flo: A visual, purely functional programming language

Elliott Lawrence

Overview

Flo is a visual, purely functional programming language. The syntax and semantics are heavily inspired by Haskell, whereas the visual editor is reminiscent of Apple's Quartz Composer. Some of flo's features include higher-order functions, parametric polymorphism, algebraic data types, non-strict semantics, strong static typing, and other features commonly shared by purely functional languages, presented in a visual manner that is intuitive and easy to learn.

The goals of this project were threefold:

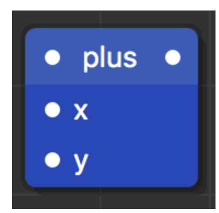
- Design the language
- Create a visual editor to write programs with
- Create the compiler

The subsequent sections in this paper explain details about the language and how the project was implemented.

Language Syntax and Features

Boxes

The most fundamental component of flo's visual syntax is boxes, which can represent functions, variables, literals, data constructors, and types. Boxes have a name, a (possibly empty) list of inputs on the left, and an output on the right. An example of the *plus* box, which adds two numbers x and y, is shown at right. The input directly to the left of the box name is used for type annotations (which will be explained later).



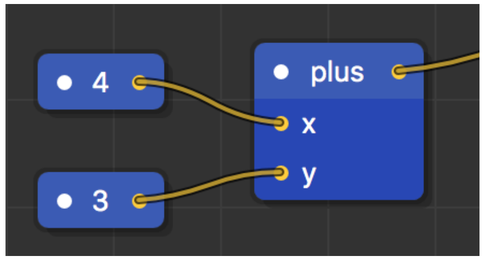
Inputs and Outputs

Boxes can have zero or more inputs, just like functions in other languages. Box inputs can be given names as a convenience for the programmer, but the names do not have to be consistent across multiple instances of the same box, since they are ignored by the compiler.

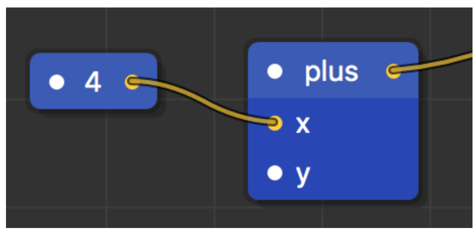
The output of a box represents the value the box returns. Since flo features higher-order functions, boxes can output other functions as well as simple values.

Cables

Cables are the second fundamental component of flo's visual syntax. They are used to connect the output of one box to the input of another, so in a sense they represent a flow of data. In the picture shown below, the numbers 4 and 3 are being input into *plus*. The result of the addition is carried off by the cable coming out the other end of *plus*.

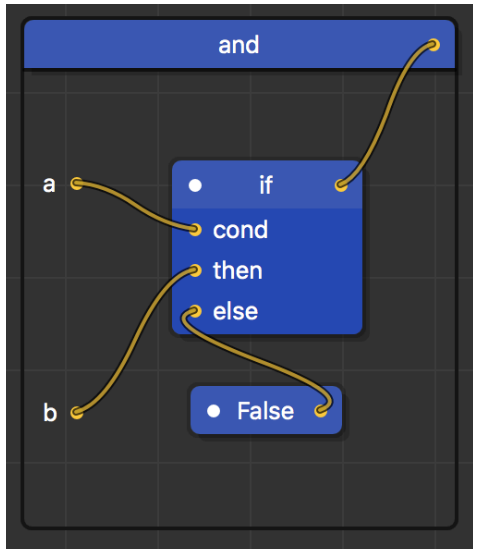


It is not necessary for all of a box's inputs to have cables attached to them. When this happens, the output is a partially applied function. So, in the example below, the output of *plus* is a new function which takes a single integer argument and adds 4 to it.

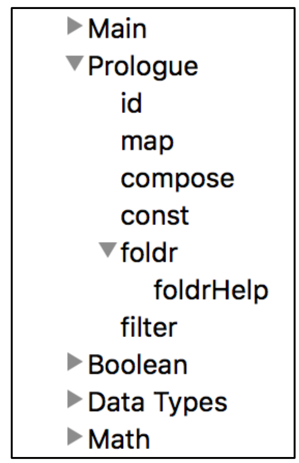


Box Definitions

When used in expressions, boxes appear as "black boxes" with unspecified implementations. The actual internals of a box are defined in its so-called box definition, which can be accessed from the list of box definitions on the left-hand side of the editor. The definition for the Boolean *and* function is shown below. Note that the output of *if* is being transmitted as the output of *and*.



Modules



A program consists of a list of modules, and in turn, a module consists of a list of box definitions. An example of a module structure for a program is shown at right. The topmost elements are modules, and all sub-elements are box definitions.

Modules provide a convenient way to organize box definitions, but they do not introduce any namespaces (as of now), as is the case with other languages. In particular, it is not allowed to have two box definitions with the same name in separate modules.

Local Definitions

Box definitions can also have their own local box definitions (which can be arbitrarily nested), whose scope is limited to the box definition they are defined in. These correspond directly to let expressions in functional languages. Local definitions can be added by clicking the “New Box Definition” button on the toolbar while viewing the parent box definition in the editor.

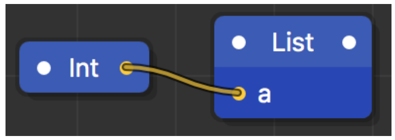
As an example, notice that in the picture on the right, *foldr* has a local box definition called *foldrHelp*.

Types

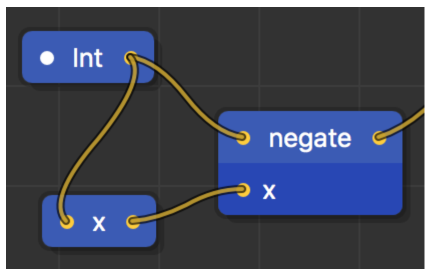
Boxes can also represent types. Types come in two forms:

- Simple types, such as *Int*, *Char*, and *Bool*
- Type constructors, which are essentially functions that take one or more types and return a new type. An example is *List* (shown below), which takes a type *a* and returns a new

type representing a list of *a* values. Type constructors do not have box definitions, nor do they perform any computations at runtime. They are only used to annotate types of expressions and are discarded by the compiler after type checking is complete.



