Generic Generation of Constrained Random Data

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Random data generation: why?

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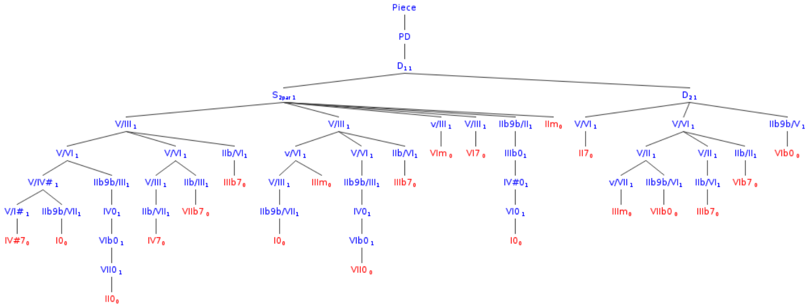

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Being able to generate random data *generically* is useful too:

- Data generators can be tedious to write; if they're generic, we don't have to write them.

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- Data generators can be tedious to write; if they're generic, we don't have to write them.
- Datatypes change, and the code to generate them must change too—unless it's generic.
- Good generators can be hard to get right; they have to take into account the size of the generated terms, ensure a fair distribution, etc. If we do it generically, the hard work is done "once and for all".

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Unfortunately, data generation is very often tied to semantics, especially for complex data:

- Generating sorted lists
- Generating balanced trees
- Generating good exercises (not too easy, not too hard)
- Generating valid programs

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- Generating good exercises (not too easy, not too hard)
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What we need is a hybrid solution, where generic programming does the "boring parts", but still allows us to specify constraints on the shape of the data generated.

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Assuming we can just generically generate random data, we could then simply *filter* the data according to some predicate.

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Assuming we can just generically generate random data, we could then simply *filter* the data according to some predicate.

In practice, however, this can be terribly inefficient, especially if the interesting data is a very small subset of all possible data. So we don't want to take this approach (but see Claessen et al.,"Generating Constrained Random Data with Uniform Distribution" @ FLOPS'14).

Outline

We're aiming at something relatively complicated, so we'll go step-by-step:

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2. Constraining constructor frequency
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4. Constraining constructor count

What we will not see:

- Efficiency concerns
- Nested datatypes, GADTs, etc.

Generic programming support: universe

We need a library for generic programming:

$$
\begin{array}{l}
\textbf{kind}\ \mathit{Univ} = \\
\quad\ \ \mathit{Data\ Symbol\ Univ} \\
\quad \mid \mathit{Con\ Symbol\ Univ} \\
\quad \mid \mathit{Unit} \\
\quad \mid \mathit{K\ ArgType} \star \\
\quad \mid \mathit{Univ} :\times: \mathit{Univ} \\
\quad \mid \mathit{Univ} :+: \mathit{Univ}
\end{array}
$$

$$
\begin{array}{llll}
\multicolumn{4}{l}{\textbf{data}\ [\![\, \upsilon :: \mathit{Univ} \,]\!] :: \star\ \textbf{where}} \\
\quad \mathit{D} & :: [\![\, \upsilon \,]\!] & & \rightarrow [\![\, \mathit{Data}\ \iota\ \upsilon \,]\!] \\
\quad \mathit{C} & :: [\![\, \upsilon \,]\!] & & \rightarrow [\![\, \mathit{Con}\ \iota\ \upsilon \,]\!] \\
\quad \mathit{Unit} & :: & & [\![\, \mathit{Unit} \,]\!] \\
\quad \mathit{K} & :: \alpha & & \rightarrow [\![\, \mathit{K}\ \iota\ \alpha \,]\!] \\
\quad (:\times:) & :: [\![\, \phi \,]\!] & \rightarrow [\![\, \psi \,]\!] & \rightarrow [\![\, \phi :\times: \psi \,]\!] \\
\quad \mathit{Left} & :: [\![\, \phi \,]\!] & & \rightarrow [\![\, \phi :+: \psi \,]\!] \\
\quad \mathit{Right} & :: [\![\, \psi \,]\!] & & \rightarrow [\![\, \phi :+: \psi \,]\!]
\end{array}
$$

$$
\begin{array}{l}
\textbf{kind}\ \mathit{ArgType} = \mathit{Par} \mid \mathit{Rec\ RecType} \mid \mathit{Unknown} \\
\textbf{kind}\ \mathit{RecType} = \mathit{Self} \mid \mathit{Other}
\end{array}
$$

Generic programming support: *to*/*from*

Witnessing the isomorphism between a datatype and its generic representation:

```
class Generic (α :: ⋆) where
  type Rep α :: Univ
  from :: α → ⟦ Rep α ⟧
  to   :: ⟦ Rep α ⟧ → α
```

