(g)ROOT
Final Report

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1 Acknowledgments

Project Mentor: Mert Erden

Professor: Richard Townsend

2 Resources

Implementing functional languages: a tutorial. Simon Peyton Jones, David R Lester. Prentice Hall, 1992.

Modern Compiler Implementation in ML. Andrew W. Appel. Cambridge University Press, 2004.

Compilers: Principles, Techniques, and Tools, 2nd Edition. Alfred V. Aho, Monica S. Lam, Ravi Sethi, Jeffrey D. Ullman. Addison-Wesley, 2006.

Engineering a Compiler, 2th Edition. Keith D. Cooper and Linda Torczon. Morgan Kaufmann, 2012.

OCaml Programming: Correct + Efficient + Beautiful, Michael R. Clarkson et al. 2022

OCaml Manual

3 Introduction

g(ROOT) is a general-purpose functional programming language, with a abbreviated and minimalist syntax that makes it useful for educational purposes, such as transitioning imperative programmers to functional languages. The language has a LISP-like syntax and offers lambda expressions, higher-order functions, inferred types, and allows top-level variable redefinitions.

g(ROOT) utilizes the Hindley-Milner type system algorithm in order to infer the types of expressions, as well as typing and variable environments in order to accomplish closure conversion to resolve lambda expressions (closures use the original values of any free variables at the time the closure was created, rather than using the most recent values of any free variables when the closure is used).

The project originally set out to give the language a built-in n-ary tree data structure as a primitive type. This is where the name and mascot "groot" originates. However, with the challenges of compiling seemingly inherent functional language features and the time constraints, trees are left as a future feature to be implemented.

This document will provide an in-depth language reference manual for g(ROOT), a language tutorial, and details of our implementations and key takeaways from this project.

4 Language Tutorial

4.1 Environment Setup

To run our language, please have the following packages installed:

- `opam-2.1`
- `llvm-13`
- `ocaml-4.13`
- `ocamlbuild-0.14.0`
- `gcc-11.3.1`

If there are compilation issues that may be due to versioning, we have a docker image that may help.

To maximize the portability of our language development environment, we developed a docker image. You may opt to install the dependencies and resolve issues on your own machine if you choose, but working within the docker image will guarantee success. To initialize the development environment docker container, simply enter:

```
make dev
```

4.2 Compile and Run

*Currently does not support linking, so all source code must be in the same file. The g(ROOT) file extension is **.gt***

Compile the g(ROOT) compiler with ONE of these two commands:

- `make`
- `make toplevel.native`

Compile and create executable and intermediate files for any given source file in our language with the format [filename].gt
Intermediate files are stored in toplevel as tmp.ll and tmp.s, respectively

- `make [filename].exe`

Run [filename].exe executable

- `./[filename].exe`

4.3 Compiler Flags and other Intermediates

The following compiler flag options are available for other intermediate representations:

```
$   ./toplevel --help
$   usage: ./toplevel.native [-a|-n|-t|-m|-h|-v|-l|-c] [file.gt]
$       -a Print the AST (default)
$       -n Print the AST (name-checking)
```

```
$       -t Print the TAST
$       -m Print the MAST
$       -h Print the HAST
$       -v Print the CAST
$       -l Print the generated LLVM IR
$       -c Check and print the generated LLVM IR
$       -help Display this list of options
$       --help Display this list of options
```

4.4 Using the Language

g(ROOT) uses Lisp-style syntax and allows higher-order functions. All expressions except literals and variable evaluations must be enclosed in parentheses. Whitespace serves no syntactic purpose except to separate tokens and aid in styling.

There is an inbuilt standard basis consisting of the basic algebraic and boolean operations and comparisons, and both named and anonymous user-defined functions can be created using `val lambda` and `lambda`, respectively.

Please reference the g(ROOT) Lexical Conventions for more details.

Simple example code:

```
(val x 42)
(printi x)
```

The above compiled code outputs:

```
$   42
```

Complex example code:

```
(val letterGrade (lambda (test)
  (if (> 90 test)
      'A'
      (if (> 80 test)
          'B'
          (if (> 70 test)
              'C'
              'D')))))

(printc (letterGrade 89))     (; this prints B ;)

(val computeGrade (lambda (test test2 test3)
  (let ([sum (+ (+ test test2) test3)])
      (let ([avg (/ sum 3)])
          (letterGrade avg)))))

(printc (computeGrade 88 90 91)) (; this prints B ;)

```

```
(val letterGrade (lambda (test)
  (if (> 85 test)
      'A'
      (if (> 75 test)
          'B'
          (if (> 65 test)
              'C'
              'D')))))

(printc (letterGrade 89))        (; this prints A ;)
(printc (computeGrade 88 90 91)) (; this prints B ;)
```

The above compiled code outputs:

```
$   B
$   B
$   A
$   B
```

Definitions and expressions are processed in order, and both local and toplevel definitions exist - local definitions take priority in-scope and disappear once the block in which they were defined is finished. Local definitions defined simultaneously cannot reference each other (let* does not exist), but nested let statements can get around this, as seen by using sum to define avg.

Redefinitions are allowed, and later usages use the updated values, though if a variable was used in the body of the closure, the closure will always use that value even if the variable is redefined later, hence why the last line prints “B” - computeGrade still uses the earlier definition of letterGrade.

5 Language Reference Manual

5.1 How to read manual

The syntax of the language will be given in BNF-like notation. Non-terminal symbol will be in italic font *like-this*, square brackets [...] denote optional components, curly braces { ... } denote zero or more repetitions of the enclosed component, and parentheses (...) denote a grouping. Note the font, as `[ ... ]` and `( ... )` are syntax requirements later in the manual.

5.2 Lexical Convention

5.2.1 Blanks

The following characters are considered as **blanks**: space, horizontal tab (‘`\t`’), newline character (‘`\n`’), and carriage return (‘`\r`’).

Blanks separate adjacent identifiers, literals, expressions, and keywords. They are otherwise ignored.

5.2.2 Comments

Comments are introduced with two adjact characters `(;` and terminated by two adjacent characters `;)`. Multiline comments are allowed with this. Single line comments using `;;` are also allowed for ease. Nested comments are not supported.

```
(; This is a comment. ;)

;; This is another comment

(; This is a
   multi-lined comment. ;)

(; This is a multi-lined comment
;; still the same comment
(; still the same comment
    comment ends ;)
This is not in a comment, will produce an error ;)
```

5.2.3 Identifiers

Identifiers are sequences of letters, digits, and ASCII characters, starting with any character that isn’t the underscore. Letters will refer to the below ranges of ASCII characters. *Identifiers may not start with an underscore character*, and may not be any of the reserved character sequences.

$\langle \mathit{ident} \rangle$ ::= *letter* { *letter* | _ }

$\langle \mathit{letter} \rangle$ ::= `!...&` | `*...:` | `<...Z` | `` ` ...z `` | `~` | |

5.2.4 Integer Literals

An integer literal is a decimal, represented by a sequence of one or more digits, optionally preceded by a minus sign.

$$\langle \textit{integer-literal} \rangle \quad ::= \; [\, \texttt{-} \,] \; \textit{digit} \; \{ \textit{digit} \}$$

$$\langle \textit{digit} \rangle \quad ::= \; \texttt{0...9}$$

5.2.5 Boolean Literals

Boolean literals are represented by two adjacent characters; the first is the octothorp character (`#`), and it is immediately followed by either the `t` or the `f` character.

$$\langle \textit{boolean-literal} \rangle \quad ::= \; \texttt{\#} \; (\; \texttt{t} \mid \texttt{f} \;)$$

5.2.6 Character Literals

Character literals are a single character enclosed by two ' (single-quote) characters.

5.3 Reserved Keywords

The below identifiers are reserved keywords and cannot be used except in their capacity as reserve keywords:

```
if     val       #t      '
let    lambda    #f      (       )
```

The following tree-related keywords are still recognized and reserved, but their uses are unimplemented. Please be aware:

```
leaf

tree
```

5.3.1 Syntax

See Definitions and Expression for concrete syntax for each definition and expressions, with detailed examples.

5.4 Values

Base Values

5.4.1 Integer numbers

Integer values are integer numbers in range from -2^{32} to $2^{32}-1$, similar to LLVM's integers, and may support a wider range of integer values on other machines, such as -2^{64} to $2^{64}-1$

on a 64-bit machine.

5.4.2 Boolean values

Booleans have two values. `#t` evaluates to the boolean value `true`, and `#f` evaluates to the boolean value `false`.

5.4.3 Characters

Character values are 8-bit integers between 0 and 255, and follow ASCII standard.

5.4.4 Functions

Functional values are mappings from values to value.

5.5 Types

g(ROOT) has an inferred typing system with Int, Char, and Bool primitive data types. The language will try its best to type expressions based on their use in the program utilizing the known types of primitives and literals. Currently, there are no predefined data structure types.

The primitive types recognized are as follows:

- `integers`
- `booleans`
- `characters`

Other types that can be inferred are `function` type and **polymorphic** type.

Most convention represent polymorphic type variable using alphabet letters, ie. `'a`. You will see these represented in g(ROOT)'s TAST and MAST with numbers, ie. `'1`.

5.5.1 Type Inferencing

g(ROOT) is a statically typed language meaning every expression is given a type at compile time. Furthermore, g(ROOT) is an implicitly typed language, meaning the types of expressions are inferred based on known primitive types and how the expressions are used. This is known as constraint-based type inference, or the Hadley-Milner type system method. At a high level, the algorithm works by assigning "type variables" to expressions whose type is still unknown. Then we proceed to gather more information about the expression by collecting more constraints and solving them through a series of substitutions. Polymorphism is supported.

5.6 Definitions and Expressions

$\langle def \rangle$ ::= (`val` *ident* *expr*)
| *expr*

$\langle expr \rangle$ ::= *literal*
| *ident*
| (*binary-operator* *expr* *expr*)
| (*ident* $\{$*expr*$\}$)
| (`let` (`[`*ident* *expr*`]` $\{$`[`*ident* *expr*`]`$\}$) *expr*)
| (`if` *expr* *expr* *expr*)
| (`lambda` ($\{$*arguments*$\}$) *expr*)

$\langle literal \rangle$ ::= *integer-literal* | *boolean-literal* | *character* | leaf

$\langle arguments \rangle$ ::= ϵ
| *ident* :: *arguments*

g(ROOT) Concrete Syntax

Expressions are values or parenthetical expressions.

5.6.1 Values

see Values.

5.6.2 Parenthetical expressions

Parenthetical expressions are always within parentheses and include function application, lambda expressions, global and local definitions, binary and unary operations, and if-statements. In the above concrete syntax, the parentheses in this font, `( ... )`, are syntax requirements, rather than denoting a grouping which is given by (...)

5.6.3 Function application

Function application in (g)ROOT always returns a value, and is written as expression to apply, followed by a list of zero or more expressions, which are its arguments. The arguments are not separated from the applied expression by parentheses. (g)ROOT has first-class functions, therefore functions can be passed as arguments. While partial application is allowed, this feature is use-at-your-own-risk as it may have undefined behavior due to a the recognized bug in type monomorphization.

Example:

```
(foo)
(bar a b)
((baz x) y)
```

5.6.4 Lambda Expression

Lambda expressions are accomplished with the `lambda` keyword, a parentheses-enclosed list of 0 or more identifiers as formal arguments, followed by the expression that may use those arguments and/or any free variables. Nesting of lambda expressions is allowed, but not recommended for the same reason stated above for why partial function application is not recommended.

Example:

```
(lambda () #t)
(lambda (x) x)
(lambda (x y) (+ x y))

(lambda (a) (add2 a b))
```

5.6.5 Global definitions

Global definitions are accomplished using the `val` keyword, followed by an identifier, followed by the expression which is to be bound to that value.

Example:

```
(val x 4)
(val y (+ x 5))
(val foo (lambda (arg) ( * arg arg)))
```

Calling a global definition with a preexisting identifier will re-bind that identifier to the new value - onlys allowed at the top level, and new definition must always of the same type as the previous definition.

5.6.6 Local definitions

Local definitions are found with the `let` expressions, which is the `let` keyword followed by the identifier(s) and the expression(s) to be bound to it, followed by the expression that local variable may be used. Let expressions must have at least one local binding.

Example:

```
(let ([x 4]) (+ 2 x))  (; return 6 ;)
(let ([x 4]) x)        (; return 4 ;)
(let () y)             (; not allowed! ;)
```

Variables defined within the let binding are not defined outside of it, while variables globally relative to the let can be accessed within it. Since let bindings are a type of expression, this allows for chained let bindings.

Example:

```
(let ([x 4])
   (let ([y 5])
```

```
        (let ([z 9])
            (+ x (- y z)))))
```

5.6.7 If-expression

If-expressions are the only form of control flow in (g)ROOT, and are always formed with the `if` keyword followed by three expressions (the *condition*, the *true case* and the *false case*). Omission of the false case is a syntax error, and the expressions are not separated by parentheses, brackets, or keywords.

Example:

```
(if #t 1 2)
(if (< 3 4)
    (+ x y)
    (- x y))
```

5.7 Functions

5.7.1 Standard Basis

All of the following primitive functions are defined in a standard basis, but can be redefined by the user at their own risk. All integer algebraic operations are signed. Bool

$$ `printi`

Type: *int* → *int*

Purpose: sends the string of an integer to standard out.

$$ `printc`

Type: *char* → *int*

Purpose: sends the string of an character to standard out.

$$ `printb`

Type: *bool* → *int*

Purpose: sends the string of a boolean to standard out using the #t or #f representation of the boolean.

$$ `+`

Type: *int int* → *int*

Purpose: integer addition

$$ `-`

Type: *int int* → *int*

Purpose: integer subtraction

$$ `*`

Type: *int int* → *int*

Purpose: integer multiplication

$$ `/`

Type: *int int* → *int*

Purpose: integer division (note - does not handle divide by zero errors, just uses the C division in which divide-by-zero is undefinable

$$ `mod`

Type: *int int* → *int*

Purpose: integer modular division

$$

Type: *int int* → *int*

Purpose: integer division (note - does not handle divide by zero errors, just uses the C division in which divide-by-zero is undefinable

int → *int*

```
~
```

int int → *int*

```
+ - / * mod
```

int int → *bool*

```
< > <= >= =i !=i
```

bool → *bool*

```
not
```

bool bool → *bool*

```
&& ||
```

5.7.2 Higher-Order Functions

User-defined functions are just like values in g(ROOT). In other words, functions may be passed as arguments to other functions, and may be returned from functions. This allows programmers to combine smaller functions into larger functions increasing the code's re-usability. Note: Passing around built-in functions as such is not supported. Here is a contrived example showing the use of higher-order functions in the g(ROOT) programming language:

```
(val foo (lambda (n) (+ n 2)))
(val bar (lambda (x) x))
(printi ((bar foo) 6))
```

Passing polymorphic functions to other polymorphic functions that apply them leads to undefined behavior and may raise an error.

Not allowed:

```
(val foo (lambda (f a) (f a)))
(val bar (lambda (x) x))
(foo bar 6)
```

6 Project Plan

6.1 Planning, Specification, and Development

Initial planning involved going through several different ideas for a language before we settled on a functional language with an achievable feature that stands out. Most members of the group primarily had experience with imperative languages, so this topic provided an interesting challenge for everyone.

We came up with a preliminary syntax for which we could parse and described in our LRM. The syntax was finalized (to include definitions) once parsing of expressions worked and as we moved on to more complex phases of the compiler.

We used GitLab for organization and version control, and relied on clear communication over text, Discord, and in-person to keep each other up-to-date with responsibilities, new tasks, scheduling, road blocks, and goals reached. Every feature was worked on a separate branch, and merges were usually done as a group to resolve merge conflicts between branches together, if any.

Phase 1 (Scanner/Parser) was done as a group. In subsequent phases, different tasks were divided amongst group members depending on interest, with frequent collaboration with project mentor and other members as the need arose and to double-check each others work. Different responsibilities are described below.

We did not have an official style-guide, and relied on everyone to keep their work readable and well-documented. A few final passes through each file was done to ensure good style.

6.2 Project Timeline

For the most part, we tried to finish as much of a deliverable as possible before a given deadline. For subtasks without any hard due dates, finish-dates became more ambiguous, because a member's work tested by another member of the group, often times, revealed a new bug or a new feature that needs to be implemented before the original task is complete. Due to some of these challenges, we often found ourselves working up to a deadline or working past an expected finish date.

Goal	**Finish or Submit Date**
Final Language Idea	Feb. 2
Project Proposal	Feb. 4
Phase 1 test script	Feb. 23
Phase 1: Scanner & Parser	Feb. 24
Language Reference Manual	Feb. 28
Final Language Syntax	Mar. 5
Start planning and implementing type-inferencer	Mar. 5
Start planning code generation	Mar. 5
Start planning closure conversion	Mar. 11
Semant for purposes of testing Conversion and Codegen	Mar. 13
Partial Semant and Codegen Module that forces a printing	Mar. 11
New phase 2 test script and reference outputs for all phases	Mar. 24
Phase 2: Hello World	Mar. 28
Conversion	Apr. 15
Codegen	Apr. 19
Extended Test Suite	Apr. 20
Type Inferencer	Apr. 23
Start Monomorphization to deal with infer's polymorphic types	Apr. 23
Debug Conversion & Codegen	Apr. 29
thread primitives through each module	Apr. 29
Debug Infer	May 2
Mono	May 2
Create HAST & Hof (conversion I) phase and fit with Conversion (conversion II) to allow HOFs	May 5
Extend testing script	May 5
Presentation slides	May 5
Presentation	May 6
Final Paper & Submission	May 7

6.3 Roles and Responsibilities

These were the originally assigned recommended roles:

Name	Role
Eliza Encherman	Manager
Sam Russo	Tester
Zachary Goldstein	Language Guru
Nickolas Gravel	System Architect
Amy Bui	Facilitator

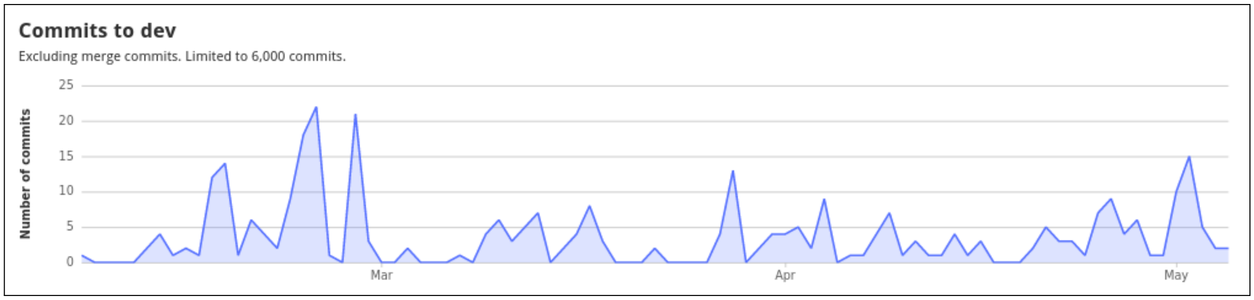
As the project progressed and implementing features of a functional language became more difficult, we abandoned these roles and each subgroup or member focused on progressively implementing different language features. Everyone was responsible initially testing their own feature and subsequent debugging, but we were also responsible for checking each others work and providing "fresh eyes" when testing someone else's implemented feature. Here is a list of each person's primary responsibility:

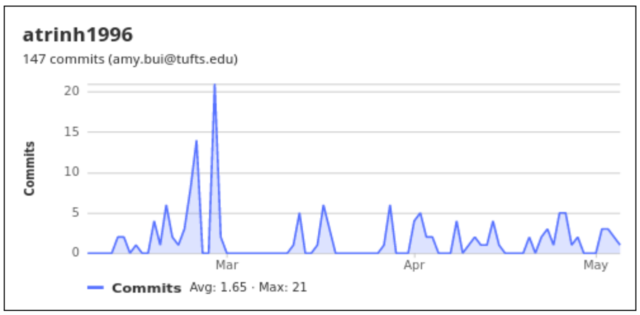
Name	Responsibilities
Eliza Encherman	Primitive function implementation across stages testing and debugging, deliverables
Sam Russo	Type Inferencer, testing
Zachary Goldstein	Errors & Warnings, test suite, Docker environment
Nickolas Gravel	Type Inferencer, test script
Amy Bui	Monomorphizer, Conversion I & II, Codegen, testing

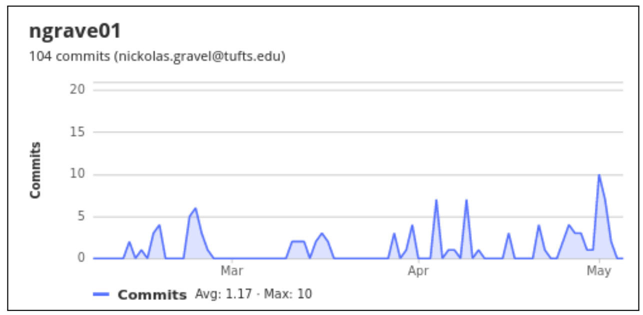
6.4 Development Tools

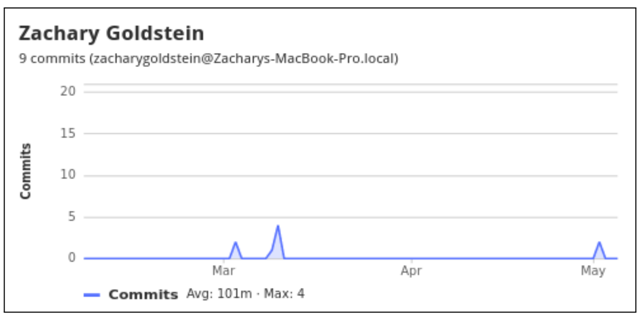
As mentioned previously, we used GitLab to manage version control and parallel development of features. Most work was done in Sublime, VSCode, or vim, and some group members used a docker image to avoid possible environment conflicts.

