



DEPARTMENT OF COMPUTER SCIENCE

Circuit: A Domain Specific Language for Dataflow Programming

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A dissertation submitted to the University of Bristol in accordance with the requirements of the degree
of Master of Engineering in the Faculty of Engineering.

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Declaration

This dissertation is submitted to the University of Bristol in accordance with the requirements of the degree of MEng in the Faculty of Engineering. It has not been submitted for any other degree or diploma of any examining body. Except where specifically acknowledged, it is all the work of the Author.

Riley Evans, Tuesday 27th April, 2021

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Notation and Acronyms

DSL Domain Specific Language

EDSL Embedded DSL

FIFO First-In First-Out

KPN Kahn Process Network

GPL General Purpose Language

DPN Data Process Network

AST Abstract Syntax Tree

Acknowledgements

Change this to something meaningful

It is common practice (although totally optional) to acknowledge any third-party advice, contribution or influence you have found useful during your work. Examples include support from friends or family, the input of your Supervisor and/or Advisor, external organisations or persons who have supplied resources of some kind (e.g., funding, advice or time), and so on.

Chapter 1

Introduction

Write an introduction (do near the end)

Chapter 2

Background

2.1 Dataflow Programming

Dataflow programming is a paradigm that models applications as a directed graph. The nodes of the graph have inputs and outputs and are pure functions, therefore have no side effects. It is possible for a node to be a: source; sink; or processing node. A source is a read-only storage: it can be used to feed inputs into processes. A sink is a write-only storage: it can be used to store the outputs of processes. Processes will read from either a source or the output of another process, and then produce a result which is either passed to another process or saved in a sink. Edges connect these nodes together, and define the flow of information.

Example - Data Pipelines A common use of dataflow programming is in pipelines that process data. This paradigm is particularly helpful as it helps the developer to focus on each specific transformation on the data as a single component. Avoiding the need for long and laborious scripts that could be hard to maintain. One example of a data pipeline tool that makes use of dataflow programming is Luigi [13]. An example dataflow graph produced by the tool is shown in Figure 2.1

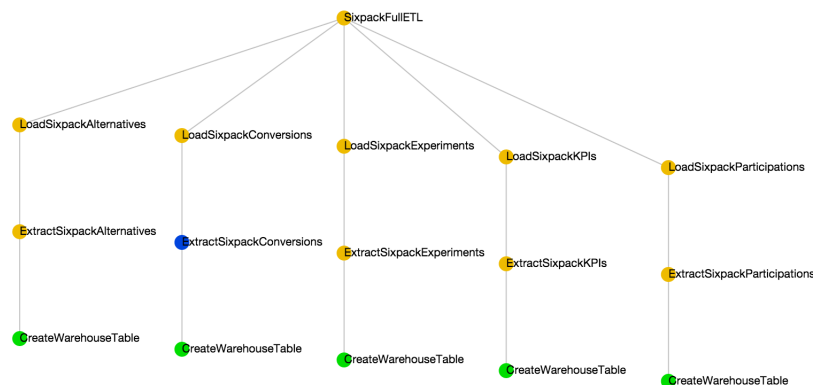


Figure 2.1: Luigi dependency graph [6]

Example - Quartz Composer Apple developed a tool included in XCode, named Quartz Composer, which is a node-based visual programming language [1]. As seen in Figure 2.2, it uses a visual approach to programming connecting nodes with edges. This allows for quick development of programs that process and render graphical data, without the user having to write a single line of code. This means that even non-programmers are able to use the tool.

Example - Spreadsheets A widely used example of dataflow programming is in spreadsheets. A cell in a spreadsheet can be thought of as a single node. It is possible to specify dependencies to other cells through the use of formulas. Whenever a cell is updated it sends its new value to those who depend on it, and so on. Work has also been done to visualise spreadsheets using dataflow diagrams, to help debug ones that are complex [5].