Generic programming support: *to*/*from*

Witnessing the isomorphism between a datatype and its generic representation:

$$
\begin{array}{l}
\textbf{class}\ \mathit{Generic}\ (\alpha :: \star)\ \textbf{where} \\
\quad \textbf{type}\ \mathit{Rep}\ \alpha :: \mathit{Univ} \\
\quad \mathit{from} :: \alpha \to [\![\, \mathit{Rep}\ \alpha \,]\!] \\
\quad \mathit{to}\ \ \ \ :: [\![\, \mathit{Rep}\ \alpha \,]\!] \to \alpha
\end{array}
$$

For example, lists:

$$
\begin{array}{l}
\textbf{instance}\ \mathit{Generic}\ [\,\alpha\,]\ \textbf{where} \\
\quad \textbf{type}\ \mathit{Rep}\ [\,\alpha\,] = \mathit{Data}\ \texttt{"[]"}\ (\quad \mathit{Con}\ \texttt{"[]"}\ \mathit{Unit} \\
\qquad\qquad\qquad\qquad\qquad\quad :\!+\!:\ \mathit{Con}\ \texttt{":"}\ \ (\quad K\ \mathit{Par}\qquad\quad \alpha \\
\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad :\!\times\!:\ K\ (\mathit{Rec}\ \mathit{Self})\ [\,\alpha\,])) \\
\quad \mathit{from}\ [\,]\qquad\ = D\ (\mathit{Left}\ (C\ \mathit{Unit})) \\
\quad \mathit{from}\ (h : t) = D\ (\mathit{Right}\ (C\ (K\ h :\!\times\!: K\ t))) \\
\quad \mathit{to}\ (D\ (\mathit{Left}\quad (C\ \mathit{Unit})))\qquad\qquad = [\,] \\
\quad \mathit{to}\ (D\ (\mathit{Right}\ (C\ (K\ h :\!\times\!: K\ t)))) = h : t
\end{array}
$$

Section 1

Generic data generation, no constraints

Generic data generation, no constraints: I

We need a user-facing class (just like *Arbitrary*):

```
class Generate α where
  gen :: Gen α
```

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```
class Generate α where
  gen :: Gen α
```

And one to define data generation generically:

```
class GGenerate (υ :: Univ) where
  gGen :: Gen (⟦ υ ⟧)
```

Generic data generation, no constraints: II

Now we can define the generic instances:

```
instance (GGenerate υ) ⇒ GGenerate (Data ι υ) where
  gGen = fmap D gGen
instance (GGenerate φ, GGenerate ψ) ⇒ GGenerate (φ :+: ψ) where
  gGen = choose [fmap Left gGen, fmap Right gGen]
instance (GGenerate υ) ⇒ GGenerate (Con ι υ) where
  gGen = fmap C gGen
instance GGenerate Unit where
  gGen = return Unit
instance (GGenerate φ, GGenerate ψ) ⇒ GGenerate (φ :×: ψ) where
  gGen = (:×:) <$> gGen <∗> gGen
instance (Generate α) ⇒ GGenerate (K ι α) where
  gGen = fmap K gen
```

Generic data generation, no constraints: III

Finally, a generic dispatcher:

$$\begin{array}{l} \mathit{genDefault} :: (\mathit{Generic}\ \alpha, \mathit{GGenerate}\ (\mathit{Rep}\ \alpha)) \Rightarrow \mathit{Gen}\ \alpha \\ \mathit{genDefault} = \mathit{fmap}\ \mathit{to}\ \mathit{gGen} \end{array}$$

Generic data generation, no constraints: III

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And we're ready to generically generate random, unconstrained data.

```
> sample (genDefault :: [Bool])
[]
[True, False, True]
[]
[False]
[]
[True, True]
[]
[False]
```

Section 2

Constructor frequency constraints

Constructor frequency constraints: I

Now let's start considering constraints. First, we want to be able to say that some constructors should occur more/less often than others.

We will need to keep track of some information during generation:

```
data MyState = MyState { envState    :: Env        -- environment
                       , dtNameState :: String }   -- datatype name
type Env     = Map ConLoc ConInfo
type ConLoc  = (String    -- datatype name
               , String)  -- constructor name
data ConInfo = ConInfo { freqInfo :: Int }
```

Constructor frequency constraints: II

We adapt the type of our functions:

$\textbf{class}\ \mathit{Generate}\ \alpha\ \textbf{where}$
$\quad \mathit{gen} :: \mathit{MyState} \rightarrow \mathit{Gen}\ \alpha$

$\textbf{class}\ \mathit{GGenerate}\ (\upsilon :: \mathit{Univ})\ \textbf{where}$
$\quad \mathit{gGen} :: \mathit{MyState} \rightarrow \mathit{Gen}\ (\llbracket\, \upsilon\, \rrbracket)$

Constructor frequency constraints: II

We adapt the type of our functions:

