(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 Manual

3 Introduction

g(ROOT) is a general-purpose functional programming language, with a pared-down and minimalistic 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 variable redefinitions.

g(ROOT) utilizes the Hindley-Milner 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-`
- `llc-`
- `gcc-`

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

4.2 Compile and Run

Currently does not support linking, so all source code must be in the same file. gROOT 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 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.

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

;; This is another comment

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

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.

⟨*ident*⟩ ::= *letter* { *letter* | _ }

⟨*letter*⟩ ::= `!...&` | `*...:` | `<...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.

⟨*integer-literal*⟩ ::= [-] *digit* {*digit*}

⟨*digit*⟩ ::= 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.

⟨*boolean-literal*⟩ ::= # (t | f)

5.2.6 Character Literals

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

5.2.7 Operators

All of the following operators are prefix characters or prefixed characters read as single token. Binary operators are expected to be followed by two expressions, unary operators are expected to be followed by one expression.

⟨*operator*⟩ ::= (*unary-operator* | *binary-operator*)

⟨*unary-operator*⟩ ::= ! | -

⟨*binary-operator*⟩ ::= + | - | * | / | mod
| == | < | > | ≤ | ≥ | !=
| && | ||

5.3 Keywords

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

```
if      val
let     lambda
```

The following character sequence are also keywords:

```
==      +       &&      >       '
!=      -       ||      mod     #t
<=      *       !       (       #f
>=      /       <       )
```

The following tree-related keywords are still recognized, but their uses are unimplemented. Please be aware: `leaf` `elm` `tree` `cld` `sib`

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

5.6 Definitions and Expressions

⟨*def*⟩ ::= `(` `val` *ident* *expr* `)`
| *expr*

⟨*expr*⟩ ::= *literal*
| *ident*
| *unary-operator* *expr*
| `(` *binary-operator* *expr* *expr* `)`
| `(` *ident* {*expr*} `)`
| `(` `let` `(` [*ident* *expr*] {[*ident* *expr*]} `)` *expr* `)`
| `(` `if` *expr* *expr* *expr* `)`
| `(` `lambda` `(` {*arguments*} `)` *expr* `)`

⟨*literal*⟩ ::= *integer-literal* | *boolean-literal* | *character* | leaf

⟨*arguments*⟩ ::= ϵ
| *ident* :: *arguments*

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))
```

5.6.8 Unary operators

Unary operations (used for boolean or signed negation) must not be enclosed in parentheses. They are accomplished with a unary operator in front of the expression they negate.

Example:

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

!#t
!x
!(expr)
```

5.6.9 Binary operators

The general use of binary operators is as follows: (*binary-operator* $expr_1$ $expr_2$)

The **arithmetic operators** (`+` , `-` , `*` , `/` , `mod`) take two expressions that evaluate to integers.

The **comparator operators** (`==` , $<$, $>$, $\leq$, $\geq$, `!=`) take two expressions that both evaluate to either integers or booleans.

The **boolean operators** (`&&` , `||`) take two expressions that evaluate to booleans.

5.7 Functions

5.7.1 Built-In Functions

Along with the primitive operators mentioned previously, this language has three built-int print functions:

- `printi`

  Usage: `(printi 42)`

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

- `printc`

  Usage: `(printi 'c')`

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

- `printb`

  Usage: `(printi #t)`

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

5.7.2 Higher-Order Functions

User-defined functions may be passed as arguments to other functions, and may be returned from functions. Passing around built-in functions as such is not supported.

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 amongsts group members depending on interest, with frequent collaboration with project mentor and other members as the need arises 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 pass 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:

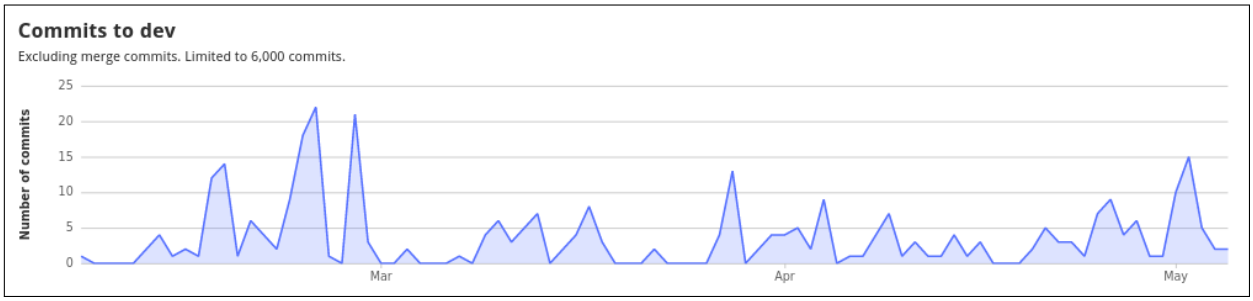
Name	Role
Eliza Encherman	Manager
Sam Russo	Tester
Zachary Goldstein	Language Guru
Nickolas Gravel	System Architect
Amy Bui	Facilitator

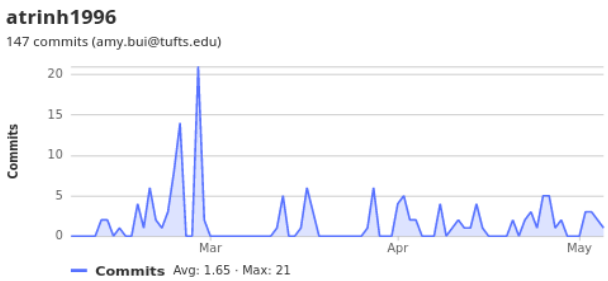
As the project progressed and implementing features of a functional language became more difficult, we abandoned these roles and each subgroup or member focused on progressively implementing different language features. Everyone was responsible intially testing their own feature and subsequent debugging, 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:

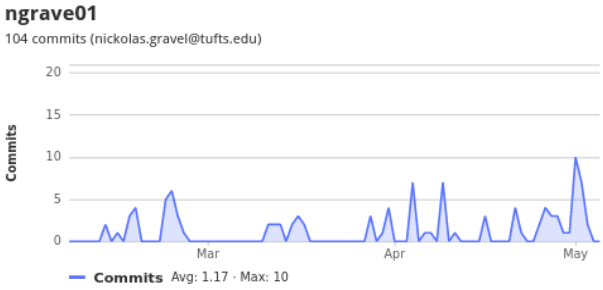
Name	Responsibilities
Eliza Encherman	Primitive recognition and testing in Scanner/Parser, Scope, Infer, Conversion, and primitive code generation
Sam Russo	Type Inferencer
Zachary Goldstein	Errors & Warnings, test suite, Docker environment
Nickolas Gravel	Type Inferencer
Amy Bui	monomorphizer, conversion I & II, codegen