Figure 2.2: Quartz composer [3]

2.1.1 The Benefits

Visual The dataflow paradigm uses graphs, which make programming visual. It allows the end-user programmer to see how data passes through the program, much easier than in an imperative approach. In many cases, dataflow programming languages use drag and drop blocks with a graphical user interface to build programs. For example, Tableau Prep [16], that makes programming more accessible to users who do not have programming skills.

Implicit Parallelism Moore's law states that the number of transistors on a computer chip doubles every two years [11]. This meant that the chips' processing speeds also increased in alignment with Moore's law. However, in recent years this is becoming harder for chip manufacturers to achieve [2]. Therefore, chip manufactures have had to turn to other approaches to increase the speed of new chips, such as multiple cores. It is this approach the dataflow programming can effectively make use of. Since each node in a dataflow is a pure function, it is possible to parallelise implicitly. No node can interact with another node, therefore there are no data dependencies outside of those encoded in the dataflow. Thus eliminating the ability for a deadlock to occur.

2.1.2 Dataflow Diagrams

Dataflow programs are typically viewed as a graph. An example dataflow graph along with its corresponding imperative approach, can be found in Figure 2.3. The nodes 100, X , and Y are sources as they are only read from. C is a sink as it is wrote to. The remaining nodes are all processes, as they have some number of inputs and compute a result.

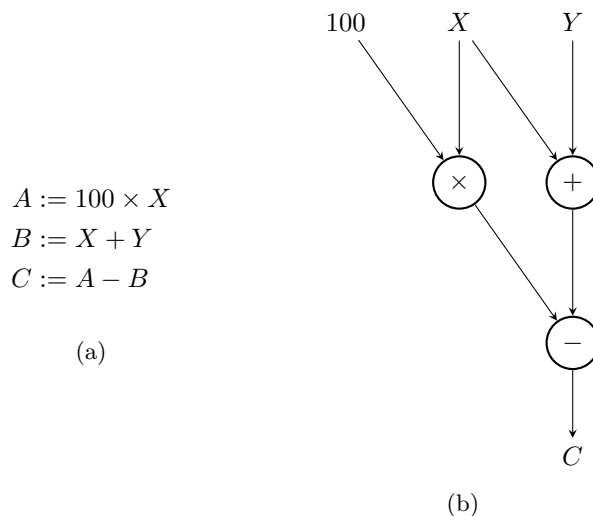


Figure 2.3: An example dataflow and its imperative approach.

In this diagram is possible to see how implicit parallelisation is possible. Both A and B can be calculated simultaneously, with C able to be evaluated after they are complete.

2.1.3 Kahn Process Networks (KPNs)

A method introduced by Gilles Kahn, Kahn Process Networks (KPNs) realised the concept of dataflow networks through the use of threads and unbounded First-In First-Out (FIFO) queues [7]. The FIFO queue is one where the items are output in the same order that they are added. A node in the dataflow becomes a thread in the process network. Each FIFO queue represents the edges connecting the nodes in a graph. The threads are then able to communicate through FIFO queues. The node can have multiple input queues and is able to read any number of values from them. It will then compute a result and add it to an output queue. Kahn imposed a restriction on a process in a KPNs that the thread is suspended if it attempts to fetch a value from an empty queue. The thread is not allowed to test for the presence of data in a queue.

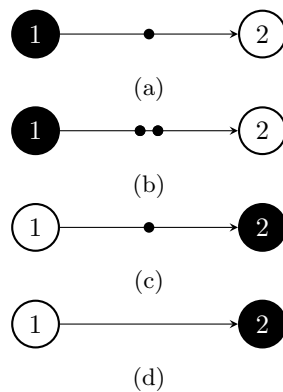


Figure 2.4: A sequence of node firings in a KPN

Parks described a variant of KPNs, called Data Process Networks (DPNs) [9]. They recognise that if functions have no side effects then they have no values to be shared between each firing. Therefore, a pool of threads can be used with a central scheduler instead.

