COMS W4115: RJEC Final Report

Really Just Elementary Concurrency

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1 Introduction

RJEC (Really Just Elementary Concurrency) is an imperative language with a primary focus on concurrent programming. It is based on Go, and its syntax and features are largely a strict subset of Go's. Like Go, RJEC is imperative, and concurrency abstractions are incorporated as language primitives. These features enable somewhat higher-level, CSP-style concurrency, which are useful in distributed systems applications.

RJEC has clear, concise, consistent, and clean syntax, allowing for convenient imperative programming. It adds syntactic sugar to help programmers write succinct and readable code. For example, limited compile-time type deduction is provided to make variable declaration clean and easy, and yeetroutines abstract away the passing of arguments and communication channels so that the programmer can focus on writing nice concurrent code.

RJEC provides basic language constructs such as arrays and structs, alongside the high-level concurrency constructs of yeetroutines and channels. These features, combined, enable the programmer to write powerful and expressive code, in both sequential and concurrent paradigms.

Note that the goal of RJEC is *concurrency*, not parallelism. Strong concurrent programming semantics enable good parallel computing, but a concurrent program does not need to be executing on multiple cores simultaneously for it to have good and correct structure. Our language is designed to enable correct high-level concurrent programming, which will remain correct even if the environment is optimized to make it parallel.

2 Tutorial

2.1 Installation

We currently support installation by Docker. Download the source code and run the following commands:

```
docker run --rm -it -v `pwd`:/home/microc -w=/home/microc
    columbiasedwards/plt
make all
```

To run the test suite, run `make` or `./testall.sh` when the compiler is already compiled.

To compile your own programs, run ./rjec.sh <filename>.rjec when the compiler is already compiled.

2.2 Language

In the words of Kernighan & Ritchie, the first program is the same for all languages:

```
func main() {
    prints("hello, world");
}
```

You may declare and initialize variables as follows.

```
var i int = 5;
```

You could also use the short-form same-line declaration and initialization syntax as follows. The type of the variable to declare is deduced from the right-hand-side expression in compile-time:

```
i := 5;
```

RJEC supports three basic data types: integers, booleans, and characters.

Composite data types such as arrays and structs are also supported. Arrays are declared with this syntax:

```
var arr [i]char;
arr2 := []bool{true, true, false};
```

You may also create and store strings as null-terminated `char` arrays:

```
str := "hello";
```

Structs are defined globally:

```
struct my_struct {
    i int;
    b bool;
    c char;
}
```

And can be declared with the following syntax. When creating struct literals and conducting value assignments, member fields are optional; if a member field value is not specified, it will be initialized with the zero value of its type.

```
s := my_struct {
    i: 1,
    c: 'a'
}
```

You can define a function as follows, where the formal arguments are in the parentheses and the return type is at the end:

```
func foo (i int, j char) int {
    printc(j);
    return i + 1;
}
```

To start a concurrent thread executing a function call, we use yeetroutines:

```
yeet foo(5);
```

To communicate between yeetroutines, we use channels, another composite data type that we support:

```
func bar(ch chan int) {
    ch <- 5;
}

func main() {
    ch := make(chan int);
    yeet bar(ch);
    printi(<- ch);
}
```

This concludes our brief tour of this language. For more details, refer to our manual below.

3 Language Reference Manual

3.1 Lexical Conventions

3.1.1 Comments

RJEC has support for multi-line comments (though they may take up a single line). Any tokens following /∗ are considered part of a comment and are essentially discarded (they are not included in further lexical analysis or parsing). A comment is over when the ∗/ token is encountered.

3.1.2 Reserved Keywords

The reserved keywords are as follows, grouped together by their particular uses:

The keywords representing data types are: `int`, `bool` (for which we have `true`, and `false`), `char`, `chan`, `struct`, `array`. Note that the first three indicate the basic data types, and the following three indicate the composite data types.

The keywords useful for dictating control flow are: `if`, `else`, `for`, `defer`, `select`, `case`, `return`, `yeet`.

The keywords necessary for long-form declarations are: `var`.

The keywords related to channels are: `make`, `close` (discussed in greater detail below).

3.1.3 Literals

Literals can be used to represent either the basic data types (`int`, `char`, `bool`), strings, or composite data types such as arrays and structs.

String literals are a sequence of characters wrapped in double quotation marks, i.e. `"rjec is the best"`. String literals do not need to be bound to a variable.

The lexer is able to identify string literals by going into a different mode of lexing when encountering a double quote (`"`) and reads contents to a buffer (which constitute the contents of a string literal) until another double quote (`"`) is encountered.

A char literal is a single character wrapped in single quotation marks, i.e. `var mychar char = 'r'`. Character literals do not necessarily have to be bound to a variable either. The user is allowed to use '
0' to represent the zero value of the `char` type (also used as null terminators for strings).

An integer literal can be any sequence of integers, each of which are between 0 and 9. The corresponding regex that is matched to by the lexer is `['0'- '9']+`.

A boolean literal can either be the `true` or `false` keyword, i.e. `var mybool bool = false`.

Array and struct literals are described in their respective sections below.

3.1.4 Separators

RJEC uses parentheses (`()`) to override any default expression precedence. Similarly, square brackets (`[]`), curly braces (`{}`) are processed as separators. White spaces are indeed separators, but are not recognized as tokens. The other potential separators include commas (`,`), semicolons (`;`), dots (`.`), and colons (`:`).

The following provide examples of usage of separators:

```
a, b := 1, 2;
/* ',' as a separator in multiple variable declaration */

var newArr [2]char = []char{'a', 'b'};
/* [] and {} for array declaration and initialization */

newArr[1] = 'c';
/* [] in array access and ';' indicate the end of a statement */

x_coord = point.x;
/* '.' to access field of a struct */

case data <- x:
/* ':' in case statement */
```

3.2 Variables

3.2.1 Variable Naming

Variable, function, and type *identifier*s must begin with a letter, and must contain only letters, numbers, and underscores. As an example `var_name_1` is a valid identifier, as is `VarName2`. `2strong` is not a valid variable, and neither is `_var_name_3`.

3.2.2 Declaring a Variable

Variables may be declared by using their names followed by their type, except in the case of arrays, for which there is a special syntax for noting their type and size, even though the length of an array is not part of its type:

vdecl:

> `var` *id-list vdecl-typ*

id-list:

> *identifier*
> *identifier* `,` *id-list*

vdecl-typ:

> `int`
> `bool`
> `char`
> `chan` *basic-typ*
> `[`*expr*`]` *typ*
> `struct` *identifier*

Variables may be declared both globally and in functions. Variables declared without being explicitly initialized are initialized to their zero value. Variables may be declared and initialized in the same line within functions. The operator *identifier* `:=` *expr* may act as shorthand for variable initialization by assigning the type of the expression to the new variable (see section 3.10.19).

As examples, the following are both valid variable initialization:

```
var i int = 5;
j := 5;
```

3.2.3 Multiple Variable Declaration

As can be seen in the grammar above, multiple variables of the same type may be declared and initialized in one line by being separated by commas. Furthermore, using the `:=` operator (as seen in the grammar in 3.10.19), multiple variables of different types may be declared in one line by being assigned. As examples:

```
var i, j int = 2, 3;
k, s := 5, "hi";
```

3.3 Typing Methodology

RJEC is statically typed and strongly typed. The language supports three basic data types: `int`, `bool`, and `char`. In addition, it also supports three composite types: `array`, `struct`, and `chan`. Note that to this end, string literals will be represented as char arrays rather than as its own type. The types are represented in RJEC's grammar as:

typ:

> `int`
> `bool`
> `char`
> `chan` *basic-typ*
> `[]` *non-arr-typ*
> `struct` *identifier*

RJEC enforces a strong typing system, which means the language does not conduct implicit type conversions or casting. Operands on both sides of binary operators have to be of the same type, and failure to abide by the typing system will lead to compiler errors. RJEC does not support type casting or implicit type conversions, although RJEC offers limited compile-time type deduction when using the `:=` operator (where type of the right-hand-side expression is used to declare the variable on the left-hand-side).

Note that unlike some other language conventions, RJEC treats `int` and `bool` as distinct types, which means statements such as `1 == true` will lead to compiler errors as well.

3.4 Basic Data Types

The basic data types in RJEC consist of the following:

basic-typ:

```
int
bool
char
```

3.4.1 `int`

The `int` type represents signed, 4-byte integer numbers. The integer values are implicitly non-negative, and negative integers are represented by prefixing the unary minus operator `-` to the numerical value. The zero value for `int` is 0.

3.4.2 `bool`

The `bool` type represents 1-byte boolean values. A `bool` type variable can have the value of either `true` or `false`. The zero value for `bool` is `false`.

3.4.3 `char`

The `char` type represents 1-byte ASCII characters. A char literal is represented by enclosing ASCII symbols in single quotes, i.e.

```
'[<ASCII_symbol>]'
```

Note that in RJEC, string literals are represented as a char array, and are represented by enclosing 0 or more ASCII symbols in double quotes, i.e.

```
"[<ASCII_symbol>]*"
```

The zero value for `char` is `'\0'`, which also represents null terminator in a string literal.

3.5 Arrays

In RJEC, `array` is a composite data type that allows for the storage of an ordered set of elements in a consecutive memory. Note that the length of an array is fixed upon declaration, though they may be declared using variables, and that all the elements in an array must be of the same data type as specified in the declaration. The data

type contained in an array can be any other data type supported by RJEC, including composite data types such as `struct` and `chan`, except for `array` (nested arrays are not supported).

3.5.1 Declaring Arrays

One declares an array by specifying the data type of the elements, the length, and the identifier of the array. The declaration takes the following form:

`var` *id-list* `[`*expr*`]`*non-arr-typ*

Where *non-arr-typ* is a type which is not an array type:

non-arr-typ:

`int`
`bool`
`char`
`chan` *basic-typ*
`struct` *identifier*

For example, to declare an integer array of length 10 and identifier "myArr":

```
var myArr [10]int;
```

Once declared, an array object has the type of `[]<data_type>`.

Note that the *expr* that specifies the length of the array must evaluate to an integer value.

3.5.2 Defining Arrays

In the grammar, an array literal is defined as:

`[`*expr*`]`*non-arr-typ* `{` *args-list* `}`

Where *expr* should evaluate to an integer value that represents the length of the array. With this, one can initialize the contents of an array upon declaration through enumeration. That is:

```
var identifier []<data-type> =
    []<data-type>{elem1, elem2, ...};
```

If the variable to be declared is to be initialized immediately in the same statement, one can also choose to use a short-form assignment statement instead:

```
identifier := []<data-type>{elem1, elem2, ...};
```

For example, here are the two ways to declare and initialize an integer array of length 3 and populate it with values:

```
var myArr [3]int = []int{1, 2, 3};
/* or equivalently */
myArr := []int{1, 2, 3};
```

Note that if an array is not immediately initialized upon declaration, its fields will be filled by the zero values of the data type specified for its elements.

One can also define an array post-declaration, either by assigning a new value to the entire array, or by accessing and modifying individual array elements with the following format:

```
identifier[index] = <new_value>;
```

3.5.3 Accessing Array Elements

One can access specific elements in an array by their index, with the following expression:

identifier `[`*expr*`]`

Note that in RJEC, the array index starts with 0, so for any array, except for the 0-length arrays, any index value between `0` and `length - 1` (inclusive) is within range.

3.6 Structs

A `struct` in RJEC is a user-defined data type that consists of fields taken up by elements of the basic data types (`int`, `char`, `bool`).

3.6.1 Defining Structs

In RJEC program files, all structs are defined globally, with all fields public. A struct can be defined with the following grammar:

sdecl:

`struct` *identifier* `{` *member-list* `}`

member-list:

identifier basic-typ`;`
member-list identifier basic-typ`;`

For example, to define a coordinate type that represents a point in a cartesian coordinate system:

```
struct coordinate {
    x int;
    y int;
}
```

Note that the RJEC compiler enforces that the identifiers for the struct need to be globally unique, and identifiers for the struct field need to be unique within the struct. Also, note again that currently RJEC does not support composite data types for struct fields.

3.6.2 Declaring and Initializing Variables of Type Struct

Once a struct type has been globally defined, one can declare variables of the struct type globally or locally, similar to how one declares objects of the primitive types. A struct literal is defined in the grammar as:

expr:

...
`struct` *identifier* `{` *element-list*$_{opt}$ `}`
...

element-list:

identifier `:` *expr*
identifier `:` *expr*`,` *element-list*

A struct object can be declared and initialized with the following syntax:

```
var identifier struct struct-id = struct struct-id {
    field-id1 : <value1>,
    field-id2 : <value2>
};
/* or equivalently */
identifier := struct struct-id {
    field-id1 : <value1>,
    field-id2 : <value2>
};
```

For example, to declare and initialize a coordinate struct object:

```
coord := struct coordinate {
    x : 1,
    y : 2
};
```

Note that similar to arrays, if a struct is declared without being immediately initialized, then all of its fields will be taken up by the zero values specified for their respective data types. Later, one can assign values to the individual struct fields with the struct access operator:

```
struct-id.field-id = <value>;
```

Furthermore, a struct literal may only mention some but not all of the member fields, in which case the remaining member fields are assigned to their zero values, as described above.

3.6.3 Accessing Fields of a Struct

All fields in a struct are public, and can be accessed through the struct access operator `.` with the following expression:

expr . *field-id*

Where the *expr* evaluates to an identifier for a struct or a struct array member.

3.7 Channels

A `chan` type, or channel, provides a way for concurrently executing yeetroutines to communicate by sending and receiving values of a specified data type.

3.7.1 Declaring and Initializing Channels

A `chan` can be declared with the following grammar:

`var` *id-list* `chan` *basic-typ*

The declared channel will then have a type specification of `chan <basic-typ>`.

In addition, a `chan` variable can be initialized by the function-like keyword `make`, which allocates resources for either an unbuffered channel, or a buffered channel with a user-defined size. The expression for initializing an unbuffered channel:

`make(chan` *basic-typ*`)`

For initializing a buffered channel:

`make(chan` *basic-typ*`,`*expr*`)`

Here, the expression used to specify the buffer size should evaluate to a non-negative integer value.

When a channel is unbuffered, or when it has a buffer size of 0, the communication succeeds only when both the sender and the receiver are ready for the transaction. When a channel has a positive buffer size, then the elements can "queue up" in the channel, and communication will succeed as long as the buffer is not full (for sending) and not empty (for receiving).

3.7.2 Sending and Receiving Items

Once a channel has been created and is shared between two subroutines, the two functions can act as sender and receiver of elements through the channel, by the use of the arrow operator `<-`.

Sending an element through a channel uses the expression:

id-or-subscript `<-` *expr*

Receiving an element uses the expression:

`<-` *id-or-subscript*

Where *id-or-subscript* is either an ID or an array member:

id-or-subscript:

identifier
identifier `[` *expr* `]`

The receive operation returns the element received. The program can also assign the received element directly to a variable by:

```
identifier := <- chan_id;
```

Note that the send and receive operations might block under the circumstances where either a buffered channel is full (for sending) or empty (for receiving), or the sender and receiver for an unbuffered channel are not both ready for the transaction.

3.7.3 Passing Channels as Function Parameters

A `chan` object can be shared between multiple concurrently executing subroutines / functions for them to communicate with each other. To do this, the channel could be locally created in one of the routines, and then passed into the other routines as a parameter. An example of this can be seen in the example code in section 6.1.1.

3.7.4 Closing Channels

The function-like keyword `close` can be used to close an existing channel. The associated expression is

`close(`*id-or-subscript*`)`

Note that a channel only needs to be closed once for a thorough cleanup. An attempt to close a channel more than once would result in an error.

After a channel is closed, an attempt to receive from the channel will result in the zero value for the specified data type being returned. However, attempt to send an item through a closed channel would result in an error. Therefore, although not enforced in the grammar, it is recommended practice to always close the channel from the sender's side.

3.8 Functions

A RJEC program consists of a sequence of global variable, function, and struct declarations, which can be defined in any order in relation to one another.

3.8.1 Defining Functions

Function definitions have the form

function-declaration:

> `func` *identifier* `(` *parameter-list*$_{opt}$ `)` *return-types*$_{opt}$ `{` *statement-list*$_{opt}$ `}`

parameter-list:

> *identifier type*
> *identifier type* `,` *parameter-list*

return-types:

> *type*

type-list:

> *type*
> *type-list* `,` *type*

statement-list:

> *statement-list statement*

A function definition notes its identifying name, its parameters, its return types, and a list of statements (which are executed in order unless otherwise specified by control flow). The grammar has the framework for supporting multiple return types, but this has not yet been implemented.

The following is a valid complete function definition:

```
func add(x int, y int) int {
    return x + y;
}
```

3.8.2 Calling Functions

Functions may be called via the following expression:

identifier (*args-list*$_{opt}$)

We list the function parameters as expressions separated by commas:

args-list:

expr
expr , *args-list*

Functions in RJEC are pass-by-value. Calling a function passes the parameters to the function by value, and then executes the statements within that function. However, note that arrays and channels store their information by reference.

3.8.3 The `main` Function

The `main` function is the entry point for code execution. It runs immediately after all global definitions are taken. It has no parameters and no return types.

```
func main() {
    /* execute code */
}
```

3.8.4 The `return` Statement

The `return` statement is defined as follows:

`return` *args-list*$_{opt}$;

The `return` statement ends execution of the current function and returns to the calling function (or in the case of the `main` function, ends execution of the program). It must be followed by a list of expressions representing the return arguments. These expressions must be of the respective return types specified in the function declaration.

3.8.5 yeeting Functions

The `yeet` statement is defined as follows:

> `yeet` *expr*`;`

Where the expression must be a function call. The function may take any number of formals, though currently the function return type of a `yeet`ed function is limited to `int` and none.

`yeet`ing a function runs that function concurrently in a separate thread. That thread terminates when the function returns.
Here is an example of a valid `yeet`:

```
yeet foo(2, 4);
```

3.9 Statements & Expressions

As noted in the previous section, a function body consists of a list of statements. A statement is defined as follows:

statement:

> *expr*`;`
> *vdecl*`;`
> *assign-stmt*`;`
> `return` *args-list*$_{opt}$`;`
> `{` *statement-list* `}`
> `if` *expr* `{` *statement-list* `}` *else-statement*$_{opt}$
> `for` *assign-stmt*$_{opt}$`;` *expr*`;` *assign-stmt*$_{opt}$ `{` *statement-list* `}`
> `for` *expr* `{` *statement-list* `}`
> `for` `{` *statement-list* `}`
> `select` `{` *case-list* `}`
> `defer` *expr*`;`
> `yeet` *expr*`;`

Most statements are expression statements; i.e. consisting of an expression (*expr*`;`). Other statements are described in their relevant sections in this document.

Expressions are defined as follows:

expr:

int-literal
string-literal
char-literal
bool-literal
`[`*expr*`]` *non-arr-typ* `{` *args-list* `}`
`struct` *identifier emph{ element-list*$_{opt}$ `}` *identifier*
expr binop expr
`-` *expr*
`!` *expr*
identifier `(` *args-list*$_{opt}$ `)`
`(` *expr* `)`
expr `.` *identifier*
identifier `[` *expr* `]`
id-or-subscript `<-` *expr*
`<-` *id-or-subscript*
`make(chan` *basic-typ* `)`
`make(chan` *basic-typ* `,` *expr* `)`
`close(` *identifier* `)`

Where *binop* is defined as the arithmetic, boolean, and logical binary operators `+`, `-`, `*`, `/`, `%`, `==`, `<`, `<=`, `&&`, and `||`.

These expressions are all explained in their various relevant sections.

3.10 Operators

3.10.1 Associativity and Order of Precedence

The associativity and order of precedence for operators in RJEC can be seen in table 3.10.1, with the various operators listed in order of precedence from top to bottom.

3.10.2 Arithmetic Operators

RJEC provides operators that perform basic arithmetic operations, as seen in the following subsections. Note that the binary operators only support integer arithmetic operations, and return an `int` value.

Operators	**Symbols**	**Associativity**
Struct access operator	`.`	left-to-right
Array access and instantiation operator	`[]`	left-to-right
Logical NOT operator and unary negation operator	`!`, `-`	right-to-left
Arrow operator	`<-`	right-to-left
Multiplication, Division and Modulo operators	`*`, `/`, `%`	left-to-right
Addition and Subtraction operators	`+`, `-`	left-to-right
Less than or equal to operators	`<=`, `<`	left-to-right
Equality operator	`==`	left-to-right
Logical AND operator	`&&`	left-to-right
Logical OR operator	`||`	left-to-right
Assignment operators	`=`, `:=`	right-to-left

3.10.3 Addition Operator

The addition binary operator `+` returns the sum of the operands. Its associated expression is:

expr `+` *expr*

3.10.4 Subtraction Operator

The subtraction operator `-` subtracts the right operand from the left operand and returns the result. Its associated expression is:

expr `-` *expr*

3.10.5 Multiplication Operator

The multiplication operator `*` returns the product of the operands. Its associated expression is:

expr `*` *expr*

3.10.6 Division Operator

The division operator `/` divides the left operand with the right operand and returns the result. Its associated expression is:

expr `/` *expr*

3.10.7 Modulo Operator

The modulo operator is used to obtain the remainder produced by dividing the left operand with the right operand. Its associated expression is:

expr `%` *expr*

3.10.8 Unary Negation Operator

The unary negation operator flips the sign of the original integer value of its operand. Its associated expression is:

`-`*expr*

3.10.9 Boolean Operators

Boolean operators are described below. They all return a `bool` value as the result.

3.10.10 Equality Operator

The equality operator `==` conducts a comparison of its two operands, and return `true` if and only if the two operands are identical by value, or `false` otherwise. This operator only supports types of `int`, `bool`, and `char`. Its associated expression is:

expr `==` *expr*

3.10.11 Less Than Operator

The less than operator `<` returns `true` if the left operand evaluates to a smaller value than its right operand, or `false` otherwise. This operator only supports types of `int` and `char`. Its associated expression is:

expr `<` *expr*

3.10.12 Less Than or Equal To Operator

The less than or equal to operator `<=` returns `true` if the left operand evaluates to a smaller value than, or is equal to its right operand, or `false` otherwise. This operator only supports types of `int` and `char`. Its associated expression is:

expr `<=` *expr*

3.10.13 Logical Operators

The logical operators are used to test the truth value of various combinations of one or two expressions. Note that these logical operators only support `bool` operands, and return a `bool` value.

3.10.14 AND Operator

The logical AND operator, or logical conjunction operator, `&&` returns `true` if and only if both operands evaluate to true, or `false` otherwise. If the left operand already evaluates to `false`, then the expression returns `false` without evaluating the right operand. Its associated expression is:

expr `&&` *expr*

3.10.15 OR Operator

The logical OR operator, or logical disjunction operator, `||` returns `true` if and only if at least one of the two operands evaluates to true, or `false` otherwise. If the left operand already evaluates to `true`, then the expression returns `true` without evaluating the right operand. Its associated expression is:

expr `||` *expr*

3.10.16 NOT Operator

The logical NOT operator, or logical negation operator, `!` flips the truth value of its operand. Its associated expression is:

`!`*expr*

3.10.17 Arrow Operator

The arrow operator `<-` is used for sending and receiving elements through objects of type `chan`. The expressions associated with this operator are:

id-or-subscript `<-` *expr*
`<-` *id-or-subscript*

For more details on its usage, see section 3.7.2.

3.10.18 Access Operators

The access operators are used to access specific items contained in the composite data types `struct` and `array`. You can use the struct access operator `.` to access the fields of a struct with the following expression:

expr . *field-id*

Where the *expr* can be either a struct identifier or an expression that evaluates to a struct type (such as access to a struct array element).

You can use the array access operator `[]` to access elements at specific indices of an array with the following expression:

array-identifier `[`*expr*`]`

See sections 3.5.3 and 3.6.3 for more usage of access operators in composite data types.

3.10.19 Assignment Operators

Assign operators `=` and `:=` are used to store values in variables. The various assignment statements are defined as such in the RJEC grammar:

assign-stmt:

id-list = args-list
vdecl = args-list
id-list := args-list

If the left-hand-side variable(s) have already been declared beforehand, then `=` is used to store the right-hand-side expression value(s) in the variables, designated by the identifier(s) on the left hand side. Both the variables and expressions are separated by commas. For example, to assign 2 integer values to two previously-declared `int` type variables:

```
a, b = 1, 2;
```

Note that the behavior of assigning multiple variables to other variables referenced in the same statement currently evaluates these assignments in order. This is a known issue; this syntax should thus currently not be used to swap variables, or similar.

The assignment operators can also be used in the case where variable(s) are declared and initialized in the same statement, in which case one could use either the long-form or the short-form assignment statements.

A long-form assignment statement first declares the variable(s) to be initialized, specifying their data type using the `var` keyword on the left hand side, and then uses the `=` operator for the assignment. For example, to declare and initialize one or two `int` variables:

```
var a int = 0;
var b, c int = 1, 2;
```

Note that in the long-form statement, if there are multiple variables to be declared, they are required to be of the same type.

A short-form assignment statement simply refers to variable(s) to be declared by their identifier(s) on the left hand side, and directly initializes each variable with its corresponding expression on the right hand side, using the `:=` operator. For example,

```
a := 0;
b, c := 1, 2;
```

Note that in this case, the variables to be declared together can have values of different data types assigned to each of them. For example,

```
d, e := 3, "4";
```

3.11 Control Flow

3.11.1 `for` Loops

`for` loops are used in order to repeat the execution of a sequence of statements and expressions for a specified number of repetitions, for until the termination condition is reached, or infinitely otherwise. The conventional `for` loop definition involves specifying the *initialize* statement (run prior to the loop), *test* boolean expression (termination condition checked after each iteration of the loop), and *step* statement (run after each iteration of the loop).

`for` *assign-stmt*$_{opt}$ `;` *expr* `;` *assign-stmt*$_{opt}$ `{` *statement-list* `}`

A `for` loop may also have the behavior of a conventional `while` loop if only the termination condition, or the *test* expression, is specified, in which case the statements will keep executing until the condition evaluates to `false`.

`for` *expr* `{` *statement-list* `}`

If no conditions are specified, the `for` loop will continue executing infinitely, unless a `return` statement is executed at some point.

`for` *{ statement-list }*

3.11.2 `if` and `else` Statements

`if` statements are used to place a condition on the execution of sequence of statements. The statements wrapped in an `if` statement will only execute if the condition expression evaluates to `true`.

The inclusion of `else` statements as well as `else if` statements are optional but can be provided in order to further specify a group of a statements for execution under additional circumstances.

In an `if` statement block, there exists one `if` condition, at most one `else`, and 0 or more `else if` conditions in-between. The conditions are evaluated in order, and statements contained in the first `true` condition will be executed. If an `else` exists, its statements are executed only after all preceding conditions have evaluated to `false`.

statement:

> ...
> `if` *expr* `{` *statement-list* `}` *else-statement*
> ...

else-statement:

> *no-else*
> `else if` *expr* `{` *statement-list* `}` *else-statement*
> `else {` *statement-list* `}`

Where *no-else* is defined as an empty token and has lower precedence than the `else` token.

3.11.3 `defer`

The defer statement is used to defer the evaluation of certain expressions until right before the current function returns.

A `defer` statement is defined as follows:

> `defer` *expr;*

Note that `defer` is currently somewhat unstable and does not work with some conditional blocks. This is a known issue. However, it still works well for the common use case of easily freeing a resource (e.g. a user-defined lock) in basic functions.

3.11.4 `select`

The `select` statement is used in order to block and wait on multiple channel-related expressions, each represented as a `case`. It then executes the statements contained in the first case that successfully executes, i.e. the first channel through which it is able to send or receive an element.

The `select` statement can be defined by the following grammar:

statement:

> *...*
> `select{` *case-list* `}`
> *...*

case-list:

> `case` *case-stmt* `:` *statement-list*
> `case` *case-stmt* `:` *statement-list case-list*

case-stmt:

> *id-or-subscript* `<-` *expr*
> `<-` *id-or-subscript*
> *assign-stmt*

Note that for each `case`, the *expr* can take the form of either sending or receiving an item through a channel object. It can also be an assignment statement where an item is received from a channel and then directly assigned / used to initialize a variable. An example of using `select` statements:

```
select {
    case a := <- my_chan:
        ...
    case my_chan_2 <- b:
        ...
}
```

3.12 Built-in functions

We support some built-in functions for printing, debugging, measurement, and utility purposes.

3.12.1 `printi`

The function `printi` takes a single `int` and prints it in its own line as an integer. It returns nothing.

3.12.2 `printb`

The function `printb` takes a single `bool` and prints it in its own line as a boolean (lowercase "true" or "false"). It returns nothing.

3.12.3 `printc`

The function `printc` takes a single `char` and prints it in its own line as a character. It returns nothing.

3.12.4 `prints`

The function `prints` takes a null-terminated `char` array (or equivalently, a string literal) and prints it in its own line as a string. It returns nothing.