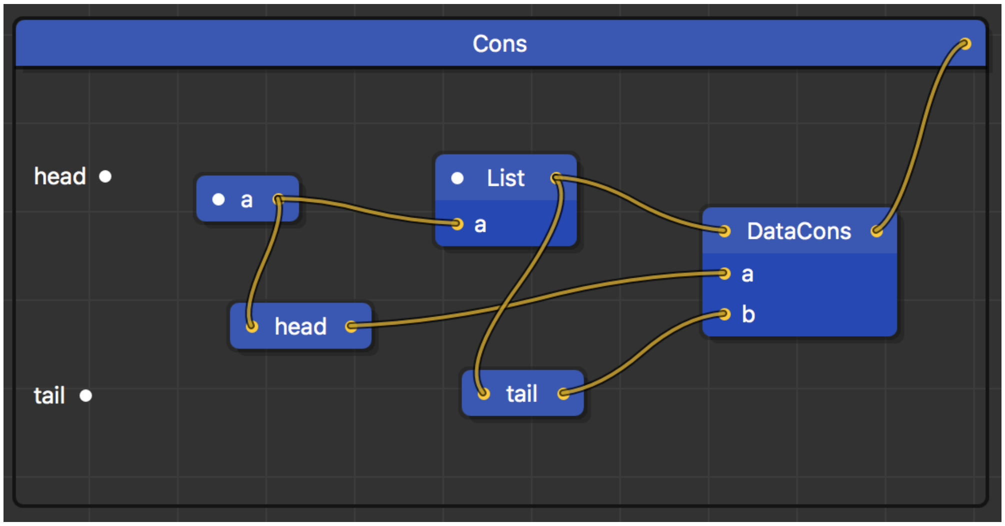
Type annotations can be added by connecting a type to the input directly to the left of a box's name. In the example below, *negate* is a function that takes an integer and multiplies it by -1. Both *x* and the output of *negate* are annotated as having type *Int*. Note that type annotations always correspond to the type of a box's output.



Flo features strong, static typing and uses the Hindley-Milner type system. This means that adding explicit type annotations is optional, since types for all expressions are inferred. Furthermore, the type checker will always deduce the most general type for any function or expression. One consequence of this is that a function that finds the length of a list, for example, can handle a list containing integers, or Boolean values, or any other type for that matter. Writing separate functions to handle different types is unnecessary if they have identical implementations.

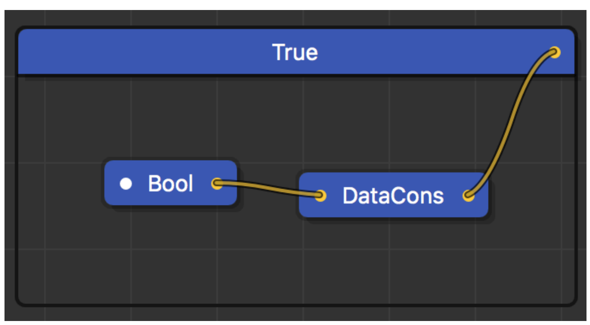
Data Constructors

Data constructors are essentially functions that have no implementation and just package up their components into a new data type. Data constructors are defined using the built-in function *DataCons*, which takes a variable number of components and returns a new data type having the same name as the surrounding box definition.



The definition for *Cons*, which represents an element of a linked list, is shown above. *Cons* has two components, the head and tail of a list. Notice that *head* is annotated as having type *a* (which is a type variable and could be anything), and *tail* is annotated as being a List of *a* values. In other words, a *Cons* cell is an element of a homogeneous list. The values *head* and *tail* are then input into *DataCons*, which packages up the components and returns the resulting *Cons* cell, which is also annotated as being a List of *a* values.

A data constructor need not have any components, as shown below in the definition for *True* (which is perhaps surprisingly not built into the language). In this case, *True* is simply defined as being a value of type *Bool*.



Literals

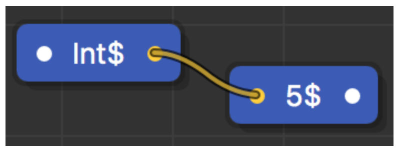
Literal values are represented as boxes which contain no inputs. The name of the box determines what type of literal it is:

- A name surrounded in double quotes is a *String*.
- A single character surrounded in single quotes is a *Char*.
- An integer is simply an *Int*.
- A number with a decimal point is a *Float*.

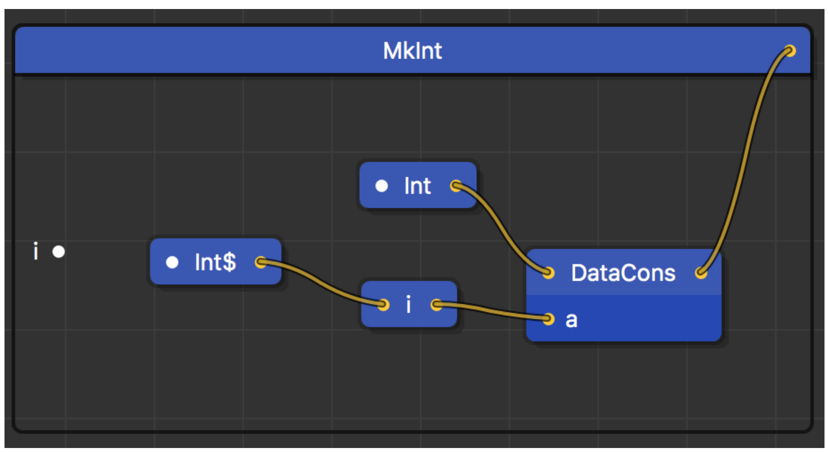
Boxed and Unboxed Values

For technical reasons, flo makes a distinction between boxed and unboxed values. Unboxed values are the "actual" values that can be manipulated by the instruction set of the machine, whereas boxed values consist of an unboxed value wrapped up by an application of an appropriate data constructor.

