Mutable Collection Types in Shallow Embedded DSLs

Mutable Arrays in mTask

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Abstract

The mTask system offers a high level and type safe way to program the Internet of Things through a paradigm known as Task Oriented Programming (TOP). TOP allows the creation of applications by combining individual tasks that can communicate with each other using Shared Data Sources (SDSs). Tasks and the way they communicate are a natural fit to the Internet of Things as they have similar properties as lightweight communicating threads (desirable on IoT devices [5]). The mTask system is embedded in Clean which also hosts iTask: a system to create task oriented programs with a web-based user interface. Notably missing from mTask (but present in iTask) is any form of collection type. This is mostly due to the limited amount of memory IoT devices have and the functionally pure nature of mTask programs. This thesis attempts resolve this discrepancy by utilzing Clean's uniqueness type system to implement functionally pure, mutable, array types. Achieving this required many changes to the mTask system. The main challenges faced were:

- The current mTask system was never created with the intent of having values of different sizes. This lead to many assumptions being made for memory management that had to be reversed.
- The current ecosystem does not have support for any kind of values whose size is unknown compile time. Again, this lead to several assumptions that had to be reversed.
- Uniqueness has not been used before inside of a task oriented DSL[1]. This required many changes to the underlying structure of mTask's compilation.

We ultimately realize that the current system cannot satisfyingly support functionally pure mutable collection types. Several contributions to mTask and towards uniqueness in an embedded DSL remain. For mTask the most notable contribution is a change to the garbage collector that now allows variable sized nodes and allows for the stack and heap to switch places in the future. For uniqueness in an embedded DSL we have shown on what areas further work is required. In particular, we have shown that the introduction of optionally unique values requires changes to the DSL that would either make the DSL very inconvenient to use or prevent the definition of functions.

[1] Uniqueness has been used inside a DSL embedded in Idris before[4]

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Contents

Chapter 1

Introduction

The modern world consists of many devices that are not full systems on their own (as a computer or smart phone might be), but are embedded in other, larger, systems (as part of a car, fridge, thermostat, etc). These *embedded systems* are often connected to the internet to form the Internet of Things (IoT). Being part of a greater system, these embedded systems are often small and cheap, while also being used to run ideally parallel control software. Writing parallel software for devices having such little computing power and memory is a task often hard to perform. Manual interleaving of computations is possible, as described in [5], but this requires quite a lot of effort from the programmer.

Task Oriented Programming (TOP) is a novel programming paradigm that enables the creation of multi-user interactions by providing a selection of tasks and a set of combinators [19]. Tasks can be considered as individual pieces of work that have to be performed by either a human or a computer system. Combinators allow for the sequential or parallel composition of these tasks. Additionally, TOP provides ways for inter-task communication through Shared Data Sources (SDSs) which can been considered as values shared by all tasks as long as the SDS is in scope. iTasks is an embedded DSL that implements TOP with Clean as the host language.

For mTask [14], the observation was made that TOP's tasks form a sort of lightweight communicating threads, ideal for use in embedded systems. As such, TOP was brought to the embedded domain as a so called class based embedded DSL in Clean (similar to iTasks). Tasks defined in the mTask DSL are compiled to an intermediate bytecode that expresses the creation of a task tree. On the embedded system, a Runtime System (RTS) receives this bytecode, interprets it to form a tree, and finally rewrites this tree to form the result of the task. Rewriting in this sense is the modifying of the tree based on a selection of specified rules, as it is in a graph rewriting setting. Multiple tasks can be evaluated by the same embedded device, either using separate programs or using one of the available task combinators. SDSs can be used to communicate between these tasks.

A feature notably missing from mTask is any form of a collection type, particularly arrays, making the creation of certain programs more difficult than it has to be. Consider, for example, the situation where we wish to turn an air-conditioner on or off depending on the current temperature. In order to account for the inaccuracy of the temperature sensor, we might want to calculate the moving average over the last ten or so seconds. Taking a single sample every second, it is relatively inconvenient to store these ten measurements when not using indexable collection types. In this thesis we will look at the implementation of this program described below and attempt to modify mTask such that it supports this program and other programs using collection types. We will go through the program section by section, the full program, and

its iterations, can be found in Appendix C.

```
DHT D1 DHT11 \dht->
sds \avg=0 In
```

First the program creates two global identifiers. The DHT (A temperature and humidity sensor) is said to be connected to Digital Pin 1 and of type DHT11. On the second line, we create a shared data source: An identifier that can be read by every task in its scope. We use this value to communicate the average temperature between two different tasks that we run in parallel.

```
fun \cal_avg=(\(i, arr, acc)->
        If (i >=. lit 10) (
                acc /. lit 10
        ) (
                cal_avg (i +. lit 1, arr, acc +. (arr !. i))
        )
) In
```

Next we define three different functions. This first function is a functionally pure function that calculates the average value of an array of length 10. It achieves this as a tail recursive function summing the array and subsequently dividing by the length of the array.

```
fun \measure=(\(i, arr)->
        delay (lit 1000)
        >>|. temperature dht
        >>~. \v
                # arr = updArray arr i v
                # x = cal_avg (lit 0, arr, lit 0)
                = sdsSet avg x
        >>|. If (i <. 9)
                (measure (i +. lit 1, arr))
                (measure (lit 0, arr))
) In
```

Subsequently we define our first of the two major tasks that will run in parallel. This task delays itself by 1000 milliseconds, such that it will run only once every second, before it reads the temperature from the global DHT sensor and places it in the array. Finally, the function calculates the new average using the function created above, updates the shared data source with this value, and calls itself with a new index value. The index value is incremented such that it will wrap around after it reaches 9.

```
fun \act=(\on->
        getSds avg
        >>*.
        [ IfValue (\v -> v >. lit 22 &. Not on) (\_ -> writeD d0 true)
        , IfValue (\v -> v <. lit 18 & on) (\_ -> writeD d0 false)
        ]
        >>=. act
) In
```

The last defined function is the `act` function. This function waits on an update of the shared data source, after which it will, depending on the value, turn our hypothetical air-conditioner on or off. If the average temperature over the last seconds was higher than 22, the air-conditioner is turned on, if it was lower than 18, the air-conditioner is turned off. After this has been done the function calls itself with an updated on/off state. Consider that the new state is set as the result of one of the two `writeD` tasks where the `writeD` results in the set value.

```
{main = measure (lit 0, array {20, 20, 20, 20, 20, 20, 20, 20, 20, 20}) .&&.
↪  (readD d0 >>=. act)}
```

Finally, in our `main` function, we start the two tasks giving a default array and air-conditioner state.

Several problems must be solved to implement this program. First, we must consider how we want to extend mTask's DSL to host functions related to arrays. Secondly, mTask was not designed to work with collection types. As such, many assumptions were made regarding memory layout. These assumptions have to be reversed. Finally, in the program above, we mutably update the array. This is done to prevent having multiple copies of the same array in memory but prevents functional purity (a property that Clean and mTask have). In this thesis we attempt to solve this problem by using Clean's uniqueness typing. This idea is not new and is based on Clean own implementation of mutable arrays.

The first chapter discusses the ecosystem in which mTask was created, it introduces a few key concepts required to understand the remainder of the thesis. The problems are individually addressed in the subsequent chapters. Finally, we discuss several other DSLs and how they accommodate mutable arrays before we consider future work that should be done to create a satisfying implementation of mutable collection types in mTask.

Chapter 2

Preliminaries

In order to comprehend later parts of this thesis, some background knowledge is required. Firstly monads, because of their important role in the back end of mTask. Secondly TOP and mTask, which form the basis of the mTask language. Finally, uniqueness, an extension to typing systems that allows mutable values in a *functionally pure* language and is used in this thesis to implement mutable arrays. This initial chapter introduces monads and mTask briefly; uniqueness and further background is given in the individual chapters as it becomes relevant.

2.1 Monads

Monads are a concept originating in category theory that, in functional programming [20], allows the composition of computation while allowing the composition to implicitly carry a certain aspect related to the computation. For example, allowing pure computations to share a mutable state, or allowing pure computations to fail. Monads are used heavily in mTask, and a certain level of understanding of their usage is thus required to understand some parts of this thesis, the same is not true for their mathematical background which is disregarded with the exception of the monad laws that are discussed in Chapter 4. Additionally, we consider the monad to be an independent class, overlooking any dependency on the (applicative) functor class.

In a functional programming setting, the monad is defined as a class containing two functions:

- The first function (defined as `return`) creates a computation that returns a given value.
- The second function (defined as `bind` or `>>=`) creates a new computation by composing a computation with the reaction on the result of said computation. The implicit aspect mentioned earlier should be explicitly handled in the instantiation of this function.

In Clean, this class can be defined as given in Listing 2.1. Where `infixl 1` defines the function as being an infix function that is weak binding and left associative.

```
class Monad m where
        (>>=) infixl 1 :: (m a) (a -> m b) -> m b
        return :: a -> m a
```

Listing 2.1: The Monad Class

```
:: Maybe a = Just a | Nothing

instance Monad Maybe
where
        (>>=) Nothing _   = Nothing
        (>>=) (Just x) f = f x
        return x = Just x
```

Listing 2.2: The `Maybe` instance of the monad class

There are many instances of the monad class, all of which implicitly handle a different aspect of computation. For brevity's sake we refer to "the x instance of the monad class" as "the x monad". For example, the state monad or the `IO` monad. One of the simplest instantiations of the monad is arguably the `Maybe` monad. In it, the implicit aspect is the optional value a computation might have. The reaction on a computation is only considered if the computation had a result. For illustration, our computation can result in either `Just x` (indicating that the result of the computation was `x`) or `Nothing` (indicating that the computation had no result). The reaction is only evaluated if the computation resulted in `Just x`.

Following the above description, the implementation in Listing 2.2 follows. Note that the decision of evaluating or not evaluating of the reaction is made explicit in the bind function as was described earlier.

A good candidate for usage of the `Maybe` monad is the evaluation of mathematical expressions, some of which (for example the trivial expression $1/0$) cannot be computed. In our `Maybe` monad, these non-computable expressions would results in `Nothing`, thus preventing further computation. Suppose we have the following ADT that describes simple mathematical expressions:

```
:: Expression = Lit Int
              | Add Expression Expression
              | Sub Expression Expression
              | Mul Expression Expression
              | Div Expression Expression
```

Here, `Div (Lit 1) (Lit 0)` represents the previously mentioned incomputable expression. An evaluator of our expression type, using the `Maybe` monad, is given in Listing 2.3. In most cases we simply calculate the value of x, the value of y, and then perform whichever calculation is indicated by the constructor. If either x or y could not be computed (i.e. resulted in `Nothing`), the monad ensures that the reaction also results in `Nothing`. For the `Div` constructor we must, however, indicate ourselves that the evaluation failed. We do this by inspecting the result of the computation of y. If the computation resulted in 0, we know that the `Div` cannot be evaluated and therefore results in `Nothing`, in all other cases we simply return the division of the two numbers. In the example `Add (Div (Lit 1) (Lit 0)) (Lit 1)`, the line evaluating `Add` does not need to check the result of the computation of x, the maybe monad does this instead. Since x results in a `Nothing`, the monad does not go on to evaluate x, instead resulting in `Nothing` immediately.

While the `Maybe` monad is a good introduction into the way monads hide implicit computational aspects from the programmer, it is not used in the implementation of mTask. A monad that is used, is the `StateT` monad. Hinted at before, this monad allows the pure computations

```
eval :: Expression -> Maybe Int
eval (Lit x) = return x
eval (Add x y) = x >>= \x -> y >>= \y -> return (x + y)
eval (Sub x y) = x >>= \x -> y >>= \y -> return (x - y)
eval (Mul x y) = x >>= \x -> y >>= \y -> return (x * y)
eval (Div x y) = x >>= \x -> y >>= \y -> case y of
        0 -> Nothing
        _ -> return (x / y)
```

Listing 2.3: An evaluator of the `Expression` type resulting in an optional value to represent incomputable expressions.

```
instance Monad (State s)
where
        (>>=) (State x) f = State (\s
                # (x, s) = x s
                # (State x') = f x
                = x' s)
        return x = State (\s -> (x, s))
```

Listing 2.4: The `State` instance of the monad class

to implicitly share a mutable state, hence the name. However, the `StateT` monad (often also called the State Transformer monad) adds needless complexity for the purpose of this thesis. As such, we will use the (less general) state monad instead. In order to implement mutability of the state, the state monad has a few auxiliary computations. The `getState` function, for example, that returns the state:

```
getState :: State s s
```

The state type itself is defined as a type with a single type constructor that takes the state and result types as arguments:

```
:: State s a = State (s -> (a, s))
```

The accompanying instance of which is defined in Listing 2.4. Take note of how the state is hidden by the instance.

Now, to use the state monad. Suppose that we, in our earlier example, we want to count the number of literals in an expression while simultaneously evaluating it. First, our state data type should be instantiated such that the result of an expression is an integer and the state is also an integer.

```
:: Expression -> State Int Int
```

Additionally, we should create an auxiliary function to increment the literal counter by 1. This, in itself, can be done using the aforementioned `state` function or `State` constructor.

```
increment :: State Int ()
increment = State (\s -> ((), s + 1))
```

As a consequence of no longer resulting in a `Maybe`, we can no longer safely compute the `Div` expression without assuming the divisor is never 0. This assumption is reflected in the new implementation of the Div case.

```
eval (Div x y) = x >>= \x -> y >>= \y -> return (x / y)
```

Finally, we must make use of the increment function to actually count the number of literals. As a side note: we use the `>>|`[1] function here, which is an alias for the "`>>= \_ ->`" construction.

```
eval (Lit x) = increment >>| return x
```

We will see later that mTask uses monads similar to this one in two of its three views.

2.2 Task Oriented Programming

Task Oriented Programming (TOP) [19] is a is a programming paradigm for the construction of distributed systems where separate entities work together on a single goal all the while values can be shared and updated immediately. Perhaps more importantly, TOP forms the basis of mTask, the subject of this thesis.

In TOP these multi-entity interactions can be defined by only defining the tasks that need to be completed and the relationships between these tasks. Defining such tasks and their relationships is done using special combinators that we will discuss later. The specific TOP implementation deals with the aspects required for an entity to perform the task. One of these aspects is *data sharing*: allowing different tasks to observe the value of another task while this task is being performed

The most well known implementation of TOP is iTasks, an embedded DSL in Clean. The following few paragraphs (including the depicted tasks) apply generally to TOP but specifically to iTasks.

TOP is very well suited to situations where multiple entities have to work together to achieve a collective goal. Each entity can simultaneously be working on a task, and data being produced by that task can be shared live amongst all other entities in the system. Even when a task has not been completed yet can its intermediate result already be shared amongst other tasks.