2.2 Domain Specific Languages (DSLs)

A DSL is a programming language that has a specialised domain or use-case. This differs from a General Purpose Language (GPL), which can be applied across a larger set of domains, and are generally turing complete. HTML is an example of a DSL: it is good for describing the appearance of websites, however, it cannot be used for more generic purposes, such as adding two numbers together.

Approaches to Implementation DSLs are typically split into two categories: standalone and embedded. Standalone DSLs require their own compiler and typically their own syntax; HTML would be an example of a standalone DSL. Embedded DSLs (EDSLs) use an existing language as a host, therefore they use the syntax and compiler from the host. This means that they are easier to maintain and often quicker to develop than standalone DSLs. An EDSL, can be implemented using two differing techniques: deep and shallow embeddings.

2.2.1 Deep Embeddings

A deep embedding is when the terms of the DSL will construct an Abstract Syntax Tree (AST) as a host language datatype. Semantics can then be provided later on with evaluation functions. Consider the example of a minimal non-deterministic parser combinator library [19].

```
data Parserd (a :: Type) where
  Satisfyd :: (Char → Bool) → Parserd Char
  Ord      :: Parserd a → Parserd a → Parserd a
```

This can be used to build a parser that can parse the characters 'a' or 'b'.

```

aorbd :: Parserd Char
aorbd = Satisfyd (≡ 'a') `Ord` Satisfyd (≡ 'b')

```

However, this parser does not have any semantics, therefore this needs to be provided by the evaluation function `parse`.

```

parsed :: Parserd a → String → [(a, String)]
parsed (Satisfyd p) = λcase
  []      → []
  (t : ts') → [(t, ts') | p t]
parsed (Ord px py) = λts → parsed px ts ++ parsed py ts

```

The program can then be evaluated by the `parsed` function. For example, `parsed aorbd "a"` evaluates to `[('a', "")]`, and `parsed aorbd "c"` evaluates to `[]`.

A key benefit for deep embeddings is that the structure can be inspected, and then modified to optimise the user code: Parsley [18] makes use of such techniques to create optimised parsers. Another benefit, is that you can provide multiple interpretations, by specifying different evaluation functions. However, they also have drawbacks - it can be laborious to add a new constructor to the language. Since it requires that all functions that use the deep embedding be modified to add a case for the new constructor [14].

2.2.2 Shallow Embeddings

In contrast, a shallow approach is when the terms of the DSL are defined as first class components of the language. For example, a function in Haskell. Components can then be composed together and evaluated to provide the semantics of the language. Again a simple parser example can be considered.

```

newtype Parsers a = Parsers { parses :: String → [(a, String)] }
ors :: Parsers a → Parsers a → Parsers a
ors (Parsers px) (Parsers py) = Parsers (λts → px ts ++ py ts)
satisfys :: (Char → Bool) → Parsers Char
satisfys p = Parsers (λcase
  []      → []
  (t : ts') → [(t, ts') | p t])

```

The same `aorbs` parser can be constructed from these functions, avoiding the need for an intermediate AST.

```

aorbs :: Parsers Char
aorbs = satisfys (≡ 'a') `ors` satisfys (≡ 'b')

```

Using a shallow implementation has the benefit of being able add new ‘constructors’ to a DSL, without having to modify any other functions. Since each ‘constructor’, produces the desired result directly. However, this causes one of the main disadvantages of a shallow embedding - the structure cannot be inspected. This means that optimisations cannot be made to the structure before evaluating it.

2.3 Higher Order Functors

It is possible to capture the shape of an abstract datatype as a `Functor`. The use of a `Functor` allows for the specification of where a datatype recurses. Consider an example on a small expression language:

```

data Expr = Add Expr Expr
          | Val Int

```

The recursion within the `Expr` datatype can be removed to form `ExprF`. The recursive steps can then be specified in the `Functor` instance.

```

data ExprF f = AddF f f
              | ValF Int

```

```
instance Functor ExprF where
  fmap f (AddF x y) = AddF (f x) (f y)
  fmap f (ValF x)   = ValF x
```

To regain a datatype that is isomorphic to the original datatype, the recursive knot need to be tied. This can be done with `Fix`, to get the fixed point of `ExprF`:

```
data Fix f = In (f (Fix f))
type Expr' = Fix ExprF
```

There is, however, one problem: a `Functor` expressing the a parser language is required to be typed. Parsers require the type of the tokens being parsed. For example, a parser reading tokens that make up an expression could have the type `Parser Expr`. A `Functor` does not retain this type information needed in a parser.

