

Comparing Approaches to Generic Programming in Haskell

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Abstract. The last decade has seen a number of approaches to datatype-generic programming: PolyP, Functorial ML, ‘Scrap Your Boilerplate’, Generic Haskell, ‘Generics for the Masses’, etc. The approaches vary in sophistication and target audience: some propose full-blown programming languages, some suggest libraries, some can be seen as categorical programming methods. In these lecture notes we compare the various approaches to datatype-generic programming in Haskell. We introduce each approach by means of example, and we evaluate it along different dimensions (expressivity, ease of use, etc).

1 Introduction

You just started implementing your third web shop in Haskell, and realize that a lot of the code you have to write is similar to the code for the previous web shops. Only the data types have changed. Unfortunately, this implies that all reporting, editing, storing and loading in the database functionality, and probably a lot more, has to be changed. You’ve heard about generic programming, a technique which can be used to automatically generate programs depending on types. But searching on the web gives you almost ten approaches to solve your problem: DrIFT, PolyP, Generic Haskell, Derivable Type Classes, Template Haskell, Scrap Your Boilerplate, Generics for the Masses, Strafunski, etc. How do you choose?

In these lecture notes we give arguments why you would choose for a particular approach to generic programming in Haskell to solve your generic programming problem. We compare different approaches to generic programming along different lines, such as for example:

- Can you use generic programs on all types definable in the programming language?
- Are generic programs compiled or interpreted?
- Can you extend a generic program in a special way for a particular data type?

Before we compare the various approaches to generic programming we first discuss in detail the criteria on which the comparison is based.

‘Generic’ is an over-used adjective in computing science in general, and in programming languages in particular. Ada has generic packages, Java has generics, Eiffel has generic classes, etc. Usually, the adjective generic is used to describe that a concept allows abstractions over a larger class of entities than was previously possible. However, broadly speaking most uses of generic refer to some form of parametric polymorphism, ad-hoc polymorphism, and/or inheritance. For a nice comparison of the different incarnations of generic concepts in different programming languages, see Garcia et al [21]. Already in the 1970s this was an active area of research [75, 57, 18].

In the context of these lecture notes, generic programming means a form of programming in which a function takes a type as argument, and its behavior depends upon the *structure* of this type. The type argument, which may be explicit or implicit, represents the type of values to which the function is applied, or which the function returns. Backhouse and Gibbons [10, 22] call this kind of generic programming *datatype-generic* programming. A typical example is the equality function, where a type argument t dictates the form of the code that performs the equality test on two values of type t . In the past we have used the term ‘*polytypic*’ instead of ‘generic’, which is less confusing and describes the concept a bit more accurate. However, the term hasn’t been picked up by other people working on conceptually the same topic, and maybe it sounds a bit scary.

The first programming languages with facilities for generic programming, beyond generating the definition of equality on user-defined data types, were Charity [16], and Haskell [72]. Since then Haskell has been the most popular testbed for generic-programming language extensions or libraries. Here is a probably incomplete list of approaches to generic programming in Haskell or based upon Haskell:

- Generic Haskell [26, 29, 61, 63].
- DrIFT [81].
- PolyP [42].
- Derivable Type Classes [35].
- Light-weight Generics and Dynamics [14].
- Scrap Your Boilerplate [54, 56, 55, 38, 37].
- Generics for the masses [30, 71].
- Clean [3, 2]. (Clean is not Haskell, but it is sufficiently close to be listed here.)
- Using Template Haskell for generic programming [70].
- Strafinski [53].
- Generic programming, Now! [36]

Although Haskell has been the most popular testbed for generic-programming extensions, many non-Haskell approaches to generic programming have been designed:

- Charity [16].

- ML [13, 20].
- Intensional type analysis [25, 17, 79].
- Extensional type analysis [19].
- Functorial ML [49, 68], the Constructor Calculus [46], the Pattern Calculus [47, 48], FISh [45].
- Dependently-typed generic programming [6, 11].
- Type-directed programming in Java [80].
- Maude [64].

We have tried to be as complete as possible, but certainly this list is not exhaustive.

In these lecture notes we compare most of the approaches to generic programming in Haskell or based upon Haskell. We do not include Strafunski and Generic programming, Now! in our comparison. Strafunski is rather similar to Scrap Your Boilerplate, and Generic programming, Now! is an advanced variant of the light-weight approaches we will discuss. Besides that, it is included in these lecture notes, and itself contains a comparison to other approaches to generic programming. In future work we hope to also compare approaches to generic programming in other programming languages.

Types play a fundamental rôle in generic programming. In an untyped or dynamically typed language, it is possible to define functions that adapt to many data structures, and one could therefore argue that it is much easier to do generic programming in these languages. We strongly disagree: since generic programming is fundamentally about programming with types, simulating generic programming in an untyped language is difficult, since the concept of types and the accompanying checks and guidance are missing. Generic programs are often complex, and feedback from the type system is invaluable in their construction. This difficulty can also be observed in our treatment of DrIFT and Template Haskell, both approaches with only limited support from the type system.

We introduce each approach to generic programming by means of a number of, more or less, canonical examples. This set of examples has been obtained by collecting the generic functions defined in almost 20 papers introducing the various approaches to generic programming. Almost all of these papers contain at least one function from the following list:

- *encode*, a function that encodes a value of any type as a list of bits. The function *encode* is a simple recursive function which ‘deconstructs’ a value of a data type into a list of bits.
- The inverse of *encode*, called *decode*, is a function which *builds* a value of a data type from a list of bits.
- *eq*, a function that takes *two* values, and compares them for equality.
- *map*, a generalization of the standard *map* function on lists. On a parameterized data type, such as lists, function *map* takes a function argument and a value of the data type, and applies the function argument to all parametric values inside the value argument. The function *map* is particularly useful when applied to type constructors, i.e., parameterized data types such as lists or trees.

- *show*, a function that shows or pretty-prints a value of a data type.
- *update*, a function that takes a value of a data type representing the structure of a company, and updates the salaries that appear in this value. The characterizing feature of this example is that *update* is only interested in values of a very small part of a possibly very large type.

The above functions all exhibit different characteristics, which we use to show differences between approaches to generic programming. We do not define all of these functions for each approach, in particular not for approaches that are very similar, but we use these examples to highlight salient points. We then investigate a number of properties for each approach. Examples of these properties are: is it possible to define a generic function on any data type that can be defined in the programming language (full reflexivity), is the programming language type safe, do generic functions satisfy desirable properties, etc. Sometimes we use examples beyond the above functions to better highlight specifics and peculiarities of a certain approach.

These notes are organized as follows. In Section 2 we discuss why generic programming matters by means of a couple of representative examples. We use these examples in Section 4 to compare the various approaches to generic programming by means of the criteria introduced and discussed in Section 3. Section 5 concludes.

2 Why generic programming matters

Software development often consists of designing a data type, to which functionality is added. Some functionality is data type specific, other functionality is defined on almost all data types, and only depends on the type structure of the data type. Examples of generic functionality defined on almost all data types are storing a value in a database, editing a value, comparing two values for equality, pretty-printing a value, etc. A function that works on many data types is called a generic function. Applications of generic programming can be found not just in the rather small programming examples mentioned, but also in

- XML tools such as XML compressors [32], and type-safe XML data binding tools [7];
- automatic testing [52];
- constructing ‘boilerplate’ code that traverses a value of a rich set of mutually-recursive data types, applying real functionality at a small portion of the data type [54, 61, 55];
- structure editors such as XML editors [24], and generic graphical user interfaces [1];
- data-conversion tools [44] which for example store a data type value in a database [24], or output it as XML, or in a binary format [77].

Change is endemic to any large software system. Business, technology, and organization frequently change during the life cycle of a software system. However, changing a large software system is difficult: localizing the code that is

responsible for a particular part of the functionality of a system, changing it, and ensuring that the change does not lead to inconsistencies in other parts of the system or in the architecture or documentation is usually a challenging task. *Software evolution* is a fact of life in the software-development industry [58, 59, 73].

If a data type changes, or a new data type is added to a piece of software, a generic program automatically adapts to the changed or new data type. An example is a generic program for calculating the total amount of salaries paid by an organization. If the structure of the organization changes, for example by removing or adding an organizational layer, the generic program still calculates the total amount of salaries paid. Since a generic program automatically adapts to changes of data types, a programmer only has to program ‘the exception’. Generic programming has the potential to solve at least an important part of the software-evolution problem [51].

In the rest of this section we show a number of examples of generic programs. We write the generic programs in Generic Haskell [26, 33, 60]. Generic Haskell is an extension of the lazy, higher-order, functional-programming language Haskell [72] that supports generic programming. Any of the other approaches to generic programming could have been chosen for the following exposition. We choose Generic Haskell simply because we have to start somewhere, and because we are responsible for the development of Generic Haskell. We use the most recent version of Generic Haskell, known as *Dependency-style Generic Haskell* [61, 60]. Dependencies both simplify and increase the expressiveness of generic programming. In Section 4 we show how these programs are written in other approaches to generic programming.

2.1 Data types in Haskell

The functional-programming language Haskell 98 provides an elegant and compact notation for declaring data types. In general, a data type introduces a number of constructors, where each constructor takes a number of arguments. Here are two example data types:

```
data CharList = Nil | Cons Char CharList
data Tree     = Empty | Leaf Int | Bin Tree Char Tree.
```

A character list, a value of type `CharList`, is often called a *string*. It is either empty, denoted by the constructor `Nil`, or it is a character `c` followed by the remainder of the character list `cs`, denoted `Cons c cs`, where `Cons` is the constructor. A tree, a value of type `Tree`, is empty, a leaf containing an integer, or a binary node containing two subtrees and a character.

These example types are of kind \star , meaning that they do not take any type arguments. A kind can be seen as the ‘type of a type’. The following type takes an argument; it is obtained by abstracting `Char` out of the `CharList` data type above:

```
data List a = Nil | Cons a (List a).
```

Here `List` is a type constructor, which, when given a type `a`, constructs the type `List a`. The type constructor `List` has the functional kind $\star \rightarrow \star$. The list data type is predefined in Haskell: the type `List a` is written `[a]`, the constructors `Nil` and `Cons x xs` are written `[]` and `x:xs`, respectively. A type can take more than one argument. If we abstract from the types `Char` and `Int` in the type `Tree`, we obtain the type `GTree` defined by:

data `GTree a b` = `GEmpty` | `GLeaf a` | `GBin` (`GTree a b`) `b` (`GTree a b`).

The type constructor `GTree` takes two type arguments, both of kind \star , and hence has kind $\star \rightarrow \star \rightarrow \star$.

Arguments of type constructors need not be of kind \star . Consider the data type of Rose trees, defined by:

data `Rose a` = `Node a` [`Rose a`].

A Rose tree is a `Node` containing an element of type `a`, and a list of child trees. Just as `List`, `Rose` has kind $\star \rightarrow \star$. If we abstract from the list type in `Rose`, we obtain the data type `GRose` defined by:

data `GRose f a` = `GNode a` (`f` (`GRose f a`)).

Here the type argument `f` has kind $\star \rightarrow \star$, just as the `List` type constructor, and it follows that `GRose` has kind $(\star \rightarrow \star) \rightarrow \star \rightarrow \star$.

All the examples of data types we have given until now are examples of so-called *regular* data types: a recursive, parametrized type whose recursive definition does not involve a change of the type parameter(s). Non-regular or *nested* types [12] are practically important since they can capture data-structural invariants in a way that regular data types cannot. For instance, the following data-type declaration defines a nested data type: the type of perfectly-balanced, binary leaf trees [27] – perfect trees for short.

data `Perfect a` = `ZeroP a` | `SuccP` (`Perfect` (`Fork a`))
data `Fork a` = `Fork a a`

This equation can be seen as a bottom-up definition of perfect trees: a perfect tree is either a singleton tree or a perfect tree that contains pairs of elements. Here is a perfect tree of type `Perfect Int`:

`SuccP (SuccP (SuccP (ZeroP (Fork (Fork (Fork 2 3)`
`(Fork 5 7))`
`(Fork (Fork 11 13)`
`(Fork 17 19)))))))).`

Note that the height of the perfect tree is encoded in the prefix of `SuccP` and `ZeroP` constructors.

2.2 Structure-representation types

To apply functions generically to all data types, we view data types in a uniform manner: every Haskell data type can be viewed as a labeled sum of possibly labeled products. This encoding is based on the following data types:

```

data a :+: b = Inl a | Inr b
data a :*: b = a :*: b
data Unit   = Unit
data Con a   = Con ConDescr a
data Label a = Label LabelDescr a.

```

The choice between *Nil* and *Cons*, for example, is encoded as a sum using the type `:+:` (nested to the right if there are more than two constructors). The constructors of a data type are encoded as sum labels, represented by the type `Con`, which contains a description of a constructor in the form of a value of type `ConDescr`. The constructors *Nil* and *Cons* are represented by `ConDescr` values *nilDescr* and *consDescr*, respectively. The exact details of how constructors are represented are omitted. Record names are encoded as product labels, represented by a value of the type `Label`, which contains a value of type `LabelDescr`. Arguments such as the `a` and `List a` of the *Cons* are encoded as products using the type `:*` (nested to the right if there are more than two arguments). In the case of *Nil*, an empty product, denoted by `Unit`, is used. The arguments of the constructors are not translated. Finally, abstract types and primitive types such as `Char` are not encoded, but left as they are.

Now we can encode `CharList`, `Tree`, and `List` as

```

type CharList° = Con Unit :+: Con (Char :*: CharList)
type Tree°     = Con Unit :+: Con Int :+: Con (Tree :*: (Char :*: Tree))
type List° a    = Con Unit :+: Con (a :*: (List a)).

```

These representations are called *structure-representation types*. A structure-representation type represents the top-level structure of a data type. A type `t` and its structure-representation type `t°` are isomorphic (ignoring undefined values). This isomorphism is witnessed by a so-called *embedding-projection pair*: a value `convt :: EP t t°` of the data type

```

data EP a b = EP (a → b) (b → a).

```

For example, for the `List` data type we have that `convList = EP fromList toList`, where `fromList` and `toList` are defined by

```

fromList           :: ∀a. List a → List° a
fromList Nil       = Inl (Con nilDescr Unit)
fromList (Cons a as) = Inr (Con consDescr (a :*: as))

toList           :: ∀a. List° a → List a
toList (Inl (Con _ Unit)) = Nil
toList (Inr (Con _ (a :*: as))) = Cons a as.

```

The Generic Haskell compiler generates the translation of a type to its structure-representation type, together with the corresponding embedding-projection pair. More details about the correspondence between these and Haskell types can be found elsewhere [29].

A generic program is defined by induction on structure-representation types. Whenever a generic program is applied to a user-defined data type, the Generic Haskell compiler takes care of the mapping between the user-defined data type and its corresponding structure-representation type. Furthermore, a generic program may also be defined directly on a user-defined data type, in which case this definition takes precedence over the automatically generated definitions. A definition of a generic function on a user-defined data type is called a *default case*. To develop a generic function, it is best to first consider a number of its instances for specific data types.

2.3 Encoding and decoding

A classic application area of generic programming is parsing and unparsing, i.e., reading values of different types from some universal representation, or writing values to that universal representation. The universal representation can be aimed at being human-readable (such as the result of Haskell's *show* function); or it can be intended for data exchange, such as XML. Other applications include encryption, transformation, or storage.

In this section we treat a very simple case of compression, by defining functions that can write to and read from a sequence of bits. A bit is defined by the following data-type declaration:

data Bit = *O* | *I*.

Here, the names *O* and *I* are used as constructors.

Function encode on CharList. To define *encode* on the data type CharList, we assume that there exists a function *encodeChar* :: Char → [Bit], which takes a character and returns a list of bits representing that character. We assume that *encodeChar* returns a list of 8 bits, corresponding to the ASCII number of the character. A value of type CharList is now encoded as follows:

$$\begin{aligned} \text{encodeCharList} &:: \text{CharList} \rightarrow [\text{Bit}] \\ \text{encodeCharList Nil} &= [O] \\ \text{encodeCharList (Cons } c \text{ cs)} &= I : \text{encodeChar } c \mathbin{++} \text{encodeCharList } cs. \end{aligned}$$

For example, applying *encodeCharList* to the string "Bonn" defined as a CharList by *bonn* = Cons 'B' (Cons 'o' (Cons 'n' (Cons 'n' Nil))) gives

ComparingGP encodeCharList bonn
 [I, O, I, O, O, O, O, I, O, I, O, I, I, O, I, I, I, I,
 O, I, I, O, I, I, I, O, I, O, I, I, O, I, I, I, O, O].

Function encode on Tree. To define *encode* on the data type *Tree*, we assume there exists, besides a function *encodeChar*, a function *encodeInt* :: *Int* → [*Bit*], which takes an integer and returns a list of bits representing that integer. A value of type *Tree* can then be encoded as follows:

$$\begin{aligned} \text{encodeTree} &:: \text{Tree} \rightarrow [\text{Bit}] \\ \text{encodeTree Empty} &= [O, O] \\ \text{encodeTree (Leaf } i) &= [O, I] \text{ ++ encodeInt } i \\ \text{encodeTree (Bin } l \text{ c } r) &= [I, O] \\ &\quad \text{++ encodeTree } l \\ &\quad \text{++ encodeChar } c \\ &\quad \text{++ encodeTree } r. \end{aligned}$$

Each of the three constructors of the *Tree* data type is encoded as a sequence of two bits.

Function encode on List a. The data type *CharList* is an instance of the data type *List a*, where *a* is *Char*. How do we define an encoding function on the data type *List a*? For character lists, we assumed the existence of an encoding function for characters. Here we take the same approach: to encode a value of type *List a*, we assume that we have a function for encoding values of type *a*. Abstracting from *encodeChar* in the definition of *encodeCharList* we obtain:

$$\begin{aligned} \text{encodeList} &:: (\text{a} \rightarrow [\text{Bit}]) \rightarrow \text{List a} \rightarrow [\text{Bit}] \\ \text{encodeList encodeA Nil} &= [O] \\ \text{encodeList encodeA (Cons } x \text{ xs)} &= I : \text{encodeA } x \\ &\quad \text{++ encodeList encodeA xs.} \end{aligned}$$

Generic encode. The encoding functions on *CharList*, *Tree* and *List a* follow the same pattern: encode the choice made for the top level constructors, and concatenate the encoding of the children of the constructor. We can capture this common pattern in a single generic definition by defining the encoding function by induction on the structure of data types. This means that we define *encode* on sums (*:+:*), on products (*:*:*), and on base types such as *Unit*, *Int* and *Char*, as well as on the sum labels (*Con*) and the product labels (*Label*).

The only place where there is a choice between different constructors is in the *:+:* type. Here, the value can be either an *Inl* or an *Inr*. If we have to encode a value of type *Unit*, it can only be *Unit*, so we need no bits to encode that knowledge. Similarly, for a product we know that the value is the first component followed by the second – we need no extra bits except the encodings of the components.

In Generic Haskell, the generic *encode* function is rendered as follows:

$$\begin{aligned} \text{encode}\{\text{a} :: *\} &:: (\text{encode}\{\text{a}\}) \Rightarrow \text{a} \rightarrow [\text{Bit}] \\ \text{encode}\{\text{Unit}\} \quad \text{Unit} &= [] \\ \text{encode}\{\text{Int}\} \quad i &= \text{encodeInt } i \end{aligned}$$

$$\begin{aligned}
\text{encode}\{\text{Char}\} \quad c &= \text{encodeChar } c \\
\text{encode}\{\alpha :+ \beta\} \quad (\text{Inl } x) &= O : \text{encode}\{\alpha\} x \\
\text{encode}\{\alpha :+ \beta\} \quad (\text{Inr } y) &= I : \text{encode}\{\beta\} y \\
\text{encode}\{\alpha :* \beta\} \quad (x_1 :* x_2) &= \text{encode}\{\alpha\} x_1 \mathrel{++} \text{encode}\{\beta\} x_2 \\
\text{encode}\{\text{Label } l \alpha\} \quad (\text{Label } a) &= \text{encode}\{\alpha\} a \\
\text{encode}\{\text{Con } c \alpha\} \quad (\text{Con } a) &= \text{encode}\{\alpha\} a.
\end{aligned}$$

There are a couple of things to note about generic function definitions:

- The function $\text{encode}\{\mathbf{a}\}$ is a type-indexed function. The type argument appears in between special parentheses $\{\}, \}$. An instance of encode is obtained by applying encode to a type. For example, $\text{encode}\{\text{CharList}\}$ is the instance of the generic function encode on the data type CharList . This instance is semantically the same as the definition of encodeCharList .
- The constraint $\text{encode}\{\mathbf{a}\}$ that appears in the type of encode says that encode depends on itself. A generic function f depends on a generic function g if there is an arm in the definition of f , for example the arm for $f\{\alpha :+ \beta\}$ that uses g on a variable in the type argument, for example $g\{\alpha\}$. If a generic function depends on itself it is defined by induction over the type structure.
- The type of encode is given for a type \mathbf{a} of kind \star . This does not mean that encode can only be applied to types of kind \star ; it only gives the type information for types of kind \star . The type of function encode on types with kinds other than \star is derived automatically from this base type. In particular, $\text{encode}\{\text{List}\}$ is translated to a value that has the type $(\mathbf{a} \rightarrow [\text{Bit}]) \rightarrow (\text{List } \mathbf{a} \rightarrow [\text{Bit}])$.

