Extend Language Final Report

Ishaan Kolluri	Jared Samet	Nigel Schuster	Kevin Ye
isk2108	jss2272	ns3158	ky2294
Project Manager	Language Guru	System Architect	Tester

December 19, 2016

Contents

1. Introduction

Extend is a declarative programming language meant to support spreadsheet-like functionality. It contains features such as side-effect free values, immutability, and automatic formula adjustments relative to rows and columns. Extend is compiled to the LLVM (Low Level Virtual Machine) intermediate representation, which in turn is reduced to machine assembly. Extend takes inspiration from software such as Microsoft Excel, which allows users to link several formulae on dependent groups of data together, but takes this technology a step further by allowing users to encapsulate such calculations as functions.

1.1 Inspiration & Use Cases

Inspiration

The design goal of our language was to be "a spreadsheet you can compile". Extend was conceptualized to address the limitations that prevented the spreadsheet environment from evolving into a compiled, flexible programming language. To create this, there were three main things that needed to be changed about the way interactive spreadsheets work:

- The language needs reusable functions as opposed to having to copy & paste a block of cells.
- Cell ranges need to be created with dynamic runtime-determined dimensions.
- Cells need to be able to contain composite values in addition to single numbers or strings.

With these changes in mind, we attempted to keep the semantics as similar as possible to traditional spreadsheet programs; this meant implementing a dynamically typed language that is tolerant of potential errors in its input data. Extend degrades gracefully in the presence of potential data errors.

Spreadsheet applications cannot be 'run' on different sets of input data. Extend was conceptualized as a standalone application that removes the manual element of entering new inputs. In building this language, our mission was to bring the best of spreadsheets and computation into one product.

Complex Calculations Across Many Inputs

Extend is spiritually closer in behavior to Microsoft Excel than other conventional programming languages. In one line of code, a single formula can be assigned to to all of the cells in a `range`, one of Extend's data types.

Flexibility

Extend allows the dimensions of ranges to be determined dynamically at runtime, and handles most type errors by degrading gracefully instead of crashing the program. The standard library that Extend delivers includes a subset of the functions that are built into conventional spreadsheet applications.

2. Language Usage Tutorial

This will cover the configuration of the user's environment and the usage of Extend's features.

2.1 Setup

The Extend compiler requires that the OCaml Language and LLVM be installed on the host machine. Development was done in a virtual machine running the 64-bit Ubuntu operating system. In order to quickly get Extend up and running, please use this virtual machine, which has been provided as part of the course.

After booting up the virtual machine, clone the Extend git repository:

```
1     git clone https://github.com/ExtendLang/Extend.git
```

2.2 Compiling and Running Extend Code

To build the Extend compiler, the first steps are the following.

```
1 cd Extend/
2 make
```

If this does not successfully build, run `eval ‘opam config env‘`, which should configure the environment to use OPAM packages. Alternatively, add this command to your bash profile.

After running `make`, you should see a `main.byte` file. To compile and run an Extend program, we have provided a shell script to simplify the process for the user:

```
1   ./compile.sh example_source_file.xtnd
```

This should produce an `out` file. Running `./out` should successfully execute the program.

2.3 Illustrating the Benefits of Extend

Spreadsheet applications require the use of manual input in order to apply the same calculation to a different set of data. Extend aims to tackle this problem by offering portability. Below is an example of a spreadsheet user calculating the unit vector of a column vector:

	A	B	C	D	E
1	1	1			0.050965
2	2	4			0.101929
3	3	9			0.152894
4	4	16			0.203859
5	5	25			0.254824
6	6	36			0.305788
7	7	49			0.356753
8	8	64			0.407718
9	9	81			0.458682
10	10	100			0.509647
11		=A!*A!	385	19.62142	=A!/D11
12			=SUM(B1:B10)	=C11^0.5	

The Excel user must manually input the data, and additionally make space for the intermediate steps of the calculation. As the data becomes more diverse and the problem becomes more complicated, more work is required. Below is the equivalent function in Extend, written to work on any column vector that is passed in:

```
normalize_column_vector([m,1] arg) {
  [m,1] squared_lengths := #arg * #arg, normalized := #arg / vector_norm;
  vector_norm := sqrt(sum(squared_lengths));
  return normalized;
}
```

Another particularly interesting example is concatenating a row of strings of variable length with a common delimiter. This in an entirely manual operation for the spreadsheet user; a step-by-step attempt is shown below.

	A	B	C	D	E	F
1	hello	world	hello again	,	<- comma, space	
2						
3	hello,	<- This fails.				
4	=CONCATENATE(A1:C1, D1)					
5						
6	hello	hello, world	hello, world, hello again			
7	=A1	=CONCATENATE(A1,D1,B1)	=CONCATENATE(B6,D1,C1)			

Performing a delimiter 'join' like the above can be performed in a simple program in Extend without knowing the size of the row.

```
main(args){
  bar := {"Hello", "Goodbye", "Hello Again"};
  str := ", ";
  return foo(bar, str);\\ prints "Hello, Goodbye, Hello Again"
}

foo([1,n] colrange, str){
  [1,n] baz;
  baz[0,0] = #colrange;
  baz[0,1:] = baz[0,[-1]] + str + colrange[0,[0]];
  return print_endline(baz[0,-1]);
}
```

As evidenced above by simple examples, Extend offers flexibility that is significantly harder to achieve with conventional spreadsheet applications. As the nature of the data grows in complexity and variety, Extend's value increases.

2.4 Writing Extend Code - The Basics

Extend code can be written in a file that contains the conventional `.xtnd` extension. It consists of optional import statements and global variables, and an optional set of functions. Runnable Extend programs must contain a `main` function, and other functions can be written into the program as well.

Below is a short tour of the features of Extend. More detail can be found in the next chapter - the Language Reference Manual.

Functions

Functions are commonplace in Extend. They are declared with the syntax `function_name([optional_dimensions] function_arguments){...}`. Below is the syntax of the `main` function, which is needed to run Extend code, within a simple Extend program.

```
1  main(args){
2      return 0;
3  }
```

The return type of a function is a value that can be of any type or dimensions. **Ranges** will be discussed in a later section of this chapter. A function is composed of variable declarations and formula assignments and concludes with the **return** statement. Note that the **return** statement is always the last statement in the function.

Function Parameters

Function parameters consist of zero or more ranges, signed with an optional dimension. If the arguments have been written with dimensions, those dimensions will be verified at runtime.

```
1      foo([m,n] arg){
2        return m * n; \\ m and n initialized through arg1
3      }
4
5      bar([1,1] arg){
6        return 0; \\ 1 by 1 ranges should be primitive data types. If arg is not, a
             runtime error will be thrown
7      }
```

Adjusting to Extend's Declarative Nature

The biggest difference between Extend and most traditional programming languages is that the concept of an imperative statement does not exist. An Extend function consists solely of variable declarations, formula assignments, and a return expression. When a function is called, its `return` expression is evaluated, along with the values of any variables that the return expression depends on. In a traditional imperative language, the order of operations is determined explicitly by the developer; in Extend, the order is determined implicitly by the desired result.

The following file compiles and prints successfully.

```
1    main(args){
2      foo := "Hello World!";     // Combined var declaration and formula assignment
3      return print_endline(foo); // Return expression is a call to print_endline().
4    }
```

However, the file below is not a legal Extend program:

```
main(args){
  foo := "Hello World!"; // OK
  print_endline(foo);    // Not OK
  return foo;
}
```

As illustrated, Extend only evaluates what is needed to produce the value required by `return`. Any non-essential declarations or formula assignments will be ignored by the program. If the user attempts to write statements like `print_endline("Hello")` by itself, the program will not compile.

Data Types

Extend has three primitive data types: Numbers, Strings, and `empty`; and one composite type, Range. An example of each is shown below.

```
myNumber    := 5;
myString    := "Hello World";
myEmpty     := empty;
my2x3Range  := {3, 4, "five"; "a", "b", "c"};
```

Variables

In Extend, `variables` are composed of cells to which formulas are assigned. The first time (and only the first time!) an individual cell is referenced by an expression, its value is calculated according to its assigned formula. A cell's value is not calculated if the cell is never referred to, and is never recalculated; all cell values are immutable. A cell's value can be any of Extend's types, and different cells of a single variable can have different types.

```
[1,2] foo; // Declares a variable with 1 row and 2 columns (2 cells total)
[1,3] bar := 4; // Declares a variable with 1 row and 3 columns and
                // assigns the literal value 4 as the formula for each cell
[1,2] baz;                 // Declares a 1x2 variable baz
baz[0,0] = "first";        // Assigns literal "first" as the formula for the
baz[0,1] = 1 + 1;          // 1st cell and the expression 1+1 for the 2nd cell
life := 6, universe := 7;  // Declares 1x1 variables life and universe
answer := life * universe; // Declares a 1x1 variable the_answer and assigns
                           // the formula life * universe to its sole cell
[1,10] half_and_half;      // Declares a 1x10 variable half_and_half
half_and_half[0,0:5] = "milk";    // Assigns "milk" to the first five cells
half_and_half[0,5:10] = "cream";  // and "cream" to the second five cells
```

Note that we declare a variable and assign a formula to all of its cells in a single line with `:=`. If the variable has already been declared, a formula must be assigned using `=` instead of `:=`. As illustrated in this example, a single formula can be assigned to multiple cells of a variable with the slice syntax. The converse is not true: multiple formulas applying to a single cell will cause a runtime error. The contents of the slice, as well as the dimensions of the variable, can be any expression that evaluates to a number, not just a literal number. For example, this code snippet assigns the dimensions based on the `howBig()` function and the "left" and "right" formulas based on the `breakpoint()` function:

```
breakpoint() {
  return 7;
}
howBig() {
  return 11;
}
```

```
7     foo_func() {
8       [1,howBig()] foo;
9       foo[0, :breakpoint()] = "left";
10      foo[0, breakpoint():-1] = "right";
11      foo[0, -1] = "last";
12      return foo;
13    }
```

This example also illustrates that the start (or end) index of a slice can be omitted if the developer wants the formula to apply from the beginning (or to the end) of the dimension, and that negative numbers can be used in a slice to count backwards from the end. As with all values in Extend, the dimensions of a variable, and the slices to which a formula applies, are immutable. The first time a variable is referred to (directly or indirectly) by the return expression, its dimensions and the formula assignment slices are computed; from that point on, they never change. In the example above, the howBig() function is invoked once, but the breakpoint() function is actually called twice: once for the "left" formula, and once for the "right" formula.

Variables vs. Ranges

A variable is not a data type; it is a collection of one or more cells with assigned formulas. A range is a value, which is internally implemented as a pointer to a subset of a variable's cells. A range is always composed of more than one value; a variable may have a single cell. The variable "backing" a range may not have been explicitly defined by the developer; for example, range literals are implemented using an anonymous variable.

Operators

Extend includes a comprehensive set of operators. Each category is listed in order of precedence. A more detailed explanation of each operator can be found in the Language Reference Manual.

Arithmetic Operators

- Unary Operations: `-`
- Binary Operations: `**`, `*`, `/`, `%`, `+`, `-`

Bitwise Operators

- Unary Operations: `~`
- Binary Operations: `«`, `»`, `&`, `|`, `^`

Boolean Operators

- Unary Operations: `!`
- Binary Operations: `==`, `!=`, `<`, `>`, `<=`, `>=`, `&&`, `||`

String Concatenation

Note that the `+` symbol can be used to perform concatenation between two strings.

```
1     "Hello " + "World\n"
```

The size and typeof operators

Extend offers a `typeof(expr)` operator, which takes an expression and returns Number, String, Range, or Empty (as a string). It also has the `size(expr)` operator, which returns the dimensions of its argument as a 1 x 2 range.

Conditionals

There are two types of conditional expressions: the if-then-else (ternary) conditional and a `switch` expression.

If-Then-Else

The two equivalent ways to write the ternary expression are as follows:

C/Java style: `condition ? expr_if_true : expr_if_false`

Spreadsheet style: `if(conditional, expr_if_true, expr_if_false)`

The Switch Expression

Below is an example of the switch expression used in a function:

```
1       odd_or_even(foo){
2         return switch(foo % 2) {
3           case 0: "Even";
4           case 1: "Odd";
5           default: "Not an integer";
6         };
7       }
```

In the example above, the `switch` expression used foo

Range Slicing & Selection

Python-style array-slicing syntax can be applied to ranges, which will return a subrange based on either absolute or relative indexing. All indices are zero-based.

```
1       foo[0,2] \\ The cell in the first row, third column
2       foo[0,:] \\ The range of cells in the first row
3       foo[0,[1]] \\ The range in the column that is 1 column right of the left-hand-
            side cell.
4       foo[,] \\ Cell in first row, first column if 1 by 1. If not, then relative first
             row and relative first column
```

More examples and detail can be found in the next chapter.

The Hash Operator

A common case for ranges in Excel is to perform calculations on specific cells. For example, `foo[,]` is commonly used to retrieve the cell that is being calculated on. Since this is a popular use case, the `#` operator will perform the same functionality.

Application on Ranges

Extend, in the vein of spreadsheets, allows the programmer to apply functions cell-wise on a range. Using the # operator, we can perform cell-wise multiplication across two ranges.

```
1       foo([m,n] arg1, [m.n] arg2){
2         [m,n] bar := #arg1 * #arg2; \\ Multiplies the cell in arg1 with the
              corresponding cell in arg2.
3         return bar;
4       }
```

This is an incredibly powerful aspect of Extend. Make sure to study it well!

Range Attribute Functions

Extend has the `row()` and `column()` functions, which respectively return the row and column of the cell that is being calculated at that point in time. There is also a `size(expr)` function, which returns a 1 by 2 range; the first cell contains the number of rows, and the second cell contains the number of columns.

Cell Evaluation, Side Effects, and Precedence Expressions

As mentioned before, a cell's value is calculated at most once. It is evaluated when it is the only cell selected from a variable, or when a selection containing the cell is assigned as a range to another cell. In general, the language is designed so you don't have to think about this! However, in the case of formulas that call functions with side effects, it's important to understand the behavior. When necessary, a precedence expression (using the `->` operator) can be used to force the evaluation of one expression before another. A precedence expression calculates the first expression, discards the result, and evaluates to the second expression. The following example should help clarify how cell evaluation is performed:

```
1   main(args) {
2     foo := print_endline("Once") -> 2;
3     bar := foo + foo;
4     return print_endline(bar);
5   }
```

This program prints "Once" and then prints 4. Before calling print_endline, Extend calculates the value of bar, which in turn requires the value of foo (twice). The first time foo's value is calculated, print_endline() is called with the argument "Once", and then foo evaluates to the constant 2. The second time that foo's value is required to calculate bar, it's already available: it is 2. Therefore, print_endline("Once") is not called a second time.

Import Statements

In Extend, you can import other Extend files at the top of your program via relative directory path. The use case is below:

```
1     import "../programs/helloworld.xtnd"
```

2.5 Standard Library Functions

Extend offers an assortment of standard library functions. Extend imports `stdlib.xtnd`, which has aggregated all the standard library functions for the user's disposal.

While their usage will be covered in more length in the Language Reference Manual, here are some of the more useful standard library functions to remember.

Basic Functions

The toString() Function

The `toString()` function takes a 1 by 1 range and renders its value as a string. This will return one of the primitive data types.

```
1       return "Hello " + toString(14); \\ "Hello 14"
```

Math Functions

Borrowing from C's standard library math functions, Extend offers: `sin, cos, tan, acos, asin, atan, sinh, cosh, tanh, exp, log, log10, sqrt, ceil, fabs` and `floor`.

```
1       main(args){
2         bar := sqrt(16);
3         return write(STDOUT, toString(bar)) -> 0; \\ Prints 4 to stdout
4       }
```

File I/O

Extend has `open, close, read, and write` functions to interact with files. Usage is as follows:

```
1     main(args){
2       return write(STDOUT, read(open("test_file.txt", "r"),5)) -> 0; \\ Writes 5
            characters from test_file.txt to stdout
3     }
```

Plotting

Extend also offers the ability to export plots to a PNG file with the `plot` function.

```
1     TODO: Demonstrate usage here.
```

3. Language Reference Manual

3.1 Introduction to Extend

Extend is a domain-specific programming language used to designate ranges of cells as reusable functions. It is a dynamically-typed, statically-scoped, declarative language that uses lazy evaluation to carry out computations. Once computed, all values are immutable. In order to offer the best performance, Extend compiles down to LLVM.

Extend's syntax is meant to provide clear punctuation and easily understandable cell range access specifications, while borrowing elements from languages with C-style syntax for ease of development. Despite these syntactic similarities, the semantics of an Extend program have more in common with a spreadsheet such as Microsoft Excel than imperative languages such as C, Java or Python.

3.2 Structure of an Extend Program

An Extend program consists of one or more source files. A source file can contain any number of import directives, function definitions, global variable declarations, and external library declarations, in any order.

Import Statements

Import statements in Extend are written with `import`, followed by the name of a file in double quotes, and terminated with a semicolon. The syntax is as follows:

```
1 import "string.xtnd";
```

Extend imports act like `#include` in C, except that multiple imports of the same file are ignored. The imports are all aggregated into a single namespace.

Function Definitions

Function definitions comprise the bulk of an Extend program. In short, a function consists of a set of variable declarations, formula assignments, and a return expression. Each variable consists of cells; the values of each cell are, if necessary, calculated according to formulas which each apply to a specified subset of the cells. Each cell value, once calculated, is immutable. A couple examples follow for context; functions are described in detail in section 3.5.

```
1 isNumber(x) {
2   return typeof(x) == "Number";
3 }
4
5 sum_column([m,1] rng) {
6   /* Returns the sum of the values in the column, skipping any values that are non-
        numeric */
7   [m,1] running_sum;
8   running_sum[0,0] = #rng;
```

```
  running_sum[1:,0] = running_sum[[-1],] + (isNumber(#rng) ? #rng : 0);
  return running_sum[-1];
}
```

Global Variables

In essence, global variable declarations function as constants in Extend. They are written with the keyword `global`, followed by a variable declaration in the combined variable declaration and assignment format described in section 3.5. As with local variables, the cell values of a global variable, once computed, are immutable. A few examples follow:

```
global pi := 3.14159265359;
global num_points := 24;
global [num_points,1]
  circle_x_vals := cos(2 * pi * row() / num_points),
  circle_y_vals := sin(2 * pi * row() / num_points);
```

External Library Declarations

An external library is declared with the `extern` keyword, followed by the name of an object file in double quotes, followed by a semicolon-delimited list of external function declarations enclosed by curly braces. A library declaration informs the compiler of the functions' names and signatures and instructs the compiler to link the object file when producing an executable. An external function declared as `foo` will call an appropriately written C function `extend_foo`. An example follows:

```
extern "mylib.o" {
  foo(arg1, arg2);
  bar();
}
```

This declaration would cause the compiler to link `mylib.o` and would make the C functions `extend_foo` and `extend_bar` available to Extend programs as `foo` and `bar` respectively. The required signature and format of the external functions is specified precisely in section 3.5.

`main` function

When a compiled Extend program is executed, the `main` function is evaluated. All computations necessary to calculate the return value of the function are performed, after which the program terminates. The `main` function must be a function of a single argument, conventionally denoted `args`, which is guaranteed to be a 1-by-n range containing the command line arguments.

Scoping and Namespace

For functions and for global variables, there is a single namespace that is shared between all files composing an Extend program, and they are visible throughout the entire program. Functions declared in external libraries share this namespace as well. For a local variable, the scope is the entire body of the function in which it is defined. Functions may declare local variables sharing a name with a global variable; inside that function, the name will refer to the local variable.

```
global x := "I'm a global";

foo() {
  y := x; // Scope of x is entire function
  x := "In here I'm a local";
  return y; // Returns "In here I'm a local"
```

```
}

bar(x) {
  return x; // Parameters mask globals; returns argument
}

baz() {
  return x; // Returns "I'm a global"
}
```

3.3 Types and Literals

Extend has three primitive data types, **Number**, **String**, and **Empty**, and one composite type, **Range**.

Primitive Data Types

A **Number** is an immutable primitive value corresponding to a double-precision 64-bit binary format IEEE 754 value. Numbers can be written in an Extend source file as either integer or floating point constants; both are represented internally as floating-point values. There is no separate type representing an integer.

A **String** is a immutable primitive value that is internally represented a C-style null-terminated byte array corresponding to ASCII values. A String can be written in an Extend source file as a sequence of characters enclosed in double quotes, with the usual escaping conventions. Extend does not allow for slicing of strings to access specific characters; access to the contents of a string will only be available through standard library functions.

The **Empty** type can be written as the keyword `empty`, and serves a similar function to `NULL` in SQL; it represents the absence of a value.

Primitive Data Types	**Examples**
Number	`42 or -5 or 2.71828 or 314159e-5`
String	`"Hello, World!\n" or "foo" or ""`
Empty	`empty`

Ranges

Extend has one composite type, **Range**. A range borrows conceptually from spreadsheets; it is a group of cells with two dimensions, described as rows and columns. Each cell is assigned a formula that either evaluates to a Number, a String, `empty`, or another Range. Cell formulas are described in detail in section 3.5. A range can either be declared as described in section 3.5 or with a range literal expression. Ranges can be nested arbitrarily deeply and can be used to represent (immutable) lists, matrices, or more complicated data structures.

Range Literals

A range literal is a semicolon-delimited list of rows, enclosed in curly brackets. Each row is a comma-delimited list of numbers, strings, or range literals. A few examples follow:

```
legal_ranges() {
  r1 := {"Don't"; "Panic"}; // two rows, one column
  r2 := {"Don't", "Think", "Twice"}; // one row, three columns
  r3 := {1,2,3;4,5,6;7,8,9}; // three rows, three columns
  r4 := {"Hello";0,1,2,3,4}; // two rows, five columns
```

```
6     r5 := {{{{{1}}}}}; // one row, one column
7     r7 := {-1.5,-2.5,{-2,"nested"},-3.5}; // one row, four columns
8     return
9       print_endline(r1) ->print_endline(r2) ->print_endline(r3) ->
10      print_endline(r4) -> print_endline(r5) -> print_endline(r7);
11  }
12
13  main(args) {
14    return legal_ranges();
15  }
```

3.4 Expressions

Expressions in Extend allow for arithmetic and boolean operations, function calls, conditional branching, extraction of contents of other variables, string concatenation, and determination of the location of the cell containing the expression. The sections for boolean and conditional operators refer to truthy and falsey values: the `Number` 0 is the only falsey value; all other values are truthy. As `empty` represents the absence of a value, it is neither truthy nor falsey.

Arithmetic Operators

The arithmetic operators listed below take one or two expressions and return a number, if both expressions are Numbers, or `empty` otherwise. Operators grouped within the same inner box have the same level of precedence, and are listed from highest precedence to lowest precedence. All of the binary operators are infix operators, and, with the exception of exponentiation, are left-associative. Exponentiation, bitwise negation, and unary negation are right-associative. All of the unary operators are prefix operators. The bitwise operators round their operands to the nearest signed 32-bit integer (rounding half to even) before performing the operation and evaluate to a Number.

Operator	Description	Definition
`~`	`Bitwise NOT`	Performs a bitwise negation on the binary representation of an expression.
`-`	`Unary negation`	A simple negative sign to negate expressions.
`**`	`Power`	Returns the first expression raised to the power of the second expression
`*`	`Multiplication`	Multiplies two expressions
`/`	`Division`	Divides first expression by second.
`%`	`Modulo`	Finds the remainder by dividing the expression on the left side of the modulo by the right side expression.
`«`	`Left Shift`	Performs a bitwise left shift on the binary representation of an expression.
`»`	`Right Shift`	Performs a sign-propagating bitwise right shift on the binary representation of an expression.
`&`	`Bitwise AND`	Performs a bitwise AND between two expressions.
`+`	`Addition`	Adds two expressions together.
`-`	`Subtraction`	Subtracts second expression from first.
`|`	`Bitwise OR`	Performs a bitwise OR between two expressions.
`^`	`Bitwise XOR`	Performs a bitwise exclusive OR between two expressions.

```
1 easy() {
2   return 3 - -3 ** 2 %5; //-1
3 }
4 g_eazy() {
5   return (((1 << 2 | 1) << 2) | 1) << 1; //42
6 }
```

Boolean Operators

These operators take one or two expressions and evaluate to `empty`, 0 or 1. Operators grouped within the same inner box have the same level of precedence and are listed from highest precedence to lowest precedence. All of these operators besides logical negation are infix, left-associative operators. The logical AND and OR operators feature short-circuit evaluation. Logical NOT is a prefix, right-associative operator. Besides logical NOT, all boolean operators have lower precedence than all arithmetic operators. For Strings, the boolean operators <, <=, >, and >= implement case-sensitive lexicographic comparison.

Operator	Description	Definition
`!`	`Logical NOT`	Evaluates to 0 or 1 given a truthy or falsey value respectively. `!empty` evaluates to `empty`. It has equal precedence with and unary minus.
`==`	`Equals`	Always evaluates to 0 if the two expressions have different types. If both expressions are primitive values, evaluates to 1 if they have the same type and the same value, or 0 otherwise. If both expressions are ranges, evaluates to 1 if the two ranges have the same dimensions and each cell of the first expression == the corresponding cell of the second expression. `empty` == `empty` evaluates to 1. Strings are compared by value.
`!=`	`Not equals`	`x != y` is equivalent to `!(x == y)`.
`<`	`Less than`	If the expressions are both Numbers or both Strings and the first expression is less than the second, evaluates to 1. If the expressions are both Numbers or both Strings and the first expression is greater than or equal to the second, evaluates to 0. Otherwise, evaluates to `empty`.
`>`	`Greater than`	Equivalent rules about typing as for `<`.
`<=`	`Less than or equal to`	Equivalent rules about typing as for `<`.
`>=`	`Greater than or equal to`	Equivalent rules about typing as for `<`.
`&&`	`Short-circuit Logical AND`	If the first expression is falsey or `empty`, evaluates to 0 or `empty` respectively. Otherwise, if the second expression is truthy, falsey, or `empty`, evaluates to 1, 0, or `empty` respectively.
`||`	`Short-circuit Logical OR`	If the first expression is truthy or `empty`, evaluates to 1 or `empty` respectively. Otherwise, if the second expression is truthy, falsey, or `empty`, evaluates to 1, 0, or `empty` respectively.

```
somethings_false() {
  return !1 != !1 || 4 <= 3;
}
somethings_empty() {
  return empty || empty <= !3 || 5 > 3;
}
somethings_true() {
  return 6 > 2 && !(1 == !1);
}
```

Conditional Expressions

There are two types of conditional expressions: a simple ternary if-then-else expression and a `switch` expression which can represent more complex logic.

Ternary Expressions

A ternary expression, written either as `cond-expr ? expr-if-true : expr-if-false` or, equivalently, `if(cond-expr, expr-if-true, expr-if-false)` evaluates to `expr-if-true` if `cond-expr` is truthy, or `expr-if-false` if `cond-expr` is falsey. If `cond-expr` is `empty`, the expression evaluates to `empty`. Both expr-if-true and expr-if-false are mandatory. `expr-if-true` is only evaluated if `cond-expr` is truthy, and `expr-if-false` is only evaluated if `cond-expr` is falsey. If `cond-expr` is `empty`, neither expression is evaluated. The ternary operator ? : has the lowest precedence level of all operators.

Switch Expressions

A `switch` expression takes a optional condition, and a list of cases and expressions that the overall expression should evaluate to if the case applies. In the event that multiple cases are true, the expression of the first matching case encountered will be evaluated. An example is provided below:

```
switch_example(foo) {
  return switch (foo) {
    case 2: "foo is 2";
    case 3,4: "foo is 3 or 4";
    default: "none of the above";
  };
}

alternate_format(foo) {
  return switch {
    case foo == 2:
      "foo is 2";
    case foo == 3, foo == 4:
      "foo is 3 or 4";
    default:
      "none of the above";
  };
}
```

The format for a `switch` statement is the keyword `switch`, optionally followed by pair of parentheses containing an expression `switch-expr`, followed by a list of case clauses enclosed in curly braces and delimited by semicolons. A case clause consists of the keyword `case` followed by a comma-separated list of expressions `case-expr1 [, case-expr2, [...]]`, a colon, and an expression `match-expr`, or the keyword `default`, a colon, and an expression `default-expr`. If `switch-expr` is omitted, the `switch` expression evaluates to the `match-expr` for the first case where one of the `case-expr`s is truthy, or `default-expr` if none of the `case-expr`s apply. If `switch-expr` is present, the `switch` expression evaluates to the `match-expr` for the first case where one of the `case-expr`s is equal (with equality defined as for the `==` operator) to `switch-expr`, or `default-expr` if none of the `case-expr`s apply.

The `switch` expression can be used to compactly represent what in most imperative languages would require a long string such as `if (cond1) {...} else if (cond2) {...}`. The `switch` operator is internally converted to an equivalent (possibly nested) ternary expression; as a result, it features short-circuit evaluation throughout.

Additional Operators

There are four additional operators available to determine the size and type of other expressions. In addition, the infix `+` operator is overloaded to perform string concatenation.

Operator	Description	Definition
`size(expr)`	`Dimensions`	Evaluates to a Range consisting of one row and two columns; the first cell contains the number of rows of `expr` and the second contains the number of columns. If `expr` is a Number, a String, or Empty, both cells will contain 1.
`typeof(expr)`	`Value Type`	Evaluates to "Number", "String", "Range", or "Empty".
`row()`	`Row Location`	No arguments; returns the row of the cell that is being calculated
`column()`	`Column Location`	No arguments; returns the column of the cell that is being calculated
`+`	`String concatenation`	"Hello, " + "World!\n" == "Hello, World!\n"

Given `[5,5]foo`, then `foo[1,4] = row() * 2 + col()` will evaluate to 6.

Function Calls

A function expression consists of an identifier and an optional list of expressions enclosed in parentheses and separated by commas. The value of the expression is the result of applying the function to the arguments passed in as expressions. The arguments are evaluated from left to right before the function is called. For more detail, see section 3.5.

Range Expressions

Range expressions are used to select part or all of a range. A range expression consists of a bare identifier, a bare range literal, or an expression and a selector. If a range expression has exactly 1 row and 1 column, the value of the expression is the value of the single cell of the range. If it has more than 1 row or more than 1 column, the value of the expression is the selected range. If the range has zero or fewer rows or zero or fewer columns, the value of the expression is `empty`. If a range expression with a selector would access a row index or column index greater than the number of rows or columns of the range, or a negative row or column index, the value of the expression is `empty`.

Slices

A slice consists of an optional integer literal or expression `start`, a colon, and an optional integer literal or expression `end`, or a single integer literal or expression `index`. If `start` is omitted, it defaults to 0. If `end` is omitted, it defaults to the length of the dimension. A single `index` with no colon is equivalent to `index:index+1`. Enclosing `start` or `end` in square brackets is equivalent to the expression `row() + start` or `row() + end`, for a row slice, or `column() + start` or `column() + end` for a column slice. The slice includes `start` and excludes `end`, so the length of a slice is `end - start`. A negative value is interpreted as the length of the dimension minus the value. As mentioned above, the value of a range that is not 1 by 1 is a range, but the value of a 1 by 1 range is essentially dereferenced to the result of the cell formula.

Selections

A selection expression consists of an expression and a pair of slices separated by a comma and enclosed in square brackets, i.e. `[row_slice, column_slice]`. If one of the dimensions of the range has length 1, the comma and the slice for that dimension can be omitted. If the comma is present but a slice is omitted, that slice defaults to `[0]` for a slice corresponding to a dimension of length greater than one, or `0` for a slice corresponding to a dimension of length one.

Corresponding Cell

A very common selection to make is the cell in the "corresponding location" of a different variable. Since this case is so common, `#var` is syntactic sugar for `var[,]`. As a result, if `var` has more than column and more than one row, `#var` is equivalent to `var[row(),column()]`. If `var` has multiple rows and one column, it is equivalent to `var[row(),0]`. If `var` has one row and multiple columns, it is equivalent to `var[0,column()]`; and if `var` has one row and one column, it is equal to `var[0,0]`.

Selection Examples

```
selection_examples() {
  foo[0,2] /* This evaluates to the cell value in the first row and third column. */
  foo[0,:] /* Evaluates to the range of cells in the first row of foo. */
  foo[:,2] /* Evaluates to the range of cells in the third column of foo. */
  foo[:,[1]] /* The internal brackets denote RELATIVE notation.
  In this case, 1 column right of the column of the left-hand-side cell. */

  foo[3,] /* Equivalent to foo[3,[0]] if foo has more than one column
  or foo[3,0] if foo has one column */

  foo[5:, 7:] /* All cells starting from the 6th row and 8th column to the bottom
      right */

  foo[[1]:[2], 0:[7]]
  /* Selects the rows between the 1st and 2nd row after LHS row, and
     all the columns up to the 7th column to the right of the LHS column */

  /* In this example, each cell of bar would be equal to the cell
   * in foo in the equivalent location plus 1. */
  [5,5] foo;
  [5,5] bar := #foo + 1; // #foo = foo[[0],[0]]

  /* In this example, bar would be a 3x5 range where in each row,
   * the value in bar is equal to the value in foo in the same column.
   * In other words, each row of bar would be a copy of foo. */
  [1,5] foo; // foo has 1 row, 5 columns
  [3,5] bar := #foo; // #foo = foo[0,[0]]

  /* In this example, the values of baz would be
   * 11, 12, 13 in the first row;
   * 21, 22, 23 in the second row;
   * 31, 32, 33 in the third row. */
  foo := {1,2,3}; // 1 row, 3 columns
  bar := {10;20;30}; // 3 rows, 1 column
  [3,3] baz := #foo + #bar; // Equivalent to foo[0,[0]] + bar[[0],0]
}
```

Precedence Expressions

A precedence expression is used to force the evaluation of one expression before another, when that order of operation is required for functions with side-effects. It consists of an expression `prec-expr`, the precedence operator `->`, and an expression `succ-expr`. The value of the expression is `succ-expr`, but the value of `prec-expr` will be calculated first and the result ignored. All functions written purely in Extend are free of side effects. However, some of the external functions provided by the standard library, such as for file I/O and plotting, do have side effects. The precedence operator has the second-lowest grammatical precedence of all operators, higher only than the ternary operator.

3.5 Functions

The bulk of an Extend program consists of functions. Although Extend has some features, such as immutability and lazy evaluation, that are inspired by functional languages, its functions are not *first class objects*. By default, the standard library is automatically compiled and linked with a program, but there are no functions built into the language itself.

Format

As in most programming languages, the header of the function declares the parameters it accepts. The body of the function consists of an optional set of variable declarations and formula assignments, which can occur in any order, and a return statement, which must be the last statement in the function body. All variable declarations and formula assignments, in addition to the return statement, must be terminated by a semicolon. This very simple function returns whatever value is passed into it:

```
1 foo(arg) {
2   return arg;
3 }
```

Variable Declarations

A variable declaration associates an identifier with a range of cells of the specified dimensions, which are listed in square brackets before the identifier. For convenience, if the square brackets and dimensions are omitted, the identifier will be associated with a single cell. In addition, multiple identifiers, separated by commas, can be listed after the dimensions; all of these identifiers will be separate ranges, but with equal dimension sizes. The dimensions can be specified as any valid expression that evaluates to a Number, which will be rounded to the nearest signed 32-bit integer. If either dimension is zero or negative, or if the expression does not evaluate to a Number, a runtime error causing the program to halt will occur.

```
1 [2, 5] foo; // Declares foo as a range with 2 rows and 5 columns
2 [m, n] bar; // Declares bar as a range with m rows and n columns
3 [3, 3] ham, eggs, spam; // Declares ham, eggs and spam as distinct 3x3 ranges
4 baz; // Declares baz as a single cell
```

Formula Assignment

A formula assignment assigns an expression to a subset of the cells of a variable. Unlike most imperative languages, this expression is not immediately evaluated, but is instead only evaluated if and when it is needed to calculate the return value of the function. A formula assignment consists of an identifier, an optional pair of slices enclosed in square brackets specifying the subset of the cells that the assignment applies to, an `=`, and an expression, followed by a semicolon. As with the expressions specifying the dimensions of a range, these slices specifying the cell subset can contain arbitrary expressions, as long as the expression taken as a

whole evaluates to a Number, which will be rounded to the nearest signed 32-bit integer. Negative numbers are legal in these slices, and correspond to (dimension length + value).

```
[5, 2] foo, bar, baz; // Declares foo, bar, and baz as distinct 5x2 ranges
foo[0,0] = 42; // Assigns the expression 42 to the first cell of the first row of foo
foo[0,1] = foo[0,0] * 2; // Assigns (foo[0,0] * 2) to the 2nd cell of the 1st row of
    foo
bar = 3.14159; // Assigns pi to every cell of every row of bar
baz[1:-1,0:1] = 2.71828; // Assigns e to cells (1,0) through (3,1), inclusive, of baz

/* The next line assigns foo[[-1],0] + 2 to every cell in
   both columns of foo, besides the first row */
foo[1:,:] = foo[[-1],0] + 2;
```

The last line of the source snippet above demonstrates the idiomatic Extend way of simulating an imperative language's loop; foo[4,0] would evaluate to 42+2+2+2+2 = 50 and foo[4,1] would evaluate to (42*2)+2+2+2+2 = 92.

Combined Variable Declaration and Formula Assignment

For convenience, a variable declaration and a formula assignment to all cells of that variable can be combined on a single line by inserting a `:=` and an expression after the identifier. Multiple variables and assignments, separated by commas, can be declared on a single line as well. All global variables must be defined using the combined declaration and formula assignment syntax.

```
/* Creates two 2x2 ranges; every cell of foo evaluates to 1 and every cell of
   bar evaluates to 2. */
[2,2] foo := 1, bar := 2;
```

Formula Assignment Errors

If the developer writes code in such a way that more than one formula applies to a cell, a runtime error will occur if the cell's value is required to compute the return expression. If there is no formula assigned to a cell, the cell will evaluate to `empty`.

Parameter Declarations

Parameters can be declared with or without dimensions. If dimensions are declared, they can either be specified as integer literals or as identifiers. If a dimension is specified as an integer literal, the program will verify the dimension of the argument before beginning to evaluate the return expression; if it does not match, a runtime error will occur causing the program to halt. If it is specified as an identifier, that variable will contain the dimension size and will be available inside the function body. If the same identifier is repeated in the function declaration, the program will verify that every parameter dimension with that identifier has equal dimension size; if they differ, a runtime error will occur causing the program to halt. A few examples follow:

```
number_of_cells([m,n] arg) {
  return m*n; // m and n are initialized with the dimensions of arg
}

die_unless_primitive([1,1] arg) {
  return 0; // If arg is not a primitive value, a runtime error will occur
}

num_cells_if_column_vector([m,1] arg) {
  // If arg has one column, return number of cells; otherwise runtime error
```

```
  return m;
}

die_unless_square([m,m] arg) {
  return 0; // Runtime error if number of rows != number of columns
}

num_cells_if_same_size([m,n] arg1, [m,n] arg2) {
  // If arguments are the same size, return # of cells, otherwise runtime error
  return m*n;
}

main(args) {
  [3,4] foo;
  [3,5] bar;
  return print_endline(num_cells_if_same_size(foo,bar));
}
```

Application on Ranges

Extend gives the developer the power to easily apply operations in a functional style on ranges. For example, the following function performs cell wise addition:

```
foo([m,n] arg1, [m,n] arg2) {
  [m,n] bar := #arg1 + #arg2;
  return bar;
}
```

This function normalizes a column vector to have unit norm:

```
normalize_column_vector([m,1] arg) {
  [m,1] squared_lengths := #arg * #arg, normalized := #arg / vector_norm;
  vector_norm := sqrt(sum(squared_lengths));
  return normalized;
}
```

Lazy Evaluation and Circular References

All cell values and variable dimensions are evaluated lazily if and when they are needed to calculate the return expression. Using lazy evaluation ensures that the cell values are calculated in a valid topological sort order and allows for detection of circular references; internally this is accomplished by constructing a function for each formula which is called the first time the cell's value is needed, and marking the cell as "in-progress" once it starts being evaluated and as "complete" once the value has been calculated. The only guarantees the language places on the order of cell evaluation are: (1) It will be a valid topological ordering; (2) In conditional expressions and in short-circuiting operator expressions, only the relevant conditional branches will be evaluated; and (3) In an expression using the precedence operator, the preceeding expression will be evaluated before the succeeding expression. A range selection consisting of multiple cells will not cause the constituent cells to be evaluated; however, selection of a single cell will cause that cell's value to be evaluated. If a program is written in such a way as to cause a circular dependency of one cell on another, and the return expression is dependent on that cell's value, a runtime error will occur. For example, in the following function:

```
maybeCircular(truth_value) {
  x := x;
  return truth_value ? x : 0;
```

```
}

main(args) {
  foo :=
    print_endline("To be or not to be?") ->
    print_endline("Enter \"Not to be\" to attempt to evaluate a circular reference.")
        ->
    readline(STDIN);

  return
    maybeCircular(foo == "Not to be" || foo == "\"Not to be\"") ->
    print_endline("Good thing I didn't look at the value of x.");
}
```

A runtime error will occur if maybeCircular(1) is called; but if maybeCircular(0) is called, the function will simply return 0.

External Libraries

Using the following library declaration:

```
extern "mylib.o" {
  foo(arg1, arg2);
  bar();
}
```

will make the functions foo (taking two arguments) and bar (taking zero arguments) available within Extend. In LLVM, the compiler will declare external functions extend_foo and extend_bar as functions of two and zero arguments respectively. All arguments must have the type value_p, and the function must have return type value_p, declared in the Extend standard library header file. In other words, the C file compiled to generate the library must have defined:

```
value_p extend_foo(value_p arg1, value_p arg2) {
  /* function body here; */
}

value_p extend_bar() {
  /* function body here; */
}
```

3.6 Introduction to Extend

Extend is a domain-specific programming language used to designate ranges of cells as reusable functions. It is a dynamically-typed, statically-scoped, declarative language that uses lazy evaluation to carry out computations. Once computed, all values are immutable. In order to offer the best performance, Extend compiles down to LLVM.

Extend's syntax is meant to provide clear punctuation and easily understandable cell range access specifications, while borrowing elements from languages with C-style syntax for ease of development. Despite these syntactic similarities, the semantics of an Extend program have more in common with a spreadsheet such as Microsoft Excel than imperative languages such as C, Java or Python.

3.7 Structure of an Extend Program

An Extend program consists of one or more source files. A source file can contain any number of import directives, function definitions, global variable declarations, and external library declarations, in any order.

Import Statements

Import statements in Extend are written with `import`, followed by the name of a file in double quotes, and terminated with a semicolon. The syntax is as follows:

```
import "string.xtnd";
```

Extend imports act like `#include` in C, except that multiple imports of the same file are ignored. The imports are all aggregated into a single namespace.

Function Definitions

Function definitions comprise the bulk of an Extend program. In short, a function consists of a set of variable declarations, formula assignments, and a return expression. Each variable consists of cells; the values of each cell are, if necessary, calculated according to formulas which each apply to a specified subset of the cells. Each cell value, once calculated, is immutable. A couple examples follow for context; functions are described in detail in section 3.5.

```
isNumber(x) {
  return typeof(x) == "Number";
}

sum_column([m,1] rng) {
  /* Returns the sum of the values in the column, skipping any values that are non-
      numeric */
  [m,1] running_sum;
  running_sum[0,0] = #rng;
  running_sum[1:,0] = running_sum[[-1],] + (isNumber(#rng) ? #rng : 0);
  return running_sum[-1];
}
```

Global Variables

In essence, global variable declarations function as constants in Extend. They are written with the keyword `global`, followed by a variable declaration in the combined variable declaration and assignment format described in section 3.5. As with local variables, the cell values of a global variable, once computed, are immutable. A few examples follow:

```
global pi := 3.14159265359;
global num_points := 24;
global [num_points,1]
  circle_x_vals := cos(2 * pi * row() / num_points),
  circle_y_vals := sin(2 * pi * row() / num_points);
```

External Library Declarations

An external library is declared with the `extern` keyword, followed by the name of an object file in double quotes, followed by a semicolon-delimited list of external function declarations enclosed by curly braces. A library declaration informs the compiler of the functions' names and signatures and instructs the compiler to link the object file when producing an executable. An external function declared as `foo` will call an appropriately written C function `extend_foo`. An example follows:

```
extern "mylib.o" {
  foo(arg1, arg2);
  bar();
}
```

This declaration would cause the compiler to link `mylib.o` and would make the C functions `extend_foo` and `extend_bar` available to Extend programs as `foo` and `bar` respectively. The required signature and format of the external functions is specified precisely in section 3.5.

`main` function

When a compiled Extend program is executed, the `main` function is evaluated. All computations necessary to calculate the return value of the function are performed, after which the program terminates. The `main` function must be a function of a single argument, conventionally denoted `args`, which is guaranteed to be a 1-by-n range containing the command line arguments.

