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Efficient and Type-Safe Generic Data Storage

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**Abstract**

In this paper we present an elegant method for sequentializing arbitrary data using the generic language extension of the functional programming language Clean. We show how the proposed operations can be used to store values of any concrete data type in several kinds of IO containers (such as files or arrays of characters), and how to manipulate stored data efficiently. Moreover, by extending stored data with

encoded type information, data manipulation will be type-safe. Defining these operations generically has the advantage that specific instances for user defined data types can be generated fully automatically. Compared to traditional sequentialization methods (or to common data manipulation, using relational data bases) our operations are an order of magnitude faster.

*Keywords:* Polytypic/generic programming, functional programming, data storage/sequentialization, type inference

# Introduction

Databases are commonly used for the efficient storage and retrieval of data. Effec- tively, they are optimized to store (large) tables in a very efficient way. For a large class of applications this type of storage is adequate enough. However, traditional databases are commonly not suited for storing recursive data structures, such as linked lists or binary trees, or even more complex data types like abstract syntax trees. In functional languages these algebraic data structures are very common. One would like to have the ability to store these algebraic data types efficiently in some database system as well. Efficient storage not only requires fast input/output operations but also the ability to update stored data selectively, i.e. without the necessity to read in and write back the complete data structure. For example, one would like to inspect the elements of a stored tree individually and update them destructively, or, re-balance the spine of the tree without retrieving/copying the elements. Furthermore, the signature of the stored data should be encoded in the

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database, such that at run time the type safety of the data read in from the database is guaranteed.

In this paper we will show how such efficient and flexible data manipulations can be realized using *generic* or *polytypical* programming techniques. With a generic function one can specify operations that work for (almost) *any* type. A generic func- tion is basically defined inductively on the structure of user-defined types. Equality and map are basic examples of functions that can be defined generically. Other well-known examples are (de)serialization functions like print and parse (resulting in a string representation of data), and (un)compress (using an efficient binary rep- resentation of data). To apply a generic function on a specific type, an instance of the generic function for that type is needed. The Clean compiler will generate this instance fully automatically, but the programmer explicitly has to ask for it via a derive statement.

All proposed IO operations in this paper are specified generically. The presented generic functions are written in Clean (see [[2](#_bookmark11)]). Due to some language specific lim- itations, the presented functions cannot be converted directly to Generic Haskell. There are some syntactic differences between Haskell and Clean. The major differ- ences will be explained on-the-fly; for a complete comparison between Clean and Haskell we refer to [[1](#_bookmark12)].

# Generic Programming

Specifying generic functions resembles defining a type class and its instances. The main difference is that a generic compiler can derive most of the instances automat- ically, given a minimal fixed set of instances for three (generic) type constructors. The derivation of instances is based on the fact that any algebraic data type can be expressed in terms of *eithers* (for distinguishing the constructors), *pairs* (for repre- senting the argument types of each constructor), and *units* (for representing 0-ary constructors).

This generic type representation, developed by Hinze [[6](#_bookmark15)], is used by Clean as well as by Generic Haskell, and is encoded by the following Clean types:

:: EITHER [2](#_bookmark1) a b = LEFT a | RIGHT b; :: PAIR a b = PAIR a b; :: UNIT = UNIT

To define a generic function, the programmer specifies its signature and provides instances for the generic types (EITHER, PAIR, and UNIT). As an example we define a generic packing program, taken from [[9](#_bookmark19)]. The basic idea of this program is simple: given a value, we construct a compact representation of that value in which data constructors are represented by as few bits as possible. E.g. for a simple binary tree this means that we distinguish leafs from internal nodes using a single bit. To abstract from the concrete container that is used to store the packed value, we first introduce

**class** GWrite io **where** writeC :: Char \*io *→* \*io

2 Defines a new data type in Clean, Haskell uses the data keyword.

Clean uses *uniqueness types* to express sharing properties of objects. A *∗* indicates that the corresponding object will be *unique* or *single-threaded* which means that there exist no further references to it. This allows the object to be updated destruc- tively. Hence, in Clean one can use explicit environment passing (the io argument in the example) instead of monads for incorporating side-effects.