The Con and the Label case are useful for generic functions that use the names of constructors and labels in some way, such as a generic show function. Most generic functions, however, essentially ignore these branches. In this case, Generic Haskell allows to omit these branches from the generic function definition.

Generic decode. The inverse of encode recovers a value from a list of bits. This inverse function is called decode , and is defined in terms of a function decodes , which takes a list of bits, and returns a list of values that are recovered from an initial segment of the list of bits. The reason we define this example as well, is that we want to show how to generically build or construct a value of a data type.

$$\begin{aligned}
\text{mapFst } f \ (x, y) &= (f \ x, y) \\
\text{decodes}\{\mathbf{a} :: \star\} &:: (\text{decodes}\{\mathbf{a}\}) \Rightarrow [\text{Bit}] \rightarrow [(\mathbf{a}, [\text{Bit}])] \\
\text{decodes}\{\text{Unit}\} \quad xs &= [(Unit, xs)] \\
\text{decodes}\{\text{Int}\} \quad xs &= \text{decodesInt } xs \\
\text{decodes}\{\text{Char}\} \quad xs &= \text{decodesChar } xs \\
\text{decodes}\{\alpha :+ \beta\} \quad (O : xs) &= \text{map } (\text{mapFst Inl}) \ (\text{decodes}\{\alpha\} \ xs) \\
\text{decodes}\{\alpha :+ \beta\} \quad (I : xs) &= \text{map } (\text{mapFst Inr}) \ (\text{decodes}\{\beta\} \ xs) \\
\text{decodes}\{\alpha :+ \beta\} \quad [] &= []
\end{aligned}$$

$$\text{decodes}\{\alpha : * : \beta\} \text{ } xs = [(y_1 : * : y_2, r_2) \mid (y_1, r_1) \leftarrow \text{decodes}\{\alpha\} \text{ } xs, (y_2, r_2) \leftarrow \text{decodes}\{\beta\} \text{ } r_1]$$

The function is a bit more involved than *encode*, because it has to deal with incorrect input, and it has to return the unconsumed part of the input. We therefore use the standard list-of-successes technique, where the input list is transformed into a list of pairs, containing all possible parses with the associated unconsumed part of the input. The decoding process is not ambiguous, so only lists of zero (indicating failure) and one (indicating success) elements occur. As with *encodeChar*, we assume a function *decodeChar* is obtained from somewhere.

A value of type *Unit* is represented using no bits at all, therefore it is decoded without consuming any input. Except for the primitive types such as *Char* and *Int*, the case for *+:* is the only place where input is consumed (as it is the only case where output is produced in *encode*), and depending on the first bit of the input, we produce an *Inl* or an *Inr*. Decoding fails if we run out of input while decoding a sum. The product case first decodes the left component, and then runs *decodes* for the right component on the rest of the input.

The inverse of *encode* is now defined by:

$$\begin{aligned} \text{decode}\{a :: *\} &:: (\text{decodes}\{a\}) \Rightarrow [\text{Bit}] \rightarrow a \\ \text{decode}\{a\} \text{ } x &= \text{case } \text{decodes}\{a\} \text{ } x \text{ of} \\ &\quad [(y, [])] \rightarrow y \\ &\quad - \rightarrow \text{error "decode: no parse"}. \end{aligned}$$

Note that although this is a generic function, it is not defined by induction on the structure of types. Instead, it is defined in terms of another generic function, *decodes*. A generic function *f* that is defined in terms of another generic function *g* is called a *generic abstraction*. Such a generic function does not depend on itself, but on *g* instead. Using a generic abstraction, we can thus define a function that depends on a type argument, but is not defined using cases on types.

For each type *t* in the domain of both *decode* and *encode*, we have that for any value *x* of type *t*

$$(\text{decode}\{t\} . \text{encode}\{t\}) \text{ } x == x.$$

2.4 Equality

The generic equality function takes *two* arguments instead of a single argument as *encode*. We define the equality function on two of the example data types given in Section 2.1. Two character lists are equal if both are empty, or if both are non-empty, the first elements are equal, and the tails of the lists are equal.

$$\begin{aligned} \text{eqCharList} &:: \text{CharList} \rightarrow \text{CharList} \rightarrow \text{Bool} \\ \text{eqCharList} \text{ } Nil \quad Nil &= \text{True} \end{aligned}$$

$$\begin{aligned} eqCharList \quad (Cons \ x \ xs) \ (Cons \ y \ ys) &= eqChar \ x \ y \wedge eqCharList \ xs \ ys \\ eqCharList \quad - \quad - &= False, \end{aligned}$$

where $eqChar$ is the equality function on characters.

Two trees are equal if both are empty, both are a leaf containing the same integer, determined by means of function $eqInt$, or if both are nodes containing the same subtrees, in the same order, and the same characters.

$$\begin{aligned} eqTree &:: Tree \rightarrow Tree \rightarrow Bool \\ eqTree \quad Empty \quad Empty &= True \\ eqTree \quad (Leaf \ i) \quad (Leaf \ j) &= eqInt \ i \ j \\ eqTree \quad (Bin \ l \ c \ r) \ (Bin \ v \ d \ w) &= eqTree \ l \ v \wedge eqChar \ c \ d \wedge eqTree \ r \ w \\ eqTree \quad - \quad - &= False \end{aligned}$$

The equality functions on `CharList` and `Tree` follow the same pattern: compare the top level constructors, and, if they are equal, pairwise compare their arguments. We can capture this common pattern in a single generic definition by defining the equality function by induction on the structure of data types.

$$\begin{aligned} eq\{a :: *\} &:: (eq\{a\}) \Rightarrow a \rightarrow a \rightarrow Bool \\ eq\{Unit\} \quad - \quad - &= True \\ eq\{Int\} \quad i \quad j &= eqInt \ i \ j \\ eq\{Char\} \quad c \quad d &= eqChar \ c \ d \\ eq\{\alpha :+ \beta\} \ (Inl \ x) \ (Inl \ y) &= eq\{\alpha\} \ x \ y \\ eq\{\alpha :+ \beta\} \ (Inl \ x) \ (Inr \ y) &= False \\ eq\{\alpha :+ \beta\} \ (Inr \ x) \ (Inl \ y) &= False \\ eq\{\alpha :+ \beta\} \ (Inr \ x) \ (Inr \ y) &= eq\{\beta\} \ x \ y \\ eq\{\alpha :* \beta\} \ (x :* y) \ (v :* w) &= eq\{\alpha\} \ x \ v \wedge eq\{\beta\} \ y \ w \end{aligned}$$

2.5 Map

The generic map function illustrates the importance of kinds in generic programming. To understand the definition of the generic *map* function, it helps to first study the generic copy function:

$$\begin{aligned} copy\{a :: *\} &:: (copy\{a\}) \Rightarrow a \rightarrow a \\ copy\{Unit\} \quad x &= x \\ copy\{Int\} \quad x &= x \\ copy\{Char\} \quad x &= x \\ copy\{\alpha :+ \beta\} \ (Inl \ x) &= Inl \ (copy\{\alpha\} \ x) \\ copy\{\alpha :+ \beta\} \ (Inr \ x) &= Inr \ (copy\{\beta\} \ x) \\ copy\{\alpha :* \beta\} \ (x :* y) &= copy\{\alpha\} \ x \ :* \ copy\{\beta\} \ y. \end{aligned}$$

Given a value, the *copy* function produces copy of that value and is thus a generic version of the identity function. Note that we have made a choice in the code above: the definition is written recursively, applying the generic copy deeply to

all parts of a value. We could have simplified the last three lines, removing the dependency of *copy* on itself:

$$\begin{aligned} \text{copy}\{\alpha :+ : \beta\} x &= x \\ \text{copy}\{\alpha :* : \beta\} x &= x. \end{aligned}$$

But retaining the dependency and applying the function recursively has an advantage: using a so-called *local redefinition* we can change the behavior of the function. As an example, we can increase all elements of a list by one, using the function

$$\text{incBy1 } x = \text{let } \text{copy}\{a\} = (+1) \text{ in } \text{copy}\{[a]\} x.$$

Here we locally redefine *copy* to behave as the function $(+1)$ on values of type a that appear in a list of type $[a]$. Note that this is something that would normally be written as an application of *map*:

$$\text{incBy1 } x = \text{map } (+1) x.$$

If we compare *map* with the locally redefined version of *copy*, then two differences spring to mind. First, the function *map* can only be used on lists, whereas *copy* can be used on other data types as well. Second, *map* has a more liberal type. If we define

$$\text{map}' f = \text{let } \text{copy}\{a\} = f \text{ in } \text{copy}\{[a]\},$$

then we can observe that *map'*, compared to *map* has a more restricted type:

$$\begin{aligned} \text{map}' &:: (a \rightarrow a) \rightarrow [a] \rightarrow [a] \\ \text{map} &:: (a \rightarrow b) \rightarrow [a] \rightarrow [b]. \end{aligned}$$

The function passed to *map* may change the type of its argument; the function passed to *map'* preserves the argument type.

Inspired by this deficiency, we can ask ourselves if it is possible to also pass a function of type $a \rightarrow b$ while locally redefining *copy*. The function $\text{copy}\{[a]\}$ has the qualified type

$$\text{copy}\{[a]\} :: (\text{copy}\{a\} :: a \rightarrow a) \Rightarrow [a] \rightarrow [a],$$

but we are now going to generalize this type to something like

$$\text{map}\{[a]\} :: (\text{map}\{a\} :: a \rightarrow b) \Rightarrow [a] \rightarrow [b],$$

thereby renaming function *copy* to *map* (but using exactly the same definition). For this to work, *map* needs a different type signature:

$$\text{map}\{a :: *, b :: *\} :: (\text{map}\{a, b\}) \Rightarrow a \rightarrow b.$$

The function is now parametrized over *two* type variables, and so is the dependency. When used at a constant type, both variables a and b are instantiated

```

map{Tree :: *} :: Tree → Tree
map{List (a :: *) :: *} ::
  ∀(a1 :: *) (a2 :: *) . (map{a} :: a1 → a2) ⇒ List a1 → List a2
map{GTree (a :: *) (b :: *) :: *} ::
  ∀(a1 :: *) (a2 :: *) (b1 :: *) (b2 :: *) . (map{a} :: a1 → a2, map{b} :: b1 → b2) ⇒
    GTree a1 a2 → GTree b1 b2
map{GRose (f :: * → *) (a :: *) :: *} ::
  ∀(f1 :: * → *) (f2 :: * → *) (a1 :: *) (a2 :: *) .
    (map{f c} :: ∀(c1 :: *) (c2 :: *) . (map{c} :: c1 → c2) ⇒ f1 c1 → f2 c2
    , map{a} :: a1 → a2
    ) ⇒ GRose f1 a1 → GRose f2 a2.

```

Fig. 1. Example types for generic applications of *map* to type arguments of different forms.

to the same type – only when locally redefining the function for a dependency variable, the additional flexibility is available. Figure 1 shows some types (with explicit kind annotations for the type variables) for applications of *map* to specific type arguments.

For example, assume the (data) types *Pair* and *Either* are defined by:

```

type Pair a b = (a, b)
data Either a b = Left a | Right b.

```

Then the expressions

```

map{[] }      (+1)      [1, 2, 3, 4, 5]
map{Pair }    (*2) ("y"++) (21, "es")
map{Either }  not id    (Left True)

```

evaluate to $[2, 3, 4, 5, 6]$, $(42, \text{"yes"})$, and *Left False*, respectively.

2.6 Show

The function *show* shows a value of an arbitrary data type. In Haskell, the definition of *show* can be derived for most data types. In this subsection we explain how to define *show* as a generic function in Generic Haskell. The function *show* is an example of a function that uses the constructor descriptor in the *Con* case. We define *show* in terms of the function *showP*, a slightly generalized variant of Haskell's *show* that takes an additional argument of type *String* → *String*. This parameter is used internally to place parentheses around a fragment of the result when needed.

```

showP{a :: *} :: (showP{a}) ⇒ (String → String) → a → String
showP{Unit }   p Unit    = ""
showP{α :+: β } p (Inl x) = showP{α } p x

```

```

showP{α :+ β} p (Inr x) = showP{β} p x
showP{α :* β} p (x1 :* x2) = showP{α} p x1 ++ " " ++ showP{β} p x2
showP{Con c α} p (Con x) = let parens x = "(" ++ x ++ ")"
                             body      = showP{α} parens x
                             in if null body
                                then conName c
                                else p (conName c ++ " " ++ body)
showP{[α]} p xs = let body = (concat
                             . intersperse " , "
                             . map (showP{α} id)
                             ) xs
                  in "[" ++ body ++ "]"

```

The type `Unit` represents a constructor with no fields. In such a situation, the constructor name alone is the representation, and it is generated from the `Con` case, so we do not need to produce any output here. We just descend through the sum structure; again, no output is produced because the constructor names are produced in the `Con` case. A product concatenates fields of a single constructor; we therefore show both components, and separate them from each other by a space.

Most of the work is done in the arm for `Con`. We show the body of the constructor, using parentheses where necessary. The body is empty if and only if there are no fields for this constructor. In this case, we only return the name of the constructor. Here we make use of the function `conName` on the constructor descriptor `c` to obtain that name. Otherwise, we connect the constructor name and the output of the body with a space, and possibly surround the result with parentheses.

The last case is for lists and implements Haskell's list syntax, with brackets and commas.

In addition to the cases above, we need cases for abstract primitive types such as `Char`, `Int`, or `Float` that implement the operation in some primitive way.

The function `show` is defined in terms of `showP` via generic abstraction, instantiating the first parameter to the identity function, because outer parentheses are not required.

```

show{a :: *} :: (showP{a}) => a -> String
show{a}      = showP{a} id

```

The definition of a generic `read` function that parses the generic string representation of a value is also possible using the `Con` case, and only slightly more involved because we have to consider partial consumption of the input string and possible failure.

2.7 Update salaries

Adapting from Lämmel and Peyton Jones [54], we use the following data types to represent the organizational structure of a company.

```

data Company = C [Dept]
data Dept     = D Name Manager [SubUnit]
data SubUnit = PU Employee | DU Dept
data Employee = E Person Salary
data Person   = P Name Address
data Salary   = S Float
type Manager = Employee
type Name    = String
type Address = String

```

We wish to update a `Company` value, which involves giving every `Person` a 15% pay rise. To do so requires visiting the entire tree and modifying every occurrence of `Salary`. The implementation requires pretty standard “boilerplate” code which traverses the data type, until it finds `Salary`, where it performs the appropriate update – itself one line of code – before reconstructing the result.

In Generic Haskell writing this function requires but a few lines. The code is based on the generic `map` function. The code to perform the updating is given by the following three lines, the first of which is the mandatory type signature, the second states that the function is based on `map`, and the third performs the update of the salary. The **extends** construct denotes that the cases of `map` are copied into `update`. These are the *default cases* described in Clarke and Löb [15].

```

update{a :: *} :: (update{a}) ⇒ a → a
update extends map
update{Salary} (S s) = S (s * (1 + 0.15))

```

3 Criteria for comparing approaches to generic programming

This section discusses the criteria we use for comparing approaches to generic programming in Haskell. This is a subset of the criteria we would use for comparing approaches to generic programming in any programming language. Together, these criteria can be viewed as a characterization of generic programming. Adding generic programming capabilities to a programming language is a programming-language design problem. Many of the criteria we give are related to or derived from programming-language design concepts. We don’t think that all criteria are equally important: some criteria discuss whether or not some functions can be defined or used on particular data types, whereas other criteria discuss more cosmetic aspects. We illustrate the criteria with an evaluation of Generic Haskell.

3.1 Structure in programming languages

Ignoring modules, many modern programming languages have a two-level structure. The bottom level, where the computations take place, consists of values.

The top level imposes structure on the value level, and is inhabited by types. On top of this, Haskell adds a level that imposes structure on the type level, namely kinds. Finally, in some dependently-typed programming languages there is a possibly infinite hierarchy of levels, where level $n + 1$ imposes structure on elements of level n .

In ordinary programming we routinely define values that depend on values, that is, functions, and types that depend on types, that is, type constructors. However, we can also imagine to have dependencies between adjacent levels. For instance, a type might depend on a value or a type might depend on a kind. The following table lists the possible combinations:

kinds depending on kinds	parametric and kind-indexed kinds
kinds depending on types	dependent kinds
types depending on kinds	polymorphic and kind-indexed types
types depending on types	parametric and type-indexed types
types depending on values	dependent types
values depending on types	polymorphic and type-indexed functions
values depending on values	ordinary functions

If a higher level depends on a lower level we have so-called dependent types or dependent kinds. Programming languages with dependent types are the subject of intensive research [66, 9]. Generic programming is concerned with the opposite direction, where a lower level depends on the same or a higher level. For instance, if a value depends on a type we either have a polymorphic or a type-indexed function. In both cases the function takes a type as an argument. What is the difference between the two? A polymorphic function is a function that happens to be insensitive to what type the values in a data type are. Take, for example, the length function that calculates the length of a list. Since it does not have to inspect the elements of an argument list, it has type $\forall a. \text{List } a \rightarrow \text{Int}$. By contrast, a type-indexed function is defined by induction on the structure of its type argument. In some sense, the type argument guides the computation which is performed on the value arguments.

Not only values may depend on types, but also types. For example, the type constructor `List` depends on a type argument. We can make a similar distinction as on the value level. A parametric type, such as `List`, does not inspect its type argument. A *type-indexed type* [34], on the other hand, is defined by induction on the structure of its type argument. An example of a type-indexed data type is the zipper data type introduced by Huet [40]. Given a data type `t`, the zipper data type corresponding to `t` can be defined by induction on the data type `t`. Finally, we can play the same game on the level of kinds. The following table summarizes the interesting cases.

kinds defined by induction on the structure of kinds	kind-indexed kinds
kinds defined by induction on the structure of types	–
types defined by induction on the structure of kinds	kind-indexed types
types defined by induction on the structure of types	type-indexed types
types defined by induction on the structure of values	–
values defined by induction on the structure of types	type-indexed values
values defined by induction on the structure of values	–

For each of the approaches to generic programming we discuss what can depend on what.

Structural dependencies. Which concepts may depend on which concepts?

Generic Haskell supports the definition of type-indexed values, as all the examples in the previous section show. Type arguments appear between special parentheses $\llbracket \cdot \rrbracket$. A type-indexed value has a kind-indexed type, of which the base case, the case for kind \star , has to be supplied by the programmer. The inductive case, the case for kind $k \rightarrow l$, cannot be specified, but is automatically generated by the compiler (as it is determined by the way Generic Haskell specializes generic functions).

Generic Haskell also supports the definition of type-indexed types. A type-indexed type is defined in the same way as a type-indexed function, apart from the facts that every line in its definition starts with **type**, and its name starts with a capital. A type-indexed type has a kind-indexed kind [34].

