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Implementing a library for scoped algebraic effects in Agda

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2020

Abstract

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Chapter 1

Introduction

1.1 Goals

Chapter 2

Preliminaries

2.1 Agda

Agda is a dependently typed functional programming language. The current version¹ was originally developed by Ulf Norell under the name Agda2 [Nor07]. Due to its type system Agda can be used as a programming language and as a proof assistant.

This section contains a short introduction to Agda, dependent types and the idea of “Propositions as types” under which Agda can be used for theorem proving.

2.1.1 Basic Syntax

Agda's syntax is similar to Haskell's. Data types are declared with syntax similar to Haskell's GADTs. Functions declarations and definitions are also similar to Haskell, except that Agda uses a single colon for the typing relation. In the following definition of `N`, `Set` is the type of all (small) types.

```
data N : Set where
  zero : N
  suc   : N → N
```

Ordinary function definitions are syntactically similar to Haskell. Agda allows the definition of infix operators. A infix operator is an arbitrary list of symbols (builtin symbols like colons are not allowed as part of operators). Underscores in the operator name are placeholders for future parameters. A infix operator can be applied partially by writing underscores for the omitted parameters.

In the following definition of plus for natural numbers `+` is a binary operator and therefore contains two underscores.

```
_+_ : N → N → N
zero + m = m
suc n + m = suc (n + m)
```

2.1.2 Dependent Types

The following type theoretic definitions are taken from the homotopy type theory book [Uni13]. In type theory a type of types is called a universe. Universes are usually denoted \mathcal{U} . A function whose codomain is a universe is called a type family or dependent type.

$$F : A \rightarrow \mathcal{U} \quad \text{where} \quad B(a) : \mathcal{U} \quad \text{for} \quad a : A$$

To avoid Russell's paradox, a hierarchy of universes $\mathcal{U}_1 : \mathcal{U}_2 : \dots$ is introduced. Usually the universes are cumulative i.e. if $\tau : \mathcal{U}_n$ then $\tau : \mathcal{U}_k$ for $k > n$. by default this is not the case in Agda. Each type is member of a unique universe, forcing us to do additional bookkeeping. Since Agda 2.6.1 an experimental `--cumulativity` flag exists.

¹<https://github.com/agda/agda>

Dependent Function Types (Π -Types) are a generalization of function types. The codomain of a Π type is not fixed, but values with the argument the function is applied to. The codomain is defined using a type family of the domain, which specifies the type of the result for each given argument.

$$\prod_{a:A} B(a) \quad \text{with} \quad B : A \rightarrow \mathcal{U}$$

An element of the above type is a function which maps every $a : A$ to a $b : B(a)$. In Agda the builtin function type \Rightarrow is a Π -type. An argument can be named by replacing the type τ with $x : \tau$, allowing us to use the value as part of later types.

Dependent Sum Types (Σ -Types) are a generalization of product types. The type of the second component of the product is not fixed, but varies with the value of the first.

$$\sum_{a:A} B(a) \quad \text{with} \quad B : A \rightarrow \mathcal{U}$$

An element of the above type is a pair consisting of an $a : A$ and a $b : B(a)$. In Agda **records** represent n -ary Σ -types. Each field can be used in the type of the following fields.

Programming with Dependent Types A common example for dependent types are fixed length vectors. The data type depends on a type **A** and a value of type **N**.

```
data Vec (A : Set) : N → Set where
  _::_ : {n : N} → A → Vec A n → Vec A (suc n)
  []   : Vec A 0
```

Arguments on the left-hand side of the colon are called parameters and are the same for all constructors. Arguments on the right-hand side of the colon are called indices and can differ for each constructor. Therefore **Vec A** is a family of types indexed by **N**.

The **[]** constructor allows us to create an empty vector of any type, but forces the index to be zero. The **_::_** constructor appends an element to the front of a vector of the same element type and increases the index by 1. Only these two constructors can be used to construct vectors. Therefore the index is always equal to the amount of elements stored in the vector.

By encoding more information about data in its type we can add extra constraints to functions working with it. The following definition of **head** avoids error handling or partiality by excluding the empty vector as a valid argument.

```
head : ∀ {A n} → Vec A (suc n) → A
head (x :: _) = x
```

When pattern matching on the argument of **head** there is no case for **[]**. The argument has type **Vec A (suc n)** and **[]** has type **Vec A 0**. Those two types cannot be unified, because **suc** and **zero** are different constructors of **N**. Therefore, the **[]** case does not apply. By constraining the type of the function we were able to avoid the case, which usually requires error handling or introduces partiality.

We can extend this idea to type safe indexing. A vector of length n is indexed by the first n natural numbers. The type **Fin n** represents the subset of natural numbers smaller than n .

```
data Fin : N → Set where
  zero : {n : N} → Fin (suc n)
  suc   : {n : N} → Fin n → Fin (suc n)
```

Because 0 is smaller than every positive natural number, **zero** can only be used to construct an element of **Fin (suc n)** i.e. for every type except **Fin 0**.

If any number is smaller than n , then its successor is smaller than $n + 1$. Therefore, if any number is an element of **Fin n** then its successor is an element of **Fin (suc n)**.

So we can construct a $k < n$ of type **Fin n** by starting with **zero** of type **Fin (n - k)** and applying **suc k** times. Using this definition of the bounded subsets of natural numbers we can define **!_** for vectors.


```

_!_ : ∀ {A n} → Vec A n → Fin n → A
(x :: _) ! zero = x
(_ :: xs) ! suc i = xs ! i

```

Notice that similar to `head` there is no case for `[]`. `n` is used as index for `Vec A` and `Fin`. The constructors for `Fin` only use `suc`, therefore the type `Fin zero` is not inhabited and the cases for `[]` do not apply.

By case splitting on the vector first we could have obtained the term `[] ! i`. By case splitting on `i` we notice that no constructor for `Fin zero` exists. Therefore, this case cannot occur, because the type of the argument is uninhabited. It's impossible to call the function, because we cannot construct an argument of the correct type. In this example we can either omit the case or explicitly state that the argument is impossible to construct, by replacing it with `()`, allowing us to omit the definition of the right-hand side of the equation.

```

[] ! () -- no right-hand side

```

The other two cases are straightforward. For index `zero` we return the head of the vector. For index `suc i` we call `_!_` recursively with the smaller index and the tail of the vector. Notice that the types for the recursive call change. The tail of the vector `xs` and the smaller index `i` are indexed over the predecessor of `n`.

2.1.3 Propositions as Types

An more in depth explanation and an overview over the history of the idea can be found in Wadlers paper of the same name [Wad15].

FOL	MLTT	Agda
$\forall x \in A : P(x)$	$\prod_{x:A} P(x)$	$(x : A) \rightarrow P\ x$
$\exists x \in A : P(x)$	$\sum_{x:A} P(x)$	$\Sigma [x \in A] P\ x$ mit $_,_ : (x : A) \rightarrow P\ x \rightarrow \Sigma A\ P$
$P \wedge Q$	$P \times Q$	$A \times B$
$P \vee Q$	$P + Q$	$A \uplus B$
$P \Rightarrow Q$	$P \rightarrow Q$	$A \rightarrow B$
t	1	tt : \top
f	0	\perp

2.1.4 Notions of Equality and Equality Types

In the last section we saw how we can encode propositions from propositional and predicate logic as types. One of the most important proposition is equality i.e. the proposition that given two terms $a, b : A$ that a and b are equal. When using Agda for theorem proving we have to express propositions like $a + b = b + a$ and $2 = 1$, which could be true or false, to be able to prove or disprove them. In type theory and therefore in Agda we have to consider different notions of equality.

When defining a program rule like `truth = 42` we are making an *equality judgement*. The symbol `truth` is *definitional equal* to `42`. A judgment is always true. We define one term to be equal to another one i.e. we allow Agda to reduce the left hand side of the equality to the right hand side.

The next notion of equality is *computational equality*. Two terms t_1 and t_2 are computational equal if they reduce to the same term. For example, given the above definition of `+` the terms $0 + (0 + n)$ and n are computational equal, because using the first rule in the definition of plus $0 + (0 + n)$ β -reduces to n . On the other hand $n + 0$ and n are not computational equal, because for a free variable n none of the program rules for `+` can be used to reduce the term further. Therefore computational equality is not the right notion of equality, because the later equality should also hold.

To talk about the equality of two terms we have to use *propositional equality* i.e. we have to define a proposition representing the fact that two terms of type A are equal. This proposition is usually encapsulated in an *equality type* of A .

```

infix 4 _≡_
data _≡_ {A : Set} (x : A) : A → Set where
  refl : x ≡ x

```

The type $x \equiv y$ represents the proposition that x and y are equal. The only way to construct evidence for the proposition is using the `refl` constructor i.e. if x and y are actually the same.

This notion of equality has the usually expected properties like transitivity, symmetry and congruence. The definition of `cong` shows the typical way of working with equality proofs.

```
cong : ∀ {A B x y} → (f : A → B) → x ≡ y → f x ≡ f y
cong f refl = refl
```

We expect that \equiv is a congruence relation i.e. if x and y are equal then fx and fy should also be equal. We cannot produce a value of type $fx \equiv fy$ because the two are not equal. By pattern matching in the argument of type $x \equiv y$ i.e. by inspecting the evidence that x and y are equal we obtain more information about the goal. Because `refl` can only be constructed if the two values are the same the two variables are unified. We therefore have to produce a proof that fx is equal to itself, which is given by reflexivity.

By pattern matching on variables used in the equality type we can obtain more information about the goal. Either because the constructors themselves restrict the use of the variables or because the terms used in the equality type can be reduced further. Consider the following example.

```
+identr : ∀ n → n + 0 ≡ n
+identr 0      = refl
+identr (suc m) = cong suc (+identr m)
```

By pattern matching on the variable n we obtain two cases, one for each constructor (this is analogous to a proof by exhaustion). In both cases the term $n + 0$ can now be reduced further. In the `0` case we obtain $0 + 0$ on the left hand side, which can be reduced to `0`. The return type simplifies to $0 \equiv 0$ for which we can simply construct evidence using `refl`.

The second case is more complex. The left hand side still contains the free variable m , but reduces to `suc (m + 0)` using the second rule for `+_+`. Using a recursive call we obtain evidence for $m + 0 \equiv m$. The recursive call to obtain evidence for a smaller case corresponds to the use of the induction hypothesis in an inductive proof. By applying `suc` on both sides of the equality we obtain a proof for the correct proposition.

We obtained a non obvious equality by using just definitional and computational equality together with the analogs of proofs by exhaustion and induction. This proof can now be used to rewrite arbitrary terms containing terms corresponding to or containing the left- or right-hand of the equality.