Scoping and Namespace

For functions and for global variables, there is a single namespace that is shared between all files composing an Extend program, and they are visible throughout the entire program. Functions declared in external libraries share this namespace as well. For a local variable, the scope is the entire body of the function in which it is defined. Functions may declare local variables sharing a name with a global variable; inside that function, the name will refer to the local variable.

```
1  global x := "I'm a global";
2
3  foo() {
4    y := x; // Scope of x is entire function
5    x := "In here I'm a local";
6    return y; // Returns "In here I'm a local"
7  }
8
9  bar(x) {
10   return x; // Parameters mask globals; returns argument
11 }
12
13 baz() {
14   return x; // Returns "I'm a global"
15 }
```

3.8 Standard Library Reference

3.9 Example Program

```
1  import "./samples/stdlib.xtnd";
2
3  main([1,n] args) {
4    /* Get a working copy */
5    return 0;
6  }
```

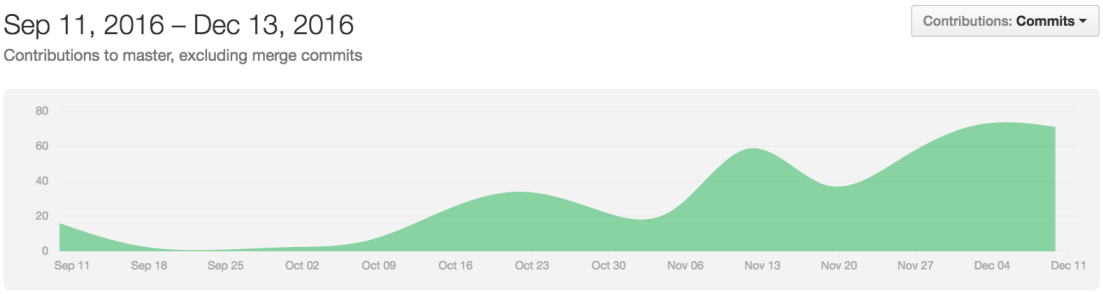
4. Project Plan

4.1 Meetings

Our goals were outlined by weekly meetings. We regularly met with Jacob Graff, our advisor throughout the development of Extend. Jacob served as a sounding board whenever Extend's fundamental design philosophy was debated, and as a guide as we determined whether we were on track. We used any leftover time on those days to set goals for the upcoming week and pair program if time permitted.

Our team also met weekly on Fridays to further discuss the progression of Extend. In the first half of the semester, the discussions were primarily philosophical, as decisions had to be made about the language grammar and behavior of certain Extend artifacts prior to development. In the second half, time was devoted to ironing out the development timeline, discussing bugs, and making compiler implementation decisions.

4.2 Development Workflow



Github & Travis CI

Our development and documentation were all done entirely through version control to maximize independent productivity. New features were introduced to the master branch through pull requests, and the team used this as a platform to peer review code to maximize code quality before such features entered production.

An important aspect of development for us was continuous integration. We used Travis CI to trigger project builds on each pull request, which kept us informed regarding unexpected hiccups that sometimes arose during development. Travis CI ensured that new features were implemented with protecting the code base in mind, and provided quick visibility as to whether a new feature would break the existing build. Any changeset to the master branch must:

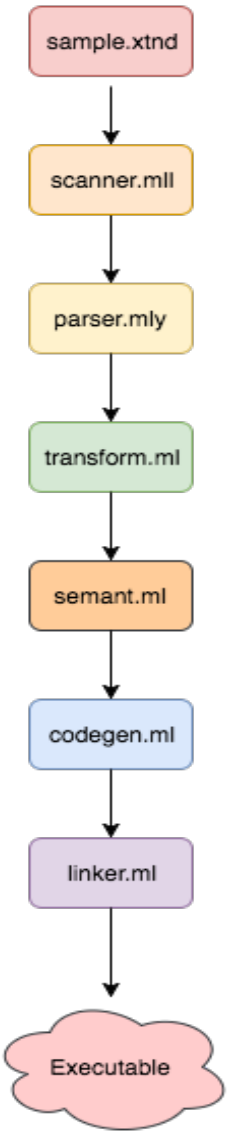
1. Pass Travis CI.
2. Be approved by another member of the team.

3. Be up to date with the master branch.

4.3 Team Member Responsibilities

Team Member	Responsibilities	GitHub Profile
Jared Samet	design philosophy, semantic transformations, code generation	oracleofnj
Nigel Schuster	development protocol, code generation, scripting	Neitsch
Ishaan Kolluri	initial LRM, Final Report, regression tests, stdlib functions, scripting	ishaankolluri
Kevin Ye	initial scanner, regression tests, stdlib functions	kevinye1

5. Extend's Internal Architecture



5.1 The Extend Compiler

The Extend compilation process consists of several source files, each of which performs a different function in the compilation pipeline.

- `scanner.mll`: OCamllex scanner - consumes tokens.
- `parser.mly`: OCamlyacc parser - represents the Extend grammar.
- `ast.ml`: Abstract Syntax Tree, created from the output of the parser and representing the structure of an Extend program.
- `transform.ml`: Performs syntactic desugaring for easier compilation.
- `semant.ml`: Analyzes the semantics of the program to ensure that the program adheres to the rules of the language.
- `codegen.ml`: The LLVM IR code generator.
- `linker.ml`: Calls intermediary compilation steps on the generated `.ll`, including external functions if needed.

The Scanner

The function of `scanner.mll` is to parse a text stream into various tokens to be used in an Extend program. Only the tokens that are valid in Extend are to be given to the parser; all others will return a syntax error marked by the line and character number.

The Parser and Abstract Syntax Tree

The parser converts the tokens read by the scanner into a syntax tree deemed acceptable grammar within the Extend Language. This is converted into an Abstract Syntax Tree, which has nodes that can be consumed by the back end of the Extend compiler.

The Transformer

The transformer expands compact statements in the Extend syntax tree into statements with equivalent functionality, but reduced breadth. This step is done to preserve the convenience for the user, but revert the code later into a form that is easier for the compiler to chew on.

The Semantic Analyzer

The semantic analyzer ensures that Extend functions, variables, expressions, and more are being used properly at compile time, and throws flavorful exceptions to the user so that they may better understand why their program was illegal.

The Code Generator

Provided that the program was deemed legal by `transform.ml`, the code generator will take the program definition in the abstract syntax tree and generate the appopriate LLVM IR to turn it into a functional program. Instructions to allocate memory, interact with external functions, and platform optimization can be found here.

The Linker

If successful LLVM IR is generated, the linker will adopt the role of building an executable object from the `.ll` file. This includes compiling it to an object file and linking the runtime environment along with other imported libraries.

6. Testing

Due to Extend being a large undertaking, we took steps to ensure that all features were working as the design of the language intended.

This was done through implementing test cases that isolated specific aspects of the Extend language to ensure that each feature worked correctly. For basic components, we wrote a plethora of tests to illustrate functionality. For undertakings that required more debate on the design of the language, other tests were created and modified throughout development.

6.1 Feature Integration & Testing

Development of new features naturally means that they must be deemed legal by the scanner, parser, semantic analyzer, and code generator. As we developed new features, the process was roughly as follows:

1. Write a simple test that illustrated the feature to test.
2. Write the expected output of the aforementioned test to a text file.
3. Confirm that the scanner consumes the tokens related to the feature.
4. Confirm that the parser grammar has been adjusted to accomodate the new feature.
5. Confirm that the semantic analyzer and transformer can properly identify and check the new feature code.
6. Confirm that code generation generates the appropriate LLVM IR for the new features - such as allocating memory, building calls, and more.
7. Ensure that the test written can write its output to stdout, to be compared with expected output.
8. Compile and test the code to ensure that the code has worked to the team's expectations.

Earlier in the development process, we tested the front end of our compiler by JSON-ifying the abstract syntax tree, printing it, and examinining it. As we settled into full-fledged development, we would test with a full-feature regression test suite. Later in the semester, JSON-ifying still proved to be useful, as it gave us the option to print debug statements if needed.

6.2 Regression Test Suite

Extend's test suite is executable through the `testscript.sh` script at the top level of the project. There are over 100 integration test files for various features of the Extend language, and a corresponding file with their expected output to `stdout`. This is to ensure that the successful implementation of one feature does not impact that of others.

Regression tests were placed in the `testcases/inputs_regression` directory. Tests that did not pass at the time were placed in the `testcases/inputs` directory. The test script compiles and executes each test, and compares it with the corresponding expected output file, living in the `testcases/expected` directory. Whenever a test passed in `inputs`, it was automatically moved over to `inputs_regression`.

Note: We have added a full test listing at the end of this document. Please refer to the chapter titled "Test Listing" for more detail.

Integration with Travis CI

The aforementioned test suite is run by Travis CI in the event that the Extend compiler is successfully built; otherwise, the build will fail and exit. In our development workflow, checking the logs during build failures sometimes revealed that tests in the regression test suite did not succeed as expected. This integration kept the far-reaching effects of newly introduced features entirely transparent throughout the process.

Using Travic CI allowed us to maintain the working ability of our compiler, as it ensured that every new feature pushed to the master branch would still result in a successful build. This proved to be invaluable when testing the compiler at a macro-level, or providing Jacob, our TA, with up-to-date demonstrations.

7. Reflection

7.1 Ishaan

When working on a long-term project, communication is paramount. Throughout this project, I realized that maximum productivity occurred when the team kept a constant line of communication open regarding language and code design. Additionally, it's important to identify where people can be most productive. If one person is more efficient at a certain task, more progress will be made if they work on similar material. Lastly, as the design of the language evolves over time, it's important to build a system that allows for flexibility, as you never know what may change later in the development process.

7.2 Jared

7.3 Nigel

7.4 Kevin

8. Extend Code Listing

8.1 scanner.mll

```
{
  open Lexing
  open Parser
  open String

  exception SyntaxError of string
  let syntax_error lexbuf = raise (SyntaxError("Invalid character: " ^ Lexing.lexeme
      lexbuf))
}

let digit = ['0'-'9']
let exp = 'e'('+'|'-')?['0'-'9']+
let flt = (digit)+ ('.' (digit)* exp?|exp)
let id = ['a'-'z' 'A'-'Z']['a'-'z' 'A'-'Z' '0'-'9' '_']*


rule token = parse
  ['\n']               { new_line lexbuf; token lexbuf }
| [' ' '\t' '\r']      { token lexbuf }   (* Whitespace *)
| "/*"                 { multiline_comment lexbuf }
| "//"                 { oneline_comment lexbuf }
| '"'                  { read_string (Buffer.create 17) lexbuf }
| '['             { LSQBRACK }
| ']'             { RSQBRACK }
| '('             { LPAREN }
| ')'             { RPAREN }
| '{'             { LBRACE }
| '}'             { RBRACE }
| ":="            { GETS }
| '='             { ASN }
| ':'             { COLON }
| ','             { COMMA }
| "->"            { PRECEDES }
| '?'             { QUESTION }
| "=="            { EQ }
| "!="            { NOTEQ }
| '<'             { LT }
| '>'             { GT }
| "<="            { LTEQ }
| ">="            { GTEQ }
| ';'             { SEMI }
```

```
| '!'              { LOGNOT }
| "&&"             { LOGAND }
| "||"             { LOGOR }
| '~'              { BITNOT }
| '&'              { BITAND }
| '|'              { BITOR }
| '^'              { BITXOR }
| '+'              { PLUS }
| '-'              { MINUS }
| '*'              { TIMES }
| '/'              { DIVIDE }
| '%'              { MOD }
| "**"             { POWER }
| "<<"             { LSHIFT }
| ">>"             { RSHIFT }
| '#'              { HASH }
| "if"             { IF }
| "empty"          { EMPTY }
| "size"           { SIZE }
| "typeof"         { TYPEOF }
| "row"            { ROW }
| "column"         { COLUMN }
| "switch"         { SWITCH }
| "case"           { CASE }
| "default"        { DEFAULT }
| "return"         { RETURN }
| "import"         { IMPORT }
| "global"         { GLOBAL }
| "extern"         { EXTERN }
| "debug"          { DEBUG }
| digit+ as lit    { LIT_INT(int_of_string lit) }
| flt as lit       { LIT_FLOAT(float_of_string lit) }
| id as lit        { ID(lit) }
| eof              { EOF }
| _                { syntax_error lexbuf }

and multiline_comment = parse
  "*/" { token lexbuf }
| '\n' { new_line lexbuf; multiline_comment lexbuf }
| _    { multiline_comment lexbuf }

and oneline_comment = parse
  '\n' { new_line lexbuf; token lexbuf }
| _    { oneline_comment lexbuf }

(* read_string mostly taken from:
https://realworldocaml.org/v1/en/html/parsing-with-ocamllex-and-menhir.html *)
and read_string buf =
  parse
  | '"'       { LIT_STRING (Buffer.contents buf) }
  | '\n'      { new_line lexbuf; Buffer.add_char buf '\n'; read_string buf lexbuf }
  | '\\' 'n'  { Buffer.add_char buf '\n'; read_string buf lexbuf }
  | '\\' 'r'  { Buffer.add_char buf '\r'; read_string buf lexbuf }
  | '\\' 't'  { Buffer.add_char buf '\t'; read_string buf lexbuf }
  | '\\' ([^'\\' 'n' 'r' 't'] as lxm)
    { Buffer.add_char buf lxm; read_string buf lexbuf }
```

```
  | [^ '"' '\\']+
    { Buffer.add_string buf (Lexing.lexeme lexbuf);
      read_string buf lexbuf
    }
  | _          { syntax_error lexbuf }
  | eof        { raise (Failure("unterminated string")) }
```

8.2 parser.mly

```
/* Ocamlyacc parser for Extend */

%{
open Ast
%}

%token LSQBRACK RSQBRACK LPAREN RPAREN LBRACE RBRACE HASH
%token COLON COMMA QUESTION IF GETS ASN SEMI PRECEDES
%token SWITCH CASE DEFAULT SIZE TYPEOF ROW COLUMN
%token PLUS MINUS TIMES DIVIDE MOD POWER LSHIFT RSHIFT
%token EQ NOTEQ GT LT GTEQ LTEQ
%token LOGNOT LOGAND LOGOR
%token BITNOT BITXOR BITAND BITOR
%token EMPTY RETURN IMPORT GLOBAL EXTERN
%token DEBUG
%token <int> LIT_INT
%token <float> LIT_FLOAT
%token <string> LIT_STRING
%token <string> ID
%token EOF

%right QUESTION
%left PRECEDES
%left LOGOR
%left LOGAND
%left EQ NOTEQ LT GT LTEQ GTEQ
%left PLUS MINUS BITOR BITXOR
%left TIMES DIVIDE MOD LSHIFT RSHIFT BITAND
%right POWER
%right BITNOT LOGNOT NEG
%left LSQBRACK

%start program
%type <Ast.raw_program> program

%%

program:
    program_piece EOF {  let (imp, glob, fnc, ext) = $1 in (List.rev imp, List.rev
        glob, List.rev fnc, List.rev ext) }

program_piece:
    /* nothing */ {([],[],[],[])}
  | program_piece import      { let (imp, glob, fnc, ext) = $1 in ($2 :: imp, glob,
      fnc, ext) }
  | program_piece global      { let (imp, glob, fnc, ext) = $1 in (imp, $2 :: glob,
```

```
      fnc, ext) }
  | program_piece func_decl   { let (imp, glob, fnc, ext) = $1 in (imp, glob, $2 ::
      fnc, ext) }
  | program_piece extern      { let (imp, glob, fnc, ext) = $1 in (imp, glob, fnc, $2
      :: ext) }

import:
    IMPORT LIT_STRING SEMI {$2}

global:
    GLOBAL varinit {$2}

extern:
    EXTERN LIT_STRING LBRACE opt_extern_list RBRACE {(Library($2, $4))}

opt_extern_list:
    /* nothing */ { [] }
  | extern_list { List.rev $1 }

extern_list:
    extern_fn { [$1] }
  | extern_list extern_fn { $2 :: $1 }

extern_fn:
    ID LPAREN func_param_list RPAREN SEMI
    { {
      extern_fn_name = $1;
      extern_fn_params = $3;
      extern_fn_libname = "";
      extern_ret_val = (None, None);
    } }

func_decl:
    ID LPAREN func_param_list RPAREN LBRACE opt_stmt_list ret_stmt RBRACE
    { {
      name = $1;
      params = $3;
      body = $6;
      raw_asserts = [];
      ret_val = ((None, None), $7)
    } }

opt_stmt_list:
    /* nothing */ { [] }
  | stmt_list { List.rev $1 }

stmt_list:
    stmt { [$1] }
  | stmt_list stmt { $2 :: $1 }

stmt:
    varinit { $1 } |  assign { $1 }

ret_stmt:
    RETURN expr SEMI {$2}

```

```
varinit:
    var_list SEMI { Varinit((None, None), List.rev $1) }
  | dim var_list SEMI { Varinit($1, List.rev $2) }

var_list:
    ID varassign { [ ($1, $2)] }
  | var_list COMMA ID varassign { ($3, $4) :: $1}

varassign:
    /* nothing */ { None }
  | GETS expr { Some $2 }

assign:
    ID lhs_sel ASN expr SEMI { Assign($1, $2, Some $4) }

expr:
    expr rhs_sel        { Selection($1, $2) }
  | HASH ID             { Selection(Id($2), (None, None)) }
  | op_expr             { $1 }
  | ternary_expr        { $1 }
  | switch_expr         { $1 }
  | func_expr           { $1 }
  | range_expr          { $1 }
  | DEBUG LPAREN expr RPAREN { Debug($3) }
  | expr PRECEDES expr  { Precedence($1, $3) }
  | LPAREN expr RPAREN  { $2 }
  | ID                  { Id($1) }
  | LIT_INT             { LitInt($1) }
  | LIT_FLOAT           { LitFlt($1) }
  | LIT_STRING          { LitString($1) }
  | EMPTY               { Empty }

op_expr:
    expr PLUS expr      { BinOp($1, Plus, $3) }
  | expr MINUS expr     { BinOp($1, Minus, $3) }
  | expr TIMES expr     { BinOp($1, Times, $3) }
  | expr DIVIDE expr    { BinOp($1, Divide, $3) }
  | expr MOD expr       { BinOp($1, Mod, $3) }
  | expr POWER expr     { BinOp($1, Pow, $3) }
  | expr LSHIFT expr    { BinOp($1, LShift, $3) }
  | expr RSHIFT expr    { BinOp($1, RShift, $3) }
  | expr LOGAND expr    { BinOp($1, LogAnd, $3) }
  | expr LOGOR expr     { BinOp($1, LogOr, $3) }
  | expr BITXOR expr    { BinOp($1, BitXor, $3) }
  | expr BITAND expr    { BinOp($1, BitAnd, $3) }
  | expr BITOR expr     { BinOp($1, BitOr, $3) }
  | expr EQ expr        { BinOp($1, Eq, $3) }
  | expr NOTEQ expr     { UnOp(LogNot,(BinOp($1, Eq, $3))) }
  | expr GT expr        { BinOp($1, Gt, $3) }
  | expr LT expr        { BinOp($1, Lt, $3) }
  | expr GTEQ expr      { BinOp($1, GtEq, $3) }
  | expr LTEQ expr      { BinOp($1, LtEq, $3) }
  | SIZE LPAREN expr RPAREN { UnOp(SizeOf, $3) }
  | TYPEOF LPAREN expr RPAREN { UnOp(TypeOf, $3) }
  | ROW LPAREN RPAREN       { UnOp(Row, Empty)}
  | COLUMN LPAREN RPAREN    { UnOp(Column, Empty)}
```

```
154   | MINUS expr %prec NEG    { UnOp(Neg, $2) }
155   | LOGNOT expr             { UnOp(LogNot, $2) }
156   | BITNOT expr             { UnOp(BitNot, $2) }
157
158 ternary_expr:
159     IF LPAREN expr COMMA expr COMMA expr RPAREN { Ternary($3, $5, $7) }
160   | expr QUESTION expr COLON expr %prec QUESTION { Ternary($1, $3, $5) }
161
162 switch_expr:
163     SWITCH LPAREN switch_cond RPAREN LBRACE default_case_list RBRACE { Switch($3, fst
          $6, snd $6) }
164   | SWITCH LBRACE default_case_list RBRACE { Switch(None, fst $3, snd $3) }
165
166 switch_cond:
167     /* nothing */ { None }
168   | expr { Some $1 }
169
170 default_case_list:
171     case_list {(List.rev $1, Empty)}
172   | case_list default_expr {(List.rev $1, $2)}
173
174 case_list:
175     case_stmt { [$1] }
176   | case_list case_stmt { $2 :: $1 }
177
178 case_stmt:
179     CASE case_expr_list COLON expr SEMI { (List.rev $2, $4) }
180
181 default_expr:
182     DEFAULT COLON expr SEMI { $3 }
183
184 case_expr_list:
185     expr { [$1] }
186   | case_expr_list COMMA expr { $3 :: $1 }
187
188 func_expr:
189     ID LPAREN opt_arg_list RPAREN { Call($1, $3) }
190
191 range_expr:
192     LBRACE row_list RBRACE { allow_range_literal (LitRange(List.rev $2)) }
193
194 row_list:
195     col_list {[List.rev $1]}
196   | row_list SEMI col_list {List.rev $3 :: $1}
197
198 col_list:
199     expr {[$1]}
200   | col_list COMMA expr {$3 :: $1}
201
202 opt_arg_list:
203     /* nothing */ {[]}
204   | arg_list { List.rev $1 }
205
206 arg_list:
207     expr {[$1]}
208   | arg_list COMMA expr {$3 :: $1}
```

```

lhs_sel:
    /* nothing */                          { (None, None) }
/* commented out: LSQBRACK lslice RSQBRACK { (Some $2, None) } */
  | LSQBRACK lslice COMMA lslice RSQBRACK { (Some $2, Some $4) }

rhs_sel:
    LSQBRACK rslice RSQBRACK              { (Some $2, None) }
  | LSQBRACK rslice COMMA rslice RSQBRACK { (Some $2, Some $4) }

lslice:
  /* commented out: nothing production { (None, None) } */
    lslice_val                            { (Some $1, None) }
  | lslice_val COLON lslice_val           { (Some $1, Some $3) }
  | lslice_val COLON                      { (Some $1, Some DimensionEnd) }
  | COLON lslice_val                      { (Some DimensionStart, Some $2) }
  | COLON                                 { (Some DimensionStart, Some DimensionEnd) }

rslice:
    /* nothing */                         { (None, None) }
  | rslice_val                            { (Some $1, None) }
  | rslice_val COLON rslice_val           { (Some $1, Some $3) }
  | rslice_val COLON                      { (Some $1, Some DimensionEnd) }
  | COLON rslice_val                      { (Some DimensionStart, Some $2) }
  | COLON                                 { (Some DimensionStart, Some DimensionEnd) }

lslice_val:
    expr { Abs($1) }

rslice_val:
    expr { Abs($1) }
  | LSQBRACK expr RSQBRACK { Rel($2) }

func_param_list:
    /* nothing */ { [] }
  | func_param_int_list { List.rev $1 }

func_param_int_list:
    func_sin_param { [$1] }
  | func_param_int_list COMMA func_sin_param { $3 :: $1 }

func_sin_param:
    ID { ((None, None), $1) }
  | dim ID { ($1, $2) }

dim:
    LSQBRACK expr RSQBRACK { (Some $2, None) }
  | LSQBRACK expr COMMA expr RSQBRACK { (Some $2, Some $4) }
```

8.3 ast.ml

```
type op       = Plus | Minus | Times | Divide | Mod | Pow |
                LShift | RShift | BitOr | BitAnd | BitXor |
                Eq | Gt | GtEq | Lt | LtEq | LogAnd | LogOr
type unop     = Neg | LogNot | BitNot | SizeOf | TypeOf | Row | Column | Truthy
```

```
5
6  type expr     = LitInt of int |
7                  LitFlt of float |
8                  LitString of string |
9                  LitRange of (expr list) list |
10                 Id of string |
11                 Empty |
12                 BinOp of expr * op * expr |
13                 UnOp of unop * expr |
14                 Ternary of expr * expr * expr |
15                 Switch of expr option * case list * expr |
16                 Call of string * expr list |
17                 Selection of expr * sel |
18                 ReducedTernary of string * string * string |
19                 Precedence of expr * expr |
20                 Debug of expr
21 and  index    = Abs of expr |
22                 Rel of expr |
23                 DimensionStart |
24                 DimensionEnd
25 and  slice    = index option * index option
26 and  sel      = slice option * slice option
27 and  case     = expr list * expr
28
29 type dim      = expr option * expr option
30 type var      = dim * string
31 type assign   = string * sel * expr option
32 type init     = string * expr option
33 type stmt     = Assign of assign |
34                 Varinit of dim * init list
35
36 type raw_func = {
37     name: string;
38     params: var list;
39     body: stmt list;
40     raw_asserts: expr list;
41     ret_val: dim * expr;
42 }
43
44 type extern_func = {
45     extern_fn_name: string;
46     extern_fn_params: var list;
47     extern_fn_libname: string;
48     extern_ret_val: dim;
49 }
50
51 type library  = Library of string * extern_func list
52 type raw_program = string list * stmt list * raw_func list * library list
53
54 (* Desugared types below *)
55 module StringMap = Map.Make(String)
56 type formula  = {
57   formula_row_start: index;
58   formula_row_end: index option;
59   formula_col_start: index;
60   formula_col_end: index option;
```

```
61    formula_expr: expr;
62  }
63
64  type dim_expr = DimOneByOne
65                | DimId of string
66
67  type variable = {
68    var_rows: dim_expr;
69    var_cols: dim_expr;
70    var_formulas: formula list;
71  }
72
73  type func_decl = {
74    func_params: var list;
75    func_body: variable StringMap.t;
76    func_asserts: expr list;
77    func_ret_val: dim * expr;
78  }
79
80  type program = (variable StringMap.t) * (func_decl StringMap.t) * (extern_func
        StringMap.t)
81
82  type listable = Inits of init list |
83                  Vars of var list |
84                  Stmts of stmt list |
85                  RawFuncs of raw_func list |
86                  Externs of extern_func list |
87                  Libraries of library list |
88                  Exprs of expr list |
89                  Rows of (expr list) list |
90                  Strings of string list |
91                  Cases of case list |
92                  Formulas of formula list
93
94  exception IllegalRangeLiteral of string
95  exception TransformedAway of string
96
97  let quote_string str =
98    let escape_characters = Str.regexp "[\n \t \r \\ \"]" in
99    let replace_fn s = match Str.matched_string s with
100     "\n" -> "\\n"   |
101     "\t" -> "\\t"   |
102     "\r" -> "\\r"   |
103     "\\" -> "\\\\"  |
104     "\"" -> "\\\""  |
105     _    -> Str.matched_string s in
106   "\"" ^ Str.global_substitute escape_characters replace_fn str ^ "\""
107
108 let string_of_op o = "\"" ^ (match o with
109     Plus -> "+" | Minus -> "-" | Times -> "*" | Divide -> "/" | Mod -> "%" | Pow ->
          "**" |
110     LShift -> "<<" | RShift -> ">>" | BitOr -> "|" | BitAnd -> "&" | BitXor -> "^" |
111     Eq -> "==" | Gt -> ">" | GtEq -> ">=" | Lt -> "<" | LtEq -> "<=" |
112     LogAnd -> "&& " | LogOr -> "||" ) ^ "\""
113
114 let string_of_unop = function
```

```
    Neg -> "\"-\"" | LogNot -> "\"!\"" | BitNot -> "\"~\"" | Truthy -> "\"truthy\"" |
    SizeOf -> "\"size\"" | TypeOf -> "\"type\"" | Row -> "\"row\"" | Column -> "\"
        column\""

let rec string_of_expr = function
    LitInt(l) ->          "{\"LitInt\":" ^ string_of_int l ^ "}"
  | LitFlt(l) ->          "{\"LitFlt\":" ^ string_of_float l ^ "}"
  | LitString(s) ->       "{\"LitString\":" ^ quote_string s ^ "}"
  | LitRange(rowlist) ->  "{\"LitRange\": " ^ string_of_list (Rows rowlist) ^ "}"
  | Id(s) ->              "{\"Id\": " ^ quote_string s ^ "}"
  | Empty ->              "\"Empty\""
  | BinOp(e1, o, e2) ->   "{\"BinOp\": {" ^
                            "\"expr1\": " ^ string_of_expr e1 ^ ", " ^
                            "\"operator\": " ^ string_of_op o ^ ", " ^
                            "\"expr2\": " ^ string_of_expr e2 ^ "}}"
  | UnOp(o, e) ->         "{\"UnOp\": {" ^
                            "\"operator\": " ^ string_of_unop o ^ ", " ^
                            "\"expr\": " ^ string_of_expr e ^ "}}"
  | Ternary(c, e1, e2) -> "{\"Ternary\": {" ^
                            "\"condition\": " ^ string_of_expr c ^ ", " ^
                            "\"ifExpr\": " ^ string_of_expr e1 ^ ", " ^
                          "\"elseExpr\": " ^ string_of_expr e2 ^ "}}"
  | ReducedTernary(s1, s2, s3) -> "{\"ReducedTernary\": {" ^
                            "\"truthiness\": " ^ quote_string s1 ^ ", " ^
                            "\"true_values\": " ^ quote_string s2 ^ ", " ^
                            "\"false_values\": " ^ quote_string s3 ^ "}}"
  | Switch(eo, cases, dflt) ->  "{\"Switch\": {" ^
                                  "\"condition\": " ^
                                    (match eo with None -> "null" | Some e ->
                                        string_of_expr e) ^ ", " ^
                                  "\"cases\": " ^ string_of_list (Cases cases) ^ ", " ^
                                  "\"defaultExpr\": " ^ string_of_expr dflt ^ "}}"
  | Call(f, arguments) -> "{\"Call\": {" ^
                            "\"function\": " ^ quote_string f ^ ", " ^
                            "\"arguments\": " ^ string_of_list (Exprs arguments) ^
                                "}}"
  | Selection(e, s) ->    "{\"Selection\": {" ^
                            "\"expr\": " ^ string_of_expr e ^ ", " ^
                            "\"slices\": " ^ string_of_sel s ^ "}}"
  | Precedence(e1, e2) -> "{\"Precedence\": { " ^
                            "\"prior_expr\": " ^ string_of_expr e1 ^ ", " ^
                          "\"dependent_expr\": " ^ string_of_expr e2 ^ "}}"
  | Debug(e) -> string_of_expr e

and string_of_case (el, e) =
    "{\"Cases\": " ^ string_of_list (Exprs el) ^ ", " ^
     "\"expr\": " ^ string_of_expr e ^ "}"

and string_of_sel (s1, s2) =
    "{\"slice1\": " ^ string_of_slice s1 ^ ", \"slice2\": " ^ string_of_slice s2 ^ "}"

and string_of_slice = function
    None -> "null"
  | Some (start_idx, end_idx) -> "{\"start\": " ^ string_of_index start_idx ^ ", \"end
      \": " ^ string_of_index end_idx ^ "}"

```

```
and string_of_index = function
    None -> "null"
  | Some(Abs(e)) -> "{\"Absolute\": " ^ string_of_expr e ^ "}"
  | Some(Rel(e)) -> "{\"Relative\": " ^ string_of_expr e ^ "}"
  | Some(DimensionStart) -> "\"DimensionStart\""
  | Some(DimensionEnd) -> "\"DimensionEnd\""

and string_of_dim (d1,d2) = "{\"d1\": " ^ (match d1 with None -> "null" | Some e ->
    string_of_expr e) ^ ", " ^
                              "\"d2\": " ^ (match d2 with None -> "null" | Some e ->
                                  string_of_expr e) ^ "}"

and string_of_var (d, s) = "{\"Dimensions\": " ^ string_of_dim d ^ ", " ^
                            "\"VarName\": " ^ quote_string s ^ "}"

and string_of_assign (s, selection, eo) =
    "{\"VarName\": " ^ quote_string s ^ ", " ^
     "\"Selection\": " ^ string_of_sel selection ^ ", " ^
    "\"expr\": " ^ (match eo with None -> "null" | Some e -> string_of_expr e) ^ "}"

and string_of_varinit (d, inits) =
  "{\"Dimensions\": " ^ string_of_dim d ^
    ",\"Initializations\": " ^ string_of_list (Inits inits) ^ "}"

and string_of_init (s, eo) =
    "{\"VarName\": " ^ quote_string s ^ ", " ^
     "\"expr\": " ^ (match eo with None -> "null" | Some e -> string_of_expr e) ^ "}"

and string_of_stmt = function
    Assign(a) -> "{\"Assign\": " ^ string_of_assign a ^ "}"
  | Varinit(d, inits) -> "{\"Varinit\": " ^ string_of_varinit (d, inits) ^ "}"

and string_of_range (d, e) = "{\"Dimensions\": " ^ string_of_dim d ^ ", " ^
                              "\"expr\": " ^ string_of_expr e ^ "}"

and string_of_raw_func fd =
    "{\"Name\": " ^ quote_string fd.name ^ "," ^
     "\"Params\": " ^ string_of_list (Vars fd.params) ^ "," ^
     "\"Stmts\": " ^ string_of_list (Stmts fd.body) ^ "," ^
     "\"Assertions\": " ^ string_of_list (Exprs fd.raw_asserts) ^ "," ^
     "\"ReturnVal\": " ^ string_of_range fd.ret_val ^ "}"

and string_of_extern_func fd =
  "{\"Name\": " ^ quote_string fd.extern_fn_name ^ "," ^
  "\"Params\": " ^ string_of_list (Vars fd.extern_fn_params) ^ "," ^
  "\"Library\": " ^ quote_string fd.extern_fn_libname ^ "," ^
  "\"ReturnDim\": " ^ string_of_dim fd.extern_ret_val ^ "}"

and string_of_library (Library(lib_name, lib_fns)) =
  "{\"LibraryName\": " ^ quote_string lib_name ^ "," ^
  "\"ExternalFunctions\": " ^ string_of_list (Externs lib_fns) ^ "}"

and string_of_dimexpr = function
    DimOneByOne -> "1"
  | DimId(s) -> quote_string s

```

```
and string_of_formula f =
  "{\"RowStart\": " ^ string_of_index (Some f.formula_row_start) ^ "," ^
  "\"RowEnd\": " ^ string_of_index (f.formula_row_end) ^ "," ^
  "\"ColumnStart\": " ^ string_of_index (Some f.formula_col_start) ^ "," ^
  "\"ColumnEnd\": " ^ string_of_index (f.formula_col_end) ^ "," ^
  "\"Formula\": " ^ string_of_expr f.formula_expr ^ "}"

and string_of_list l =
  let stringrep = (match l with
    Inits (il) -> List.map string_of_init il
  | Vars(vl) -> List.map string_of_var vl
  | Stmts(sl) -> List.map string_of_stmt sl
  | RawFuncs(fl) -> List.map string_of_raw_func fl
  | Externs(efl) -> List.map string_of_extern_func efl
  | Libraries(libl) -> List.map string_of_library libl
  | Exprs(el) -> List.map string_of_expr el
  | Rows(rl) -> List.map (fun (el : expr list) -> string_of_list (Exprs el)) rl
  | Strings(sl) -> List.map quote_string sl
  | Cases(cl) -> List.map string_of_case cl
  | Formulas(fl) -> List.map string_of_formula fl)
  in "[" ^ String.concat ", " stringrep ^ "]"

let string_of_raw_program (imp, glb, fs, exts) =
    "{\"Program\": {" ^
      "\"Imports\": " ^ string_of_list (Strings imp) ^ "," ^
      "\"Globals\": " ^ string_of_list (Stmts glb) ^ "," ^
      "\"ExternalLibraries\": " ^ string_of_list (Libraries exts) ^ "," ^
      "\"Functions\": " ^ string_of_list (RawFuncs fs) ^ "}}"

let string_of_variable v =
  "{\"Rows\": " ^ string_of_dimexpr v.var_rows ^ "," ^
  "\"Columns\": " ^ string_of_dimexpr v.var_cols ^ "," ^
  "\"Formulas\": " ^ string_of_list (Formulas v.var_formulas) ^ "}"

let string_of_map value_desc val_printing_fn m =
  let f_key_val_list k v l = (
    "{\"" ^ value_desc ^ "Name\": " ^ quote_string k ^ ", " ^
    "\"" ^ value_desc ^ "Def\": " ^ val_printing_fn v ^ "}"
  ) :: l in
  "[" ^ String.concat ", " (List.rev (StringMap.fold f_key_val_list m [])) ^ "]"

let string_of_funcdecl f =
  "{\"Params\": " ^ string_of_list (Vars f.func_params) ^ "," ^
  "\"Variables\": " ^ string_of_map "Variable" string_of_variable f.func_body ^ "," ^
  "\"Assertions\": " ^ string_of_list (Exprs f.func_asserts) ^ "," ^
  "\"ReturnVal\": " ^ string_of_range f.func_ret_val ^ "}"

let string_of_program (glb, fs, exts) =
  "{\"Program\": {" ^
    "\"Globals\": " ^ string_of_map "Variable" string_of_variable glb ^ "," ^
    "\"Functions\": " ^ string_of_map "Function" string_of_funcdecl fs ^ "," ^
    "\"ExternalFunctions\": " ^ string_of_map "ExternalFunctions"
        string_of_extern_func exts ^ "}}"

let allow_range_literal = function
    LitRange(rowlist) ->
```

```
276       let rec check_range_literal rl =
277         List.for_all (fun exprs -> List.for_all check_basic_expr exprs) rl
278       and check_basic_expr = function
279           LitInt(_) | UnOp(Neg, LitInt(_)) | LitFlt(_) | UnOp(Neg, LitFlt(_)) |
                LitString(_) | Empty -> true
280         | LitRange(rl) -> check_range_literal rl
281         | _ -> false in
282
283       if check_range_literal rowlist then LitRange(rowlist)
284       else raise(IllegalRangeLiteral(string_of_expr (LitRange(rowlist))))
285   | e -> raise(IllegalRangeLiteral(string_of_expr e))
```