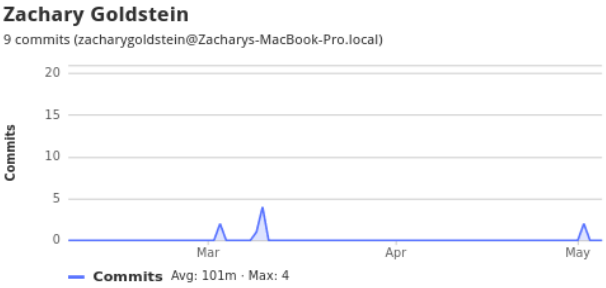
6.4 Development Tools

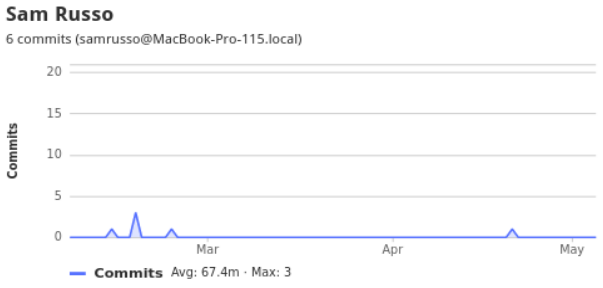
6.5 Project Logs

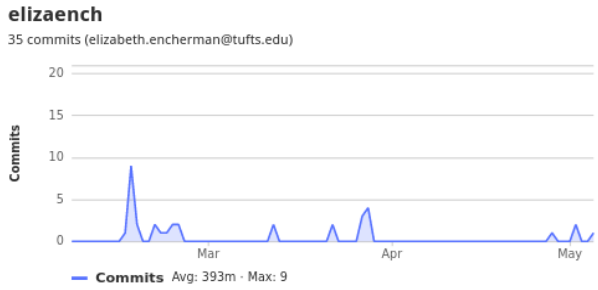




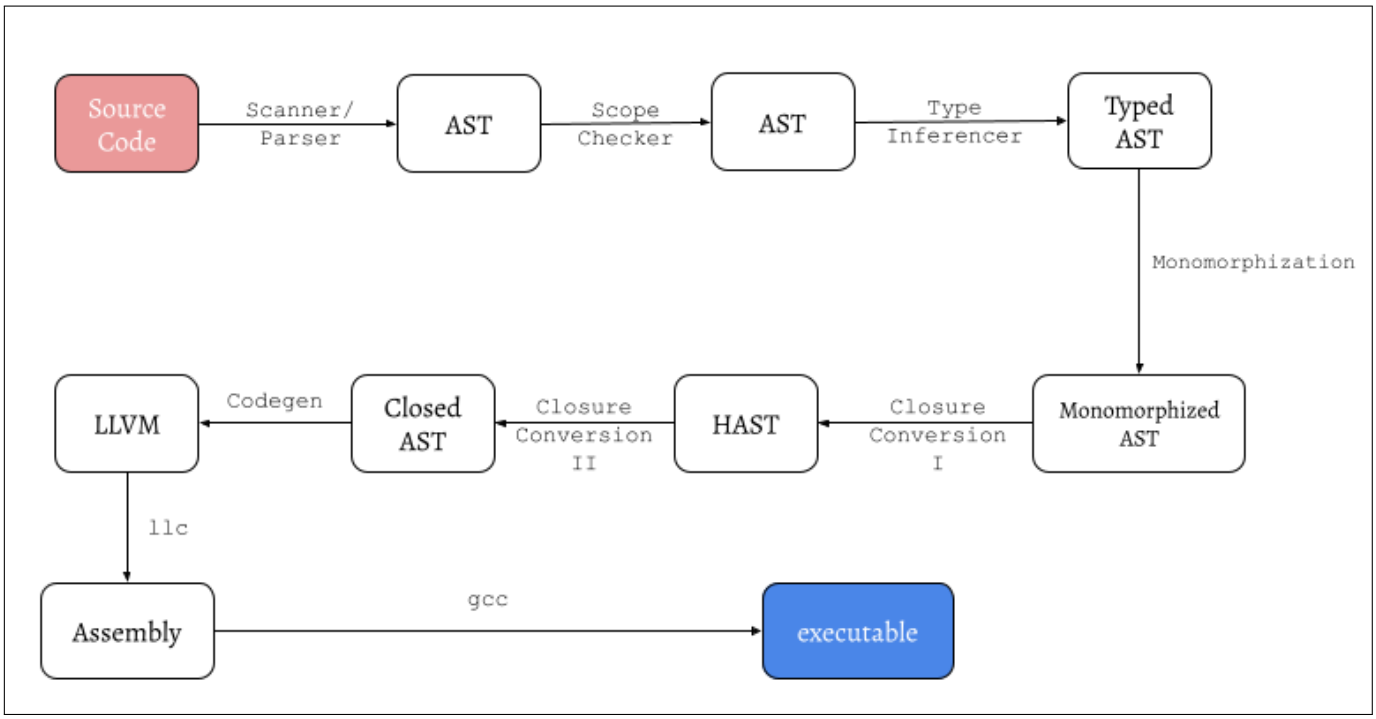








7 Architectural Design



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

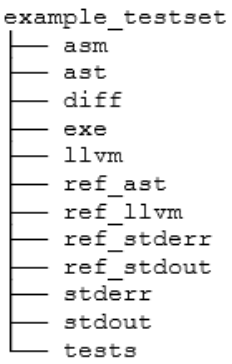
Professor Richard Townsend's testing script used in his MicroC compiler, testall.sh, was adapted to perform testing for the g(ROOT) compiler. Changes were made to add support for .gt files, and support the testing file directory tree we had decided upon, however, the general control flow and output remains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