2.1.5 Termination Checking

The definition of non-terminating functions entails logical inconsistency. Agda therefore only allows the definition of terminating functions. Due to the undecidability of the halting problem Agda uses a heuristic termination checker. The termination checker proves termination by observing structural recursion. Consider the following definitions of `List` and `map`.

```
data List (A : Set) : Set where
  _::_ : A → List A → List A
  []    : List A

map : {A B : Set} → (A → B) → (List A → List B)
map f (x :: xs) = f x :: map f xs
map f []       = []
```

The `[]` case does not contain a recursive call. In the `_::_` case the recursive call to `map` occurs on a structural smaller argument i.e. xs is a subterm of the argument $x :: xs$. Because elements of `List A` are finite the function `map` terminates for every argument.

Sized Types

In more complex recursive functions the structural recursion can be obscured. Agda does not inline functions containing pattern matches during termination checking and therefore cannot prove the termination. A common example are recursive calls in lambdas, which are passed to higher order functions like `map` and `>>=`.

Consider a monad like `List` or `Maybe`. It is not obvious that the argument of the continuation of `>>=` is a subterm of the first argument.

TODO: explain better via [SEMI-CONTINUOUS SIZED TYPES AND TERMINATION ABEL]

A possibility to still proof termination are Sized Types. Agda has a special builtin, well-ordered type `Size`.

```
open import Agda.Builtin.Size public
renaming ( SizeU to SizeUniv ) -- sort SizeUniv
using ( Size                -- Size : SizeUniv
      ; Size<_              -- Size<_ : Size → SizeUniv
      ; ↑_                  -- ↑_ : Size → Size
      ; _⊔^s_               -- _⊔^s_ : Size → Size → Size
      ; ∞ )                -- ∞ : Size
```

By augmenting a data type with an index of type `Size` its size can be represented on the type level. If a value of type `Size` decreases with every recursive call, the functions has to termination, because there exist no infinitely decreasing chains on elements of `Size`.

A common idiom for data types is to mark all non-inductive constructors and recursive occurrences with an arbitrary size i and all inductive constructors with the next larger size $↑ i$. The size therefore corresponds to the height of the tree described by the term (+ the initial height for the lowest non-inductive constructor).

A common example for sized types are rose trees. The size index can be intuitively thought of as the height of the tree.

```
data Rose (A : Set) : Size → Set where
  rose : ∀ {i} → A → List (Rose A i) → Rose A (↑ i)
```

When `fmap` for rose trees is defined in terms of `map` the termination is obscured. The argument of the functions passed to `map` is not recognized as structurally smaller than the given rose tree. Using size annotations we can fix this problem.

```
map-rose : {A B : Set} {i : Size} → (A → B) → (Rose A i → Rose B i)
map-rose f (rose x xs) = rose (f x) (map (map-rose f) xs)
```

By pattern matching on the argument of type `Rose A` of size $↑ i$ we obtain a `List` of trees of size i . The recursive calls via `map` therefore occur on smaller trees. Therefore the functions has to terminates.

In this case inlining the call of `map` would also solve the termination problem. When generalizing the definition of the tree from `List` to an arbitrary functor this wouldn't be possible. In many cases inlining all helper functions is either not feasible or would lead to large and unreadable programs.

2.1.6 Strict Positivity

In a type system with arbitrary recursive types, it is possible to to implement a fixpoint combinator and therefore non terminating functions without explicit recursion. As explained in section 2.1.5 this entails logical inconsistency. Agda allows only strictly positive data types. A data type D is strictly positive if all constructors are of the form

$$A_1 \rightarrow A_2 \rightarrow \dots \rightarrow A_n \rightarrow D$$

where A_i is either not inductive (does not mention D) or are of the form

$$A_1 \rightarrow B_2 \rightarrow \dots \rightarrow B_n \rightarrow D$$

where B_j is not inductive. By restricting recursive occurrences of a data type in its definition to strict positive positions strong normalization is preserved.

Container

Because of the strict positivity requirement it is not allowed to apply generic type constructors to inductive occurrences of a data type in its definition. The reason for this restriction is that

a type constructor is not required to use its argument only in strictly positive positions. To still work generically with type constructors or more precise functors we need a more restrictive representation, which only uses its argument in a strictly positive position. One representation of such functors are containers.

Containers are a generic representation of data type, which store values of an arbitrary type. They were introduced by Abbott, Altenkirch and Ghani [AAG03]. A container is defined by a type of shapes S and a type of positions for each of its shapes $P : S \rightarrow \mathcal{U}$. Usually containers are denoted $S \triangleright P$. A common example are lists. The shape of a list is defined by its length, therefore the shape type is \mathbb{N} . A list of length n has exactly n places or positions containing data. Therefore, the type of positions is $\prod_{n:\mathbb{N}} \text{Fin } n$ where $\text{Fin } n$ is the type of natural numbers smaller than n . The extension of a container is a functor $\llbracket S \triangleright P \rrbracket$, whose lifting of types is given by

$$\llbracket S \triangleright P \rrbracket X = \sum_{s:S} P s \rightarrow X.$$

A lifted type corresponds to the container storing elements of the given type e.g. $\llbracket \mathbb{N} \triangleright \text{Fin} \rrbracket A \cong \text{List } A$. The second element of the dependent pair sometimes called position function. It assigns each position a stored value. The functors action on functions is given by

$$\llbracket S \triangleright P \rrbracket f \langle s, pf \rangle = \langle s, f \circ pf \rangle.$$

We can translate these definition directly to Agda. Instead of a `data` declaration we can use `record` declarations. Similar to other languages `records` are pure product types. A `record` in Agda is an n -ary dependent product type i.e. the type of each field can contain all previous values.

```
record Container : Set1 where
  constructor _▷_
  field
    Shape : Set
    Pos : Shape → Set
  open Container public
```

As expected, a container consists of a type of shapes and a dependent type of positions. Notice that `Container` is an element of `Set1`, because it contains a type from `Set` and therefore has to be larger. Next we define the lifting of types i.e. the container extension, as a function between universes.

```
open import Data.Product using (Σ-syntax; _,_) -- TODO: define and explain earlier
open import Function using (_◦_)
[ ] : Container → Set → Set
[ S ▷ P ] A = Σ[ s ∈ S ] (P s → A)
```

Using this definition we can define `fmap` for containers.

```
fmap : ∀ {A B C} → (A → B) → ([ C ] A → [ C ] B)
fmap f (s , pf) = (s , f ◦ pf)
```

2.2 Curry

Curry [HKM95] is a functional logic programming language. It combines paradigms from functional programming languages like Haskell with those logical languages Prolog. Curry is based on Haskell i.e. its syntax and semantics not involving nondeterminism closely resemble Haskell. Curry integrates logical features, such as nondeterminism and free variables with a few additional concepts.

When defining a function with overlapping patterns on the left-hand side of equations all matching right-hand sides are executed. This introduces non determinism. Nondeterminism is integrated as an ambient effect i.e. the effect is not represented at type level. The simplest example of a nondeterministic function is the choice operator `?`.

```

(?) :: A -> A -> A
x ? _ = x
_ ? y = y

```

Both equations always match, therefore both arguments are returned i.e. `?` introduces a nondeterministic choice between its two arguments. Using choice we can define a simple nondeterministic program.

```

coin :: Int
coin = 0 ? 1

twoCoins :: Int
twoCoins = coin + coin

```

`coin` chooses non-deterministically between 0 and 1. Executing `coin` therefore yields these two results. When executing `twoCoins` the two calls of `coin` are independent. Both choose between 0 and 1, therefore `twoCoins` yields the results 0, 1, 1 and 2.

2.2.1 Call-Time-Choice

Next we will take a look at the interactions between nondeterminism and function calls.

```

double :: Int -> Int
double x = x + x

doubleCoin :: Int
doubleCoin = double coin

```

When calling `double` with a nondeterministic value two behaviors are conceivable. The first possibility is that the choice is moved into the function i.e. both `x` chose independent of each other yielding the results 0, 1, 1 and 2. The second possibility is choosing a value before calling the function and choosing between the results for each possible argument. In this case both `x` have the same value, therefore the possible results are 0 and 2. This option is called Call-Time-Choice and it is the one implemented by Curry.

Similar to Haskell, Curry programs are evaluated lazily. The evaluation of an expression is delayed until its result is needed and each expression is evaluated at most once. The later is important when expressions are named and reused via `let` bindings or lambda abstraction. The named expression is evaluated the first time it is needed. If the result is needed again the old value is reused. This behavior is called sharing. Usually function application is defined using the `let` primitive. Applying a non variable expression to a function introduces a new intermediate result, which bound using `let`.

$$(\lambda x.\sigma)\tau = \text{let } y = \tau \text{ in } \sigma[x \mapsto y]$$

We therefore expect a variable bound by a `let` to behave similar to one bound by a function. This naturally extends Call-Time-Choice to `let`-bindings in lazily evaluated languages.

```

sumCoin :: Int
sumCoin = let x = coin in x + x

```

As expected this function yields the results 0 and 2.

2.2.2 Permutation Sort

Introduce Free Variables + Explain for Later Example

Chapter 3

Algebraic Effects

Algebraic effects are computational effects, which can be described using an algebraic theory. Examples of effects include I/O, exceptions, nondeterminism, state, delimited continuations and more [Bau18]. Handlers for algebraic effects were first presented by Gordon and Plotkin as a generalization of exception handlers []. Handlers can be used to describe non-algebraic operations, which include operations with scopes such as `catch` and `once`. Wu et al. describe a problem with this approach when multiple handlers interact. The ordering of handlers induces a semantic for the program, but simultaneously the handlers also delimit scopes. The correct ordering for scoping and semantics maybe not coincide. Wu et al. fix this problem by introducing new syntactic constructs to delimit scopes, removing the responsibility from the handler [WSH14; Pir+18].

Section 3.1 gives a concrete definition for algebraic effects. Section 3.2 describes the implementation using free monads in Agda. The following sections describe the implementation of unscoped and scoped effects in the first order setting. They focus on implementation details specific to Agda like termination checks. The scoped effects are implemented using explicit scope delimiters as described by Wu et al. [WSH14].

3.1 Definition

The following definition is similar to the one given by Bauer [Bau18].