8.4 transform.ml

```
1  open Ast
2  open Lexing
3  open Parsing
4  open Semant
5
6  module StringSet = Set.Make (String);;
7  let importSet = StringSet.empty;;
8
9  let idgen =
10   (* from http://stackoverflow.com/questions/10459363/side-effects-and-top-level-
        expressions-in-ocaml*)
11   let count = ref (-1) in
12   fun prefix -> incr count; "_tmp_" ^ prefix ^ string_of_int !count;;
13
14 let expand_file include_stdlib filename =
15   let print_error_location filename msg lexbuf =
16     let pos = lexbuf.lex_curr_p in
17     prerr_endline ("Syntax error in \"" ^ filename ^ "\": " ^ msg) ;
18     prerr_endline ("Line " ^ (string_of_int pos.pos_lnum) ^ " at character " ^ (
          string_of_int (pos.pos_cnum - pos.pos_bol))) in
19
20   let rec expand_imports processed_imports globals fns exts dir = function
21       [] -> ([], globals, fns, exts)
22     | (import, use_dir) :: imports ->
23       (* print_endline "---------";
24       print_endline ("Working on: " ^ import) ;
25       print_endline ("Already processed:"); *)
26       (* StringSet.iter (fun a -> print_endline a) processed_imports; *)
27       let in_chan = open_in import in
28       let lexbuf = (Lexing.from_channel (in_chan)) in
29       let (file_imports, file_globals, file_functions, file_externs) =
30         try Parser.program Scanner.token lexbuf
31         with
32           Parsing.Parse_error -> print_error_location import "" lexbuf ; exit(-1)
33         | Scanner.SyntaxError(s) -> print_error_location import s lexbuf ; exit(-1)
34       in
35       let file_imports = List.map (fun file -> (if use_dir then (dir ^ "/") else "") ^
             file) file_imports in
36       let new_proc = StringSet.add import processed_imports and _ = close_in in_chan
           in
37       (* print_endline ("Now I'm done with: ") ; *)
```

```
38        (* StringSet.iter (fun a -> print_endline a) new_proc; *)
39        let first_im_hearing_about imp = not (StringSet.mem imp new_proc || List.mem imp
              (List.map fst imports)) in
40        let new_imports = List.map (fun e -> (e, true)) (StringSet.elements (StringSet.
              of_list (List.filter first_im_hearing_about file_imports))) in
41        (* print_endline ("First I'm hearing about:") ; *)
42        (* List.iter print_endline new_imports; *)
43        expand_imports new_proc (globals @ file_globals) (fns @ file_functions) (exts @
              file_externs) (Filename.dirname import) (imports @ new_imports) in
44    expand_imports
45      StringSet.empty [] [] []
46      (Filename.dirname filename)
47      (if include_stdlib then [(filename, true); ("src/stdlib/stdlib.xtnd", false)] else
            [(filename, true)])
48
49  let expand_expressions (imports, globals, functions, externs) =
50    let lit_zero = LitInt(0) in let abs_zero = Abs(lit_zero) in
51    let lit_one  = LitInt(1) in let abs_one  = Abs(lit_one)  in
52    let one_by_one = (Some lit_one, Some lit_one) in
53    let zero_comma_zero = (Some (Some abs_zero, Some abs_one),
54                           Some (Some abs_zero, Some abs_one)) in
55    let entire_dimension = (Some DimensionStart, Some DimensionEnd) in
56    let entire_range = (Some entire_dimension, Some entire_dimension) in
57
58    let expand_expr expr_loc = function
59      (* Create a new variable for all expressions on the LHS to hold the result;
60         return the new expression and whatever new statements are necessary to create
               the new variable *)
61        Empty     -> raise (IllegalExpression("Empty not allowed in " ^ expr_loc))
62      | LitString(s) -> raise (IllegalExpression("String literal " ^ quote_string s ^ "
            not allowed in " ^ expr_loc))
63      | LitRange(rl) -> raise (IllegalExpression("Range literal " ^ string_of_list (Rows
            rl) ^ " not allowed in " ^ expr_loc))
64      | e         -> let new_id = idgen expr_loc in (
65          Id(new_id),
66          [Varinit (one_by_one, [(new_id, None)]);
67           Assign (new_id, zero_comma_zero, Some e)]) in
68
69    let expand_index index_loc = function
70      (* Expand one index of a slice if necessary. *)
71        Abs(e) -> let (new_e, new_stmts) = expand_expr index_loc e in
72        (Abs(new_e), new_stmts)
73      | DimensionStart -> (DimensionStart, [])
74      | DimensionEnd -> (DimensionEnd, [])
75      | Rel(_) -> raise (IllegalExpression("relative - this shouldn't be possible")) in
76
77    let expand_slice slice_loc = function
78      (* Expand one or both sides as necessary. *)
79        None -> (entire_dimension, [])
80      | Some (Some (Abs(e)), None) ->
81        let (start_e, start_stmts) = expand_expr (slice_loc ^ "_start") e in
82        ((Some (Abs(start_e)), None), start_stmts)
83      | Some (Some idx_start, Some idx_end) ->
84        let (new_start, new_start_exprs) = expand_index (slice_loc ^ "_start") idx_start
              in
85        let (new_end, new_end_exprs) = expand_index (slice_loc ^ "_end") idx_end in
```

```
86        ((Some new_start, Some new_end), new_start_exprs @ new_end_exprs)
87      | Some (Some _, None) | Some (None, _) -> raise (IllegalExpression("Illegal slice
            - this shouldn't be possible")) in
88
89    let expand_assign asgn_loc (var_name, (row_slice, col_slice), formula) =
90      (* expand_assign: Take an Assign and return a list of more
91         atomic statements, with new variables replacing any
92         complex expressions in the selection slices and with single
93         index values desugared to expr:expr+1. *)
94      try
95        let (new_row_slice, row_exprs) = expand_slice (asgn_loc ^ "_" ^ var_name ^ "_row
              ") row_slice in
96        let (new_col_slice, col_exprs) = expand_slice (asgn_loc ^ "_" ^ var_name ^ "_col
              ") col_slice in
97        Assign(var_name, (Some new_row_slice, Some new_col_slice), formula) :: (
              row_exprs @ col_exprs)
98      with IllegalExpression(s) ->
99        raise (IllegalExpression("Illegal expression (" ^ s ^ ") in " ^
100                                 string_of_assign (var_name, (row_slice, col_slice),
                                     formula))) in
101
102   let expand_init (r, c) (v, e) =
103     Varinit((Some r, Some c), [(v, None)]) ::
104     match e with
105       None -> []
106     | Some e -> [Assign (v, entire_range, Some e)] in
107
108   let expand_dimension dim_loc = function
109       None -> expand_expr dim_loc (LitInt(1))
110     | Some e -> expand_expr dim_loc e in
111
112   let expand_varinit fname ((row_dim, col_dim), inits) =
113     (* expand_varinit: Take a Varinit and return a list of more atomic
114        statements. Each dimension will be given a temporary ID, which
115        will be declared as [1,1] _tmpXXX; the formula for tmpXXX will be
116        set as a separate assignment; the original variable will be
117        declared as [_tmpXXX, _tmpYYY] var; and the formula assignment
118        will be applied to [:,:]. *)
119     try
120       let (row_e, row_stmts) = expand_dimension (fname ^ "_" ^ (String.concat "_" (
              List.map fst inits)) ^ "_row_dim") row_dim in
121       let (col_e, col_stmts) = expand_dimension (fname ^ "_" ^ (String.concat "_" (
              List.map fst inits)) ^ "_col_dim") col_dim in
122       row_stmts @ col_stmts @ List.concat (List.map (expand_init (row_e, col_e)) inits
              )
123     with IllegalExpression(s) ->
124       raise (IllegalExpression("Illegal expression (" ^ s ^ ") in " ^
125                                string_of_varinit ((row_dim, col_dim), inits))) in
126
127   let expand_stmt fname = function
128     Assign(a) -> expand_assign fname a
129   | Varinit(d, inits) -> expand_varinit fname (d, inits) in
130
131   let expand_stmt_list fname stmts = List.concat (List.map (expand_stmt fname) stmts)
        in
132
```

```
133  let expand_params fname params =
134    let needs_sizevar = function
135        ((None, None), _) -> false
136      | _ -> true in
137    let params_with_sizevar = List.map (fun x -> (idgen (fname ^ "_" ^ (snd x) ^ "
         _size"), x)) (List.filter needs_sizevar params) in
138    let expanded_args = List.map (fun (sv, ((rv, cv), s)) -> ((sv, s), [((sv, abs_zero
         ), rv); ((sv, abs_one), cv)])) params_with_sizevar in
139    let (sizes, inits) = (List.map fst expanded_args, List.concat (List.map snd
         expanded_args)) in
140    let add_item (varset, (assertlist, initlist)) ((sizevar, pos), var) =
141      (match var with
142         Some Id(s) ->
143         if StringSet.mem s varset then
144           (* We've seen this variable before; don't initialize it, just assert it *)
145           (varset, (BinOp(Id(s), Eq, Selection(Id(sizevar), (Some(Some(pos), None),
                None))) :: assertlist, initlist))
146         else
147           (* We're seeing a string for the first time; don't assert it, just create
                it *)
148           (StringSet.add s varset, (assertlist,
149                                     Assign(s, zero_comma_zero, Some (Selection(Id(
                                         sizevar), (Some(Some(pos), None), None)))) ::
150                                     Varinit(one_by_one, [(s, None)]) ::
151                                     initlist))
152       | Some LitInt(i) -> (* Seeing a number; don't do anything besides create an
             assertion *)
153         (varset, (BinOp(LitInt(i), Eq, Selection(Id(sizevar), (Some(Some(pos), None),
                None))) :: assertlist, initlist))
154       | Some e -> raise (IllegalExpression("Illegal expression (" ^ string_of_expr e
             ^ ") in function signature"))
155       | _ -> raise (IllegalExpression("Cannot supply a single dimension in function
             signature"))) in
156    let (rev_assertions, rev_inits) = snd (List.fold_left add_item (StringSet.empty,
         ([], [])) inits) in
157    let create_sizevar (sizevar,arg) = [
158      Varinit(one_by_one, [(sizevar, None)]);
159      Assign(sizevar, entire_range, Some(UnOp(SizeOf,Id(arg))))] in
160    (List.concat (List.map create_sizevar sizes), List.rev rev_assertions, List.rev
         rev_inits) in
161
162  let expand_function f =
163    let (new_sizevars, assertions, size_inits) = expand_params f.name f.params in
164    let new_retval_id = idgen (f.name ^ "_retval") in
165    let new_retval = Id(new_retval_id) in
166    let retval_inits = [Varinit (one_by_one, [(new_retval_id, None)]);
167                        Assign (new_retval_id, zero_comma_zero, Some (snd f.ret_val))]
                              in
168    let new_assert_id = idgen (f.name ^ "_assert") in
169    let add_assert al a = BinOp(al, LogAnd, a) in
170    let new_assert_expr = List.fold_left add_assert (LitInt(1)) assertions in
171    let new_assert = Id(new_assert_id) in
172    let assert_inits = [Varinit (one_by_one, [(new_assert_id, None)]);
173                        Assign (new_assert_id, zero_comma_zero, Some new_assert_expr)]
                              in
174    {
```

```
175       name = f.name;
176       params = f.params;
177       raw_asserts = [new_assert];
178       body = new_sizevars @ size_inits @ retval_inits @ assert_inits @
              expand_stmt_list f.name f.body;
179       ret_val = (fst f.ret_val, new_retval)
180     } in
181   (imports, expand_stmt_list "global" globals, List.map expand_function functions,
        externs);;
182
183 let create_maps (imports, globals, functions, externs) =
184   let vd_of_vi = function
185     (*  vd_of_vi--- Take a bare Varinit from the previous transformations
186         and return a (string, variable) pair    *)
187       Varinit((Some r, Some c), [(v, None)]) -> (v, {
188         var_rows = (match r with
189               LitInt(1) -> DimOneByOne
190             | Id(s) -> DimId(s)
191             | _ -> raise (LogicError("Unrecognized expression for rows of " ^ v)));
192         var_cols = (match c with
193               LitInt(1) -> DimOneByOne
194             | Id(s) -> DimId(s)
195             | _ -> raise (LogicError("Unrecognized expression for rows of " ^ v)));
196         var_formulas = [];
197       })
198     | _ -> raise (LogicError("Unrecognized format for post-desugaring Varinit")) in
199
200   let add_formula m = function
201        Varinit(_,_) -> m
202      | Assign(var_name, (Some (Some row_start, row_end), Some (Some col_start, col_end
           )), Some e) ->
203        if StringMap.mem var_name m
204        then (let v = StringMap.find var_name m in
205              StringMap.add var_name {v with var_formulas = v.var_formulas @ [{
206                  formula_row_start = row_start;
207                  formula_row_end = row_end;
208                  formula_col_start = col_start;
209                  formula_col_end = col_end;
210                  formula_expr = e;
211                }]} m)
212        else raise (UnknownVariable(string_of_stmt (Assign(var_name, (Some (Some
               row_start, row_end), Some (Some col_start, col_end)), Some e))))
213      | Assign(a) -> raise (LogicError("Unrecognized format for post-desugaring Assign:
             " ^ string_of_stmt (Assign(a)))) in
214
215   let vds_of_stmts stmts =
216     let is_varinit = function Varinit(_,_) -> true | _ -> false in
217     let varinits = List.filter is_varinit stmts in
218     let vars_just_the_names = map_of_list (List.map vd_of_vi varinits) in
219     List.fold_left add_formula vars_just_the_names stmts in
220
221   let fd_of_raw_func f = (f.name, {
222       func_params = f.params;
223       func_body = vds_of_stmts f.body;
224       func_ret_val = f.ret_val;
225       func_asserts = f.raw_asserts;
```

```
226     }) in
227
228   let tupleize_library (Library(lib_name, lib_fns)) =
229     List.map (fun ext_fn -> (ext_fn.extern_fn_name, {ext_fn with extern_fn_libname =
          lib_name})) lib_fns in
230
231   (vds_of_stmts globals,
232    map_of_list (List.map fd_of_raw_func functions),
233    map_of_list (List.concat (List.map tupleize_library externs)))
234
235 let single_formula e = {
236   formula_row_start = DimensionStart;
237   formula_row_end = Some DimensionEnd;
238   formula_col_start = DimensionStart;
239   formula_col_end = Some DimensionEnd;
240   formula_expr = e;
241 }
242
243 let ternarize_exprs (globals, functions, externs) =
244   let rec ternarize_expr lhs_var = function
245       BinOp(e1, LogAnd, e2) ->
246       let (new_e1, new_e1_vars) = ternarize_expr lhs_var e1 in
247       let (new_e2, new_e2_vars) = ternarize_expr lhs_var e2 in
248       (Ternary(UnOp(Truthy,new_e1), UnOp(Truthy,new_e2), LitInt(0)), new_e1_vars @
            new_e2_vars)
249     | BinOp(e1, LogOr, e2) ->
250       let (new_e1, new_e1_vars) = ternarize_expr lhs_var e1 in
251       let (new_e2, new_e2_vars) = ternarize_expr lhs_var e2 in
252       (Ternary(UnOp(Truthy,new_e1), LitInt(1), UnOp(Truthy,new_e2)), new_e1_vars @
            new_e2_vars)
253     | BinOp(e1, op, e2) ->
254       let (new_e1, new_e1_vars) = ternarize_expr lhs_var e1 in
255       let (new_e2, new_e2_vars) = ternarize_expr lhs_var  e2 in
256       (BinOp(new_e1, op, new_e2), new_e1_vars @ new_e2_vars)
257     | UnOp(op, e) ->
258       let (new_e, new_e_vars) = ternarize_expr lhs_var e in
259       (UnOp(op, new_e), new_e_vars)
260     | Ternary(cond, e1, e2) ->
261       let (new_cond, new_cond_vars) = ternarize_expr lhs_var cond in
262       let (new_e1, new_e1_vars) = ternarize_expr lhs_var e1 in
263       let (new_e2, new_e2_vars) = ternarize_expr lhs_var e2 in
264       (Ternary(new_cond, new_e1, new_e2), new_cond_vars @ new_e1_vars @ new_e2_vars)
265     | Call(fname, args) ->
266       let new_args_and_vars = List.map (ternarize_expr lhs_var) args in
267       (Call(fname, (List.map fst new_args_and_vars)), List.concat (List.map snd
            new_args_and_vars))
268     | Selection(e, (sl1, sl2)) ->
269       let (new_e, new_e_vars) = ternarize_expr lhs_var e in
270       let (new_sl1, new_sl1_vars) = ternarize_slice lhs_var sl1 in
271       let (new_sl2, new_sl2_vars) = ternarize_slice lhs_var sl2 in
272       (Selection(new_e, (new_sl1, new_sl2)), new_e_vars @ new_sl1_vars @ new_sl2_vars)
273     | Precedence(e1, e2) ->
274       let (new_e1, new_e1_vars) = ternarize_expr lhs_var e1 in
275       let (new_e2, new_e2_vars) = ternarize_expr lhs_var e2 in
276       (Precedence(new_e1, new_e2), new_e1_vars @ new_e2_vars)
277     | Switch(cond, cases, dflt) ->
```

```
      ternarize_switch lhs_var cases dflt cond
    | Debug(e) ->
      let (new_e, new_e_vars) = ternarize_expr lhs_var e in
      (Debug(new_e), new_e_vars)
    | e -> (e, [])
  and ternarize_switch lhs_var cases dflt cond =
    let (new_cond_expr, new_cond_vars) = (match cond with
          Some cond_expr ->
          let (lhs_varname, lhs_vardef) = lhs_var in
          let new_id = idgen (lhs_varname ^ "_switch_cond") in
          let (new_e, new_e_vars) = ternarize_expr lhs_var cond_expr in
          (Some (Selection(Id(new_id),(Some(Some(Rel(LitInt(0))),None),Some(Some(Rel(
              LitInt(0))),None)))),
           (new_id, {lhs_vardef with var_formulas = [single_formula new_e]}) ::
           new_e_vars)
        | None ->
          (None,[])
    ) in
    let new_cases_and_vars = List.map (ternarize_case lhs_var new_cond_expr) cases in
    let new_cases = List.map fst new_cases_and_vars in
    let new_case_vars = List.concat (List.map snd new_cases_and_vars) in
    let (new_dflt, new_dflt_vars) = ternarize_expr lhs_var dflt in
    let rec combine_everything = function
        [] -> new_dflt
      | (combined_cases, e) :: more_cases -> Ternary(combined_cases, e,
          combine_everything more_cases) in
    (combine_everything new_cases, new_cond_vars @ new_case_vars @ new_dflt_vars)
  and ternarize_case lhs_var cond (conds, e) =
    let new_conds_and_vars = List.map (ternarize_expr lhs_var) conds in
    let new_conds = List.map fst new_conds_and_vars in
    let new_cond_vars = List.concat (List.map snd new_conds_and_vars) in
    let (new_e, new_e_vars) = ternarize_expr lhs_var e in
    let unify_case_cond_and_switch_cond case_cond = function
        None -> case_cond
      | Some switch_cond -> BinOp(switch_cond,Eq,case_cond) in
    let rec unify_switch_cond_and_case_conds switch_cond = function
        [case_cond] -> unify_case_cond_and_switch_cond case_cond switch_cond
      | case_cond :: case_conds ->
        let (combined_expr, _) = ternarize_expr lhs_var
            (BinOp(unify_case_cond_and_switch_cond case_cond switch_cond, LogOr,
                unify_switch_cond_and_case_conds switch_cond case_conds)) in
        combined_expr
      | [] -> raise(LogicError("Empty case condition list")) in
    ((unify_switch_cond_and_case_conds cond new_conds, new_e),new_cond_vars @
       new_e_vars)
  and ternarize_slice lhs_var = function
      None -> (None, [])
    | Some (i1, i2) ->
      let (new_i1, new_i1_vars) = ternarize_index lhs_var i1 in
      let (new_i2, new_i2_vars) = ternarize_index lhs_var i2 in
      (Some (new_i1, new_i2), new_i1_vars @ new_i2_vars)
  and ternarize_index lhs_var = function
      Some Abs(e) ->
      let (new_e, new_e_vars) = ternarize_expr lhs_var e in
      (Some(Abs(new_e)), new_e_vars)
    | Some Rel(e) ->
```

```
330       let (new_e, new_e_vars) = ternarize_expr lhs_var e in
331       (Some(Rel(new_e)), new_e_vars)
332     | i -> (i, []) in
333   let ternarize_formula lhs_var f =
334     let (new_expr, new_vars) = ternarize_expr lhs_var f.formula_expr in
335     ({f with formula_expr = new_expr}, new_vars) in
336   let ternarize_variable varname vardef =
337     let new_formulas_and_vars = List.map (ternarize_formula (varname, vardef)) vardef.
          var_formulas in
338     ({vardef with var_formulas = List.map fst new_formulas_and_vars}, List.concat (
          List.map snd new_formulas_and_vars)) in
339   let ternarize_variables fn_name m =
340     let new_variables_and_maps = StringMap.mapi (fun varname vardef ->
          ternarize_variable (fn_name ^ "_" ^ varname) vardef) m in
341     let add_item var_name (orig_var, new_vars) l = ((var_name, orig_var) :: fst l,
          new_vars :: snd l) in
342     let combined_list = StringMap.fold add_item new_variables_and_maps ([],[]) in
343     map_of_list (List.rev (fst combined_list) @ List.concat (snd combined_list)) in
344   let ternarize_function fn_name fn_def = {fn_def with func_body = ternarize_variables
        fn_name fn_def.func_body} in
345   (ternarize_variables "global" globals, StringMap.mapi ternarize_function functions,
       externs)
346
347 let reduce_ternaries (globals, functions, externs) =
348   let rec reduce_expr lhs_var = function
349     | BinOp(e1, op, e2) ->
350       let (new_e1, new_e1_vars) = reduce_expr lhs_var e1 in
351       let (new_e2, new_e2_vars) = reduce_expr lhs_var  e2 in
352       (BinOp(new_e1, op, new_e2), new_e1_vars @ new_e2_vars)
353     | UnOp(op, e) ->
354       let (new_e, new_e_vars) = reduce_expr lhs_var e in
355       (UnOp(op, new_e), new_e_vars)
356     | Ternary(cond, e1, e2) -> reduce_ternary lhs_var cond e1 e2
357     | Call(fname, args) ->
358       let new_args_and_vars = List.map (reduce_expr lhs_var) args in
359       (Call(fname, (List.map fst new_args_and_vars)), List.concat (List.map snd
            new_args_and_vars))
360     | Selection(e, (sl1, sl2)) ->
361       let (new_e, new_e_vars) = reduce_expr lhs_var e in
362       let (new_sl1, new_sl1_vars) = reduce_slice lhs_var sl1 in
363       let (new_sl2, new_sl2_vars) = reduce_slice lhs_var sl2 in
364       (Selection(new_e, (new_sl1, new_sl2)), new_e_vars @ new_sl1_vars @ new_sl2_vars)
365     | Precedence(e1, e2) ->
366       let (new_e1, new_e1_vars) = reduce_expr lhs_var e1 in
367       let (new_e2, new_e2_vars) = reduce_expr lhs_var e2 in
368       (Precedence(new_e1, new_e2), new_e1_vars @ new_e2_vars)
369     | Debug(e) ->
370       let (new_e, new_e_vars) = reduce_expr lhs_var e in
371       (Debug(new_e), new_e_vars)
372     | e -> (e, [])
373   and reduce_ternary lhs_var cond e1 e2 =
374     let (new_cond, new_cond_vars) = reduce_expr lhs_var cond in
375     let (new_true_e, new_true_vars) = reduce_expr lhs_var e1 in
376     let (new_false_e, new_false_vars) = reduce_expr lhs_var e2 in
377     let (lhs_varname, lhs_vardef) = lhs_var in
378     let new_cond_id = idgen (lhs_varname ^ "_truthiness") in
```

```
    let new_true_id = idgen (lhs_varname ^ "_values_if_true") in
    let new_false_id = idgen (lhs_varname ^ "_values_if_false") in
    (ReducedTernary(new_cond_id, new_true_id, new_false_id),
     (new_cond_id, {lhs_vardef with var_formulas = [single_formula (UnOp(Truthy,
        new_cond))]}) ::
     (new_true_id, {lhs_vardef with var_formulas = [single_formula new_true_e]}) ::
     (new_false_id, {lhs_vardef with var_formulas = [single_formula new_false_e]}) ::
     (new_cond_vars @ new_true_vars @ new_false_vars))
  and reduce_slice lhs_var = function
      None -> (None, [])
    | Some (i1, i2) ->
      let (new_i1, new_i1_vars) = reduce_index lhs_var i1 in
      let (new_i2, new_i2_vars) = reduce_index lhs_var i2 in
      (Some (new_i1, new_i2), new_i1_vars @ new_i2_vars)
  and reduce_index lhs_var = function
      Some Abs(e) ->
      let (new_e, new_e_vars) = reduce_expr lhs_var e in
      (Some(Abs(new_e)), new_e_vars)
    | Some Rel(e) ->
      let (new_e, new_e_vars) = reduce_expr lhs_var e in
      (Some(Rel(new_e)), new_e_vars)
    | i -> (i, []) in
  let reduce_formula lhs_var f =
    let (new_expr, new_vars) = reduce_expr lhs_var f.formula_expr in
    ({f with formula_expr = new_expr}, new_vars) in
  let reduce_variable varname vardef =
    let new_formulas_and_vars = List.map (reduce_formula (varname, vardef)) vardef.
       var_formulas in
    ({vardef with var_formulas = List.map fst new_formulas_and_vars}, List.concat (
       List.map snd new_formulas_and_vars)) in
  let reduce_variables fn_name m =
    let new_variables_and_maps = StringMap.mapi (fun varname vardef -> reduce_variable
        (fn_name ^ "_" ^ varname) vardef) m in
    let add_item var_name (orig_var, new_vars) l = ((var_name, orig_var) :: fst l,
       new_vars :: snd l) in
    let combined_list = StringMap.fold add_item new_variables_and_maps ([],[]) in
    map_of_list (List.rev (fst combined_list) @ List.concat (snd combined_list)) in
  let reduce_function fn_name fn_def = {fn_def with func_body = reduce_variables
      fn_name fn_def.func_body} in
  (reduce_variables "global" globals, StringMap.mapi reduce_function functions,
     externs)

let create_ast filename =
  let ast_imp_res = expand_file true filename in
  let ast_expanded = expand_expressions ast_imp_res in
  let ast_mapped = create_maps ast_expanded in check_semantics ast_mapped ;
  let ast_ternarized = ternarize_exprs ast_mapped in
  let ast_reduced = reduce_ternaries ast_ternarized in check_semantics ast_reduced ;
  ast_reduced
```

8.5 semant.ml

```
open Ast

exception IllegalExpression of string;;
```

```
4  exception DuplicateDefinition of string;;
5  exception UnknownVariable of string;;
6  exception UnknownFunction of string;;
7  exception WrongNumberArgs of string;;
8  exception LogicError of string;;
9
10 type symbol = LocalVariable of int | GlobalVariable of int | FunctionParameter of int
       | ExtendFunction of int
11 and  symbolTable = symbol StringMap.t
12 and  symbolTableType = Locals | Globals | ExtendFunctions
13
14 let map_of_list list_of_tuples =
15   (*  map_of_list: Take a list of the form [("foo", 2); ("bar", 3)]
16       and create a StringMap using the first value of the tuple as
17       the key and the second value of the tuple as the value. Raises
18       an exception if the key appears more than once in the list. *)
19   let rec aux acc = function
20       [] -> acc
21     | t :: ts ->
22       if (StringMap.mem (fst t) acc) then raise(DuplicateDefinition(fst t))
23       else aux (StringMap.add (fst t) (snd t) acc) ts in
24   aux StringMap.empty list_of_tuples
25
26 let index_map table_type m =
27   let add_item key _ (accum_map, accum_idx) =
28     let index_val = match table_type with Locals -> LocalVariable(accum_idx) | Globals
           -> GlobalVariable(accum_idx) | ExtendFunctions -> ExtendFunction(accum_idx) in
29     (StringMap.add key index_val accum_map, accum_idx + 1) in
30   StringMap.fold add_item m (StringMap.empty, 0)
31
32 let create_symbol_table global_symbols fn_def =
33   let (local_indices, _) = index_map Locals fn_def.func_body in
34   let add_param (st, idx) param_name =
35     let new_st = StringMap.add param_name (FunctionParameter(idx)) st in
36     (new_st, idx + 1) in
37   let (params_and_globals, _) = List.fold_left add_param (global_symbols, 0) (List.map
         snd fn_def.func_params) in
38   StringMap.fold StringMap.add local_indices params_and_globals
39
40 let check_semantics (globals, functions, externs) =
41   let fn_signatures = map_of_list
42       ((StringMap.fold (fun s f l -> (s, List.length f.func_params) :: l) functions
             []) @
43        (StringMap.fold (fun s f l -> (s, List.length f.extern_fn_params) :: l) externs
              [])) in
44   let (global_symbols, _) = index_map Globals globals in
45
46   let check_call context called_fname num_args =
47     if (not (StringMap.mem called_fname fn_signatures)) then
48       (print_endline ("In " ^ context ^ "(), the undefined function " ^ called_fname ^
             "() was called") ;
49        raise(UnknownFunction(context ^ "," ^ called_fname)))
50     else let signature_args = StringMap.find called_fname fn_signatures in
51       if num_args != signature_args then
52         (print_endline ("In " ^ context ^ "(), the function " ^ called_fname ^ "() was
              called with " ^
```

```
53                        string_of_int num_args ^ " arguments " ^ "but the signature
                              specifies "
54                        ^ string_of_int signature_args) ;
55          raise(WrongNumberArgs(context ^ "," ^ called_fname)))
56       else () in
57
58   let rec check_expr fname symbols = function
59       BinOp(e1,_,e2) -> check_expr fname symbols e1 ; check_expr fname symbols e2
60     | UnOp(_, e) -> check_expr fname symbols e
61     | Ternary(cond, e1, e2) -> check_expr fname symbols cond ; check_expr fname
         symbols e1 ; check_expr fname symbols e2
62     | ReducedTernary(s1, s2, s3) -> check_expr fname symbols (Id(s1)) ; check_expr
         fname symbols (Id(s2)) ; check_expr fname symbols (Id(s3))
63     | Id(s) -> if StringMap.mem s symbols then () else raise(UnknownVariable(fname ^
         "(): " ^ s))
64     | Switch(Some e, cases, dflt) -> check_expr fname symbols e ; List.iter (fun c ->
         check_case fname symbols c) cases ; check_expr fname symbols dflt
65     | Switch(None, cases, dflt) -> List.iter (fun c -> check_case fname symbols c)
         cases ; check_expr fname symbols dflt
66     | Call(called_fname, args) ->
67       check_call fname called_fname (List.length args) ;
68       List.iter (fun a -> check_expr fname symbols a) args
69     | Selection(e, (sl1, sl2)) -> check_expr fname symbols e ; check_slice fname
         symbols sl1 ; check_slice fname symbols sl2
70     | Precedence(e1, e2) -> check_expr fname symbols e1 ; check_expr fname symbols e2
71     | Debug(e) -> check_expr fname symbols e;
72     | LitInt(_) | LitFlt(_) | LitRange(_) | LitString(_) | Empty -> ()
73   and check_case fname symbols (conds, e) = List.iter (fun c -> check_expr fname
       symbols c) conds ; check_expr fname symbols e
74   and check_slice fname symbols = function
75       None -> ()
76     | Some (i1, i2) -> check_index fname symbols i1 ; check_index fname symbols i2
77   and check_index fname symbols = function
78       Some Abs(e) -> check_expr fname symbols e
79     | Some Rel(e) -> check_expr fname symbols e
80     | _ -> () in
81   let check_formula fname symbols f =
82     check_index fname symbols (Some f.formula_row_start) ;
83     check_index fname symbols f.formula_row_end ;
84     check_index fname symbols (Some f.formula_col_start) ;
85     check_index fname symbols f.formula_col_end ;
86     check_expr fname symbols f.formula_expr in
87   let check_dim fname symbols = function
88       DimOneByOne -> ()
89     | DimId(s) -> check_expr fname symbols (Id(s)) in
90   let check_variable fname symbols v =
91     check_dim fname symbols v.var_rows ;
92     check_dim fname symbols v.var_cols ;
93     List.iter (fun f -> check_formula fname symbols f) v.var_formulas in
94   let check_variables context symbols vars =
95     StringMap.iter (fun _ v -> check_variable context symbols v) vars in
96
97   let check_function fname f =
98     if StringMap.mem fname externs then raise(DuplicateDefinition(fname ^ "() is
         defined as both an external and local function")) else ();
99     let locals = f.func_body in
```

```
    let params = List.map snd f.func_params in
    List.iter
      (fun param ->
         if StringMap.mem param locals then raise(DuplicateDefinition(param ^ " is
             defined multiple times in " ^ fname ^ "()"))
         else ())
      params ;
    let local_symbols = create_symbol_table global_symbols f in
    check_variables fname local_symbols f.func_body ;
    check_expr fname local_symbols (snd f.func_ret_val)

  in check_variables "global_variables" global_symbols globals ; StringMap.iter
      check_function functions
```

8.6 codeGenTypes.ml

```
type something = {
  var_instance_t : Llvm.lltype;
  subrange_t : Llvm.lltype;
  resolved_formula_t : Llvm.lltype;
  value_t : Llvm.lltype;
  dimensions_t : Llvm.lltype;
  var_defn_t : Llvm.lltype;
  var_defn_p : Llvm.lltype;
  string_t : Llvm.lltype;
  number_t : Llvm.lltype;
  extend_scope_t : Llvm.lltype;
  formula_t : Llvm.lltype;
  formula_call_t : Llvm.lltype;
  formula_p : Llvm.lltype;
  formula_call_p : Llvm.lltype;
  var_instance_p : Llvm.lltype;
  subrange_p : Llvm.lltype;
  resolved_formula_p : Llvm.lltype;
  value_p : Llvm.lltype;
  extend_scope_p : Llvm.lltype;
  string_p : Llvm.lltype;
  string_p_p : Llvm.lltype;
  var_instance_p_p : Llvm.lltype;
  int_t : Llvm.lltype;
  long_t : Llvm.lltype;
  flags_t : Llvm.lltype;
  char_t : Llvm.lltype;
  bool_t : Llvm.lltype;
  void_t : Llvm.lltype;
  char_p : Llvm.lltype;
  char_p_p : Llvm.lltype;
  (*void_p : Llvm.lltype;*)
  float_t : Llvm.lltype;
  rhs_index_t : Llvm.lltype;
  rhs_slice_t : Llvm.lltype;
  rhs_selection_t : Llvm.lltype;
  rhs_index_p : Llvm.lltype;
  rhs_slice_p : Llvm.lltype;
  rhs_selection_p : Llvm.lltype;
```

```
};;

type scope_field_type = VarDefn | VarInst | VarNum | ScopeRefCount | FunctionParams
let scope_field_type_index = function
    VarDefn -> 0
  | VarInst -> 1
  | VarNum -> 2
  | ScopeRefCount -> 3
  | FunctionParams -> 4

type value_field_flags = Empty | Number | String | Range
let value_field_flags_index = function
    Empty -> 0
  | Number -> 1
  | String -> 2
  | Range -> 3
let int_to_type_array = [|"Empty"; "Number"; "String"; "Range"|]

type value_field = Flags | Number | String | Subrange
let value_field_index = function
    Flags -> 0
  | Number -> 1
  | String -> 2
  | Subrange -> 3

type var_defn_field = Rows | Cols | NumFormulas | Formulas | OneByOne | VarName
let var_defn_field_index = function
    Rows -> 0
  | Cols -> 1
  | NumFormulas -> 2
  | Formulas -> 3
  | OneByOne -> 4
  | VarName -> 5

type formula_field  = FromFirstRow | RowStartNum | ToLastRow | RowEndNum |
    FromFirstCols | ColStartNum | ToLastCol | ColEndNum | IsSingleRow | IsSingleCol |
    FormulaCall
let formula_field_index = function
    FromFirstRow -> 0
  | RowStartNum -> 1
  | ToLastRow -> 2
  | RowEndNum -> 3
  | FromFirstCols -> 4
  | ColStartNum -> 5
  | ToLastCol -> 6
  | ColEndNum -> 7
  | IsSingleRow -> 8
  | IsSingleCol -> 9
  | FormulaCall -> 10

type var_instance_field = Rows | Cols | NumFormulas | Formulas | Closure | Values |
    Status
let var_instance_field_index = function
    Rows -> 0
  | Cols -> 1
  | NumFormulas -> 2
```

```
  | Formulas -> 3
  | Closure -> 4
  | Values -> 5
  | Status -> 6

type var_instance_status_flags = NeverExamined | Calculated | InProgress
let var_instance_status_flags_index = function
    NeverExamined -> 0
  | Calculated -> 2
  | InProgress -> 4

type subrange_field = BaseRangePtr | BaseOffsetRow | BaseOffsetCol | SubrangeRows |
    SubrangeCols
let subrange_field_index = function
    BaseRangePtr -> 0
  | BaseOffsetRow -> 1
  | BaseOffsetCol -> 2
  | SubrangeRows -> 3
  | SubrangeCols -> 4

type dimensions_field = DimensionRows | DimensionCols
let dimensions_field_index = function
    DimensionRows -> 0
  | DimensionCols -> 1

type string_field = StringCharPtr | StringLen | StringRefCount
let string_field_index = function
    StringCharPtr -> 0
  | StringLen -> 1
  | StringRefCount -> 2

type rhs_index_field = RhsExprVal | RhsIndexType
let rhs_index_field_index = function
    RhsExprVal -> 0
  | RhsIndexType -> 1

type rhs_index_type_flags = RhsIdxAbs | RhsIdxRel | RhsIdxDimStart | RhsIdxDimEnd
let rhs_index_type_flags_const = function
    RhsIdxAbs -> 0
  | RhsIdxRel -> 1
  | RhsIdxDimStart -> 2
  | RhsIdxDimEnd -> 4 (* No 3 *)

type rhs_slice_field = RhsSliceStartIdx | RhsSliceEndIdx
let rhs_slice_field_index = function
    RhsSliceStartIdx -> 0
  | RhsSliceEndIdx -> 1

type rhs_selection_field = RhsSelSlice1 | RhsSelSlice2
let rhs_selection_field_index = function
    RhsSelSlice1 -> 0
  | RhsSelSlice2 -> 1

let setup_types ctx =
  let var_instance_t = Llvm.named_struct_type ctx "var_instance" (*Range struct is a 2
      D Matrix of values*)
```

```
147   and subrange_t = Llvm.named_struct_type ctx "subrange" (*Subrange is a wrapper
          around a range to cut cells*)
148   and int_t = Llvm.i32_type ctx (*Integer*)
149   and long_t = Llvm.i64_type ctx
150   and float_t = Llvm.double_type ctx
151   and flags_t = Llvm.i8_type ctx (*Flags for statuses*)
152   and char_t = Llvm.i8_type ctx (*Simple ASCII character*)
153   and bool_t = Llvm.i1_type ctx (*boolean 0 = false, 1 = true*)
154   and void_t = Llvm.void_type ctx (**)
155   and value_t = Llvm.named_struct_type ctx "value" (*Value encapsulates the content of
           a cell*)
156   and dimensions_t = Llvm.named_struct_type ctx "dimensions" (**)
157   and resolved_formula_t = Llvm.named_struct_type ctx "resolved_formula"
158   and extend_scope_t = Llvm.named_struct_type ctx "extend_scope"
159   and var_defn_t = Llvm.named_struct_type ctx "var_def"
160   and formula_t = Llvm.named_struct_type ctx "formula"
161   and string_t = Llvm.named_struct_type ctx "string" in
162   let var_instance_p = (Llvm.pointer_type var_instance_t)
163   and var_defn_p = Llvm.pointer_type var_defn_t
164   and resolved_formula_p = (Llvm.pointer_type resolved_formula_t)
165   and subrange_p = (Llvm.pointer_type subrange_t)
166   and value_p = (Llvm.pointer_type value_t)
167   and value_p_p = (Llvm.pointer_type (Llvm.pointer_type value_t))
168   and extend_scope_p = (Llvm.pointer_type extend_scope_t)
169   and char_p = (Llvm.pointer_type char_t)
170   and string_p = (Llvm.pointer_type string_t)
171   and char_p_p = (Llvm.pointer_type (Llvm.pointer_type char_t))
172   and string_p_p = (Llvm.pointer_type (Llvm.pointer_type string_t))
173   and number_t = float_t
174   and formula_p = (Llvm.pointer_type formula_t) in
175   let rhs_index_t = Llvm.named_struct_type ctx "rhs_index"
176   and rhs_slice_t = Llvm.named_struct_type ctx "rhs_slice"
177   and rhs_selection_t = Llvm.named_struct_type ctx "rhs_selection" in
178   let rhs_index_p = Llvm.pointer_type rhs_index_t
179   and rhs_slice_p = Llvm.pointer_type rhs_slice_t
180   and rhs_selection_p = Llvm.pointer_type rhs_selection_t
181   (*and void_p = (Llvm.pointer_type void_t)*) in
182   let var_instance_p_p = (Llvm.pointer_type var_instance_p)
183   and formula_call_t = (Llvm.function_type value_p [|extend_scope_p(*scope*); int_t(*
          row*); int_t(*col*)|]) in
184   let formula_call_p = Llvm.pointer_type formula_call_t in
185   let _ = Llvm.struct_set_body rhs_index_t (Array.of_list [
186       value_p (*val_of_expr*);
187       char_t (*rhs_index_type*);
188     ]) false in
189   let _ = Llvm.struct_set_body rhs_slice_t (Array.of_list [
190       rhs_index_p (*slice start index*);
191       rhs_index_p (*slice end index*);
192     ]) false in
193   let _ = Llvm.struct_set_body rhs_selection_t (Array.of_list [
194       rhs_slice_p (*first slice*);
195       rhs_slice_p (*second slice*);
196     ]) false in
197   let _ = Llvm.struct_set_body var_instance_t (Array.of_list [
198       int_t(*rows*);
199       int_t(*columns*);
```

```
      int_t(*numFormulas*);
      resolved_formula_p(*formula with resolved dimensions*);
      extend_scope_p(*scope that contains all variables of a function*);
      value_p_p(*2D array of cell values*);
      char_p(*2D array of calculation status for each cell*);
      char_p(*Name*);
    ]) false
  and _ = Llvm.struct_set_body var_defn_t (Array.of_list [
      int_t(*Rows*);
      int_t(*Cols*);
      int_t(*Number of formulas*);
      formula_p;
      char_t(*Is one by one range*);
      char_p(*Name*);
    ]) false
  and _ = Llvm.struct_set_body formula_t (Array.of_list [
      char_t (*from First row*);
      int_t (*row Start num*);
      char_t (*to last row*);
      int_t (*row end num*);
      char_t (*from first col*);
      int_t (*col start*);
      char_t (*to last col*);
      int_t (*col end num*);
      char_t (* is single row *);
      char_t (* is single col *);
      formula_call_p (*formula to call*);
    ]) false
  and _ = Llvm.struct_set_body extend_scope_t (Array.of_list [
      var_defn_p(*variable definitions*);
      var_instance_p_p(*variable instances*);
      int_t(*number of variables*);
      int_t(*reference count*);
      Llvm.pointer_type value_p;
    ]) false
  and _ = Llvm.struct_set_body subrange_t (Array.of_list [
      var_instance_p(*The target range*);
      int_t(*row offset*);
      int_t(*column offset*);
      int_t(*row count*);
      int_t(*column count*)
    ]) false
  and _ = Llvm.struct_set_body value_t (Array.of_list [
      flags_t (*First bit indicates whether it is an int or a range*);
      number_t (*Numeric value of the cell*);
      string_p (*String value of the cell if applicable*);
      subrange_p (*Range value of the cell if applicable*);
      (*float_t (Double value of the cell*)
    ]) false
  and _ = Llvm.struct_set_body string_t (Array.of_list [
      char_p (*Pointer to null-terminated string*);
      long_t (*Length of string*);
      int_t (*Reference count*)
    ]) false
  and _ = Llvm.struct_set_body dimensions_t (Array.of_list [int_t; int_t]) false in
  {
```

```
    var_instance_t = var_instance_t;
    value_t = value_t;
    subrange_t = subrange_t;
    resolved_formula_t = resolved_formula_t;
    dimensions_t = dimensions_t;
    number_t = number_t;
    string_t = string_t;
    extend_scope_t = extend_scope_t;
    formula_t = formula_t;
    formula_call_t = formula_call_t;

    var_defn_t = var_defn_t;
    var_defn_p = var_defn_p;
    var_instance_p = var_instance_p;
    subrange_p = subrange_p;
    value_p = value_p;
    resolved_formula_p = resolved_formula_p;
    string_p = string_p;
    char_p = char_p;
    extend_scope_p = extend_scope_p;
    formula_p = formula_p;
    formula_call_p = formula_call_p;

    var_instance_p_p = var_instance_p_p;

    int_t = int_t;
    long_t = long_t;
    float_t = float_t;
    flags_t = flags_t;
    bool_t = bool_t;
    char_t = char_t;
    void_t = void_t;
    char_p_p = char_p_p;
    string_p_p = string_p_p;

    rhs_index_t = rhs_index_t;
    rhs_slice_t = rhs_slice_t;
    rhs_selection_t = rhs_selection_t;
    rhs_index_p = rhs_index_p;
    rhs_slice_p = rhs_slice_p;
    rhs_selection_p = rhs_selection_p;
  }
```