```
class Generate α where
  gen   :: MyState → Gen α
class GGenerate (υ :: Univ) where
  gGen :: MyState → Gen (⟦ υ ⟧)
```

And each of the generic cases:

```
instance (SingI ι, GGenerate υ) ⇒ GGenerate (Data ι υ) where
  gGen s = fmap D (gGen (s { dtNameState = fromSing (sing :: Sing ι) }))
instance (GGenerate υ) ⇒ GGenerate (Con ι υ) where
  gGen = fmap C ∘ gGen
instance GGenerate Unit where
  gGen _ = return Unit
instance (GGenerate φ, GGenerate ψ) ⇒ GGenerate (φ :×: ψ) where
  gGen s = (:×:) <$> gGen s <*> gGen s
instance (Generate α) ⇒ GGenerate (K ι α) where
  gGen = fmap K ∘ gen
```

Constructor frequency constraints: III

The interesting case is that of sums:

```
instance (GGenerate α, GConNames α
         , GGenerate β, GConNames β) ⇒ GGenerate (α :+: β) where
  gGen s = let aNames = gconNames (Proxy :: Proxy (⟦ α ⟧))
               bNames = gconNames (Proxy :: Proxy (⟦ β ⟧))
               dtName = dtNameState s
               env    = envState s
               aFreq  = frequencies aNames dtName env
               bFreq  = frequencies bNames dtName env
           in frequency [( aFreq, fmap Left  (gGen s))
                        ,( bFreq, fmap Right (gGen s))]

frequencies :: [String] → String → Env → Int
frequencies []       _      _   = 0
frequencies (s : ss) dtName env =
  let freqS = maybe 1 freqInfo (lookup (dtName, s) env)
  in freqS + frequencies ss dtName env

frequency :: [(Int, Gen α)] → Gen α
```

Constructor frequency constraints: IV

We need to be able to collect the names of all constructors of a datatype:

$$
\begin{array}{l}
\textbf{data}\ \mathit{Proxy}\ \alpha = \mathit{Proxy} \\
\textbf{class}\ \mathit{GConNames}\ (\upsilon :: \mathit{Univ})\ \textbf{where} \\
\quad \mathit{gconNames} :: \mathit{Proxy}\ (\llbracket\ \upsilon\ \rrbracket) \to [\mathit{String}] \\
\textbf{instance}\ (\mathit{GConNames}\ \upsilon) \Rightarrow \mathit{GConNames}\ (\mathit{Data}\ \iota\ \upsilon)\ \textbf{where} \\
\quad \mathit{gconNames}\ \_ = \mathit{gconNames}\ (\mathit{Proxy} :: \mathit{Proxy}\ (\llbracket\ \upsilon\ \rrbracket)) \\
\textbf{instance}\ (\mathit{GConNames}\ \phi, \mathit{GConNames}\ \psi) \Rightarrow \mathit{GConNames}\ (\phi :+: \psi)\ \textbf{where} \\
\quad \mathit{gconNames}\ \_ = \quad\ \mathit{gconNames}\ (\mathit{Proxy} :: \mathit{Proxy}\ (\llbracket\ \phi\ \rrbracket)) \\
\qquad\qquad\qquad\quad +\!\!+ \mathit{gconNames}\ (\mathit{Proxy} :: \mathit{Proxy}\ (\llbracket\ \psi\ \rrbracket)) \\
\textbf{instance}\ (\mathit{SingI}\ \iota) \Rightarrow \mathit{GConNames}\ (\mathit{Con}\ \iota\ \upsilon)\ \textbf{where} \\
\quad \mathit{gconNames}\ \_ = [\mathit{fromSing}\ (\mathit{sing} :: \mathit{Sing}\ \iota)] \\
\\
\textbf{class}\ \mathit{ConNames}\ (\alpha :: \star)\ \textbf{where} \\
\quad \mathit{conNames} :: \mathit{Proxy}\ \alpha \to [\mathit{String}]
\end{array}
$$

Constructor frequency constraints: V

Now we can constrain constructor frequency!

