(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.

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

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 `;)`. Nested comments are currently not allowed. Multiline comments are allowed.

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

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

5.2.3 Identifiers

Identifiers are sequences of letters, digits, and ASCII characters, starting with a letter. Letters consist of the 26 lowercase and 26 uppercase characters from the ASCII set. Identifiers may not start with an underscore character, and may not be any of the reserved character sequences.

⟨*ident*⟩	::=	*letter* (*letter* | *digit* | _)
⟨*letter*⟩	::=	`a...z` | `A...Z`
⟨*digit*⟩	::=	`0...9`

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
leaf    elm         tree
cld     sib         lambda
```

The following character sequence are also keywords:

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

5.3.1 Syntax

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

5.4.5 N-Ary Tree Compound Type

A core feature of (g)ROOT is its n-ary tree compound value type. Every tree value consists of three components: an element, it's right-immediate sibling, and it's first child. This allows for the convenient implementation of robust recursive algorithms with an arbitrary branching factor.

Every tree value in (g)ROOT may be either a full tree instance with an element, sibling, and child, or a leaf. The leaf value in (g)ROOT represents the nullary, or empty, tree.

The tree type in (g)ROOT is modeled after a left-child right-sibling binary tree, where each node contains a reference to its first child and reference to its next sibling. This allows each node in (g)ROOT to have any number of children, while constraining the maximum number of fields per tree instance to three (element, sibling, and child).

The tree type is very similar in usage to the one-dimensional list type present in many other functional languages, but enforces two additional invariants that empower programmers to shoot themselves in their foot less often.

1. The element of a tree instance may not be itself a tree. An element may be a value of any other type. This enforces a consistent structure among all trees that could be created in (g)ROOT.

   Note: it is possible to circumvent this requirement by wrapping a tree instance in a no-args lambda closure. This is a reasonable means of achieving nested data structures as it prevents the accidental creation of nested values; programmers who wrap tree instances in lambda closures likely did so with intention.

2. Every tree node must have a single immediate sibling and a single immediate child. This forces programmers to think in a purely recursive manner about their solutions.

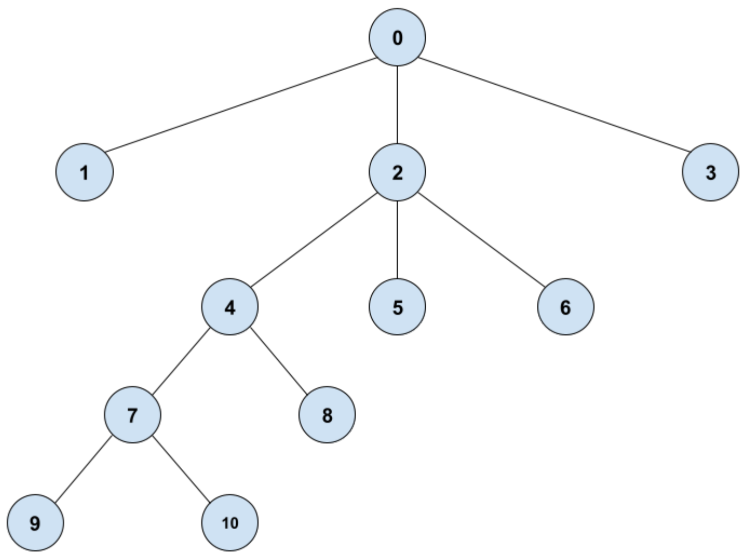
   Trees may be conveniently constructed in-place using the following construction syntax:

```
'(value sibling-tree child-tree)
```

   For example:

```
'(0 leaf (1 (2 (3 leaf leaf) (4 (5 (6 (leaf leaf)) leaf))) (7 (8 leaf leaf)
    (9 (10 leaf leaf) leaf))))
```

   represents the following tree (as drawn in normal binary tree form):



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 withing 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 the function `ID` followed by a list of zero or more expressions, which are its arguments. The arguments are not separated from the ID by parentheses. (g)ROOT has first-class functions, therefore functions can be passed as arguments. Currying is allowed.

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 not allowed.

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

Note: Throughout this section, the character pair `tr` is used as shorthand to represent a tree value, an identifier bound to a tree value.

There are four built-in functions which are integral to the tree data type. It is a checked-runtime error to call `elm, sib, cld` on a `leaf`:

1. `elm`

   Usage: `(elm tr)`

   Purpose: returns the element of the provided tree value `(tr)`

2. `sib`

   Usage: `(sib tr)`

   Purpose: returns the sibling tree of the provided tree value `(tr)`

3. `cld`

   Usage: `(cld tr)`

   Purpose: returns the child tree of the provided tree value `(tr)`

4. `leaf?`

   Usage: `(leaf?  tr)`

   Purpose: Returns boolean val `#t` iff `tr` is a leaf.

5. `tree`

   Usage: `(tree ELEMENT SIBLING CHILD)`

   Purpose: constructs a tree value containing the value ELEMENT, with sibling SIBLING and child CHILD

5.7.2 Standard Library Functions

Note: Throughout this section, the character pair `tr` is used as shorthand to represent a tree value, an identifier bound to a tree value.

The first set of functions introduced in the standard library allow for programmers to use some of their beloved list functions present in other languages:

1. `(cons a b)`

   Creates a 1-ary tree approximating the functionality of single-dimensional list in other functional languages. `a` is any value not a tree, `b` may be `leaf` or `nil`.

2. `(car tr)`

   Extracts the first value in the pair.

3. `(cdr tr)`

   Extracts the second value in the pair.

4. `(null? tr)`

   A predicate function that evaluates to true iff the pseudo-list is empty.

5. `(val nil leaf)`

   A value `nil` that mirrors the built-in keyword leaf.

6. `(append xs ys)`

   Append the list of elements in `ys` to the end of `xs`.

7. `(revapp xs ys)`

   Append the list of elements in `ys` to the reverse of `xs`.

Now some useful tree functions!

1. `(graft oak fir)`

   Appends a sibling tree `fir` to some other tree `oak`. The result of calling this function is a new tree in which `fir` is the rightmost sibling of `oak`. This function is extremely useful when re-shaping trees.

2. `(level-flatten tr)`

   Flattens the provided tree to a 1-ary tree, arranging elements in level-order.

3. `(pre-flatten tr)`

   Flattens the provided tree to a 1-ary tree, arranging elements in pre-order.

4. `(post-flatten tr)`

   Flattens the provided tree to a 1-ary tree, arranging elements in post-order.

5. `(map f tr)` Maps a function `f` over every element of the provided tree `tr`.

6. `(filter p? tr)`

   Constructs a new tree containing only elements that satisfy the predicate function `p?`, which must return a boolean value.

7. `(level-fold fn base tr)`

   Folds a tree, visiting each element in a level-order traversal. Note that the accumulation function `fn` must take TWO arguments, the first of which is the current element, and second is the rest of the tree.

8. `(pre-fold fn base tr)`

   Folds a tree, visiting each element in a pre-order traversal. Note that the accumulation function `fn` must take TWO arguments, the first of which is the current element, and second is the rest of the tree.

9. `(post-fold fn base tr)`

   Folds a tree, visiting each element in a post-order traversal. Note that the accumulation function `fn` must take TWO arguments, the first of which is the current element, and second is the rest of the tree.

10. `(fold fn base tr)`

    Folds a tree, in a more intuitively tree-like manner. Note that the accumulation function `fn` must take THREE arguments: the value of the current node, the sibling accumulator, and the child.accumulator.

11. `(node-count tr)`

    Evaluates to the number of nodes in the provided tree.

12. `(height tr)`

    Evaluates to the height of the provided tree.

Higher-Order Functions:

1. `(curry f)`

   Allows for the partial application of a two-argument function.

2. `(uncurry f)`

   Uncurries a previously curried function such that both of its arguments must be provided at the same time.

3. `(o f g)`

   Given two single-argument functions, returns a single function which is the composition of `f` and `g`.

4. `(flip f)`

   Given a two argument function, reverses the order in which the arguments are evaluated and passed to the function.

5. `(flurry f)`

   Given a two argument function, reverses the order in which the arguments are evaluated and passed to the function, and allows for the partial application of that function. This function both flips and curries `f` (hence the fun name).

5.8 LRM Appendix