An algebraic theory consists of a signature describing the syntax of the operations together with a set of equations. A signature is a set of operation symbols together with an arity set and an additional parameter. Operations of this form are usually denoted with a colon and \rightsquigarrow between the three sets, suggesting that they describe special functions.

$$\Sigma = \{\text{op}_i : P_i \rightsquigarrow A_i\}_{i \in \mathbb{N}}$$

Given a signature Σ we can build terms over a set of variables \mathbb{X} .

$$x \in \text{Term}_\Sigma(\mathbb{X}) \quad \text{for } x \in \mathbb{X} \quad \text{op}_i(p, \kappa) \in \text{Term}_\Sigma(\mathbb{X}) \quad \text{for } p \in P_i, \kappa : A_i \rightarrow \text{Term}_\Sigma(\mathbb{X})$$

Terms can be used to form equations of the form $x \mid l = r$. Each equation consists of two terms l and r over a set of variables x . A signature Σ_T together with a set of equations \mathcal{E}_T forms an algebraic theory T .

$$T = (\Sigma_T, \mathcal{E}_T)$$

An interpretation I of a signature is given by a carrier set $|I|$ and an interpretation for each operation $\llbracket \cdot \rrbracket_I$. An interpretation of an operation op_i is given by a functions to the carrier set $|I|$, that takes an additional parameter from P_i and $|A_i|$ parameters as a function from the arity set to the carrier set $|I|$.

$$\llbracket \text{op}_i \rrbracket_I : P_i \times |I|^{A_i} \rightarrow |I|$$

Given a function $\iota : \mathbb{X} \rightarrow |I|$, assigning each variable a value, we can give an interpretation for terms $\llbracket \cdot \rrbracket_{(I, \iota)}$.

$$\begin{aligned} \llbracket x \rrbracket_{(I, \iota)} &= \iota(x) \\ \llbracket \text{op}_i(p, \kappa) \rrbracket_{(I, \iota)} &= \llbracket \text{op}_i \rrbracket_I(p, \kappa \circ \llbracket \cdot \rrbracket_{(I, \iota)}) \end{aligned}$$

An interpretation for T is called T -model if it validates all equations in \mathcal{E}_T .

3.1.1 Free Model

For each algebraic theory T we can generate a so called free model $\text{Free}_T(\mathbb{X})$, which validates all equations.

3.2 Free Monads

The syntax of an algebraic effect is described using the free monad. The usual definition of the free monad in Haskell is the following.

```
data Free f a = Pure a | Impure (f (Free f a))

instance (Functor f) => Monad (Free f) where
  return = Pure

  Pure x    >>= k = k x
  Impure fa >>= k = Impure (fmap (>>= k) fa)
```

As the name suggests, the free monad is the free object in the category of monads, therefore the following holds.

1. For every (endo)functor F the functor $\text{Free } F$ is a monad
2. For every natural transformation from an (endo)functor F to a monad G exists a monad homomorphism from $\text{Free } F$ to G
3. As a consequence of (2) taking the natural transformation to be the identity on F , for every monad exists a monad homomorphism from a Free monad.
4. The Free functor is left adjoint and therefore preserves coproducts i.e. $\text{Free } F \oplus \text{Free } G \cong \text{Free } (F \oplus G)$

When defining the free monad in Agda we cannot use an arbitrary functor as in Haskell, because it would violate the strict positivity requirement. Instead we will represent the functor as the extension of a container as described in section 2.1.6.

```
data Free' (C : Container) (A : Set) : Set where
  pure : A → Free' C A
  impure : [ C ] (Free' C A) → Free' C A
```

The free monad represents an arbitrary branching tree with values of type A in its leafs. The **pure** constructor builds leafs containing just a value of type A . The **impure** constructor takes a value of the **Free** monad lifted by the container functor of C . Based on the choice of container the actual value could contain an arbitrary number of values i.e. **Free** monads or subtrees. Furthermore for each shape from the **Shape** type the number of subtrees can differ or contain additional arbitrary values. The container has no access to the type parameter of the free monad.

The \gg operator for free monads traverses the trees and applies the continuation to the values stored in the leafs, replacing them. \gg therefore substitutes leafs with new subtrees generated from the values stored in each leaf.

3.2.1 Functors à la carte

When modelling effects each functor represents the syntax i.e. the operations of an effect. For containers each shape corresponds to an operation symbol and the type of position for a shape corresponds to the arity set for the operation. The additional parameter of an operation is embedded in the shape. The free monad over a container describes a program using the effects syntax i.e. its the free model for the algebra without the equations. To combine the syntax of multiple effects we can combine the underlying functors, because the free monad preserves coproducts.

The approach described by Wu et al. is based on “Data types à la carte”[Swi08]. The functor coproduct is modelled as the data type `data (f :+: g) a = Inl (f a) | Inr (g a)`, which is again a **Functor** in **a**.

In Agda functors are represented as containers, a concrete data type not a type class. Containers are closed under multiple operations, coproducts being one of them [AAG03]. The coproduct of two containers F and G is the container whose **shape** is the disjoint union of F 's and G 's shapes and whose position function **pos** is the coproduct mediator of F 's and G 's position functions.

```
_⊕_ : Container → Container → Container
(Shape1 ▷ Pos1) ⊕ (Shape2 ▷ Pos2) = (Shape1 ⊔ Shape2) ▷ [ Pos1 , Pos2 ]
```

The functor represented by the coproduct of two containers is isomorphic to the functor coproduct of their representations. The container without shapes is neutral element for the coproduct of containers. This allows us to define n -ary coproducts for containers.

```
sum : List Container → Container
sum = foldr (_⊕_) (⊥ ▷ λ())
```

To generically work with arbitrary coproducts of functors we will define two utility functions. Given a value $x : A$ we want to be able to inject it into any coproduct mentioning A . Given any coproduct mentioning A we want to be able to project a value of type A from the coproduct, if A is the currently held alternative.

In the “Data types à la carte”[Swi08] approach the type class $:<:$ is introduced. $:<:$ relates a functor to a coproduct of functors, marking it as an option in the coproduct. $:<:$'s functions can be used to inject values into or maybe extract values from a coproduct. The two instances for $:<:$ mark F as an element of the coproduct if it's an on the left-hand side of the coproduct (in the head) or if it's already in the right-hand side (in the tail).

```
class (Syntax sub, Syntax sup) => sub :<: sup where
  inj :: sub m a -> sup m a
  prj :: sup m a -> Maybe (sub m a)

instance {-# OVERLAPPABLE #-} (Syntax f, Syntax g) => f :<: (f :+: g) where
  inj = Inl
  prj (Inl a) = Just a
  prj _ = Nothing

instance {-# OVERLAPPABLE #-} (Syntax h, f :<: g) => f :<: (h :+: g) where
  inj = Inr . inj
  prj (Inr ga) = prj ga
  prj _ = Nothing
```

The two instances overlap resulting in possible slower instance resolution. Furthermore, $:+:$ is assumed to be right associative and only to be used in a right associative way to avoid backtracking.

Because in Agda the result of **_⊕_** is another container, not just a value of a simple data type, instance resolution using **_⊕_** is not as straight forward as in Haskell and in some cases extremely slow¹.

This implementation of the free monad uses an approach similar to the Idris effect library [Bra13]. The free monad is not parameterised over a single container, but a list *ops* of containers. This has the benefit that we cannot associate coproducts to the left by accident. The elements of the list are combined later using **sum**. To track which functors are part of the coproduct we introduce the new type **_∈_**.

```
data _∈_ {ℓ : Level} {A : Set ℓ} (x : A) : List A → Set ℓ where
  instance
    here : ∀ {xs} → x ∈ x :: xs
    there : ∀ {y xs} → [ x ∈ xs ] → x ∈ y :: xs
```

The type $x \in xs$ represents the proposition that x is an element of xs . The two constructors can be read as rules of inference. One can always construct a proof that x is in a list with x in its head and given a proof that $x \in xs$ one can construct a proof that x is also in the extended list $y :: xs$.

¹I encountered cases where type checking of overlapping instances involving **_⊕_** did not seem to terminate.

The two instances still overlap resulting in $\mathcal{O}(c^n)$ instance resolution. Using Agdas internal instance resolution can be avoided by using a tactic to infer `__` arguments. For simplicity the following code will still use instance arguments. This version can easily be adapted to one using macros, by replacing the instance arguments with correctly annotated hidden ones.

Using this proposition we can define functions for injection into and maybe projection out of coproducts.

```

inject : ∀ {C ops ℓ} {A : Set ℓ} → C ∈ ops → [ C ] A → [ sum ops ] A
inject here      (s , pf) = (inj1 s) , pf
inject (there [ p ]) prog   with inject p prog
... | s , pf = (inj2 s) , pf

project : ∀ {C ops ℓ} {A : Set ℓ} → C ∈ ops → [ sum ops ] A → Maybe ([ C ] A)
project here      (inj1 s , pf) = just (s , pf)
project here      (inj2 _ , _) = nothing
project there      (inj1 _ , _) = nothing
project (there [ p ]) (inj2 s , pf) = project p (s , pf)

```

Both `inject` and `project` require a proof/evidence that specific container is an element of the list used to construct the coproduct.

Let us consider `inject` first. By pattern matching on the evidence we acquire more information about type `sum ops`. In case of `here` we know that `op` is in the head of the list i.e. that the given value `C` is the same as the one in the head of the list. Therefore the `Shape` types are the same and we can use our given `s` and `pf` to construct the coproduct. In case of `there` we obtain a proof that the container is in the tail of the list, which we can use to make a recursive call. By pattern matching on and repackaging the result we obtain a value of the right type.

`project` functions similarly. By pattern matching on the proof we either know that the value we found has the correct type or we obtain a proof for the tail of the list allowing us to make a recursive call.

3.2.2 The Free Monad for Effect Handling

Using the coproduct machinery we can now define a version of the free monad, suitable for working with effects. In contrast to the first definition, this free monad is parameterized over a list of containers. In the `impure` constructor the containers are combined using `sum`. The parameterization over a list ensures that the containers are not combined prematurely.

```

data Free (ops : List Container) (A : Set) : {Size} → Set where
  pure : ∀ {i} → A → Free ops A {i}
  impure : ∀ {i} → [ sum ops ] (Free ops A {i}) → Free ops A {↑ i}

```

Next we define utility functions for working with the free monad. `inj` and `prj` provide the same functionality as the ones used by Wu et al. `inj` allows to inject syntax into a program whose signature allows the operation. `prj` allows to inspect the next operation of a program, restricted to a specific signature. Furthermore we add the functions `op` and `upcast`. `op` generates the generic operation for any operation symbol. `upcast` transforms a program using any signature to one using a larger signature. Notice that `upcast` preserves the size of its input, because it just traverses the tree and repackages the contents.

```

inj : ∀ {C ops A} → [ C ∈ ops ] → [ C ] (Free ops A) → Free ops A
inj [ p ] = impure ∘ inject p

prj : ∀ {C ops A i} → [ C ∈ ops ] → Free ops A {↑ i} → Maybe ([ C ] (Free ops A {i}))
prj [ p ] (pure x) = nothing
prj [ p ] (impure x) = project p x

op : ∀ {C ops} → [ C ∈ ops ] → (s : Shape C) → Free ops (Pos C s)
op s = inj (s , pure)

upcast : ∀ {C ops A i} → Free ops A {i} → Free (C :: ops) A {i}

```

$\text{upcast } (\text{pure } x) = \text{pure } x$
 $\text{upcast } (\text{impure } (s, \kappa)) = \text{impure } (\text{inj}_2 s, \text{upcast } \circ \kappa)$

The free monad is indexed over an argument of Type **Size**. **pure** values have an arbitrary size. When constructing an **impure** value the new value is strictly larger than the ones produced by the containers position function. The size annotation therefore corresponds to the height of the tree described by the free monad. Using the annotation it's possible to prove that functions preserve the size of a value or that complex recursive functions terminate.

Consider the following definition of **fmap** for the free monad².