To indicate if the result of a task has been finalized (i.e. if the task has produced its final result, an intermediate result, or has not yet produced as result), three different kinds of values exists; Stable, Unstable, and NoValue. Stable values are those that will not change; evaluating the task now will result in the same value as evaluating it any time in the future. Stable values are also used to indicate that a task has finalized its result. Unstable values are concrete values that are subject to change over time. Finally, NoValue indicates a task that cannot currently produce any complete value. Consider a simple task where a user is presented with some form asking

[1] >> in Haskell.

them to enter their age in years. While the entry field is empty, the editor (input field) cannot emit a value and will therefore emit "NoValue". Suppose our user is 25 years old, once the user has entered the number 2 the field contains an integer, even if it is not the final value. As such, the editor will emit a "Unstable 2". Of course, even when the user has entered 25, the result is still an "Unstable 25". Converting to a stable value can be done using a combinator that adds a button to the bottom of the form that, when pressed, finalizes the result. Figure 2.1 shows these intermediate steps and the stability of the value entered. Note that, once the task has completed and value has been said to be stable, the value can no longer be changed. Additionally, the task as a whole (the editor task with the step combinator) will emit NoValue as long as the step has not been performed. Once it has been performed, it emits whatever the result of its right hand-side is. The stabilities shown in the images are those of the editor in the first two and of a simple show task after the step in the last image.

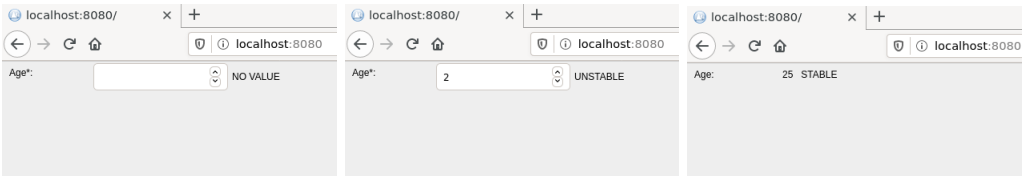


Figure 2.1: The stability of the values in iTask

Many tasks, especially those interacting with the outside world, are always subject to change and will never emit a stable value. An obvious example is the task that reads the current time and returns it, but as we have seen before, the same is also true for all editors (input fields for the user). Specifically for mTask, any task that reads a value from a sensor or pin results in an unstable value. Recall our example program where we read the temperature from the connected temperature sensor. Since the temperature can always change over time, this task will always result in an unstable value. Other tasks, most notably tasks that simply return a constant value, are never subject to change and will therefore always return a stable value.

New tasks can be created using existing tasks and the sequential and parallel task combinators. The sequential (or step) combinator allows the programmer to define the continuation of a task and takes two arguments: the first task in the step and the possible continuations. (It is, for example, used to create the button yielding a stable value in the example above.) The possible continuations are defined in a list, each with a predicate defining when this continuation must be chosen.

```
(>>*) infixl 1 :: (Task a) [TaskCont a (Task b)] -> Task b
```

For convenience, there are several macros of this combinator that provide less general behavior in return for a simpler interface:

```
(>>=) infixl 1 :: (Task a) (a -> Task b) -> Task b
(>>|) infixl 1 :: (Task a) (Task b) -> Task b
```

Where the `>>=` combinator can be compared to the bind function in the sense that it takes the result from the first task and passes it as an argument to the next task. The `>>|` function sequentially combines tasks. The result of the first task is ignored. In our example program we see mTask's equivalent `>>*.`, `>>=.` and `>>|.`. An attentive reader might realize that these

functions use the same identifiers as those used by the monad class[2]. While their behavior is indeed similar, it is worth noting that there exists no task monad.

The parallel combinator allows for multiple tasks to be performed simultaneously, but also allows the programmer to define when the parallel combination should be completed. For example, the `-&&-` is a parallel combinator that combines two tasks into a single task resulting in a tuple. This tuple will only be stable when both arguments of the combinator are also stable. In contrast, the `-||-` combinator emits a stable value as soon as either of its argument tasks emits a stable value. The difference between these combinators is reflected in their type.

```
(-&&-) infixr 4 :: (Task a) (Task b) -> Task (a, b)
(-||-) infixr 3 :: (Task a) (Task a) -> Task a
```

In our example program we see that we use mTask's equivalent `.&&.` to start the rewriting of the two tasks. Since neither task will ever return, it would also be totally valid to use the `.||.` combinator here.

Collaborating tasks might often want to share data without passing it explicitly. Additionally, the specific location or method by which the data is stored is often irrelevant. To achieve this, TOP includes Shared Data Sources (SDSs), abstract interfaces that allow reading, writing and updating values atomically [17, 19]. As long as an SDS is in scope, a task can access or modify the data whenever. The average temperature in our example program is an SDS to allow the `measure` and `act` tasks to communicate the value. For the remainder of this thesis the details of SDSs are not essential. As such, we will not discuss them much further.

Purely as illustration, the following code is a reimplementation of the example program from the introduction in iTasks. Note that that iTasks does not have certain tasks implemented that mTask does have implemented, the pinIO tasks for example are not implemented in iTasks. Additionally, the array function as used in the example do not exist in Clean's standard array library.

2.3 mTask

TOP for embedded systems is implemented by mTask. Integrated with iTasks, it allows the creation of special tasks that run on IoT devices as apposed to interacting with a user. These tasks might include reading the temperature from a sensor or setting the value of a digital or analogue pin. mTask does this using two distinct components; a DSL integrated in Clean, and an RTS running on the IoT[3] device.

The mTask DSL is a shallowly embedded class based (or tagless) DSL [14]; it consists of a series of classes instantiated by a selection of views. This is unlike iTasks which is built from native Clean functions with expressions simply being Clean expressions. This approach cannot be taken by mTask as it was desired that multiple views could instantiate the different classes. Unfortunately, this means that mTask cannot use the same operators as iTasks or Clean expressions, instead mTask operators are extended with a single period: "+" becomes "+.", ">>=" becomes ">>=.", etc.

A few of the most important classes of mTask are arguably the `expr`, and the `step` and the parallel combinator classes. Globally, we can separate all of mTask's functions in two groups: the expressions and the tasks. Expressions host all calculations needed to create the tasks and

[2]In a more recent version of iTasks these functions have been renamed. This change has not been incorporated in mTask however, and so the choice was made to use the old names instead

[3]mTask also support running the RTS on non-embedded devices, but this is not mTask's goal.

```
avgSDS :: SimpleSDSLens Int
avgSDS = sharedStore "avgSDS" 20

cal_avg :: Int {Int} Int -> Int
cal_avg 10 _ acc = acc / 10
cal_avg i arr acc = cal_avg (i + 1) arr (acc + (select arr i))

measure :: Int {Int} -> Task a
measure i arr =
            waitForTimer False 1
        >>| temperature dht
        >>~ \v
                # arr = update arr i v
                # x = cal_avg 0 arr 0
                = set x avgSDS
        >>| if (i < 9)
                (measure (i + 1) arr)
                (measure 0 arr)

act :: Bool -> Task a
act on =
            get avgSDS
        >>*
        [ OnValue (ifValue (\v -> v > 22 && not on) (\_ -> writeD d0 True))
        , OnValue (ifValue (\v -> v < 18 && on) (\_ -> writeD d0 False))
        ]
        >>= act

airco :: Task ((), ())
airco = measure 0 (createArray 10 20) -&&- (readD d0 >>? act)
```

Listing 2.5: An illustrative reimplementation of the mTask example program in iTasks.

tasks form the overall work of the program. As a parallel to Clean's iTasks, the expressions are all Clean functions used to create an iTasks program. In our example program the `cal_avg` function that takes an array and calculates the average is an expression. It hosts no tasks and all calculations are functionally pure. The `measure` function on the other hand is a task. It consists of tasks that are combined using mTask's combinators. Note that this function does indeed contain several expressions, the array update for example but also the incrementing of `i`. A more in-depth look into mTask's DSL is presented in Chapter 3.

The mTask RTS is a small RTS that interprets the mTask tasks after they have been compiled to an intermediate bytecode by one of the views mentioned earlier. The result of the task is sent back to the server on every change, so that it can then used by the Clean host program. Figure 2.2 shows the architecture including the path an mTask task might take. The left-hand side shows the server with the three on the same program. Once an mTask program has been compiled

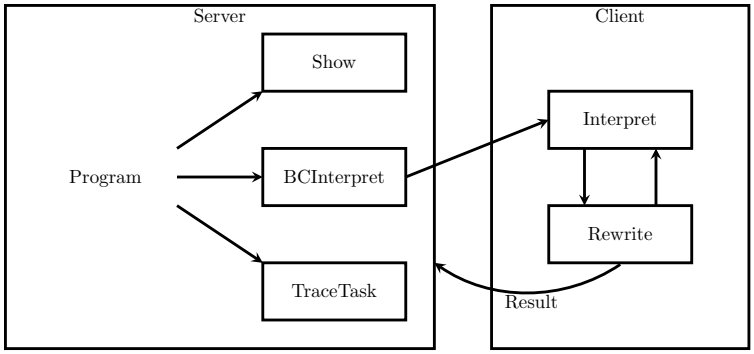


Figure 2.2: The mTask architecture which shows the path from program to result

by the BCInterpret view the resulting bytecode is sent to the client. The client will register all information pertaining to the task and will then start the interpretation of the bytecode. During this first interpretation phase, the client evaluates one or more expressions that, together, eventually create a task tree. Once interpretation has finished and the main function has been evaluated, the first rewrite phase takes place. In the rewrite phase the task tree is rewritten as far as possible. Based on the type of nodes in the task tree, it is entirely possible that the rewriting of a node requires another interpretation phase to occur. Once a single value node remains after rewriting, it is sent back to the server as the result of the program. Chapter 5 will go into more detail on how exactly mTask programs are evaluated.

Chapter 3

DSL Extension

This chapter considers mTask's DSL and how it is best extended to incorporate arrays. To achieve this, the chapter is broken up into three distinct sections. In the first, we look at the current DSL. In the second, we consider, based on the previous section, how arrays would fit naturally in the DSL. It is important here that we balance the natural integration with mTask (i.e. adhere to the current syntax and use of the language) with creating functions that are within scope of the implementation. Finally, we define our solution and instantiate it with the different views. For the remainder of this chapter we will use the terms "mTask's DSL", "the DSL" and "mTask" interchangeably.

3.1 mTask's DSL

To understand how our implementation of arrays would best fit in mTask, it is best to first understand the anatomy of an mTask program. For the following section we will use our previous example (repeated in Listing 3.1) to identify the different parts.

In general, the DSL is built of a collection of classes with every class serving a specific purpose. This separation of purposes allows certain views to only implement a selection of the classes, something we will make use of later. Despite the different classes however, all of the functions of these classes can be grouped into two main groups and one additional group:

The first group is the task group. In TOP, tasks are the pieces of work that have to be performed by users or, in mTask's case, embedded systems. Tasks can be inherently functionally impure as they represent the work that is performed, not the result of that work. In our moving average example we utilize several functions that yield tasks. The `readA :: (v APin) -> MTask v Int` task for example is the task that reads a value from the specified pin. As a function this would be functionally impure.

All task combinators are also part of this group, as they allow the combination of several tasks. In our example we use several combinators, most of which are part of the `step` class. The notable exception being the `.&&.` combinator used in the main function.

The `step` class is rather unique in its behavior in that some of its are defined as a higher order function. The `>>*.`, for example, is a task that takes a task and a list of possible continuations. These continuations take the form of one of these:

```
DHT D1 DHT11 \dht->
sds \avg=0 In
fun \cal_avg=(\(i, arr, acc)->
        If (i >=. lit 10) (
                acc /. lit 10
        ) (
                cal_avg (i +. lit 1, arr, acc +. (arr !. i))
        )
) In
fun \measure=(\(i, arr)->
        delay (lit 1000)
        >>|. temperature dht
        >>~. \v
                # arr = updArray arr i v
                # x = cal_avg (lit 0, arr, lit 0)
                = sdsSet avg x
        >>|. If (i <. 9)
                (measure (i +. lit 1, arr))
                (measure (lit 0, arr))
) In
fun \act=(\on->
        getSds avg
        >>*.
        [ IfValue (\v -> v >. lit 22 &. Not on) (\_ -> writeD d0 true)
        , IfValue (\v -> v <. lit 18 & on) (\_ -> writeD d0 false)
        ]
        >>=. act
) In
{main = measure (lit 0, array {20, 20, 20, 20, 20, 20, 20, 20, 20, 20}) .&&.
↪  (readD d0 >>=. act)}
```

Listing 3.1: An mTask program utilizing several array functions that controls an air-conditioner based on the moving average of the last ten seconds

```
:: Step v t u
  = IfValue    ((v t) -> v Bool) ((v t) -> MTask v u)
  | IfStable   ((v t) -> v Bool) ((v t) -> MTask v u)
  | IfUnstable ((v t) -> v Bool) ((v t) -> MTask v u)
  | IfNoValue                             (MTask v u)
  | Always                                (MTask v u)
```

In general, this type indicates a sequential task composed of a left-hand side resulting in a value of type t and yielding a task resulting in a value of type u (v is a type related to the views which is discussed shortly). Its constructors indicate what kind of value the left-hand side of the combinators must have resulted in before this step is considered. The function resulting in a boolean allows the user to define a predicate on the value of the result of the left-hand side. Only when this predicate is true is the final task evaluated. Upon evaluation of the `>>*.` it

selects the first member of the continuation list for which both the constructor and predicate match and evaluates the associated task. Take the following snippet from our example program as illustration:

```
getSds avg
>>*.
[ IfValue (\v -> v >. lit 22 &. Not on) (\_ -> writeD d0 true)
, IfValue (\v -> v <. lit 18 & on) (\_ -> writeD d0 false)
]
```

Both continuations of this step combinator are only considered if the task on the left-hand side produced a value. For `getSds` this is always. The combinator will then go on and check the predicates of each of the possible continuations. Suppose our room temperate over the past 10 seconds was 17 degrees and that our air-conditioner is currently on. The step combinator will check the first predicate, determine it is false (as per our hypothetical situation) and subsequently assess the second predicate. It will determine that this predicate is indeed true, and will result in the `writeD d0 false` task. This task will then go on to turn off the air-conditioning.