```
(; We can define standard list functions with our tree data type! Fun! ;)

(define (cons a b) (tree a leaf (tree b leaf leaf)))
(define (car  tr) (elm tr))
(define (cdr  tr) (cld tr))
(define (nil    ) leaf)
(define (null? tr) (leaf? tree))

(; a list function! ;)
(define append (xs ys)
    (if (null? xs)
        ys
        (cons (car xs) (append (cdr xs) ys))
    )
)

(; another list function! ;)
(define revapp (xs ys) ; (reverse xs) followed by ys
    (if (null? xs)
        ys
        (revapp (cdr xs) (cons (car xs) ys))
    )
)

(; appends a sibling tree (fir) to tree (oak) ;)
(define (graft oak fir)
    (if (leaf? oak)
        fir
        (tree (elm oak) (graft (sib oak) fir) (cld oak))
    )
)

(; attempt 4
   this function flattens a tree, level-order ;)
(define (level-flatten tr)
    (if (leaf? tr)
        leaf
        (tree
            (elm tr)
            leaf
            (level-flatten (graft (sib tr) (cld tr)))
        )
    )
)
```

flattening functions!

```
(; this function flattens a tree, pre-order ;)
```

```
(define (pre-flatten tr)
    (if (leaf? tr)
        leaf
        (tree
            (elm tr)
            leaf
            (pre-flatten (graft (cld tr) (sib tr)))
        )
    )
)


(; this function flattens a tree, post-order ;)
(define (post-flatten tr)
    (if (leaf? tr)
        leaf
        (if (leaf? (cld tr))
            (tree
                (elm tr)
                leaf
                (post-flatten (sib tr)))
            (post-flatten (graft
                                (graft
                                    (cld tr)
                                    (tree (elm tr) leaf leaf))
                                (sib tr))
            )
        )
    )
)
```

Let's create some higher order functions! Yay!

```
(define (curry f)   (lambda (x)  (lambda (y) (f x y))))
(define (uncurry f) (lambda (x y) ((f x) y)))
(define (o     f g) (lambda (x) (f (g x))))
(define (flip  f)   (lambda (x)  (lambda (y) (f y x))))
```

function: (flurry func)

- precondition:

  func is a function that takes exactly two args

- evalutation:

  evaluates to a curried form of func, where:

  1. the first value passed to the curried function is treated as the second argument to (func).
  2. the second value passed to the curried function is treated as the first argument

to (func).

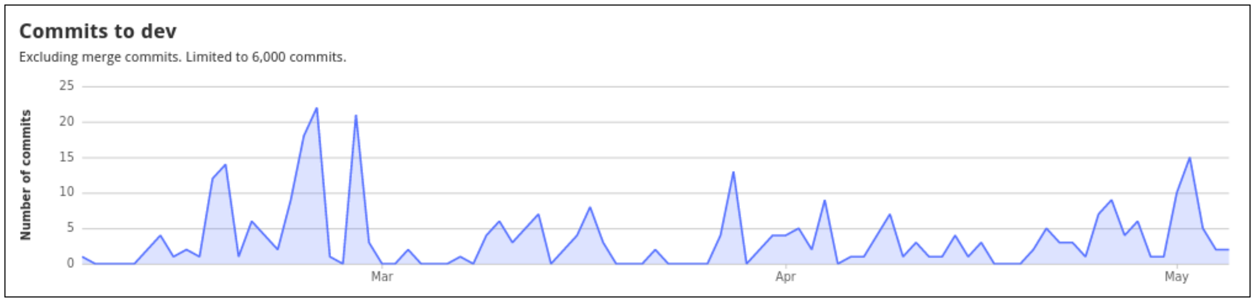
- note: flurry is a contraction of "flip & curry", and we're very proud of the wordplay there.

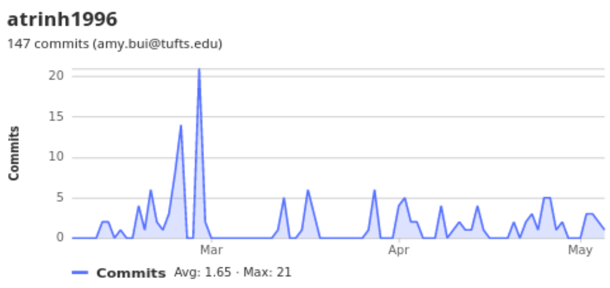
```
(define flurry (func)
    (curry (lambda (a b) (func b a)))
)



(; mapping function! ;)
(define (map f tr)
    (if (leaf? tr)
        leaf
        (tree
            (f (elm tr))
            (map f (sib tr))
            (map f (cld tr))
        )
    )
)



(; filter function! ;)
(define filter (p? tr)
    (if (leaf? tr)
        leaf
        (if (p? (elm tr))
            (tree (elm tr) (filter p? (sib tr)) (filter p? (cld tr)))
            (filter p? (graft (cld tr) (sib tr)))
        )
    )
)





(; folding functions! ;)

(; attempt 4
   this function folds a tree, level-order ;)
(define (level-fold fn base tr)
    (if (leaf? tr)
        base
        (fn
            (elm tr)
            (level-fold (graft (sib tr) (cld tr)))
        )
    )
)
```

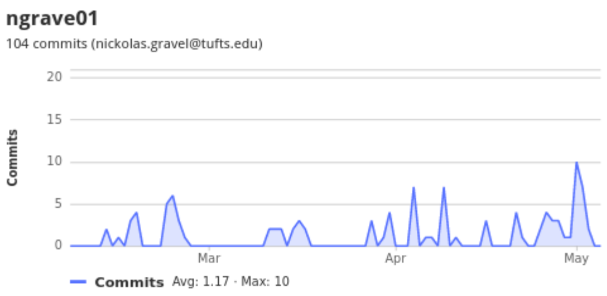
```
(; this function folds a tree, pre-order ;)
(define (pre-fold fn base tr)
    (if (leaf? tr)
        base
        (fn
            (elm tr)
            (pre-fold (graft (cld tr) (sib tr)))
        )
    )
)

(; this function folds a tree, post-order ;)
(define (post-fold fn base tr)
    (if (leaf? tr)
        base
        (if (leaf? (cld tr))
            (fn (elm tr) (post-fold (sib tr)))
            (post-fold (graft
                            (graft (cld tr) (tree (elm tr) leaf leaf))
                                (sib tr)
                        )
            )
        )
    )
)

(; once we implement first-class functions, we
   should find that the behaviors of these three
   functions are exactly equivalent to their
   lower-class cousins ;)
(define (level-fold-flatten tr) (level-fold cons nil tr))
(define (pre-fold-flatten tr) (pre-fold cons nil tr))
(define (post-fold-flatten tr) (post-fold cons nil tr))

(; this function folds a tree, in a more intuitively
   tree-like manner
   fn must take in three params:
   - the current value
   - the sibling accumulator
   - the child accumulator ;)
(define (fold fn base tr)
    (if (leaf? tr)
        base
        (fn
            (elm tr)
            (fold fn base (sib tr))
            (fold fn base (cld tr))
        )
    )
)