3.12.5 `time`

The function `time` takes no formal arguments. It returns the wall clock time, in microseconds, as an `int`.

4 Project Plan

4.1 Planning, Specification, Development, and Testing

RJEC was developed over the course of the semester in a series of full-group pair-coding meetings. During these pair-coding meetings, one person would share their screen and the team as a whole would make progress towards the code writing. These longer meetings would proceed as follows: at the start, we would review the features (usually one or two) we aimed to complete by the end of the meeting. Then, after debugging, we would immediately follow the feature creation with test writing in parallel. We maintained this procedure throughout, making sure to test immediately after feature completion and frequently, to ensure accurate and thorough feature implementation.

In addition, we scheduled and participated in weekly Friday meetings during which we discussed design decisions, reflected on progress, aligned project visions, identified areas of confusion that should be communicated with the TA or professor, performed sprint planning for the next deliverable, and scheduled the next sprint's group-coding sessions. We roughly identify sprints as 2 week-long periods of execution, with anywhere from 3-4 or more full-group pair-coding sessions, depending on member availability and sprint plans.

When specifying project scope, our team worked with the professor in order to narrow the scope in order to ensure that it was feasible.

Alongside assignment deadlines, which we used for major checkpoints, we also scheduled our own soft deadlines before each course milestone. In this way, we were able to ensure that we would have time after completing each iteration in order to review the work before submitting and make any final changes accordingly.

4.2 Style Guide

RJEC was written with a combination of OCaml as well as C. Language definition was largely written in OCaml, and C was utilized in order to interface with system calls and the Libmill library to support concurrency-related features.

In an effort to write clean code and streamline development, we adhered to the following style guidelines for code:

1. When naming variable and function names, utilize the professor's naming conventions if we are referencing them.
2. Match statements should be written in vertical blocks where all the bars are aligned.
3. Wild cards for invalid patterns in match statements should raise an error. If they are intended to cover future features, they should take the of the form of "⟨feature⟩ not implemented," in which case this wild card should be removed when the feature is implemented.
4. "TODO" comments should be made to note features to be implemented in the future, along with a short description or ideation of potential feature implementation. This would be replaced with appropriate code later in development when the feature is completed.
5. Use snake_case for variable naming.
6. Follow the DRY principle, and make code as modular and reusable as possible. If a helper function would be used repeatedly in the code, define it in the scope accessible to all its use cases to avoid code duplication.
7. When working on each complex feature, write robust and exhaustive test cases to see if the feature is functioning as expected. Include both cases that should work and cases that shouldn't.
8. Write clean and concise code where possible.
9. Work on complex features in their own branches and merge into master after the feature is complete and well tested.
10. Follow K&R style for braces and naming in C code.
11. Follow Go braces style in RJEC code, though non-cuddled else statements are allowed.

4.3 Project Timeline

The planning of our project was centered around the idea of iterative development.

We started out with brainstorming sessions where we fleshed out the syntax and semantics of the language, with which we finished the first draft of the Language

Date	Checkpoint	Deadline
Jan 15-21	Project idea brainstorming	
Feb 1	Proposal finalized	
Feb 3		Proposal
Feb 19	Scanner and Parser finalized	
Feb 21-23	LRM writing	
Feb 24		Parser and LRM
March 21	Hello world program working	
March 24		Hello world
April 2	Variable declaration and assignment working	
April 7	Struct-related features working	
April 8	Function-related features working	
April 10	Control flow features working	
April 18	`chan` and `yeet` working	
April 19	`select` working	
April 21	Array and string-related features working	
April 22-24	Wrap-up, report writing, final presentation prep	
April 25		Final presentation
April 26		Final report

Table 1: Project Timeline

Reference Manual. Then, based on the established high-level ideas, we implemented the scanner and the parser to formalize the language into a context-free grammar, and resolved all reduce/reduce and shift/reduce conflicts to make sure the grammar is unambiguous.

We then worked on all components of the compiler, including the semantic checker and code generator in iterations, progressing one feature at a time. We started by trying to get the `hello world` program working, and then basic arithmetic operations and printing. We then built incrementally upon each feature to finish the next, from variable declaration and assignment, structs, function definitions and function calls, control flow (`if`, `for`, `defer`), concurrency features (`yeet`, `chan`, `select`), and finally arrays. We also implemented related test cases for each feature along the way.

With this principle, our eventual timeline is shown in table 1.

4.4 Team Roles and Responsibilities

We assigned the following preliminary roles:

Managers: Caroline Hoang, Elaine Wang
Language Gurus: Justin Chen, Riya Chakraborty
Systems Architects: Riya Chakraborty, Justin Chen
Testing: Elaine Wang, Caroline Hoang

In practice, everyone worked on everything in the code. As mentioned above, we worked in full group programming sessions, so for the most part, everyone was aware of everything which was done in the project.

4.5 Software Development Environment

We developed in Docker. The image can be pulled from ‘columbiasedwards/plt‘. The environment uses Ubuntu 18.04.1 LTS.

We also did some early development in macOS 10.14 Mojave, but later switched fully to Docker for a consistent development environment.

Languages, libraries, and build tools:
OCaml 4.05.0
OCaml LLVM 6.0.0
LLVM 6.0.0
OCamlbuild 0.12.0
C11 with GNU extensions
GCC 7.3.0
glibc 2.27
GNU Make 4.1
CMake 3.10.2
GNU bash 4.4.19(1)
Libmill 1.18

We developed using VS Code with the official OCaml and clangd language servers. We used GitHub and git for version control. For the project reports, we used LaTeX, on Overleaf.

4.6 Project Log

```
commit ae8836c6cd4ce79d0fb0847fd4f8c910f46045d9
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Apr 25 15:23:49 2021 -0700

    re-sign codegen

Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Apr 25 11:26:59 2021 -0700

    fix more signing

commit cd84f61fd4a3c79792f54f357d30209a1dafa16d
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 15:22:37 2021 -0400

    fix signing

commit 33eda83476a1755f6193e0b9b0b48befd0240caf
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 05:36:00 2021 -0400

    update latex compiler scripts

commit 12a252b2182b1017696123a782de7b491fc33755
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 04:57:39 2021 -0400

    add latex conversion scripts

commit 284d76e4fb8301ae3935e19722a656f0d533100b
Merge: a840262 4f24368
Author: Cremebrutale <caroline.hoang@columbiaspectator.com>
Date:   Fri Apr 23 04:25:31 2021 -0400

    Merge branch 'master' of https://github.com/PLT-Project/RJEC

commit a8402624c6f43c14ea1853b626a2bd340cd4e309
Author: Cremebrutale <caroline.hoang@columbiaspectator.com>
Date:   Fri Apr 23 04:22:53 2021 -0400

    rjecparse.mly additional changes

commit d420c53bbeb753e4c67d7b3691f6066b90fed53b
Author: Cremebrutale <caroline.hoang@columbiaspectator.com>
```

```
Date:   Fri Apr 23 04:21:18 2021 -0400

    cleaned rjecparse.mly

commit 8c9cb8bdc2f4bdcd85cbb074267ed6c90daf2c6a
Author: Cremebrutale <caroline.hoang@columbiaspectator.com>
Date:   Fri Apr 23 04:04:15 2021 -0400

    cleaned up ast.ml

commit 4f243685c1d512fb6fc0cef6ea162af73c237d91
Author: Riya Chakraborty <47572810+ayirr7@users.noreply.github.com>
Date:   Fri Apr 23 02:50:35 2021 -0500

    Update README.md

commit da61608656418553edb5dee4ea33fd5856308572
Author: Riya Chakraborty <47572810+ayirr7@users.noreply.github.com>
Date:   Fri Apr 23 02:50:19 2021 -0500

    Update README.md

commit 73cb936027651c145e332497c160f1aae9b071b6
Author: Cremebrutale <caroline.hoang@columbiaspectator.com>
Date:   Fri Apr 23 03:45:26 2021 -0400

    cleaned up codegen.ml

commit 0456bc1d62dbfe0be9690df81bb801201c6f5186
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 02:26:56 2021 -0400

    update README

commit 0f68a230bed79ee974eb8ebe85c405d3e8248aa1
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 02:14:40 2021 -0400

    update README

commit 45e8909790d676f83775eb8dd530ec41b94ae6e6
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 02:14:00 2021 -0400

    add README
```

```
commit 245460c2fd0973e0d5e9ea9a995e24d29b574fe6
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 01:18:50 2021 -0400

    limit equality to basic types

commit c438fa43084f9d8986b8f15e170dad780705fece
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 01:03:41 2021 -0400

    clean up comments

commit 3e8d3c1bf80c41164d9deb4fd9d9a0bd2ddb71eb
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 00:58:06 2021 -0400

    code signing

commit 0c0383ab732e75d92fe1732b4c57fbba076eae71
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Apr 23 00:55:46 2021 -0400

    code signing and cleanup

commit 18a8c8a6addf61de1463bb0534e0add835662241
Merge: c027b81 d0c3f38
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 18:01:44 2021 -0400

    Merge branch 'master' of https://github.com/PLT-Project/RJEC

commit c027b8124b16556f07037c1538e4c4f09c3c1793
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 18:01:39 2021 -0400

    mutex demo

commit d0c3f387e567ef1387143f5101856914d2e871c5
Merge: d511c1b 94d9397
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Thu Apr 22 16:29:58 2021 -0500

    Merge branch 'master' of https://github.com/PLT-Project/RJEC into
       fail_cases

commit d511c1b20242d728609022fdbdd728c365d1a9c0
```

```
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Thu Apr 22 16:29:49 2021 -0500

    modified parser and fail cases

commit 94d9397bbe88390b5adcd823eb1c299085c8050b
Merge: eb07e60 a7fcd97
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 17:21:35 2021 -0400

    Merge branch 'master' of https://github.com/PLT-Project/RJEC

commit eb07e60c81af90369781d990ee1a0225f5f45531
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 17:21:31 2021 -0400

    cleanup mapreduce

commit 9da2aabd2c3a184ced9539403d586f1b79a22c39
Merge: 828481a a7fcd97
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Thu Apr 22 15:39:17 2021 -0500

    Merge branch 'master' of https://github.com/PLT-Project/RJEC into
       fail_cases
    Merge master

commit 828481a0f15fb9173383215a38f33f5525f6df2a
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Thu Apr 22 15:39:06 2021 -0500

    add more fail cases

commit a7fcd9790f044e8dad160e751c00d8f569a95aab
Merge: 67cca4a f0d39ba
Author: Yuanyuting (Elaine) Wang <33389045+wangyyt1013@users.noreply.
   github.com>
Date:   Thu Apr 22 16:29:48 2021 -0400

    Merge pull request #9 from PLT-Project/comp-warnings

    fixed basic compilation warnings

commit f0d39ba474471c25dba573d2466296ee4b337b7f
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Thu Apr 22 16:24:45 2021 -0400
```

```
    fixed basic compilation warnings

commit 554ab6bdbbda2e8051e3b52bf40e66c55adfd4f6
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 15:45:36 2021 -0400

    fix bug in mapreduce

commit 67cca4a2a9019a41bb7167db508c17023774910c
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 14:42:02 2021 -0400

    add timing and comparison with iterative solution for mapreduce

commit 7207f176573db693e6c65440d159d77b9683f199
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 05:46:57 2021 -0400

    add mapreduce demo and fix local variable size array declaration

commit 16ba82517fbf5be0161af736f2420cdc82ca986a
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 03:16:22 2021 -0400

    compiler script + begin demo programs

commit 035ba55d301bc6068e8a7f61e5e15f551d2d8068
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 03:00:24 2021 -0400

    add timer built-in function

commit 8c64fc554637cc4c16f76eb467211633a6df2b7b
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 02:20:39 2021 -0400

    channels working with send/receive/select and array subscript

commit 0a66e0c493de51b3e622ec8994ce3c29734176cf
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 01:37:30 2021 -0400

    parser and ast for arrays of channels

commit 1292c558c18974cfc5a700aa6f9bf0900b922d02
```

```
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Apr 22 01:35:30 2021 -0400

    update grammar to support arrays of chans for send/recv/select

commit 3dcb48cab9c1890ade971c8b746a84393eed6a45
Merge: a5bd492 e06261c
Author: Yuanyuting (Elaine) Wang <33389045+wangyyt1013@users.noreply.
   github.com>
Date:   Wed Apr 21 02:10:07 2021 -0400

    Merge pull request #8 from PLT-Project/array

    Array

commit e06261c4f84961c936d3d4ebb9923893f6c98279
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Wed Apr 21 02:02:59 2021 -0400

    added '\0'

commit aa9a553619f5a7fee6aebb510428974a18225fe8
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Wed Apr 21 01:46:31 2021 -0400

    string literal <-> char arrays kinda working

commit 2bb290962af4771b2a9bd1a41c86cff91912386d
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Wed Apr 21 01:17:04 2021 -0400

    select/array of chans test case

commit 037d4c85c5ed9ed0e6ad808c67c0fd8442817c96
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Wed Apr 21 00:58:23 2021 -0400

    array literals

commit f7e15810e0a3a2ee04cdadcc2c90469c06856981
Merge: d96a793 a5bd492
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Tue Apr 20 23:45:00 2021 -0400

    Merge branch 'master' of https://github.com/PLT-Project/RJEC
```

```
commit d96a7933201ff5b657cb209b7f92ca7aa501b3b7
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Tue Apr 20 23:44:54 2021 -0400

    array access & assign; syntax such as a[i].x valid

commit a5bd492ecbd9993205f0a0b7aa130bdf89eae029
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Apr 20 23:29:59 2021 -0400

    add producer consumer test case

commit 15a183eee65a29200a0fe526018a04a01e2ad154
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Tue Apr 20 22:01:41 2021 -0400

    array declaration and subscript working?? need to fix subscript and
        access parsing

commit ca4fab2a2492b1ac66d2d2cf8e36dc51332f83b0
Merge: 98b0f6b 0cd9ad2
Author: Justin Chen <41352045+justinbchen@users.noreply.github.com>
Date:   Tue Apr 20 04:35:05 2021 -0400

    Merge pull request #7 from PLT-Project/select

    Implementation of select

commit 0cd9ad214f46678a442032ee8b6c183a3383af2f
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Apr 20 04:30:20 2021 -0400

    switch-branching codegen and test cases for select

commit 89296f2e6c7ecdf804314eddd6ff948b5b2c5429
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Apr 20 00:42:05 2021 -0400

    semant and partial codegen (pass clauses into C function) for
       select

commit 1175c1bc018c0f708be0ecb2cdd21c34ced738d7
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Apr 19 16:07:17 2021 -0400

    C code, parser, and AST for select
```

```
commit 98b0f6bde9cdacbd918930d98163e76258ea1f6f
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Apr 19 01:42:37 2021 -0400

    delete accidentally commited file

commit f1ee3c1ef2eaba2fd5bd3e8b616d659bbf484fe8
Merge: b44dd22 fd88571
Author: Yuanyuting (Elaine) Wang <33389045+wangyyt1013@users.noreply.
   github.com>
Date:   Mon Apr 19 00:39:55 2021 -0400

    Merge pull request #6 from PLT-Project/chan

    Chan

commit fd88571005035655db3ade17d197fa5806d116ce
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Mon Apr 19 00:35:48 2021 -0400

    modified test case for close

commit 7545f255fa00de9ef54308a90bfb76d03f8a45c8
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Sun Apr 18 23:49:23 2021 -0400

    channel with close kinda working (block on receive when channel is
       closed)

commit 9035eb70ac26de709e6d9859f2b21957a24d4e2d
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Sun Apr 18 23:10:35 2021 -0400

    send and recv working (?)

commit cb7553e751b21245bab9459b212fbb114beae0ec
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Sun Apr 18 21:58:36 2021 -0400

    declaring and assigning channels working?

commit b44dd2204808a50b0e89a2b97478d11766eea37c
Merge: f456924 7e79ede
Author: Yuanyuting (Elaine) Wang <33389045+wangyyt1013@users.noreply.
   github.com>
```

```
Date:   Sun Apr 18 20:57:45 2021 -0400

    Merge pull request #5 from PLT-Project/yeet

    Yeet

commit 7e79ede692e273dbca7e232f7f47dedcc1c57835
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Sun Apr 18 19:44:02 2021 -0400

    yeet working

commit 833481474c9c7ba13e0c5249aa570c8d3555295d
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Sun Apr 18 19:26:55 2021 -0400

    yeet kinda working?? but struct literal had issues

commit 810f28617316aa4e259c2bd4f08d9bbec5fd3b71
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Sun Apr 18 18:46:46 2021 -0400

    mismatch in function type

commit f456924c4e617e0a5aeff4036ee53123a79725b3
Merge: 6186c11 eaad431
Author: Yuanyuting (Elaine) Wang <33389045+wangyyt1013@users.noreply.
   github.com>
Date:   Sun Apr 18 17:55:31 2021 -0400

    Merge pull request #4 from PLT-Project/function_void_ptr_args

    in codegen, all functions get void* as input arg

commit eaad4316456b53c032d875ddf4e5b42a13a6d5a6
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Sun Apr 18 17:49:20 2021 -0400

    in codegen, all functions get void* as input arg

commit 6186c11c88f97883ab55bdb8a31d1404246fbf30
Merge: 6f8b5b1 1971f49
Author: Justin Chen <41352045+justinbchen@users.noreply.github.com>
Date:   Sun Apr 18 17:01:21 2021 -0400

    Merge pull request #3 from PLT-Project/concurrency
```

```
    Concurrency library setup

commit 1971f49d14d42f97f83a1ba74a33e49ba4a4e165
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Apr 18 17:00:20 2021 -0400

    switch to void * function and cleanup

commit 0647ce9d9831b776dd01163b49fae1a33e9ff53f
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Apr 12 03:30:58 2021 -0400

    completed library setup for libmill

commit 64fb2a9d961cadc3c388b854533e016f8f897615
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Apr 12 02:37:59 2021 -0400

    library build setup

commit eff65372451af196074898400ace7937f7d87a63
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Apr 12 02:31:05 2021 -0400

    copy newer version of libmill

commit 70c61bc066ebdbd72b70ef37b861ba801166e1a1
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Apr 12 01:45:20 2021 -0400

    add libmill library

commit 6f8b5b182cadde8531aaab66cb6b51833a2b2720
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Mon Apr 12 00:10:16 2021 -0400

    implemented defer

commit 1900ae51ff3c5130162018d3d05aa38a60382824
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Sat Apr 10 00:49:15 2021 -0500

    added support for for loops and tests

commit 796a0bac82e3591399cd9b38f2f58fec92acfd53
```

```
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Fri Apr 9 23:11:16 2021 -0500

    added modification of struct members and tests

commit 790b8bd973c88f0a84eecfd48ae553615c82f25c
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Fri Apr 9 20:34:33 2021 -0500

    added support for Init operator

commit b642f8214e41d0a4805499401ad2752f0af9a0d2
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Fri Apr 9 19:29:28 2021 -0500

    test cases for decl + assign

commit 987aac2c5b4578a7b35a95bca51af9beeba80901
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Fri Apr 9 19:18:06 2021 -0500

    Decl + Assign same line

commit fd140ff34a37061f10a535841e33f3c7853e6237
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Thu Apr 8 01:35:08 2021 -0400

    functions with single return typ working

commit cb0d4b2ece769b89a7f30d07ec66a231dba69228
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Wed Apr 7 23:57:39 2021 -0400

    structs working

commit d80d7dfa430322e55e039fa44e56c28efbc17c18
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Wed Apr 7 23:20:57 2021 -0400

    struct lit & access; test still broken

commit d82c45100b89460927e293e050ce5b1f2c6f42d2
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Wed Apr 7 21:36:20 2021 -0400

    struct declaration working
```

```
commit 494b020ee51ade7d1e6a0f9e36b30d887ed6862b
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Tue Apr 6 02:16:51 2021 -0400

    added support for structlit in semant; added struct_decls in
       codegen

commit ec7b3ae764197bb884a3ae9439bf93a2c65dd6b9
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Mon Apr 5 23:50:39 2021 -0400

    changed semant for dealing with multiple return types

commit 0319197e8f9fdb54c976468b98f7c2a13ff3fb28
Merge: 4838813 96dc946
Author: Riya Chakraborty <47572810+ayirr7@users.noreply.github.com>
Date:   Fri Apr 2 14:27:24 2021 -0500

    Merge pull request #2 from PLT-Project/local_vars

    Supporting Local Variable Declarations

commit 96dc946e0e8fd1e7900386b92ab777460535d677
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Fri Apr 2 14:26:23 2021 -0500

    tests for local variable decls

commit 523e0d4c9c0ca97e46ab836098baabf88073c8f9
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Fri Apr 2 14:25:09 2021 -0500

    completed codegen for local variable decls

commit 687caa6983c9c86f9dc21ebe31b12017b447b300
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Thu Apr 1 02:05:49 2021 -0400

    halfway through working with codegen for local vars

commit 483881316b7011ddfd1921b4b1ecc2ccbebecc2f
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Thu Apr 1 01:40:45 2021 -0400

    Fixed indentation for codegen
```

```
commit 18a90965929f0e3042c5cf9ab6a898f3ba016866
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Thu Apr 1 01:10:05 2021 -0400

    updated semant for local vars and scopes

commit af97606a8a84a3aa5ada6833f90d9902aca13945
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Fri Mar 26 21:38:05 2021 -0500

    More assign tests

commit 684ae42d231d6643b5c58670ed5ac80473221c29
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Fri Mar 26 21:22:23 2021 -0500

    Add assign and tests

commit c71e08cad92079c4da24259677f7729e1b5729a2
Author: Riya Chakraborty <riyamch@yahoo.com>
Date:   Fri Mar 26 23:59:01 2021 +0000

    added if/ops tests

commit 4343d49cff2d44bb090bb9539077ee1d23cbe468
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Mar 23 00:03:59 2021 -0400

    unsuccessful attempt at printf

commit 7024295b0d5f8dc511866d26ec6f19293ed3d31b
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Mar 22 19:38:41 2021 -0400

    working print for string and char

commit 8715ec256fcb1cd10b649525f632514522c413b2
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Mar 22 04:37:52 2021 -0400

    fix assignstmt fix

commit d812a7b63342d91717c7fa2fce7554093e68bf06
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Mar 22 04:17:48 2021 -0400
```

```
    remove unused trd function

commit 6b81ae8a3d5a29e9654287af5a6756ac66bccd4f
Merge: 0105727 7e52cf0
Author: Justin Chen <41352045+justinbchen@users.noreply.github.com>
Date:   Sun Mar 21 17:03:02 2021 -0400

    Merge pull request #1 from PLT-Project/hello

    Hello World

commit 7e52cf0f80e9801860217b95d599f3473c996677
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Mar 21 17:01:52 2021 -0400

    working regression test for hello

commit 57de2b6fa987f77b12b40d6c6ebc2706a0987d4c
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Mar 21 16:37:44 2021 -0400

    working hello world (but with non-zero return value)

commit 94641a3666d7aa17130794cf7ad9810a433f1386
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Mar 19 22:01:34 2021 -0400

    first attempt on code gen

commit 0105727bab9370a328e7c976f732c1e482b69a8a
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Mar 19 17:00:04 2021 -0400

    fix func type definition in semantic checking

commit cc0ddf23d02eebec88806cdb5520ea00426cd470
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Mar 16 22:05:19 2021 -0400

    preliminary semantic checking

commit 06261f3132fa5bf8d967a1ca5149fbb6dae5b258
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Thu Mar 11 16:09:02 2021 -0500
```

```
    replace While with For and MakeBuffered with Make with optional
       buffer

commit 5725627ad56b53f31ce185ad768a38e2115533e2
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Mar 7 22:54:01 2021 -0500

    first compiling AST

commit 9d1a9bb5cdc14ee005adfefac0c9e0ca3bb91520
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Mar 7 21:30:01 2021 -0500

    add AST from microC

commit 02031ff27db6672aa51af00be4bf83f14369c9bd
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Mar 2 21:27:02 2021 -0500

    remove TYPE from scanner

commit 1084a522ba8d0f0a8a128717322a5391c3724d5a
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Wed Feb 24 00:10:04 2021 -0500

    fix typo in case grammar

commit 0aea34939c7bc349b57ff18df132bbd4985412c9
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Feb 23 23:59:59 2021 -0500

    fix issues with case grammar

commit b367292fc0dd5ea023cd3e63c463df413baf3cec
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Feb 23 23:45:42 2021 -0500

    define array and struct literals; change struct definition format

commit f4288a6740ec095daddc31daf6956eaf254fd7d4
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Feb 23 22:42:51 2021 -0500

    for statements use assign-stmt

commit 26eb977960f5552585409829e62ac87d2d8fedfe
```

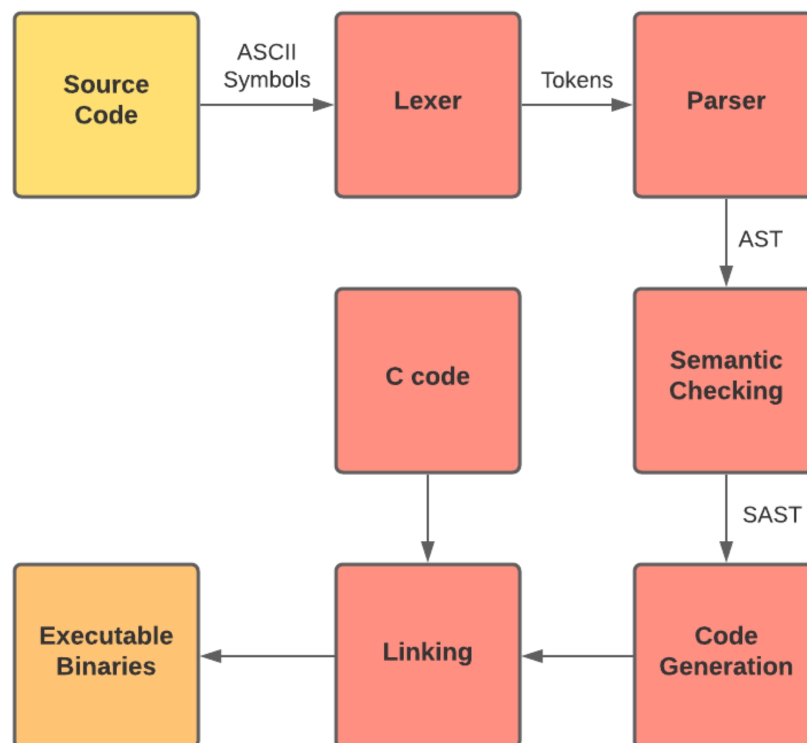
```
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Feb 23 22:30:03 2021 -0500

    struct takes only basic types as members

commit 30a8424aac854acee483130e4f02f1111928371e
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Feb 23 03:00:55 2021 -0500

    allow variable declaration without assignment inside functions

commit 8def2ab9507349e0208ce7729ce817cdeb4eb901
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Feb 23 02:57:12 2021 -0500

    rename typ_opt to return_types and typ_formal_opt to typ_opt

commit 2efbf4b7426f30ebfdb9996d10b413efc3672e61
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Feb 23 02:55:15 2021 -0500

    rename chan_typ to basic_typ

commit fb0616e0754282805ca60d97520d3cad92e1b50f
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Tue Feb 23 02:53:22 2021 -0500

    move assign_stmt to be with the other statements

commit 273b527744f640840e9e7e137bed06a59d776276
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Feb 22 20:23:50 2021 -0500

    fix channel type definition

commit d44c9d33e08e17a20f297115d7340bf5e8448a5f
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Mon Feb 22 18:40:11 2021 -0500

    add back unary minus

commit 832337b9be6843186e0f1c1b4819dcbe232b4508
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Feb 21 18:29:10 2021 -0500

    fixed grammar for function return types
```

```
commit 358c90d546cdfae43b5f710d8cda83759c8fda61
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Feb 21 18:14:53 2021 -0500

    fix else if + preliminary function type as parameter

commit 21d507bc4a09595132e4d45ec792031ed2d4b988
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Sun Feb 21 17:38:03 2021 -0500

    support multiple return, assignment, declaration

commit 7ab3a99737e36bd049296e504bcb6ad5099b9378
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Feb 19 23:56:55 2021 -0500

    array with size

commit 59465eaa98772efebde95bba9f0883c1c8879b4e
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Feb 19 23:40:32 2021 -0500

    fixed Blocks and redundant vdecl list

commit 80667a1690a7ae8bb7bae341ede7f943ddb224e6
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Feb 19 23:04:20 2021 -0500

    first attempt at scanner/parser

commit 83d0eec586c2b39161673485d1d943c7136b2843
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Feb 19 17:42:07 2021 -0500

    copy over scanner/parser/dockerfile

commit eaf5c96ed80e85a3b9ba17225f02b9a2c5696b0c
Author: Justin Chen <justinbrianchen@yahoo.com>
Date:   Fri Feb 19 17:39:45 2021 -0500

    move microc stuff into their own folder

commit 1fd0ddaebda4727148133e1af1fa8ef42b1b7540
Author: Yuanyuting Wang <yw3241@columbia.edu>
Date:   Sun Feb 14 22:16:16 2021 -0500
```

```
inital commit
```

5 Architectural Design

The RJEC compiler consists of several components that, through an established flow, converts a source code for a RJEC program into an executable file. The overall architecture is shown below:



5.1 Lexer

The lexer, implemented in `scanner.mll`, takes in a stream of ASCII symbols from the source code, and outputs a series of tokens to be parsed in the parser. Tokens supported by the parser, including their associativity and precedence, are defined

in the `rjecparse.mly` file. Since RJEC supports multi-line comments, the scanner ignores all the symbols after each opening comment token `/*`, and only returns to the normal parsing mode after encountering an ending comment token `*/`. If any invalid combination of symbols is found, the lexer will throw an error.

