The MicroC Compiler

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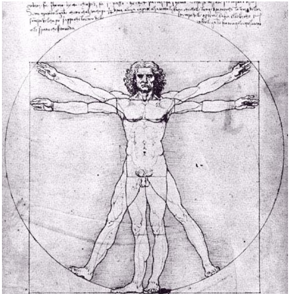


The MicroC Language

A very stripped-down dialect of C

Functions, global variables, and most expressions and statements, but only integer variables.

```
/* The GCD algorithm in MicroC */

gcd(a, b) {
  while (a != b) {
    if (a > b) a = a - b;
    else b = b - a;
  }
  return a;
}

main()
{
  print(gcd(2,14));
  print(gcd(3,15));
  print(gcd(99,121));
}
```

The Front-End

Tokenize and parse to produce
an Abstract Syntax Tree

The first part of any compiler or interpreter

The Scanner (scanner.mll)

```
{ open Parser }                          (* Get the token types *)

rule token = parse
  [' ' '\t' '\r' '\n'] { token lexbuf }             (* Whitespace *)
| "/*"                 { comment lexbuf }           (* Comments *)
| '('      { LPAREN }          | ')'      { RPAREN }  (* Punctuation *)
| '{'      { LBRACE }          | '}'      { RBRACE }
| ';'      { SEMI }            | ','      { COMMA }
| '+'      { PLUS }            | '-'      { MINUS }
| '*'      { TIMES }           | '/'      { DIVIDE }
| '='      { ASSIGN }          | "=="     { EQ }
| "!="     { NEQ }             | '<'      { LT }
| "<="     { LEQ }             | ">"      { GT }
| ">="     { GEQ }
| "else"   { ELSE }            | "if"     { IF }      (* Keywords *)
| "while"  { WHILE }           | "for"    { FOR }
| "int"    { INT }             | "return" { RETURN }
| eof      { EOF }                                    (* End-of-file *)
| ['0'-'9']+ as lxm { LITERAL(int_of_string lxm) }  (* integers *)
| ['a'-'z' 'A'-'Z']['a'-'z' 'A'-'Z' '0'-'9' '_']* as lxm { ID(lxm) }
| _ as char { raise (Failure("illegal character " ^
                             Char.escaped char)) }

and comment = parse
  "*/" { token lexbuf }     (* End-of-comment *)
| _    { comment lexbuf }   (* Eat everything else *)
```

The AST (ast.ml)

```
type op = Add | Sub | Mult | Div | Equal | Neq | Less | Leq | Greater

type expr =                            (* Expressions *)
    Literal of int                     (* 42 *)
  | Noexpr                             (* for (;;) *)
  | Id of string                       (* foo *)
  | Assign of string * expr            (* foo = 42 *)
  | Binop of expr * op * expr          (* a + b *)
  | Call of string * expr list         (* foo(1, 25 *)

type stmt =                              (* Statements *)
    Block of stmt list                   (* { ... } *)
  | Expr of expr                         (* foo = bar + 3; *)
  | Return of expr                       (* return 42; *)
  | If of expr * stmt * stmt             (* if (foo == 42) {} else {} *)
  | For of expr * expr * expr * stmt (* for (i=0;i<10;i=i+1) { ... } *
  | While of expr * stmt                 (* while (i<10) { i = i + 1 } *)

type func_decl = {
    fname : string;          (* Name of the function *)
    formals : string list;   (* Formal argument names *)
    locals : string list;    (* Locally defined variables *)
    body : stmt list;
  }
type program = string list * func_decl list (* global vars, funcs *)
```

The Parser (parser.mly)

```
%{ open Ast %}

%token SEMI LPAREN RPAREN LBRACE RBRACE COMMA PLUS MINUS TIMES DIVIDE
%token ASSIGN EQ NEQ LT LEQ GT GEQ RETURN IF ELSE FOR WHILE INT EOF
%token <int> LITERAL
%token <string> ID

%nonassoc NOELSE  /* Precedence and associativity of each operator */
%nonassoc ELSE
%right ASSIGN
%left EQ NEQ
%left LT GT LEQ GEQ
%left PLUS MINUS
%left TIMES DIVIDE

%start program                 /* Start symbol */
%type <Ast.program> program  /* Type returned by a program */

%%

program:
  decls EOF { $1 }
```

Declarations

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

fdecl:
   ID LPAREN formals_opt RPAREN LBRACE vdecl_list stmt_list RBRACE
                            { { fname   = $1;
                                formals = $3;
                                locals  = List.rev $6;
                                body    = List.rev $7 } }
formals_opt:
    /* nothing */           { [] }
  | formal_list             { List.rev $1 }