8.7 codegen.ml

```
(* Extend code generator *)

open Ast
open Semant
open CodeGenTypes
exception NotImplemented

let runtime_functions = Hashtbl.create 20

let (=>) struct_ptr elem = (fun val_name builder ->
```

```
11      let the_pointer = Llvm.build_struct_gep struct_ptr elem "the_pointer" builder in
12      Llvm.build_load the_pointer val_name builder);;
13
14  let ($>) val_to_store (struct_ptr, elem)  = (fun builder ->
15      let the_pointer = Llvm.build_struct_gep struct_ptr elem "" builder in
16      Llvm.build_store val_to_store the_pointer builder);;
17
18  (* from http://stackoverflow.com/questions/243864/what-is-the-ocaml-idiom-equivalent-
       to-pythons-range-function without the infix *)
19  let zero_until i =
20    let rec aux n acc =
21      if n < 0 then acc else aux (n-1) (n :: acc)
22    in aux (i-1) []
23
24  let create_runtime_functions ctx bt the_module =
25    let add_runtime_func fname returntype arglist =
26      let the_func = Llvm.declare_function fname (Llvm.function_type returntype arglist)
           the_module
27      in Hashtbl.add runtime_functions fname the_func in
28    add_runtime_func "strlen" bt.long_t [|bt.char_p|];
29    add_runtime_func "strcmp" bt.long_t [|bt.char_p; bt.char_p|];
30    add_runtime_func "pow" bt.float_t [|bt.float_t; bt.float_t|] ;
31    add_runtime_func "lrint" bt.int_t [|bt.float_t|] ;
32    add_runtime_func "llvm.memcpy.p0i8.p0i8.i64" bt.void_t [|bt.char_p; bt.char_p; bt.
        long_t; bt.int_t; bt.bool_t|] ;
33    add_runtime_func "incStack" bt.void_t [||] ;
34    add_runtime_func "getVal" bt.value_p [|bt.var_instance_p; bt.int_t; bt.int_t|] ;
35    add_runtime_func "rg_eq" bt.int_t [|bt.value_p; bt.value_p|] ;
36    add_runtime_func "clone_value" bt.value_p [|bt.value_p;|] ;
37    (* add_runtime_func "freeMe" (Llvm.void_type ctx) [|bt.extend_scope_p;|] ; *)
38    add_runtime_func "getSize" bt.value_p [|bt.var_instance_p;|] ;
39    add_runtime_func "get_variable" bt.var_instance_p [|bt.extend_scope_p; bt.int_t|] ;
40    add_runtime_func "null_init" (Llvm.void_type ctx) [|bt.extend_scope_p|] ;
41    add_runtime_func "debug_print" (Llvm.void_type ctx) [|bt.value_p ; bt.char_p|] ;
42    add_runtime_func "new_string" bt.value_p [|bt.char_p|] ;
43    add_runtime_func "deref_subrange_p" bt.value_p [|bt.subrange_p|];
44    add_runtime_func "debug_print_selection" (Llvm.void_type ctx) [|bt.rhs_selection_p
        |];
45    add_runtime_func "extract_selection" bt.value_p [|bt.value_p; bt.rhs_selection_p; bt
        .int_t; bt.int_t|];
46    add_runtime_func "box_command_line_args" bt.value_p [|bt.int_t; bt.char_p_p|];
47    add_runtime_func "verify_assert" (Llvm.void_type ctx) [|bt.value_p; bt.char_p|];
48    ()
49
50  let translate (globals, functions, externs) =
51
52    (* LLVM Boilerplate *)
53    let context = Llvm.global_context () in
54    let base_module = Llvm.create_module context "Extend" in
55    let base_types = setup_types context in
56
57    (* Declare the runtime functions that we need to call *)
58    create_runtime_functions context base_types base_module ;
59
60    (* Build function_llvalues, which is a StringMap from function name to llvalue.
61     * It includes both functions from external libraries, such as the standard library,
```

```
62    * and functions declared within Extend. *)
63   let declare_library_function fname func accum_map =
64     let llvm_ftype = Llvm.function_type base_types.value_p (Array.of_list (List.map (
          fun a -> base_types.value_p) func.extern_fn_params)) in
65     let llvm_fname = "extend_" ^ fname in
66     let llvm_fn = Llvm.declare_function llvm_fname llvm_ftype base_module in
67     StringMap.add fname llvm_fn accum_map in
68   let library_functions = StringMap.fold declare_library_function externs StringMap.
       empty in
69   let define_user_function fname func =
70     let llvm_fname = "extend_" ^ fname in
71     let llvm_ftype = Llvm.function_type base_types.value_p (Array.of_list (List.map (
          fun a -> base_types.value_p) func.func_params)) in
72     let llvm_fn = Llvm.define_function llvm_fname llvm_ftype base_module in
73     (func, llvm_fn) in
74   let extend_functions = StringMap.mapi define_user_function functions in
75   let function_llvalues = StringMap.fold StringMap.add (StringMap.map snd
       extend_functions) library_functions in
76
77   (* Build the global symbol table *)
78   let (global_symbols, num_globals) = index_map Globals globals in
79   let (extend_fn_numbers, num_extend_fns) = index_map ExtendFunctions extend_functions
        in
80
81   (* Create the global array that will hold each function's array of var_defns. *)
82   let vardefn_ptr = Llvm.const_pointer_null base_types.var_defn_p in
83   let vardefn_array = Array.make (StringMap.cardinal extend_functions) vardefn_ptr in
84   let array_of_vardefn_ptrs = Llvm.define_global "array_of_vardefn_ptrs" (Llvm.
       const_array base_types.var_defn_p vardefn_array) base_module in
85
86   (* Create the pointer to the global scope object *)
87   let global_scope_loc = Llvm.define_global "global_scope_loc" (Llvm.
       const_pointer_null base_types.extend_scope_p) base_module in
88
89   let main_def = Llvm.define_function "main" (Llvm.function_type base_types.int_t [|
       base_types.int_t; base_types.char_p_p|]) base_module in
90   let main_bod = Llvm.builder_at_end context (Llvm.entry_block main_def) in
91
92   let init_def = Llvm.define_function "initialize_vardefns" (Llvm.function_type (Llvm.
       void_type context) [||]) base_module in
93   let init_bod = Llvm.builder_at_end context (Llvm.entry_block init_def) in
94
95   let literal_def = Llvm.define_function "initialize_literals" (Llvm.function_type (
       Llvm.void_type context) [||]) base_module in
96   let literal_bod = Llvm.builder_at_end context (Llvm.entry_block literal_def) in
97
98   (* Create the array of value_ps that will contain the responses to TypeOf(val) *)
99   let null_val_ptr = Llvm.const_pointer_null base_types.value_p in
100  let null_val_array = Array.make (Array.length int_to_type_array) null_val_ptr in
101  let array_of_typeof_val_ptrs = Llvm.define_global "array_of_val_ptrs" (Llvm.
       const_array base_types.value_p null_val_array) base_module in
102  let create_typeof_string i s =
103    let sp = Llvm.build_global_stringptr s "global_typeof_stringptr" literal_bod in
104    let vp = Llvm.build_call (Hashtbl.find runtime_functions "new_string") [|sp|] "
         global_typeof_string" literal_bod in
105    let vp_dst = Llvm.build_in_bounds_gep array_of_typeof_val_ptrs [|Llvm.const_int
```

```
       base_types.int_t 0; Llvm.const_int base_types.int_t i|] ("global_typeof_dst")
       literal_bod in
106    let _ = Llvm.build_store vp vp_dst literal_bod in
107    () in
108  Array.iteri create_typeof_string int_to_type_array ;
109
110  (* Look these two up once and for all *)
111  (* let deepCopy = Hashtbl.find runtime_functions "deepCopy" in *)
112  (* let freeMe = Hashtbl.find runtime_functions "freeMe" in *)
113  let getVal = Hashtbl.find runtime_functions "getVal" in (*getVal retrieves the value
       of a variable instance for a specific x and y*)
114  let getVar = Hashtbl.find runtime_functions "get_variable" in (*getVar retrieves a
       variable instance based on the offset. It instanciates the variable if it does
       not exist yet*)
115
116  (* build_formula_function takes a symbol table and an expression, builds the LLVM
       function, and returns the llvalue of the function *)
117  let build_formula_function (varname, formula_idx) symbols formula_expr =
118    let form_decl = Llvm.define_function ("formula_fn_" ^ varname ^ "_num_" ^ (
         string_of_int formula_idx)) base_types.formula_call_t base_module in
119    let builder_at_top = Llvm.builder_at_end context (Llvm.entry_block form_decl) in
120    let local_scope = Llvm.param form_decl 0 in
121    let cell_row = Llvm.param form_decl 1 in
122    let cell_col = Llvm.param form_decl 2 in
123    let global_scope = Llvm.build_load global_scope_loc "global_scope" builder_at_top
         in
124
125    (* Some repeated stuff to avoid cut & paste *)
126    let empty_type = (Llvm.const_int base_types.char_t (value_field_flags_index Empty)
         ) in
127    let number_type = (Llvm.const_int base_types.char_t (value_field_flags_index
         Number)) in
128    let string_type = (Llvm.const_int base_types.char_t (value_field_flags_index
         String)) in
129    let range_type = (Llvm.const_int base_types.char_t (value_field_flags_index Range)
         ) in
130    let make_block blockname =
131      let new_block = Llvm.append_block context blockname form_decl in
132      let new_builder = Llvm.builder_at_end context new_block in
133      (new_block, new_builder) in
134    let store_number value_ptr store_builder number_llvalue =
135      let sp = Llvm.build_struct_gep value_ptr (value_field_index Number) "num_pointer
           " store_builder in
136      let _ = Llvm.build_store number_type (Llvm.build_struct_gep value_ptr (
           value_field_index Flags) "" store_builder) store_builder in
137      ignore (Llvm.build_store number_llvalue sp store_builder) in
138    let store_empty value_ptr store_builder =
139      ignore (Llvm.build_store empty_type (Llvm.build_struct_gep value_ptr (
           value_field_index Flags) "" store_builder) store_builder) in
140
141    let make_truthiness_blocks blockprefix ret_val =
142      let (merge_bb, merge_builder) = make_block (blockprefix ^ "_merge") in
143
144      let (make_true_bb, make_true_builder) = make_block (blockprefix ^ "_true") in
145      let _ = store_number ret_val make_true_builder (Llvm.const_float base_types.
           float_t 1.0) in
```

```
146       let _ = Llvm.build_br merge_bb make_true_builder in
147
148       let (make_false_bb, make_false_builder) = make_block (blockprefix ^ "_false") in
149       let _ = store_number ret_val make_false_builder (Llvm.const_float base_types.
              float_t 0.0) in
150       let _ = Llvm.build_br merge_bb make_false_builder in
151
152       let (make_empty_bb, make_empty_builder) = make_block (blockprefix ^ "_empty") in
153       let _ = store_empty ret_val make_empty_builder  in
154       let _ = Llvm.build_br merge_bb make_empty_builder in
155
156       (make_true_bb, make_false_bb, make_empty_bb, merge_builder) in
157
158     let rec build_expr old_builder exp = match exp with
159         LitInt(i) -> let vvv = Llvm.const_float base_types.float_t (float_of_int i) in
160         let ret_val = Llvm.build_malloc base_types.value_t "int_ret_val" old_builder
                in
161         let _ = store_number ret_val old_builder vvv in
162         (ret_val, old_builder)
163       | LitFlt(f) -> let vvv = Llvm.const_float base_types.float_t f in
164         let ret_val = Llvm.build_malloc base_types.value_t "flt_ret_val" old_builder
                in
165         let _ = store_number ret_val old_builder vvv in
166         (ret_val, old_builder)
167       | UnOp(Neg, LitInt(i)) -> build_expr old_builder (LitInt(-i))
168       | UnOp(Neg, LitFlt(f)) -> build_expr old_builder (LitFlt(-.f))
169       | Empty ->
170         let ret_val = Llvm.build_malloc base_types.value_t "empty_ret_val" old_builder
                 in
171         let _ = store_empty ret_val old_builder in
172         (ret_val, old_builder)
173       | Debug(e) ->
174         let (ret_val, new_builder) = build_expr old_builder e in
175         let _ = Llvm.build_call (Hashtbl.find runtime_functions "debug_print") [|
              ret_val; Llvm.const_pointer_null base_types.char_p|] "" new_builder in
176         (ret_val, new_builder)
177       | Id(name) ->
178         let create_and_deref_subrange appropriate_scope i =
179           let llvm_var = Llvm.build_call getVar [|appropriate_scope; Llvm.const_int
                base_types.int_t i|] "llvm_var" old_builder in
180           let base_var_num_rows = (llvm_var => (var_instance_field_index Rows)) "
                base_var_num_rows" old_builder in
181           let base_var_num_cols = (llvm_var => (var_instance_field_index Cols)) "
                base_var_num_rows" old_builder in
182           let subrange_ptr = Llvm.build_alloca base_types.subrange_t "subrange_ptr"
                old_builder in
183           let _ = (llvm_var $> (subrange_ptr, (subrange_field_index BaseRangePtr)))
                old_builder in
184           let _ = ((Llvm.const_null base_types.int_t) $> (subrange_ptr, (
                subrange_field_index BaseOffsetRow))) old_builder in
185           let _ = ((Llvm.const_null base_types.int_t) $> (subrange_ptr, (
                subrange_field_index BaseOffsetCol))) old_builder in
186           let _ = (base_var_num_rows $> (subrange_ptr, (subrange_field_index
                SubrangeRows))) old_builder in
187           let _ = (base_var_num_cols $> (subrange_ptr, (subrange_field_index
                SubrangeCols))) old_builder in
```

```
188           (Llvm.build_call (Hashtbl.find runtime_functions "deref_subrange_p") [|
                  subrange_ptr|] "local_id_ret_val" old_builder, old_builder) in
189         (
190           match (try StringMap.find name symbols with Not_found -> raise(LogicError("
                  Something went wrong with your semantic analysis - " ^ name ^ " not found
                  "))) with
191             LocalVariable(i) -> create_and_deref_subrange local_scope i
192           | GlobalVariable(i) -> create_and_deref_subrange global_scope i
193           | FunctionParameter(i) ->
194             let paramarray = (local_scope => (scope_field_type_index FunctionParams))
                    "paramarray" old_builder in
195             let param_addr = Llvm.build_in_bounds_gep paramarray [|Llvm.const_int
                    base_types.int_t i|] "param_addr" old_builder in
196             let param = Llvm.build_load param_addr "param" old_builder in
197             (Llvm.build_call (Hashtbl.find runtime_functions "clone_value") [|param|]
                    "function_param_ret_val" old_builder, old_builder)
198           | ExtendFunction(i) -> raise(LogicError("Something went wrong with your
                  semantic analyis - function " ^ name ^ " used as variable in RHS for " ^
                  varname))
199         )
200       | ReducedTernary(cond_var, true_var, false_var) ->
201         let get_llvm_var name getvar_builder =
202           match (try StringMap.find name symbols with Not_found -> raise(LogicError("
                  Something went wront with your transformation - Reduced Ternary name " ^
                  name ^ " not found"))) with
203             LocalVariable(i) -> Llvm.build_call getVar [|local_scope; Llvm.const_int
                    base_types.int_t i|] "llvm_var" getvar_builder
204           | GlobalVariable(i) -> Llvm.build_call getVar [|global_scope; Llvm.const_int
                    base_types.int_t i|] "llvm_var" getvar_builder
205           | _ -> raise(LogicError("Something went wront with your transformation -
                  Reduced Ternary name " ^ name ^ " not a local or global variable")) in
206
207         let (empty_bb, empty_builder) = make_block "empty" in
208         let (not_empty_bb, not_empty_builder) = make_block "not_empty" in
209         let (truthy_bb, truthy_builder) = make_block "truthy" in
210         let (falsey_bb, falsey_builder) = make_block "falsey" in
211         let (merge_bb, merge_builder) = make_block "merge" in
212
213         let ret_val_addr = Llvm.build_alloca base_types.value_p "tern_ret_val_addr"
                old_builder in
214         let cond_llvm_var = get_llvm_var cond_var old_builder in
215         let cond_val = Llvm.build_call getVal [|cond_llvm_var; cell_row; cell_col|] "
                cond_val" old_builder in
216         let cond_val_type = (cond_val => (value_field_index Flags)) "cond_val_type"
                old_builder in
217         let is_empty = Llvm.build_icmp Llvm.Icmp.Eq empty_type cond_val_type "is_empty
                " old_builder in
218         let _ = Llvm.build_cond_br is_empty empty_bb not_empty_bb old_builder in
219
220         (* Empty basic block: *)
221         let ret_val_empty = Llvm.build_malloc base_types.value_t "tern_empty"
                empty_builder in
222         let _ = store_empty ret_val_empty empty_builder in
223         let _ = Llvm.build_store ret_val_empty ret_val_addr empty_builder in
224         let _ = Llvm.build_br merge_bb empty_builder in
225
```

```
226         (* Not empty basic block: *)
227         let the_number = (cond_val => (value_field_index Number)) "the_number"
                not_empty_builder in
228         let is_not_zero = Llvm.build_fcmp Llvm.Fcmp.One the_number (Llvm.const_float
                base_types.number_t 0.0) "is_not_zero" not_empty_builder in (* Fcmp.One =
                Not equal *)
229         let _ = Llvm.build_cond_br is_not_zero truthy_bb falsey_bb not_empty_builder
                in
230
231         (* Truthy basic block: *)
232         let truthy_llvm_var = get_llvm_var true_var truthy_builder in
233         let truthy_val = Llvm.build_call getVal [|truthy_llvm_var; cell_row; cell_col
                |] "truthy_val" truthy_builder in
234         let _ = Llvm.build_store truthy_val ret_val_addr truthy_builder in
235         let _ = Llvm.build_br merge_bb truthy_builder in
236
237         (* Falsey basic block: *)
238         let falsey_llvm_var = get_llvm_var false_var falsey_builder in
239         let falsey_val = Llvm.build_call getVal [|falsey_llvm_var; cell_row; cell_col
                |] "falsey_val" falsey_builder in
240         let _ = Llvm.build_store falsey_val ret_val_addr falsey_builder in
241         let _ = Llvm.build_br merge_bb falsey_builder in
242
243         let ret_val = Llvm.build_load ret_val_addr "tern_ret_val" merge_builder in
244         (ret_val, merge_builder)
245       | Selection(expr, sel) ->
246         let (expr_val, expr_builder) = build_expr old_builder expr in
247         let build_rhs_index idx_builder = function
248             Abs(e) ->
249             let (idx_expr_val, next_builder) = build_expr idx_builder e in
250             let rhs_idx_ptr = Llvm.build_alloca base_types.rhs_index_t "idx_ptr"
                    next_builder in
251             let _ = (idx_expr_val $> (rhs_idx_ptr, (rhs_index_field_index RhsExprVal))
                    ) next_builder in
252             let _ = ((Llvm.const_int base_types.char_t (rhs_index_type_flags_const
                    RhsIdxAbs)) $> (rhs_idx_ptr, (rhs_index_field_index RhsIndexType)))
                    next_builder in
253             (rhs_idx_ptr, next_builder)
254           | Rel(e) ->
255             let (idx_expr_val, next_builder) = build_expr idx_builder e in
256             let rhs_idx_ptr = Llvm.build_alloca base_types.rhs_index_t "idx_ptr"
                    next_builder in
257             let _ = (idx_expr_val $> (rhs_idx_ptr, (rhs_index_field_index RhsExprVal))
                    ) next_builder in
258             let _ = ((Llvm.const_int base_types.char_t (rhs_index_type_flags_const
                    RhsIdxRel)) $> (rhs_idx_ptr, (rhs_index_field_index RhsIndexType)))
                    next_builder in
259             (rhs_idx_ptr, next_builder)
260           | DimensionStart ->
261             let rhs_idx_ptr = Llvm.build_alloca base_types.rhs_index_t "idx_ptr"
                    idx_builder in
262             let _ = ((Llvm.const_pointer_null base_types.value_p) $> (rhs_idx_ptr, (
                    rhs_index_field_index RhsExprVal))) idx_builder in
263             let _ = ((Llvm.const_int base_types.char_t (rhs_index_type_flags_const
                    RhsIdxDimStart)) $> (rhs_idx_ptr, (rhs_index_field_index RhsIndexType))
                    ) idx_builder in
```

```
264             (rhs_idx_ptr, idx_builder)
265           | DimensionEnd ->
266             let rhs_idx_ptr = Llvm.build_alloca base_types.rhs_index_t "idx_ptr"
                    idx_builder in
267             let _ = ((Llvm.const_pointer_null base_types.value_p) $> (rhs_idx_ptr, (
                    rhs_index_field_index RhsExprVal))) idx_builder in
268             let _ = ((Llvm.const_int base_types.char_t (rhs_index_type_flags_const
                    RhsIdxDimEnd)) $> (rhs_idx_ptr, (rhs_index_field_index RhsIndexType)))
                    idx_builder in
269             (rhs_idx_ptr, idx_builder) in
270         let build_rhs_slice slice_builder = function
271             (Some start_idx, Some end_idx) ->
272             let rhs_slice_ptr = Llvm.build_alloca base_types.rhs_slice_t "slice_ptr"
                    slice_builder in
273             let (start_idx_ptr, next_builder) = build_rhs_index slice_builder
                    start_idx in
274             let (end_idx_ptr, last_builder) = build_rhs_index next_builder end_idx in
275             let _ = (start_idx_ptr $> (rhs_slice_ptr, (rhs_slice_field_index
                    RhsSliceStartIdx))) last_builder in
276             let _ = (end_idx_ptr $> (rhs_slice_ptr, (rhs_slice_field_index
                    RhsSliceEndIdx))) last_builder in
277             (rhs_slice_ptr,last_builder)
278           | (Some single_idx, None) ->
279             let rhs_slice_ptr = Llvm.build_alloca base_types.rhs_slice_t "slice_ptr"
                    slice_builder in
280             let (single_idx_ptr, last_builder) = build_rhs_index slice_builder
                    single_idx in
281             let _ = (single_idx_ptr $> (rhs_slice_ptr, (rhs_slice_field_index
                    RhsSliceStartIdx))) last_builder in
282             let _ = ((Llvm.const_pointer_null base_types.rhs_index_p) $> (
                    rhs_slice_ptr, (rhs_slice_field_index RhsSliceEndIdx))) last_builder in
283             (rhs_slice_ptr,last_builder)
284           | (None, None) ->
285             let rhs_slice_ptr = Llvm.build_alloca base_types.rhs_slice_t "slice_ptr"
                    slice_builder in
286             let _ = ((Llvm.const_pointer_null base_types.rhs_index_p) $> (
                    rhs_slice_ptr, (rhs_slice_field_index RhsSliceStartIdx))) slice_builder
                     in
287             let _ = ((Llvm.const_pointer_null base_types.rhs_index_p) $> (
                    rhs_slice_ptr, (rhs_slice_field_index RhsSliceEndIdx))) slice_builder
                    in
288             (rhs_slice_ptr,slice_builder)
289           | (None, Some illegal_idx) -> print_endline (string_of_expr exp) ; raise (
                  LogicError("This slice should not be grammatically possible")) in
290         let build_rhs_sel sel_builder = function
291             (Some first_slice, Some second_slice) ->
292             let rhs_selection_ptr = Llvm.build_alloca base_types.rhs_selection_t "
                    selection_ptr" sel_builder in
293             let (first_slice_ptr, next_builder) = build_rhs_slice sel_builder
                    first_slice in
294             let (second_slice_ptr, last_builder) = build_rhs_slice next_builder
                    second_slice in
295             let _ = (first_slice_ptr $> (rhs_selection_ptr, (rhs_selection_field_index
                     RhsSelSlice1))) last_builder in
296             let _ = (second_slice_ptr $> (rhs_selection_ptr, (
                    rhs_selection_field_index RhsSelSlice2))) last_builder in
```

```
297             (rhs_selection_ptr,last_builder)
298           | (Some single_slice, None) ->
299             let rhs_selection_ptr = Llvm.build_alloca base_types.rhs_selection_t "
                    selection_ptr" sel_builder in
300             let (single_slice_ptr, last_builder) = build_rhs_slice sel_builder
                    single_slice in
301             let _ = (single_slice_ptr $> (rhs_selection_ptr, (
                    rhs_selection_field_index RhsSelSlice1))) last_builder in
302             let _ = ((Llvm.const_pointer_null base_types.rhs_slice_p) $> (
                    rhs_selection_ptr, (rhs_selection_field_index RhsSelSlice2)))
                    last_builder in
303             (rhs_selection_ptr,last_builder)
304           | (None, None) ->
305             let rhs_selection_ptr = Llvm.build_alloca base_types.rhs_selection_t "
                    selection_ptr" sel_builder in
306             let _ = ((Llvm.const_pointer_null base_types.rhs_slice_p) $> (
                    rhs_selection_ptr, (rhs_selection_field_index RhsSelSlice1)))
                    sel_builder in
307             let _ = ((Llvm.const_pointer_null base_types.rhs_slice_p) $> (
                    rhs_selection_ptr, (rhs_selection_field_index RhsSelSlice2)))
                    sel_builder in
308             (rhs_selection_ptr,sel_builder)
309           | (None, Some illegal_idx) -> print_endline (string_of_expr exp) ; raise (
                  LogicError("This selection should not be grammatically possible")) in
310         let (selection_ptr, builder_to_end_all_builders) = build_rhs_sel expr_builder
                sel in
311         (* let _ = Llvm.build_call (Hashtbl.find runtime_functions "
                debug_print_selection") [|selection_ptr|] "" builder_to_end_all_builders in
                 *)
312         let ret_val = Llvm.build_call (Hashtbl.find runtime_functions "
                extract_selection") [|expr_val; selection_ptr; cell_row; cell_col|] "
                ret_val" builder_to_end_all_builders in
313         (* let _ = Llvm.build_call (Hashtbl.find runtime_functions "debug_print") [|
                ret_val; Llvm.const_pointer_null base_types.char_p|] ""
                builder_to_end_all_builders in *)
314         (ret_val, builder_to_end_all_builders)
315       | Precedence(a,b) -> let (_, new_builder) = build_expr old_builder a in
              build_expr new_builder b
316       | LitString(str) ->
317         let initbod_charptr = Llvm.build_global_stringptr str "initbod_charptr"
                literal_bod in
318         let initbod_val_p = Llvm.build_call (Hashtbl.find runtime_functions "
                new_string") [|initbod_charptr|] "initbod_val_p" literal_bod in
319         let global_val_p_p = Llvm.define_global "global_litstring_p" (Llvm.
                const_pointer_null base_types.value_p) base_module in
320         let _ = Llvm.build_store initbod_val_p global_val_p_p literal_bod in
321
322         let local_val_p = Llvm.build_load global_val_p_p "local_value_p" old_builder
                in
323         let ret_val = Llvm.build_call (Hashtbl.find runtime_functions "clone_value")
                [|local_val_p|] "ret_val" old_builder in
324         (ret_val, old_builder)
325       | LitRange(rl) ->
326         let num_rows = List.length rl in
327         let num_cols = List.fold_left max 0 (List.map List.length rl) in
328         if num_rows = 1 && num_cols = 1 then build_expr old_builder (List.hd (List.hd
```

```
            rl))
329         else
330           let global_val_p_p = Llvm.define_global "global_litrange_p" (Llvm.
                const_pointer_null base_types.value_p) base_module in
331           let initbod_val_p = Llvm.build_malloc base_types.value_t "initbod_val_p"
                literal_bod in
332           let _ = Llvm.build_store initbod_val_p global_val_p_p literal_bod in
333           let _ = (range_type $> (initbod_val_p, (value_field_index Flags)))
                literal_bod in
334           let anonymous_subrange_p = Llvm.build_malloc base_types.subrange_t "
                anonymous_subrange" literal_bod in
335           let _ = (anonymous_subrange_p $> (initbod_val_p, (value_field_index Subrange
                ))) literal_bod in
336
337           let _ = ((Llvm.const_int base_types.int_t 0) $> (anonymous_subrange_p, (
                subrange_field_index BaseOffsetRow))) literal_bod in
338           let _ = ((Llvm.const_int base_types.int_t 0) $> (anonymous_subrange_p, (
                subrange_field_index BaseOffsetCol))) literal_bod in
339           let _ = ((Llvm.const_int base_types.int_t num_rows) $> (anonymous_subrange_p
                , (subrange_field_index SubrangeRows))) literal_bod in
340           let _ = ((Llvm.const_int base_types.int_t num_cols) $> (anonymous_subrange_p
                , (subrange_field_index SubrangeCols))) literal_bod in
341           let anonymous_var_inst_p = Llvm.build_malloc base_types.var_instance_t "
                anonymous_var_inst" literal_bod in
342           let _ = (anonymous_var_inst_p $> (anonymous_subrange_p, (
                subrange_field_index BaseRangePtr))) literal_bod in
343
344           let _ = ((Llvm.const_int base_types.int_t num_rows) $> (anonymous_var_inst_p
                , (var_instance_field_index Rows))) literal_bod in
345           let _ = ((Llvm.const_int base_types.int_t num_cols) $> (anonymous_var_inst_p
                , (var_instance_field_index Cols))) literal_bod in
346           let _ = ((Llvm.const_int base_types.int_t 0) $> (anonymous_var_inst_p, (
                var_instance_field_index NumFormulas))) literal_bod in
347           let _ = ((Llvm.const_pointer_null base_types.resolved_formula_p) $> (
                anonymous_var_inst_p, (var_instance_field_index Formulas))) literal_bod
                in
348           let _ = ((Llvm.const_pointer_null base_types.extend_scope_p) $> (
                anonymous_var_inst_p, (var_instance_field_index Closure))) literal_bod in
349           let vals_array = Llvm.build_array_malloc base_types.value_p (Llvm.const_int
                base_types.int_t (num_rows * num_cols)) "vals_array" literal_bod in
350           let _ = (vals_array $> (anonymous_var_inst_p, (var_instance_field_index
                Values))) literal_bod in
351           let status_array = Llvm.build_array_malloc base_types.char_t (Llvm.const_int
                 base_types.int_t (num_rows * num_cols)) "status_array" literal_bod in
352           let _ = (status_array $> (anonymous_var_inst_p, (var_instance_field_index
                Status))) literal_bod in
353
354           let get_val_p e = let (vp, _) = build_expr literal_bod e in vp in
355           let val_p_list_list = List.map (fun x -> List.map get_val_p x) rl in
356           let cellnums = zero_until (num_rows * num_cols) in
357           let build_empty x =
358             let emptyval = Llvm.build_malloc base_types.value_t ("" ^ (string_of_int x
                  )) literal_bod in
359             let _ = store_empty emptyval literal_bod in
360             let emptydst = Llvm.build_in_bounds_gep vals_array [|Llvm.const_int
                base_types.int_t x|] "" literal_bod in
```

```
361             let _ = Llvm.build_store emptyval emptydst literal_bod in
362             let statusdst = Llvm.build_in_bounds_gep status_array [|Llvm.const_int
                    base_types.int_t x|] "" literal_bod in
363             let _ = Llvm.build_store (Llvm.const_int base_types.char_t (
                    var_instance_status_flags_index Calculated)) statusdst literal_bod in
364             () in
365           List.iter build_empty cellnums ;
366           let store_val r c realval =
367             let realdst = Llvm.build_in_bounds_gep vals_array [|Llvm.const_int
                    base_types.int_t (r * num_cols + c)|] ("litrangeelemdst" ^ (
                    string_of_int r) ^ "_" ^ (string_of_int c)) literal_bod in
368             let _ = Llvm.build_store realval realdst literal_bod in
369             () in
370           let store_row r cols = List.iteri (fun c v -> store_val r c v) cols in
371           List.iteri store_row val_p_list_list ;
372           (* let _ = Llvm.build_call (Hashtbl.find runtime_functions "debug_print") [|
                  initbod_val_p; Llvm.const_pointer_null base_types.char_p|] "" literal_bod
                   in *)
373
374           let local_val_p = Llvm.build_load global_val_p_p "local_value_p" old_builder
                   in
375           (* let _ = Llvm.build_call (Hashtbl.find runtime_functions "debug_print") [|
                  local_val_p; Llvm.const_pointer_null base_types.char_p|] "" old_builder
                  in *)
376           let ret_val = Llvm.build_call (Hashtbl.find runtime_functions "clone_value")
                   [|local_val_p|] "ret_val" old_builder in
377           (* let _ = Llvm.build_call (Hashtbl.find runtime_functions "debug_print") [|
                  ret_val; Llvm.const_pointer_null base_types.char_p|] "" old_builder in *)
378           (ret_val, old_builder)
379       | Call(fn,exl) -> (*TODO: Call needs to be reviewed. Possibly switch call
              arguments to value_p*)
380         let build_one_expr (arg_list, intermediate_builder) e =
381           let (arg_val, next_builder) = build_expr intermediate_builder e in
382           (arg_val :: arg_list, next_builder) in
383         let (reversed_arglist, call_builder) = List.fold_left build_one_expr ([],
                old_builder) exl in
384         let args = Array.of_list (List.rev reversed_arglist) in
385         let result = Llvm.build_call (
386           StringMap.find fn function_llvalues
387           ) args "call_ret_val" call_builder in
388         (result, call_builder)
389       | BinOp(expr1,op,expr2) -> (
390           let (val1, builder1) = build_expr old_builder expr1 in
391           let (val2, int_builder) = build_expr builder1 expr2 in
392           let bit_shift = (Llvm.const_int base_types.char_t 4) in
393           let expr1_type = (val1 => (value_field_index Flags)) "expr1_type"
                  int_builder in
394           let expr2_type = (val2 => (value_field_index Flags)) "expr2_type"
                  int_builder in
395           let expr1_type_shifted = Llvm.build_shl expr1_type bit_shift "
                  expr_1_type_shifted" int_builder in
396           let combined_type = Llvm.build_add expr1_type_shifted expr2_type "
                  combined_type" int_builder in
397           let number_number = Llvm.const_add (Llvm.const_shl number_type bit_shift)
                  number_type in
398           let string_string = Llvm.const_add (Llvm.const_shl string_type bit_shift)
```

```
            string_type in
399         let empty_empty = Llvm.const_add (Llvm.const_shl empty_type bit_shift)
            empty_type in
400         let range_range = Llvm.const_add (Llvm.const_shl range_type bit_shift)
            range_type in
401         let build_simple_binop oppp int_builder =
402           (let ret_val = Llvm.build_malloc base_types.value_t "binop_minus_ret_val"
                int_builder in
403            let _ = Llvm.build_store
404                (
405                  Llvm.const_int
406                  base_types.char_t
407                  (value_field_flags_index Empty)
408                ) (
409                  Llvm.build_struct_gep
410                  ret_val
411                  (value_field_index Flags)
412                  ""
413                  int_builder
414                )
415                int_builder
416            in
417            let bailout = (Llvm.append_block context "" form_decl) in
418            let bbailout = Llvm.builder_at_end context bailout in
419            let (numnum_bb, numnum_builder) = make_block "numnum" in
420            let numeric_val_1 = (val1 => (value_field_index Number)) "number_one"
                numnum_builder in
421            let numeric_val_2 = (val2 => (value_field_index Number)) "number_two"
                numnum_builder in
422            let numeric_res = oppp numeric_val_1 numeric_val_2 "numeric_res"
                numnum_builder in
423            let _ = Llvm.build_store
424                numeric_res (
425                  Llvm.build_struct_gep
426                  ret_val
427                  (value_field_index Number)
428                  ""
429                  numnum_builder
430                )
431                numnum_builder in
432            let _ = Llvm.build_store
433                (
434                  Llvm.const_int
435                  base_types.char_t
436                  (value_field_flags_index Number)
437                ) (
438                  Llvm.build_struct_gep
439                  ret_val
440                  (value_field_index Flags)
441                  ""
442                  numnum_builder
443                )
444                numnum_builder in
445            let _ = Llvm.build_br bailout numnum_builder in
446            let _ = Llvm.build_cond_br (Llvm.build_icmp Llvm.Icmp.Eq combined_type
                number_number "" int_builder) numnum_bb bailout int_builder in
```

```
447                 (ret_val, bbailout)
448             )
449             and build_simple_int_binop oppp int_builder =
450               (let ret_val = Llvm.build_malloc base_types.value_t "binop_minus_ret_val"
                      int_builder in
451                 let _ = Llvm.build_store
452                     (
453                       Llvm.const_int
454                       base_types.char_t
455                       (value_field_flags_index Empty)
456                     ) (
457                       Llvm.build_struct_gep
458                       ret_val
459                       (value_field_index Flags)
460                       ""
461                       int_builder
462                     )
463                     int_builder
464                 in
465                 let bailout = (Llvm.append_block context "" form_decl) in
466                 let bbailout = Llvm.builder_at_end context bailout in
467                 let (numnum_bb, numnum_builder) = make_block "numnum" in
468                 let roundfl x = Llvm.build_call (Hashtbl.find runtime_functions "lrint
                      ") [|x|] "" numnum_builder in
469                 let numeric_val_1 = roundfl ((val1 => (value_field_index Number)) "
                      number_one" numnum_builder) in
470                 let numeric_val_2 = roundfl ((val2 => (value_field_index Number)) "
                      number_two" numnum_builder) in
471                 let numeric_res = oppp numeric_val_1 numeric_val_2 "numeric_res"
                      numnum_builder in
472                 let _ = Llvm.build_store
473                     (Llvm.build_sitofp numeric_res base_types.float_t "" numnum_builder
                         )
474                     (
475                       Llvm.build_struct_gep
476                       ret_val
477                       (value_field_index Number)
478                       ""
479                       numnum_builder
480                     )
481                     numnum_builder in
482                 let _ = Llvm.build_store
483                     (
484                       Llvm.const_int
485                       base_types.char_t
486                       (value_field_flags_index Number)
487                     ) (
488                       Llvm.build_struct_gep
489                       ret_val
490                       (value_field_index Flags)
491                       ""
492                       numnum_builder
493                     )
494                     numnum_builder in
495                 let _ = Llvm.build_br bailout numnum_builder in
496                 let _ = Llvm.build_cond_br (Llvm.build_icmp Llvm.Icmp.Eq combined_type
```

```
                  number_number "" int_builder) numnum_bb bailout int_builder in
497               (ret_val, bbailout)
498            ) in
499          let build_boolean_op numeric_comparator string_comparator int_builder =
500            let ret_val = Llvm.build_malloc base_types.value_t "binop_gt_ret_val"
                   int_builder in
501            let (make_true_bb, make_false_bb, make_empty_bb, merge_builder) =
                   make_truthiness_blocks "binop_eq" ret_val in
502
503            let (numnum_bb, numnum_builder) = make_block "numnum" in
504            let numeric_val_1 = (val1 => (value_field_index Number)) "number_one"
                   numnum_builder in
505            let numeric_val_2 = (val2 => (value_field_index Number)) "number_two"
                   numnum_builder in
506            let numeric_greater = Llvm.build_fcmp numeric_comparator numeric_val_1
                   numeric_val_2 "numeric_greater" numnum_builder in
507            let _ = Llvm.build_cond_br numeric_greater make_true_bb make_false_bb
                   numnum_builder in
508
509            let (strstr_bb, strstr_builder) = make_block "strstr" in
510            let str_p_1 = (val1 => (value_field_index String)) "string_one"
                   strstr_builder in
511            let str_p_2 = (val2 => (value_field_index String)) "string_two"
                   strstr_builder in
512            let char_p_1 = (str_p_1 => (string_field_index StringCharPtr)) "char_p_one
                   " strstr_builder in
513            let char_p_2 = (str_p_2 => (string_field_index StringCharPtr)) "char_p_two
                   " strstr_builder in
514            let strcmp_result = Llvm.build_call (Hashtbl.find runtime_functions "
                   strcmp") [|char_p_1; char_p_2|] "strcmp_result" strstr_builder in
515            let string_greater = Llvm.build_icmp string_comparator strcmp_result (Llvm
                   .const_null base_types.long_t) "string_greater" strstr_builder in
516            let _ = Llvm.build_cond_br string_greater make_true_bb make_false_bb
                   strstr_builder in
517
518            let switch_inst = Llvm.build_switch combined_type make_empty_bb 2
                   int_builder in (* Incompatible ===> default to empty *)
519            Llvm.add_case switch_inst number_number numnum_bb;
520            Llvm.add_case switch_inst string_string strstr_bb;
521            (ret_val, merge_builder) in
522          match op with
523            Minus -> build_simple_binop Llvm.build_fsub int_builder
524          | Plus ->
525              let result = Llvm.build_malloc base_types.value_t "" int_builder
526              and stradd = (Llvm.append_block context "" form_decl)
527              and numadd = (Llvm.append_block context "" form_decl)
528              and bailout = (Llvm.append_block context "" form_decl)
529              and numorstrorother = (Llvm.append_block context "" form_decl)
530              and strorother = (Llvm.append_block context "" form_decl)
531              in
532              let bstradd = Llvm.builder_at_end context stradd
533              and bnumadd = Llvm.builder_at_end context numadd
534              and bnumorstrorother = Llvm.builder_at_end context numorstrorother
535              and bstrorother = Llvm.builder_at_end context strorother
536              and bbailout = Llvm.builder_at_end context bailout
537              and _ = Llvm.build_store (Llvm.const_int base_types.char_t (
```

```
                value_field_flags_index Empty)) (Llvm.build_struct_gep result (
                value_field_index Flags) "" int_builder) int_builder
538             in
539             let isnumber = Llvm.build_icmp Llvm.Icmp.Eq (Llvm.build_load (Llvm.
                build_struct_gep val1 (value_field_index Flags) "" bnumorstrorother)
                "" bnumorstrorother) (Llvm.const_int base_types.char_t (
                value_field_flags_index Number)) "" bnumorstrorother
540             and isstring = Llvm.build_icmp Llvm.Icmp.Eq (Llvm.build_load (Llvm.
                build_struct_gep val1 (value_field_index Flags) "" bstrorother) ""
                bstrorother) (Llvm.const_int base_types.char_t (
                value_field_flags_index String)) "" bstrorother
541             and isnumorstring = Llvm.build_icmp Llvm.Icmp.Eq (Llvm.build_load (Llvm.
                build_struct_gep val1 (value_field_index Flags) "" int_builder) ""
                int_builder) (Llvm.build_load (Llvm.build_struct_gep val2 (
                value_field_index Flags) "" int_builder) "" int_builder) ""
                int_builder
542             and _ = Llvm.build_store (Llvm.build_fadd (Llvm.build_load (Llvm.
                build_struct_gep val1 (value_field_index Number) "" bnumadd) ""
                bnumadd) (Llvm.build_load (Llvm.build_struct_gep val2 (
                value_field_index Number) "" bnumadd) "" bnumadd) "" bnumadd) (Llvm.
                build_struct_gep result (value_field_index Number) "" bnumadd)
                bnumadd
543             and _ = Llvm.build_store (Llvm.const_int base_types.char_t (
                value_field_flags_index Number)) (Llvm.build_struct_gep result (
                value_field_index Flags) "" bnumadd) bnumadd
544             and str1 = Llvm.build_load (Llvm.build_struct_gep val1 (
                value_field_index String) "" bstradd) "" bstradd
545             and str2 = Llvm.build_load (Llvm.build_struct_gep val2 (
                value_field_index String) "" bstradd) "" bstradd
546             and newstr = (Llvm.build_malloc base_types.string_t "" bstradd) in
547             let len1 = Llvm.build_load (Llvm.build_struct_gep str1 (
                string_field_index StringLen) "" bstradd) "" bstradd
548             and len2 = Llvm.build_load (Llvm.build_struct_gep str2 (
                string_field_index StringLen) "" bstradd) "" bstradd
549             and p1 = Llvm.build_load (Llvm.build_struct_gep str1 (string_field_index
                 StringCharPtr) "" bstradd) "" bstradd
550             and p2 = Llvm.build_load (Llvm.build_struct_gep str2 (string_field_index
                 StringCharPtr) "" bstradd) "" bstradd
551             and dst_char_ptr_ptr = (Llvm.build_struct_gep newstr (string_field_index
                 StringCharPtr) "" bstradd)
552             and _ = Llvm.build_store (Llvm.const_int base_types.char_t (
                value_field_flags_index String)) (Llvm.build_struct_gep result (
                value_field_index Flags) "" bstradd) bstradd
553             and _ = Llvm.build_store newstr (Llvm.build_struct_gep result (
                value_field_index String) "" bstradd) bstradd in
554             let fullLen = Llvm.build_nsw_add (Llvm.build_nsw_add len1 len2 ""
                bstradd) (Llvm.const_int base_types.long_t 1) "" bstradd
555             and extra_byte2 = (Llvm.build_add len2 (Llvm.const_int base_types.long_t
                 1) "" bstradd) in
556             let dst_char = Llvm.build_array_malloc base_types.char_t (Llvm.
                build_trunc fullLen base_types.int_t "" bstradd) "" bstradd in
557             let dst_char2 = Llvm.build_in_bounds_gep dst_char [|len1|] "" bstradd in
558             let _ = Llvm.build_call (Hashtbl.find runtime_functions "llvm.memcpy.
                p0i8.p0i8.i64") [|dst_char; p1; len1; (Llvm.const_int base_types.
                int_t 0); (Llvm.const_int base_types.bool_t 0)|] "" bstradd
559             and _ = Llvm.build_call (Hashtbl.find runtime_functions "llvm.memcpy.
```

```
                p0i8.p0i8.i64") [|dst_char2; p2; extra_byte2; (Llvm.const_int
                base_types.int_t 0); (Llvm.const_int base_types.bool_t 0)|] ""
                bstradd
560           and _ = Llvm.build_store dst_char dst_char_ptr_ptr bstradd
561           in
562           let _ = Llvm.build_store (Llvm.build_nsw_add fullLen (Llvm.const_int
                base_types.long_t (-1)) "" bstradd) (Llvm.build_struct_gep newstr (
                string_field_index StringLen) "" bstradd) bstradd
563           in
564           let _ = Llvm.build_cond_br isnumorstring numorstrorother bailout
                int_builder
565           and _ = Llvm.build_cond_br isnumber numadd strorother bnumorstrorother
566           and _ = Llvm.build_cond_br isstring stradd bailout bstrorother
567           and _ = Llvm.build_br bailout bstradd
568           and _ = Llvm.build_br bailout bnumadd
569           in
570           (result, bbailout)
571       | Times -> build_simple_binop Llvm.build_fmul int_builder
572       | Eq ->
573         (* let _ = Llvm.build_call (Hashtbl.find runtime_functions "debug_print")
                [|val1; Llvm.build_global_stringptr "Eq operator - value 1" ""
                old_builder|] "" int_builder in
574         let _ = Llvm.build_call (Hashtbl.find runtime_functions "debug_print") [|
                val2; Llvm.build_global_stringptr "Eq operator - value 2" ""
                old_builder|] "" int_builder in *)
575         let ret_val = Llvm.build_malloc base_types.value_t "binop_eq_ret_val"
                int_builder in
576         let (make_true_bb, make_false_bb, _, merge_builder) =
                make_truthiness_blocks "binop_eq" ret_val in
577
578         let (numnum_bb, numnum_builder) = make_block "numnum" in
579         let numeric_val_1 = (val1 => (value_field_index Number)) "number_one"
                numnum_builder in
580         let numeric_val_2 = (val2 => (value_field_index Number)) "number_two"
                numnum_builder in
581         let numeric_equality = Llvm.build_fcmp Llvm.Fcmp.Oeq numeric_val_1
                numeric_val_2 "numeric_equality" numnum_builder in
582         let _ = Llvm.build_cond_br numeric_equality make_true_bb make_false_bb
                numnum_builder in
583
584         let (strstr_bb, strstr_builder) = make_block "strstr" in
585         let str_p_1 = (val1 => (value_field_index String)) "string_one"
                strstr_builder in
586         let str_p_2 = (val2 => (value_field_index String)) "string_two"
                strstr_builder in
587         let char_p_1 = (str_p_1 => (string_field_index StringCharPtr)) "char_p_one
                " strstr_builder in
588         let char_p_2 = (str_p_2 => (string_field_index StringCharPtr)) "char_p_two
                " strstr_builder in
589         let strcmp_result = Llvm.build_call (Hashtbl.find runtime_functions "
                strcmp") [|char_p_1; char_p_2|] "strcmp_result" strstr_builder in
590         let string_equality = Llvm.build_icmp Llvm.Icmp.Eq strcmp_result (Llvm.
                const_null base_types.long_t) "string_equality" strstr_builder in
591         let _ = Llvm.build_cond_br string_equality make_true_bb make_false_bb
                strstr_builder in
592
```

```
593             let (rngrng_bb, rngrng_builder) = make_block "rngrng" in
594             (* TODO: Make this case work *)
595             let eqt = Llvm.build_is_not_null (Llvm.build_call (Hashtbl.find
                    runtime_functions "rg_eq") [|val1; val2|] "" rngrng_builder) ""
                    rngrng_builder in
596             let _ = Llvm.build_cond_br eqt make_true_bb make_false_bb rngrng_builder
                    in
597
598             let switch_inst = Llvm.build_switch combined_type make_false_bb 4
                    int_builder in (* Incompatible ===> default to false *)
599             Llvm.add_case switch_inst number_number numnum_bb;
600             Llvm.add_case switch_inst string_string strstr_bb;
601             Llvm.add_case switch_inst range_range rngrng_bb;
602             Llvm.add_case switch_inst empty_empty make_true_bb; (* Nothing to check in
                     this case, just return true *)
603             (ret_val, merge_builder)
604           | Gt -> build_boolean_op Llvm.Fcmp.Ogt Llvm.Icmp.Sgt int_builder
605           | GtEq -> build_boolean_op Llvm.Fcmp.Oge Llvm.Icmp.Sge int_builder
606           | Lt -> build_boolean_op Llvm.Fcmp.Olt Llvm.Icmp.Slt int_builder
607           | LtEq -> build_boolean_op Llvm.Fcmp.Ole Llvm.Icmp.Sle int_builder
608           | LogAnd | LogOr -> raise (TransformedAway("&& and || should have been
                  transformed into a short-circuit ternary expression! Error in the
                  following expression:\n" ^ string_of_expr exp))
609           | Divide-> build_simple_binop Llvm.build_fdiv int_builder
610           | Mod-> build_simple_binop Llvm.build_frem int_builder
611           | Pow-> (
612             let powcall numeric_val_1 numeric_val_2 valname b =
613               Llvm.build_call (Hashtbl.find runtime_functions "pow") [|numeric_val_1;
                      numeric_val_2|] "" b in
614             build_simple_binop powcall int_builder)
615           | LShift-> build_simple_int_binop Llvm.build_shl int_builder
616           | RShift-> build_simple_int_binop Llvm.build_lshr int_builder
617           | BitOr-> build_simple_int_binop Llvm.build_or int_builder
618           | BitAnd-> build_simple_int_binop Llvm.build_and int_builder
619           | BitXor-> build_simple_int_binop Llvm.build_xor int_builder
620         )
621       | UnOp(SizeOf,expr) ->
622         let ret_val = Llvm.build_malloc base_types.value_t "unop_size_ret_val"
                old_builder in
623
624         (* TODO: We actually have to keep track of these anonymous objects somewhere
                so we can free them *)
625         let _ = (range_type $> (ret_val, (value_field_index Flags))) old_builder in
626         let anonymous_subrange_p = Llvm.build_malloc base_types.subrange_t "
                anonymous_subrange" old_builder in
627         let _ = (anonymous_subrange_p $> (ret_val, (value_field_index Subrange)))
                old_builder in
628
629         let _ = ((Llvm.const_int base_types.int_t 0) $> (anonymous_subrange_p, (
                subrange_field_index BaseOffsetRow))) old_builder in
630         let _ = ((Llvm.const_int base_types.int_t 0) $> (anonymous_subrange_p, (
                subrange_field_index BaseOffsetCol))) old_builder in
631         let _ = ((Llvm.const_int base_types.int_t 1) $> (anonymous_subrange_p, (
                subrange_field_index SubrangeRows))) old_builder in
632         let _ = ((Llvm.const_int base_types.int_t 2) $> (anonymous_subrange_p, (
                subrange_field_index SubrangeCols))) old_builder in
```

```
633         let anonymous_var_inst_p = Llvm.build_malloc base_types.var_instance_t "
                anonymous_var_inst" old_builder in
634         let _ = (anonymous_var_inst_p $> (anonymous_subrange_p, (subrange_field_index
                BaseRangePtr))) old_builder in
635
636         let _ = ((Llvm.const_int base_types.int_t 1) $> (anonymous_var_inst_p, (
                var_instance_field_index Rows))) old_builder in
637         let _ = ((Llvm.const_int base_types.int_t 2) $> (anonymous_var_inst_p, (
                var_instance_field_index Cols))) old_builder in
638         let _ = ((Llvm.const_int base_types.int_t 0) $> (anonymous_var_inst_p, (
                var_instance_field_index NumFormulas))) old_builder in
639         let _ = ((Llvm.const_pointer_null base_types.resolved_formula_p) $> (
                anonymous_var_inst_p, (var_instance_field_index Formulas))) old_builder in
640         let _ = ((Llvm.const_pointer_null base_types.extend_scope_p) $> (
                anonymous_var_inst_p, (var_instance_field_index Closure))) old_builder in
641         let num_rows_val = Llvm.build_malloc base_types.value_t "num_rows_val"
                old_builder in
642         let num_cols_val = Llvm.build_malloc base_types.value_t "num_cols_val"
                old_builder in
643         let vals_array = Llvm.build_array_malloc base_types.value_p (Llvm.const_int
                base_types.int_t 2) "vals_array" old_builder in
644         let _ = (vals_array $> (anonymous_var_inst_p, (var_instance_field_index Values
                ))) old_builder in
645         let _ = Llvm.build_store num_rows_val (Llvm.build_in_bounds_gep vals_array [|
                Llvm.const_int base_types.int_t 0|] "" old_builder) old_builder in
646         let _ = Llvm.build_store num_cols_val (Llvm.build_in_bounds_gep vals_array [|
                Llvm.const_int base_types.int_t 1|] "" old_builder) old_builder in
647         let status_array = Llvm.build_array_malloc base_types.char_t (Llvm.const_int
                base_types.int_t 2) "status_array" old_builder in
648         let _ = (status_array $> (anonymous_var_inst_p, (var_instance_field_index
                Status))) old_builder in
649         let _ = Llvm.build_store (Llvm.const_int base_types.char_t (
                var_instance_status_flags_index Calculated)) (Llvm.build_in_bounds_gep
                status_array [|Llvm.const_int base_types.int_t 0|] "" old_builder)
                old_builder in
650         let _ = Llvm.build_store (Llvm.const_int base_types.char_t (
                var_instance_status_flags_index Calculated)) (Llvm.build_in_bounds_gep
                status_array [|Llvm.const_int base_types.int_t 1|] "" old_builder)
                old_builder in
651
652         let (expr_val, expr_builder) = build_expr old_builder expr in
653         let val_flags = (expr_val => (value_field_index Flags)) "val_flags"
                expr_builder in
654         let is_subrange = Llvm.build_icmp Llvm.Icmp.Eq val_flags range_type "
                is_subrange" expr_builder in
655
656         let (merge_bb, merge_builder) = make_block "merge" in
657
658         let (primitive_bb, primitive_builder) = make_block "primitive" in
659         let _ = store_number num_rows_val primitive_builder (Llvm.const_float
                base_types.float_t 1.0) in
660         let _ = store_number num_cols_val primitive_builder (Llvm.const_float
                base_types.float_t 1.0) in
661         let _ = Llvm.build_br merge_bb primitive_builder in
662
663         let (subrange_bb, subrange_builder) = make_block "subrange" in
```

```
664         let subrange_ptr = (expr_val => (value_field_index Subrange)) "subrange_ptr"
                subrange_builder in
665         let rows_as_int = (subrange_ptr => (subrange_field_index SubrangeRows)) "
                rows_as_int" subrange_builder in
666         let cols_as_int = (subrange_ptr => (subrange_field_index SubrangeCols)) "
                cols_as_int" subrange_builder in
667         let rows_as_float = Llvm.build_sitofp rows_as_int base_types.float_t "
                rows_as_float" subrange_builder in
668         let cols_as_float = Llvm.build_sitofp cols_as_int base_types.float_t "
                cols_as_float" subrange_builder in
669         let _ = store_number num_rows_val subrange_builder rows_as_float in
670         let _ = store_number num_cols_val subrange_builder cols_as_float in
671         let _ = Llvm.build_br merge_bb subrange_builder in
672
673         let _ = Llvm.build_cond_br is_subrange subrange_bb primitive_bb expr_builder
                in
674         (ret_val, merge_builder)
675       | UnOp(Truthy, expr) ->
676         let ret_val = Llvm.build_malloc base_types.value_t "unop_truthy_ret_val"
                old_builder in
677         let (expr_val, expr_builder) = build_expr old_builder expr in
678
679         let (truthy_bb, falsey_bb, empty_bb, merge_builder) = make_truthiness_blocks "
                unop_truthy" ret_val in
680
681         let expr_flags = (expr_val => (value_field_index Flags)) "expr_flags"
                expr_builder in
682         let is_empty_bool = (Llvm.build_icmp Llvm.Icmp.Eq expr_flags (Llvm.const_int
                base_types.flags_t (value_field_flags_index Empty)) "is_empty_bool"
                expr_builder) in
683         let is_empty = Llvm.build_zext is_empty_bool base_types.char_t "is_empty"
                expr_builder in
684         let is_empty_two = Llvm.build_shl is_empty (Llvm.const_int base_types.char_t
                1) "is_empty_two" expr_builder in
685         let is_number = Llvm.build_icmp Llvm.Icmp.Eq expr_flags (Llvm.const_int
                base_types.flags_t (value_field_flags_index Number)) "is_number"
                expr_builder in
686         let the_number = (expr_val => (value_field_index Number)) "the_number"
                expr_builder in
687         let is_zero = Llvm.build_fcmp Llvm.Fcmp.Oeq the_number (Llvm.const_float
                base_types.number_t 0.0) "is_zero" expr_builder in
688         let is_numeric_zero_bool = Llvm.build_and is_zero is_number "
                is_numeric_zero_bool" expr_builder in
689         let is_numeric_zero = Llvm.build_zext is_numeric_zero_bool base_types.char_t "
                is_numeric_zero" expr_builder in
690         let switch_num = Llvm.build_add is_empty_two is_numeric_zero "switch_num"
                expr_builder in
691         let switch_inst = Llvm.build_switch switch_num empty_bb 2 expr_builder in
692         Llvm.add_case switch_inst (Llvm.const_int base_types.char_t 0) truthy_bb; (*
                empty << 1 + is_zero == 0 ===> truthy *)
693         Llvm.add_case switch_inst (Llvm.const_int base_types.char_t 1) falsey_bb; (*
                empty << 1 + is_zero == 1 ===> falsey *)
694         (ret_val, merge_builder)
695       | UnOp(LogNot, expr) ->
696         let (truth_val, truth_builder) = build_expr old_builder (UnOp(Truthy, expr))
                in
```

```
697         let the_number = (truth_val => (value_field_index Number)) "the_number"
                truth_builder in
698         let not_the_number = Llvm.build_fsub (Llvm.const_float base_types.float_t 1.0)
                 the_number "not_the_number" truth_builder in
699         let sp = Llvm.build_struct_gep truth_val (value_field_index Number) "
                num_pointer" truth_builder in
700         let _ = Llvm.build_store not_the_number sp truth_builder in
701         (truth_val, truth_builder)
702       | UnOp(Neg, expr) ->
703         let ret_val = Llvm.build_malloc base_types.value_t "unop_truthy_ret_val"
                old_builder in
704         let _ = store_empty ret_val old_builder in
705         let (expr_val, expr_builder) = build_expr old_builder expr in
706         let expr_type = (expr_val => (value_field_index Flags)) "expr_type"
                expr_builder in
707         let is_number = Llvm.build_icmp Llvm.Icmp.Eq expr_type number_type "is_number"
                 expr_builder in
708         let (finish_bb, finish_builder) = make_block "finish" in
709
710         let (number_bb, number_builder) = make_block "number" in
711         let the_number = (expr_val => (value_field_index Number)) "the_number"
                number_builder in
712         let minus_the_number = Llvm.build_fneg the_number "minus_the_number"
                number_builder in
713         let _ = store_number ret_val number_builder minus_the_number in
714         let _ = Llvm.build_br finish_bb number_builder in
715
716         let _ = Llvm.build_cond_br is_number number_bb finish_bb expr_builder in
717         (ret_val, finish_builder)
718       | UnOp(BitNot, expr) ->
719         let ret_val = Llvm.build_malloc base_types.value_t "unop_truthy_ret_val"
                old_builder in
720         let (expr_val, expr_builder) = build_expr old_builder expr in
721
722         let (numnum_bb, numnum_builder) = make_block "numnum" in
723         let (make_empty_bb, make_empty_builder) = make_block ("" ^ "_empty") in
724         let (finish_bb, finish_builder) = make_block "finish" in
725
726         let _ = store_empty ret_val make_empty_builder  in
727         let _ = Llvm.build_br finish_bb make_empty_builder in
728
729         let expr_type = (expr_val => (value_field_index Flags)) "expr_type"
                expr_builder in
730         let is_number = Llvm.build_icmp Llvm.Icmp.Eq expr_type number_type "is_number"
                 expr_builder in
731         let _ = Llvm.build_cond_br is_number numnum_bb make_empty_bb expr_builder in
732
733         let expr_num = Llvm.build_call (Hashtbl.find runtime_functions "lrint") [|((
                expr_val => (value_field_index Number)) "expr_type" numnum_builder)|] ""
                numnum_builder in
734         let _ = store_number ret_val numnum_builder (Llvm.build_sitofp (Llvm.build_not
                 expr_num "" numnum_builder) base_types.float_t "" numnum_builder) in
735         let _ = Llvm.build_br finish_bb numnum_builder in
736
737         (ret_val, finish_builder)
738       | UnOp(TypeOf, expr) ->
```

```
739         let (expr_val, expr_builder) = build_expr old_builder expr in
740         let expr_type = (expr_val => (value_field_index Flags)) "expr_type"
                expr_builder in
741         let vp_to_clone_loc = Llvm.build_in_bounds_gep array_of_typeof_val_ptrs [|Llvm
                .const_int base_types.int_t 0; expr_type|] ("vp_to_clone_log") expr_builder
                 in
742         let vp_to_clone = Llvm.build_load vp_to_clone_loc "vp_to_clone" expr_builder
                in
743         let ret_val = Llvm.build_call (Hashtbl.find runtime_functions "clone_value")
                [|vp_to_clone|] "typeof_ret_val" expr_builder in
744         (ret_val, expr_builder)
745       | UnOp(Row, _) ->
746         let row_as_int = cell_row in
747         let row_as_float = Llvm.build_sitofp row_as_int base_types.float_t "
                row_as_float" old_builder in
748         let ret_val = Llvm.build_malloc base_types.value_t "ret_val" old_builder in
749         let _ = store_number ret_val old_builder row_as_float in
750         (ret_val, old_builder)
751       | UnOp(Column, _) ->
752         let col_as_int = cell_col in
753         let col_as_float = Llvm.build_sitofp col_as_int base_types.float_t "
                col_as_float" old_builder in
754         let ret_val = Llvm.build_malloc base_types.value_t "ret_val" old_builder in
755         let _ = store_number ret_val old_builder col_as_float in
756         (ret_val, old_builder)
757       | Switch(_,_,_) | Ternary(_,_,_) -> raise(TransformedAway("These expressions
              should have been transformed away")) in
758       (* | unknown_expr -> print_endline (string_of_expr unknown_expr);raise
              NotImplemented in *)
759     let (ret_value_p, final_builder) = build_expr builder_at_top formula_expr in
760     let _ = Llvm.build_ret ret_value_p final_builder in
761     form_decl in
762
763   (*build formula creates a formula declaration in a separate method from the function
          it belongs to*)
764   let build_formula (varname, idx) formula_array element symbols =
765     let storage_addr = Llvm.build_in_bounds_gep formula_array [|Llvm.const_int
          base_types.int_t idx|] "" init_bod in
766     let getStarts = function (* Not really just for starts *)
767         Abs(LitInt(1)) | Abs(LitInt(0)) | DimensionStart | DimensionEnd -> (1, -1)
768       | Abs(Id(s)) ->
769         (match StringMap.find s symbols with
770            LocalVariable(i) | GlobalVariable(i) -> (0, i)
771          | _ -> raise(TransformedAway("Error in " ^ varname ^ ": The LHS expresssions
                  should always either have dimension length 1 or be the name of a variable
                  in their own scope.")))
772       | _ -> print_endline ("Error in " ^ varname ^ " formula number " ^ string_of_int
              idx); raise(LogicError("Something wrong with the index of formula: " ^
            string_of_formula element)) in
773     let getEnds = function
774         Some x -> let (b, c) = getStarts x in (b, c, 0)
775       | None -> (0, -1, 1) in
776     let (fromStartRow, rowStartVarnum) = getStarts element.formula_row_start in
777     let (fromStartCol, colStartVarnum) = getStarts element.formula_col_start in
778     let (toEndRow, rowEndVarnum, isSingleRow) = getEnds element.formula_row_end in
779     let (toEndCol, colEndVarnum, isSingleCol) = getEnds element.formula_col_end in
```

```
780
781     let _ = Llvm.build_store (Llvm.const_int base_types.char_t fromStartRow) (Llvm.
            build_struct_gep storage_addr (formula_field_index FromFirstRow) "" init_bod)
            init_bod in
782     let _ = Llvm.build_store (Llvm.const_int base_types.int_t rowStartVarnum) (Llvm.
            build_struct_gep storage_addr (formula_field_index RowStartNum) "" init_bod)
            init_bod in
783     let _ = Llvm.build_store (Llvm.const_int base_types.char_t toEndRow) (Llvm.
            build_struct_gep storage_addr (formula_field_index ToLastRow) "" init_bod)
            init_bod in
784     let _ = Llvm.build_store (Llvm.const_int base_types.int_t rowEndVarnum) (Llvm.
            build_struct_gep storage_addr (formula_field_index RowEndNum) "" init_bod)
            init_bod in
785     let _ = Llvm.build_store (Llvm.const_int base_types.char_t isSingleRow) (Llvm.
            build_struct_gep storage_addr (formula_field_index IsSingleRow) "" init_bod)
            init_bod in
786
787     let _ = Llvm.build_store (Llvm.const_int base_types.char_t fromStartCol) (Llvm.
            build_struct_gep storage_addr (formula_field_index FromFirstCols) "" init_bod)
            init_bod in
788     let _ = Llvm.build_store (Llvm.const_int base_types.int_t colStartVarnum) (Llvm.
            build_struct_gep storage_addr (formula_field_index ColStartNum) "" init_bod)
            init_bod in
789     let _ = Llvm.build_store (Llvm.const_int base_types.char_t toEndCol) (Llvm.
            build_struct_gep storage_addr (formula_field_index ToLastCol) "" init_bod)
            init_bod in
790     let _ = Llvm.build_store (Llvm.const_int base_types.int_t colEndVarnum) (Llvm.
            build_struct_gep storage_addr (formula_field_index ColEndNum) "" init_bod)
            init_bod in
791     let _ = Llvm.build_store (Llvm.const_int base_types.char_t isSingleCol) (Llvm.
            build_struct_gep storage_addr (formula_field_index IsSingleCol) "" init_bod)
            init_bod in
792
793     let form_decl = build_formula_function (varname, idx) symbols element.formula_expr
             in
794     let _ = Llvm.build_store form_decl (Llvm.build_struct_gep storage_addr (
            formula_field_index FormulaCall) "" init_bod) init_bod in
795     () in
796
797   (* Builds a var_defn struct for each variable *)
798   let build_var_defn defn varname va symbols =
799     let numForm = List.length va.var_formulas in
800     let formulas = Llvm.build_array_malloc base_types.formula_t (Llvm.const_int
            base_types.int_t numForm) "" init_bod in
801     (*getDefn simply looks up the correct definition for a dimension declaration of a
            variable. Note that currently it is ambiguous whether it is a variable or a
            literal. TOOD: consider negative numbers*)
802     let getDefn = function
803         DimId(a) -> (match StringMap.find a symbols with LocalVariable(i) -> i |
                GlobalVariable(i) -> i | _ -> raise(TransformedAway("Error in " ^ varname ^
                 ": The LHS expresssions should always either have dimension length 1 or be
                 the name of a variable in their own scope.")))
804       | DimOneByOne -> 1 in
805     let _ = (match va.var_rows with
806           DimOneByOne -> Llvm.build_store (Llvm.const_int base_types.char_t 1) (Llvm.
                build_struct_gep defn (var_defn_field_index OneByOne) "" init_bod)
```

```
              init_bod
807         | DimId(a) -> (
808             let _ = Llvm.build_store (Llvm.const_int base_types.char_t 0) (Llvm.
                    build_struct_gep defn (var_defn_field_index OneByOne) "" init_bod)
                    init_bod in ();
809             let _ = Llvm.build_store (Llvm.const_int base_types.int_t (getDefn va.
                    var_rows)) (Llvm.build_struct_gep defn (var_defn_field_index Rows) ""
                    init_bod) init_bod in ();
810             Llvm.build_store (Llvm.const_int base_types.int_t (getDefn va.var_cols)) (
                    Llvm.build_struct_gep defn (var_defn_field_index Cols) "" init_bod)
                    init_bod
811           )
812       ) in
813     let _ = Llvm.build_store (Llvm.const_int base_types.int_t numForm) (Llvm.
            build_struct_gep defn (var_defn_field_index NumFormulas) "" init_bod) init_bod
814     and _ = Llvm.build_store formulas (Llvm.build_struct_gep defn (
            var_defn_field_index Formulas) "" init_bod) init_bod
815     and _ = Llvm.build_store (Llvm.build_global_stringptr varname "" init_bod) (Llvm.
            build_struct_gep defn (var_defn_field_index VarName) "" init_bod) init_bod in
816     List.iteri (fun idx elem -> build_formula (varname, idx) formulas elem symbols) va
            .var_formulas in
817
818   (* Creates a scope object and inserts the necessary instructions into main to
          populate the var_defns, and
819    * into the function specified by builder to populate the scope object. *)
820   let build_scope_obj
821       fname (* The function name, or "globals" *)
822       symbols (* The symbols to use when creating the functions *)
823       vars (* The variables to build definitions and formula-functions for *)
824       static_location_ptr (* The copy of the global pointer used in main *)
825       var_defns_loc (* The copy of the global pointer used in the local function *)
826       num_params (* How many parameters the function takes *)
827       builder (* The LLVM builder for the local function *)
828     =
829     let cardinal = Llvm.const_int base_types.int_t (StringMap.cardinal vars) in
830     let build_var_defns =
831       let static_var_defns = Llvm.build_array_malloc base_types.var_defn_t cardinal (
              fname ^ "_static_var_defns") init_bod in
832       let _ = Llvm.build_store static_var_defns static_location_ptr init_bod in
833       let add_variable varname va (sm, count) =
834         let fullname = fname ^ "_" ^ varname in
835         let defn = (Llvm.build_in_bounds_gep static_var_defns [|Llvm.const_int
                base_types.int_t count|] (fullname ^ "_defn") init_bod) in
836         let _ = build_var_defn defn fullname va symbols in
837         (StringMap.add varname count sm, count + 1) in
838       ignore (StringMap.fold add_variable vars (StringMap.empty, 0)) in
839
840     let var_defns = Llvm.build_load var_defns_loc (fname ^ "_global_defn_ptr_loc")
            builder in
841     let var_insts = Llvm.build_array_malloc base_types.var_instance_p cardinal "
            var_insts" builder in
842     let scope_obj = Llvm.build_malloc base_types.extend_scope_t "scope_obj" builder in
843
844     (*Store variable definition and instance*)
845     let _ = Llvm.build_store var_defns (Llvm.build_struct_gep scope_obj (
            scope_field_type_index VarDefn) "" builder) builder in
```

```
846     let _ = Llvm.build_store var_insts (Llvm.build_struct_gep scope_obj (
            scope_field_type_index VarInst) "" builder) builder in
847     let _ = Llvm.build_store cardinal (Llvm.build_struct_gep scope_obj (
            scope_field_type_index VarNum) "" builder) builder in
848     let _ = Llvm.build_store (Llvm.const_int base_types.int_t 0) (Llvm.
            build_struct_gep scope_obj (scope_field_type_index ScopeRefCount) "" builder)
            builder in
849     let paramarray = if num_params > 0 then Llvm.build_array_malloc base_types.value_p
             (Llvm.const_int base_types.int_t num_params) "paramarray" builder else Llvm.
            const_pointer_null (Llvm.pointer_type base_types.value_p) in
850     let _ = Llvm.build_store paramarray (Llvm.build_struct_gep scope_obj (
            scope_field_type_index FunctionParams) "" builder) builder in
851     let copy_fn_arg i =
852       let param_addr = Llvm.build_in_bounds_gep paramarray [|Llvm.const_int base_types
              .int_t i|] (fname ^ "_param_" ^ string_of_int i ^ "_loc") builder in
853       ignore (Llvm.build_store (Llvm.param (StringMap.find fname function_llvalues) i)
              param_addr builder) in
854     List.iter copy_fn_arg (zero_until num_params);
855     let _ = Llvm.build_call (Hashtbl.find runtime_functions "null_init") [|scope_obj|]
             "" builder in
856     build_var_defns ; scope_obj in
857   (* End of build_scope_obj *)
858
859   let build_function fname (fn_def, fn_llvalue) =
860     (* Build the symbol table for this function *)
861     let symbols = create_symbol_table global_symbols fn_def in
862     let fn_idx = match StringMap.find fname extend_fn_numbers with ExtendFunction(i)
            -> i | _ -> raise(LogicError(fname ^ " not in function table")) in
863     let builder = Llvm.builder_at_end context (Llvm.entry_block fn_llvalue) in
864     let static_location_ptr = Llvm.build_in_bounds_gep array_of_vardefn_ptrs [|Llvm.
            const_int base_types.int_t 0; Llvm.const_int base_types.int_t fn_idx|] (fname ^
             "_global_defn_ptr") init_bod in
865     let var_defns_loc = Llvm.build_in_bounds_gep array_of_vardefn_ptrs [|Llvm.
            const_int base_types.int_t 0; Llvm.const_int base_types.int_t fn_idx|] (fname ^
             "_local_defn_ptr") builder in
866     let scope_obj = build_scope_obj fname symbols fn_def.func_body static_location_ptr
             var_defns_loc (List.length fn_def.func_params) builder in
867     let get_special_val special_name = function
868         Id(s) -> (match (try StringMap.find s symbols with Not_found -> raise(
                LogicError("Something went wrong with your semantic analysis - " ^ s ^ "
                not found"))) with
869             LocalVariable(i) ->
870             let llvm_var = Llvm.build_call getVar [|scope_obj; Llvm.const_int
                    base_types.int_t i|] (special_name ^ "_var") builder in
871             Llvm.build_call getVal [|llvm_var; Llvm.const_int base_types.int_t 0; Llvm
                    .const_int base_types.int_t 0|] (special_name ^ "_val") builder
872           | _ -> raise(TransformedAway("Error in " ^ fname ^ ": The " ^ special_name ^
                    " value should always have been transformed into a local variable")))
873       | _ -> raise(TransformedAway("Error in " ^ fname ^ ": The " ^ special_name ^ "
             value should always have been transformed into a local variable")) in
874     let assert_val = get_special_val "assert" (List.hd fn_def.func_asserts) in
875     let _ = Llvm.build_call (Hashtbl.find runtime_functions "verify_assert") [|
            assert_val; Llvm.build_global_stringptr fname "" builder|] "" builder in
876     let ret_val = get_special_val "return" (snd fn_def.func_ret_val) in
877     let _ = Llvm.build_ret ret_val builder in () in
878   (* End of build_function *)
```

```
879
880   (* Build the global scope object *)
881   let vardefn_p_p = Llvm.build_alloca base_types.var_defn_p "v_p_p" init_bod in
882   let global_scope_obj = build_scope_obj "globals" global_symbols globals vardefn_p_p
          vardefn_p_p 0 init_bod in
883   let _ = Llvm.build_call (Hashtbl.find runtime_functions "incStack") [||] "" init_bod
           in
884   let _ = Llvm.build_store global_scope_obj global_scope_loc init_bod in
885
886   (*iterates over function definitions*)
887   StringMap.iter build_function extend_functions ;
888
889   (* Define the LLVM entry point for the program *)
890   let extend_entry_point = StringMap.find "main" function_llvalues in
891   let _ = Llvm.build_ret_void init_bod in
892   let _ = Llvm.build_ret_void literal_bod in
893   let _ = Llvm.build_call init_def [||] "" main_bod in
894   let _ = Llvm.build_call literal_def [||] "" main_bod in
895   let cmd_line_args = Llvm.build_call (Hashtbl.find runtime_functions "
          box_command_line_args") [|Llvm.param main_def 0; Llvm.param main_def 1|] "
          cmd_line_args" main_bod in
896   let _ = Llvm.build_call extend_entry_point [|cmd_line_args|] "" main_bod in
897   let _ = Llvm.build_ret (Llvm.const_int base_types.int_t 0) main_bod in
898
899   base_module
900
901 let build_this ast_mapped =
902   let modu = (translate ast_mapped) in
903   let _ = Llvm_analysis.assert_valid_module modu in
904   modu
```