5.2 Parser

The parser, implemented in `rjecparse.mly`, parses the stream of tokens inputted from the lexer, and outputs an abstract syntax tree (AST) according to the context-less grammar rules specified in the parser. The valid nodes for the AST are defined in `ast.ml`. If there's any token pattern that violates the grammar rules specified, a parsing error will be thrown.

5.3 Semantic Checking and Transformation

The semantic checker, implemented in `semant.ml`, takes in an AST outputted from the parser and outputs a semantically-checked AST (SAST). The semantic checker recursively walks through the AST, checking for type errors in the evaluation of each node. It also checks for scoping errors by constructing C-styled symbol tables that register all variables that the currently executing statement/expression has access to. The semantic checker then convert a valid AST into a SAST with semantically-checked nodes, which are defined in the `sast.ml` file.

Some semantic transformation is also performed here. For instance, in the short-form variable declaration, the evaluated type of the expression is used as the type for the variable declaration stored in the SAST.

5.4 Code Generation

The SAST outputted by the semantic checker is then passed into the LLVM code generator, implemented in `codegen.ml`, which generates an intermediate representation of the program in an LLVM module.

For basic operations such as arithmetics, code generator directly makes calls to the LLVM library in OCaml.

For variable declarations and assignments, the code generator constructs symbol tables that store the currently declared variables, their type specifications, as well

as their memory locations, and keep track of the tables as it goes through variable declaration / assignment statements.

For structs, the code generator converts struct definitions in the source code into LLVM types defined by the member fields of each struct definition. When a struct variable is declared, the code generator allocates a memory space for this user-defined type, and stores its member fields, which can only have basic types, by value. Upon declaration, the member fields are initialized with their default values. When assigning a struct variable or passing it into a function, a copy of the struct value is passed around.

For arrays, the code generator allocates space on the heap for a fixed number of data of the specific type for each array. The fixed array size comes from evaluating the array size expression during runtime, which means it can come from a variable. All the elements in an array are also initialized by their default values upon declaration.

For support of concurrency features, including channels, yeetroutines, and select, the code generator interfaces with our imported C code, which uses the Libmill library that provides go-like concurrency features implemented in C. For select especially, we also conducted control flow manipulation in the code generator so that the case where the send/receive through a channel is successful gets executed.

5.5 Imported C Code

Part of our built-in functions, such as `time`, the printing suite and the functions related to concurrency, are written in C, linked into the compilation, and called in the LLVM code. Aside from the common C libraries (`stdbool.h`, `string.h`, `sys/time.h`, `stdint.h`, `stdio.h`), we also imported the Libmill library by Martin Sustrik (`libmill/libmill.h` and `libmill/chan.h`).

5.6 Division of Labor

Everyone participated in the collective brainstorming and iterative design of the RJEC grammar, syntax, and semantics. Everyone also equally contributed during group meetings and group programming sessions where we fleshed out further implementation details of the overall architecture.

6 Test Plan

6.1 Example Test Programs

6.1.1 Single Producer-Consumer

RJEC Code:

```
/* simple producer-consumer problem */

func foo(ch1 chan char, ch2 chan int, quit chan bool) {
    for {
        select {
        case ch1 <- 'a':
            prints("sending a in foo...");
        case val2 := <- ch2:
            prints("receiving in foo:");
            printi(val2);
        case q := <- quit:
            printb(q);
            if q {
                prints("quitting...");
            }
            return;
        }
    }
}

func main() {
    ch1 := make(chan char);
    ch2 := make(chan int);
    quit := make(chan bool, 10);
    yeet foo(ch1, ch2, quit);
    for i := 0; i < 5; i = i + 1 {
        c := <-ch1;
        prints("received in main:");
        printc(c);
        prints("sending i in main...");
        ch2 <- i;
    }
    quit <- true;
}
```

LLVM Code:

```
; ModuleID = 'RJEC'
source_filename = "RJEC"

@fmt = private unnamed_addr constant [4 x i8] c"%d\0A\00"
@fmt.1 = private unnamed_addr constant [4 x i8] c"%c\0A\00"
@fmt.2 = private unnamed_addr constant [4 x i8] c"%s\0A\00"
@strlit = private unnamed_addr constant [18 x i8] c"received in main
    :\00"
@strlit.3 = private unnamed_addr constant [21 x i8] c"sending i in
    main...\00"
@fmt.4 = private unnamed_addr constant [4 x i8] c"%d\0A\00"
@fmt.5 = private unnamed_addr constant [4 x i8] c"%c\0A\00"
@fmt.6 = private unnamed_addr constant [4 x i8] c"%s\0A\00"
@strlit.7 = private unnamed_addr constant [20 x i8] c"sending a in
    foo...\00"
@strlit.8 = private unnamed_addr constant [18 x i8] c"receiving in
    foo:\00"
@strlit.9 = private unnamed_addr constant [12 x i8] c"quitting
    ...\00"

declare i32 @printf(i8*, ...)

declare i32 @get_time()

declare i32 @printbool(i1)

declare void @yeet(i32 (i8*)*, i8*)

declare i8* @makechan(i8, i32)

declare void @send(i8*, i8, i32)

declare i32 @recv_int(i8*)

declare i1 @recv_bool(i8*)

declare i8 @recv_char(i8*)

declare void @closechan(i8*, i8)

declare i32 @selectchan({ i8, i8*, i8*, i64 }*, i32)

define i32 @main(i8*) {
entry:
```

```
  %main_args_ptr = bitcast i8* %0 to {}*
  %main_args = load {}, {}* %main_args_ptr
  %ch1 = alloca i8*
  store i8* null, i8** %ch1
  %makechan = call i8* @makechan(i8 99, i32 0)
  store i8* %makechan, i8** %ch1
  %ch2 = alloca i8*
  store i8* null, i8** %ch2
  %makechan1 = call i8* @makechan(i8 105, i32 0)
  store i8* %makechan1, i8** %ch2
  %quit = alloca i8*
  store i8* null, i8** %quit
  %makechan2 = call i8* @makechan(i8 98, i32 10)
  store i8* %makechan2, i8** %quit
  %quit3 = load i8*, i8** %quit
  %ch24 = load i8*, i8** %ch2
  %ch15 = load i8*, i8** %ch1
  %malloccall = tail call i8* @malloc(i32 trunc (i64 mul nuw (i64
     ptrtoint (i1** getelementptr (i1*, i1** null, i32 1) to i64),
     i64 3) to i32))
  %foo_args = bitcast i8* %malloccall to { i8*, i8*, i8* }*
  %arg_0 = insertvalue { i8*, i8*, i8* } zeroinitializer, i8* %ch15,
      0
  %arg_1 = insertvalue { i8*, i8*, i8* } %arg_0, i8* %ch24, 1
  %arg_2 = insertvalue { i8*, i8*, i8* } %arg_1, i8* %quit3, 2
  store { i8*, i8*, i8* } %arg_2, { i8*, i8*, i8* }* %foo_args
  %foo_arg_pointer = bitcast { i8*, i8*, i8* }* %foo_args to i8*
  call void @yeet(i32 (i8*)* @foo, i8* %foo_arg_pointer)
  %i = alloca i32
  store i32 0, i32* %i
  store i32 0, i32* %i
  br label %while

while:                                            ; preds = %
    while_body, %entry
  %i13 = load i32, i32* %i
  %tmp14 = icmp slt i32 %i13, 5
  br i1 %tmp14, label %while_body, label %merge

while_body:                                       ; preds = %while
  %c = alloca i8
  store i8 0, i8* %c
  %ch16 = load i8*, i8** %ch1
  %recv_int = call i8 @recv_char(i8* %ch16)
  store i8 %recv_int, i8* %c
```

```
  %printf = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
      ([4 x i8], [4 x i8]* @fmt.2, i32 0, i32 0), i8* getelementptr
      inbounds ([18 x i8], [18 x i8]* @strlit, i32 0, i32 0))
  %c7 = load i8, i8* %c
  %printf8 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
      ([4 x i8], [4 x i8]* @fmt.1, i32 0, i32 0), i8 %c7)
  %printf9 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
      ([4 x i8], [4 x i8]* @fmt.2, i32 0, i32 0), i8* getelementptr
      inbounds ([21 x i8], [21 x i8]* @strlit.3, i32 0, i32 0))
  %ch210 = load i8*, i8** %ch2
  %i11 = load i32, i32* %i
  call void @send(i8* %ch210, i8 105, i32 %i11)
  %i12 = load i32, i32* %i
  %tmp = add i32 %i12, 1
  store i32 %tmp, i32* %i
  br label %while

merge:                                            ; preds = %while
  %quit15 = load i8*, i8** %quit
  call void @send(i8* %quit15, i8 98, i32 -1)
  ret i32 0
}

define i32 @foo(i8*) {
entry:
  %foo_args_ptr = bitcast i8* %0 to { i8*, i8*, i8* }*
  %foo_args = load { i8*, i8*, i8* }, { i8*, i8*, i8* }* %
      foo_args_ptr
  %ch1 = extractvalue { i8*, i8*, i8* } %foo_args, 0
  %ch2 = extractvalue { i8*, i8*, i8* } %foo_args, 1
  %quit = extractvalue { i8*, i8*, i8* } %foo_args, 2
  %ch11 = alloca i8*
  store i8* %ch1, i8** %ch11
  %ch22 = alloca i8*
  store i8* %ch2, i8** %ch22
  %quit3 = alloca i8*
  store i8* %quit, i8** %quit3
  br label %while

while:                                            ; preds = %merge,
   %entry
  br i1 true, label %while_body, label %merge25

while_body:                                       ; preds = %while
  %malloccall = tail call i8* @malloc(i32 mul (i32 ptrtoint ({ i8,
```

```
    i8*, i8*, i64 }* getelementptr ({ i8, i8*, i8*, i64 }, { i8,
    i8*, i8*, i64 }* null, i32 1) to i32), i32 3))
  %1 = bitcast i8* %malloccall to { i8, i8*, i8*, i64 }*
  %ch14 = load i8*, i8** %ch11
  %2 = alloca i8
  store i8 97, i8* %2
  %clause = insertvalue { i8, i8*, i8*, i64 } { i8 115, i8* null, i8
    * null, i64 0 }, i8* %ch14, 1
  %clause5 = insertvalue { i8, i8*, i8*, i64 } %clause, i8* %2, 2
  %clause6 = insertvalue { i8, i8*, i8*, i64 } %clause5, i64
    ptrtoint (i8* getelementptr (i8, i8* null, i32 1) to i64), 3
  %3 = getelementptr { i8, i8*, i8*, i64 }, { i8, i8*, i8*, i64 }*
    %1, i32 0
  store { i8, i8*, i8*, i64 } %clause6, { i8, i8*, i8*, i64 }* %3
  %ch27 = load i8*, i8** %ch22
  %4 = alloca i32
  store i32 0, i32* %4
  %5 = bitcast i32* %4 to i8*
  %clause8 = insertvalue { i8, i8*, i8*, i64 } { i8 114, i8* null,
    i8* null, i64 0 }, i8* %ch27, 1
  %clause9 = insertvalue { i8, i8*, i8*, i64 } %clause8, i8* %5, 2
  %clause10 = insertvalue { i8, i8*, i8*, i64 } %clause9, i64
    ptrtoint (i32* getelementptr (i32, i32* null, i32 1) to i64),
    3
  %6 = getelementptr { i8, i8*, i8*, i64 }, { i8, i8*, i8*, i64 }*
    %1, i32 1
  store { i8, i8*, i8*, i64 } %clause10, { i8, i8*, i8*, i64 }* %6
  %quit11 = load i8*, i8** %quit3
  %7 = alloca i1
  store i1 false, i1* %7
  %8 = bitcast i1* %7 to i8*
  %clause12 = insertvalue { i8, i8*, i8*, i64 } { i8 114, i8* null,
    i8* null, i64 0 }, i8* %quit11, 1
  %clause13 = insertvalue { i8, i8*, i8*, i64 } %clause12, i8* %8, 2
  %clause14 = insertvalue { i8, i8*, i8*, i64 } %clause13, i64
    ptrtoint (i1* getelementptr (i1, i1* null, i32 1) to i64), 3
  %9 = getelementptr { i8, i8*, i8*, i64 }, { i8, i8*, i8*, i64 }*
    %1, i32 2
  store { i8, i8*, i8*, i64 } %clause14, { i8, i8*, i8*, i64 }* %9
  %select = call i32 @selectchan({ i8, i8*, i8*, i64 }* %1, i32 3)
  %recv_val = load i32, i32* %4
  %val2 = alloca i32
  store i32 0, i32* %val2
  store i32 %recv_val, i32* %val2
  %recv_val20 = load i1, i1* %7
```

```
  %q = alloca i1
  store i1 false, i1* %q
  store i1 %recv_val20, i1* %q
  switch i32 %select, label %merge [
    i32 0, label %case
    i32 1, label %case15
    i32 2, label %case19
  ]

merge:                                            ; preds = %
    while_body, %case15, %case
  br label %while

case:                                             ; preds = %
    while_body
  %printf = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
      ([4 x i8], [4 x i8]* @fmt.6, i32 0, i32 0), i8* getelementptr
      inbounds ([20 x i8], [20 x i8]* @strlit.7, i32 0, i32 0))
  br label %merge

case15:                                           ; preds = %
    while_body
  %printf16 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
      ([4 x i8], [4 x i8]* @fmt.6, i32 0, i32 0), i8* getelementptr
      inbounds ([18 x i8], [18 x i8]* @strlit.8, i32 0, i32 0))
  %val217 = load i32, i32* %val2
  %printf18 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
      ([4 x i8], [4 x i8]* @fmt.4, i32 0, i32 0), i32 %val217)
  br label %merge

case19:                                           ; preds = %
    while_body
  %q21 = load i1, i1* %q
  %printbool = call i32 @printbool(i1 %q21)
  %q22 = load i1, i1* %q
  br i1 %q22, label %then, label %else

merge23:                                          ; preds = %else, %
    then
  ret i32 0

then:                                             ; preds = %case19
  %printf24 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
      ([4 x i8], [4 x i8]* @fmt.6, i32 0, i32 0), i8* getelementptr
      inbounds ([12 x i8], [12 x i8]* @strlit.9, i32 0, i32 0))
```

```
  br label %merge23

else:                                             ; preds = %case19
  br label %merge23

merge25:                                          ; preds = %while
  ret i32 0
}

declare noalias i8* @malloc(i32)
```

6.1.2 Implementation of C-Styled Mutex

RJEC Code:

```
/* implementation of a mutex using channels and demonstration with
   defer */

func make_mutex() chan bool {
    mu := make(chan bool, 1);
    mu <- true;
    return mu;
}

func lock(mu chan bool) {
    <- mu;
}

func unlock(mu chan bool) {
    mu <- true;
}

func foo(n int, mu chan bool) {
    if 30 < n {
        return;
    } else {
        lock(mu);
        defer unlock(mu);
    }

    for i := n; i < n + 10; i = i + 1 {
        printi(i);
    }
```

```
}

func main() {
    mu := make_mutex();
    yeet foo(0, mu);
    yeet foo(25, mu);
    yeet foo(-100, mu);
    foo(-5, mu);
}
```

LLVM Code:

```
; ModuleID = 'RJEC'
source_filename = "RJEC"

@fmt = private unnamed_addr constant [4 x i8] c"%d\0A\00"
@fmt.1 = private unnamed_addr constant [4 x i8] c"%c\0A\00"
@fmt.2 = private unnamed_addr constant [4 x i8] c"%s\0A\00"
@fmt.3 = private unnamed_addr constant [4 x i8] c"%d\0A\00"
@fmt.4 = private unnamed_addr constant [4 x i8] c"%c\0A\00"
@fmt.5 = private unnamed_addr constant [4 x i8] c"%s\0A\00"
@fmt.6 = private unnamed_addr constant [4 x i8] c"%d\0A\00"
@fmt.7 = private unnamed_addr constant [4 x i8] c"%c\0A\00"
@fmt.8 = private unnamed_addr constant [4 x i8] c"%s\0A\00"
@fmt.9 = private unnamed_addr constant [4 x i8] c"%d\0A\00"
@fmt.10 = private unnamed_addr constant [4 x i8] c"%c\0A\00"
@fmt.11 = private unnamed_addr constant [4 x i8] c"%s\0A\00"
@fmt.12 = private unnamed_addr constant [4 x i8] c"%d\0A\00"
@fmt.13 = private unnamed_addr constant [4 x i8] c"%c\0A\00"
@fmt.14 = private unnamed_addr constant [4 x i8] c"%s\0A\00"

declare i32 @printf(i8*, ...)

declare i32 @get_time()

declare i32 @printbool(i1)

declare void @yeet(i32 (i8*)*, i8*)

declare i8* @makechan(i8, i32)

declare void @send(i8*, i8, i32)

declare i32 @recv_int(i8*)
```

```
declare i1 @recv_bool(i8*)

declare i8 @recv_char(i8*)

declare void @closechan(i8*, i8)

declare i32 @selectchan({ i8, i8*, i8*, i64 }*, i32)

define i32 @main(i8*) {
entry:
  %main_args_ptr = bitcast i8* %0 to {}*
  %main_args = load {}, {}* %main_args_ptr
  %mu = alloca i8*
  store i8* null, i8** %mu
  %malloccall = tail call i8* @malloc(i32 0)
  %make_mutex_args = bitcast i8* %malloccall to {}*
  store {} zeroinitializer, {}* %make_mutex_args
  %make_mutex_arg_pointer = bitcast {}* %make_mutex_args to i8*
  %make_mutex_result = call i8* @make_mutex(i8* %
     make_mutex_arg_pointer)
  store i8* %make_mutex_result, i8** %mu
  %mu1 = load i8*, i8** %mu
  %malloccall2 = tail call i8* @malloc(i32 ptrtoint ({ i32, i8* }*
     getelementptr ({ i32, i8* }, { i32, i8* }* null, i32 1) to i32)
     )
  %foo_args = bitcast i8* %malloccall2 to { i32, i8* }*
  %arg_1 = insertvalue { i32, i8* } zeroinitializer, i8* %mu1, 1
  store { i32, i8* } %arg_1, { i32, i8* }* %foo_args
  %foo_arg_pointer = bitcast { i32, i8* }* %foo_args to i8*
  call void @yeet(i32 (i8*)* @foo, i8* %foo_arg_pointer)
  %mu3 = load i8*, i8** %mu
  %malloccall4 = tail call i8* @malloc(i32 ptrtoint ({ i32, i8* }*
     getelementptr ({ i32, i8* }, { i32, i8* }* null, i32 1) to i32)
     )
  %foo_args5 = bitcast i8* %malloccall4 to { i32, i8* }*
  %arg_16 = insertvalue { i32, i8* } { i32 25, i8* null }, i8* %mu3,
      1
  store { i32, i8* } %arg_16, { i32, i8* }* %foo_args5
  %foo_arg_pointer7 = bitcast { i32, i8* }* %foo_args5 to i8*
  call void @yeet(i32 (i8*)* @foo, i8* %foo_arg_pointer7)
  %mu8 = load i8*, i8** %mu
  %malloccall9 = tail call i8* @malloc(i32 ptrtoint ({ i32, i8* }*
     getelementptr ({ i32, i8* }, { i32, i8* }* null, i32 1) to i32)
     )
```

```
  %foo_args10 = bitcast i8* %malloccall9 to { i32, i8* }*
  %arg_111 = insertvalue { i32, i8* } { i32 -100, i8* null }, i8* %
     mu8, 1
  store { i32, i8* } %arg_111, { i32, i8* }* %foo_args10
  %foo_arg_pointer12 = bitcast { i32, i8* }* %foo_args10 to i8*
  call void @yeet(i32 (i8*)* @foo, i8* %foo_arg_pointer12)
  %mu13 = load i8*, i8** %mu
  %malloccall14 = tail call i8* @malloc(i32 ptrtoint ({ i32, i8* }*
     getelementptr ({ i32, i8* }, { i32, i8* }* null, i32 1) to i32)
     )
  %foo_args15 = bitcast i8* %malloccall14 to { i32, i8* }*
  %arg_116 = insertvalue { i32, i8* } { i32 -5, i8* null }, i8* %
     mu13, 1
  store { i32, i8* } %arg_116, { i32, i8* }* %foo_args15
  %foo_arg_pointer17 = bitcast { i32, i8* }* %foo_args15 to i8*
  %1 = call i32 @foo(i8* %foo_arg_pointer17)
  ret i32 0
}

define i32 @foo(i8*) {
entry:
  %foo_args_ptr = bitcast i8* %0 to { i32, i8* }*
  %foo_args = load { i32, i8* }, { i32, i8* }* %foo_args_ptr
  %n = extractvalue { i32, i8* } %foo_args, 0
  %mu = extractvalue { i32, i8* } %foo_args, 1
  %n1 = alloca i32
  store i32 %n, i32* %n1
  %mu2 = alloca i8*
  store i8* %mu, i8** %mu2
  %n3 = load i32, i32* %n1
  %tmp = icmp slt i32 30, %n3
  br i1 %tmp, label %then, label %else

merge:                                            ; preds = %else
  %i = alloca i32
  store i32 0, i32* %i
  %n8 = load i32, i32* %n1
  store i32 %n8, i32* %i
  br label %while

then:                                             ; preds = %entry
  ret i32 0

else:                                             ; preds = %entry
  %mu4 = load i8*, i8** %mu2
```

```
  %malloccall = tail call i8* @malloc(i32 ptrtoint (i1**
      getelementptr (i1*, i1** null, i32 1) to i32))
  %lock_args = bitcast i8* %malloccall to { i8* }*
  %arg_0 = insertvalue { i8* } zeroinitializer, i8* %mu4, 0
  store { i8* } %arg_0, { i8* }* %lock_args
  %lock_arg_pointer = bitcast { i8* }* %lock_args to i8*
  %1 = call i32 @lock(i8* %lock_arg_pointer)
  %mu5 = load i8*, i8** %mu2
  %malloccall6 = tail call i8* @malloc(i32 ptrtoint (i1**
      getelementptr (i1*, i1** null, i32 1) to i32))
  %unlock_args = bitcast i8* %malloccall6 to { i8* }*
  %arg_07 = insertvalue { i8* } zeroinitializer, i8* %mu5, 0
  store { i8* } %arg_07, { i8* }* %unlock_args
  %unlock_arg_pointer = bitcast { i8* }* %unlock_args to i8*
  br label %merge

while:                                            ; preds = %
    while_body, %merge
  %i12 = load i32, i32* %i
  %n13 = load i32, i32* %n1
  %tmp14 = add i32 %n13, 10
  %tmp15 = icmp slt i32 %i12, %tmp14
  br i1 %tmp15, label %while_body, label %merge16

while_body:                                       ; preds = %while
  %i9 = load i32, i32* %i
  %printf = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
      ([4 x i8], [4 x i8]* @fmt.3, i32 0, i32 0), i32 %i9)
  %i10 = load i32, i32* %i
  %tmp11 = add i32 %i10, 1
  store i32 %tmp11, i32* %i
  br label %while

merge16:                                          ; preds = %while
  %2 = call i32 @unlock(i8* %unlock_arg_pointer)
  ret i32 0
}

define i32 @unlock(i8*) {
entry:
  %unlock_args_ptr = bitcast i8* %0 to { i8* }*
  %unlock_args = load { i8* }, { i8* }* %unlock_args_ptr
  %mu = extractvalue { i8* } %unlock_args, 0
  %mu1 = alloca i8*
  store i8* %mu, i8** %mu1
```

```
  %mu2 = load i8*, i8** %mu1
  call void @send(i8* %mu2, i8 98, i32 -1)
  ret i32 0
}

define i32 @lock(i8*) {
entry:
  %lock_args_ptr = bitcast i8* %0 to { i8* }*
  %lock_args = load { i8* }, { i8* }* %lock_args_ptr
  %mu = extractvalue { i8* } %lock_args, 0
  %mu1 = alloca i8*
  store i8* %mu, i8** %mu1
  %mu2 = load i8*, i8** %mu1
  %recv_bool = call i1 @recv_bool(i8* %mu2)
  ret i32 0
}

define i8* @make_mutex(i8*) {
entry:
  %make_mutex_args_ptr = bitcast i8* %0 to {}*
  %make_mutex_args = load {}, {}* %make_mutex_args_ptr
  %mu = alloca i8*
  store i8* null, i8** %mu
  %makechan = call i8* @makechan(i8 98, i32 1)
  store i8* %makechan, i8** %mu
  %mu1 = load i8*, i8** %mu
  call void @send(i8* %mu1, i8 98, i32 -1)
  %mu2 = load i8*, i8** %mu
  ret i8* %mu2
}

declare noalias i8* @malloc(i32)
```

6.1.3 Arrays of Structs

RJEC Code:

```
struct foo {
    x int;
    y int;
    z bool;
}
```

```
func change_struct(x []struct foo) {
    x[0].x = x[1].x + 1;
    x[1].y = x[2].y - 2;
    x[2].z = true;
}

func main() {
    var x [10]struct foo;
    x[0] = struct foo { x: 1, y: 2 };
    x[1] = struct foo { x: 3, y: 5, z: true };
    x[2] = struct foo { x: 0, y: 7};
    change_struct(x);
    printi(x[0].x);
    printi(x[1].y);
    printb(x[2].z);
}
```