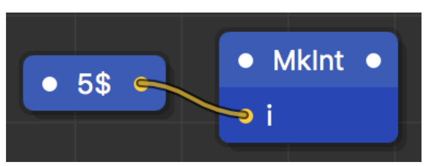
Unboxed values can be integers, floating point numbers, or strings. Unboxed literals are denoted by a box with no inputs, whose name is the literal value with a dollar sign appended to it. In the example below, *5$* is the unboxed integer 5, and it has type *Int$*.



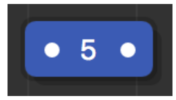
Boxed values are created by applying a data constructor to an unboxed value. Below is the definition for *MkInt*, which takes an unboxed *Int$* as an argument and packages it up into a data type of type *Int*. Note that while *Int$*, the type of unboxed integers, is built-in to the language, the type *Int* is not. It is defined by the code below as the type of whatever *MkInt* returns.



Now, *MkInt* can be used as follows to create the boxed integer 5:



As it turns out, functions that exhibit parametric polymorphism cannot accept unboxed values as arguments due to the special way they are handled by the compiler. For this reason, boxed values are intended to be used a majority of the time. In fact, the literal *5* is translated by the compiler into an application of *MkInt* to *5$*, so the code immediately above and below are equivalent.

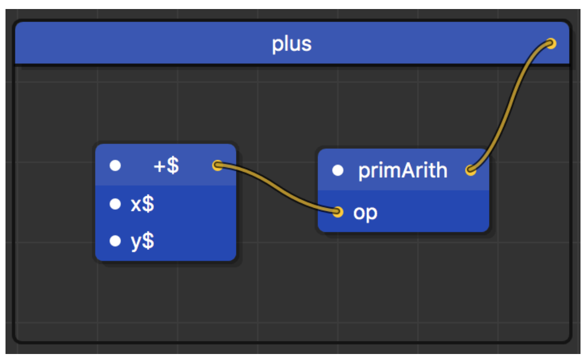


The literals described in the previous section are all boxed and are desugared by the compiler in a similar fashion.

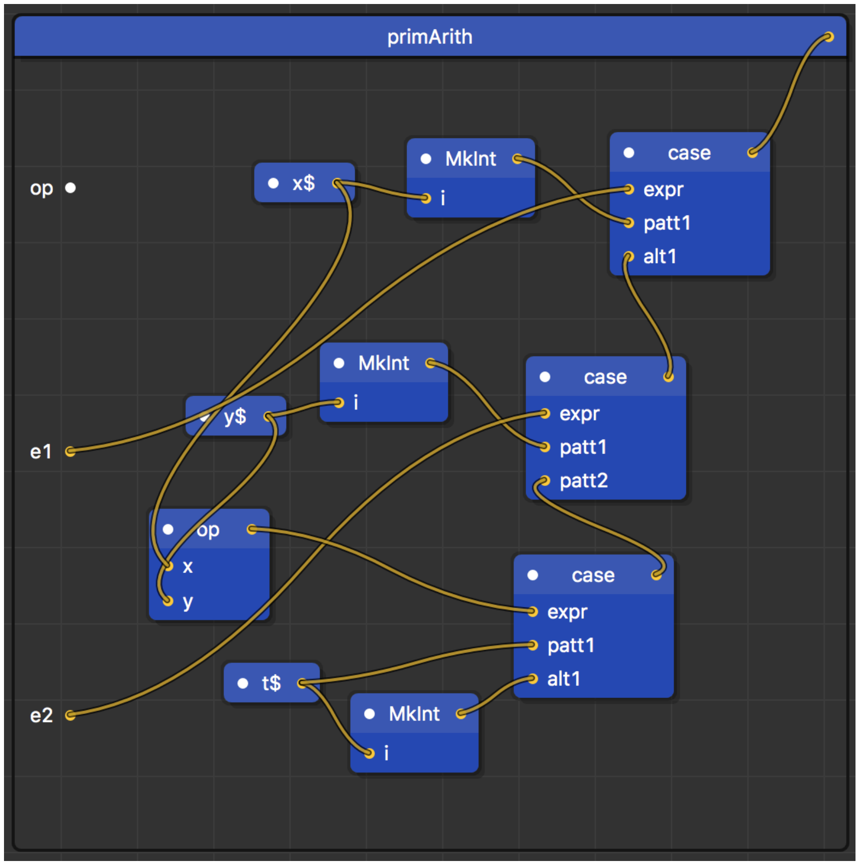
Primitive Functions

Certain arithmetic and Boolean operators are built-in to the language (they are specially recognized by the compiler) and operate over unboxed values. These so-called primitive functions are as follows: *+$, -$, *$, /$, %$, ==$,* and *<$*. Ignoring the dollar signs, these operators are the same as the operators in C.

Since unboxed values are not intended to be used very often, neither are these primitive functions. Instead, their non-primitive counterparts *plus*, *minus*, *multiply*, *divide*, etc. are much more useful since they operate over boxed values instead. The definition for *plus* is shown below.



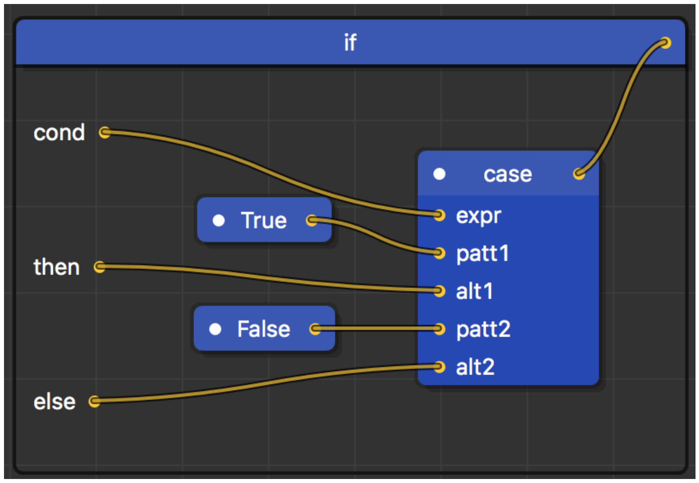
Plus, as well as the other arithmetic functions, is defined in terms of a more general function *primArith* (shown below), which takes a primitive operator and two boxed numbers as arguments. It unboxes the numbers, applies the operator to them, and then boxes up the result. The code below uses case expressions, which are explained later. Note that in the definition for *plus*, since *+$* does not have any cables connected to its inputs, the actual function *+$* is being passed as an argument to *primArith*.