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

vdecl_list:
    /* nothing */           { [] }
  | vdecl_list vdecl        { $2 :: $1 }

vdecl:
   INT ID SEMI              { $2 }
```

Statements

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

stmt:
    expr SEMI                                    { Expr($1) }
  | RETURN expr SEMI                             { Return($2) }
  | LBRACE stmt_list RBRACE                      { Block(List.rev $2) }
  | IF LPAREN expr RPAREN stmt %prec NOELSE { If($3, $5, Block([])) }
  | IF LPAREN expr RPAREN stmt ELSE stmt    { If($3, $5, $7) }
  | FOR LPAREN expr_opt SEMI expr_opt SEMI expr_opt RPAREN stmt
                                                 { For($3, $5, $7, $9) }
  | WHILE LPAREN expr RPAREN stmt                { While($3, $5) }

expr_opt:
    /* nothing */ { Noexpr }
  | expr          { $1 }
```

Expressions

```
expr:
    LITERAL                              { Literal($1) }
  | ID                                   { Id($1) }
  | expr PLUS   expr                     { Binop($1, Add,   $3) }
  | expr MINUS  expr                     { Binop($1, Sub,   $3) }
  | expr TIMES  expr                     { Binop($1, Mult,  $3) }
  | expr DIVIDE expr                     { Binop($1, Div,   $3) }
  | expr EQ     expr                     { Binop($1, Equal, $3) }
  | expr NEQ    expr                     { Binop($1, Neq,   $3) }
  | expr LT     expr                     { Binop($1, Less,  $3) }
  | expr LEQ    expr                     { Binop($1, Leq,   $3) }
  | expr GT     expr                     { Binop($1, Greater,  $3) }
  | expr GEQ    expr                     { Binop($1, Geq,   $3) }
  | ID ASSIGN expr                       { Assign($1, $3) }
  | ID LPAREN actuals_opt RPAREN         { Call($1, $3) }
  | LPAREN expr RPAREN                   { $2 }

actuals_opt:
    /* nothing */ { [] }
  | actuals_list  { List.rev $1 }

actuals_list:
    expr                           { [$1] }
  | actuals_list COMMA expr        { $3 :: $1 }
```

Testing with menhir

```
$ menhir --interpret --interpret-show-cst parser.mly
ID LPAREN RPAREN LBRACE ID LPAREN LITERAL RPAREN SEMI RBRACE EOF
ACCEPT
```

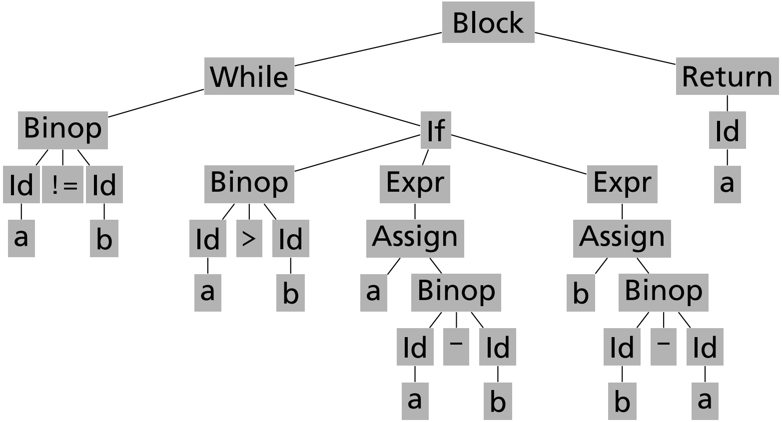
```
main() {
  print(42);
}
```

```
[program:
  [decls:
    [decls:]
    [fdecl:
      ID
      LPAREN
      [formals_opt:]
      RPAREN
      LBRACE
      [vdecl_list:]
      [stmt_list:
        [stmt_list:]
        [stmt:
          [expr:
            ID
            LPAREN
            [actuals_opt: [actuals_list: [expr: LITERAL]]]
            RPAREN
          ]
          SEMI
        ]
      ]
      RBRACE
    ]
  ]
  EOF
]
```

AST for the GCD Example

```
gcd(a, b) {
  while (a != b)
    if (a > b) a = a - b;
    else b = b - a;
  return a;
}
```

```
fname = gcd
formals = [a, b]
locals = []
body =
```



