Functional Programming

SS 2023

Torsten Grust
University of Tübingen

Haskell Ramp-Up (Part 2)

- Haskell's system of types is extensible. Users may
    - introduce synonyms for existing types (using keyword `type`)

      or

    - define entirely new types (using keywords `newtype` and `data`).
- We are focusing on `data` and **algebraic data types** now.

Algebraic Data Types (Sum-of-Product Types)

- Recall: `[]` and `(:)` are the value constructors for type `[a]`.
- We can define an entirely new type T and its constructors K_i:

```
data T a₁ a₂ … aₙ = K₁ b₁₁ … b₁₍ₙ₁₎
                  | K₂ b₂₁ … b₂₍ₙ₂₎
                  ⋮
                  | Kᵣ bᵣ₁ … bᵣ₍ₙᵣ₎
```

  - Defines **type constructor** T and r **value constructors** K_i ($1 \leqslant i \leqslant r$) with types

```
Kᵢ :: bᵢ₁ -> … -> bᵢ₍ₙᵢ₎ -> T a₁ a₂ … aₙ
```

K_i: identifier with uppercase first letter or symbol starting with a colon (`:`).

Algebraic Data Types can be Sum Types

- Example (**sum type**, or: enumeration, choice):
  no value constructor has any argument (all n_i = 0).

File: weekday.hs

```
-- A sum type (enumeration)

data Weekday = Mon | Tue | Wed | Thu | Fri | Sat | Sun

-- Is this day on a weekend?
weekend :: Weekday -> Bool
weekend Sat = True
weekend Sun = True
weekend _   = False

main :: IO ()
main = print (weekend Thu, weekend Sat)
```

Algebraic Data Types (deriving)

- Add `deriving (c, c, …)` to `data` declaration to define canonical operations for the new data type:

c (class)	operations
Eq	equality (==, /=)
Show	printing (show)
Ord	ordering (<, <=, max, …)
Enum	enumeration ([x..y], …)
Bounded	bounds (minBound, maxBound)

Algebraic Data Types can be Product Types

- Example (**product type**):
  r = 1 (single constructor), with n_1 = 2 (pair).

File: sequence.hs

```
-- A product type (single constructor)

data Sequence a = S Int [a]
  deriving (Eq, Show)

fromList :: [a] -> Sequence a
fromList xs = S (length xs) xs

(+++) :: Sequence a -> Sequence a -> Sequence a
S lx xs +++ S ly ys = S (lx + ly) (xs ++ ys)

len :: Sequence a -> Int
len (S l _) = l

main :: IO ()
main = print $ len (fromList ['a'..'m'] +++ fromList ['n'..'z'])
```

Algebraic Data Types in General: Sum of Product Types

- Examples (**sum-of-product types**):

```
data Maybe a = Nothing                   -- "optional a"
             | Just a


data Either a b = Left a                 -- "either a or b"
                | Right b


data List a = Nil                        -- "list of a" (recursive ⚠)
            | Cons a (List a)
```

Types [a] and List a are Isomorphic

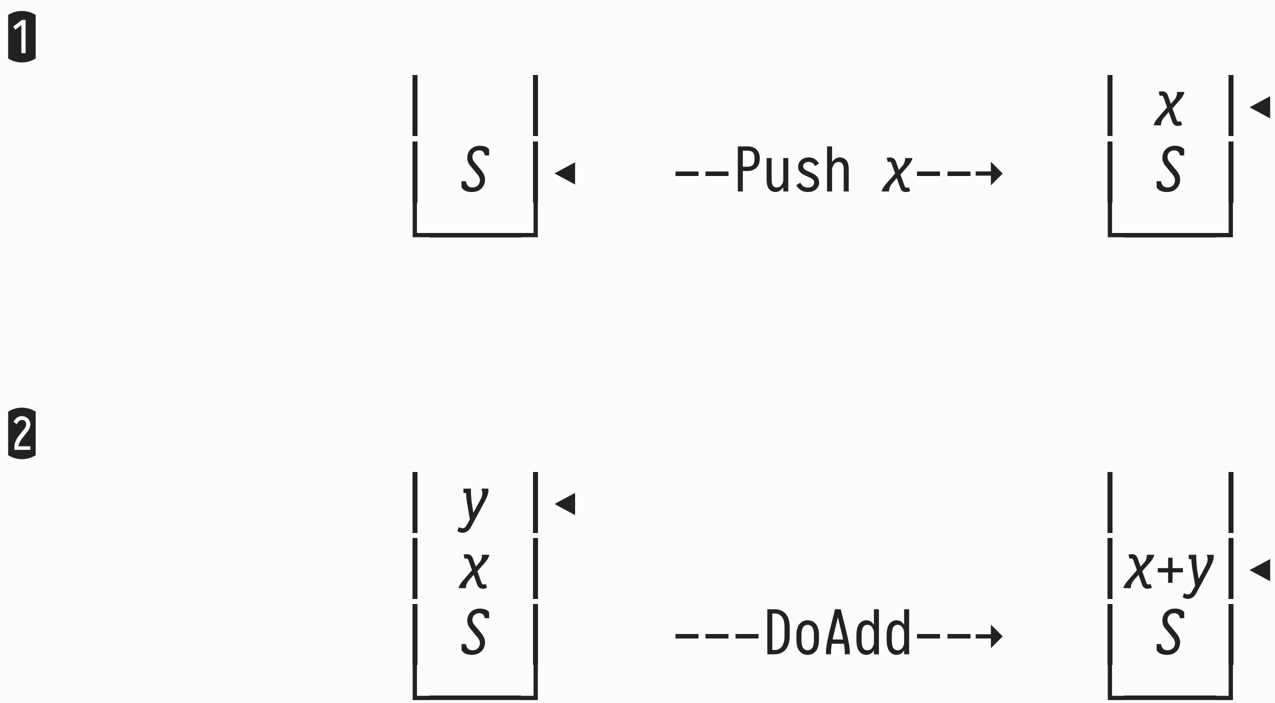
- The built-in list type [a] is not special.