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`

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
```

8.2 Test Samples

8.2.1 Sample 1: Closure

8.2.2 Sample 2: 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 2 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, a
  %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, i
  %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, 
  %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, 
  %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, i
  %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
}
```

```
165
166 define i32 @_anon9(i32 %x) {
167 entry:
168   %x1 = alloca i32, align 4
169   store i32 %x, i32* %x1, align 4
170   %x2 = load i32, i32* %x1, align 4
171   ret i32 %x2
172 }
173
174 define i8* @_anon6(%_anon7_struct* %func, i8* %arg) {
175 entry:
176   %func1 = alloca %_anon7_struct*, align 8
177   store %_anon7_struct* %func, %_anon7_struct** %func1, align 8
178   %arg2 = alloca i8*, align 8
179   store i8* %arg, i8** %arg2, align 8
180   %func3 = load %_anon7_struct*, %_anon7_struct** %func1, align 8
181   %arg4 = load i8*, i8** %arg2, align 8
182   %function_access = getelementptr inbounds %_anon7_struct, %_anon7_struct* %func3, i32 0, i32 0
183   %function_call = load i8* (i8*)*, i8* (i8*)** %function_access, align 8
184   %function_result = call i8* %function_call(i8* %arg4)
185   ret i8* %function_result
186 }
187
188 define i8* @_anon7(i8* %x) {
189 entry:
190   %x1 = alloca i8*, align 8
191   store i8* %x, i8** %x1, align 8
192   %x2 = load i8*, i8** %x1, align 8
193   ret i8* %x2
194 }
195
196 define i32 @_anon5(%_anon1_struct* %func, i32 %arg) {
197 entry:
198   %func1 = alloca %_anon1_struct*, align 8
199   store %_anon1_struct* %func, %_anon1_struct** %func1, align 8
200   %arg2 = alloca i32, align 4
201   store i32 %arg, i32* %arg2, align 4
202   %func3 = load %_anon1_struct*, %_anon1_struct** %func1, align 8
203   %arg4 = load i32, i32* %arg2, align 4
204   %function_access = getelementptr inbounds %_anon1_struct, %_anon1_struct* %func3, i32 0, i32 0
205   %function_call = load i32 (i32)*, i32 (i32)** %function_access, align 8
206   %function_result = call i32 %function_call(i32 %arg4)
207   ret i32 %function_result
208 }
209
210 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 *)
  | _ ->
```

```
42      let ast' = Scope.check ast in
43      match !action with
44      | Ast -> ()
45      | Name_Check -> print_string (Ast.string_of_prog ast')
46      | _ ->
47        let tast = Infer.type_infer ast' in
48        match !action with
49        | Tast -> print_string (Tast.string_of_tprog tast)
50        | _ ->
51          let mast = Mono.monomorphize tast in
52          match !action with
53          | Mast -> print_string (Mast.string_of_mprog mast)
54          | _ ->
55            let hast = Hof.clean mast in
56            match !action with
57            | Hast -> print_string (Hast.string_of_hprog hast)
58            | _ ->
59            let cast = Conversion.conversion hast in
60              match !action with
61              | Cast -> print_string (Cast.string_of_cprog cast)
62              | LLVM_IR ->
63                  print_string (Llvm.string_of_llmodule (Codegen.translate cast))
64              | Compile ->
65                  let the_module = Codegen.translate cast in
66                  Llvm_analysis.assert_valid_module the_module;
67                  print_string (Llvm.string_of_llmodule the_module)
68              | _ -> 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
```

```
90            (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
```

```
44
45  %%
46
47  prog:
48    | defn_list EOF                { $1 }
49
50  defn_list:
51    | /* nothing */                { [] }
52    | defn defn_list               { $1 :: $2 }
53
54  defn:
55    | expr                         { Expr($1) }
56    | LPAREN VAL ID expr RPAREN     { Val($3, $4) }
57
58  formals_opt:
59    | /* nothing */                { [] }
60    | formal_list                  { $1 }
61
62  formal_list:
63    | ID                           { [$1] }
64    | ID formal_list               { $1 :: $2 }
65
66
67  /* Rules */
68  value:
69    | CHAR                         { Char($1) }
70    | INT                          { Int($1) }
71    | BOOL                         { Bool($1) }
72    | tree                         { Root($1) }
73    /* ! Note: tree is not a token - no need for a ROOT token while scanning */
74
75
76  tree:
77    | LEAF                                  { Leaf }
78    | LPAREN BRANCH expr tree tree RPAREN   { Branch($3, $4, $5) }
79
80
81  let_binding_list:
82    | /* nothing */                              { [] }
83    | LSQUARE RSQUARE let_binding_list
84      { Diagnostic.warning (Diagnostic.parse_warning "empty let binding" 1); $3 }
85      /* NON FATAL */
86    | LSQUARE expr RSQUARE let_binding_list
87      { Diagnostic.error (Diagnostic.parse_error ("let binding must contain"
88        ^ " id and value") 2) } /* FATAL */
89    | LSQUARE ID expr RSQUARE let_binding_list  { ($2, $3) :: $5 }
```

```
90
91
92  expr_list:
93    | /* null */         { [] }
94    | expr expr_list     { $1 :: $2 }
95
96
97  expr:
98    | value                                                 { Literal($1) }
99    | ID                                                    { Var($1) }
100   | LPAREN expr expr_list RPAREN                          { Apply($2, $3) }
101   | LPAREN LET LPAREN let_binding_list RPAREN expr RPAREN { Let($4, $6)}
102   | LPAREN IF expr expr expr RPAREN                       { If($3, $4, $5) }
103   | 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
```

```
44          | Expr exp -> let () = checkExpr exp env in env)
45      in checkDef rest env'
46  in
47  let _ = checkDef defns nameEnv in
48
49  (* Returns the AST if no error raised *)
50  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
```

```
90
91  (* compose - applies the substitutions in theta1 to theta2 *)
92  let compose theta1 theta2 =
93    (* sub_one - takes a single substitution in theta1 and applies it to theta2 *)
94    let sub_one cn =
95      List.fold_left
96        (fun (acc : tyvar * gtype) (one_sub : tyvar * gtype) ->
97           match (acc, one_sub) with
98           | (a1, TYVAR a2), (s1, TYVAR s2) ->
99             if s1 = a1 then (s1, TYVAR a2)
100            else if s1 = a2 then (a1, TYVAR s2)
101            else acc
102          | (a1, a2), (s1, TYVAR _) -> if a1 = s1 then (s1, a2) else acc
103          | (a1, _), (s1, s2) -> if a1 = s1 then (s1, s2) else acc)
104       cn theta1
105   in
106   List.map sub_one theta2
107
108 (* solve': solves a single constraint 'c' *)
109 let rec solve' (c : gtype * gtype) =
110   match c with
111   | TYVAR t1, TYVAR t2 -> [ (t1, TYVAR t2) ]
112   | TYVAR t1, TYCON t2 -> [ (t1, TYCON t2) ]
113   | TYVAR t1, CONAPP t2 ->
114     if is_ftv t1 (CONAPP t2) then
115       Diagnostic.error (Diagnostic.TypeError "type variable is not free type in type constructor")
116     else [ (t1, CONAPP t2) ]
117   | TYCON t1, TYVAR t2 -> solve' (TYVAR t2, TYCON t1)
118   | TYCON (TArrow (TYVAR t1)), TYCON t2 -> [ (t1, TYCON t2) ]
119   | TYCON t1, TYCON (TArrow (TYVAR t2)) -> [ (t2, TYCON t1) ]
120   | TYCON t1, TYCON t2 ->
121     if t1 = t2 then []
122     else
123       Diagnostic.error (Diagnostic.TypeError
124         ("type constructor mismatch " ^ string_of_tycon t1
125          ^ " != " ^ string_of_tycon t2))
126   | TYCON t1, CONAPP t2 ->
127     Diagnostic.error (Diagnostic.TypeError
128       ("type constructor mismatch " ^ string_of_tycon t1
129       ^ " != " ^ string_of_conapp t2))
130   | CONAPP t1, TYVAR t2 -> solve' (TYVAR t2, CONAPP t1)
131   | CONAPP t1, TYCON t2 ->
132     Diagnostic.error (Diagnostic.TypeError
133       ("type constructor mismatch " ^ string_of_conapp t1
134        ^ " != " ^ string_of_tycon t2))
135   | CONAPP t1, CONAPP t2 -> (
```

```
136       match (t1, t2) with
137       | (TArrow t1, tys1), (TArrow t2, tys2) ->
138         solve ((t1, t2) :: List.combine tys1 tys2)
139       | _ ->
140         Diagnostic.error (Diagnostic.TypeError
141           ("type constructor mismatch " ^ string_of_conapp t1
142            ^ " != " ^ string_of_conapp t2)))
143
144
145 (* solve - solves a list of constraints, calls 'solver' to iterate through the
146            constraint list, once constraint list has been iterated 'compose' is
147            called to tie 'theta1' and 'theta2' together, returns theta *)
148 and solve (constraints : (gtype * gtype) list) =
149   let solver cns =
150     match cns with
151     | [] -> []
152     | cn :: cns ->
153       let theta1 = solve' cn in
154       let theta2 = solve (sub theta1 cns) in
155       (compose theta2 theta1) @ theta2
156   in solver constraints
157
158
159 (* generate_constraints gctx e:
160      infers the type of expression 'e' and a generates a set of constraints,
161      'gctx' refers to the global context 'e' can refer to.
162
163    Type References:
164         ctx : (ident * tyscheme) list == (ident * (tyvar list * gtype)) list
165    tyscheme : (tyvar list * gtype)
166       retty : gtype * (gtype * gtype) list * (gtype * tx) *)
167 let rec generate_constraints gctx e =
168   let rec constrain ctx e =
169     match e with
170     | Literal e -> value e
171     | Var name ->
172       let _, (_, tau) = List.find (fun x -> fst x = name) ctx in
173       (tau, [], (tau, TypedVar name))
174     | If (e1, e2, e3) ->
175       let t1, c1, tex1 = generate_constraints ctx e1 in
176       let t2, c2, tex2 = generate_constraints ctx e2 in
177       let t3, c3, tex3 = generate_constraints ctx e3 in
178       let c = [ (booltype, t1); (t3, t2) ] @ c1 @ c2 @ c3 in
179       let tex = TypedIf (tex1, tex2, tex3) in
180       (t3, c, (t3, tex))
181     | Apply (f, args) ->
```

```
182       let t1, c1, tex1 = generate_constraints ctx f in
183       let ts2, c2, texs2 =
184         List.fold_left
185           (fun acc e ->
186              let t, c, x = generate_constraints ctx e in
187              let ts, cs, xs = acc in
188              (t :: ts, c @ cs, x :: xs))
189           ([], c1, []) (List.rev args)
190       in
191       (* reverse args to maintain arg order *)
192       let retType = fresh () in
193       ( retType,
194         (t1, Tast.functiontype retType ts2) :: c2,
195         (retType, TypedApply (tex1, texs2)) )
196     | Let (bindings, expr) ->
197       let l = List.map (fun (_, e) -> generate_constraints ctx e) bindings in
198       let cns = List.concat (List.map (fun (_, c, _) -> c) l) in
199       let taus = List.map (fun (t, _, _) -> t) l in
200       let asts = List.map (fun (_, _, a) -> a) l in
201       let names = List.map fst bindings in
202       let ctx_addition =
203         List.map (fun (n, t) -> (n, ([], t))) (List.combine names taus)
204       in
205       let new_ctx = ctx_addition @ ctx in
206       let b_tau, b_cns, b_tast = generate_constraints new_ctx expr in
207       (b_tau, b_cns @ cns, (b_tau, TypedLet (List.combine names asts, b_tast)))
208     | Lambda (formals, body) ->
209       let binding = List.map (fun x -> (x, ([], fresh ()))) formals in
210       let new_context = binding @ ctx in
211       let t, c, tex = generate_constraints new_context body in
212       let _, tyschms = List.split binding in
213       let _, formaltys = List.split tyschms in
214       let typedFormals = List.combine formaltys formals in
215       ( Tast.functiontype t formaltys,
216         c,
217         (Tast.functiontype t formaltys, TypedLambda (typedFormals, tex)) )
218   and value v =
219     match v with
220     | Int  e -> (inttype, [],  (inttype,  TLiteral (TInt e)))
221     | Char e -> (chartype, [], (chartype, TLiteral (TChar e)))
222     | Bool e -> (booltype, [], (booltype, TLiteral (TBool e)))
223     | Root t -> tree t
224   and tree t =
225     match t with
226     | Leaf     -> Diagnostic.error (Diagnostic.Unimplemented "contraint generation for Leaf")
227     | Branch _ -> Diagnostic.error (Diagnostic.Unimplemented "contraint generation for Branch")
```

```
228   in
229   constrain gctx e
230
231
232 (* get_constraints - returns a list of Tasts
233         Tast : [ (ident * (gtype * tx)) ] = [ (ident * texpr) | texpr ] = [ tdefns ]
234     tyscheme : (tyvar list * gtype) *)
235 let get_constraints (ctx : (ident * tyscheme) list) (d : defn) =
236   match d with
237   | Val (name, e) ->
238     let t, c, tex = generate_constraints ctx e in
239     (t, c, TVal (name, tex))
240   | Expr e ->
241     let (t, c, tex) = generate_constraints ctx e in
242     (t, c, TExpr tex)
243
244
245 (*  input: (tyvar * gtype) list *)
246 (*  retty: tdefn -> tdefn *)
247 let apply_subs (sub : (tyvar * gtype) list) =
248   match sub with
249   | [] -> (fun x -> x)
250   | xs ->
251     let final_ans =
252       (fun tdef ->
253          (* xs - the list of substitutions we want to apply *)
254          (* tdef - the tdefn we want to apply the substitutions to *)
255          let rec expr_only_case (x : texpr) =
256            List.fold_left
257              (* anon fun - takes one texpr and takes one substitution and subs substitution into the tex
258              (fun (tast_gt, tast_tx) (tv, gt) ->
259                 (* updated_tast_tx - matches texpr with tx and recurses on expressions *)
260                 let updated_tast_tx = match tast_tx with
261                   | TypedIf (x, y, z) ->
262                       TypedIf (expr_only_case x, expr_only_case y, expr_only_case z)
263                   | TypedApply (x, xs) ->
264                     let txs = List.map expr_only_case xs in
265                     TypedApply (expr_only_case x, txs)
266                   | TypedLet ((its), x) -> TypedLet (List.map (fun (x, y) ->
267                     (x, expr_only_case y)) its, expr_only_case x)
268                   | TypedLambda (tyformals, body) ->
269                     TypedLambda ((List.map (fun (x, y) -> (tysubst (tv, gt) x, y))
270                                     tyformals), expr_only_case body)
271                   | TLiteral x -> TLiteral x
272                   | TypedVar x -> TypedVar x
273                 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
```

```
44
45
46  type polyty_env = mexpr StringMap.t
47
48  type mprog = mdefn list
49
50
51
52  (* Pretty printer *)
53
54  (* String of mtypes *)
55  let rec string_of_mtype = function
56    | Mtycon ty -> string_of_mtycon ty
57    | Mconapp con -> string_of_mconapp con
58    | Mtyvar i -> "'" ^ string_of_int i
59  and string_of_mtycon = function
60    | MIntty -> "int"
61    | MBoolty -> "bool"
62    | MCharty -> "char"
63    | MTarrow (retty) -> string_of_mtype retty
64  and string_of_mconapp (tyc, tys) =
65    string_of_mtycon tyc ^ " ("
66    ^ String.concat " " (List.map string_of_mtype tys) ^ ")"
67
68
69  (* String of a typed expression (mexpr) == (type, m-expression) *)
70  let rec string_of_mexpr (typ, exp) =
71    "[" ^ string_of_mtype typ ^ "] " ^ string_of_mx exp
72  and string_of_mx = function
73    | MLiteral v -> string_of_mvalue v
74    | MVar id -> id
75    | MIf (e1, e2, e3) ->
76      "(if "  ^ string_of_mexpr e1 ^ " "
77      ^ string_of_mexpr e2 ^ " "
78      ^ string_of_mexpr e3 ^ ")"
79    | MApply (f, args) ->
80      "(" ^ string_of_mexpr f ^ " "
81      ^ String.concat " " (List.map string_of_mexpr args) ^ ")"
82    | MLet (binds, body) ->
83      let string_of_binding (id, e) =
84        "[" ^ id ^ " " ^ (string_of_mexpr e) ^ "]"
85      in
86      "(let ("  ^ String.concat " " (List.map string_of_binding binds) ^ ") "
87      ^ string_of_mexpr body ^ ")"
88    | MLambda (formals, body) ->
89      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