We assume that writing separate bits is not directly supported. Hence, we keep track of some additional information for collecting bits until we have a complete byte that can be written. This is all hidden in the abstract data type CSt used in the function compressBit :: Bool (CSt \*io) *→* (CSt \*io) | GWrite io [3](#_bookmark2) The packing function itself is straightforward:

**generic** gCompress a :: a *→* (CSt \*io) *→* (CSt \*io) | GWrite io gCompress *{|*UNIT*|}* x = id

gCompress *{|*PAIR*|}* cx cy (PAIR x y) = cy y o [4](#_bookmark3) cx x

gCompress *{|*EITHER*|}* cl cr (LEFT l) = cl l o compressBit False gCompress *{|*EITHER*|}* cl cr (RIGHT r)= cr r o compressBit True gCompress *{|*OBJECT*|}* co (OBJECT x) = co x

gCompress *{|*CONS*|}* cc (CONS x) = cc x

Unlike instances for ordinary classes, we define type instances for gCompress using the special parentheses *{| |}* . Moreover, the actual number of arguments of each instance depends on the arity (actually the *kind* ) of the used type constructor. For example, the instance for PAIR as well as for EITHER are supplied with two extra parameters that can be used to compress the arguments of these types. Finally, the (auxiliary) types OBJECT and CONS, were added to the set of generic types in Clean to give access to concrete information about the original type definition (via OBJECT) and data constructors (via CONS). In this example this information is not used, but in section [5](#_bookmark10) it plays a crucial role.

The generic instances for other types that are actually used inside a program are automatically derived. For example, if one needs an instance of gCompress for the following Tree type

:: Tree a = Leaf | Node a (Tree a) (Tree a)

it suffices to declare **derive** gCompress Tree. For certain types, such as function types and abstract types, the generic function cannot be derived automatically. The programmer can, however, define specialized instances for these types explicitly.

In contrast to Generic Haskell, the implementation of generics in Clean is based on type classes. Each generic function gives rise to a collection of so-called *kind indexed* type classes, i.e. classes of which the signatures are obtained from the type of the generic function via *kind indexing* [[2](#_bookmark11)]. These generic type classes can be used as any other type class. Therefore, they are allowed in contexts of type signatures or can be applied in expressions like any other overloaded operation.

3 Clean separates argument types by whitespace, instead of *→*, and uses a | to announce context restrictions. In Haskell this would be written as (GWrite io) *⇒ ·· ·*.

4 The operator o is function composition.

# Basic generic IO operations

In this section we will introduce two generic functions, write and read, that serve as a basis for defining our set of general data storage operations. In essence, the write function is an ‘aligned’ version of gCompress as defined in the previous section: for the representation of constructors write always uses one byte whereas gCompress represented constructors by a bit sequence of variable size. Besides the class GWrite for writing, we define the class GRead for reading characters from an IO container.

**class** GRead st **where** readC :: \*io *→* (Maybe Char, \*io)

Two instances of both GWrite and GRead are predefined:

**instance** GWrite GString, GFile; **instance** GRead GString, GFile

The types GString and GFile are basically strings (arrays of characters) and files. Objects of these can be created (opened) and released (closed) by using the following functions

openString :: \*String *→* \*GString; closeString :: \*GString *→* \*String openFile :: !String !\*World *→* (Maybe \*GFile, \*World); closeFile :: !\*GFile !\*World *→* \*World

In Clean the (unique) World type is special: it has only one inhabitant which, in essence, encapsulates the complete status of the machine. This world-object corre- sponds to the hidden state of the IO monad in Haskell, and is used, for instance, to perform I/0.