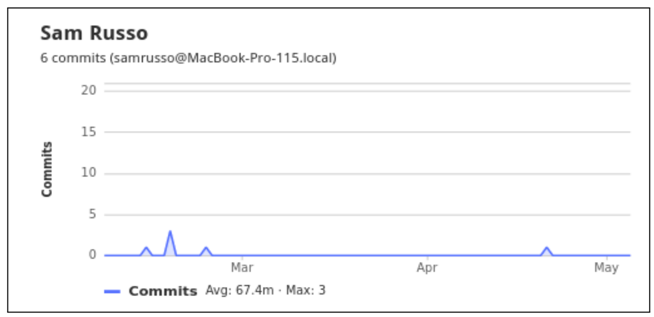
6.5 Project Logs

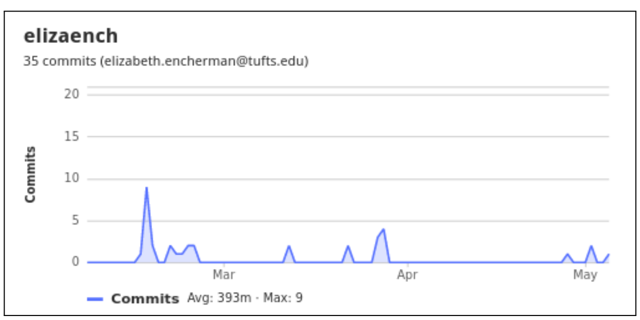




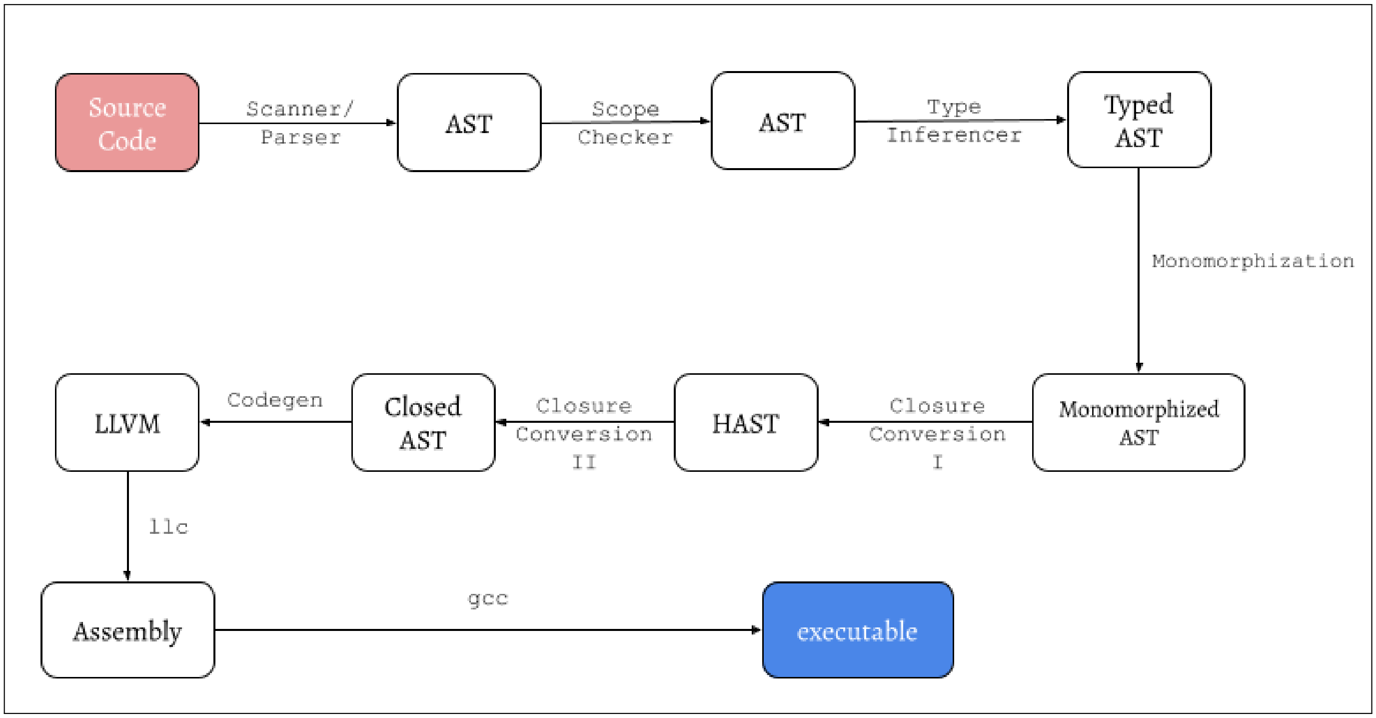








7 Architectural Design



7.1 Scanner/Parser

- Given the groot source code, the Scanner/Parser scans and tokenizes sequences of characters to build the basic abstract syntax tree of the program.
- *Authored by the whole group. Final syntax incorporated into Scanner/Parser done by Zach.*

7.2 Scope Checker

- This module performs a partial semantic check on a given abstract syntax tree, in which any variable name used has been bound and is used in the scope that it is allowed. The module reports an unbound variable, if any; otherwise, the same abstract syntax tree it receives is outputted.
- *Authored by Amy, with help incorporating primitives from Eliza.*

7.3 Type Inferencer

- The type inference takes an abstract syntax tree, and assumes all named variables are bound to some value. (g)ROOT is implicitly typed, so this module detects the types of all expressions and definitions. We follow the Hindley-Milner type system method in order to infer types. Using the types already given by primitives and literals, the inferencer generates constraints and then solves those constraints in order to deduce the type of the current definition it is inferring; those constraints are then used to infer the type of the rest of the program. The type inferencer will throw an error if it catches any type errors, such as type mismatches in function application of arguments. The module allows for polymorphism, so a definition may be typed to a type variable; however, to make resolving polymorphic types easier, this module also disallows nested lambdas. The inferencer outputs the final typed abstract syntax tree, or TAST.

- *Authored by Sam and Nik, with help from Mert. Primitives were incorporated by Eliza.*

7.4 Monomorphization

- This module takes a typed abstract syntax tree, which may or may not have any type variables, and monomorphizes it, getting rid of any polymorphism such that the tree has concrete types for everything. This is accomplished by tagging expressions that are polymorphic, finding where they are used (application), and using the types of the arguments it is used with to match type variables to concrete types; a mono-typed definition of the original polymorphic variable is then inserted into the program for that specific use case. The module outputs a monomorphic-typed abstract syntax tree.
- Bug: The algorithm we implemented for this resolves polymorphic types for non-nested lambda definitions, but cannot resolve them for nested lambdas which involves partial function application in order to get concrete types for each type variables. We concluded additional passes to resolve polymorphic types was required, but ran out of time for this. So, to ensure no type variables leak through to subsequent phases, Mono does one additional pass through the program, re-typing any leftover type variables to our int type. It is a recognized bug, so nested lambdas may result in undefined behavior or llc will raise an error regarding any type mismatches.
- *Authored by Amy.*

7.5 Closure Conversion I (Hof)

- Conversion I (or Hof) takes a monomorphic-typed abstract syntax tree, and creates partial closures for every lambda expression by re-typing every lambda expression from a function type to a new abstract type we called a closure type. Conversion I's closure types will carry a unique name to associate with the lambda expression (generated in the module), the original lambda's return type, the list of the formal types, AND a list of the types of the free variables. This is considered "partial" because no closure thus far is closed with the values or a reference to the values of the free variables.

  Re-typing in this module helps subsequent modules deal with higher-order functions more easily, because Conversion I finds uses of a Hof, and re-types the function type to the appropriate closure type in function application

  This module returns a h-abstract syntax tree. As indicated by the name, this intermediate phase makes handling higher-order functions easier in the next module.

- *Authored by Amy.*

7.6 Closure Conversion II (Conversion)

- Conversion II takes a h-abstract syntax tree, and finishes creating closures for every lambda expression. The new closure type in this module now caries the unique name previously described in Conversion I appended with a string to indicate it is referring t othe type of the lambda, the lambda's function type augmented to include the types of the free variables appended to the list of the formal types, and a separate list of just the types of the free variables, if any. A closed lambda expression itself caries the original unique name, which will link it to its function definition later, and a list of the free variables converted into typed variable expressions. The closed lambda no longer carries the expression representing the body of the lambda, because this module creates a record type that represents a function defintion for the lambda, which does carry the lambda's body expression and has a function name that matches the name of the lambda. These function definitions are set aside in a separate list to be passed to the next phase. Also being passed to the next phase is a list of all closure types created.

  The other significant task this module has is to track the number of times a named variable is redefined; this allows closures to use the original value of the free variable it was closed with even after that variable gets redefined elsewhere.

  The final output of this module is a struct containing the closed abstract syntax tree, list of function definitions, list of closure types generated during this phase, and a map of names to a list of their occurrences and types.

- *Authored by Amy, with help from Mert, and with help incorporating primitives from Eliza.*

7.7 Code Generation

- Code generation produces the llvm instruction for each definition and expression in the program. Each kind of definition and expression produce a particular pattern of llvm instructions. Given the information described in Closure Conversion II, code generation has four major steps to accomplish this:

  1. Every "closure type" mentioned previously gets declared a named struct type in the llvm (using the available function type and free variable types); they all have the following common structure:

     $\{$ `fptr* ;` $\{$ `typ ;` $\}$ $\}$

     Where the first struct member is always a pointer to the function created as a lambda's function definition, and all subsequent member(s), if any, are where the values of free variables will get stored.

  2. Every named variable (including versions of it, should it have been defined multiple times) is globally defined and initialized to zero or nullptr depending on whether or not it is a function type, struct type, or some constant. When global

variables are referred to in the program, it is either to assign them a value or use them. Because all definitons are evaluated in order in a main function (discussed next), no variable is used before a value is stored in them in the llvm.

3. Every definition/expression in the closed ast gets turned into llvm instructions and put in a “main” function body. This allows us to mimic sequential execution.

4. Every “function definition” mentioned previously is declared and defined by generating llvm instruction for the body’s expression.

- *Authored by Amy and Eliza.*

8 Test Plan

8.1 Test Method

Professor Richard Townsend's testing script used in his MicroC compiler, testall.sh, was adapted to perform testing for the g(ROOT) compiler. Changes were made to add support for .gt files, and support the testing file directory tree we had decided upon, however, the general control flow and output remains the same.

As our compiler matured, the testing script also needed to mature. Based on the compiler's current phase, different components needed to be tested to ensure they all were in working order. In addition to the testing script, many printing functions were written to assist in the debugging process. The most critical change to the testing script was the inclusion of test sets. Tests are grouped according to language aspect, and each test set in run individually. The testing script no longer executes a set of tests; now it processes a series of test sets, each containing a set of tests pertaining to that testset. This allows us to organize our tests logically and helps us localize bugs quickly. In our submission, the folder containing the test sets is simply called "testsets". The test sets therein are listed below:

```
testsets
├── apply
├── arithmetic_binops
├── boolean_binops
├── comparison_binops
├── conditionals
├── inference
├── lambda
├── let
├── sanity_checks
├── semantics
├── types
├── unops
└── val
```

Each test set has several subdirectories. The "tests" subdirectory contains the g(ROOT) files comprising each test. The "ref_ast", "ref_llvm", "ref_stderr", and "ref_stdout" subdirectories contain the reference output for each aspect of the compilation (ASTs, LLVM, errors, and output). When the testing script is run, additional subdirectories are generated, each containing some of the output from the tests. The "asm", "ast", "diff", "exe", "llvm", "stderr", and "stdout" subdirectories contain the assembly, ASTs, diff output, LLVM, errors, and output respectively. An example testset structure is given below.

We established various roles for each member of the group. Each role was made to divide key responsibilities that person was responsible for. though as we progressed through the development process these roles tended to be passed amongst other group members depending on various factors (i.e. availability) and simply what made the most practical sense. For instance, testing was a role that was shared across group members. The testing script was largely modified and updated by Nickolas Gravel and Zach Goldstein because they had the most experience working in bash than other members of the group. Furthermore, all members spent time creating tests and test references for modules.

```
example_testset
├── asm
├── ast
├── diff
├── exe
├── llvm
├── ref_ast
├── ref_llvm
├── ref_stderr
├── ref_stdout
├── stderr
├── stdout
└── tests
```

Note that there are three tests that still fail; these all pertain to the propagation of free variables in nested lambda expressions and nested let expressions. The current type inferencer implementation is not able to consistently resolve the type of free variables in nested expressions containing several levels of lets or lambdas.

`let/test-let`

`lambda/test-lambda`

`inference/test-nlambda4`

8.2 Three Test Samples

8.2.1 Sample 1: Nested If

```
(val a 'a')
(val b 'b')

(if (if (=i 0 0)
        #t
        #f)
    (printc a)
    (printc b))
```

Sample Test 1 Nested If-expression

LLVM IR output:

```
; ModuleID = 'gROOT'
source_filename = "gROOT"

@fmt = private unnamed_addr constant [4 x i8] c"%d\0A\00", align 1
@boolT = private unnamed_addr constant [3 x i8] c"#t\00", align 1
@boolF = private unnamed_addr constant [3 x i8] c"#f\00", align 1
@_a_1 = global i8* null
@_b_1 = global i8* null
@globalChar = private unnamed_addr constant [2 x i8] c"a\00", align 1
@globalChar.1 = private unnamed_addr constant [2 x i8] c"b\00", align 1

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

declare i32 @puts(i8*)

define i32 @main() {
entry:
  %spc = alloca i8*, align 8
  %loc = getelementptr i8*, i8** %spc, i32 0
  store i8* getelementptr inbounds ([2 x i8], [2 x i8]* @globalChar, i32 0, i32 0), i8** %loc, align 8
  %character_ptr = load i8*, i8** %spc, align 8
  store i8* %character_ptr, i8** @_a_1, align 8
  %spc1 = alloca i8*, align 8
  %loc2 = getelementptr i8*, i8** %spc1, i32 0
  store i8* getelementptr inbounds ([2 x i8], [2 x i8]* @globalChar.1, i32 0, i32 0), i8** %loc2, align
  %character_ptr3 = load i8*, i8** %spc1, align 8
  store i8* %character_ptr3, i8** @_b_1, align 8
  %if-res-ptr = alloca i32, align 4
  %if-res-ptr4 = alloca i1, align 1
  br i1 true, label %then, label %else
```

```

merge:                                            ; preds = %else, %then
  %if-res-val = load i1, i1* %if-res-ptr4, align 1
  br i1 %if-res-val, label %then6, label %else7

then:                                             ; preds = %entry
  store i1 true, i1* %if-res-ptr4, align 1
  br label %merge

else:                                             ; preds = %entry
  store i1 false, i1* %if-res-ptr4, align 1
  br label %merge

merge5:                                           ; preds = %else7, %then6
  %if-res-val9 = load i32, i32* %if-res-ptr, align 4
  ret i32 0

then6:                                            ; preds = %merge
  %_a_1 = load i8*, i8** @_a_1, align 8
  %printc = call i32 @puts(i8* %_a_1)
  store i32 %printc, i32* %if-res-ptr, align 4
  br label %merge5

else7:                                            ; preds = %merge
  %_b_1 = load i8*, i8** @_b_1, align 8
  %printc8 = call i32 @puts(i8* %_b_1)
  store i32 %printc8, i32* %if-res-ptr, align 4
  br label %merge5
}
```

8.2.2 Sample 2: Closure

```
(val x 42)
(val retx (lambda (n) x))
(printi (retx 6))
```

Sample Test 2 Closure

LLVM IR output:

```
; ModuleID = 'gROOT'
source_filename = "gROOT"

%_anon1_struct = type { i32 (i32, i32)*, i32 }
%_anon0_struct = type { i32 (i32, i32)*, i32 }

@fmt = private unnamed_addr constant [4 x i8] c"%d\0A\00", align 1
@boolT = private unnamed_addr constant [3 x i8] c"#t\00", align 1
@boolF = private unnamed_addr constant [3 x i8] c"#f\00", align 1
@__anon0_1 = global i32 (i32, i32)* null
@__anon1_1 = global i32 (i32, i32)* null
@_retx_2 = global %_anon1_struct* null
@_retx_1 = global %_anon0_struct* null
@_x_1 = global i32 0

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

declare i32 @puts(i8*)

define i32 @main() {
entry:
  store i32 42, i32* @_x_1, align 4
  %gstruct = alloca %_anon0_struct, align 8
  %funcField = getelementptr inbounds %_anon0_struct, %_anon0_struct* %gstruct, i32 0, i32 0
  store i32 (i32, i32)* @_anon0, i32 (i32, i32)** %funcField, align 8
  %_x_1 = load i32, i32* @_x_1, align 4
  %freeField = getelementptr inbounds %_anon0_struct, %_anon0_struct* %gstruct, i32 0, i32 1
  store i32 %_x_1, i32* %freeField, align 4
  store %_anon0_struct* %gstruct, %_anon0_struct** @_retx_1, align 8
  %gstruct1 = alloca %_anon1_struct, align 8
  %funcField2 = getelementptr inbounds %_anon1_struct, %_anon1_struct* %gstruct1, i32 0, i32 0
  store i32 (i32, i32)* @_anon1, i32 (i32, i32)** %funcField2, align 8
  %_x_13 = load i32, i32* @_x_1, align 4
  %freeField4 = getelementptr inbounds %_anon1_struct, %_anon1_struct* %gstruct1, i32 0, i32 1
  store i32 %_x_13, i32* %freeField4, align 4
  store %_anon1_struct* %gstruct1, %_anon1_struct** @_retx_2, align 8
  %_retx_2 = load %_anon1_struct*, %_anon1_struct** @_retx_2, align 8
```

```
  %freePtr = getelementptr inbounds %_anon1_struct, %_anon1_struct* %_retx_2, i32 0, i32 1
  %freeVal = load i32, i32* %freePtr, align 4
  %function_access = getelementptr inbounds %_anon1_struct, %_anon1_struct* %_retx_2, i32 0, i32 0
  %function_call = load i32 (i32, i32)*, i32 (i32, i32)** %function_access, align 8
  %function_result = call i32 %function_call(i32 6, i32 %freeVal)
  %printi = call i32 (i8*, ...) @printf(i8* getelementptr inbounds ([4 x i8], [4 x i8]* @fmt, i32 0, i32
  ret i32 0
}

define i32 @_anon1(i32 %n, i32 %_x_1) {
entry:
  %n1 = alloca i32, align 4
  store i32 %n, i32* %n1, align 4
  %_x_12 = alloca i32, align 4
  store i32 %_x_1, i32* %_x_12, align 4
  %_x_13 = load i32, i32* %_x_12, align 4
  ret i32 %_x_13
}

define i32 @_anon0(i32 %n, i32 %_x_1) {
entry:
  %n1 = alloca i32, align 4
  store i32 %n, i32* %n1, align 4
  %_x_12 = alloca i32, align 4
  store i32 %_x_1, i32* %_x_12, align 4
  %_x_13 = load i32, i32* %_x_12, align 4
  ret i32 %_x_13
}
```

8.2.3 Sample 3: Higher-Order Function

```
(val add1 (lambda (x) (+ x 1)))

(val sub1 (lambda (x) (- x 1)))

(val retx (lambda (x) x))

(val callFunc (lambda (func arg) (func arg)))

(val retDoubleLambda (lambda () (lambda (x) ( * x 2))))

(printi (callFunc add1 41))                        (; prints 42 ;)
(printi (callFunc sub1 43))                        (; prints 42 ;)
(printc (callFunc retx 'c'))                       (; prints c  ;)
(printi (callFunc (lambda (x) ( * x x)) 2))        (; prints 4 ;)
(printi (callFunc retx 42))                        (; prints 42 ;)
(printb (callFunc retx #t))                        (; prints #t ;)
(printi ((retDoubleLambda) 500))                   (; prints 1000 ;)
(printi ((retx add1) 5))                           (; prints 6;)
```