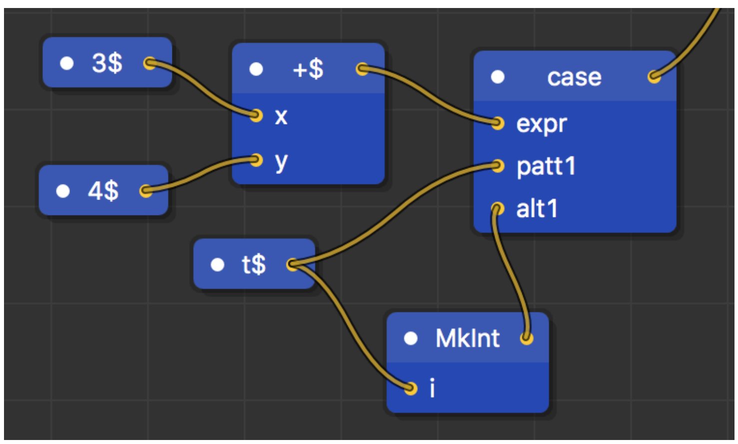
Case Expressions

Just as data constructors are used to package up their components, case expressions are used to extract them. The first input to the built-in *case* function is an expression to evaluate. The remaining inputs are pairs that consist of a particular data constructor and an expression to return if the original expression matches that constructor.

The definition for *if* is shown below. First, the condition is evaluated. If the condition turns out to be true, the *then* expression is returned. Otherwise, the *else* expression is returned.



Case expressions can also serve to evaluate primitive functions. In the example below, the expression 3 + 4 is evaluated. The result will not be a data constructor, but rather an unboxed integer, which is denoted with the name *t$*. This form of case expression is not intended to be used very often, but it is used in the definition of *primArith*, which was shown earlier.



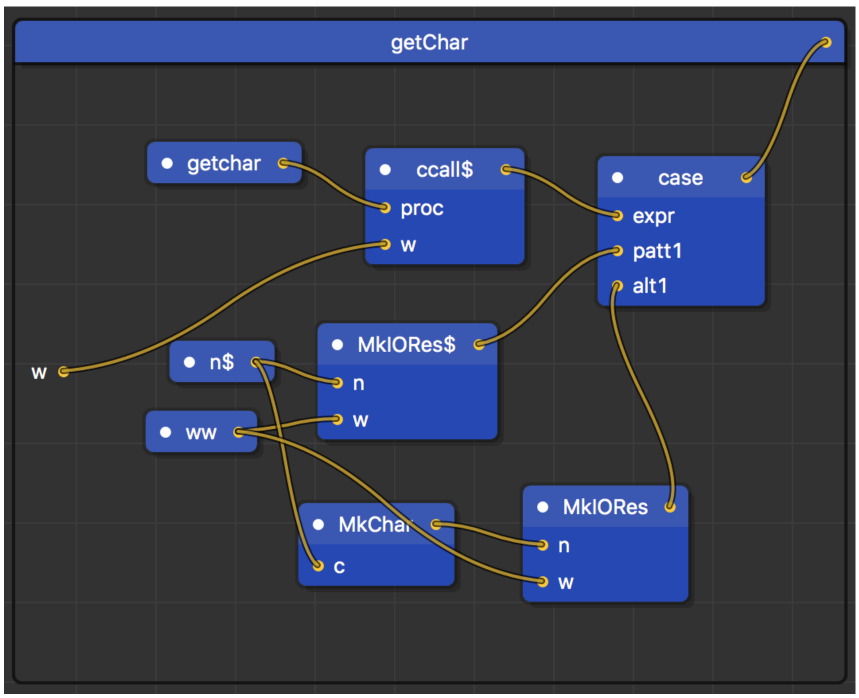
IO

Input and output are implemented with the same technique used by Haskell, namely, monadic IO. An IO action is a function that takes a value of type World and returns a data constructor *MkIORes*, whose components are the result of the computation and the new world value.

IO actions can be composed to form larger, more complicated IO actions. In fact, the *main* function (which is the entry point of every program) is a single, potentially huge IO action. The two most important combinators are *return*, which returns a regular value as an IO value, and *bind*, which executes two IO actions in sequence, with the output of the first action being used as input to the second action.

Some examples of IO actions are *getChar* and *putChar*, which get a character from standard input and print a character to the console, respectively. They are implemented using a special primitive function *ccall$,* which can call an arbitrary function in C. The parameters to *ccall$* are the literal name of the C function to call, the arguments to the function, and the current world value. The function is actually called by evaluating it with a case expression. The result of *ccall$* is an application of the *MkIORes$* data constructor, which contains the integer return value of the function that was called, along with the new world value.

The definition for *getChar* is shown below. First the C function *getchar* is called using *ccall$.* The result, *n$*, is an unboxed integer representing the ASCII value for the character that was just retrieved. This value is converted into a boxed character by sending it through the *MkChar* data constructor. The resulting character and world value are packaged up with *MkIORes*, which is the final return value for *getChar*.