The basis of our generic sequentialization operations are two generic functions:

**generic** write a :: Int a \*io *→* \*io | GWrite io

**generic** read a :: Int \*io *→* (Maybe a, \*io) | GRead io

The integer parameter is an auxiliary argument. In case a constructor is writ- ten/read, this argument contains the number of that constructor (i.e. the construc- tor’s position in the corresponding algebraic type definition). However, for top level calls the value of this argument is ignored: we will usually supply 0 as a default argument.

Suppose we want to use these operations to sequentialize a tree. The values stored in the tree are elements each consisting of an (integer) key and a record containing names and email addresses of persons.

:: Elem a [5](#_bookmark4) = *{* key :: Int, rec :: a *}*

:: Person = *{* name :: [Char], email :: [Char] *}*

We can now use the operations on a tree object as defined in the previous section by first declaring the necessary generic instances:

**derive** write Tree, Elem, Person, [ ] ; **derive** read Tree, Elem, Person, [ ]

To store a tree of 4 records (created by createTree) to the file fname we simply write:

writeTreeToFile fname world

(Just file, world) [6](#_bookmark5) = openFile fname world

5 Record types in Clean are surrounded by *{* and *}*.

6 This is not a cyclic letdefinition: the # introduces a new scope for id’s on the LHS.

= closeFile (write*{| |}*[7](#_bookmark6) 0 (createTree 4) file) world

**where**

createTree size = foldl (*λ*l k *→* Node *{*key = k, rec = record k*}* l Leaf) Leaf [1..size]

record k

[8](#_bookmark7) kl = fromString (toString k)

= *{*name = [’John Doe’]++kl, email = [’john.doe’]++kl++[’@cs.ru.nl’]*}*

The generic implementations of read and write (used to generate instances for concrete types) are rather straightforward. As with gCompress, each constructor is represented by a number corresponding to the constructor’s position in the type definition. Because write is almost identical to gCompress, we restrict ourselves to the definition of read. The instance for the OBJECT case takes care of reading the constructor’s id. To get the bits of this id in the right order (such that the EITHER alternative can choose the correct LEFT or RIGHT branch on the basis of the least significant bit) they are swapped first before passing them to the continuation.

read *{|*UNIT*|}* \_ io = (Just UNIT, io) read *{|*EITHER*|}* read\_a read\_b i io

| i bitand 1 */*=0= read\_b (i *>>* 1) io *>>*= RIGHT

| otherwise = read\_a (i *>>* 1) io *>>*= LEFT read *{|*PAIR*|}* read\_a read\_b \_ io

= **case** read\_a 0 io **of** (Just x, io) *→* read\_b 0 io *>>*= PAIR x

(Nothing,io) *→* (Nothing, io) read *{|*OBJECT **of** *{*gtd\_num\_conses*}|}* read\_a \_ io

= **case** readC gtd\_num\_conses io **of**

(Just cn, io) *→* read\_a (swap cn gtd\_num\_conses) io *>>*= OBJECT

(\_, io) *→* (Nothing, io)

read *{|*CONS*|}* read\_a \_ io = read\_a 0 io *>>*= CONS

(*>>*=) (mb, io) f = **case** mb **of** Just x *→* (Just (f x), io); Nothing *→* (Nothing, io)

# Updatable data storage

One of the main disadvantages of the proposed IO operations is that they do not allow updates of existing data without reading in and writing back all the original information. Particularly, when large amounts of data are involved this can be very inconvenient or even unacceptable. In this section we present an extension of our library with so-called *chunks*. Chunks can be seen as references to data still residing in the IO container. By wrapping data in a chunk, the user indicates that this information remains in the container when the data structure containing this wrapped data is read into the application. As soon as this data is really needed it can be read explicitly via a special chunkValue operation. Moreover, and this is possibly the most important improvement, it can be selectively updated, using the updateChunk operation. Hence, this chunk mechanism provides selective read/write access to data without the requirement of reading/writing the entire data structure.