$\text{fmap } _ \langle \$ \rangle _ : \{F : \text{List Container}\} \{i : \text{Size}\} \rightarrow (A \rightarrow B) \rightarrow \text{Free } F A \{i\} \rightarrow \text{Free } F B \{i\}$
 $f \langle \$ \rangle \text{pure } x = \text{pure } (f x)$
 $f \langle \$ \rangle \text{impure } (s, pf) = \text{impure } (s, (f \langle \$ \rangle _) \circ pf)$
 $\text{fmap} = _ \langle \$ \rangle _$

fmap applies the given function f to the values stored in the **pure** leafs. The height of the tree is left unchanged. This fact is witnessed by the same index i on the argument and return type.

In contrast to **fmap**, **bind** does not preserve the size. **bind** replaces every **pure** leaf with a subtree, which is generated from the stored value. The resulting tree is therefore at least as high as the given one. Because there is no $+$ for sized types the only correct size estimate for the returned value is “unbounded”. The return type is not explicitly indexed, because the compiler correctly infers ∞ .

$_ \gg _ : \forall \{ops\} \rightarrow \text{Free } ops A \rightarrow (A \rightarrow \text{Free } ops B) \rightarrow \text{Free } ops B$
 $\text{pure } x \gg k = k x$
 $\text{impure } (s, pf) \gg k = \text{impure } (s, (_ \gg k) \circ pf)$
 $_ \gg _ : \forall \{ops\} \rightarrow \text{Free } ops A \rightarrow \text{Free } ops B \rightarrow \text{Free } ops B$
 $ma \gg mb = ma \gg \lambda _ \rightarrow mb$

To complete our basic set of monadic functions we also define **ap**.

$_ \circledast _ \langle * \rangle _ : \forall \{ops\} \rightarrow \text{Free } ops (A \rightarrow B) \rightarrow \text{Free } ops A \rightarrow \text{Free } ops B$
 $\text{pure } f \circledast ma = f \langle * \rangle ma$
 $\text{impure } (s, pf) \circledast ma = \text{impure } (s, (_ \circledast ma) \circ pf)$
 $_ \langle * \rangle _ = _ \circledast _$

3.2.3 Properties

This definition of the free monad is a functor because it satisfies the two functor laws. Both properties are proven by structural induction over the free monad. Notice that to proof the equality of the position functions, in the induction step, the axiom of extensionality is invoked.

$\text{fmap-id} : \forall \{ops\} \rightarrow (p : \text{Free } ops A) \rightarrow \text{fmap id } p \equiv p$
 $\text{fmap-id } (\text{pure } x) = \text{refl}$
 $\text{fmap-id } (\text{impure } (s, pf)) = \text{cong } (\text{impure } \circ (s, _)) (\text{extensionality } (\text{fmap-id } \circ pf))$ (1)

$\text{fmap-}\circ : \forall \{ops\} (f : B \rightarrow C) (g : A \rightarrow B) (p : \text{Free } ops A) \rightarrow$
 $\text{fmap } (f \circ g) p \equiv (\text{fmap } f \circ \text{fmap } g) p$
 $\text{fmap-}\circ f g (\text{pure } x) = \text{refl}$
 $\text{fmap-}\circ f g (\text{impure } (s, pf)) = \text{cong } (\text{impure } \circ (s, _)) (\text{extensionality } (\text{fmap-}\circ f g \circ pf))$ (2)

This definition of the free monad also satisfies the three monad laws.

$\text{bind-ident}^1 : \forall \{ops\} (f : A \rightarrow \text{Free } ops B) (x : A) \rightarrow (\text{pure } x \gg f) \equiv f x$
 $\text{bind-ident}^1 f x = \text{refl}$ (3)

²in the following code A , B and C are arbitrary types

$$\begin{aligned}
\text{bind-ident}' &: \forall \{ops\} (x : \text{Free } ops \ A) \rightarrow (x \gg \text{pure}) \equiv x \\
\text{bind-ident}' (\text{pure } x) &= \text{refl} \\
\text{bind-ident}' (\text{impure } (s, pf)) &= \text{cong } (\text{impure} \circ (s, _)) (\text{extensionality } (\text{bind-ident}' \circ pf))
\end{aligned} \tag{4}$$

$$\begin{aligned}
\text{bind-assoc} &: \forall \{ops\} (f : A \rightarrow \text{Free } ops \ B) (g : B \rightarrow \text{Free } ops \ C) (p : \text{Free } ops \ A) \rightarrow \\
&\quad ((p \gg f) \gg g) \equiv (p \gg (\lambda x \rightarrow f x \gg g)) \\
\text{bind-assoc } f g (\text{pure } x) &= \text{refl} \\
\text{bind-assoc } f g (\text{impure } (s, pf)) &= \text{cong } (\text{impure} \circ (s, _)) (\text{extensionality } (\text{bind-assoc } f g \circ pf))
\end{aligned} \tag{5}$$

3.3 Handler

An effect handler interprets and removes the syntax of an effect and injects corresponding code into the program. Some handlers manipulate syntax of other effects or the structure of the program itself. The handler for an algebraic effect defines its semantics.

All handlers will have the same basic structure. They will take a program i.e. a variable of type $\text{Free } C \ A$, where the head of C is the effect interpreted by the handler. Each handler produces a program without the interpreted syntax i.e. just the tail of C in its effect stack and potentially modify the type A to one modelling the result of the effect. For example a handler for exceptions would remove exception syntax and transform a program producing a value of type A to one producing a value of type $E \uplus A$, either an exception or a result.

A simple but important handler is the one handling the empty effect stack and therefore the **Void** effect. A program containing just **Void** syntax contains no impure constructors, because **Void** has no operations. Therefore, we can always produce a value of type A . This handler is important, because it can be used to escape the **Free** context after all other effects are handled.

```

run : Free [] A → A
run (pure x) = x

```

3.3.1 Nondeterministic Choice

The nondeterminism effect has two operations `__??__` and `fail`. `__??__` introduces a nondeterministic choice between two execution paths and `fail` discards the current path. We therefore have a nullary and a binary operation, both without additional parameters.

$$\Sigma_{\text{Nondet}} = \{?? : \mathbf{1} \rightsquigarrow \mathbf{2}, \text{fail} : \mathbf{1} \rightsquigarrow \mathbf{0}\}$$

Expressed as a container we have a shape with two constructors, one for each operation and both without parameters.

```

data Nondets : Set where ??s fails : Nondets

```

When constructing the container we assign the correct arities to each shape.

```

Nondet : Container
Nondet = Nondets ▷ λ where
  ??s → Bool
  fails → ⊥

```

We can now define smart constructors for each operation. These are not the generic operations, but helper functions based on them. The generic operations take no parameters and always use **pure** as continuation. These versions of the operations already process the continuations parameter.

```

__??__ : ∀ {ops} → [ Nondet ∈ ops ] → Free ops A → Free ops A → Free ops A
p ?? q = inj (??s, (if_then p else q))

fail : ∀ {ops} → [ Nondet ∈ ops ] → Free ops A
fail = inj (fails, λ())

```

With the syntax in place we can now move on to semantics and define a handler for the effect. By introducing **pattern** declarations for each operations the handler can be simplified. Furthermore we introduce a **pattern** for other operations, i.e. those who are not part of the currently handled signature.

```

pattern Other  $s \kappa = \text{impure } (\text{inj}_2 \ s, \kappa)$ 
pattern Fail  $\kappa = \text{impure } (\text{inj}_1 \ \text{fail}^s, \kappa)$ 
pattern Choice  $\kappa = \text{impure } (\text{inj}_1 \ \text{??}^s, \kappa)$ 

```

The handler interprets **Nondet** syntax and removes it from the program. Therefore **Nondet** is removed from the front of the effect stack and the result is wrapped in a **List**. The **List** contains the results of all successful execution paths.

```

solutions :  $\forall \{ops\} \rightarrow \text{Free } (\text{Nondet} :: ops) \ A \rightarrow \text{Free } ops \ (\text{List } A)$ 

```

The **pure** constructor represents a program without effects. The singleton list is returned, because no nondeterminism is used in a **pure** calculation.

```

solutions (pure  $x$ )      = pure ( $x :: []$ )

```

The **fail** constructor represents an unsuccessful calculation. No result is returned.

```

solutions (Fail  $\kappa$ )      = pure []

```

In case of a **Choice** both paths can produce an arbitrary number of results. We execute both programs recursively using **solutions** and collect the results in a single **List**.

```

solutions (Choice  $\kappa$ ) = _++_  $\langle \$ \rangle$  solutions ( $\kappa \ \text{true}$ )  $\otimes$  solutions ( $\kappa \ \text{false}$ )

```

In case of syntax from another effect we just execute **solutions** on every subtree by mapping the function over the container. Note that the newly constructed value has a different type. Since **Nondet** syntax was removed from the tree the proof for **_∈_**, which is passed to **impure** changes.

```

solutions (Other  $s \kappa$ ) = impure ( $s, \text{solutions} \circ \kappa$ )

```

3.3.2 State

The state effect has two operations **get** and **put**. The whole effect is parameterized over the state type s .

get simply returns the current state. The operation takes no additional parameters and has s positions. This can either be interpreted as **get** being an s -ary operation (one child for each possible state) or simply the parameter of the continuation being a value of type s .

put updates the current state. The operation takes an additional parameter, the new state. The operation itself is unary i.e. there is no return value, therefore **tt** is passed to the rest of the program.

$$\Sigma_{\text{State}} = \{\text{get} : \mathbf{1} \rightsquigarrow s, \text{put} : s \rightsquigarrow \mathbf{1}\}$$

As before we will translate this definition in a corresponding container.

```

data States ( $S : \text{Set}$ ) : Set where
  gets : States  $S$ 
  puts :  $S \rightarrow \text{State}^s S$ 

State :  $\text{Set} \rightarrow \text{Container}$ 
State  $S = \text{State}^s S \triangleright \lambda \text{ where}$ 
  gets       $\rightarrow S$ 
  (puts  $\_$ )    $\rightarrow \top$ 

pattern Get  $\kappa = \text{impure } (\text{inj}_1 \ \text{get}^s, \kappa)$ 
pattern Put  $s \kappa = \text{impure } (\text{inj}_1 \ (\text{put}^s \ s), \kappa)$ 

```

To simplify working with the **State** effect we add smart constructors. These correspond to the generic operations.

```

get : ∀ {ops S} → { State S ∈ ops } → Free ops S
get = inj (gets, pure)

put : ∀ {ops S} → { State S ∈ ops } → S → Free ops ⊤
put s = inj (puts s, pure)

```

Using these definitions for the syntax we can define the handler for **State**.