Sample Test 3 demonstrating higher-order functions

LLVM IR output:

```
; ModuleID = 'gROOT'
source_filename = "gROOT"

%_anon11_struct = type { i1 (i1)* }
%_anon0_struct = type { i32 (i32)* }
%_anon1_struct = type { i32 (i32)* }
%_anon7_struct = type { i8* (i8*)* }
%_anon9_struct = type { i32 (i32)* }
%_anon10_struct = type { i1 (%_anon11_struct*, i1)* }
%_anon8_struct = type { i32 (%_anon9_struct*, i32)* }
%_anon6_struct = type { i8* (%_anon7_struct*, i8*)* }
%_anon5_struct = type { i32 (%_anon1_struct*, i32)* }
%_anon4_struct = type { i32 (%_anon0_struct*, i32)* }
%_anon2_struct = type { i32 (i32)* }

@fmt = private unnamed_addr constant [4 x i8] c"%d\0A\00", align 1
@boolT = private unnamed_addr constant [3 x i8] c"#t\00", align 1
@boolF = private unnamed_addr constant [3 x i8] c"#f\00", align 1
@__anon0_1 = global i32 (i32)* null
@__anon1_1 = global i32 (i32)* null
@__anon10_1 = global i1 (%_anon11_struct*, i1)* null
@__anon11_1 = global i1 (i1)* null
@__anon2_1 = global i32 (i32)* null
@__anon4_1 = global i32 (%_anon0_struct*, i32)* null
@__anon5_1 = global i32 (%_anon1_struct*, i32)* null
@__anon6_1 = global i8* (%_anon7_struct*, i8*)* null
```

```
@__anon7_1 = global i8* (i8*)* null
@__anon8_1 = global i32 (%_anon9_struct*, i32)* null
@__anon9_1 = global i32 (i32)* null
@_add1_1 = global %_anon0_struct* null
@_callFunc_5 = global %_anon10_struct* null
@_callFunc_4 = global %_anon8_struct* null
@_callFunc_3 = global %_anon6_struct* null
@_callFunc_2 = global %_anon5_struct* null
@_callFunc_1 = global %_anon4_struct* null
@_retx_4 = global %_anon11_struct* null
@_retx_3 = global %_anon9_struct* null
@_retx_2 = global %_anon7_struct* null
@_retx_1 = global %_anon2_struct* null
@_sub1_1 = global %_anon1_struct* null
@globalChar = private unnamed_addr constant [2 x i8] c"c\00", align 1

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

declare i32 @puts(i8*)

define i32 @main() {
entry:
  %gstruct = alloca %_anon0_struct, align 8
  %funcField = getelementptr inbounds %_anon0_struct, %_anon0_struct* %gstruct, i32 0, i32 0
  store i32 (i32)* @_anon0, i32 (i32)** %funcField, align 8
  store %_anon0_struct* %gstruct, %_anon0_struct** @_add1_1, align 8
  %gstruct1 = alloca %_anon1_struct, align 8
  %funcField2 = getelementptr inbounds %_anon1_struct, %_anon1_struct* %gstruct1, i32 0, i32 0
  store i32 (i32)* @_anon1, i32 (i32)** %funcField2, align 8
  store %_anon1_struct* %gstruct1, %_anon1_struct** @_sub1_1, align 8
  %gstruct3 = alloca %_anon2_struct, align 8
  %funcField4 = getelementptr inbounds %_anon2_struct, %_anon2_struct* %gstruct3, i32 0, i32 0
  store i32 (i32)* @_anon2, i32 (i32)** %funcField4, align 8
  store %_anon2_struct* %gstruct3, %_anon2_struct** @_retx_1, align 8
  %gstruct5 = alloca %_anon4_struct, align 8
  %funcField6 = getelementptr inbounds %_anon4_struct, %_anon4_struct* %gstruct5, i32 0, i32 0
  store i32 (%_anon0_struct*, i32)* @_anon4, i32 (%_anon0_struct*, i32)** %funcField6, align 8
  store %_anon4_struct* %gstruct5, %_anon4_struct** @_callFunc_1, align 8
  %_callFunc_1 = load %_anon4_struct*, %_anon4_struct** @_callFunc_1, align 8
  %_add1_1 = load %_anon0_struct*, %_anon0_struct** @_add1_1, align 8
  %function_access = getelementptr inbounds %_anon4_struct, %_anon4_struct* %_callFunc_1, i32 0, i32 0
  %function_call = load i32 (%_anon0_struct*, i32)*, i32 (%_anon0_struct*, i32)** %function_access, alig
  %function_result = call i32 %function_call(%_anon0_struct* %_add1_1, i32 41)
  %printi = call i32 (i8*, ...) @printf(i8* getelementptr inbounds ([4 x i8], [4 x i8]* @fmt, i32 0, i32
  %gstruct7 = alloca %_anon5_struct, align 8
  %funcField8 = getelementptr inbounds %_anon5_struct, %_anon5_struct* %gstruct7, i32 0, i32 0
```

```
  store i32 (%_anon1_struct*, i32)* @_anon5, i32 (%_anon1_struct*, i32)** %funcField8, align 8
  store %_anon5_struct* %gstruct7, %_anon5_struct** @_callFunc_2, align 8
  %_callFunc_2 = load %_anon5_struct*, %_anon5_struct** @_callFunc_2, align 8
  %_sub1_1 = load %_anon1_struct*, %_anon1_struct** @_sub1_1, align 8
  %function_access9 = getelementptr inbounds %_anon5_struct, %_anon5_struct* %_callFunc_2, i32 0, i32 0
  %function_call10 = load i32 (%_anon1_struct*, i32)*, i32 (%_anon1_struct*, i32)** %function_access9, al
  %function_result11 = call i32 %function_call10(%_anon1_struct* %_sub1_1, i32 43)
  %printi12 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds ([4 x i8], [4 x i8]* @fmt, i32 0, i3
  %gstruct13 = alloca %_anon7_struct, align 8
  %funcField14 = getelementptr inbounds %_anon7_struct, %_anon7_struct* %gstruct13, i32 0, i32 0
  store i8* (i8*)* @_anon7, i8* (i8*)** %funcField14, align 8
  store %_anon7_struct* %gstruct13, %_anon7_struct** @_retx_2, align 8
  %gstruct15 = alloca %_anon6_struct, align 8
  %funcField16 = getelementptr inbounds %_anon6_struct, %_anon6_struct* %gstruct15, i32 0, i32 0
  store i8* (%_anon7_struct*, i8*)* @_anon6, i8* (%_anon7_struct*, i8*)** %funcField16, align 8
  store %_anon6_struct* %gstruct15, %_anon6_struct** @_callFunc_3, align 8
  %_callFunc_3 = load %_anon6_struct*, %_anon6_struct** @_callFunc_3, align 8
  %_retx_2 = load %_anon7_struct*, %_anon7_struct** @_retx_2, align 8
  %spc = alloca i8*, align 8
  %loc = getelementptr i8*, i8** %spc, i32 0
  store i8* getelementptr inbounds ([2 x i8], [2 x i8]* @globalChar, i32 0, i32 0), i8** %loc, align 8
  %character_ptr = load i8*, i8** %spc, align 8
  %function_access17 = getelementptr inbounds %_anon6_struct, %_anon6_struct* %_callFunc_3, i32 0, i32 0
  %function_call18 = load i8* (%_anon7_struct*, i8*)*, i8* (%_anon7_struct*, i8*)** %function_access17, a
  %function_result19 = call i8* %function_call18(%_anon7_struct* %_retx_2, i8* %character_ptr)
  %printc = call i32 @puts(i8* %function_result19)
  %gstruct20 = alloca %_anon9_struct, align 8
  %funcField21 = getelementptr inbounds %_anon9_struct, %_anon9_struct* %gstruct20, i32 0, i32 0
  store i32 (i32)* @_anon9, i32 (i32)** %funcField21, align 8
  store %_anon9_struct* %gstruct20, %_anon9_struct** @_retx_3, align 8
  %gstruct22 = alloca %_anon8_struct, align 8
  %funcField23 = getelementptr inbounds %_anon8_struct, %_anon8_struct* %gstruct22, i32 0, i32 0
  store i32 (%_anon9_struct*, i32)* @_anon8, i32 (%_anon9_struct*, i32)** %funcField23, align 8
  store %_anon8_struct* %gstruct22, %_anon8_struct** @_callFunc_4, align 8
  %_callFunc_4 = load %_anon8_struct*, %_anon8_struct** @_callFunc_4, align 8
  %_retx_3 = load %_anon9_struct*, %_anon9_struct** @_retx_3, align 8
  %function_access24 = getelementptr inbounds %_anon8_struct, %_anon8_struct* %_callFunc_4, i32 0, i32 0
  %function_call25 = load i32 (%_anon9_struct*, i32)*, i32 (%_anon9_struct*, i32)** %function_access24, a
  %function_result26 = call i32 %function_call25(%_anon9_struct* %_retx_3, i32 42)
  %printi27 = call i32 (i8*, ...) @printf(i8* getelementptr inbounds ([4 x i8], [4 x i8]* @fmt, i32 0, i3
  %gstruct28 = alloca %_anon11_struct, align 8
  %funcField29 = getelementptr inbounds %_anon11_struct, %_anon11_struct* %gstruct28, i32 0, i32 0
  store i1 (i1)* @_anon11, i1 (i1)** %funcField29, align 8
  store %_anon11_struct* %gstruct28, %_anon11_struct** @_retx_4, align 8
  %gstruct30 = alloca %_anon10_struct, align 8
  %funcField31 = getelementptr inbounds %_anon10_struct, %_anon10_struct* %gstruct30, i32 0, i32 0
```

```
  store i1 (%_anon11_struct*, i1)* @_anon10, i1 (%_anon11_struct*, i1)** %funcField31, align 8
  store %_anon10_struct* %gstruct30, %_anon10_struct** @_callFunc_5, align 8
  %_callFunc_5 = load %_anon10_struct*, %_anon10_struct** @_callFunc_5, align 8
  %_retx_4 = load %_anon11_struct*, %_anon11_struct** @_retx_4, align 8
  %function_access32 = getelementptr inbounds %_anon10_struct, %_anon10_struct* %_callFunc_5, i32 0, i32
  %function_call33 = load i1 (%_anon11_struct*, i1)*, i1 (%_anon11_struct*, i1)** %function_access32, al
  %function_result34 = call i1 %function_call33(%_anon11_struct* %_retx_4, i1 true)
  %printb = call i32 @puts(i8* getelementptr inbounds ([3 x i8], [3 x i8]* @boolF, i32 0, i32 0))
  ret i32 0
}

define i1 @_anon10(%_anon11_struct* %func, i1 %arg) {
entry:
  %func1 = alloca %_anon11_struct*, align 8
  store %_anon11_struct* %func, %_anon11_struct** %func1, align 8
  %arg2 = alloca i1, align 1
  store i1 %arg, i1* %arg2, align 1
  %func3 = load %_anon11_struct*, %_anon11_struct** %func1, align 8
  %arg4 = load i1, i1* %arg2, align 1
  %function_access = getelementptr inbounds %_anon11_struct, %_anon11_struct* %func3, i32 0, i32 0
  %function_call = load i1 (i1)*, i1 (i1)** %function_access, align 8
  %function_result = call i1 %function_call(i1 %arg4)
  ret i1 %function_result
}

define i1 @_anon11(i1 %x) {
entry:
  %x1 = alloca i1, align 1
  store i1 %x, i1* %x1, align 1
  %x2 = load i1, i1* %x1, align 1
  ret i1 %x2
}

define i32 @_anon8(%_anon9_struct* %func, i32 %arg) {
entry:
  %func1 = alloca %_anon9_struct*, align 8
  store %_anon9_struct* %func, %_anon9_struct** %func1, align 8
  %arg2 = alloca i32, align 4
  store i32 %arg, i32* %arg2, align 4
  %func3 = load %_anon9_struct*, %_anon9_struct** %func1, align 8
  %arg4 = load i32, i32* %arg2, align 4
  %function_access = getelementptr inbounds %_anon9_struct, %_anon9_struct* %func3, i32 0, i32 0
  %function_call = load i32 (i32)*, i32 (i32)** %function_access, align 8
  %function_result = call i32 %function_call(i32 %arg4)
  ret i32 %function_result
}
```

```

define i32 @_anon9(i32 %x) {
entry:
  %x1 = alloca i32, align 4
  store i32 %x, i32* %x1, align 4
  %x2 = load i32, i32* %x1, align 4
  ret i32 %x2
}

define i8* @_anon6(%_anon7_struct* %func, i8* %arg) {
entry:
  %func1 = alloca %_anon7_struct*, align 8
  store %_anon7_struct* %func, %_anon7_struct** %func1, align 8
  %arg2 = alloca i8*, align 8
  store i8* %arg, i8** %arg2, align 8
  %func3 = load %_anon7_struct*, %_anon7_struct** %func1, align 8
  %arg4 = load i8*, i8** %arg2, align 8
  %function_access = getelementptr inbounds %_anon7_struct, %_anon7_struct* %func3, i32 0, i32 0
  %function_call = load i8* (i8*)*, i8* (i8*)** %function_access, align 8
  %function_result = call i8* %function_call(i8* %arg4)
  ret i8* %function_result
}

define i8* @_anon7(i8* %x) {
entry:
  %x1 = alloca i8*, align 8
  store i8* %x, i8** %x1, align 8
  %x2 = load i8*, i8** %x1, align 8
  ret i8* %x2
}

define i32 @_anon5(%_anon1_struct* %func, i32 %arg) {
entry:
  %func1 = alloca %_anon1_struct*, align 8
  store %_anon1_struct* %func, %_anon1_struct** %func1, align 8
  %arg2 = alloca i32, align 4
  store i32 %arg, i32* %arg2, align 4
  %func3 = load %_anon1_struct*, %_anon1_struct** %func1, align 8
  %arg4 = load i32, i32* %arg2, align 4
  %function_access = getelementptr inbounds %_anon1_struct, %_anon1_struct* %func3, i32 0, i32 0
  %function_call = load i32 (i32)*, i32 (i32)** %function_access, align 8
  %function_result = call i32 %function_call(i32 %arg4)
  ret i32 %function_result
}

define i32 @_anon4(%_anon0_struct* %func, i32 %arg) {
```

```
entry:
  %func1 = alloca %_anon0_struct*, align 8
  store %_anon0_struct* %func, %_anon0_struct** %func1, align 8
  %arg2 = alloca i32, align 4
  store i32 %arg, i32* %arg2, align 4
  %func3 = load %_anon0_struct*, %_anon0_struct** %func1, align 8
  %arg4 = load i32, i32* %arg2, align 4
  %function_access = getelementptr inbounds %_anon0_struct, %_anon0_struct* %func3, i32 0, i32 0
  %function_call = load i32 (i32)*, i32 (i32)** %function_access, align 8
  %function_result = call i32 %function_call(i32 %arg4)
  ret i32 %function_result
}

define i32 @_anon2(i32 %x) {
entry:
  %x1 = alloca i32, align 4
  store i32 %x, i32* %x1, align 4
  %x2 = load i32, i32* %x1, align 4
  ret i32 %x2
}

define i32 @_anon1(i32 %x) {
entry:
  %x1 = alloca i32, align 4
  store i32 %x, i32* %x1, align 4
  %x2 = load i32, i32* %x1, align 4
  %subtraction = sub i32 %x2, 1
  ret i32 %subtraction
}

define i32 @_anon0(i32 %x) {
entry:
  %x1 = alloca i32, align 4
  store i32 %x, i32* %x1, align 4
  %x2 = load i32, i32* %x1, align 4
  %addition = add i32 %x2, 1
  ret i32 %addition
}
```

9 Lessons Learned

9.1 Amy Bui

My main takeaway is that compiler writing, or even writing just a single optimization for a compiler, is a very complicated endeavor. We did not end up with a lot of our original goals and features we intended for our functional language, but the detours we took while exploring this whole other paradigm was very enriching, and I was never bored and always challenged. Everyone should write a compiler at least once before graduating. This was a great project in demonstrating the practical application of the concepts and theory we learnt in 170 and 105, and I'd recommend taking both classes before 107 or at the same time for a more comfortable time. I have a lot of appreciation for people who do research and contribute to the field of functional languages, and the complexity of lambda calculus. My advice to future students is that you should have a burning desire to implement type inferencing and lambda calculus before you settle on a a functional language as your project topic; I never knew how much we took static typing and statment blocks for granted. Or you can get a thrill from just taking on this challenge.

9.2 Nickolas Gravel

Compiler writing is a long, long journey filled with various pitfalls, unexpected challenges, dragons, and possibly avocados. For myself, I found the learning curve to be slightly steeper than my peers. Before this class, I had not taken CS105 Programming Languages or had any experience coding in a functional language. So, in the beginning, I encountered some tribulation understanding these concepts. Effectively, I not only needed to learn the basics of compiler writing, but needed to learn the basic components of a programming language, and the basics of coding in a functional language as well.

Then came type inferencing, a module that we had greatly underestimated the amount of time and work it would take to implement. I was one of the main programmers that worked on implementing this module. Again, I found that having some previous experience with type inferencing would have been a huge help here...but we persevered! I dove into the Hadley-Milner type system algorithm, and with the guidance of Mert and Michael Ryan Clarkson, after about a month of coding the and a week of debugging we had a working type inferencer!

All in all, building a compiler is no joke. Even seemingly trivial steps in implementing a compiler were found to be not so trivial, requiring us to brain storm creative solutions to get to the next step. For anyone building a compiler, I recommend spending ample time writing up a thorough design. Having a written design indicating which data structures and data types were being passed and returned from each module would have helped in overall organization and may have prevented some of the various bugs that we encountered. Future students, if you are set on building a language with inferred types make sure you have a strong understanding how to implement type inferencing and design your inferencer thoroughly before implementing it.

Designing a programming language and building a compiler for it was riveting experience. I learned so much about functional languages, type inferencing, and what it really takes to compile source code down to a final executable. Everyone with any interest in low-level programming should take this course, but I would recommend taking a course in programming languages more gradual learning curve.

9.3 Sam Russo

There are so many independent aspects to working on a compiler, from language design/syntax to memory to warnings to additional features. Coming up with solutions to the problems that we found in each of these domains and dealing with bugs was challenging, but it was also hard to ensure that the choices we made in each of the domains worked well with each other. If one person decided to do thing x while working in one area, sometimes we would realize later that that decision was incompatible or poorly compatible with a decision someone else made in a different domain at the same time.

Working with a group as big as ours for as long as we did (and I know in the scheme of things our team wasn't that big and we weren't working together for that long) is really hard. Challenges were mostly accountability (definitely including my own) and stemmed from everyone's having different schedules and different workloads. Different workloads meant that people 1) prioritized our project different amounts, 2) had differing amounts of time to dedicate to it, and 3) had different ideas of how to spend the time when we worked on it together. Specifically, the grad students in our group had much more time to work on the project, which led to pretty different levels of contribution. For future mixed grad-undergrad groups, I would think about this before committing to such a group, and if people decide to stick with it, then they should be very clear around group expectations.

9.4 Eliza Encherman

I learned a great deal about languages and compilers from this project - I definitely agree with Amy that everyone should write a compiler before graduating, and I'd recommend the language creation step as well, as I feel like I really understand the code I write and see better, as well as understand some of the thought processes behind some the peculiarities of different languages. I also whole-heartedly agree with my groupmates about the difficulties involved with inplementing functional languages and type inferencing - this project very much reinforced how what is simpler for the user is often far more complicated to implement than something like static typing, that's a little more work on the user's side but much easier to check.

I also would emphasize the importance of good practices like documentation, throwing specific error statements, and making functions to print structures as you introduce structures - I frequently would be spending hours in debugging just finding where a specific error was coming from, which would then often be followed by hours more because it was hard to understand what a function did or what a variable was at a certain moment in time.

9.5 Zachary Goldstein

Upon reflection I have the following takeaways:

- It is critically important to ensure that all group members understand every aspect of the language design and how each module interfaces with other modules. Throughout the development of the compiler, different group members working on different modules made different assumptions about the structure of each augmented AST; this led to some frustrating refactoring when we brought all the pieces together.
- I benefit a great deal from synchronous, in-person work sessions. When working alone on the project, I found I used my time less effectively than when working in a shared space with other group members. Unfortunately, the group was not able to meet for more than an hour or two a week (which is to be expected for a group of 5 busy collegians), and nearly all of our meetings were virtual.

To future groups I give the following advice:

- When designing the language and deciding what features you will implement, prioritize feasibility. While type-inferencing is useful and interesting, our choice to implement an inferencer came at the expense of several other features that were ultimately more integral to our design goals.
- While functional languages are beautifully simple for programmers, they are not so simple to compile. Most of the functional features that we implemented/attempted (like higher-order functions, lambda closures, and inferred polymorphism) are not native to the imperative LLVM IR. It may be easier to design an imperative side-effecting language given the time constraints of the course. This is especially true if group members are unfamiliar with functional programming.
- Decide upon a consistent interface for each module.
- Work in person whenever possible. Spending time in a shared space increases the accountability of yourself and others, and allows for quick and easy idea sharing.