```
data Choice = A | B | C | D

testChoice :: IO ()
testChoice = let s      = MyState (fromList reqEnv) ""
                 reqEnv = [(("Choice","A"), ConInfo 1)
                          ,(("Choice","B"), ConInfo 2)
                          ,(("Choice","C"), ConInfo 3)
                          ,(("Choice","D"), ConInfo 4)]
             in testM (genDefault s :: Gen Choice) 1000 >>= mapM_ print

testM :: Gen α → Int → IO [(Int, α)]
  -- takes a generator, generates n samples, groups them
```

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testM :: Gen α → Int → IO [(Int, α)]
  -- takes a generator, generates n samples, groups them

> testChoice
(99,  A)
(212, B)
(314, C)
(376, D)
```

Constructor frequency constraints: VI

We can even forbid certain constructors, and (indirectly) influence size:

```
testListBool :: IO ()
testListBool = let s      = MyState (fromList reqEnv) ""
                   reqEnv = [(("Bool","True")  , ConInfo 1)
                            ,(("Bool","False"), ConInfo 0)
                            ,(("[]",":")       , ConInfo 3)
                            ,(("[]","[]")      , ConInfo 1)]
               in testM (genDefault s :: Gen [Bool]) 10 >>= mapM_ print
```

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                            ,(("Bool","False"), ConInfo 0)
                            ,(("[]",":")      , ConInfo 3)
                            ,(("[]","[]")     , ConInfo 1)]
               in testM (genDefault s :: Gen [Bool]) 10 >>= mapM_ print
```

```
> testListBool
(3,[])
(3,[True])
(1,[True, True])
(1,[True, True, True])
(3,[True, True, True, True])
```

Section 3

Size and order constraints

Size and order constraints: I

Another type of constraint is enforcing *order* on the *size* of a specific argument to a constructor. We will need to carry more state:

```
data MyState = MyState { envState      :: Env
                       , dtNameState   :: String
                       , ctNameState   :: String    -- constructor name
                       , argIndexState :: Int }     -- argument index

type Env     = Map ConLoc ConInfo

type ConLoc  = (String,String)
type ArgLoc  = Int

data ConInfo = ConInfo { freqInfo :: Int
                       , argInfo  :: Map ArgLoc ArgInfo }

data ArgInfo = ArgInfo { ordInfo :: Ordering    -- ordering
                       , sizeInfo :: Int }       -- size
```

Size and order constraints: I

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                       , argInfo  :: Map ArgLoc ArgInfo }
data ArgInfo = ArgInfo { ordInfo :: Ordering   -- ordering
                       , sizeInfo :: Int }     -- size
```

. . . and now we'll have to update the state during generation!

Size and order constraints: II

Our generator now behaves like a state monad:

$\textbf{class}\ \mathit{Generate}\ \alpha\ \textbf{where}$
$\quad \mathit{gen}\ \ :: \mathit{MyState} \rightarrow (\mathit{Gen}\ \alpha, \mathit{MyState})$

$\textbf{class}\ \mathit{GGenerate}\ (\upsilon :: \mathit{Univ})\ \textbf{where}$
$\quad \mathit{gGen} :: \mathit{MyState} \rightarrow (\mathit{Gen}\ (\llbracket\, \upsilon\, \rrbracket), \mathit{MyState})$

At every step, we might change the state, returning an updated version.

Size and order constraints: III

The important changes are in the case for constructor arguments:

```
instance (Elements α, Generate α) ⇒ GGenerate (K ι α) where
  gGen s = let info       = ...   -- lookups
               arg o i    = (elements (elems i), next o i)
               next EQ    = id
               next GT    = pred
               next LT    = succ
           in case info of
               Nothing      → fmapL K (gen s)
               Just (ai, ci) → let (e, i) = arg (ordInfo ai) (sizeInfo ai)
                               in (fmap K e, updSize s i)
```

```
fmapL    :: (α → β) → (α,γ) → (β,γ)
updSize  :: MyState → Int → MyState
elements :: [α] → Gen α
```

Size and order constraints: IV

Generation of elements constrained by size is best done by *enumeration*. Here's a naive generic enumerator:

```
class GElements (υ :: Univ) where
  gelements :: Int → [ ⟦ υ ⟧ ]
instance GElements Unit where
  gelements 0 = [ Unit ]
  gelements _ = []
instance (GElements α, GElements β) ⇒ GElements (α :+: β) where
  gelements n = map Left (gelements n) ++ map Right (gelements n)
instance (Elements α) ⇒ GElements (K ι α) where
  gelements n = map K (elements n)
```

Size and order constraints: V

For products, we consider all possible size distributions:

```
instance (GElements α, GElements β) ⇒ GElements (α :×: β) where
   gelements n = [l :×: r | (a,b) ← split n
                          , l     ← gelements a
                          , r     ← gelements b]

split :: Int → [(Int,Int)]
split n = [(a,n − a) | a ← [0 . . n]]
```