The implementation of chunks requires that the IO streams provide random access. This is achieved via an extra type class:

7 write*{*|\*|*}* denotes the overloaded write operation for kind \*.

8 Clean supports let-before (#) to increase readability.

**class** GIO io | GWrite io & GRead io **where**

position :: \*io *→* (Int, \*io); seek :: Int \*io *→* \*io

The contexts GWrite and GRead are added for convenience. Chunks and the signatures of the operations on chunks are defined as follows.

:: Chunk a; :: \*CHS io [9](#_bookmark8)

openChunks :: \*io *→* (Bool,Chunk a,CHS \*io) | GIO io closeChunks :: (CHS \*io) *→* \*io

newChunk :: a (CHS \*io) *→* (Chunk a, CHS \*io) | write*{| |}* a& GIO io chunkValue :: (Chunk a) (CHS \*io) *→* (a, CHS \*io) | read*{| |}* a& GIO io updateChunk :: (Chunk a) a (CHS \*io) *→* CHS \*s | write*{| |}* a& GIO io

The type Chunk for representing chunk objects is abstract. The other abstract type, called CHS, is used to allocate new chunks and to sequentialize the other chunk operations. By making this type unique, single threadedness is guaranteed, hence in-place updates can be performed safely. The operation openChunks first inspects the container to determine whether or not it is empty. In case of an empty container, a new empty chunk (the so-called *root chunk* ) is created. Otherwise, the root chunk of the container is read. The boolean result value indicates which of these possibilities occurred.

To illustrate the use of these operations we return to our Tree example. The idea is to wrap the stored records in chunks so that they will be left in the container when the tree data structure is read in.

First, we inject the tree built by createTree with chunks. By using a *generic state map* this can be specified easily in just a few lines of code.

addChunks :: (a (Elem b)) (CHS \*c) *→* (a (Elem (Chunk b)), CHS \*c) | write*{| |}* b& GIO c&

gMapLSt *{|*\* *→* \**|}* a

addChunks tr io = gMapLSt *{|*\* *→* \**|}* addChunk tr io **where**

addChunk *{*key,rec*}* [10](#_bookmark9) io = **let** (ch, nio)= newChunk rec io **in** (*{* key = key, rec = ch *}*, nio)

The generic function gMapLSt from the standard Clean library maps a state transition function (in this case addChunk) over the tree tr. The effect of applying addChunks is that the original records are stored in the IO container and the tree is updated with references to these records. Note that addChunks is overloaded in gMapLSt *{|*\* *→* \**|}* which means that it actually can be applied to *any* data type of kind \* *→* \*. The tree structure itself is stored in the root chunk. The complete program looks as follows:

writeChunkTreeToFile fname world

(Just file, world) = openFile fname world

(ok, chunk, chunks)= openChunks file

(ch\_tree, chunks)= addChunks (createTree 100000) chunks

= closeFile (closeChunks (updateChunk chunk ch\_tree chunks)) world

The tree constructed by createTree above is completely out of balance: all elements are stored in the right branches. The use of chunks enables us to re-balance the tree without touching the stored records. This can be achieved as follows (we left out the open and close operations which are the same as in the previous example).

9 An abstract data type in Clean. The \* before CHS indicates that any CHS-object must always be unique. Therefore, the \* can then be omitted in the rest of the code.

10 *{*f,g*}* denotes the (lazy) selection of the fields f and g from the record argument.

Below, balance takes an arbitrary tree and converts it into a balanced one.

(unbal\_tree, chunks)= chunkValue chunk chunks

chunks = updateChunk chunk (balance unbal\_tree) chunks

Obviously, after balancing the tree we now can quickly find a particular record and update its contents directly via an updateChunk.

