The MicroC Compiler

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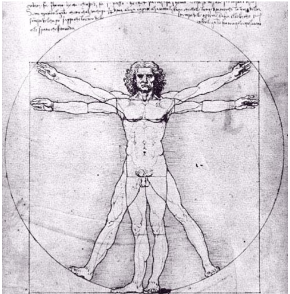
Fall 2016



The Front-End

Static Semantic Checking

Code Generation

The Top-Level

The MicroC Language

A very stripped-down dialect of C

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

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

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

int main()
{
  print(gcd(2,14));
  print(gcd(3,15));
  print(gcd(99,121));
  return 0;
}
```

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 }

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

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

The AST (ast.ml)

```
type op = Add | Sub | Mult | Div | Equal | Neq |
          Less | Leq | Greater | Geq | And | Or
type uop = Neg | Not
type typ = Int | Bool | Void
type bind = typ * string

type expr = Literal of int                   | BoolLit of bool
          | Id of string                     | Noexpr
          | Binop of expr * op * expr        | Unop of uop * expr
          | Assign of string * expr          | Call of string * expr list

type stmt = Block of stmt list               | Expr of expr
          | If of expr * stmt * stmt
          | For of expr * expr * expr * stmt
          | While of expr * stmt             | Return of expr

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

type program = bind list * func_decl list
```

The Parser (parser.mly)

```
%{ open Ast %}

%token SEMI LPAREN RPAREN LBRACE RBRACE COMMA
%token PLUS MINUS TIMES DIVIDE ASSIGN NOT
%token EQ NEQ LT LEQ GT GEQ TRUE FALSE AND OR
%token RETURN IF ELSE FOR WHILE INT BOOL VOID

%token <int> LITERAL
%token <string> ID
%token EOF

%nonassoc NOELSE
%nonassoc ELSE
%right ASSIGN
%left OR
%left AND
%left EQ NEQ
%left LT GT LEQ GEQ
%left PLUS MINUS
%left TIMES DIVIDE
%right NOT NEG

%start program
%type <Ast.program> program

%%
```

Declarations

```
program:  decls EOF { $1 }

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

fdecl:
   typ ID LPAREN formals_opt RPAREN LBRACE vdecl_list stmt_list RBRACE
      { { typ = $1; fname = $2; formals = $4;
          locals = List.rev $7; body = List.rev $8 } }

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

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

typ: INT  { Int }
   | BOOL { Bool }
   | VOID { Void }

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

vdecl:  typ ID SEMI { ($1, $2) }
```

Statements

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

stmt:
    expr SEMI                                  { Expr $1 }
  | RETURN SEMI                                { Return Noexpr }
  | 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 SEMI expr_opt RPAREN stmt
                                               { For($3, $5, $7, $9) }
  | WHILE LPAREN expr RPAREN stmt              { While($3, $5) }
```

Expressions

```
expr:
    LITERAL                  { Literal($1) }
  | TRUE                     { BoolLit(true) }
  | FALSE                    { BoolLit(false) }
  | 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) }
  | expr AND    expr         { Binop($1, And,     $3) }
  | expr OR     expr         { Binop($1, Or,      $3) }
  | MINUS expr %prec NEG     { Unop(Neg, $2) }
  | NOT expr                 { Unop(Not, $2) }
  | ID ASSIGN expr           { Assign($1, $3) }
  | LPAREN expr RPAREN       { $2 }
  | ID LPAREN actuals_opt RPAREN { Call($1, $3) }
```