3.2 The Type Completeness Principle

The Type Completeness Principle [78] says that no programming-language operation should be arbitrarily restricted in the types of its operands, or, equivalently, all programming-language operations should be applicable to all operands for which they make sense. For example, in Haskell, a function can take an argument of any type, including a function type, and a tuple may contain a function. To a large extent, Haskell satisfies the type completeness principle on the value level. There are exceptions, however. For example, it is not possible to pass a polymorphic function as argument. Pascal does not satisfy the type completeness principle, since, for example, procedures cannot be part of composite values.

The type completeness principle leads to the following criteria.

Full reflexivity. A generic programming language is fully reflexive if a generic function can be used on *any* type that is definable in the language.

Generic Haskell is fully reflexive with respect to the types that are definable in Haskell 98, except for constraints in data-type definitions. So a data type of the form

```
data Eq a  $\Rightarrow$  Set a = NilSet | ConsSet a (Set a)
```

is not dealt with correctly. However, constrained data types are a corner case in Haskell and can easily be simulated using other means. Furthermore, Nogueira [69] shows how to make Generic Haskell work for data types with constraints.

Generic functions cannot be used on existential data types, such as for example

```
data Foo =  $\forall a$ . MkFoo a (a  $\rightarrow$  Bool)
         | Foo.
```

Although such types are not part of Haskell 98, they are supported by most compilers and interpreters for Haskell. Furthermore, generic functions cannot be applied to *generalized algebraic data types* (GADTs), a recent extension in GHC, of which the following type `Term`, representing typed terms, is an example:

```
data Term :: *  $\rightarrow$  * where
  Lit    :: Int  $\rightarrow$  Term Int
  Succ   :: Term Int  $\rightarrow$  Term Int
  IsZero :: Term Int  $\rightarrow$  Term Bool
  If      :: Term Bool  $\rightarrow$  Term a  $\rightarrow$  Term a  $\rightarrow$  Term a
  Pair   :: Term a  $\rightarrow$  Term b  $\rightarrow$  Term (a, b).
```

Note that the result types of the constructors are restricted for *Terms*, so that if we pattern match on a `Term Bool`, for example, we already know that it cannot be constructed by means of `Lit`, `Succ` or `Pair`. The structural representation using sums of products that Generic Haskell uses to process data types uniformly is not directly applicable to data types containing existential components or to GADTs. Generic Haskell is thus not fully reflexive with respect to modern extensions of Haskell.

Type universes. Some generic functions only make sense on a particular set of data types, or on a subset of all data types. For example, the *catamorphism* [65] only makes sense for regular data types, see Section 4.2, and many generic functions, such as `show` and `equality`, cannot sensibly be defined on the type of functions. Is it possible to define generic functions on a particular set of data types, or on a subset of data types? Can we describe *type universes* [11]?

Generic Haskell has some facilities to support defining generic functions on a particular set of data types. If we only want to use a generic function on a particular set of data types, we can define it for just those data types. This is roughly equivalent to defining a class and providing instances of the class for the given data types.

Furthermore, by not giving a case for the function space (or other basic types for which we do not want to define the generic function), a generic function is not defined for data types containing function spaces, and the compiler complains if the generic function is used on a data type containing function spaces.

Finally, Generic Haskell supports so-called *generic views* [39] on data types, by means of which we can view the structure of data types in different ways. Using generic views, we can for example view (a subset of) data types as fixed points of regular functors, which enables the definition of the catamorphism.

First-class generic functions. Can a generic function take a generic function as an argument? We will also use the term higher-order generic functions for first-class generic functions. An example where a higher-order generic function might be useful is in a generic show function that only prints part of its input, depending on whether or not some property holds for the input.

Generic Haskell does not have first-class generic functions. To a certain extent first-class generic functions can be mimicked by means of dependencies and extending existing generic functions, but it is impossible to pass a generic function as an argument to another (generic) function. The reason for this is that generic functions in Generic Haskell are translated by means of specialization. Specialization eliminates the type arguments from the code, and specialized instances are used on the different types. Specialization has the advantage that types do not appear in the generated code, but the disadvantage that specializing higher-order generic programs becomes difficult: it is hard to determine which translated components are used where.

Multiple type arguments. Can a function be generic in more than one type argument? Induction over multiple types is for example useful when generically transforming values from one type structure into another type structure [8].

Generic functions in Generic Haskell can be defined by induction on a single type. It is impossible to induct over multiple types. If induction on multiple types is needed, the typical solution is to define two generic functions, with a universal data type in between them.

Transforming values from one type structure into another type structure is the only example we have encountered for which multiple type arguments would be useful. Usually, transforming one type structure into another can be achieved by combining two single-argument generic functions – one that maps a value into a universal structure, and another that recovers a value from the universal structure. Hence we do not weigh this aspect heavily in our comparison.

3.3 Well-typed expressions do not go wrong

Well-typed expressions in the Hindley-Milner type system [67] do not go wrong. Does the same hold for generic functions?

Type system. Do generic functions have types?

In Generic Haskell, generic functions have explicit types. Type-correctness is only partially checked by the Generic Haskell compiler. Haskell type checks the generated code. Both Löb [60] and Hinze [28] describe a type system for Generic Haskell.

Type safety. Is the generic-programming language type safe? By this we mean: is a type-correct generic function translated to a type-correct instance? And does a compiled program not crash because a non-existing instance of a generic function is called?

Generic Haskell is type safe in both aspects.

3.4 Information in types

What does the type of a generic function reveal about the function? Can we infer a property of a generic function from its type? Since generic programming is about programming with types, questions about the type language are particularly interesting.

The type of a generic function. Do types of generic functions in some way correspond to intuition? A generic function $f\{a\}$ that has type $a \rightarrow a \rightarrow \text{Bool}$ is probably a comparison function. But what does a function of type $(\forall a\ b. \text{Data } a \Rightarrow f(a \rightarrow b) \rightarrow a \rightarrow f\ b) \rightarrow (\forall a. a \rightarrow f\ a) \rightarrow a \rightarrow f\ a$ do (this is a rather powerful combinator, which we will encounter again in one of the approaches)? This question is related to the possibility to infer useful properties, like free theorems [76], for a generic function from its type.

Generic Haskell's types of generic functions are relatively straightforward: a type like

$$eq\{a :: \star\} :: (eq\{a\}) \Rightarrow a \rightarrow a \rightarrow \text{Bool}$$

is close to the type you would expect for the equality function, maybe apart from the dependency. The type for *map*:

$$map\{a :: \star, b :: \star\} :: (map\{a, b\}) \Rightarrow a \rightarrow b.$$

is perhaps a little bit harder to understand, but playing with instances of the type of *map* for particular types, in particular for type constructors, probably helps understanding why this type is the one required by *map*.

Properties of generic functions. Is the approach based on a theory for generic functions? Do generic functions satisfy algebraic properties? How easy is it to reason about generic functions?

In his habilitation thesis [28], Hinze discusses generic programming and generic proofs in the context (of a 'core' version) of Generic Haskell. He shows a number of properties satisfied by generic functions, and he shows how to reason about generic functions.

3.5 Integration with the underlying programming language

How well does the generic-programming language extension integrate with the underlying programming language, in our case Haskell?

A type system can be *nominal* (based on the names of the types), *structural* (based on the structure of the types), or a mixture of the two. If a type system is nominal, it can distinguish types with exactly the same structure, but with different names. Generic functions are usually defined on a structural representation of types. Can such a generic function be extended in a non-generic way, for example for a particular, named, data type? Or even for a particular constructor? The general question here is: how does generic programming interact with the typing system?

A generic program can be used on many data types. But how much work needs to be done to use a generic function on a new data type? Is it simply a matter of writing **deriving** ... in a data-type declaration, or do we also have to implement the embedding-projection pair for the data type, for example?

Using default cases, a generic function can be extended in a non-generic way in Generic Haskell. The *update* function defined in Section 2.7 provides an example. Generic functions can even be specialized for particular constructors. Generic functions can be used on data types with no extra work. Generic Haskell generates the structure-representation types, the embedding-projection pairs, and the bimap behind the scenes.

3.6 Tools

Of course, a generic-programming language extension is only useful if there exists an interpreter or compiler that understands the extension. Some ‘light-weight’ approaches to generic programming require no additional language support: the compiler for the underlying programming language is sufficient. However, most approaches require tools to be able to use them, and we can ask the following questions.

Specialization versus interpretation. Is a generic function interpreted at run-time on data types to which it is applied, or is it specialized at compile-time? The latter approach allows the optimization of generated code.

Generic Haskell specializes applications of generic functions at compile-time.

Code optimization. How efficient is the code generated for instances of generic functions? What is the speed of the generated code?

Generic Haskell does not optimize away the extra marshaling that is introduced by the compiler for instances of generic functions. This might be an impediment for some applications.

Separate compilation. Can a generic function that is defined in one module be used on a data type defined in another module without having to recompile the module in which the generic function is defined?

Generic Haskell provides separate compilation.

Practical aspects. Does there exist an implementation? Is it maintained? On multiple platforms? Is it documented? What is the quality of the error messages given by the tool?

Generic Haskell is available on several platforms: Windows, Linux and Mac-OSX. The latest release is from January 14, 2005. A new release is expected in the second half of 2006. The distribution comes with a User Guide, which explains how to install Generic Haskell, how to use it, and introduces the functions that are in the library of Generic Haskell. The Generic Haskell compilers reports syntax errors. Type errors, however, are only reported when the file generated by Generic Haskell is compiled by a Haskell compiler. Type systems for Generic Haskell have been published [28, 61, 60], but not implemented.

3.7 Other criteria

This section lists some of the criteria that do not fall in the categories discussed in the previous subsections, or that are irrelevant for comparing the generic-programming approaches in Haskell, but might be relevant for comparing approaches to generic programming in different programming languages.

Type-language expressiveness of the underlying programming language. If a programming language has no types, it is impossible to define a function the behavior of which depends on a type, and hence it is impossible to define generic functions. But then, of course, there is no need for defining generic functions either.

The type languages of programming languages with type systems vary widely. Flexible and powerful type languages are desirable, but the more expressive a type language, the harder it becomes to write generic programs. What kind of data types can be expressed in the type language?

Haskell has a very powerful, flexible, and expressive type language. This makes generic programming in Haskell particularly challenging.

Size matters. The size of a program matters – some people are even paid per line of code –, and the same holds for a generic program. It is usually easier to read and maintain a single page of code than many pages of code, although sometimes extra information, such as type information, properties satisfied by a program, test cases for a program, are useful to have. So code size matters, but not always. Except for some obvious cases, we will not say much about code size in our comparisons.

Ease of learning. Some programming approaches are easier to learn than others. Since there are so many factors to the question how easy it is to learn a programming language, and since it is hard to quantify, we refrain from making statements about this question, other than whether or not the approach to generic programming is documented. However, it is an important question.

4 Comparing approaches to generic programming

In this section we describe eight different approaches to generic programming. We give a brief introduction to each approach, and evaluate it using the criteria introduced in the previous section.

We can distinguish three groups of approaches with similar characteristics among the approaches to generic programming in Haskell.

- Generic Haskell and Clean are programming-language extensions based on Hinze’s theory of type-indexed functions with kind-indexed types [29].
- DrIFT and implementations of generic programming using Template Haskell are based on a kind of reflection mechanism.

- Derivable Type Classes, Light-weight Generics and Dynamics, and Generics for the Masses are light-weight approaches that do not require reflection or programming-language extensions.

PolyP and Strap Your Boilerplate are sufficiently different to not be placed in one of these groups. We evaluate the approaches in the groups together, since most aspects of the evaluation are the same. Of course, we already evaluated Generic Haskell in the previous section, so Clean is evaluated separately.

4.1 Clean

Clean’s generic-programming extension [3, 2] is just as Generic Haskell based on Hinze’s work on type-indexed functions with kind-indexed types [29].

The language of data types in Clean is very similar to that of Haskell, and the description from Section 2.1 on how to convert between data types and their structure-representation types in terms of binary sums of binary products applies to Clean as well, only that the unit type is called **UNIT**, the sum type **EITHER**, and the product type **PAIR**. There are special structural markers for constructors and record field names called **CONS** and **FIELD**, and one for objects called **OBJECT**.

Clean’s generic functions are integrated with its type-class system. Each generic function defines a kind-indexed family of type classes, the generic function itself being the sole method of these classes. Let us look at an example.

Function encode. Here is the code for the generic function *encode*.

```
generic encode a :: a → [Bit]
encode{UNIT}      UNIT      = []
encode{Int}       i         = encodeInt i
encode{Char}      c         = encodeChar c
encode{EITHER}    enca encb (LEFT x) = [O : enca x]
encode{EITHER}    enca encb (RIGHT y) = [I : encb y]
encode{PAIR}      enca encb (PAIR x y) = enca x ++ encb y
encode{CONS}      enca      (CONS x)   = enca x
encode{FIELD}     enca      (FIELD x)  = enca x
encode{OBJECT}    enca      (OBJECT x) = enca x
derive encode Tree
```

The keyword **generic** introduces the type signature of a generic function, which takes the same form as a type signature in Generic Haskell, but without dependencies. Each generic function automatically depends on itself in Clean, and in the cases for types of higher kinds such as **EITHER**::* → * → * or **CONS**::* → *, additional arguments are passed to the generic function representing the recursive calls. This is very close to Hinze’s theory [29] which states that the type of *encode* is based on the kind of the type argument as follows:

$$\text{encode}\{\mathbf{a} :: \kappa\} :: \text{Encode}\{\kappa\} \mathbf{a}$$

$$\begin{aligned} \text{Encode}\{\{*\}\} \quad a &= a \rightarrow [\text{Bit}] \\ \text{Encode}\{\{\kappa \rightarrow \kappa'\}\} \quad a &= \forall b :: \kappa. \text{Encode}\{\{\kappa\}\} \, b \rightarrow \text{Encode}\{\{\kappa'\}\} \, (a \, b). \end{aligned}$$

In particular, if we instantiate this type to the kinds $*$, $* \rightarrow *$, and $* \rightarrow * \rightarrow *$, we get the types of the **UNIT**, **EITHER**, **CONS** cases of the definition of *encode*, respectively:

$$\begin{aligned} \text{encode}\{a :: *\} &:: a \rightarrow [\text{Bit}] \\ \text{encode}\{f :: * \rightarrow *\} &:: (a \rightarrow [\text{Bit}]) \rightarrow (f \, a \rightarrow [\text{Bit}]) \\ \text{encode}\{f :: * \rightarrow * \rightarrow *\} &:: (a \rightarrow [\text{Bit}]) \rightarrow (b \rightarrow [\text{Bit}]) \rightarrow (f \, a \, b \rightarrow [\text{Bit}]). \end{aligned}$$

The **derive** statement is an example of how generic behavior must be explicitly derived for additional data types. If **Tree** is a type that we want to encode, we have to request this using a **derive** statement.

Because generic functions automatically define type classes in Clean, the type arguments (but not the kind arguments) can usually be inferred automatically. The function *encode* can thus be invoked on a tree $t :: \text{Tree}$ by calling $\text{encode}\{*\} \, t$.

If $\text{encode}\{*\} \, x$ is used in another function on a value $x :: a$, then a class constraint of the form $\text{encode}\{*\} \, a$ arises and is propagated as usual. Other first-order kinds can be passed to *encode*, but Clean does not currently support generic functions on higher-order kinds, maybe because uniqueness annotations for higher-order kinded types are not supported.

Functions decode, eq, map and show. Apart from the already mentioned differences and a few syntactic differences between Clean and Haskell, many of the other example functions can be implemented exactly as in Generic Haskell. We therefore present only *map* as another example:

```

generic map a b :: a → b
map {UNIT}      x      = x
map {Int}       i      = i
map {Char}      c      = c
map {EITHER}    mapa mapb (LEFT x)  = LEFT (mapa x)
map {EITHER}    mapa mapb (RIGHT y) = RIGHT (mapb y)
map {PAIR}      mapa mapb (PAIR x1 x2) = PAIR (mapa x1) (mapb x2)
map {CONS}      mapa      (CONS x)      = CONS (mapa x)
map {FIELD}     mapa      (FIELD x)     = FIELD (mapa x)
map {OBJECT}    mapa      (OBJECT x)    = OBJECT (mapa x)

```

Function update. A function such as *update* cannot currently be defined in Clean, because there is no support for higher-order generic functions, nor are there default cases as in Generic Haskell.

Evaluation

Structural dependencies. Clean supports the definition of generic functions in the style of Generic Haskell. It does not support type-indexed data types.

Full reflexivity. Generic functions in Clean do not work for types with higher-order kinds, so the generic-programming extension of Clean is not fully reflexive.

Type universes. Clean can define generic functions on subsets of data types in the same way as Generic Haskell, but it does not support default cases or generic views.

First-class generic functions. Generic functions are treated as kind-indexed families of type classes. Type classes are not first-class, so generic functions are not first-class either.

Multiple type arguments. Clean allows the definition of classes with multiple type arguments. All type arguments, however, must be instantiated to the same type at the call site. Therefore, true multi-argument generic functions are not supported.

Type system. Generic functions are fully integrated into Clean's type system, by mapping each generic function to a family of type classes. The compiler ensures type-correctness.

Type safety. Clean's generic programming extension is fully type safe.

The type of a generic function. The type of a generic function is declared using the **generic** construct. The types are very similar in nature to those of Generic Haskell. They lack dependencies, which makes them a bit less expressive, but in turn a bit easier to understand.

Properties of generic functions. Again, Hinze's theory is the basis of Clean's generic-programming extension. Therefore it is possible to state and prove theorems following his formalism.

Integration with the underlying programming language. Generic programming is fully integrated with the Clean language. Only the module **StdGeneric** must be imported in order to define new generic functions. To use a generic function *g* on a data type *t* we write **derive** *g t*, no type-specific code is needed.

Specialization versus interpretation. Clean uses specialization to compile generic functions. Specialization is explicit, using the **derive** construct.

Code optimization Because Clean uses the same theory as Generic Haskell, specialized code is inherently inefficient: data is converted between its original form and a structural view several times during the call of a generic functions. There is extensive work on optimizing specialized code for generic functions generated by Clean [4, 5], and the resulting code is almost as efficient as hand-written specialized code.

Separate compilation. Generic programming is integrated into Clean, and Clean supports separate compilation.

Practical aspects. Clean is maintained and runs on several platforms. However, the documentation of generic programming in Clean is lacking. The chapter in the Clean documentation is missing, and there's a gap between the syntax used in papers and the implementation. Furthermore, the error messages of the Clean compiler with respect to generic functions are not very good. Nevertheless, generic programming in Clean seems very usable and has been used, for example, to implement a library for generating test data [52] as well as a GUI library [1].

4.2 PolyP

PolyP [42] is an extension of Haskell with a construct for defining so-called polytypic programs.

PolyP allows the definition of generic functions on *regular* data types of kind $\star \rightarrow \star$. A data type is regular if it does not contain function spaces, and if the arguments of the data type constructor on the left- and right-hand sides in its definition are the same. Examples of regular data types are `List a`, `Rose a`, and `Fork a`. The data types `CharList`, `Tree`, and `GRose` are regular, but have kind \star, \star , and $(\star \rightarrow \star) \rightarrow \star \rightarrow \star$, respectively. The data type `Perfect a` is not regular: in the right-hand side `Perfect` is applied to `Fork a` instead of `a`. Another example of a data type that is not regular is the data type `Flip` defined by `data Flip a b = MkFlip a (Flip b a)`.

PolyP is rather similar to Generic Haskell in that it translates data types to structure-representation types. The structure-representation types are then used together with polytypic definitions to generate Haskell code for (applications of) generic functions. The structure-representation type of a data type `d a` is given by

$$\text{Mu (FunctorOf } d \text{ a),}$$

where `FunctorOf d` is a type constructor of kind $\star \rightarrow \star \rightarrow \star$ representing the recursive structure of the data type `d`, and the data type `Mu` takes a type constructor and a type variable of kind \star , and returns the fixed point of the type constructor:

$$\text{data Mu f a = Inn (f a (Mu f a)).}$$

`FunctorOf d` is sometimes also called the *bifunctor* of `d`. The isomorphism between a data type and its structure-representation type is witnessed by the functions *inn* and *out*.

$$\begin{aligned} \text{inn} &:: \text{FunctorOf } d \text{ a (d a)} \rightarrow d \text{ a} \\ \text{inn} &= \text{Inn} \\ \text{out} &:: d \text{ a} \rightarrow \text{FunctorOf } d \text{ a (d a)} \\ \text{out (Inn } x) &= x \end{aligned}$$

The restriction to regular data types imposed by PolyP is caused by the way the structure-representation types are built up.