Besides the `>>*.` combinators, other functions of the class implement less general versions using one of these continuations. For example the `>>=.` task:

```
(>>=.) infixl 0 :: (MTask v t) ((v t) -> MTask v u) -> MTask v u
(>>=.) ma amb = ma >>*. [IfValue (\_->lit True) amb]
```

Every program (but not every function) created with mTask has to be a task. One of the simplest tasks (and thus mTask programs) you could define would be:

```
{main = rtrn (lit 42)}
```

Where the `rtrn` task takes a value and turns it into a task resulting in the value.

The second group is the expression class and all its functions. Functions in this group are completely evaluated during the interpretation phase. In our example the entire implementation of the `cal_avg` function is part of this domain. The same is true for all other mathematical expressions in the example. In iTasks, this domain is inhabited by all native Clean expressions. Of course this is not possible for mTask whose expressions depend on values stored on the embedded device. Instead, mTask has a class specifically inhabiting this domain, the `expr` class.

The additional group is the group that lives outside of the main function, in our moving average example these would be the `sds` and `fun` functions. Classes in this category usually serve to create some construct whose scope is the entire program. Other classes with functions in this domain are the peripheral classes, classes that interact with some sensor or actuator on the embedded systems. Several functions that take some value that was created by a function in this group are tasks. This has to do with the functional impurity of certain functions in this group.

An excerpt of a selection of mTask's classes relevant to our example is given in Listing 3.2. In them, `v` is a type constructor with kind `* -> *`, that expresses a view on the DSL. There are three views implemented on mTask's classes, two of which are evaluated using a monad, the last

```
class expr v where
        lit :: t -> (v t)
        (+.) infixl 6 :: (v t) (v t) -> (v t) | + t
        (/.) infixl 6 :: (v t) (v t) -> (v t) | / t
        If :: (v Bool) (v t) (v t) -> v t

class step v | expr v where
        (>>*.) infixl 1 :: (MTask v t) [Step v t u] -> MTask v u
        (>>=.) infixl 0 :: (MTask v t) ((v t) -> MTask v u) -> MTask v u
        (>>|.) infixl 0 :: (MTask v t) (MTask v u) -> MTask v u

class (.&&.) infixr 4 v :: (MTask v a) (MTask v b) -> MTask v (a, b)
```

Listing 3.2: Excerpts of classes definitions relevant to our air-conditioner example

(TraceTask) lives inside iTasks and is evaluated as an iTask task. For our instances of the three views we will deviate from our normal example for a while, instead using the following example to dramatically decrease verbosity:

```
rtrn (lit 1) >>=. \i -> rtrn (i +. lit 1)
```

3.1.1 The Show View

Firstly, there is the show view whose purpose is to convert the mTask task into a human readable string. Listing 3.3 displays the show instance for the classes depicted in Listing 3.2. Where `show` and `binop` are implemented as such:

```
show :: String -> Show a
show s = Show \st -> (undef, st +++ s)

binop x o y = show "(" >>| x >>| show o >>| y >>| show ")"
```

and with a show type that keeps track of the current state. Holding, for example, the current level of indentation and a list of identifiers.

```
:: Show a = Show (ShowState -> (a, ShowState))
```

It is worth noting that the show view in mTask does not produce a `String`. Rather, for efficiency reasons[1], it produces a `[String]`.

Our small example program results in the following:

```
(rtrn 1) >>= \a0.(rtrn (a0+1))
```

[1] An String in Clean is represented as an array of Char. Constantly appending or prepending is very inefficient. This appending and prepending is avoided by using a lazy list of String.

```
instance expr Show where
        lit   t   = show (toString t)
        (+.)  x y = binop x "+" y
        (/.)  x y = binop x "/" y
        If c t e  = show "If" >>| show " " >>| c >>| t >>| e


instance step Show
where
        (>>*.) e l = e >>| show " >>*" >>| indent >>| nl
                >>| show "[" >>| showSteps l >>| show "]" >>| unIndent >>| nl
        (>>=.) e l = e >>| show " >>= " >>| indent >>| nl >>| fresh "a" >>=
        \i->show ("\\" + i + ".") >>| f (show i) >>| unIndent
        (>>|.) e l = e >>| show " >>| " >>| indent >>| nl >>| f >>| unIndent

instance .&&. Show where (.&&.) x y = x >>| nl >>| show ".&&." >>| nl >>| y >>|
        return undef
```

Listing 3.3: The Show instance of the classes given in Listing 3.2

```
instance expr Interpret where
        lit t    = tell (BCPush (toByteCode t))
        (+.) a b = a >>| b >>| tell (binop a BCAddI BCAddL BCAddR)
        (-.) a b = a >>| b >>| tell (binop a BCSubI BCSubL BCSubR)
        (/.) a b = a >>| b >>| tell (binop a BCDivI BCDivL BCDivR)
        If c t e = freshlabel >>= \elselabel->freshlabel >>= \endiflabel->
                c >>| tell (BCJumpF elselabel) >>|
                t >>| tell` [BCJump endiflabel, BCLabel elselabel] >>|
                e >>| tell (BCLabel endiflabel)
```

Listing 3.4: The Interpret instance of the `expr` class as defined in Listing 3.2

Note that the identifier of the lambda's argument is lost during Clean's compilation. As such, a new identifier (`a0`) was created by the view.

3.1.2 The Interpret View

In addition to the show view, mTask also contains a view to compile the mTask to bytecode. This bytecode is sent to the RTS where it is interpreted. The concept behind the interpret view is that every function generates its own code, this code is then collected into a single program by the monad. Additionally, the monad has functions that deal with other aspects of compilation e.g. a function exists that returns a new free identifier. Consider the subset of the `expr` class from before, but this time instantiated by the interpret view in Listing 3.4.

To fully understand this instance, we must take a small detour to the monad used here. This monad[2] (which we will call the interpret monad for now), is very similar in behavior to the State

[2]In reality this monad is a StateT monad holding a Writer monad, but this detail can be overlooked. It is only

```
binop :: (v a) BCInstr BCInstr BCInstr -> BCInstr | type a
binop a i l r = if (byteWidth a == one) i
        (if (isReal (cast1 a)) r l)
```

Listing 3.5: The `binop` function found in the mTask system

monad if the state were a tuple of two values. These values would be a record with type `BCState` (holding data needed for compilation) and the final program represented as a `[BCInstr]`. The `tell` function appends instructions to this second state.

Additionally, we must quickly describe how code is evaluated on the embedded devices in general, a more detailed version is discussed in Chapter 5. For evaluation of mTask programs there are two relevant memory sections: the stack and the heap. The stack is used primarily during the interpretation of the expressions of group two. The heap is used to store the task nodes that form the task tree. In our example, for instance, the `sdsSet` function creates a `sdsSet`-node on the heap. The value `x` that was created from an expression is, at this point, copied from the stack to the heap, being part of this `sdsSet`-node.

Given these explanations, we can now see that the `lit` function transforms a value to its byte representation and pairs that with an instruction that pushes these bytes to the stack. The addition does something a little more interesting, in that it first determines what type we are trying to add. Based on the type, it will then select the appropriate addition instruction. Listing 3.5 show this function. The `byteWidth` function is used to determine if the value is an integer as integers are the only values occupying a single stack space. Reals and Longs both occupy two stack cells and such a different function is used here, the `isReal` function results in true only if its argument has type `:: Real`. Finally, the `cast1` function is a function with type signature `cast1 :: (v a) -> a` required to access the type contained in `v`.

Consider first only `rtrn (lit 1)` and how it compiles before we see at how it integrates with the task as a whole. First, 1 should be pushed onto the stack, this is performed using the `BCPush` instruction. Thereafter, the top of the stack should be used to create a task node, this is achieved using the `BCMkTask` instruction, where the argument should be `BCStable`. In short, we end up with the following list of instructions to create a stable node holding the number 1.

```
0: BCPush 0 1                   // Push 1 on the stack, the values 0 and 1 form
                                // the byte representation of the 16 bit integer
                                ↪  1.
4: BCMkTask BCStable1           // Create a single stable node containing the
                                // value. The 1 is the value's stackwidth
```

This stable node is used as an argument for the step node, whose other argument is a pointer to the function on its right side. During interpretation, the step node will use the value on the left side as an argument for the function(s) on its right side. To do this, it evaluates its left side fully (pushing it on the stack), checks if the value matches the predicate (which is always true in our case), and then interprets the right-hand side. The right-hand side finally uses the value on the stack as an argument.

In the end, the program will look as given in Listing 3.6, where all instructions are accompanied by a comment describing them.

important that the behavior of the `tell` function is introduced.

```
0:  BCJump 15                  // Jump to the main function
3:  BCArg 0                    // Take argument 0 and push it on the stack
5:  BCPush 0 1                 // Push 1 on the stack
9:  BCAddI                     // Add the two integers on top of the stack
10: BCMkTask BCStable1         // Create a stable node containing
                               // the top of the stack
12: BCReturn 1 2               // Return the result from this function
15: BCPush 0 1                 // Push 1 on the stack
19: BCMkTask BCStable1         // Create a stable node containing
                               // the top of the stack
21: BCMkTask BCStepStable 1 3 // Create the step task, with 1 denoting the
                               // stackwidth of the value and
                               // the function starting at 3 as the function
26: BCReturn 1 0               // Return top of the stack with width 1 knowing
                               // that this function had 0 arguments
```

Listing 3.6: The bytecode instructions compiled from `rtrn (lit 1) >>=. \i -> rtrn (i +. (lit 1))` accompanied by a summary of their semantics

3.1.3 The TraceTask View

Lastly, there exists the TraceTask view, an interpreter of the tasks written in Clean and incorporated into the library. This view is itself integrated into iTask, in the uniqueness chapter we will discuss this detail further. The result of the tracetask view on our small example is a stable 2.

3.1.4 Interpretation

Once the bytecode is generated, it is interpreted in the RTS where it is used to build a tree, this tree is then rewritten in a later phase. We already saw that the main function of our example program creates a stable node containing the value 1, but let's now consider the entire program and the tree it builds. Figure 3.1 shows the interpretation of the main function step by step. The stack and tree are shown as they would be after the interpretation of the instruction. Due to the way the bytecode in mTask is laid out, the first instruction is a jump, this jump jumps to the entry point of the main function. The second instruction pushes a value to the stack. In the third instruction this value is used to create the first node of the tree, a stable node. This node holds the value that was earlier pushed to the stack. In addition to the creation of the stable node, this instruction also pushes a reference to the newly created node to the stack. The next (fourth) instruction creates a step node. The two integer arguments of this instruction depict the width of the argument and function reference respectively. The step node has two references, the first references the value of the lhs, this side has already been evaluated to be "Stable 1". The "3" references the entry point of the function on the rhs of the step combinator. The final instruction moves the reference to the step node into the return space on the stack and deals with the frame pointer and other bookkeeping.

After the completion of the main function, the rewriting of the graph will begin. Rewriting the graph starts at the root node (the StepStable node in this case). The StepStable node is special in the sense that it will rewrite its left hand side, and then interpret the function on its right hand side. This behavior is depicted in Figure 3.2. Once the stable node has been

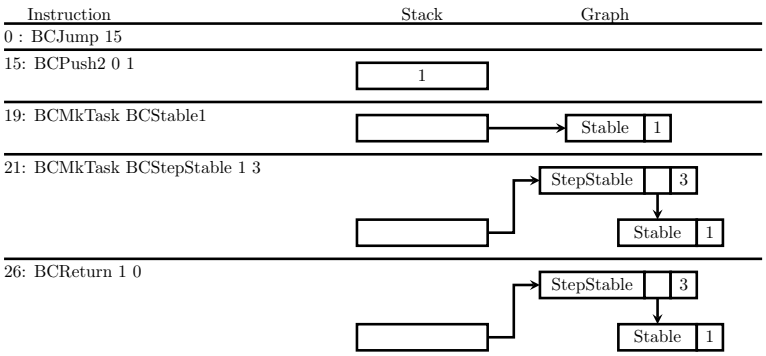


Figure 3.1: The interpretation of the main function

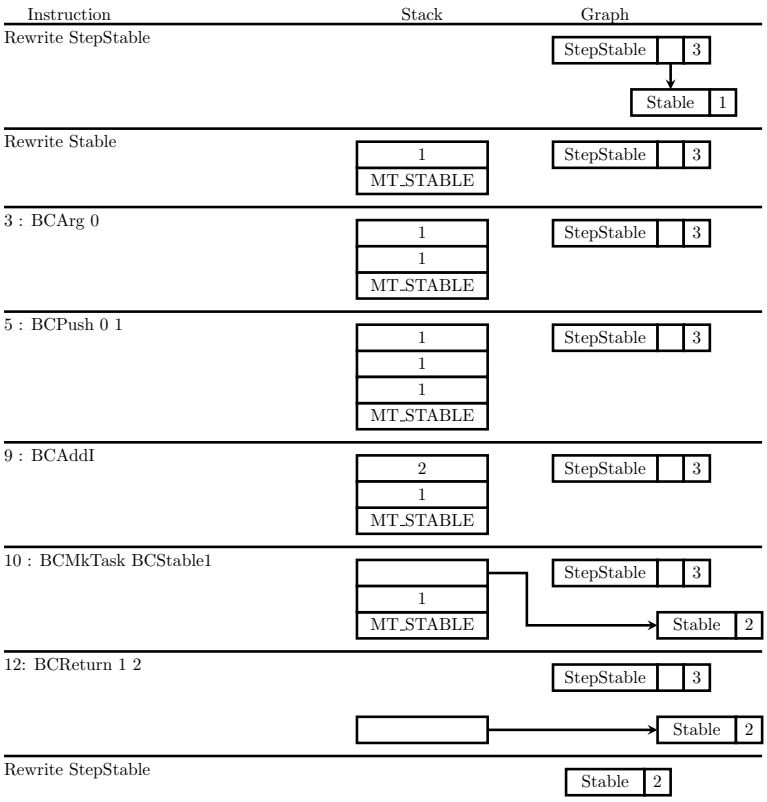


Figure 3.2: The continuation of the interpretation in Figure 3.1. `MT_STABLE` indicates that the value pushed to the stack was a stable value. In this case it refers to the value 1.

rewritten, interpretation of the function starting at 3 begins. This function pushes a value to the stack and adds the top two values of the stack to form 2. Finally, a stable node is created from the value on the stack. After the return we continue the rewriting of the step node, whose final task is marking itself as garbage.

3.2 Expression versus Task

In the example program it is shown that we have chosen to implement arrays as being part of expressions. This can be seen in the way arrays are used directly in the expressions. Another option would be creating the array with a function in the first group (outside the main function) and then having all operations on the array yield tasks. In reality, this was never a consideration but it is important to see why. So in this section we consider why we found expressions to be best suited to host arrays, and differences in implementation that would arise.