8.8 linker.ml

```
1  module StringSet = Set.Make(String)
2  let link xtndOut ast compiler outputFile =
3    let tmpFilenameLL = Filename.temp_file "" ".ll"
4    and tmpFilenameC = Filename.temp_file "" ".o"
5    and getExterns (_,_,extern) =
6      StringSet.elements
7        (Ast.StringMap.fold
8          (fun key value store -> StringSet.add value.Ast.extern_fn_libname store)
9          extern
10         StringSet.empty) in
11   let tmpChan = open_out tmpFilenameLL in
12   output_string tmpChan xtndOut; close_out tmpChan;
13   let call1 = (String.concat " " ("llc-3.8" :: "-filetype=obj" :: tmpFilenameLL :: "-o
          " :: tmpFilenameC :: [])) 
14   and call2 = (String.concat " " (compiler :: "-o" :: outputFile :: tmpFilenameC :: (
          getExterns ast) @ ["runtime.o"])) ^ " -lm" in
15   let resc1 = Sys.command call1 in
16   if resc1 == 0 then (
17     Sys.remove tmpFilenameLL;
18     let resc2 = Sys.command call2 in
19       Sys.remove tmpFilenameC;
20       if resc2 == 0 then () else raise Not_found
```

```
    )
  else (Sys.remove tmpFilenameC;raise Not_found)
```

8.9 main.ml

```
open Ast;;

let print_ast = ref false
let compile_ast = ref false
let link = ref false
let output = ref "./out"
let compiler = ref "gcc"
let working_dir = ref "."

let the_ast = ref (StringMap.empty, StringMap.empty, StringMap.empty)
let just_one_please = ref false

let speclist = [
                ("-p", Arg.Set print_ast, "Print the AST");
                ("-c", Arg.Set compile_ast, "Compile the program");
                ("-l", Arg.Set link, "Link the program");
                ("-cc", Arg.Set_string compiler, "Compiler to use");
                ("-o", Arg.Set_string output, "Location to output to");
                ("-w", Arg.Set_string working_dir, "Working directory");
]

let usage_message = "Welcome to Extend!\n\nUsage: extend <options> <source-file>\n\
    nOptions are:"

let parse_ast filename =
  if !just_one_please
  then print_endline "Any files after the first one are ignored."
  else just_one_please := true ; the_ast := (Transform.create_ast filename);;

Arg.parse speclist parse_ast usage_message;
Sys.chdir !working_dir;
if not !just_one_please then Arg.usage speclist usage_message else ();
if !print_ast then print_endline (string_of_program !the_ast) else ();
if !compile_ast then
  let compiled = (Llvm.string_of_llmodule (Codegen.translate !the_ast))
  in
    if not (!link) then print_endline compiled
    else Linker.link compiled !the_ast !compiler !output
else ();
```

8.10 lib.c

```
#include<stdio.h>
#include<stdlib.h>
#include<math.h>
#include<string.h>
#include<stdbool.h>
/* #include <sys/time.h> */
#include <time.h>
#include "runtime.h"
```

```
9
10 #define MAX_FILES 255
11 FILE *open_files[1 + MAX_FILES] = {NULL};
12 int open_num_files = 0;
13
14 value_p extend_print(value_p whatever, value_p text) {
15   if(!assertSingleString(text)) return new_val();
16   if(!assertText(text)) return new_val();
17   printf("%s", text->str->text);
18   return new_val();
19 }
20
21 value_p extend_printv(value_p whatever, value_p text) {
22   printf("%s", text->str->text);
23   return new_val();
24 }
25
26 value_p extend_printd(value_p whatever, value_p text) {
27   printf("%f\n", text->numericVal);
28   value_p result = malloc(sizeof(struct value_t));
29   return result;
30 }
31
32 value_p extend_to_string(value_p val) {
33     if(assertSingleNumber(val)) {
34       double possible_num = val->numericVal;
35       int rounded_int = (int) lrint(possible_num);
36       char *converted_str;
37       if (fabs(possible_num - rounded_int) < FLOAT_CUTOFF) {
38         int size = snprintf(NULL, 0, "%d", rounded_int);
39         converted_str = malloc(size + 1);
40         sprintf(converted_str, "%d", rounded_int);
41       } else {
42         int size = snprintf(NULL, 0, "%f", possible_num);
43         converted_str = malloc(size + 1);
44         sprintf(converted_str, "%f", possible_num);
45       }
46       value_p result = new_string(converted_str);
47       return result;
48     }
49     else if(assertSingleString(val)) return val;
50     else if(val->flags == FLAG_EMPTY) {
51       value_p _new = new_val();
52       setString(_new, "empty", 5);
53       return _new;
54     }
55     else if(val->flags == FLAG_SUBRANGE) {
56       int i,j,len;
57       value_p value;
58       char *result, *res;
59       len = 0;
60       subrange_p sr = val->subrange;
61       value_p *strs = malloc(sizeof(value_p) * sr->subrange_num_cols * sr->
             subrange_num_rows);
62       for(i = 0; i < sr->subrange_num_rows; i++) {
63         for(j = 0; j < sr->subrange_num_cols; j++) {
```

```
64            value = extend_to_string(getValSR(sr, i, j));
65            //debug_print(value, "");
66            strs[i * sr->subrange_num_cols + j] = value;
67            len += value->str->length;
68          }
69        }
70        len += sr->subrange_num_rows * sr->subrange_num_cols + 1 /*closing paren*/;
71        res = result = malloc(len + 1/*terminal character*/);
72        *result = '{';
73        result++;
74        for(i = 0; i < sr->subrange_num_rows; i++) {
75          for(j = 0; j < sr->subrange_num_cols; j++) {
76            memcpy(result,strs[i * sr->subrange_num_cols + j]->str->text, strs[i * sr->
                  subrange_num_cols + j]->str->length);
77            result += strs[i * sr->subrange_num_cols + j]->str->length;
78            if(j != sr->subrange_num_cols - 1) {
79              *result = ',';
80              result++;
81            }
82          }
83          if(i != sr->subrange_num_rows - 1) {
84            *result = ';';
85            result++;
86          }
87        }
88        *result = '}';
89        value_p ret_val = new_val();
90        setString(ret_val, res, len);
91        return ret_val;
92      } else {
93        __builtin_unreachable();
94      }
95      // If the struct does not hold a string or number, return empty?
96      return new_val();
97  }
98
99  #define EXPOSE_MATH_FUNC(name) value_p extend_##name(value_p a){if(!assertSingleNumber
        (a)) return new_val();double val = name(a->numericVal);return new_number(val);}
100 EXPOSE_MATH_FUNC(sin)
101 EXPOSE_MATH_FUNC(cos)
102 EXPOSE_MATH_FUNC(tan)
103 EXPOSE_MATH_FUNC(acos)
104 EXPOSE_MATH_FUNC(asin)
105 EXPOSE_MATH_FUNC(atan)
106 EXPOSE_MATH_FUNC(sinh)
107 EXPOSE_MATH_FUNC(cosh)
108 EXPOSE_MATH_FUNC(tanh)
109 EXPOSE_MATH_FUNC(exp)
110 EXPOSE_MATH_FUNC(log)
111 EXPOSE_MATH_FUNC(log10)
112 EXPOSE_MATH_FUNC(sqrt)
113 EXPOSE_MATH_FUNC(ceil)
114 EXPOSE_MATH_FUNC(fabs)
115 EXPOSE_MATH_FUNC(floor)
116
117 value_p extend_get_stdin() {
```

```
118   if (open_num_files + 1 > MAX_FILES) {
119     return new_val();
120   } else {
121     open_num_files++;
122     open_files[open_num_files] = stdin;
123     return new_number((double) open_num_files);
124   }
125 }
126
127 value_p extend_get_stdout() {
128   if (open_num_files + 1 > MAX_FILES) {
129     return new_val();
130   } else {
131     open_num_files++;
132     open_files[open_num_files] = stdout;
133     return new_number((double) open_num_files);
134   }
135 }
136
137 value_p extend_get_stderr() {
138   if (open_num_files + 1 > MAX_FILES) {
139     return new_val();
140   } else {
141     open_num_files++;
142     open_files[open_num_files] = stderr;
143     return new_number((double) open_num_files);
144   }
145 }
146
147 value_p extend_open(value_p filename, value_p mode){
148   FILE *val;
149   if (   !assertSingleString(filename)
150       || !assertSingleString(mode)
151       || open_num_files + 1 > MAX_FILES) {
152         return new_val();
153   }
154   val = fopen(filename->str->text, mode->str->text);
155   if(val == NULL) return new_val();
156   open_num_files++;
157   open_files[open_num_files] = val;
158   return new_number((double) open_num_files);
159 }
160
161 value_p extend_close(value_p file_handle) {
162   if(!assertSingleNumber(file_handle)) {
163     // Per the LRM this is actually supposed to crash the program.
164     fprintf(stderr, "EXITING - Attempted to close something that was not a valid file
          pointer\n");
165     exit(-1);
166   }
167   int fileNum = (int) file_handle->numericVal;
168
169   if (fileNum > open_num_files || open_files[fileNum] == NULL) {
170     // Per the LRM this is actually supposed to crash the program.
171     fprintf(stderr, "EXITING - Attempted to close something that was not a valid file
          pointer\n");
```

```
172     exit(-1);
173   }
174   fclose(open_files[fileNum]);
175   open_files[fileNum] = NULL; // Empty the container for the pointer.
176   return new_val(); // asssuming it was an open valid handle, close() is just supposed
          to return empty
177 }
178
179 value_p extend_read(value_p file_handle, value_p num_bytes){
180   if(!assertSingleNumber(file_handle) || !assertSingleNumber(num_bytes)) return
          new_val();
181   int max_bytes;
182   int fileNum = (int) file_handle->numericVal;
183   if (fileNum > open_num_files || open_files[fileNum] == NULL)  return new_val();
184   FILE *f = open_files[fileNum];
185   max_bytes = (int) num_bytes->numericVal;
186   if (max_bytes == 0) {
187     long cur_pos = ftell(f);
188     fseek(f, 0, SEEK_END);
189     long end_pos = ftell(f);
190     fseek(f, cur_pos, SEEK_SET);
191     max_bytes = end_pos - cur_pos;
192   }
193   char *buf = malloc(sizeof(char) * (max_bytes + 1));
194   int bytes_read = fread(buf, sizeof(char), max_bytes, f);
195   buf[bytes_read] = 0;
196   value_p result = new_string(buf);
197   free(buf);
198   return result;
199   //edge case: how to return the entire contents of the file if n == empty?
200 }
201
202 value_p extend_readline(value_p file_handle) {
203   int i=0, buf_size = 256;
204   char next_char;
205   if (!assertSingleNumber(file_handle)) return new_val();
206   int fileNum = (int) file_handle->numericVal;
207   FILE *f = open_files[fileNum];
208   if (fileNum > open_num_files || open_files[fileNum] == NULL) {
209     return new_val();
210   }
211   char *buf = (char *) malloc (buf_size * sizeof(char));
212   while ((next_char = fgetc(f)) != '\n') {
213     buf[i++] = next_char;
214     if (i == buf_size - 2) {
215       buf_size *= 2;
216       char *new_buf = (char *) malloc (buf_size * sizeof(char));
217       memcpy(new_buf, buf, i);
218       free(buf);
219       buf = new_buf;
220     }
221   }
222   buf[i] = '\0';
223   value_p result = new_string(buf);
224   free(buf);
225   return result;
```

```
226 }
227
228 value_p extend_write(value_p file_handle, value_p buffer){
229   if(!assertSingleNumber(file_handle) || !assertSingleString(buffer)) return new_val()
        ;
230   int fileNum = (int) file_handle->numericVal;
231   if (fileNum > open_num_files || open_files[fileNum] == NULL) {
232     // Per the LRM this is actually supposed to crash the program.
233     fprintf(stderr, "EXITING - Attempted to write to something that was not a valid
          file pointer\n");
234     exit(-1);
235   }
236   fwrite(buffer->str->text, 1, buffer->str->length, open_files[fileNum]);
237   // TODO: make this return empty once compiler handles Id(s)
238   // RN: Use the return value to close the file
239   return new_number((double) fileNum);
240 }
241
242 value_p extend_current_hour() {
243   time_t ltime;
244   struct tm info;
245   ltime = time(&ltime);
246   localtime_r(&ltime, &info);
247   return new_number((double) info.tm_hour);
248 }
249
250 value_p extend_isNaN(value_p val) {
251   if (!assertSingleNumber(val)) return new_val();
252   double d = val->numericVal;
253   return isnan(d) ? new_number(1.0) : new_number(0.0);
254 }
255
256 value_p extend_isInfinite(value_p val) {
257   if (!assertSingleNumber(val)) return new_val();
258   double d = val->numericVal;
259   if (isinf(d)) {
260       return d < 0 ? new_number(-1.0) : new_number(1.0);
261   } else {
262     return new_number(0.0);
263   }
264 }
265
266 value_p extend_toASCII(value_p val) {
267   if (!assertSingleString(val)) return new_val();
268   value_p *val_arr = malloc(sizeof(value_p) * val->str->length);
269   int i;
270   for(i = 0; i < val->str->length; i++) {
271     value_p my_val = malloc(sizeof(struct value_t));
272     my_val->flags = FLAG_NUMBER;
273     my_val->numericVal = (double)val->str->text[i];
274     val_arr[i] = my_val;
275   }
276   value_p _new = new_subrange(1,val->str->length, val_arr);
277   return _new;
278 }
279
```

```
value_p extend_fromASCII(value_p val) {
  value_p result = new_val();
  if(val->flags == FLAG_NUMBER) {
    char xxx = ((char)lrint(val->numericVal));
    setString(result, &xxx, 1);
  }
  else if(val->flags == FLAG_SUBRANGE) {
    int rows, cols, len;
    rows = val->subrange->subrange_num_rows;
    cols = val->subrange->subrange_num_cols;
    if(rows > 1 && cols > 1) return result;
    else len = rows == 1 ? cols : rows;
    char *text = malloc(sizeof(char) * len);
    for(rows = 0; rows < val->subrange->subrange_num_rows; rows++) {
      for(cols = 0; cols < val->subrange->subrange_num_cols; cols++) {
        value_p single = getValSR(val->subrange, rows, cols);
        if(single->flags != FLAG_NUMBER) {
          free(text);
          return result;
        }
        text[rows + cols] = (char)lrint(single->numericVal);
      }
    }
    setString(result, text, len);
  }
  return result;
}
```