Bifunctors are defined by:

```

data (g + h) a b = InL (g a b) | InR (h a b)
data (g * h) a b = g a b :: h a b
data Par a b    = ParF {unParF :: a}
data Rec a b    = RecF {unRecF :: b}
data (d@g) a b  = CompF {unCompF :: d (g a b)}
data Const t    = ConstF {unConstF :: t}
data Empty      = EmptyF.

```

Binary functors are sums (+, with constructors *InL* and *InR*) of products (*, with constructor *::*) of either the parameter type of kind \star (represented by *Par*, with constructor *ParF* and destructor *unParF*), the data type itself (represented by *Rec*, with constructor *RecF* and destructor *unRecF*), compositions of data types and bifunctors (represented by @, with constructor *CompF* and destructor *unCompF*), or constant types (represented by *Const t* where *t* may be any of *Float*, *Int*, etc., with constructor *ConstF* and destructor *unConstF*). An empty product is represented by the unit type (represented by *Empty*). For example, for the data types *List a*, *Rose a*, and *Fork a* PolyP uses the following internal representations:

```

FunctorOf List  == Empty + Par * Rec
FunctorOf Rose  == Par * List@Rec
FunctorOf Fork  == Par * Par.

```

This encoding of data types is similar to the encoding in Generic Haskell, but there is an important difference. In Generic Haskell the structure types only represent the top-level structure of a value, whereas in PolyP the encoding of values is *deep*: the original data type has disappeared in the encoded structure.

An important recursion combinator in PolyP is the *catamorphism* [65], which is defined in PolyLib, the library of PolyP [43]. The catamorphism is a generalization of Haskell's *foldr* to an arbitrary data type. It takes an algebra as argument, and is defined in terms of a polytypic function *fmap2*, representing the action of the bifunctor of the data type on functions.

```

cata      :: Regular d => (FunctorOf d a b -> b) -> (d a -> b)
cata alg = alg . fmap2 id (cata alg) . out

```

Function *fmap2* is a polytypic function, the two-argument variant of *map*. It is defined by induction over the structure of bifunctors. It takes two functions *p* and *r* as arguments, and applies *p* to occurrences of the parameter, and *r* to occurrences of the recursive data type.

```

polytypic fmap2 :: (a -> c) -> (b -> d) -> f a b -> f c d
              = λp r ->

```

```

case f of
  g + h  → (fmap2 p r) ++- (fmap2 p r)
  g * h  → (fmap2 p r) -*- (fmap2 p r)
  Empty  → λEmptyF → EmptyF
  Par    → ParF . p .                               unParF
  Rec    → RecF . r .                               unRecF
  d@g    → CompF . pmap (fmap2 p r) . unCompF
  Const t → ConstF .                               unConstF

```

Here $++-$ and $-*-$ have the following types:

```

(++-) :: (g a b → g c d) → (h a b → h c d) → ((g + h) a b → (g + h) c d)
(-*-) :: (g a b → g c d) → (h a b → h c d) → ((g * h) a b → (g * h) c d),

```

where $+$ and $*$ are the internal sum and product types used by PolyP.

Function encode. Function *encode* takes an encoder for parameter values as argument, and recurses over its argument by means of a catamorphism. The algebra of the catamorphism is given by the polytypic function *fencode*. The choice between an *O* and an *I* is made, again, in the sum case. The encoder for parameter values is applied in the *Par* case. The other cases are standard.

```

encode      :: Regular d ⇒ (a → [Bit]) → d a → [Bit]
encode enca = cata (fencode enca)

polytypic fencode :: (a → [Bit]) → f a [Bit] → [Bit] =
  λenca →
    case f of
      g + h      → (λx → O : fencode enca x) 'foldSum'
                  (λy → I : fencode enca y)
      g * h      → λ(x :*: y) → fencode enca x ++ fencode enca y
      Empty      → const []
      Par        → enca . unParF
      Rec        → unRecF
      d@g        → encode (fencode enca) . unCompF
      Const Int  → encodeInt . unConstF
      Const Char → encodeChar . unConstF

foldSum :: (g a b → c) → (h a b → c) → ((g + h) a b → c)

```

Function decode. Function *decode* is the inverse of function *encode*.

```

data Dec a = Dec ([Bit] → (a, [Bit]))
apply :: Dec a → [Bit] → (a, [Bit])
apply (Dec f) = f

instance Monad Dec where
  return x    = Dec (λbits → (x, bits))

```

```

Dec f >>= g = Dec (λbits → let (result, rest) = f bits
                               Dec g'      = g result
                               in  g' rest
                               )
decode      :: Regular d ⇒ Dec a → Dec (d a)
decode deca = liftM inn (fdecode deca (decode deca))
polytypic fdecode :: Dec a → Dec b → Dec (f a b) =
  λdeca decb →
    case f of
      g + h      →
        Dec (λbits → case bits of
                    O : bs → mapFst InL
                        (apply (fdecode deca decb) bs)
                    I : bs → mapFst InR
                        (apply (fdecode deca decb) bs)
                    )
      g * h      → fdecode deca decb >>= λx →
                    fdecode deca decb >>= λy →
                    return (x *: y)
      Empty      → return EmptyF
      Par        → deca >>= (return . ParF)
      Rec        → decb >>= (return . RecF)
      d@g        → decode (fdecode deca decb) >>= (return . CompF)
      Const Int  → decodeInt >>= (return . ConstF)
      Const Char → decodeChar >>= (return . ConstF)

```

where $liftM :: Monad\ m \Rightarrow (a \rightarrow b) \rightarrow (m\ a \rightarrow m\ b)$ lifts a function to the level of monads. Given the definition of function *encode*, the definition of function *decode* is rather standard.

The definition of the polytypic functions *eq* and *map* contain no surprises: both are similar to the definitions of function *fmap2* and *encode*, and can be found in PolyLib.

Function update. Function *update* is the same as the polytypic copy or identity function, except for a special case for the structure representation type *Const Salary*.

```

update :: Regular d ⇒ d a → d a
update = inn . fupdate id update . out
polytypic fupdate :: (a → b) → (c → d) → f a c → f b d =
  λp r →
    case f of
      g + h      → fupdate p r +- fupdate p r
      g * h      → fupdate p r -* fupdate p r
      Empty      → λEmptyF → EmptyF
      Par        → ParF . p . unParF

```

Rec	$\rightarrow \text{RecF} \quad . r$	$. \text{unRecF}$
d@g	$\rightarrow \text{CompF} . \text{update} . \text{pmap} (\text{fupdate } p \ r)$	$. \text{unCompF}$
Const Salary	$\rightarrow \text{ConstF} . \text{updateSalary}$	$. \text{unConstF}$
Const t	$\rightarrow \text{ConstF} . \text{id}$	$. \text{unConstF}$

$\text{updateSalary } (S \ f) = S \ (f * (1 + 0.15))$

PolyP does not support default cases as in Generic Haskell, so it is impossible to extend the identity function with new behavior in PolyP.

Evaluation

Structural dependencies. PolyP adds polytypic functions, which depend on types, to Haskell.

Full reflexivity. PolyP is not fully reflexive: polytypic functions can only be used on regular data types of kind $\star \rightarrow \star$. Important classes of data types for which polytypic functions do not work are mutually-recursive data types and data types of kind \star .

Type universes. PolyP only works on regular data types of kind $\star \rightarrow \star$. Besides the obvious disadvantages, this has an advantage as well: since the structure of regular data types of kind $\star \rightarrow \star$ can be described by a bifunctor, we can define functions like the catamorphism on arbitrary data types in PolyP. The catamorphism cannot be defined in Generic Haskell without the concept of generic views. PolyP supports defining generic functions on particular data types using the `Const` case.

First-class generic functions. Polytypic functions are not first class.

Multiple type arguments. Polytypic functions are defined by induction over a single bifunctor.

Type system. Polytypic functions are explicitly typed. The compiler checks type-correctness of polytypic functions.

Type safety. Type-correct polytypic functions are translated to type-correct Haskell functions. Forgetting an arm in the case expression of a polytypic function leads to an error when the generated Haskell is compiled or interpreted.

The type of a generic function. Types of polytypic functions are direct abstractions of types on normal data types, and closely correspond to intuition.

Properties of generic functions. Jansson and Jeuring [50, 44] show how to reason about polytypic functions, and how to derive a property of a polytypic function from its type.

Integration with the underlying programming language. The integration of polytypic programming and Haskell is not completely seamless. PolyP does not know about classes, about types of kind other than $\star \rightarrow \star$, and lacks several syntactic constructions that are common in Haskell, such as **where** and operator sections. It is wise to separate the polytypic functions from other functions in a separate file, and only compile this file with PolyP.

Polytypic functions can be used on values of data types without any extra work. It is not necessary to specify a type argument: PolyP infers the data types on which a polytypic function is called, and uses this information to specialize a polytypic function for a particular data type.

Specialization versus interpretation. PolyP specializes applications of polytypic functions at compile-time.

Code optimization Like Generic Haskell, PolyP does not optimize away the extra marshaling that is introduced by the compiler for instances of polytypic functions. This might be an impediment for some applications.

Separate compilation. PolyP provides separate compilation.

Practical aspects. A compiler for PolyP can be downloaded. It is usable on the platforms on which GHC is available. It is not very actively maintained anymore: the latest release is from 2004. It is reasonably well documented, although not all limitations are mentioned in the documentation. PolyP's error messages can be improved.

4.3 Scrap Your Boilerplate

Scrap Your Boilerplate (SYB) [54, 56] is a library that provides combinators to build traversals and queries in Haskell. A traversal processes and selectively modifies a possibly complex data structure, whereas a query collects specific information from a data structure. Using SYB one can extend basic traversals and queries with type-specific information, thereby writing generic functions.

Generic functions in SYB are applicable to all data types of the type class *Data*. This class provides fundamental operations to consume or build values of a data type, as well as general information about the structure of a data type. All other functions are built on top of methods of the class *Data*.

A partial definition of the class *Data* is shown in Figure 2.

The functions *toConstr* yields information about the data constructor that has constructed the given value. The data type *Constr* is abstract and can be queried for information such as the name of the constructor, or the data type it belongs to.

Similarly, *dataTypeOf* returns information about the data type of a value, again encapsulated in an abstract data type *DataType*.

The function *gfoldl* is a very general function that allows the destruction of a single input value – the third argument – of type *a* into a result of type *f a*.

```

class (Typeable a) => Data a where
  toConstr    :: a -> Constr
  dataTypeOf  :: a -> DataType
  gfoldl      :: ∀f .
                (∀a b. Data a => f (a -> b) -> a -> f b)
                -> (∀a . a -> f a)
                -> a -> f a

```

Fig. 2. Partial definition of the type class *Data*

Almost any Haskell value is an application of a data constructor to other values. This is the structure that *gfoldl* works on. If a value *v* is of the form

$$C \ v_1 \ v_2 \ \dots \ v_n$$

then *gfoldl* (\diamond) *c v* is

$$(\dots ((c \ C \diamond v_1) \diamond v_2) \diamond \dots \diamond v_n).$$

The second argument *c* is applied to the data constructor *C*, and each application is replaced by the first argument (\diamond). In particular,

$$unId . gfoldl (\lambda x \ y \rightarrow Id \ (unId \ x \ y)) \ Id$$

is the identity on types of class *Data*. Here, the auxiliary type

$$\text{newtype } Id \ a = Id \{ unId :: a \}$$

is used, because the result type of *f a* of *gfoldl* can be instantiated to *Id a*, but not directly to *a* in Haskell. If we could, then

$$gfoldl \ (\$) \ id$$

would be the identity, making the role of *gfoldl* more obvious.

With the help of *gfoldl*, a basic query combinator can be defined, which also forms part of the SYB library:

$$gmapQ :: \forall a. Data \ a \Rightarrow (\forall b. Data \ b \Rightarrow b \rightarrow c) \rightarrow a \rightarrow [c].$$

A call *gmapQ q x* takes a query *q* (of type $\forall b. Data \ b \Rightarrow b \rightarrow c$) and applies it to the immediate subterms of *x*, collecting the results in a list.

Function encode. A good example of a function using *gmapQ* is the function *encode*, which can be written using the SYB library as follows:

$$\begin{aligned}
encode &:: Data \ a \Rightarrow a \rightarrow [Bit] \\
encode \ x &= concat \ (encodeConstr \ (toConstr \ x) : gmapQ \ encode \ x).
\end{aligned}$$

The function *encodeConstr* takes the current constructor and encodes it as a list of bits:

$$\begin{aligned} \text{encodeConstr} &:: \text{Constr} \rightarrow [\text{Bit}] \\ \text{encodeConstr } c &= \text{intinrange2bits } (\text{maxConstrIndex } (\text{constrType } c)) \\ &\quad (\text{constrIndex } c - 1). \end{aligned}$$

The function *intinrange2bits*, which encodes a natural number in a given range as a list of bits, comes from a separate Haskell module for manipulating bits. In *encode*, the constructor for the current value *x* is encoded, and we use *gmapQ* to recursively encode the subterms of *x*.

With *encode*, we can for instance encode booleans, lists, trees etc: we have a generic function. However, the default behavior is unsuitable for handling base types such as *Int* and *Char*. If we want to use type-specific behavior such as *encodeInt* and *encodeChar*, the SYB library allows us to extend a query with a type-specific case, using *extQ*:

$$\text{extQ} :: \forall a \, b \, c. (\text{Typeable } a, \text{Typeable } b) \Rightarrow (a \rightarrow c) \rightarrow (b \rightarrow c) \rightarrow (a \rightarrow c).$$

This function makes use of run-time type information which is encapsulated in the type class *Typeable* and available for all types in *Data*, as *Typeable* is a superclass of *Data*. It is essentially a one-branch *type-case*. Using *extQ*, we can write *encode* with type-specific behavior for *Ints* and *Chars*:

$$\begin{aligned} \text{encode} &:: \text{Data } a \Rightarrow a \rightarrow [\text{Bit}] \\ \text{encode} &= (\lambda x \rightarrow \text{concat } (\text{encodeConstr } (\text{toConstr } x) : \text{gmapQ } \text{encode } x)) \\ &\quad \text{'extQ' } \text{encodeInt} \\ &\quad \text{'extQ' } \text{encodeChar}. \end{aligned}$$

Note that we cannot reuse the previously defined version of *encode* in this new definition, because the recursive call to *encode* that appears as an argument to *gmapQ* must point to the extended function (this is solved by the modified approach discussed in the section on “SYB with Class”).

Function decode. The *gfoldl* combinator is only suitable for *processing* values. In order to write a generic *producer* such as *decode*, a different combinator is required. The *Data* class provides one, called *gunfold*:

$$\begin{aligned} \text{gunfold} &:: \forall a \, f. \\ &\quad (\forall a \, b. \text{Data } a \Rightarrow f (a \rightarrow b) \rightarrow f b) \\ &\quad \rightarrow (\forall a. a \rightarrow f a) \\ &\quad \rightarrow \text{Constr} \rightarrow f a. \end{aligned}$$

If *d* :: *Constr* is the constructor information for the data constructor *C*, which takes *n* arguments, then *gunfold app c d* is

$$\text{app } (\dots (\text{app } (c \, C)) \dots),$$

thus *app* applied *n* times to *c* *C*. As with *gfoldl*, SYB provides several combinators built on top of *gunfold*, the most useful being *fromConstrM*, which monadically constructs a value of a certain constructor:

$$\begin{aligned} \text{fromConstrM} &:: \forall a f. (Data\ a, Monad\ f) \Rightarrow (\forall b. Data\ b \Rightarrow f\ b) \rightarrow \\ &\quad Constr \rightarrow f\ a \\ \text{fromConstrM}\ p &= \text{gunfold}\ ('ap'\ p)\ \text{return}. \end{aligned}$$

Here, $ap :: \forall a b f. Monad\ f \Rightarrow f\ (a \rightarrow b) \rightarrow f\ a \rightarrow f\ b$ is lifted function application.

Using *fromConstrM*, we can define *decodes*, a monadic version of *decode* that keeps the “current” list of bits as state in a state monad:

```
decodes :: Data a => State [Bit] a
decodes  = decodes' ⊥
          'extR' decodesInt
          'extR' decodesChar

where
  decodes'      :: Data a => a → State [Bit] a
  decodes' dummy =
    do let d = dataTypeOf dummy
        l   = length (int2bits (length (dataTypeConstrs d) - 1))
        c ← consume l
        let con = decodeConstr c d
        fromConstrM decodes con.
```

A few remarks are in order. The function *decodes* calls *decodes'* with \perp . This is a convenient way to obtain a value of the result type *a*, so that we can apply *dataTypeOf* to it. The function *decodes'* reads in *l* bits from the input via *consume*, interprets these bits as a constructor *con* using *decodeConstr*, and finally employs *fromConstrM* to decode the children of the constructor recursively. Both *consume* and *decodeConstr* are easy to define. Type-specific behavior for integers and characters is added to the function using the SYB extension operator *extR*, which plays a role analogous to *extQ*, in the context of monadic generic producers:

$$\text{extR} :: \forall a b f. (Monad\ f, Typeable\ a, Typeable\ b) \Rightarrow f\ a \rightarrow f\ b \rightarrow f\ a.$$

From *decodes*, we get *decode* in the obvious way:

```
decode :: Data a => [Bit] → a
decode bs = case runState decodes bs of
  (r, []) → r
  _       → error "decode: no parse".
```

Function eq. The definition of generic equality in SYB is simple, but requires yet another combinator:

```

eq :: Data a => a -> a -> Bool
eq = eq'
eq' :: (Data a, Data b) => a -> b -> Bool
eq' x y = toConstr x == toConstr y & and (gzipWithQ eq' x y).

```

The function *eq* is a type-restricted variant of *eq'*, which accepts two arguments of potentially different types. The constructors of the two values are compared, and *gzipWithQ* is used to pairwise compare the subterms of the two values recursively.

The combinator *gzipWithQ* is a two-argument variant of *mapQ*. It is a bit tricky to define, but it can be defined in terms of *gfoldl*.

Note that *eq'* requires the relaxed type, because the subterms of *x* and *y* only have compatible types if they really are of the same data constructor. If we compare unequal values, we are likely to get incompatible types sooner or later.

The trick to relax the type of a generic function is not always applicable. For example, if we also want to extend equality on an abstract type for which we only have a normal equality function (one that expects two arguments of the same type), we have to make sure that both arguments are indeed of the same type. In this case, we can use the dynamically available type information from class *Typeable* to define a unification function

```
unify :: (Typeable a, Typeable b) => Maybe (a -> b)
```

and then call *unify* to coerce the types where necessary.

Function map. A generic function such as *map* that abstracts over a type constructor cannot be defined using SYB, because the *Data* class contains only types of kind ***. It is possible to define variants of *map*, such as traversals that increase all integers in a complex data structure, but it isn't possible to define a function of type

$$\forall a \, b \, f. (a \rightarrow b) \rightarrow f \, a \rightarrow f \, b,$$

where the arguments of the container type *f* are modified, and the function is parametrically polymorphic in *a* and *b* (cf. the section on “SYB Revolutions” below)

Function show. We define *show* in two steps, as we have done in the Generic Haskell case. The function *showP* takes an additional string transformer that encodes whether to place surrounding parentheses on non-atomic expressions or not.

We have already seen how constructor information can be accessed in the definition of *encode*. Therefore, the definition of *showP* does not come as a surprise:

```

showP :: Data a => (String -> String) -> a -> String
showP p = (\x -> showApp (showConstr (toConstr x))

```

```

                                (gmapQ ((+) " " . showP parens) x))
    'ext1Q' showList
    'extQ' (Prelude.show :: String → String)
where
    parens x = "(" ++ x ++ ")"
    showApp :: String → [String] → String
    showApp x [] = x
    showApp x xs = p (concat (x : xs))
    showList :: Data a ⇒ [a] → String
    showList xs =
        "[" ++ concat (intersperse ", " (map (showP id) xs)) ++ "]"

```

We feed each constructor application to *showApp*. On atomic subexpressions, *showApp* never produces parentheses, otherwise it consults *p*.