```

```
44
45  (* Takes a type environment and a string key "id". Returns the
46       value (mtype) that the key mapts to. *)
47  let lookup (id : mname) (gamma : polyty_env) =
48    StringMap.find id gamma
49  in
50
51
52  (* Takes a name and an polyty_env, and inserts it into the map *)
53  let set_aside (id : mname) ((ty, exp) : mexpr) (gamma : polyty_env) =
54    StringMap.add id (ty, exp) gamma
55  in
56
57
58  (* Returns true if ty is a type variable *)
59  let isTyvar (ty : mtype) = match ty with
60      Mtycon _  -> false
61    | Mtyvar _  -> true
62    | Mconapp _ -> false
63  in
64
65  (* Returns true if ty is a function type *)
66  let isFunctionType (ty : mtype) = match ty with
67      Mconapp (MTarrow _, _)  -> true
68    | _                       -> false
69  in
70
71
72  (* (fty, exp) == poly lambda expression
73     (ty) == mono function type *)
74  let resolve (prog : mprog) (id : mname) (ty : mtype) ((fty, exp) : mexpr) =
75    (* Given a function type, returns the list of the types of the arguments *)
76    let get_type_of_args = function
77        Mconapp (MTarrow _, formaltys) -> formaltys
78      | _ -> Diagnostic.error
79             (Diagnostic.MonoError "cannot monomorphize non-function type")
80    in
81
82    let formaltys     = get_type_of_args ty  in (* mono *)
83    let polyargtys    = get_type_of_args fty in (* poly *)
84    let substitutions = List.combine polyargtys formaltys in
85
86    (* Given a (polymorphic) mtype, returns the monomorphic version *)
87    let resolve_mty (mty : mtype) =
88      let apply_subs typ (arg, sub) =
89        if isTyvar arg
```

```
90          then
91            let tyvarID =
92              (match arg with
93                 Mtyvar i -> i
94               | _ -> Diagnostic.error
95                        (Diagnostic.MonoError "non-tyvar substitution"))
96            in
97            let rec search_mtype = function
98                Mtycon tyc -> Mtycon (search_tycon tyc)
99              | Mtyvar i   -> if i = tyvarID then sub else Mtyvar i
100             | Mconapp con -> Mconapp (search_con con)
101           and search_tycon = function
102               MIntty  -> MIntty
103             | MCharty -> MCharty
104             | MBoolty -> MBoolty
105             | MTarrow retty -> MTarrow (search_mtype retty)
106           and search_con (tyc, mtys) =
107             (search_tycon tyc, List.map search_mtype mtys)
108           in search_mtype typ
109       else typ
110     in List.fold_left apply_subs mty substitutions
111   in
112
113   (* Given an (polymorphic) mx, returns the monomorphic version, with an
114      updated program, if any. *)
115   let rec resolve_mx pro = function
116       MLiteral l -> (MLiteral l, pro)
117     | MVar     v -> (MVar v, pro)
118     | MIf ((t1, e1), (t2, e2), (t3, e3)) ->
119         let t1' = resolve_mty t1 in
120         let t2' = resolve_mty t2 in
121         let t3' = resolve_mty t3 in
122         let (e1', pro1) = resolve_mx pro  e1 in
123         let (e2', pro2) = resolve_mx pro1 e2 in
124         let (e3', pro3) = resolve_mx pro2 e3 in
125         (MIf ((t1', e1'), (t2', e2'), (t3', e3')), pro3)
126     | MApply ((appty, app), args) ->
127         (* resolve the expression thats applied *)
128         let appty' = resolve_mty appty in
129         let (app', pro') = resolve_mx pro app in
130         (* resolve the arguments of the application *)
131         let (argtys, argexps) = List.split args in
132         let argtys' = List.map resolve_mty argtys in
133         let (argexps', pro'') = resolve_listOf_mx pro' argexps in
134         let args' = List.combine argtys' argexps' in
135         (MApply ((appty', app'), args'), pro'')
```

```
136       | MLet (bs, body) ->
137           let (names, bexprs) = List.split bs in
138           let (btys, bmxs) = List.split bexprs in
139           let btys' = List.map resolve_mty btys in
140           let (bmxs', pro') = resolve_listOf_mx pro bmxs in
141           let bs' = List.combine names (List.combine btys' bmxs') in
142           let (body', pro'') = resolve_mexpr pro' body in
143           (MLet (bs', body'), pro'')
144       | MLambda  (formals, body) ->
145           let (formaltys, names) = List.split formals in
146           let formaltys' = List.map resolve_mty formaltys in
147           let formals' = List.combine formaltys' names in
148           let (body', pro') = resolve_mexpr pro body in
149           let lambdaExp = MLambda (formals', body') in
150           let pro'' = (MVal (id, (ty, lambdaExp))) :: pro' in
151           (lambdaExp, pro'')
152     and resolve_mexpr pro ((ty, mexp) : mexpr) =
153         let ty' = resolve_mty ty in
154         let (mexp', pro') = resolve_mx pro mexp in
155         let monoexp' = (ty', mexp') in
156         (monoexp', pro')
157     and resolve_listOf_mx pro (mxs : mx list) =
158         let (mx', pro') =
159           List.fold_left
160             (fun (mexlist, prog) mex ->
161                 let (mex', prog') = resolve_mx prog mex in
162                 (mex' :: mexlist, prog'))
163             ([], pro) mxs
164         in
165         let mx' = List.rev mx' in
166         (mx', pro')
167     in
168
169     let (exp', prog') = resolve_mx prog exp in
170     ((ty, exp'), prog')
171
172   in
173
174
175
176
177   (* Takes a texpr and returns the equivalent mexpr
178      and the prog (list of mdefns) *)
179   let rec expr (gamma : polyty_env) (prog : mprog) ((ty, ex) : texpr) =
180     match ex with
181       TLiteral l -> ((ofGtype ty, MLiteral (value l)), prog)
```

```
182     | TypedVar v ->
183         (* let () = print_endline ("looking for: " ^ v) in  *)
184         let vartyp = (try fst (lookup v gamma)
185                       with Not_found ->
186                           (* let () = print_endline "didn't find it" in  *)
187                           ofGtype ty) in
188         let actualtyp = ofGtype ty in
189         if (isPolymorphic vartyp) && (isFunctionType vartyp)
190           then
191             let polyexp = lookup v gamma in
192             let (_, prog') = resolve prog v actualtyp polyexp in
193             ((actualtyp, MVar v), prog')
194         else
195           ((actualtyp, MVar v), prog)
196     | TypedIf  (t1, t2, t3) ->
197         let (mexp1, prog1) = expr gamma prog t1 in
198         let (mexp2, prog2) = expr gamma prog1 t2 in
199         let (mexp3, prog3) = expr gamma prog2 t3 in
200         ((fst mexp3, MIf (mexp1, mexp2, mexp3)), prog3)
201     | TypedApply (f, args) ->
202         let (f', prog') = expr gamma prog f in
203         let (args', prog'') =
204           List.fold_left
205             (fun (arglst, pro) arg ->
206               let (arg', pro') = expr gamma pro arg in
207               (arg' :: arglst, pro'))
208             ([], prog') args
209         in
210         let args' = List.rev args' in
211         ((ofGtype ty, MApply (f', args')), prog'')
212     | TypedLet (bs, body) ->
213         let binding (x, e) =  let (e', _) = expr gamma prog e in (x, e') in
214         let bs' = List.map binding bs in
215         let (body', prog') = expr gamma prog body in
216         ((ofGtype ty, MLet (bs', body')), prog')
217     | TypedLambda (formals, body) ->
218         let (formaltys, names) = List.split formals in
219         let formaltys' = List.map ofGtype formaltys in
220         let formals'   = List.combine formaltys' names in
221         let gamma' = List.fold_left
222                        (fun env (ty, name) ->
223                         if isPolymorphic ty
224                            then set_aside name (ty, MVar name) env
225                         else env)
226                        gamma
227                        formals' in
```

```
228         let (body', prog') = expr gamma' prog body in
229         ((ofGtype ty, MLambda (formals', body')), prog')
230   and value = function
231     | TChar c -> MChar c
232     | TInt  i -> MInt i
233     | TBool b -> MBool b
234     | TRoot t -> MRoot (tree t)
235   and tree = function
236     | TLeaf               -> MLeaf
237     | TBranch (v, t1, t2) -> MBranch (value v, tree t1, tree t2)
238   in
239
240
241   (* Takes the current mprog built so far, and one tdefn, and adds
242      the monomorphized version to the mprog. Returns a new mprog
243      with the new definition added in.  *)
244   let mono ((gamma, prog) : polyty_env * mprog) = function
245       TVal (id, (ty, texp)) ->
246         let ((mty, mexp), prog') = expr gamma prog (ty, texp) in
247         if isPolymorphic mty
248           then
249             let gamma' = set_aside id (mty, mexp) gamma in
250             (gamma', MVal (id, (mty, mexp)) :: prog')
251         else (gamma, MVal (id, (mty, mexp)) :: prog')
252     | TExpr (ty, texp) ->
253         let ((mty, mexp), prog') = expr gamma prog (ty, texp) in
254         let () = if isPolymorphic mty then
255           Diagnostic.warning
256             (Diagnostic.MonoWarning ("polymorphic type leftover;"
257                                      ^ " resolving to integers"))
258         else ()
259         in (gamma, MExpr (mty, mexp) :: prog')
260
261         (* if isPolymorphic mty
262           then (gamma, prog')
263         else (gamma, MExpr (mty, mexp) :: prog') *)
264   in
265
266   let (_, program) = List.fold_left mono (StringMap.empty, []) tdefns in
267
268
269
270
271   (* Bug/Bandaid - unable to resolve polymorphism.
272      Iterate through the current "mono" typed program.
273      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
```

```
320
321     (* Resolve the given mdefn *)
322     match def with
323     | MVal (id, ex) -> MVal  (id, resolve_expr ex) :: prog
324     | MExpr ex      -> MExpr (resolve_expr ex) :: prog
325   in
326
327   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 *)
```

```
136 let string_of_hprog hdefns =
137   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
```

```
44
45  (* Returns true if the given name id is already bound in the given