The effect handler for **State** takes an initial state together with a program containing the effect syntax. The final state is returned in addition to the result.

```

runState : ∀ {ops S} → S → Free (State S :: ops) A → Free ops (S × A)

```

A **pure** calculation doesn't change the current state. Therefore, the initial is also the final state and returned in addition to the result of the calculation.

```

runState s0 (pure x) = pure (s0, x)

```

The continuation/position function for **get** takes the current state to the rest of the calculation. By applying s_0 to κ we obtain the rest of the computation, which we can evaluate recursively.

```

runState s0 (Get κ) = runState s0 (κ s0)

```

put updates the current state, therefore we pass the new state s_1 to the recursive call of **runState**.

```

runState _ (Put s1 κ) = runState s1 (κ tt)

```

Similar to the handler for **Nondet** we apply the handler to every subterm of non **State** operations.

```

runState s0 (Other s κ) = impure (s, runState s0 κ)

```

Example

Here is a simple example for a function using the **State** effect. The function **tick** returns **tt** and as side effect increases the state.

```

tick : ∀ {ops} → { State ℕ ∈ ops } → Free ops ⊤
tick = do i ← get ; put (1 + i)

```

Using the **runState** handler we can evaluate programs, which use the **State** effect.

```

(run $ runState 0 $ tick >> tick) ≡ (2, tt)

```

Properties

```

module StateLaws (S : Set) (ops : List Container) (s0 : S) where
  go : Free (State S :: ops) A → Free ops (S × A)
  go = runState { _ } { ops } s0

  put-put : {s1 s2 : S} → (go $ put s1 >> put s2) ≡ (go $ put s2)
  put-put = refl

  put-get : {s : S} → (go $ put s >> get) ≡ (go $ put s >> pure s)
  put-get = refl

  get-get : {k : S → S → Free (State S :: ops) A}
    → (go $ get >> λ s → get >> k s) ≡ (go $ get >> λ s → k s s)
  get-get = refl

  get-put : (go $ get >> put) ≡ (go $ pure tt)
  get-put = refl

```

3.4 Scoped Effects

- Modularity - Combination of Effects - Semantics chosen by order of handlers - problem with scoping operations and syntax of different effects

To correctly handle operations with local scopes Wu et al. introduced scoped effects [WSH14]. They presented two solutions to explicitly declare how far an operations scopes over a program using arbitrary syntax. In the following section we will implement the scoped effect `Cut` using the first order approach in Agda. The central idea is to add new effect syntax, representing explicit scope delimiters. Whenever an opening delimiter is encountered the handler can be run again on the scoped program.

3.4.1 Cut and Call

First we will define the syntax for the new effect and its delimiters.

```
data Cuts : Set where cutfails : Cuts
data Calls : Set where bcalls ecalls : Calls

pattern Cutfail = impure (inj1 cutfails , _)
pattern BCall κ = impure (inj1 bcalls , κ)
pattern ECall κ = impure (inj1 ecalls , κ)

Cut Call : Container
Cut = Cuts ▷ λ _ → ⊥
Call = Calls ▷ λ _ → ⊤
```

The `Cut` effect has just a single operation, `cutfail`. `cutfail` can only be used in a context with nondeterminism. When `cutfail` is called it will prunes all unexplored branches and call `fail`. The Agda implementation of the handlers is identical to the one by Wu et al.

The handler itself calls the function `go`, which accumulates the unexplored alternatives in its second argument. `fail` is the neutral element for `??` and therefore the default argument. Since this handler is not orthogonal (i.e it interacts with another effect) `Nondet` is required to be in scope, but its position is irrelevant.

To prove termination we mark the second argument with an arbitrary but fixed size i . The position functions for each case return subterms indexed with a smaller size. Recursive calls to `go` with these terms as argument therefore terminate.

```
call : { [ Nondet ∈ ops ] } → Free (Cut :: ops) A → Free ops A
call = go fail
where
  go : { [ Nondet ∈ ops ] } → Free ops A → Free (Cut :: ops) A {i} → Free ops A
```

In case of a `pure` value no `cutfail` happened. We therefore return a calculation choosing between the value and the earlier separated alternatives.

$$\text{go } q \text{ (pure } a) = (\text{pure } a) \text{ ?? } q$$

In case of a `cutfail` we terminate the current computation by calling `fail` and prune the alternatives by ignoring q .

$$\text{go } _ \text{ Cutfail} = \text{fail}$$

To interact with `Nondet` syntax we have to find it. We have a proof that the `Nondet` effect is an element of the effect list. Whenever we find syntax from another effect we can therefore try to project the `Nondet` option from the coproduct. Notice that `prj` hides the structural recursion but decreases the `Size` index. We can therefore still proof that the function terminates.

$$\text{go } q \text{ p@ (Other } s \text{ } \kappa) \text{ with prj } \{ \text{Nondet} \} \text{ } p$$

The case for `??` separates the main branch from the alternative. Using `go` the `Cut` syntax is removed from both alternatives, but the results are handled asymmetrically. The left option is

directly passed to the recursive call of `go`. The handed right option is the new alternative for the left one and therefore could be pruned if left contains a `cutfail` call.

$$\dots \mid \text{just } (??^s, \kappa') = \text{go } (q (\kappa' \text{ false})) (\kappa' \text{ true})$$

When encountering a `fail` we continue with the accumulated alternatives.

$$\dots \mid \text{just } (\text{fail}^s, _) = q$$

Syntax from other effects is handled as usual.

$$\dots \mid \text{nothing} = \text{impure } (s, \text{go } q \circ \kappa)$$

With the handler for `Cut` in place we can define the handler for the scope delimiters. The implementation is again similar to the one presented by Wu et al., but to proof termination we again have to add `Size` annotations to the functions.

The `bcall` and `ecall` handler remove the scope delimiter syntax from the program and run `call` (the handler for `cut`) at the beginning of each scope. Whenever a `BCall` is found the handler `ecall` is used to handle the rest of the program. `ecall` searches for the end of the scope and returns the program up to that point. The rest of the program is the result of the returned program.

A valid upper bound for the size of the rest of the program is i , the size of the program before separating the syntax after the closing delimiter. This fact is curcial to proof that the recursive calls to `bcall` and `ecall` using \gg terminate.

Calling the handler on the extracted program guaranties that the handler does not interact with syntax outside the intended scope. Nested scopes are handled using recursive calls to `ecall` if `BCall` operations are encountered while searching a closing delimiter.

Since the delimiters could be placed freely it is possible to mismatch them. If we encounter a closing before and operening delimiter, we know that they are mismatched. Wu et al. use Haskell's `error` function to terminate the program. In Agda we are not allowed to define partial functions, therefore we have to handle the error. We could either correct the error and just continue or short circuit the calculation using exceptions in form of e.g. a `Maybe` monad. For simplicity we will use the former approach. In a real application it would be advisable to inform the programmer about the error, either using exceptions or at least trace the error.

```

bcall : { Nondet ∈ ops } → Free (Call :: Cut :: ops) A {i} → Free (Cut :: ops) A
ecall : { Nondet ∈ ops } → Free (Call :: Cut :: ops) A {i}
       → Free (Cut :: ops) (Free (Call :: Cut :: ops) A {i})

bcall (pure x)      = pure x
bcall (BCall κ)     = upcast (call (ecall (κ tt))) >> bcall
bcall (ECall κ)     = bcall (κ tt) -- Unexpected ECall! We just fix the error.
bcall (Other s κ)   = impure (s, bcall ∘ κ)

ecall (pure x)      = pure (pure x)
ecall (BCall κ)     = upcast (call (ecall (κ tt))) >> ecall
ecall (ECall κ)     = pure (κ tt)
ecall (Other s κ)   = impure (s, ecall ∘ κ)

```

Using the handlers defined above we can define a handler for scoped `Cut` syntax, which removes `Cut` and `Call` syntax simultaneously. The delimiters and correctly scoped `Cut` syntax is removed using `bcall` and potential unscoped `Cut` syntax is removed with a last use of `call`. The function `call'` is a smart constructor for the scope delimiters.

```

runCut : { Nondet ∈ ops } → Free (Call :: Cut :: ops) A → Free ops A
runCut = call ∘ bcall

call' : { Call ∈ ops } → Free ops A → Free ops A
call' p = do op bcalls; x ← p; op ecalls; pure x

```

3.5 Call-Time Choice as Effect

Bunkenburg presented an approach to model call-time choice as a stack of scoped algebraic effects [Bun19]. In this section we will extend the nondeterminism effect from section 3.3.1 to one modelling call-time choice.

As explained in section 2.2.1, call-time choice semantics describe the interaction between sharing and nondeterminism. The current implementation of `Nondet` does not support sharing i.e. it is not possible for two choice to be linked. Based on Bunkenburgs implementation we will make two changes to the nondeterminism effect. Each choice is augmented with an optional identifier consisting of a triple of natural numbers, called *choice id*. The first two are used to identity the current scope and will be refereed to as *scope id*. The third number identifies the choice inside its scope. Furthermore, instead of producing a list the handler will now produce a tree of choices. This change allows to choose the evaluation strategy, e.g. depth first or breath first search, independent of the handler.

3.5.1 Effectful Data Structures

In Haskell and Curry ambient effects, like partiality, tracing and nondeterminism, can occur in components of data structures. Each argument of a constructor could be an effectful computation. For example, in Curry the tail of a list could be a nondeterministic choice between two possible tails.

We want to simulate this behavior with algebraic effects. The effects have to be modelled explicitly using the `Free` type. We will lift data types using a standard construction, which is commonly used to simulate ambient effects [Abe+05; DCT19; CDB19]. The following example of an effectful `List` demonstrates the the general construction³.

```
data ListM (ops : List Container) (A : Set) : {Size} → Set where
  nil  : ListM ops A {i}
  cons : Free ops A → Free ops (ListM ops A {i}) → ListM ops A {↑ i}
```

`ListM ops A` represents a `List A` in whose components effects from the given effect stack `ops` can occur. To easily construct and work with lifted values we introduce smart constructors in the form of pattern synonyms.

```
pattern []M           = pure nil
pattern _::M _ mx mxs = pure (cons mx mxs)
```

The size annotations on the lifted data structures are needed to proof termination of structural recursive functions. To pattern match on a lifted value we have to use `>>=`. Therefore the structural recursion is obscured.

```
_++M_ : Free ops (ListM ops A {i}) → Free ops (ListM ops A) → Free ops (ListM ops A)
mxs ++M mys = mxs >>= λ where
  nil           → mys
  (cons mx mxs') → mx ::M mxs' ++M mys
```

Normalization of Effectful Data

Based on Bunkenburg's code [Bun19] we will introduce a type class for normalizing effectful data structures i.e. moving interleaved `Free` layers to the outside using `>>=`.

```
record Normalform (ops : List Container) (A B : Set) : Set where
  field
    nf : A → Free ops B
  open Normalform [ ... ] public

!_ : [ Normalform ops A B ] → Free ops A → Free ops B
! mx = mx >>= nf
```

³In the following code effectful data structures and lifted versions of functions are marked with a suffix ^M

The type class allow to normalize elements of type A (intuitively containing effectful calculations) to computations producing of elements of type B (intuitively a version of B without the effects). Instead of A and B we could have parameterized the type class over a type family of an effect stack, with `nf` producing an element of the type family applied to an empty stack. This implementation would allow us to restrict the normalizable types, but prohibit us from producing elements of standard data types.