The strongest case for integrating arrays with expressions is a conceptual one. The array functions deal with pure values, they do not belong in the domain that hosts functionally impure tasks and their combinators.

Additionally, there is a distinct difference in the number of rewriting and interpretation phases that need to take place to achieve the same outcome. Suppose we have some function: `(!.) infixl 9 :: (v {a}) (v Int) -> v a` we could then write:

```
rtrn (array {1,2,3} !. (lit 0) +. (lit 1))
```

This entire task requires a single interpretation and rewriting phase, where the only node rewritten during the rewriting phase is the Stable node created by the `rtrn` function. The same is not true if we decide to implement the arrays as tasks, where the following would be equivalent:

```
(!.) infixl 9 :: (v {a}) (v Int) -> MTask v a
(array {1,2,3}) !. (lit 0) >>=. \x -> rtrn (x +. (lit 1))
```

Here, both the interpretation and the rewriting phase will happen twice. First, the array and selection are evaluated in the first interpret phase, resulting in the value `1`. This value is then used in the creation of the step node which is rewritten in the first rewriting phase. During this rewriting, the step node will call for interpretation of its right-hand side (forming the second interpret phase). Finally, the result of this second interpret phase is used to create a stable node which is ultimately rewritten during the final rewriting phase and sent back to the server.

The above is not to say that arrays in the task domain have no advantage. However, the only advantages are that we (1) need not worry about functional purity and (2) could implement the arrays as shares, making the implementation much easier because no effort would need to be made in modifying the garbage collector. However, this would never allow the use of arrays in expressions and would therefore make the RTS slower in most applications (having to constantly switch between interpretation and rewriting). Additionally, a lot of space would be used in the storage of the array. Memory that might not be needed when having the array live in garbage collectable memory. Most of all, this would never allow for arrays whose size is determined at runtime. Upon receival of a task all memory needed for the SDSs is allocated. As such, arrays implemented as shares (in their current implementation) are required to specify their size upon creation.

Concluding, while implementing arrays as tasks is much less complex, it would reduce the efficiency of the RTS and prevent arrays from changing in size as a consequence of the way they are currently stored while having no other benefits. On the other hand, implementing them as expressions takes more effort but results in a more satisfying and arguably better implementation.

3.3 The array class

Now that we have decided on a domain, a logical continuation is to decide on the functions needed to implement arrays and how we represent them in mTask. Obviously, we need some way to create arrays. In our example program we saw the use of the `array` function, when it seems the `lit` function as described in the previous section should also suffice. This is because the `lit` cannot be used in its current state, which has to do with the implementation of the function; a value passed to `lit` will be converted to its bytecode representation using the `toByteCode` function which is then pushed on the stack in the RTS.

```
lit t = tell (BCPush (toByteCode t))
```

We will see later (in Chapter 5) that we want the arrays to live on the heap. Implying that the lit function is not suited for arrays. For now, this means we can either change the implementation of the `lit` function, or create a separate `array` function. The difference being that the `array` function allows all array related functions to be in a single class. Furthermore, in Chapter 4, we will introduce uniqueness to the arrays, requiring a separation of functions either way[3].

Given the above, the choice was made to create a separate `array` function.

```
array :: {a} -> v {a}
```

While it does not have the versatility of the `lit` function (not allowing simple creation of arrays in tuples for example), it does allow for a much cleaner implementation while not convoluting the language by a significant amount. Similarly named functions can also be found in the likes of `sds` and the peripheral constructors. Additionally, we need some way to read data from the array. We have already seen this function above in the examples.

```
select :: (v {a}) (v Int) -> v a
```

And some way to update the elements in the array[4].

```
update :: (v {a}) (v Int) (v a) -> v {a}
```

The above functions are good in design, but functions with the same name as `select` and `update` already exist in an existing Clean module (_SystemArray). As such, we should rename them to something else, i.e. to:

```
(!.) infixl 9 :: (v {a}) (v Int) -> v a
updArray :: (v {a}) (v Int) (v a) -> v {a}
```

The current `expr` class is given in Listing 3.7. We could extend this class to include the array functions described above, or we could decide to implement them as their own class:

[3]Not separating functions could potentially allow user of mTask to create non-unique arrays. Something we wish to avoid.

[4]Another option was a function of the type `update :: (v a) (v Int) ((v a) -> v a) -> v {a}` but higher order functions are not supported in expressions by the current mTask ecosystem.

```
class expr v where
        lit :: t -> v t
        (+.) infixl 6 :: (v t) (v t) -> v t | + t
        (-.) infixl 6 :: (v t) (v t) -> v t | - t
        (*.) infixl 7 :: (v t) (v t) -> v t | * t
        (/.) infixl 7 :: (v t) (v t) -> v t | / t
        (&.) infixr 3 :: (v Bool) (v Bool) -> v Bool
        (|.) infixr 2 :: (v Bool) (v Bool) -> v Bool
        Not           :: (v Bool) -> v Bool
        (==.) infix 4 :: (v a) (v a) -> v Bool | Eq a
        (!=.) infix 4 :: (v a) (v a) -> v Bool | Eq a
        (<.)  infix 4 :: (v a) (v a) -> v Bool | Ord a
        (>.)  infix 4 :: (v a) (v a) -> v Bool | Ord a
        (<=.) infix 4 :: (v a) (v a) -> v Bool | Ord a
        (>=.) infix 4 :: (v a) (v a) -> v Bool | Ord a
        If :: (v Bool) (v t) (v t) -> v t
```

Listing 3.7: The `expr` class as defined for mTask

```
instance array BCInterpret
where
        array arr = tell
                [ BCPush (toByteCode arr)
                , BCArrCreate (elemWidth arr) (size arr)
                ]
        (!.) arr i = arr >>| i >>| tell [BCArrSelect]
        updArray arr i a = a >>| arr >>| i >>| tell [BCArrUpdate]
```

Listing 3.8: The Interpret instance of the `array` class

```
class array v where
        array :: {a} -> v {a} | type a
        (!.) infixl 9 :: (v {a}) (v Int) -> v a | type a
        updArray :: (v {a}) (v Int) (v a) -> v {a} | type a
```

Arguably, the array functions do not fit in the `expr` class, where nearly all functions are designed to work on any basic type. Additionally, a separate class allows the views to chose not to implement the arrays[5]. As such, we will use the second option of implementing their own class.

3.3.1 The Interpret View

All operations on arrays can not rely on current instructions since mTask does not currently produce any bytecode that deals with memory management. Unfortunately, this leaves us with

[5] In Chapter 4 we will run into a situation where we do indeed discover that one of the views no longer supports arrays.

```
instance array Show
where
        array arr = show "array " >>| show (toString arr)
        (!.) arr i = arr >>| show "!." >>| i >>| pure undef
        updArray arr i a = show "updArray" >>| arr >>| i >>| a >>| pure undef
```

Listing 3.9: The Show instance of the `array` class

not much of a choice regarding compilation to bytecode. Every function should simply be compiled to a new instruction as depicted in Listing 3.8. This listing also shows how similar the `lit` and `array` functions are, with the `array` function simply appending an additional function that reads the previously pushed data from the stack and creates an array node. Of course, another option was to make use of the lit function:

```
array arr = lit arr >>| tell (BCArrCreate (elemWidth arr) (size arr))
```

But being reliant on a function of another class adds a dependency to the class and the implementation.

3.3.2 The Show View

The show instance of the array class as shown in Listing 3.9 is relatively trivial. Simply replacing all the functions with a textual representation.

3.3.3 The TraceTask View

In Chapter 4 we will discover that this class cannot be implemented to the degree we want it to. This has to do with the fact that this view is an iTask, and that iTasks cannot operate on (optionally) unique values. As such, there exists no implementation for this view of the `array` class. Due to the nature of mTask's class based structure this does not pose a problem, as long as we do not attempt to trace a task containing one or more functions from the array class. Should we attempt to do so, the Clean compiler will throw an error and fail to compile our program.

Chapter 4

Uniqueness

Clean is a functionally pure programming language, i.e. every function is guaranteed to:

1. Produce the same output given the same arguments
2. Produce no side effects

While this has many advantages, two major disadvantages of its implementation are the *space behavior problem* and the usage of *inherently impure computations*. The space behavior problem references the fact that values cannot be updated destructively. Consider for example the following program:

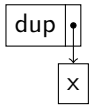
```
f :: {Int} -> ({Int}, Int)
f a = (update a 0 2, select a 0)

Start = f {1,2,3}
```

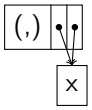
Let it be known that `select` is given `{1,2,3}` and `0` as arguments through `Start`. If we assume `update` updates the array destructively, the result of this program is `({2,2,3}, 2)`. However, when we change the `Start` to `Start = snd (f {1,2,3})`, update is omitted due to lazy evaluation and the result is `1`, violating requirement one of functional purity. To solve this, functionally pure languages copy every value that is changed. For the `update` function, a copy of the full array is made where the first element is replaced with a 2. The original array is still passed to the `select` resulting in the value `({2,2,3}, 1)`.

This is obviously not ideal for embedded systems that (in general) do not have much memory. For mTask the decision was made that arrays should only be implemented if it were possible to do this in a destructive manner to avoid this memory issue. A possible solution, in the form of uniqueness typing, is presented in this chapter. As a quick introduction, uniqueness typing enforces that only a single reference may exists to a value at any one time. This allows mutable updates to take place without producing side effects. Of course this comes with disadvantages, code written without uniqueness in mind does not always have an equivalent unique alternative. Additionally, writing code with uniqueness in mind is not a trivial endeavour and comes with its own set of challenges.

Uniqueness is first introduced after which, in the second section, we attempt to write the mTask ecosystem in such a way that it is able to support uniqueness typing, thus enabling functionally pure mutable arrays.



(a) The graph when x is passed to `dup` but the function has not yet been evaluated.



(b) After the evaluation of `dup`, the tuple node shows that multiple references to a single value can exist.

Figure 4.1: The evaluation of a simple `dup` function duplicating some non-unique value.

4.1 Uniqueness

Uniqueness typing is a type system introduced by Barendsen and Smetsers [2] in an effort to solve the *space behaviour problem* and the problem regarding functionally impure operations in a graph rewriting setting. A value is said to be unique if it is guaranteed there exists at most one reference to it. This single reference guarantee allows the programmer to write code that destructively updates said value without modifying the semantics of the program (the *space behavior problem*). Additionally, it allows for *functionally impure* computations such as I/O. File I/O, for example, is handled in Clean using unique file handles, preventing any non-sequential writes to a file. For mTask's arrays, we are mostly interested in the solution to the space behavior problem, but a global understanding is still desirable.

To achieve this single reference property, the system extends conventional Milner/Mycroft typing with uniqueness annotations. In Clean, a type can be annotated using one of three annotations, giving four options in total:

```
a
*a
.a
u:a (where u is any identifier)
```

Normally Clean places no restrictions on the way a value is used. It is perfectly fine to create two references to a single value in the graph. In fact this is one of the strengths of graph rewriting over naive term rewriting because it avoids copying a value needlessly. In the following example for instance, we create a tuple holding the same value twice:

```
dup :: a -> (a, a)
dup x = (x, x)
```

Internally, the result of `dup` would be represented as a node with two references to the same value. Figure 4.1 shows exactly this concept by applying `dup` to some value `x`.

Annotating a type with "$*$" enforces that there exists at most one reference to the value. For instance, we cannot implement our `dup` function in the same way as above if we want to change the type to accept a unique argument:

```
dupu :: *a -> (*a, *a)
```

This is due to the fact that the `dup` function creates two references to our unique value, violating the single reference constraint. In fact, it is impossible to create a total function with this type.

The above mentioned problem also holds when using the following type for `dup`:

```
dupo :: .a -> (.a, .a)
```

Here, `a` is a value that is optionally unique (i.e. both non-unique and unique values should be accepted by this function). This means that the implementation must be valid regardless of whether the value of type `a` is unique, which might not be the case. The following program demonstrates this fact:

```
Start = dupo i
where
        i :: Int
        i = 42
```

As with our `dupu` function, no implementation of this function exists.

Finally, uniqueness variables can be used to enforce the same attribute on multiple types, or in coercion statements to enforce relations on the uniqueness attributes, which allow the programmer to place restrictions on the uniqueness attributes of types in relation to each other. The uniqueness inequality `u <= v` enforces that u is unique if v is unique. This is often used in situations where one value is wrapped in another. For example, a tuple containing one or more unique values should be unique itself as expressed in the following type.

```
tuple :: v:a w:b -> u:(v:a, w:b), [u <= v, u <= w]
```

Given that a function is guaranteed to have a unique reference to a unique value, the compiler can compile this function in such a way that it destructively updates the unique value. This is what we meant earlier when we talked about the *space behaviour problem* and is incredibly powerful in the sense that it can prevent the constant copying of large nodes. It is for this reason the Clean standard library (StdEnv) makes heavy use of uniqueness in its Array module (`_SystemArray`) where many functions come in pairs of two, with one accepting non-unique arrays and the other accepting the unique counterpart. Consider the `size :: {e} -> Int` function for example, if the `size` function would naively accept unique arrays, the array would be consumed, and it would no longer be possible to pass the array to another function as well. Instead, a unique version of the function should also return the unique array such that it can be used elsewhere. Their difference is reflected in their types:

```
size :: {e} -> Int
usize :: u:{e} -> *(Int, u:{e})
```

This construct, where the unique counterpart of a function returns a tuple with the intended result and the unique argument can be found in many places dealing with uniqueness, another example being the `StdFile` library.

4.2 The Unique Array Class

Now that we have introduced uniqueness and have shown that it can be used to create mutable values, we should change our array class to produce unique arrays. This way, interpretation can happen in a destructive manner while preserving functional purity. We eluded to the fact that

functions for unique arrays have a different signature than functions for non-unique arrays, in that unique values should be part of the result of a function such that they can be used again. In our previously defined array class, we should take these differences into account. Recall the class defined earlier, but extended with the uniqueness annotations we want the class to have.

```
class array v where
        array :: *{a} -> *(v *{a}) | type a
        (!.) infixl 9 :: *(v *{a}) (v Int) -> v a | type a
        updArray :: *(v *{a}) (v Int) (v a) -> *v *{a} | type a
```

Here, the `(!.)` function consumes the array, something we wish to avoid. In order to fix this, the function type should be modified such that it returns not only the value we wish to select from the array, but also the array itself:

```
class array v where
        array :: *{a} -> *(v *{a}) | type a
        (!.) infixl 9 :: *(v *{a}) (v Int) -> *v (a, *{a}) | type a
        updArray :: *(v *{a}) (v Int) (v a) -> *v *{a} | type a
```

Of course, this change should also be reflected in our example program. We will have to constantly pass the array as to not lose our single reference to it. Listing 4.1 show the updated version of our earlier example using the new array class and demonstrating the fact that the array must be passed from one function to another.