46     StringMap env. False otherwise *)
47  let isBound id env = StringMap.mem id env
48
49  (* Returns the first element of th value that "id" is bound to in the given
50     StringMap env. If the binding doesn't exist, Not_Found exception
51     is raised. *)
52  let find id env =
53    let occursList = StringMap.find id env in List.nth occursList 0
54
55  (* Adds a binding of k to v in the global StringMap env *)
56  let bindGamma k v = res.gamma <-
57    let currList =  if isBound k res.gamma
58                    then StringMap.find k res.gamma else [] in
59    let newList = v :: currList in
60    StringMap.add k newList res.gamma
61
62  let addHofs id lambda = res.hofs <- StringMap.add id lambda res.hofs
63
64  (* Adds a local binding of k to v in the given StringMap env *)
65  let bindLocal map k v =
66    let currList = if isBound k map then StringMap.find k map else [] in
67    let localList = (0, v) :: currList in
68    StringMap.add k localList map
69
70  (* Given a h-closure type, returns the closure's id *)
71  let getClosureId (cls : htype) = match cls with
72      HTycon (HCls (id, _, _, _)) -> id
73    | _ -> Diagnostic.error
74           (Diagnostic.TypeError ("Nonclosure-type accessed when"
75                                  ^ " trying to get closure ID"))
76
77
78  (* Converts a mtype to a htype *)
79  let rec ofMtype = function
80      Mtycon ty    -> HTycon (ofTycon ty)
81    | Mtyvar _     -> Diagnostic.error
82                        (Diagnostic.TypeError ("unresolved polymorphic type"))
83    | Mconapp con  -> HConapp (ofConapp con)
84  and ofTycon = function
85      MIntty         -> HIntty
86    | MBoolty        -> HBoolty
87    | MCharty        -> HCharty
88    | MTarrow retty -> HTarrow (ofMtype retty)
89  and ofConapp (tyc, tys) = (ofTycon tyc, List.map ofMtype tys)
```

```
90
91
92
93
94  (* Returns true if given htype is a function type *)
95  let rec isFunctionType = function
96      HTycon t  -> hof_tycon t
97    | HConapp t -> hof_conapp t
98  and hof_tycon = function
99      HIntty | HCharty | HBoolty -> false
100   | HTarrow _ -> true
101   | HCls (_, retty, argsty, _) ->
102       isFunctionType retty
103       || (List.fold_left
104             (fun init argty -> init || (isFunctionType argty))
105             false argsty)
106 and hof_conapp (tyc, tys) =
107       hof_tycon tyc
108       || (List.fold_left
109             (fun init typ -> init || (isFunctionType typ))
110             false tys)
111
112 (* Returns true if the given htype indicates a higher order function *)
113 let isHOF = function
114     HTycon (HCls (_, retty, argsty, _)) ->
115       isFunctionType retty
116       || (List.fold_left
117             (fun init argty -> init || (isFunctionType argty))
118             false argsty)
119   | _ -> false
120
121
122
123 (* Given expression an a string name n, returns true if n is
124    a free variable in the expression *)
125 let freeIn exp n =
126   let rec free (_, e) = match e with
127     | MLiteral _        -> false
128     | MVar s            -> s = n
129     | MIf (m1, m2, m3)  -> free m1 || free m2 || free m3
130     | MApply (f, args)  -> free f  || List.fold_left
131                              (fun a b -> a || free b)
132                              false args
133     | MLet (bs, body) -> List.fold_left (fun a (_, e) -> a || free e) false bs
134                          || (free body && not (List.fold_left
135                                                (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 =
```

```
182           (match fst f' with
183             HTycon (HCls (_, ret, _, _)) -> ret
184           | _ -> intTy)
185         in (retty, HApply (f', args'))
186     | HLet (bs, body) ->
187         let bs' = List.map (fun (name, exp) -> (name, h_expr env exp)) bs in
188         let local_env = List.fold_left (fun map (name, (ty, _)) ->
189                                           bindLocal map name ty)
190                                        env bs' in
191         let body' = h_expr local_env body in
192         (fst body, HLet (bs', body'))
193     | HLambda (formals, body) ->
194         let local_env = List.fold_left (fun map (ty, name) ->
195                                           bindLocal map name ty)
196                                        env formals in
197         let body' = h_expr local_env body in
198         (fst body, HLambda (formals, body'))
199   in
200
201   (* Given a mexpr, returns the equivalent hexpr *)
202   let rec expr (env : ty_env) (mexp : mexpr) =
203     let rec expr' (ty, exp) = match exp with
204         MLiteral l -> (ofMtype ty, HLiteral (value l))
205       | MVar v -> let (_, typ) = find v env in (typ, HVar v)
206       | MIf (e1, e2, e3) ->
207           let e1' = expr' e1 in
208           let e2' = expr' e2 in
209           let e3' = expr' e3 in
210           (fst e2', HIf (e1', e2', e3'))
211       | MApply (f, args) ->
212           let (fty, f') = expr' f in
213           let args' = List.map expr' args in
214           if isHOF fty
215             then let (retty, fty') = resolveHOF env fty args' in
216                  (retty, HApply ((fty', f'), args'))
217           else (ofMtype ty, HApply ((fty, f'), args'))
218       | MLet (bs, body) ->
219           let bs' = List.map (fun (name, e) -> (name, expr' e)) bs in
220           let local_env = List.fold_left (fun map (name, (typ, _)) ->
221                                             bindLocal map name typ)
222                                          env bs' in
223           let body' = expr local_env body in
224           (fst body', HLet (bs', body'))
225       | MLambda (formals, body) ->
226           (* name the closure *)
227           let id = anon ^ string_of_int !count in
```

```
228           let () = count := !count + 1 in
229
230           (* Put the formals in the environment *)
231           let (formaltys, formalnames) = List.split formals in
232           let formaltys' = List.map ofMtype formaltys in
233           let formals' = List.combine formaltys' formalnames in
234           let local_env = List.fold_left (fun map (typ, name) ->
235                                             bindLocal map name typ)
236                                          env formals' in
237           let body' = expr local_env body in
238           let retty = fst body' in
239           let freetys = freeTypesOf (formals, body) env in
240
241           (* Create new closure type *)
242           let closureType =
243                   partialClosurety (id, retty, formaltys', freetys) in
244           (closureType, HLambda (formals', body'))
245       and value = function
246         | MChar c -> HChar c
247         | MInt  i -> HInt  i
248         | MBool b -> HBool b
249         | MRoot t -> HRoot (tree t)
250       and tree = function
251         | MLeaf -> HLeaf
252         | MBranch (v, t1, t2) -> HBranch (value v, tree t1, tree t2)
253       and resolveHOF (env : ty_env) (closuretype : htype)
254                      (arguments : hexpr list) =
255           (* Extract argument actual types, and name of closure
256              being referenced *)
257           let (argtypes, _) = List.split arguments in
258           let cloName = getClosureId closuretype in
259           let (id, (_, lambdaexp)) = StringMap.find cloName res.hofs in
260           (* Function returns the subexpressions of a lambda expression *)
261           let get_lambda_subxs = function
262               HLambda (formals, body) -> (formals, body)
263             | _ -> Diagnostic.error
264                    (Diagnostic.TypeError ("Nonclosure-type accessed when"
265                      ^ " tryong to get lambda subexpressions"))
266           in
267           (* Function replaces return types and argument types of a closure
268              type with the new given types passed in. *)
269           let resolve_cls_ty retty argtys = function
270               HTycon (HCls (id, _, _, freetys)) ->
271                    HTycon (HCls (id, retty, argtys, freetys))
272             | _ -> Diagnostic.error
273                    (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
```

```
136   | CChar c -> String.make 1 c
137   | CInt  i -> string_of_int i
138   | CBool b -> if b then "#t" else "#f"
139   | CRoot t -> string_of_ctree t
140 and string_of_ctree = function
141   | CLeaf -> "leaf"
142   | CBranch (v, sib, child) ->
143     "(tree " ^ string_of_cvalue v ^ " "
144     ^ string_of_ctree sib ^ " "
145     ^ string_of_ctree child ^ ")"
146
147 (* stingifies a cdefn *)
148 let string_of_cdefn = function
149   | CVal (id, e) -> "(val " ^ id ^ " " ^ string_of_cexpr e ^ ")"
150   | CExpr (cexp) -> string_of_cexpr cexp
151
152 let string_of_main main =
153   String.concat "\n" (List.map string_of_cdefn main) ^ "\n"
154
155 (* stringifies a ist of fdefs *)
156 let string_of_functions (funcs : fdef list) =
157   let string_of_fdef ret_string {
158       rettyp = return;
159       fname = fname;
160       formals = formals;
161       frees = frees;
162       body = body;
163     } =
164     let string_of_formal  (ty, para) = string_of_ctype ty ^ " " ^ para in
165     let args = formals @ frees in
166     let def = string_of_ctype return ^ " " ^ fname ^ " ("
167               ^ String.concat ", " (List.map string_of_formal args)
168               ^ ")\n{\n"
169               ^ string_of_cexpr body  ^ "\n}\n"
170     in ret_string ^ def ^ "\n"
171   in List.fold_left string_of_fdef "" funcs
172
173 (* stringifies the variable lookup table *)
174 let string_of_rho rho =
175   StringMap.fold (fun id occursList s ->
176       let (num, ty) = List.nth occursList 0 in
177       s ^ id ^ ": " ^ string_of_ctype ty
178       ^ " " ^ id ^ string_of_int num
179       ^ "\n"
180         )
181     rho ""
```

```
182
183 (* Returns string of the list of closure/struct types *)
184 let string_of_structures structss =
185   let string_of_struct tyc = "struct " ^ string_of_ctype tyc