8.11 runtime.c

```
#include<stdio.h>
#include<stdlib.h>
#include<math.h>
#include<sys/resource.h>
#include<string.h>
#include<stdbool.h>
#include "runtime.h"

struct value_t zero_val = {FLAG_NUMBER, 0.0, NULL, NULL};
struct value_t one_val = {FLAG_NUMBER, 1.0, NULL, NULL};
struct rhs_index absolute_zero = {&zero_val, RHS_IDX_ABSOLUTE};
struct rhs_index absolute_one = {&one_val, RHS_IDX_ABSOLUTE};
struct rhs_slice zero_to_one = {&absolute_zero, &absolute_one};
struct rhs_slice corresponding_cell = {NULL, NULL};

void debug_print_subrange(subrange_p subrng);

void debug_print(value_p val, char *which_value) {
  char *flag_meanings[4] = {"Empty", "Number", "String", "Subrange"};
  fprintf(stderr, "-------Everything you ever wanted to know about %s:-------\n",
      which_value == NULL ? "some anonymous variable" : which_value);
  fprintf(stderr, "Memory address: %p\n", val);
  if (val == NULL) {
    fprintf(stderr, "--------------Nice try asking me to dereference a null pointer\n
        --------------");
```

```
24      return;
25    }
26    fprintf(stderr, "Flags: %d (%s)\n", val->flags, flag_meanings[val->flags]);
27    fprintf(stderr, "NumericVal: %f\n", val->numericVal);
28    fprintf(stderr, "String contents: Probably safer not to check that pointer (%p)
          blindly\n", val->str);
29    if (val->flags == FLAG_STRING && val->str != NULL) {
30      fprintf(stderr, "It says it's a string and it's not a NULL pointer though, so here
            you go:\n");
31      fprintf(stderr, "String refcount: %d\n", val->str->refs);
32      fprintf(stderr, "String length: %ld\n", val->str->length);
33      fprintf(stderr, "String char* memory address: %p\n", val->str->text);
34      if (val->str->text == NULL) {
35        fprintf(stderr, "Not going to print the contents of NULL!\n");
36      } else {
37        fprintf(stderr, "String char* contents:\n%s\n", val->str->text);
38      }
39    }
40    fprintf(stderr, "Subrange contents: Probably safer not to check that pointer (%p)
          blindly either\n", val->subrange);
41    if (val->flags == FLAG_SUBRANGE && val->subrange != NULL) {
42      fprintf(stderr, "It says it's a subrange and it's not a NULL pointer though, so
            here you go:\n");
43      debug_print_subrange(val->subrange);
44    }
45    fprintf(stderr, "-------That's all I've got to say about %s:-------\n", which_value ==
          NULL ? "some anonymous variable" : which_value);
46  }
47
48  void debug_print_formula(struct ExtendFormula *fdef) {
49    fprintf(stderr, "-------Everything you ever wanted to know about your favorite
          formula:-------\n");
50    fprintf(stderr, "RowStart varnum: %d %d\n", fdef->rowStart_varnum, fdef->
          fromFirstRow);
51    fprintf(stderr, "RowEnd varnum: %d %d\n", fdef->rowEnd_varnum, fdef->toLastRow);
52    fprintf(stderr, "ColStart varnum: %d %d\n", fdef->colStart_varnum, fdef->
          fromFirstCol);
53    fprintf(stderr, "ColEnd varnum: %d %d\n", fdef->colEnd_varnum, fdef->toLastCol);
54  }
55
56  void debug_print_res_formula(struct ResolvedFormula *rdef) {
57    fprintf(stderr, "Some formula with function pointer %p applies to: [%d:%d,%d:%d]\n",
          rdef->formula, rdef->rowStart, rdef->rowEnd, rdef->colStart, rdef->colEnd);
58  }
59
60  void debug_print_vardefn(struct var_defn *pdef) {
61    fprintf(stderr, "-------Everything you ever wanted to know about var defn %s:-------\n
          ", pdef->name);
62    fprintf(stderr, "Row varnum: %d\n", pdef->rows_varnum);
63    fprintf(stderr, "Col varnum: %d\n", pdef->cols_varnum);
64    fprintf(stderr, "Num formulas: %d\n", pdef->numFormulas);
65    fprintf(stderr, "Formula defs: \n");
66    int i;
67    for (i=0; i < pdef->numFormulas; i++) {
68      debug_print_formula(pdef->formulas + i);
69    }
```

```
70    fprintf(stderr, "Is 1x1: %d\n", pdef->isOneByOne);
71  }
72
73  void debug_print_varinst(struct var_instance *inst) {
74    fprintf(stderr, "-------Everything you ever wanted to know about var %s:-------\n",
          inst->name);
75    fprintf(stderr, "Rows: %d\n", inst->rows);
76    fprintf(stderr, "Cols: %d\n", inst->cols);
77    fprintf(stderr, "Num formulas: %d\n", inst->numFormulas);
78    fprintf(stderr, "*****Formulas:*****\n");
79    int i;
80    for (i = 0; i < inst->numFormulas; i++) {
81      debug_print_res_formula(inst->formulas + i);
82    }
83    fprintf(stderr, "**** End of Formulas *** \n");
84    fprintf(stderr, "~~~~~~~~Cells:~~~~~~~~\n");
85    fprintf(stderr, "Status memory address: %p\n", inst->status);
86    for (i = 0; i < inst->rows * inst->cols; i++) {
87      printf("%s[%d,%d]: Status=%d\n", inst->name, i / inst->cols, i % inst->cols, inst
            ->status[i]);
88      if (inst->status[i] == CALCULATED) {
89        printf("%s[%d,%d] Value:\n", inst->name, i / inst->cols, i % inst->cols);
90        debug_print(inst->values[i], inst->name);
91      }
92    }
93    fprintf(stderr, "~~~ End of Cells: ~~~\n");
94  }
95
96  void debug_print_subrange(subrange_p subrng) {
97    fprintf(stderr, "--------Everything you wanted to know about this subrange-------\n");
98    fprintf(stderr, "Offset: [%d,%d]\n", subrng->base_var_offset_row, subrng->
          base_var_offset_col);
99    fprintf(stderr, "Dimensions: [%d,%d]\n", subrng->subrange_num_rows, subrng->
          subrange_num_cols);
100   fprintf(stderr, "Subrange of: \n");
101   debug_print_varinst(subrng->range);
102 }
103
104 void debug_print_index(struct rhs_index *idx) {
105   if (idx == NULL) {
106     fprintf(stderr, "I'd rather not try to print out the contents of a NULL index.\n")
            ;
107     exit(-1);
108   }
109   fprintf(stderr, "Index type: ");
110   switch(idx->rhs_index_type) {
111     case RHS_IDX_ABSOLUTE:
112       fprintf(stderr, "Absolute\n");
113       if (idx->val_of_expr == NULL) {
114         fprintf(stderr, "I wasn't expecting this, but the value pointer is NULL. Maybe
                there's a good reason for it, so I'll keep going...\n");
115       } else {
116         debug_print(idx->val_of_expr, "an absolute index");
117       }
118       break;
119     case RHS_IDX_RELATIVE:
```

```
120       fprintf(stderr, "Relative\n");
121       if (idx->val_of_expr == NULL) {
122         fprintf(stderr, "I wasn't expecting this, but the value pointer is NULL. Maybe
                there's a good reason for it, so I'll keep going...\n");
123       } else {
124         debug_print(idx->val_of_expr, "a relative index");
125       }
126       break;
127     case RHS_IDX_DIM_START:
128       fprintf(stderr, "DimensionStart\n");
129       if (idx->val_of_expr != NULL) {
130         fprintf(stderr, "This definitely isn't supposed to happen — the value pointer
                isn't NULL. You should look into that.\n");
131         exit(-1);
132       }
133       break;
134     case RHS_IDX_DIM_END:
135       fprintf(stderr, "DimensionEnd\n");
136       if (idx->val_of_expr != NULL) {
137         fprintf(stderr, "This definitely isn't supposed to happen — the value pointer
                isn't NULL. You should look into that.\n");
138         exit(-1);
139       }
140       break;
141   }
142 }
143
144 void debug_print_slice(struct rhs_slice *sl) {
145   if (sl == NULL) {
146     fprintf(stderr, "I'd rather not try to print out the contents of a NULL slice.\n")
          ;
147     exit(-1);
148   }
149   fprintf(stderr, "————————Everything about this slice————————\n");
150   fprintf(stderr, "Start and end index memory addresses: %p and %p\n", sl->
        slice_start_index, sl->slice_end_index);
151   if (sl->slice_start_index != NULL) {
152     fprintf(stderr, "Start index info:\n");
153     debug_print_index(sl->slice_start_index);
154     if (sl->slice_end_index != NULL) {
155       fprintf(stderr, "End index info:\n");
156       debug_print_index(sl->slice_end_index);
157     }
158   } else {
159     if (sl->slice_end_index != NULL) {
160       fprintf(stderr, "Start index is NULL but end index is not NULL. That should
              never happen.\n");
161       fprintf(stderr, "Attempting to print contents anyway:\n");
162       fflush(stderr);
163       debug_print_index(sl->slice_end_index);
164     }
165   }
166 }
167
168 void debug_print_selection(struct rhs_selection *sel) {
169   if (sel == NULL) {
```

```
170     fprintf(stderr, "I'd rather not try to print out the contents of a NULL selection
            .\n");
171     exit(-1);
172   }
173   fprintf(stderr, "--------Everything about this selection-------\n");
174   fprintf(stderr, "Slice memory addresses: %p and %p\n", sel->slice1, sel->slice2);
175   if (sel->slice1 != NULL) {
176     fprintf(stderr, "Slice 1 info:\n");
177     debug_print_slice(sel->slice1);
178     if (sel->slice2 != NULL) {
179       fprintf(stderr, "Slice 2 info:\n");
180       debug_print_slice(sel->slice2);
181     }
182   } else {
183     if (sel->slice2 != NULL) {
184       fprintf(stderr, "Slice 1 is NULL but slice 2 is not NULL. That should never
              happen.\n");
185       fprintf(stderr, "Attempting to print contents anyway:\n");
186       fflush(stderr);
187       debug_print_slice(sel->slice2);
188     }
189   }
190   fprintf(stderr, "--------That's all I've got about that selection-------\n\n");
191 }
192
193 int rg_eq(value_p val1, value_p val2) {
194   int res = 1;
195   if(val1->flags != val2->flags) res = 0;
196   else if(val1->flags == FLAG_EMPTY) ;
197   else if(val1->flags == FLAG_NUMBER && val1->numericVal != val2->numericVal) res = 0;
198   else if(val1->flags == FLAG_STRING && strcmp(val1->str->text, val2->str->text)) res
          = 0;
199   else if(val1->flags == FLAG_SUBRANGE) {
200     subrange_p sr1 = val1->subrange;
201     subrange_p sr2 = val2->subrange;
202     if(sr1->subrange_num_cols != sr2->subrange_num_cols || sr1->subrange_num_rows !=
            sr2->subrange_num_rows) {
203       return 0;
204     } else {
205       int i, j;
206       value_p v1, v2;
207       for(i = 0; i < sr1->subrange_num_rows; i++) {
208         for(j = 0; j < sr1->subrange_num_cols; j++) {
209           v1 = getValSR(sr1, i, j);
210           v2 = getValSR(sr2, i, j);
211           if(rg_eq(v1, v2) == 0) {
212             return 0;
213           }
214         }
215       }
216     }
217   }
218   return res;
219 }
220
221 void incStack() {
```

```
  const rlim_t kStackSize = 64L * 1024L * 1024L;
  struct rlimit rl;
  int result;

  result = getrlimit(RLIMIT_STACK, &rl);
  rl.rlim_cur = rl.rlim_max;
  result = setrlimit(RLIMIT_STACK, &rl);
}

double setNumeric(value_p result, double val) {
  result->flags = FLAG_NUMBER;
  return (result->numericVal = val);
}

char* setString(value_p result, char *str, int length) {
  result->flags = FLAG_STRING;
  result->str = malloc(sizeof(struct string_t));
  result->str->length = length;
  return (result->str->text = str);
}

double setFlag(value_p result, double flag_num) {
  return (result->flags = flag_num);
}

int assertSingle(value_p value) {
  /* TODO: dereference 1 by 1 subrange */
  return !(value->flags == FLAG_SUBRANGE);
}

int assertSingleNumber(value_p p) {
  if (!assertSingle(p)) {
    return 0;
  }
  return (p->flags == FLAG_NUMBER);
}

int assertText(value_p my_val) {
  return (my_val->flags == FLAG_STRING);
}

int assertSingleString(value_p p) {
  if (!assertSingle(p)) {
    return 0;
  }
  return (p->flags == FLAG_STRING);
}

int assertEmpty(value_p p) {
  if (!assertSingle(p)) {
    return 0;
  }
  return (p->flags == FLAG_EMPTY);
}

value_p new_val() {
```

```
278   value_p empty_val = malloc(sizeof(struct value_t));
279   setFlag(empty_val, FLAG_EMPTY);
280   return empty_val;
281 }
282
283 value_p new_number(double val) {
284   value_p new_v = malloc(sizeof(struct value_t));
285   setFlag(new_v, FLAG_NUMBER);
286   setNumeric(new_v, val);
287   return new_v;
288 }
289
290 value_p new_string(char *s) {
291   if (s == NULL) return new_val();
292   value_p new_v = malloc(sizeof(struct value_t));
293   setFlag(new_v, FLAG_STRING);
294   string_p new_str = malloc(sizeof(struct string_t));
295   long len = strlen(s);
296   new_str->text = malloc(len+1);
297   strcpy(new_str->text, s);
298   new_str->length = len;
299   new_str->refs = 1;
300   new_v->str = new_str;
301   return new_v;
302 }
303
304 struct ExtendScope *global_scope;
305
306 void null_init(struct ExtendScope *scope_ptr) {
307   int i;
308   for(i = 0; i < scope_ptr->numVars; i++)
309     scope_ptr->vars[i] = NULL;
310 }
311
312 int getIntFromOneByOne(struct ExtendScope *scope_ptr, int varnum) {
313   if (!scope_ptr->defns[varnum].isOneByOne) {
314     fprintf(stderr, "The variable you claimed (%s) was one by one is not defined that
          way.\n", scope_ptr->defns[varnum].name);
315   }
316   struct var_instance *inst = get_variable(scope_ptr, varnum);
317   if (inst->rows != 1 || inst->cols != 1) {
318     fprintf(stderr, "The variable you claimed (%s) was one by one is actually %d by %d
          .\n", inst->name, inst->rows, inst->cols);
319     debug_print_varinst(inst);
320     exit(-1);
321   }
322   value_p val = getVal(inst, 0, 0);
323   if (!assertSingleNumber(val)) {
324     fprintf(stderr, "The variable you claimed (%s) was a number isn't.\n", inst->name)
          ;
325     debug_print(val, inst->name);
326     exit(-1);
327   }
328   return (int) lrint(val->numericVal);
329 }
330
```

```
331 struct var_instance *instantiate_variable(struct ExtendScope *scope_ptr, struct
        var_defn def) {
332   struct var_instance *inst = malloc(sizeof(struct var_instance));
333   if(def.isOneByOne) {
334     inst->rows = 1;
335     inst->cols = 1;
336   } else {
337     inst->rows = getIntFromOneByOne(scope_ptr, def.rows_varnum);
338     inst->cols = getIntFromOneByOne(scope_ptr, def.cols_varnum);
339   }
340   // TODO: do the same thing for each FormulaFP to turn an ExtendFormula into a
         ResolvedFormula
341   inst->numFormulas = def.numFormulas;
342   inst->closure = scope_ptr;
343   inst->name = def.name;
344   int size = inst->rows * inst->cols;
345   inst->values = malloc(sizeof(value_p) * size);
346   memset(inst->values, 0, sizeof(value_p) * size);
347   inst->status = malloc(sizeof(char) * size);
348   memset(inst->status, 0, sizeof(char) * size);
349   inst->formulas = malloc(sizeof(struct ResolvedFormula) * inst->numFormulas);
350   //debug_print_vardefn(&def);
351   //debug_print_varinst(inst);
352   int i, j;
353   for(i = 0; i < inst->numFormulas; i++) {
354
355     // Set the formula function pointer to the pointer from the definition
356     inst->formulas[i].formula = def.formulas[i].formula;
357
358     if (def.isOneByOne) {
359       inst->formulas[i].rowStart = 0;
360       inst->formulas[i].rowEnd = 1;
361       inst->formulas[i].colStart = 0;
362       inst->formulas[i].colEnd = 1;
363     } else {
364       if(def.formulas[i].fromFirstRow) {
365         inst->formulas[i].rowStart = 0;
366       } else {
367         inst->formulas[i].rowStart = getIntFromOneByOne(scope_ptr, def.formulas[i].
              rowStart_varnum);
368         if (inst->formulas[i].rowStart < 0) {
369           inst->formulas[i].rowStart += inst->rows;
370         }
371         if (inst->formulas[i].rowStart < 0 || inst->formulas[i].rowStart >= inst->rows
              ) {
372           //Doesn't matter, but will never get called
373         }
374       }
375       if (def.formulas[i].isSingleRow) {
376         inst->formulas[i].rowEnd = inst->formulas[i].rowStart + 1;
377       } else if (def.formulas[i].toLastRow) {
378         inst->formulas[i].rowEnd = inst->rows;
379       } else {
380         inst->formulas[i].rowEnd = getIntFromOneByOne(scope_ptr, def.formulas[i].
              rowEnd_varnum);
381         if (inst->formulas[i].rowEnd < 0) {
```

```
382           inst->formulas[i].rowEnd += inst->rows;
383         }
384       }
385       if(def.formulas[i].fromFirstCol) {
386         inst->formulas[i].colStart = 0;
387       } else {
388         inst->formulas[i].colStart = getIntFromOneByOne(scope_ptr, def.formulas[i].
              colStart_varnum);
389         if (inst->formulas[i].colStart < 0) {
390           inst->formulas[i].colStart += inst->cols;
391         }
392         if (inst->formulas[i].colStart < 0 || inst->formulas[i].colStart >= inst->cols
              ) {
393           //Doesn't matter, but will never get called
394         }
395       }
396       if (def.formulas[i].isSingleCol) {
397         inst->formulas[i].colEnd = inst->formulas[i].colStart + 1;
398       } else if (def.formulas[i].toLastCol) {
399         inst->formulas[i].colEnd = inst->cols;
400       } else {
401         inst->formulas[i].colEnd = getIntFromOneByOne(scope_ptr, def.formulas[i].
              colEnd_varnum);
402         if (inst->formulas[i].colEnd < 0) {
403           inst->formulas[i].colEnd += inst->cols;
404         }
405       }
406     }
407   }
408
409   for (i = 1; i < inst->numFormulas; i++) {
410     for (j = 0; j < i; j++) {
411       int intersectRowStart = (inst->formulas[i].rowStart > inst->formulas[j].rowStart
              ) ? inst->formulas[i].rowStart : inst->formulas[j].rowStart;
412       int intersectColStart = (inst->formulas[i].colStart > inst->formulas[j].colStart
              ) ? inst->formulas[i].colStart : inst->formulas[j].colStart;
413       int intersectRowEnd = (inst->formulas[i].rowEnd < inst->formulas[j].rowEnd) ?
              inst->formulas[i].rowEnd : inst->formulas[j].rowEnd;
414       int intersectColEnd = (inst->formulas[i].colEnd < inst->formulas[j].colEnd) ?
              inst->formulas[i].colEnd : inst->formulas[j].colEnd;
415       if (intersectRowEnd > intersectRowStart && intersectColEnd > intersectColStart)
              {
416         fprintf(stderr, "Runtime error: Multiple formulas were assigned to %s[%d:%d,%d
              :%d].\n", inst->name,
417                         intersectRowStart, intersectRowEnd, intersectColStart,
                              intersectColEnd);
418         exit(-1);
419       }
420     }
421   }
422
423   scope_ptr->refcount++;
424   return inst;
425 }
426
427 struct var_instance *get_variable(struct ExtendScope *scope_ptr, int varnum) {
```

```
428   if (varnum >= scope_ptr->numVars) {
429     fprintf(stderr, "Runtime error: Asked for nonexistant variable number\n");
430     exit(-1);
431   }
432   if (scope_ptr->vars[varnum] == NULL) {
433     scope_ptr->vars[varnum] = instantiate_variable(scope_ptr, scope_ptr->defns[varnum
          ]);
434   }
435   return scope_ptr->vars[varnum];
436 }
437
438 char assertInBounds(struct var_instance *defn, int r, int c) {
439   return (
440     r >= 0 && r < defn->rows &&
441     c >= 0 && c < defn->cols
442   );
443 }
444
445 value_p calcVal(struct var_instance *inst, int r, int c) {
446   int i;
447   for (i = 0; i < inst->numFormulas; i++) {
448     if (
449       r >= inst->formulas[i].rowStart && r < inst->formulas[i].rowEnd &&
450       c >= inst->formulas[i].colStart && c < inst->formulas[i].colEnd
451     ) {
452       return (inst->formulas[i].formula)(inst->closure, r, c);
453     }
454   }
455   return new_val();
456 }
457
458 value_p clone_value(value_p old_value) {
459   value_p new_value = (value_p) malloc(sizeof(struct value_t));
460   new_value->flags = old_value->flags;
461   switch (new_value->flags) {
462     case FLAG_EMPTY:
463       break;
464     case FLAG_NUMBER:
465       new_value->numericVal = old_value->numericVal;
466       break;
467     case FLAG_STRING:
468       new_value->str = old_value->str;
469       new_value->str->refs++;
470       break;
471     case FLAG_SUBRANGE:
472       new_value->subrange = (subrange_p) malloc(sizeof(struct subrange_t));
473       memcpy(new_value->subrange, old_value->subrange, sizeof(struct subrange_t));
474       if (new_value->subrange->range->closure != NULL) {
475         new_value->subrange->range->closure->refcount++; /* Not sure about this one */
476       }
477       break;
478     default:
479       fprintf(stderr, "clone_value(%p): Illegal value of flags: %c\n", old_value,
            new_value->flags);
480       exit(-1);
481       break;
```

```
482   }
483   return new_value;
484 }
485
486 void delete_string_p(string_p old_string) {
487   old_string->refs--;
488   if (old_string->refs == 0) {
489     /* free(old_string); */
490   }
491 }
492
493 void delete_subrange_p(subrange_p old_subrange) {
494   if (old_subrange->range->closure != NULL) {
495     old_subrange->range->closure->refcount--;
496   }
497   free(old_subrange);
498 }
499
500 void delete_value(value_p old_value) {
501   switch (old_value->flags) {
502     case FLAG_EMPTY:
503       break;
504     case FLAG_NUMBER:
505       break;
506     case FLAG_STRING:
507       delete_string_p(old_value->str); /* doesn't do anything besides decrement the
              ref count now */
508       break;
509     case FLAG_SUBRANGE:
510       delete_subrange_p(old_value->subrange);
511       break;
512     default:
513       fprintf(stderr, "delete_value(%p): Illegal value of flags: %c\n", old_value,
              old_value->flags);
514       exit(-1);
515       break;
516   }
517 }
518
519 value_p deref_subrange_p(subrange_p subrng) {
520   if (subrng == NULL) {
521     fprintf(stderr, "Exiting - asked to dereference a NULL pointer.\n");
522     exit(-1);
523   }
524   if (subrng->subrange_num_rows == 1 && subrng->subrange_num_cols == 1) {
525     return getVal(subrng->range, subrng->base_var_offset_row, subrng->
          base_var_offset_col);
526   } else {
527     value_p new_value = (value_p) malloc (sizeof(struct value_t));
528     new_value->flags = FLAG_SUBRANGE;
529     new_value->numericVal = 0.0;
530     new_value->str = NULL;
531     new_value->subrange = (subrange_p) malloc (sizeof(struct subrange_t));
532     memcpy(new_value->subrange, subrng, sizeof(struct subrange_t));
533     if (new_value->subrange->range->closure != NULL) {
534       new_value->subrange->range->closure->refcount++;
```

```
535     }
536     return new_value;
537   }
538 }
539
540 value_p new_subrange(int num_rows, int num_cols, value_p *vals) {
541   /* This function does not check its arguments; if you supply fewer
542    * than num_rows * num_cols elements in vals, it will crash.
543    * Only use this function if you know what you're doing. */
544    struct subrange_t sr;
545    sr.range = (struct var_instance *) malloc (sizeof(struct var_instance));
546    sr.base_var_offset_row = 0;
547    sr.base_var_offset_col = 0;
548    sr.subrange_num_rows = num_rows;
549    sr.subrange_num_cols = num_cols;
550    sr.range->rows = num_rows;
551    sr.range->cols = num_cols;
552    sr.range->numFormulas = 0;
553    sr.range->formulas = NULL;
554    sr.range->closure = NULL;
555    sr.range->values = (value_p *) malloc(num_rows * num_cols * sizeof(value_p));
556    sr.range->status = (char *) malloc (num_rows * num_cols * sizeof(char));
557    sr.range->name = NULL;
558    int i;
559    for (i = 0; i < num_rows * num_cols; i++) {
560      sr.range->values[i] = clone_value(vals[i]);
561      sr.range->status[i] = CALCULATED;
562    }
563    return deref_subrange_p(&sr);
564 }
565
566 value_p box_command_line_args(int argc, char **argv) {
567   value_p *vals = (value_p *) malloc (argc * sizeof(value_p));
568   int i;
569   for (i = 0; i < argc; i++) {
570     vals[i] = new_string(argv[i]);
571   }
572   value_p ret = new_subrange(1, argc, vals);
573   for (i = 0; i < argc; i++) {
574     free(vals[i]);
575   }
576   free(vals);
577   return ret;
578 }
579
580 char resolve_rhs_index(struct rhs_index *index, int dimension_len, int
       dimension_cell_num, int *result_ptr) {
581   if (index == NULL) {
582     fprintf(stderr, "Exiting - asked to dereference a NULL index\n");
583     exit(-1);
584   }
585   int i;
586   switch(index->rhs_index_type) {
587     case RHS_IDX_ABSOLUTE:
588       if (!assertSingleNumber(index->val_of_expr)) return false;
589       i = (int) lrint(index->val_of_expr->numericVal);
```

```
590       if (i >= 0) {
591         *result_ptr = i;
592       } else {
593         *result_ptr = i + dimension_len;
594       }
595       return true;
596       break;
597     case RHS_IDX_RELATIVE:
598       if (!assertSingleNumber(index->val_of_expr)) return false;
599       *result_ptr = dimension_cell_num + (int) lrint(index->val_of_expr->numericVal);
600       return true;
601       break;
602     case RHS_IDX_DIM_START:
603       *result_ptr = 0;
604       return true;
605       break;
606     case RHS_IDX_DIM_END:
607       *result_ptr = dimension_len;
608       return true;
609       break;
610     default:
611       fprintf(stderr, "Exiting - illegal index type\n");
612       exit(-1);
613       break;
614   }
615 }
616 
617 char resolve_rhs_slice(struct rhs_slice *slice, int dimension_len, int
        dimension_cell_num, int *start_ptr, int *end_ptr) {
618   char start_success, end_success;
619   if (slice == NULL) {
620     fprintf(stderr, "Exiting - asked to dereference a NULL slice\n");
621     exit(-1);
622   }
623   if (slice->slice_start_index == NULL) {
624     if (slice->slice_end_index != NULL) {
625       fprintf(stderr, "Exiting - illegal slice\n");
626       exit(-1);
627     }
628     if (dimension_len == 1) {
629       *start_ptr = 0;
630       *end_ptr = 1;
631       return true;
632     } else {
633       *start_ptr = dimension_cell_num;
634       *end_ptr = dimension_cell_num + 1;
635       return true;
636     }
637   } else {
638     start_success = resolve_rhs_index(slice->slice_start_index, dimension_len,
          dimension_cell_num, start_ptr);
639     if (!start_success) return false;
640     if (slice->slice_end_index == NULL) {
641       *end_ptr = *start_ptr + 1;
642       return true;
643     } else {
```

```
644       end_success = resolve_rhs_index(slice->slice_end_index, dimension_len,
              dimension_cell_num, end_ptr);
645       return end_success;
646     }
647   }
648 }
649
650 value_p extract_selection(value_p expr, struct rhs_selection *sel, int r, int c) {
651   int expr_rows, expr_cols;
652   struct subrange_t subrange;
653   struct rhs_slice *row_slice_p, *col_slice_p;
654   int row_start, row_end, col_start, col_end;
655   char row_slice_success, col_slice_success;
656
657   if (expr == NULL || sel == NULL) {
658     fprintf(stderr, "Exiting - asked to extract a selection using a NULL pointer.\n");
659     exit(-1);
660   }
661   switch(expr->flags) {
662     case FLAG_EMPTY:
663       return new_val();
664       break;
665     case FLAG_NUMBER: case FLAG_STRING:
666       expr_rows = 1;
667       expr_cols = 1;
668       break;
669     case FLAG_SUBRANGE:
670       expr_rows = expr->subrange->subrange_num_rows;
671       expr_cols = expr->subrange->subrange_num_cols;
672       break;
673     default:
674       fprintf(stderr, "Exiting - invalid value type\n");
675       exit(-1);
676       break;
677   }
678   if (sel->slice1 == NULL) {
679     if (sel->slice2 != NULL) {
680       fprintf(stderr, "Exiting - illegal selection\n");
681       exit(-1);
682     }
683     row_slice_p = &corresponding_cell;
684     col_slice_p = &corresponding_cell;
685   } else {
686     if (sel->slice2 == NULL) {
687       if (expr_rows == 1) {
688         row_slice_p = &zero_to_one;
689         col_slice_p = sel->slice1;
690       } else if (expr_cols == 1) {
691         row_slice_p = sel->slice1;
692         col_slice_p = &zero_to_one;
693       } else {
694         return new_val();
695 /*      Alternately:
696         fprintf(stderr, "Runtime error: Only given one slice for a value with multiple
              rows and multiple columns\n");
697         debug_print(expr);
```

```
698         exit(-1); */
699       }
700     } else {
701       row_slice_p = sel->slice1;
702       col_slice_p = sel->slice2;
703     }
704   }
705   row_slice_success = resolve_rhs_slice(row_slice_p, expr_rows, r, &row_start, &
        row_end);
706   col_slice_success = resolve_rhs_slice(col_slice_p, expr_cols, c, &col_start, &
        col_end);
707   if (!row_slice_success || !col_slice_success) return new_val();
708   if (row_start < 0) row_start = 0;
709   if (col_start < 0) col_start = 0;
710   if (row_end > expr_rows) row_end = expr_rows;
711   if (col_end > expr_cols)  col_end = expr_cols;
712   if (row_end <= row_start || col_end <= col_start) return new_val();
713   if (expr->flags == FLAG_NUMBER || expr->flags == FLAG_STRING) {
714     /* You would have thought we could figure this out a lot further up
715      * in the code, but had to be sure that (row_start, row_end, col_start, col_end)
716      * actually ended up as (0, 1, 0, 1) */
717     return clone_value(expr);
718   } else {
719     subrange.range = expr->subrange->range;
720     subrange.base_var_offset_row = expr->subrange->base_var_offset_row + row_start;
721     subrange.base_var_offset_col = expr->subrange->base_var_offset_col + col_start;
722     subrange.subrange_num_rows = row_end - row_start;
723     subrange.subrange_num_cols = col_end - col_start;
724     return deref_subrange_p(&subrange);
725   }
726 }
727
728 value_p getValSR(struct subrange_t *sr, int r, int c) {
729   if(sr->subrange_num_rows <= r || sr->subrange_num_cols <= c || r < 0 || c < 0)
730     return new_val();
731   return getVal(sr->range, r + sr->base_var_offset_row, c + sr->base_var_offset_col);
732 }
733
734 void verify_assert(value_p val, char *fname) {
735   if ((!assertSingleNumber(val)) || val->numericVal != 1.0) {
736     fprintf(stderr, "EXITING - The function %s was called with arguments of the wrong
          dimensions.\n", fname);
737     exit(-1);
738   }
739 }
740
741 value_p getVal(struct var_instance *inst, int r, int c) {
742   /* If we're going to return new_val() then we have to
743    * do clone_value(). Otherwise the receiver won't know
744    * whether or not they can free the value_p they get back.
745    * I think this should return, dangerously, return NULL if it's
746    * invalid, and the callers will have to be careful to check the value.
747    * The alternative is to always clone_value - safer, but much slower
748    * and makes our memory issues even bigger.
749    * Right now there are only a few places that call this. */
750
```

```
751   if(!assertInBounds(inst, r, c)) return NULL;
752   int cell_number = r * inst->cols + c;
753   char cell_status = inst->status[cell_number];
754   switch(cell_status) {
755     case NEVER_EXAMINED:
756       inst->status[cell_number] = IN_PROGRESS;
757       inst->values[cell_number] = calcVal(inst, r, c);
758       inst->status[cell_number] = CALCULATED;
759       break;
760     case IN_PROGRESS:
761       fprintf(stderr, "EXITING - Circular reference in %s[%d,%d]\n", inst->name, r, c)
              ;
762       exit(-1);
763       break;
764     case CALCULATED:
765       if (inst->values[cell_number] == NULL) {
766         fprintf(stderr, "Supposedly, %s[%d,%d] was already calculated, but there is a
              null pointer there.\n", inst->name, r, c);
767         fprintf(stderr, "Attempting to print contents of the variable instance where
              this occurred:\n");
768         fflush(stderr);
769         debug_print_varinst(inst);
770         exit(-1);
771       }
772       break;
773     default:
774       fprintf(stderr, "Unrecognized cell status %d (row %d, col %d)!\n", cell_status,
              r, c);
775       fprintf(stderr, "Attempting to print contents of the variable instance where
              this occurred:\n");
776       fflush(stderr);
777       debug_print_varinst(inst);
778       exit(-1);
779       break;
780   }
781   return inst->values[cell_number];
782 }
```

8.12 stdlib.xtnd

```
1  extern "stdlib.o" {
2    current_hour();
3    print(whatever, text);
4    printv(whatever, text);
5    printd(whatever, text);
6    to_string(val);
7    sin(val);
8    cos(val);
9    tan(val);
10   acos(val);
11   asin(val);
12   atan(val);
13   sinh(val);
14   cosh(val);
15   tanh(val);
```

```
  exp(val);
  log(val);
  log10(val);
  sqrt(val);
  ceil(val);
  fabs(val);
  floor(val);
  isNaN(val);
  isInfinite(val);
  get_stdin();
  get_stdout();
  get_stderr();
  open(filename, mode);
  close(file_handle);
  read(file_handle, num_bytes);
  readline(file_handle);
  write(file_handle, buffer);
  toASCII(val);
  fromASCII(val);
}

global STDIN := get_stdin();
global STDOUT := get_stdout();
global STDERR := get_stderr();

print_endline(val) {
  return write(STDOUT, to_string(val) + "\n");
}
```

9. Tests and Output

helloworld.xtnd

```
main(args) {
  foo := printv(1,"Hello World\n") -> 0;
  return foo;
}
```

helloworld.xtnd - Expected Output

```
Hello World
```

test-access-cell.xtnd

```
main([1,n] args) {
  [2,2] foo := "string";
  bar := foo[1,1];
  return print(1,to_string(bar)) -> print(1, "\n") -> 0;
}
```

test-access-cell.xtnd - Expected Output

```
string
```

test-access-column-cell.xtnd

```
main([1,n] args) {
  [4,1] foo := "string";
  return print(1,to_string( foo[1,0])+"\n") -> 0;
}
```

test-access-column-cell.xtnd - Expected Output

```
string
```

test-access-hashtag-multi-dim.xtnd

```
main([1,n] args) {
  [4,4] foo := "string";
  return print(1,to_string( #foo)+"\n") -> 0;
}
```

test-access-hashtag-multi-dim.xtnd - Expected Output

```
string
```

test-access-hashtag-single-dim.xtnd

```
main([1,n] args) {
  [1,1] foo := "string";
  return print(1,to_string( #foo)+"\n") -> 0;
}
```

test-access-hashtag-single-dim.xtnd - Expected Output

```
string
```

test-access-relative-range.xtnd

```
main([1,n] args) {
  [4,4] foo := "string";
  return print(1,to_string( foo[,[1]])+"\n") -> 0;
}
```

test-access-relative-range.xtnd - Expected Output

```
string
```

test-acos.xtnd

```
main(args) {
  return printd(1, acos(0.0)) -> 0;
}
```

test-acos.xtnd - Expected Output

```
1.570796
```

test-addition.xtnd

```
main(args){
  return print(1,to_string( 5 + 7)+"\n") -> 0;
}
```

test-addition.xtnd - Expected Output

```
12
```

test-addition-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty + 5)+"\n") -> 0;
}
```

test-addition-empty.xtnd - Expected Output

```
empty
```

test-asin.xtnd

```
main([1,n] args) {
  return printd(1, asin(0.5)) -> 0;
}
```

test-asin.xtnd - Expected Output

```
0.523599
```

test-atan.xtnd

```
main([1,n] args) {
  return printd(1, atan(45.0)) -> 0;
}
```

test-atan.xtnd - Expected Output

```
1.548578
```

test-basic-func.xtnd

```
main([1,n] args) {
  foo := 2;
  bar := 3;
  foobar := foo + bar;
  return print(1,to_string( 0)+"\n") -> 0;
}
```

test-basic-func.xtnd - Expected Output

```
0
```

test-bitnot.xtnd

```
main(args) {
  return print_endline(~{"a",1}) -> print_endline(~1) -> print_endline(~0) ->
      print_endline(~"a") -> print_endline(empty);
}
```

test-bitnot.xtnd - Expected Output

```
empty
-2
-1
empty
empty
```

test-bitwise-and.xtnd

```
main([1,1] args){
  return print(1,to_string( 23 & 12)+"\n") -> 0;
}
```

test-bitwise-and.xtnd - Expected Output

```
4
```

test-bitwise-and-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty & 4)+"\n") -> 0;
}
```

test-bitwise-and-empty.xtnd - Expected Output

```
empty
```

test-bitwise-left.xtnd

```
main([1,1] args){
  return print(1,to_string( 14 << 2)+"\n") -> 0;
}
```

test-bitwise-left.xtnd - Expected Output

```
56
```

test-bitwise-left-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty >> 1)+"\n") -> 0;
}
```

test-bitwise-left-empty.xtnd - Expected Output

```
empty
```

test-bitwise-not.xtnd

```
main([1,1] args){
  /* Should return -89 */
  return print(1,to_string( ~88)+"\n") -> 0;
}
```

test-bitwise-not.xtnd - Expected Output

```
-89
```

test-bitwise-not-empty.xtnd

```
main([1,1] args){
  /* Should return empty */
  return print(1,to_string( ~empty)+"\n") -> 0;
}
```

test-bitwise-not-empty.xtnd - Expected Output

```
empty
```

test-bitwise-or.xtnd

```
main([1,1] args){
  return print(1,to_string( 14 | 12)+"\n") -> 0;
}
```

test-bitwise-or.xtnd - Expected Output

```
14
```

test-bitwise-or-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty | 2)+"\n") -> 0;
}
```

test-bitwise-or-empty.xtnd - Expected Output

```
empty
```

test-bitwise-right.xtnd

```
main([1,1] args){
  return print(1,to_string( 12 >> 2)+"\n") -> 0;
}
```

test-bitwise-right.xtnd - Expected Output

```
3
```

test-bitwise-right-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty >> 2)+"\n") -> 0;
}
```

test-bitwise-right-empty.xtnd - Expected Output

```
empty
```

test-bitwise-xor.xtnd

```
main([1,1] args){
  return print(1,to_string( 14 ^ 12)+"\n") -> 0;
}
```

test-bitwise-xor.xtnd - Expected Output

```
2
```

test-bitwise-xor-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty ^ 2)+"\n") -> 0;
}
```

test-bitwise-xor-empty.xtnd - Expected Output

```
empty
```

test-boolean-equals.xtnd

```
main([1,1] args){
  return print(1,to_string( 5 == 6)+"\n") -> 0;
}
```

test-boolean-equals.xtnd - Expected Output

```
0
```

test-boolean-equals-both-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty == empty)+"\n") -> 0;
}
```

test-boolean-equals-both-empty.xtnd - Expected Output

```
1
```

test-boolean-equals-harder.xtnd

```
main([1,1] args){
  return
    printv(1, "True cases for ==\n") ->
    printd(1,  (5 == 5)) ->
    printd(1,  (5 == 5.0)) ->
    printd(1,  (0.5 == 5e-1)) ->
    printd(1,  (50 == 5e1)) ->
    printd(1,  2 + 2 == 4) ->
    printd(1,  "foo" == "foo") ->
    printd(1,  "" == "") ->
    printd(1,  empty == empty) ->
    printd(1,  empty == !empty) ->
    printd(1,  !"foo" == !"bar") ->
    printd(1, (2 ? 3 : 4) == ("foo" ? 3 : "not 4") ) ->

    printv(1, "\nFalse cases for ==\n") ->
    printd(1,  (5 == 6)) ->
    printd(1,  (5 == 5.01)) ->
    printd(1,  (0.5 == 5e-2)) ->
    printd(1,  (50 == 5e2)) ->
    printd(1,  2 + 2 == 5) ->
    printd(1,  "foo" == "bar") ->
    printd(1,  "" == "foo") ->
    printd(1,  "" == empty) ->
    printd(1,  2 == empty) ->
    printd(1,  empty == 2) ->
    printd(1, (2 ? 3 : 4) == ("foo" ? "not 3" : 4) ) ->

    printv(1, "\nTrue cases for !=\n") ->
    printd(1,  (5 != 6)) ->
    printd(1,  (5 != 5.01)) ->
    printd(1,  (0.5 != 5e-2)) ->
    printd(1,  (50 != 5e2)) ->
    printd(1,  2 + 2 != 5) ->
    printd(1,  "foo" != "bar") ->
    printd(1,  "" != "foo") ->
    printd(1,  "" != empty) ->
    printd(1,  2 != empty) ->
    printd(1,  empty != 2) ->
    printd(1, (2 ? 3 : 4) != ("foo" ? "not 3" : 4) ) ->

    printv(1, "\nFalse cases for !=\n") ->
    printd(1,  (5 != 5)) ->
    printd(1,  (5 != 5.0)) ->
    printd(1,  (0.5 != 5e-1)) ->
    printd(1,  (50 != 5e1)) ->
    printd(1,  2 + 2 != 4) ->
    printd(1,  "foo" != "foo") ->
    printd(1,  "" != "") ->
    printd(1,  empty != empty) ->
    printd(1,  empty != !empty) ->
    printd(1,  !"foo" != !"bar") ->
    printd(1, (2 ? 3 : 4) != ("foo" ? 3 : "not 4") ) ->

    0;
```

```
}
```

test-boolean-equals-harder.xtnd - Expected Output

```
True cases for ==
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000

False cases for ==
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000

True cases for !=
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000
1.000000

False cases for !=
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
0.000000
```

test-boolean-equals-one-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty == 5)+"\n") -> 0;
}
```

test-boolean-equals-one-empty.xtnd - Expected Output

```
0
```

test-boolean-logical-not-equals.xtnd

```
main([1,1] args){
  return print(1,to_string( 6 != 7)+"\n") -> 0;
}
```

test-boolean-logical-not-equals.xtnd - Expected Output

```
1
```

test-boolean-logical-not-equals-both-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty != empty)+"\n") -> 0;
}
```

test-boolean-logical-not-equals-both-empty.xtnd - Expected Output

```
0
```

test-boolean-logical-not-equals-one-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty != 5)+"\n") -> 0;
}
```

test-boolean-logical-not-equals-one-empty.xtnd - Expected Output

```
1
```

test-calling-func-from-import.xtnd

```
import "../../samples/gcd_func.xtnd";

main([1,n] args){
  return print(1,to_string( gcd(70, 55))+"\n") -> 0;
}
```

test-calling-func-from-import.xtnd - Expected Output

```
5
```

test-ceil.xtnd

```
main([1,n] args) {
  return printd(1, ceil(10.45)) -> 0;
}
```

test-ceil.xtnd - Expected Output

```
11.000000
```

test-cos.xtnd

```
main([1,n] args) {
  return printd(1, cos(45.0)) -> 0;
}
```

test-cos.xtnd - Expected Output

```
0.525322
```

test-cosh.xtnd

```
main([1,n] args) {
  return printd(1, cosh(45.0)) -> 0;
}
```

test-cosh.xtnd - Expected Output

```
17467135528742547456.000000
```

test-division.xtnd

```
main([1,1] args){
  /* Should evaluate to 4 */
  return print(1,to_string( 20 / 5)+"\n") -> 0;
}
```

test-division.xtnd - Expected Output

```
4
```

test-division-empty.xtnd

```
main([1,n] args){
  /* Should return empty */
  return print(1,to_string( empty / 5)+"\n") -> 0;
}
```

test-division-empty.xtnd - Expected Output

```
empty
```

test-exp.xtnd

```
main([1,n] args) {
  return printd(1, exp(2.0)) -> 0;
}
```

test-exp.xtnd - Expected Output

```
7.389056
```

test-fabs.xtnd

```
main([1,n] args) {
  return printd(1, fabs(-45.0)) -> 0;
}
```

test-fabs.xtnd - Expected Output

```
45.000000
```

test-file-close.xtnd

```
main(args){
  return close(open("testcases/assets/test_file.txt", "r")) -> print(1,"Made it this
      far\n") -> 0;
}
```

test-file-close.xtnd - Expected Output

```
Made it this far
```

test-file-read.xtnd

```
main(args){
  return print(1, read(open("testcases/assets/test_file.txt", "r"),5)) -> 0;
}
```

test-file-read.xtnd - Expected Output

```
This
```

test-file-slurp.xtnd

```
main(args){
  return
    print(1, read(open("testcases/assets/test_file.txt", "r"),0)) ->
    0;
}
```

test-file-slurp.xtnd - Expected Output

```
This is a test file!
```

test-file-write.xtnd

```
main(args){
  handle := open("testcases/assets/test_file_write.out", "w");
  return
    write(handle, "Hello") ->
    close(handle) ->
    print(1,"Made it this far\n") ->
    0;
}
```

test-file-write.xtnd - Expected Output

```
Made it this far
```

test-floor.xtnd

```
main([1,n] args) {
  return printd(1, floor(10.45)) -> 0;
}
```

test-floor.xtnd - Expected Output

```
10.000000
```

test-func-params.xtnd

```
main([1,n] args) {
  return print(1,to_string( foo("string"))+"\n") -> 0;
}
foo([1,1] arg) {
  return arg;
}
```

test-func-params.xtnd - Expected Output

```
string
```

test-func-params-omit-dim.xtnd

```
main([1,n] args) {
  return print(1,to_string( foo("string"))+"\n") -> 0;
}
foo([1,1] arg) {
  return arg;
}
```

test-func-params-omit-dim.xtnd - Expected Output

```
string
```

test-global-hello.xtnd

```
bar() {
  foo := 5;
  return 2;
}

global foo := printv(1,"Hello Globals!\n") -> 0;

main(args) {
  return foo;
}
```

test-global-hello.xtnd - Expected Output

```
Hello Globals!
```

test-global-masking.xtnd

```
bar() {
  foo := 5;
  return 2;
}

global foo := printv(1,"Hello Globals!\n") -> 0;

main(args) {
  foo := printv(1,"Hello Locals!\n") -> 0;
  return foo;
}
```

test-global-masking.xtnd - Expected Output

```
Hello Locals!
```

test-globals-between-imports.xtnd

```
import "../../testcases/assets/string.xtnd";
global foo;
global [2, 5] bar;
import "../../testcases/assets/string.xtnd";
```

test-globals-between-imports.xtnd - Expected Output

```
Hello
```

test-greater-than.xtnd

```
main([1,1] args){
  return print(1,to_string( 6 > 5)+"\n") -> 0;
}
```

test-greater-than.xtnd - Expected Output

```
1
```

test-greater-than-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty > 5)+"\n") -> 0;
}
```

test-greater-than-empty.xtnd - Expected Output

```
empty
```

test-greater-than-or-equal.xtnd

```
main([1,1] args){
  return print(1,to_string( 7 >= 7)+"\n") -> 0;
}
```

test-greater-than-or-equal.xtnd - Expected Output

```
1
```

test-greater-than-or-equal-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty >= 7)+"\n") -> 0;
}
```

test-greater-than-or-equal-empty.xtnd - Expected Output

```
empty
```

test-less-than.xtnd

```
main([1,1] args){
  return print(1,to_string( 6 < 7)+"\n") -> 0;
}
```

test-less-than.xtnd - Expected Output

```
1
```

test-less-than-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty > 5)+"\n") -> 0;
}
```

test-less-than-empty.xtnd - Expected Output

```
empty
```

test-less-than-or-equal.xtnd

```
main([1,1] args){
  return print(1,to_string( 7 <= 5)+"\n") -> 0;
}
```

test-less-than-or-equal.xtnd - Expected Output

```
0
```

test-less-than-or-equal-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty <= 8)+"\n") -> 0;
}
```

test-less-than-or-equal-empty.xtnd - Expected Output

```
empty
```

test-log.xtnd

```
main([1,n] args) {
  return printd(1, log(10.0)) -> 0;
}
```

test-log.xtnd - Expected Output

```
2.302585
```

test-log10.xtnd

```
main([1,n] args) {
  return printd(1, log10(100.0)) -> 0;
}
```

test-log10.xtnd - Expected Output

```
2.000000
```

test-logical-and.xtnd

```
main([1,1] args){
  return print(1,to_string( 1 && 6)+"\n") -> 0;
}
```

test-logical-and.xtnd - Expected Output

```
1
```

test-logical-and-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty && 1)+"\n") -> 0;
}
```

test-logical-and-empty.xtnd - Expected Output

```
empty
```

test-logical-not.xtnd

```
main([1,1] args){
  return print(1,to_string( !5)+"\n") -> 0;
}
```

test-logical-not.xtnd - Expected Output

```
0
```

test-logical-not-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( !empty)+"\n") -> 0;
}
```

test-logical-not-empty.xtnd - Expected Output

```
empty
```

test-logical-or.xtnd

```
main([1,1] args){
  return print(1,to_string( 5 || 6)+"\n") -> 0;
}
```

test-logical-or.xtnd - Expected Output

```
1
```

test-logical-or-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty || 4)+"\n") -> 0;
}
```

test-logical-or-empty.xtnd - Expected Output

```
empty
```

test-modulo.xtnd

```
main([1,n] args){
  /* Should return 1 */
  return print(1,to_string( 5 % 4)+"\n") -> 0;
}
```

test-modulo.xtnd - Expected Output

```
1
```

test-modulo-empty.xtnd

```
main([1,n] args){
  /* Should return empty */
  return print(1,to_string( empty % 5)+"\n") -> 0;
}
```

test-modulo-empty.xtnd - Expected Output

```
empty
```

test-multiple-imports.xtnd

```
import "../../testcases/assets/string.xtnd";
import "../../testcases/assets/string.xtnd";
```

test-multiple-imports.xtnd - Expected Output

```
Hello
```

test-multiplication.xtnd

```
main([1,n] args){
  /* Should evaluate to 35 */
  return print(1,to_string( 7 * 5)+"\n") -> 0;
}
```

test-multiplication.xtnd - Expected Output

```
35
```

test-multiplication-empty.xtnd

```
main([1,n] args){
  /* Should evaluate to empty */
  return print(1,to_string( empty * 5)+"\n") -> 0;
}
```

test-multiplication-empty.xtnd - Expected Output

```
empty
```

test-nan-and-infinity.xtnd

```
main(args) {
  should_be_nan := sqrt(-1);
  should_also_be_nan := 0 / 0;
  should_be_plus_inf := 2 / 0;
  should_be_minus_inf := -3 / 0;
  should_be_normal := 4;
  foo := "Hello";
  bar := empty;
  [3,3] baz := row() * column();

  return
    print_endline(typeof(should_be_nan)) -> // "Number"
    print_endline(typeof(should_also_be_nan)) -> // "Number"
    print_endline(typeof(should_be_plus_inf)) -> // "Number"
    print_endline(typeof(should_be_minus_inf)) -> // "Number"
```

```
    print_endline(typeof(should_be_normal)) -> // "Number"
    print_endline(typeof(foo)) -> // "String"
    print_endline(typeof(bar)) -> // "Empty"
    print_endline(typeof(baz)) -> // "Range"
    print_endline("") ->

    print_endline(isNaN(should_be_nan)) -> // 1
    print_endline(isNaN(should_also_be_nan)) -> // 1
    print_endline(isNaN(should_be_plus_inf)) -> // 0
    print_endline(isNaN(should_be_minus_inf)) -> // 0
    print_endline(isNaN(should_be_normal)) -> // 0
    print_endline(isNaN(foo)) -> // 0
    print_endline(isNaN(bar)) -> // 0
    print_endline(isNaN(baz)) -> // 0
    print_endline("") ->

    print_endline(isInfinite(should_be_nan)) -> // 0
    print_endline(isInfinite(should_also_be_nan)) -> // 0
    print_endline(isInfinite(should_be_plus_inf)) -> // 1
    print_endline(isInfinite(should_be_minus_inf)) -> // -1
    print_endline(isInfinite(should_be_normal)) -> // 0
    print_endline(isInfinite(foo)) -> // 0
    print_endline(isInfinite(bar)) -> // 0
    print_endline(isInfinite(baz)) -> // 0

    0;
}
```

test-nan-and-infinity.xtnd - Expected Output

```
Number
Number
Number
Number
Number
String
Empty
Range

1
1
0
0
0
empty
empty
empty

0
0
1
-1
0
empty
empty
empty
```

test-parse-error.xtnd

```
main(args){
  foo := 5$5;
  return foo;
}
```

test-parse-error.xtnd - Expected Output

```
Syntax error in "./testcases/inputs_regression/test_parse_error.xtnd": Invalid character: $
Line 2 at character 11
```

test-parse-error-after-multiline-comment.xtnd

```
main(args){
/* This is a comment spanning multiple lines.
20 of them, in fact. */
  foo := 5/5;
  bar := $$$$
  return foo;
}
```

test-parse-error-after-multiline-comment.xtnd - Expected Output

```
Syntax error in "./testcases/inputs_regression/test_parse_error_after_multiline_comment.xtnd": Invalid character: $
Line 23 at character 10
```

test-parse-error-comment.xtnd

```
main(args){
  foo := 5/5;
  /* Test comment */ foo := 5$5;
  return foo;
}
```

test-parse-error-comment.xtnd - Expected Output

```
Syntax error in "./testcases/inputs_regression/test_parse_error_comment.xtnd": Invalid character: $
Line 3 at character 30
```

test-parse-error-missing-semicolon.xtnd

```
main([1,1] args){
  x := switch() {
    case 1 > 2: 100;
    case 3 > 0: 200
  };
  return printf(1,toString(x)+"\n") -> 0;
}
```

test-parse-error-missing-semicolon.xtnd - Expected Output

```
Syntax error in "./testcases/inputs_regression/test_parse_error_missing_semicolon.xtnd
    ":
Line 5 at character 2
```

test-parse-error-newlines.xtnd

```
main(args){
  foo := 5/5;
  bar := "\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n\n"$5;
  return foo;
}
```

test-parse-error-newlines.xtnd - Expected Output

```
Syntax error in "./testcases/inputs_regression/test_parse_error_newlines.xtnd":
    Invalid character: $
Line 3 at character 52
```

test-parse-error-string.xtnd

```
main(args){
  foo := "Hello";$$$;
  return foo;
}
```

test-parse-error-string.xtnd - Expected Output

```
Syntax error in "./testcases/inputs_regression/test_parse_error_string.xtnd": Invalid
    character: $
Line 2 at character 18
```

test-power.xtnd

```
main([1,n] args){
  /* Should return 216 */
  return print(1,to_string( 6**3)+"\n") -> 0;
}
```

test-power.xtnd - Expected Output