Now that we have modified our example program, we should ensure that the entire ecosystem has support for our unique arrays. The remainder of this chapter attempts this.

4.3 The Unique Monad

We have seen earlier that the mTask DSL (and TOP in general) has many similarities to a Monad. Additionally, we have seen that Monads are widely used in the compilation and printing of mTask. Now that the DSL produces optionally unique values, mTask's backend must be able to handle them. This leaves us with two possibilities; we either create a monad class that can result in optionally unique values, or we rewrite every backend of mTask to no longer make use of any monad. The second option is not viable and would result in code that is very convoluted. As such, this section is dedicated to creating a new definition of the monad class that can be used in mTasks backend to allow unique arrays.

Before we dive into the implementation of our uniqueness monad, we should quickly discuss the work by Jennifer Paykin and Steven Zdancewic on their linearity monad [18]. A critical difference in the monad they implemented and the monad we will implement below is that our monad does not deal with a linear state, rather, it is supposed to be able to result in unique values (the unique arrays). Additionally, it is important to introduce a set of constraints. Any instantion of the monad class as defined in Chapter 2 should (but is not forced to) abide to the so called *monad laws*, ensuring that the implemented functions abide to their descriptions. These *monad laws* are as follows. For every `a, h, k, m` it holds that:

Left Identity: `return a >>= k = k a`

Right Identity: `m >>= return = m`

Associativity: `m >>= (\x -> k x >>= h) = (m >>= k) >>= h`

Here the identity laws ensure that the return function only creates a computation that returns the provided value (as described in the description of the return function in Chapter 2). Should the return function perform any implicit computation, one or both of these laws will not hold. The Associativity law, on the other hand, concerns itself with the second description of Chapter 2, ensuring the associativity of the bind composition. As an example, the proof of these laws for the maybe monad is, due to its length, given in Appendix A.

Given this background, we can attempt to implement our unique monad. Ideally, our `Monad` class would be defined as such:

```
DHT D1 DHT11 \dht->
sds \avg=0 In
fun \cal_avg=(\(i, arr, acc)->
        If (i >=. lit 10) (
                (acc /. lit 10, arr)
        ) (
                let (e, arr) = (arr !. i) in
                cal_avg (i +. 1, arr, acc +. e)
        )
) In
fun \measure=(\(i, arr)->
        delay (lit 1000)
        >>|. temperature dht
        >>~. \v
                # arr = updArray arr i v
                # (x, arr) = cal_avg (0, arr, 0)
                = sdsSet avg x
        >>|. If (i <. 9)
                (measure (i +. lit 1, arr))
                (measure (lit 0, arr))
) In
fun \act=(\on->
        getSds avg
        >>*.
        [ IfValue (\v -> v >. lit 22 &. Not on) (\_ -> writeD d0 true)
        , IfValue (\v -> v <. lit 18 & on) (\_ -> writeD d0 false)
        ]
        >>=. act
) In
{main = measure (lit 0, array {20, 20, 20, 20, 20, 20, 20, 20, 20, 20}) .&&.
↪  (readD d0 >>=. act)}
```

Listing 4.1: An iteration of the example program utilizing the new array class incorporating uniqueness. Lines changed from the previous iteration are highlighted.

```
class Monad m | Applicative m
where
        bind :: u:(m .b) .(.b -> v:(m .c)) -> v:(m .c)
```

Unfortunately, this is not allowed. Every type variable in a function type must have the same uniqueness attribute. A possible solution would be to implement the bind outside the Monad class or extend the Monad class to take three arguments[1]:

```
class Monad m n o | Applicative m
                  & Applicative n
                  & Applicative o
where
        bind :: u:(m .b) .(.b -> v:(n .c)) -> v:(o .c)
```

This is not ideal, but something we might consider nonetheless. The previously mentioned show instance could have the accompanying bind type or class instance:

```
bind :: u:(ShowM .b) .(.b -> v:(ShowM .c)) -> v:(ShowM .c)

instance Monad ShowM ShowM ShowM
```

With:

```
:: ShowM a = ShowM .(ShowState -> .(a, ShowState))
```

For now, we will only consider the bind function separately from the Monad class. Of course it could still be placed back into the class if necessary.

The issue with the aforementioned type signature becomes apparent when trying to create an accompanying implementation. Let's try to derive the uniqueness constraints of the following function where all uniqueness attributes are variables for clarity.

```
bind :: u:(ShowM v:a) w:(v:a -> x:(ShowM y:b)) -> x:(ShowM y:b)
bind (ShowM a) f = ShowM (\s
                 # (v, s`) = a s
                 # (ShowM a`) = f v
                 = a` s`)
```

Given that the u in u:(ShowM v:a) propagates as such:

```
:: u:ShowM v:a = u:ShowM u:(ShowState -> u:(v:a, ShowState))
```

We get

[1]Note that these two solutions are essentially the same. The return statement needs to be lifted out of Monad class any way, or a choice needs to made as to which class argument the return should operate on.

```
[u <= v, x <= y]
```

We also know that the `u` is propagated to `(v, s`)`, whose type is `u:(v:a, ShowState)`. Since this tuple with uniqueness annotation `u` is used the construction of the final value, we have `[x <= u]`. This fact can also be demonstrated with the following function:

```
f :: u:a -> x:(b -> b), [x <= u]
f a = \s
        # _ = a
        = s
```

Where, though the result of a is not used, it is part of the ultimate construction, coercing the uniqueness of the result. This same reasoning can be applied to `[x <= w]`, giving us our final list of inequalities:

```
bind :: u:(ShowM v:a) w:(v:a -> x:(ShowM y:b)) -> x:(ShowM y:b)
        , [u <= v, x <= y, x <= u, x <= w]
```

Consequently, as soon as we have one unique value in our monad, every subsequent `m` must also be unique. Essentially, this means that every function operating in the context of this monad instance has to assume the encapsulating data type is unique. This is not a problem, but does mean that the above type has no distinct advantage over the less generic type:

```
class Monad m where
        bind :: *(m .a) (.a -> *(m .b)) -> *(m .b)
        return :: .a -> *(m .a)
```

Since there is no advantage of the more generic type, this type was chosen instead. With this change of the monad, all auxiliary functions and the DSL classes must also be modified to support the new unique type. All modifications to the auxiliary functions happened without much effort, and we will thus not discuss them in this thesis. The new classes were forced to have a unique `v` in every function. The `array`, for example, was modified to be:

```
class array v where
        array :: *{a} -> *(v *{a}) | type a
        (!.) infixl 9 :: *(v *{a}) *(v Int) -> *v (a, *{a}) | type a
        updArray :: *(v *{a}) *(v Int) *(v a) -> *v *{a} | type a
```

Finally, after creating this new monad class definition, we should consider its relation to the monad laws described in the preliminaries. As a recap, there are three laws that a monad must abide by in order to satisfy two desired properties: the left identity, the right identity and the associativity laws. Now, of course these laws are only relevant when considering some instantiation of the class, but the class itself should at least not reject these laws by default, i.e. these laws should still be typeable in given the new class. Once typeable, we need not prove the laws for the unique instances because we have not changed their semantics. Looking at the monad laws (repeated below), the only possible problem is the reuse of identifiers on the left and right side of the equals sign. However, the sign denotes mathematical equality, outside the scope of uniqueness, and thus poses no problem.

1. `return a >>= k  = k a`
2. `m >>= return = m`
3. `m >>= (\x -> k x >>= h) = (m >>= k) >>= h`

As stated above, and assuming that the state monad abides by the monad laws[2], this means that the modifications made to the monad class do not result in monad instances that do not abide by the monad laws.

4.4 The Unique Interpret View

Now that we have a monad class that can handle uniqueness, we can begin rewriting the backend to make use of this monad in order to support unique values. This in turn allows unique arrays which then grants us functionally pure mutability. In the interpret view, most interpret instances were trivially rewritten to deal with uniqueness, with a few notable exceptions.

Firstly, many classes use a value twice, once to push it to the stack, and a second time to inspect the stack width of the value. Inspecting the stack width happens using the `toByteWidth`[3] class. Luckily, this class does not actually evaluate its argument:

```
instance toByteWidth Bool where toByteWidth _ = 1
instance toByteWidth Int where toByteWidth _ = 1
instance toByteWidth Long where toByteWidth _ = 2
instance toByteWidth Char where toByteWidth _ = 1
instance toByteWidth Real where toByteWidth _ = 2
...
```

The same is true for the `expr` class shown in Chapter 3, whose interpret instance is given in Listing 3.4. In the instance, the `binop` function only uses the value `a` to determine which addition instruction should be used. For both these instances we have implemented a function:

```
duplicate :: .a -> .(.a, .a)
duplicate x = (undef, x)
```

Where `undef` is a value that aborts the program when evaluated with type: `undef :: .a`. However, since the `undef` value is only passed to functions where it is not evaluated, this is safe. Listing 4.2 show the interpret instance of the `expr` class (without the `If` function) using this `duplicate` function. As modified version of the `binop` function is also given in the same listing.

Secondly, Clean's `if` construct is defined as part of the language's core with the type being something along the lines of: `if :: .Bool .a .a -> .a`. This is in itself not a problem, but does allow the function to behave in ways undefinable in Clean itself[4]. Listing 4.4 shows two functions that both return `42`. The second program, however, does not type check.

[2] In [11] it is shown that Haskell's implementation of the state monad does actually not abide by the monad laws.

[3] Despite what the name suggests, this function does not return the width of the value in bytes. Instead it returns the width in terms of the number of stack cells a value of the type occupies.

[4] Technically, the if construct is part of Clean, what is meant here is a version of Clean that does not have the `if` construct.

```
        instance expr Interpret where
                lit t    = tell (BCPush (toByteCode t))
                (+.)  a b
                        # (at, a) = duplicate a
                        = a >>| b >>| tell [binop at BCAddI BCAddL BCAddR]
                (-.)  a b
                        # (at, a) = duplicate a
                        = a >>| b >>| tell [binop at BCSubI BCSubL BCSubR]
                (/.)  a b
                        # (at, a) = duplicate a
                        = a >>| b >>| tell [binop at BCDivI BCDivL BCDivR]

binop :: .(v .a) BCInstr BCInstr BCInstr -> BCInstr | type, isReal a
binop v i l r
# (a, v) = cast1 v
= if (byteWidth v == one) i
        (if (isReal a) r l)
```

Listing 4.2: The instance of the `expr` class using the `duplicate` function

```
f :: Bool *Int -> *Int
f b i = if b i i

Start = f True uniqueInt
where
        uniqueInt :: *Int
        uniqueInt = 42
```

Figure 4.2: Clean's `if` construct allows two references to a single unique value

```
f :: Bool *Int -> *Int
f b i = my_if b i i
where
        my_if :: Bool .a .a -> .a
        my_if b t e = if b t e

Start = f True uniqueInt
where
        uniqueInt :: *Int
        uniqueInt = 42
```

Figure 4.3: Replication the duplication that is possible with the `if`

Figure 4.4: Clean's `if` construct allows the creation of multiple references to a unique value as shown in the first listing. Replicating this behavior using a function defined in Clean (as shown in the second listing) is not possible.

Appendix B shows other implementations of this function, none of which pass the uniqueness type checking. When considering the definition of unique values, one might think that the first program should not type check either. After all, creating two references to a single value is not allowed. However, the `if` construct needs not create two references, since it can guarantee that only one of the two unique values is evaluated. Currently, Clean's compiler is not powerful enough to identify that the second implementation does indeed also only ever evaluate one of the two values. This becomes an issue when implementing the step combinator for unique values. Recall that the step combinator takes a list of possible continuations as an argument, based on

predicates the suitable continuation is then selected. For this selection, mTask uses the internal `If` function that is part of the `expr` class. By implementing uniqueness the type of the `If` function was modified to: `:: *(v Bool) *(v .a) *(v .a) -> *(v .a)`. Thus resulting in our problem. Using mTask's `If` does not allow for continuation if any of the branches use the same (optionally) unique value. The only solution we found was lifting the implementation of the `If` function directly into the implementation of the step combinator (i.e. the code used to create the if function was used directly in the step combinator). Code copying was avoided using a Clean macro (where the compiler will perform the code duplication before type checking takes place). Recall our example program where we use an if statement to determine the argument for the recursive call of `measure`. Here, this exact problem also takes place. As a workaround, the if was only used to determine the value of `i`, as given in the version in Listing 4.3. Also take note of the `nunique` function used in the continuations of the step in our example program. The step function should be able to apply predicates on unique values. Of course, this means the predicate itself should also return the value. For those situations where we do not want to pass our argument back, we can use this `nunique f :== \p -> (f p, p)` macro to wrap the function with.

Finally, Clean's compiler does not allow uniqueness annotating in class constraints. The following program, for example, does not typecheck:

```
class f a b :: a -> b

g :: *(*v a, *v a) -> Int | f (*v a, *v a) Int
g x = f x
```

Instead showing an error that annotating `v` in the class constraint of `g` is not allowed. Generally this is not a problem, since uniqueness attributes in the classes themselves can often be used to express unique types. When uniqueness attributes are added to nested data types (as seen above), however, this can no longer be done. The problem is best described using mTask's `fun` class which allows the definition of functions and is defined as such:

```
class fun a v :: ((a -> v s) -> In (a -> v s) (Main (MTask v u)))
        -> Main (MTask v u)
```

Which was modified as follows to support unique values:

```
class fun a v :: ((*a -> *(v .s)) -> In (*a -> *(v .s)) (Main (MTask *v .u)))
        -> Main (MTask *v .u)
```

Where `MTask` is a type synonym for `v (.TaskValue a)`. In the `mtaskfuns` (a class that must be implemented by the views to allow the use of functions) class every possible arrangement of arguments is a separate constraint:

```
DHT D1 DHT11 \dht->
sds \avg=0 In
fun \cal_avg=(\(i, arr, acc)->
        If (i >=. lit 10) (
                (acc /. lit 10, arr)
        ) (
                let (e, arr) = (arr !. i) in
                cal_avg (i +. 1, arr, acc +. e)
        )
) In
fun \measure=(\(i, arr)->
        delay (lit 1000)
        >>|. temperature dht
        >>~. \v
                # arr = updArray arr i v
                # (x, arr) = cal_avg (0, arr, 0)
                = sdsSet avg x
        >>=. \_
        # i = If (i <. 9) (i +. lit 1) (lit 0)
        = measure (i, arr)
) In
fun \act=(\on->
        getSds avg
        >>*.
        [ IfValue (nunique (\v -> v >. lit 22 &. Not on)) (\_ -> writeD d0
↪  true)
        , IfValue (nunique (\v -> v <. lit 18 & on)) (\_ -> writeD d0 false)
        ]
        >>=. act
) In
{main = measure (lit 0, array {20, 20, 20, 20, 20, 20, 20, 20, 20, 20}) .&&.
↪  (readD d0 >>=. act)}
```

Listing 4.3: A second iteration of example program utilizing uniqueness. In this version the `If` function is used differently to avoid creating two references to the same unique array. Additionally, the `nunique` is introduced. Differences with the previous iteration are highlighted.

```
class mtaskfuns v
        | fun () v
        & fun (v DPin) v
        ...
        & fun (v Real) v
        & fun (v DPin, v DPin) v
        & fun (v DPin, v Bool) v
        ...
        & fun (v Real, v Real) v
        & fun (v DPin, v DPin, v DPin) v
        & fun (v DPin, v DPin, v Bool) v
        ...
        & fun (v Real, v Real, v Real) v
```

When incorporating uniqueness, we would ideally have every `v` in the class constraints be a unique view, but, as written above, these are ignored by the compiler. Of course, the uniqueness attribute as defined in the `fun` class, do propagate to functions with an arity of one since these are not nested types.