LLVM Code:

```
; ModuleID = 'RJEC'
source_filename = "RJEC"

@fmt = private unnamed_addr constant [4 x i8] c"%d\0A\00"
@fmt.1 = private unnamed_addr constant [4 x i8] c"%c\0A\00"
@fmt.2 = private unnamed_addr constant [4 x i8] c"%s\0A\00"
@fmt.3 = private unnamed_addr constant [4 x i8] c"%d\0A\00"
@fmt.4 = private unnamed_addr constant [4 x i8] c"%c\0A\00"
@fmt.5 = private unnamed_addr constant [4 x i8] c"%s\0A\00"

declare i32 @printf(i8*, ...)

declare i32 @get_time()

declare i32 @printbool(i1)

declare void @yeet(i32 (i8*)*, i8*)

declare i8* @makechan(i8, i32)

declare void @send(i8*, i8, i32)

declare i32 @recv_int(i8*)

declare i1 @recv_bool(i8*)
```

```
declare i8 @recv_char(i8*)

declare void @closechan(i8*, i8)

declare i32 @selectchan({ i8, i8*, i8*, i64 }*, i32)

define i32 @main(i8*) {
entry:
  %main_args_ptr = bitcast i8* %0 to {}*
  %main_args = load {}, {}* %main_args_ptr
  %malloccall = tail call i8* @malloc(i32 mul (i32 ptrtoint ({ i32,
     i32, i1 }* getelementptr ({ i32, i32, i1 }, { i32, i32, i1 }*
     null, i32 1) to i32), i32 10))
  %1 = bitcast i8* %malloccall to { i32, i32, i1 }*
  %x = alloca { i32, i32, i1 }*
  store { i32, i32, i1 }* %1, { i32, i32, i1 }** %x
  %malloccall1 = tail call i8* @malloc(i32 ptrtoint ({ i32, i32, i1
     }* getelementptr ({ i32, i32, i1 }, { i32, i32, i1 }* null, i32
      1) to i32))
  %foo = bitcast i8* %malloccall1 to { i32, i32, i1 }*
  store { i32, i32, i1 } { i32 1, i32 2, i1 false }, { i32, i32, i1
     }* %foo
  %tmp = load { i32, i32, i1 }, { i32, i32, i1 }* %foo
  %tmp2 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x
  %2 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %tmp2, i32
     0
  store { i32, i32, i1 } %tmp, { i32, i32, i1 }* %2
  %malloccall3 = tail call i8* @malloc(i32 ptrtoint ({ i32, i32, i1
     }* getelementptr ({ i32, i32, i1 }, { i32, i32, i1 }* null, i32
      1) to i32))
  %foo4 = bitcast i8* %malloccall3 to { i32, i32, i1 }*
  store { i32, i32, i1 } { i32 3, i32 5, i1 true }, { i32, i32, i1
     }* %foo4
  %tmp5 = load { i32, i32, i1 }, { i32, i32, i1 }* %foo4
  %tmp6 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x
  %3 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %tmp6, i32
     1
  store { i32, i32, i1 } %tmp5, { i32, i32, i1 }* %3
  %malloccall7 = tail call i8* @malloc(i32 ptrtoint ({ i32, i32, i1
     }* getelementptr ({ i32, i32, i1 }, { i32, i32, i1 }* null, i32
      1) to i32))
  %foo8 = bitcast i8* %malloccall7 to { i32, i32, i1 }*
  store { i32, i32, i1 } { i32 0, i32 7, i1 false }, { i32, i32, i1
     }* %foo8
```

```
  %tmp9 = load { i32, i32, i1 }, { i32, i32, i1 }* %foo8
  %tmp10 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x
  %4 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %tmp10, i32
      2
  store { i32, i32, i1 } %tmp9, { i32, i32, i1 }* %4
  %x11 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x
  %malloccall12 = tail call i8* @malloc(i32 ptrtoint (i1**
     getelementptr (i1*, i1** null, i32 1) to i32))
  %change_struct_args = bitcast i8* %malloccall12 to { { i32, i32,
     i1 }* }*
  %arg_0 = insertvalue { { i32, i32, i1 }* } zeroinitializer, { i32,
      i32, i1 }* %x11, 0
  store { { i32, i32, i1 }* } %arg_0, { { i32, i32, i1 }* }* %
     change_struct_args
  %change_struct_arg_pointer = bitcast { { i32, i32, i1 }* }* %
     change_struct_args to i8*
  %5 = call i32 @change_struct(i8* %change_struct_arg_pointer)
  %x13 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x
  %6 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %x13, i32 0
  %7 = load { i32, i32, i1 }, { i32, i32, i1 }* %6
  %x14 = extractvalue { i32, i32, i1 } %7, 0
  %printf = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
     ([4 x i8], [4 x i8]* @fmt, i32 0, i32 0), i32 %x14)
  %x15 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x
  %8 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %x15, i32 1
  %9 = load { i32, i32, i1 }, { i32, i32, i1 }* %8
  %y = extractvalue { i32, i32, i1 } %9, 1
  %printf16 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds
      ([4 x i8], [4 x i8]* @fmt, i32 0, i32 0), i32 %y)
  %x17 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x
  %10 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %x17, i32
     2
  %11 = load { i32, i32, i1 }, { i32, i32, i1 }* %10
  %z = extractvalue { i32, i32, i1 } %11, 2
  %printbool = call i32 @printbool(i1 %z)
  ret i32 0
}

define i32 @change_struct(i8*) {
entry:
  %change_struct_args_ptr = bitcast i8* %0 to { { i32, i32, i1 }* }*
  %change_struct_args = load { { i32, i32, i1 }* }, { { i32, i32, i1
      }* }* %change_struct_args_ptr
  %x = extractvalue { { i32, i32, i1 }* } %change_struct_args, 0
  %x1 = alloca { i32, i32, i1 }*
```

```
  store { i32, i32, i1 }* %x, { i32, i32, i1 }** %x1
  %x2 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x1
  %1 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %x2, i32 0
  %2 = load { i32, i32, i1 }, { i32, i32, i1 }* %1
  %x3 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x1
  %3 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %x3, i32 1
  %4 = load { i32, i32, i1 }, { i32, i32, i1 }* %3
  %x4 = extractvalue { i32, i32, i1 } %4, 0
  %tmp = add i32 %x4, 1
  %x5 = insertvalue { i32, i32, i1 } %2, i32 %tmp, 0
  %tmp6 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x1
  %5 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %tmp6, i32
     0
  store { i32, i32, i1 } %x5, { i32, i32, i1 }* %5
  %x7 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x1
  %6 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %x7, i32 1
  %7 = load { i32, i32, i1 }, { i32, i32, i1 }* %6
  %x8 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x1
  %8 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %x8, i32 2
  %9 = load { i32, i32, i1 }, { i32, i32, i1 }* %8
  %y = extractvalue { i32, i32, i1 } %9, 1
  %tmp9 = sub i32 %y, 2
  %y10 = insertvalue { i32, i32, i1 } %7, i32 %tmp9, 1
  %tmp11 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x1
  %10 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %tmp11,
     i32 1
  store { i32, i32, i1 } %y10, { i32, i32, i1 }* %10
  %x12 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x1
  %11 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %x12, i32
     2
  %12 = load { i32, i32, i1 }, { i32, i32, i1 }* %11
  %z = insertvalue { i32, i32, i1 } %12, i1 true, 2
  %tmp13 = load { i32, i32, i1 }*, { i32, i32, i1 }** %x1
  %13 = getelementptr { i32, i32, i1 }, { i32, i32, i1 }* %tmp13,
     i32 2
  store { i32, i32, i1 } %z, { i32, i32, i1 }* %13
  ret i32 0
}

declare noalias i8* @malloc(i32)
```

6.2 Test Suite Design

Individual features were built on branches or on the master branch directly, depending on the anticipated duration, difficulty, and/or unpredictability of said feature. Those that fell in the latter categories were developed on branches to provide for an isolated setting for development and testing. Once we had a feature working, we immediately wrote tests, to understand and verify the behavior of the feature we had just built. As a result, a feature and its associated integration tests, going hand-in-hand, were committed together.

Within our integration tests, we have both success and fail test cases, which cover code both in semant (for typing) and in codegen (for other compilation errors). There are a total of 98 test cases.

6.2.1 Test Automation and Scripts

All tests are in the `/test/` folder. Success test cases have the format `test-*.rjec`, with expected output stored in the corresponding `test-*.out`. Failure test cases are denoted as `fail-*.rjec`, with expected Failure in `fail-*.err`.

Testing automation is based off the MicroC testing suite. The `testall.sh` script compiles and runs `*.rjec` files under `/tests/`. It compares with expected output (in `*.out, *.err`), and yields `*.diff` and actual `*.out, *.err` files when the test fails/doesn't match with anticipated output. `testall.sh` is run automatically when RJEC is built and compiled with `make`.

6.3 Division of Labor

We wrote tests alongside the implemented features, largely during our group programming sessions. As such, everyone wrote tests and helped write tests. While wrapping up our language, we also worked on augmenting our test suite in a group session.

7 Lessons Learned

7.1 Riya

Working on this project together, and seeing it evolve steadily throughout the semester from where we began (a MicroC-based template) to where we are now (a functioning

language with CSP-style concurrency features) has been truly a rewarding experience. I found it particularly interesting to see concepts and theoretical pieces taught in class translate to our application of them while coding up our compiler in OCaml.

Having had some experience with functional programming (Haskell) from the previous semester, it was really cool to see it in the specific context of building a complete compiler. With this project, I continued to see the benefits of writing such concise and clean, yet clearly impactful code; moreover, I feel that the functional programming ”mindset” has left its mark in the way I think about coding in general.

I was definitely more new to some of the (Go-like) concurrency features we ended up implementing in our language, and I think our pair programming sessions and associated discussions were very helpful for me to understand both how we would incorporate these aspects (via linking of open-source C libraries) and what kinds of interesting programs we could support with these features (Producer-Consumer, Mutex implementation, MapReduce).

Finally, I found our method of coordinating work and completing pieces of the compiler to be engaging and supportive - we did most of our coding in said sessions where every member was present, and I believe this method gave us a sense of togetherness and helped us learn from each other continuously, something I really valued during this remote semester.

7.2 Justin

This project was a fascinating hands-on experience in building a compiler. It was extremely rewarding to start from barely anything and slowly combine it together into a fully-fledged language. Go has been one of my favorite languages for a long time now, and to me, this language is a labor of love to better understand the design of this language and how it can be implemented.

This class has also been my first experience with functional programming. It took time to get used to, but programming the compiler with OCaml was a very interesting experience and I have learned a lot doing it this way. The paradigm has affected my thinking across my programming in general, and I understand now why Professor Edwards is such a proponent of it, especially for compiler work.

Our team was well-organized, with regularly scheduled weekly meetings and de-

tailed written notes/plans. Our model of programming everything together worked very well for us, although it may not be the most time efficient, it was very useful for knowing the project and learning everything. I would absolutely recommend this technique of group programming to future teams.

Overall, this has been a very fulfilling learning experience. It's not often that a class makes me want to stay up all night working on it, but this project has certainly done this to me.

7.3 Elaine

It was really amazing to see a project evolve from a very high-level and general idea in the beginning, to a fully functioning and relatively low-level code implementation in the end. Learning about syntactic and semantic analysis during the lecture felt completely different from actually trying to figure out how to apply these concepts in code, including how to devise an unambiguous grammar, as well as how to define succinct types for the AST and SAST that cover the entire set of syntactic and semantic rules.

Building out the features in `semant.ml` and `codegen.ml` was also a fascinating learning experience. After struggling with it for a while, we finally gained enough experience in OCaml, a really eye-opening functional programming language to have learned, to be able to design more intricate infrastructure and mechanisms in the code in order to optimize our codebase. It was really fun to derive from the expected behavior of certain features what their underlying implementation should be, and how they fit into the existing code structure we already had. If nothing else, it definitely was a great opportunity for me personally to reflect on language design conventions in a completely new light.

I am especially grateful for the fact that we also decided to take a stab at concurrency in our features. This motivated us to survey the internet for potentially helpful libraries, and in this process, we learned how to incorporate and interface external libraries and code with our main pipeline. Finally, the process of trying to come up with test cases for all kinds of edge cases was also nerve-racking but exciting, especially when we manage to discover obscure new bugs and resolve them.

7.4 Caroline

This project was an interesting opportunity in order to use functional coding (in OCaml) to apply the theoretical concepts behind language design and implementation (as discussed in class) in a practical setting.

The stark contrast between class material and tribulations of working in an unfamiliar coding scheme certainly made it a challenging but rewarding experience. In the code there were real consequences for poor language design and implementation (ambiguous grammars, etc.), and these errors could be tough to resolve due to the succinct and compact nature of OCaml. This was also a first for me with regards to coding functionally rather than imperatively, let alone at such a low level.

Like a past student has said, I agree that I have never had to think so long before composing code. Premature decisions often resulted in needing to make corrections later in order to accommodate other features and make them work. The question of whether or not we would support one edge case or another based on what has already been written has arisen many a time. This made me have to think harder about what aspects of Go we truly wanted to adhere to and what we would inevitably adapt.

Furthermore, this experience was also an opportunity for me to learn more about concurrency from my peers, since it was a fresh topic for me coming in. Having had limited experience with Go as a language, there was a lot to familiarize myself with. To this end, I really valued our pair-coding sessions since a lot could be thought through and discussed during development. Overall, I would say that this was certainly a valuable learning experience.

8 Acknowledgements

We would like to thank Professor Edwards for his tireless effort to educate us in functional programming and compilers, and for creating MicroC, which formed the initial base for our compiler. We would additionally like to thank Shoo as an exemplary past project which helped us with implementing many of our features, as well as Harmonica as an example of a past project with concurrency.

We would also like to thank Martin Sustrik for his Libmill library, which we used to implement our concurrency constructs. Finally, Go is a wonderful language which served as primary inspiration for our language, for which we offer our gratitude.

Talks by its creators, such as Rob Pike's "Concurrency is Not Parallelism," were instrumental in realizing our language's philosophy and focus on enabling correct, clean, concurrent code.

9 Appendix

9.1 rjec.ml

```
(* Top-level of the RJEC compiler: scan & parse the input,
 * check the resulting AST and generate an SASP from it, generate
    LLVM IR,
 * and dump the module
 * Initially based on MicroC
 * Written by Elaine Wang, Justin Chen, Riya Chakraborty, and
    Caroline Hoang
 *)

type action = Ast | Sast | LLVM_IR | Compile

let () =
  let action = ref Compile in
  let set_action a () = action := a in
  let speclist = [
    ("-a", Arg.Unit (set_action Ast), "Print the AST");
    ("-s", Arg.Unit (set_action Sast), "Print the SAST");
    ("-l", Arg.Unit (set_action LLVM_IR), "Print the generated LLVM
       IR");
    ("-c", Arg.Unit (set_action Compile),
      "Check and print the generated LLVM IR (default)");
  ] in
  let usage_msg = "usage: ./rjec.native [-a|-s|-l|-c] [file.rjec]"
     in
  let channel = ref stdin in
  Arg.parse speclist (fun filename -> channel := open_in filename)
     usage_msg;

  let lexbuf = Lexing.from_channel !channel in
  let ast = Rjecparse.program Scanner.token lexbuf in
  match !action with
    Ast -> print_string (Ast.string_of_program ast)
  | _ -> let sast = Semant.check ast in
    match !action with
```

```
      Ast     -> ()
    | Sast    -> print_string (Sast.string_of_sprogram sast)
    | LLVM_IR -> print_string (Llvm.string_of_llmodule (Codegen.
      translate sast))
    | Compile -> let m = Codegen.translate sast in
        Llvm_analysis.assert_valid_module m;
        print_string (Llvm.string_of_llmodule m)
```

9.2 scanner.mll

```
(* Ocamllex scanner for RJEC
 * Initially based on MicroC, with inspiration from Shoo
 * Written largely by Justin Chen in collaboration with Riya, Elaine
    , Caroline
 *)

{ open Rjecparse }

let digit = ['0' - '9']
let digits = digit+

rule token = parse
  [' ' '\t' '\r' '\n'] { token lexbuf } (* Whitespace *)
| "/*"     { comment lexbuf }           (* Comments *)
| '('      { LPAREN }
| ')'      { RPAREN }
| '{'      { LBRACE }
| '}'      { RBRACE }
| '['      { LSQUARE }
| ']'      { RSQUARE }
| ':'      { COLON }
| '.'      { DOT }
| ';'      { SEMI }
| ','      { COMMA }
| '+'      { PLUS }
| '-'      { MINUS }
| '*'      { TIMES }
| '/'      { DIVIDE }
| '%'      { MOD }
| '='      { ASSIGN }
| ":="     { INIT }
| "=="     { EQ }
| '<'      { LT }
```

```
| "<="     { LEQ }
| "&&"     { AND }
| "||"     { OR }
| "!"      { NOT }
| "<-"     { ARROW }
| "if"     { IF }
| "else"   { ELSE }
| "for"    { FOR }
| "defer"  { DEFER }
| "select" { SELECT }
| "case"   { CASE }
| "return" { RETURN }
| "int"    { INT }
| "bool"   { BOOL }
| "char"   { CHAR }
| "chan"   { CHAN }
| "struct" { STRUCT }
| "var"    { VAR }
| "func"   { FUNC }
| "yeet"   { YEET }
| "make"   { MAKE }
| "close"  { CLOSE }
| "true"   { BLIT(true)  }
| "false"  { BLIT(false) }
| digits as lxm { ILIT(int_of_string lxm) }
| '\"'     { str (Buffer.create 16) lexbuf }
| "\'\\0\'"    { CLIT(0) }
| '\'' _ '\'' as lxm { CLIT(Char.code (String.get lxm 1)) }
| ['a'-'z' 'A'-'Z']['a'-'z' 'A'-'Z' '0'-'9' '_']*     as lxm { ID(
   lxm) }
| eof { EOF }
| _ as char { raise (Failure("illegal character " ^ Char.escaped
   char)) }

and comment = parse
  "*/" { token lexbuf }
| _    { comment lexbuf }

and str buf = parse
  '\"' { SLIT(Buffer.contents buf) }
| [^ '\"'] { Buffer.add_string buf (Lexing.lexeme lexbuf); str buf
   lexbuf }
```

9.3 ast.ml

```
(* Abstract Syntax Tree and functions for printing it
 * Initially based on MicroC, with inspiration from Shoo
 * Written by Justin Chen, Elaine Wang, Riya Chakraborty, and
    Caroline Hoang
 *)

type op = Add | Sub | Mult | Div | Mod | Equal | Less | Leq | And |
   Or

type uop = Neg | Not

type typ = Int | Bool | Char
  | Chan of typ
  | Array of typ
  | Struct of string

type bind = typ * string

type expr =
    IntLit of int
  | StrLit of string
  | CharLit of int
  | BoolLit of bool
  | ArrLit of typ * expr list
  | StructLit of string * (string * expr) list
  | Id of string
  | Binop of expr * op * expr
  | Unop of uop * expr
  | Call of string * expr list
  | Access of expr * string
  | Subscript of string * expr
  | Send of expr * expr
  | Recv of expr
  | Make of typ * (expr option)
  | Close of expr
  | Noexpr

type vdecl_typ = Int | Bool | Char
  | Chan of typ
  | ArrayInit of expr * typ
  | Struct of string

type vdecl = vdecl_typ * string list
```

```
type assign_stmt =
    DeclAssign of vdecl * expr list
  | Assign of expr list * expr list
  | Init of expr list * expr list

type stmt =
    Block of stmt list
  | Expr of expr
  | VdeclStmt of vdecl
  | AssignStmt of assign_stmt
  | Return of expr list
  | If of expr * stmt * stmt
  | For of (assign_stmt option) * expr * (assign_stmt option) * stmt
  | While of expr * stmt
  | Select of (stmt * stmt list) list
  | Defer of expr
  | Yeet of expr

type func_decl = {
    types   : typ list;
    fname   : string;
    formals : bind list;
    body    : stmt list;
  }

type sdecl = string * bind list

type program = vdecl list * (func_decl list * sdecl list)

(* Pretty-printing functions *)

let string_of_op = function
    Add   -> "+"
  | Sub   -> "-"
  | Mult  -> "*"
  | Div   -> "/"
  | Mod   -> "%"
  | Equal -> "=="
  | Less  -> "<"
  | Leq   -> "<="
  | And   -> "&&"
  | Or    -> "||"

let string_of_uop = function
    Neg   -> "-"
```

```
    | Not   -> "!"

let rec string_of_typ = function
      Array(t)  -> "[]" ^ string_of_typ t
    | Int       -> "int"
    | Bool      -> "bool"
    | Char      -> "char"
    | Struct(t) -> t
    | Chan(t)   -> "chan " ^ string_of_typ t

let rec string_of_expr = function
      IntLit(l)          -> string_of_int l
    | StrLit(l)          -> l
    | CharLit(l)         -> String.make 1 (Char.chr l)
    | BoolLit(true)      -> "true"
    | BoolLit(false)     -> "false"
    | ArrLit(t, el)      -> "[]" ^ string_of_typ t
        ^ "{" ^ String.concat ", " (List.map string_of_expr el) ^ "}"
    | StructLit(n, m) -> "struct " ^ n ^ "{" ^ String.concat ", "
        (List.map (fun (n, v) -> (n ^ ": " ^ string_of_expr (v))) m) ^
            "}"
    | Id(s)              -> s
    | Binop(e1, o, e2)   ->
        string_of_expr e1 ^ " " ^ string_of_op o ^ " " ^
            string_of_expr e2
    | Unop(o, e) -> string_of_uop o ^ string_of_expr e
    | Call(f, el)        ->
        f ^ "(" ^ String.concat ", " (List.map string_of_expr el) ^ ")
            "
    | Access(s, m)       -> (string_of_expr s) ^ "." ^ m
    | Subscript(a, i)    -> a ^ "[" ^ string_of_expr i ^ "]"
    | Send(c, e)         -> string_of_expr c ^ "<-" ^ string_of_expr e
    | Recv(c)            -> "<-" ^ string_of_expr c
    | Make(t, e)         -> "make" ^ "(" ^ "chan " ^ string_of_typ t ^
        (match e with None -> "" | Some(ex) -> "," ^ string_of_expr ex
            ) ^ ")"
    | Close(c)           -> "close" ^ "(" ^ string_of_expr c ^ ")"
    | Noexpr             -> ""

let rec string_of_stmt = function
      Block(stmts)       ->
        "{\n" ^ String.concat "" (List.map string_of_stmt stmts) ^ "}\
            n"
    | Expr(expr)         -> string_of_expr expr ^ ";\n";
    | AssignStmt(s)      -> let string_of_assign = function
```

```
      Assign(v, e)    -> (String.concat ", " (List.map
          string_of_expr v))
           ^ " = " ^ (String.concat ", " (List.map string_of_expr e))
                ^ ";\n"
    | _               ->  "??????\n"
    in string_of_assign s
  | Return(expr)      -> "return " ^
      String.concat ", " (List.map string_of_expr expr) ^ ";\n"
  | If(e, s, Block([])) -> "if (" ^ string_of_expr e ^ ")\n" ^
     string_of_stmt s
  | If(e, s1, s2) ->  "if (" ^ string_of_expr e ^ ")\n" ^
      string_of_stmt s1 ^ "else\n" ^ string_of_stmt s2
  | _ -> "??????\n" (* unimplemented pretty-print *)

let string_of_vdecl_typ = function
    ArrayInit(i, t) -> "[" ^ string_of_expr i ^ "]" ^ string_of_typ
       t
  | Int             -> "int"
  | Bool            -> "bool"
  | Char            -> "char"
  | Struct(t)       -> t
  | Chan(t)         -> "chan " ^ string_of_typ t

let string_of_vdecl (vd : vdecl) : string = "var " ^ String.concat
   ", " (snd vd)
    ^ string_of_vdecl_typ (fst vd) ^ " " ^ ";\n"

let string_of_fdecl fdecl =
  fdecl.fname ^ "(" ^ String.concat ", " (List.map snd fdecl.formals
     ) ^
  ") (" ^ String.concat ", " (List.map string_of_typ fdecl.types) ^
  ")\n{\n" ^
  String.concat "" (List.map string_of_stmt fdecl.body) ^
  "}\n"

let string_of_program (vars, (funcs, _)) =
  String.concat "" (List.map string_of_vdecl vars) ^ "\n" ^
  String.concat "\n" (List.map string_of_fdecl funcs)
```

9.4 rjecparse.mly

```
/* Ocamlyacc parser for RJEC
 * Initially based on MicroC, with inspiration from Shoo
```

```
 * Written by Justin Chen, Elaine Wang, Riya Chakraborty, and
    Caroline Hoang
 */

%{
open Ast
%}

%token SEMI LPAREN RPAREN LBRACE RBRACE LSQUARE RSQUARE DOT COMMA
   COLON
%token PLUS MINUS TIMES DIVIDE MOD ASSIGN INIT
%token NOT EQ LT LEQ AND OR
%token RETURN IF ELSE FOR WHILE INT BOOL CHAR CHAN STRUCT
%token VAR FUNC YEET MAKE CLOSE
%token ARROW DEFER SELECT CASE
%token <int> ILIT CLIT
%token <bool> BLIT
%token <string> SLIT ID
%token EOF

%start program
%type <Ast.program> program

%nonassoc NOELSE
%nonassoc ELSE
%right ASSIGN INIT
%left OR
%left AND
%left EQ
%left LT LEQ
%left PLUS MINUS
%left TIMES DIVIDE MOD
%right ARROW
%right NOT
%left DOT

%%

program:
  decls EOF { $1 }

decls:
   /* nothing */ { ([], ([], []))                } 
 | decls vdecl SEMI { (($2 :: fst $1), (fst (snd $1), snd (snd $1)))
     }
```

```
 | decls fdecl { (fst $1, (($2 :: fst (snd $1)), snd (snd $1))) }
 | decls sdecl { (fst $1, (fst (snd $1), ($2 :: snd (snd $1)))) }

fdecl:
   FUNC ID LPAREN formals_opt RPAREN return_types LBRACE stmt_list
      RBRACE
     { {  fname   = $2;
          formals = List.rev $4;
          types   = List.rev $6;
          body    = List.rev $8   } }

formals_opt:
    /* nothing */ { [] }
  | formal_list   { $1 }

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

return_types:
    /* nothing */ {   [] }
  | typ           { [$1] }

typ:
    INT                                { Int   }
  | BOOL                               { Bool  }
  | CHAR                               { Char }
  | CHAN basic_typ                     { Chan($2)  }
  | LSQUARE RSQUARE non_arr_typ        { Array($3) }
  | STRUCT ID                          { Struct($2) }

basic_typ:
    INT                                { Int   }
  | BOOL                               { Bool  }
  | CHAR                               { Char }

non_arr_typ:
    INT                                { Int   }
  | BOOL                               { Bool  }
  | CHAR                               { Char }
  | CHAN basic_typ                     { Chan($2)  }
  | STRUCT ID                          { Struct($2) }

vdecl_typ:
    INT                                { Int   }
```

```
  | BOOL                              { Bool  }
  | CHAR                              { Char }
  | CHAN basic_typ                    { Chan($2)  }
  | LSQUARE expr RSQUARE non_arr_typ  { ArrayInit($2, $4) }
  | STRUCT ID                         { Struct($2) }

vdecl:
    VAR id_list vdecl_typ { ($3, List.rev $2) }

id_list:
    ID { [$1] }
  | id_list COMMA ID { $3 :: $1 }

sdecl:
    STRUCT ID LBRACE member_list RBRACE { ($2, $4) }

member_list:
    ID basic_typ SEMI             { [($2,$1)]     }
  | member_list ID basic_typ SEMI { ($3,$2) :: $1 }

stmt_list:
    /* nothing */  { [] }
  | stmt_list stmt { $2 :: $1 }

stmt:
    expr SEMI                                       { Expr $1
                     }
  | vdecl SEMI                                      { VdeclStmt $1
              }
  | assign_stmt SEMI                                { AssignStmt $1
             }
  | RETURN args_opt SEMI                            { Return $2
                 }
  | LBRACE stmt_list RBRACE                         { Block(List.rev $2)
        }
  | IF expr LBRACE stmt_list RBRACE else_opt
                                    {  If($2, Block(List.rev $4), $6
                                       ) }
  | FOR assign_stmt_opt SEMI expr SEMI assign_stmt_opt LBRACE
     stmt_list RBRACE
                                { For($2, $4, $6, Block(List.rev $8)
                                   ) }
  | FOR expr LBRACE stmt_list RBRACE
                                  { While($2, Block(List.rev $4)
                                     ) }
```

```
  | FOR LBRACE stmt_list RBRACE
                        {  While(BoolLit(true), Block(List.rev $3)
                           ) }
  | SELECT LBRACE case_list RBRACE            { Select(List.rev $3)
      }
  | DEFER expr SEMI                           { Defer($2)
                }
  | YEET expr SEMI                            { Yeet($2)
                 }

else_opt:
    %prec NOELSE                                          { Block
      ([]) }
  | ELSE IF expr LBRACE stmt_list RBRACE else_opt
                                  {  If($3, Block(List.rev $5), $7
                                     ) }
  | ELSE LBRACE stmt_list RBRACE                {  Block(List.rev $3
     ) }

case_list:
    CASE case_stmt COLON stmt_list           { [($2, List.rev $4)]
           }
  | case_list CASE case_stmt COLON stmt_list { ($3, List.rev $5) ::
     $1 }

case_stmt:
    id_subscript ARROW expr           { Expr (Send ($1, $3))     }
  | ARROW id_subscript                { Expr (Recv $2)           }
  | assign_stmt                       { AssignStmt $1            }

assign_stmt:
  | vdecl ASSIGN args_list            { DeclAssign($1, List.rev $3)
          }
  | args_list ASSIGN args_list        { Assign(List.rev $1, List.rev
      $3) }
  | args_list INIT   args_list        { Init(List.rev $1, List.rev
     $3)   }


assign_stmt_opt:
     /* nothing */ { None }
  |  assign_stmt   { Some($1) }

expr:
    ILIT                                          { IntLit($1)
```

```
                    }
  | SLIT                                                  { StrLit($1)
                   }
  | CLIT                                                  { CharLit($1
   )               }
  | BLIT                                            { BoolLit($1)
                 }
  | LSQUARE RSQUARE non_arr_typ LBRACE args_opt RBRACE
                                                    { ArrLit($3, $5)
                                                               }
  | STRUCT ID LBRACE element_list_opt RBRACE
                                                    { StructLit($2, $4
                                                      )       }
  | ID                                              { Id($1)
                      }
  | expr PLUS   expr                                { Binop($1, Add,
      $3)   }
  | expr MINUS  expr                                { Binop($1, Sub,
      $3)   }
  | expr TIMES  expr                                { Binop($1, Mult,
     $3)   }
  | expr DIVIDE expr                                { Binop($1, Div,
      $3)   }
  | expr MOD    expr                                { Binop($1, Mod,
      $3)   }
  | expr EQ     expr                                { Binop($1, Equal,
     $3)   }
  | expr LT     expr                                { Binop($1, Less,
     $3)   }
  | expr LEQ    expr                                { Binop($1, Leq,
      $3)   }
  | expr AND    expr                                { Binop($1, And,
      $3)   }
  | expr OR     expr                                { Binop($1, Or,
       $3)   }
  | MINUS expr %prec NOT                            { Unop(Neg, $2)
               }
  | NOT expr                                        { Unop(Not, $2)
               }
  | ID LPAREN args_opt RPAREN                       { Call($1, $3)
                }
  | LPAREN expr RPAREN                              { $2
                          }
  | expr DOT ID                                     { Access($1, $3)
             }
```

```
  | ID LSQUARE expr RSQUARE                        { Subscript($1, $3
     )      }
  | id_subscript ARROW expr                        { Send($1, $3)
            }
  | ARROW id_subscript                             { Recv($2)
                }
  | MAKE LPAREN CHAN basic_typ RPAREN              { Make($4, None)
          }
  | MAKE LPAREN CHAN basic_typ COMMA expr RPAREN   { Make($4, Some($6
     ))     }
  | CLOSE LPAREN expr RPAREN                       { Close($3)
               }

id_subscript:
    ID                         { Id($1) }
  | ID LSQUARE expr RSQUARE    { Subscript($1, $3) }

args_opt:
    /* nothing */ { [] }
  | args_list     { List.rev $1 }

args_list:
    expr                     { [$1] }
  | args_list COMMA expr     { $3 :: $1 }

element_list_opt:
    /* nothing */ { [] }
  | element_list  { List.rev $1 }

element_list:
    ID COLON expr                      { [($1,$3)]     }
  | element_list COMMA ID COLON expr   { ($3,$5) :: $1 }
```