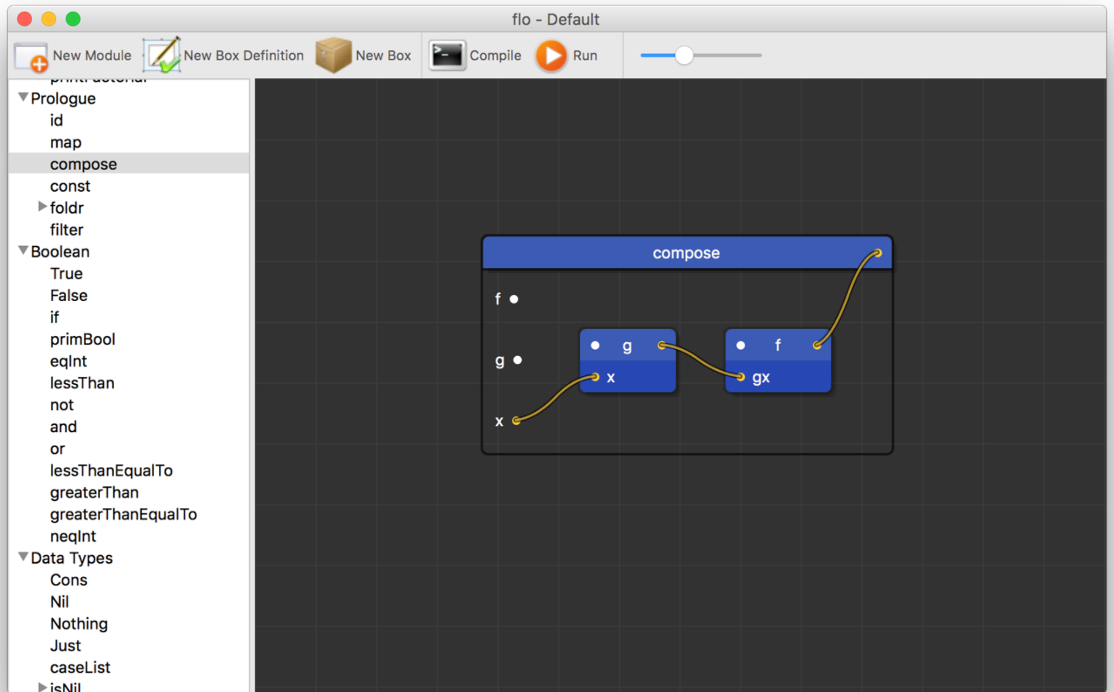


ccall$ is a useful but dangerous primitive. On the one hand, its power means that the entire IO subsystem can be defined within flo itself and extended without requiring changes to the compiler, but when used irresponsibly it can violate the functional purity. For this reason, it is not intended to be used outside of the IO subsystem, and even then there is a burden of proof on the programmer to show that any side effects do not affect the behavior of the rest of the program.

Editor Features

Editor Overview

A screenshot of the editor is shown below. The toolbar at the top has buttons for some commonly used actions. The tree view on the left-hand side displays a list of modules and box definitions. The center area is called the canvas, and it displays the box definition for the currently selected item in the tree view.



Default Library

Many of the functions mentioned in this paper and other common ones are included in the default library that is automatically loaded every time the flo editor is run. This includes standard list-processing functions, common data type definitions, arithmetic operators, and IO functions and combinators.

Toolbar

The toolbar contains the following items:

- The “New Module” button adds a new module to the program.
- The “New Box Definition” button creates a new box definition. If the currently selected item in the tree is a module, a box definition is added to the module, and if the currently selected item is a box definition, then a new local box definition is added.
- The “New Box” button adds a new box to the canvas.
- The “Compile” button compiles the program. The output of the compilation will be displayed in the console, including any errors or warnings.
- The “Run” button executes the program.

- The slider zooms in and out on the canvas.

Editing Boxes

Box names can be changed by double clicking their name and editing the text.

Inputs can be added by double clicking anywhere on the box where there isn't text. Double clicking an input's name and clearing the text will delete the input from the box.

Editor Implementation

MVC

The graphical editor is implemented in Java using the Standard Widget Toolkit (SWT), and the system architecture is based on the Model View Controller (MVC) pattern. The breakdown of the model, view, and controller are as follows:

- The controller consists of the Observer interface and Observable class, which handle events and event listeners. There are classes for various types of events that occur during editing, such as BoxAddedEvent, BoxDefinitionRemovedEvent, ModuleRenamedEvent, and so on.
- The model consists of the program that's being edited. Its representation is described in more detail later. The classes that make up the model primarily extend Observable.
- The view consists of the GUI components, which primarily implement Observer. These components listen for changes in the model (they "observe" the "observables") and are immediately updated to reflect those changes.

FloGraph

Various components of programs have a direct correspondence to classes in Java. For example, there are classes called Module, BoxDefinition, Cable, Input, and Output, which represent exactly what you'd expect. Programs are represented as instances of the class FloGraph, which is a composition of the classes just mentioned.

This underlying representation of a program is modified as the programmer makes changes in the editor. When the program is saved as a .flo file, the FloGraph object (and its components) is serialized into a JSON format. When a .flo file is opened, the editor parses the JSON data and constructs a FloGraph object out of it.

Tree

The tree view on the left-hand side of the editor stays current by simply attaching itself as a listener to the current FloGraph object. Any time a module or box definition is added, removed, or renamed, an event is triggered and the tree updates itself accordingly.

Canvas

The canvas has various methods for drawing different visual components, such as drawBox(), drawInput(), and drawCables(), and it also has methods for calculating sizes, such as calculateBoxSize().

The canvas also has listeners for various types of events, such as whenever the current box definition changes, whenever the user clicks and drags, and whenever the user double clicks. To keep track of what parts of the canvas the user can click on or interact with, the canvas has a list of “hotspots.” If the user double clicks on a certain type of hotspot, for example, an event associated with that hotspot is triggered, whereas if the user double clicks on an empty part of the grid, nothing happens since there is no hotspot there.