The most interesting part is how to define type-specific behavior for lists and strings. Placing strings between double quotes is achieved by the standard Haskell *show* function using the *extQ* extension operator. However, the more general syntactic sugar for lists (placed between square brackets, elements separated by commas) is not achieved so easily, because *showList* is a polymorphic function, and *extQ* only works if the second argument is of monomorphic type. SYB therefore provides a special, polymorphic, extension operator

$$\text{ext1Q} :: \forall a \, c. (\text{Typeable1 } f, \text{Data } a) \Rightarrow (a \rightarrow c) \rightarrow (\forall b. \text{Data } b \Rightarrow f \, b \rightarrow c) \rightarrow (a \rightarrow c).$$

Note that polymorphic extension requires a separate operator for each kind, and also a separate variant of the cast operation: the run-time type information of the type constructor *f* of kind $* \rightarrow *$ is made available using the type class *Typeable1* rather than *Typeable*.

Function update. Traversals that update a large heterogeneous data structure in selective places were one of the main motivations for designing SYB. Therefore, it isn't surprising that defining such a traversal is extremely simple:

```

update :: Data a ⇒ a → a
update = everywhere (id 'extT' (λ(S s) → S (s * (1 + 0.15)))).

```

The argument to *everywhere* is the identity function, extended with a type-specific case for the type *Salary*. The function *everywhere* is a SYB combinator that applies a function at any point in a data structure. It is defined in terms of

$$\text{gmapT} :: \forall a. \text{Data } a \Rightarrow (\forall b. \text{Data } b \Rightarrow b \rightarrow b) \rightarrow (a \rightarrow a),$$

a variant of *gmapQ* that applies a given generic function to the immediate sub-terms of a value. The *gmapT* can again be defined using *gfoldl*.

Derived work: SYB with Class. Lämmel and Peyton Jones have shown [55] that using type classes rather than run-time type casts can make generic programming using SYB more flexible. Their work aims at replacing SYB extension operators such as *extQ* and *extR*: each generic function is then defined as a class with a default behavior, and type-specific behavior can be added by defining specific instances of the class.

This approach is a bit more verbose, but has a significant advantage: instances of classes can be added in a modular way, also at a later stage. There is always the possibility to extend an already existing generic function with new behavior, without modification of already written code. For instance, we can solve the problem of adding type-specific cases for `Int` and `Char` to the *encode* function above. The function *encode* would be defined in a type class, and adding the additional cases would amount to adding two additional instances for `Int` and `Char` that override the generic behavior.

Derived work: SYB Reloaded and Revolutions. In their SYB Reloaded and Revolutions papers, Hinze, Löb and Oliveira [38, 37] demonstrate that SYB’s *gfoldl* function is in essence a catamorphism on the `Spine` data type, which can be defined as follows:

```
data Spine a where
  Constr :: Constr → a → Spine a
  (◇)    :: Data a ⇒ Spine (a → b) → a → Spine b.
```

Furthermore, a “type spine” type is given as a replacement for *gunfold*, and a “lifted spine” type for generic functions that are parameterized over type constructors. For example, using the lifted spine type, *map* can be defined.

Evaluation

Structural dependencies. SYB allows the definition of generic functions. There is no support for defining type-indexed data types.

Full reflexivity. The SYB approach is not fully reflexive. Generic functions are only applicable to data types for which a *Typeable* instance can be specified. This implies, amongst others, that higher-order kinded data types such as `GRose` cannot be turned into instance declarations as this requires so-called *higher-order contexts*. The original proposal for Derivable Type Classes (discussed in Section 4.5) recognizes this shortcoming and proposes a solution in the form of higher-order contexts, but this extension has never been implemented.

Type-specific behavior is only possible for types of kind `*`.

Type universes. There is no support for type universes in SYB. All generic functions are supposed to work on all types in the *Typeable* class.

First-class generic functions. In SYB, generic functions are normal polymorphic Haskell functions, and as such are first-class under the precondition of arbitrary-rank polymorphism.

Multiple type arguments. There is no restriction on the number of type arguments that a generic function can have in SYB, although the basic combinators are tailored for functions of the form

$$\text{Data } a \Rightarrow a \rightarrow \dots$$

that consume a single value.

Type system. SYB is completely integrated in Haskell’s type system.

Type safety. SYB is type-safe, but type-specific extensions of generic functions rely on run-time type casting via the *Typeable* class. It is possible for a user to break type safety by defining bogus instances for the *Typeable* class. The implementation could be made more robust if user-defined instances of class *Typeable* would not be allowed, and all *Typeable* instances would be derived automatically by the compiler.

The type of a generic function. Types of generic functions have one or more constraints for the *Data* class. The types are intuitive.

Properties of generic functions. The use of type classes *Data* and *Typeable* at the basis of SYB makes proving properties relatively difficult. Instances for these classes can be generated automatically, but automatic generation is only described informally. User-defined instances of these classes can cause unintended behavior. There is no small set of fundamental data types (such as Generic Haskell’s unit, binary sum, and binary pair types) to which Haskell data types are reduced. Lämmel and Peyton Jones state a few properties of basic SYB combinators in the original paper, but provide no proof. The only work we are aware of trying to prove properties about SYB is of Reig [74], but he translates SYB combinators into Generic Haskell to do so.

Integration with the underlying programming language. SYB is fully integrated into Haskell. The module `Data.Generics` contains all SYB combinators. The options `-fglasgow-exts` is required for GHC to support the higher-ranked types of some of the SYB combinators. No extra work is needed to use a generic function on a data type other than writing `deriving (Data, Typeable)` after the data-type declaration.

Specialization versus interpretation. The SYB approach makes use of run-time type information. Generic functions have *Data* class constraints. Most Haskell compilers implement type classes using *dictionary passing*: for each *Data* constraint, a record containing the appropriate class methods is passed along at run-time. The *Data* is a subclass of *Typeable*, which provides the actual structure of the type at run-time. This information is used to provide run-time type casts to enable type-specific behavior.

Code optimization. As SYB is a Haskell library, the code is not optimized in any special way. The implementation of generic functions is relatively direct, the only overhead is due to the passing of class dictionaries and the use of many higher-order functions.

Separate compilation. Generic functions are normal Haskell functions, and can be placed in different modules and compiled separately. Generic functions themselves are not extensible, however. If new specific cases must be added to a generic function, the whole definition has to be repeated. This restriction is lifted by “SYB with Class”.

Practical aspects. SYB is shipped as a library with current releases of GHC and supported. It is planned to provide the functionality of “SYB with Class” in future releases of GHC. The `Spine` data type from “SYB Reloaded” is not yet used in the official release, but might be integrated in the future.

4.4 Approaches based on reflection

Both DrIFT [81] and generic programming approaches using Template Haskell [70] use a kind of reflection mechanism to generate instances of generic functions for a data type. Generic functions are defined on an abstract syntax for data types. This section introduces and evaluates these two approaches.

DrIFT

DrIFT is a type sensitive preprocessor for Haskell. It extracts type declarations and directives from Haskell modules. The directives cause rules to be fired on the parsed type declarations, generating new code which is then appended to the bottom of the input file. An example of a directive is:

```
{- ! for Foo derive : update, Show -} .
```

Given such a directive in a module that defines the data type `Foo`, and rules for generating instances of the function `update` and the class `Show`, DrIFT generates a definition of the function `update` on the data type `Foo`, and an instance of `Show` for `Foo`. The rules are expressed as Haskell code, and a user can add new rules as required.

DrIFT comes with a number of predefined rules, for example for the classes derivable in Haskell and for several marshaling functions between Haskell data and, for example, XML, ATerm, and a binary data format.

A type is represented within DrIFT using the following data definition.

```
data Statement = DataStmt | NewTypeStmt
data Data = D { name      :: Name      -- type name
               , constraints :: [(Class, Var)] -- constraints on type vars
               , vars      :: [Var]     -- parameters
```

```

        , body      :: [Body]      -- the constructors
        , derives   :: [Class]    -- derived classes
        , statement :: Statement  -- data or newtype
      }
type Name    = String
type Var     = String
type Class   = String

```

A value of type `Data` represents one parsed data or newtype statement. These are held in a `D` constructor record. The body of a data type is represented by a value of type `Body`. It holds information about a single constructor.

```

data Body = Body{ constructor :: Constructor -- constructor name
                  , labels     :: [Name]    -- label names
                  , types      :: [Type]    -- type representations
                }
type Constructor = String

```

The definition of `Type` is as follows.

```

data Type = Arrow Type Type -- function type
          | Apply Type Type -- application
          | Var String      -- variable
          | Con String      -- constant
          | Tuple [Type]    -- tuple
          | List Type       -- list
          deriving (Eq, Show)

```

For example, the data type `CharList` is represented internally by:

```

reprCharList = D{ name      = "CharList"
                  , constraints = []
                  , vars      = []
                  , body      = [bodyNil, bodyCons]
                  , derives   = []
                  , statement = DataStmt
                }
bodyNil      = Body{ constructor = "Nil"
                    , labels     = []
                    , types      = []
                  }
bodyCons     = Body{ constructor = "Cons"
                    , labels     = []
                    , types      = [Con "Char"
                                     , Con "CharList"]
                  }

```

A rule consists of a name and a function that takes a **Data** and returns a document, a value of type **Doc**, containing the textual code of the rule for the **Data** value. The type **Doc** is defined in a module for pretty printing, and has several operators defined on it, for putting two documents beside each other ($<+>$) (list version *hsep*), above each other $\\$\\$$ (list version *vcats*), for printing texts (*text* and *texts*), etc [41]. Constructing output using pretty-printing combinators is easier and more structured than manipulating strings.

Function encode. We now explain the rules necessary for obtaining a definition of function *encode* on an arbitrary data type. For that purpose, we define the following class in our test file.

```
class Encode a where
  encode :: a → [Bit]
```

and ask DrIFT to generate instances of this class for all data types by means of the directive `{- ! global : encode -}`. For example, for the type **CharList** it should generate:

```
instance Encode CharList where
  encode Nil          = [O]
  encode (Cons aa ab) = [I] ++ encode aa ++ encode ab.
```

Rules for generating such instances have to be added to the file **UserRules.hs**.

```
encodefn  :: Data → Doc
encodefn d =
  instanceSkeleton "Encode"
    [(makeEncodefn (mkBits (body d)), empty)]
    d

mkBits    :: [Body] → Constructor → String
mkBits bodies c = ( show
  . intinrange2bits (length bodies)
  . fromJust
  . elemIndex c
  . map constructor
  ) bodies
```

The function *encodefn* generates an instance of the class *Encode* using the utility function *instanceSkeleton*. It applies *makeEncodefn* to each *Body* of a data type, and adds the *empty* document at the end of the definition. The function *mkBits* takes a list of bodies, and returns a function that when given a constructor returns the list of bits for the constructor in its data type. For example, the list of bits for a data type with three constructors are $[[O, O], [O, I], [I, O]]$. As before, we use the utility function *intinrange2bits* to encode a natural number in a given range.

The function *makeEncodefn* takes an encoding function and a body, and returns a document containing the definition of function *encode* on the constructor

represented by the body. If the constructor has no arguments, *encode* returns the list of bits for the constructor, obtained by means of the encoding function that is passed as an argument. If the constructor does have arguments, *encode* returns the list of bits for the constructor, followed by the encodings of the arguments of the constructor. For the argument of *encode* on the left-hand side of the definition we have to generate as many variables as there are arguments to the constructor. These variables are returned by the utility function *varNames*. Function *varNames* takes a list, and returns a list, the length of which is equal to the length of the argument list, of variable names. The constructor pattern is now obtained by prefixing the list generated by *varNames* with the constructor. This is *conPat* in the definition below. The encodings of the arguments of the constructor are obtained by prefixing the generated variables with the function *encode*, and separating the elements in the list with the list-concatenation operator $\mathrel{++}$. Finally, *equals* is a utility function that returns the document containing an equality sign, '='.

```

makeEncodefn :: (Constructor → String) → (Body → Doc)
makeEncodefn enc (Body{ constructor = constructor, types = types }) =
  let bits = text (enc constructor)
      encodeText = text "encode"
      constrText = text constructor
  in let newVars = varNames types
      conPat    = parens . hsep $ constrText : newVars
      lhs      = encodeText <+> conPat
      rhs      = ( fsep
                  . sepWith (text "++")
                  . (bits:)
                  . map (λn → encodeText <+> n)
                  ) newVars
  in lhs <+> equals <+> rhs

```

Function decode. Decoding is a bit more complicated. First, we define the following class in our test file.

```

class Decode a where
  decodes    :: [Bit] → (a, [Bit])
  decode     :: [Bit] → a
  decode bits = let (a, rest) = decodes bits
                in if null rest
                   then a
                   else error "decode: non-empty rest"

```

Then we ask DrIFT to generate instances of this class for all data types by means of the directive `{- ! global : decode -}`. For example, for the type `CharList` it should generate:

```

instance Decode CharList where
  decodes (O : xs) = (Nil, xs)
  decodes (I : xs) = let (res1, xs1) = decodes xs
                      (res2, xs2) = decodes xs1
                      in (Cons res1 res2, xs2)
  decodes []      = error "decodes".

```

The decode function generates an instance of the class *Decode*. It adds the declaration of *decodes* on the empty list as the last line in each class instance.

```

decodefn  :: Data → Doc
decodefn d =
  instanceSkeleton "Decode"
    [(mkDecodefn (mkBitsPattern (body d))
      , text "decodes [] = error \"decodes\"" )
    ]
  d

```

Here, function *mkBitsPattern* is almost the same as function *mkBits*, except for the way in which the list of bits is shown. We omit its definition.

The function *mkDecodefn* produces the cases for the different constructors. The left-hand side of these cases are obtained by constructing the appropriate bits pattern. The right-hand side is obtained by means of the function *decodechildren*, and returns a constructor (applied to its arguments). If a constructor has no arguments this is easy: return the constructor. If a constructor does have arguments, we first *decode* the arguments, and use the results of these decodings as arguments to the constructor.

```

mkDecodefn :: (Constructor → String) → (Body → Doc)
mkDecodefn enc body =
  let decodesText = text "decodes"
  decodechildren b =
    let nrOfArgs  = length (types b)
        argsList = [1 .. nrOfArgs]
        listOfArgs = text "xs" : map ((text "xs" <>) . int) argsList
        listOfRess = map ((text "res" <>) . int) argsList
        listOfRests = map ((text "xs" <>) . int) argsList
        constrText = text (constructor b)
    in if nrOfArgs == 0
      then parens (constrText <+> comma <+> text "xs")
      else text "let"
          $$ vcat (map (nest 2)
            (zipWith3
              (λr rs arg →
                parens (r <+> comma <+> rs)
              <+> equals
              <+> decodesText

```

```

                                <+> arg
                                ) listOfRess listOfRests listOfArgs
                                )
                                )
    $$ text "in"
    <+> parens (
        ( constrText
          <+> hsep listOfRess
          <+> comma
          <+> text "xs" <> int nrOfArgs
        )
    in      decodesText
    <+> parens (text (enc (constructor body)) <> text "xs")
    <+> equals
    <+> nest 6 (decodechildren body)

```

Instances of class Eq. The rules necessary for generating an instance of the class *Eq* for a data type are very similar to the rules for generating an instance of the class *Encode*. These rules are omitted, and can be found in the file `StandardRules.hs` in the distribution of DrIFT.

Function map. The rules for generating instances of the *map* function on different data types differ from the rules given until now. The biggest difference is that we do not generate instances of a class. Any class definition is of the form **class** *C* *t* **where** ..., in which the kind of the type *t* is fixed. So suppose we define the following class for *map*:

```

class Map t where
  map :: (a → b) → t a → t b.

```

Then we can only instantiate this class with types of kind $\star \rightarrow \star$. Since the data type of generalized trees *GTree* has kind $\star \rightarrow \star \rightarrow \star$, we cannot represent the ‘standard’ *map* function on *GTree* by means of an instance of this class. Instead, we generate a separate *map* function on each data type. For example, on the type *GTree* we obtain:

```

mapGTree fa fb GEmpty      = GEmpty
mapGTree fa fb (GLeaf a)   = GLeaf (fa a)
mapGTree fa fb (GBin l v r) = GBin (mapGTree fa fb l)
                               (fb v)
                               (mapGTree fa fb r).

```

The function *mapfn* generates a definition of *map* for each constructor using *mkMapfn*. The function *mkMapfn* takes as arguments the name of the data type (for generating the name of the *map* function on the data type) and the variables of the data type (for generating the names of the function arguments of *map*).

```

mapfn :: Data → Doc
mapfn (D{ name = name, vars = vars, body = body }) =
  vcat (map (mkMapfn name vars) body)

```

Function *mkMapfn* creates the individual arms of the *map* function. For generating the right-hand side, it recurses over the type of the constructor in the declaration *rhsfn*.

```

mkMapfn name vars (Body{ constr = constructor, types = types }) =
  let mt name = text ("map" ++ name)
      mapArgs = hsep (texts (map (λv → 'f' : v) vars))
      newVars = varNames types
      conPat   = parens . hsep $ text constr : newVars
      lhs      = mt name <+> mapArgs <+> conPat
      rhs      = hsep (text constr
                        : map (parens . rhsfn) (zip newVars types)
                        )
      rhsfn    = λ(newVar, rhstype) →
                  case rhstype of
                    LApply t ts → hsep
                                (mt (getName t)
                                 : hsep (map mkMapName ts)
                                 ++ [newVar]
                                )
                    Var v      → text ('f' : v) <+> newVar
                    Con s      → mt s <+> newVar
                    List t      → text "map"
                                <+> parens (mt (getName t)
                                <+> mapArgs
                                )
                                <+> newVar
                                x      → newVar
  in lhs <+> equals <+> rhs

```

The utility functions *mkMapName* and *getName* return the name of the function to be applied to the arguments of a constructor, and the name of a type, respectively.

```

mkMapName (LApply s t) = parens (mkMapName s
                                   <+> hsep (map mkMapName t)
                                   )
mkMapName (Var s)      = text ('f' : s)
mkMapName (Con s)      = text ("map" ++ s)
mkMapName (List t)     = text "map" <+> mkMapName t
mkMapName _            = error "mkMapName"
getName (LApply s t)   = getName s
getName (Var s)        = s

```

```

getName (Con s)      = s
getName (List t)     = getName t
getName _            = error "getName"

```

Template Haskell

Template Haskell is a language extension that allows meta-programming within the Haskell language. Template Haskell consists of multiple components.

A library (exported by *Language.Haskell.TH*) provides access to the abstract syntax of the Haskell language. This makes it possible to analyze and construct Haskell programs within Haskell. A monad **Q** is provided to generate fresh names on demand.

Haskell expressions can be *quoted* to easily construct terms in the abstract syntax. For example,

```
[[2 + 2]] :: Q Exp.
```

Template Haskell supports reflection (*reification*), so that it is possible to analyze the structure of an already defined value or data type:

```
reify :: Name → Q Info.
```

The **Info** data type has multiple constructors corresponding to different kinds of declarations, but in particular, there is a constructor for data types:

```

data Info = ...
           | TyConI Dec
data Dec = ...
           | DataD Cxt Name [Name] [Con] [Name]
data Con = NormalC Name [StrictType]
           | RecC Name [VarStrictType]
           | InfixC StrictType Name StrictType
           | ForallC [Name] Cxt Con.

```

Each data type comprises a context (possible class constraints), a name, a list of parameters, a list of constructors, and a list of classes it automatically derives. Constructors can either be normal constructors, records, infix constructors, or constructors with quantification. A **StrictType** is a type with a possible strictness annotation, a **VarStrictType** additionally contains a record label.

Finally, in Template Haskell we can *splice* values constructed in the abstract syntax into Haskell programs, making it possible to run programs that are generated by meta-programs. Splicing is dual to quoting, so that

```
$( [[2 + 2]] ) :: Int
```

results in 4.

By its very nature, Template Haskell can be used to write programs that cannot be expressed, or are at least difficult to express, in the Haskell language, such as generic programs. With Template Haskell, we can analyze data-type definitions, and depending on their structure, generate specialized code.