It is best to look at an example. Consider the `fun (v Real) v` and `fun (v Real, v Real) v` instantiations. The first results in a `fun` function with the following type:

```
fun :: ((*(v Real) -> *(v .s)) -> In (*(v Real) -> *(v .s)) (Main (MTask *v
↪  .u)))
        -> Main (MTask *v .u)
```

Where it is indeed true that every `v` is unique. However, when instantiating the second type, we end up with this:

```
fun :: ((*(v Real, v Real) -> *(v .s)) -> In (*(v Real, v Real) -> *(v .s))
        (Main (MTask *v .u))) -> Main (MTask *v .u)
```

In which not every `v` is unique. Right now, this means that the `mtaskfuns` class has only the following constraints:

```
class mtaskfuns v
        | fun () v
        & fun (v DPin) v
        & fun (v Bool) v
        & fun (v Int) v
        & fun (v Long) v
        & fun (v Real) v
```

Disallowing any function with an arity higher than one. A possible solution is to split the fun class into three separate classes, all describing a function with a different arity. These classes could possibly look like this:

```
class fun1 a v :: ((*a -> *(v .s)) -> In (*a -> *(v .s)) (Main (MTask *v .u)))
        -> Main (MTask *v .u)
class fun2 a b v :: (((*a, *b) -> *(v .s)) -> In ((*a, *b) -> *(v .s)) (Main
        (MTask *v .u))) -> Main (MTask *v .u)
class fun3 a b c v :: (((*a, *b, *c) -> *(v .s)) -> In ((*a, *b, *c) -> *(v
↪   .s))
        (Main (MTask *v .u))) -> Main (MTask *v .u)
```

Attentive readers might realize that these classes still do not allow unique arrays as arguments. This can be achieved by further modifying the classes such that they either: only accept (optionally) unique values or have separate classes for arrays. Both solutions are not ideal, the first because we really do not want basic values to ever have to be unique and the second because it adds even more classes. For the sake of completeness, separating the classes even further would result in the following list:

```
class fun1 a v
class fun1a a v
class fun2 a b v
class fun2a1 a b v
class fun2a2 a b v
class fun2a12 a b v
class fun3 a b c v
class fun3a1 a b c v
class fun3a2 a b c v
class fun3a3 a b c v
class fun3a12 a b c v
class fun3a13 a b c v
class fun3a23 a b c v
class fun3a123 a b c v
```

In turn resulting the updated version of our example program as shown in Listing 4.4. While the current `mtaskfuns` is already far from ideal, it should be clear that this approach is even worse and further changes are needed before even considering allowing arrays to be used as arguments for mTask functions. Ultimately, this means that arrays cannot currently be implemented in a good enough way for them to make a useful addition to mTask.

4.5 The Unique Show and TraceTask View

The show view often does not deal with duplicate values, and such was translated to a unique version without much effort. The tracetask view, however, is, as mentioned in the Chapter 3, an iTask. Unfortunately, iTasks does not currently support the use of unique (or optionally unique) values. In the future, it would ideally be extended to have support for unique values (if possible), but until that time the tracetask view cannot be implemented for out unique version of mTask.

```
DHT D1 DHT11 \dht->
sds \avg=0 In
fun3a2 \cal_avg=(\(i, arr, acc)->
        If (i >=. lit 10) (
                (acc /. lit 10, arr)
        ) (
                let (e, arr) = (arr !. i) in
                cal_avg (i +. 1, arr, acc +. e)
        )
) In
fun2a2 \measure=(\(i, arr)->
        delay (lit 1000)
        >>|. temperature dht
        >>~. \v
                # arr = updArray arr i v
                # (x, arr) = cal_avg (0, arr, 0)
                = sdsSet avg x
        >>=. \_
        # i = If (i <. 9) (i +. lit 1) (lit 0)
        = measure (i, arr)
) In
fun1 \act=(\on->
        getSds avg
        >>*.
        [ IfValue (nunique (\v -> v >. lit 22 &. Not on)) (\_ -> writeD d0
↪  true)
        , IfValue (nunique (\v -> v <. lit 18 & on)) (\_ -> writeD d0 false)
        ]
        >>=. act
) In
{main = measure (lit 0, array {20, 20, 20, 20, 20, 20, 20, 20, 20, 20}) .&&.
↪  (readD d0 >>=. act)}
```

Listing 4.4: A third iteration of example program utilizing uniqueness. In this version we no longer use the `fun` function, instead using a selection of different function to avoid a typing problem with classes and uniqueness. Differences with the previous iteration are highlighted.

4.6 Concluding

We started this chapter reimplementing the array class with our desired uniqueness annotations. After an attempt at implementing the monad, however, the ideal approach was deemed impossible. Instead, we created an alternative version where all views are unique. Subsequently, we ran into a problem with mTask's implementation of functions. Currently, class constraints ignore uniqueness annotations. We proposed a workaround for this problem, but ultimately stated that uniqueness is not (currently) a satisfying method of implementing mutability for values.

Chapter 5

Runtime System

In the beginning of this thesis, we mentioned that the current RTS was not made having mutable collection types in mind. In particular, it has no support for any kind of nodes larger than a typical combinator node. If we want to implement arrays in mTask, we will have to change this, requiring changes to many parts of mTask's RTS. In this chapter of the thesis we first introduce the current RTS to get familiar with the parts that need changing. Given this basis, we will then modify the RTS to support arrays.

5.1 The RTS

To understand what parts of the RTS do not support what is needed for arrays, it is best to first take a global look at its implementation, highlighting everything that must be modified. All information in this section describes the runtime system as it was before any changes were made towards implementing arrays.

5.1.1 Memory Layout

Earlier we saw that, during interpretation, the mTask RTS needs at least a stack (to store expression values on and to return the pointer to the root node) and a heap (to store the nodes that make up the task tree). In addition to those sections of memory, mTask also contains a task heap that is used to store information about the tasks received from the server, including but not limited to: an identifier, bytecode, a pointer to the root node and a section reserved for the return value. mTask's memory layout is depicted in Figure 5.1 each section of which will be discussed below.

The Heap

The heap in mTask's RTS stores the tree of all tasks currently being worked on by the RTS. Nodes in this section of memory are managed by the garbage collector, which we will discuss later. The tree consists of a collection of nodes, with every node having zero or more references to children and no two nodes having references to the same node (this property allows mTask not to have a dedicated garbage marking phase). Figure 5.2a shows the general layout of a single node where the data is dependent on whichever type the node has. The `task_type` of the node represents the kind of data this node stores and is used during rewriting to determine in what way the node should be rewritten. `trash` is a flag that indicates if the node should be garbage

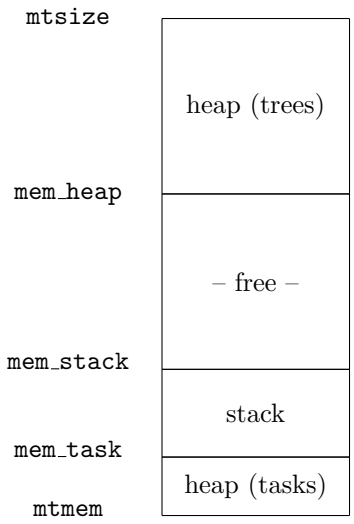


Figure 5.1: A global overview of the memory layout used by the RTS. The labels on the left hand side of the figure show the variables that identify the bounds of the memory sections. Being low in the figure indicates that a block is also low in memory.

collected the next time the garbage collector runs, and the `ptr` field holds a reference to the parent of the node. This pointer is used in updating the reference to the current node when it is moved in memory. For instance, during garbage collection.

Regardless of the actual size the node needs, the data allocated by a node is always the same (i.e. an `and`-node containing just two (16 bit) references will have the same size as a Stable node containing 8 bytes of data). This is one of the assumptions that needs to be changed for the RTS to accommodate arrays since arrays will take up however many bytes they need to store their elements. Of course, this is only true because we decided to place arrays on the heap, we discuss why this is the case later this chapter. The specific layout of the aforementioned `and`-node and the padding that ensures the node is the same size as the other nodes is depicted in Figure 5.2b.

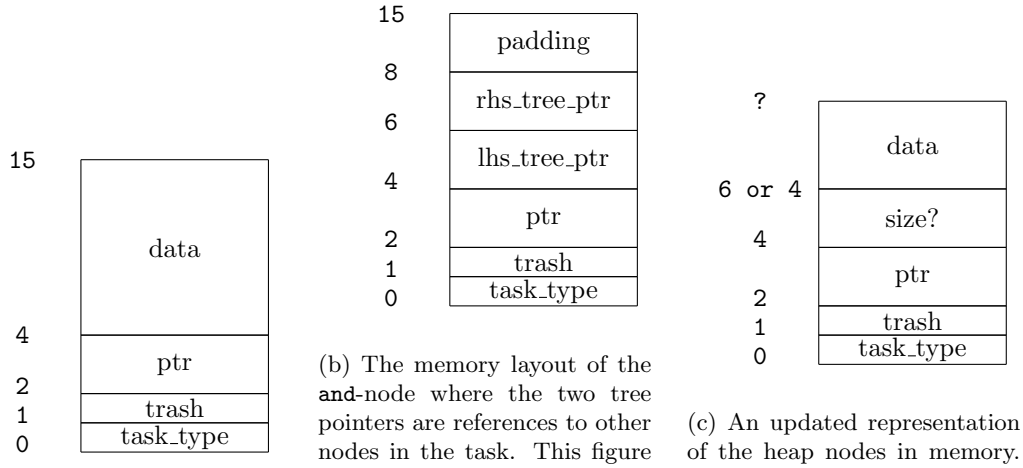
The Stack

We do not need to know all details of the stack in order to understand the rest of this thesis. What is important to know is that the stack grows from low in memory to high in memory[1] and that a stack cell is two bytes wide which works nicely with the fact that pointers in the mTask RTS are also 2 bytes.

The Task Heap

Every task received from the server stores values required for its own evaluation on this special task heap. The memory layout of a task is depicted in Figure 5.3. The `taskid` holds the unique identifier of the task and is shared with the server program. The value last returned by a task is defined by the stability, the returnwidth and the returnvalue. Note that (like the `sdsses`, `peripherals` and `bytes` fields) the return value is of variable size, the sizes of these fields are therefore stored as a separate value in the task itself. The `sdsses` field stores the SDSs shared

[1] This is contrary to the most common approach of having it grow downwards.



(a) The general layout of a node allocated on the RTS heap.

(b) The memory layout of the `and`-node where the two tree pointers are references to other nodes in the task. This figure also shows the implicit padding present in the nodes to ensure all nodes have the same size.

(c) An updated representation of the heap nodes in memory. Note the addition of the optional size field in comparison to Figure 5.2a.

Figure 5.2: Nodes as they are represented on mTask's tree heap.

between subtasks. The penultimate two fields (`peripherals` and `bytes`) store the information of the connected peripherals and their configuration, and the bytecode that is to be interpreted, respectively. Despite some fields being of variable size, they do not change in size once the task has been received from the server. This is not ideal if we want it to be possible for the sizes of our arrays to be determined at runtime. Note that, as we discussed in Chapter 3, this is currently not the case. However, we should be prepared for such functions as their implementation is relatively likely in the future. Lastly, the tree field stores a reference to the root node of the tree belonging to this task.

5.1.2 Garbage Collection

We saw earlier that the RTS' memory contains two separate heaps. One stores the trees of the tasks being evaluated, and the other stores all tasks that have been received from the server (and have not finished being evaluated). Both of these regions of memory are subjected to garbage collection by the RTS in their own ways: Nodes on the task heap are marked when they lose their last reference (most often when their parent gets rewritten), tasks on the task heap are marked as garbage when they have returned a stable value or when they are deleted explicitly by the server. As a consequence of these ways of marking, the RTS does not mark garbage in a dedicated phase.

In order to deal with the two separate heaps, garbage collection in mTask is split into two phases. The first phase collects the garbage from the task heap and the second from the task tree heap. We will focus on the garbage collection of the task tree, since this is the garbage collection that was actually changed to accommodate arrays.

We saw earlier that every node on the heap has the same size. This allows the garbage collector to start at the root of the heap (high in memory) and work its way down. The pseudocode of the garbage collector can be found in Algorithm 2. Figure 5.4 accompanies this listing and shows a run of the garbage collector where the hole and walker references are represented by colored arrows. We will see later that the current approach of using the constant `NODESIZE` is problematic when trying to accommodate bounded types.

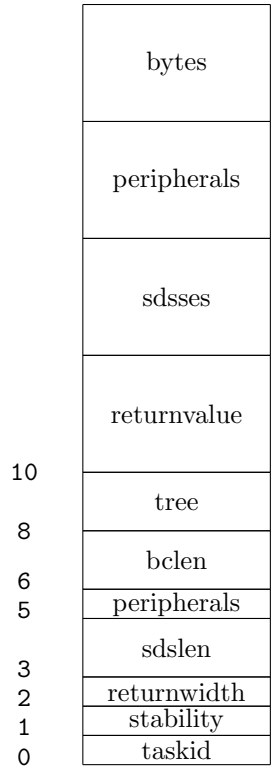


Figure 5.3: The memory layout of a task on the task heap. Missing numbers indicate the variable length of these fields. The tree field is a reference to a node on the task heap.