  Our own sum-of-product type List a has the same structure and can fully replace [a]:

$$
\begin{tikzcd}
\texttt{List a} \arrow[r, "\texttt{fromList}"] \arrow[d, "g"'] \arrow[dr, phantom, "."] & \texttt{[a]} \arrow[d, "f"] \\
\texttt{List b} & \texttt{[b]} \arrow[l, "\texttt{toList}"]
\end{tikzcd}
\qquad\qquad g \equiv \texttt{toList} \;.\; f \;.\; \texttt{fromList}
$$

A Super-Simple Stack Machine

- Operations Push and DoAdd act on the machine's stack (S denotes arbitrary stack contents, ◂ is the top of the stack):



- Once all operations have been processed, the top of the stack holds the answer of the machine.

Type Classes

- Haskell's type system implements **type classes**, the instances of which implement a common set of operations, each in a type-specific fashion.

  Type classes allow for **ad-hoc polymorphism** (or **overloading**).

- **Example:** We want to express equality for all sorts of types (`Int`, `String`, `(a,b)`, `[a]`, `Exp a`):

  1. Want to continue to use the single symbol `==` (not `eqInt`, `eqString`, ...).
  2. Obviously, the type-specific implementations of `==` need to differ.
  3. Some types may not be able to implement `==` at all (consider `a -> b`).

Type Classes

- A **type class** C defines a family of n functions f_i ("methods") which all **instances** of C must implement:

```
class C a where                    -- class name C: Uppercase
  f₁ :: t₁
       ⋮
  fₙ :: tₙ
```

  - Read: "*If type a is an instance of C, then all methods f_i are implemented for a.*"
  - The types t_i *must* mention type a.
  - For any f_i, the class may provide a **default** definition (that instances may overwrite).

Type Classes

- **Example** (type class `Eq` defines what it means for type `a` to support equality comparisons):

```
class  Eq a  where
   (==) :: a -> a -> Bool
   (/=) :: a -> a -> Bool

   x /= y = not (x == y)     -- default definitions
   x == y = not (x /= y)
```

  - If type `a` wants to support equality (*i.e.*, be a member of class `Eq`), defining either `==` or `/=` suffices.

Type Classes: Class Constraints

- A **class constraint**

$$e :: \underbrace{C\ a}^{\textbf{class constraint}} \Rightarrow t$$
$$e = \cdots$$

(where t mentions a) says that expression e has type t *only if* type a is an instance of class C.

$\Longrightarrow$ In the definition of e (here: $\cdots$) we may use the methods of class C on values of type a.