AST for the GCD Example

```
gcd(a, b) {
  while (a != b)
    if (a > b) a = a - b;
    else b = b - a;
  return a;
}
```

```
fname = gcd
formals = [a, b]
locals = []
body =
```

```
[While (Binop (Id a) Neq (Id b))
       (Block [(If (Binop (Id a) Greater (Id b))
                   (Expr (Assign a
                            (Binop (Id a) Sub (Id b))))
                   (Expr (Assign b
                            (Binop (Id b) Sub (Id a)))))
              ]),
 Return (Id a)]
```

An Interpreter

Run the program directly
from the structure of the
Abstract Syntax Tree

Not part of a true compiler

Shown here to illustrate the semantics of MicroC

The Interpreter (interpret.ml)

```
open Ast

module NameMap = Map.Make(String)

(* Symbol table for variables: map from variable names to values *)
type vsymtab = int NameMap.t

(* Execution environment: local variables * global variables *)
type env = vsymtab * vsymtab

(* Used to handle the "return" statement: (value, global variables) *)
exception ReturnException of int * vsymtab

(* Main entry point: run a program *)
let run ((vars, funcs) : program) : unit =

  (* Build a symbol table for function declarations *)
  let func_decls : (func_decl NameMap.t) = List.fold_left
      (fun funcs fdecl -> NameMap.add fdecl.fname fdecl funcs)
      NameMap.empty funcs
  in

  (* Invoke a function and return an updated global symbol table *)
  let rec call (fdecl : func_decl) (actuals : int list)
                  (globals : vsymtab) : vsymtab =
```

eval: Evaluating an expression

```
(* Evaluate an expression; return value and updated environment *)
let rec eval (env : env) (exp : expr) : int * env = match exp with

    Literal(i) -> i, env  (* Simplest case: 1 is just 1 *)

  | Noexpr -> 1, env (* must be non-zero for the for loop predicate *)
```

MicroC has only a single built-in function, *print*; this is an easy way to implement it. Your compiler should have very few exceptions like this.

```
  | Call("print", [e]) ->
      let v, env = eval env e in
      print_endline (string_of_int v);
      0, env
```

eval: Handling variables

What can happen when you refer to a variable?

What are MicroC's *scoping rules*?

```
int a;     /* Global variable */
int c;

foo(a) {   /* Formal argument */
  int b;   /* Local variable  */
  ... a = ... a ...
  ... b = ... b ...
  ... c = ... c ...
  ... d = ... d ...
}
```

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What are MicroC's *scoping rules*?

```
int a;     /* Global variable */
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foo(a) {   /* Formal argument */
  int b;   /* Local variable  */
  ... a = ... a ...
  ... b = ... b ...
  ... c = ... c ...
  ... d = ... d ...
}
```

```
| Id(var) ->
    let locals, globals = env in
    if NameMap.mem var locals then
      (NameMap.find var locals), env
    else if NameMap.mem var globals then
      (NameMap.find var globals), env
    else raise (Failure ("undeclared identifier " ^ var))
| Assign(var, e) ->
    let v, (locals, globals) = eval env e in
    if NameMap.mem var locals then
      v, (NameMap.add var v locals, globals)
    else if NameMap.mem var globals then
      v, (locals, NameMap.add var v globals)
    else raise (Failure ("undeclared identifier " ^ var))
```

eval: Binary operators

In MicroC, an expression may have a side effect: modify local or global variables.

Side effects must be handled explicitly in OCaml.

```
a = 42;
b = 17;
c = (a = 3) + (b = 4) + a;
```

eval: Binary operators

In MicroC, an expression may have a side effect: modify local or global variables.

```
a = 42;
b = 17;
c = (a = 3) + (b = 4) + a;
```

Side effects must be handled explicitly in OCaml.

```
  | Binop(e1, op, e2) ->
      let v1, env = eval env e1 in
      let v2, env = eval env e2 in
      let boolean i = if i then 1 else 0 in
      (match op with
        Add -> v1 + v2
      | Sub -> v1 - v2
      | Mult -> v1 * v2
      | Div -> v1 / v2
      | Equal -> boolean (v1 = v2)
      | Neq -> boolean (v1 != v2)
      | Less -> boolean (v1 < v2)
      | Leq -> boolean (v1 <= v2)
      | Greater -> boolean (v1 > v2)
      | Geq -> boolean (v1 >= v2)), env
```

Actual arguments to function calls must be evaluated and their side-effects retained.