10 Appendix

10.1 toplevel.ml

Author(s): Sam, Eliza, Amy, Nik, Zach

```
(* Top-level of the groot compiler: scan & parse input,
    build the AST, generate LLVM IR *)

type action =
  | Ast
  | Name_Check
  | Tast
  | Mast
  | Hast
  | Cast
  | LLVM_IR
  | Compile


let () =
  let action = ref Ast in
  let set_action a () = action := a in
  let speclist = [
    ("-a", Arg.Unit (set_action Ast),                 "Print the AST (default)");
    ("-n", Arg.Unit (set_action Name_Check),         "Print the AST (name-checking)");
    ("-t", Arg.Unit (set_action Tast),                 "Print the TAST");
    ("-m", Arg.Unit (set_action Mast),         "Print the MAST");
    ("-h", Arg.Unit (set_action Hast),         "Print the HAST");
    ("-v", Arg.Unit (set_action Cast),         "Print the CAST");
    ("-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");
  ] in


  let usage_msg =
      "usage: ./toplevel.native [-a|-n|-t|-m|-h|-v|-l|-c] [file.gt]" 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 = Parser.prog Scanner.tokenize lexbuf in
  match !action with
  (* Default action - print the AST using ast *)
  | Ast -> print_string (Ast.string_of_prog ast)
  (* All other action needs to generate an SAST, store in variable sast *)
  | _ ->
```

```
    let ast' = Scope.check ast in
    match !action with
    | Ast -> ()
    | Name_Check -> print_string (Ast.string_of_prog ast')
    | _ ->
      let tast = Infer.type_infer ast' in
      match !action with
      | Tast -> print_string (Tast.string_of_tprog tast)
      | _ ->
        let mast = Mono.monomorphize tast in
        match !action with
        | Mast -> print_string (Mast.string_of_mprog mast)
        | _ ->
          let hast = Hof.clean mast in
          match !action with
          | Hast -> print_string (Hast.string_of_hprog hast)
          | _ ->
          let cast = Conversion.conversion hast in
            match !action with
            | Cast -> print_string (Cast.string_of_cprog cast)
            | LLVM_IR ->
                print_string (Llvm.string_of_llmodule (Codegen.translate cast))
            | Compile ->
                let the_module = Codegen.translate cast in
                Llvm_analysis.assert_valid_module the_module;
                print_string (Llvm.string_of_llmodule the_module)
            | _ -> print_string usage_msg
```

10.2 ast.ml

Author(s): Sam, Eliza, Amy, Nik, Zach

```
(* Abstract Syntax Tree (AST) for Groot *)

(* Type of Variable Names *)
type ident = string

type expr =
  | Literal of value
  | Var     of ident
  | If      of expr * expr * expr
  | Apply   of expr * expr list
  | Let     of (ident * expr) list * expr
  | Lambda  of ident list * expr
and value =
  |Char    of char
  | Int     of int
  | Bool    of bool
  | Root    of tree
and tree =
  |Leaf
  | Branch of expr * tree * tree

type defn =
  | Val of ident * expr
  | Expr of expr

type prog = defn list


(* Pretty printing functions *)

(* toString for Ast.expr *)
let rec string_of_expr = function
  | Literal(lit) -> string_of_value lit
  | Var(v) -> v
  | If(condition, true_branch, false_branch) ->
    "(if "  ^ string_of_expr condition ^ " "
    ^ string_of_expr true_branch ^ " "
    ^ string_of_expr false_branch ^ ")"
  | Apply(f, args) ->
    "(" ^ string_of_expr f ^ " "
    ^ String.concat " " (List.map string_of_expr args) ^ ")"
  | Let(binds, body)   ->
    let string_of_binding = function
```

```
        (id, e) -> "[" ^ id ^ " " ^ (string_of_expr e) ^ "]"
    in
    "(let (" ^ String.concat " " (List.map string_of_binding binds) ^ ") "
    ^ string_of_expr body ^ ")"
  | Lambda(formals, body) ->
    "(lambda (" ^ String.concat " " formals ^ ") "
    ^ string_of_expr body ^ ")"

(* toString for Ast.value *)
and string_of_value = function
  | Char(c)     -> "'" ^ String.make 1 c ^ "'"
  | Int(i)      -> string_of_int i
  | Bool(b)     -> if b then "#t" else "#f"
  | Root(tr)    -> string_of_tree tr
(*| Closure(a,b,c) -> "CLOSURE: string_of_closure unimplemented" *)
(*| Primitive(p, vals) -> "PRIMITIVE: string_of_primitive unimplemented" *)

(* toString for Ast.tree *)
and string_of_tree = function
  | Leaf -> "leaf"
  | Branch(ex, sib, child) ->
    (* Branch type is given by "tree" string *)
    "(tree " ^ string_of_expr ex ^ " "
    ^ string_of_tree sib ^ " "
    ^ string_of_tree child ^ ")"

(* toString for Ast.defn *)
let string_of_defn = function
  | Val(id, e) -> "(val " ^ id ^ " " ^ string_of_expr e ^ ")"
  | Expr(e)    -> string_of_expr e

(* toString for Ast.prog *)
let string_of_prog defns =
  String.concat "\n" (List.map string_of_defn defns) ^ "\n"
```

10.3 scanner.mll

Author(s): Sam, Eliza, Amy, Nik, Zach

```
(*
    scanner.mll

  Lexer file to create a lexical analyzer from a set of regular expressions.

  Compile with command to produce scanner.ml with the ocaml code:
        ocamllex scanner.mll
*)

(* Header *)
{
  open Parser
}

(* Regular Expressions *)
let digit = ['0'-'9']
let integer = ['-']?['0'-'9']+
let alpha = ['a'-'z']
let leaf = ("leaf"|"()")
let chrcode = digit+

(* all visible characters, excluding ()'[]\;{}| *)
let ident = ['!'-'&' '*'-':' '<'-'Z' '`'-'z' '~' '|']
            ['!'-'&' '*'-':' '<'-'Z' '^'-'z' '~' '|']*


(* ToKeNiZe *)
rule tokenize = parse
  | [' ' '\n' '\t' '\r'] { tokenize lexbuf }
  | ";;"                 { single_comment lexbuf }
  | "(;"                 { multi_comment lexbuf }
  | '('                  { LPAREN }
  | ')'                  { RPAREN }
  | '['                  { LSQUARE }
  | ']'                  { RSQUARE }
  | "tree"               { BRANCH }
  | "leaf"               { LEAF }
  | "if"                 { IF }
  | "'"                  { apos_handler lexbuf }
  | integer as ival      { INT(int_of_string ival) }
  | "#t"                 { BOOL(true) }
  | "#f"                 { BOOL(false) }
  | "lambda"             { LAMBDA }
```

```
  | "let"                 { LET }
  | "val"                 { VAL }
  | ident as id           { ID(id) }
  | eof                   { EOF }
  | _                     { Diagnostic.error(Diagnostic.lex_error "unrecognized character" lexbuf) }
and single_comment = parse
  | '\n'                  { tokenize lexbuf }
  | eof                   { EOF }
  | _                     { single_comment lexbuf }
and multi_comment  = parse
  | ";)"                  { tokenize lexbuf }
  | eof                   { EOF }
  | _                     { multi_comment lexbuf }

(* apostrophe handler *)
and apos_handler = parse
  | '('[^''']       { tree_builder lexbuf }
  | '''             { Diagnostic.error (Diagnostic.lex_error "empty character literal" lexbuf) }
  | '\\'            { escaped_char_handler lexbuf }
  | _ as c          { char_builder c lexbuf }

and tree_builder = parse
  | _ { Diagnostic.error (Diagnostic.Unimplemented "in-place tree syntax") }

and char_builder c = parse
  | '''    { CHAR(c) }
  | _ { Diagnostic.error
          (Diagnostic.lex_error ("character literal contains more "
           ^ "than one token") lexbuf) }

and escaped_char_handler = parse
  | '\\' { char_builder '\\' lexbuf }
  | '"'  { char_builder '\"' lexbuf }
  | '''  { char_builder '\'' lexbuf }
  | 'n'  { char_builder '\n' lexbuf }
  | 'r'  { char_builder '\r' lexbuf }
  | 't'  { char_builder '\t' lexbuf }
  | 'b'  { char_builder '\b' lexbuf }
  | ' '  { char_builder '\ ' lexbuf }
  | chrcode as ord
         { print_string ord; if int_of_string ord > 255
           then Diagnostic.error
                (Diagnostic.lex_error "invalid escape sequence ASCII value"
                lexbuf)
           else char_builder (Char.chr (int_of_string ord)) lexbuf }
  | _    { Diagnostic.error
```

```
          (Diagnostic.lex_error "unrecognized escape sequence" lexbuf) }
```

10.4 parser.mly

Author(s): Sam, Eliza, Amy, Nik, Zach

```
/*
 *  parser.mly
 *    produces a parser from a context-free grammar specification
 *
 *    Compile with command to produce parser.ml with the ocaml code:
 *      ocamlyacc parser.mly
 */

/* Header */
%{
    open Ast
%}

/* Tokens */
%token LPAREN  RPAREN
%token LSQUARE RSQUARE
%token PLUS MINUS TIMES DIVIDE MOD
%token EQ NEQ LT GT LEQ GEQ AND OR NOT
%token IF
%token <char> CHAR
%token <int>  INT
%token <bool> BOOL
%token <string> ID
%token BRANCH LEAF
%token EOF
%token LAMBDA LET VAL

/* Precedence */
%nonassoc OR
%nonassoc AND
%nonassoc LT GT
%nonassoc EQ NEQ
%nonassoc LEQ GEQ
%nonassoc PLUS MINUS
%nonassoc TIMES DIVIDE
%nonassoc NEG
%nonassoc NOT
%nonassoc BRANCH LEAF


/* Declarations */
%start prog
%type <Ast.prog> prog
```

```
%%

prog:
  | defn_list EOF                  { $1 }

defn_list:
  | /* nothing */                  { [] }
  | defn defn_list                 { $1 :: $2 }

defn:
  | expr                           { Expr($1) }
  | LPAREN VAL ID expr RPAREN      { Val($3, $4) }

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

formal_list:
  | ID                             { [$1] }
  | ID formal_list                 { $1 :: $2 }


/* Rules */
value:
  | CHAR                           { Char($1) }
  | INT                            { Int($1) }
  | BOOL                           { Bool($1) }
  | tree                           { Root($1) }
  /* ! Note: tree is not a token - no need for a ROOT token while scanning */


tree:
  | LEAF                                   { Leaf }
  | LPAREN BRANCH expr tree tree RPAREN    { Branch($3, $4, $5) }


let_binding_list:
  | /* nothing */                                { [] }
  | LSQUARE RSQUARE let_binding_list
    { Diagnostic.warning (Diagnostic.parse_warning "empty let binding" 1); $3 }
    /* NON FATAL */
  | LSQUARE expr RSQUARE let_binding_list
    { Diagnostic.error (Diagnostic.parse_error ("let binding must contain"
      ^ " id and value") 2) } /* FATAL */
  | LSQUARE ID expr RSQUARE let_binding_list  { ($2, $3) :: $5 }
```

```


expr_list:
  | /* null */          { [] }
  | expr expr_list      { $1 :: $2 }


expr:
  | value                                                 { Literal($1) }
  | ID                                                    { Var($1) }
  | LPAREN expr expr_list RPAREN                          { Apply($2, $3) }
  | LPAREN LET LPAREN let_binding_list RPAREN expr RPAREN { Let($4, $6)}
  | LPAREN IF expr expr expr RPAREN                       { If($3, $4, $5) }
  | LPAREN LAMBDA LPAREN formals_opt RPAREN expr RPAREN   { Lambda($4, $6) }
```

10.5 scope.ml

Author(s): Amy, Eliza

```
(* Name (scope) checks variable names *)
open Ast

(* toplevel naming environment, preloaded with built-ins *)
let nameEnv = List.fold_right List.cons [ "printi"; "printb"; "printc";
                                          "+"; "-"; "*"; "/"; "mod";
                                          "<"; ">"; ">="; "<="; "~";
                                          "!=i"; "=i"; "&&"; "||"; "not"  ] []

(* Takes and AST and checks if variables are bound in scope.
   Returns same AST if so, otherwise raises Unbound variable error
   if a variable is unbound. *)
let check defns =

  (* Recursively checks the scope of variables names used in an expression *)
  let rec checkExpr expression rho =
    let rec exp e = match e with
        Literal _ -> ()
      | Var id ->
          if List.mem id rho then ()
          else Diagnostic.error (Diagnostic.Unbound id)
      | If (e1, e2, e3) ->
          let (_, _, _) = (exp e1, exp e2, exp e3) in ()
      | Apply (f, args) ->
          let _ = exp f in List.iter exp args
      | Let (bs, body) ->
          let (xs, es) = List.split bs in
          let () = List.iter exp es in
          checkExpr body (List.fold_right List.cons xs rho)
      | Lambda (formals, body) ->
          checkExpr body (List.fold_right List.cons formals rho)
    in exp expression
  in

  let rec checkDef ds env =
    match ds with
      [] -> env
    | f :: rest ->
      let env' =
        (match f with
           Val (id, exp) ->
           let () = checkExpr exp env in
           id :: env
```

```
        | Expr exp -> let () = checkExpr exp env in env)
    in checkDef rest env'
in
let _ = checkDef defns nameEnv in

(* Returns the AST if no error raised *)
defns
```

10.6 tast.ml

Author(s): Sam, Nik

```
(*
    TAST
    Type inference.
*)

open Ast

exception Type_error of string

let type_error msg = raise (Type_error msg)


type gtype =
  | TYCON of tycon
  | TYVAR of tyvar
  | CONAPP of conapp
and tycon =
  | TyInt
  | TyBool
  | TyChar
  | TArrow of gtype
and tyvar =
  | TVariable of int
and conapp = (tycon * gtype list)

type tyscheme = tyvar list * gtype



let inttype = TYCON TyInt
let chartype = TYCON TyChar
let booltype = TYCON TyBool
let functiontype resultType formalsTypes =
  CONAPP (TArrow resultType, formalsTypes)


(* TAST expression *)
type texpr = gtype * tx
and tx =
  | TLiteral     of tvalue
  | TypedVar     of ident
  | TypedIf      of texpr * texpr * texpr
  | TypedApply   of texpr * texpr list
```

```
  | TypedLet     of (ident * texpr) list * texpr
  | TypedLambda  of (gtype * ident) list * texpr
and tvalue = TChar of char | TInt of int | TBool of bool | TRoot of ttree
and ttree = TLeaf | TBranch of tvalue * ttree * ttree

type tdefn = TVal of ident * texpr | TExpr of texpr
type tprog = tdefn list

(* Pretty printer *)

(* String of gtypes *)
let rec string_of_ttype = function
  | TYCON ty -> string_of_tycon ty
  | TYVAR tp -> string_of_tyvar tp
  | CONAPP con -> string_of_conapp con
and string_of_tycon = function
  | TyInt -> "int"
  | TyBool -> "bool"
  | TyChar -> "char"
  | TArrow (retty) -> string_of_ttype retty

and string_of_tyvar = function
  | TVariable n -> "'" ^ string_of_int n
and string_of_conapp (tyc, tys) =
  string_of_tycon tyc ^ " (" ^ String.concat " " (List.map string_of_ttype tys) ^ ")"
and string_of_constraint (t1, t2) = "(" ^ string_of_ttype t1 ^ ", " ^ string_of_ttype t2 ^ ")"
and string_of_constraints cs =
  "[ " ^ String.concat " , " (List.map string_of_constraint cs) ^ " ]"

and string_of_subs = function
  | [] -> ""
  | (t1, t2) :: cs ->
    "(" ^ string_of_tyvar t1 ^ ", " ^ string_of_ttype t2 ^ ") "
    ^ string_of_subs cs

and string_of_context = function
  | [] -> ""
  | (ident, (tvs, gt)) :: ctx ->
    "\n=: " ^ ident ^ ", (["
    ^ String.concat ", " (List.map string_of_tyvar tvs)
    ^ "], " ^ string_of_ttype gt ^ ")" ^ string_of_context ctx

and string_of_tyformals (gt, ident) =
  "(" ^ ident ^ " : " ^ string_of_ttype gt ^ ")"

(* String of a typed expression (texpr) == (type, t-expression) *)
```

```
let rec string_of_texpr (typ, exp) =
  "[" ^ string_of_ttype typ ^ "] " ^ string_of_tx exp
and string_of_tx = function
    TLiteral v -> string_of_tvalue v
  | TypedVar id -> id
  | TypedIf (te1, te2, te3) ->
    "(if "  ^ string_of_texpr te1 ^ " "
    ^ string_of_texpr te2 ^ " "
    ^ string_of_texpr te3 ^ ")"
  | TypedApply (f, args) ->
    "(" ^ string_of_texpr f ^ " "
    ^ String.concat " " (List.map string_of_texpr args) ^ ")"
  | TypedLet (binds, body) ->
    let string_of_binding (id, e) =
      "[" ^ id ^ " " ^ (string_of_texpr e) ^ "]"
    in
    "(let ("  ^ String.concat " " (List.map string_of_binding binds) ^ ") "
    ^ string_of_texpr body ^ ")"
  | TypedLambda (formals, body) ->
    let formalStringlist = List.map (fun (ty, x) ->
        string_of_ttype ty ^ " " ^ x) formals in
    "(lambda (" ^ String.concat ", "  formalStringlist
    ^ ") " ^ string_of_texpr body ^ ")"

(* toString for Sast.svalue *)
and string_of_tvalue = function
  | TChar c -> String.make 1 c
  | TInt i -> string_of_int i
  | TBool b -> if b then "#t" else "#f"
  | TRoot tr -> string_of_ttree tr

(* toString for Sast.stree *)
and string_of_ttree = function
    TLeaf -> "leaf"
  | TBranch (v, sib, child) ->
    "(tree " ^ string_of_tvalue v ^ " "
    ^ string_of_ttree sib ^ " "
    ^ string_of_ttree child ^ ")"


(* String of a typed defn (tdefn) *)
let string_of_tdefn = function
  | TVal (id, te) -> "(val " ^ id ^ " " ^ string_of_texpr te ^ ")"
  | TExpr te    -> string_of_texpr te
```

```
(* String of the tprog == tdefn list *)
let string_of_tprog tdefns =
  String.concat "\n" (List.map string_of_tdefn tdefns) ^ "\n"
```

