OK, passed 100 tests.
41% 0.
38% 1.
14% 2.
6% 3.
1% 5.
```

Why so short???

What's the Probability a Random List is Ordered?

Length	Ordered?
0	100%
1	100%
2	50%
3	17%
4	4%

Generating Ordered Lists

- Generating random lists and choosing ordered ones is silly
- Better to generate ordered lists to begin with—but how?
- One idea:
  - Choose a number for the first element
  - Choose a *positive* number to add to it for the next
  - And so on

The Ordered List Generator

```
orderedList :: Gen [Integer]
orderedList =
  do n <- arbitrary
     listFrom n
  where listFrom n =
          frequency
           [(1, return []),
            (5, do i <- arbitrary
                   ns <- listFrom (n + abs i)
                   return (n:ns))]
```

Trying it

```
Main> sample orderedList
[10,21,29,31,40,49,54,55]
[3,5,5,7,10]
[0,1,2]
[7,7,11,19,28,36,42,51,61]
[]
```

Making QuickCheck use a Custom Generator

- Can't redefine arbitrary: the *type* doesn't say we should use orderedList
- Make a **new type**

A new type

data OrderedList = Ordered [Integer]

with a datatype invariant

Making QuickCheck use a Custom Generator

- Make a **new type**

```
data OrderedList = Ordered [Integer]
  deriving Show
```

- Make an instance of Arbitrary

```
instance Arbitrary OrderedList where
  arbitrary =
    do xs <- orderedList
       return (Ordered xs)
```

Testing insert Correctly

```
prop_insert :: Integer -> OrderedList -> Bool
prop_insert x (Ordered xs) =
    ordered (insert x xs)
```

```
Main> quickCheck prop_insert
OK, passed 100 tests.
```

Collecting Data

```
prop_insert x (Ordered xs) =
    collect (length xs) $
    ordered (insert x xs)
```

```
Main> quickCheck prop_insert
OK, passed 100 tests.
17% 1.
16% 0.
12% 3.
12% 2….
```

Wide variety of lengths

Summary

- We have seen how to generate test data for quickCheck
  - Custom datatypes (Card etc)
  - Custom invariants (ordered lists)
- Seen that **IO A** and **Gen A** are members of the **Monad** class (the class of "instructions")
- Later: how to create our own "instructions" (i.e. creating an instance of Monad)

Reading

- About I/O:
  - Chapter 9 (Hutton)
  - Chapter 18 (Thompson)
- About QuickCheck: read the *manual* linked from the course web page.
  - There are also several research papers about QuickCheck, and advanced tutorial articles.