In contrast to Bunkenburg's implementation we do not expect a lifted argument. Simplifying the type and introducing the helper function `!_` removes the need for auxiliary normalization lemmas for `pure` and `impure` values in proofs. The extra degree of freedom, introduced by a monadic argument, was not used in the original implementation.

```
instance
  N-normalform : Normalform ops N N
  Normalform.nf N-normalform = pure

  ListM-Normalform : (Normalform ops A B) →
    Normalform ops (ListM ops A {i}) (List B)
  Normalform.nf ListM-Normalform nil = pure []
  Normalform.nf ListM-Normalform (cons mx mxs) = (! mx :: ! mxs)
```

The data stored in an effectful list could also be effectful and therefore has to be normalized. We simply require a `Normalform` instance for the stored type. To allow normalization of general types and effectful data structures containing them, we have to implement dummy instances for data types like builtin natural numbers or booleans.

3.5.2 Sharing Handler

The idea of the following sharing handler is identical to the one presented by Bunkenburg. Thanks to the more flexible infrastructure described in the earlier sections we are able to define a more modular handler and avoid some inlining, necessary to prove termination in Coq. Similar to `Cut` the sharing handler is not orthogonal to other effects, but interacts with existing `Nondet` syntax.

The scoping operation `share` takes an additional argument, the unique identifier for the created scope. Similar to `put` the parameter is part of the container shape.

```
data Shares : Set where bshares eshares : N × N → Shares
pattern BShare n κ = impure (inj1 (bshares n) , κ)
pattern EShare n κ = impure (inj1 (eshares n) , κ)

Share : Container
Share = Shares ▷ λ _ → T

bshare : (NonDet ∈ ops) → Free (Share :: ops) A {i} → Free ops A
eshare : (NonDet ∈ ops) → N → N × N → Free (Share :: ops) A {i}
        → Free ops (Free (Share :: ops) A {i})

bshare (pure x) = pure x
bshare (BShare sid κ) = eshare 0 sid (κ tt) >>= bshare
bshare (EShare sid κ) = bshare (κ tt) -- mismatched scopes, we just continue!
bshare (Other s κ) = impure (s , bshare ∘ κ)

eshare next sid (pure x) = pure (pure x)
eshare next sid (BShare sid' κ) = eshare 0 sid' (κ tt) >>= eshare next sid
eshare next sid (EShare sid' κ) = pure (κ tt) -- usually test that sid' = sid
eshare next sid p@(Other s κ) with prj {NonDet} p
... | just (??s _ , κ') = inj $ ??s (just $ sid , next) , eshare (1 + next) sid ∘ κ'
... | just (fails , κ') = inj $ fails , λ()
... | nothing = impure (s , eshare next sid ∘ κ)
```

Next we will define the `share` operator as described by Bunkenburg. The operator generates new unique identifiers using a `State` effect.

```

record Shareable (ops : List Container) (A : Set) : Set1 where
  field
    shareArgs : A → Free ops A
open Shareable { ... } public

begin end : { Share ∈ ops } → ℕ × ℕ → Free ops T
begin id = op (bshares id)
end id = op (eshares id)

share : { Shareable ops A } → { Share ∈ ops } → { State (ℕ × ℕ) ∈ ops } →
  Free ops A → Free ops (Free ops A)
share p = do
  (i , j) ← get
  put (1 + i , j)
  pure do
    begin (i , j)
    put (i , 1 + j)
    x ← p
    x' ← shareArgs x
    put (1 + i , j)
    end (i , j)
  pure x'

instance
  shareable-ℕ : Shareable ops ℕ
  Shareable.shareArgs shareable-ℕ = pure

```

3.5.3 Examples

```

CTC : List Container
CTC = State (ℕ × ℕ) :: Share :: NonDet :: []

runCTC : { Normalform CTC A B } → Free CTC A → List B
runCTC p = dfs empty $ run $ runNonDet $ bshare $ evalState (0 , 0) (! p)

coin : { NonDet ∈ ops } → Free ops ℕ
coin = pure 0 ??' pure 1

doubleCoin : { Share ∈ ops } → { State (ℕ × ℕ) ∈ ops } → { NonDet ∈ ops } →
  Free ops ℕ
doubleCoin = share coin ≫ λ c → ( c + c )

runDoubleCoin : runCTC doubleCoin ≡ 0 :: 2 :: []
runDoubleCoin = refl

```

3.5.4 Laws of Sharing

Chapter 4

Higher Order

To address problems of the first order approach, like mismatched scope delimiters and explicit control over the continuation, Wu et al. introduced a second approach utilizing higher order syntax [WSH14]. Bunkenburg already tried to implement some scoped effects using this approach, but failed due to limitations of Coq [Bun19].

Chapter 3 demonstrated how the first order approach could be transferred to Agda utilizing container representations for functors and sized types. This chapter focuses on the implementation of effects using higher order syntax. It partially follows Bunkenburg’s approach, because the limitation of Coq described by him does not exist in Agda. Therefore this chapter focuses on expanding his approach further. Due to other limitations, needed for the consistency of Agda, this approach ultimately failed again.

4.1 Higher Order Syntax

In the first order approach effects only store possible continuations. In the higher order approach by Wu et al. scoped effects store possible continuations as well as the part of the program in their scope.

In the first order approach the functors, which describe the syntax, are applied to types of the form `Free F A` i.e. programs consisting of syntax as described by `Free F`, which produce values of type `A`. In the higher order approach these functors are generalized to higher order functors i.e. in Haskell a data type of kind `(* -> *) -> * -> *`. These functors are applied to `Free F` and `A` separately.

Because the program type is separated in syntax and result type it is possible to store programs, which use the same signature but produce values of different types. Consider the following definition of the higher order exception syntax as given by Wu et al.

```
data HExc e m a = Throw e | forall x. Catch (m x) (e -> m x) (x -> m a)
```

The catch operation stores the computation in the scope of the catch block `m x`, the handler producing an alternative value in case of an error `e -> m x` as well as the continuation `x -> m a`. The three programs agree on an arbitrary, but per catch fixed type `x`.

4.2 Representing Strictly Positive Higher Order Functors

```
record Container : Set2 where
  constructor _<_/_
  field
    Shape : Set1
    Pos : Shape -> Set
    Ctx : (s : Shape) -> Pos s -> Set -> Set
```

Chapter 5

Scoped Algebras

5.1 The Monad E

Piróg et al. describe a monad, which is suited for modelling operations with scopes [Pir+18]. The monad is the result of rewriting a slightly modified version of the monad from “Effect Handlers in Scope” i.e. the monad used in chapter 4. They separate the signature into one describing effects with scopes Γ and one describing the algebraic effects Σ . The monad E can be described as the fixpoint of the following equation, where the coend (the integral sign) denotes an existential types.

$$EA \cong A + \Sigma(EA) + \int^{X \in \mathcal{C}} \Gamma(EX) \times (EA)^X$$

This representation looks appropriate considering our earlier definition. An element of the monad is either a value of A , an operation without scopes, i.e. a functor applied to `Free F A` or an operation with scopes. Operations with scopes (e.g. `catch`) always quantified over some type to store subprograms over the same signature but with different local result type. Furthermore they provided a continuation, which transformed values of the internal result type to the result type of the whole program. [GAMMA] The following Agda data type represents the above monad.

```
data ProgE (Σ Γ : Container) (A : Set) : Set₁ where
  var : A → ProgE Σ Γ A
  op  : [ Σ ] (ProgE Σ Γ A) → ProgE Σ Γ A
  scp : {X : Set} → [ Γ ] (ProgE Σ Γ X) → (X → ProgE Σ Γ A) → ProgE Σ Γ A
```

Notice again that this definition requires X to be a smaller type than E i.e. it’s not sufficient to model deep effects as explained in chapter 4. Piróg et al. also not size issues with this definition.

Piróg et al. rewrite this definition using a left Kan extension and derive the following equivalent monad without the existential type.

$$EA \cong A + \Sigma(EA) + \Gamma(E(EA))$$

An equivalent monad without the existential type is a promising candidate for modelling deep effects in Agda, because it avoids the size issues.

5.2 The Prog Monad

In this section we will define the central monad for this approach. Because signatures are split into effects with and without scopes we will define effects as pairs of functors and therefore `Containers`.

```
record Effect : Set₁ where
  field
    Ops Scps : Container
  open Effect public
```

The functions `ops` and `scps` combine the corresponding signatures of a `List` of `Effects`.

```

ops scps : List Effect → Container
ops  = sum ∘ mapL Ops
scps = sum ∘ mapL Scps

```

Using these helper functions we can define a modular version of the monad by Piróg et al [Pir+18]. It's equivalent to the fixpoint and the Haskell definition from the paper (assuming that signatures are given by strictly positive functors).

```

data Prog (effs : List Effect) (A : Set) : Set where
  var : A → Prog effs A
  op  : [ ops effs ] (Prog effs A) → Prog effs A
  scp : [ scps effs ] (Prog effs (Prog effs A)) → Prog effs A

```

Piróg et al. also derive algebras for the above monad, which correctly model scoped effects. To implement their recursion scheme we have to define \gg for $\text{Prog } \text{effs } A$. Notice that Prog is a truly nested or non-regular data type [BM98].

Defining recursive functions for these data types is more complicated. The “direct” implementations of fmap and \gg do not obviously terminate. Augmenting Prog with size annotations leads to problems when proving the monad laws¹. Instead we will define a generic fold , which we can reuse for all functions traversing elements of $\text{Prog } \text{effs } A$.

5.2.1 Folds for Nested Data Types

Defining recursion schemes for complex recursive data types is a common problem. Fu and Selinger demonstrate a general construction of a folds for nested data types in Agda [FS18]. Following their construction and adapting it to arbitrary branching trees leads to a sufficiently strong fold to define all important functions for $\text{Prog } \text{effs } A$.

Index Type The first part of the construction by Fu and Selinger is to define the correct index type for the data structure. The index type describes the recursive structure of the data type i.e. how the type variables at each level are instantiated. For complex mutual recursive data types the index type takes the form of a branching tree. For $\text{Prog } \text{effs}$ the one type variable is either instantiated with the value type A (pure) or some number of $\text{Prog } \text{effs}$ layers applied to the current type variable (op , scp). Our index type therefore just counts the number of $\text{Prog } \text{effs}$ layers. Natural numbers are sufficient.