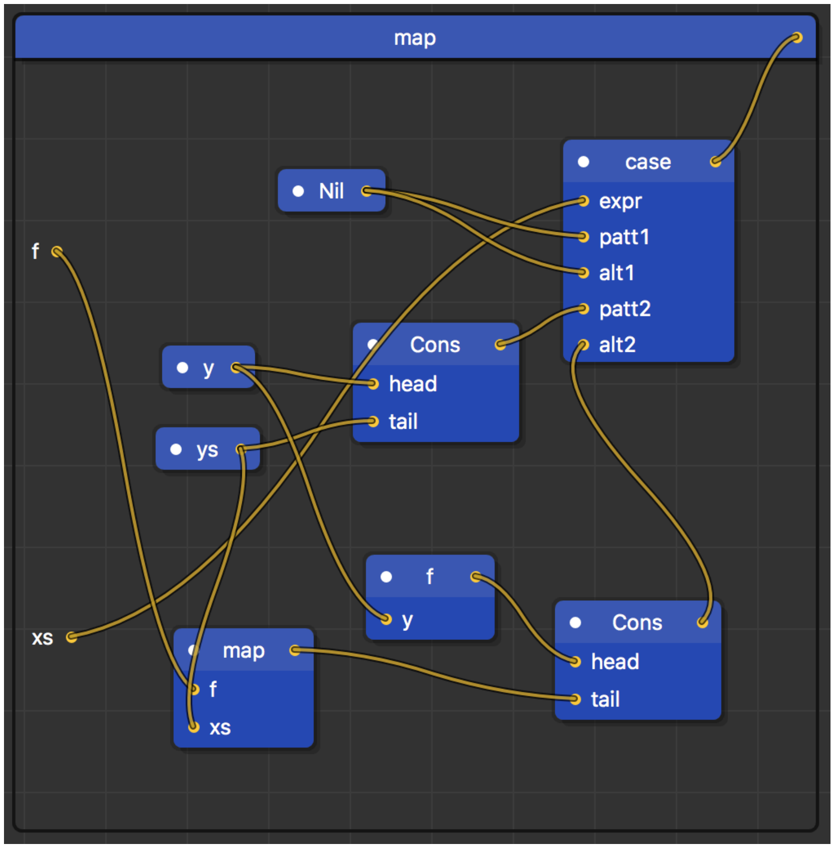
The Compiler

The Compilation Process

The compiler is written in Haskell and carries out a series of transformations to turn a .flo file into an executable. These steps are explained in greater detail in subsequent sections, but the general outline is as follows:

- A .flo file is parsed into the FloGraph data type.
- FloGraph is converted into the FloProgram data type.
- From here, the compiler can take either of two alternatives:
    - Compile to Haskell
        - FloProgram is converted to the HaskellProgram data type.
        - HaskellProgram is printed out as Haskell source code and the Haskell compiler is run.
    - Compile to C
        - Type checking is performed.
        - FloProgram is converted to the STG data type.
        - STG is converted into the AbstractC data type.
        - AbstractC is printed out as C source code and gcc is run, which generates the final executable.

To illustrate this process, I will show the output at each step for the compilation of the function *map*, which takes a function and a list and applies the function to each element of a list. The flo code for *map* is shown below.



.flo File Format

The compilation process begins with a .flo file, which is really just JSON. The snippet of the file that corresponds to *map* is shown below (parts of it have been omitted for brevity).

```
{
  "boxDefinitions": [],
  "boxInterface": {
    "name": "map",
    "inputs": [
      {
        "parentID": -1,
        "name": "f"
      },
      {
        "parentID": -1,
        "name": "xs"
      }
    ]
  },
  "boxes": [
    {
      "ID": 0,
      "boxInterface": {
        "name": "case",
        "inputs": [
          {
            "parentID": 0,
            "name": "expr"
          },
          {
            "parentID": 0,
            "name": "patt1"
          },
          {
            "parentID": 0,
            "name": "alt1"
          },
          {
            "parentID": 0,
            "name": "patt2"
          },
          {
            "parentID": 0,
            "name": "alt2"
          }
        ]
      },
      "location": {
        "x": -35,
        "y": 2
```

```
      }
    },
    {
      "ID": 1,
      "boxInterface": {
        "name": "Nil",
        "inputs": []
      },
      "location": {
        "x": -210,
        "y": 20
      }
    },
    {
      "ID": 2,
      "boxInterface": {
        "name": "Cons",
        "inputs": [
          {
            "parentID": 2,
            "name": "head"
          },
          {
            "parentID": 2,
            "name": "tail"
          }
        ]
      },
      "location": {
        "x": -164,
        "y": 114
      }
    },
    {
      "ID": 3,
      "boxInterface": {
        "name": "y",
        "inputs": []
      },
      "location": {
        "x": -281,
        "y": 128
      }
    }
  ],
  "cables": [
    {
      "input": {
        "parentID": 0,
        "name": "expr"
      },
      "output": {
        "parentID": -1,
        "endInputName": "xs"
      }
    },
    {
      "input": {
        "parentID": -1,
        "name": "endInput"
      },
      "output": {
        "parentID": 0,
        "endInputName": "endInput"
      }
    },
    {
      "input": {
        "parentID": 0,
        "name": "patt1"
      },
      "output": {
        "parentID": 1,
        "endInputName": "endInput"
      }
    },
    {
      "input": {
        "parentID": 0,
        "name": "alt1"
      },
      "output": {
        "parentID": 1,
        "endInputName": "endInput"
      }
    }
  ],
  "offset": {
    "x": 103,
    "y": -175
  }
}
```


FloGraph

First, the compiler loads up a .flo file and parses it into the FloGraph data type. This data type is similar to the FloGraph class in the editor, with a few minor differences. Irrelevant information such as box locations on the canvas is discarded, but otherwise, no major transformations are made. This data type can be printed out, an example of which is shown below for *map*.

```
Box: map
Inputs: Input: f, -1
        Input: xs, -1
```

```
Boxes: 0: Box: case
          Inputs: Input: expr, 0
                  Input: patt1, 0
                  Input: alt1, 0
                  Input: patt2, 0
                  Input: alt2, 0
       1: Box: Nil
          Inputs:
       2: Box: Cons
          Inputs: Input: head, 2
                  Input: tail, 2
       3: Box: y
          Inputs:
       4: Box: ys
          Inputs:
       5: Box: Cons
          Inputs: Input: head, 5
                  Input: tail, 5
       6: Box: f
          Inputs: Input: y, 6
       7: Box: map
          Inputs: Input: f, 7
                  Input: xs, 7
Cables: Output: -1 :-: Input: expr, 0
        Output: 0 :-: Input: endInput, -1
        Output: 1 :-: Input: patt1, 0
        Output: 1 :-: Input: alt1, 0
        Output: 3 :-: Input: head, 2
        Output: 2 :-: Input: patt2, 0
        Output: 4 :-: Input: tail, 2
        Output: 5 :-: Input: alt2, 0
        Output: 3 :-: Input: y, 6
        Output: 6 :-: Input: head, 5
        Output: 7 :-: Input: tail, 5
        Output: -1 :-: Input: f, 7
        Output: 4 :-: Input: xs, 7
Definitions:
```

FloProgram

Next, the FloGraph is converted into the FloProgram data type. Whereas FloGraph represents a program in terms of its visual components (boxes, cables, etc.), a FloProgram represents a program in terms of functions and expressions (in other words, it represents the abstract syntax tree of the program). The translation is relatively straightforward given the interpretation of the visual syntax in previous sections. Essentially, to convert a box definition to a function definition, start from the output and follow the cable until a box is reached. The box will be translated to a certain type of expression depending on what it is (*case, DataCons*, a primitive function, or a regular box). In order to create this expression, the box's inputs must also be converted into expressions, so the cables attached to those inputs are followed, and the process continues until all the boxes and cables in the box definition have been traversed.