# Type-safe IO operations

Another serious disadvantage of the sequentialization method from the previous section, and in fact of almost any compress/uncompress, pack/unpack, or read/show operation, is that the written information is untyped. Structures written as trees can be read back as lists sometimes leading to a crash or maybe without being noticed. In this section we will show how to extend our IO operations such that they are *type safe*. Note that this problem cannot be solved statically, the data in underlying IO containers (strings, files etc) is untyped. We have to add type information about the actual data to the data that is stored. But all our operations are defined in a generic way. How do we dynamically derive types of objects such that this information can be stored in the container and retrieved from it when it is re-opened for reading?

The solution is to use generics again. Remember that the generic compiler is able to construct a version of a generic function for any concrete type. Unfortu- nately, the concrete type on which a generic function is applied is not known. The reason is that generic functions are defined on type *constructors*, not on concrete types. In both the generic definition on type OBJECT and type CONS we can inspect a representation of the type *deﬁnition* corresponding to the actual type construc- tor and concrete data constructor on which the generic function is applied. We therefore have to define a generic function type that uses these type definitions to construct a representation of the actual type. For non recursive types the construc- tion is straightforward. Recursion however, requires a more subtle approach. The main problem with recursion is that, in order to derive an exact representation of the actual type, one has to traverse the generic representation of that type in such a way that all type information is indeed collected without getting into a infinite loop.

As a starting point for our description we define the signature of type as follows:

**generic** type a :: (Maybe a, Type)

:: TypeCons :== String

:: TypeVar :== Int

:: Type = TVar TypeVar | TApp TypeCons [Type] | TArr Type Type | TBas BType | TEmp

Type is used for representing types as values. We use integers and strings to identify type variables and type constructors, respectively. The auxiliary TEmp constructor is intended to be used as an initial or default value. Note that, although we are only interested in the type, we are forced to use the generic type variable a in the type signature. The use of Maybe allows us to deliver Nothing as a concrete dummy value.

In the library itself, this result is used to construct a default value of the requested type which can, for instance, be used to initialize new objects.

Before explaining the working of the generic type construction we illustrate its use. The aim is to define a type safe version of our basic generic IO operations. We first introduce a wrapper type to include type information in the type of the IO container, together with a function for constructing such a container. This function also takes care of the type checking.

:: \*GStream a io = *{* state :: io *}*

openStream :: \*io *→* (Bool, GStream a \*io) | GIO io & type*{| |}* a openStream io

(m, t)= type*{| |}*

io = forceType io m

| isEmptyIO io

= (True, *{* state = write*{| |}* 0 t io *}*)

(maybe, io)= read*{| |}* 0 io

= (isJust maybe && fromJust maybe == t, *{* state = io *}*)

**where**

forceType :: (GStream a \*io) (Maybe a) *→* GStream a \*io forceType io y = io

isEmptyIO checks whether io is empty. In that case the type representation (yielded by the generic type function) is written to the container. If the io is not empty, read tries to read the type of the data that has been stored previously, and compares it to the requested type. forceType is just an auxiliary function connecting the value type of the stream to the value type of m. Without forceType there would be no connection between those two, leading to a (static) internal overloading error. All other operations are simple wrappers.

writeValue :: a (GStream a \*io) *→* GStream a \*io | GIO io & write*{| |}* a writeValue val io=:*{*state*}* = *{* io & state = write*{| |}* 0 val state *}*

readValue :: (GStream a \*io) *→* (Maybe a,GStream a \*io) | GIO io & read*{| |}* a readValue io=:*{*state*}* = **let** (v, nst)= read*{| |}* 0 state **in** = (v, *{* io & state = nst *}*)

closeStream :: (GStream a \*io) *→* \*io closeStream *{*state*}* = state

The next small program shows how our example tree (this time without chunks) can be read from a file. Note that the additional Stream layer makes the type safety checks completely invisible.

readTree :: String \*World *→* (Maybe (Tree (Elem Person)) ,\*World) readTree tree\_file world

(Just file, world)= openFile tree\_file world

(ok, stream) = openStream file

| ok(val, stream)= readValue stream

= (val, closeFile (closeStream stream) world)

= (Nothing, closeFile (closeStream stream) world)

To adjust readTree such that it can read a possibly completely different structure it suffices to change the result type only. The fact that readTree indeed reads a tree of the specified type is completely determined by that type and not by the code.