9.5 sast.ml

```
(* Semantically-checked Abstract Syntax Tree and functions for
   printing it
 * Initially based on MicroC, with inspiration from Shoo
 * Written by Elaine Wang, Justin Chen, Riya Chakraborty, and
    Caroline Hoang
 *)

open Ast
```

```
type sexpr = typ * sx
and sx =
    SIntLit of int
  | SStrLit of string
  | SCharLit of int
  | SBoolLit of bool
  | SStructLit of string * (string * sexpr) list
  | SArrLit of typ * sexpr list
  | SId of string
  | SBinop of sexpr * op * sexpr
  | SUnop of uop * sexpr
  | SCall of string * sexpr list
  | SAccess of sx * string * string
  | SMake of typ * sexpr
  | SSend of sexpr * sexpr
  | SRecv of sexpr * typ
  | SClose of sexpr * typ
  | SSubscript of string * sexpr
  | SNoexpr

type svdecl_typ = SInt | SBool | SChar
  | SArrayInit of svdecl_typ * sexpr
  | SChan of svdecl_typ
  | SStruct of string

type sassign_stmt =
  | SAssign of (sexpr * sexpr) list
  | SDeclAssign of ((string * svdecl_typ) list) * ((string * sexpr)
     list)
  | SInit of sassign_stmt list

type sstmt =
    SBlock of sstmt list
  | SExpr of sexpr
  | SAssignStmt of sassign_stmt
  | SReturn of sexpr list
  | SIf of sexpr * sstmt * sstmt
  | SFor of sstmt * sexpr * sstmt * sstmt
  | SWhile of sexpr * sstmt
  | SVdeclStmt of (string * svdecl_typ) list
  | SDefer of sexpr
  | SYeet of sx
  | SSelect of (sx * sstmt) list
```

```
  type sfunc_decl = {
    stypes : typ list;
    sfname : string;
    sformals : bind list;
    sbody : sstmt list;
  }

type sprogram = bind list * sfunc_decl list

(* Pretty-printing functions *)

let rec string_of_sexpr (t, e) =
  "(" ^ string_of_typ t ^ " : " ^ (match e with
    SIntLit(l) -> string_of_int l
  | SStrLit(l) -> l
  | SCharLit(l) -> String.make 1 (Char.chr l)
  | SBoolLit(true) -> "true"
  | SBoolLit(false) -> "false"
  | SId(s) -> s
  | SBinop(e1, o, e2) ->
      string_of_sexpr e1 ^ " " ^ string_of_op o ^ " " ^
          string_of_sexpr e2
  | SUnop(o, e) -> string_of_uop o ^ string_of_sexpr e
  | SCall(f, el) ->
      f ^ "(" ^ String.concat ", " (List.map string_of_sexpr el) ^
          ")"
  | SNoexpr -> ""
  | _ -> "general sexpr string"
                                ) ^ ")"

let rec string_of_sstmt = function
    SBlock(stmts) ->
      "{\n" ^ String.concat "" (List.map string_of_sstmt stmts) ^
          "}\n"
  | SExpr(expr) -> string_of_sexpr expr ^ ";\n";
  | SReturn(exprs) -> "return " ^ (String.concat ", " (List.map
     string_of_sexpr exprs)) ^ ";\n";
  | SIf(e, s, SBlock([])) ->
      "if (" ^ string_of_sexpr e ^ ")\n" ^ string_of_sstmt s
  | SIf(e, s1, s2) ->  "if (" ^ string_of_sexpr e ^ ")\n" ^
      string_of_sstmt s1 ^ "else\n" ^ string_of_sstmt s2
  | SFor(e1, e2, e3, s) ->
      "for (" ^ string_of_sstmt e1  ^ " ; " ^ string_of_sexpr e2 ^ "
          ; " ^
      string_of_sstmt e3  ^ ") " ^ string_of_sstmt s
```

```
  | SWhile(e, s) -> "while (" ^ string_of_sexpr e ^ ") " ^
      string_of_sstmt s
  | _ -> "general sstmt string"

let string_of_sfdecl fdecl =
  fdecl.sfname ^ "(" ^ String.concat ", " (List.map snd fdecl.
      sformals) ^
  ") (" ^ String.concat ", " (List.map string_of_typ fdecl.stypes) ^
  ")\n{\n" ^
  String.concat "" (List.map string_of_sstmt fdecl.sbody) ^
  "}\n"

let string_of_globals (t, id) = string_of_typ t ^ " " ^ id ^ ";\n"

let string_of_sprogram (vars, funcs, _) =
  String.concat "" (List.map string_of_globals vars) ^ "\n" ^
  String.concat "\n" (List.map string_of_sfdecl funcs)
```

9.6 semant.ml

```
(* Semantic checking for the RJEC compiler
 * Initially based on MicroC, with inspiration from Shoo
 * Written by Elaine Wang, Justin Chen, Riya Chakraborty, and
    Caroline Hoang
 *)

open Ast
open Sast

module StringMap = Map.Make(String)

(* Semantic checking of the AST. Returns an SAST if successful,
   throws an exception if something is wrong.

   Check each global variable, then check each function *)

let check (globals, (functions, structs)) =

  let vdecl_typ_to_typ : vdecl_typ -> typ = function
      Int -> Int
    | Bool -> Bool
    | Char -> Char
    | Chan(t) -> Chan(t)
```

```
    | ArrayInit(_, t) -> Array(t)
    | Struct(s) -> Struct(s)
  in

  let typ_to_vdecl_typ : typ -> vdecl_typ = function
      Int -> Int
    | Bool -> Bool
    | Char -> Char
    | Chan(t) -> Chan(t)
    | Array(_) -> raise (Failure("array not implemented"))
    | Struct(s) -> Struct(s)
  in

  let default_vals_in_sexpr : typ -> typ * sx = function
      Int -> (Int, SIntLit 0)
    | Bool -> (Bool, SBoolLit false)
    | Char -> (Char, SCharLit 0)
    | _ -> raise(Failure("composite types have to be checked
       separately for their default values"))
  in
  let flatten_global global = List.map
    (fun name -> (vdecl_typ_to_typ (fst global), name)) (snd global)
  in

  (* Add global names to symbol table *)
  let add_global map vd =
    let dup_err = "duplicate global " ^ snd vd
    and make_err er = raise (Failure er)
    and n = snd vd
    and typ = fst vd
    in match n with (* No duplicate globals *)
       | _ when StringMap.mem n map -> make_err dup_err
       | _ ->  StringMap.add n typ map
  in
  let check_global map global =
    List.fold_left add_global map (flatten_global global)
  in
  let global_decls = List.fold_left check_global StringMap.empty
      globals
  in

  (* Verify a list of bindings has no duplicate names *)
  let check_binds (kind : string) (binds : bind list) =
    let rec dups = function
        [] -> ()
```

```
      | ((_,n1) :: (_,n2) :: _) when n1 = n2 ->
    raise (Failure ("duplicate " ^ kind ^ " " ^ n1))
      | _ :: t -> dups t
    in dups (List.sort (fun (_,a) (_,b) -> compare a b) binds)
  in

  (* Add structs to symbol table *)
  let add_struct smap sd =
    let dup_err = "duplicate struct " ^ (fst sd)
    and make_err er = raise (Failure er)
    and n = fst sd
    in match n with (* No duplicate globals *)
      | _ when StringMap.mem n smap -> make_err dup_err
      | _ -> check_binds ("member in definition of struct " ^ (fst
         sd) ^ " :") (snd sd);
      let members = List.fold_left (fun m (t, n) -> StringMap.add n
         t m) StringMap.empty (snd sd) in
      StringMap.add n members smap
    in
  let struct_decls = List.fold_left add_struct StringMap.empty
     structs
  in

  (**** Check functions ****)

  (* Collect function declarations for built-in functions: no bodies
      *)
  let built_in_decls =
    let add_bind map (name, ty) = StringMap.add name {
      types = [];
      fname = name;
      formals = [(ty, "x")];
      body = [] } map
    in
    let print_decls = List.fold_left add_bind StringMap.empty [ ("
       printi", Int);
                                                ("printb", Bool);
                                                ("printc", Char);
                                                ("prints", Array(
                                                   Char)) ]
    in StringMap.add "time" {
      types = [Int];
      fname = "time";
      formals = [];
      body = [] } print_decls
```

```
  in

  (* Add function name to symbol table *)
  let add_func map fd =
    let built_in_err = "built-in function " ^ fd.fname ^ " is
        already defined"
    and dup_err = "duplicate function " ^ fd.fname
    and make_err er = raise (Failure er)
    and n = fd.fname (* Name of the function *)
    in match fd with (* No duplicate functions or redefinitions of
        built-ins *)
          _ when StringMap.mem n built_in_decls -> make_err
             built_in_err
        | _ when StringMap.mem n map -> make_err dup_err
        | _ ->  StringMap.add n fd map
  in

  (* Collect all function names into one symbol table *)
  let function_decls = List.fold_left add_func built_in_decls
      functions
  in

  (* Return a function from our symbol table *)
  let find_func s =
    try StringMap.find s function_decls
    with Not_found -> raise (Failure ("unrecognized function " ^ s))
  in

  let find_struct s =
    try StringMap.find s struct_decls
    with Not_found -> raise (Failure ("unrecognized struct " ^ s))
  in

  let _ = find_func "main" in (* Ensure "main" is defined *)

  let check_function func =
    (* Make sure no formals or locals are duplicates *)
    check_binds "formal" func.formals;

    (* Raise an exception if the given rvalue type cannot be
        assigned to
       the given lvalue type *)
    let check_assign lvaluet rvaluet err =
       if lvaluet = rvaluet then lvaluet else raise (Failure err)
    in
```

```
let add_to_scope (v_type : typ) (v_name : string)
    (scope : typ StringMap.t list) =
  let map = List.hd scope in
  try
    match (StringMap.find v_name map) with
      _ -> raise (Failure ("local variable " ^ v_name ^ " has
          already been declared"))
  with Not_found ->
    let newMap = StringMap.add v_name v_type map in
    newMap::List.tl scope
in

let create_scope list =
  let rec helper m = function
      [] -> m
    | (t, n)::tl ->
      let new_m = StringMap.add n t m in
      helper new_m tl
  in helper StringMap.empty list
in

let scope = [ create_scope func.formals; global_decls ]
in

(* Return a variable from our local symbol table *)
let rec type_of_identifier (v_name : string) (scope : typ
   StringMap.t list) =
  try
    StringMap.find v_name (List.hd scope)
  with Not_found -> match List.tl scope with
      [] -> raise (Failure("undeclared reference " ^ v_name))
    | tail -> type_of_identifier v_name tail
in

let check_chan : typ -> typ = function
    Chan(t) -> t
  | _ -> raise(Failure("tried to perform channel operation
      through a non-channel variable"))
in

let rec vdecl_to_svdecl_typ (t: vdecl_typ) (scope: _) :
   svdecl_typ = match t with
    Int -> SInt
  | Bool -> SBool
```

```
    | Char -> SChar
    | Chan(t) -> SChan(vdecl_to_svdecl_typ (typ_to_vdecl_typ t)
      scope)
    | Struct(s) -> SStruct(s)
    | ArrayInit(e, t) ->
        let (t', e') = expr scope e in
        if t' <> Int then raise(Failure("array size can only be
            integer expressions"));
        SArrayInit(vdecl_to_svdecl_typ (typ_to_vdecl_typ t) scope,
             (t', e'))
  and
  (* Return a semantically-checked expression, i.e., with a type
     *)
  expr (scope : typ StringMap.t list) (e : expr) : sexpr = match e
       with
      IntLit  l -> (Int, SIntLit l)
    | StrLit l  -> (Array(Char), SStrLit l)
    | CharLit l  -> (Char, SCharLit l)
    | BoolLit l  -> (Bool, SBoolLit l)
    | ArrLit(t, el) ->
      let check_elem e =
        let (t', e') = expr scope e in
        if t' <> t then raise(Failure("array element doesn't match
             declared array type"));
        (t', e')
      in
      let selems = List.map check_elem el in
      (Array(t), SArrLit(t, selems))
    | StructLit(sn, ml) ->
      let smembers = find_struct sn in
      let check_member sname members vm (n, e) =
        let (t, e') = expr scope e in
        match n with
          _ when ((StringMap.mem n members) && (t = StringMap.find
              n members)) -> StringMap.add n (t, e') vm
        | _ -> raise(Failure("unknown member " ^ n ^ " of type " ^
             (string_of_typ t)
                              ^ " in definition of struct " ^ sname
                                 )) in
      let member_vals = List.fold_left (check_member sn smembers)
         StringMap.empty ml in
      let full_member_vals = List.fold_left (fun m (n, t) -> match
          n with
          _ when StringMap.mem n m -> m
        | _ -> StringMap.add n (default_vals_in_sexpr t) m
```

```
          ) member_vals (StringMap.bindings smembers) in
          (Struct(sn), SStructLit(sn, StringMap.bindings
             full_member_vals))
        | Id s       -> (type_of_identifier s scope, SId s)
        | Unop(op, e) as ex ->
            let (t, e') = expr scope e in
            let ty = match op with
              Neg when t = Int -> t
            | Not when t = Bool -> Bool
            | _ -> raise (Failure ("illegal unary operator " ^
                                   string_of_uop op ^ string_of_typ t
                                       ^
                                   " in " ^ string_of_expr ex))
            in (ty, SUnop(op, (t, e')))
        | Binop(e1, op, e2) as e ->
            let (t1, e1') = expr scope e1
            and (t2, e2') = expr scope e2 in
            (* All binary operators require operands of the same type
               *)
            let same = t1 = t2 in
            (* Determine expression type based on operator and operand
                types *)
            let ty : typ = match op with
              Add | Sub | Mult | Div | Mod when same && t1 = Int   ->
                  Int
            | Equal    when same  && (t1 = Int || t1 = Char || t1 =
                 Bool)  -> Bool
            | Less | Leq
                       when same && (t1 = Int || t1 = Char) -> Bool
            | And | Or when same && t1 = Bool -> Bool
            | _ -> raise (
                Failure ("illegal binary operator " ^
                         string_of_typ t1 ^ " " ^ string_of_op op ^ "
                             " ^
                         string_of_typ t2 ^ " in " ^ string_of_expr e)
                             )
            in (ty, SBinop((t1, e1'), op, (t2, e2')))
        | Make(t, buf_raw) ->
          let check_buf (buf_raw : expr option) : sexpr = match
              buf_raw with
              None -> (Int, SIntLit 0)
            | Some(e) -> let (t', e') = expr scope e in
                           if t' <> Int then raise(Failure("non-
                               integer used for channel buffer size"))
                           else (t', e') in
```

```
          let buf = check_buf buf_raw in
          (Chan(t), SMake(t, buf))
        | Send(n, e) ->
          let (ct, ce) = expr scope n in
          let chan_type = check_chan ct in
          let (t', e') = expr scope e in
          if t' <> chan_type then raise(Failure("Channel type mismatch
              with type of element to send"));
          (t', SSend((ct, ce), (t', e')))
        | Recv n ->
          let (ct, ce) = expr scope n in
          let chan_type = check_chan ct in
          (chan_type, SRecv((ct, ce), chan_type))
        | Close n ->
          let (ct, ce) = expr scope n in
          let chan_type = check_chan ct in
          (chan_type, SClose((ct, ce), chan_type))
        | Access(e, mn) ->
          let e' = expr scope e in
          let extract_struct_name (t : typ) = match t with
              Struct(n) -> n
            | _ -> raise(Failure("Invalid syntax: access member field
                of non-struct object\n")) in
          let check_struct_or_arr_field e' = match (snd e') with
              SId(n) -> extract_struct_name (type_of_identifier n
                  scope)
            | SSubscript(an, _) -> (function
                Array(Struct(n)) -> n
              | _ -> raise(Failure("subscript on non-struct array
                  element!"))
            ) (type_of_identifier an scope)
            | _ -> raise(Failure("invalid access; should've checked in
                semant!")) in
          let sn = check_struct_or_arr_field e' in
          let smembers = find_struct sn in
          let t = match sn with
            _ when StringMap.mem mn smembers -> StringMap.find mn
                smembers
          | _ -> raise(Failure("unknown field " ^ mn ^ " in struct " ^
              sn)) in
          (t, SAccess((snd e'), sn, mn))
        | Subscript(s, e) ->
          let arr = expr scope (Id s) in
          let array_t = (function
                              Array(t) -> t
```

```
                    | _ -> raise(Failure("using subscript on non
                       -array object!"))) (fst arr) in
        let index = expr scope e in
        if (fst index) <> Int then raise(Failure("subscript with non
           -integer expression!"));
        (array_t, SSubscript(s, index))
      | Call(fname, args) as call ->
          let fd = find_func fname in
          let param_length = List.length fd.formals in
          if List.length args != param_length then
            raise (Failure ("expecting " ^ string_of_int
               param_length ^
                          " arguments in " ^ string_of_expr call))
          else let check_call (ft, _) e =
            let (et, e') = expr scope e in
            let err = "illegal argument found " ^ string_of_typ et ^
              " expected " ^ string_of_typ ft ^ " in " ^
                 string_of_expr e
            in (check_assign ft et err, e')
          in
          let args' = List.map2 check_call fd.formals args in
          (* fix multiple returns later *)
          let rt_type : typ = match fd.types with
              [] -> Int
            | t :: [] -> t
            | _ -> raise(Failure("Multiple return types not
               implemented yet")) in
          (rt_type, SCall(fname, args'))
        | _ -> raise (Failure ("not yet implemented"))
    in

    let check_assign_var scope var e =
      let lt = type_of_identifier var scope and (rt, e') = expr
         scope e in
       let err = "illegal assignment " ^ string_of_typ lt ^ " = " ^
      string_of_typ rt
      in ignore(check_assign lt rt err); (var, (rt, e'))
    in

    let check_bool_expr scope e =
      let (t', e') = expr scope e
      and err = "expected Boolean expression in " ^ string_of_expr e
      in if t' != Bool then raise (Failure err) else (t', e')
    in
```

```
(* Return a semantically-checked statement i.e. containing
   sexprs *)
let rec check_stmt scope = function
    Expr e -> (SExpr(expr scope e), scope)
  | If(p, b1, b2) ->
    let (sstmt1, _) = check_stmt scope b1
    and (sstmt2, _) = check_stmt scope b2 in
    (SIf(check_bool_expr scope p, sstmt1, sstmt2), scope)
  | For(e1, e2, e3, st) ->
    let rec forbid_defer = function
        Defer _ -> raise(Failure("defer statement inside of
           while block"))
      | Block sl -> List.iter forbid_defer sl
      | _ -> () in
    forbid_defer st;

    let (sstmt, nscope) =
    (function
        None      -> (SExpr(Int, SNoexpr), scope)
      | Some(s)   -> check_stmt scope (AssignStmt s)
    ) e1 in

    let sexpr = check_bool_expr nscope e2 in

    let (sstmt3, nscope) = (fun scope e -> match e with
        Some(Assign(_, _) as e') -> check_stmt scope (AssignStmt
            e')
      | None          -> (SExpr(Int, SNoexpr), scope)
      | _             -> raise(Failure("variable declaration
         misplaced in for loop"))
    ) nscope e3 in

    let (sstmt4, _) = check_stmt nscope st in
    (SFor(sstmt, sexpr, sstmt3, sstmt4), scope)
  | While(e, s) ->
    let rec forbid_defer = function
        Defer _ -> raise(Failure("defer statement inside of
           while block"))
      | Block sl -> List.iter forbid_defer sl
      | _ -> () in
    forbid_defer s;
    let (sstmt, nscope) = check_stmt scope s in
    (SWhile(check_bool_expr nscope e, sstmt), nscope)

  | Return el ->
```

```
        if (List.length el <> List.length func.types) then
          raise(Failure("The function '" ^ func.fname ^ "' has " ^
                        string_of_int (List.length func.types) ^
                        " return types, but only " ^ string_of_int (
                            List.length el) ^
                        " expressions were returned"));
        let check_return_typ e rt =
          let (t, e') = expr scope e in
          if t = rt then (t, e')
          else raise (Failure ("return gives " ^ string_of_typ t ^ "
               expected " ^
                       string_of_typ rt ^ " in " ^ string_of_expr e))
        in
        (SReturn(List.map2 check_return_typ el func.types), scope)
            (* A block is correct if each statement is correct and
               nothing
               follows any Return statement.  Nested blocks are
                  flattened. *)
      | Yeet e ->
          let scall = (function
              Call(f, _) as call ->
                let fdecl = find_func f in
                if (fdecl.types <> []) && (fdecl.types <> [Int])
                  then raise(Failure("a yeet function call can only
                     return int or nothing"));
                snd (expr scope call)
            | _ -> raise(Failure("can't yeet a non-function call"))
          ) e in (SYeet(scall), scope)
      | AssignStmt s ->
          let check_assign_stmt = function
              Assign(vl, el)  ->
                let helper v e =
                  let (mt, e') = expr scope v in
                  (function
                       SId s ->
                         let (_, e') = check_assign_var scope s e in
                         ((fst e', SId(s)), e')
                     | SAccess (n, sn, mn) ->
                       let (t, e') = expr scope e in
                       if mt <> t then raise(Failure("illegal
                          assignment " ^ string_of_typ mt ^ " = " ^
                         string_of_typ t)); ((mt, SAccess(n, sn, mn))
                              , (t, e'))
                     | SSubscript (an, index) ->
                       let mt = type_of_identifier an scope in
```

```
                let (t, e') = expr scope e in
                if mt <> Array(t) then raise(Failure("illegal
                    assignment of element to array"));
                ((mt, SSubscript(an, index)), (t, e'))
              | _      -> raise(Failure("invalid assignment"))
            ) e'
          in
        (SAssign (List.map2 helper vl el), scope)

      | DeclAssign(vd, el) -> let (_, nscope) = check_stmt
          scope (VdeclStmt vd) in
          let vdl = List.map (fun n -> (n, vdecl_to_svdecl_typ
               (fst vd) scope) ) (snd vd) in
          let assl = List.map2 (check_assign_var nscope) (snd
              vd) el in
          (SDeclAssign(vdl, assl), nscope)
      | Init(vl, el) ->
          let helper (ll, scope) v e =
               let s = (function
                   Id s -> s
                 | _      -> raise(Failure("trying to initialize
                     non-identifier"))
               ) v in

               let (t, e') = expr scope e in
               let nscope = add_to_scope t s scope in
               let lhs_svdecl = (function
                   (_, SArrLit(elem_t, el)) ->
                     let arr_len = List.length el in
                     SArrayInit(
                       vdecl_to_svdecl_typ (typ_to_vdecl_typ
                           elem_t) scope,
                       (Int, SIntLit(arr_len))
                     )
                 | (_, SStrLit l) -> SArrayInit(SChar, (Int,
                     SIntLit((String.length l) + 1)))
                 | (Array(elem_t), _) -> SArrayInit(
                     vdecl_to_svdecl_typ (typ_to_vdecl_typ
                         elem_t) scope,
                     (Int, SIntLit(1))
                   )
                 | _ -> vdecl_to_svdecl_typ (typ_to_vdecl_typ t
                     ) scope
               ) (t, e')
               in
```

```
                    (SDeclAssign([(s, lhs_svdecl)], [(s, (t, e'))])
                       :: ll,
                     nscope)
               in
             let (dal, nscope) = List.fold_left2 helper ([], scope)
                 vl el
             in (SInit(List.rev dal), nscope)

         in let (sassign, sscope) = check_assign_stmt s in
         (SAssignStmt(sassign), sscope)
     | VdeclStmt s ->
         let (t, nl) = s in
         let (nscope, vdecls) = List.fold_left (fun (scope, vdecls)
             n ->
           (add_to_scope (vdecl_typ_to_typ t) n scope, (n,
              vdecl_to_svdecl_typ t scope)::vdecls)
         ) (scope, []) nl
         in (SVdeclStmt(vdecls), nscope)
     | Defer e ->
       (function
         Call(_, _) -> (SDefer(expr scope e), scope)
       | _ -> raise(Failure("defering a non-function call"))
       ) e
     | Select cl ->
       let rec check_case_list scope = function
           (case, sl) :: tl ->
             let case_instr = (function
                 Expr(Send(c, e)) -> SSend(expr scope c, expr scope
                     e)
               | Expr(Recv(c)) | AssignStmt(DeclAssign(_, [Recv(c)
                  ]))
                 | AssignStmt(Assign(_, [Recv(c)]))
                 | AssignStmt(Init(_, [Recv(c)])) ->
                   let (ct, ce) = expr scope c in
                   let chan_type = check_chan ct in
                   SRecv((ct, ce), chan_type)
               | _ -> raise(Failure("wrong case format in semant"))
             ) case in
             let blockstmt = Block(case :: sl) in
             let (ret, _) = check_stmt scope blockstmt in
             let ret2 = check_case_list scope tl in
             ((case_instr, ret) :: ret2)
         | [] -> []
       in
       (SSelect(check_case_list scope cl), scope)
```

```
      | Block sl ->
          let bscope = (create_scope []) :: scope in
          let rec check_stmt_list scope = function
              [Return _ as s] ->
                let (ret, _) = check_stmt scope s in ([ret], scope)
            | Return _ :: _   -> raise (Failure "nothing may follow
                a return")
            | s :: ss         ->
              let (ret, nscope) = check_stmt scope s in
              let (ret2, nscope2) = check_stmt_list nscope ss in
              (ret :: ret2, nscope2)
            | []              -> ([], scope)
          in let (bret, _) = check_stmt_list bscope sl
          in (SBlock(bret), scope)

    in (* body of check_function *)
    { stypes = func.types;
      sfname = func.fname;
      sformals = func.formals;
      sbody = match check_stmt scope (Block func.body) with
        (SBlock(sl), _) -> sl
      | _ -> raise (Failure ("internal error: block didn't become a
         block?"))
    }
  in (List.flatten (List.map flatten_global globals),
        List.map check_function functions, structs)
```