The *return* statement throws an exception with the return value and the updated globals (locals are discarded).

```
foo() {
  ... gcd(c = d + 5, e = f + 6) ...
  ... c ... e ...
}

gcd(a, b) {
  int c;
  ...
  return ...
}
```

Actual arguments to function calls must be evaluated and their side-effects retained.

```
foo() {
  ... gcd(c = d + 5, e = f + 6) ...
  ... c ... e ...
}

gcd(a, b) {
  int c;
  ...
  return ...
}
```

The *return* statement throws an exception with the return value and the updated globals (locals are discarded).

```
| Call(f, actuals) ->
    let fdecl =
      try NameMap.find f func_decls
      with Not_found -> raise (Failure ("undefined function " ^ f))
    in
    let ractuals, env = List.fold_left
        (fun (actuals, env) actual ->
          let v, env = eval env actual in v :: actuals, env)
        ([], env) actuals
    in
    let (locals, globals) = env in
    try
      let globals = call fdecl (List.rev ractuals) globals
      in  0, (locals, globals)
    with ReturnException(v, globals) -> v, (locals, globals)
```

exec: Running a statement

Type signature of *exec* designed to work with *fold_left*.

Expression statement is for side effects only: result discarded

Remember side-effects in *if* predicate.

```
if ( (a = foo()) == b )
  c = a;
else
  d = a + 1;
```

exec: Running a statement

Type signature of *exec* designed to work with *fold_left*.

Expression statement is for side effects only: result discarded

Remember side-effects in *if* predicate.

```
if ( (a = foo()) == b )
  c = a;
else
  d = a + 1;
```

```
(* Execute a statement and return an updated environment *)
let rec exec (env : env) (stmt : stmt) : env = match stmt with

    Block(stmts) -> List.fold_left exec env stmts

  | Expr(e) -> let _, env = eval env e in env

  | If(e, s1, s2) ->
      let v, env = eval env e in
      exec env (if v != 0 then s1 else s2)
```

Statements: *While*, *For*, and *Return*

```
    | While(e, s) ->
      let rec loop env =
        let v, env = eval env e in
        if v != 0 then loop (exec env s) else env
      in loop env

    | For(e1, e2, e3, s) ->
      let _, env = eval env e1 in
      let rec loop env =
        let v, env = eval env e2 in
        if v != 0 then
          let _, env = eval (exec env s) e3 in
          loop env
        else
          env
      in loop env

    | Return(e) ->
      let v, (locals, globals) = eval env e in
      raise (ReturnException(v, globals))
  in
```

Body of *call*: bind arguments; run body

```
foo() {
  ... gcd(10 + 5, 42) ...
}

gcd(a, b) {
  int c;
  ...
}
```

At the call of *gcd*,

actuals = [15, 42]
fdecl.formals = ["a", "b"]
fdecl.locals = ["c"]

Body of *call*: bind arguments; run body

```
foo() {
  ... gcd(10 + 5, 42) ...
}

gcd(a, b) {
  int c;
  ...
}
```

At the call of *gcd*,

actuals = [15, 42]
fdecl.formals = [“a”, “b”]
fdecl.locals = [“c”]

```
(* Body of "call": bind actual values to formal arguments *)
let locals : vsymtab =
  try List.fold_left2
    (fun locals formal actual -> NameMap.add formal actual locals)
    NameMap.empty fdecl.formals actuals
  with Invalid_argument(_) ->
    raise (Failure ("wrong number of arguments to " ^ fdecl.fname))
in
let locals : vsymtab = List.fold_left (* Set local variables to 0 *)
    (fun locals local -> NameMap.add local 0 locals)
    locals fdecl.locals

in (* Execute each statement; return updated global symbol table *)
snd (List.fold_left exec (locals, globals) fdecl.body)
```

Body of *run*: initialize globals; run *main*

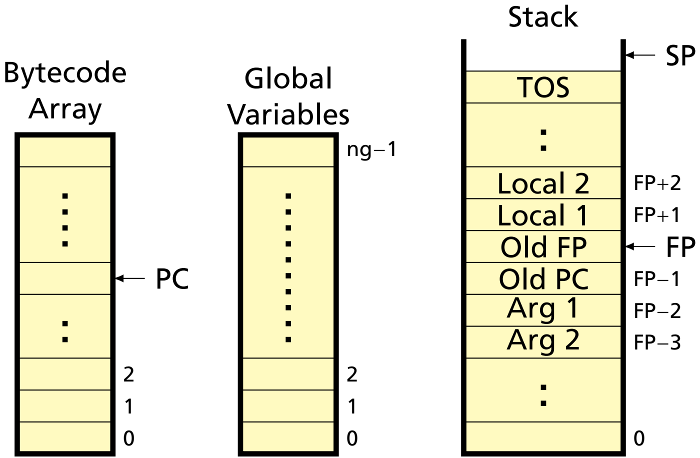
```
(* Body of "run" *)

(* Set each global variable to 0 *)
in let globals : vsymtab = List.fold_left
    (fun globals vdecl -> NameMap.add vdecl 0 globals)
    NameMap.empty vars

in try

  (* Execute the "main" function; discard final state of globals *)
  ignore (call (NameMap.find "main" func_decls) [] globals)

with Not_found ->
  raise (Failure ("did not find the main() function"))
```