(; some more fun folding functions! ;)
(define (node-count tr)
    (pre-fold (lambda (elem count) (+ 1 count)) 0 tr)
)

(; this uses the tree fold to calculate the height! ;)
(define (height tr)
    (fold
        (lambda (elem clds sibs) (+ 1 (max clds sibs)))
        0 tr
    )
)

(define (height-no-fold tr)
    (if (leaf? tr)
        0
        (max (height (sib tr))
            (+ 1 (height (cld tr)))
        )
    )
)
```

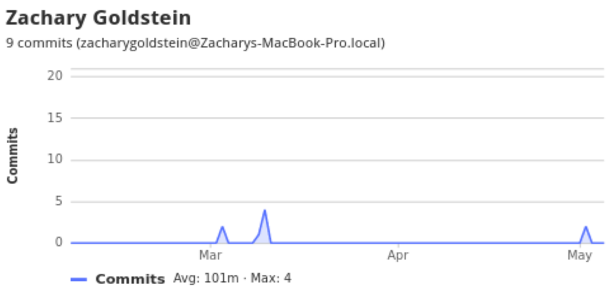
6 Project Plan

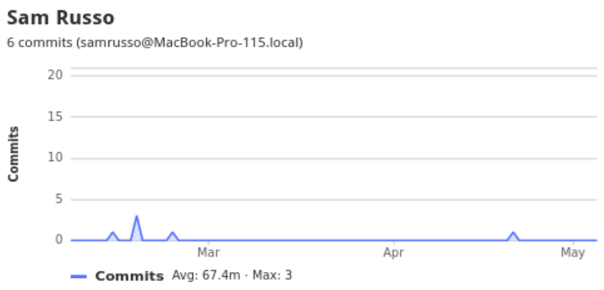
6.1 Project Logs

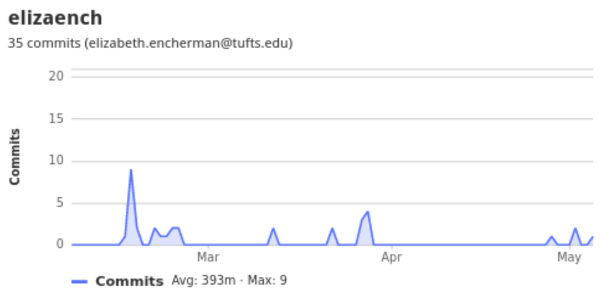




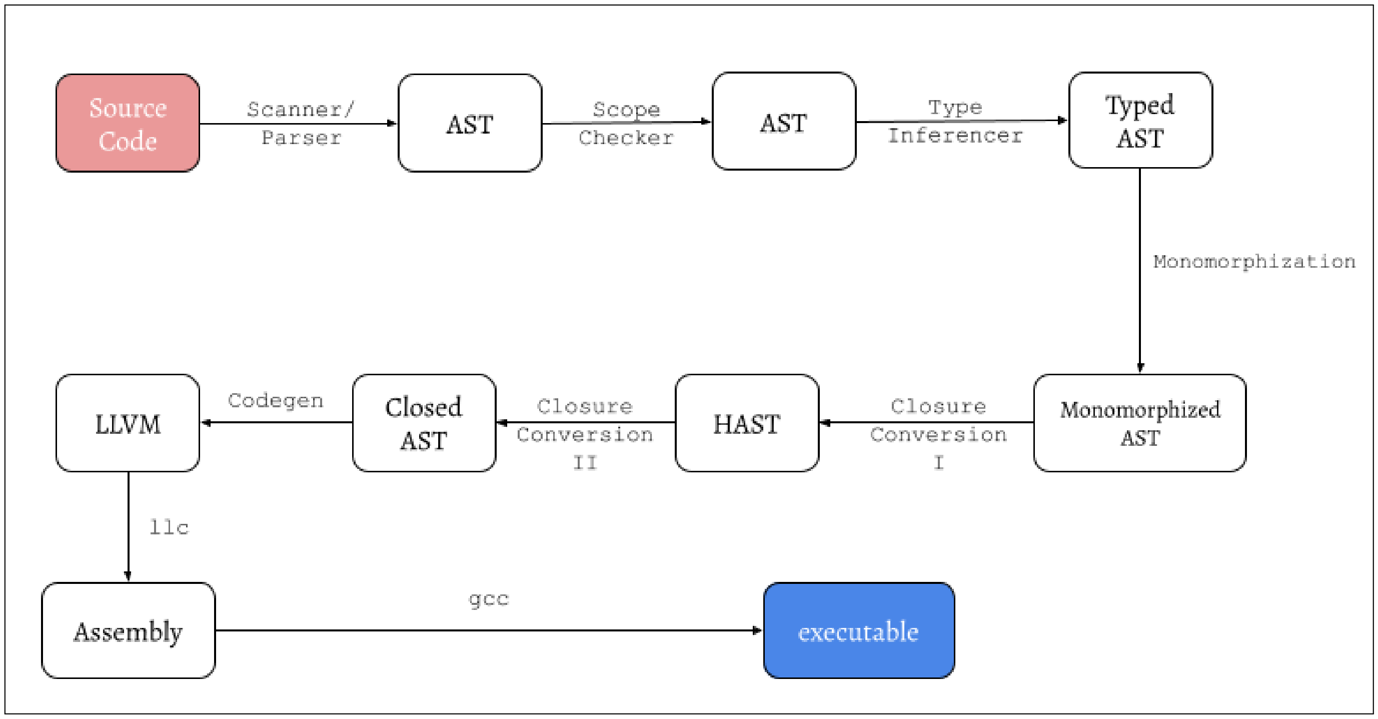








7 Architectural Design



8 Test Plan

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

- Takeaway:
- Advice:

9.3 Sam Russo

- Takeaway:
- Advice:

9.4 Eliza Encherman

- Takeaway:
- Advice:

9.5 Zachary Goldstein

- Takeaway:
- Advice:

10 Appendix

10.1 toplevel.ml

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

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

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


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


let usage_msg =
    "usage: ./toplevel.native [-a|-n|-t|-m|-h|-v|-l|-c] [file.gt]" in
let channel = ref stdin in
Arg.parse speclist (fun filename -> channel := open_in filename) usage_msg;
let lexbuf = Lexing.from_channel !channel in
let ast = Parser.prog Scanner.tokenize lexbuf in
match !action with
(* Default action - print the AST using ast *)
| Ast -> print_string (Ast.string_of_prog ast)
(* All other action needs to generate an SAST, store in variable sast *)
| _ ->
  let ast' = Scope.check ast in
  match !action with
  | Ast -> ()
| Name_Check -> print_string (Ast.string_of_prog ast')
| _ ->
  let tast = Infer.type_infer ast' in
  match !action with
  | Tast -> print_string (Tast.string_of_tprog tast)
  | _ ->
    let mast = Mono.monomorphize tast in
    match !action with
    | Mast -> print_string (Mast.string_of_mprog mast)
    | _ ->
      let hast = Hof.clean mast in
      match !action with
      | Hast -> print_string (Hast.string_of_hprog hast)
      | _ ->
      let cast = Conversion.conversion hast in
        match !action with
        | Cast -> print_string (Cast.string_of_cprog cast)
        | LLVM_IR ->
            print_string (Llvm.string_of_llmodule (Codegen.translate cast))
        | Compile ->
            let the_module = Codegen.translate cast in
            Llvm_analysis.assert_valid_module the_module;
            print_string (Llvm.string_of_llmodule the_module)
        | _ -> print_string usage_msg
```

10.2 ast.ml

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

```
(* Abstract Syntax Tree (AST) for Groot *)
(* Type of Variable Names *)
type ident = string

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

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

type prog = defn list


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