It is important to realize that Template Haskell itself is not an approach to generic programming, but more like an implementation technique. Template Haskell gives the programmer a lot of power and freedom, but does not provide any guidance or even a framework for generic programming.

While DrIFT’s main focus is to generate type-class instances, we can use Template Haskell much more flexibly:

- we can generate the structure-representation type (like in Generic Haskell) for a given data type, plus the embedding-projection pairs;
- for a generic function, we can construct a recipe that uses the abstract syntax of a data type to construct the abstract syntax of a specialized instance of the generic function;
- we can generate instances of a type class, both for a generic function directly (like in DrIFT, Derivable Type Classes, or Generics for the Masses), or for a powerful combinator like *gfold* in Scrap Your Boilerplate.

In principle, Template Haskell can be used to simulate or support any approach to generic programming in Haskell. However, we also run into many of the problems that we encountered in DrIFT:

- everything happens at the syntactic level, not the semantic level. While constructing generic functions, we have to pay attention to low-level concepts such as free and bound variables;
- the analysis of data types is also purely syntactic. We do not have access to kind information, or recursion on the type level, directly, but have to infer that from the definitions; writing generic functions for mutually recursive data types or higher-order data types is difficult, because we have to implement parts of a compiler;
- there is no guarantee that the meta-programs produce correct code under all circumstances. The generated code is type-checked, so we are safe from errors in the end, but this is a much weaker guarantee than we get from other approaches such as Generic Haskell, where we know that the type-correctness of a generic definition implies the type-correctness of all instances.

Because of the above-mentioned freedom, it is difficult to implement the canonical examples for generic programming using Template Haskell: there is no single idiomatic version of a generic function, but there are many different possibilities. We therefore don’t include specific examples in this document.

We are aware of one attempt to provide a serious framework for generic programming within Template Haskell: Norell and Jansson [70] present a very sophisticated encoding of both PolyP and Generic Haskell into Template Haskell. Among other things, they describe how to define generic *map* in the two different encodings.

Evaluation

Structural dependencies. DrIFT and Template Haskell support the definition of functions that take the abstract syntax of a data type as an argument, and return executable Haskell code. In principle, both DrIFT and Template Haskell can generate any document, even type-indexed data types. Especially for DrIFT, generating anything else than class instances amounts to writing part of a compiler for generic programming. In Template Haskell, it is feasible to design at least a reusable framework for such advanced tasks. Both systems provide no way to access type or kind information of the analyzed code. In particular, the lack of kind inference for data types makes the creation of generic programs on complex data types tedious.

Full reflexivity. DrIFT is not fully reflexive with respect to the set of data types definable in Haskell 98: it cannot handle data types with type variables of higher-order kinds, such as `GRose`. Just as Generic Haskell, DrIFT cannot generate instances of functions on existential types or on GADTs.

We see, however, no reason in principle why DrIFT cannot be fully reflexive with respect to the data types definable in Haskell 98.

Template Haskell’s abstract syntax handles all of Haskell 98 and beyond. It does not yet support GADTs, but there is no reason why it could not be extended in that way. Full reflexivity therefore depends on the generic-programming approach one tries to simulate within Template Haskell.

Type universes. There is no support for type universes in DrIFT. Neither does Template Haskell have any direct support for this concept.

First-class generic functions. DrIFT rules are plain Haskell functions, they can take rules as arguments. First-class rules are inherited from Haskell. But it needs a lot of imagination to see rules as generic programs. And an instance of a class cannot be explicitly passed as an argument to a function or a class instance, so a rule that generates an instance of a class (the only supported kind of definition in DrIFT) cannot be passed as argument to a rule that generates a function or a class instance.

Similarly, we have all the abstraction possibilities of Haskell for generic programs within Template Haskell. We can write generic meta-programs that are parameterized over other generic meta-programs.

However, both DrIFT and Template Haskell are two-level approaches. DrIFT always needs to be invoked before compilation of a Haskell module to fill in the missing code. Template Haskell requires splicing of the generated code. Splicing is a syntactic construct which is foreign to the Haskell language and furthermore underlies certain restrictions (sometimes, code that contributes to Template Haskell programs must reside in several modules). Therefore, DrIFT and Template Haskell cannot provide generic functions that are truly first-class.

Multiple type arguments. Rules cannot take multiple type arguments in DrIFT. In Template Haskell, there are no theoretical limits.

Type system. Rules for generic functions all have the same type in DrIFT: $\text{Data} \rightarrow \text{Doc}$. There is no separate type system for rules; rules are ordinary Haskell functions. In Template Haskell, the situation is similar. All Haskell expressions, for instance, are of type `Exp` in the abstract syntax of expressions, but no further type information about the actual constructed expression is maintained. In particular, it is possible to construct type-incorrect expressions, causing type errors only when spliced.

Type safety. A type-correct rule does not guarantee that the generated code is type correct, as well. It is easy to define a type-correct rule that generates code that does not type-check in Haskell. DrIFT is not type safe. The same holds for Template Haskell, where the type correctness of a meta-program does not imply that the use of that meta-program produces type-correct code.

The type of a generic function. In DrIFT, every rule has type $\text{Data} \rightarrow \text{Doc}$. Thus it is impossible to distinguish generic functions by type. For Template Haskell, the type of generic functions depend completely on the approach that is simulated. Generally, however, not much of a generic function's type is reflected in the type of the meta-program: as in DrIFT, generic functions in Template Haskell typically map the abstract syntax of one or more data types to a number of Haskell declarations.

Properties of generic functions. Since rules generate pretty-printed documents (syntax), it is virtually impossible to specify properties of rules. For Template Haskell, it is similarly impossible to specify properties. However, libraries for generic programming defined in Template Haskell may allow to state and prove properties.

Integration with the underlying programming language. If a user wants to implement and use a new rule, DrIFT has to be recompiled. If a user wants to use a rule, adding a directive to a Haskell file suffices. Template Haskell is superior here, because Template Haskell code can almost freely be mixed with normal Haskell code. Sometimes, code has to be divided in separate modules.

Specialization versus interpretation. DrIFT specializes rules on data types following directives. Template Haskell also generates the programs in advance, but a hybrid approach is thinkable: in the simulation of a light-weight approach, some code would be generated for each data type, but a generic function would be interpreted.

Code optimization Code can be optimized by hand by specifying a more efficient rule or meta-program. There need not be an efficiency penalty when using DrIFT or Template Haskell.

Separate compilation. It is easy to use rules on data types that appear in a new module. Rules are separately compiled in DrIFT, and can then be used in any module. Separate compilation in Template Haskell is possible because of its integration with Haskell.

Practical aspects. DrIFT is actively maintained. The last release is from April 2006. It runs on many platforms. The user guide explains how to use DrIFT. Template Haskell is actively maintained as part of GHC, the flag `-fth` must be passed to GHC to be able to use it. Template Haskell is, however, still in development, with new GHC releases regularly changing the interface in an incompatible way. Documentation for the current state of affairs is difficult to come by, but this situation is likely to improve when the speed of development slows down.

No error messages are given for data types for which DrIFT cannot generate code. Error messages provided by Template Haskell are often in terms of the generated code and difficult to interpret for the user of a generic-programming library.

4.5 Light-weight approaches to generic programming

Due to Haskell’s advanced type language and type classes it is possible to write generic programs in Haskell itself, without extending the language. An approach in which generic programs are plain Haskell programs is called a light-weight approach. Light-weight approaches to generic programming in Haskell have become popular in the last couple of years. In this section we discuss three relatively light-weight approaches to generic programming: “A Light-weight Implementation of Generics and Dynamics”, “Generics for the Masses”, and “Derivable Type Classes”. The latter approach is actually a language extension, but since it shares many characteristics with the other two approaches, it is listed here.

Light-weight Implementation of Generics and Dynamics

Light-weight Implementation of Generics and Dynamics [14] (LIGD) is an approach to embedding generic functions and dynamic values into Haskell 98 augmented with existential types. For the purposes of these lecture notes we concentrate on the generics (which slightly simplifies the presentation). For the treatment of dynamics the interested reader is referred to the original paper [14] or to the companion lecture notes “Generic Programming, Now!”, which elaborate on a closely related approach to generic programming.

A generic function in Generic Haskell is parameterized by type, essentially performing a dispatch on the type argument. The basic idea of the light-weight approach is to reflect the type argument onto the value level so that the type-case can be implemented by ordinary pattern matching. As a first try, we could, for instance, assign the generic *encode* function the type $\forall t. \text{Rep} \rightarrow t \rightarrow [\text{Bit}]$, where *Rep* is the type of type representations. A moment’s reflection, however, reveals that this won’t work. The parametricity theorem [76] implies that a function of this type necessarily ignores its second argument. The trick is to use a parametric type for type representations: $\text{encode} :: \forall t. \text{Rep } t \rightarrow t \rightarrow [\text{Bit}]$. Here *Rep t* is the type representation of *t*. The one-million-dollar question is, of course, how can we define such a type?

Using a recent extension to Haskell, so-called generalized algebraic data types, `Rep` can be defined directly in Haskell, see also “Generic Programming, Now!”.

```
data Rep ::  $\star \rightarrow \star$  where
  Unit :: Rep Unit
  Int  :: Rep Int
  Sum  :: Rep a  $\rightarrow$  Rep b  $\rightarrow$  a :+: b
  Pair :: Rep a  $\rightarrow$  Rep b  $\rightarrow$  a :* b
```

A type t is represented by a term of type `Rep t`. Note that the above declaration cannot be introduced by a Haskell 98 data declaration since none of the data constructors has result type `Rep a`.

If one wants to stick to Haskell 98 (or modest extensions thereof), one has to encode the representation type somehow. We discuss a direct encoding in the sequel and a more elaborate one in Section 4.5. The idea is to assign, for instance, `Int`, the representation of `Int`, the type `Rep t` with the additional constraint that $t = \text{Int}$. The type equality is then encoded using the equivalence type $a \leftrightarrow b$ (the type is the same as the EP type of Section 2.2).

```
data a  $\leftrightarrow$  b = EP { from :: a  $\rightarrow$  b, to :: b  $\rightarrow$  a }
```

An element of $t \leftrightarrow t'$ can be seen as a ‘proof’ that the two types are equal. Of course, in Haskell, an equivalence pair only guarantees that t can be cast to t' and vice versa. This, however, turns out to be enough for our purposes. Figure 3 displays the full-fledged version of `Rep` that uses equivalence types. The constructors `Unit`, `Int`, `Char`, `Sum`, `Pair` and `Con` correspond to the type

```
data Rep t =
  | Unit      (t  $\leftrightarrow$  Unit)
  | Int       (t  $\leftrightarrow$  Int)
  | Char      (t  $\leftrightarrow$  Char)
  |  $\forall a\ b.$  Sum (Rep a) (Rep b) (t  $\leftrightarrow$  (a :+: b))
  |  $\forall a\ b.$  Pair (Rep a) (Rep b) (t  $\leftrightarrow$  (a :* b))
  |  $\forall a.$  Type  (Rep a) (t  $\leftrightarrow$  a)
  | Con String (Rep t)
```

Fig. 3. A type-representation type.

patterns `Unit`, `Int`, `Char`, `:+:`, `:*` and `Con` in Generic Haskell. The constructor `Type` is used for representing user-defined data types, see below.

In general, approaches to generics contain three components: code for generic values, per data type code, and shared library code. In Generic Haskell and other approaches the per data type code is not burdened upon the programmer but is generated automatically. Here the programmer is responsible for supplying the required definitions. (Of course, she or he may use tools such as DrIFT or

Template Haskell to generate the code automatically.) To see what is involved, re-consider the `List` data type

```
data List a = Nil | Cons a (List a),
```

and recall that the structure type of `List a` is `Unit :+: (a :*: (List a))`. To turn `List a` into a *representable type*, a type on which a generic function can be used, we define

```
list  :: ∀a . Rep a → Rep (List a)
list a = Type ((Con "Nil" unit) + (Con "Cons" (a * (list a))))
        (EP fromList toList),
```

where *unit*, *+* and *** are smart versions of the respective constructors (defined in the LIGD library) and *fromList* and *toList* convert between the type `List` and its structure type.

```
fromList      :: ∀a . List a → Unit :+: (a :*: (List a))
fromList Nil  = Inl Unit
fromList (Cons a as) = Inr (a :*: as)
toList       :: ∀a . Unit :+: (a :*: (List a)) → List a
toList (Inl Unit) = Nil
toList (Inr (a :*: as)) = Cons a as
```

Note that the representation of the structure type records the name of the constructors.

So, whenever we define a new data type and we intend to use a generic function on that type, we have to do a little bit of extra work. However, this has to be done only once.

Function encode. The definition of *encode* is very similar to the Generic Haskell definition.

```
encode :: ∀t . Rep t → t → [Bit]
encode (Unit      ep) t = case from ep t of
                        Unit → []
encode (Char      ep) t = encodeChar (from ep t)
encode (Int       ep) t = encodeInt (from ep t)
encode (Sum a b ep) t = case from ep t of
                        Inl x → O : encode a x
                        Inr y → I : encode b y
encode (Pair a b ep) t = case from ep t of
                        x :*: y → encode a x ++ encode b y
encode (Type a ep) t = encode a (from ep t)
encode (Con s a) t = encode a t
```

The main difference is that we have to use an explicit cast, *from ep*, to turn the second argument of type `t` into a character, an integer, and so forth. In Generic Haskell this cast is automatically inserted by the compiler.

Function decode. For *decode* we have to cast an integer and values of other types into an element of the result type *t* using *to ep*.

```

decodes :: ∀t. Rep t → [Bit] → [(t, [Bit])]
decodes (Unit    ep) bs = [(to ep Unit, bs)]
decodes (Char    ep) bs = map (mapFst (to ep)) (decodesChar bs)
decodes (Int     ep) bs = map (mapFst (to ep)) (decodesInt bs)
decodes (Sum a b ep) [] = []
decodes (Sum a b ep) (O : bs) = map (mapFst (to ep . Inl)) (decodes a bs)
decodes (Sum a b ep) (I : bs) = map (mapFst (to ep . Inr)) (decodes b bs)
decodes (Pair a b ep) bs = [(to ep (x :* y), ds)
                             | (x, cs) ← decodes a bs
                             , (y, ds) ← decodes b cs]
decodes (Type a ep) bs = map (mapFst (to ep)) (decodes a bs)
decodes (Con s a)    bs = decodes a bs

```

A big plus of the light-weight approach is that *encode* and *decode* are ordinary Haskell functions. We can, for instance, pass them to other functions or we can define other functions in terms of them.

```

decode :: Rep a → [Bit] → a
decode a bs = case decodes a bs of
  [(x, [])] → x
  _         → error "decode: no parse"

```

Function eq. The equality function is again very similar to the version in Generic Haskell.

```

eq :: ∀t. Rep t → t → t → Bool
eq (Int    ep) t1 t2 = from ep t1 == from ep t2
eq (Char   ep) t1 t2 = from ep t1 == from ep t2
eq (Unit   ep) t1 t2 = case (from ep t1, from ep t2) of
  (Unit, Unit) → True
eq (Sum a b ep) t1 t2 = case (from ep t1, from ep t2) of
  (Inl a1, Inl a2) → eq a a1 a2
  (Inr b1, Inr b2) → eq b b1 b2
  _                → False
eq (Pair a b ep) t1 t2 = case (from ep t1, from ep t2) of
  (a1 :* b1, a2 :* b2) → eq a a1 a2 ∧ eq b b1 b2
eq (Type a ep) t1 t2 = eq a (from ep t1) (from ep t2)
eq (Con s a) t1 t2   = eq a t1 t2

```

Function map. The function *map* abstracts over a type constructor of kind $\star \rightarrow \star$, or is indexed by kind as in Generic Haskell. Defining such a version of *map* requires a different type representation. A discussion of the design space can be found in the companion lecture notes “Generic Programming, Now!”.

Function show. The implementation of *show* is again straightforward. The constructor names can be accessed using the *Con* pattern (an analogous approach can be used for record labels).

```

shows :: ∀t. Rep t → t → ShowS
shows (Int      ep) t    = showsInt (from ep t)
shows (Char     ep) t    = showsChar (from ep t)
shows (Unit     ep) t    = showString ""
shows (Sum a b ep) t    = case from ep t of
    Inl a1 → shows a a1
    Inr b1 → shows b b1
shows (Pair a b ep) t    = case from ep t of
    (a1 :* b1) → shows a a1
                  · showString " "
                  · shows b b1

shows (Type a   ep) t    = shows a (from ep t)
shows (Con s (Unit ep)) t = showString s
shows (Con s a) t        = showChar ' ( '
                          · showString s
                          · showChar ' '
                          · shows a t
                          · showChar ') '

```

Since types are reflected onto the value level, we can use the full convenience of Haskell pattern matching. For instance, in the definition of *shows* we treat nullary constructors in a special way (omitting parentheses) through the use of the pattern *Con s (Unit ep)*.

Function update. An implementation of *update* requires an extension of the *Rep* data type, which means that one has to modify the source of the library. Alternatively, one could turn *Rep* into a so-called *open data type* [62]. The code for *update* is then entirely straightforward and omitted for reasons of space.

Generics for the masses

Generics for the masses [30, 31] (GM) is similar in spirit to LIGD. The approach shows that one can program generically within Haskell 98 obviating to some extent the need for fancy type systems or separate tools. Like LIGD, generics for the masses builds upon an encoding of the type-representation type *Rep*, this time a class-based one. The details of the encoding are not relevant here; the interested reader is referred to the journal paper [31].

Function encode. To define a generic function the generic programmer has to provide a signature and an implementation. Rather unusually, the type of a generic function is specified using a **newtype** declaration.

```
newtype Encode a = Encode { applyEncode :: a → [Bit] }
```

We already know that the generic function *encode* cannot be a genuine polymorphic function of type $a \rightarrow [\text{Bit}]$. Data compression does not work for arbitrary types, but only for types that are *representable*. Representable means that the *type* can be represented by a certain *value*. Here a type representation is simply an overloaded value called *rep*. The first part of the generic compression function is then given by the following definition.

```
encode :: (Rep a) ⇒ a → [Bit]
encode = applyEncode rep
```

Loosely speaking, we apply the generic function to the type representation *rep*. Of course, this is not the whole story. The code above defines only a convenient shortcut. The actual definition of *encode* is provided by an instance declaration, but you should read it instead as just a generic definition.

```
instance Generic Encode where
  unit = Encode (λx → [])
  plus = Encode (λx → case x of   Inl l → O : encode l
                                Inr r → I : encode r)
  pair = Encode (λx → encode (outl x) ++ encode (outr x))
  datatype descr iso
    = Encode (λx → encode (fromData iso x))
  char = Encode (λx → encodeChar x)
  int   = Encode (λx → encodeInt  x)
```

Most of the cases are familiar – just read the method definitions as type cases. To encode an element of an arbitrary data type, we first convert the element into a sum of products, which is then encoded. That said is becomes clear that GM uses the same structure types as Generic Haskell. The function *fromData* is an accessor of the data type *Iso* (which is the same as the *EP* type of Section 2.2).

```
data Iso a b = Iso { fromData :: b → a, toData :: a → b }
```

That's it, at least, as far as the generic function is concerned. Before we can actually compress data to strings of bits, we first have to turn the types of the to-be-compressed values into representable types. Consider as an example the type of binary leaf trees.

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

We have to show that this type is representable. To this end we exhibit an isomorphic type built from representable type constructors. This is the familiar *structure type* of *Tree*, denoted *Tree'*.

```
type Tree' a = (Constr a) :+: (Constr ((Tree a) :* (Tree a)))
```

The main work goes into defining two mappings, *fromTree* and *toTree*, which certify that *Tree a* and its structure type *Tree' a* are indeed isomorphic.

```

fromTree      :: Tree a → Tree' a
fromTree (Leaf x)      = Inl (Con x)
fromTree (Fork l r)    = Inr (Con (l :* r))
toTree        :: Tree' a → Tree a
toTree (Inl (Con x))   = Leaf x
toTree (Inr (Con (l :* r))) = Fork l r

```

The *Con* constructor just marks the position of the original data constructors *Leaf* and *Fork*. The isomorphism is then used to turn *Tree* into a representable type.

```

instance (Rep a) ⇒ Rep (Tree a) where
  rep = datatype ("Leaf" ./ 1 | "Fork" ./ 2) -- syntax
        (Iso fromTree toTree)              -- semantics

```

The declaration specifies the syntax – name and arity of the constructors – and the semantics – the structure – of the tree data type. Such a declaration has to be provided once per data type and is used for all the generic functions.