Next Fu and Selinger define a type level function, which translates a value of the index type to its corresponding type. For $\text{Prog } \text{effs } A$ this function just applies $\text{Prog } \text{effs } n$ times to A . The operator $\hat{_}$ applies a function n -times to a given argument x i.e. it represents n -fold function application, usually denoted $f^n(x)$.

$$\begin{aligned}
 \hat{_} &: \forall \{ \ell \} \{ C : \text{Set } \ell \} \rightarrow (C \rightarrow C) \rightarrow \mathbb{N} \rightarrow C \rightarrow C \\
 (f \hat{_} 0) & \quad x = x \\
 (f \hat{_} \text{succ } n) & \quad x = f ((f \hat{_} n) x)
 \end{aligned}$$

Recursion Scheme Next we will define fold for $\text{Prog } \text{effs } A$. The fold produces an arbitrary \mathbb{N} indexed value. The type family P determines the result type at each index. The fold produces a value of type $P n$ for a given value of type $(\text{Prog } \text{effs } \hat{_} n) A$. Furthermore the fold takes functions for processing substructures. As usual, the arguments of these function correspond to those of the constructors they processes with recursive occurrences of the type itself already processed. The cases are obtained by pattern matching on the index type and the value of type $(\text{Prog } \text{effs } \hat{_} n) A$ i.e. the value of the type depending on the index.

$$\begin{aligned}
 \text{fold} &: (P : \mathbb{N} \rightarrow \text{Set}) \rightarrow \forall n \rightarrow \\
 & \quad (A \rightarrow P 0) \rightarrow \\
 & \quad (\forall \{ n \} \rightarrow P n \rightarrow P (\text{succ } n)) \rightarrow
 \end{aligned}$$

¹As in chapter 4 the monad laws only hold for size ∞ , but working with size ∞ in proofs leads to termination problems. The scp constructor can produce an arbitrary number of $\text{Prog } \text{effs}$ layers. This forces us to use our induction hypothesis on not obviously smaller terms, but the size annotation is assumed to be ∞ .

$$\begin{aligned}
& (\forall \{n\} \rightarrow \llbracket \text{ops } \text{effs} \rrbracket (P (\text{succ } n)) \rightarrow P (\text{succ } n)) \rightarrow \\
& (\forall \{n\} \rightarrow \llbracket \text{scps } \text{effs} \rrbracket (P (\text{succ } (\text{succ } n))) \rightarrow P (\text{succ } n)) \rightarrow \\
& (\text{Prog } \text{effs} \wedge n) A \rightarrow P n \\
& \text{fold } P \ 0 \quad a \ v \ o \ s \ x \quad = \ a \ x \\
& \text{fold } P (\text{succ } n) \ a \ v \ o \ s \ (\text{var } x) = v \ (\quad \text{fold } P \ n \quad a \ v \ o \ s \ x) \\
& \text{fold } P (\text{succ } n) \ a \ v \ o \ s \ (\text{op } x) = o \ (\text{map } (\quad \text{fold } P (\text{succ } n) \quad a \ v \ o \ s \ x) \\
& \text{fold } P (\text{succ } n) \ a \ v \ o \ s \ (\text{scp } x) = s \ (\text{map } (\quad \text{fold } P (\text{succ } (\text{succ } n)) \quad a \ v \ o \ s \ x)
\end{aligned}$$

Notices that for the **op** and **scp** constructors the recursive occurrences and potential additional values are determined by the **Container**. The functions therefore processor arbitrary **Container** extensions, which contain solutions for the corresponding index. When implementing those two cases we cannot apply **fold** directly to recursive occurrences, because those depend on the choice of **Container**. **map** for **Containers** exactly captures the correct behavior.

Example Using **fold** we can implement \gg for **Prog effs** A . The continuations k passed to \gg should just effect the inner most layer. Intuitively, when using **bind** an a value constructed with **scp** we traverse the outer layer and call **bind** on the inner one recursively. To implement \gg we fold over the first argument. We could fix the arbitrary n to be 1, but defining a version generic in n is useful for later proofs. The \mathbb{N} indexed type **bind-P** defines the type for the intermediate result at every layer.

$$\begin{aligned}
& \text{bind-P} : \forall A B \text{ effs} \rightarrow \mathbb{N} \rightarrow \text{Set} \\
& \text{bind-P } A B \text{ effs } 0 = A \\
& \text{bind-P } A B \text{ effs } (\text{succ } n) = \text{Prog } \text{effs} \wedge (\text{succ } n) \$ B
\end{aligned}$$

\gg corresponds to variable substitution i.e. it replaces the values stored in **var** leafs with subtrees generated from these values. Calling k on a program with zero layers (a value of type A) would produce a program with one layer. Therefore, \gg can only be called on programs with at least one layer. The lowest layer is extended with the result of k . For all numbers greater than zero we produce a program with the same structure but a different value type. For layer zero (i.e. values) we could either produce a value of type **Prog effs** B or leave the value of type A unchanged. In both cases we have to handle the lowest **var** constructors differently.

$$\begin{aligned}
& \text{bind} : \forall n \rightarrow (\text{Prog } \text{effs} \wedge \text{succ } n) A \rightarrow (A \rightarrow \text{Prog } \text{effs} B) \rightarrow \\
& (\text{Prog } \text{effs} \wedge \text{succ } n) B \\
& \text{bind } \{ \text{effs} \} \{ A \} \{ B \} \ n \ ma \ k = \text{fold } (\text{bind-P } A B \text{ effs}) (\text{succ } n) \text{id } (\lambda \text{ where} \\
& \quad \{ 0 \} \quad x \rightarrow k \ x \\
& \quad \{ \text{succ } n \} \ x \rightarrow \text{var } x \\
& \quad) \text{ op scp } ma
\end{aligned}$$

We left the values unchanged, therefore the **var** constructor at layer zero has to produce value of type **Prog effs** B by calling k . In all other cases we replace each constructor with itself to leave these parts unchanged.

Using \gg for a program with one layer and **var** as **return** we can define a monad instance for **Prog effs**. In contrast to Haskell this automatically defines a functor and an applicative instances, because these can be defined in terms of \gg and **return**².

$$\begin{aligned}
& \text{instance} \\
& \text{Prog-RawMonad} : \text{RawMonad } (\text{Prog } \text{effs}) \\
& \text{Prog-RawMonad} = \text{record } \{ \text{return} = \text{var} ; _ \gg _ = \text{bind } 0 \}
\end{aligned}$$

The record (which is used as a type class) is part of the Agda standard library. It is named **RawMonad**, because it does not enforce the monad laws. We will prove the laws in section 5.2.3 using a technique from section 5.2.2.

5.2.2 Induction Schemes for Nested Data Types

$$\begin{aligned}
& \text{ind} : (P : (n : \mathbb{N}) \rightarrow (\text{Prog } \text{effs} \wedge n) A \rightarrow \text{Set}) \rightarrow \forall n \rightarrow \\
& (\forall \{x\} \quad \rightarrow A \quad \rightarrow P \ 0 \ x) \quad \rightarrow
\end{aligned}$$

²We automatically obtain the functions \ll , $\langle * \rangle$, **pure** and \gg .

$$\begin{aligned}
& (\forall \{n\} x \rightarrow P\ n\ x \rightarrow P\ (\text{succ } n)\ (\text{var } x)) \rightarrow \\
& (\forall \{n\} s \{ \kappa \} \rightarrow ((p : \text{Pos } (\text{ops } \text{effs})\ s) \rightarrow P\ (\text{succ } n)\ (\kappa\ p)) \rightarrow P\ (\text{succ } n)\ (\text{op } (s, \kappa))) \rightarrow \\
& (\forall \{n\} s \{ \kappa \} \rightarrow ((p : \text{Pos } (\text{scps } \text{effs})\ s) \rightarrow P\ (\text{succ } (\text{succ } n))\ (\kappa\ p)) \rightarrow P\ (\text{succ } n)\ (\text{scp } (s, \kappa))) \rightarrow \\
& (x : (\text{Prog } \text{effs } n)\ A) \rightarrow P\ n\ x \\
& \text{ind } P\ 0\ a\ v\ o\ s\ x = a\ x \\
& \text{ind } P\ (\text{succ } n)\ a\ v\ o\ s\ (\text{var } x) = v\ (\text{ind } P\ n\ a\ v\ o\ s\ x) \\
& \text{ind } P\ (\text{succ } n)\ a\ v\ o\ s\ (\text{op } (c, \kappa)) = o\ c\ (\text{ind } P\ (\text{succ } n)\ a\ v\ o\ s\ \circ\ \kappa) \\
& \text{ind } P\ (\text{succ } n)\ a\ v\ o\ s\ (\text{scp } (c, \kappa)) = s\ c\ (\text{ind } P\ (\text{succ } (\text{succ } n))\ a\ v\ o\ s\ \circ\ \kappa)
\end{aligned}$$

5.2.3 Proving the Monad Laws

Left Identity First we will prove the left identity law. Because the value passed to \gg constructed using **return** i.e. **var** both sides of the equality can be directly evaluated to $k\ a$.

$$\begin{aligned}
& \text{bind-ident}^l : \forall \{A\} \{B : \text{Set}\} \{a\} \{k : A \rightarrow \text{Prog } \text{effs } B\} \rightarrow \\
& (\text{return } a \gg k) \equiv k\ a \\
& \text{bind-ident}^l = \text{refl}
\end{aligned}$$

Right Identity When proving the right identity the value passed to \gg can be an arbitrarily complex program. Therefore the proposition is not “obvious” as it was the case with **bind-ident**^l.

$$\begin{aligned}
& \text{bind-ident}^r : \{A : \text{Set}\} (ma : \text{Prog } \text{effs } A) \rightarrow \\
& (ma \gg \text{return}) \equiv ma
\end{aligned}$$

\gg is recursive in its first argument, therefore we will prove the proposition by induction on ma . To use the induction scheme we have to define a proposition for every layer. Since \gg does not change values we simply produce a value of type \top at layer zero. For all other we proof the proposition for the appropriate **bind** i.e. the one called by **fold** to handle a value for the given n .

$$\text{bind-ident}^r \{ \text{effs} \} \{ A \} = \text{ind } (\lambda \{ 0 _ \rightarrow \top ; (\text{succ } n)\ p \rightarrow \text{bind } n\ p\ \text{var} \equiv p \})$$

We call the induction scheme with the given value with one layer, therefore the initial n is **1**. The “proof” for values can be inferred, because for each value it’s just a value of the unit type.

1 $_$

To proof that the proposition holds for values constructed using **var** we have to case split on the number of layers n . For **0** we have to proof that **var** x is equal to itself, because \gg leaves values unchanged. This proof forms the basis for our induction.