```
    "(lambda (" ^ String.concat " " formals ^ ") "
    ^ string_of_expr body ^ ")"

(* toString for Ast.value *)
and string_of_value = function
  | Char(c)    -> "'" ^ String.make 1 c ^ "'"
  | Int(i)     -> string_of_int i
  | Bool(b)    -> if b then "#t" else "#f"
  | Root(tr)   -> string_of_tree tr

(* 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

```
(* 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 }
  | "(;"                 { 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 comment = parse
  | ";)"                 { tokenize lexbuf }
  | _                    { comment lexbuf }

(* apostrophe handler *)
and apos_handler = parse
  | '('[^''']      { tree_builder lexbuf }
  | '''            { Diagnostic.error
```

```
                  (Diagnostic.lex_error "empty character literal" lexbuf) }
  | '\\'          { escaped_char_handler lexbuf }
  | _ as c        { char_builder c lexbuf }

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

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

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

10.4 parser.mly

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

```
/* Header */
%{ open Ast %}

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

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


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

%%

prog:
  | defn_list EOF              { $1 }

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

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

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

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


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


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


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


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


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

10.5 scope.ml

Author(s): Amy, Eliza

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

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

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

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

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

```
let _ = checkDef defns nameEnv in

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

10.6 tast.ml

Author(s): Sam, Nik

```
(* TAST -- Type inference. *)

open Ast

exception Type_error of string
let type_error msg = raise (Type_error msg)

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

type tyscheme = tyvar list * gtype

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


(* TAST expression *)
type texpr = gtype * tx
and tx =
  | TLiteral    of tvalue
  | TypedVar    of ident
  | TypedIf     of texpr * texpr * texpr
  | TypedApply  of texpr * texpr list
  | TypedLet    of (ident * texpr) list * texpr
  | TypedLambda of (gtype * ident) list * texpr
and tvalue = TChar of char | TInt of int | TBool of bool | TRoot of ttree
and ttree = TLeaf | TBranch of tvalue * ttree * ttree

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

(* Pretty printer *)
(* String of gtypes *)
let rec string_of_ttype = function
  | TYCON ty -> string_of_tycon ty
  | TYVAR tp -> string_of_tyvar tp
  | CONAPP con -> string_of_conapp con
and string_of_tycon = function
  | TyInt -> "int"
  | TyBool -> "bool"
  | TyChar -> "char"
  | TArrow (retty) -> string_of_ttype retty
and string_of_tyvar = function
  | TVariable n -> "'" ^ string_of_int n
and string_of_conapp (tyc, tys) =
string_of_tycon tyc ^ " ("
    ^ String.concat " " (List.map string_of_ttype tys) ^ ")"

and string_of_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 * (tycon * gtype list) *)
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)


(* 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) ((tv, gt) : tyvar * gtype) ->
         match (c1, c2) with
         | TYVAR t1, TYVAR t2 ->
           if tv = t1 then (gt, c2) else if tv = t2 then (c1, gt) else (c1, c2)
         | TYVAR t1, _ -> if tv = t1 then (gt, c2) else (c1, c2)
         | _, TYVAR t2 -> if tv = t2 then (c1, gt) else (c1, c2)
         | _, _ -> (c1, c2))
      cn theta
  in
  List.map sub_one cns