186   in String.concat "\n" (List.map string_of_struct structss)
187
188
189 (* Returns string of a cprog *)
190 let string_of_cprog { main = main; functions = functions;
191                       rho = rho;   structures = structures } =
192   "Main:\n" ^
193   string_of_main main ^ "\n\n" ^
194   "Functions:\n" ^
195   string_of_functions functions ^ "\n\n" ^
196   "Rho:\n" ^
197   string_of_rho rho ^ "\n\n" ^
198   "Structures:\n" ^
199   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, 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 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
```

```
90    let localList = (0, ty) :: currList in
91    StringMap.add k localList map
92
93  (* Given expression an a string name n, returns true if n is
94     a free variable in the expression *)
95  let freeIn exp n =
96    let rec free (_, e) = match e with
97      | HLiteral _        -> false
98      | HVar s            -> s = n
99      | HIf (s1, s2, s3)  -> free s1 || free s2 || free s3
100     | HApply (f, args)  -> free f  || List.fold_left
101                              (fun a b -> a || free b)
102                              false args
103     | HLet (bs, body) -> List.fold_left (fun a (_, e) -> a || free e) false bs
104                          || (free body && not (List.fold_left
105                                                  (fun a (x, _) -> a || x = n)
106                                                  false bs))
107     | HLambda (formals, body) ->
108       let (_, names) = List.split formals in
109       free body && not (List.fold_left (fun a x -> a || x = n) false names)
110   in free (intTy, exp)
111
112
113 (* Given the formals list and body of a lambda (xs, e), and a
114    variable environment, the function returns an environment with only
115    the free variables of this lambda. The environment of frees shall
116    not inculde the names of built-in functions and primitives *)
117 let improve (xs, e) rho =
118   StringMap.filter
119     (fun n _ ->
120        if List.mem n ignores
121        then false
122        else freeIn (HLambda (xs, e)) n)
123     rho
124
125
126 (* Given a var_env, returns a (ctype  * name) list version *)
127 let toParamList (venv : var_env) =
128   StringMap.fold
129     (fun id occursList res ->
130       let (num, ty) = List.nth occursList 0 in
131       let id' = if num = 0 then id
132         else "_" ^ id ^ "_" ^ string_of_int num in
133       (ty, id') :: res)
134     venv []
135
```

```
136 (* turns a list of ty * name list to a Var list  *)
137 let convertToVars (frees : (ctype * cname) list) =
138   List.map (fun (t, n) -> (t, CVar n)) frees
139
140
141
142 (* Generate a new function type for lambda expressions in order to account
143    for free variables, when given the original function type and an
144    association list of gtypes and var names to add to the new formals list
145    of the function type. *)
146 let newFuntype  (origTyp : htype) (newRet : ctype)
147     (toAdd : (ctype * cname) list) =
148   (match origTyp with
149      HTycon (HCls (_, _, argsty, _)) ->
150      let newFormalTys = List.map ofHtype argsty in
151      let (newFreeTys, _) = List.split toAdd in
152      funty (newRet, newFormalTys @ newFreeTys)
153    | _ -> raise (Failure "Non-function function type"))
154
155
156
157 (* Converts given sexpr to cexpr, and returns the cexpr *)
158 let rec hexprToCexpr (env : var_env) (e : hexpr)  =
159   let rec expr ((typ, ex) : hexpr) = match ex with
160     | HLiteral v -> (ofHtype typ, CLiteral (value v))
161     | HVar s     ->
162         (* In case s is a name of a define, get the closure type *)
163         let (occurs, ctyp) = find s env in
164         (* to match the renaming convention in svalToCval, and to ignore
165            built in prints *)
166         let vname = if occurs = 0
167                     then s
168                   else "_" ^ s ^ "_" ^ string_of_int occurs
169         in (ctyp, CVar (vname))
170     | HIf (e1, e2, e3) ->
171         let e1' = expr e1
172         and e2' = expr e2
173         and e3' = expr e3 in
174         (fst e2', CIf (e1', e2', e3'))
175     | HApply (f, args) ->
176         let (ctyp, f') = expr f in
177         let normalargs = List.map expr args in
178         (* actual type of the function application is the type of the return*)
179         let (retty, freesCount) =
180           (match ctyp with
181              Tycon (Clo (_, functy, freetys)) ->
```

```
182              (match functy with
183                 Conapp (Tarrow ret, _) -> (ret, List.length freetys)
184               | _ -> raise (Failure "Non-function function type"))
185             | _ -> (intty, 0)) in
186         (retty, CApply ((ctyp, f'), normalargs, freesCount))
187     | HLet (bs, body) ->
188         let bs' = List.map (fun (name, hex) -> (name, expr hex)) bs in
189         let local_env =
190             List.fold_left (fun map (name, (ty, _)) ->
191                                 bindLocal map name ty)
192                            env bs' in
193         let (ctyp, body') = hexprToCexpr local_env body  in
194         (ctyp, CLet (bs', (ctyp, body')))
195     (* Supose we hit a lambda expression, turn it into a closure *)
196     | HLambda (formals, body) -> create_anon_function formals body typ env
197   and value = function
198     | HChar c             -> CChar c
199     | HInt  i             -> CInt  i
200     | HBool b             -> CBool b
201     | HRoot t             -> CRoot (tree t)
202   and tree = function
203     | HLeaf               -> CLeaf
204     | HBranch (v, t1, t2) -> CBranch (value v, tree t1, tree t2)
205   in expr e
206 (* When given just a lambda expresion withot a user defined identity/name
207    this function will generate a name and give the function a body --
208    Lambda lifting. *)
209 and create_anon_function  (fformals : (htype * hname) list) (fbody : hexpr)
210                           (closurety : htype) (env : var_env) =
211
212
213   let fformals' = List.map (fun (hty, x) -> (ofHtype hty, x)) fformals in
214   let local_env = List.fold_left
215                     (fun map (formtyp, name) ->
216                       bindLocal map name formtyp)
217                     env fformals' in
218   let func_body = hexprToCexpr local_env fbody in
219   let rettype = fst func_body in
220   let freeformals = toParamList (improve (fformals, fbody) env) in
221
222   (* All anonymous functions are named the same and numbered. *)
223   (* Given a h-closure type, returns the closure's id *)
224   let getClsID (cls : htype) = match cls with
225       HTycon (HCls (id, _, _, _)) -> id
226     | _ -> Diagnostic.error
227            (Diagnostic.TypeError ("Conversion: Nonclosure-type accessed"
```

```
228                                   ^ " when trying to get closure ID"))
229   in
230   let id = getClsID closurety in
231
232   (* Create the record that represents the function body and definition *)
233   let func_def =
234     {
235       body    = func_body;
236       rettyp  = rettype;
237       fname   = id;
238       formals = fformals';
239       frees   = freeformals;
240     }
241   in
242   let () = addFunction func_def in
243
244   (* New function type will include the types of free arguments *)
245   let anonFunTy = newFuntype closurety rettype freeformals in
246   (* Record the type of the anonymous function and its "rea" ftype *)
247   let () = bind id (1, anonFunTy) in
248   (* The value of a Lambda expression is a Closure -- new type construction
249      will help create the structs in codegen that represents the closure *)
250   let (freetys, _) = List.split freeformals in
251   let clo_ty = closuretype (id ^ "_struct", anonFunTy, freetys) in
252   let () = addClosure clo_ty in
253   let freeVars = convertToVars freeformals in
254   (clo_ty, CLambda (id, freeVars))
255
256
257
258 (* Converts given SVal to CVal, and returns the CVal *)
259 let hvalToCval (id, (ty, e)) =
260   (* check if id was already defined in rho, in order to get
261      the actual frequency the variable name was defined.
262      The (0, inttype is a placeholder) *)
263   let (occurs, _) = if (isBound id res.rho)
264                     then (find id res.rho)
265                   else (0, intty) in
266   (* Modify the name to account for the redefinitions, and so old closures
267      can access original variable values *)
268   let id' = "_" ^ id ^ "_" ^ string_of_int (occurs + 1) in
269   let (ty', cexp) = hexprToCexpr res.rho (ty, e) in
270   (* bind original name to the number of occurrances and the variable's type *)
271   let () = bind id (occurs + 1, ty') in
272   (* Return the possibly new CVal definition *)
273   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
```

```
90              (Diagnostic.GenerationError "declaration of lambda that is non-closure type")
91    in
92    let structs = List.rev structures in
93    let rec declare_structs clsTyList result =
94      match clsTyList with
95        [] -> result
96      | front :: rest ->
97          (try
98              let result' = gen_struct_def result front in
99              declare_structs rest result'
100          with Not_found ->
101             let rest' = rest @ [front] in
102             declare_structs rest' result)
103   in declare_structs structs StringMap.empty
104 in
105
106
107 (* Lookup table of function names (lambdas) to
108    (function block, function def) *)
109 let function_decls : (L.llvalue * fdef) StringMap.t =
110   let define_func map def =
111     let name = def.fname
112     and formal_types =
113       Array.of_list (List.map (fun (t, _) -> ltype_of_type struct_table t)
114                       (def.formals @ def.frees))
115     in
116     let ftype = L.function_type
117                   (ltype_of_type struct_table def.rettyp)
118                   formal_types
119     in StringMap.add name (L.define_function name ftype the_module, def) map
120   in List.fold_left define_func StringMap.empty functions
121 in