For the second case we are given a program x with **succ** n layers and an induction hypothesis IH that the proposition holds for a call to **bind** n . We have to prove that the proposition holds for **bind** (**succ** n) and the new program **var** x . By applying the \gg rule for **var** (for n greater than zero) we can move **var** to the outside. The new proposition is **var** (**bind** n) \equiv **var** x . This proposition is equal to the induction hypothesis with **var** applied to both sides. Therefore we can proof it using congruence.

$$(\lambda \{ \{ 0 \} \} (\text{tt}) \rightarrow \text{refl} ; \{ \text{succ } n \} IH \rightarrow \text{cong } \text{var } IH)$$

The proofs for the **op** and **scp** are identical and similar to the **var** case. For each shape s we are given a proof for each position of the given shape. We have to proof that the proposition holds for a new program constructed using either **op** or **scp**. For both constructors **bind** n calls itself recursively on the all contained values i.e. the results of the position function. Using congruence we can simplify the equality to the equality of the position functions. By invoking the axiom of extensionality we can prove the equality for each position. This equality is exactly the one given by the induction hypothesis.

$$\begin{aligned}
& (\lambda\ s\ IH \rightarrow \text{cong } (\text{op } \circ\ (s, _))\ (\text{extensionality } IH)) \\
& (\lambda\ s\ IH \rightarrow \text{cong } (\text{scp } \circ\ (s, _))\ (\text{extensionality } IH))
\end{aligned}$$

Associativity The proof for associativity follows the same pattern as the one for the right identity. \gg is defined by recursion on its first argument. We therefore proof the proposition by induction on ma . In all cases the left-hand side reduces to the induction hypothesis in the same manner as before. Therefore these cases look identical.

```

bind-assoc :  $\forall \{A B C\}$ 
  ( $f : A \rightarrow \text{Prog } \text{effs } B$ ) ( $g : B \rightarrow \text{Prog } \text{effs } C$ ) ( $ma : \text{Prog } \text{effs } A$ )  $\rightarrow$ 
  ( $ma \gg f \gg g$ )  $\equiv$  ( $ma \gg \lambda a \rightarrow f a \gg g$ )
bind-assoc  $f g = \text{ind}$ 
  ( $\lambda \text{ where}$ 
    0  $p \rightarrow \top$ 
    ( $\text{suc } n$ )  $p \rightarrow \text{bind } n (\text{bind } n p f) g \equiv \text{bind } n p \lambda a \rightarrow \text{bind } 0 (f a) g$ )
  ) 1  $\_$ 
  ( $\lambda \{ \{0\} \_ \rightarrow \text{refl} ; \{\text{suc } n\} IH \rightarrow \text{cong var } IH \}$ )
  ( $\lambda s IH \rightarrow \text{cong } (\text{op} \circ (s, \_)) (\text{extensionality } IH)$ )
  ( $\lambda s IH \rightarrow \text{cong } (\text{scp} \circ (s, \_)) (\text{extensionality } IH)$ )

```

Functor and Applicative Laws The monad laws imply the functor and applicative laws. We can proof them without using explicit induction by just rewriting equations involving \gg . These proofs are simpler than the ones explicitly involving the definition of \gg using `fold`. We can write them using the chain reasoning operators as described by Norell [Nor07].

```

fmap-id :  $\forall \{ \text{effs} \} \{A B : \text{Set}\} \rightarrow (ma : \text{Prog } \text{effs } A) \rightarrow (\text{id} \lessgtr ma) \equiv ma$ 
fmap-id  $ma = \text{begin}$ 
  ( $\text{id} \lessgtr ma$ )  $\equiv \langle \rangle$  -- definition of  $\lessgtr$ 
  ( $ma \gg \lambda a \rightarrow \text{var } (\text{id } a)$ )  $\equiv \langle \rangle$  -- definition of  $\text{id}$  and  $\eta$ -conversion
  ( $ma \gg \text{var}$ )  $\equiv \langle \text{bind-ident}^r ma \rangle$ 
   $ma$   $\blacksquare$ 

```

5.3 Combining Effects

```

variable
  C : Container
  Cs : List Container
  e : Effect

infix 3  $\_ \in \_$ 
 $\_ \in \_ : \forall \{a\} \{A : \text{Set } a\} \rightarrow A \rightarrow \text{List } A \rightarrow \text{Set } a$ 
 $x \in xs = \text{Any } (\_ \equiv \_ x) xs$ 

instance
   $\in\text{-head} : \forall \{a\} \{A : \text{Set } a\} \{x : A\} \{xs\} \rightarrow x \in x :: xs$ 
   $\in\text{-head} = \text{here refl}$ 

   $\in\text{-tail} : \forall \{a\} \{A : \text{Set } a\} \{x y : A\} \{xs\} \rightarrow \llbracket x \in xs \rrbracket \rightarrow x \in y :: xs$ 
   $\in\text{-tail} \llbracket p \rrbracket = \text{there } p$ 

inj :  $C \in Cs \rightarrow \llbracket C \rrbracket A \rightarrow \llbracket \text{sum } Cs \rrbracket A$ 
inj (here refl) ( $s, \kappa$ ) = inj1  $s, \kappa$ 
inj (there p) q with inj p q
... |  $s, \kappa$  = inj2  $s, \kappa$ 

prj :  $C \in Cs \rightarrow \llbracket \text{sum } Cs \rrbracket A \rightarrow \text{Maybe } (\llbracket C \rrbracket A)$ 
prj (here refl) (inj1  $s, \kappa$ ) = just ( $s, \kappa$ )
prj (here refl) (inj2  $s, \kappa$ ) = nothing
prj (there p) (inj1  $s, \kappa$ ) = nothing
prj (there p) (inj2  $s, \kappa$ ) = prj p ( $s, \kappa$ )

```



```

opsInj : (e ∈ effs) → Ops e ∈ mapL Ops effs
opsInj (here refl) = here refl
opsInj (there p) = there (opsInj p)

scpsInj : (e ∈ effs) → Scps e ∈ mapL Scps effs
scpsInj (here refl) = here refl
scpsInj (there p) = there (scpsInj p)

Op : [ e ∈ effs ] → [ Ops e ] (Prog effs A) → Prog effs A
Op [ p ] = op ∘ inj (opsInj p)

Scp : [ e ∈ effs ] → [ Scps e ] (Prog effs (Prog effs A)) → Prog effs A
Scp [ p ] = scp ∘ inj (scpsInj p)

```

5.4 Nondet

```

data Choices : Set where ??s fails : Choices
data Onces : Set where onces : Onces

Nondet : Effect
Ops Nondet = Choices ▷ λ{ ??s → Bool ; fails → ⊥ }
Scps Nondet = Onces ▷ const ⊤

```

5.4.1 As Scoped Algebra

```

record ScopedAlgebra (E : Effect) (C : ℕ → Set) : Set where
  constructor ⟨_,_,_⟩
  field
    p : ∀ {n} → C n → C (1 + n)
    d : ∀ {n} → [ Scps E ] (C (2 + n)) → C (1 + n)
    a : ∀ {n} → [ Ops E ] (C (1 + n)) → C (1 + n)
open ScopedAlgebra

foldP : ∀ {C : Set → ℕ → Set} → ScopedAlgebra e (C A) → Prog (e :: []) (C A 0) → C A 1
foldP {C = C} ⟨ p , d , a ⟩ = fold (C _) 1 id p
  (λ{ (inj1 s , κ) → a (s , κ) } λ{ (inj1 s , κ) → d (s , κ) }

NondetAlg : ScopedAlgebra Nondet (λ i → List ^ i $ A)
p NondetAlg = _:: []
a NondetAlg (??s , κ) = κ true ++ κ false
a NondetAlg (fails , κ) = []
d NondetAlg (onces , κ) with κ tt
... | [] = []
... | x :: _ = x

runNondetP : Prog (Nondet :: []) A → List A
runNondetP = foldP {C = λ A i → List ^ i $ A} NondetAlg

```

5.4.2 As Modular Handler

```

pattern Other s κ = (inj2 s , κ)
pattern Choice κ = (inj1 ??s , κ)
pattern Fail = (inj1 fails , _)
pattern Once κ = (inj1 onces , κ)

```

```

runNondet : Prog (Nondet :: effs) A → Prog effs (List A)
runNondet {effs} {A} = fold (λ i → (Prog effs ∘ List) ^ i $ A) 1 id
  (pure ∘ (λ _ :: []))
  (λ where
    (Choice κ) → (κ true ++ κ false)
    Fail       → pure []
    (Other s κ) → op (s, κ)
  ) λ where
    (Once κ) → κ tt >> λ where
      [] → var []
      (x :: _) → x
    (Other s κ) → scp (s, λ p → hdl <<> κ p)
  where
    hdl : ∀ {A} → List (Prog effs (List A)) → Prog effs (List A)
    hdl [] = pure []
    hdl (mx :: mxs) = (κ mx ++ hdl mxs)

```

5.5 Exceptions

```

data Throws (E : Set) : Set where throws : (e : E) → Throws E
data Catchs : Set where catchs : Catchs
data Catchp (E : Set) : Set where
  mainp : Catchp E
  handlep : (e : E) → Catchp E

```

```

Exc : Set → Effect
Ops (Exc E) = Throws E ▷ const ⊥
Scps (Exc E) = Catchs ▷ const (Catchp E)

```

```

pattern Throw e = (inj1 (throws e), _)
pattern Catch κ = (inj1 catchs, κ)

```

```

runExc : Prog (Exc E :: effs) A → Prog effs (E ⊔ A)
runExc {E} {effs} {A} = fold (λ i → (Prog effs ∘ (E ⊔ _)) ^ i $ A) 1 id
  (pure ∘ inj2)
  (λ where
    (Throw e) → pure (inj1 e)
    (Other s κ) → op (s, κ)
  ) λ where
    (Catch κ) → κ mainp >> λ where
      (inj2 x) → x
      (inj1 e) → κ (handlep e) >> λ where
        (inj1 e) → pure (inj1 e)
        (inj2 x) → x
    (Other s κ) → scp (s, λ p → [ pure ∘ inj1, id ] <<> κ p)

```

```

throw : {Exc E ∈ effs} → E → Prog effs A
throw e = Op (throws e, λ())

```

```

_catch_ : {Exc E ∈ effs} → Prog effs A → (E → Prog effs A) → Prog effs A
p catch h = Scp $ catchs, λ where
  mainp → pure <<> p
  (handlep e) → pure <<> h e

```

5.6 State

```

data States (S : Set) : Set where
  puts : (s : S) → States S
  gets : States S

State : Set → Effect
Ops (State S) = (States S) ▷ λ{ (puts s) → ⊤ ; gets → S }
Scps (State S) = Void

pattern Get κ = (inj1 gets , κ)
pattern Put s1 κ = (inj1 (puts s1) , κ)

eval : A × (A → B) → B
eval (a , f) = f a

runState : Prog (State S :: effs) A → S → Prog effs (S × A)
runState {S} {effs} {A} = fold (λ i → (λ X → S → Prog effs (S × X)) ^ i $ A) 1 id
  (λ x s0 → pure (s0 , x))
  (λ where
    (Put s1 κ) _ → κ tt s1
    (Get κ) s0 → κ s0 s0
    (Other s κ) s0 → op (s , λ p → κ p s0)
  ) λ where
    (Other s κ) s0 → scp (s , λ p → eval <$> κ p s0)

get : { S : State S ∈ effs } → Prog effs S
get = Op (gets , pure)

put : { S : State S ∈ effs } → S → Prog effs ⊤
put s = Op (puts s , pure)

```

5.7 Share

Chapter 6

Conclusion

6.1 Summary

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