The question that remains is how to define type such that it will derive proper types. As usual, we have to provide instances for our predefined generic type con-

structors. This time, however, the alternative for OBJECT plays a crucial role. As said before, one of our main concerns is not getting into an infinite computation. To illustrate the danger, we start with the instance of type that will be generated for lists by writing **derive** type []. The structure of this generated function, say type\_List, is completely determined by the definition of the list type.

:: List a = Nil | Cons a (List a)

type\_List type\_a = bimap (type\_OBJECT (type\_EITHER

(type\_CONS type\_UNIT) (type\_CONS (type\_PAIR type\_a (type\_List type\_a)))))

The function bimap takes care the conversions between list object and its generic rep- resentation. The precise structure of this function is irrelevant to this presentation. If, on the right-hand side of type\_List, each instance function would directly call its continuation this would finally lead to a call of type\_List itself and thus to an infinite computation. To prevent this we supply type with an auxiliary *history* argument containing a description of the subsequent calls done so far. The idea is to mark an edge in the (directed) calling graph that leads form a data constructor *C* to a type constructor *T* , say via *C*’s *nth* argument, by the formal type belonging to that ar- gument. E.g. in the above list example the recursive call to type\_List will be marked with List (TVar n), i.e. the formal type of Cons’ second argument. The number n of the type variable is supposed to be *fresh*, i.e. not used before. Assigning such fresh numbers to new variables requires an additional argument for type maintaining the variable counter.

When entering type\_List it is checked whether the corresponding calling edge already occurs in the history. If so, the function returns immediately. Otherwise the underlying type is constructed by calling the continuation. However, in some cases a single traversal of a type is not sufficient to derive a type completely. Consider for example the following definition of an alternating list.

:: AList a b = ANil | ACons a (AList b a)

To obtain the representation of, for example, AList Int Char the instance of type for AList has to pass through type\_AList twice. Our ‘cycle detection mechanism’ auto- matically takes care of that. The latter also counts for more complex types like

:: Rose a = Rose a (List (Rose a))

and even for *non-uniform recursive data types*, such as the following rather exotic type definition

:: Exot a = ENil | ECons a (Exot (Exot a))

The fresh variables are not only used for creating auxiliary unique markers but also for the construction of the requested type. Pieces of this type are collected little by little and connected to each other via *uniﬁcation*. This requires instantiation of data constructor types each time a new type constructor is encountered. All this is taken care of by the instance of type for OBJECT. One further detail of our implementation is that unification is not performed on–the–fly but deferred until all information about the type has been gathered. For this reason, all type equations

resulting from the encountered dependencies are collected, and solved at the end of the type construction process. All this leads to the following signature for type.

:: History :== [TYPE]; :: Marker :== Type

:: TypeSt = *{* fresh :: Int, equa :: [(Type,Type)]*}*

**generic** type a :: Type History Marker TypeSt *→* (Maybe a, TypeSt)

The first argument of type is the type requested by the context. As soon as an instance of type produces a concrete type, the equation of this type and the requested one is added to the list of equations. For example, the instance of type for Int is defined as:

type *{|*Int*|}* rt history mark ts = (Nothing, *{* ts & equa = [(rt, TBas BInt) : ts.equa]*}*)

¿From the explanation above, it should be clear that the instance for OBJECT is much more involved than the previous one for Int. Due to space limitations it is omitted, so are the almost trivial definitions for UNIT, EITHER and PAIR.