10.7 infer.ml

Author(s): Sam, Eliza, Nik

```
open Ast
open Tast
module StringMap = Map.Make (String)

(* prims - initializes context with built-in functions with their types *)
(* prims : (id * (tyvar list * gtype)) *)
let prims =
  [
    ("printb",  ([ TVariable (-1) ], Tast.functiontype inttype [ booltype ]));
    ("printi",  ([ TVariable (-2) ], Tast.functiontype inttype [ inttype ]));
    ("printc",  ([ TVariable (-3) ], Tast.functiontype inttype [ chartype ]));
    ("+",       ([ TVariable (-4) ], Tast.functiontype inttype [ inttype; inttype ]));
    ("-",       ([ TVariable (-4) ], Tast.functiontype inttype [ inttype; inttype ]));
    ("/",       ([ TVariable (-4) ], Tast.functiontype inttype [ inttype; inttype ]));
    ("*",       ([ TVariable (-4) ], Tast.functiontype inttype [ inttype; inttype ]));
    ("mod",     ([ TVariable (-4) ], Tast.functiontype inttype [ inttype; inttype ]));
    ("<",       ([ TVariable (-5) ], Tast.functiontype booltype [ inttype; inttype ]));
    (">",       ([ TVariable (-5) ], Tast.functiontype booltype [ inttype; inttype ]));
    ("<=",      ([ TVariable (-5) ], Tast.functiontype booltype [ inttype; inttype ]));
    (">=",      ([ TVariable (-5) ], Tast.functiontype booltype [ inttype; inttype ]));
    ("=i",      ([ TVariable (-5) ], Tast.functiontype booltype [ inttype; inttype ]));
    ( "!=i",    ([ TVariable (-5) ], Tast.functiontype booltype [ inttype; inttype ]) );
    ( "&&",     ([ TVariable (-6) ], Tast.functiontype booltype [ booltype; booltype ]) );
    ( "||",     ([ TVariable (-6) ], Tast.functiontype booltype [ booltype; booltype ]) );
    ("not",     ([ TVariable (-7) ], Tast.functiontype booltype [ booltype ]));
    ("~",       ([ TVariable (-2) ], Tast.functiontype inttype [ inttype ]))
  ]

(* is_ftv - returns true if 'gt' is equal to free type variable 'var'
    (i.e. 'gt' is a type variable and 'var' is a free type variable). For the
    conapp case, we recurse over the conapp's gtype list searching for any free
    type variables. When this function returns true it means the type variable
    is matching *)
let rec is_ftv (var : tyvar) (gt : gtype) =
  match gt with
  | TYCON _ -> false
  | TYVAR v -> v = var
  | CONAPP (_, gtlst) ->
    (* if any x in gtlst is ftv this returns true, else returns false *)
    List.fold_left (fun acc x -> is_ftv var x || acc) false gtlst

(* ftvs - returns a list of free type variables amongst a collection of gtypes *)
(* retty : tyvar list *)
```

```
let rec ftvs (ty : gtype) =
  match ty with
  | TYVAR t -> [ t ]
  | TYCON _ -> []
  | CONAPP (_, gtlst) -> List.fold_left (fun acc x -> acc @ ftvs x) [] gtlst

(* fresh - returns a fresh gtype variable (integer) *)
let fresh =
  let k = ref 0 in
  (* fun () -> incr k; TVariable !k *)
  fun () -> incr k; TYVAR (TVariable !k)


(* gimme_tycon_gtype - sort of a hack function that we made to solve the bug we
   came across in applying substitutions, called in tysubst *)
   let gimme_tycon_gtype _ = function
   | TYCON x -> x
   | TYVAR x ->
     Diagnostic.error (Diagnostic.TypeError ("the variable " ^ string_of_tyvar x
                        ^ " has type tyvar but an expression was exprected of type tycon"))
   | CONAPP x ->
     Diagnostic.error (Diagnostic.TypeError ("the constructor " ^ string_of_conapp x
                        ^ " has type conapp but an expression was exprected of type tycon"))


(* tysubst - subs in the type in place of type variable  *)
let rec tysubst (one_sub : tyvar * gtype) (t : gtype) =
  match (one_sub, t) with
  | (x, y), TYVAR z -> if x = z then y else TYVAR z
  | _, TYCON (TArrow retty) -> TYCON (TArrow (tysubst one_sub retty))
  | _, TYCON c -> TYCON c
  | (x, _), CONAPP (a, bs) ->
    let tycn = gimme_tycon_gtype x in
    CONAPP (tycn (tysubst one_sub (TYCON a)), (List.map (tysubst one_sub)) bs)


(* sub - updates a list of constraints with substitutions in theta *)
let sub (theta : (tyvar * gtype) list) (cns : (gtype * gtype) list) =
  (* sub_one - takes in single constraint and updates it with substitution in theta *)
  let sub_one (cn : gtype * gtype) =
    List.fold_left
      (fun ((c1, c2) : gtype * gtype) (sub : tyvar * gtype) ->
        (tysubst sub c1, tysubst sub c2))
      cn theta
  in
  List.map sub_one cns
```

```

(* compose - applies the substitutions in theta1 to theta2 *)
let compose theta1 theta2 =
  (* sub_one - takes a single substitution in theta1 and applies it to theta2 *)
  let sub_one cn =
    List.fold_left
      (fun (acc : tyvar * gtype) (one_sub : tyvar * gtype) ->
         match (acc, one_sub) with
         | (a1, TYVAR a2), (s1, TYVAR s2) ->
           if s1 = a1 then (s1, TYVAR a2)
           else if s1 = a2 then (a1, TYVAR s2)
           else acc
         | (a1, a2), (s1, TYVAR _) -> if a1 = s1 then (s1, a2) else acc
         | (a1, _), (s1, s2) -> if a1 = s1 then (s1, s2) else acc)
      cn theta1
  in
  List.map sub_one theta2

(* solve': solves a single constraint 'c' *)
let rec solve' (c : gtype * gtype) =
  match c with
  | TYVAR t1, TYVAR t2 -> [ (t1, TYVAR t2) ]
  | TYVAR t1, TYCON t2 -> [ (t1, TYCON t2) ]
  | TYVAR t1, CONAPP t2 ->
    if is_ftv t1 (CONAPP t2) then
      Diagnostic.error (Diagnostic.TypeError "type variable is not free type in type constructor")
    else [ (t1, CONAPP t2) ]
  | TYCON t1, TYVAR t2 -> solve' (TYVAR t2, TYCON t1)
  | TYCON (TArrow (TYVAR t1)), TYCON t2 -> [ (t1, TYCON t2) ]
  | TYCON t1, TYCON (TArrow (TYVAR t2)) -> [ (t2, TYCON t1) ]
  | TYCON t1, TYCON t2 ->
    if t1 = t2 then []
    else
      Diagnostic.error (Diagnostic.TypeError
        ("type constructor mismatch " ^ string_of_tycon t1
         ^ " != " ^ string_of_tycon t2))
  | TYCON t1, CONAPP t2 ->
    Diagnostic.error (Diagnostic.TypeError
      ("type constructor mismatch " ^ string_of_tycon t1
      ^ " != " ^ string_of_conapp t2))
  | CONAPP t1, TYVAR t2 -> solve' (TYVAR t2, CONAPP t1)
  | CONAPP t1, TYCON t2 ->
    Diagnostic.error (Diagnostic.TypeError
      ("type constructor mismatch " ^ string_of_conapp t1
       ^ " != " ^ string_of_tycon t2))
  | CONAPP t1, CONAPP t2 -> (
```

```
      match (t1, t2) with
      | (TArrow t1, tys1), (TArrow t2, tys2) ->
        solve ((t1, t2) :: List.combine tys1 tys2)
      | _ ->
        Diagnostic.error (Diagnostic.TypeError
          ("type constructor mismatch " ^ string_of_conapp t1
           ^ " != " ^ string_of_conapp t2)))


(* solve - solves a list of constraints, calls 'solver' to iterate through the
           constraint list, once constraint list has been iterated 'compose' is
           called to tie 'theta1' and 'theta2' together, returns theta *)
and solve (constraints : (gtype * gtype) list) =
  let solver cns =
    match cns with
    | [] -> []
    | cn :: cns ->
      let theta1 = solve' cn in
      let theta2 = solve (sub theta1 cns) in
      (compose theta2 theta1) @ theta2
  in solver constraints


(* generate_constraints gctx e:
     infers the type of expression 'e' and a generates a set of constraints,
     'gctx' refers to the global context 'e' can refer to.

   Type References:
        ctx : (ident * tyscheme) list == (ident * (tyvar list * gtype)) list
   tyscheme : (tyvar list * gtype)
      retty : gtype * (gtype * gtype) list * (gtype * tx) *)
let rec generate_constraints gctx e =
  let rec constrain ctx e =
    match e with
    | Literal e -> value e
    | Var name ->
      let _, (_, tau) = List.find (fun x -> fst x = name) ctx in
      (tau, [], (tau, TypedVar name))
    | If (e1, e2, e3) ->
      let t1, c1, tex1 = generate_constraints ctx e1 in
      let t2, c2, tex2 = generate_constraints ctx e2 in
      let t3, c3, tex3 = generate_constraints ctx e3 in
      let c = [ (booltype, t1); (t3, t2) ] @ c1 @ c2 @ c3 in
      let tex = TypedIf (tex1, tex2, tex3) in
      (t3, c, (t3, tex))
    | Apply (f, args) ->
```

```
    let t1, c1, tex1 = generate_constraints ctx f in
    let ts2, c2, texs2 =
      List.fold_left
        (fun acc e ->
           let t, c, x = generate_constraints ctx e in
           let ts, cs, xs = acc in
           (t :: ts, c @ cs, x :: xs))
        ([], c1, []) (List.rev args)
    in
    (* reverse args to maintain arg order *)
    let retType = fresh () in
    ( retType,
      (t1, Tast.functiontype retType ts2) :: c2,
      (retType, TypedApply (tex1, texs2)) )
  | Let (bindings, expr) ->
    let l = List.map (fun (_, e) -> generate_constraints ctx e) bindings in
    let cns = List.concat (List.map (fun (_, c, _) -> c) l) in
    let taus = List.map (fun (t, _, _) -> t) l in
    let asts = List.map (fun (_, _, a) -> a) l in
    let names = List.map fst bindings in
    let ctx_addition =
      List.map (fun (n, t) -> (n, ([], t))) (List.combine names taus)
    in
    let new_ctx = ctx_addition @ ctx in
    let b_tau, b_cns, b_tast = generate_constraints new_ctx expr in
    (b_tau, b_cns @ cns, (b_tau, TypedLet (List.combine names asts, b_tast)))
  | Lambda (formals, body) ->
    let binding = List.map (fun x -> (x, ([], fresh ()))) formals in
    let new_context = binding @ ctx in
    let t, c, tex = generate_constraints new_context body in
    let _, tyschms = List.split binding in
    let _, formaltys = List.split tyschms in
    let typedFormals = List.combine formaltys formals in
    ( Tast.functiontype t formaltys,
      c,
      (Tast.functiontype t formaltys, TypedLambda (typedFormals, tex)) )
and value v =
  match v with
  | Int  e -> (inttype, [],  (inttype,  TLiteral (TInt e)))
  | Char e -> (chartype, [], (chartype, TLiteral (TChar e)))
  | Bool e -> (booltype, [], (booltype, TLiteral (TBool e)))
  | Root t -> tree t
and tree t =
  match t with
  | Leaf     -> Diagnostic.error (Diagnostic.Unimplemented "contraint generation for Leaf")
  | Branch _ -> Diagnostic.error (Diagnostic.Unimplemented "contraint generation for Branch")
```

```
  in
  constrain gctx e


(* get_constraints - returns a list of Tasts
        Tast : [ (ident * (gtype * tx)) ] = [ (ident * texpr) | texpr ] = [ tdefns ]
    tyscheme : (tyvar list * gtype) *)
let get_constraints (ctx : (ident * tyscheme) list) (d : defn) =
  match d with
  | Val (name, e) ->
    let t, c, tex = generate_constraints ctx e in
    (t, c, TVal (name, tex))
  | Expr e ->
    let (t, c, tex) = generate_constraints ctx e in
    (t, c, TExpr tex)


(*  input: (tyvar * gtype) list *)
(*  retty: tdefn -> tdefn *)
let apply_subs (sub : (tyvar * gtype) list) =
  match sub with
  | [] -> (fun x -> x)
  | xs ->
    let final_ans =
      (fun tdef ->
         (* xs - the list of substitutions we want to apply *)
         (* tdef - the tdefn we want to apply the substitutions to *)
         let rec expr_only_case (x : texpr) =
           List.fold_left
             (* anon fun - takes one texpr and takes one substitution and subs substitution into the tex
             (fun (tast_gt, tast_tx) (tv, gt) ->
                (* updated_tast_tx - matches texpr with tx and recurses on expressions *)
                let updated_tast_tx = match tast_tx with
                  | TypedIf (x, y, z) ->
                      TypedIf (expr_only_case x, expr_only_case y, expr_only_case z)
                  | TypedApply (x, xs) ->
                    let txs = List.map expr_only_case xs in
                    TypedApply (expr_only_case x, txs)
                  | TypedLet ((its), x) -> TypedLet (List.map (fun (x, y) ->
                      (x, expr_only_case y)) its, expr_only_case x)
                  | TypedLambda (tyformals, body) ->
                    TypedLambda ((List.map (fun (x, y) -> (tysubst (tv, gt) x, y))
                                    tyformals), expr_only_case body)
                  | TLiteral x -> TLiteral x
                  | TypedVar x -> TypedVar x
                in
```

```
                let temp = (tysubst (tv, gt) tast_gt, updated_tast_tx) in temp) x xs in
          match tdef with
          | TVal (name, x) -> TVal (name, (expr_only_case x))
          (* Do we need to do anything with updating context here? *)
          | TExpr x -> TExpr (expr_only_case x)
      )
    in final_ans

(* update_ctx - if the typed definition is a TVal this function will make sure
   there are no unbound type variables and tha *)
let update_ctx ctx tydefn =
  match tydefn with
  | TVal (name, (gt, _)) ->
    (name, (List.filter (fun x -> List.exists (fun y -> y = x) (ftvs gt)) (ftvs gt), gt))::ctx
  | TExpr _ -> ctx


(* type_infer
      input : ( ident | ident * expr ) list
    returns : ( ident * (gtype * tx) ) list *)

let type_infer (ds : defn list) =
  let rec infer_defns ctx defn =
    match defn with
    | [] -> []
    | d :: ds ->
      (* get the constraints for the defn *)
      let _, cs, tex = get_constraints ctx d in
      (* subs -> (Infer.tyvar * Infer.gtype) list *)
      let subs = solve cs in
      (* apply subs to tdefns *)
      let tdefn = (apply_subs subs) tex in
      (* update ctx *)
      let ctx' = update_ctx ctx tdefn in
      (* recurse *)
      tdefn :: infer_defns ctx' ds
  in
  infer_defns prims ds

(* type_infer
      input : ( ident | ident * expr ) list
    returns : ( ident * (gtype * tx) ) list *)
```

10.8 mast.ml

Author(s): Amy

```
(* MAST -- monomorphized AST where pholymorphism is removed *)
module StringMap = Map.Make(String)

type mname = string

type mtype =
    Mtycon of mtycon
  | Mtyvar of int
  | Mconapp of mconapp
and mtycon =
    MIntty
  | MCharty
  | MBoolty
  | MTarrow of mtype
and mconapp = (mtycon * mtype list)

let integerTy  = Mtycon MIntty
let characterTy = Mtycon MCharty
let booleanTy = Mtycon MBoolty
let functionTy (ret, args) = Mconapp (MTarrow ret, args)



type mexpr = mtype * mx
and mx =
  | MLiteral  of mvalue
  | MVar      of mname
  | MIf       of mexpr * mexpr * mexpr
  | MApply    of mexpr * mexpr list
  | MLet      of (mname * mexpr) list * mexpr
  | MLambda   of (mtype * mname) list * mexpr
and mvalue =
  | MChar     of char
  | MInt      of int
  | MBool     of bool
  | MRoot     of mtree
and mtree =
  | MLeaf
  | MBranch   of mvalue * mtree * mtree

type mdefn =
  | MVal      of mname * mexpr
  | MExpr     of mexpr
```

```


type polyty_env = mexpr StringMap.t

type mprog = mdefn list



(* Pretty printer *)

(* String of mtypes *)
let rec string_of_mtype = function
  | Mtycon ty -> string_of_mtycon ty
  | Mconapp con -> string_of_mconapp con
  | Mtyvar i -> "'" ^ string_of_int i
and string_of_mtycon = function
  | MIntty -> "int"
  | MBoolty -> "bool"
  | MCharty -> "char"
  | MTarrow (retty) -> string_of_mtype retty
and string_of_mconapp (tyc, tys) =
  string_of_mtycon tyc ^ " ("
  ^ String.concat " " (List.map string_of_mtype tys) ^ ")"


(* String of a typed expression (mexpr) == (type, m-expression) *)
let rec string_of_mexpr (typ, exp) =
  "[" ^ string_of_mtype typ ^ "] " ^ string_of_mx exp
and string_of_mx = function
  | MLiteral v -> string_of_mvalue v
  | MVar id -> id
  | MIf (e1, e2, e3) ->
    "(if "  ^ string_of_mexpr e1 ^ " "
    ^ string_of_mexpr e2 ^ " "
    ^ string_of_mexpr e3 ^ ")"
  | MApply (f, args) ->
    "(" ^ string_of_mexpr f ^ " "
    ^ String.concat " " (List.map string_of_mexpr args) ^ ")"
  | MLet (binds, body) ->
    let string_of_binding (id, e) =
      "[" ^ id ^ " " ^ (string_of_mexpr e) ^ "]"
    in
    "(let ("  ^ String.concat " " (List.map string_of_binding binds) ^ ") "
    ^ string_of_mexpr body ^ ")"
  | MLambda (formals, body) ->
    let formalStringlist = List.map (fun (ty, x) -> string_of_mtype ty ^ " " ^ x) formals in
```

```
    "(lambda (" ^ String.concat ", "  formalStringlist
    ^ ") " ^ string_of_mexpr body ^ ")"
(* toString for Mast.mvalue *)
and string_of_mvalue = function
  | MChar c -> String.make 1 c
  | MInt i -> string_of_int i
  | MBool b -> if b then "#t" else "#f"
  | MRoot tr -> string_of_mtree tr
(* toString for Mast.mtree *)
and string_of_mtree = function
  | MLeaf -> "leaf"
  | MBranch (v, sib, child) ->
    "(tree " ^ string_of_mvalue v ^ " "
    ^ string_of_mtree sib ^ " "
    ^ string_of_mtree child ^ ")"



(* String of a mono typed defn (mdefn) *)
let string_of_mdefn = function
  | MVal (id, me) -> "(val " ^ id ^ " " ^ string_of_mexpr me ^ ")"
  | MExpr me    -> string_of_mexpr me


(* String of the mprog == mdefn list *)
let string_of_mprog mdefns =
  String.concat "\n" (List.map string_of_mdefn mdefns) ^ "\n"
```

10.9 mono.ml

Author(s): Amy

```
(* Monopmorphizes a typed (incl poly) program *)

open Tast
open Mast


(* Function takes a tprog (list of typed definitions),
   and monomorphizes it. to produce a mprog *)
let monomorphize (tdefns : tprog) =

  (* Takes a Tast.gtype and returns the equivalent Mast.mtype *)
  let rec ofGtype = function
      TYCON ty    -> Mtycon  (ofTycon ty)
    | TYVAR tp    -> Mtyvar   (ofTyvar tp)
    | CONAPP con  -> Mconapp (ofConapp con)
  and ofTycon = function
      TyInt        -> MIntty
    | TyBool       -> MBoolty
    | TyChar       -> MCharty
    | TArrow rety  -> MTarrow (ofGtype rety)
  and ofTyvar = function
      TVariable n -> n
  and ofConapp (tyc, tys) = (ofTycon tyc, List.map ofGtype tys)
  in




  (* Takes an mtype, and returns true if it is polymorphic, false o.w. *)
  let rec isPolymorphic (typ : mtype) = match typ with
    | Mtycon  t -> poly_tycon t
    | Mtyvar  _ -> true
    | Mconapp c -> poly_conapp c
  and poly_tycon = function
      MIntty | MBoolty | MCharty -> false
    | MTarrow t -> isPolymorphic t
  and poly_conapp (tyc, mtys) =
    (poly_tycon tyc)
    || (List.fold_left (fun init mtyp -> init || (isPolymorphic mtyp))
          false mtys)
  in