A Bytecode Compiler

Translate the AST into bytecode:
machine language for a virtual machine

This is compilation: a syntax-directed translation into a more detailed representation of the program

Bytecode Machine Programmers' Model



Stack-based virtual machine with three registers:

Program counter, Stack pointer (top of stack), and
Frame pointer (base of current function's activation record)

Bytecode Instructions

```
type binst =
    Lit of int    (* Push a literal *)
  | Drp           (* Discard a value *)
  | Bin of Ast.op (* Perform arithmetic on top of stack *)
  | Lod of int    (* Fetch global variable *)
  | Str of int    (* Store TOS as global variable *)
  | Lfp of int    (* Load frame pointer relative *)
  | Sfp of int    (* Store TOS frame pointer relative *)
  | Jsr of int    (* Push PC, jump to function *)
  | Ent of int    (* Push FP, FP -> SP, SP += i *)
  | Rts of int    (* Restore FP, SP, consume formals, push result *)
  | Beq of int    (* Branch relative if top-of-stack is zero *)
  | Bne of int    (* Branch relative if top-of-stack is non-zero *)
  | Bra of int    (* Branch relative *)
  | Hlt           (* Terminate *)

type prog = {
    num_globals : int;  (* Number of global variables *)
    text : binst array; (* Code for all the functions *)
  }
```

Bytecode Examples

```
foo () {
  int a;
  a = 42;
  print(a);
}
```

```
Lit 42   # Push 42
Sfp 1    # Store local variable "a"
Drp      # Discard 42

Lfp 1    # Load local variable "a"
Jsr -1   # Call print
Drp      # Discard result
```

```
foo (a, b) {
  a = a - b;
}
```

```
Lfp -2   # Push first argument, "a"
Lfp -3   # Push second argument, "b"
Sub      # Calculate a - b
Sfp -2   # Store result in "a"
Drp      # Drop stack contents
```

Complete Bytecode for GCD

```
gcd(a, b) {
  while (a != b) {
    if (a > b)
      a = a - b;
    else
      b = b - a;
  }
  return a;
}

main()
{
  print(
    gcd(2,14));
  print(
    gcd(3,15));
  print(
    gcd(99,121));
}
```

```
 0 Jsr 2   #main()
 1 Hlt

 2 Ent 0   #main() func
 3 Lit 14
 4 Lit 2
 5 Jsr 20 #gcd(2,14)
 6 Jsr -1 #print()
 7 Drp

 8 Lit 15
 9 Lit 3
10 Jsr 20 #gcd(3,15)
11 Jsr -1 #print()
12 Drp

13 Lit 121
14 Lit 99
15 Jsr 20 #gcd(99,121)
16 Jsr -1 #print()
17 Drp

18 Lit 0
19 Rts 0
```

```
20 Ent 0    # gcd() func
21 Bra 16   # goto 37

22 Lfp -2   # a > b?
23 Lfp -3
24 Gt
25 Beq 7    # else 32

26 Lfp -2   # a = a - b
27 Lfp -3
28 Sub
29 Sfp -2
30 Drp
31 Bra 6    # goto 37

32 Lfp -3   # b = b - a
33 Lfp -2
34 Sub
35 Sfp -3
36 Drp

37 Lfp -2   # a != b?
38 Lfp -3
39 Neq
40 Bne -18 # 22

41 Lfp -2   # return a
42 Rts 2
43 Lit 0
44 Rts 2
```