9.7 codegen.ml

```
(* Code generation: translate takes a semantically checked AST and
 * Initially based on MicroC, with inspiration from Shoo
 * Written by Elaine Wang, Justin Chen, Riya Chakraborty, and
    Caroline Hoang
 *)

module L = Llvm
module A = Ast
open Sast

module StringMap = Map.Make(String)

(* translate : Sast.program -> Llvm.module *)
let translate (globals, functions, structs) =
```

```
let context    = L.global_context () in

(* Create the LLVM compilation module into which
   we will generate code *)
let the_module = L.create_module context "RJEC" in

(* Get types from the context *)
let i64_t      = L.i64_type    context
and i32_t      = L.i32_type    context
and i8_t       = L.i8_type     context
and i1_t       = L.i1_type     context
and void_t     = L.void_type   context
and void_ptr_t = L.pointer_type (L.i8_type context) in
let func_t     = L.pointer_type (L.function_type i32_t [|
    void_ptr_t |]) in

let rec generate_seq n = if n >= 0 then (n :: (generate_seq (n-1))
    ) else [] in

let struct_decls : ((A.typ StringMap.t) * L.lltype) StringMap.t =
  let add_struct m (n, ml) =
    let ltype_of_basic_typ ((t, _) : (A.typ * string)) : L.lltype
        = match t with
         A.Int   -> i32_t
       | A.Bool  -> i1_t
       | A.Char  ->  i8_t
       | _       -> raise(Failure("Struct member typ not basic --
          should've been checked in parser!\n"))
    in
    let compare_by (_, n1) (_, n2) = compare n1 n2 in
    let member_typs = Array.of_list (List.map ltype_of_basic_typ (
        List.sort compare_by ml)) in
    let struct_t = L.struct_type context member_typs in
    let member_names = List.fold_left (fun m (t, n) -> StringMap.
        add n t m) StringMap.empty ml in
    StringMap.add n (member_names, struct_t) m
  in List.fold_left add_struct StringMap.empty structs
in

(* Return the LLVM type for a RJEC type *)
let rec ltype_of_typ : A.typ -> L.lltype = function
    A.Int       -> i32_t
  | A.Bool      -> i1_t
  | A.Char      ->  i8_t
  | A.Struct(n) -> snd (StringMap.find n struct_decls)
```

```
    | A.Chan(_)   -> void_ptr_t
    | A.Array(t)  -> L.pointer_type (ltype_of_typ t)
  in

  let typ_to_typ_char (t : A.typ) = match t with
      A.Int   -> L.const_int i8_t (Char.code 'i')
    | A.Bool  -> L.const_int i8_t (Char.code 'b')
    | A.Char  -> L.const_int i8_t (Char.code 'c')
    | _       -> raise(Failure("non-basic type for chan; should've
       checked in parser"))
  in

  (* Create a map of global variables after creating each *)
  let global_vars : L.llvalue StringMap.t =
    let global_var m (t, n) =
      let init = match t with
          _ -> L.const_int (ltype_of_typ t) 0
          (* TODO: add other cases *)
      in StringMap.add n (L.define_global n init the_module) m in
    List.fold_left global_var StringMap.empty globals in

  let printf_t : L.lltype =
      L.var_arg_function_type i32_t [| L.pointer_type i8_t |] in
  let printf_func : L.llvalue =
      L.declare_function "printf" printf_t the_module in

  let gettime_t : L.lltype =
    L.function_type i32_t [| |] in
  let gettime_func : L.llvalue =
    L.declare_function "get_time" gettime_t the_module in

  let printbool_t : L.lltype =
      L.function_type i32_t [| i1_t |] in
  let printbool_func : L.llvalue =
      L.declare_function "printbool" printbool_t the_module in

  let yeet_t : L.lltype =
      L.function_type void_t [| func_t ; void_ptr_t |] in
  let yeet_func : L.llvalue =
      L.declare_function "yeet" yeet_t the_module in

  let makechan_t : L.lltype =
      L.function_type void_ptr_t [| i8_t ; i32_t |] in
  let makechan_func : L.llvalue =
    L.declare_function "makechan" makechan_t the_module in
```

```
let send_t : L.lltype =
  L.function_type void_t [| void_ptr_t ; i8_t ; i32_t |] in
let send_func : L.llvalue =
  L.declare_function "send" send_t the_module in

let recv_int_t : L.lltype =
  L.function_type i32_t [| void_ptr_t |] in
let recv_bool_t : L.lltype =
  L.function_type i1_t [| void_ptr_t |] in
let recv_char_t : L.lltype =
  L.function_type i8_t [| void_ptr_t |] in
let recv_int_func : L.llvalue =
  L.declare_function "recv_int" recv_int_t the_module in
let recv_bool_func : L.llvalue =
  L.declare_function "recv_bool" recv_bool_t the_module in
let recv_char_func : L.llvalue =
  L.declare_function "recv_char" recv_char_t the_module in

let closechan_t : L.lltype =
  L.function_type void_t [| void_ptr_t ; i8_t |] in
let closechan_func : L.llvalue =
  L.declare_function "closechan" closechan_t the_module in

let clause_member_typs = [| i8_t ; void_ptr_t ; void_ptr_t ; i64_t
    |] in
let clause_t = L.struct_type context clause_member_typs in
let select_t : L.lltype =
  L.function_type i32_t [| L.pointer_type clause_t ; i32_t |] in
let select_func : L.llvalue =
  L.declare_function "selectchan" select_t the_module in

let function_arg_structs =
  let add_function_arg_struct m fdecl =
    let member_typs = Array.of_list (List.map (fun (t, _) ->
        ltype_of_typ t) fdecl.sformals) in
    let struct_t = L.struct_type context member_typs in
    StringMap.add fdecl.sfname struct_t m
  in
  List.fold_left add_function_arg_struct StringMap.empty functions
in

(* Define each function (arguments and return type) so we can
   call it even before we've created its body *)
let function_decls : (L.llvalue * sfunc_decl) StringMap.t =
```

```
    let function_decl m fdecl =
      let name = fdecl.sfname in
    (* TODO: actually handle the multiple return types. *)
      let rt_type = match fdecl.stypes with
          []      -> i32_t
        | t :: [] -> ltype_of_typ t
        | _       -> raise(Failure("Multiple return types not
            implemented yet")) in
      let ftype = L.function_type rt_type [| void_ptr_t |] in
      StringMap.add name (L.define_function name ftype the_module,
          fdecl) m in
    List.fold_left function_decl StringMap.empty functions in

  (* Fill in the body of the given function *)
  let build_function_body fdecl =
    let (the_function, _) = StringMap.find fdecl.sfname
        function_decls in
    let builder = L.builder_at_end context (L.entry_block
        the_function) in

    let int_format_str = L.build_global_stringptr "%d\n" "fmt"
        builder
    and char_format_str = L.build_global_stringptr "%c\n" "fmt"
        builder
    and str_format_str = L.build_global_stringptr "%s\n" "fmt"
        builder in
    (* TODO: reevaluate string formatting *)

    (* Construct the function's "locals": formal arguments and
        locally
       declared variables.  Allocate each on the stack, initialize
           their
       value, if appropriate, and remember their values in the "
           locals" map *)

    let formal_vals =
      let args_type = StringMap.find fdecl.sfname
          function_arg_structs in
      let void_ptr = List.hd (Array.to_list (L.params the_function))
           in
      let ptr = L.build_bitcast void_ptr (L.pointer_type args_type)
          (fdecl.sfname ^ "_args_ptr") builder in
      let args = L.build_load ptr (fdecl.sfname ^ "_args") builder
          in
      let idxs = List.rev (generate_seq ((List.length fdecl.sformals
```

```
        ) - 1)) in
      let args_list = List.fold_left (fun l idx ->
        let arg = L.build_extractvalue args idx (
          fdecl.sfname ^ "_arg_" ^ (string_of_int idx)
        ) builder in arg::l
      ) [] idxs in
      List.rev args_list
    in

    let local_vars =
      let add_formal m (t, n) p =
        L.set_value_name n p;
        let local =
          let create_local (t: A.typ) = match t with
              A.Struct(_) as t  -> L.build_malloc (ltype_of_typ t) n
                  builder
            | _                 -> L.build_alloca (ltype_of_typ t) n
                builder in
          create_local t in
        ignore (L.build_store p local builder);
        StringMap.add n local m

      (* Allocate space for any locally declared variables and add
        the
       * resulting registers to our map *)
      and add_local m (t, n) =
        let local_var = L.build_alloca (ltype_of_typ t) n builder
        in StringMap.add n local_var m
      in

      let formals = List.fold_left2 add_formal StringMap.empty fdecl
          .sformals
          formal_vals in
      List.fold_left add_local formals []
    in

    (* Return the value for a variable or formal argument.
       Check local names first, then global names *)
    let rec lookup n ml = try StringMap.find n (List.hd ml) with
      Not_found -> match List.tl ml with
          [] -> raise (Failure("codegen lookup: undeclared reference
              " ^ n))
        | tail -> lookup n tail
    in
```

```
let defered_el = [] in

let rec svdecl_typ_to_typ : svdecl_typ -> A.typ = function
    SInt              -> A.Int
  | SBool             -> A.Bool
  | SChar             -> A.Char
  | SChan(t)          -> A.Chan(svdecl_typ_to_typ t)
  | SArrayInit(t, _)  -> A.Array(svdecl_typ_to_typ t)
  | SStruct(s)        -> A.Struct(s)
in

let default_value_of_typ (t: A.typ) builder = match t with
    A.Int | A.Bool | A.Char -> L.const_int (ltype_of_typ t) 0
  | A.Chan(_)   -> L.const_pointer_null void_ptr_t
  | A.Struct(n) ->
    let (member_names, struct_t) = StringMap.find n struct_decls
        in
    let compare_by (n1, _) (n2, _) = compare n1 n2 in
    let members = List.sort compare_by
      (StringMap.bindings member_names) in
    let idxs = List.rev (generate_seq ((List.length members) -
       1)) in
    let v = List.fold_left2 (fun agg i member ->
      let (n, t) = member in
      (L.build_insertvalue agg (L.const_int (ltype_of_typ t) 0)
         i n builder))
     (L.const_null struct_t) idxs members in v
  | A.Array(t') -> L.const_pointer_null (L.pointer_type (
      ltype_of_typ t'))
in

(* Construct code for an expression; return its value *)
let rec expr m builder ((_, e) : sexpr) = match e with
    SIntLit i   -> L.const_int i32_t i
  | SStrLit s   -> L.build_global_stringptr s "strlit" builder
  | SCharLit c  -> L.const_int i8_t c
  | SBoolLit b  -> L.const_int i1_t (if b then 1 else 0)
  | SStructLit(sn, ml) ->
    let (_, struct_t) = StringMap.find sn struct_decls in
    let compare_by (n1, _) (n2, _) = compare n1 n2 in
    let sorted_vals = List.map (fun (_, sexpr) -> expr m builder
        sexpr) (List.sort compare_by ml) in
    let idxs = List.rev (generate_seq ((List.length sorted_vals)
        - 1)) in
    let v = List.fold_left2 (fun agg i v ->
```

```
          L.build_insertvalue agg v i "tmp" builder)
        (L.const_null struct_t) idxs sorted_vals in
        let local = L.build_malloc struct_t sn builder in
        ignore(L.build_store v local builder); local
      | SArrLit(t, el) ->
        let arr_len = List.length el in
        let arr_t = ltype_of_typ t in
        let arr = L.build_array_malloc arr_t (L.const_int i32_t
            arr_len) "arrlit" builder in
        let elems = List.map (expr m builder) el in
        let idxs = List.rev (generate_seq (List.length el - 1)) in
        List.iter2 (fun i elem ->
          let arr_ptr = L.build_gep arr [| (L.const_int i32_t i) |]
              "" builder in
          let elem_ptr = L.build_pointercast arr_ptr (L.pointer_type
               arr_t) "" builder in
          ignore(L.build_store elem elem_ptr builder)
        ) idxs elems; arr
      | SNoexpr -> L.const_int i32_t 0
      | SId s   -> L.build_load (lookup s m) s builder
      | SBinop (e1, op, e2) ->
        let e1' = expr m builder e1
        and e2' = expr m builder e2 in
        (match op with
          A.Add     -> L.build_add
        | A.Sub     -> L.build_sub
        | A.Mult    -> L.build_mul
        | A.Div     -> L.build_sdiv
        | A.Mod     -> L.build_srem
        | A.And     -> L.build_and
        | A.Or      -> L.build_or
        | A.Equal   -> L.build_icmp L.Icmp.Eq
        | A.Less    -> L.build_icmp L.Icmp.Slt
        | A.Leq     -> L.build_icmp L.Icmp.Sle
        ) e1' e2' "tmp" builder
      | SUnop (op, ((_, _) as e)) ->
        let e' = expr m builder e in
        (match op with
          A.Neg                  -> L.build_neg
        | A.Not                  -> L.build_not) e' "tmp" builder

      | SCall ("printi", [e]) ->
        L.build_call printf_func [| int_format_str ; (expr m builder
            e) |]
          "printf" builder
```

```
      | SCall ("printc", [e]) ->
        L.build_call printf_func [| char_format_str ; (expr m
           builder e) |]
          "printf" builder

      | SCall ("prints", [e]) ->
        L.build_call printf_func [| str_format_str ; (expr m builder
            e) |]
        "printf" builder

      | SCall ("printb", [e]) ->
        L.build_call printbool_func [| (expr m builder e) |]
        "printbool" builder

      | SCall ("time", _) ->
          L.build_call gettime_func [| |]
          "get_time" builder

      | SCall (f, args) ->
        let (fdef, local, result) = construct_func_call f args m
           builder in
        L.build_call fdef [| local |] result builder
      | SMake (t, buf) ->
        let t_char = typ_to_typ_char t in
        let ll_buf = expr m builder buf in
        L.build_call makechan_func [| t_char ; ll_buf |] "makechan"
           builder
      | SSend (n, e) ->
        let chan = expr m builder n in
        let value = expr m builder e in
        L.build_call send_func [| chan ; typ_to_typ_char (fst e) ;
            L.build_intcast value i32_t "tmp" builder |] "" builder
      | SRecv (n, t) ->
        let chan = expr m builder n in
        let recv_by_typ (t : A.typ) = match t with
            A.Int  -> L.build_call recv_int_func [| chan |] "
               recv_int" builder
          | A.Bool -> L.build_call recv_bool_func [| chan |] "
              recv_bool" builder
          | A.Char -> L.build_call recv_char_func [| chan |] "
              recv_int" builder
          | _ -> raise(Failure("trying to receive non-basic type
              from channel; should've checked in parser")) in
        recv_by_typ t
```

```
    | SClose (n, t) ->
      let chan = expr m builder n in
      L.build_call closechan_func [| chan ; typ_to_typ_char t |]
         "" builder
    | SAccess (sx, sn, mn) ->
      let struct_val = expr m builder (A.Struct(sn), sx) in
      let (member_names, _) = StringMap.find sn struct_decls in
      let compare_by (n1, _) (n2, _) = compare n1 n2 in
      let sorted_names = List.map (fun (n, _) -> n) (List.sort
         compare_by (StringMap.bindings member_names)) in
      let name_idx_pairs = List.mapi (fun i n -> (n, i))
         sorted_names in
      let idx = snd (List.hd (List.filter (fun (n, _) -> n = mn)
         name_idx_pairs)) in
      L.build_extractvalue struct_val idx mn builder
    | SSubscript (n, e) ->
      let arr = expr m builder (A.Int, SId(n)) in
      let idx = expr m builder e in
      L.build_load (L.build_gep arr [| idx |] "" builder) ""
         builder
  and
  construct_func_call f args m builder =
    let (fdef, fdecl) = StringMap.find f function_decls in
    let args_t = StringMap.find f function_arg_structs in
    let llargs = List.rev (List.map (
      fun arg -> match arg with
          (_, SStructLit(s, _)) -> let p = expr m builder arg in
                                   L.build_load p (s ^ "_lit")
                                      builder
        | (_, SStrLit l) ->
          let arr_len = (String.length l) + 1 in
          let arr_t = (ltype_of_typ A.Char) in
          let arr = L.build_array_malloc arr_t (L.const_int i32_t
             arr_len) "arrlit" builder in
          let idxs = List.rev (generate_seq (arr_len - 1)) in

          List.iter (fun i ->
            let c = (if i = (String.length l) then 0 else Char.
               code (String.get l i)) in
            let elem = L.const_int i8_t c in
            let arr_ptr = L.build_gep arr [| (L.const_int i32_t i)
                |] "" builder in
            let elem_ptr = L.build_pointercast arr_ptr (L.
               pointer_type arr_t) "" builder in
            ignore(L.build_store elem elem_ptr builder)
```

```
           ) idxs; arr
         | _ -> expr m builder arg
    ) (List.rev args)) in

    let local = L.build_malloc args_t (f ^ "_args") builder in
    let idxs  = List.rev (generate_seq ((List.length fdecl.
        sformals) - 1)) in
    let args  = List.fold_left2 (fun agg i llarg ->
      (L.build_insertvalue agg llarg i ("arg_" ^ string_of_int i)
         builder))
    (L.const_null args_t) idxs llargs in
    ignore(L.build_store args local builder);
    (* TODO: fix multiple return types later *)
    let result = (match fdecl.stypes with
        [] -> ""
      | _ :: [] -> f ^ "_result"
      | _ -> raise(Failure("Multiple return types not implemented
         yet"))) in

    let void_ptr_arg = L.build_bitcast local void_ptr_t (f ^ "
        _arg_pointer") builder in
    (fdef, void_ptr_arg, result)
  in

  (* LLVM insists each basic block end with exactly one "
     terminator"
     instruction that transfers control.  This function runs "
        instr builder"
     if the current block does not already have a terminator.
        Used,
     e.g., to handle the "fall off the end of the function" case.
        *)
  let add_terminal builder instr =
    match L.block_terminator (L.insertion_block builder) with
          Some _  -> ()
    | None    -> ignore (instr builder) in

  (* Build the code for the given statement; return the builder
     for
     the statement's successor (i.e., the next instruction will be
         built
     after the one generated by this call) *)

  let rec stmt m dl builder = function
          SBlock sl ->
```

```
        let stmt_list builder ml dl sl =
          let helper (bldr, map, dl) = stmt map dl bldr in
          let (b, mm, ndl) = List.fold_left helper (builder, ml,
              dl) sl
          in (b, List.tl mm, ndl)
        in
      stmt_list builder (StringMap.empty::m) dl sl

  | SVdeclStmt vdl ->
      let declare_var (builder, mm, dl) ((n, t) : (string *
          svdecl_typ)) =
        let store_default_val = function
            SInt | SBool | SChar | SChan(_) ->
              let local = L.build_alloca (ltype_of_typ (
                  svdecl_typ_to_typ t)) n builder in
              let default_value = (default_value_of_typ (
                  svdecl_typ_to_typ t) builder) in
              ignore(L.build_store default_value local builder);
                  local
          | SStruct(_) ->
              let local = L.build_malloc (ltype_of_typ (
                  svdecl_typ_to_typ t)) n builder in
              let v = default_value_of_typ (svdecl_typ_to_typ t)
                  builder in
              ignore(L.build_store v local builder); local
          | SArrayInit(t, e) ->
              let array_t = ltype_of_typ (svdecl_typ_to_typ t)
                  in
              let array_len = expr m builder e in
              let ptr = L.build_array_malloc array_t array_len
                  "" builder in
              let local = L.build_alloca (L.pointer_type array_t
                  ) n builder in
              ignore(L.build_store ptr local builder); local in
        let local = store_default_val t in
        (* TODO: add to the symbol table?/manage scope? *)
        let new_m = StringMap.add n local (List.hd mm)
        in (builder, new_m::(List.tl mm), dl)
      in List.fold_left declare_var (builder, m, dl) vdl
  | SExpr e   -> ignore(expr m builder e); (builder, m, dl)
  | SReturn e -> (* TODO: fix multiple return types later *)
    ignore(List.map (fun (fdef, llargs, result) ->
      L.build_call fdef llargs result builder) dl);
    ignore(match fdecl.stypes with
        (* Special "return nothing" instr *)
```

```
            [] -> L.build_ret (L.const_int i32_t 0) builder
            (* Build return statement *)
          | _ :: [] -> L.build_ret (expr m builder (List.hd e))
             builder
          | _ -> raise(Failure("Multiple return types not
             implemented yet")));
        (builder, m, [])
      | SYeet(SCall(f, args)) ->
        let (fdef, local, _) = construct_func_call f args m builder
           in
        (* let local_void_ptr = L.build_bitcast local void_ptr_t (f
           ^ "_arg_ptr") builder in *)
        ignore(L.build_call yeet_func [| fdef ; local |] "" builder)
           ; (builder, m, dl)
      | SAssignStmt s   -> let assign_stmt builder = function
          SAssign sl  ->
            let extract_value e = match e with
                (_, SStructLit(_, _)) -> let ptr = expr m builder e
                   in
                                       L.build_load ptr "tmp"
                                          builder
              | (_, SStrLit l) ->
                let arr_len = (String.length l) + 1 in
                let arr_t = (ltype_of_typ A.Char) in
                let arr = L.build_array_malloc arr_t (L.const_int
                   i32_t arr_len) "arrlit" builder in
                let idxs = List.rev (generate_seq (arr_len - 1)) in

                List.iter (fun i ->
                  let c = (if i = (String.length l) then 0 else Char
                     .code (String.get l i)) in
                  let elem = L.const_int i8_t c in
                  let arr_ptr = L.build_gep arr [| (L.const_int
                     i32_t i) |] "" builder in
                  let elem_ptr = L.build_pointercast arr_ptr (L.
                     pointer_type arr_t) "" builder in
                  ignore(L.build_store elem elem_ptr builder)
                ) idxs; arr
              | _ -> expr m builder e
            in
            let eval_assign_lhs ee e = match ee with
                (_, SId(s)) ->
                  let value = extract_value e in
                  ignore(L.build_store value (lookup s m) builder);
                     builder
```

```
                | (_, SSubscript(an, index)) ->

                  let value = extract_value e in
                  let arr = L.build_load (lookup an m) "tmp" builder
                      in
                  let idx = expr m builder index in
                  let ptr = L.build_gep arr [| idx |] "" builder in
                  ignore(L.build_store value ptr builder); builder
                | (_, SAccess(sx, sn, mn)) ->
                  let struct_val = expr m builder (A.Struct(sn), sx)
                      in
                  let (member_names, _) = StringMap.find sn
                      struct_decls in
                  let compare_by (n1, _) (n2, _) = compare n1 n2 in
                  let sorted_names = List.map (fun (n, _) -> n) (List.
                      sort compare_by (StringMap.bindings member_names)
                      ) in
                  let name_idx_pairs = List.mapi (fun i n -> (n, i))
                      sorted_names in
                  let idx = snd (List.hd (List.filter (fun (n, _) -> n
                       = mn) name_idx_pairs)) in
                  let e' = expr m builder e in
                  let v = L.build_insertvalue struct_val e' idx mn
                      builder in

                  let insert_value sx = match sx with
                      SId(n) -> L.build_store v (lookup n m) builder
                    | SSubscript(an, index) ->
                      let arr = L.build_load (lookup an m) "tmp"
                          builder in
                      let idx = expr m builder index in
                      L.build_store v (L.build_gep arr [| idx |] ""
                          builder) builder
                    | _ -> raise(Failure("invalid access; should've
                        checked in semant!"))
                  in
                  ignore(insert_value sx); builder
                | _ -> raise(Failure("invalid assign lhs; should've
                    checked in semant!"))
              in
              ignore(List.map (fun (ee, e) -> eval_assign_lhs ee e) sl
                  ); (builder, m, dl)

            | SDeclAssign (vdl, assl) -> let (_, mm, dl) = stmt m dl
               builder (SVdeclStmt vdl) in
```

```
                let new_assl = List.map (fun (s, e) -> ((
                    svdecl_typ_to_typ (snd (List.hd vdl)), SId(s)), e
                    )) assl in
                stmt mm dl builder (SAssignStmt(SAssign(new_assl)))
          | SInit dal -> List.fold_left (fun (builder, m, dl) da ->
              stmt m dl builder(SAssignStmt da)) (builder, m, dl) dal
        in assign_stmt builder s

      | SIf (predicate, then_stmt, else_stmt) ->
        let bool_val = expr m builder predicate in
              let merge_bb = L.append_block context "merge"
                  the_function in
        let build_br_merge = L.build_br merge_bb in (* partial
            function *)

        let then_bb = L.append_block context "then" the_function in
        let (builder1, _, dl) = stmt m dl (L.builder_at_end context
            then_bb) then_stmt in
        add_terminal builder1 build_br_merge;

        let else_bb = L.append_block context "else" the_function in
        let (builder2, _, dl) = stmt m dl (L.builder_at_end context
            else_bb) else_stmt in
        add_terminal builder2 build_br_merge;

        ignore(L.build_cond_br bool_val then_bb else_bb builder);
        ((L.builder_at_end context merge_bb), m, dl)


      | SWhile (predicate, body) ->
        let pred_bb = L.append_block context "while" the_function in
        ignore(L.build_br pred_bb builder);

        let body_bb = L.append_block context "while_body"
            the_function in
        let (builder, mm, dl) = stmt m dl (L.builder_at_end context
            body_bb) body in
        add_terminal builder (L.build_br pred_bb);

        let pred_builder = L.builder_at_end context pred_bb in
        let bool_val = expr mm pred_builder predicate in

        let merge_bb = L.append_block context "merge" the_function
            in
        ignore(L.build_cond_br bool_val body_bb merge_bb
```

```
            pred_builder);
          (L.builder_at_end context merge_bb, mm, dl)

        | SFor (e1, e2, e3, body) -> stmt m dl builder
          ( SBlock [e1 ; SWhile (e2, SBlock [body ; e3]) ] )

        | SDefer(_, SCall(f, args)) ->

          let construct_call = function
              "printb" -> (printbool_func, [| (expr m builder (List.hd
                  args)) |], "printbool")
            | "prints" -> (printf_func, [| str_format_str ; (expr m
                builder (List.hd args)) |], "printf")
            | "printc" -> (printf_func, [| char_format_str ; (expr m
                builder (List.hd args)) |], "printf")
            | "printi" -> (printf_func, [| int_format_str ; (expr m
                builder (List.hd args)) |], "printf")
            | "time" -> (gettime_func, [| |], "get_time")
            | _ ->
              let (fdef, local, result) = construct_func_call f args m
                  builder in
              (fdef, [| local |], result) in

          (builder, m, (construct_call f)::dl)
        | SSelect cl ->
            (* create array of clause structs *)
            let num_elems = List.length cl in
            let ptr = L.build_array_malloc clause_t
                (L.const_int i32_t num_elems) "" builder
            in
            let val_ptrs = List.mapi (fun i clause ->
              let op = (function
                  (SSend(_), _) -> L.const_int i8_t (Char.code 's')
                | (SRecv(_), _) -> L.const_int i8_t (Char.code 'r')
                | _ -> raise(Failure("invalid select clause in codegen
                   "))
              ) clause in
              let chexpr = (function
                  (SSend(c, _), _)  -> c
                | (SRecv(c, _), _)  -> c
                | _ -> raise(Failure("invalid select clause in codegen
                   "))
              ) clause in
              let chan  = expr m builder chexpr in
              let chtyp = (function
```

```
          (SSend(_, (t, _)), _) -> t
        | (SRecv(_, t), _)      -> t
        | _ -> raise(Failure("invalid select clause in codegen
          "))
      ) clause in
      let local = L.build_alloca (ltype_of_typ chtyp) ""
         builder in
      let value = (function
          (SSend(_, e), _)  -> expr m builder e
        | (SRecv(_), _)     -> L.const_int (ltype_of_typ chtyp
          ) 0
        | _ -> raise(Failure("invalid select clause in codegen
          "))
      ) clause in
      ignore(L.build_store value local builder);
      let void_ptr_val = L.build_bitcast local void_ptr_t ""
         builder in
      let len   = L.size_of (ltype_of_typ chtyp) in
      let idxs  = List.rev (generate_seq (4 - 1)) in
      let elem  = List.fold_left2 (fun agg i v ->
        L.build_insertvalue agg v i "clause" builder)
        (L.const_null clause_t) idxs [op ; chan ; void_ptr_val
            ; len] in
      let idx   = L.const_int i32_t i in
      let eptr  = L.build_gep ptr [|idx|] "" builder in
      let cptr  = L.build_pointercast eptr
          (L.pointer_type (L.type_of elem)) "" builder in
      let _     = (L.build_store elem cptr builder)
      in local) cl
    in
    (* call C function *)
    let selected_clause = L.build_call select_func
      [| ptr ; L.const_int i32_t num_elems |] "select" builder
    in
    (* branch to selected case *)
    let merge_bb = L.append_block context "merge" the_function
         in
    let build_br_merge = L.build_br merge_bb in
    let (_, case_bbs) = List.fold_left2 (fun (i, cases) clause
         val_ptr ->
        let case_bb = L.append_block context "case"
            the_function in
        let case_stmt, mm = (function
            SBlock(SAssignStmt(sass) :: case_block) ->
              (* assign received value *)
```

```
                    let e' = L.build_load val_ptr "recv_val" builder
                        in
                    let rec handle_case_pred = function
                        SAssign([((_, SId(id)), _)]) ->
                          ignore(L.build_store e' (lookup id m)
                              builder); m
                      | SDeclAssign([(id, vdt)], _) ->
                          let (_, mm, _) = stmt m dl builder (
                              SVdeclStmt [(id, vdt)])
                          in
                          ignore(L.build_store e' (lookup id mm)
                              builder); mm
                      | SInit([sa]) -> handle_case_pred(sa)
                      | _ -> raise(Failure("invalid case predicate
                         detected in codegen"))
                    in
                    let mm = handle_case_pred sass in
                    SBlock(case_block), mm
                  | SBlock(_ :: case_block) -> SBlock(case_block), m
                  | _ -> raise(Failure("internal error: invalid case
                      block in codegen"))
              ) (snd clause) in
            let (builder1, _, _) = stmt mm dl (L.builder_at_end
                context case_bb)
              case_stmt in
            add_terminal builder1 build_br_merge;
            (i+1, case_bb :: cases))
            (0, []) cl val_ptrs in
          let sw = L.build_switch selected_clause merge_bb num_elems
              builder in
          List.iteri (fun i case_bb ->
            L.add_case sw (L.const_int i32_t i) case_bb;
          ) (List.rev case_bbs);
          ((L.builder_at_end context merge_bb), m, dl)
    | _ -> raise(Failure("statement not implemented; should've
          checked in semant!"))
  in

  (* Build the code for each statement in the function *)

  let (builder, _, ndl) = stmt [local_vars ; global_vars]
      defered_el builder (SBlock fdecl.sbody) in

  match L.block_terminator (L.insertion_block builder) with
      Some _ -> ()
```

```
      | None -> ignore(List.map (fun (fdef, llargs, result) ->
        L.build_call fdef llargs result builder) ndl);

    (* Add a return if the last block falls off the end *)
    (* TODO: fix later *)
    add_terminal builder (L.build_ret (L.const_int i32_t 0))
      (*(match fdecl.styp with
        A.Void -> L.build_ret_void
      | t -> L.build_ret (L.const_int (ltype_of_typ t) 0))*)
    in
    ignore(List.iter build_function_body functions);
    the_module
```