```

```
(* Takes a type environment and a string key "id". Returns the
     value (mtype) that the key mapts to. *)
let lookup (id : mname) (gamma : polyty_env) =
  StringMap.find id gamma
in


(* Takes a name and an polyty_env, and inserts it into the map *)
let set_aside (id : mname) ((ty, exp) : mexpr) (gamma : polyty_env) =
  StringMap.add id (ty, exp) gamma
in


(* Returns true if ty is a type variable *)
let isTyvar (ty : mtype) = match ty with
    Mtycon _  -> false
  | Mtyvar _  -> true
  | Mconapp _ -> false
in

(* Returns true if ty is a function type *)
let isFunctionType (ty : mtype) = match ty with
    Mconapp (MTarrow _, _)  -> true
  | _                       -> false
in


(* (fty, exp) == poly lambda expression
   (ty) == mono function type *)
let resolve (prog : mprog) (id : mname) (ty : mtype) ((fty, exp) : mexpr) =
  (* Given a function type, returns the list of the types of the arguments *)
  let get_type_of_args = function
      Mconapp (MTarrow _, formaltys) -> formaltys
    | _ -> Diagnostic.error
            (Diagnostic.MonoError "cannot monomorphize non-function type")
  in

  let formaltys     = get_type_of_args ty  in (* mono *)
  let polyargtys    = get_type_of_args fty in (* poly *)
  let substitutions = List.combine polyargtys formaltys in

  (* Given a (polymorphic) mtype, returns the monomorphic version *)
  let resolve_mty (mty : mtype) =
    let apply_subs typ (arg, sub) =
      if isTyvar arg
```

```
      then
        let tyvarID =
          (match arg with
             Mtyvar i -> i
           | _ -> Diagnostic.error
                    (Diagnostic.MonoError "non-tyvar substitution"))
        in
        let rec search_mtype = function
            Mtycon tyc -> Mtycon (search_tycon tyc)
          | Mtyvar i   -> if i = tyvarID then sub else Mtyvar i
          | Mconapp con -> Mconapp (search_con con)
        and search_tycon = function
            MIntty  -> MIntty
          | MCharty -> MCharty
          | MBoolty -> MBoolty
          | MTarrow retty -> MTarrow (search_mtype retty)
        and search_con (tyc, mtys) =
          (search_tycon tyc, List.map search_mtype mtys)
        in search_mtype typ
    else typ
  in List.fold_left apply_subs mty substitutions
in

(* Given an (polymorphic) mx, returns the monomorphic version, with an
   updated program, if any. *)
let rec resolve_mx pro = function
    MLiteral l -> (MLiteral l, pro)
  | MVar     v -> (MVar v, pro)
  | MIf ((t1, e1), (t2, e2), (t3, e3)) ->
      let t1' = resolve_mty t1 in
      let t2' = resolve_mty t2 in
      let t3' = resolve_mty t3 in
      let (e1', pro1) = resolve_mx pro  e1 in
      let (e2', pro2) = resolve_mx pro1 e2 in
      let (e3', pro3) = resolve_mx pro2 e3 in
      (MIf ((t1', e1'), (t2', e2'), (t3', e3')), pro3)
  | MApply ((appty, app), args) ->
      (* resolve the expression thats applied *)
      let appty' = resolve_mty appty in
      let (app', pro') = resolve_mx pro app in
      (* resolve the arguments of the application *)
      let (argtys, argexps) = List.split args in
      let argtys' = List.map resolve_mty argtys in
      let (argexps', pro'') = resolve_listOf_mx pro' argexps in
      let args' = List.combine argtys' argexps' in
      (MApply ((appty', app'), args'), pro'')
```

```
      | MLet (bs, body) ->
          let (names, bexprs) = List.split bs in
          let (btys, bmxs) = List.split bexprs in
          let btys' = List.map resolve_mty btys in
          let (bmxs', pro') = resolve_listOf_mx pro bmxs in
          let bs' = List.combine names (List.combine btys' bmxs') in
          let (body', pro'') = resolve_mexpr pro' body in
          (MLet (bs', body'), pro'')
      | MLambda  (formals, body) ->
          let (formaltys, names) = List.split formals in
          let formaltys' = List.map resolve_mty formaltys in
          let formals' = List.combine formaltys' names in
          let (body', pro') = resolve_mexpr pro body in
          let lambdaExp = MLambda (formals', body') in
          let pro'' = (MVal (id, (ty, lambdaExp))) :: pro' in
          (lambdaExp, pro'')
  and resolve_mexpr pro ((ty, mexp) : mexpr) =
      let ty' = resolve_mty ty in
      let (mexp', pro') = resolve_mx pro mexp in
      let monoexp' = (ty', mexp') in
      (monoexp', pro')
  and resolve_listOf_mx pro (mxs : mx list) =
      let (mx', pro') =
        List.fold_left
          (fun (mexlist, prog) mex ->
              let (mex', prog') = resolve_mx prog mex in
              (mex' :: mexlist, prog'))
          ([], pro) mxs
      in
      let mx' = List.rev mx' in
      (mx', pro')
  in

  let (exp', prog') = resolve_mx prog exp in
  ((ty, exp'), prog')

in




(* Takes a texpr and returns the equivalent mexpr
   and the prog (list of mdefns) *)
let rec expr (gamma : polyty_env) (prog : mprog) ((ty, ex) : texpr) =
  match ex with
    TLiteral l -> ((ofGtype ty, MLiteral (value l)), prog)
```

```
    | TypedVar v ->
        (* let () = print_endline ("looking for: " ^ v) in  *)
        let vartyp = (try fst (lookup v gamma)
                      with Not_found ->
                          (* let () = print_endline "didn't find it" in  *)
                          ofGtype ty) in
        let actualtyp = ofGtype ty in
        if (isPolymorphic vartyp) && (isFunctionType vartyp)
          then
            let polyexp = lookup v gamma in
            let (_, prog') = resolve prog v actualtyp polyexp in
            ((actualtyp, MVar v), prog')
        else
          ((actualtyp, MVar v), prog)
    | TypedIf  (t1, t2, t3) ->
        let (mexp1, prog1) = expr gamma prog t1 in
        let (mexp2, prog2) = expr gamma prog1 t2 in
        let (mexp3, prog3) = expr gamma prog2 t3 in
        ((fst mexp3, MIf (mexp1, mexp2, mexp3)), prog3)
    | TypedApply (f, args) ->
        let (f', prog') = expr gamma prog f in
        let (args', prog'') =
          List.fold_left
            (fun (arglst, pro) arg ->
              let (arg', pro') = expr gamma pro arg in
              (arg' :: arglst, pro'))
            ([], prog') args
        in
        let args' = List.rev args' in
        ((ofGtype ty, MApply (f', args')), prog'')
    | TypedLet (bs, body) ->
        let binding (x, e) =  let (e', _) = expr gamma prog e in (x, e') in
        let bs' = List.map binding bs in
        let (body', prog') = expr gamma prog body in
        ((ofGtype ty, MLet (bs', body')), prog')
    | TypedLambda (formals, body) ->
        let (formaltys, names) = List.split formals in
        let formaltys' = List.map ofGtype formaltys in
        let formals'   = List.combine formaltys' names in
        let gamma' = List.fold_left
                        (fun env (ty, name) ->
                         if isPolymorphic ty
                            then set_aside name (ty, MVar name) env
                         else env)
                        gamma
                        formals' in
```

```
      let (body', prog') = expr gamma' prog body in
      ((ofGtype ty, MLambda (formals', body')), prog')
and value = function
  | TChar c -> MChar c
  | TInt  i -> MInt i
  | TBool b -> MBool b
  | TRoot t -> MRoot (tree t)
and tree = function
  | TLeaf                -> MLeaf
  | TBranch (v, t1, t2) -> MBranch (value v, tree t1, tree t2)
in


(* Takes the current mprog built so far, and one tdefn, and adds
   the monomorphized version to the mprog. Returns a new mprog
   with the new definition added in.  *)
let mono ((gamma, prog) : polyty_env * mprog) = function
    TVal (id, (ty, texp)) ->
      let ((mty, mexp), prog') = expr gamma prog (ty, texp) in
      if isPolymorphic mty
        then
          let gamma' = set_aside id (mty, mexp) gamma in
          (gamma', MVal (id, (mty, mexp)) :: prog')
      else (gamma, MVal (id, (mty, mexp)) :: prog')
  | TExpr (ty, texp) ->
      let ((mty, mexp), prog') = expr gamma prog (ty, texp) in
      let () = if isPolymorphic mty then
        Diagnostic.warning
          (Diagnostic.MonoWarning ("polymorphic type leftover;"
                                    ^ " resolving to integers"))
      else ()
      in (gamma, MExpr (mty, mexp) :: prog')

      (* if isPolymorphic mty
        then (gamma, prog')
      else (gamma, MExpr (mty, mexp) :: prog') *)
in

let (_, program) = List.fold_left mono (StringMap.empty, []) tdefns in




(* Bug/Bandaid - unable to resolve polymorphism.
   Iterate through the current "mono" typed program.
   Insert integer type wherever leftover type variables remain *)
```

```
let buggy_resolve (prog : mprog) (def : mdefn) =

  (* resolves any remaining polymorphism in an mexpr to integer type *)
  let rec resolve_expr ((ty, exp) : mexpr) =
    (* turns tyvar into int type *)
    let rec resolve_mty = function
      | Mtycon  t -> Mtycon (resolve_tycon t)
      | Mtyvar  _ -> Mtycon MIntty
      | Mconapp c -> Mconapp (resolve_conapp c)
    and resolve_tycon = function
      | MIntty    -> MIntty
      | MBoolty   -> MBoolty
      | MCharty   -> MCharty
      | MTarrow t -> MTarrow (resolve_mty t)
    and resolve_conapp (tyc, mtys) =
          (resolve_tycon tyc, List.map resolve_mty mtys)
    in

    (* finds and resolves any nested tyvars to int type *)
    let resolve_mx = function
      | MLiteral l -> MLiteral l
      | MVar v     -> MVar v
      | MIf (e1, e2, e3) ->
          let r1 = resolve_expr e1 in
          let r2 = resolve_expr e2 in
          let r3 = resolve_expr e3 in
          MIf (r1, r2, r3)
      | MApply (f, args) ->
          let f' = resolve_expr f in
          let args' = List.map resolve_expr args in
          MApply (f', args')
      | MLet (bs, body) ->
          let bs' = List.map (fun (name, mex) ->
                                (name, resolve_expr mex))
                             bs in
          let body' = resolve_expr body in
          MLet (bs', body')
      | MLambda (formals, body) ->
          let formals' =
            List.map (fun (mty, name) -> (resolve_mty mty, name)) formals in
          let body' = resolve_expr body in
          MLambda (formals', body')
    in

    (resolve_mty ty, resolve_mx exp)
  in
```

```

    (* Resolve the given mdefn *)
    match def with
    | MVal (id, ex) -> MVal  (id, resolve_expr ex) :: prog
    | MExpr ex      -> MExpr (resolve_expr ex) :: prog
  in

  List.fold_left buggy_resolve [] program
```

10.10 hast.ml

Author(s): Amy

```
(* HAST - resolves function types involved in the uses of HOFs *)

module StringMap = Map.Make(String)

type hname = string

type htype =
    HTycon of htycon
  | HConapp of hconapp
and htycon =
    HIntty
  | HCharty
  | HBoolty
  | HTarrow of htype
  (* H-closures come with return type, formal types, free types *)
  | HCls of hname * htype * htype list * htype list
and hconapp = (htycon * htype list)

let intTy  = HTycon HIntty
let charTy = HTycon HCharty
let boolTy = HTycon HBoolty

let partialClosurety (id, retty, formaltys, freetys) =
  HTycon (HCls (id, retty, formaltys, freetys))


type hexpr = htype * hx
and hx =
  | HLiteral  of hvalue
  | HVar      of hname
  | HIf       of hexpr * hexpr * hexpr
  | HApply    of hexpr * hexpr list
  | HLet      of (hname * hexpr) list * hexpr
  | HLambda   of (htype * hname) list * hexpr
and hvalue =
  | HChar     of char
  | HInt      of int
  | HBool     of bool
  | HRoot     of htree
and htree =
  | HLeaf
  | HBranch   of hvalue * htree * htree

```

```
type hdefn =
  | HVal      of hname * hexpr
  | HExpr     of hexpr


type ty_env = ((int * htype) list) StringMap.t
type hof_env = (hname * hexpr) StringMap.t
let emptyEnvironment = StringMap.empty
let emptyListEnv = []


type hrec =
  {
    mutable program : hdefn list;
    mutable gamma   : ty_env;
    mutable hofs    : hof_env;
  }

type hprog = hdefn list



(* Pretty printer *)
let rec string_of_htype = function
    HTycon tyc -> string_of_htycon tyc
  | HConapp con -> string_of_hconapp con
and string_of_htycon = function
    HIntty -> "int"
  | HCharty -> "char"
  | HBoolty -> "bool"
  | HTarrow retty -> string_of_htype retty
  | HCls (id, retty, formaltys, freetys) ->
      let string_of_list tys =
          String.concat ", " (List.map string_of_htype tys) in
      id ^ "{ " ^
      string_of_htype retty
      ^ " (" ^
      string_of_list formaltys ^ " :: " ^
      string_of_list freetys
      ^ ") }"
and string_of_hconapp (tyc, tys) =
      string_of_htycon tyc ^ " ("
      ^ String.concat " " (List.map string_of_htype tys) ^ ")"


(* String of a h-expression *)
```

```
let rec string_of_hexpr (typ,exp) =
  "[" ^ string_of_htype typ ^ "] " ^ string_of_hx exp
and string_of_hx = function
  | HLiteral v -> string_of_hvalue v
  | HVar id -> id
  | HIf (e1, e2, e3) ->
    "(if "  ^ string_of_hexpr e1 ^ " "
    ^ string_of_hexpr e2 ^ " "
    ^ string_of_hexpr e3 ^ ")"
  | HApply (f, args) ->
    "(" ^ string_of_hexpr f ^ " "
    ^ String.concat " " (List.map string_of_hexpr args) ^ ")"
  | HLet (binds, body) ->
    let string_of_binding (id, e) =
      "[" ^ id ^ " " ^ (string_of_hexpr e) ^ "]"
    in
    "(let ("  ^ String.concat " " (List.map string_of_binding binds) ^ ") "
    ^ string_of_hexpr body ^ ")"
  | HLambda (formals, body) ->
    let formalStringlist = List.map (fun (ty, x) ->
                                      string_of_htype ty ^ " " ^ x)
                                    formals in
    "(lambda (" ^ String.concat ", "  formalStringlist
    ^ ") " ^ string_of_hexpr body ^ ")"
(* toString for Hast.hvalue *)
and string_of_hvalue = function
  | HChar c -> String.make 1 c
  | HInt i -> string_of_int i
  | HBool b -> if b then "#t" else "#f"
  | HRoot tr -> string_of_htree tr
(* toString for Hast.htree *)
and string_of_htree = function
  | HLeaf -> "leaf"
  | HBranch (v, sib, child) ->
    "(tree " ^ string_of_hvalue v ^ " "
    ^ string_of_htree sib ^ " "
    ^ string_of_htree child ^ ")"



(* String of a hdefn *)
let string_of_hdefn = function
  | HVal (id, e) -> "(val " ^ id ^ " " ^ string_of_hexpr e ^ ")"
  | HExpr e    -> string_of_hexpr e

(* Returns the string of an hprog *)
```

```
let string_of_hprog hdefns =
  String.concat "\n" (List.map string_of_hdefn hdefns) ^ "\n"
```

10.11 hof.ml

Author(s): Amy

```
(* Resolve higher order function uses (takes or returns functions)
   to take or return closures. *)
open Mast
open Hast
module StringMap = Map.Make(String)

(* name used for anonymizing lambda functions *)
let anon = "_anon"
let count = ref 0

(* Pre-load rho with prints built in *)
let prerho env =
  let add_prints map (k, v) =
    StringMap.add k [v] map
  in List.fold_left add_prints env
     [("printi", (0, intTy));   ("printb", (0, boolTy));
      ("printc", (0, charTy));  ("+", (0, intTy));
      ("-", (0, intTy));        ("*", (0, intTy));
      ("/", (0, intTy));        ("mod", (0, intTy));
      ("<", (0, boolTy));       (">", (0, boolTy));
      ("<=", (0, boolTy));      (">=", (0, boolTy));
      ("!=i", (0, boolTy));     ("=i", (0, boolTy));
      ("&&", (0, boolTy));      ("||", (0, boolTy));
      ("not", (0, boolTy));     ("~", (0, intTy))          ]

(* list of variable names that get ignored/are not to be considered frees *)
let ignores = [ "printi"; "printb"; "printc";
                "+"; "-"; "*"; "/"; "mod";
                "<"; ">"; ">="; "<=";
                "!=i"; "=i"; "~";
                "&&"; "||"; "not"            ]


(* partial hprog to return from this module *)
let res =
  {
    program  = emptyListEnv;
    gamma    = prerho emptyEnvironment;
    hofs     = emptyEnvironment;
  }

(* Inserts a hdefn into main hdefn list *)
let addMain d = res.program <- d :: res.program
```

```
(* Returns true if the given name id is already bound in the given
   StringMap env. False otherwise *)
let isBound id env = StringMap.mem id env

(* Returns the first element of th value that "id" is bound to in the given
   StringMap env. If the binding doesn't exist, Not_Found exception
   is raised. *)
let find id env =
  let occursList = StringMap.find id env in List.nth occursList 0

(* Adds a binding of k to v in the global StringMap env *)
let bindGamma k v = res.gamma <-
  let currList =  if isBound k res.gamma
                  then StringMap.find k res.gamma else [] in
  let newList = v :: currList in
  StringMap.add k newList res.gamma

let addHofs id lambda = res.hofs <- StringMap.add id lambda res.hofs

(* Adds a local binding of k to v in the given StringMap env *)
let bindLocal map k v =
  let currList = if isBound k map then StringMap.find k map else [] in
  let localList = (0, v) :: currList in
  StringMap.add k localList map

(* Given a h-closure type, returns the closure's id *)
let getClosureId (cls : htype) = match cls with
    HTycon (HCls (id, _, _, _)) -> id
  | _ -> Diagnostic.error
        (Diagnostic.TypeError ("Nonclosure-type accessed when"
                               ^ " trying to get closure ID"))


(* Converts a mtype to a htype *)
let rec ofMtype = function
    Mtycon ty    -> HTycon (ofTycon ty)
  | Mtyvar _     -> Diagnostic.error
                    (Diagnostic.TypeError ("unresolved polymorphic type"))
  | Mconapp con  -> HConapp (ofConapp con)
and ofTycon = function
    MIntty        -> HIntty
  | MBoolty       -> HBoolty
  | MCharty       -> HCharty
  | MTarrow retty -> HTarrow (ofMtype retty)
and ofConapp (tyc, tys) = (ofTycon tyc, List.map ofMtype tys)
```

```
(* Returns true if given htype is a function type *)
let rec isFunctionType = function
    HTycon t  -> hof_tycon t
  | HConapp t -> hof_conapp t
and hof_tycon = function
    HIntty | HCharty | HBoolty -> false
  | HTarrow _ -> true
  | HCls (_, retty, argsty, _) ->
      isFunctionType retty
      || (List.fold_left
            (fun init argty -> init || (isFunctionType argty))
            false argsty)
and hof_conapp (tyc, tys) =
      hof_tycon tyc
      || (List.fold_left
            (fun init typ -> init || (isFunctionType typ))
            false tys)

(* Returns true if the given htype indicates a higher order function *)
let isHOF = function
    HTycon (HCls (_, retty, argsty, _)) ->
      isFunctionType retty
      || (List.fold_left
            (fun init argty -> init || (isFunctionType argty))
            false argsty)
  | _ -> false



(* Given expression an a string name n, returns true if n is
   a free variable in the expression *)
let freeIn exp n =
  let rec free (_, e) = match e with
    | MLiteral _        -> false
    | MVar s            -> s = n
    | MIf (m1, m2, m3)  -> free m1 || free m2 || free m3
    | MApply (f, args)  -> free f  || List.fold_left
                              (fun a b -> a || free b)
                              false args
    | MLet (bs, body) -> List.fold_left (fun a (_, e) -> a || free e) false bs
                         || (free body && not (List.fold_left
                                                  (fun a (x, _) -> a || x = n)
```

```
                                              false bs))
    | MLambda (formals, body) ->
      let (_, names) = List.split formals in
      free body && not (List.fold_left (fun a x -> a || x = n) false names)
  in free (integerTy, exp)

(* Given the formals list and body of a lambda (xs, e), and a
   variable environment, the function returns a list of the types of the
   free variables of the expression. The list of free tyes shall
   not inculde those of built-in functions and primitives *)
let freeTypesOf (xs, e) gamma =
  let freeGamma =
    StringMap.filter
      (fun n _ ->
         if List.mem n ignores
          then false
         else freeIn (MLambda (xs, e)) n)
      gamma
  in
  let getTy _ occursList res =
    let (_, ty) = List.nth occursList 0 in
    (* let id' = if num = 0 then id else "_" ^ id "_" ^ string_of_int num in  *)
    (* (ty, id') :: res  *)
    ty :: res
  in
  StringMap.fold getTy freeGamma []


(* Resolves all lamdba's function types, and uses of these expressions
   to a new closure type. *)
let clean (mdefns : mprog) =

  (* Given a hexpr, returns a possibly updated hexpr using the given
     environment.  *)
  let rec h_expr (env : ty_env) ((typ, exp) : hexpr) = match exp with
    | HLiteral l -> (typ, HLiteral l)
    | HVar v -> let (_, typ') = find v env in (typ', HVar v)
    | HIf (e1, e2, e3) ->
        let e1' = h_expr env e1 in
        let e2' = h_expr env e2 in
        let e3' = h_expr env e3 in
        (fst e2', HIf (e1', e2', e3'))
    | HApply (f, args) ->
        let f' = h_expr env f in
        let args' = List.map (h_expr env) args in
        let retty =
```

```
        (match fst f' with
          HTycon (HCls (_, ret, _, _)) -> ret
        | _ -> intTy)
      in (retty, HApply (f', args'))
  | HLet (bs, body) ->
      let bs' = List.map (fun (name, exp) -> (name, h_expr env exp)) bs in
      let local_env = List.fold_left (fun map (name, (ty, _)) ->
                                        bindLocal map name ty)
                                     env bs' in
      let body' = h_expr local_env body in
      (fst body, HLet (bs', body'))
  | HLambda (formals, body) ->
      let local_env = List.fold_left (fun map (ty, name) ->
                                        bindLocal map name ty)
                                     env formals in
      let body' = h_expr local_env body in
      (fst body, HLambda (formals, body'))
in

(* Given a mexpr, returns the equivalent hexpr *)
let rec expr (env : ty_env) (mexp : mexpr) =
  let rec expr' (ty, exp) = match exp with
      MLiteral l -> (ofMtype ty, HLiteral (value l))
    | MVar v -> let (_, typ) = find v env in (typ, HVar v)
    | MIf (e1, e2, e3) ->
        let e1' = expr' e1 in
        let e2' = expr' e2 in
        let e3' = expr' e3 in
        (fst e2', HIf (e1', e2', e3'))
    | MApply (f, args) ->
        let (fty, f') = expr' f in
        let args' = List.map expr' args in
        if isHOF fty
          then let (retty, fty') = resolveHOF env fty args' in
               (retty, HApply ((fty', f'), args'))
        else (ofMtype ty, HApply ((fty, f'), args'))
    | MLet (bs, body) ->
        let bs' = List.map (fun (name, e) -> (name, expr' e)) bs in
        let local_env = List.fold_left (fun map (name, (typ, _)) ->
                                          bindLocal map name typ)
                                       env bs' in
        let body' = expr local_env body in
        (fst body', HLet (bs', body'))
    | MLambda (formals, body) ->
        (* name the closure *)
        let id = anon ^ string_of_int !count in
```

```
        let () = count := !count + 1 in

        (* Put the formals in the environment *)
        let (formaltys, formalnames) = List.split formals in
        let formaltys' = List.map ofMtype formaltys in
        let formals' = List.combine formaltys' formalnames in
        let local_env = List.fold_left (fun map (typ, name) ->
                                    bindLocal map name typ)
                                 env formals' in
        let body' = expr local_env body in
        let retty = fst body' in
        let freetys = freeTypesOf (formals, body) env in

        (* Create new closure type *)
        let closureType =
                partialClosurety (id, retty, formaltys', freetys) in
        (closureType, HLambda (formals', body'))
  and value = function
    | MChar c -> HChar c
    | MInt  i -> HInt  i
    | MBool b -> HBool b
    | MRoot t -> HRoot (tree t)
  and tree = function
    | MLeaf -> HLeaf
    | MBranch (v, t1, t2) -> HBranch (value v, tree t1, tree t2)
  and resolveHOF (env : ty_env) (closuretype : htype)
                 (arguments : hexpr list) =
        (* Extract argument actual types, and name of closure
           being referenced *)
        let (argtypes, _) = List.split arguments in
        let cloName = getClosureId closuretype in
        let (id, (_, lambdaexp)) = StringMap.find cloName res.hofs in
        (* Function returns the subexpressions of a lambda expression *)
        let get_lambda_subxs = function
            HLambda (formals, body) -> (formals, body)
          | _ -> Diagnostic.error
                  (Diagnostic.TypeError ("Nonclosure-type accessed when"
                    ^ " tryong to get lambda subexpressions"))
        in
        (* Function replaces return types and argument types of a closure
           type with the new given types passed in. *)
        let resolve_cls_ty retty argtys = function
            HTycon (HCls (id, _, _, freetys)) ->
              HTycon (HCls (id, retty, argtys, freetys))
          | _ -> Diagnostic.error
                  (Diagnostic.TypeError ("Nonclosure-type accessed when"
```

```
                    ^ " tyring to resolve closure type"))
        in
        (* Lambda subexpressions *)
        let (formals, body) = get_lambda_subxs lambdaexp in
        let (_, formalnames) = List.split formals in
        let formals' = List.combine argtypes formalnames in

        let local_env = List.fold_left (fun map (typ, name) ->
                                          bindLocal map name typ)
                                       env formals'  in
        let body' = h_expr local_env body in
        let retty = fst body' in
        (* Resolve new closure types within closure types *)
        let newClsty = resolve_cls_ty retty argtypes closuretype in
        let newLambDef = HVal (id, (newClsty, HLambda (formals', body'))) in
        let () = addMain newLambDef in
        (retty, newClsty)

  in expr' mexp
in


(* iterate through each defn and remove the hofs uses *)
let hofDef (def : mdefn) = match def with
    MVal (id, ex) ->
      let (occurs, _) = if (isBound id res.gamma)
                          then (find id res.gamma)
                        else (0, intTy) in
      let (ty, ex') = expr res.gamma ex in
      let () = bindGamma id (occurs + 1, ty) in
      if isHOF ty then addHofs (getClosureId ty) (id, (ty, ex'))
      else addMain (HVal (id, (ty, ex')))
  | MExpr ex ->
      let hexp = expr res.gamma ex in addMain (HExpr hexp)

in

let _ = List.iter hofDef mdefns in
List.rev res.program
```