The Compiler (compile.ml)

```
open Ast
open Bytecode

module StringMap = Map.Make(String)

(* Environment: symbol tables for functions, global, and local vars *)
type env = {
    function_index : int StringMap.t; (* Index for each function *)
    global_index   : int StringMap.t; (* Address for global vars *)
    local_index    : int StringMap.t; (* FP offset for args, locals *)
  }

(* enum : int -> int -> 'a list -> (int * 'a) list *)
(* enum 1 2 [14,23,42] = [ (2,14), (3,23), (4,43) ] *)
let rec enum stride n = function
    [] -> []
  | hd::tl -> (n, hd) :: enum stride (n+stride) tl

(* string_map_pairs:StringMap 'a -> (int * 'a) list -> StringMap 'a *)
let string_map_pairs map pairs =
  List.fold_left (fun m (i, n) -> StringMap.add n i m) map pairs
```

```
(** Translate a program in AST form into a bytecode program. Throw an
    exception if something is wrong, e.g., a reference to an unknown
    variable or function *)
let translate (globals, functions) =

  (* Allocate "addresses" for each global variable *)
  let global_indexes =
    string_map_pairs StringMap.empty (enum 1 0 globals) in

  (* Assign indexes to function names; built-in "print" is special *)
  let built_in_functions =
    StringMap.add "print" (-1) StringMap.empty in
  let function_indexes = string_map_pairs built_in_functions
      (enum 1 1 (List.map (fun f -> f.fname) functions)) in

  (* Translate an AST function to a list of bytecode statements *)
  let translate env fdecl =
    (* Bookkeeping: FP offsets for locals and arguments *)
    let num_formals = List.length fdecl.formals
    and num_locals = List.length fdecl.locals
    and local_offsets = enum 1 1 fdecl.locals
    and formal_offsets = enum (-1) (-2) fdecl.formals in
    let env = { env with local_index = string_map_pairs
                  StringMap.empty (local_offsets @ formal_offsets) } in
```

expr: Literals, Variables

```
int a;

foo(b) {
  int c;
  c = a;
  print(c);
  a = b;
  print(a);
}
```

```
Lod 0  # a
Sfp 1  # c <-
Drp
Lfp 1  # c
Jsr -1 # print()
Drp
Lfp -2 # b
Str 0  # a <-
Drp
Lod 0  # a
Jsr -1 # print()
Drp
```

expr: Literals, Variables

```
int a;

foo(b) {
  int c;
  c = a;
  print(c);
  a = b;
  print(a);
}
```

```
Lod 0  # a
Sfp 1  # c <-
Drp
Lfp 1  # c
Jsr -1 # print()
Drp
Lfp -2 # b
Str 0  # a <-
Drp
Lod 0  # a
Jsr -1 # print()
Drp
```

```
let rec expr : expr -> binst list = function
    Literal i -> [Lit i]
  | Id s ->
      (try [Lfp (StringMap.find s env.local_index)]
      with Not_found -> try
        [Lod (StringMap.find s env.global_index)]
      with Not_found ->
        raise (Failure ("undeclared variable " ^ s)))
  | Assign (s, e) -> expr e @
      (try [Sfp (StringMap.find s env.local_index)]
      with Not_found -> try
        [Str (StringMap.find s env.global_index)]
      with Not_found ->
        raise (Failure ("undeclared variable " ^ s)))
```

expr: Binary operators, function calls

```
add(a, b)
{
  return a + b;
}

main()
{
  int a;
  a = add(39, 3);
}
```

```
Lfp -2 # a
Lfp -3 # b
Add    # a + b

Lit 3  # second arg
Lit 39 # first arg
Jsr 13 # add()
Sfp 1  # a <-
Drp
```

expr: Binary operators, function calls

```
add(a, b)
{
  return a + b;
}

main()
{
  int a;
  a = add(39, 3);
}
```

```
Lfp -2 # a
Lfp -3 # b
Add    # a + b

Lit 3  # second arg
Lit 39 # first arg
Jsr 13 # add()
Sfp 1  # a <-
Drp
```

```
      | Noexpr -> []

      | Binop (e1, op, e2) -> expr e1 @ expr e2 @ [Bin op]

      | Call (fname, actuals) -> (try
          (List.concat (List.map expr (List.rev actuals))) @
          [Jsr (StringMap.find fname env.function_index) ]
        with Not_found ->
          raise (Failure ("undefined function " ^ fname)))
```

Statements

```
foo(a, b, c) {
 int d;
 if (a == 3)
   d = b;
 else
   d = c;
}
```

```
11 Lfp -2
# if a == 3
12 Lit 3
13 Eql
14 Beq 5    # -> 19

15 Lfp -3   # d = b
16 Sfp 1
17 Drp
18 Bra 4    # goto 22

19 Lfp -4   # c
20 Sfp 1    # d
21 Drp

22 ...
```