For reference, Figure 4 lists the definition of the class *Generic* (*g* is the type of a generic function).

Function decode. The definition of *decodes* follows exactly the same scheme.

```

newtype Decodes a = Decodes { applyDecodes :: [Bit] → [(a, [Bit])] }
decodes :: (Rep a) ⇒ [Bit] → [(a, [Bit])]
decodes = applyDecodes rep
instance Generic Decodes where
  unit = Decodes (λbs → [(Unit, bs)])
  plus = Decodes (λbs → case bs of [] → []
                                   O : bs → map (mapFst Inl)
                                                (decodes bs)
                                   I : bs → map (mapFst Inr)
                                                (decodes bs)
  pair = Decodes (λbs → [(x :* y, ds) | (x, cs) ← decodes bs
                                         , (y, ds) ← decodes cs])
  datatype descr iso
    = Decodes (λbs → map (mapFst (toData iso)) (decodes bs))
  char = Decodes (λbs → decodesChar bs)
  int  = Decodes (λbs → decodesInt bs)

```

It is worth noting that Haskell’s overloading resolution automatically determines the instance types: we just call *decodes* rather than *decodes{t}*.

The function *decode* can easily be defined in terms of *decodes*.

```

class Generic g where
  unit    :: g Unit
  plus    :: (Rep a, Rep b) => g (a :+: b)
  pair    :: (Rep a, Rep b) => g (a :*: b)
  datatype :: (Rep a) => DataDescr -> Iso a b -> g b
  char    :: g Char
  int     :: g Int
  list    :: (Rep a) => g [a]
  constr  :: (Rep a) => g (Constr a)
  list    = datatype ("[]" ./ 0 ./ "|" ./ 2) (Iso fromList toList)
  constr  = datatype ("Con" ./ 1) (Iso arg Con)

data DataDescr = NoData
               | DataDescr { name :: String,    arity :: Int }
               | Alt       { getl  :: DataDescr, getr  :: DataDescr }

infix 2 ./
infixr 1 .|
f ./ n = DataDescr { name = f,    arity = n }
d1 .| d2 = Alt { getl  = d1, getr  = d2 }
newtype Constr a = Con { arg :: a }

```

Fig. 4. The class *Generic*.

```

decode :: (Rep a) => [Bit] -> a
decode a bs = case decodes a bs of
  [(x, [])] -> x
  _          -> error "decode: no parse"

```

Note that the class context only records that *decode* depends on some generic function. This is in sharp contrast to DTC where the context precisely records, on which overloaded function(s) *decode* depends: $(Binary\ a) \Rightarrow [Bit] \rightarrow a$.

Function eq. The definition of *eq* is straightforward.

```

newtype Equal a = Equal { applyEqual :: a -> a -> Bool }
eq :: (Rep a) => a -> a -> Bool
eq = applyEqual rep

instance Generic Equal where
  unit = Equal (\x1 x2 -> True)
  plus = Equal (\x1 x2 -> case (x1, x2) of
    (Inl a1, Inl a2) -> eq a1 a2
    (Inr b1, Inr b2) -> eq b1 b2
    _                 -> False)
  pair = Equal (\x1 x2 -> eq (outl x1) (outl x2) & eq (outr x1) (outr x2))
  datatype descr iso
    = Equal (\x1 x2 -> eq (fromData iso x1) (fromData iso x2))

```



```

pair    = Shows' (λd x → shows (outl x)
                  · showChar ' '
                  · shows (outr x))
char    = Shows' (λd x → showsChar x)
int     = Shows' (λd x → showsInt  x)
list    = Shows' (λd x → showsl shows x)
datatype descr iso
        = Shows' (λd x → shows' descr (fromData iso x))
constr  = Shows' (λd x → if arity d == 0 then
                  showString (name d)
                  else
                  showChar ' (' · showString (name d)
                  · showChar ' ' · shows (arg x)
                  · showChar ')')
```

The implementation of *shows'* has a special case for lists which are converted to Haskell list syntax, with brackets and commas. The helper function *showsl* does the main work.

```

showsl :: (a → ShowS) → ([a] → ShowS)
showsl p []          = showString "[]"
showsl p (a : as)    = showChar ' [' · p a · rest as
  where rest []       = showChar ']'
        rest (x : xs) = showChar ' , ' · p x · rest xs
```

Function update. An implementation of *update* requires an extension of the class *Generic*, which means that one has to modify the source of the library. An alternative approach based on subclasses is described in a recent paper [71].

Derivable Type Classes

Haskell's major innovation is its support for *overloading*, based on type classes. For example, the Haskell Prelude defines the class *Eq* (slightly simplified):

```

class Eq a where
  eq :: a → a → Bool.
```

This *class declaration* defines an overloaded top-level function, called *method*, whose type is

```
eq :: ∀a. (Eq a) ⇒ a → a → Bool.
```

Before we can use *eq* on values of, say *Int*, we explain how to take equality over *Int* values:

```

instance Eq Int where
  eq = eqInt.
```

This *instance declaration* makes `Int` an element of the type class *Eq* and says ‘the *eq* function at type `Int` is implemented by *eqInt*’. As a second example consider equality of lists. Two lists are equal if they have the same length and corresponding elements are equal. Hence, we require equality over the element type:

```
instance (Eq a) => Eq (List a) where
  eq Nil Nil           = True
  eq Nil (Cons a2 as2) = False
  eq (Cons a1 as1) Nil = False
  eq (Cons a1 as1) (Cons a2 as2) = eq a1 a2 & eq as1 as2.
```

This instance declaration says ‘if `a` is an instance of *Eq*, then `List a` is an instance of *Eq*, as well’.

Though type classes bear a strong resemblance to generic definitions, they do not support generic programming. A type-class declaration corresponds roughly to the type signature of a generic definition – or rather, to a collection of type signatures. Instance declarations are related to the type cases of a generic definition. The crucial difference is that a generic definition works for all types, whereas instance declarations must be provided explicitly by the programmer for each newly defined data type. There is, however, one exception to this rule. For a handful of built-in classes Haskell provides special support, the so-called ‘**deriving**’ mechanism. For instance, if you define

```
data List a = Nil | Cons a (List a) deriving (Eq)
```

then Haskell generates the ‘obvious’ code for equality. What ‘obvious’ means is specified informally in an Appendix of the language definition [72]. *Derivable type classes* (DTCs) [35] generalize this feature to arbitrary user-defined classes: generic definitions are used to specify *default methods* so that the programmer can define her own derivable classes.

Functions encode and decode. A type class usually gathers a couple of related methods. For that reason, we put *encode* and *decode* into a single class, called *Binary*.

```
class Binary a where
  encode :: a -> [Bit]
  decode :: [Bit] -> [(a, [Bit])]
```

Using two generic definitions we provide default methods for both *encode* and *decode*.

```
encode{Unit} Unit = []
encode{b :+ c} (Inl x) = O : encode x
encode{b :+ c} (Inr y) = I : encode y
encode{b :* c} (x :* y) = encode x ++ encode y
```

```

decodes{Unit} bs      = [(Unit, bs)]
decodes{b :+: c} []   = []
decodes{b :+: c} (O : bs) = [(Inl x, cs) | (x, cs) ← decodes bs]
decodes{b :+: c} (I : bs) = [(Inr y, cs) | (y, cs) ← decodes bs]
decodes{b :* c} bs     = [(x :* y, ds) | (x, cs) ← decodes bs
                               , (y, ds) ← decodes cs]

```

Incidentally, DTCs use the same structure-representation types as Generic Haskell, so the corresponding definitions can be copied almost verbatim. There is one small difference though: explicit type arguments, written in curly braces, are only specified on the left-hand side of default method definitions. Elsewhere, Haskell's overloading resolution automatically determines the instance types, as for every other class method.

The function *decode* is defined in terms of *decodes*. We decided to turn the latter function into an overloaded function rather than a class method since its code is the same for all instances.

```

decode :: (Binary a) => [Bit] -> a
decode bs = case decodes bs of
    [(x, [])] -> x
    _         -> error "decode: no parse"

```

Now, if we intend to use *encode* or *decode* on a particular type, we must first provide an instance declaration. However, by virtue of the default methods the instance declaration may be empty.

```

instance Binary CharList
instance Binary Tree
instance (Binary a) => Binary [a]

```

The compiler then automatically fills in the missing method definitions. However, if we say

```

instance (Binary a) => Binary [a] where
    encode xs    = encode (length xs) ++ concatMap encode xs
    decodes bs   = [(xs, ds) | (n, cs) ← decodes bs
                               , (xs, ds) ← times n decodes cs]

    times :: Int -> ([Bit] -> [(a, [Bit])]) -> ([Bit] -> [(a, [Bit])])
    times 0      p bs = [([], bs)]
    times (n + 1) p bs = [(x : xs, ds) | (x, cs) ← p bs, (xs, ds) ← times n p cs]

```

then this programmer-supplied code is used. Thus, the programmer can override the generic definition on a type-by-type basis. This ability is crucial to support *abstract types*. We can also use, indeed, we must use ordinary instance declarations to specify what a generic definition should do on primitive types such as `Char` or `Int`.

```

instance Binary Char where
    encode  = encodeChar
    decodes = decodesChar
instance Binary Int where
    encode  = encodeInt
    decodes = decodesInt

```

Function eq. The predefined *Eq* class can be thought of as a derivable type class.

```

class Eq a where
    eq, neq :: a → a → Bool
    eq {Unit}   Unit   Unit   = True
    eq {b :+ c} (Inl x) (Inl v) = eq x v
    eq {b :+ c} (Inl x) (Inr w) = False
    eq {b :+ c} (Inr y) (Inl v) = False
    eq {b :+ c} (Inr y) (Inr w) = eq y w
    eq {b :* c} (x :* y) (v :* w) = eq x v ∧ eq y w
    neq x y = not (eq x y)

```

The class definition contains an ordinary default definition for inequality and a generic one for equality. Equality on characters and integers is specified using ordinary instance declarations.

```

instance Eq Char where
    eq = eqChar
instance Eq Int where
    eq = eqInt

```

Function map. Generic definitions for default methods may only be given for type classes whose type parameter ranges over types of kind \star . For that reason, we cannot specify a generic mapping function. There is, however, no principle hindrance in adding this feature.

Function show. The definition of *show* is similar to the one for Generic Haskell and hence omitted. Like equality, *show* is a class method of a built-in derivable type class.

Function update. We can define *update* as a variant of the generic identity, or copy function.

```

class Update a where
    update :: a → a
    update {Unit}   Unit   = Unit
    update {b :+ c} (Inl x) = Inl (update x)

```

$$\begin{aligned} \text{update}\{\mathbf{b} \text{ :+ : } \mathbf{c}\} (\text{Inr } y) &= \text{Inr } (\text{update } y) \\ \text{update}\{\mathbf{b} \text{ :* : } \mathbf{c}\} (x \text{ :* : } y) &= \text{update } x \text{ :* : } \text{update } y \end{aligned}$$

Again, we have to provide instance declarations for all the types, on which we wish to use *update*.

```
instance Update Char where
  update = id
instance (Update a) => Update [a]
instance Update Company
instance Update Dept
instance Update SubUnit
instance Update Employee
instance Update Person
instance Update Salary where
  update (S s) = S (s * (1 + 0.15))
```

All the instance declarations are trivial except the one for salary which specifies the salary increase.

Evaluation

Structural dependencies. All light-weight approaches support the definition of \star -indexed functions in the style of Generic Haskell. Type-indexed data types are out of reach.

Using a different representation type in LIGD we can also define generic functions that are indexed by first- or higher-order kinds (this is not detailed in the original paper).

GM supports the definition of generic functions on types and type constructors. For each brand of generic functions a tailor-made *Generic* class must be used. Because of the class-based encoding the code looks somewhat different to that of Generic Haskell. The difference is, however, only superficial.

Full reflexivity. LIGD is in principle fully reflexive. However, to support types of arbitrary ranks, so-called *rank- n types* are required (a function has rank 2 if it takes a *polymorphic function* as an argument). Most Haskell implementations support rank- n types.

GM is in principle fully reflexive. Rank- n types are required in order to support types of higher kinds. Furthermore, if one wants to use the convenience of the *Rep* class, one additionally needs higher-order contexts, see the evaluation of SYB.

DTCs also share the limitations of class-based systems: higher-order contexts are needed to apply generic functions to higher-order kinded data types such as GRose.

Type universes. By changing the classes for type representations used in LIGD and GM other type universes can be introduced and used. Since type representations are given by the user, they are very flexible.

DTCs support default cases, but otherwise the type universe is fixed.

First-class generic functions. In LIGD, a generic function is an ordinary polymorphic Haskell function of type $\forall t. \text{Rep } t \rightarrow \text{Poly } t$. As such it is first-class, assuming that rank- n functions are supported.

Similarly, in GM a generic function is an ordinary polymorphic Haskell function of type $\forall t. (\text{Rep } t) \Rightarrow \text{Poly } t$. Again, in a language with rank- n types, generic functions are first-class citizens.

In DTCs, generic functions are tied to class methods. However, type classes are not first-class citizens. Consequently, generic functions are not first class either.

Multiple type arguments. In both LIGD and GM a generic function may have multiple type arguments. Derivable type classes may only abstract over a single type argument.

Type system. All approaches are fully integrated into Haskell's type system.

Type safety. All approaches are fully type-safe. A missing type-case in LIGD, however, only generates a warning at compile-time. Depending on the complexity of the 'type' patterns it may not be detected at all (in particular, if patterns are used in conjunction with guards). In this case, we get a pattern-matching failure at run-time. In GM a missing case branch issues a warning at compile-time (about a missing method). Since instance declaration must be explicitly provided, missing instances in DTCs are detected at compile-time.

The type of a generic function. The types are intuitive; we only have to prefix a ' $\text{Rep } t \rightarrow$ ' or a ' $(\text{Rep } t) \Rightarrow$ ' context for LIGD and GM, respectively. The types of DTCs are familiar to Haskell programmers.

Properties of generic functions. For all approaches, properties of a generic function can be stated and proven as in Generic Haskell.

Integration with the underlying programming language. All approaches are fully integrated into Haskell. For DTCs, only the module `Data.Generics` must be imported and the options `-fglasgow-exts`, and `-fgenerics` must be passed to the Glasgow Haskell Compiler (GHC).

In LIGD and GM the user has to specify the structure representation type and the embedding-projection pair between the data type and the structure representation type for every data type on which generic functions are used.

In DTCs, a generic function g , implemented in the class G , can be used on a data type t by writing `instance G t`. No other data-type-specific code is needed.

Specialization versus interpretation. Representations of types are passed and analyzed at run-time in LIGD. A generic function can be seen as an interpreter. In GM, instances of generic functions are assembled at compile-time. In DTCs, generic code is specialized for each instance.

Code optimization In LIGD, the run-time passing of type representations incurs a small overhead compared to Generic Haskell. For GM and DTCs the overhead is similar to that of Generic Haskell. The code quality possibly depends a bit more on GHC’s optimizer.

Separate compilation. All approaches support separate compilation.

Practical aspects. The implementation of LIGD consists of a few dozen lines of code (see Appendix A of the original paper). So it can be easily integrated into one’s programs and also be adapted to one’s needs (for instance, if additional type cases are required).

GM comprises three major implementations of generics and a few variations. The approach is extremely light weight; each implementation consists of roughly two dozen lines of Haskell code. It is less suited as a library (unless one makes do with the predefined types cases), but it can easily be adopted to one’s needs.

The original DTCs proposal is partially implemented in GHC, the standard compiler for Haskell. A missing feature is the `c of a` construct, with which one can access the names of constructors and labels. So, currently, one cannot define a generic version of `show` or `read`. The documentation is integrated into GHC’s user guide (Section 7.11, ”Generic classes”). Error messages are usually good.

5 Conclusions and future work

In this section we draw conclusions from the evaluations in the previous section. Using these conclusions, we try to answer the question we posed in the introduction of these lecture notes: ‘How do you choose between the different approaches to generic programming in Haskell?’ This question is a bit similar to the question how you choose a programming language for solving a programming problem. Answers to this question usually contain ‘religious’ aspects. We try to avoid religion as much as possible, and answer the question in two ways. First, we summarize the evaluations of the previous section, and draw conclusions about the suitability of the different approaches for different generic programming concepts. Second, to end on a positive note, for each approach we try to give arguments why you would use it. Furthermore, we describe future work.

5.1 Suitability for generic programming concepts.

Figure 5 shows the results of our evaluations of the different approaches to generic programming in Haskell. Such a presentation does not offer the possibility to make subtle distinctions, but it does give an overview of the evaluation

results. We use the following categories in this table:

- ++ : satisfies (almost) all requirements.
- + : satisfies the requirements except for some small details.
- o : satisfies a number of requirements.
- : satisfies just a few of the requirements.
- : does not satisfy the requirements.

The results are obtained by an informal translation our evaluations into points on this five-point scale.

	Structure	Completeness	Safe	Info	Integration	Tools
GH	++	+	++	++	++	+
Clean	o	+	++	++	++	+
PolyP	o	-	+	+	+	-
SYB	o	+	++	+	++	+
DrIFT	+	o	--	-	+	+
TH	+	+	-	-	++	o
LIGD	o	+	++	++	++	+
GM	o	+	++	++	++	+
DTCs	o	o	++	++	++	+

Fig. 5. Evaluation results for approaches to generic programming

Structure in programming languages. Generic Haskell allows the definition of type-indexed functions with kind-indexed types, and type-indexed data type with kind-indexed kinds. Since DrIFT and Template Haskell can generate anything, they can also be used to generate type-indexed types. There is no support (library, predefined constructs) for doing so, however. The other approaches only allow the definition of type-indexed functions.

The type completeness principle. No approach truly satisfies the type completeness principle.

SYB, GM, and DTCs suffer from the fact that higher-order contexts (not implemented in Haskell) are needed to generate instances of generic functions on higher-order kinded data types. On the other hand, both SYB and GM allow higher-order generic functions. Just as with classes, DTCs cannot represent higher-order generic functions. Furthermore, DTCs cannot access constructor names, which limits their usability a bit. LIGD allows higher-order generic functions and generic functions on almost all data types definable in Haskell. However, it is impossible to define the generic map function in LIGD and SYB.

GM allows higher-order generic functions, and the definition of generic map, but needs different classes for different brands of generic functions.

Generic Haskell and Clean do not offer higher-order generic functions, but generic functions work on almost any data type definable in the underlying programming language, and defining the generic map function is no problem. Higher-orderness does not really play a rôle in DrIFT and Template Haskell, and DrIFT cannot handle higher-order kinded data types. PolyP does not allow higher-order generic functions either and only works for regular data types of kind $\star \rightarrow \star$.

Generic views in Generic Haskell allow defining generic functions for different views on data types, which can be used to specify different type universes. LIGD and GM allow very flexible sets of types on which generic functions can be defined, and it is possible to define many type universes. Clean, PolyP, SYB, and DTCs have a fixed type universe. DrIFT and Template Haskell offer no support for type universes.

Well-typed expressions do not go wrong. Generic Haskell, Clean, SYB, LIGD, GM, and DTCs are type safe. PolyP does not complain about undefined arms, but otherwise type checks generic functions. DrIFT offers no safety at all: a generated document can represent a completely bogus program. Template Haskell offers very limited safety: splicing in code may lead to type errors.

Information in types. In Generic Haskell, Clean, PolyP, and LIGD types of generic functions generally correspond to intuition, and there exists a theory of generic functions by means of which properties for generic functions can be proved. Proving properties of generic functions in SYB is hard because they rely on properties of, possibly user-defined, instances of the classes *Data* and *Typeable*.

In DrIFT all rules have the same type, namely $\mathbf{Data} \rightarrow \mathbf{Doc}$, and it is virtually impossible to prove anything about the functions represented by the documents. The same holds for Template Haskell, although libraries for generic programming defined in Template Haskell may allow to state and prove properties.