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

```
          if s1 = a1 then (s1, TYVAR a2)
          else if s1 = a2 then (a1, TYVAR s2)
          else acc
        | (a1, a2), (s1, TYVAR _) -> if a1 = s1 then (s1, a2) else acc
        | (a1, _), (s1, s2) -> if a1 = s1 then (s1, s2) else acc)
     cn theta1
  in
  List.map sub_one theta2

(* solve': solves a single constraint 'c' *)
let rec solve' (c : gtype * gtype) =
  match c with
  | TYVAR t1, TYVAR t2 -> [ (t1, TYVAR t2) ]
  | TYVAR t1, TYCON t2 -> [ (t1, TYCON t2) ]
  | TYVAR t1, CONAPP t2 ->
    if is_ftv t1 (CONAPP t2) then
      Diagnostic.error (Diagnostic.TypeError "type variable is not free type in
          type constructor")
    else [ (t1, CONAPP t2) ]
  | TYCON t1, TYVAR t2 -> solve' (TYVAR t2, TYCON t1)
  | TYCON (TArrow (TYVAR t1)), TYCON t2 -> [ (t1, TYCON t2) ]
  | TYCON t1, TYCON (TArrow (TYVAR t2)) -> [ (t2, TYCON t1) ]
  | TYCON t1, TYCON t2 ->
    if t1 = t2 then []
    else
      Diagnostic.error (Diagnostic.TypeError
        ("type constructor mismatch " ^ string_of_tycon t1
          ^ " != " ^ string_of_tycon t2))
  | TYCON t1, CONAPP t2 ->
    Diagnostic.error (Diagnostic.TypeError
      ("type constructor mismatch " ^ string_of_tycon t1
      ^ " != " ^ string_of_conapp t2))
  | CONAPP t1, TYVAR t2 -> solve' (TYVAR t2, CONAPP t1)
  | CONAPP t1, TYCON t2 ->
    Diagnostic.error (Diagnostic.TypeError
      ("type constructor mismatch " ^ string_of_conapp t1
        ^ " != " ^ string_of_tycon t2))
  | CONAPP t1, CONAPP t2 -> (
      match (t1, t2) with
      | (TArrow t1, tys1), (TArrow t2, tys2) ->
        solve ((t1, t2) :: List.combine tys1 tys2)
      | _ ->
        Diagnostic.error (Diagnostic.TypeError
          ("type constructor mismatch " ^ string_of_conapp t1
            ^ " != " ^ string_of_conapp t2)))


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


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

    Type References:
        ctx : (ident * tyscheme) list == (ident * (tyvar list * gtype)) list
    tyscheme : (tyvar list * gtype)
      retty : gtype * (gtype * gtype) list * (gtype * tx) *)
let rec generate_constraints gctx e =
  let rec constrain ctx e =
    match e with
    | Literal e -> value e
    | Var name ->
      let _, (_, tau) = List.find (fun x -> fst x = name) ctx in
      (tau, [], (tau, TypedVar name))
    | If (e1, e2, e3) ->
      let t1, c1, tex1 = generate_constraints gctx e1 in
      let t2, c2, tex2 = generate_constraints gctx e2 in
      let t3, c3, tex3 = generate_constraints gctx e3 in
      let c = [ (booltype, t1); (t3, t2) ] @ c1 @ c2 @ c3 in
      let tex = TypedIf (tex1, tex2, tex3) in
      (t3, c, (t3, tex))
    | Apply (f, args) ->
      let t1, c1, tex1 = generate_constraints ctx f in
      let ts2, c2, texs2 =
        List.fold_left
          (fun acc e ->
              let t, c, x = generate_constraints ctx e in
              let ts, cs, xs = acc in
              (t :: ts, c @ cs, x :: xs))
          ([], c1, []) (List.rev args)
      in
      (* reverse args to maintain arg order *)
      let retType = fresh () in
      ( retType,
        (t1, Tast.functiontype retType ts2) :: c2,
        (retType, TypedApply (tex1, texs2)) )
    | Let (bindings, expr) ->
      let l = List.map (fun (_, e) -> generate_constraints ctx e) bindings in
      let cns = List.concat (List.map (fun (_, c, _) -> c) l) in
      let taus = List.map (fun (t, _, _) -> t) l in
      let asts = List.map (fun (_, _, a) -> a) l in
      let names = List.map fst bindings in
      let ctx_addition =
        List.map (fun (n, t) -> (n, ([], t))) (List.combine names taus)
      in
      let new_ctx = ctx_addition @ ctx in
      let b_tau, b_cns, b_tast = generate_constraints new_ctx expr in
      (b_tau, b_cns @ cns, (b_tau, TypedLet (List.combine names asts, b_tast)))
    | Lambda (formals, body) ->
      let binding = List.map (fun x -> (x, ([], fresh ()))) formals in
      let new_context = binding @ ctx in
      let t, c, tex = generate_constraints new_context body in
      let _, tyschms = List.split binding in
      let _, formaltys = List.split tyschms in
      let typedFormals = List.combine formaltys formals in
      ( Tast.functiontype t formaltys,
        c,
        (Tast.functiontype t formaltys, TypedLambda (typedFormals, tex)) )
  and value v =
    match v with
    | Int  e -> (inttype, [], (inttype, TLiteral (TInt e)))
    | Char e -> (chartype, [], (chartype, TLiteral (TChar e)))
    | Bool e -> (booltype, [], (booltype, TLiteral (TBool e)))
    | Root t -> tree t
  and tree t =
    match t with
    | Leaf    -> Diagnostic.error (Diagnostic.Unimplemented "contraint
        generation for Leaf")
    | Branch _ -> Diagnostic.error (Diagnostic.Unimplemented "contraint
        generation for Branch")
  in
  constrain gctx e


(* 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)

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


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

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


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

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

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

10.8 mast.ml

Author(s): Amy

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

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

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



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

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


type polyty_env = mexpr StringMap.t
type mprog = mdefn list


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


(* String of a typed expression (mexpr) == (type, m-expression) *)
let rec string_of_mexpr (typ, exp) =
  "[" ^ string_of_mtype typ ^ "] " ^ string_of_mx exp
and string_of_mx = function
  | MLiteral v -> string_of_mvalue v
  | MVar id -> id
  | MIf (e1, e2, e3) ->
    "(if " ^ string_of_mexpr e1 ^ " "
    ^ string_of_mexpr e2 ^ " "
    ^ string_of_mexpr e3 ^ ")"
  | MApply (f, args) ->
    "(" ^ string_of_mexpr f ^ " "
    ^ String.concat " " (List.map string_of_mexpr args) ^ ")"
  | MLet (binds, body) ->
    let string_of_binding (id, e) =
      "[" ^ id ^ " " ^ (string_of_mexpr e) ^ "]"
    in
    "(let (" ^ String.concat " " (List.map string_of_binding binds) ^ ") "
    ^ string_of_mexpr body ^ ")"
  | MLambda (formals, body) ->
    let formalStringlist = List.map (fun (ty, x) -> string_of_mtype ty ^ " " ^ x
      ) formals in
    "(lambda (" ^ String.concat ", " formalStringlist
    ^ ") " ^ string_of_mexpr body ^ ")"
(* toString for Mast.mvalue *)
and string_of_mvalue = function
  | MChar c -> String.make 1 c
  | MInt i -> string_of_int i
  | MBool b -> if b then "#t" else "#f"
  | MRoot tr -> string_of_mtree tr
```

```
(* toString for Mast.mtree *)
and string_of_mtree = function
  | MLeaf -> "leaf"
  | MBranch (v, sib, child) ->
    "(tree " ^ string_of_mvalue v ^ " "
    ^ string_of_mtree sib ^ " "
    ^ string_of_mtree child ^ ")"



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


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

10.9 mono.ml

Author(s): Amy

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

open Tast
open Mast


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

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




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



  (* Takes a type environment and a string key "id". Returns the
       value (mtype) that the key mapts to. *)
```

```
let lookup (id : mname) (gamma : polyty_env) =
  StringMap.find id gamma
in


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


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

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


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

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

  (* Given a (polymorphic) mtype, returns the monomorphic version *)
  let resolve_mty (mty : mtype) =
    let apply_subs typ (arg, sub) =
      if isTyvar arg
        then
          let tyvarID =
            (match arg with
                Mtyvar i -> i
              | _ -> Diagnostic.error
                     (Diagnostic.MonoError "non-tyvar substitution"))
          in
          let rec search_mtype = function
              Mtycon tyc -> Mtycon (search_tycon tyc)
            | Mtyvar i  -> if i = tyvarID then sub else Mtyvar i
            | Mconapp con -> Mconapp (search_con con)
          and search_tycon = function
              MIntty -> MIntty
            | MCharty -> MCharty
            | MBoolty -> MBoolty
            | MTarrow retty -> MTarrow (search_mtype retty)
          and search_con (tyc, mtys) =
            (search_tycon tyc, List.map search_mtype mtys)
          in search_mtype typ
      else typ
    in List.fold_left apply_subs mty substitutions
  in

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

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

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

in




(* Takes a texpr and returns the equivalent mexpr
   and the prog (list of mdefns) *)
let rec expr (gamma : polyty_env) (prog : mprog) ((ty, ex) : texpr) =
  match ex with
    TLiteral l -> ((ofGtype ty, MLiteral (value l)), prog)
  | TypedVar v ->
      (* let () = print_endline ("looking for: " ^ v) in *)
      let vartyp = (try fst (lookup v gamma)
                   with Not_found ->
                       (* let () = print_endline "didn't find it" in *)
                       ofGtype ty) in
      let actualtyp = ofGtype ty in
      if (isPolymorphic vartyp) && (isFunctionType vartyp)
        then
          let polyexp = lookup v gamma in
          let (_, prog') = resolve prog v actualtyp polyexp in
          ((actualtyp, MVar v), prog')
      else
        ((actualtyp, MVar v), prog)
  | TypedIf (t1, t2, t3) ->
      let (mexp1, prog1) = expr gamma prog t1 in
      let (mexp2, prog2) = expr gamma prog1 t2 in
      let (mexp3, prog3) = expr gamma prog2 t3 in
      ((fst mexp3, MIf (mexp1, mexp2, mexp3)), prog3)
  | TypedApply (f, args) ->
      let (f', prog') = expr gamma prog f in
      let (args', prog'') =
        List.fold_left
          (fun (arglst, pro) arg ->
            let (arg', pro') = expr gamma pro arg in
            (arg' :: arglst, pro'))
          ([], prog') args
      in
      let args' = List.rev args' in
      ((ofGtype ty, MApply (f', args')), prog'')
  | TypedLet (bs, body) ->
      let binding (x, e) = let (e', _) = expr gamma prog e in (x, e') in
      let bs' = List.map binding bs in
      let (body', prog') = expr gamma prog body in
      ((ofGtype ty, MLet (bs', body')), prog')
  | TypedLambda (formals, body) ->
      let (formaltys, names) = List.split formals in
      let formaltys' = List.map ofGtype formaltys in
      let formals'  = List.combine formaltys' names in
      let gamma' = List.fold_left
                     (fun env (ty, name) ->
                       if isPolymorphic ty
                         then set_aside name (ty, MVar name) env
                       else env)
                     gamma
                     formals' in
      let (body', prog') = expr gamma' prog body in
      ((ofGtype ty, MLambda (formals', body')), prog')
and value = function
  | TChar c -> MChar c
  | TInt i -> MInt i
  | TBool b -> MBool b
  | TRoot t -> MRoot (tree t)
and tree = function
  | TLeaf              -> MLeaf
  | TBranch (v, t1, t2) -> MBranch (value v, tree t1, tree t2)
in


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

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

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




(* Bug/Bandaid - unable to resolve polymorphism.
    Iterate through the current "mono" typed program.
    Insert integer type wherever leftover type variables remain *)
let buggy_resolve (prog : mprog) (def : mdefn) =

  (* resolves any remaining polymorphism in an mexpr to integer type *)
  let rec resolve_expr ((ty, exp) : mexpr) =
    (* turns tyvar into int type *)
    let rec resolve_mty = function
      | Mtycon t -> Mtycon (resolve_tycon t)
      | Mtyvar _ -> Mtycon MIntty
      | Mconapp c -> Mconapp (resolve_conapp c)
    and resolve_tycon = function
      | MIntty   -> MIntty
      | MBoolty  -> MBoolty
      | MCharty  -> MCharty
      | MTarrow t -> MTarrow (resolve_mty t)
    and resolve_conapp (tyc, mtys) =
          (resolve_tycon tyc, List.map resolve_mty mtys)
    in
    (* finds and resolves any nested tyvars to int type *)
    let resolve_mx = function
      | MLiteral l -> MLiteral l
      | MVar v    -> MVar v
      | MIf (e1, e2, e3) ->
          let r1 = resolve_expr e1 in
          let r2 = resolve_expr e2 in
          let r3 = resolve_expr e3 in
          MIf (r1, r2, r3)
      | MApply (f, args) ->
          let f' = resolve_expr f in
          let args' = List.map resolve_expr args in
          MApply (f', args')
      | MLet (bs, body) ->
          let bs' = List.map (fun (name, mex) ->
                              (name, resolve_expr mex))
                             bs in
          let body' = resolve_expr body in
          MLet (bs', body')
      | MLambda (formals, body) ->
          let formals' =
            List.map (fun (mty, name) -> (resolve_mty mty, name)) formals in
          let body' = resolve_expr body in
          MLambda (formals', body')
    in

    (resolve_mty ty, resolve_mx exp)
  in

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

List.fold_left buggy_resolve [] program
```