IFunctors Instead a type class called `IFunctor` — also known as `HFunctor` — can be used, which is able to maintain the type indicies [10]. This makes use of \rightsquigarrow , which represents a natural transformation from f to g . `IFunctor` can be thought of as a functor transformer: it is able to change the structure of a functor, whilst preserving the values inside it [8]. Whereas a functor changes the values inside a structure.

```
type ( $\rightsquigarrow$ ) f g =  $\forall a. f a \rightarrow g a$ 
class IFunctor iF where
  imap :: (f  $\rightsquigarrow$  g)  $\rightarrow$  iF f  $\rightsquigarrow$  iF g
```

The shape of `Parser` can be seen in `ParserF` where the f marks the recursive spots. The type f represents the type of the children of that node. In most cases this will be itself.

```
data ParserF (f :: *  $\rightarrow$  *) (a :: *) where
  SatisfyF :: (Char  $\rightarrow$  Bool)  $\rightarrow$  ParserF f Char
  OrF      :: f a  $\rightarrow$  f a  $\rightarrow$  ParserF f a
```

An `IFunctor` instance can be defined, which follow the same structure as a standard `Functor` instance.

```
instance IFunctor ParserF where
  imap _ (SatisfyF s) = SatisfyF s
  imap f (OrF px py) = OrF (f px) (f py)
```

`Fix` is used to get the fixed point of a `Functor`, to get the indexed fixed point `IFix` can be used.

```
newtype IFix iF a = In (iF (IFix iF) a)
```

The fixed point of `ParserF` is `Parser3`.

```
type Parserfixed = IFix ParserF
```

In a deep embedding, the **AST** can be traversed and modified to make optimisations, however, it may not be the best representation when evaluating it. This means that it might be transformed to a different representation. In the case of a parser, this could be a stack machine. Now that the recursion in the datatype has been generalised, it is possible to create a mechanism to perform this transformation. An indexed *catamorphism* is one such way to do this, it is a generalised way of folding an abstract datatype. The use of a catamorphism removes the recursion from any folding of the datatype. This means that the algebra can focus on one layer at a time. This also ensures that there is no re-computation of recursive calls, as this is all handled by the catamorphism. The commutative diagram below describes how to define a catamorphism, that folds an `IFix iF a` to a `f a`.

$$\begin{array}{ccc}
\text{iF (IFix iF) a} & \xrightarrow{\text{imap (icata alg)}} & \text{iF f a} \\
\text{inop} \uparrow \downarrow \text{In} & & \downarrow \text{alg} \\
\text{IFix iF a} & \xrightarrow{\text{icata alg}} & \text{f a}
\end{array}$$

`icata` is able to fold an `IFix iF a` and produce an item of type `f a`. It uses the algebra argument as a specification of how to transform a single layer of the datatype.

```
icata :: IFunctor iF => (iF f ~> f) -> IFix iF ~> f
icata alg (lIn x) = alg (imap (icata alg) x)
```

The resulting type of `icata` is `f a`, therefore the `f` is a syntactic **Functor**. This could be `IFix ParserF`, which would be a transformation to the same structure, possibly applying optimisations to the **AST**.

is this the
right ter-
minology?

2.4 Data types à la carte

When building a **DSL** one problem that becomes quickly prevalent, the so called *Expression Problem* [17]. The expression problem is a trade off between a deep and shallow embedding. In a deep embedding, it is easy to add multiple interpretations to the **DSL** - just add a new evaluation function. However, it is not easy to add a new constructor, since all functions will need to be modified to add a new case for the constructor. The opposite is true in a shallow embedding.