9.8 concurrency.c

```
/*
 *  RJEC concurrency functions
 *  Written by Justin Chen and Elaine Wang
 *  in collaboration with Riya and Caroline
 */

#include "libmill/libmill.h"
#include "libmill/chan.h"
#include <stdbool.h>
#include <string.h>
#include <sys/time.h>
#include <stdint.h>

void yeet(int (*start_routine)(void *), void *args)
{
    go(start_routine(args));
}

void *makechan(char typ, int buf)
{
    chan ch;
    switch(typ) {
        case 'i':
            ch = chmake(int, buf);
            break;
        case 'c':
            ch = chmake(char, buf);
            break;
```

```
        case 'b':
            ch = chmake(bool, buf);
            break;
    }
    return ch;
}

void send(void *ch_void_ptr, char typ, int val)
{
    chan ch = ch_void_ptr;
    switch(typ) {
        case 'i':
            chs(ch, int, val);
            break;
        case 'c':
            chs(ch, char, (char)val);
            break;
        case 'b':
            chs(ch, bool, (bool)val);
            break;
    }
}

int recv_int(void *ch_void_ptr)
{
    chan ch = ch_void_ptr;
    return chr(ch, int);
}

bool recv_bool(void *ch_void_ptr)
{
    chan ch = ch_void_ptr;
    return chr(ch, bool);
}

char recv_char(void *ch_void_ptr)
{
    chan ch = ch_void_ptr;
    return chr(ch, char);
}

void closechan(void *ch_void_ptr, char typ)
{
    chan ch = ch_void_ptr;
    switch(typ) {
```

```
        case 'i':
            chdone(ch, int, 0);
            break;
        case 'c':
            chdone(ch, char, 0);
            break;
        case 'b':
            chdone(ch, bool, 0);
            break;
    }
}

struct select_clause {
    char op;
    void *ch;
    void *val;
    long len;
};

int selectchan(struct select_clause *clauses, int nclauses)
{
    mill_choose_init_(MILL_HERE_);
    int mill_idx = -2;
    while(1) {
        struct mill_clause mill_clauses[nclauses];
        for (int i = 0; i < nclauses; ++i) {
            if (clauses[i].op == 's') {
                mill_choose_out_((void *) &mill_clauses[i], clauses[
                    i].ch,
                     clauses[i].val, clauses[i].len, i);
            }
            else if (clauses[i].op == 'r') {
                mill_choose_in_((void *) &mill_clauses[i], clauses[i
                    ].ch,
                     clauses[i].len, i);
            }
            else {
                mill_panic("invalid clause type");
            }
        }
        mill_idx = mill_choose_wait_();

        if (mill_idx != -2) {
            if (mill_idx < 0 || mill_idx >= nclauses) {
                mill_panic("invalid clause index");
```

```
            }
            if (clauses[mill_idx].op == 'r') {
                memcpy(clauses[mill_idx].val,
                    mill_choose_val_(clauses[mill_idx].len),
                    clauses[mill_idx].len);
            }
            break;
        }
    }
    // printf("select: got index %d\n", mill_idx);
    return mill_idx;
}

int get_time()
{
    struct timeval tv;
    gettimeofday(&tv, NULL);
    return (((int64_t)tv.tv_sec * 1000000) + tv.tv_usec);
}

// test function for select
int food(chan ch1, chan ch2, chan quit)
{
    while (1) {
        bool q = 0;
        char val1 = 'a';
        int val2;

        /* libmill syntax:
        choose {
        out(ch1, char, val1):
            printf("Value %c sent.\n", val1);
        in(ch2, int, val2):
            printf("Value %d received.\n", val2);
        in(quit, bool, q):
            printf("Bool value %d received\n", q);
            if (q) {
                printf("quitting...\n");
            }
            return 0;
        end
        }*/

        struct select_clause clauses[] = {
            {'s', ch1, &val1, sizeof(val1)},
```

```
            {'r', ch2, &val2, sizeof(val2)},
            {'r', quit, &q, sizeof(q)}
        };
        int rc = selectchan(clauses, 3);
        if (rc == 0) {
            printf("Value %c sent.\n", val1);
        }
        if (rc == 1) {
            printf("Value %d received.\n", val2);
        }
        if (rc == 2) {
            printf("Bool value %d received\n", q);
            if (q) {
                printf("quitting...\n");
            }
            return 0;
        }
    }
    return 0;
}

/* test driver for select test:
int main()
{
    chan ch1 = chmake(char, 0);
    chan ch2 = chmake(int, 0);
    chan quit = chmake(bool, 10);
    go(food(ch1, ch2, quit));
    for (int i = 0; i < 5; ++i) {
        printf("%c\n", chr(ch1, char));
        chs(ch2, int, i);
    }
    chs(quit, bool, true);
}*/
```

9.9 printbool.c

```
/*
 *  RJEC printbool function
 *  Written by Riya Chakraborty
 *  in collaboration with Elaine, Caroline, and Justin
 */
```

```
#include <stdio.h>

void printbool(int b)
{
    if (b) {
        printf("true\n");
    }
    else {
        printf("false\n");
    }
}
```

9.10 Makefile

```
# Makefile for building RJEC compiler
# Initially based on MicroC
# Written by Justin Chen, Elaine Wang, Riya Chakraborty, and
   Caroline Hoang

LDFLAGS = -L libmill/
LDLIBS = -lmill

# "make test" Compiles everything and runs the regression tests

.PHONY : test
test : all testall.sh
        ./testall.sh

# "make all" builds the executable as well as the "printbig" library
    designed
# to test linking external code

.PHONY : all
all : rjec.native printbool.o libmill/libmill.a concurrency.o

# builds the libmill library used for concurrency in RJEC
libmill/libmill.a :
        ./buildlibmill.sh

# "make rjec.native" compiles the compiler
#
# The _tags file controls the operation of ocamlbuild, e.g., by
   including
```

```
# packages, enabling warnings
#
# See https://github.com/ocaml/ocamlbuild/blob/master/manual/manual.
   adoc

rjec.native :
        opam config exec -- \
        ocamlbuild -X libmill/ -use-ocamlfind rjec.native

# "make clean" removes all generated files

.PHONY : clean
clean :
        ocamlbuild -clean
        rm -rf testall.log ocamlllvm *.diff
        rm *.o *.ll *.s *.exe
```

9.11 buildlibmill.sh

```
#!/bin/sh

# builds the libmill library used for concurrency in RJEC
# written by Justin Chen

cd libmill
cmake --configure .
cmake --build .
cd ..
```

9.12 rjec.sh

```
#!/bin/sh

# adapted from testall.sh, which is based on MicroC
# Written by Justin Chen

# Path to the LLVM interpreter
LLI="lli"

# Path to the LLVM compiler
```

```
LLC="llc"

# Path to the C compiler
CC="cc"

# Path to the rjec compiler.  Usually "./rjec.native"
# Try "_build/rjec.native" if ocamlbuild was unable to create a
    symbolic link.
RJEC="./rjec.native"

if [ -z "$1" ]
  then
    echo "Usage: ./rjec.sh <filename.rjec>"
    exit 1
fi

keep=0

if [ -z "$LD_LIBRARY_PATH" ]
then
    LD_LIBRARY_PATH=$(pwd)/libmill
    export LD_LIBRARY_PATH
else
    echo "check that LD_LIBRARY_PATH is exported!"
fi

basename=`echo $1 | sed 's/.*\\///
                             s/.rjec//'`

generatedfiles=""

generatedfiles="$generatedfiles ${basename}.ll ${basename}.s ${
    basename}.exe ${basename}.out" &&
eval "$RJEC" "$1" ">" "${basename}.ll" &&
eval "$LLC" "-relocation-model=pic" "${basename}.ll" ">" "${basename
    }.s" &&
eval "$CC" "-o" "${basename}.exe" "${basename}.s" "printbool.o" "
    concurrency.o" "-L" "libmill/" "-lmill" &&
eval "./${basename}.exe"

if [ $keep -eq 0 ] ; then
    rm -f $generatedfiles
fi
```

9.13 testall.sh

```
#!/bin/sh

# Regression testing script for RJEC
# Initially based on MicroC
# Written by Justin Chen, Elaine Wang, Riya Chakraborty, and
   Caroline Hoang
# Step through a list of files
#  Compile, run, and check the output of each expected-to-work test
#  Compile and check the error of each expected-to-fail test

# Path to the LLVM interpreter
LLI="lli"
#LLI="/usr/local/opt/llvm/bin/lli"

# Path to the LLVM compiler
LLC="llc"

# Path to the C compiler
CC="cc"

# Path to the rjec compiler.  Usually "./rjec.native"
# Try "_build/rjec.native" if ocamlbuild was unable to create a
   symbolic link.
RJEC="./rjec.native"
#RJEC="_build/rjec.native"

# Set time limit for all operations
ulimit -t 30

globallog=testall.log
rm -f $globallog
error=0
globalerror=0

keep=0

if [ -z "$LD_LIBRARY_PATH" ]
then
    LD_LIBRARY_PATH=$(pwd)/libmill
    export LD_LIBRARY_PATH
    echo "export LD_LIBRARY_PATH=$(pwd)/libmill"
else
```

```
    echo "check that LD_LIBRARY_PATH is exported!"
fi

Usage() {
    echo "Usage: testall.sh [options] [.rjec files]"
    echo "-k    Keep intermediate files"
    echo "-h    Print this help"
    exit 1
}

SignalError() {
    if [ $error -eq 0 ] ; then
        echo "FAILED"
        error=1
    fi
    echo "  $1"
}

# Compare <outfile> <reffile> <difffile>
# Compares the outfile with reffile.  Differences, if any, written
   to difffile
Compare() {
    generatedfiles="$generatedfiles $3"
    echo diff -b $1 $2 ">" $3 1>&2
    diff -b "$1" "$2" > "$3" 2>&1 || {
        SignalError "$1 differs"
        echo "FAILED $1 differs from $2" 1>&2
    }
}

# Run <args>
# Report the command, run it, and report any errors
Run() {
    echo $* 1>&2
    eval $* || {
        SignalError "$1 failed on $*"
        return 1
    }
}

# RunFail <args>
# Report the command, run it, and expect an error
RunFail() {
    echo $* 1>&2
    eval $* && {
```

```
        SignalError "failed: $* did not report an error"
        return 1
    }
    return 0
}

Check() {
    error=0
    basename=`echo $1 | sed 's/.*\\///
                             s/.rjec//'`
    reffile=`echo $1 | sed 's/.rjec$//'`
    basedir="`echo $1 | sed 's/\/[^\/]*$//'`/."

    echo -n "$basename..."

    echo 1>&2
    echo "###### Testing $basename" 1>&2

    generatedfiles=""

    generatedfiles="$generatedfiles ${basename}.ll ${basename}.s ${
       basename}.exe ${basename}.out" &&
    Run "$RJEC" "$1" ">" "${basename}.ll" &&
    Run "$LLC" "-relocation-model=pic" "${basename}.ll" ">" "${
       basename}.s" &&
    Run "$CC" "-o" "${basename}.exe" "${basename}.s" "printbool.o" "
       concurrency.o" "-L" "libmill/" "-lmill" &&
    Run "./${basename}.exe" > "${basename}.out" &&
    Compare ${basename}.out ${reffile}.out ${basename}.diff

    # Report the status and clean up the generated files

    if [ $error -eq 0 ] ; then
        if [ $keep -eq 0 ] ; then
            rm -f $generatedfiles
        fi
        echo "OK"
        echo "###### SUCCESS" 1>&2
    else
        echo "###### FAILED" 1>&2
        globalerror=$error
    fi
}

CheckFail() {
```

```
    error=0
    basename=`echo $1 | sed 's/.*\\///
                         s/.rjec//'`
    reffile=`echo $1 | sed 's/.rjec$//'`
    basedir="`echo $1 | sed 's/\/[^\/]*$//'`/."

    echo -n "$basename..."

    echo 1>&2
    echo "###### Testing $basename" 1>&2

    generatedfiles=""

    generatedfiles="$generatedfiles ${basename}.err ${basename}.diff
       " &&
    RunFail "$RJEC" "<" $1 "2>" "${basename}.err" ">>" $globallog &&
    Compare ${basename}.err ${reffile}.err ${basename}.diff

    # Report the status and clean up the generated files

    if [ $error -eq 0 ] ; then
        if [ $keep -eq 0 ] ; then
            rm -f $generatedfiles
        fi
        echo "OK"
        echo "###### SUCCESS" 1>&2
    else
        echo "###### FAILED" 1>&2
        globalerror=$error
    fi
}

while getopts kdpsh c; do
    case $c in
        k) # Keep intermediate files
            keep=1
            ;;
        h) # Help
            Usage
            ;;
    esac
done

shift `expr $OPTIND - 1`
```

```
LLIFail() {
  echo "Could not find the LLVM interpreter \"$LLI\"."
  echo "Check your LLVM installation and/or modify the LLI variable
      in testall.sh"
  exit 1
}

which "$LLI" >> $globallog || LLIFail

if [ $# -ge 1 ]
then
    files=$@
 else
     files="tests/test-*.rjec tests/fail-*.rjec"
fi

for file in $files
do
    case $file in
        *test-*)
            Check $file 2>> $globallog
            ;;
        *fail-*)
            CheckFail $file 2>> $globallog
            ;;
        *)
            echo "unknown file type $file"
            globalerror=1
            ;;
    esac
done

exit $globalerror
```

9.14 tests/

9.14.1 fail-array1.err

```
Fatal error: exception Parsing.Parse_error
```

9.14.2 fail-array1.rjec

```
func main() {
    var x [10][]int;
}
```

9.14.3 fail-array2.err

```
Fatal error: exception Failure("array size can only be integer
   expressions")
```

9.14.4 fail-array2.rjec

```
func main() {
    var x [true]int;
}
```

9.14.5 fail-array3.err

```
Fatal error: exception Failure("illegal assignment of element to
   array")
```

9.14.6 fail-array3.rjec

```
struct foo {
    x int;
    y char;
    z bool;
}

func main () {
    var a [10]struct foo;
    for i := 0; i < 10; i = i + 1 {
        a[i] = i;
    }
}
```

9.14.7 fail-array4.err

```
Fatal error: exception Failure("array element doesn't match declared
    array type")
```

9.14.8 fail-array4.rjec

```
func main() {
    x := []bool {1, 2, 3, 4, 5};
}
```

9.14.9 fail-chan1.err

```
Fatal error: exception Failure("tried to perform channel operation
   through a non-channel variable")
```

9.14.10 fail-chan1.rjec

```
func main () {
    ch := 5;
        ch <- 10;
        printi(<-ch);

}
```

9.14.11 fail-decl1.err

```
Fatal error: exception Failure("duplicate global i")
```

9.14.12 fail-decl1.rjec

```
var i int;
var i bool;
```

```
func main() {
    printi(2);
}
```

9.14.13 fail-decl2.err

```
Fatal error: exception Failure("duplicate global i")
```

9.14.14 fail-decl2.rjec

```
var i int;
var i int;

func main() {
    printi(2);
}
```

9.14.15 fail-decl3.err

```
Fatal error: exception Failure("local variable i has already been
   declared")
```

9.14.16 fail-decl3.rjec

```
func main() {

    i, i := 2, 3;

}
```

9.14.17 fail-decl4.err

```
Fatal error: exception Failure("duplicate struct foo")
```

9.14.18 fail-decl4.rjec

```
struct foo {
    x bool;
    y int;
}

struct foo {
    x int;
    y int;
}


func main() {

}
```

9.14.19 fail-decl5.err

```
Fatal error: exception Failure("duplicate member in definition of
   struct foo : x")
```

9.14.20 fail-decl5.rjec

```
struct foo {
    x bool;
    x int;
}

func main() {

}
```

9.14.21 fail-decl6.err

```
Fatal error: exception Failure("duplicate formal a")
```

9.14.22 fail-decl6.rjec

```
func foo(a int, a bool) bool {
    return true;
}

func main() {

}
```

9.14.23 fail-defer1.err

```
Fatal error: exception Failure("defer statement inside of while
   block")
```

9.14.24 fail-defer1.rjec

```
func main() {
    for i := 2; i < 3; i = i + 1 {
        defer printi(i);
    }
}
```

9.14.25 fail-defer2.err

```
Fatal error: exception Failure("defer statement inside of while
   block")
```

9.14.26 fail-defer2.rjec

```
func main() {
    i := 1;
    for i < 3 {
        defer printi(i);
        i = i + 1;
    }
```

```
}
```

9.14.27 fail-defer3.err

```
Fatal error: exception Failure("defer statement inside of while
   block")
```

9.14.28 fail-defer3.rjec

```
func main() {
    for i := 2; i < 3; i = i + 1 {
        j := 0;
        for j < 5 {
            {
                defer printi(j);
            }
            j = j + 1;
        }
    }
}
```

9.14.29 fail-func1.err

```
Fatal error: exception Failure("unrecognized function foo")
```

9.14.30 fail-func1.rjec

```
func main() {
    foo();
}
```

9.14.31 fail-func2.err

```
Fatal error: exception Failure("duplicate function baz")
```

9.14.32 fail-func2.rjec

```
func baz(x int, y bool) bool {
    return x;
}

func baz(z int) {
    printi(z);
}

func main(){

}
```

9.14.33 fail-func3.err

```
Fatal error: exception Failure("built-in function printi is already
   defined")
```

9.14.34 fail-func3.rjec

```
func printi(x int) {
    printi(x);
}

func main() {

}
```

9.14.35 fail-struct1.err

```
Fatal error: exception Failure("unrecognized struct foo")
```

9.14.36 fail-struct1.rjec

```
func main() {
```

```
    var i struct foo;
    i = struct foo {
        x : 1,
        y : true,
        z : 'a'
    };
    printi(i.x);
    printb(i.y);
    printc(i.z);
}
```

9.14.37 fail-struct2.err

```
Fatal error: exception Failure("undeclared reference foo")
```

9.14.38 fail-struct2.rjec

```
func main() {
    printi(foo.x);
}
```

9.14.39 fail-struct3.err

```
Fatal error: exception Failure("unknown field v in struct foo")
```

9.14.40 fail-struct3.rjec

```
struct foo {
    x int;
    y bool;
    z char;
}

func main() {
    var i struct foo;
    i = struct foo {
        x : 1,
```

```
        y : true,
        z : 'a'
    };
    printi(i.v);
}
```

9.14.41 fail-yeet1.err

```
Fatal error: exception Failure("a yeet function call can only return
    int or nothing")
```

9.14.42 fail-yeet1.rjec

```
func isEven (x int) bool {
    return x % 2 == 0;
}

func main () {
    yeet isEven(4);
}
```

9.14.43 fail-yeet2.err

```
Fatal error: exception Failure("can't yeet a non-function call")
```

9.14.44 fail-yeet2.rjec

```
func main () {
    yeet 1 + 2;
}
```

9.14.45 test-array1.out

```
0
```

```
0
0
0
0
0
0
0
0
0
```

9.14.46 test-array1.rjec

```
func main () {
    var x, y [10]int;
    for i := 0; i < 10; i = i + 1 {
        printi(x[i]);
    }
}
```

9.14.47 test-array10.out

```
10
10
10
10
```

9.14.48 test-array10.rjec

```
func foo (x []int) []int{
    y := x;
    return y;
}

func main () {
    x := []int {1, 2, 3, 4, 5};
    y := foo(x);
    y[1] = 10;
    printi(y[1]);
```

```
    printi(x[1]);

    z := []int {1, 2, 3, 4, 5};
    t := z;
    z[1] = 10;
    printi(z[1]);
    printi(t[1]);
}
```

9.14.49 test-array11.out

```
5
0
```

9.14.50 test-array11.rjec

```
func main() {
    n := 5;
    printi(n);
    var arr [n]int;
    printi(arr[2]);
}
```

9.14.51 test-array2.out

```
0
false
0
false
0
false
0
false
0
false
0
false
0
false
```

```
0
false
0
false
0
false
```

9.14.52 test-array2.rjec

```
struct foo {
    x int;
    y char;
    z bool;
}

func main () {
    var a [10]struct foo;
    for i := 0; i < 10; i = i + 1 {
        s := a[i];
        printi(s.x);
        printb(s.z);
    }
}
```

9.14.53 test-array3.out

```
0
false
0
false
0
false
0
false
0
false
a
a
a
```

9.14.54 test-array3.rjec

```
struct foo {
    x int;
    y char;
    z bool;
}

func my_func (n int, c chan int) {
    var a [n]struct foo;
    for i := 0; i < n; i = i + 1 {
        s := a[i];
        printi(s.x);
        printb(s.z);
    }
    for {
        s := a[<- c];
        printc('a');
    }
}

func main() {
    c := make(chan int);
    yeet my_func(5, c);

    c <- 1;
    c <- 2;
    c <- 3;
}
```

9.14.55 test-array4.out

```
0
2
4
6
8
```

9.14.56 test-array4.rjec

```
func foo (n int) {
    var x [n]int;
    for i := 0; i < n ; i = i + 1 {
        x[i] = i * 2;
    }
    for i := 0; i < n ; i = i + 1 {
        printi(x[i]);
    }
}

func main () {
    foo(5);
}
```

9.14.57 test-array5.out

```
0
false
0
false
0
false
0
false
0
false
a
a
a
```

9.14.58 test-array5.rjec

```
struct foo {
    x int;
    y char;
    z bool;
}

func my_func (n int, c chan int) {
    var a [n]struct foo;
```

```
    for i := 0; i < n; i = i + 1 {
        printi(a[i].x);
        a[i].y = 'a';
        printb(a[i].z);
    }
    for {
        printc(a[<- c].y);
    }
}

func main() {
    c := make(chan int);
    yeet my_func(5, c);

    c <- 1;
    c <- 2;
    c <- 3;
}
```

9.14.59 test-array6.out

```
6
```

9.14.60 test-array6.rjec

```
func foo(x []int) {
    x[0] = x[0] + 2;
}

func main() {
    var x [10]int;
    x[0] = 4;
    foo(x);
    printi(x[0]);
}
```

9.14.61 test-array7.out

```
4
5
true
```

9.14.62 test-array7.rjec

```
struct foo {
    x int;
    y int;
    z bool;
}

func change_struct(x []struct foo) {
    x[0].x = x[1].x + 1;
    x[1].y = x[2].y - 2;
    x[2].z = true;
}

func main() {
    var x [10]struct foo;
    x[0] = struct foo { x: 1, y: 2 };
    x[1] = struct foo { x: 3, y: 5, z: true };
    x[2] = struct foo { x: 0, y: 7};
    change_struct(x);
    printi(x[0].x);
    printi(x[1].y);
    printb(x[2].z);
}
```

9.14.63 test-array8.out

```
1
2
3
4
5
```

9.14.64 test-array8.rjec

```
func main () {
    x := []int{1, 2, 3, 4, 5};
    for i := 0; i < 5; i = i + 1 {
        printi(x[i]);
    }
}
```

9.14.65 test-array9.out

```
120
```

9.14.66 test-array9.rjec

```
func factorial (x []int, l int) int{
    ret := 1;
    for i := 0; i < l; i = i + 1 {
        ret = ret * x[i];
    }
    return ret;
}
func main () {
    printi(factorial([]int{1, 2, 3, 4, 5}, 5));
}
```

9.14.67 test-assign1.out

```
52
false
true
```

9.14.68 test-assign1.rjec

```
var i int;
var b bool;
var j int;
```

```
func main() {
  i = 42;
  j = 10;
  printi(i + j);
  printb(b);
  b = true;
  printb(b);
}
```

9.14.69 test-assign2.out

```
52
```

9.14.70 test-assign2.rjec

```
var i, j int;

func main() {
  i = 10;
  j = 42;
  printi(i + j);
}
```

9.14.71 test-assign3.out

```
52
```

9.14.72 test-assign3.rjec

```
var i, j int;

func main() {
  i, j = 10, 42;
  printi(i + j);
}
```

9.14.73 test-assign4.out

```
0
0
5
6
6
11
```

9.14.74 test-assign4.rjec

```
var i, j, k int;

func main() {
    printi(i);
    printi(j);
    i, j = 5, 6;
    k = i+j;
    printi(i);
    i = i+1;
    printi(i);
    printi(j);
    printi(k);
}
```

9.14.75 test-assign5.out

```
0
0
5
6
5
6
```

9.14.76 test-assign5.rjec

```
/* TO DO: either implement or raise error */
var i, j int;
```

```
func main() {
    printi(i);
    printi(j);
    i, j = 5, 6;
    printi(i);
    printi(j);
    /* i, j = j, i; */
    printi(i);
    printi(j);
}
```

9.14.77 test-chan1.out

```
```

9.14.78 test-chan1.rjec

```
func main() {
    var foo chan int;
    foo = make(chan int);
    foo2 := make(chan bool, 10);
}
```

9.14.79 test-chan2.out

```
10
2
8
```

9.14.80 test-chan2.rjec

```
func main () {
    ch := make(chan int, 3);
        ch <- 10;
        ch <- 2;
        ch <- 8;
        printi(<-ch);
```

```
        printi(<-ch);
        printi(<-ch);
}
```

9.14.81 test-chan3.out

```
r
j
e
c
```

9.14.82 test-chan3.rjec

```
func foo(x chan char){
    for {
        a := <- x;
        printc(a);
    }
}

func main () {
    x := make(chan char);
    yeet foo(x);
    x <- 'r';
    x <- 'j';
    x <- 'e';
    x <- 'c';
}
```

9.14.83 test-chan4.out

```
receiver:
2
sender:
1
receiver:
3
sender:
2
```

```
receiver:
5
sender:
4
receiver:
9
sender:
8
receiver:
17
sender:
16
receiver:
33
sender:
32
receiver:
65
sender:
64
receiver:
129
sender:
128
receiver:
257
sender:
256
receiver:
513
sender:
512
```

9.14.84 test-chan4.rjec

```
func foo1 (r chan int, s chan int) {
    for {
        a := <- r;
        prints("receiver:");
        printi(a + 1);
        s <- (a * 2);
    }
}
```

```
func main () {
    s, r := make(chan int), make(chan int);
    yeet foo1(s, r);
    for a := 1; a < 1000 ; a = (<- r) {
        s <- a;
        prints("sender:");
        printi(a);
    }
}
```

9.14.85 test-chan5.out

```
1
2
3
0
0
```

9.14.86 test-chan5.rjec

```
func foo (c chan int) {
    c <- 1;
    c <- 2;
    c <- 3;

    close(c);
}
func main () {
    c := make(chan int, 3);
    yeet foo(c);
    for i := 0; i < 5; i = i + 1 {
        a := <- c;
        printi(a);
    }
}
```

9.14.87 test-decl-assign1.out

```
42
30
```

9.14.88 test-decl-assign1.rjec

```
func main() {
  var i int = 42;
  var j int = 30;

  printi(i);
  printi(j);

}
```

9.14.89 test-decl-assign2.out

```
42
30
r
j
e
c
```

9.14.90 test-decl-assign2.rjec

```
func main() {

    var x, y int = 42, 30;
    printi(x);
    printi(y);

    var r, j, e, c char = 'r', 'j', 'e', 'c';
    printc(r);
    printc(j);
    printc(e);
    printc(c);

}
```

9.14.91 test-decl-assign3.out

```
true
12
```

9.14.92 test-decl-assign3.rjec

```
struct foo {
    x bool;
    y int;
}

func main() {

    var i struct foo = struct foo {
        x : true,
        y : 12
    };

    printb(i.x);
    printi(i.y);

}
```

9.14.93 test-decl-assign4.out

```
42
30
60
52
42
60
```

9.14.94 test-decl-assign4.rjec

```
func main() {
  var i,j int = 42, 30;
  printi(i);
  printi(j);

  if true {
      j = 60;
      printi(j);
      var i int = 52;
      printi(i);
  }

  printi(i);
  printi(j);
}
```

9.14.95 test-decl1.out

```
52
false
true
```

9.14.96 test-decl1.rjec

```
func main() {

  var i int;
  var b bool;
  var j int;

  i = 42;
  j = 10;
  printi(i + j);
  printb(b);
  b = true;
  printb(b);
}
```

9.14.97 test-decl2.out

```
42
false
true
```

9.14.98 test-decl2.rjec

```
var i int;

func main() {
  i = 42;
  printi(i);
  var i bool;
  printb(i);
  i = true;
  printb(i);
}
```