Once again, the FloProgram data type can be printed out, and the output for *map* is shown below. Here I arranged for the output to look like Haskell code.

```
map f xs = case xs of Nil -> Nil
                      Cons y ys -> Cons (f y) (map f ys)
```

HaskellProgram

The first alternative the compiler can take is to convert everything to Haskell. I implemented this route for testing purposes before I had finished the "proper" compiler, but this method of compilation can be useful in its own right since it allows programs written in flo to use any Haskell library functions.

The translation consists of converting the FloProgram data type into the HaskellProgram data type, which represents the abstract syntax tree for Haskell code. This conversion is extremely simple, as there are only minor differences between the two data types. A HaskellProgram can then be printed out to generate Haskell source code, and the Haskell compiler is run to generate the final executable.

In the case of *map,* the Haskell code that is generated is identical to the code that was shown in the previous section.

Type Checking

The second alternative the compiler can take is to convert everything into C, which is the "official" compilation process.

The next step in this process is type checking. The type checker takes an abstract syntax tree and attempts to infer types for all expressions in the program, and the algorithm it uses is called Algorithm W. The type checker is capable of inferring the most general type of an expression (allowing for parametric polymorphism), and it will throw an error if a particular expression is inferred to have two incompatible types. As of now, the type checker is only partially implemented, so it is not currently being run. So far, the type checker is capable of inferring types for arbitrary expressions, but it cannot yet handle type checking for an entire program, which may include user-defined data types.

STG

There are many ways to implement lazy functional languages, but the particular implementation I chose is called the Spineless Tagless G-machine (STG), which is described in a paper by Simon Peyton Jones (1992). The STG machine is also what the Haskell compiler uses (or at least, a modified, more complicated version of it).

The next step in the compilation is to convert the FloProgram data type into STG, which is a simple functional language designed specifically for the STG machine. The STG language has only the following types of expressions:

- Function applications, which are self explanatory. One of the restrictions that STG imposes is that function arguments have to be either simple variables or literal values, so nested function calls are not allowed.
- Let expressions, which allow expressions to have their own local variable or function definitions. Let expressions are a ubiquitous construct in functional languages.
- Case expressions, which evaluate data constructors or primitive values and switch to an appropriate code segment based on the result. These are analogous to switch statements in imperative languages.
- Data constructor applications, which are similar to function applications. The same restriction as before applies, in that all data constructor arguments must be simple variables or literals. In addition, data constructors cannot be partially applied; they must accept all their arguments at once (flo does not have this restriction).
- Primitive (built-in) operations, such as *+$, -$, <$, ==$,* etc. As with data constructors, these operators also cannot be partially applied.
- Literal values, such as 3, 6.7, etc.

The general transformation of FloProgram into STG consists of the following steps:

- If a data constructor or built-in operation is partially applied, a new function binding is created which accepts any remaining arguments and applies them to the constructor or operator. For example, using Haskell syntax, the partial application `Cons x` is converted into `f xs = Cons x xs`.
- Function arguments which are not simple variables or literals are given a name, which is defined in a newly-introduced let expression that surrounds the function application. For example, the function application `f (g x)` would be converted into: `let {y = g x} in f y`.
- Function bindings are annotated with a list of variables that appear free in their definition. For example, in the function definition `f x = x + y`, y would be a free variable since it is not an argument to the function. The concept of free variables in this sense is borrowed from the lambda calculus.
- Variables which are bound by a let expression are given a name that is unique within the entire program. This is necessary because two different let expressions could define the variable x, which would cause a name clash when code is finally generated.

The STG code for *map* is shown below. Note that for each function definition there are two sets of curly braces. The first one contains the list of free variables, whereas the second contains the list of function arguments (so the arguments to *map* are *f* and *xs*). This code looks somewhat similar to Haskell, but it is clearly more verbose due to the previously discussed restrictions that STG imposes.

```
map = {} \n {f,xs} -> case xs of
                        Nil {} -> Nil {}
                        Cons {y,ys} -> let t1 = {f,y} \u {} -> f {y}
                                           t2 = {f,ys} \u {} -> map {f,ys}
                                       in Cons {t1,t2}
```

AbstractC

The final step is to convert STG code into the AbstractC data type, which represents the abstract syntax tree for C. This data type can be printed out to generate C code, at which point gcc can be run to compile the code into the final executable.

C is used as the target language primarily because it is portable (gcc can be run on many different platforms), and it is treated by the STG implementation essentially as a high-level assembler. The stack and heap are mapped to explicit arrays, and function arguments are passed via the stack instead of the usual mechanism used by C. Global variables are used to simulate different registers, such as the stack and heap pointers.

The Tiny Interpreter

The execution of the program is controlled by a tiny interpreter in main(), shown below. The variable *cont* is initialized to point to the function main_entry(), which is the entry point of every program. In general, *cont* points to the function to call next. In the while loop, this function is called, and it returns the address of the next function to call, which is assigned to cont. This process repeats until *cont* is assigned the address of main(), at which point execution stops.

```
int main() {
    function f_main = (function)main;
    function cont = main_entry;
    while (cont != f_main) {
        cont = (function)(*cont)();
    }
    return 0;
}
```

The Heap

The heap is a collection of closures, which are contiguous blocks of memory that contain information about different functions, variables, and data constructors in the program. The first word of every closure is the info pointer, which points to the C function that is generated for that particular language construct (more about code generation later). Followed by this is a series of pointers which point to either the free variables that are used by the function or variable, or the fields of the data constructor. Finally, there is a series of non-pointer words, which represent literal values (such as integers). Note that a boxed integer is represented as a closure in the heap containing a field whose value is the unboxed integer.