One possible attempt at fixing the expression problem is data types à la carte [15]. It combines constructors using the co-product of their signatures. This is defined as:

```
data (f :+: g) a = L (f a) | R (g a)
```

It is also the case that if both `f` and `g` are **Functors** then so is `f :+: g`.

```
instance (Functor f, Functor g) => Functor (f :+: g) where
  fmap f (L x) = L (fmap f x)
  fmap f (R y) = R (fmap f y)
```

For each constructor it is possible to define a new data type and a **Functor** instance specifying where it recurses.

```
data ValF2 f = ValF2 Int
data MulF2 f = MulF2 f f
instance Functor ValF2 where
  fmap f (ValF2 x) = ValF2 x
instance Functor MulF2 where
  fmap f (MulF2 x y) = MulF2 (f x) (f y)
```

By using `Fix` to tie the recursive knot, the `Fix (Val :+: Mul)` data type would be isomorphic to the original `Expr` datatype found in Section 2.3.

One problem that now exist, however, is that it is now rather difficult to create expressions, take a simple example of 12×34 .

```
exampleExpr :: Fix (ValF2 :+: MulF2)
exampleExpr = In (R (MulF2 (In (L (ValF2 12))) (In (L (ValF2 34)))))
```

It would be beneficial if there was a way to add these `Ls` and `Rs` automatically. Fortunately there is a method using injections. The `:<` type class captures the notion of subtypes between **Functors**.

```
class (Functor f, Functor g) => f :<: g where
  inj :: f a -> g a
instance Functor f => f :<: f where
  inj = id
instance (Functor f, Functor g) => f :<: (f :+: g) where
  inj = L
instance (Functor f, Functor g, Functor h, f :<: g) => f :<: (h :+: g) where
  inj = R . inj
```

Using this type class, smart constructors can be defined.

```
inject :: (g :<: f) => g (Fix f) -> Fix f
inject = In . inj
val :: (ValF2 :<: f) => Int -> Fix f
```

```

val x = inject (ValF2 x)
mul :: (MulF2 :-: f) ⇒ Fix f → Fix f → Fix f
mul x y = inject (MulF2 x y)

```

Expressions can now be built using the constructors, such as `val 12 `mul` val 34`.

A modular algebra can now be defined that provides an interpretation of this datatype.

```

class Functor f ⇒ EvalAlg f where
  evalAlg :: f Int → Int
instance (EvalAlg f, EvalAlg g) ⇒ EvalAlg (f :+: g) where
  evalAlg (L x) = evalAlg x
  evalAlg (R y) = evalAlg y
instance EvalAlg MulF2 where
  evalAlg (MulF2 x y) = x * y
instance EvalAlg ValF2 where
  evalAlg (ValF2 x) = x
cata :: Functor f ⇒ (f a → a) → Fix f → a
cata alg (In x) = alg (fmap (cata alg) x)
eval :: EvalAlg f ⇒ Fix f → Int
eval = cata evalAlg

```

One benefit to this approach is that an interpretation is only needed for expressions that only use `MulF` and `ValF`. If a new constructor such as `SubF` was added to the language and it would never be given to this fold, then it would not require an instance. This helps to solve the expression problem.

2.5 Dependently Typed Programming

Although Haskell does not officially support dependently typed programming, there are techniques available that together can be used to replicate the experience.

2.5.1 DataKinds Language Extension

Through the use of the `DataKinds` language extension [20], all data types can be promoted to also be kinds and their constructors to be type constructors. When constructors are promoted to type constructors, they are prefixed with a `'`. This allows for more interesting and restrictive types.