10.12 cast.ml

Author(s): Amy

```
(*
    Closure converted Abstract Syntax tree
    Assumes name-check and type-check have already happened
*)


module StringMap = Map.Make(String)

type cname = string

type ctype =
    Tycon of tycon
  | Conapp of conapp
and tycon =
    Intty
  | Charty
  | Boolty
  | Tarrow of ctype
  | Clo of cname * ctype * ctype list
and conapp = (tycon * ctype list)


let intty = Tycon Intty
let charty = Tycon Charty
let boolty = Tycon Boolty

let funty (ret, args) =
  Conapp (Tarrow ret, args)
let closuretype (id, functy, freetys) =
  Tycon (Clo (id, functy, freetys))

(* int StringMap.t - for our rho/variable environment
   (DOES NOT MAP TO VALUES) *)
type var_env = ((int * ctype) list) StringMap.t
let emptyEnv = StringMap.empty
let emptyList = []




type cexpr = ctype * cx
and cx =
  | CLiteral  of cvalue
```

```
  | CVar      of cname
  | CIf       of cexpr * cexpr * cexpr
  | CApply    of cexpr * cexpr list * int
  | CLet      of (cname * cexpr) list * cexpr
  | CLambda   of cname * cexpr list
and cvalue =
  | CChar     of char
  | CInt      of int
  | CBool     of bool
  | CRoot     of ctree
and ctree =
  | CLeaf
  | CBranch   of cvalue * ctree * ctree

type cdefn =
  | CVal      of cname * cexpr
  | CExpr     of cexpr


(* function definiton record type (imperative style to record information) *)
type fdef =
  {
    body    : cexpr;
    rettyp  : ctype;
    fname   : cname;
    formals : (ctype * cname) list;
    frees   : (ctype * cname) list;
  }


(* closure is specifically a Tycon (Clo (struct name, function type field, frees field)) *)
type closure = ctype

(* a CAST *)
type cprog =
  {
    mutable main        : cdefn list; (* list for main instruction *)
    mutable functions   : fdef list;   (* table of function definitions *)
    mutable rho         : var_env;    (* variable declaration table *)
    mutable structures  : closure list;
  }


(* Pretty Print *)
(* returns string of a ctype *)
let rec string_of_ctype = function
```

```
    Tycon ty -> string_of_tycon ty
  | Conapp con -> string_of_conapp con
and string_of_tycon = function
    Intty  -> "int"
  | Charty -> "char"
  | Boolty -> "bool"
  | Tarrow (retty) -> string_of_ctype retty
  | Clo (sname, funty, freetys) ->
    sname
    (* ^ " {}" *)
    ^ " { "
    ^ string_of_ctype funty ^ "; "
    ^ String.concat ", " (List.map string_of_ctype freetys)
    ^ "}"
and string_of_conapp (tyc, tys) =
  string_of_tycon tyc ^ " ("
  ^ String.concat ", " (List.map string_of_ctype tys) ^ ")"


(* stringifies cexpr *)
let rec string_of_cexpr (_, e) =
  (* "["  *)
  (* ^ string_of_ctype ty ^ " : "  *)
  (* ^  *)
  string_of_cx e
(* ^ "]" *)
and string_of_cx = function
  | CLiteral v -> string_of_cvalue v
  | CVar n -> n
  | CIf (e1, e2, e3) ->
    "(if "  ^ string_of_cexpr e1 ^ " "
    ^ string_of_cexpr e2 ^ " "
    ^ string_of_cexpr e3 ^ ")"
  | CApply (f, args, _) ->
    "(" ^ string_of_cexpr f ^ " "
    ^ String.concat " " (List.map string_of_cexpr args) ^ ")"
  | CLet (binds, body) ->
    let string_of_binding (id, e) =
      "[" ^ id ^ " " ^ (string_of_cexpr e) ^ "]"
    in "(let ("  ^ String.concat " " (List.map string_of_binding binds)
       ^ ") " ^ string_of_cexpr body ^ ")"
  | CLambda (id, frees) ->
    "(" ^ id ^ " "
    ^ String.concat " " (List.map string_of_cexpr frees)
    ^ ")"
and string_of_cvalue = function
```

```
  | CChar c -> String.make 1 c
  | CInt  i -> string_of_int i
  | CBool b -> if b then "#t" else "#f"
  | CRoot t -> string_of_ctree t
and string_of_ctree = function
  | CLeaf -> "leaf"
  | CBranch (v, sib, child) ->
    "(tree " ^ string_of_cvalue v ^ " "
    ^ string_of_ctree sib ^ " "
    ^ string_of_ctree child ^ ")"

(* stingifies a cdefn *)
let string_of_cdefn = function
  | CVal (id, e) -> "(val " ^ id ^ " " ^ string_of_cexpr e ^ ")"
  | CExpr (cexp) -> string_of_cexpr cexp

let string_of_main main =
  String.concat "\n" (List.map string_of_cdefn main) ^ "\n"

(* stringifies a ist of fdefs *)
let string_of_functions (funcs : fdef list) =
  let string_of_fdef ret_string {
      rettyp = return;
      fname = fname;
      formals = formals;
      frees = frees;
      body = body;
    } =
    let string_of_formal  (ty, para) = string_of_ctype ty ^ " " ^ para in
    let args = formals @ frees in
    let def = string_of_ctype return ^ " " ^ fname ^ " ("
              ^ String.concat ", " (List.map string_of_formal args)
              ^ ")\n{\n"
              ^ string_of_cexpr body  ^ "\n}\n"
    in ret_string ^ def ^ "\n"
  in List.fold_left string_of_fdef "" funcs

(* stringifies the variable lookup table *)
let string_of_rho rho =
  StringMap.fold (fun id occursList s ->
      let (num, ty) = List.nth occursList 0 in
      s ^ id ^ ": " ^ string_of_ctype ty
      ^ " " ^ id ^ string_of_int num
      ^ "\n"
        )
    rho ""
```

```
(* Returns string of the list of closure/struct types *)
let string_of_structures structss =
  let string_of_struct tyc = "struct " ^ string_of_ctype tyc
  in String.concat "\n" (List.map string_of_struct structss)


(* Returns string of a cprog *)
let string_of_cprog { main = main; functions = functions;
                      rho = rho;   structures = structures } =
  "Main:\n" ^
  string_of_main main ^ "\n\n" ^
  "Functions:\n" ^
  string_of_functions functions ^ "\n\n" ^
  "Rho:\n" ^
  string_of_rho rho ^ "\n\n" ^
  "Structures:\n" ^
  string_of_structures structures ^ "\n\n"
```

10.13 conversion.ml

Author(s): Amy, Eliza

```
(* Closure conversion for groot compiler *)
open Hast
open Cast

module StringMap = Map.Make(String)

(**********************************************************************)

(* Pre-load rho with prints built in *)
let prerho env =
  let add_prints map (k, v) =
    StringMap.add k [v] map
  in List.fold_left add_prints env
     [("printi", (0, funty (intty, [intty])));
      ("printb", (0, funty (boolty, [boolty])));
      ("printc", (0, funty (charty, [charty])));
      ("+", (0, funty (intty, [intty; intty])));
      ("-", (0, funty (intty, [intty; intty])));
      ("*", (0, funty (intty, [intty; intty])));
      ("/", (0, funty (intty, [intty; intty])));
      ("mod", (0, funty (intty, [intty; intty])));
      ("<", (0, funty (boolty, [intty; intty])));
      (">", (0, funty (boolty, [intty; intty])));
      ("<=", (0, funty (boolty, [intty; intty])));
      (">=", (0, funty (boolty, [intty; intty])));
      ("!=i", (0, funty (boolty, [intty; intty])));
      ("=i", (0, funty (boolty, [intty; intty])));
      ("&&", (0, funty (boolty, [boolty; boolty])));
      ("||", (0, funty (boolty, [boolty; boolty])));
      ("not", (0, funty (boolty, [boolty])));
      ("~", (0, funty (intty, [intty])))       ]

(* list of variable names that get ignored/are not to be considered frees *)
let ignores = [ "printi"; "printb"; "printc";
                "+"; "-"; "*"; "/"; "mod";
                "<"; ">"; ">="; "<="; "!=i"; "=i";
                "&&"; "||"; "not"; "~"            ]


(* partial cprog to return from this module *)
let res =
  {
    main        = emptyList;
```

```
    functions   = emptyList;
    rho         = prerho emptyEnv;
    structures  = emptyList
  }




(* Converts a htype to a ctype *)
let rec ofHtype = function
    HTycon ty    -> Tycon (ofTycon ty)
  | HConapp con  -> Conapp (ofConapp con)
and ofTycon = function
    HIntty        -> Intty
  | HBoolty       -> Boolty
  | HCharty       -> Charty
  | HTarrow retty -> Tarrow (ofHtype retty)
  | HCls (id, retty, argsty, freetys) ->
      let retty' = ofHtype retty in
      let argsty' = List.map ofHtype argsty in
      let freetys' = List.map ofHtype freetys in
      Clo (id ^ "_struct", funty (retty', argsty' @ freetys'), freetys')
and ofConapp (tyc, tys) = (ofTycon tyc, List.map ofHtype tys)


(* puts the given cdefn into the main list *)
let addMain d = res.main <- d :: res.main

(* puts the given function name (id) mapping to its definition (f) in the
   functions StringMap *)
let addFunction f = res.functions <- f :: res.functions

let getFunction id =
  List.find (fun frecord -> id = frecord.fname) res.functions

let addClosure elem = res.structures <- elem :: res.structures

(* Returns true if the given name id is already bound in the given
   StringMap env. False otherwise *)
let isBound id env = StringMap.mem id env

(* Adds a binding of k to v in the global StringMap env *)
let bind k v = res.rho <-
    let currList = if isBound k res.rho then StringMap.find k res.rho else [] in
    let newList = v :: currList in
    StringMap.add k newList res.rho
```

```

(* Returns the value id is bound to in the given StringMap env. If the
   binding doesn't exist, Not_Found exception is raised. *)
let find id env =
  let occursList = StringMap.find id env in List.nth occursList 0

(* Adds a local binding of k to ctype in the given StringMap env *)
let bindLocal map k ty =
  let currList = if isBound k map then StringMap.find k map else [] in
  let localList = (0, ty) :: currList in
  StringMap.add k localList map

(* Given expression an a string name n, returns true if n is
   a free variable in the expression *)
let freeIn exp n =
  let rec free (_, e) = match e with
    | HLiteral _        -> false
    | HVar s            -> s = n
    | HIf (s1, s2, s3)  -> free s1 || free s2 || free s3
    | HApply (f, args)  -> free f  || List.fold_left
                             (fun a b -> a || free b)
                             false args
    | HLet (bs, body) -> List.fold_left (fun a (_, e) -> a || free e) false bs
                         || (free body && not (List.fold_left
                                                (fun a (x, _) -> a || x = n)
                                                false bs))
    | HLambda (formals, body) ->
      let (_, names) = List.split formals in
      free body && not (List.fold_left (fun a x -> a || x = n) false names)
  in free (intTy, exp)


(* Given the formals list and body of a lambda (xs, e), and a
   variable environment, the function returns an environment with only
   the free variables of this lambda. The environment of frees shall
   not inculde the names of built-in functions and primitives *)
let improve (xs, e) rho =
  StringMap.filter
    (fun n _ ->
       if List.mem n ignores
       then false
       else freeIn (HLambda (xs, e)) n)
    rho


(* Given a var_env, returns a (ctype  * name) list version *)
```

```
let toParamList (venv : var_env) =
  StringMap.fold
    (fun id occursList res ->
      let (num, ty) = List.nth occursList 0 in
      let id' = if num = 0 then id
        else "_" ^ id ^ "_" ^ string_of_int num in
      (ty, id') :: res)
    venv []

(* turns a list of ty * name list to a Var list  *)
let convertToVars (frees : (ctype * cname) list) =
  List.map (fun (t, n) -> (t, CVar n)) frees



(* Generate a new function type for lambda expressions in order to account
   for free variables, when given the original function type and an
   association list of gtypes and var names to add to the new formals list
   of the function type. *)
let newFuntype  (origTyp : htype) (newRet : ctype)
    (toAdd : (ctype * cname) list) =
  (match origTyp with
     HTycon (HCls (_, _, argsty, _)) ->
     let newFormalTys = List.map ofHtype argsty in
     let (newFreeTys, _) = List.split toAdd in
     funty (newRet, newFormalTys @ newFreeTys)
   | _ -> raise (Failure "Non-function function type"))



(* Converts given sexpr to cexpr, and returns the cexpr *)
let rec hexprToCexpr (env : var_env) (e : hexpr)  =
  let rec expr ((typ, ex) : hexpr) = match ex with
    | HLiteral v -> (ofHtype typ, CLiteral (value v))
    | HVar s     ->
        (* In case s is a name of a define, get the closure type *)
        let (occurs, ctyp) = find s env in
        (* to match the renaming convention in svalToCval, and to ignore
           built in prints *)
        let vname = if occurs = 0
                      then s
                    else "_" ^ s ^ "_" ^ string_of_int occurs
        in (ctyp, CVar (vname))
    | HIf (e1, e2, e3) ->
        let e1' = expr e1
        and e2' = expr e2
```

```
        and e3' = expr e3 in
        (fst e2', CIf (e1', e2', e3'))
    | HApply (f, args) ->
        let (ctyp, f') = expr f in
        let normalargs = List.map expr args in
        (* actual type of the function application is the type of the return*)
        let (retty, freesCount) =
          (match ctyp with
             Tycon (Clo (_, functy, freetys)) ->
             (match functy with
                Conapp (Tarrow ret, _) -> (ret, List.length freetys)
              | _ -> raise (Failure "Non-function function type"))
           | Conapp (Tarrow ret, _) -> (ret, 0)
           | _ -> (intty, 0)) in
        (retty, CApply ((ctyp, f'), normalargs, freesCount))
    | HLet (bs, body) ->
        let bs' = List.map (fun (name, hex) -> (name, expr hex)) bs in
        let local_env =
            List.fold_left (fun map (name, (ty, _)) ->
                              bindLocal map name ty)
                           env bs' in
        let (ctyp, body') = hexprToCexpr local_env body  in
        (ctyp, CLet (bs', (ctyp, body')))
    (* Supose we hit a lambda expression, turn it into a closure *)
    | HLambda (formals, body) -> create_anon_function formals body typ env
  and value = function
    | HChar c             -> CChar c
    | HInt  i             -> CInt  i
    | HBool b             -> CBool b
    | HRoot t             -> CRoot (tree t)
  and tree = function
    | HLeaf               -> CLeaf
    | HBranch (v, t1, t2) -> CBranch (value v, tree t1, tree t2)
  in expr e
(* When given just a lambda expresion withot a user defined identity/name
   this function will generate a name and give the function a body --
   Lambda lifting. *)
and create_anon_function  (fformals : (htype * hname) list) (fbody : hexpr)
                          (closurety : htype) (env : var_env) =


  let fformals' = List.map (fun (hty, x) -> (ofHtype hty, x)) fformals in
  let local_env = List.fold_left
                    (fun map (formtyp, name) ->
                      bindLocal map name formtyp)
                    env fformals' in
```

```
  let func_body = hexprToCexpr local_env fbody in
  let rettype = fst func_body in
  let freeformals = toParamList (improve (fformals, fbody) env) in

  (* All anonymous functions are named the same and numbered. *)
  (* Given a h-closure type, returns the closure's id *)
  let getClsID (cls : htype) = match cls with
      HTycon (HCls (id, _, _, _)) -> id
    | _ -> Diagnostic.error
           (Diagnostic.TypeError ("Conversion: Nonclosure-type accessed"
                                  ^ " when trying to get closure ID"))
  in
  let id = getClsID closurety in

  (* Create the record that represents the function body and definition *)
  let func_def =
    {
      body    = func_body;
      rettyp  = rettype;
      fname   = id;
      formals = fformals';
      frees   = freeformals;
    }
  in
  let () = addFunction func_def in

  (* New function type will include the types of free arguments *)
  let anonFunTy = newFuntype closurety rettype freeformals in
  (* Record the type of the anonymous function and its "rea" ftype *)
  let () = bind id (1, anonFunTy) in
  (* The value of a Lambda expression is a Closure -- new type construction
     will help create the structs in codegen that represents the closure *)
  let (freetys, _) = List.split freeformals in
  let clo_ty = closuretype (id ^ "_struct", anonFunTy, freetys) in
  let () = addClosure clo_ty in
  let freeVars = convertToVars freeformals in
  (clo_ty, CLambda (id, freeVars))



(* Converts given SVal to CVal, and returns the CVal *)
let hvalToCval (id, (ty, e)) =
  (* check if id was already defined in rho, in order to get
     the actual frequency the variable name was defined.
     The (0, inttype is a placeholder) *)
  let (occurs, _) = if (isBound id res.rho)
```

```
                      then (find id res.rho)
                    else (0, intty) in
  (* Modify the name to account for the redefinitions, and so old closures
     can access original variable values *)
  let id' = "_" ^ id ^ "_" ^ string_of_int (occurs + 1) in
  let (ty', cexp) = hexprToCexpr res.rho (ty, e) in
  (* bind original name to the number of occurrances and the variable's type *)
  let () = bind id (occurs + 1, ty') in
  (* Return the possibly new CVal definition *)
  CVal (id', (ty', cexp))
(************************************************************************)



(* Given an hprog (which is an hdefn list), convert returns a
   cprog version. *)
let conversion hdefns =
  (* With a given sdefn, function converts it to the appropriate CAST type
     and sorts it to the appropriate list in a cprog type. *)
  let convert = function
    | HVal (id, (ty, hexp)) ->
        let cval = hvalToCval (id, (ty, hexp)) in addMain cval
    | HExpr e ->
        let cexp = hexprToCexpr res.rho e in addMain (CExpr cexp)
  in

  let _ = List.iter convert hdefns in
  {
    main       = List.rev res.main;
    functions  = res.functions;
    rho        = res.rho;
    structures = res.structures
  }
```

10.14 llgtype.ml

Author(s): Amy

```
(*  llgtype.ml
    Creates a context and puts types in it to use in the LLVM code.*)
module L = Llvm

(* creates the glocal context instance *)
let context = L.global_context ()

(* Add types to the context to use in the LLVM code *)
let int_ty      = L.i32_type  context
let char_ty     = L.i8_type   context
let char_ptr_ty = L.pointer_type char_ty
let bool_ty     = L.i1_type   context
let string_ty   = L.struct_type context [| L.pointer_type char_ty |]
let zero = L.const_int int_ty 0
(* REMOVE VOID later *)
(* let void_ty    = L.void_type context *)

let lltrue = L.const_int bool_ty 1

(* "tree_struct" will appear as the struct name in llvm code *)
let tree_struct_ty = L.named_struct_type context "tree_struct"
let tree_struct_ptr_ty = L.pointer_type tree_struct_ty
let () = L.struct_set_body
            tree_struct_ty
            [|
              int_ty;
              tree_struct_ptr_ty;
              tree_struct_ptr_ty
            |]
            false
```