10.10 hast.ml

Author(s): Amy

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

module StringMap = Map.Make(String)

type hname = string

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

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

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


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

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

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


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

type hprog = hdefn list



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


(* String of a h-expression *)
let rec string_of_hexpr (typ,exp) =
  "[" ^ string_of_htype typ ^ "] " ^ string_of_hx exp
and string_of_hx = function
  | HLiteral v -> string_of_hvalue v
  | HVar id -> id
  | HIf (e1, e2, e3) ->
```

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



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

(* Returns the string of an hprog *)
let string_of_hprog hdefns =
  String.concat "\n" (List.map string_of_hdefn hdefns) ^ "\n"
```

10.11 hof.ml

Author(s): Amy

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

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

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

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


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

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

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

```
let isBound id env = StringMap.mem id env

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

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

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

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

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


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




(* Returns true if given htype is a function type *)
let rec isFunctionType = function
```

```
    HTycon t -> hof_tycon t
  | HConapp t -> hof_conapp t
and hof_tycon = function
    HIntty | HCharty | HBoolty -> false
  | HTarrow _ -> true
  | HCls (_, retty, argsty, _) ->
      isFunctionType retty
      || (List.fold_left
            (fun init argty -> init || (isFunctionType argty))
            false argsty)
and hof_conapp (tyc, tys) =
    hof_tycon tyc
    || (List.fold_left
          (fun init typ -> init || (isFunctionType typ))
          false tys)

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



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

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


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

  (* Given a hexpr, returns a possibly updated hexpr using the given
      environment. *)
  let rec h_expr (env : ty_env) ((typ, exp) : hexpr) = match exp with
    | HLiteral l -> (typ, HLiteral l)
    | HVar v -> let (_, typ') = find v env in (typ', HVar v)
    | HIf (e1, e2, e3) ->
        let e1' = h_expr env e1 in
        let e2' = h_expr env e2 in
        let e3' = h_expr env e3 in
        (fst e2', HIf (e1', e2', e3'))
    | HApply (f, args) ->
        let f' = h_expr env f in
        let args' = List.map (h_expr env) args in
        let retty =
          (match fst f' with
            HTycon (HCls (_, ret, _, _)) -> ret
          | _ -> intTy)
        in (retty, HApply (f', args'))
    | HLet (bs, body) ->
        let bs' = List.map (fun (name, exp) -> (name, h_expr env exp)) bs in
        let local_env = List.fold_left (fun map (name, (ty, _)) ->
                                    bindLocal map name ty)
                                env bs' in
        let body' = h_expr local_env body in
        (fst body, HLet (bs', body'))
    | HLambda (formals, body) ->
```

```
      let local_env = List.fold_left (fun map (ty, name) ->
                                  bindLocal map name ty)
                               env formals in
      let body' = h_expr local_env body in
      (fst body, HLambda (formals, body'))
in

(* Given a mexpr, returns the equivalent hexpr *)
let rec expr (env : ty_env) (mexp : mexpr) =
  let rec expr' (ty, exp) = match exp with
      MLiteral l -> (ofMtype ty, HLiteral (value l))
    | MVar v -> let (_, typ) = find v env in (typ, HVar v)
    | MIf (e1, e2, e3) ->
        let e1' = expr' e1 in
        let e2' = expr' e2 in
        let e3' = expr' e3 in
        (fst e2', HIf (e1', e2', e3'))
    | MApply (f, args) ->
        let (fty, f') = expr' f in
        let args' = List.map expr' args in
        if isHOF fty
          then let (retty, fty') = resolveHOF env fty args' in
               (retty, HApply ((fty', f'), args'))
        else (ofMtype ty, HApply ((fty, f'), args'))
    | MLet (bs, body) ->
        let bs' = List.map (fun (name, e) -> (name, expr' e)) bs in
        let local_env = List.fold_left (fun map (name, (typ, _)) ->
                                  bindLocal map name typ)
                               env bs' in
        let body' = expr local_env body in
        (fst body', HLet (bs', body'))
    | MLambda (formals, body) ->
        (* name the closure *)
        let id = anon ^ string_of_int !count in
        let () = count := !count + 1 in

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

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

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

```
  in expr' mexp
in


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

in

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

10.12 cast.ml

Author(s): Amy

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

module StringMap = Map.Make(String)

type cname = string

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


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

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

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



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

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


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


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

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


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


(* stringifies cexpr *)
let rec string_of_cexpr (_, e) =
  (* "[" *)
  (* ^ string_of_ctype ty ^ " : " *)
  (* ^ *)
  string_of_cx e
  (* ^ "]" *)
and string_of_cx = function
  | CLiteral v -> string_of_cvalue v
  | CVar n -> n
  | CIf (e1, e2, e3) ->
    "(if " ^ string_of_cexpr e1 ^ " "
    ^ string_of_cexpr e2 ^ " "
    ^ string_of_cexpr e3 ^ ")"
  | CApply (f, args, _) ->
    "(" ^ string_of_cexpr f ^ " "
    ^ String.concat " " (List.map string_of_cexpr args) ^ ")"
  | CLet (binds, body) ->
    let string_of_binding (id, e) =
      "[" ^ id ^ " " ^ (string_of_cexpr e) ^ "]"
    in "(let (" ^ String.concat " " (List.map string_of_binding binds)
      ^ ") " ^ string_of_cexpr body ^ ")"
  | CLambda (id, frees) ->
    "(" ^ id ^ " "
    ^ String.concat " " (List.map string_of_cexpr frees)
    ^ ")"
and string_of_cvalue = function
  | CChar c -> String.make 1 c
  | CInt i -> string_of_int i
  | CBool b -> if b then "#t" else "#f"
  | CRoot t -> string_of_ctree t
and string_of_ctree = function
  | CLeaf -> "leaf"
  | CBranch (v, sib, child) ->
    "(tree " ^ string_of_cvalue v ^ " "
    ^ string_of_ctree sib ^ " "
    ^ string_of_ctree child ^ ")"