Algorithm 2 Linear Garbage Collection

```
walker ← mtsize − NODESIZE
hole ← mtsize − NODESIZE
while walker ≥ mem_heap do
    if walker.trash then
        walker ← walker − NODESIZE
    else if walker = hole then
        walker ← walker − NODESIZE
        hole ← hole − NODESIZE
    else
        move_node(walker, hole)
        walker ← walker − NODESIZE
        hole ← hole − NODESIZE
    end if
end while
```

5.1.3 Returning Values

After the completion of the rewriting phase, the value left on the stack will be considered for being returned to the server. To prevent the constant resending of identical values, mTask checks

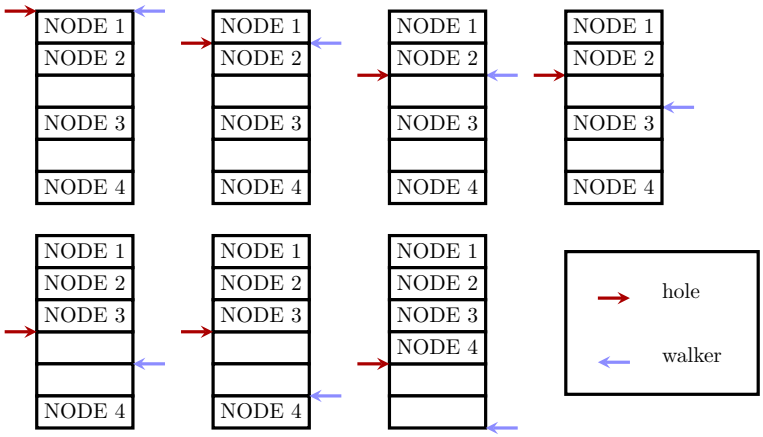


Figure 5.4: A step by step overview of mTask's garbage collector.

if the new value is the same as the one sent previously. Only if the values differ in some way is the byte representation of the new value actually sent back to the server.

In order to compare to the previous value, a section of memory the size of the return width is allocated as part of every task when the task is first received from the server. Every time a new value is sent to the server, this section is updated to hold this new value. Keep in mind that mTask values are constant in size, i.e. the comparison of the old and new value happens in constant time. This is even true for mTask's only compound type, tuples, where the sum of the size of the constant sized children is still constant.

5.2 Considerations

Given the architecture as described above, we should consider how arrays best fit into the current RTS. In mTask, all values present in expressions are stored on the RTS' stack. Only when required by an instruction that constructs a node, are they moved potentially to the heap as part of said node. A similar approach could be taken for arrays. Unfortunately, the size of arrays is not known at compile time. In fact, it is impossible to determine the size an array will have during compile time in a general manner when additional functions are added to the array class. This conflicts with the way the RTS returns values; every function will allocate n bytes on the stack (with n the size of the return value) before the function is evaluated. An additional n bytes is needed to perform operations on the array. Additionally, we want our arrays to be mutable, another problem not present in any other value. A solution akin to the one found in C, where arrays are passed by reference and cannot be returned, only works as long as arrays do not grow, at which point they must be reallocated.

Given these problems, our best possible course of action is implementing arrays in such a way that they are stored on the heap that also stores the tree. We will then have the stack width of the arrays be 1 in the sense that we push a reference on the stack instead of the entire array. This also allows the array to be returned through the reference.

There are two major problems that need to be addressed before we can implement arrays themselves. Firstly, there is the problem that the RTS cannot handle nodes of different sizes[2].

[2]Tuples are implemented as a linked list of nodes.

Secondly, we need to find a way to mark the arrays as garbage. We will discuss both problems independently.

5.3 Variable Sized Nodes

Previously, we concluded two things. Firstly, the current RTS assumes all nodes on the heap have the same size. Note that not every node necessarily represents a single value, or one at all. Tuple values, for example, form a sort of linked list of constant sized nodes in mTask's RTS. Secondly, arrays are to be stored on the heap. Keeping in mind that we may want to allow the size of arrays to be computed at runtime in the future, we can conclude that we must modify the RTS to work with variable sized nodes. Using a linked list to represent arrays (in an approach similar to tuples) would not lead to an efficient implementation with access being $O(n)$.

Before we can start modifying the RTS, we should identify what parts of it assume fixed sized nodes. Firstly, there is the garbage collector. In Algorithm 2 we saw that it would walk through the heap with a constant pace. This is no longer possible when the nodes vary in size. Secondly, there is the fact that, during rewriting, certain nodes are overwritten by nodes holding their result. This way, the heap stays small and references need not always be updated. This also needs to be considered.

5.3.1 The Garbage Collector

First, we will look at the garbage collector and how to modify it to support variable sized nodes. Recall Algorithm 2. As a first attempt in making the garbage collector (GC) compatible with variable sized nodes, we might be tempted to add the size to the metadata, and subsequently fetch that data from the node before walking to the next node. However, recall the fact that the metadata of the nodes is stored lower in memory than the data they belong to. This makes it impossible for us to access the size, i.e. we do not know where the size is stored relative to the current walker and hole pointers. There are multiple potential solutions to this problem, we will discuss only two.

A first possible solution is to avoid the problem all together. Instead of changing the garbage collector fundamentally, we modify the layout of the memory in such a way that variable sized nodes work with the current design. This would require one of two things. Either move the metadata to be above the data in memory, or move the entire heap in the memory layout such that the heap can grow up in memory. The second option arguably the best and the one most commonly found in ABIs, most notably the System V ABI [13]. Unfortunately, it was out of scope for this thesis due to the amount of changes the RTS would have to undergo. The first option (moving the metadata) would change the RTS to such an extent that the second option would be harder to implement in the future. This is not ideal since, ultimately, the second option should be implemented.

Instead, our ideal solution would be one that:

1. Does not modify the structure of the nodes (such that they can be used in their current form when the stack and heap switch places).

2. Changes the garbage collector in such a way that it allows for easy swapping of the heap and stack.

This can be achieved by rewriting the garbage collector such that it already assumes the heap and stack have switched, and then extending it with additional passes that account for this false

assumption. In the future, the additional passes could be removed and the garbage collector would still work.

Modifying the garbage collector such that it assumes the heap grows upwards is trivial. We simply reverse the direction it walks, and replace the constant node size with a lookup into the node[3]. However, since this assumption is false, our heap now has a problem: all nodes find themselves lower in memory then they are supposed to be i.e. there is empty space higher in memory than the nodes. This can be seen in Figure 5.5 just after the first phase.

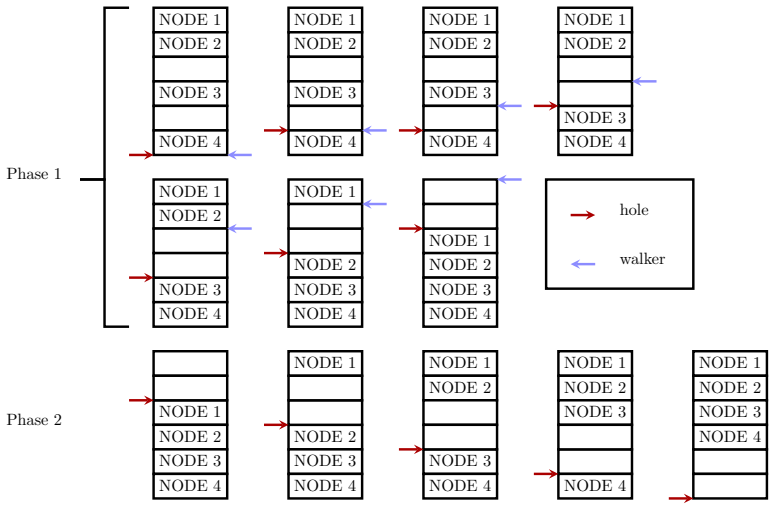


Figure 5.5: A step by step overview of the first two phases of the updated garbage collector.

To fix this, we can implement a pass that moves all nodes back to the start of the heap. Unfortunately, this cannot be done naively by moving the data directly because it would result in wrong references (i.e. pointer to the children of nodes would still point to the old location). If we want to do it intelligently we run into the same problem as before: we cannot start from the top (high in memory) because we cannot access the size of the top node. Alternatively, we can start low in memory, but this can be dangerous as nodes might override each other. Instead, we can add a third pass that updates all pointers by adding the moved amount.

In conclusion, the new garbage collector consists of three passes, the first of which works in such a way that it can still be used once the heap and stack have switched places in memory, and the other two exist only to correct the false assumption the first pass makes (that the heap already grows up in memory). Even more concise:

1. Collect garbage as normal, but in the opposite direction[4]
2. Move all nodes back to the top of the heap
3. Update all pointers with the shifted amount

This change, and the two additional passes can be seen in Algorithm 3. Similarly to Figure 5.4, Figure 5.5 shows an example of the updated garbage collector.

[3]In practice this lookup is not always performed, but this will be discussed later in this chapter.
[4]As we would if the stack and heap had switched

Algorithm 3 Linear Garbage Collection for Variable Sized Nodes

```
walker ← mem_heap
hole ← meam_heap
while walker ≤ memsize do
    node_size ← lookup_size(walker)
    if walker.trash then
        walker ← walker + node_size
    else if walker = hole then
        hole ← walker + node_size
        walker ← walker + node_size
    else
        move_node(walker, hole)
        hole ← walker + node_size
        walker ← walker + node_size
    end if
end while
dist ← memsize − hole
walker ← memsize − 1
hole ← hole − 1
while hole ≥ mem_heap do
    ∗walker ← ∗hole
    walker ← walker − 1
    hole ← hole − 1
end while
mem_heap ← mem_heap + dist
walker ← mem_heap
while walker < memsize do
    mem_update_ptrs(walker, dist)
    walker ← walker + lookup_size(walker)
end while
```

5.3.2 Rewriting and Variable Sized Nodes

Rewriting in mTask's RTS often replaces the node being rewritten by its result. This is more space efficient and has the added benefit that the references of the parent node need not always be updated. Ideally, we would like to retain these benefits when implementing the variable sized nodes. In mTask this is done by specifying a set of nodes that should share a minimal size. Before we look at how this is achieved, it is important to note that mTask now has two types of values that live on the heap. In the mTask library we therefore have two different Algebraic Data Types to represent these different types. First there is `:: BCTaskType` that identifies all nodes that are part of the tree and secondly there is `:: BCValueType` that is currently defined as:

```
:: BCValueType = BCArray
```

In the future this ADT could be extended to include other values that also live on the heap. Tuples, for instance, could be changed from a linked list of nodes to a single node.

In order to define what the heap behavior of these values should be, we introduce a class instantiated by all heap nodes that returns a `HeapWidth`:

```
:: HeapWidth = SizeOfUnion | Lookup
```

Where `SizeOfUnion` will set the size to the maximum of all other nodes that set their size to `SizeOfUnion`, and `Lookup` will tell the RTS to lookup the size of the nodes in the meta data of this node.

```
class toHeapWidth a :: a -> HeapWidth
```

For now, all nodes are set to the size of the union to preserve the properties mentioned above:

```
instance toHeapWidth BCTaskType
where
        toHeapWidth _ = SizeOfUnion

instance toHeapWidth BCValueType
where
        toHeapWidth BCArray = Lookup
```

Ideally, however, an analysis would be made to determine which nodes often replace their parent and an instantiation based on this analysis would be made. Note that setting the heap width of the array to "Lookup" does not interfere with these properties since arrays are never rewritten in place, arrays only live in the tree as children of "Stable" nodes or nodes that produce stable nodes containing the array when they are rewritten.

This class and its instances are used by a tool to generate a header file that is subsequently included by the RTS. This header file contains an integer array that looks something like this:

```
static const uint8_t heap_size_lookup[42] =
        { sizeof(union tree_node_union)
        ...
        , sizeof(union tree_node_union)
        , 0
        };
```

Additionally, every `BCTaskType` and `BCValueType` are mapped to a unique integer used as an index in this array. 0 is a reserved value to indicate that the RTS should perform a lookup in the node's meta data. Of course the nodes should be modified such that they support this lookup in the first place. For this reason an optional field is added to node's meta data, as shown in Figure 5.2c. This field is optional in the sense that it is only present if the value is defined as a "Lookup" node. Recall, for instance, the updated garbage collector in Algorithm 3 that performs this lookup using a function to get the size of the next node.

Concluding, the fixed sized nodes in mTask came with a distinct advantage: nodes could be rewritten in place. When implementing variable sized nodes naively, this advantage would be lost. Instead the RTS was modified in such a way that support for variable sized nodes was added, while still preserving the advantageous property of fixed sized nodes. This was achieved by allowing the user to specify what nodes are fixed sized and which are variable in size. The RTS then uses this information to decide runtime what approach should be used.

5.3.3 Marking the Arrays

Earlier, we decided that arrays are best suited to be stored on the heap. However, unlike all other nodes, they are not part of the task tree. This means that they will not be marked by the RTS when losing their last reference. Changing this is hard because array references will live on the stack during interpretation, but still need to be marked after the interpretation phase if they are not part of the tree. If we do not mark them, the heap will soon fill with arrays whose references have been lost from the stack. There are two solution for this:

1. After a return statement, figure out which values on the stack are references and mark them as garbage
2. Mark all arrays as garbage by default, and unset them when they become part of the task tree

The first solution allows for something the second one does not: garbage collection during interpretation. Should we do that with the second solution, we risk collecting arrays that will be lifted into the task tree at a later point. Unfortunately, this first solution does require us to be able to distinguish between pointer values and normal values during runtime by looking at the stack. The ideal implementation of this is to determine statically (during compilation) which byte code instructions get a pointer as an argument. Any push to the stack can then tag the data as being a pointer or a value. We could for example reserve a single bit for every element on the stack and use this bit as a flag to indicate references. However, this additional tag would require quite a lot of data in a system that already has little memory. Alternatively, we store this additional memory as part of the return statements. Unfortunately, this is not generally possible. In the following C function, for example, the location of the second buffer on the stack is dependent on j.

```
void f(uint8_t j) {
        char[j] buffer1;
        char[10] buffer2;
}
```

As such, it is impossible to generically automatically infer the location of any value (including pointers) on the stack during compile time. Note that, in mTask this is indeed currently possible as the size of values is known at compile time. For arrays whose values can depend on run time values, however, this would no longer be the case.

There are some other possibilities, interesting ones including guessing which values are pointer based on what value they hold. Since this is not quite needed however, these options were not explored further. A paper by Agesen and Detlefs [1] discusses these options in detail.