9.14.99 test-decl3.out

```
42
30
60
52
42
60
```

9.14.100 test-decl3.rjec

```
func main() {
  var i int;
  var j int;

  i = 42;
  printi(i);
  j = 30;
  printi(j);

  if true {
```

```
        j = 60;
        printi(j);
        var i int;
        i = 52;
        printi(i);
    }

    printi(i);
    printi(j);
}
```

9.14.101 test-defer1.out

```
2
3
1
```

9.14.102 test-defer1.rjec

```
func foo (x int){
    printi(x);
}

func main() {
    defer foo(1);
    foo(2);
    foo(3);
}
```

9.14.103 test-defer2.out

```
4
5
3
2
1
```

9.14.104 test-defer2.rjec

```
func foo (x int){
    printi(x);
}

func main() {
    defer printi(1);
    defer printi(2);
    defer foo(3);

    foo(4);
    printi(5);
}
```

9.14.105 test-defer3.out

```
3
8
2
8
18
7
126
16
```

9.14.106 test-defer3.rjec

```
func foo (x int, y int) int {
    defer printi(x);
    defer printi(y);

    z := x * y;
    x = x + 1;
    printi(x);
    return z;
}

func main() {
    x, y := 2, 8;
    defer printi(foo(x, y));
```

```
    for i := 0; i < 5; i = i + 1 {
        x = x + 1;
        y = y + 2;
    }
    printi(foo(x, y));
}
```

9.14.107 test-defer4.out

```
3
2
1
```

9.14.108 test-defer4.rjec

```
func main() {
    if true {
        defer printi(1);
        if true {
            defer printi(2);
        }
        defer printi(3);
    }
}
```

9.14.109 test-for1.out

```
5
4
3
2
1
```

9.14.110 test-for1.rjec

```
func main() {
```

```
    i := 5;
    for 0 < i {
        printi(i);
        i = i - 1;
    }

}
```

9.14.111 test-for2.out

```
5
4
3
2
1
```

9.14.112 test-for2.rjec

```
func main() {

    for i := 5; 0 < i; i = i - 1  {
        printi(i);
    }

}
```

9.14.113 test-for3.out

```
5
4
3
2
1
5
4
3
2
1
```

9.14.114 test-for3.rjec

```
func main() {
    i := 5;

    for ; 0 < i; i = i - 1  {
        printi(i);
    }

    for j := 5; 0 < j;  {
        printi(j);
        j = j - 1;
    }

}
```

9.14.115 test-for4.out

```
2
4
6
8
10
12
14
16
18
20
```

9.14.116 test-for4.rjec

```
func foo(x int, y int) bool {
    return !(y % x == 0);

}

func main() {
    i, j := 11, 2;

    for ; foo(i, j); j = j + 2  {
```

```
        printi(j);
    }


}
```

9.14.117 test-for5.out

```
0
1
2
3
1
2
3
4
2
3
4
5
3
4
5
6
```

9.14.118 test-for5.rjec

```
func main() {
    for i:=0; i<4; i=i+1 {
        for j:=0; j<4; j=j+1 {
            printi(i+j);
        }
    }
}
```

9.14.119 test-func1.out

```
3
```

9.14.120 test-func1.rjec

```
func foo (x int) int {
    return x + 2;
}

func main() {
    var i int;
    i = foo(1);
    printi(i);
}
```

9.14.121 test-func2.out

```
true
false
false
3
0
```

9.14.122 test-func2.rjec

```
func isEven (x int, y bool) bool {
    if (x % 2 == 0 && y) {
        return true;
    } else {
        return false;
    }
    return true;
}

func foo (x int) {
    printi(x % 4);
}

func main() {
    printb(isEven(2, true));
    printb(isEven(3, true));
    printb(isEven(4, false));
```

```
    printi(foo(3));
}
```

9.14.123 test-func3.out

```
1
8
11
1
```

9.14.124 test-func3.rjec

```
func gcd (a int, b int) int {
    if (a < b) {
        return gcd(b, a);
    }
    if (b == 0) {
        return a;
    }
    return gcd(b, a % b);
}

func main () {
    printi(gcd(32, 3));
    printi(gcd(16, 56));
    printi(gcd(869, 143));
    printi(gcd(349, 1837));
}
```

9.14.125 test-func4.out

```
2
3
```

9.14.126 test-func4.rjec

```
struct dummy {
    x int;
    y int;
}

func foo (x int, y int) struct dummy {
    var i struct dummy;
    i = struct dummy {
        x : x,
        y : y
    };
    return i;
}

func main () {
    var i struct dummy;
    i = foo(2, 3);
    printi(i.x);
    printi(i.y);
}
```

9.14.127 test-func5.out

```
2
3
false
z
10
```

9.14.128 test-func5.rjec

```
struct dummy {
    x int;
    y int;
    z bool;
    t char;
}

func foo (x int, y int, z struct dummy) struct dummy {
    var i struct dummy;
```

```
    i = struct dummy {
        x : x,
        y : y,
        z : z.z,
        t : z.t
    };
    z = struct dummy {
        x : 5
    };
    return i;
}

func main () {
    var i, j struct dummy;
    j = struct dummy {
        x : 10,
        t : 'z'
    };
    i = foo(2, 3, j);

    printi(i.x);
    printi(i.y);
    printb(i.z);
    printc(i.t);

    printi(j.x);
}
```

9.14.129 test-hello.out

```
hello world
321
888
true
false
r
J
e
C
```

9.14.130 test-hello.rjec

```
func main() {
  prints("hello world");
  printi(321);
  printi(888);
  printb(true);
  printb(false);
  printc('r');
  printc('J');
  printc('e');
  printc('C');
}
```

9.14.131 test-if1.out

```
321
888
Hi friends
```

9.14.132 test-if1.rjec

```
func main() {
  if true {
    printi(321);
    printi(888);
  }
  prints("Hi friends");

}
```

9.14.133 test-if2.out

```
42
Hi friends
```

9.14.134 test-if2.rjec

```
func main() {
  if true {
    printi(42);
  }
  else {
    printi(8);
  }

  prints("Hi friends");

}
```

9.14.135 test-if3.out

```
Hi friends
```

9.14.136 test-if3.rjec

```
func main() {
  if false {
    prints("no");
  }

  prints("Hi friends");

}
```

9.14.137 test-if4.out

```
8
Hi friends
```

9.14.138 test-if4.rjec

```
func main() {
  if false {
```

```
    prints("no");
  }
  else {
    printi(8);
  }

  prints("Hi friends");

}
```

9.14.139 test-if5.out

```
8
Hi friends
```

9.14.140 test-if5.rjec

```
func main() {
  if false {
    prints("no");
  }
  else if true {
    printi(8);
  }

  prints("Hi friends");

}
```

9.14.141 test-if6.out

```
2
Hi friends
```

9.14.142 test-if6.rjec

```
func main() {
  if false {
    prints("no");
  }
  else if true {
    if 1+1==2 {
        printi(2);
    }
    else{
        printi(100);
    }
  }
  else {
      prints("bye");
  }

  prints("Hi friends");

}
```

9.14.143 test-init1.out

```
42
30
true
60
52
42
60
```

9.14.144 test-init1.rjec

```
func main() {
  i, j := 42, 30;
  b := true;
  printi(i);
  printi(j);
  printb(b);

  if true {
```

```
      j = 60;
      printi(j);
      i := 52;
      printi(i);
  }

  printi(i);
  printi(j);
}
```

9.14.145 test-init2.out

```
1
r
false
2
j
false
1
r
false
2
j
false
3
1
r
false
```

9.14.146 test-init2.rjec

```
struct my_struct {
    a int;
    b char;
    c bool;
}

func foo(x int, y char) struct my_struct {
    i := struct my_struct {
        a : x,
        b : y
```

```
    };
    printi(i.a);
    printc(i.b);
    printb(i.c);

    return i;
}

func main() {

    t, k, l := foo(1, 'r'), foo(2, 'j'), 3;
    printi(t.a);
    printc(t.b);
    printb(t.c);

    printi(k.a);
    printc(k.b);
    printb(k.c);

    printi(l);

    a, b, c := t.a, t.b, t.c;
    printi(a);
    printc(b);
    printb(c);

}
```

9.14.147 test-ops1.out

```
3
-1
2
50
0
99
false
true
99
true
false
99
true
```

```
true
false
99
```

9.14.148 test-ops1.rjec

```
func main() {
  printi(1 + 2);
  printi(1 - 2);
  printi(1 * 2);
  printi(100 / 2);
  printi(4 % 2);
  printi(99);
  printb(1 == 2);
  printb(1 == 1);
  printi(99);
  printb(1 < 2);
  printb(2 < 1);
  printi(99);
  printb(1 <= 2);
  printb(1 <= 1);
  printb(2 <= 1);
  printi(99);

}
```

9.14.149 test-ops2.out

```
true
false
true
false
false
false
true
true
true
false
true
false
-10
```

9.14.150 test-ops2.rjec

```
func main() {
  printb(true);
  printb(false);
  printb(true && true);
  printb(true && false);
  printb(false && true);
  printb(false && false);
  printb(true || true);
  printb(true || false);
  printb(false || true);
  printb(false || false);
  printb(!false);
  printb(!true);
  printi(-10);
}
```

9.14.151 test-select1.out

```
777
888
1313
```

9.14.152 test-select1.rjec

```
func foo(a chan int, b chan int, c chan int) {
    for {
        select {
        case i := <- a:
            printi(i);
        case j := <- b:
            printi(j);
        case k := <- c:
            printi(k);
        }
    }
```

```
}

func main() {
    a := make(chan int);
    b := make(chan int);
    c := make(chan int);
    yeet foo(a, b, c);
    a <- 777;
    b <- 888;
    c <- 1313;
}
```

9.14.153 test-select2.out

```
777
true
a
```

9.14.154 test-select2.rjec

```
func foo(a chan int, b chan bool, c chan char) {
    for {
        select {
        case i := <- a:
            printi(i);
        case j := <- b:
            printb(j);
        case k := <- c:
            printc(k);
        }
    }
}

func main() {
    a := make(chan int);
    b := make(chan bool);
    c := make(chan char);
    yeet foo(a, b, c);
    a <- 777;
    b <- true;
    c <- 'a';
```

```
}
```

9.14.155 test-select3.out

```
777
888
1313
```

9.14.156 test-select3.rjec

```
func foo(a chan int, b chan int, c chan int) {
    for {
        var i int;
        select {
        case i = <- a:
            printi(i);
        case var j int = <- b:
            printi(j);
        case k := <- c:
            printi(k);
        }
    }
}

func main() {
    a := make(chan int);
    b := make(chan int);
    c := make(chan int);
    yeet foo(a, b, c);
    a <- 777;
    b <- 888;
    c <- 1313;
}
```

9.14.157 test-select4.out

```
777
777
888
```

```
888
1313
1313
```

9.14.158 test-select4.rjec

```
func foo(a chan int, b chan int, c chan int) {
    val := 1313;
    for {
        select {
        case a <- 777:
            printi(777);
        case b <- 888:
            printi(888);
        case c <- val:
            printi(val);
        }
    }
}

func main() {
    a := make(chan int);
    b := make(chan int);
    c := make(chan int);
    yeet foo(a, b, c);
    printi(<-a);
    printi(<-b);
    printi(<-c);
}
```

9.14.159 test-select5.out

```
0
1
```

9.14.160 test-select5.rjec

```
func foo(a chan int, b chan int) {
    idx := -1;
```

```
    for {
        select {
        case i := <- a:
            idx = 0;
        case j := <- b:
            idx = 1;
        }
        printi(idx);
    }
}

func main() {
    a := make(chan int);
    b := make(chan int);
    yeet foo(a, b);
    a <- 0;
    b <- 1;
}
```

9.14.161 test-select6.out

```
sending:
a
a
receiving:
0
sending:
a
a
receiving:
1
sending:
a
a
receiving:
2
sending:
a
a
receiving:
3
sending:
a
```

```
a
receiving:
4
true
quitting...
```

9.14.162 test-select6.rjec

```
func foo(ch1 chan char, ch2 chan int, quit chan bool) {
    for {
        select {
        case ch1 <- 'a':
            prints("sending:");
            printc('a');
        case val2 := <- ch2:
            prints("receiving:");
            printi(val2);
        case q := <- quit:
            printb(q);
            if q {
                prints("quitting...");
            }
            return;
        }
    }
}

func main() {
    ch1 := make(chan char);
    ch2 := make(chan int);
    quit := make(chan bool, 10);
    yeet foo(ch1, ch2, quit);
    for i := 0; i < 5; i = i + 1 {
        printc(<-ch1);
        ch2 <- i;
    }
    quit <- true;
}
```

9.14.163 test-select7.out

```
1
2
3
4
5
6
7
8
9
10
```

9.14.164 test-select7.rjec

```
func producer (data chan int, quit chan int) {
    i := 0;
    for {
        i = i + 1;
        select {
            case data <- i:
            case <- quit:
                close(data);
                return;
        }
    }
}

func main () {
    data := make(chan int);
    quit := make(chan int);

    yeet producer(data, quit);

    for i := <-data; !(i == 0); i = <-data {
        printi(i);
        if i == 10 {
            quit <- 1;
            close(quit);
        }
    }
}
```

9.14.165 test-select8.out

```
sent 1 through c2
sent 1 through c2
1
2
10
2
2
```

9.14.166 test-select8.rjec

```
/* NOTE: might be race conditions causing variations of the test
   output */

func foo (x []chan int){
    c0, c1, c2, c3 := x[0], x[1], x[2], x[3];
    for {
        select {
        case i := <- c0:
            printi(i);
        case j := <- c1:
            printi(j);
        case c2 <- 1:
            prints("sent 1 through c2");
        case c3 <- 2:
        }
    }
}

func main () {
    x := []chan int {
        make(chan int),
        make(chan int, 2),
        make(chan int, 2),
        make(chan int)
    };

    yeet foo(x);
    c0, c1, c2, c3 := x[0], x[1], x[2], x[3];

    c0 <- 1;
```

```
    c0 <- 2;
    c1 <- 10;
    printi(<- c3);
    printi(<- c3);
}
```

9.14.167 test-select9.out

```
sent 1 through c2
sent 1 through c2
1
2
10
2
2
```

9.14.168 test-select9.rjec

```
/* NOTE: might be race conditions causing variations of the test
   output */

func foo (x []chan int){
    for {
        select {
        case i := <- x[0]:
            printi(i);
        case j := <- x[1]:
            printi(j);
        case x[2] <- 1:
            prints("sent 1 through c2");
        case x[3] <- 2:
        }
    }
}

func main () {
    x := []chan int {
        make(chan int),
        make(chan int, 2),
        make(chan int, 2),
        make(chan int)
```

```
    };

    yeet foo(x);

    x[0] <- 1;
    x[0] <- 2;
    x[1] <- 10;
    printi(<- x[3]);
    printi(<- x[3]);
}
```

9.14.169 test-string1.out

```
e
l
l
o
```

9.14.170 test-string1.rjec

```
func main () {
    var x [5]char;
    x = "ello";
    for i := 0; i < 4; i = i + 1 {
        printc(x[i]);
    }
}
```

9.14.171 test-string2.out

```
e
l
l
o
ello
e
l
l
```

```
e
elle
```

9.14.172 test-string2.rjec

```
func main () {
    x := "ello";
    for i := 0; i < 4; i = i + 1 {
        printc(x[i]);
    }
    prints(x);

    x[1] = x[2];
    x[3] = x[0];
    for i := 0; i < 4; i = i + 1 {
        printc(x[i]);
    }
    prints(x);
}
```

9.14.173 test-string3.out

```
hello world
```

9.14.174 test-string3.rjec

```
func foo (x []char) {
    prints(x);
}

func main () {
    foo("hello world");
}
```

9.14.175 test-string4.out

```
e
l
l
o
ello
e
l
l
ell
```

9.14.176 test-string4.rjec

```
func main () {
    x := "ello";
    for i := 0; !(x[i] == '\0'); i = i + 1 {
        printc(x[i]);
    }
    prints(x);

    x[1] = x[2];
    x[3] = '\0';
    for i := 0; !(x[i] == '\0'); i = i + 1 {
        printc(x[i]);
    }
    prints(x);
}
```

9.14.177 test-struct1.out

```
1
true
a
```

9.14.178 test-struct1.rjec

```
struct foo {
    x int;
    y bool;
```

```
    z char;
}

func main() {
    var i struct foo;
    i = struct foo {
        x : 1,
        y : true,
        z : 'a'
    };
    printi(i.x);
    printb(i.y);
    printc(i.z);
}
```

9.14.179 test-struct2.out

```
false
0
```

9.14.180 test-struct2.rjec

```
struct foo {
    x bool;
    y int;
}

func main() {
    var i struct foo;

    printb(i.x);
    printi(i.y);
}
```

9.14.181 test-struct3.out

```
false
0
true
```

```
false
10
false
```

9.14.182 test-struct3.rjec

```
struct foo {
    x bool;
    y int;
    z bool;
}

func main() {
    var i struct foo;
    i = struct foo {
        x : false,
        z : true
    };
    printb(i.x);
    printi(i.y);
    printb(i.z);

    i = struct foo {
        y : 10
    };
    printb(i.x);
    printi(i.y);
    printb(i.z);
}
```

9.14.183 test-struct4.out

```
true
9
true
```

9.14.184 test-struct4.rjec

```
struct foo {
    x bool;
    y int;
    z bool;
}

func main() {
    var i struct foo;
    i.x = true;
    i.y = 9;
    i.z = true;

    printb(i.x);
    printi(i.y);
    printb(i.z);

}
```

9.14.185 test-struct5.out

```
false
0
true
false
10
true
```

9.14.186 test-struct5.rjec

```
struct foo {
    x bool;
    y int;
    z bool;
}

func main() {
    var i struct foo;
    i = struct foo {
        x : false,
        z : true
```

```
    };
    printb(i.x);
    printi(i.y);
    printb(i.z);

    i.y = 10;

    printb(i.x);
    printi(i.y);
    printb(i.z);
}
```

9.14.187 test-struct6.out

```
10
r
false
20
j
false
10
r
false
```

9.14.188 test-struct6.rjec

```
struct my_struct {
    a int;
    b char;
    c bool;
}

func foo(i struct my_struct, x int, y char) {
    i.a = x;
    i.b = y;

    printi(i.a);
    printc(i.b);
    printb(i.c);
}
```

```
func main() {

    j := struct my_struct {
        a : 10,
        b : 'r'
    };

    printi(j.a);
    printc(j.b);
    printb(j.c);

    foo(j, 20, 'j');

    printi(j.a);
    printc(j.b);
    printb(j.c);

}
```

9.14.189 test-time1.out

```
time elapsed greater than 0:
true
```

9.14.190 test-time1.rjec

```
func main()
{
    i := time();
    prints("time elapsed greater than 0:");
    printb(i < time());
}
```

9.14.191 test-yeet1.out

```
3
4
7
```

9.14.192 test-yeet1.rjec

```
func foo (x int, y int) int {
    printi(x);
    printi(y);
    printi(x + y);
    return x + y;
}

func main() {
    yeet foo(3, 4);
}
```

9.14.193 test-yeet2.out

```
1
3
false
```

9.14.194 test-yeet2.rjec

```
struct lol {
    x int;
    y int;
    z bool;
}

func foo (x struct lol) {
    y := struct lol {
        x : x.x,
        y : x.y + 1
    };

    printi(y.x);
    printi(y.y);
    printb(y.z);
}

func main() {
    yeet foo(struct lol {
```

```
        x : 1,
        y : 2
    });
}
```

9.14.195 test-yeet3.out

```
2
2
2
```

9.14.196 test-yeet3.rjec

```
func foo1 () int {
    return 1 + 2;
}
func foo2 (x int, y bool) int {
    if (x == 2 && y) {
        printi(x);
    } else {
        printi(x + 1);
    }
    return x;
}

func main() {
    yeet foo1();
    yeet foo2(2, true);
    yeet foo2(1, true);
    yeet foo2(1, false);
}
```

9.15 demo/

9.15.1 mapreduce.rjec

```
/* by Justin Chen
 * mapreduce to count randomly generated primes vs composite ints
```

```
 * compares time length of iterative vs concurrent solutions
 * based on noun/verb count mapreduce by appliedgo.net */

/* mapper receives a channel of ints and counts the number of prime
   and
 * composite ints. It sends the resulting counts to the output
    channels.
 */
func mapper(in chan int, out_prime chan int, out_composite chan int)
    {
    num_prime := 0;
    num_composite := 0;
    for i := <- in; !(i == 0); i = <- in {
        if is_prime(i) {
            num_prime = num_prime + 1;
        } else {
            num_composite = num_composite + 1;
        }
    }
    out_prime <- num_prime;
    out_composite <- num_composite;
    close(out_prime);
    close(out_composite);
}

/* checks if positive integer is prime, using pseudocode from
   Wikipedia */
func is_prime(n int) bool {
    if n <= 3 {
        return 1 < n;
    }
    if n % 2 == 0 || n % 3 == 0 {
        return false;
    }
    for i := 5; i * i <= n; i = i + 6 {
        if n % i == 0 || n % (i + 2) == 0 {
            return false;
        }
    }
    return true;
}

/* reducer receives a channel of ints and adds up all ints until it
   receives the
 * quit signal
```

```
 */
func reducer(in chan int, out chan int, quit chan bool) {
    sum := 0;
    for {
        select {
        case n := <- in:
            sum = sum + n;
        case <- quit:
            out <- sum;
            close(out);
        }
    }
}

/* basic linear congruential generator for random positive int */
func rand(seed int) int {
    rand_int := (1103515245 * seed + 12345) % 2147483648;
    if rand_int < 0 {
        return -1 * rand_int;
    }
    if rand_int == 0 {
        return 1;
    }
    return rand_int;
}

/* receives output channels and sends each of them random positive
   integers */
func input_reader(out []chan int, num_mappers int, num_ints int,
   rand_ints []int) {
    for i := 0; i < num_mappers; i = i + 1 {
        yeet input_helper(out[i], num_ints / num_mappers, rand_ints,
             num_ints / num_mappers * i);
    }
}

func input_helper(ch chan int, num_ints int, rand_ints []int, idx
   int) {
    for i := 0; i < num_ints; i = i + 1 {
        ch <- rand_ints[idx + i];
    }
    close(ch);
}

/* gets two arrays of input channels containing for prime and
```

```
   composite.
 * the input channels are merged into single outputs for prime and
    composite.
 */
func shuffler(in_prime []chan int, in_composite []chan int, out []
   chan int, num_mappers int, quit []chan bool) {
    var done [num_mappers]chan bool;
    for i := 0; i < num_mappers; i = i + 1 {
        done[i] = make(chan bool);
        yeet shuffler_helper(in_prime[i], in_composite[i], out, done
            [i]);
    }
    for i := 0; i < num_mappers; i = i + 1 {
        <- done[i];
    }
    quit[0] <- true;
    quit[1] <- true;
    close(out[0]);
    close(out[1]);
}

func shuffler_helper(in_prime chan int, in_composite chan int, out
   []chan int, done chan bool) {
    out[0] <- (<- in_prime);
    out[1] <- (<- in_composite);
    done <- true;
}

/* writes out the counts that it receives from each channel.
 */
func output_writer(in []chan int) {
    prints("number of primes:");
    printi(<- in[0]);
    prints("number of composites:");
    printi(<- in[1]);
}

/* struct for iterative mapreduce */
struct count_t {
    count_prime int;
    count_composite int;
}

/* iterative mapreduce */
func primes_iterative(num_ints int, num_mappers int, rand_ints []int
```

```
    ) {
    var counts [num_mappers]struct count_t;
    idx := 0;
    for i := 0; i < num_mappers; i = i + 1 {
        var rand_ints_slice [num_ints / num_mappers]int;
        for j := 0; j < num_ints / num_mappers; j = j + 1 {
            rand_ints_slice[j] = rand_ints[idx];
            idx = idx + 1;
        }
        counts[i] = count_primes_iterative(num_ints / num_mappers,
            rand_ints_slice);
    }

    count := reduce_counts_iterative(counts, num_mappers);

    prints("number of primes:");
    printi(count.count_prime);
    prints("number of composites:");
    printi(count.count_composite);
}

func count_primes_iterative(num_ints int, rand_ints []int) struct
    count_t {
    counts := struct count_t {
        count_prime    : 0,
        count_composite: 0
    };

    for i := 0; i < num_ints; i = i + 1 {
        if is_prime(rand_ints[i]) {
            counts.count_prime = counts.count_prime + 1;
        } else {
            counts.count_composite = counts.count_composite + 1;
        }
    }

    return counts;
}

func reduce_counts_iterative(counts []struct count_t, num_mappers
    int) struct count_t {
    count := struct count_t{
        count_prime    : 0,
        count_composite: 0
    };
```

```
    for i := 0; i < num_mappers; i = i + 1 {
        count.count_prime = count.count_prime + counts[i].
            count_prime;
        count.count_composite = count.count_composite + counts[i].
            count_composite;
    }
    return count;
}

/* pregenerate array of num_ints ints */
func generate_ints(num_ints int) []int {
    var rand_ints [num_ints]int;
    for i := 0; i < num_ints; i = i + 1 {
        rand_ints[i] = rand(time());
    }
    return rand_ints;
}

func main() {
    num_ints := 1000000;
    rand_ints := generate_ints(num_ints);
    prints("number of random ints generated:");
    printi(num_ints);

    /* Set up all channels used for passing data between the workers
       . */
    size := 10;
    num_mappers := 10;
    var text [num_mappers]chan int;
    var map_prime [num_mappers]chan int;
    var map_composite [num_mappers]chan int;
    for i := 0; i < num_mappers; i = i + 1 {
        text[i] = make(chan int, size);
        map_prime[i] = make(chan int, size);
        map_composite[i] = make(chan int, size);
    }
    reduce := []chan int{make(chan int, size), make(chan int, size)
       };
    count := []chan int{make(chan int, size), make(chan int, size)};

    quit := []chan bool{make(chan bool), make(chan bool)};

    /* Start all workers in separate yeetroutines, chained together
       via channels. */
    yeet input_reader(text, num_mappers, num_ints, rand_ints);
```

```
    for i := 0; i < num_mappers; i = i + 1 {
        yeet mapper(text[i], map_prime[i], map_composite[i]);
    }
    yeet shuffler(map_prime, map_composite, reduce, num_mappers,
       quit);
    yeet reducer(reduce[0], count[0], quit[0]);
    yeet reducer(reduce[1], count[1], quit[1]);

    start := time();
    /* The output_writer runs in the main thread. */
    output_writer(count);
    prints("time taken for mapreduce (us):");
    time_mapreduce := time() - start;
    printi(time_mapreduce);

    new_start := time();
    primes_iterative(num_ints, num_mappers, rand_ints);
    prints("time taken for iterative (us):");
    printi(time() - new_start);
}
```

9.15.2 mutex.rjec

```
/* implementation of a mutex using channels and demonstration with
   defer */
/* written by Justin Chen */

func make_mutex() chan bool {
    mu := make(chan bool, 1);
    mu <- true;
    return mu;
}

func lock(mu chan bool) {
    <- mu;
}

func unlock(mu chan bool) {
    mu <- true;
}

func foo(n int, mu chan bool) {
    if 30 < n {
```

```
        return;
    } else {
        lock(mu);
        defer unlock(mu);
    }

    for i := n; i < n + 10; i = i + 1 {
        printi(i);
    }
}

func main() {
    mu := make_mutex();
    yeet foo(0, mu);
    yeet foo(25, mu);
    yeet foo(-100, mu);
    foo(-5, mu);
}
```

9.15.3 producer_consumer.rjec

```
/* simple producer-consumer problem */
/* written by Justin Chen */

func foo(ch1 chan char, ch2 chan int, quit chan bool) {
    for {
        select {
        case ch1 <- 'a':
            prints("sending a in foo...");
        case val2 := <- ch2:
            prints("receiving in foo:");
            printi(val2);
        case q := <- quit:
            printb(q);
            if q {
                prints("quitting...");
            }
            return;
        }
    }
}

func main() {
```

```
    ch1 := make(chan char);
    ch2 := make(chan int);
    quit := make(chan bool, 10);
    yeet foo(ch1, ch2, quit);
    for i := 0; i < 5; i = i + 1 {
        c := <-ch1;
        prints("received in main:");
        printc(c);
        prints("sending i in main...");
        ch2 <- i;
    }
    quit <- true;
}
```

9.15.4 rand_ints.rjec

```
/* generates 1,000,000 random integers in an array and prints every
   10,000th */
/* written by Justin Chen */

func rand(seed int) int {
    return (1103515245 * seed + 12345) % 2147483648;
}

func main() {
    start := time();
    var rand_ints [1000000]int;
    for i := 0; i < 1000000; i = i + 1 {
        rand_ints[i] = rand(time());
        if i % 10000 == 0 {
            printi(rand_ints[i]);
        }
    }
    end := time();
    prints("time taken (us):");
    printi(end - start);
}
```

9.16 libmill/

Source code for the Libmill library may be found at `https://github.com/sustrik/libmill`.