Type Classes: Class Inheritance

- Defining

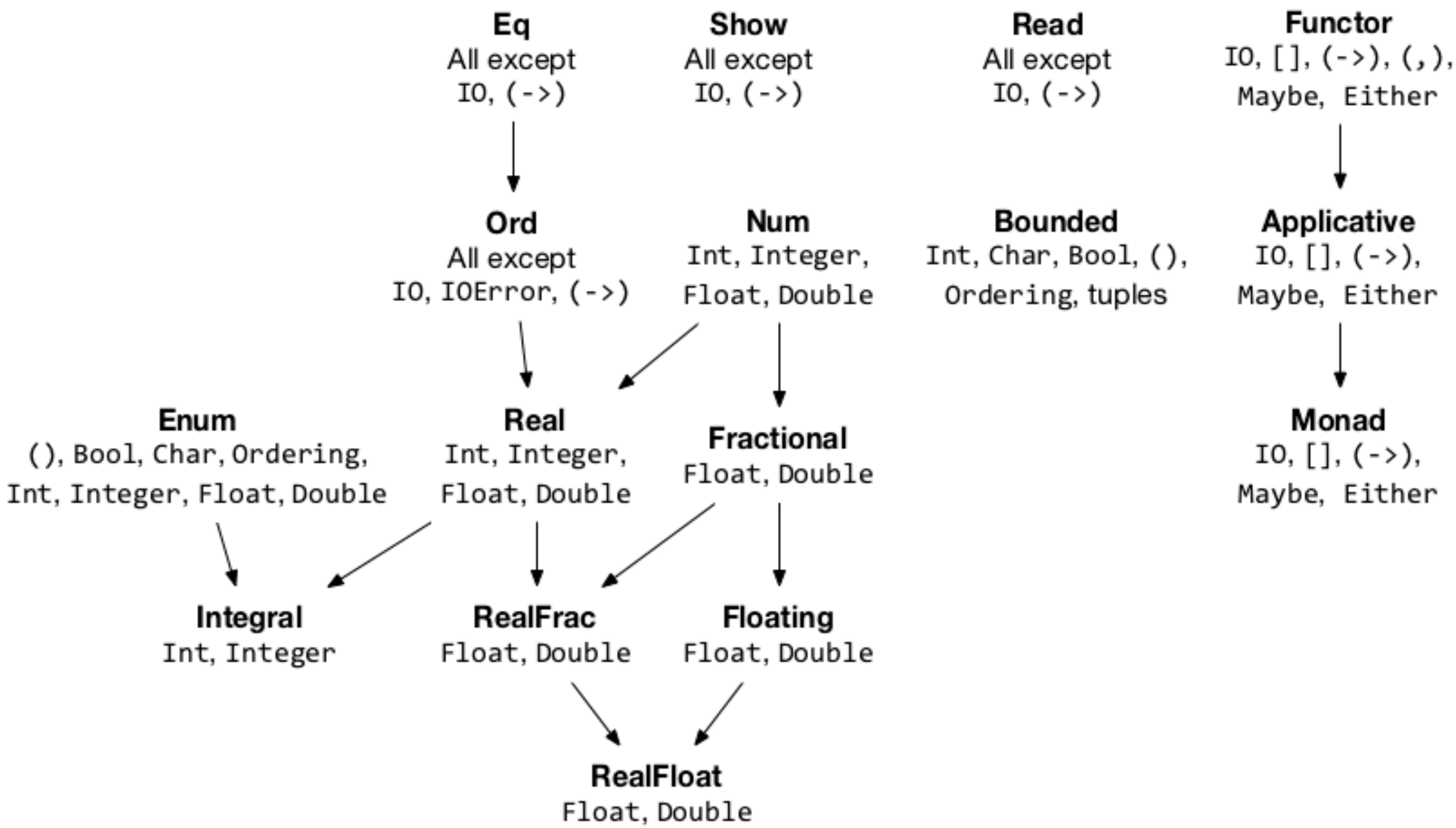
```
class (C₁ a, C₂ a, …) => C a where …
```

makes type class C a **subclass** of the classes C_i. C inherits all C_i methods.

  - The class constraint `C a => t` thus implies the larger constraint `(C₁ a, C₂ a, …, C a) => t`:

    Writing the type `f :: Ord a => a -> a -> Bool` abbreviates `f :: (Eq a, Ord a) => a -> a -> Bool` and function `f` may, e.g., use `<=` as well as `==` on values of type `a`.

Type Classes: Class Inheritance



Inheritance of standard Haskell type classes (⟶ ≡ superclass of)

Type Classes: Class Instances

- Now: Define type-specific behavior for the class methods (⇒ **overloading**).

- Implementing all methods of class C makes t an **instance** of C:

```
instance  C t  where
  f₁ = ‹def of f₁›      -- all fᵢ may be provided, minimal
     ⋮                  --   complete definition must be provided
  fₙ = ‹def of fₙ›      -- types must match definition of C
```

  - Class constraint C t is satisfied from now on.

- **Example:**

```
instance Eq Bool where
    x == y = (x && y) || (not x && not y)
```

Type Classes: Class Instances

- An instance definition for **type constructor** *t* may formulate type constraints for its argument types *a*, *b*, ...:

```
instance (C₁ a, C₂ a, C₃ b, …) => C (t a b …) where
  …
```

- **Example:**

```
-- print sequences as «3|[10,20,30]»
instance (Show a) => Show (Sequence a) where
  show (Sequence l xs) = "«" ++ show l ++ "|" ++ show xs ++ "»"
```

  - ⚠️ This makes use of two other `Show` instances:
    1. `instance Show Int`
    2. `instance (Show a) => Show [a]`

Type Classes: Deriving Class Instances

- Automatically make user-defined data types (data ...) instances of classes $C_i \in$ {Eq, Ord, Enum, Bounded, Show, Read}:

```
data T a₁ a₂ … aₙ = …        -- } regular algebraic
                  | …        -- } data type definition
  deriving (C₁, C₂, …)
```

C	Semantics of derived instance
Eq	for all sum-of-prod types, equality of constructors, recursive equality of components
Ord	for all sum-of-prod types, lexicographic ordering of constructors in data definition
Enum	only for sum types, nth constructor mapped to n-1
Bounded	only for sum types, minBound/maxBound ≡ first/last constructor
Show	show generates syntactically correct Haskell presentation
Read	read reads string generated by Show instance