Statements

```
foo(a, b, c) {
 int d;
 if (a == 3)
   d = b;
 else
   d = c;
}
```

```
11 Lfp -2
# if a == 3
12 Lit 3
13 Eql
14 Beq 5   # -> 19

15 Lfp -3  # d = b
16 Sfp 1
17 Drp
18 Bra 4   # goto 22

19 Lfp -4  # c
20 Sfp 1   # d
21 Drp

22 ...
```

```
(* Translate a statement *)
in let rec stmt : stmt -> binst list = function
    Block sl     -> List.concat (List.map stmt sl)

  | Expr e       -> expr e @ [Drp] (* Discard result *)

  | Return e     -> expr e @ [Rts num_formals]

  | If (p, t, f) -> let t' = stmt t and f' = stmt f in
    expr p @ [Beq(2 + List.length t')] @
    t' @ [Bra(1 + List.length f')] @ f'
```

Statements

```
int i;
for ( i = 5 ; i > 0 ; i = i - 1 )
  print(i);
```

```
int i;
i = 5;
while (i > 0) {
  print(i);
  i = i - 1;
}
```

```
 3 Lit 5
 4 Sfp 1   # i = 51
 5 Drp
 6 Bra 9   # -> 15
 7 Lfp 1
 8 Jsr -1  # print(i)
 9 Drp
10 Lfp 1
11 Lit 1
12 Sub
13 Sfp 1   # i = i - 1
14 Drp
15 Lfp 1
16 Lit 0
17 Gt      # i > 0
18 Bne -11 # -> 7
```

Statements

```
int i;
for ( i = 5 ; i > 0 ; i = i - 1 )
  print(i);
```

```
int i;
i = 5;
while (i > 0) {
  print(i);
  i = i - 1;
}
```

```
 3 Lit 5
 4 Sfp 1     # i = 51
 5 Drp
 6 Bra 9     # -> 15
 7 Lfp 1
 8 Jsr -1    # print(i)
 9 Drp
10 Lfp 1
11 Lit 1
12 Sub
13 Sfp 1     # i = i - 1
14 Drp
15 Lfp 1
16 Lit 0
17 Gt        # i > 0
18 Bne -11 # -> 7
```

```
    | For (e1, e2, e3, b) -> (* Rewrite into a while statement *)
      stmt (Block([Expr(e1); While(e2, Block([b; Expr(e3)]))]))

    | While (e, b) ->
      let b' = stmt b and e' = expr e in
      [Bra (1+ List.length b')] @ b' @ e' @
      [Bne (-(List.length b' + List.length e'))]
```

Translate a whole function

```
foo(a, b)
{
  int c;
  int d;
  int e;
  print(a);
  e = a + b + 10;
  print(e);
}
```

```
 9 Ent 3   # Make space for c, d, and e
10 Lfp -2
11 Jsr -1  # print(a)
12 Drp
13 Lfp -2
14 Lfp -3
15 Add     # a + b
16 Lit 10
17 Add     # a + b + 10
18 Sfp 3   # e
19 Drp
20 Lfp 3
21 Jsr -1  # print(c)
22 Drp
23 Lit 0   # Implicit return value
24 Rts 2   # Discard a, b arguments
```

```
    (* Translate a whole function *)
    in [Ent num_locals] @        (* Entry: allocate space for locals *)
    stmt (Block fdecl.body) @    (* Body *)
    [Lit 0; Rts num_formals]     (* Default = return 0 *)
```

```
in let env = { function_index = function_indexes;
               global_index = global_indexes;
               local_index = StringMap.empty } in

(* Code executed to start the program: Jsr main; halt *)
let entry_function = try
    [Jsr (StringMap.find "main" function_indexes); Hlt]
  with Not_found -> raise (Failure ("no \"main\" function"))
in

(* Compile the functions *)
let func_bodies = entry_function ::
                  List.map (translate env) functions in

(* Calculate function entry points by adding their lengths *)
let (fun_offset_list, _) = List.fold_left
    (fun (l,i) f -> (i :: l, (i + List.length f))) ([],0)
    func_bodies in
let func_offset = Array.of_list (List.rev fun_offset_list) in

{ num_globals = List.length globals;
  (* Concatenate the compiled functions and replace the function
     indexes in Jsr statements with PC values *)
  text = Array.of_list (List.map (function
      Jsr i when i > 0 -> Jsr func_offset.(i)
    | _ as s -> s) (List.concat func_bodies))
}
```

A Bytecode Interpreter

A virtual machine that executes bytecode

This is one way to run the program;
could also translate bytecode into C, assembly, etc.