```
216
```

test-power-empty.xtnd

```
main([1,n] args){
  /* Should return empty */
  return print(1,to_string( empty**5)+"\n") -> 0;
}
```

test-power-empty.xtnd - Expected Output

```
empty
```

test-print-empty.xtnd

```
main([1,n] args) {
  foo := empty;
  return print(1,to_string( foo)+"\n") -> 0;
}
```

test-print-empty.xtnd - Expected Output

```
empty
```

test-print-nums.xtnd

```
main([1,n] args) {
  foo := 1;
  return print(1,to_string( foo)+"\n") -> 0;
}
```

test-print-nums.xtnd - Expected Output

```
1
```

test-print-str.xtnd

```
main([1,n] args) {
  foo := "string";
  return print(1,to_string( foo)+"\n") -> 0;
}
```

test-print-str.xtnd - Expected Output

```
string
```

test-range-equality.xtnd

```
main(args) {
  my1 := {"Hello, world", "Goodbye, world"};
  my2 := {"Hello, world", "Goodbye, world"};
  my3 := {3,4,5,{"Hello, world", "Goodbye, world"},6,7,8};
  my4 := {3,empty,5,{"Hello, world", "Goodbye, world"},6,7,8};
  my5 := {3,4,5,{"Hello, world"; "Goodbye, world"},6,7,8};
  [2,2] foo := my1;
  [2,1] bar := my1;
  [3,3] ident := row() == column();
  ident_lit := {1,0,0;0,1,0;0,0,1};
  [3,3] all_ones := 1;
  baz := my2;
  return
    // True cases
    print_endline(my1 == my2) ->
    print_endline(baz == my1) ->
    print_endline(foo[0,0] == my2) ->
    print_endline(foo[0,1] == my2) ->
    print_endline(foo[0,0] == foo[1,1]) ->
    print_endline(foo[:,0] == bar) ->
```

```
    print_endline(my3[3] == my1) ->
    print_endline(ident == ident_lit) ->
    print_endline("") ->

    // False cases
    print_endline(my3 == my5) ->
    print_endline(my3 == my4) ->
    print_endline(foo == bar) ->
    print_endline(foo == foo[0,0]) ->
    print_endline(ident == all_ones) ->
    print_endline(ident == 1) ->
    print_endline(all_ones == 1) ->
    0
    ;
}
```

test-range-equality.xtnd - Expected Output

```
1
1
1
1
1
1
1
1

0
0
0
0
0
0
0
```

test-ref-between-globals.xtnd

```
global [2,2] foo;
global [2,2] bar;
main([1,n] args) {
  foo := 1;
  bar := foo;
  return print(1,to_string( bar)+"\n") -> 0;
}
```

test-ref-between-globals.xtnd - Expected Output

```
1
```

test-short-circuiting-and.xtnd

```
main([1,1] args){
  return 0 && print(1,"FAIL\n") -> print(1,"PASS\n") -> 0;
}
```

test-short-circuiting-and.xtnd - Expected Output

```
PASS
```

test-short-circuiting-and2.xtnd

```
main([1,1] args){
  return 1 && print(1,"PASS1\n") -> print(1,"PASS2\n") -> 0;
}
```

test-short-circuiting-and2.xtnd - Expected Output

```
PASS1
PASS2
```

test-short-circuiting-or.xtnd

```
main([1,1] args){
  return 0 || print(1,"PASS1\n") -> print(1,"PASS2\n") -> 0;
}
```

test-short-circuiting-or.xtnd - Expected Output

```
PASS1
PASS2
```

test-short-circuiting-or2.xtnd

```
main([1,1] args){
  return 1 || print(1,"FAIL\n") -> print(1,"PASS\n") -> 0;
}
```

test-short-circuiting-or2.xtnd - Expected Output

```
PASS
```

test-signature-vars.xtnd

```
foo([m,n] arg) {
  return "I was called with an argument with " + to_string(m) + " rows and " +
      to_string(n) + " columns.";
}

main([1,1] args) {
  [42,17] x;
  return print(1,foo(x)+"\n") -> 0;
}
```

test-signature-vars.xtnd - Expected Output

```
I was called with an argument with 42 rows and 17 columns.
```

test-sin.xtnd

```
main([1,n] args) {
  return printd(1, sin(45.0)) -> 0;
}
```

test-sin.xtnd - Expected Output

```
0.850904
```

test-sin-through-function.xtnd

```
internal_sin(x,y,z) {
  return sin(z);
}

main([1,n] args) {
  return printd(1, internal_sin(1,2,45.0)) -> 0;
}
```

test-sin-through-function.xtnd - Expected Output

```
0.850904
```

test-sin-through-function-and-global.xtnd

```
global theta := 45.0;

internal_sin(x,y,z) {
  return sin(z);
}

main([1,n] args) {
  return printd(1, internal_sin(1,2,theta)) -> 0;
}
```

test-sin-through-function-and-global.xtnd - Expected Output

```
0.850904
```

test-single-import.xtnd

```
import "../../samples/gcd_func.xtnd";

main([1,n] args) {
  return print(1, to_string(gcd(70, 55)) + "\n") -> 0;
}
```

test-single-import.xtnd - Expected Output

```
5
```

test-sinh.xtnd

```
main([1,n] args) {
  return printd(1, sinh(45.0)) -> 0;
}
```

test-sinh.xtnd - Expected Output

```
17467135528742547456.000000
```

test-sqrt.xtnd

```
main([1,n] args) {
  return printd(1, sqrt(9.0)) -> 0;
}
```

test-sqrt.xtnd - Expected Output

```
3.000000
```

test-string-concatenation.xtnd

```
main(args) {
  foo :=
    printv(1,"Hello " + "World\n") ->
    printv(1,"Hello " + "World" + "\n") ->
    printv(1,("Hello " + "World") + ("" + "\n")) ->
     0;
  return foo;
}
```

test-string-concatenation.xtnd - Expected Output

```
Hello World
Hello World
Hello World
```

test-subtraction.xtnd

```
main([1,1] args){
  return print(1,to_string( 7 - 5)+"\n") -> 0;
}
```

test-subtraction.xtnd - Expected Output

```
2
```

test-subtraction-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty - 2)+"\n") -> 0;
}
```

test-subtraction-empty.xtnd - Expected Output

```
empty
```

test-switch-v1.xtnd

```
main([1,1] args){
  x := switch(1) {
    case 1: 100;
    case 2: 200;
    default: 300;
  };
  return print(1,to_string(x)+"\n") -> 0;
}
```

test-switch-v1.xtnd - Expected Output

```
100
```

test-switch-v10.xtnd

```
main([1,1] args){
  x := switch {
    case 0: 100;
    case "also true": 200;
    default: 99;
  };
  return printd(1,x) -> 0;
}
```

test-switch-v10.xtnd - Expected Output

```
200.000000
```

test-switch-v11.xtnd

```
main([1,1] args){
  x := switch {
    case 0: 100;
    default: 99;
  };
  return printd(1,x) -> 0;
}
```

test-switch-v11.xtnd - Expected Output

```
99.000000
```

test-switch-v2.xtnd

```
main([1,1] args){
  x := switch(2) {
    case 1: 100;
    case 2: 200;
    default: 300;
  };
  return print(1,to_string(x)+"\n") -> 0;
}
```

test-switch-v2.xtnd - Expected Output

```
200
```

test-switch-v3.xtnd

```
main([1,1] args){
  x := switch(3) {
    case 1: 100;
    case 2: 200;
    default: 300;
  };
  return print(1,to_string(x)+"\n") -> 0;
}
```

test-switch-v3.xtnd - Expected Output

```
300
```

test-switch-v4.xtnd

```
main([1,1] args){
  x := switch(2) {
    case 1, 2: 100;
    default: 300;
  };
  return print(1,to_string(x)+"\n") -> 0;
}
```

test-switch-v4.xtnd - Expected Output

```
100
```

test-switch-v5.xtnd

```
main([1,1] args){
  x := switch(3) {
    case 1, 2: 100;
    default: 300;
  };
  return print(1,to_string(x)+"\n") -> 0;
}
```

test-switch-v5.xtnd - Expected Output

```
300
```

test-switch-v6.xtnd

```
main([1,1] args){
  x := switch(3) {
    case 1, 2: 100;
    case 0, 3: 200;
    default: 300;
  };
  return print(1,to_string(x)+"\n") -> 0;
}
```

test-switch-v6.xtnd - Expected Output

```
200
```

test-switch-v7.xtnd

```
main([1,1] args){
  x := switch(4) {
    case 1, 2: 100;
    case 0, 3: 200;
  };
  return print(1,to_string(x)+"\n") -> 0;
}
```

test-switch-v7.xtnd - Expected Output

```
empty
```

test-switch-v8.xtnd

```
main([1,1] args){
  x := switch() {
    case 1 > 2: 100;
    case 3 > 0: 200;
  };
  return print(1,to_string(x)+"\n") -> 0;
}
```

test-switch-v8.xtnd - Expected Output

```
200
```

test-switch-v9.xtnd

```
main([1,1] args){
  x := switch {
    case "true": 100;
    case "also true": 200;
  };
  return printd(1,x) -> 0;
}
```

test-switch-v9.xtnd - Expected Output

```
100.000000
```

test-tan.xtnd

```
main([1,n] args) {
  return printd(1, tan(45.0)) -> 0;
}
```

test-tan.xtnd - Expected Output

```
1.619775
```

test-tanh.xtnd

```
main([1,n] args) {
  return printd(1, tanh(45.0)) -> 0;
}
```

test-tanh.xtnd - Expected Output

```
1.000000
```

test-ternary-conditional.xtnd

```
main([1,1] args){
  return print(1,to_string(5 ? 2 : 3) + "\n") -> 0;
}
```

test-ternary-conditional.xtnd - Expected Output

```
2
```

test-ternary-conditional-empty.xtnd

```
main([1,1] args){
  return print(1,to_string( empty ? 5 : 6)+"\n") -> 0;
}
```

test-ternary-conditional-empty.xtnd - Expected Output

```
empty
```

test-unary-negation.xtnd

```
main([1,n] args){
  /* Should return -33 */
  return print(1,to_string( -33)+"\n") -> 0;
}
```

test-unary-negation.xtnd - Expected Output

```
−33
```

test-unary-negation-empty.xtnd

```
main([1,n] args){
  return print(1,to_string( −empty)+"\n") −> 0;
}
```