The Stacks

There is one array allocated for stack space, but it actually consists of two stacks that grow towards each other. The A stack is used for pointers, whereas the B stack is used for unboxed values as well as return addresses (described later).

Code Generation

This section describes the code that is generated for each construct in the STG language.

- Top-level function definitions: First, the body of the function is compiled. Then, a closure is created for the function, but instead of it being allocated in the heap, it is statically allocated as a C array.
- Function applications: First, the arguments to the function are pushed onto the appropriate stacks (A stack if the argument is a pointer, B stack if the argument is an unboxed value). The stack pointers are then adjusted, and the address of the function to call is returned.
- Let expressions: Each of the bindings in a let expression is compiled into a separate C function in the same way that top-level function definitions are compiled. The actual code for a let expression consists of the following: First, space is allocated in the heap to create a closure for each of the let bindings. The closures are then filled in with the addresses of their free variables, as well as any unboxed values they may need. Followed by this is the code for the body of the let expression.
- Case expressions: Case expressions consist of an expression to evaluate and a series of alternative code paths which could possibly be taken.
    - The alternatives are compiled into a separate C function containing a switch statement. Each data constructor in the program is given a unique integer ID, and this ID will be assigned to the global variable RTag when the case expression has been evaluated. The switch statement selects a case based on the value of RTag, and each case contains the code that is compiled for that particular alternative. For case expressions that evaluate primitive operations, instead of switching on RTag, they switch on the result of the operation, which is stored in the global variable IntReg if the result is an integer, for example.
    - The code generated for the actual case expression is as follows: First, any variables in the heap used by the alternatives are saved on the stacks (since a variable's offset from the heap pointer may change by an unpredictable amount after an expression is evaluated). Next, the address of the function containing the code for the alternatives (the so-called return address) is pushed onto the B stack. Followed by this is the code generated for the expression that is to be scrutinized.
- Data constructors: Each data constructor is compiled into its own C function that simply pops off a return address from the B stack and jumps to it.
- Primitive operations: First, the appropriate operation is performed, and the result is saved in a global variable. For example, if 3 + 4 is being evaluated, the result, 7, would be stored in the global variable IntReg. A return address is then popped off the B stack, and control continues at this address.
- Literal values: The literal value is stored in an appropriate global variable, such as IntReg if the literal is an integer. As with primitive operations, a return address is then popped off the B stack and jumped to.

- ccall$: As mentioned before, ccall$ is the only extra thing the compiler needs to handle in order for input and output to work. It is translated very simply into a direct call to a function in C. The result of this function call is stored in the data constructor MkIORes$. For the function *getchar*, for example, the value that is returned is the ASCII code for the character that was retrieved.

The final code that is generated for *map* is shown below, with map_entry() being the main entry point. Note that map_t1_entry() and map_t2_entry() correspond to the let-bound variables *t1* and *t2* in the STG code. The function alt1() contains the code for the alternatives, one for an empty list (RTag = 4), and one for a non-empty list (RTag = 3).

```
pointer map_entry() {
    /* Save local environment */
    /* Push return address */
    SpB[1] = (pointer)(alt1);
    SpB = SpB + 1;
    /* Evaluate body */
    pointer a0 = SpA[0];           /* Grab f into a local variable */
    pointer a1 = SpA[1];           /* Grab xs into a local variable */
    Node = (pointer*)(a1);         /* Grab xs into Node */
    ENTER((pointer**)Node);        /* Enter xs */
}

pointer map_t1_entry() {
    SpA[-1] = (pointer)(Node[2]);  /* Push y onto stack */
    SpA = SpA - 1;                 /* Adjust SpA */
    Node = (pointer*)(Node[1]);    /* Grab f into Node */
    ENTER((pointer**)Node);        /* Enter f */
}

pointer map_t2_entry() {
    SpA[-1] = (pointer)(Node[2]);  /* Push ys onto stack */
    SpA[-2] = (pointer)(Node[1]);  /* Push f onto stack */
    SpA = SpA - 2;                 /* Adjust SpA */
    Node = (pointer*)(map_closure); /* Grab map into Node */
    ENTER((pointer**)Node);        /* Enter map */
}

pointer alt1() {
    switch (RTag) {
        case 4:
        {
            Hp = Hp - 1;                   /* Allocate some heap */
            if (Hp < HLimit) {
                printf("Error: Out of heap space\n");
                exit(0);
            }
            /* Fill in closure for Nil */
            Hp[0] = (pointer)(Nil_info);
            SpA = SpA + 2;                 /* Adjust SpA */
            Node = (pointer*)(Hp);         /* Grab Nil into Node */
            ENTER((pointer**)Node);        /* Enter Nil */
            break;
        }
        case 3:
        {
```

```
            Hp = Hp - 6;                    /* Allocate some heap */
            if (Hp < HLimit) {
                printf("Error: Out of heap space\n");
                exit(0);
            }
            /* Fill in closure for map_t1 */
            Hp[0] = (pointer)(map_t1_info);
            Hp[1] = (pointer)(SpA[0]);     /* f */
            Hp[2] = (pointer)(Node[1]);    /* y */
            /* Fill in closure for map_t2 */
            Hp[3] = (pointer)(map_t2_info);
            Hp[4] = (pointer)(SpA[0]);     /* f */
            Hp[5] = (pointer)(Node[2]);    /* ys */
            /* Evaluate body */
            Hp = Hp - 3;                    /* Allocate some heap */
            if (Hp < HLimit) {
                printf("Error: Out of heap space\n");
                exit(0);
            }
            /* Fill in closure for Cons */
            Hp[0] = (pointer)(Cons_info);
            Hp[1] = (pointer)(Hp + 3);     /* map_t1 */
            Hp[2] = (pointer)(Hp + 6);     /* map_t2 */
            SpA = SpA + 2;                 /* Adjust SpA */
            Node = (pointer*)(Hp);         /* Grab Cons into Node */
            ENTER((pointer**)Node);        /* Enter Cons */
            break;
        }
    }
    JUMP(main);
}
```