The generic type function is not suited for being used by programmers. First of all, there are several arguments that are only used internally. Secondly, it does not yield a type but a set of equalities that still have to be solved. We can hide this implementation specific information by using the following wrapper.

defaultType :: (Maybe a, Type) | type*{| |}* a defaultType

fv = TVar 0

(m, ts)= type*{| |}* fv [] TEmp *{* fresh = 1, equa = [ ] *}*

subst = unify ts.equa *{*TEmp *\\* \_ *←* [0 .. ts.fresh]*}*

= (m, Subst fv subst)

We use the (fresh) variable 0 as requested type for the top call of type. Both history and (recursion) marker are empty, indicated by [] end TEmp respectively. After calling type, the collected equations are passed to unify. This standard unification algorithm takes a list of type equations as well as a substitution as input and produces a new substitution solving those equations. We represent the substitution by an array of types in which type variables are used as indices. We start with an empty substitution which then will be updated (destructively) by unify. To obtain the final type this unifier is applied to variable 0.

# Related Work

To the best of the authors knowledge the use of generic programming techniques for the creation of a type safe destructive database system is new.

Serialization and de-serialization are standard examples in any introductory pa- per on generic or type driven programming techniques [[8](#_bookmark18),[7](#_bookmark17),[10](#_bookmark20)]. Data which is se- rialized in such a way can be stored and retrieved from persistent memory, but it lacks the ability to destructively update substructures. This is an absolutely neces- sary feature for any real world database system. Instead of using generic techniques one can of course also use the overloading mechanism [[14](#_bookmark24)]. However, this has the disadvantage that the programmer has to provide the proper instances for reading and writing of data explicitly.

In [[5](#_bookmark16)] a persistent storage for Haskell is presented. The basic idea is to extend the application memory with a persistent memory. When data is (explicitly) shifted from one memory to another, the internal representation of data in the application is converted to the external representation in the storage, and backwards. For the conversions support of the run time system is needed. Destructive updating is not provided, but when structures are modified, sharing is maintained in the storage in the same way as it is common in the application memory. The approach cannot be used to exchange data between different applications.

In Amber [[4](#_bookmark14)], CAML [[11](#_bookmark21)] and Clean [[12](#_bookmark22)] one can store and retrieve values of any type by wrapping them into a *Dynamic*. A Dynamic contains both a representation of a value and a representation of it’s type. This method does enable the type safe exchange of data between applications, but one needs support from the compiler and run time system to be able to check the type consistency and take care of the conversions. In Clean it is even possible to exchange *functions* between applications [[15](#_bookmark25)]. Part of the run time systems is a dynamic linker which can extend a running executable with additional functionality by loading the corresponding code needed for the evaluation of new functions. However, none of the Dynamic approaches provide support for destructive updates.

# Conclusions

In this paper we have presented a set of generic IO operations that are flexible, efficient and type-safe. They are flexible because with a simple derive statement data of any concrete type can be stored and retrieved. They are efficient because data structures can be partially read in and stored data can be updated destructively. They are type safe because a representation of the concrete type of the data that is written is stored as well. This type is checked against the type of data requested by the reader, before the data structure can be read in.

We have tested the operations with fair-sized data sets (100,000 records) and the efficiency appeared to be sufficient for most cases. However, if performance is critical the overhead introduced by the common generic code generation scheme can be fully eliminated by using the extended fusion technique described in [[3](#_bookmark13)]. The resulting code appears to be very efficient. Our tests showed that our system can be one to two orders of magnitude faster than standard sequentialization methods or data base implementations.

Our system has been integrated in the iTask Workflow System [[13](#_bookmark23)]. It allows the high level specification of interactive workflows from which a multi-user web-based workflow system is generated fully automatically. In a workflow system, storage and retrieval of information plays a vital role. However, a programmer specifying a workflow in the iTask system does not have to worry anymore about the low level details commonly attached to database access. Any type of information can now be stored and retrieved automatically making use of our generic read and write functions. In this way database access can be completely hidden for the workflow programmer. It furthermore enables the definition of re-usable workflow schemes

on a high level of abstraction. In this way one can focus on the specification of the actual workflow. Without our generic data storage approach this would not have been possible.

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