Expressions concluded

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

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
INT ID LPAREN RPAREN LBRACE ID LPAREN LITERAL RPAREN SEMI RBRACE EOF
ACCEPT
```

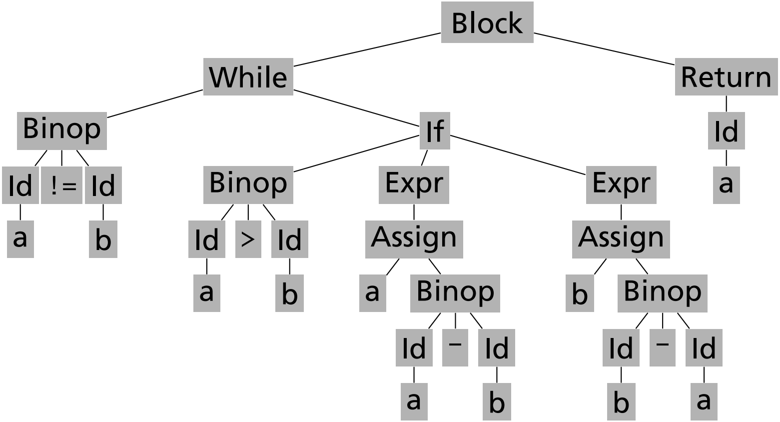
```
[program:
  [decls:
    [decls:]
    [fdecl:
      [typ: INT]
      ID
      LPAREN
      [formals_opt:]
      RPAREN
      LBRACE
      [vdecl_list:]
      [stmt_list:
        [stmt_list:]
        [stmt:
          [expr:
            ID
            LPAREN
            [actuals_opt: [actuals_list: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

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

AST for the GCD Example

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

```
typ = Int
fname = gcd
formals = [Int a; Int b]
locals = []
body =
```



AST for the GCD Example

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

```
typ = Int
fname = gcd
formals = [Int a; Int 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)]
```

Static Semantic Checking

Walk over the AST
Verify each node
Establish existence of each identifier
Establish type of each expression
Validate statements in functions

The Semantic Checker (semant.ml)

```
open Ast

module StringMap = Map.Make(String)

(* Semantic checking of a program. Returns void if successful,
   throws an exception if something is wrong.
   Check each global variable, then check each function *)

let check (globals, functions) =
```

Used to check for identically named globals, functions, formal arguments, and local variables

```
  (* Raise an exception if the given list has a duplicate *)
  let report_duplicate exceptf list =
    let rec helper = function
        n1 :: n2 :: _ when n1 = n2 -> raise (Failure (exceptf n1))
      | _ :: t -> helper t
      | [] -> ()
    in helper (List.sort compare list)
  in
```

Helper functions

Used to check for *void* globals, formal arguments, and locals

```
(* Raise an exception if a given binding is to a void type *)
let check_not_void exceptf = function
    (Void, n) -> raise (Failure (exceptf n))
  | _ -> ()
in
```

In the assignment *lvalue* = *rvalue*,
can the type of *rvalue* be assigned to *lvalue*?

Used to test assignments and function calls

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

Global Variables, Function Names

```
(**** Checking Global Variables ****)

List.iter (check_not_void (fun n -> "illegal void global " ^ n))
          globals;

report_duplicate (fun n -> "duplicate global " ^ n)
                 (List.map snd globals);
```

```
(**** Checking Functions ****)

if List.mem "print" (List.map (fun fd -> fd.fname) functions)
then raise (Failure ("function print may not be defined")) else ();

report_duplicate (fun n -> "duplicate function " ^ n)
  (List.map (fun fd -> fd.fname) functions);
```

Function Symbol Table

```
(* Function declaration for a named function *)
let built_in_decls =  StringMap.add "print"
   { typ = Void; fname = "print"; formals = [(Int, "x")];
     locals = []; body = [] } (StringMap.singleton "printb"
   { typ = Void; fname = "printb"; formals = [(Bool, "x")];
     locals = []; body = [] })
in
```

MicroC has two built-in functions, *print* and *printb*; this is an easy way to implement it. Your compiler should have very few exceptions like this.

```
let function_decls =
   List.fold_left (fun m fd -> StringMap.add fd.fname fd m)
                  built_in_decls functions
in

let function_decl s = try StringMap.find s function_decls
  with Not_found -> raise (Failure ("unrecognized function " ^ s))
in

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

Check a Function

```
let check_function func =

  List.iter (check_not_void (fun n ->
       "illegal void formal " ^ n ^ " in " ^ func.fname))
    func.formals;

  report_duplicate (fun n ->
       "duplicate formal " ^ n ^ " in " ^ func.fname)
    (List.map snd func.formals);