122
123
124 (* creates a global pointer to some variable's value *)
125 let create_global id ty =
126   let lltyp = ltype_of_type struct_table ty in
127   let rec const_typ = function
128       Tycon ty    -> const_tycon ty
129     (* | Tyvar tp    -> const_tyvar tp *)
130     | Conapp con  -> const_conapp con
131   and const_tycon = function
132       Intty           -> L.const_int  lltyp 0
133     | Boolty          -> L.const_int  lltyp 0
134     | Charty          -> L.const_pointer_null  lltyp
135     | Tarrow _        -> L.const_pointer_null lltyp
```

```
136       | Clo _             -> L.const_pointer_null lltyp
137     and const_conapp (_, _) = L.const_pointer_null lltyp
138     in
139     let init = const_typ ty in
140     L.define_global id init the_module
141   in
142
143   (* A lookup table of named globals to represent named values *)
144   let globals : L.llvalue StringMap.t =
145     let global_vars k occursList map =
146       let glo_var map' (num, typ) =
147         if num = 0
148         then map'
149         else  let id = "_" ^ k ^ "_" ^ string_of_int num in
150           StringMap.add id (create_global id typ) map'
151       in List.fold_left glo_var map occursList
152     in
153     StringMap.fold global_vars rho StringMap.empty
154   in
155
156
157   (* Looks for variable named id in the local or global environment *)
158   let lookup id locals =
159     try StringMap.find id locals
160     with Not_found -> StringMap.find id globals
161   in
162
163   (* Add terminal instruction to a block *)
164   let add_terminal builder instr =
165     match L.block_terminator (L.insertion_block builder) with
166       Some _ -> ()
167     | None -> ignore (instr builder) in
168
169
170   (* Construct constants code for literal values.
171      Function takes a builder and Sast.svalue, and returns the constructed
172      llvalue  *)
173   let const_val builder = function
174     (* create the "string" constant in the code for the char *)
175       CChar c ->
176         let spc = L.build_alloca char_ptr_ty "spc" builder in
177         let globalChar =
178           L.build_global_string (String.make 1 c) "globalChar" builder in
179         let newStr = L.build_bitcast globalChar char_ptr_ty "newStr" builder in
180         let loc = L.build_gep spc [| zero |] "loc" builder in
181         let _ = L.build_store newStr loc builder in
```

```
182         L.build_load spc "character_ptr" builder
183     | CInt  i -> L.const_int int_ty i
184     (* HAS to be an i1 lltype for the br instructions *)
185     | CBool b -> L.const_int bool_ty (if b then 1 else 0)
186     | CRoot _ -> Diagnostic.error
187                  (Diagnostic.Unimplemented "codegen SRoot Literal")
188
189   in
190
191
192
193   (* Construct code for expressions
194      Arguments: llbuilder, lookup table of local variables,
195      current llblock, and Cast.cexpr.
196      Constructs the llvm where builder is located;
197      Returns an llbuilder and the llvalue representation of code. *)
198   let rec expr builder lenv block (etyp, e) =
199     match e with
200       CLiteral v   -> (builder, const_val builder v)
201     | CVar     s  ->
202         let varValue =
203           (try L.build_load (lookup s lenv) s builder
204            with Not_found -> Diagnostic.error
205                              (Diagnostic.Unbound ("name \"" ^ s
206                                ^ "\" not found in codegen")))
207         in (builder, varValue)
208     | CIf (e1, (t2, e2), e3) ->
209         (* allocate space for result of the if statement *)
210         let result =
211           L.build_alloca (ltype_of_type struct_table t2) "if-res-ptr" builder
212         in
213
214         (* set aside the result of the condition expr *)
215         let (newbuilder, bool_val) = expr builder lenv block e1 in
216
217         (* Create the merge block for after exec of then or the else block *)
218         let merge_bb = L.append_block context "merge" block in
219         let branch_instr = L.build_br merge_bb in
220
221         (* Create the "then" block *)
222         let then_bb = L.append_block context "then" block in
223         let (then_builder, then_res) =
224           expr (L.builder_at_end context then_bb) lenv block (t2, e2) in
225         let _ = L.build_store then_res result then_builder in
226         let () = add_terminal then_builder branch_instr in
227
```

```
228         (* Create the "else" block *)
229         let else_bb = L.append_block context "else" block in
230         let (else_builder, else_res) =
231           expr (L.builder_at_end context else_bb) lenv block e3 in
232         let _ = L.build_store else_res result else_builder in
233         let () = add_terminal else_builder branch_instr in
234 
235         (* Complete the if-then-else block, return should be llvalue *)
236         (* let _ = L.build_cond_br bool_val then_bb else_bb builder in *)
237         let _ = L.build_cond_br bool_val then_bb else_bb newbuilder in
238         (* Get the result of either the the or the else block *)
239         let merge_builder = L.builder_at_end context merge_bb in
240         let result_value = L.build_load result "if-res-val" merge_builder in
241         (merge_builder, result_value)
242     | CApply ((_, CVar "printi"), [arg], _) ->
243         let (builder', argument) = expr builder lenv block arg in
244         let instruction = L.build_call  printf_func
245             [| int_format_str ; argument |]
246             "printi" builder'
247         in (builder', instruction)
248     | CApply ((_, CVar "printc"), [arg], _) ->
249         let (builder', argument) = expr builder lenv block arg in
250         let instruction = L.build_call  puts_func
251             [| argument |]
252             "printc" builder'
253         in (builder', instruction)
254     | CApply ((_, CVar "printb"), [arg], _) ->
255         let (builder', condition) = expr builder lenv block arg in
256         let bool_stringptr =
257           if condition = lltrue then print_true
258           else print_false in
259         let instruction = L.build_call  puts_func
260             [| bool_stringptr |]
261             "printb" builder'
262         in (builder', instruction)
263     | CApply ((_, CVar "~"), [arg], _) ->
264         let (builder', e) = expr builder lenv block arg in
265         let instruction = L.build_neg e "~" builder'
266         in (builder', instruction)
267     | CApply ((_, CVar "not"), [arg], _) ->
268         let (builder', e) = expr builder lenv block arg in
269         let instruction = L.build_not e "not" builder'
270         in (builder', instruction)
271     (* BINOP PRIMITIVES - Int and Boolean Algebra *)
272     | CApply ((_, CVar "+"), arg1::[arg2], _) ->
273         let (builder', e1) = expr builder lenv block arg1 in
```

```
274         let (builder'', e2) = expr builder' lenv block arg2 in
275         let instruction = L.build_add e1 e2 "addition" builder''
276         in (builder'', instruction)
277     | CApply ((_, CVar "-"), arg1::[arg2], _) ->
278         let (builder', e1) = expr builder lenv block arg1 in
279         let (builder'', e2) = expr builder' lenv block arg2 in
280         let instruction = L.build_sub e1 e2 "subtraction" builder''
281         in (builder'', instruction)
282     | CApply ((_, CVar "/"), arg1::[arg2], _) ->
283         let (builder', e1) = expr builder lenv block arg1 in
284         let (builder'', e2) = expr builder' lenv block arg2 in
285         let instruction = L.build_sdiv e1 e2 "division" builder''
286         in (builder'', instruction)
287     | CApply ((_, CVar "*"), arg1::[arg2], _) ->
288         let (builder', e1) = expr builder lenv block arg1 in
289         let (builder'', e2) = expr builder' lenv block arg2 in
290         let instruction = L.build_mul e1 e2 "multiply" builder''
291         in (builder'', instruction)
292     | CApply ((_, CVar "mod"), arg1::[arg2], _) ->
293         let (builder', e1) = expr builder lenv block arg1 in
294         let (builder'', e2) = expr builder' lenv block arg2 in
295         let instruction = L.build_srem e1 e2 "modulus" builder''
296         in (builder'', instruction)
297     | CApply ((_, CVar "&&"), arg1::[arg2], _) ->
298         let (builder', e1) = expr builder lenv block arg1 in
299         let (builder'', e2) = expr builder' lenv block arg2 in
300         let instruction = L.build_and e1 e2 "logAND" builder''
301         in (builder'', instruction)
302     | CApply ((_, CVar "||"), arg1::[arg2], _) ->
303         let (builder', e1) = expr builder lenv block arg1 in
304         let (builder'', e2) = expr builder' lenv block arg2 in
305         let instruction = L.build_or e1 e2 "logOR" builder''
306         in (builder'', instruction)
307     (* BINOP PRIMITIVES - Comparisons *)
308     | CApply ((_, CVar "<"), arg1::[arg2], _) ->
309         let (builder', e1) = expr builder lenv block arg1 in
310         let (builder'', e2) = expr builder' lenv block arg2 in
311         let instruction = L.build_icmp L.Icmp.Slt e1 e2 "lt" builder''
312         in (builder'', instruction)
313     | CApply ((_, CVar ">"), arg1::[arg2], _) ->
314         let (builder', e1) = expr builder lenv block arg1 in
315         let (builder'', e2) = expr builder' lenv block arg2 in
316         let instruction = L.build_icmp L.Icmp.Sgt e1 e2 "gt" builder''
317         in (builder'', instruction)
318     | CApply ((_, CVar "<="), arg1::[arg2], _) ->
319         let (builder', e1) = expr builder lenv block arg1 in
```

```
320         let (builder'', e2) = expr builder' lenv block arg2 in
321         let instruction = L.build_icmp L.Icmp.Sle e1 e2 "leq" builder''
322         in (builder'', instruction)
323     | CApply ((_, CVar ">="), arg1::[arg2], _) ->
324         let (builder', e1) = expr builder lenv block arg1 in
325         let (builder'', e2) = expr builder' lenv block arg2 in
326         let instruction = L.build_icmp L.Icmp.Sge e1 e2 "geq" builder''