Integration with the underlying programming language. Generic Haskell, Clean, SYB, Template Haskell, LIGD, GM, and DTCs are fully integrated with the underlying programming language, where Clean, SYB, Template Haskell, LIGD, GM, and DTCs don't even need a separate compiler. PolyP can only deal with a subset of Haskell. DrIFT has to be recompiled if a new generic function is added to the rules.

To use a generic function on a new data type, almost no work is required in Generic Haskell, Clean, PolyP, SYB, DrIFT, Template Haskell, and DTCs. In the light-weight approaches LIGD and GM the structure representation type and the embedding-projection pair between the structure representation type and the original data type have to be supplied.

Tools. Generic Haskell, LIGD, GM, and DTCs do not do any optimization on the generic code, but otherwise provide good error messages. Clean does optimize the generated code, but provides no error messages. PolyP is not very actively maintained anymore. SYB is shipped as a library of GHC, and is fully supported. The latest versions of SYB have not been included yet in GHC, which means that the current version still suffers from some of the limitations of previous versions of SYB, in particular the limitation that generic functions cannot be extended. DrIFT is maintained, but also provides no error messages. Template Haskell is maintained, but the documentation is outdated, and error messages are not always very helpful.

5.2 Why would I use this approach?

- Use Generic Haskell if you want to experiment with type-indexed functions with kind-indexed types and/or type-indexed data types, in particular if you want to play with higher-order kinded and/or nested data types. Generic Haskell is probably the most expressive generic programming extension of Haskell. A disadvantage of using Generic Haskell is that the generated code contains quite a number of mappings from data types to structure types and back again, and hence not as efficient as hand-written code might be.
- Use Clean if you want to use an approach to generic programming that is similar to Generic Haskell, is fully integrated in its underlying programming language, and generates nearly optimal code for generic functions. Clean does not support the advanced features of Generic Haskell such as dependencies, type-indexed data types, and default cases.
- Use PolyP if you want to define generic functions that use the recursive structure of data types, such as a generalization of the *foldr* function on lists, the catamorphism. Remember that PolyP only generates code for data types of kind $\star \rightarrow \star$.
- Use Scrap Your Boilerplate if you want to manipulate a value of a large abstract syntax at a particular place in the abstract syntax, and if you want to have an approach to generic programming that is fully integrated in the underlying programming language.
- Use DrIFT if you want a lot of flexibility in the way you generate code, or if you want to format the code you generate in a particular way. Make sure you don't generate code on data types that use higher-order kinds.
- Use Template Haskell if you want to experiment with different implementations of generic programming styles.
- Use the Light-weight approach if you want to use a simple but expressive library for generic programming, and your generic functions don't have to work on many different data types.
- Use Generics for the Masses if you want a fully Haskell 98 compatible library that supports generic programming.
- Use Derivable Type Classes if you want (limited) Generic Haskell like generic programming functionality fully integrated in the underlying programming

language. DTCs don't support type-indexed data types, or types with higher-order kinds.

We distinguished three related groups between the nine approaches to generic programming in Haskell described in these lecture notes:

- Generic Haskell and Clean.
- DrIFT and TH.
- Light-weight approaches: Light-weight Generics and Dynamics, Generics for the Masses, and Derivable Type Classes.

The difference between Generic Haskell and Clean is that Generic Haskell is more expressive and provides more features, whereas Clean produces better code. The various light-weight approaches can be compared as follows. GM and DTCs use classes for defining generic functions, so higher-order kinded data types are out of reach for these approaches. DTCs automatically generate the conversion functions for instances of generic functions, something that has to be done by hand for LIGD and GM. Also, DTCs allow to extend generic functions with new, type-specific cases without modifying already existing code.

5.3 Future work

These lecture notes only compare approaches to generic programming in Haskell. The only approaches to generic programming in Haskell we have not addressed are Strafunski, which is rather similar to SYB, and Generic programming, Now!, which is described at length, including a comparison to other approaches, in this volume.

We have yet to perform the same exercise for approaches to generic programming in different programming languages.

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References

1. Peter Achten, Marko van Eekelen, and Rinus Plasmeijer. Generic Graphical User Interfaces. In *The 15th International Workshop on the Implementation of Functional Languages, IFL 2003, Selected Papers*, volume 3145 of *LNCS*, pages 152–167. Springer-Verlag, 2004.
2. Artem Alimarine. *Generic Functional Programming - Conceptual Design, Implementation and Applications*. PhD thesis, University of Nijmegen, The Netherlands, 2005.
3. Artem Alimarine and Rinus Plasmijer. A generic programming extension for Clean. In Thomas Arts and Markus Mohnen, editors, *The 13th International workshop on the Implementation of Functional Languages, IFL 2001, Selected Papers*, volume 2312 of *LNCS*, pages 168–186. Springer-Verlag, 2002.

4. Artem Alimarine and Sjaak Smetsers. Optimizing generic functions. In Dexter Kozen, editor, *Proceedings of the 7th International Conference on Mathematics of Program Construction, MPC 2004*, volume 3125 of *LNCS*, pages 16–31. Springer-Verlag, 2004.
5. Artem Alimarine and Sjaak Smetsers. Improved fusion for optimizing generics. In *Proceedings of Seventh International Symposium on Practical Aspects of Declarative Languages, PADL 2005*, volume 3350 of *LNCS*, pages 203–218. Springer-Verlag, 2005.
6. Thorsten Altenkirch and Conor McBride. Generic programming within dependently typed programming. In Gibbons and Jeuring [23], pages 1–20.
7. Frank Atanassow, Dave Clarke, and Johan Jeuring. Scripting XML with Generic Haskell. In *Proceedings of the 7th Brazilian Symposium on Programming Languages, SBLP 2003*, 2003. An extended version of this paper appears as ICS, Utrecht University, technical report UU-CS-2003-023.
8. Frank Atanassow and Johan Jeuring. Inferring type isomorphisms generically. In Dexter Kozen, editor, *Proceedings of the 7th International Conference on Mathematics of Program Construction, MPC 2004*, volume 3125 of *LNCS*, pages 32–53. Springer-Verlag, 2004.
9. L. Augustsson. Cayenne — a language with dependent types. *ACM SIGPLAN Notices*, 34(1):239–250, 1998. Presented at ICFP’98.
10. Roland Backhouse and Jeremy Gibbons. The esprc project on datatype-generic programming. <http://web.comlab.ox.ac.uk/oucl/research/pdt/ap/dgp/>, 2003–2006.
11. Marcin Benke, Peter Dybjer, and Patrik Jansson. Universes for generic programs and proofs in dependent type theory. *Nordic JOURNAL of Computing*, 10(4):265–289, 2003.
12. Richard Bird and Lambert Meertens. Nested datatypes. In Johan Jeuring, editor, *Mathematics of Program Construction*, volume 1422 of *LNCS*, pages 52–67. Springer-Verlag, 1998.
13. Juan Chen and Andrew W. Appel. Dictionary passing for polytypic polymorphism. Technical Report TR-635-01, Princeton University, 2001.
14. James Cheney and Ralf Hinze. A lightweight implementation of generics and dynamics. In Manuel Chakravarty, editor, *Haskell ’02: Proceedings of the 2002 ACM SIGPLAN workshop on Haskell*, pages 90–104. ACM Press, 2002.
15. Dave Clarke and Andres Löb. Generic Haskell, specifically. In Gibbons and Jeuring [23], pages 21–48.
16. Robin Cockett and Tom Fukushima. About Charity. Yellow Series Report No. 92/480/18, Dep. of Computer Science, Univ. of Calgary, 1992.
17. Karl Crary, Stephanie Weirich, and J. Gregory Morrisett. Intensional polymorphism in type-erasure semantics. In *Proceedings of the ACM SIGPLAN International Conference on Functional Programming, ICFP 1998*, pages 301–312. ACM Press, 1998.
18. Alan Demers, James Donahue, and Glenn Skinner. Data types as values: polymorphism, type-checking, encapsulation. In *Conference Record of POPL ’78: The 5th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, pages 23–30. ACM Press, 1978.
19. C. Dubois, F. Rouaix, and P. Weis. Extensional polymorphism. In *22nd Symposium on Principles of Programming Languages, POPL ’95*, pages 118–129, 1995.
20. Jun Furuse. Generic polymorphism in ML. In *Journées Francophones des Langues Applicatifs*, January 2001.

21. Ronald Garcia, Jaakko Jarvi, Andrew Lumsdaine, Jeremy G. Siek, and Jeremiah Willcock. A comparative study of language support for generic programming. In *OOPSLA '03: Proceedings of the 18th annual ACM SIGPLAN conference on Object-oriented programming, systems, languages, and applications*, pages 115–134. ACM Press, 2003.
22. Jeremy Gibbons. Datatype-generic programming. In Roland Backhouse, Jeremy Gibbons, Ralf Hinze, and Johan Jeuring, editors, *Generic Programming, Advanced Lectures*, LNCS. Springer-Verlag, 2006. This volume.
23. Jeremy Gibbons and Johan Jeuring, editors. *Generic Programming*, volume 243 of *IFIP*. Kluwer Academic Publishers, 2003.
24. Paul Hagg. A framework for developing generic XML Tools. Master’s thesis, Department of Information and Computing Sciences, Utrecht University, 2002.
25. Robert Harper and Greg Morrisett. Compiling polymorphism using intensional type analysis. In *22nd Symposium on Principles of Programming Languages, POPL '95*, pages 130–141, 1995.
26. Ralf Hinze. A generic programming extension for Haskell. In Erik Meijer, editor, *Proceedings of the Third Haskell Workshop*, Technical report of Utrecht University, UU-CS-1999-28, 1999.
27. Ralf Hinze. Functional pearl: Perfect trees and bit-reversal permutations. *Journal of Functional Programming*, 10(3):305–317, 2000.
28. Ralf Hinze. *Generic Programs and Proofs*. 2000. Habilitationsschrift, Bonn University.
29. Ralf Hinze. Polytypic values possess polykinded types. *Science of Computer Programming*, 43(2-3):129–159, 2002.
30. Ralf Hinze. Generics for the masses. In *Proceedings of the ACM SIGPLAN International Conference on Functional Programming, ICFP 2004*, pages 236–243. ACM Press, 2004.
31. Ralf Hinze. Generics for the masses. *Journal of Functional Programming*, 2006. to appear.
32. Ralf Hinze and Johan Jeuring. Generic Haskell: applications. In *Generic Programming, Advanced Lectures*, volume 2793 of *LNCS*, pages 57–97. Springer-Verlag, 2003.
33. Ralf Hinze and Johan Jeuring. Generic Haskell: practice and theory. In *Generic Programming, Advanced Lectures*, volume 2793 of *LNCS*, pages 1–56. Springer-Verlag, 2003.
34. Ralf Hinze, Johan Jeuring, and Andres Löh. Type-indexed data types. *Science of Computer Programming*, 51((1-2)):117–151, 2004.
35. Ralf Hinze and Simon Peyton Jones. Derivable type classes. In Graham Hutton, editor, *Proceedings of the Fourth Haskell Workshop*, 2000.
36. Ralf Hinze and Andres Löh. Generic programming, now! In Roland Backhouse, Jeremy Gibbons, Ralf Hinze, and Johan Jeuring, editors, *Generic Programming, Advanced Lectures*, LNCS. Springer-Verlag, 2006. This volume.
37. Ralf Hinze and Andres Löh. “Scrap Your Boilerplate” revolutions. In Tarmo Uustalu, editor, *Proceedings of the Eighth International Conference on Mathematics of Program Construction, MPC 2006*, volume 4014 of *LNCS*, pages 180–208. Springer-Verlag, 2006.
38. Ralf Hinze, Andres Löh, and Bruno C. d. S. Oliveira. “Scrap Your Boilerplate” reloaded. In Philip Wadler and Masimi Hagiya, editors, *Proceedings of the Eighth International Symposium on Functional and Logic Programming, FLOPS 2006*, LNCS. Springer-Verlag, 2006.

39. Stefan Holdermans, Johan Jeuring, Andres Löb, and Alexey Rodriguez. Generic views on data types. In Tarmo Uustalu, editor, *Proceedings 8th International Conference on Mathematics of Program Construction, MPC'06*, volume 4014 of *LNCS*, pages 209–234. Springer-Verlag, 2006.
40. Gérard Huet. The zipper. *Journal of Functional Programming*, 7(5):549–554, 1997.
41. J. Hughes. The design of a pretty-printing library. In Johan Jeuring and Erik Meijer, editors, *Advanced Functional Programming*, volume 925 of *LNCS*. Springer-Verlag, 1995.
42. Patrik Jansson and Johan Jeuring. PolyP — a polytypic programming language extension. In *Conference Record of POPL '97: The 24th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, pages 470–482. ACM Press, 1997.
43. Patrik Jansson and Johan Jeuring. PolyLib – a polytypic function library. In *Workshop on Generic Programming, Marstrand*, June 1998.
44. Patrik Jansson and Johan Jeuring. Polytypic data conversion programs. *Science of Computer Programming*, 43(1):35–75, 2002.
45. C. Barry Jay. Programming in FISh. *International Journal on Software Tools for Technology Transfer*, 2:307–315, 1999.
46. C. Barry Jay. Distinguishing data structures and functions: the constructor calculus and functorial types. In S. Abramsky, editor, *Typed Lambda Calculi and Applications: 5th International Conference TLCA 2001, Kraków, Poland, May 2001 Proceedings*, volume 2044 of *LNCS*, pages 217–239. Springer-Verlag, 2001.
47. C. Barry Jay. The pattern calculus. *ACM Trans. Program. Lang. Syst.*, 26(6):911–937, 2004.
48. C. Barry Jay and Delia Kesner. Pure pattern calculus. In Peter Sestoft, editor, *Programming Languages and Systems. 15th European Symposium on Programming, ESOP 2006*, volume 3924 of *LNCS*. Springer-Verlag, 2006.
49. C.B. Jay, G. Bellè, and E. Moggi. Functorial ML. *Journal of Functional Programming*, 8(6):573–619, 1998.
50. J. Jeuring and P. Jansson. Polytypic programming. In J. Launchbury, E. Meijer, and T. Sheard, editors, *Advanced Functional Programming '96*, volume 1129 of *LNCS*, pages 68–114. Springer-Verlag, 1996.
51. Johan Jeuring and Rinus Plasmeijer. Generic programming for software evolution. In *Informal proceedings of the ERCIM workshop on Software Evolution*, 2006.
52. Pieter Koopman, Artem Alimarine, Jan Tretmans, and Rinus Plasmeijer. Gast: Generic Automated Software Testing. In Ricardo Peña, editor, *The 14th International Workshop on the Implementation of Functional Languages, IFL 2002, Selected Papers*, volume 2670 of *LNCS*. Springer-Verlag, 2003.
53. R. Lämmel and J. Visser. Typed Combinators for Generic Traversal. In *Proceedings Practical Aspects of Declarative Programming, PADL 2002*, volume 2257 of *LNCS*, pages 137–154. Springer-Verlag, 2002.
54. Ralf Lämmel and Simon Peyton Jones. Scrap your boilerplate: a practical approach to generic programming. *ACM SIGPLAN Notices*, 38(3):26–37, 2003. TLDI'03.
55. Ralf Lämmel and Simon Peyton Jones. Scrap your boilerplate with class: extensible generic functions. *Proceedings of the ACM SIGPLAN International Conference on Functional Programming, ICFP 2005*, 40(9):204–215, 2005.
56. Ralf Lämmel and Simon Peyton Jones. Scrap more boilerplate: reflection, zips, and generalised casts. In *Proceedings of the ACM SIGPLAN International Conference on Functional Programming, ICFP 2004*, pages 244–255. ACM Press, 2004.

57. Bernard Lang. Threshold evaluation and the semantics of call by value, assignment and generic procedures. In *Conference Record of POPL '77: The 4th ACM SIGPLAN-SIGACT Symposium on Principles of Programming Languages*, pages 227–237. ACM Press, 1977.
58. M.M. Lehman. Programs, life cycles and the laws of software evolution. *Proc. IEEE*, 68(9):1060–1078, 1980.
59. M.M. Lehman and L.A. Belady. *Program Evolution: Processes of Software Change*. Academic Press, London, 1985.
60. Andres Löb. *Exploring Generic Haskell*. PhD thesis, Utrecht University, 2004.
61. Andres Löb, Dave Clarke, and Johan Jeuring. Dependency-style Generic Haskell. In Olin Shivers, editor, *Proceedings of the ACM SIGPLAN International Conference on Functional Programming, ICFP 2003*, pages 141–152. ACM Press, August 2003.
62. Andres Löb and Ralf Hinze. Open data types. Submitted for publication, 2006.
63. Andres Löb and Johan Jeuring (editors). The Generic Haskell user’s guide, Version 1.42 - Coral release. Technical Report UU-CS-2005-004, Utrecht University, 2005.
64. N. Marti-Oliet M. Clavel, F. Duran. Polytropic programming in maude. In *WRLA 2000*, 2000.
65. G. Malcolm. Data structures and program transformation. *Science of Computer Programming*, 14:255–279, 1990.
66. Conor McBride. Epigram: practical programming with dependent types. In Varmo Vene and Tarmo Uustalu, editors, *Advanced Functional Programming*, volume 3622 of *LNCS*, pages 130–170. Springer-Verlag, 2005.
67. R. Milner. A theory of type polymorphism in programming. *Journal of Computer and Systems Sciences*, 17:348–375, 1978.
68. E Moggi, Bellè, and C.B. Jay. Monads, shapely functors and traversals. In M. Hoffman, Pavlović, and P. Rosolini, editors, *Proceedings of the Eighth Conference on Category Theory and Computer Science (CTCS'99)*, volume 24 of *Electronic Lecture Notes in Computer Science*, pages 265–286. Elsevier, 1999.
69. Pablo Nogueira. Context-parametric polykinded types. In Ralf Hinze, editor, *Proceedings of the of the ACM SIGPLAN Workshop on Generic Programming 2006*. ACM Press, 2006. To appear.
70. Ulf Norell and Patrik Jansson. Prototyping generic programming in Template Haskell. In Dexter Kozen, editor, *Proceedings of the 7th International Conference on Mathematics of Program Construction, MPC 2004*, volume 3125 of *LNCS*, pages 314–333. Springer-Verlag, 2004.
71. Bruno C. d. S. Oliveira, Ralf Hinze, and Andres Löb. Generics as a library. In Henrik Nilsson, editor, *Proceedings of the Seventh Symposium on Trends in Functional Programming, April 19–21, 2006, Nottingham, UK*, 2006.
72. Simon Peyton Jones et al. *Haskell 98, Language and Libraries. The Revised Report*. Cambridge University Press, 2003. A special issue of the Journal of Functional Programming.
73. A.L. Powell. A literature review on the quantification of software change. Technical Report YCS 305, Computer Science, University of York, 1998.
74. Fermín Reig. Generic proofs for combinator-based generic programs. In Hans-Wolfgang Loidl, editor, *Trends in Functional Programming*, volume 5. Intellect, 2006.
75. Stephen A. Schuman. On generic functions. In Stephen A. Schuman, editor, *First IFIP WG 2.1 Working Conference on New Directions in Algorithmic Languages 1975*, pages 169–192. IRIA, 1975.

- 76. P. Wadler. Theorems for free! In *Functional Programming Languages and Computer Architecture, FPCA '89*, pages 347–359. ACM Press, 1989.
- 77. M. Wallace and C. Runciman. Heap compression and binary I/O in Haskell. In *2nd ACM Haskell Workshop*, 1997.
- 78. David A. Watt. *Programming Language Design Concepts*. John Wiley & Sons, Ltd, 2004.
- 79. Stephanie Weirich. Higher-order intensional type analysis. In D. Le Métayer, editor, *Proceedings of the 11th European Symposium on Programming, ESOP 2002*, volume 2305 of *LNCS*, pages 98–114. Springer-Verlag, 2002.
- 80. Stephanie Weirich and Liang Huang. A design for type-directed programming in Java. In *Workshop on Object-Oriented Developments, WOOD 2004*, 2004.
- 81. Noel Winstanley and John Meacham. The DrIFT manual. <http://repetae.net/~john/computer/haskell/DrIFT/>, 1997–2005.