A possible implementation of solution two (marking as trash as default, and only marking as non trash when lifted to the task tree) is rather more attractive. We modify every instruction used to lift a value from the stack into the task tree, and create a separate version of it for arrays. Since we know during compilation what the type of the values is, we can then use this new version instead. It is this solution that was ultimately implemented in mTask. In order to implement it, we needed to branch based on the type of a value. This is relatively easy in Clean through the use of the classes, allowing us to create the following class and instances:

```
class isArray a :: a -> Bool

instance isArray a where
        isArray _ = False

instance isArray {a} where
        isArray _ = True
```

Instead of using the normal `BCMkTask` instruction, an array uses the `BCMKTaskPtr` instruction that initializes trash as true. During interpretation the referenced value is simply set to non trash.

In addition, we make use of this different instruction to flag the node the reference becomes part of as containing a pointer. This flag allows the recursive garbage marking, that occasionally takes place when a task has been fully rewritten, to follow the pointer to the array and mark it as garbage. For example, the value of a normal stable node should not be followed, when this stable node contains a reference however, it most definitely should. Right now every node only has a single bit indicating that its values are references. Of course, a single bit is not completely expressive, in a node containing multiple values, a value cannot be uniquely identified using a single bit. For this reason, an array in mTask can only contain values that are not references and do not contain references. As such, in the future, a different solution should be found. Possibly setting a bitmask in the node's meta data based on the node type.

In conclusion, while we would ideally be able to identify which values on the stack are references to tree nodes, this is not feasible in the current setup. Instead, we opt to drop the possibility of ever being able to garbage collect during interpretation, and have arrays be marked as trash by default. Note that this is already the standard for mTask, although (up to now) there was no reason it could not still be implemented. Only when they become part of the task tree are they set as non-garbage. Additionally, we use a free bit in every node to indicate whether it holds a pointer.

5.3.4 Returning the Arrays

Once a task has been fully rewritten, the result is sent back to the server where it can then be used in the host program. Values are only sent back after comparing the value left on the stack with the value sent previously. If no change is detected, no value is sent. Comparing the values happens per 16 bits meaning that, for a given type, comparing happens in $O(1)$. Despite the fact that arrays vary in size, we would ideally have this property persist. To achieve this, we cannot compare every 16 bits, which would obviously be $O(n)$. Instead, we use another free bit in the array node's meta data as a dirty bit. Any operation that changes the contents of the array should then set this bit. When performing many updates of an array this is of course less efficient. The bit is reset whenever the array is sent to the server.

To distinguish the reference from a normal value, we extend the tasks received from the server with an additional boolean. This boolean is set to true by the server if the type system indicates that final result of the task is an array.

Chapter 6

Conclusion

This thesis discussed the possibility of implementing arrays in a functionally pure embedded DSL by answer a set of research questions:

Extension What changes have to be made to the current DSL to incorporate bounded types?

Incorporation How should the array type fit in the current RTS?

Garbage Collection In what way must the garbage collector be changed to allow nodes other than the tree nodes to inhabit the heap?

Uniqueness Can we enforce uniqueness on the bounded types in the DSL to allow mutability?

Where the third question only arose after the second had already been answered. To most of these answers we found a satisfying answer; for *extension* we added a new class that encompasses the array, for *incorporation* we discussed how the arrays should be stored on the heap and thus discovered that the *garbage collection* should be changed to allow for the proposed method. Unfortunately, the same was not true for the *uniqueness* question, where we found the reliance on iTasks for the `TraceTask` view was too much of an obstacle. Additionally, we found that the current approach of integrating functions in mTask is somewhat limited by Clean's compiler and does not allow for a satisfying way of allowing unique arguments. All in all this means that the work done for this thesis can only be partially integrated into mTask. The work done on *garbage collection* and the *incorporation* of variable sized nodes allows for certain optimizations that are not yet present in mTask.

More generally we have found that uniqueness does not fit well in an embedded DSL due to certain limitations brought forth in this thesis. Foremost, using uniqueness limits the functions that can be implemented in a DSL. It is impossible to use the same unique value in two separate branches due to the limitation that a user defined `If` cannot accept the same unique value twice. Additionally, defining functions in a class based DSL creates an unintuitive interface for the user where the uniqueness attributes of the type must be incorporated in the identifier of the class member. Note that these are not necessarily problems with uniqueness, a language other than Clean that supports uniqueness (take Idris [3] for example) possibly solves these issues (we have not looked at this). Optionally, Clean might even support such constructions in the future.

Additionally, we have made some progress in creating an embedded DSL that uses uniqueness to implement mutable values. While this work is not yet done, at least it has been set in motion.

```
uint8_t *list8Cons(uint8_t w, uint8_t *l) {
        byte *newList;
        newList = listAlloc(l[1]+1);
        if (newList) {
                newList[1] = l[1] + 1;
                newList[2] = w;
                memcpy(&newList[3], &l[2], l[1]);
        }
        listFree(l);
        if (l[0] == 0)
                haskinoFree(l);
        return newList;
}
```

Listing 6.1: A snippet of Haskino's RTS showing the implementation of the cons instruction.

6.1 Related Work

There are many alternatives to mTask as an embedded DSL with arrays. In this section we will take a look at some of these alternatives and discuss their methods of dealing with functional purity and arrays.

Haskino's [6] second version is most like mTask in that it is a DSL embedded in Haskell for Arduino's. Similarly to mTask it is possible to run a plethora of tasks on a single embedded system by sending an intermediate representation to the Arduino. Haskino has support for lists (implemented as arrays) of bytes with a selection of operations: selection, construction, appending, reversing, dropping, etc. To guarantee functional purity Haskino has opted to reallocate a copy of the list (internally implemented as arrays) whenever an element is updated. Only when the reference count of the list reaches 0 is the list freed. The implementation of the `list8Cons` instruction (shown in Listing 6.1) in Haskino's RTS shows this. Our implementation has the advantage that it does not require the copying of arrays, increasing efficiency.

Nikola [15] is another DSL embedded in Haskell but this time compiling to GPUs via CUDA. Its implementation is based heavily on the already available vector package that implements its mutable vectors as a monad. The monad allows the retaining of functional purity while also allowing mutability. In our domain this would relate to having the array operations be tasks instead of expressions. To see why this approach was not taken refer to Chapter 3.

Two other projects: frp_arduino [12] and Arduino-Copilot [10] (both based on Functional Reactive Programming) operate almost exclusively on streams. Both have support for arrays, but the only operations allows on them do not modify the array.

Finally, there is Juniper [8]. Unlike mTask however, Juniper is not a functional language in the same sense as Clean/Haskell and does not guarantee functional purity. It is also not a shallow embedded language. These properties allow it to implement mutability in a more imperative way. To create a mutable value in Juniper, the `mutable` keyword can be used. The Juniper language documentation provides the example in Listing 6.2.

Although there are several functionally pure languages that implement mutable arrays using uniqueness typing (Clean, Single Assignment C [7] and Futhark [9] all do this), this is to our knowledge, the first project to use this technique in a shallow embedded DSL for embedded systems.

```
fun addOne<;n>(arr : int32[n]) : int32[n] = (
        let mutable ret = arr;
        for i : uint32 in 0 to n - 1 do
                set ret[i] = ret[i] + 1
        end;
        ret
)
```

Listing 6.2: An example from provided by Juniper's documentation that shows the usage of a mutable array.

A final approach of enforcing a certain safety on mutable values is found in Rust [16] and to an extend in Idris [3]. During compilation, Rust's compiler checks that at no single point will there be two mutable references to the same value (similar to the guarantee uniqueness provides). The major advantage of this approach is that the user of the programming language does not have to constantly pass the value back as a result. A disadvantage is that this approach is not very suitable for lazily evaluated languages, as the order in which their functions are evaluated cannot be determined statically in a general manner. Idris solves this problem by allowing unique values to be turned into a borrowed value only if the value is used exclusively in a pattern match or passed to another function where the other function satisfies the same constraint.

6.2 Future Work

Currently the integration of mutable arrays in mTask is being held back by the two aforementioned issues: iTask does not allow optionally unique values, and the class based functions are not currently able to support unique values. Both of these issues have to be addressed in one way or another. For the first issue iTask should be extended to allow uniqueness in some of its combinators. For the second, the compiler would ideally be extended to allow for uniqueness constraints to be present in class constraints (if this is theoretically and technically possible).

Other than these two issues, there are many things that make the current implementation of variable sized nodes suboptimal, the most obvious of which being the additional passes of the garbage collector. In the relevant chapter we suggest reversing the direction the heap and stack grow, allowing for more standard garbage collection. Additionally, the variable sized nodes are currently not utilized to their full potential. Ideally, research would be conducted to see which nodes are often rewritten to what other nodes, and a partial ordering would be made from this research. Using this ordering, the proper minimal sizes could then be set for each individual node, creating a smaller heap without losing much efficiency. Alternatively, an empirically determined minimum size could be chosen.

Finally, the array class needs to be extended. We already saw that effort was put into the possibility of having the size of arrays be determined at runtime. This could include prepending, appending and concatenation.

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Appendices

Appendix A

Monad Laws Proof for the Maybe Monad

```
Left Identity:
        return a >>= k
        = (Just a) >>= k
        = k a
```

```
Right Identity:
        m >>= return
                case 1: m = Just x
                        = (Just x) >>= return
                        = return x
                        = Just x
                        = m
                case 2: m = Nothing
                        = Nothing >>= return
                        = Nothing
                        = m
```

```
Associativity:
        m >>= (\x -> k x >>= h)
        = m >>= (\x -> case k x of
                Nothing -> Nothing
                Just x -> h x)
                case 1: m = Nothing
                        = Nothing >>= (\x -> case k x of
                Nothing -> Nothing
                Just x -> h x)
                        = Nothing
                        = Nothing >>= h
                        = (Nothing >>= k) >>= h
```

```
        = (m >>= k) >>= h
case 2: m = Just a
        = Just a >>= (\x -> case k x of
                Nothing -> Nothing
                Just x -> h x)
        = (\x -> case k x of
                Nothing -> Nothing
                Just x -> h x) a
        = case k a of
                Nothing -> Nothing
                Just x -> h x
        case 1: k a = Nothing
                = Nothing
                = Nothing >>= h
                = k a >>= h
                = (Just a >>= k) >>= h
                = (m >>= k) >>= h
        case 2: k a = Just b
                = h b
                = Just b >>= h
                = k a >>= h
                = (Just a >>= k) >>= h
                = (m >>= k) >>= h
```

Appendix B

A Unique If Function

```
module if

// ALLOWED
f :: Bool *Int -> *Int
f b i = if b i i

// NOT ALLOWED
g :: Bool *Int -> *Int
g b i = my_if b i i
where
        my_if :: Bool .a .a -> .a
        my_if b t e = if b t e

h :: Bool *Int -> *Int
h b i = my_if b i i
where
        my_if :: Bool .a .a -> .a
        my_if True t _ = t
        my_if _ _ e = e

k :: Bool *Int -> *Int
k b i = my_if b i i
where
        my_if :: Bool .a .a -> .a
        my_if b t e
        | b = t
        | otherwise = e

Start =
        [ f True uniqueInt
        , g True uniqueInt
        , h True uniqueInt
        , k True uniqueInt
```

```
        ]
where
        uniqueInt :: *Int
        uniqueInt = 42
```

Appendix C

Moving Average

C.1 Non-Unique

```
DHT D1 DHT11 \dht->
sds \avg=0 In
fun \cal_avg=(\(i, arr, acc)->
        If (i >=. lit 10) (
                acc /. lit 10
        ) (
                cal_avg (i +. lit 1, arr, acc +. (arr !. i))
        )
) In
fun \measure=(\(i, arr)->
        delay (lit 1000)
        >>|. temperature dht
        >>~. \v
                # arr = updArray arr i v
                # x = cal_avg (lit 0, arr, lit 0)
                = sdsSet avg x
        >>|. If (i <. 9)
                (measure (i +. lit 1, arr))
                (measure (lit 0, arr))
) In
fun \act=(\on->
        getSds avg
        >>*.
        [ IfValue (\v -> v >. lit 22 &. Not on) (\_ -> writeD d0 true)
        , IfValue (\v -> v <. lit 18 & on) (\_ -> writeD d0 false)
        ]
        >>=. act
) In
{main = measure (lit 0, array {20, 20, 20, 20, 20, 20, 20, 20, 20, 20}) .&&.
↪  (readD d0 >>=. act)}
```

C.2 Unique With If Problem

```
DHT D1 DHT11 \dht->
sds \avg=0 In
fun \cal_avg=(\(i, arr, acc)->
        If (i >=. lit 10) (
                (acc /. lit 10, arr)
        ) (
                let (e, arr) = (arr !. i) in
                cal_avg (i +. 1, arr, acc +. e)
        )
) In
fun \measure=(\(i, arr)->
        delay (lit 1000)
        >>|. temperature dht
        >>~. \v
                # arr = updArray arr i v
                # (x, arr) = cal_avg (0, arr, 0)
                = sdsSet avg x
        >>|. If (i <. 9)
                (measure (i +. lit 1, arr))
                (measure (lit 0, arr))
) In
fun \act=(\on->
        getSds avg
        >>*.
        [ IfValue (\v -> v >. lit 22 &. Not on) (\_ -> writeD d0 true)
        , IfValue (\v -> v <. lit 18 & on) (\_ -> writeD d0 false)
        ]
        >>=. act
) In
{main = measure (lit 0, array {20, 20, 20, 20, 20, 20, 20, 20, 20, 20}) .&&.
↪  (readD d0 >>=. act)}
```

C.3 Unique Without If Problem

```
DHT D1 DHT11 \dht->
sds \avg=0 In
fun \cal_avg=(\(i, arr, acc)->
        If (i >=. lit 10) (
                (acc /. lit 10, arr)
        ) (
                let (e, arr) = (arr !. i) in
                cal_avg (i +. 1, arr, acc +. e)
        )
) In
fun \measure=(\(i, arr)->
```

```
        delay (lit 1000)
        >>|. temperature dht
        >>~. \v
                # arr = updArray arr i v
                # (x, arr) = cal_avg (0, arr, 0)
                = sdsSet avg x
        >>=. \_
        # i = If (i <. 9) (i +. lit 1) (lit 0)
        = measure (i, arr)
) In
fun \act=(\on->
        getSds avg
        >>*.
        [ IfValue (nunique (\v -> v >. lit 22 &. Not on)) (\_ -> writeD d0
↪  true)
        , IfValue (nunique (\v -> v <. lit 18 & on)) (\_ -> writeD d0 false)
        ]
        >>=. act
) In
{main = measure (lit 0, array {20, 20, 20, 20, 20, 20, 20, 20, 20, 20}) .&&.
↪  (readD d0 >>=. act)}
```