10.15 codegen.ml

Author(s): Amy, Eliza

```
(* Code Generation : Create a llmodule with llvm code from CAST *)
open Llgtype
open Cast


(* translate sdefns - Given an CAST (type cprog, a record type), the function
   returns an LLVM module (llmodule type), which is the code generated from
   the CAST. Throws exception if something is wrong. *)
let translate { main = main;  functions = functions;
                rho = rho;    structures = structures } =


  (* Convert Cast.ctype types to LLVM types *)
  let ltype_of_type (struct_table : L.lltype StringMap.t) (ty : ctype) =
    let rec ltype_of_ctype = function
        Tycon ty -> ltype_of_tycon ty
      | Conapp con -> ltype_of_conapp con
    and ltype_of_tycon = function
        Intty                -> int_ty
      | Boolty               -> bool_ty
      | Charty               -> char_ptr_ty
      | Tarrow ret           -> ltype_of_ctype ret
      | Clo (sname, _, _)    ->
          L.pointer_type (StringMap.find sname struct_table)
    and ltype_of_conapp (tyc, ctys) =
          let llretty = ltype_of_tycon tyc in
          let llargtys = List.map ltype_of_ctype ctys in
          L.pointer_type (L.function_type llretty (Array.of_list llargtys))
    in  ltype_of_ctype ty
  in

  (* Create an LLVM module (container into which we'll
     generate actual code) *)
  let the_module = L.create_module context "gROOT" in


  (* DECLARE a print function (std::printf in C lib) *)
  let printf_ty : L.lltype =
    L.var_arg_function_type int_ty [| char_ptr_ty |] in
  let printf_func : L.llvalue =
    L.declare_function "printf" printf_ty the_module in

  let puts_ty : L.lltype =
```

```
    L.function_type int_ty [| char_ptr_ty |] in
  let puts_func : L.llvalue =
    L.declare_function "puts" puts_ty the_module in

  (* Create a "main" function that takes nothing, and returns an int. *)
  let main_ty = L.function_type int_ty [|  |] in
  let the_main = L.define_function "main" main_ty the_module in


  (* create a builder for the whole program, start it in main block *)
  let main_builder = L.builder_at_end context (L.entry_block the_main) in


  (* Format strings to use with printf for our literals *)
  let int_format_str  = L.build_global_stringptr "%d\n" "fmt"   main_builder

  (* string constants for printing booleans *)
  and boolT           = L.build_global_stringptr "#t"   "boolT" main_builder
  and boolF           = L.build_global_stringptr "#f"   "boolF" main_builder
  in

  let zero = L.const_int int_ty 0 in
  let print_true = L.build_in_bounds_gep boolT [| zero |] "" main_builder in
  let print_false = L.build_in_bounds_gep boolF [| zero |] "" main_builder in

  (* helper to construct named structs  *)
  let create_struct (name : cname) (membertys : ctype list)
      (map : L.lltype StringMap.t) =
    let llmembertys = List.map (ltype_of_type map) membertys in
    let new_struct_ty = L.named_struct_type context name in
    let () =
      L.struct_set_body
        new_struct_ty
        (Array.of_list llmembertys)
        false
    in new_struct_ty
  in


  (* Declare the NAMED struct definitions *)
  let struct_table : L.lltype StringMap.t =
    let gen_struct_def map closure = match closure with
        Tycon (Clo (name, anonFunTy, freetys)) ->
          let v = create_struct name (anonFunTy :: freetys) map in
          StringMap.add name v map
      | _ -> Diagnostic.error
```

```ocaml
            (Diagnostic.GenerationError "declaration of lambda that is non-closure type")
  in
  let structs = List.rev structures in
  let rec declare_structs clsTyList result =
    match clsTyList with
      [] -> result
    | front :: rest ->
        (try
            let result' = gen_struct_def result front in
            declare_structs rest result'
         with Not_found ->
            let rest' = rest @ [front] in
            declare_structs rest' result)
  in declare_structs structs StringMap.empty
in


(* Lookup table of function names (lambdas) to
   (function block, function def) *)
let function_decls : (L.llvalue * fdef) StringMap.t =
  let define_func map def =
    let name = def.fname
    and formal_types =
      Array.of_list (List.map (fun (t, _) -> ltype_of_type struct_table t)
                      (def.formals @ def.frees))
    in
    let ftype = L.function_type
                  (ltype_of_type struct_table def.rettyp)
                  formal_types
    in StringMap.add name (L.define_function name ftype the_module, def) map
  in List.fold_left define_func StringMap.empty functions
in


(* creates a global pointer to some variable's value *)
let create_global id ty =
  let lltyp = ltype_of_type struct_table ty in
  let rec const_typ = function
      Tycon ty    -> const_tycon ty
    (* | Tyvar tp    -> const_tyvar tp *)
    | Conapp con  -> const_conapp con
  and const_tycon = function
      Intty           -> L.const_int  lltyp 0
    | Boolty          -> L.const_int  lltyp 0
    | Charty          -> L.const_pointer_null  lltyp
    | Tarrow _        -> L.const_pointer_null lltyp
```

```
    | Clo _            -> L.const_pointer_null lltyp
  and const_conapp (_, _) = L.const_pointer_null lltyp
  in
  let init = const_typ ty in
  L.define_global id init the_module
in

(* A lookup table of named globals to represent named values *)
let globals : L.llvalue StringMap.t =
  let global_vars k occursList map =
    let glo_var map' (num, typ) =
      if num = 0
      then map'
      else  let id = "_" ^ k ^ "_" ^ string_of_int num in
        StringMap.add id (create_global id typ) map'
    in List.fold_left glo_var map occursList
  in
  StringMap.fold global_vars rho StringMap.empty
in


(* Looks for variable named id in the local or global environment *)
let lookup id locals =
  try StringMap.find id locals
  with Not_found -> StringMap.find id globals
in

(* Add terminal instruction to a block *)
let add_terminal builder instr =
  match L.block_terminator (L.insertion_block builder) with
    Some _ -> ()
  | None -> ignore (instr builder) in


(* Construct constants code for literal values.
   Function takes a builder and Sast.svalue, and returns the constructed
   llvalue  *)
let const_val builder = function
  (* create the "string" constant in the code for the char *)
    CChar c ->
      let spc = L.build_alloca char_ptr_ty "spc" builder in
      let globalChar =
        L.build_global_string (String.make 1 c) "globalChar" builder in
      let newStr = L.build_bitcast globalChar char_ptr_ty "newStr" builder in
      let loc = L.build_gep spc [| zero |] "loc" builder in
      let _ = L.build_store newStr loc builder in
```

```
        L.build_load spc "character_ptr" builder
    | CInt  i -> L.const_int int_ty i
    (* HAS to be an i1 lltype for the br instructions *)
    | CBool b -> L.const_int bool_ty (if b then 1 else 0)
    | CRoot _ -> Diagnostic.error
                  (Diagnostic.Unimplemented "codegen SRoot Literal")

  in



  (* Construct code for expressions
     Arguments: llbuilder, lookup table of local variables,
     current llblock, and Cast.cexpr.
     Constructs the llvm where builder is located;
     Returns an llbuilder and the llvalue representation of code. *)
  let rec expr builder lenv block (etyp, e) =
    match e with
      CLiteral v   -> (builder, const_val builder v)
    | CVar     s  ->
        let varValue =
          (try L.build_load (lookup s lenv) s builder
           with Not_found -> Diagnostic.error
                             (Diagnostic.Unbound ("name \"" ^ s
                               ^ "\" not found in codegen")))
        in (builder, varValue)
    | CIf (e1, (t2, e2), e3) ->
        (* allocate space for result of the if statement *)
        let result =
          L.build_alloca (ltype_of_type struct_table t2) "if-res-ptr" builder
        in

        (* set aside the result of the condition expr *)
        let (newbuilder, bool_val) = expr builder lenv block e1 in

        (* Create the merge block for after exec of then or the else block *)
        let merge_bb = L.append_block context "merge" block in
        let branch_instr = L.build_br merge_bb in

        (* Create the "then" block *)
        let then_bb = L.append_block context "then" block in
        let (then_builder, then_res) =
          expr (L.builder_at_end context then_bb) lenv block (t2, e2) in
        let _ = L.build_store then_res result then_builder in
        let () = add_terminal then_builder branch_instr in

```

```
        (* Create the "else" block *)
        let else_bb = L.append_block context "else" block in
        let (else_builder, else_res) =
          expr (L.builder_at_end context else_bb) lenv block e3 in
        let _ = L.build_store else_res result else_builder in
        let () = add_terminal else_builder branch_instr in

        (* Complete the if-then-else block, return should be llvalue *)
        (* let _ = L.build_cond_br bool_val then_bb else_bb builder in *)
        let _ = L.build_cond_br bool_val then_bb else_bb newbuilder in
        (* Get the result of either the the or the else block *)
        let merge_builder = L.builder_at_end context merge_bb in
        let result_value = L.build_load result "if-res-val" merge_builder in
        (merge_builder, result_value)
    | CApply ((_, CVar "printi"), [arg], _) ->
        let (builder', argument) = expr builder lenv block arg in
        let instruction = L.build_call  printf_func
            [| int_format_str ; argument |]
            "printi" builder'
        in (builder', instruction)
    | CApply ((_, CVar "printc"), [arg], _) ->
        let (builder', argument) = expr builder lenv block arg in
        let instruction = L.build_call  puts_func
            [| argument |]
            "printc" builder'
        in (builder', instruction)
    | CApply ((_, CVar "printb"), [arg], _) ->
        let (builder', condition) = expr builder lenv block arg in
        let bool_stringptr =
          if condition = lltrue then print_true
          else print_false in
        let instruction = L.build_call  puts_func
            [| bool_stringptr |]
            "printb" builder'
        in (builder', instruction)
    | CApply ((_, CVar "~"), [arg], _) ->
        let (builder', e) = expr builder lenv block arg in
        let instruction = L.build_neg e "~" builder'
        in (builder', instruction)
    | CApply ((_, CVar "not"), [arg], _) ->
        let (builder', e) = expr builder lenv block arg in
        let instruction = L.build_not e "not" builder'
        in (builder', instruction)
    (* BINOP PRIMITIVES - Int and Boolean Algebra *)
    | CApply ((_, CVar "+"), arg1::[arg2], _) ->
        let (builder', e1) = expr builder lenv block arg1 in
```

```
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_add e1 e2 "addition" builder''
      in (builder'', instruction)
    | CApply ((_, CVar "-"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_sub e1 e2 "subtraction" builder''
      in (builder'', instruction)
    | CApply ((_, CVar "/"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_sdiv e1 e2 "division" builder''
      in (builder'', instruction)
    | CApply ((_, CVar "*"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_mul e1 e2 "multiply" builder''
      in (builder'', instruction)
    | CApply ((_, CVar "mod"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_srem e1 e2 "modulus" builder''
      in (builder'', instruction)
    | CApply ((_, CVar "&&"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_and e1 e2 "logAND" builder''
      in (builder'', instruction)
    | CApply ((_, CVar "||"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_or e1 e2 "logOR" builder''
      in (builder'', instruction)
    (* BINOP PRIMITIVES - Comparisons *)
    | CApply ((_, CVar "<"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_icmp L.Icmp.Slt e1 e2 "lt" builder''
      in (builder'', instruction)
    | CApply ((_, CVar ">"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_icmp L.Icmp.Sgt e1 e2 "gt" builder''
      in (builder'', instruction)
    | CApply ((_, CVar "<="), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
```

```
        let (builder'', e2) = expr builder' lenv block arg2 in
        let instruction = L.build_icmp L.Icmp.Sle e1 e2 "leq" builder''
        in (builder'', instruction)
    | CApply ((_, CVar ">="), arg1::[arg2], _) ->
        let (builder', e1) = expr builder lenv block arg1 in
        let (builder'', e2) = expr builder' lenv block arg2 in
        let instruction = L.build_icmp L.Icmp.Sge e1 e2 "geq" builder''
        in (builder'', instruction)
    | CApply ((_, CVar "=i"), arg1::[arg2], _) ->
        let (builder', e1) = expr builder lenv block arg1 in
        let (builder'', e2) = expr builder' lenv block arg2 in
        let instruction = L.build_icmp L.Icmp.Eq e1 e2 "eqI" builder''
        in (builder'', instruction)
    | CApply ((_, CVar "!=i"), arg1::[arg2], _) ->
        let (builder', e1) = expr builder lenv block arg1 in
        let (builder'', e2) = expr builder' lenv block arg2 in
        let instruction = L.build_icmp L.Icmp.Ne e1 e2 "neqI" builder''
        in (builder'', instruction)
    | CApply (f, args, numFrees) ->
        (* Since all normal function application is as struct value,
          call to the function at member index 0 of the struct *)
        let (builder', applyClosure) = expr builder lenv block f in
        (* List of llvalues representing the actual arguments *)
        let (builder'', llargs) =
          List.fold_left  (fun (bld, arglist) arg ->
              let (bld', llarg) = expr bld lenv block arg in
              (bld', llarg :: arglist))
            (builder', []) args
        in let llargs = List.rev llargs in
        (* List of llvalues representing the hidden frees to be
          passed as arguments *)
        let llfrees =
          let rec get_free idx frees =
            if idx > numFrees then List.rev frees
            else
              let struct_freeMemPtr =
                L.build_struct_gep applyClosure idx "freePtr" builder'' in
              let struct_freeMem =
                L.build_load struct_freeMemPtr "freeVal" builder'' in
              let frees' = struct_freeMem :: frees
              in get_free (idx + 1) frees'
          in get_free 1 []
        in
        (* Get the struct member at index 0, which is the function, call it *)
        let ptrFuncPtr =
          L.build_struct_gep applyClosure 0 "function_access" builder'' in
```

```
        let funcPtr = L.build_load ptrFuncPtr "function_call" builder'' in
        let instruction = L.build_call  funcPtr
            (Array.of_list (llargs @ llfrees))
            "function_result" builder''
        in (builder'', instruction)
    | CLet (bs, body) ->
        (* create each value in bs, and bind it to the name *)
        let (builder', local_env) =
          List.fold_left
            (fun (bld, map) (name, (ty, cexp)) ->
                let loc = L.build_alloca
                            (ltype_of_type struct_table ty) name bld in
                let (bld', llcexp) = expr bld lenv block (ty, cexp) in
                let _ = L.build_store llcexp loc bld' in
                let map' = StringMap.add name loc map in
                (bld', map'))
            (builder, lenv) bs
            (* Evaulate the body *)
        in expr builder' local_env block body
    | CLambda (id, freeargs)->
      (match etyp with
         Tycon (Clo (clo_name, _, _)) ->
            (* alloc and declare a new struct object *)
            let struct_ty = StringMap.find clo_name struct_table in
            let struct_obj = L.build_alloca struct_ty "gstruct" builder in
            (* Set the function field of the closure *)
            let struct_fmem =
              L.build_struct_gep struct_obj 0 "funcField" builder in
            let (fblock, _) = StringMap.find id function_decls in
            let _ = L.build_store fblock struct_fmem builder in
            (* Set each subsequent field of the frees *)
            let (builder', llFreeArgs) =
              List.fold_left
                (fun (bld, arglist) arg ->
                    let (bld', llarg) = expr bld lenv block arg in
                    (bld', llarg :: arglist))
                (builder, []) freeargs in
            let llFreeArgs = List.rev llFreeArgs in
            let numFrees = List.length freeargs in
            let structFields =
              (* Create pointers to struct members 1 to n *)
              let rec generate_field_access idx fields =
                if idx > numFrees then List.rev fields
                else
                  let struct_freeMem =
                    L.build_struct_gep struct_obj idx "freeField" builder' in
```

```
                  let fields' = struct_freeMem :: fields in
                  generate_field_access (idx + 1) fields'
              in generate_field_access 1 []
            in
            let _ =
              let set_free arg field = L.build_store arg field builder'
              in List.map2 set_free llFreeArgs structFields
            in
            (builder', struct_obj)
      | _ -> Diagnostic.error
                (Diagnostic.GenerationError "application of lambda that is non-closure type"))
  in


  (* generate code for a particular definition; returns an llbuilder. *)
  let build_def builder = function
    | CVal (id, (ty, e)) ->
        (* assign a global define of a variable to a value *)
        let (builder', e') = expr builder StringMap.empty the_main (ty, e) in
        let _ = L.build_store e' (lookup id StringMap.empty) builder' in
        builder'
    | CExpr e ->
        let (builder', _) = expr builder StringMap.empty the_main e in
        builder'
  in

  (* procedure to generate code for each definition in main block.
     Takes a current llbuilder where to put instructions, and a
     list of definitions. Returns a builder of the last location
     to put final instruction. *)
  let rec build_main builder = function
      [] -> builder
    | front :: rest ->
        let builder' = build_def builder front in
        build_main builder' rest
  in

  let main_builder' = build_main main_builder main in
  (* Every function definition needs to end in a ret.
     Puts a return at end of main *)
  let _ = L.build_ret (L.const_int int_ty 0) main_builder' in



  (* Build function block bodies *)
  let build_function_body fdef =
```

```
    let (function_block, _) = StringMap.find fdef.fname function_decls in
    let fbuilder = L.builder_at_end context (L.entry_block function_block) in

    (* For each param, load them into the function body.
        locals : llvalue StringMap.t*)
    let locals =
      let add_formal map (ty, nm) p =
        let () = L.set_value_name nm p in
        let local = L.build_alloca
                      (ltype_of_type struct_table ty) nm fbuilder in
        let _ = L.build_store p local fbuilder in
        StringMap.add nm local map
      in
      List.fold_left2
        add_formal
        StringMap.empty
        (fdef.formals @ fdef.frees)
        (Array.to_list (L.params function_block))
    in

    (* Build the return  *)
    let (fbuilder', result) = expr fbuilder locals function_block fdef.body in

    (* Build instructions for returns based on the rettype *)
    let build_ret t =
      let rec ret_of_typ = function
          Tycon ty    -> ret_of_tycon ty
        (* | Tyvar tp     -> ret_of_tyvar tp *)
        | Conapp con  -> ret_of_conapp con
      and ret_of_tycon = function
          Intty       -> L.build_ret result
        | Boolty      -> L.build_ret result
        | Charty      -> L.build_ret result
        | Tarrow _    -> L.build_ret result
        | Clo _       -> L.build_ret result
      and ret_of_conapp (tyc, _) = ret_of_tycon tyc
      in ret_of_typ t
    in
    add_terminal fbuilder' (build_ret fdef.rettyp)
  in

  (* iterate through each function def we need to build and build it *)
  let _ = List.iter build_function_body functions in

  (* Return an llmodule *)
  the_module
```

10.16 diagnostic.ml

Author(s): Zach

```
(* exception definition and pretty printing *)
(* maybe rename module to Diagnostic *)



(* character formatting functions *)
(* uses the \027 (ESC) ANSI escape codes *)

(*let red  s = "\027[0m\027[31m" ^ s ^ "\027[0m"
  let bold s = "\027[0m\027[1"   ^ s ^ "\027[0m"*)
(*let red_bold s = "\027[0m\027[5;1;31m" ^ s ^ "\027[0m"

  let purple_bold s = "\027[0m\027[1;35m" ^ s ^ "\027[0m"*)


(* Codes and explanations taken from:
           https://stackoverflow.com/questions/4842424/list-of-ansi-color-escape-sequences
*)

(* character styling *)
let reset      = "0" (* all attributes off *)
let bold       = "1" (* bold or increased intensity *)
let faint      = "2" (* faint (decreased intensity) Not widely supported. *)
let italic     = "3" (* italic. Not widely supported. Sometimes treated as inverse.*)
let underline  = "4" (* underline text *)
let blink      = "5" (* slow Blink less than 150 per minute *)
let reverse    = "7" (* swap foreground and background colors *)

(* foreground colors *)
let fg_black   = "30"
let fg_red     = "31"
let fg_green   = "32"
let fg_yellow  = "33"
let fg_blue    = "34"
let fg_magenta = "35"
let fg_cyan    = "36"
let fg_white   = "37"

(* background colors *)
let bg_black   = "40"
let bg_red     = "41"
let bg_green   = "42"
let bg_yellow  = "43"
```

```
let bg_blue    = "44"
let bg_magenta = "45"
let bg_cyan    = "46"
let bg_white   = "47"

(* preset effects lists for particular message types *)
let error_fx   = [fg_red;bold]
let warning_fx = [fg_magenta;bold]
let note_fx    = [fg_cyan;bold;italic;underline]

let strfx fx str =
  "\027[" ^ String.concat ";" fx ^ "m" ^ str ^ "\027[0m"

(* allowing for an exception to propogate will cause that pesky phrase
 * "Fatal error: exception" to be printed; this avoids that
*)
let warning exn = try raise(exn) with _ -> prerr_endline (Printexc.to_string exn)
let error   exn = try raise(exn) with _ -> prerr_endline (Printexc.to_string exn); exit 1


exception LexingError    of string
exception ParsingError   of string
exception ParsingWarning of string

(* errors with positions, used while scanning and parsing *)
(* Courtesy of:
           https://stackoverflow.com/questions/14046392/verbose-error-with-ocamlyacc
*)
let pos_fault msg (start : Lexing.position) (finish : Lexing.position)  =
  Printf.sprintf "(line %d, col %d-%d): %s" start.pos_lnum
    (start.pos_cnum - start.pos_bol) (finish.pos_cnum - finish.pos_bol) msg

let lex_error msg lexbuf =
  LexingError ((pos_fault ("(" ^ (Lexing.lexeme lexbuf) ^ ")") (Lexing.lexeme_start_p lexbuf) (Lexing.le

let parse_error msg nterm =
  ParsingError (pos_fault msg (Parsing.rhs_start_pos nterm) (Parsing.rhs_end_pos nterm))

let parse_warning msg nterm =
  ParsingWarning (pos_fault msg (Parsing.rhs_start_pos nterm) (Parsing.rhs_end_pos nterm))
(* end courtesy of *)

exception Unimplemented of string
exception Unbound of string
exception EmptyLetBinding
exception TypeError of string
```

```
exception GenerationError of string
exception MonoError of string
exception MonoWarning of string
let () =
  Printexc.register_printer (function
      | Unimplemented   s -> Some ((strfx error_fx   "Unimplemented Error: ") ^ s)
      | Unbound         s -> Some ((strfx error_fx   "Unbound Error: "      ) ^ s)
      | TypeError       s -> Some ((strfx error_fx   "Type Error: "         ) ^ s)
      | GenerationError s -> Some ((strfx error_fx   "Generation Error: "   ) ^ s)
      | MonoError       s -> Some ((strfx error_fx   "Mono Error: "         ) ^ s)
      | MonoWarning     s -> Some ((strfx warning_fx   "Polymorphic Warning: ") ^ s)
      | ParsingWarning  s -> Some ((strfx warning_fx "Parsing Warning: "    ) ^ s)
      | LexingError     s -> Some ((strfx error_fx   "Lexing Error: "       ) ^ s)
      | ParsingError    s -> Some ((strfx error_fx   "Parsing Error: "      ) ^ s)
      | _ -> None)



(*let () = (strfx) : string list * string -> string*)
(*let () = print_string ((strfx [bg_black;fg_white;blink] " hello ") ^ "\n")*)
(*let () =
    Printexc.register_printer (function
        | Unimplemented s -> Some ("\027[1;31mUnimplemented:\027[0m " ^ s)

        | _ -> None)
*)
```