Consider the example of a vector that also maintains its length. Peano numbers can be used to keep track of the length, which prevents a negative length for a vector. This is where numbers are defined as zero or a number `n` incremented by 1.

```

data Nat = Zero
         | Succ Nat

```

A vector type can now be defined that makes use of the promoted `Nat` kind.

```

data Vec :: Type → Nat → Type where
  Nil    :: Vec a 'Zero
  Cons :: a → Vec a n → Vec a ('Succ n)

```

The use of `DataKinds` can enforce stronger types. For example a function can now require that a specific length of vector is given as an argument. With standard lists, this would not be possible, which could result in run-time errors when the incorrect length is used. For example, getting the head of a list. Getting the head of an empty list an error will be thrown. For a vector, a `safeHead` function can be defined that will not type check if the vector is empty.

```

safeHead :: Vec a ('Succ n) → a
safeHead (Cons x _) = x

```

2.5.2 Singletons

DataKinds are useful for adding extra information back into the types, but how can information be recovered from the types? For example, could a function that gets the length of a vector be defined?

```
vecLength :: Vec a n → Nat
```

This is enabled through the use of singletons [4]. A singleton in Haskell is a type that has just one inhabitant. That is that there is only one possible value for each type. They are written in such a way that pattern matching reveals the type parameter. For example, the corresponding singleton instance for Nat is SNat. The structure for SNat closely flows that of Nat.

```
data SNat (n :: Nat) where
  SZero :: SNat 'Zero
  SSucc :: SNat n → SNat ('Succ n)
```

A function that fetches the length of a vector can now be definable.

```
vecLength2 :: Vec a n → SNat n
vecLength2 Nil      = SZero
vecLength2 (Cons x xs) = SSucc (vecLength2 xs)
```

2.5.3 Type Families

Now consider the possible scenario of appending two vectors together. How would the type signature look? This leads to the problem where two type-level Nats need to be added together. This is where Type Families [12] become useful, they allow for the definition of functions on types. Consider the example of appending two vectors together, this would require type-level arithmetic — adding the lengths together.

```
vecAppend :: Vec a n → Vec a m → Vec a (n :+ m)
```

This requires a `:+` type family that can add two Nats together.

```
type family (a :: Nat) :+ (b :: Nat) where
  a :+'Zero    = a
  a :+'Succ b = 'Succ (a :+ b)
```

2.5.4 Summary

Together these features allow for dependently typed programming in Haskell:

- DataKinds allow for values to be promoted to types
- Singletons allow types to be demoted to values
- Type Families can be used to define functions that manipulate types.

Chapter 3

The Language

3.1 Language Requirements

For the design of the language to be considered a success, several criteria need to be met:

- **Easy to build** — This is critical to the success of the language, if it is not simple to use then no one will want to use it. It is important that when defining an application the programmer has a clear understanding of how it will behave.
- **Type-safe** — A feature missing in many Python dataflow tools is the lack of type checking. This causes problems later on in the development process with more debugging and testing needed. The language should be type-safe to avoid any run-time errors occurring where types do not match.

3.2 Tasks

Tasks are the core construct in the language. They are responsible for reading from an input data source, completing some operation on the input, then finally writing to an output data sink. Tasks could take many different forms, for example they could be:

- A pure function - a function with type $a \rightarrow b$
- An external operation - interacting with some external system. For example, calling a terminal command.

A task could have a single input or multiple inputs, however, for now just a single input task will be considered. Multi-input tasks are explained further in Sub-Section [3.4.3](#)

3.2.1 Data Stores

Data stores are used to pass values between different tasks, this ensures that the input and output of tasks are closely controlled. A data store can be defined as a type class, with two methods `fetch` and `save`:

```
class DataStore f a where
  fetch :: f a → IO a
  save  :: f a → a → IO (f a)
```

A `DataStore` is typed, where `f` is the type of `DataStore` being used and `a` is the type of the value stored inside it. The aptly named methods describe their intended function: `fetch` will fetch a value from a `DataStore`, and `save` will save a value. The `fetch` method takes a `DataStore` as input and will return the value stores inside. However, the `save` method may not be as self explanatory, since it has an extra `f a` argument. This argument can be thought of as a pointer to a `DataStore`: it contains the information needed to save. For example, in the case of a file store it could be the file name.