The Bytecode Interpreter (execute.ml)

```
open Ast
open Bytecode

let execute_prog prog =
  let stack = Array.make 1024 0
  and globals = Array.make prog.num_globals 0 in

  let rec exec fp sp pc = match prog.text.(pc) with
    Lit i  -> stack.(sp) <- i ; exec fp (sp+1) (pc+1)
  | Drp    -> exec fp (sp-1) (pc+1)
  | Bin op -> let op1 = stack.(sp-2) and op2 = stack.(sp-1) in
      stack.(sp-2) <- (let boolean i = if i then 1 else 0 in
      match op with
        Add     -> op1 + op2
      | Sub     -> op1 - op2
      | Mult    -> op1 * op2
      | Div     -> op1 / op2
      | Equal   -> boolean (op1 =  op2)
      | Neq     -> boolean (op1 != op2)
      | Less    -> boolean (op1 <  op2)
      | Leq     -> boolean (op1 <= op2)
      | Greater -> boolean (op1 >  op2)
      | Geq     -> boolean (op1 >= op2)) ;
      exec fp (sp-1) (pc+1)
```

The Bytecode Interpreter (execute.ml)

```
| Lod i    -> stack.(sp)    <- globals.(i)  ; exec fp (sp+1) (pc+1)
| Str i    -> globals.(i)  <- stack.(sp-1) ; exec fp sp     (pc+1)
| Lfp i    -> stack.(sp)    <- stack.(fp+i) ; exec fp (sp+1) (pc+1)
| Sfp i    -> stack.(fp+i) <- stack.(sp-1) ; exec fp sp     (pc+1)
| Jsr(-1) -> print_endline (string_of_int stack.(sp-1)) ;
             exec fp sp (pc+1)
| Jsr i    -> stack.(sp)    <- pc + 1       ; exec fp (sp+1) i
| Ent i    -> stack.(sp)    <- fp           ; exec sp (sp+i+1) (pc+1)
| Rts i    -> let new_fp = stack.(fp) and new_pc = stack.(fp-1) in
             stack.(fp-i-1) <- stack.(sp-1) ;
             exec new_fp (fp-i) new_pc
| Beq i    -> exec fp (sp-1)
              (pc + if stack.(sp-1) =  0 then i else 1)
| Bne i    -> exec fp (sp-1)
              (pc + if stack.(sp-1) != 0 then i else 1)
| Bra i    -> exec fp sp (pc+i)
| Hlt      -> ()

in exec 0 0 0
```

The Top Level (microc.ml)

```
type action = Ast | Interpret | Bytecode | Compile

let _ =
  let action = if Array.length Sys.argv > 1 then
    List.assoc Sys.argv.(1) [ ("-a", Ast);
                              ("-i", Interpret);
                              ("-b", Bytecode);
                              ("-c", Compile) ]
  else Compile in

  let lexbuf = Lexing.from_channel stdin in
  let program = Parser.program Scanner.token lexbuf in

  match action with
    Ast -> let listing = Ast.string_of_program program
           in print_string listing
  | Interpret -> ignore (Interpret.run program)
  | Bytecode -> let listing = Bytecode.string_of_prog
                                (Compile.translate program)
                in print_endline listing
  | Compile -> Execute.execute_prog (Compile.translate program)
```

Source Code Statistics

File	Lines	Role
scanner.mll	36	Token rules
parser.mly	93	Context-free grammar
ast.ml	66	Abstract syntax tree & pretty printer
interpret.ml	123	AST interpreter
bytecode.ml	51	Bytecode type and pretty printer
compile.ml	104	AST-to-bytecode compiler
execute.ml	51	Bytecode interpreter
microc.ml	20	Top-level
Total	544	

Test Case Statistics

File	Lines	File	Lines	Role
test-arith1.mc	4	test-arith1.out	1	basic arithmetic
test-arith2.mc	4	test-arith2.out	1	precedence, associativity
test-fib.mc	15	test-fib.out	6	recursion
test-for1.mc	8	test-for1.out	6	for loop
test-func1.mc	11	test-func1.out	1	user-defined function
test-func2.mc	18	test-func2.out	1	argument eval. order
test-func3.mc	12	test-func3.out	4	argument eval. order
test-gcd.mc	14	test-gcd.out	3	greatest common divisor
test-global1.mc	29	test-global1.out	4	global variables
test-hello.mc	6	test-hello.out	3	printing
test-if1.mc	5	test-if1.out	2	if statements
test-if2.mc	5	test-if2.out	2	else
test-if3.mc	5	test-if3.out	1	false predicate
test-if4.mc	5	test-if4.out	2	false else
test-ops1.mc	27	test-ops1.out	24	all binary operators
test-var1.mc	6	test-var1.out	1	local variables
test-while1.mc	10	test-while1.out	6	while loop
Total	184		68	