327         in (builder'', instruction)
328     | CApply ((_, CVar "=i"), arg1::[arg2], _) ->
329         let (builder', e1) = expr builder lenv block arg1 in
330         let (builder'', e2) = expr builder' lenv block arg2 in
331         let instruction = L.build_icmp L.Icmp.Eq e1 e2 "eqI" builder''
332         in (builder'', instruction)
333     | CApply ((_, CVar "!=i"), arg1::[arg2], _) ->
334         let (builder', e1) = expr builder lenv block arg1 in
335         let (builder'', e2) = expr builder' lenv block arg2 in
336         let instruction = L.build_icmp L.Icmp.Ne e1 e2 "neqI" builder''
337         in (builder'', instruction)
338     | CApply (f, args, numFrees) ->
339         (* Since all normal function application is as struct value,
340           call to the function at member index 0 of the struct *)
341         let (builder', applyClosure) = expr builder lenv block f in
342         (* List of llvalues representing the actual arguments *)
343         let (builder'', llargs) =
344           List.fold_left  (fun (bld, arglist) arg ->
345               let (bld', llarg) = expr bld lenv block arg in
346               (bld', llarg :: arglist))
347             (builder', []) args
348         in let llargs = List.rev llargs in
349         (* List of llvalues representing the hidden frees to be
350           passed as arguments *)
351         let llfrees =
352           let rec get_free idx frees =
353             if idx > numFrees then List.rev frees
354             else
355               let struct_freeMemPtr =
356                 L.build_struct_gep applyClosure idx "freePtr" builder'' in
357               let struct_freeMem =
358                 L.build_load struct_freeMemPtr "freeVal" builder'' in
359               let frees' = struct_freeMem :: frees
360               in get_free (idx + 1) frees'
361           in get_free 1 []
362         in
363         (* Get the struct member at index 0, which is the function, call it *)
364         let ptrFuncPtr =
365           L.build_struct_gep applyClosure 0 "function_access" builder'' in
```

```
366         let funcPtr = L.build_load ptrFuncPtr "function_call" builder'' in
367         let instruction = L.build_call  funcPtr
368             (Array.of_list (llargs @ llfrees))
369             "function_result" builder''
370         in (builder'', instruction)
371     | CLet (bs, body) ->
372         (* create each value in bs, and bind it to the name *)
373         let (builder', local_env) =
374           List.fold_left
375             (fun (bld, map) (name, (ty, cexp)) ->
376                 let loc = L.build_alloca
377                             (ltype_of_type struct_table ty) name bld in
378                 let (bld', llcexp) = expr bld lenv block (ty, cexp) in
379                 let _ = L.build_store llcexp loc bld' in
380                 let map' = StringMap.add name loc map in
381                 (bld', map'))
382             (builder, lenv) bs
383             (* Evaulate the body *)
384         in expr builder' local_env block body
385     | CLambda (id, freeargs)->
386       (match etyp with
387          Tycon (Clo (clo_name, _, _)) ->
388             (* alloc and declare a new struct object *)
389             let struct_ty = StringMap.find clo_name struct_table in
390             let struct_obj = L.build_alloca struct_ty "gstruct" builder in
391             (* Set the function field of the closure *)
392             let struct_fmem =
393               L.build_struct_gep struct_obj 0 "funcField" builder in
394             let (fblock, _) = StringMap.find id function_decls in
395             let _ = L.build_store fblock struct_fmem builder in
396             (* Set each subsequent field of the frees *)
397             let (builder', llFreeArgs) =
398               List.fold_left
399                 (fun (bld, arglist) arg ->
400                     let (bld', llarg) = expr bld lenv block arg in
401                     (bld', llarg :: arglist))
402                 (builder, []) freeargs in
403             let llFreeArgs = List.rev llFreeArgs in
404             let numFrees = List.length freeargs in
405             let structFields =
406               (* Create pointers to struct members 1 to n *)
407               let rec generate_field_access idx fields =
408                 if idx > numFrees then List.rev fields
409                 else
410                   let struct_freeMem =
411                     L.build_struct_gep struct_obj idx "freeField" builder' in
```

```
412                 let fields' = struct_freeMem :: fields in
413                 generate_field_access (idx + 1) fields'
414             in generate_field_access 1 []
415           in
416           let _ =
417             let set_free arg field = L.build_store arg field builder'
418             in List.map2 set_free llFreeArgs structFields
419           in
420           (builder', struct_obj)
421       | _ -> Diagnostic.error
422                (Diagnostic.GenerationError "application of lambda that is non-closure type"))
423   in
424
425
426   (* generate code for a particular definition; returns an llbuilder. *)
427   let build_def builder = function
428     | CVal (id, (ty, e)) ->
429         (* assign a global define of a variable to a value *)
430         let (builder', e') = expr builder StringMap.empty the_main (ty, e) in
431         let _ = L.build_store e' (lookup id StringMap.empty) builder' in
432         builder'
433     | CExpr e ->
434         let (builder', _) = expr builder StringMap.empty the_main e in
435         builder'
436   in
437
438   (* procedure to generate code for each definition in main block.
439      Takes a current llbuilder where to put instructions, and a
440      list of definitions. Returns a builder of the last location
441      to put final instruction. *)
442   let rec build_main builder = function
443       [] -> builder
444     | front :: rest ->
445         let builder' = build_def builder front in
446         build_main builder' rest
447   in
448
449   let main_builder' = build_main main_builder main in
450   (* Every function definition needs to end in a ret.
451      Puts a return at end of main *)
452   let _ = L.build_ret (L.const_int int_ty 0) main_builder' in
453
454
455
456   (* Build function block bodies *)
457   let build_function_body fdef =
```

```
458     let (function_block, _) = StringMap.find fdef.fname function_decls in
459     let fbuilder = L.builder_at_end context (L.entry_block function_block) in
460
461     (* For each param, load them into the function body.
462         locals : llvalue StringMap.t*)
463     let locals =
464       let add_formal map (ty, nm) p =
465         let () = L.set_value_name nm p in
466         let local = L.build_alloca
467                       (ltype_of_type struct_table ty) nm fbuilder in
468         let _ = L.build_store p local fbuilder in
469         StringMap.add nm local map
470       in
471       List.fold_left2
472         add_formal
473         StringMap.empty
474         (fdef.formals @ fdef.frees)
475         (Array.to_list (L.params function_block))
476     in
477
478     (* Build the return  *)
479     let (fbuilder', result) = expr fbuilder locals function_block fdef.body in
480
481     (* Build instructions for returns based on the rettype *)
482     let build_ret t =
483       let rec ret_of_typ = function
484           Tycon ty    -> ret_of_tycon ty
485         (* | Tyvar tp    -> ret_of_tyvar tp *)
486         | Conapp con  -> ret_of_conapp con
487       and ret_of_tycon = function
488           Intty       -> L.build_ret result
489         | Boolty      -> L.build_ret result
490         | Charty      -> L.build_ret result
491         | Tarrow _    -> L.build_ret result
492         | Clo _       -> L.build_ret result
493       and ret_of_conapp (tyc, _) = ret_of_tycon tyc
494       in ret_of_typ t
495     in
496     add_terminal fbuilder' (build_ret fdef.rettyp)
497   in
498
499   (* iterate through each function def we need to build and build it *)
500   let _ = List.iter build_function_body functions in
501
502   (* Return an llmodule *)
503   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"
```

```
44  let bg_blue    = "44"
45  let bg_magenta = "45"
46  let bg_cyan    = "46"
47  let bg_white   = "47"
48
49  (* preset effects lists for particular message types *)
50  let error_fx   = [fg_red;bold]
51  let warning_fx = [fg_magenta;bold]
52  let note_fx    = [fg_cyan;bold;italic;underline]
53
54  let strfx fx str =
55    "\027[" ^ String.concat ";" fx ^ "m" ^ str ^ "\027[0m"
56
57  (* allowing for an exception to propogate will cause that pesky phrase
58   * "Fatal error: exception" to be printed; this avoids that
59  *)
60  let warning exn = try raise(exn) with _ -> prerr_endline (Printexc.to_string exn)
61  let error   exn = try raise(exn) with _ -> prerr_endline (Printexc.to_string exn); exit 1
62
63
64  exception LexingError    of string
65  exception ParsingError   of string
66  exception ParsingWarning of string
67
68  (* errors with positions, used while scanning and parsing *)
69  (* Courtesy of:
70             https://stackoverflow.com/questions/14046392/verbose-error-with-ocamlyacc
71  *)
72  let pos_fault msg (start : Lexing.position) (finish : Lexing.position)  =
73    Printf.sprintf "(line %d, col %d-%d): %s" start.pos_lnum
74      (start.pos_cnum - start.pos_bol) (finish.pos_cnum - finish.pos_bol) msg
75
76  let lex_error msg lexbuf =
77    LexingError ((pos_fault ("(" ^ (Lexing.lexeme lexbuf) ^ ")") (Lexing.lexeme_start_p lexbuf) (Lexing.le
78
79  let parse_error msg nterm =
80    ParsingError (pos_fault msg (Parsing.rhs_start_pos nterm) (Parsing.rhs_end_pos nterm))
81
82  let parse_warning msg nterm =
83    ParsingWarning (pos_fault msg (Parsing.rhs_start_pos nterm) (Parsing.rhs_end_pos nterm))
84  (* end courtesy of *)
85
86  exception Unimplemented of string
87  exception Unbound of string
88  exception EmptyLetBinding
89  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)
*)
```