By implementing as a type class, there can be many different implementations of a `DataStore`. The library comes with several pre-defined `DataStores`, such as a `VariableStore`. This can be thought of as an in memory storage between tasks.

```

data VariableStore a = Var a | Empty
instance DataStore VariableStore a where
  fetch (Var x) = return x
  save Empty x = return (Var x)

```

The `VariableStore` is the most basic example of a `DataStore`, a more complex example could be the aforementioned `FileStore`:

```

newtype FileStore a = FileStore String
instance DataStore FileStore String where
  fetch (FileStore fname) = readFile fname
  save (FileStore fname) x = writeFile fname x >> return (FileStore fname)
instance DataStore FileStore [String] where
  fetch (FileStore fname) = readFile fname >> return . lines
  save (FileStore fname) x = writeFile fname (unlines x) >> return (FileStore fname)

```

The `FileStore` is only defined to store two different types: `String` and `[String]`. If a user attempts to store anything other than these two types then a compiler error will be thrown, for example:

```

ghci> save (FileStore "test.txt") (123 :: Int)
> No instance for (DataStore FileStore Int) arising from a use of ‘save’

```

Although a small set of `DataStores` are included in the library, the user is also able to add new instances of the type class with their own `DataStores`. Some example expansions, could be supporting writing to a database table, or a Hadoop file system.

3.2.2 Task Constructor

A task’s type details the type of the input and outputs. It requires two arguments to the constructor, the function that will be invoked and an output `DataStore`. The constructor makes use of GADTs syntax so that constraints can be placed on the types used. It enforces that a `DataStore` must exist for the input and output types. This allows the task to make use of the `fetch` and `save` functions.

```

data Task (f :: Type → Type) (a :: Type) (g :: Type → Type) (b :: Type) where
  Task :: (DataSource f a, DataSource g b) ⇒ (f a → g b → IO (g b)) → g b → Task f a g b

```

When a `Task` is executed the stored function is executed, with the input being passed in as the first argument and the output “pointer” as the second argument. This returns an output `DataStore` that can be passed on to another `Task`

3.3 Chains

In a dataflow programming, one of the key aspects is the definition of dependencies between tasks in the flow. One possible approach to encoding this concept in the language is to make use of sequences of tasks — also referred to as chains. These chains compose tasks, based on their dependencies. For example a chain operator `>>>` can be defined:

```

(>>>) :: Task f a g b → Task g b h c → Task f a h c

```

3.3.1 Idea behind them

3.3.2 Joining Chains into a tree

PIDs

3.3.3 Examples

3.3.4 Benefits

3.3.5 Problems

3.4 Circuit

3.4.1 Idea

More likened to a way to construct a workflow by its corresponding dataflow graph.

3.4.2 Typing

3.4.3 Tasks with multiple inputs

Apply

3.4.4 Examples

Song aggregation

lhs2tex Build System

3.4.5 Benefits

3.4.6 Problems

where does mapC operator go?

Chapter 4

Process Network

4.1 Requirements

- Typesafe
- Parallel
- Competitive Speed
- Failure Tolerance

4.2 Scheduler & Typed Graph

4.2.1 Problems representing a typed graph as a AST

4.3 Kahn Process Network

4.3.1 Network Typeclass

Interaction with Network

4.3.2 Steps of translation

icataM

4.3.3 UUIDS

Why are they needed?

How are they added?

4.4 Failure in the Process Network

Why?

4.4.1 Maybe Monad

No error messages

4.4.2 Except Monad

based on Either

Chapter 5

Critical Evaluation

5.1 Runtime comparison

5.1.1 Lazy evaluation problems

5.2 Use of Library

Something about how DataStores prevent the need for `luigi.ExternalTask` at the beginning.

5.2.1 Other Libraries

How does it compare?

Luigi Object-orientated approach Python library

Funflow Uses arrows to compose flows sequentially.

5.3 Type safety

Chapter 6

Conclusion

Todo list

Change this to something meaningful	ix
Write an introduction (do near the end)	1
is this the right terminology?	8
where does mapC operator go?	13

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