(* stingifies a cdefn *)
```

```ocaml
let string_of_cdefn = function
  | CVal (id, e) -> "(val " ^ id ^ " " ^ string_of_cexpr e ^ ")"
  | CExpr (cexp) -> string_of_cexpr cexp

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

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

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

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


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

```
string_of_rho rho ^ "\n\n" ^
"Structures:\n" ^
string_of_structures structures ^ "\n\n"
```

10.13 conversion.ml

Author(s): Amy, Eliza

```
(* Closure conversion for groot compiler *)
open Hast
open Cast
module StringMap = Map.Make(String)

(*******************************************************************)
(* Pre-load rho with prints built in *)
let prerho env =
  let add_prints map (k, v) =
    StringMap.add k [v] map
  in List.fold_left add_prints env
     [("printi", (0, 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
  let localList = (0, ty) :: currList in
  StringMap.add k localList map

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


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


(* Given a var_env, returns a (ctype * name) list version *)
let toParamList (venv : var_env) =
  StringMap.fold
    (fun id occursList res ->
      let (num, ty) = List.nth occursList 0 in
      let id' = if num = 0 then id
        else "_" ^ id ^ "_" ^ string_of_int num in
      (ty, id') :: res)
    venv []

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



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



(* Converts given sexpr to cexpr, and returns the cexpr *)
let rec hexprToCexpr (env : var_env) (e : hexpr) =
  let rec expr ((typ, ex) : hexpr) = match ex with
    | HLiteral v -> (ofHtype typ, CLiteral (value v))
    | HVar s    ->
        (* In case s is a name of a define, get the closure type *)
        let (occurs, ctyp) = find s env in
        (* to match the renaming convention in svalToCval, and to ignore
           built in prints *)
        let vname = if occurs = 0
                    then s
                    else "_" ^ s ^ "_" ^ string_of_int occurs
        in (ctyp, CVar (vname))
    | HIf (e1, e2, e3) ->
        let e1' = expr e1
        and e2' = expr e2
        and e3' = expr e3 in
        (fst e2', CIf (e1', e2', e3'))
    | HApply (f, args) ->
        let (ctyp, f') = expr f in
        let normalargs = List.map expr args in
        (* actual type of the function application is the type of the return*)
        let (retty, freesCount) =
          (match ctyp with
              Tycon (Clo (_, functy, freetys)) ->
              (match functy with
                Conapp (Tarrow ret, _) -> (ret, List.length freetys)
              | _ -> raise (Failure "Non-function function type"))
            | _ -> (intty, 0)) in
        (retty, CApply ((retty, f'), normalargs, freesCount))
    | HLet (bs, body) ->
        let bs' = List.map (fun (name, hex) -> (name, expr hex)) bs in
        let local_env =
            List.fold_left (fun map (name, (ty, _)) ->
                              bindLocal map name ty)
                            env bs' in
        let (ctyp, body') = hexprToCexpr local_env body in
        (ctyp, CLet (bs', (ctyp, body')))
    (* Supose we hit a lambda expression, turn it into a closure *)
    | HLambda (formals, body) -> create_anon_function formals body typ env
  and value = function
```

```
    | HChar c           -> CChar c
    | HInt i            -> CInt i
    | HBool b           -> CBool b
    | HRoot t           -> CRoot (tree t)
  and tree = function
    | HLeaf             -> CLeaf
    | HBranch (v, t1, t2) -> CBranch (value v, tree t1, tree t2)
  in expr e
(* When given just a lambda expresion withot a user defined identity/name
   this function will generate a name and give the function a body --
   Lambda lifting. *)
and create_anon_function (fformals : (htype * hname) list) (fbody : hexpr)
                        (closurety : htype) (env : var_env) =


  let fformals' = List.map (fun (hty, x) -> (ofHtype hty, x)) fformals in
  let local_env = List.fold_left
                  (fun map (formtyp, name) ->
                    bindLocal map name formtyp)
                  env fformals' in
  let func_body = hexprToCexpr local_env fbody in
  let rettype = fst func_body in
  let freeformals = toParamList (improve (fformals, fbody) env) in

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

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

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



(* Converts given SVal to CVal, and returns the CVal *)
let hvalToCval (id, (ty, e)) =
  (* check if id was already defined in rho, in order to get
     the actual frequency the variable name was defined.
     The (0, inttype is a placeholder) *)
  let (occurs, _) = if (isBound id res.rho)
                     then (find id res.rho)
                   else (0, intty) in
  (* Modify the name to account for the redefinitions, and so old closures
     can access original variable values *)
  let id' = "_" ^ id ^ "_" ^ string_of_int (occurs + 1) in
  let (ty', cexp) = hexprToCexpr res.rho (ty, e) in
  (* bind original name to the number of occurrances and the variable's type *)
  let () = bind id (occurs + 1, ty') in
  (* Return the possibly new CVal definition *)
  CVal (id', (ty', cexp))
(***************************************************************************)


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

10.14 llgtype.ml

Author(s): Amy

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

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

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

let lltrue = L.const_int bool_ty 1

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

10.15 codegen.ml

Author(s): Amy, Eliza

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


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

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

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


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

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

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


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


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

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

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

(* helper to construct named structs *)
let create_struct (name : cname) (membertys : ctype list)
    (map : L.lltype StringMap.t) =
  let new_struct_ty = L.named_struct_type context name in
  let () =
    L.struct_set_body
      new_struct_ty
      (Array.of_list (List.map (ltype_of_type map) membertys))
      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
           (Diagnostic.GenerationError "lambda is non-closure type")
  in
  let structs = List.rev structures in
  List.fold_left gen_struct_def StringMap.empty structs
in

(* Lookup table of function names (lambdas) to
    (function block, function def) *)
```

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


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

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


(* Looks for variable named id in the local or global environment *)
```

```
let lookup id locals =
  try StringMap.find id locals
  with Not_found -> StringMap.find id globals
in

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


(* Construct constants code for literal values.
   Function takes a builder and Sast.svalue, and returns the constructed
   llvalue *)
let const_val builder = function
  (* create the "string" constant in the code for the char *)
    CChar c ->
      let spc = L.build_alloca char_ptr_ty "spc" builder in
      let globalChar =
        L.build_global_string (String.make 1 c) "globalChar" builder in
      let newStr = L.build_bitcast globalChar char_ptr_ty "newStr" builder in
      let loc = L.build_gep spc [| zero |] "loc" builder in
      let _ = L.build_store newStr loc builder in
      L.build_load spc "character_ptr" builder
  | CInt i -> L.const_int int_ty i
  (* HAS to be an i1 lltype for the br instructions *)
  | CBool b -> L.const_int bool_ty (if b then 1 else 0)
  | CRoot _ -> Diagnostic.error
              (Diagnostic.Unimplemented "codegen SRoot Literal")