test-unary-negation-empty.xtnd - Expected Output

```
empty
```

10. Git Logs

```
23c2ae6 2016-12-17T13:00:05-05:00 GitHub: Merge pull request #123 from ExtendLang/size-asserts
4c51203 2016-12-17T11:59:30-05:00 oracleofnj: Right confusion
c05cf61 2016-12-17T11:52:34-05:00 oracleofnj: Fix import dir bug
39edbb4 2016-12-17T11:46:06-05:00 oracleofnj: Merge branch 'master' into size-asserts
339cb1f 2016-12-17T11:45:54-05:00 oracleofnj: Fix merge conflict
7462381 2016-12-17T11:44:50-05:00 GitHub: Merge pull request #122 from ExtendLang/split-stdlib
61ac8f2 2016-12-17T11:38:19-05:00 oracleofnj: Size asserts
606af9f 2016-12-17T11:22:36-05:00 oracleofnj: Transform asserts into more useful form; add calc of assert value to codegen
ee4f369 2016-12-17T10:40:17-05:00 oracleofnj: Combine asserts into a single expression
0f0f1c8 2016-12-17T10:38:56-05:00 Nigel Schuster: Added right and left to stdlib
fa43425 2016-12-17T10:30:23-05:00 oracleofnj: Split stdlib
824c53c 2016-12-17T10:11:13-05:00 Nigel Schuster: Added toUpper and toLower
ec24177 2016-12-17T10:02:30-05:00 Nigel Schuster: Implemented to and from ASCII
ab2e8f8 2016-12-17T09:15:39-05:00 GitHub: Merge pull request #116 from ExtendLang/line-plus
5d1610b 2016-12-17T09:08:57-05:00 GitHub: Merge branch 'master' into line-plus
df3a827 2016-12-17T09:08:48-05:00 GitHub: Merge pull request #117 from ExtendLang/cmd-args
32a3487 2016-12-17T09:02:27-05:00 GitHub: Merge branch 'master' into cmd-args
a8f9d33 2016-12-17T09:00:23-05:00 Nigel Schuster: Args
bfccf0c 2016-12-17T08:58:08-05:00 Nigel Schuster: Cut down line count for plus
a6bc89a 2016-12-17T08:48:31-05:00 GitHub: Merge pull request #114 from ExtendLang/only-new-string
5c96b7f 2016-12-17T08:03:27-05:00 GitHub: Merge pull request #109 from ExtendLang/unop-bitnot
3834210 2016-12-17T00:33:37-05:00 oracleofnj: Get rid of box string in favor of new_string_all_the_way, renamed new_string
375bea7 2016-12-16T23:56:35-05:00 oracleofnj: Merge branch 'unop-bitnot' into remove-interpreter
fb1bd77 2016-12-16T23:54:43-05:00 oracleofnj: Clean up; remove interpreter; change DimInt to DimOneByOne
539dd75 2016-12-16T23:46:35-05:00 GitHub: Merge branch 'master' into unop-bitnot
5668e53 2016-12-16T23:43:57-05:00 Nigel Schuster: Using lrint instead of fptosi
45691eb 2016-12-16T23:35:38-05:00 GitHub: Merge pull request #111 from ExtendLang/global-semant
2cdfb8b 2016-12-16T23:33:26-05:00 GitHub: Merge branch 'master' into global-semant
c9500d9 2016-12-16T23:33:14-05:00 GitHub: Merge pull request #112 from ExtendLang/remove-function-signatures
0c24f54 2016-12-16T23:25:23-05:00 oracleofnj: Remove return signature from grammar and all test cases
e7f2864 2016-12-16T23:03:53-05:00 oracleofnj: Merge branch 'cleanup-1' into global-
```

```
    semant
32  567507e 2016-12-16T22:53:20-05:00 oracleofnj: Check globals; use same symbol_table
    function for semant and codegen
33  55d8185 2016-12-16T22:00:30-05:00 Nigel Schuster: Removed comments and unneccessary
    files
34  629042f 2016-12-16T21:37:07-05:00 GitHub: Merge branch 'master' into unop-bitnot
35  48b139a 2016-12-16T21:34:09-05:00 Nigel Schuster: Implemented unary bitnot
36  39b02cd 2016-12-16T21:27:22-05:00 oracleofnj: Merge branch 'master' into global-semant
37  28c0983 2016-12-16T21:27:05-05:00 oracleofnj: Remove leftover printf
38  dc182df 2016-12-16T21:09:00-05:00 GitHub: Merge pull request #105 from ExtendLang/rg-
    eq
39  8cdf5c4 2016-12-16T19:31:26-05:00 oracleofnj: Expand test cases for range equality
40  41a3ccc 2016-12-16T19:18:44-05:00 GitHub: Merge branch 'master' into rg-eq
41  8dbebc1 2016-12-16T19:18:15-05:00 GitHub: Merge pull request #104 from ExtendLang/
    prevent-overlapping-formulas
42  c1431b5 2016-12-16T18:55:07-05:00 Nigel Schuster: Implemented basic subrange
    comparison
43  546536e 2016-12-16T18:47:12-05:00 oracleofnj: Detect overlapping formulas and give
    runtime error if present
44  3562e1b 2016-12-16T18:45:12-05:00 oracleofnj: Merge branch 'sr-val-fix' into prevent-
    overlapping-formulas
45  8713fa0 2016-12-16T18:42:40-05:00 oracleofnj: Checking
46  77d80b9 2016-12-16T18:26:31-05:00 Nigel Schuster: Fixed check for subrange
47  962c744 2016-12-16T12:09:00-05:00 GitHub: Merge pull request #101 from ExtendLang/
    finishing-these-range-literals
48  f234e00 2016-12-16T00:21:06-05:00 oracleofnj: Merge branch 'more-stdlib-functions'
    into finishing-these-range-literals
49  c9246ce 2016-12-16T00:20:59-05:00 oracleofnj: testing testing
50  6914039 2016-12-16T00:14:09-05:00 oracleofnj: Third time's the charm
51  4617e44 2016-12-16T00:01:12-05:00 oracleofnj: It compiles now
52  1d8e290 2016-12-15T23:42:43-05:00 oracleofnj: Fingers crossed
53  c9d28d3 2016-12-15T21:50:01-05:00 oracleofnj: Move all initializations into their own
    function; only box strings once
54  1cfdd16 2016-12-15T18:47:30-05:00 oracleofnj: Merge branch 'master' into more-stdlib-
    functions
55  19c2beb 2016-12-15T18:40:12-05:00 oracleofnj: Try a couple more things out
56  845cb04 2016-12-15T18:33:07-05:00 GitHub: Merge pull request #96 from ExtendLang/
    ternary-fix
57  4bfb3bc 2016-12-15T18:23:00-05:00 oracleofnj: Merge branch 'ternary-fix' into more-
    stdlib-functions
58  ae55ca4 2016-12-15T18:21:58-05:00 oracleofnj: Define cell_row, cell_col
59  30a5db6 2016-12-15T18:19:56-05:00 oracleofnj: Merge branch 'ternary-fix' into more-
    stdlib-functions
60  b9f1f10 2016-12-15T18:17:53-05:00 oracleofnj: What is truth?
61  ac84c2f 2016-12-15T18:15:37-05:00 oracleofnj: Fix ternary to work properly with ranges
62  1f57d91 2016-12-15T17:03:26-05:00 oracleofnj: Look at this one
63  437ba46 2016-12-15T16:56:04-05:00 oracleofnj: Try this one
64  f0edf5b 2016-12-15T16:46:52-05:00 oracleofnj: Fixing bug
65  5ba31e6 2016-12-15T14:17:52-05:00 GitHub: Merge pull request #94 from ExtendLang/nan-
    inf
66  67c5739 2016-12-15T14:17:46-05:00 GitHub: Merge pull request #93 from ExtendLang/type-
    typeof
67  48a3d5c 2016-12-15T14:05:37-05:00 oracleofnj: Improve test case
68  8f08227 2016-12-15T13:58:46-05:00 oracleofnj: Add isNaN and isInfinite to stdlib
69  cbeec74 2016-12-15T13:30:31-05:00 oracleofnj: Rename token
70  9582228 2016-12-15T13:18:09-05:00 oracleofnj: Rename type to typeof
```

```
d1422c7 2016-12-15T10:42:19-05:00 GitHub: Merge pull request #92 from ExtendLang/
    compiler
66689bb 2016-12-15T09:08:56-05:00 Nigel Schuster: added working directory option,
    doing testing completely in tmp
a13ae93 2016-12-15T09:08:31-05:00 GitHub: Merge pull request #91 from ExtendLang/
    sizeof
a31add9 2016-12-15T09:08:13-05:00 GitHub: Merge pull request #90 from ExtendLang/
    subselect-C-side
2e67e06 2016-12-15T09:01:06-05:00 Nigel Schuster: Added option to specify compiler,
    using clang
c171450 2016-12-15T02:33:48-05:00 oracleofnj: SizeOf
c168044 2016-12-15T00:48:35-05:00 oracleofnj: Add row(), column() to codegen, add
    print_endline() to stdlib.xtnd
bf9426d 2016-12-15T00:27:13-05:00 oracleofnj: Print subrange
407ce41 2016-12-14T23:02:02-05:00 oracleofnj: Merge in subrange_string
756ea8e 2016-12-14T22:51:00-05:00 oracleofnj: Ranges
27a8e79 2016-12-14T22:16:13-05:00 oracleofnj: Resolve RHS slice
876d056 2016-12-14T22:02:56-05:00 oracleofnj: Resolve RHS index
b59e022 2016-12-14T21:46:00-05:00 Nigel Schuster: Added method to print subragne as
    string
a7d53a8 2016-12-14T19:55:38-05:00 oracleofnj: Merge branch 'master' into subselect-C-
    side
362e85b 2016-12-14T19:55:23-05:00 GitHub: Merge pull request #88 from ExtendLang/
    subselect
4912fa3 2016-12-14T19:40:10-05:00 oracleofnj: Add debug print info for slice
    structures
c1b33f4 2016-12-14T18:58:45-05:00 oracleofnj: Builder to end all builders
5d400c2 2016-12-14T18:55:06-05:00 oracleofnj: Add selection builders
29f6e28 2016-12-14T18:20:51-05:00 oracleofnj: Make additional infix operator for
    populating structure element
046d096 2016-12-14T17:49:19-05:00 oracleofnj: Set up RHS slice types
b25c2f5 2016-12-14T16:49:17-05:00 GitHub: Merge pull request #87 from ExtendLang/make-
    a-selection
7a12082 2016-12-14T16:43:38-05:00 oracleofnj: Move selection test cases back into
    inputs
e2c08d5 2016-12-14T16:31:00-05:00 oracleofnj: Make IDs work with deref_subrange
02f2f0c 2016-12-14T15:21:31-05:00 GitHub: Merge pull request #86 from ExtendLang/
    include-stdlib
8b0503f 2016-12-14T15:18:14-05:00 GitHub: Merge branch 'master' into include-stdlib
1f034a0 2016-12-14T15:17:52-05:00 GitHub: Merge pull request #84 from ExtendLang/math-
    linker
1e6dd91 2016-12-14T14:58:44-05:00 oracleofnj: Add expected output for slurp
ff1a5e3 2016-12-14T14:53:38-05:00 oracleofnj: Remove extend_ prefix from all sample
    code
81a2828 2016-12-14T14:48:38-05:00 oracleofnj: Automatically add extend_ prefix to
    external functions
dcc1ed3 2016-12-14T14:30:52-05:00 oracleofnj: Fix samples
9b2c28f 2016-12-14T12:39:45-05:00 oracleofnj: Include stdlib automatically
13650ce 2016-12-14T12:35:21-05:00 Nigel Schuster: Merge branch 'math-linker' of https
    ://github.com/ExtendLang/Extend into math-linker
2e0d90d 2016-12-14T12:35:06-05:00 Nigel Schuster: Merge branch 'math-linker' of https
    ://github.com/ExtendLang/Extend into math-linker
83c689e 2016-12-14T12:34:14-05:00 Nigel Schuster: Merge branch 'math-linker' of https
    ://github.com/ExtendLang/Extend into math-linker
127f600 2016-12-14T12:34:07-05:00 Nigel Schuster: Include sys/resources
b34d97a 2016-12-14T12:03:44-05:00 GitHub: Merge branch 'master' into math-linker
```

```
8297f33 2016-12-14T12:01:47-05:00 GitHub: Merge pull request #85 from ExtendLang/put-lt-back
6b0c74f 2016-12-14T11:33:45-05:00 Nigel Schuster: Include sys/resources
37470e9 2016-12-14T11:14:06-05:00 oracleofnj: Put back LT, comment out sys/time.h
6bde590 2016-12-14T11:12:16-05:00 Nigel Schuster: Increasing stack size
6acc621 2016-12-14T11:03:31-05:00 Nigel Schuster: Disabled linking math when creating an intermediate
d87b73c 2016-12-14T10:51:58-05:00 GitHub: Merge pull request #82 from ExtendLang/hard-to-repro-bug
d126e3c 2016-12-14T00:51:00-05:00 oracleofnj: Try with time.h instead of sys/time.h
a535612 2016-12-14T00:48:35-05:00 oracleofnj: Remove lrints
e844853 2016-12-14T00:34:37-05:00 oracleofnj: Initialize all variables and remove pointer math; bug appears fixed
4c1a421 2016-12-13T22:55:07-05:00 oracleofnj: Some formula is weird
5dbd409 2016-12-13T22:43:19-05:00 oracleofnj: Merge branch 'hard-to-repro-bug' of https://github.com/ExtendLang/Extend into hard-to-repro-bug
879eaf3 2016-12-13T22:43:17-05:00 oracleofnj: Testing
37f5ce2 2016-12-13T22:42:40-05:00 GitHub: Merge pull request #83 from ExtendLang/rounding-for-read
a1cfc5a 2016-12-13T22:34:21-05:00 Nigel Schuster: Added rounding at several places
e20f7e4 2016-12-13T21:36:13-05:00 oracleofnj: Half the time it works
61bc9b6 2016-12-13T20:33:27-05:00 GitHub: Merge pull request #81 from ExtendLang/fix-em-all
4a810df 2016-12-13T19:34:29-05:00 Nigel Schuster: Corrected testcase outputs
ae5b8a8 2016-12-13T19:08:43-05:00 GitHub: Merge pull request #80 from ExtendLang/select
70b2704 2016-12-13T19:02:32-05:00 oracleofnj: No C99
15fd762 2016-12-13T18:42:21-05:00 oracleofnj: Merge branch 'master' into select
8e6e9ba 2016-12-13T18:42:05-05:00 GitHub: Merge pull request #78 from ExtendLang/unop-unary-minus
7a93885 2016-12-13T18:41:49-05:00 oracleofnj: Calculate all formula indices
07e63dc 2016-12-13T18:19:58-05:00 oracleofnj: Properly build instantiate var
1a29129 2016-12-13T17:24:16-05:00 oracleofnj: Replace bools with chars for compatibility between C and LLVM
12e78a3 2016-12-13T17:17:54-05:00 oracleofnj: Added debug output
a483282 2016-12-13T16:13:30-05:00 oracleofnj: Merge branch 'master' into unop-unary-minus
f8c9b43 2016-12-13T16:13:09-05:00 oracleofnj: Make TypeOf work
8146d04 2016-12-13T16:12:17-05:00 GitHub: Merge pull request #75 from ExtendLang/fix-more-tc
94afc93 2016-12-13T16:02:35-05:00 Nigel Schuster: Corrected expected TC
f6f8276 2016-12-13T16:00:59-05:00 Nigel Schuster: Fixed string.xtnd file
dcd5766 2016-12-13T15:44:38-05:00 GitHub: Merge pull request #74 from ExtendLang/fix-tc
bfe1c07 2016-12-13T15:39:45-05:00 oracleofnj: Merge branch 'master' into unop-unary-minus
d9abfc0 2016-12-13T15:38:38-05:00 GitHub: Merge branch 'master' into fix-tc
50ed49c 2016-12-13T15:38:04-05:00 oracleofnj: Merging in main
23328f1 2016-12-13T15:37:18-05:00 GitHub: Merge pull request #73 from ExtendLang/and-or-xor
324779a 2016-12-13T15:32:26-05:00 Nigel Schuster: Corrected expected value
fafe2e6 2016-12-13T15:29:21-05:00 Nigel Schuster: Fixed string tc
022f05c 2016-12-13T15:23:59-05:00 Nigel Schuster: Fixed testcase
b12fe37 2016-12-13T15:18:57-05:00 Nigel Schuster: Implemented and, or and xor
90cbaa0 2016-12-13T15:16:31-05:00 Nigel Schuster: Added left and right shift
571ee7e 2016-12-13T14:56:05-05:00 Nigel Schuster: Merge branch 'power' of https://
```

```
    github.com/ExtendLang/Extend into power
148 aeab40d 2016-12-13T14:55:57-05:00 Nigel Schuster: Removed unneccessary level of
    indirection
149 e377567 2016-12-13T14:53:28-05:00 GitHub: Merge branch 'master' into power
150 6ad8512 2016-12-13T14:53:11-05:00 GitHub: Merge pull request #69 from ExtendLang/unop-
    unary-minus
151 71f395d 2016-12-13T14:46:27-05:00 Nigel Schuster: Power to the people of Extend
152 6a04209 2016-12-13T14:45:46-05:00 oracleofnj: Fix merge conflict
153 edb0ecc 2016-12-13T14:43:32-05:00 oracleofnj: Add unary minus
154 668a0eb 2016-12-13T14:37:19-05:00 GitHub: Merge pull request #68 from ExtendLang/mod-
    div
155 866b68f 2016-12-13T14:32:18-05:00 Nigel Schuster: Added modulo and division operation
156 46d5aa6 2016-12-13T14:26:35-05:00 oracleofnj: Merge branch 'master' into unop-typeof
157 84dfc33 2016-12-13T14:26:25-05:00 Nigel Schuster: Crunched some code
158 76210eb 2016-12-13T14:26:18-05:00 oracleofnj: Start on it
159 f4d5a81 2016-12-13T14:22:12-05:00 Nigel Schuster: Merge branch 'master' into
    simplification
160 f873242 2016-12-13T14:21:26-05:00 GitHub: Merge pull request #65 from ExtendLang/
    subtraction
161 fc94112 2016-12-13T14:20:35-05:00 Nigel Schuster: Added multiplication
162 6c26c2c 2016-12-13T14:19:07-05:00 GitHub: Merge branch 'master' into subtraction
163 4afd78e 2016-12-13T14:18:55-05:00 GitHub: Merge pull request #64 from ExtendLang/
    refactor-boolean-binops
164 d4d4388 2016-12-13T14:15:58-05:00 GitHub: Merge branch 'master' into refactor-boolean-
    binops
165 bd90241 2016-12-13T14:14:17-05:00 GitHub: Merge branch 'master' into subtraction
166 4042259 2016-12-13T14:13:09-05:00 Nigel Schuster: Added subtraction
167 663f399 2016-12-13T14:12:57-05:00 oracleofnj: Remove wildcard from BinOp pattern match
168 82a3db2 2016-12-13T14:11:31-05:00 Nigel Schuster: Merge branch 'master' into
    subtraction
169 1bf6bed 2016-12-13T14:09:47-05:00 oracleofnj: Add TransformedAway exception for LogAnd
     and LogOr
170 c7d4162 2016-12-13T14:02:13-05:00 GitHub: Merge pull request #63 from ExtendLang/more-
    binops
171 952778e 2016-12-13T14:01:54-05:00 oracleofnj: Change Lt, Lte in grammar; implement GTE
172 97821c8 2016-12-13T13:47:52-05:00 oracleofnj: GT
173 1e1f973 2016-12-13T13:44:36-05:00 Nigel Schuster: Subtraction
174 e0a883a 2016-12-13T13:37:57-05:00 oracleofnj: Remove NotEq from AST since != is parsed
     to UnOp(LogNot,BinOp(Eq,...))
175 cc40008 2016-12-13T12:49:33-05:00 GitHub: Merge pull request #60 from ExtendLang/
    addition2
176 7123ebc 2016-12-13T12:41:09-05:00 GitHub: Merge branch 'master' into addition2
177 a656f57 2016-12-13T12:38:12-05:00 GitHub: Merge pull request #61 from ExtendLang/debug
    -unop
178 eb134b3 2016-12-13T12:29:53-05:00 Nigel Schuster: Moved testcases
179 044c6bd 2016-12-13T12:29:07-05:00 Nigel Schuster: Fixed off by one error
180 a64cc15 2016-12-13T12:14:45-05:00 oracleofnj: Add Debug expr
181 59858a0 2016-12-13T11:33:12-05:00 oracleofnj: Whoops no space
182 0426f34 2016-12-13T11:30:26-05:00 oracleofnj: Add test case
183 49ffa86 2016-12-13T11:19:14-05:00 GitHub: Merge branch 'master' into addition2
184 81533f4 2016-12-13T11:13:44-05:00 GitHub: Merge pull request #59 from ExtendLang/equal
    -rights
185 3cdaa5a 2016-12-13T11:12:41-05:00 Nigel Schuster: String addition
186 64d1760 2016-12-13T11:04:55-05:00 oracleofnj: Wake up please, GitHub
187 840aeaf 2016-12-13T10:48:03-05:00 oracleofnj: Remove usage demonstration
188 61ff439 2016-12-13T03:26:35-05:00 oracleofnj: Add string equality and test cases
```

```
f3112e9 2016-12-13T01:57:10-05:00 oracleofnj: Reduce cut & paste
08ce677 2016-12-13T01:35:46-05:00 oracleofnj: Remove obsolete testing file
ae8a07e 2016-12-13T01:23:26-05:00 oracleofnj: Merge branch 'print_value_p' into equal-rights
6090713 2016-12-13T01:22:47-05:00 oracleofnj: Use correct printf specifier
862b38c 2016-12-13T01:19:14-05:00 oracleofnj: Merge branch 'print_value_p' into equal-rights
5e913ad 2016-12-13T01:16:07-05:00 oracleofnj: Add debug_print; remove print statement that was causing us to falsely pass test cases from to_string; show usage in UnOp(Neg)
50281b1 2016-12-13T00:47:28-05:00 oracleofnj: Numeric equality
0f76aa4 2016-12-12T22:30:15-05:00 oracleofnj: Remove print flags
200b8b6 2016-12-12T22:16:15-05:00 GitHub: Merge pull request #57 from ExtendLang/addition2
da7c543 2016-12-12T12:43:31-05:00 Nigel Schuster: Setting flag for addition
7e7276b 2016-12-12T12:37:35-05:00 Nigel Schuster: Merge branch 'master' into addition2
8834635 2016-12-12T10:18:51-05:00 GitHub: Merge pull request #55 from ExtendLang/runtime
53ae9e0 2016-12-12T10:06:24-05:00 GitHub: Merge branch 'master' into runtime
6ed303e 2016-12-12T09:43:57-05:00 GitHub: Merge pull request #56 from ExtendLang/truthy-fix
ae49ce6 2016-12-12T01:15:29-05:00 oracleofnj: Remove extra file
7fe6a22 2016-12-12T01:11:53-05:00 oracleofnj: Falsey fix
d1e196d 2016-12-12T00:23:13-05:00 Nigel Schuster: Extracted runtime into seperate file
ecc620e 2016-12-12T00:17:06-05:00 GitHub: Merge pull request #54 from ExtendLang/final-draft-for-real
4c8caa5 2016-12-12T00:09:16-05:00 GitHub: Merge branch 'master' into final-draft-for-real
04d3b57 2016-12-12T00:00:29-05:00 GitHub: Merge pull request #39 from ExtendLang/more-lrm-ed
39025b0 2016-12-11T23:59:18-05:00 Nigel Schuster: Fixed examples, made small corrections
a875b41 2016-12-11T23:51:30-05:00 GitHub: Merge pull request #53 from ExtendLang/truthy
616dd34 2016-12-11T23:15:54-05:00 oracleofnj: Merge branch 'master' into truthy
0fa8255 2016-12-11T23:14:42-05:00 oracleofnj: Apparently still needs some work
78584d7 2016-12-11T23:09:07-05:00 oracleofnj: Thanks a lot Travis
b5673d2 2016-12-11T22:51:52-05:00 oracleofnj: TERRRRRRRRR NARRRRRRR EEEEEEEEEEEEEEEEEE
b81bc1b 2016-12-11T22:04:25-05:00 oracleofnj: Maybe Truthy
b95d14f 2016-12-11T21:02:28-05:00 GitHub: Merge pull request #50 from ExtendLang/builder-hotfix
6dea96f 2016-12-11T20:40:47-05:00 oracleofnj: So many builders
8aa125f 2016-12-11T20:15:52-05:00 Nigel Schuster: Made som rpgroess
2a905c7 2016-12-11T19:15:47-05:00 GitHub: Merge pull request #47 from ExtendLang/function-parameter
2bc6c85 2016-12-11T19:11:33-05:00 oracleofnj: Add combined test case
860a11b 2016-12-11T19:04:35-05:00 oracleofnj: Merge branch 'master' into function-parameter
8c3499e 2016-12-11T19:03:39-05:00 oracleofnj: Remove extraneous printlines
99418c0 2016-12-11T19:02:31-05:00 oracleofnj: Make function parameters work
6c00a72 2016-12-11T18:45:46-05:00 Nigel Schuster: Some progress
387559b 2016-12-11T18:39:00-05:00 oracleofnj: First attempt
18fc1be 2016-12-11T18:08:11-05:00 GitHub: Merge pull request #45 from ExtendLang/empty
f7e9be8 2016-12-11T16:30:05-05:00 GitHub: Merge branch 'master' into empty
f1dd8a5 2016-12-11T16:18:44-05:00 GitHub: Merge pull request #46 from ExtendLang/
```

```
    actually-make-global-scope
229 50366f4 2016-12-11T15:38:05-05:00 oracleofnj: Make sure locals are properly masking
    globals
230 046c7cc 2016-12-11T15:30:53-05:00 oracleofnj: Make globals work, fix bug
231 a844a46 2016-12-11T15:14:09-05:00 oracleofnj: So close
232 18db166 2016-12-11T15:05:42-05:00 GitHub: Merge branch 'master' into empty
233 67849f0 2016-12-11T15:01:52-05:00 oracleofnj: Make the global scope object
234 393d02c 2016-12-11T14:25:02-05:00 Nigel Schuster: Implemented empty, small flag
    setting fix
235 3c4681d 2016-12-11T13:31:12-05:00 GitHub: Merge pull request #44 from ExtendLang/float
    -display-hotfix
236 7be1001 2016-12-11T13:26:55-05:00 GitHub: Merge branch 'master' into float-display-
    hotfix
237 abcffd0 2016-12-11T13:19:05-05:00 GitHub: Merge pull request #42 from ExtendLang/
    encapsulate-build-scope
238 556da44 2016-12-11T13:18:15-05:00 oracleofnj: Floating point math hotfix
239 0ad195e 2016-12-11T12:42:42-05:00 oracleofnj: Merge branch 'master' into encapsulate-
    build-scope
240 9caf464 2016-12-11T12:41:40-05:00 oracleofnj: Encapsulate a little more of building
    the scope
241 d65aad4 2016-12-11T12:09:28-05:00 GitHub: Merge pull request #40 from ExtendLang/make-
    global-scope
242 0f5a6ba 2016-12-11T12:04:05-05:00 oracleofnj: Merge branch 'master' into make-global-
    scope
243 56b58d9 2016-12-11T12:01:28-05:00 oracleofnj: Encapsulate build_var_defns
244 f25e5b3 2016-12-11T11:43:19-05:00 oracleofnj: Only construct var_defns once
245 9cee2fc 2016-12-11T10:07:36-05:00 Nigel Schuster: Testcases (#38)
246 f3f4bef 2016-12-11T00:45:44-05:00 oracleofnj: Make global variable to hold vardefns
247 a0ed757 2016-12-10T23:31:38-05:00 Nigel Schuster: Edited explanation for row() and
    column()
248 7c50ef2 2016-12-10T23:27:07-05:00 Nigel Schuster: Added info for strings
249 738e41b 2016-12-10T23:24:20-05:00 Nigel Schuster: Added boolean example
250 5377fdf 2016-12-10T23:19:26-05:00 Nigel Schuster: Added arithmetic example
251 a8f4ad9 2016-12-10T21:28:18-05:00 oracleofnj: Isolate the part of building a scope for
     reuse with global variables
252 58f7a4d 2016-12-10T18:05:01-05:00 Nigel Schuster: Performing copy before returning, so
     that memory can be freed with alloca
253 c0e56aa 2016-12-10T17:07:00-05:00 GitHub: Merge pull request #37 from ExtendLang/
    dereference
254 a4b35df 2016-12-10T16:42:17-05:00 Nigel Schuster: Removed obsolete methods
255 cf08a8c 2016-12-10T16:36:20-05:00 GitHub: Merge branch 'master' into dereference
256 ef0e5e7 2016-12-10T16:36:03-05:00 GitHub: Merge pull request #36 from ExtendLang/comp-
    warn
257 0177dc2 2016-12-10T16:35:50-05:00 GitHub: Merge pull request #35 from ExtendLang/
    linker
258 127f99d 2016-12-10T16:35:41-05:00 GitHub: Merge pull request #34 from ExtendLang/rel-
    import
259 b2e881d 2016-12-10T16:35:31-05:00 GitHub: Merge pull request #33 from ExtendLang/ts-
    fix
260 ce833d4 2016-12-10T16:14:34-05:00 Nigel Schuster: Dereferencing 1x1 subrange
261 e259556 2016-12-10T13:53:12-05:00 Nigel Schuster: Removed nodefaultlibs directive
262 09c3961 2016-12-10T13:50:19-05:00 Nigel Schuster: Modified linker to work for travis
263 36d662a 2016-12-10T13:37:27-05:00 Nigel Schuster: Attempt to link math
264 2d4564a 2016-12-10T13:22:14-05:00 Nigel Schuster: Linking math library
265 38ba6e6 2016-12-10T13:18:39-05:00 Nigel Schuster: Suppressing compiler warnings
266 9deac9b 2016-12-10T13:06:39-05:00 Nigel Schuster: Modified compile script. Removed
```

```
    debug output
d35607b 2016-12-10T13:04:30-05:00 Nigel Schuster: Simpler testscript
d37dac2 2016-12-10T12:36:45-05:00 Nigel Schuster: Fixed duplicate import issue
31c26bc 2016-12-10T12:30:29-05:00 Nigel Schuster: Added cmd args to link file
a350720 2016-12-10T11:40:50-05:00 Nigel Schuster: Switched import style from root
    directory to relative path
90e39b0 2016-12-10T11:24:19-05:00 Nigel Schuster: Fixed issue in testscript that might
     report false results when it fails early
718ecd3 2016-12-10T03:09:18-05:00 oracleofnj: Some changes to LRM; add if(a,b,c)
6a8f836 2016-12-09T18:29:22-05:00 GitHub: Merge pull request #24 from ExtendLang/final
    -draft-lrm
fc886a9 2016-12-09T18:23:52-05:00 oracleofnj: Merge branch 'final-draft-lrm'
cda63cb 2016-12-09T18:23:24-05:00 oracleofnj: Fix merge conflict
eac9e77 2016-12-09T18:04:08-05:00 GitHub: Merge pull request #29 from ExtendLang/
    refactor
fe825f4 2016-12-09T17:55:39-05:00 oracleofnj: Compact last bit
b02dbbe 2016-12-09T17:49:00-05:00 oracleofnj: Give formula functions names
edd7aa4 2016-12-09T17:40:57-05:00 Nigel Schuster: Removed artifcats
9b49e20 2016-12-09T17:37:59-05:00 Nigel Schuster: Fixed I/O testcases
a4ad4b1 2016-12-09T17:18:13-05:00 Nigel Schuster: Merge
b07398b 2016-12-09T17:17:19-05:00 Nigel Schuster: Added macro for function definition
ed01567 2016-12-09T17:17:06-05:00 oracleofnj: Make sizeof not break tests
a0a7054 2016-12-09T17:01:20-05:00 oracleofnj: Use symbol table
56fd61b 2016-12-09T16:11:10-05:00 oracleofnj: Merge branch 'refactor' of https://
    github.com/ExtendLang/Extend into refactor
38aedba 2016-12-09T16:10:35-05:00 oracleofnj: Create symbol table
dfb702e 2016-12-09T16:01:08-05:00 Nigel Schuster: Converted more to value_p from
    subrange_p
e963186 2016-12-09T15:42:35-05:00 Nigel Schuster: Made example TC work
eb76234 2016-12-09T11:14:58-05:00 Nigel Schuster: Made Hello World work again
08aeb70 2016-12-09T02:13:09-05:00 oracleofnj: Done for the night
cb39114 2016-12-09T01:35:36-05:00 oracleofnj: More refactoring
7974bbd 2016-12-08T23:53:31-05:00 oracleofnj: Banish the term extern
49af972 2016-12-08T23:45:30-05:00 oracleofnj: Add a couple comments
0fbf461 2016-12-08T21:52:24-05:00 oracleofnj: Get my bearings
5ecb599 2016-12-08T19:47:51-05:00 Nigel Schuster: Added some documentation
65066fc 2016-12-08T12:18:57-05:00 Nigel Schuster: Added name display for variable
fb18949 2016-12-07T23:44:17-05:00 oracleofnj: Merge branch 'master' into final-draft-
    lrm
4aab3dc 2016-12-07T23:43:25-05:00 oracleofnj: Update PDF
ed44d27 2016-12-07T23:43:01-05:00 oracleofnj: Fix failing test cases
9354fa7 2016-12-07T23:06:36-05:00 oracleofnj: Final draft candidate
78649f4 2016-12-07T18:09:46-05:00 oracleofnj: Almost done
05ded19 2016-12-07T15:47:52-05:00 oracleofnj: More work
f985cc8 2016-12-07T12:14:59-05:00 Nigel Schuster: Merge branch 'finish-transformations
    ' into get-val-rev
4b58ce9 2016-12-07T12:13:23-05:00 Nigel Schuster: Tried to add more instructions
0722412 2016-12-07T11:32:11-05:00 oracleofnj: Working
099efe7 2016-12-07T10:48:35-05:00 Nigel Schuster: Making progress on evaluating
    dimensions
fa09df7 2016-12-07T09:51:23-05:00 Nigel Schuster: Finally it works
cbb0577 2016-12-07T02:35:06-05:00 oracleofnj: Still WIP
e3c9436 2016-12-07T00:44:22-05:00 oracleofnj: WIP
b265e74 2016-12-07T00:41:23-05:00 Nigel Schuster: test commit to look at
18bb182 2016-12-07T00:35:06-05:00 oracleofnj: Still work in progress
a4554c0 2016-12-06T23:14:32-05:00 Nigel Schuster: At least it compiles
```

```
3432484 2016-12-06T22:42:22-05:00 Nigel Schuster: Getting closer. Need to add var_defn wrapper in build_formula
05145ca 2016-12-06T21:10:11-05:00 Nigel Schuster: Minor fix
af69b92 2016-12-06T17:23:45-05:00 oracleofnj: More updates
a65c24e 2016-12-06T16:14:10-05:00 oracleofnj: Merge branch 'master' into finish-transformations
85a4ccb 2016-12-06T16:12:31-05:00 oracleofnj: LRM update part 1
174a7b8 2016-12-06T11:09:31-05:00 Nigel Schuster: Made partial progress on implementing variable instanciation and such
90fc58e 2016-12-05T22:14:41-05:00 GitHub: Merge pull request #23 from ExtendLang/read-empty
767851d 2016-12-05T16:18:17-05:00 Nigel Schuster: Finished C side implementation of getVal
6b837d4 2016-12-05T16:06:34-05:00 Nigel Schuster: Merge branch 'master' into get-val
04c2c65 2016-12-05T15:53:35-05:00 oracleofnj: Add slurp by passing 0 max bytes
d8cf316 2016-12-05T14:46:46-05:00 oracleofnj: Start handling empty
910bd01 2016-12-05T14:27:07-05:00 GitHub: Merge pull request #21 from ExtendLang/fileio
1ce7f83 2016-12-05T14:18:41-05:00 oracleofnj: Create patch file
88480fb 2016-12-05T13:36:28-05:00 GitHub: Merge branch 'master' into fileio
29d02d9 2016-12-05T13:34:27-05:00 oracleofnj: Fix merge conflict - keep expr_loc
52e7a8a 2016-12-05T13:32:54-05:00 GitHub: Merge pull request #22 from ExtendLang/rm-micro
bfa906b 2016-12-05T13:28:03-05:00 oracleofnj: Fix off-by-one bug
eb8dd71 2016-12-05T13:20:03-05:00 oracleofnj: Address issues
f1b11ee 2016-12-05T12:46:35-05:00 Nigel Schuster: Skeleton for get_val
e4e5e26 2016-12-05T09:25:17-05:00 Nigel Schuster: Removed microc reference implementation
270da2b 2016-12-05T02:40:59-05:00 GitHub: Merge branch 'master' into fileio
b928e98 2016-12-05T02:40:10-05:00 Ishaan: Remove bloat
894b511 2016-12-05T02:32:49-05:00 Ishaan: Added testcase
62b8e83 2016-12-05T02:30:16-05:00 Ishaan: Added fwrite implementation
77a23ae 2016-12-05T01:39:30-05:00 Ishaan: Added read
46e9b58 2016-12-05T00:07:16-05:00 Ishaan: Make refactoring changes and new helpers
a5b9066 2016-12-04T14:00:30-05:00 GitHub: Merge pull request #20 from ExtendLang/lhs-all-ids
35e9471 2016-12-04T13:38:44-05:00 oracleofnj: Put back Id(s) as it was
641d454 2016-12-04T13:36:36-05:00 oracleofnj: Always transform to ID on LHS, even for LitInts
0e8398f 2016-12-04T13:23:27-05:00 oracleofnj: Transform all LHS expressions including integers to IDs; check for strings or range literals and disallow
f47f2ba 2016-12-04T10:30:44-05:00 oracleofnj: Add error handling to close() and add a couple test cases
e95a95a 2016-12-04T10:07:01-05:00 oracleofnj: Add assertSingleNumber and get_number to eliminate more copy & paste
543e720 2016-12-04T09:47:03-05:00 oracleofnj: Add new_number() to eliminate some copy and paste
d7f10c9 2016-12-04T02:31:03-05:00 Ishaan: Tentative drafts of fileio functions
7d81e43 2016-12-04T00:15:20-05:00 oracleofnj: add diagnostic prinfs
868d9a4 2016-12-03T23:46:01-05:00 Ishaan: Cleanup
aa1e014 2016-12-03T23:42:46-05:00 Ishaan: Add file pointer array
88d05de 2016-12-03T18:38:34-05:00 Ishaan: Working on fopen
36f5848 2016-12-03T14:07:39-05:00 oracleofnj: Merge branch 'master' into finish-transformations
2ae2b83 2016-12-03T14:06:40-05:00 GitHub: Merge pull request #15 from ExtendLang/stdlib-fun
```

```
7c78a23 2016-12-03T14:02:51-05:00 oracleofnj: Move test_fabs out of regression test suite
0a8055b 2016-12-03T13:48:19-05:00 oracleofnj: make test | grep REGRESSION
a24742b 2016-12-02T22:50:43-05:00 Kevin: Merged stdlib with master
5243c5a 2016-12-02T18:16:36-05:00 Kevin: Removed magic numbers and add fabs test
330bec3 2016-12-02T13:49:34-05:00 oracleofnj: Merge branch 'master' into finish-transformations
8a60995 2016-12-01T23:38:54-05:00 GitHub: Merge pull request #18 from ExtendLang/parser-error
f0d33e2 2016-12-01T23:18:39-05:00 oracleofnj: Move error handling
3b24c3a 2016-12-01T23:16:53-05:00 oracleofnj: Adjust test script
60a732f 2016-12-01T22:55:28-05:00 oracleofnj: Merge branch 'master' into parser-error
5dec6a2 2016-12-01T22:55:05-05:00 oracleofnj: Thank you Nigel!!!
96a3028 2016-12-01T22:19:21-05:00 GitHub: Merge pull request #16 from ExtendLang/fail-silent
6c3696c 2016-12-01T21:59:40-05:00 oracleofnj: Figure out why test is failing
7912d5a 2016-12-01T21:26:03-05:00 GitHub: Merge branch 'master' into fail-silent
9702e5b 2016-12-01T21:14:35-05:00 oracleofnj: Merge branch 'master' into finish-transformations
5bdd52c 2016-12-01T21:13:45-05:00 GitHub: Merge pull request #17 from ExtendLang/lexbuf-pos
8893255 2016-12-01T20:35:04-05:00 oracleofnj: Add a couple test cases
2868653 2016-12-01T20:23:01-05:00 oracleofnj: Use lexbuf.lex_curr_p to calculate position
8c7b6ce 2016-12-01T18:59:49-05:00 GitHub: Merge pull request #11 from ExtendLang/parse_error
2885ac7 2016-12-01T18:56:15-05:00 Ishaan: Added test case for string
047cfec 2016-12-01T18:42:04-05:00 oracleofnj: Add short circuiting test cases
6acd7f6 2016-12-01T18:31:33-05:00 oracleofnj: Merge remote-tracking branch 'origin/fail-silent' into finish-transformations
72360f4 2016-12-01T17:09:08-05:00 Nigel Schuster: Minified error output for outputs that have not passed yet
5762112 2016-12-01T16:04:06-05:00 oracleofnj: Get rid of wildcard pattern match in interpreter
a90a343 2016-12-01T15:59:40-05:00 oracleofnj: Merge branch 'master' into finish-transformations
85bc21d 2016-12-01T15:59:05-05:00 oracleofnj: Remove unnecessary file
81fe565 2016-12-01T15:58:40-05:00 oracleofnj: Finish range literals
e9fb1c2 2016-12-01T15:04:03-05:00 Ishaan: Added increment to string buffer and tests
eb7c1e8 2016-12-01T15:04:03-05:00 Ishaan: Add partial character indexing
df09aea 2016-12-01T15:04:03-05:00 Ishaan: Add expected parse testcase intermediate
712a710 2016-12-01T15:04:03-05:00 Ishaan: Added tentative scanner-level line number
bf4ee6c 2016-12-01T15:04:03-05:00 Ishaan: Added SyntaxError Exception at scan level
da41520 2016-12-01T14:54:21-05:00 oracleofnj: So close
7abb394 2016-12-01T14:07:58-05:00 GitHub: Merge pull request #14 from ExtendLang/sinner
e0b7fdb 2016-12-01T14:05:38-05:00 Nigel Schuster: Rename empty to new_val
2cabadc 2016-12-01T11:58:03-05:00 oracleofnj: Merge branch 'master' into finish-transformations
6ea8cff 2016-12-01T10:10:26-05:00 Nigel Schuster: Using define instead of magic numbers
cd7d261 2016-12-01T10:07:10-05:00 Nigel Schuster: Merge branch 'master' into sinner
13cd317 2016-12-01T10:06:25-05:00 GitHub: Merge pull request #13 from ExtendLang/value_p
cf36f70 2016-12-01T09:47:38-05:00 oracleofnj: Sample digits function
4eeed07 2016-12-01T01:02:56-05:00 Ishaan: Change print return type to empty
```

```
fa42f27 2016-12-01T00:41:47-05:00 Kevin: Fixed acos function
53d34ad 2016-12-01T00:29:32-05:00 Nigel Schuster: Moved double values type to numeric
f769c61 2016-12-01T00:18:07-05:00 Nigel Schuster: Merge branch 'sinner' into stdlib-
    fun
3986f38 2016-12-01T00:17:21-05:00 Nigel Schuster: Merge branch 'value_p' into sinner
5bd87f9 2016-12-01T00:14:45-05:00 Nigel Schuster: Explicitly declaring to link math
    library
4604545 2016-12-01T00:12:08-05:00 Nigel Schuster: Consistently using floats
38b9824 2016-11-30T23:46:14-05:00 Nigel Schuster: Merge branch 'value_p' into sinner
3303575 2016-11-30T23:45:25-05:00 Nigel Schuster: Explicitly declaring to link math
    library
31a74ec 2016-11-30T23:35:34-05:00 Nigel Schuster: Merge branch 'master' into value_p
7f0bc86 2016-11-30T23:04:34-05:00 Kevin: Finished remainder of stdlib
cd160df 2016-11-30T22:50:18-05:00 Kevin: Added more c functions to stdlib
e085977 2016-11-30T19:59:57-05:00 Nigel Schuster: Made sin function work
206ee5a 2016-11-30T19:07:28-05:00 Nigel Schuster: Moved all function signatures to
    value_p return value
effc20b 2016-11-30T18:45:52-05:00 GitHub: Merge pull request #12 from ExtendLang/easy-
    compile
3b6d7b7 2016-11-30T17:51:19-05:00 Nigel Schuster: Added script to compile and link
febcff8 2016-11-30T15:54:45-05:00 oracleofnj: Add oddball formula test case and try
    out theory for range literal
4a1ff4f 2016-11-30T14:54:05-05:00 oracleofnj: Finish reducing Ternary to
    ReducedTernary
8f0a981 2016-11-30T12:35:43-05:00 oracleofnj: Working on reducing ternaries
d3c5812 2016-11-30T02:39:58-05:00 oracleofnj: Finish desugaring switch
0a22713 2016-11-30T00:09:10-05:00 oracleofnj: Getting ready to ternarize switch
84f016a 2016-11-29T21:54:15-05:00 oracleofnj: Fix bug in switch() with default case
d331b7a 2016-11-29T17:33:41-05:00 oracleofnj: Give desugaring variables easier-to-read
     names for debugging purposes
36f8de5 2016-11-29T16:14:46-05:00 oracleofnj: Missed one
d96da34 2016-11-29T16:13:21-05:00 oracleofnj: Transform &&, || into ternary
    expressions to support proper short-circuit evaluation
3a8efbc 2016-11-28T23:05:28-05:00 GitHub: Merge pull request #9 from ExtendLang/func-
    calls
7a2af49 2016-11-28T20:33:53-05:00 Nigel Schuster: Removed another ocaml 4.3 dep
468e79f 2016-11-28T19:50:53-05:00 Nigel Schuster: Added ocaml 4.3 as dep for travis (
    hopefully this works)
a408761 2016-11-28T19:35:49-05:00 Nigel Schuster: Fixed String.equal
90c3caf 2016-11-27T22:52:14-05:00 Nigel Schuster: Fixed interpreter for now
a18da78 2016-11-27T22:42:27-05:00 Nigel Schuster: Added accidentally created file
5647312 2016-11-27T22:41:22-05:00 Nigel Schuster: Made extern function calls work
872aa8c 2016-11-27T13:52:44-05:00 Nigel Schuster: Merge branch 'func-calls' of https
    ://github.com/ExtendLang/Extend into func-calls
26ef1cc 2016-11-27T13:51:06-05:00 Nigel Schuster: Merging list of functions
877336f 2016-11-27T12:15:11-05:00 GitHub: Merge branch 'master' into func-calls
5b3edb0 2016-11-27T12:14:43-05:00 GitHub: Merge pull request #8 from ExtendLang/stdlib
    -template
374273f 2016-11-27T12:13:52-05:00 Nigel Schuster: Function calls work now
952aab8 2016-11-27T09:54:12-05:00 Nigel Schuster: Merge extern
ac6268f 2016-11-26T23:06:00-05:00 Nigel Schuster: Boxing ints, added unop sizeof,
    actually returning subrange not dummy object
ca07be3 2016-11-26T21:27:19-05:00 Nigel Schuster: Unboxing hello world to and from
    subrange
aef6c19 2016-11-26T16:55:48-05:00 Nigel Schuster: Made Hello World somewhat workable
cfb637e 2016-11-25T18:27:37-05:00 Nigel Schuster: Fixed faulty setup on call
```

```
ebf926a 2016-11-25T17:48:57-05:00 Nigel Schuster: Added template in C
554fbb2 2016-11-23T22:28:29-05:00 oracleofnj: Better error message for WrongNumberArgs
f09e40e 2016-11-23T12:47:39-05:00 oracleofnj: Make sequence work
053980b 2016-11-22T16:02:27-05:00 oracleofnj: Actually commit all the extern stuff
0e0fa23 2016-11-22T14:36:54-05:00 Nigel Schuster: Added extern in Ast
aac63be 2016-11-21T23:52:25-05:00 oracleofnj: Better duplicate definition checking
08e2d07 2016-11-21T23:29:28-05:00 oracleofnj: Check assertions before evaluating fn
    return expression
69fa332 2016-11-21T18:01:23-05:00 oracleofnj: Add size assertions
22541c4 2016-11-21T12:48:34-05:00 oracleofnj: Fix bug in Call()
9a1d24b 2016-11-21T12:39:41-05:00 oracleofnj: Working on crazy bug
a485cee 2016-11-20T22:13:46-05:00 oracleofnj: Add test case for foo([m, n] arg)
10afe9a 2016-11-20T22:07:17-05:00 oracleofnj: Expand function signature
325e9ba 2016-11-20T18:53:52-05:00 oracleofnj: Well, this is awkward
0a76dc9 2016-11-20T18:41:12-05:00 oracleofnj: Add check of return value
488e34e 2016-11-20T18:31:39-05:00 oracleofnj: Add sample #1
93eebc5 2016-11-20T18:27:23-05:00 oracleofnj: Add semantic checking to make sure
    functions and variables on RHS exist
881f164 2016-11-20T17:22:40-05:00 oracleofnj: Check RHS slice to ensure end > start,
    otherwise evaluate to empty
442ae91 2016-11-20T11:42:54-05:00 GitHub: Merge pull request #73 from Neitsch/
    interpreter-global
f7f701d 2016-11-20T11:30:06-05:00 Nigel Schuster: Added use of global variables to
    interpreter, fixed specs for logical or and and testcases with empty
367bc2b 2016-11-20T00:33:17-05:00 GitHub: Merge pull request #72 from Neitsch/codegen-
    part-app-fix
bdca834 2016-11-20T00:31:04-05:00 GitHub: Merge branch 'master' into codegen-part-app-
    fix
e956238 2016-11-20T00:28:49-05:00 GitHub: Merge pull request #71 from Neitsch/tc-fixes
9b742d1 2016-11-20T00:24:39-05:00 Nigel Schuster: Fixed partial function application
    warning
32f2989 2016-11-20T00:20:51-05:00 GitHub: Merge branch 'master' into tc-fixes
f87cb94 2016-11-20T00:20:35-05:00 GitHub: Merge pull request #69 from Neitsch/
    regression-tests
842ee5a 2016-11-20T00:18:56-05:00 GitHub: Merge branch 'master' into regression-tests
6d73717 2016-11-19T23:55:35-05:00 GitHub: Merge pull request #66 from Neitsch/fix-test
    -cases
05f317a 2016-11-19T22:37:36-05:00 Nigel Schuster: Fixed output on TCs
aa1d974 2016-11-19T22:33:40-05:00 Nigel Schuster: Fixed expected value for ternary
ab7653a 2016-11-19T22:32:27-05:00 Nigel Schuster: Fixed import testcases
848066c 2016-11-19T22:24:55-05:00 Nigel Schuster: Moved testcase asset to asset folder
53c9206 2016-11-19T22:21:48-05:00 Nigel Schuster: Corrected use of global variable in
    test_globals
5fe74a8 2016-11-19T22:21:00-05:00 Nigel Schuster: Fixed expected output for
    test_access_column_cells
214ab9d 2016-11-19T22:10:33-05:00 Nigel Schuster: Merge
fb31505 2016-11-19T22:08:42-05:00 Nigel Schuster: Passing testcases are in separate
    directory. Output of stats
5e39ba7 2016-11-19T21:55:03-05:00 Nigel Schuster: Merge
25263fe 2016-11-19T21:51:31-05:00 Nigel Schuster: Removed travis from build, removed
    super verbose output
0554ad9 2016-11-19T21:42:28-05:00 Nigel Schuster: Using precise lli version
04e5c4a 2016-11-19T18:30:32-05:00 oracleofnj: Add more operators to interpreter
e4a190c 2016-11-19T17:14:04-05:00 oracleofnj: Add argument to main and remove
    _expected from filenames
7cd2b3a 2016-11-19T16:53:12-05:00 oracleofnj: Merge branch 'master' into fix-test-
```

```
    cases
d1fddfd 2016-11-19T16:52:48-05:00 oracleofnj: Merge branch 'fix-test-cases' of https
    ://github.com/Neitsch/plt into fix-test-cases
36f72a1 2016-11-19T16:49:34-05:00 GitHub: Merge pull request #67 from Neitsch/
    test_cases
c46c87b 2016-11-19T16:47:26-05:00 GitHub: Merge branch 'master' into test_cases
642ce76 2016-11-19T16:39:50-05:00 Kevin: Fixed helloworld bug
ac3d7fa 2016-11-19T16:10:53-05:00 Kevin: Added corresponding AST result for gcd
    function
7b6b79e 2016-11-19T14:31:39-05:00 GitHub: Merge branch 'master' into fix-test-cases
a9320f3 2016-11-19T14:29:51-05:00 oracleofnj: Merge branch 'master' into fix-test-
    cases
24a3625 2016-11-19T14:27:48-05:00 oracleofnj: Add switch tests
de262b4 2016-11-19T14:24:39-05:00 GitHub: Merge pull request #60 from Neitsch/box-args
75e3f71 2016-11-18T20:39:23-05:00 oracleofnj: Fix parsing errors in test cases
4e38757 2016-11-18T16:00:10-05:00 GitHub: Merge branch 'master' into box-args
7146dce 2016-11-18T15:59:54-05:00 GitHub: Merge pull request #64 from Neitsch/reorg-
    test
f483ac7 2016-11-18T14:10:32-05:00 Kevin: Updated print statement for each test
09cb42f 2016-11-18T14:07:39-05:00 oracleofnj: Fix parse difference
39634bb 2016-11-18T14:01:21-05:00 oracleofnj: Remove unnecessary files
d772725 2016-11-18T14:01:02-05:00 oracleofnj: Make inputs work with interpreter
f4456f8 2016-11-18T13:17:25-05:00 GitHub: Merge branch 'master' into test_cases
00aafb7 2016-11-18T13:16:08-05:00 Kevin: Renamed inputs folder
99db652 2016-11-18T12:51:40-05:00 Kevin: Renamed expected output extension and created
     input folder for test cases
2825ada 2016-11-18T12:51:33-05:00 Nigel Schuster: Added branch to build
aafabb2 2016-11-18T12:50:56-05:00 Nigel Schuster: Verbose output for travis debug
124d61e 2016-11-18T12:44:50-05:00 GitHub: Merge pull request #61 from Neitsch/reorg-
    test
82cf599 2016-11-18T12:34:57-05:00 oracleofnj: Modify test script to compare
    interpreter and compiler with expected
faecfa1 2016-11-18T01:48:44-05:00 oracleofnj: Fix merge conflict in box_args
41a81ce 2016-11-18T01:40:11-05:00 oracleofnj: Move argument boxing into a function
6f63e89 2016-11-18T00:48:07-05:00 GitHub: Merge pull request #59 from Neitsch/hello-
    hello
088dc45 2016-11-18T00:29:45-05:00 Nigel Schuster: Merge
012caaa 2016-11-18T00:12:40-05:00 GitHub: Merge pull request #58 from Neitsch/copy-
    argv
f84757b 2016-11-18T00:02:34-05:00 Nigel Schuster: Removed unneccessary files
18fbff1 2016-11-18T00:01:49-05:00 Nigel Schuster: Removed dummy arg reading, added
    printing to interpreter - helloworld TC passes
b866da3 2016-11-17T23:31:42-05:00 Nigel Schuster: Made hello world work
9463afa 2016-11-17T23:12:41-05:00 oracleofnj: Merge branch 'copy-argv' of https://
    github.com/Neitsch/plt into copy-argv
54858ab 2016-11-17T23:11:29-05:00 oracleofnj: Add => infix operator to cut down on all
     the build_struct_gep calls
bb11d6d 2016-11-17T23:10:24-05:00 GitHub: Merge branch 'master' into copy-argv
e123652 2016-11-17T22:28:12-05:00 oracleofnj: Add byte for zero
26a03b7 2016-11-17T22:24:17-05:00 oracleofnj: Add new_string function
b8028f9 2016-11-17T20:27:37-05:00 Kevin: Removed files from test folder
c85d9b7 2016-11-17T20:25:21-05:00 Kevin: Move testcases to testcases directory
f17c6b6 2016-11-17T20:21:38-05:00 Kevin Ye: Complete testcases for List/Range/Function
    /Expression with expected outputs
5e63cee 2016-11-17T17:40:31-05:00 GitHub: Merge pull request #54 from Neitsch/
    operation_tests
```

```
4a4a806 2016-11-17T17:19:13-05:00 GitHub: Merge branch 'master' into operation_tests
cafe20e 2016-11-17T17:19:11-05:00 GitHub: Merge pull request #52 from Neitsch/one-main
    -arg
4b28df2 2016-11-17T17:17:44-05:00 GitHub: Merge branch 'master' into operation_tests
b728e2e 2016-11-17T17:16:20-05:00 GitHub: Merge branch 'master' into one-main-arg
d43a87b 2016-11-17T17:15:28-05:00 GitHub: Merge pull request #55 from Neitsch/shell-
    fix
b1238a0 2016-11-17T17:08:56-05:00 Nigel Schuster: Shell is not my strength
a6cc0ea 2016-11-17T17:05:09-05:00 Nigel Schuster: Screw you bourne shell
51fbe67 2016-11-17T16:59:50-05:00 Nigel Schuster: Using bourne shell style redirection
    :
3255e1b 2016-11-17T16:38:53-05:00 Ishaan: Modify test suite specs
f0ab4d8 2016-11-17T16:38:53-05:00 Ishaan: Moved expected output text files to
    directory
06d330c 2016-11-17T16:38:53-05:00 Ishaan: 75% through operator cases
e490548 2016-11-17T15:50:35-05:00 GitHub: Merge branch 'master' into one-main-arg
a4cf367 2016-11-17T15:50:29-05:00 GitHub: Merge pull request #51 from Neitsch/test-
    script
79ee3de 2016-11-17T15:18:58-05:00 oracleofnj: Call main() with first argument <empty>
    in interpreter
c4f7437 2016-11-17T14:39:38-05:00 Nigel Schuster: Removed version specific lli
7b2236b 2016-11-17T14:35:55-05:00 Nigel Schuster: Fixed if no flag is given
e10f656 2016-11-17T14:24:20-05:00 Nigel Schuster: Outputting diff only if -p flag is
    given
2d29597 2016-11-17T14:19:30-05:00 Nigel Schuster: Added it as build target
7af929a 2016-11-17T14:12:19-05:00 GitHub: Merge pull request #50 from Neitsch/test-
    script
6ea43f6 2016-11-17T13:54:55-05:00 Nigel Schuster: Added more env variables to avoid
    copy paste
05f27a2 2016-11-17T12:45:11-05:00 Nigel Schuster: Made simple testscript
aca43c1 2016-11-17T11:08:11-05:00 Nigel Schuster: Removed accidentally added files
9228eac 2016-11-17T04:52:31-05:00 Kevin Ye: Test cases for List of Tests and Range/
    Function/Expression Tests
7feb392 2016-11-17T00:28:53-05:00 GitHub: Merge pull request #48 from Neitsch/
    testing_list
6e42afa 2016-11-17T00:27:13-05:00 GitHub: Merge branch 'master' into testing_list
e40734b 2016-11-16T23:25:01-05:00 Ishaan: Added more test scenarios
41ef578 2016-11-16T17:50:03-05:00 GitHub: Merge pull request #49 from Neitsch/consume-
    command-line-args
3cbf089 2016-11-16T17:45:58-05:00 oracleofnj: Fix merge conflict
1570836 2016-11-16T16:51:05-05:00 GitHub: Merge pull request #45 from Neitsch/doc
a8fbced 2016-11-16T16:38:49-05:00 Nigel Schuster: Fixed minor syntax error
c2f37c8 2016-11-16T16:30:43-05:00 Nigel Schuster: Merge
2fa73be 2016-11-16T16:05:37-05:00 oracleofnj: Set return code to length of argv[1]
bc21af6 2016-11-16T15:54:12-05:00 Ishaan: Added initial testing list
cd0d156 2016-11-16T15:50:39-05:00 oracleofnj: Start processing command line args
4a1fcac 2016-11-16T13:55:46-05:00 GitHub: Merge pull request #46 from Neitsch/number-
    type
f1b481e 2016-11-16T11:04:44-05:00 Nigel Schuster: Added number type that defaults to
    int
8944b9a 2016-11-16T00:19:33-05:00 GitHub: Merge pull request #44 from Neitsch/fix-arg
92fb7a3 2016-11-15T23:57:37-05:00 Nigel Schuster: Added a little documentation
bcbde36 2016-11-15T23:49:07-05:00 GitHub: Merge branch 'master' into fix-arg
fa1741a 2016-11-15T23:03:23-05:00 GitHub: Merge pull request #43 from Neitsch/more-
    llvm-gen-js
57b2162 2016-11-15T22:39:38-05:00 Nigel Schuster: Using subranges instead of ranges
```

```
    everywhere
556 9407677 2016-11-15T22:31:03-05:00 oracleofnj: Add hash table for common functions and
    add dereference-the-range
557 46e1fd5 2016-11-15T21:38:51-05:00 oracleofnj: Eliminate some copy & paste
558 660c049 2016-11-15T20:54:33-05:00 GitHub: Merge pull request #42 from Neitsch/llvm-gen
559 25b23cd 2016-11-15T17:23:54-05:00 Nigel Schuster: Fixed column retrieval for 1x1
560 3f02203 2016-11-15T17:17:02-05:00 Nigel Schuster: Fixed tests
561 26b8fcf 2016-11-15T17:15:08-05:00 Nigel Schuster: Merge
562 e347a87 2016-11-15T17:12:26-05:00 Nigel Schuster: Using more generic flag for values
563 aed28b3 2016-11-15T17:08:07-05:00 oracleofnj: Add is_subrange_1x1
564 cf5cbf0 2016-11-15T14:51:40-05:00 oracleofnj: Merge branch 'llvm-gen' of https://
    github.com/Neitsch/plt into llvm-gen
565 c71d469 2016-11-15T14:51:19-05:00 oracleofnj: Replace String.equal with =
566 4b34abd 2016-11-15T14:41:37-05:00 GitHub: Merge branch 'master' into llvm-gen
567 a80a6d0 2016-11-15T14:41:07-05:00 oracleofnj: Add compile option to main
568 8ad5a19 2016-11-15T14:33:40-05:00 GitHub: Merge pull request #40 from Neitsch/
    interpreter
569 3f0362a 2016-11-15T14:28:44-05:00 GitHub: Merge branch 'master' into interpreter
570 c0c95a2 2016-11-15T14:16:13-05:00 Nigel Schuster: Merge
571 d5f4024 2016-11-15T13:44:44-05:00 Nigel Schuster: Moved failing TCs
572 42fd9ef 2016-11-15T12:21:57-05:00 oracleofnj: Fix bug in import
573 9c567c9 2016-11-15T11:11:30-05:00 Nigel Schuster: Working on imports, fixed most
    testcases
574 aa61ac9 2016-11-15T09:31:42-05:00 Nigel Schuster: Allocating scope object
575 cf1ebf9 2016-11-13T23:09:30-05:00 oracleofnj: Rewrite main to take options; fix bug
    where import didn't know about first filename
576 5749538 2016-11-13T21:59:28-05:00 Nigel Schuster: Added main function
577 d6daff3 2016-11-13T20:26:14-05:00 GitHub: Merge pull request #41 from Neitsch/
    LRM_String_Update
578 0a5d484 2016-11-13T18:45:29-05:00 oracleofnj: Revert "Generating function header"
579 6afe599 2016-11-13T18:44:58-05:00 Ishaan Kolluri: Added changes relating to strings.
580 137d7e2 2016-11-13T18:39:33-05:00 oracleofnj: Merge branch 'interpreter' of https://
    github.com/Neitsch/plt into interpreter
581 118bfc5 2016-11-13T18:38:34-05:00 oracleofnj: Allow single slice on RHS; make hashtag
    work
582 e376270 2016-11-13T17:55:41-05:00 Nigel Schuster: Added type arguments for functions
583 5cfb519 2016-11-13T17:26:23-05:00 Nigel Schuster: Set more types up
584 bf1d8bb 2016-11-13T15:30:35-05:00 Nigel Schuster: Merge branch 'interpreter' of https
    ://github.com/Neitsch/plt into interpreter
585 f83a0bc 2016-11-13T15:30:28-05:00 Nigel Schuster: Generating function header
586 3addcc8 2016-11-13T14:38:11-05:00 oracleofnj: Make size(expr) an operator instead of
    built-in function
587 9a74e14 2016-11-13T14:22:44-05:00 oracleofnj: Changing size() to be an operator
588 d6d2eaa 2016-11-13T00:08:41-05:00 oracleofnj: Add closure to interpreter_variable
589 64fba82 2016-11-12T22:38:39-05:00 oracleofnj: Added bsearch to show logic bug
590 66ffdb1 2016-11-12T19:21:07-05:00 oracleofnj: Add alpha version of function calls
591 376b29a 2016-11-12T17:17:23-05:00 oracleofnj: Add string as value type
592 08c61ee 2016-11-12T17:14:47-05:00 oracleofnj: Clean up discrepancies
593 a18d5fc 2016-11-08T11:38:22-05:00 oracleofnj: Fix bug with x[-1]
594 962f812 2016-11-07T23:27:08-05:00 oracleofnj: Refactor scope for interpreter; resolve
    variables on demand; make selections work properly
595 47bbef1 2016-11-06T22:05:55-05:00 oracleofnj: Minor adjustments to interpreter to work
     with mapped AST
596 fddc6bc 2016-11-06T18:32:17-05:00 oracleofnj: Eliminate extraneous nulls in JSON
597 ffddb17 2016-11-06T18:15:40-05:00 oracleofnj: Turn statement and function lists into
    StringMaps
```

```
6810003 2016-11-05T19:47:57-04:00 oracleofnj: Fix pattern matching warning
7107a46 2016-11-05T18:01:34-04:00 oracleofnj: Add function to check range literals for
    legality at parse time
80b13d1 2016-11-05T15:13:10-04:00 oracleofnj: Handle selections better
6cbb009 2016-11-04T15:48:58-04:00 oracleofnj: Count to 1,000,000 using tail-recursive
    versions of List.map and cartesian product
9b2252d 2016-11-04T15:25:13-04:00 oracleofnj: Show enter and exit
3585e43 2016-11-04T02:21:38-04:00 oracleofnj: See how high it can count recursively
38cf541 2016-11-04T02:15:50-04:00 oracleofnj: Get the easy parts of the interpreter
    working
5d81d6e 2016-11-03T17:17:51-04:00 oracleofnj: Start working on interpreter
0078cee 2016-11-01T23:40:57-04:00 oracleofnj: Got a non-tail-recursive version of
    topological sort working
85df175 2016-11-01T15:39:10-04:00 oracleofnj: Irrelevant highlighting thing
84c719a 2016-11-01T14:39:49-04:00 oracleofnj: Rearrange nested functions
557dc4e 2016-11-01T13:50:52-04:00 oracleofnj: Add circular import test case
c476798 2016-11-01T13:35:46-04:00 oracleofnj: Fix syntax errors
af5a31d 2016-11-01T13:31:49-04:00 GitHub: Merge pull request #37 from Neitsch/import-
    rec
d451cc4 2016-11-01T13:31:33-04:00 GitHub: Merge pull request #38 from Neitsch/import-
    load
02ca24f 2016-11-01T13:30:47-04:00 GitHub: Merge pull request #39 from Neitsch/wild-exc
6fa0e39 2016-10-31T16:43:17-04:00 Neitsch: Raising exceptions on certain values
e673dca 2016-10-31T15:56:43-04:00 Neitsch: Loading data from all imports
6a28c05 2016-10-31T15:40:41-04:00 Neitsch: Recursively looking up dependencies
3f28289 2016-10-31T11:53:10-04:00 GitHub: Merge pull request #36 from Neitsch/import-
    arrange
4eaef3b 2016-10-31T11:01:00-04:00 Neitsch: Removed obsolete parts
7d7b1e5 2016-10-31T10:59:12-04:00 Neitsch: Added unsorted function, globals and
    imports
7d70af2 2016-10-30T15:23:04-04:00 oracleofnj: Add some explanatory comments
40d6b16 2016-10-30T15:03:32-04:00 oracleofnj: More expansion samples
af9b01c 2016-10-30T14:48:44-04:00 oracleofnj: Refactor expansion code
903bc3f 2016-10-30T00:19:10-04:00 oracleofnj: Add test output
68b7b03 2016-10-30T00:17:02-04:00 oracleofnj: Add test case
a8bdf33 2016-10-30T00:04:05-04:00 oracleofnj: Add LHS slice expansion
4ee6fdf 2016-10-29T17:36:17-04:00 oracleofnj: Add output
2b8bced 2016-10-29T17:27:22-04:00 oracleofnj: Expand dimension expressions
443a818 2016-10-26T16:31:51-04:00 GitHub: Merge pull request #35 from ishaankolluri/
    master
9ba3c65 2016-10-26T16:31:00-04:00 Ishaan Kolluri: Add UNIs
022e8cd 2016-10-26T16:25:57-04:00 GitHub: Merge pull request #34 from ishaankolluri/
    master
808aae5 2016-10-26T16:22:10-04:00 Ishaan Kolluri: Added change to precedence operators
0bd9c4a 2016-10-26T15:59:53-04:00 GitHub: Merge pull request #33 from Neitsch/final-
    slicing-comments
fb2b382 2016-10-26T15:54:11-04:00 oracleofnj: Thats all for now folks
e7020ec 2016-10-26T15:00:11-04:00 GitHub: Merge pull request #32 from Neitsch/final-
    lrm-edits
4683f14 2016-10-26T14:48:41-04:00 oracleofnj: Flesh out switch expressions, add
    precedence
4b7984a 2016-10-26T11:15:03-04:00 GitHub: Merge pull request #31 from Neitsch/more-lrm
    -edits
3d587c5 2016-10-26T11:10:15-04:00 oracleofnj: Incorporate requested edits and a few
    more clarifications
0c42b9c 2016-10-26T09:22:08-04:00 GitHub: Merge pull request #30 from ishaankolluri/
```

```
    LRM_update
cd81040 2016-10-26T03:30:20-04:00 ishaankolluri: Added changes to first half of LRM
63fb02b 2016-10-26T02:13:17-04:00 GitHub: Merge pull request #29 from Neitsch/lrm-
    edits
0941e96 2016-10-26T02:04:47-04:00 oracleofnj: Rebuild PDF
cb04069 2016-10-26T02:04:01-04:00 oracleofnj: Add built in functions
4abf638 2016-10-26T01:56:38-04:00 oracleofnj: Add built in functions
7661925 2016-10-26T00:04:22-04:00 oracleofnj: Initial comments
5932551 2016-10-25T21:30:40-04:00 GitHub: Merge pull request #28 from Neitsch/func-doc
    -fix
cc66297 2016-10-25T20:14:27-04:00 Nigel Schuster: Fixed mistakes in functions part of
    the doc
b978f00 2016-10-25T13:04:05-04:00 GitHub: Merge pull request #27 from ishaankolluri/
    master
125a5bb 2016-10-25T12:49:38-04:00 Ishaan Kolluri: Removed AUX file
2e1ea60 2016-10-25T11:30:35-04:00 GitHub: Merge pull request #26 from Neitsch/better-
    regexp
84b03ee 2016-10-25T01:22:31-04:00 oracleofnj: Fix let order
91b40c5 2016-10-25T01:14:43-04:00 oracleofnj: Improve regexp
eb24036 2016-10-24T23:55:38-04:00 GitHub: Merge pull request #23 from Neitsch/file-io
991c918 2016-10-24T23:20:12-04:00 oracleofnj: Replace fopen, fclose etc. with open,
    close etc.
338faa0 2016-10-24T23:14:30-04:00 oracleofnj: Fix file inclusion and rebuild PDF
b24edd3 2016-10-24T23:11:50-04:00 oracleofnj: Merge in expressions section
44a1cc5 2016-10-24T23:06:07-04:00 oracleofnj: Merge scanner changes and add regexp to
    properly escape strings
2f09a64 2016-10-24T15:52:10-04:00 Kevin: Added the Expression Section 4 to LRM
1ea3c28 2016-10-24T15:26:16-04:00 oracleofnj: Merge branch 'master' into file-io
ec7cc9c 2016-10-24T15:21:23-04:00 Jared Samet: Replace repetitive code with more
    idiomatic OCaml
8cd39ac 2016-10-24T11:05:33-04:00 Kevin: Added string literals to scanner
e5d2478 2016-10-24T11:00:39-04:00 Kevin: Added string literals to scanner
a692466 2016-10-24T01:09:21-04:00 oracleofnj: Fix tests until strings ready
8553a50 2016-10-24T01:08:29-04:00 oracleofnj: Fix tests until string ready
0ed4ad7 2016-10-24T00:55:08-04:00 oracleofnj: Add File IO, Entry point and Example to
    LRM
71e0b1c 2016-10-23T22:58:21-04:00 oracleofnj: Fix section reference
92ac506 2016-10-23T22:39:06-04:00 Ishaan Kolluri: Make small change to data type
    section
6abb290 2016-10-23T22:34:42-04:00 oracleofnj: Initial commit for File I/O section
67b4b65 2016-10-23T19:30:03-04:00 Nigel Schuster: Reduce eye pain
2824ee9 2016-10-23T19:03:24-04:00 GitHub: Merge pull request #20 from Neitsch/samples
f8ae543 2016-10-23T18:23:11-04:00 GitHub: Merge branch 'master' into samples
13d0896 2016-10-23T18:20:03-04:00 GitHub: Merge pull request #19 from Neitsch/sequence
    -operator
e0c702d 2016-10-23T18:17:58-04:00 Neitsch: Fixed .gitignore
3a2cd60 2016-10-23T18:16:35-04:00 GitHub: Merge branch 'master' into sequence-operator
e42fe94 2016-10-23T18:05:48-04:00 Neitsch: Added code in LRM to test code samples
9d2cd17 2016-10-23T17:24:15-04:00 Neitsch: Merge branch 'master' into samples
167ddd2 2016-10-23T17:18:35-04:00 Neitsch: Removed test output
57319c4 2016-10-23T17:11:13-04:00 oracleofnj: Remove intermediate files
53824ea 2016-10-23T17:10:39-04:00 oracleofnj: Flip precedence of -> and ?: (?: is now
    lowest)
7dedf93 2016-10-23T17:05:23-04:00 oracleofnj: Add sequence operator to scanner/parser/
    AST
9805753 2016-10-23T17:01:31-04:00 GitHub: Merge pull request #17 from Neitsch/make-
```

```
    correction
e0c7aed 2016-10-23T16:59:33-04:00 Neitsch: Fixed test
ec3d682 2016-10-23T16:41:00-04:00 GitHub: Merge branch 'master' into make-correction
ea05658 2016-10-23T16:40:24-04:00 Neitsch: Moved sequence file
0ca56a0 2016-10-23T16:10:14-04:00 Neitsch: Merge
9d1094e 2016-10-23T16:08:59-04:00 Neitsch: Added simple TCs, Moved Makefile to oasis
    config
0a28413 2016-10-23T16:08:59-04:00 Neitsch: Completed initial functions section doc
0797f32 2016-10-23T16:08:12-04:00 Neitsch: Changed subsection header
9df31f7 2016-10-23T16:08:12-04:00 Neitsch: Added dimension section
8939903 2016-10-23T16:07:26-04:00 Neitsch: Started working on Functions
cae3b37 2016-10-23T16:06:27-04:00 Neitsch: Added dimension section
049c95d 2016-10-23T16:06:08-04:00 Neitsch: Started working on Functions
84d20b5 2016-10-23T16:01:00-04:00 Neitsch: Comparing sample code with correctly parsed
     code in samples_comp
3f015ee 2016-10-23T15:52:01-04:00 GitHub: Merge pull request #18 from Neitsch/grammar-
    bug-fixes
7e558c1 2016-10-23T15:44:20-04:00 GitHub: Merge branch 'master' into make-correction
edf3dea 2016-10-23T15:44:20-04:00 GitHub: Merge branch 'master' into grammar-bug-fixes
d4961eb 2016-10-23T15:43:16-04:00 GitHub: Merge pull request #15 from Neitsch/
    functions-doc
0e0bda5 2016-10-23T15:05:42-04:00 GitHub: Merge branch 'master' into functions-doc
4652c67 2016-10-23T15:00:35-04:00 Neitsch: Added simple TCs, Moved Makefile to oasis
    config
b45718d 2016-10-23T02:27:36-04:00 oracleofnj: Modify grammar to allow [m,n] foo, bar,
    baz;
143fcba 2016-10-22T23:23:10-04:00 GitHub: Merge pull request #16 from Neitsch/more-AST
a726236 2016-10-22T20:51:27-04:00 oracleofnj: Add comments and sample program
8db4098 2016-10-22T19:44:48-04:00 oracleofnj: Fix minor grammar bug
80754c3 2016-10-22T18:19:27-04:00 oracleofnj: Hook up scanner and parser
660de8c 2016-10-22T13:54:32-04:00 GitHub: Add stuff to the grammar, minor corrections
    (#14)
cfe827d 2016-10-21T20:50:51-04:00 Nigel Schuster: Completed initial functions section
    doc
3609366 2016-10-20T21:14:00-04:00 GitHub: Update scanner.mll
0d57652 2016-10-20T21:10:27-04:00 Kevin: Fixed bug in scanner
1848813 2016-10-20T20:21:49-04:00 Kevin: Made scanner
1b610ac 2016-10-20T13:50:22-04:00 Nigel Schuster: Merge
acb9b93 2016-10-20T13:44:06-04:00 Nigel Schuster: Changed subsection header
b95d039 2016-10-20T13:43:51-04:00 Nigel Schuster: Added dimension section
71b93bb 2016-10-20T13:43:09-04:00 Nigel Schuster: Started working on Functions
a15772c 2016-10-20T13:38:08-04:00 GitHub: Merge pull request #10 from ishaankolluri/
    LRM
dee63c7 2016-10-20T13:26:28-04:00 GitHub: Merge pull request #1 from Neitsch/grammar-
    doc
dc93dbf 2016-10-20T13:18:29-04:00 Nigel Schuster: Grammar import
4d763cb 2016-10-20T12:44:52-04:00 Ishaan Kolluri: Made refactor and edits to intro
    section of LRM
e7443cc 2016-10-20T11:46:54-04:00 Ishaan Kolluri: Merging
7542b5d 2016-10-20T11:16:35-04:00 Nigel Schuster: Added dimension section
995cf83 2016-10-19T12:28:09-04:00 Nigel Schuster: Started working on Functions
40c2a5a 2016-10-19T03:43:06-04:00 ishaankolluri: Initial LRM Commit part 1
02a5c17 2016-10-18T18:38:21-04:00 Ishaan Kolluri: Added LRM initial info
d8794e9 2016-10-17T19:47:42-04:00 GitHub: Merge pull request #9 from Neitsch/
    documentation
70aa1b9 2016-10-16T13:36:23-04:00 Nigel Schuster: Added PDF Latex template
```

```
5111202 2016-10-14T19:59:45-04:00 GitHub: Added a bunch of stuff to the grammar: (#8)
da967e4 2016-10-12T13:24:50-04:00 Jared Samet: CFG Grammar (#6)
fea4e4b 2016-10-08T11:42:39-04:00 GitHub: There is no need to constantly build all
    branches. (#2)
7a5ccfc 2016-10-08T11:31:31-04:00 Nigel Schuster: Added greeting and newlines (#4)
10b17f7 2016-10-08T11:31:08-04:00 GitHub: Imported microc (#5)
726456f 2016-09-20T09:45:07-04:00 Nigel Schuster: [test] Add sample greeting to repo
    (#3)
9a2183d 2016-09-15T18:44:00-04:00 Nigel Schuster: Added merlin config
163e176 2016-09-14T18:51:53-04:00 Nigel Schuster: Moved whole build to script
d401eea 2016-09-14T18:43:58-04:00 Nigel Schuster: Added oasis opam package
ba7fd9c 2016-09-14T18:38:58-04:00 Nigel Schuster: Added ocaml configure (maybe this
    helps travis)
a461eae 2016-09-14T18:26:10-04:00 Nigel Schuster: Configuring opam environment for
    travis
ba2df2f 2016-09-14T18:19:26-04:00 Nigel Schuster: Added ocaml native compiler to apt
    package list
a8e5958 2016-09-14T17:24:36-04:00 Nigel Schuster: Added some more (possibly necessary
    opam packages
c54f5e3 2016-09-14T17:18:32-04:00 Nigel Schuster: Missed opam option
b10adf0 2016-09-14T17:13:57-04:00 Nigel Schuster: Fixed opam install
124f7f3 2016-09-14T17:08:09-04:00 Nigel Schuster: Fixed YML error
4909fa8 2016-09-14T17:03:54-04:00 Nigel Schuster: Using avsm source
4b24046 2016-09-14T16:58:33-04:00 Nigel Schuster: Allow sudo
e7b50db 2016-09-14T16:56:57-04:00 Nigel Schuster: Fixed setup order
f6d7ac4 2016-09-14T16:50:02-04:00 Nigel Schuster: Manually installing apt packages
f4084ab 2016-09-14T16:40:55-04:00 Nigel Schuster: Test commit
d7c5e9a 2016-09-14T13:15:43-04:00 Nigel Schuster: Initial commit
```

11. Special Thanks

We'd like to thank Bruce Verderaime for the `gdchart` library, which we modified and shipped to provide Extend with graph plotting functionality. Additionally, we'd like to credit Thomas Boutell for the `gd` library, on which `gdchart` relies. The copyright notice is in the repository.