As usual, we provide a user-facing class, and instances for base types:

```
class Elements α where
   elements :: Int → [α]

instance Elements Bool where
   elements 1 = [False, True]
   elements _ = []
```

Size and order constraints: VI

Now we can generate lists of lists of increasing or decreasing length, for example:

```
-- increasing
[[],[False],[True,False],[True,False,False],[True,False,False,False]]
-- decreasing
[[True,True,False,True],[False,False,True],[True,False]]
-- equal
[[False,True],[False,False],[True,False],[True,False],[False,True]]
```

And we can still provide constructor probabilities!

Size and order constraints: VI

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[[False,True],[False,False],[True,False],[True,False],[False,True]]
```

And we can still provide constructor probabilities!

Question: how about constraining the order of the arguments themselves, so we can produce *sorted* lists? It's slightly trickier. . .

Section 4

Constructor count constraints

Constructor count constraints: I

Finally, let us try to constrain constructors to occur a *minimum* or *maximum* number of times:

```
data MyState = MyState { envState      :: Env
                       , dtNameState   :: String
                       , ctNameState   :: String
                       , argIndexState :: Int }

type Env     = Map ConLoc ConInfo

data ConInfo = ConInfo { freqInfo :: Int
                       , minInfo  :: Int   -- minimum count
                       , maxInfo  :: Int   -- maximum count
                       , argInfo  :: Map ArgLoc ArgInfo }
```

Constructor count constraints: II

The interesting case is at the sum. We assume right-nesting, so there's one argument to the left of a sum, and (potentially) multiple to the right:

```
instance (GGenerate α, GConNames α
         , GGenerate β, GConNames β) ⇒ GGenerate (α :+: β) where
  gGen s =
    let aNames = ...
        dir = pickLR (dtNameState s) aNames bNames (envState s)
        aFreq = if dir ≡ GoRight then 0 else frequencies ...
        bFreq = if dir ≡ GoLeft  then 0 else frequencies ...
        (genL, sL) = fmapL Left  (gGen s)
        (genR, sR) = fmapL Right (gGen s)
    in (frequency [(aFreq, genL), (bFreq, genR)], s)   -- s?
```

Constructor count constraints: III

For each constructor, we'll check whether we should or shouldn't produce it:

```
data CanGo = Yes | No | DontCare

instance Monoid CanGo where
  mempty = DontCare

  mappend DontCare x        = x
  mappend x        DontCare = x
  mappend No       _        = No
  mappend _        No       = No
  mappend Yes      Yes      = Yes
```

Constructor count constraints: IV

We use this information to decide whether to go left or right:

```
data Dir = GoLeft | GoRight | DoesntMatter
pickLR :: String → [String] → [String] → Env → Dir
pickLR dn cnsL cnsR env =
  let goHere cn = case lookup (dn, cn) env of
                    Nothing → DontCare
                    Just i  → if maxInfo i ≡ 0 then No
                              else if minInfo i > 0 then Yes
                                   else DontCare
  in case (mconcat (map goHere cnsL), mconcat (map goHere cnsR)) of
     (No, No) → DoesntMatter
     (Yes, _) → GoLeft
     (No, _)  → GoRight
     _        → if any (≡ Yes) (map goHere cnsR) then GoRight
                else if all (≡ No) (map goHere cnsR) then GoLeft
                     else DoesntMatter
```

Constructor count constraints: V

Now we can generate lists of length between 3 and 7 without *False*s:

[*True*, *True*, *True*]
[*True*, *True*, *True*, *True*, *True*]
[*True*, *True*, *True*, *True*]

Constructor count constraints: V

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. . . but a number of problems remain:

- We're too eager to reach the requested minimum; if we request lists with a minimum of one [], we only generate empty lists.

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- It doesn't really work on types like [[*Int*]]

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. . . but a number of problems remain:

- We're too eager to reach the requested minimum; if we request lists with a minimum of one [], we only generate empty lists.
- It doesn't really work on types like [[*Int*]]
- . . . or on mutually recursive types in general:

data $A = A_1\ B\ B \mid A_2\ B$
data $B = B_1$

Section 5

Conclusion

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We've seen a first attempt at generic generation of constrained random data, with a number of limitations:

- How to distinguish the inner and outer constructors of a type such as $[[\mathit{Int}]]$?

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We've seen a first attempt at generic generation of constrained random data, with a number of limitations:

- How to distinguish the inner and outer constructors of a type such as $[[Int]]$?
- Backtracking?

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- Other types of constraints