in



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

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

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

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

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

      (* Complete the if-then-else block, return should be llvalue *)
      let _ = L.build_cond_br bool_val then_bb else_bb builder in
      (* Get the result of either the the or the else block *)
      let merge_builder = L.builder_at_end context merge_bb in
      let result_value = L.build_load result "if-res-val" merge_builder in
      (merge_builder, result_value)
  | CApply ((_, CVar "printi"), [arg], _) ->
      let (builder', argument) = expr builder lenv block arg in
      let instruction = L.build_call printf_func
          [| int_format_str ; argument |]
          "printi" builder'
      in (builder', instruction)
  | CApply ((_, CVar "printc"), [arg], _) ->
      let (builder', argument) = expr builder lenv block arg in
      let instruction = L.build_call puts_func
          [| argument |]
          "printc" builder'
      in (builder', instruction)
  | CApply ((_, CVar "printb"), [arg], _) ->
      let (builder', condition) = expr builder lenv block arg in
      let bool_stringptr =
        if condition = lltrue then print_true
        else print_false in
      let instruction = L.build_call puts_func
          [| bool_stringptr |]
          "printb" builder'
      in (builder', instruction)
  | CApply ((_, CVar "~"), [arg], _) ->
      let (builder', e) = expr builder lenv block arg in
      let instruction = L.build_neg e "~" builder'
      in (builder', instruction)
  | CApply ((_, CVar "not"), [arg], _) ->
      let (builder', e) = expr builder lenv block arg in
      let instruction = L.build_not e "not" builder'
      in (builder', instruction)
  (* BINOP PRIMITIVES - Int and Boolean Algebra *)
  | CApply ((_, CVar "+"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_add e1 e2 "addition" builder''
      in (builder'', instruction)
  | CApply ((_, CVar "-"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_sub e1 e2 "subtraction" builder''
      in (builder'', instruction)
  | CApply ((_, CVar "/"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_sdiv e1 e2 "division" builder''
      in (builder'', instruction)
  | CApply ((_, CVar "*"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_mul e1 e2 "multiply" builder''
      in (builder'', instruction)
  | CApply ((_, CVar "mod"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_srem e1 e2 "modulus" builder''
      in (builder'', instruction)
  | CApply ((_, CVar "&&"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_and e1 e2 "logAND" builder''
      in (builder'', instruction)
  | CApply ((_, CVar "||"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_or e1 e2 "logOR" builder''
```

```
      in (builder'', instruction)
  (* BINOP PRIMITIVES - Comparisons *)
  | CApply ((_, CVar "<"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_icmp L.Icmp.Slt e1 e2 "lt" builder''
      in (builder'', instruction)
  | CApply ((_, CVar ">"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_icmp L.Icmp.Sgt e1 e2 "gt" builder''
      in (builder'', instruction)
  | CApply ((_, CVar "<="), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_icmp L.Icmp.Sle e1 e2 "leq" builder''
      in (builder'', instruction)
  | CApply ((_, CVar ">="), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_icmp L.Icmp.Sge e1 e2 "geq" builder''
      in (builder'', instruction)
  | CApply ((_, CVar "=i"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_icmp L.Icmp.Eq e1 e2 "eqI" builder''
      in (builder'', instruction)
  | CApply ((_, CVar "!=i"), arg1::[arg2], _) ->
      let (builder', e1) = expr builder lenv block arg1 in
      let (builder'', e2) = expr builder' lenv block arg2 in
      let instruction = L.build_icmp L.Icmp.Ne e1 e2 "neqI" builder''
      in (builder'', instruction)
  | CApply (f, args, numFrees) ->
      (* Since all normal function application is as struct value,
        call to the function at member index 0 of the struct *)
      let (builder', applyClosure) = expr builder lenv block f in
      (* List of llvalues representing the actual arguments *)
      let (builder'', llargs) =
        List.fold_left (fun (bld, arglist) arg ->
            let (bld', llarg) = expr bld lenv block arg in
            (bld', llarg :: arglist))
          (builder', []) args
      in let llargs = List.rev llargs in
      (* List of llvalues representing the hidden frees to be
        passed as arguments *)
      let llfrees =
        let rec get_free idx frees =
          if idx > numFrees then List.rev frees
          else
            let struct_freeMemPtr =
              L.build_struct_gep applyClosure idx "freePtr" builder'' in
            let struct_freeMem =
              L.build_load struct_freeMemPtr "freeVal" builder'' in
            let frees' = struct_freeMem :: frees
            in get_free (idx + 1) frees'
        in get_free 1 []
      in
      (* Get the struct member at index 0, which is the function, call it *)
      let ptrFuncPtr =
        L.build_struct_gep applyClosure 0 "function_access" builder'' in
      let funcPtr = L.build_load ptrFuncPtr "function_call" builder'' in
      let instruction = L.build_call funcPtr
          (Array.of_list (llargs @ llfrees))
          "function_result" builder''
      in (builder'', instruction)
  | CLet (bs, body) ->
      (* create each value in bs, and bind it to the name *)
      let (builder', local_env) =
        List.fold_left
          (fun (bld, map) (name, (ty, cexp)) ->
             let loc = L.build_alloca
                        (ltype_of_type struct_table ty) name bld in
             let (bld', llcexp) = expr bld lenv block (ty, cexp) in
             let _ = L.build_store llcexp loc bld' in
             let map' = StringMap.add name loc map in
             (bld', map'))
          (builder, StringMap.empty) bs
          (* Evaualate the body *)
      in expr builder' local_env block body
  | CLambda (id, freeargs)->
    (match etyp with
        Tycon (Clo (clo_name, _, _)) ->
          (* alloc and declare a new struct object *)
          let struct_ty = StringMap.find clo_name struct_table in
          let struct_obj = L.build_alloca struct_ty "gstruct" builder in
          (* Set the function field of the closure *)
          let struct_fmem =
            L.build_struct_gep struct_obj 0 "funcField" builder in
          let (fblock, _) = StringMap.find id function_decls in
          let _ = L.build_store fblock struct_fmem builder in
          (* Set each subsequent field of the frees *)
          let (builder', llFreeArgs) =
            List.fold_left
             (fun (bld, arglist) arg ->
                 let (bld', llarg) = expr bld lenv block arg in
                 (bld', llarg :: arglist))
             (builder, []) freeargs in
          let llFreeArgs = List.rev llFreeArgs in
```

```
          let numFrees = List.length freeargs in
          let structFields =
            (* Create pointers to struct members 1 to n *)
            let rec generate_field_access idx fields =
              if idx > numFrees then List.rev fields
              else
                let struct_freeMem =
                  L.build_struct_gep struct_obj idx "freeField" builder' in
                let fields' = struct_freeMem :: fields in
                generate_field_access (idx + 1) fields'
            in generate_field_access 1 []
          in
          let _ =
            let set_free arg field = L.build_store arg field builder'
            in List.map2 set_free llFreeArgs structFields
          in
          (builder', struct_obj)
      | _ -> Diagnostic.error
              (Diagnostic.GenerationError "lambda is non-closure type"))
in


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

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

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

```
(* Build function block bodies *)
let build_function_body fdef =
  let (function_block, _) = StringMap.find fdef.fname function_decls in
  let fbuilder = L.builder_at_end context (L.entry_block function_block) in

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

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

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

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

```
(* Return an llmodule *)
the_module
```

10.16 diagnostic.ml

Author(s): Zach

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



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

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

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


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

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

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

(* background colors *)
let bg_black  = "40"
let bg_red    = "41"
let bg_green  = "42"
let bg_yellow = "43"
let bg_blue   = "44"
let bg_magenta = "45"
let bg_cyan   = "46"
let bg_white  = "47"

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

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

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


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

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

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

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

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

exception Unimplemented of string
exception Unbound of string
exception EmptyLetBinding
exception TypeError of string
exception GenerationError of string
exception MonoError of string
exception MonoWarning of string
let () =
Printexc.register_printer (function
    | Unimplemented s -> Some ((strfx error_fx "Unimplemented Error: ") ^ s)
    | Unbound       s -> Some ((strfx error_fx "Unbound Error: "   ) ^ s)
    | TypeError     s -> Some ((strfx error_fx "Type Error: "      ) ^ s)
    | GenerationError s -> Some ((strfx error_fx "Generation Error: " ) ^ s)
    | MonoError     s -> Some ((strfx error_fx "Mono Error: "      ) ^ s)
    | MonoWarning   s -> Some ((strfx error_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)
```