  List.iter (check_not_void (fun n ->
       "illegal void local " ^ n ^ " in " ^ func.fname))
    func.locals;

  report_duplicate (fun n ->
       "duplicate local " ^ n ^ " in " ^ func.fname)
    (List.map snd func.locals);
```

Variable Symbol Table

What can happen when you refer to a variable?

What are MicroC's *scoping rules*?

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

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

```
(* Variable symbol table: type of each global, formal, local *)
let symbols = List.fold_left
                (fun m (t, n) -> StringMap.add n t m)
                StringMap.empty
                ( globals @ func.formals @ func.locals )
in

let type_of_identifier s =
  try StringMap.find s symbols
  with Not_found ->
    raise (Failure ("undeclared identifier " ^ s))
in
```

Expressions

The key semantic-checking operation: establish the type of each subexpression.

```
(* Return the type of an expression or throw an exception *)
let rec expr = function
    Literal _ -> Int
  | BoolLit _ -> Bool
  | Noexpr    -> Void
```

An identifier: does it exist? What is its type?

```
  | Id s      -> type_of_identifier s
```

Assignment: need to know the types of the *lvalue* and *rvalue*, and whether one can be assigned to the other.

```
  | Assign(var, e) as ex -> let lt = type_of_identifier var
                            and rt = expr e in
    check_assign lt rt
         (Failure ("illegal assignment " ^ string_of_typ lt ^
          " = " ^ string_of_typ rt ^ " in " ^ string_of_expr ex))
```

Operators

What types can be added? Subtracted? Compared for equality? Negated?

```
| Binop(e1, op, e2) as e -> let t1 = expr e1
                            and t2 = expr e2 in
  (match op with
    Add | Sub | Mult | Div     when t1 = Int && t2 = Int   -> Int
  | Equal | Neq                when t1 = t2                -> Bool
  | Less | Leq | Greater | Geq when t1 = Int && t2 = Int   -> Bool
  | And | Or                   when t1 = Bool && t2 = Bool -> Bool
  | _ -> raise (Failure ("illegal binary operator " ^
                 string_of_typ t1 ^ " " ^ string_of_op op ^ " " ^
                 string_of_typ t2 ^ " in " ^ string_of_expr e))
  )

| Unop(op, e) as ex -> let t = expr e in
   (match op with
     Neg when t = Int  -> Int
   | Not when t = Bool -> Bool
   | _ -> raise (Failure ("illegal unary operator " ^
                  string_of_uop op ^ string_of_typ t ^
                  " in " ^ string_of_expr ex)))
```

Function Calls

Number and type of formals and actuals must match

```
void foo(t1 f1, t2 f2) { ... }
```

```
... = ... foo(expr1, expr2) ...
```

The callsite behaves like

```
f1 = expr1;
f2 = expr2;
```

```
  | Call(fname, actuals) as call -> let fd = function_decl fname in
     if List.length actuals != List.length fd.formals then
       raise (Failure ("expecting " ^ string_of_int
         (List.length fd.formals) ^ " arguments in " ^
         string_of_expr call))
     else
       List.iter2 (fun (ft, _) e -> let et = expr e in
          ignore (check_assign ft et
            (Failure ("illegal actual argument found " ^
               string_of_typ et ^ " expected " ^
               string_of_typ ft ^ " in " ^ string_of_expr e))))
          fd.formals actuals;
       fd.typ (* Finally, the call returns the function's type *)
in
```

Statements

Make sure an expression is Boolean: used in *if*, *for*, *while*.

```
let check_bool_expr e = if expr e != Bool
 then raise (Failure ("expected Boolean expression in " ^
                      string_of_expr e))
 else () in
```

Checking a statement: make sure it is well-formed or throw an exception

```
(* Verify a statement or throw an exception *)
let rec stmt = function
    Expr e -> ignore (expr e)

  | If(p, b1, b2) -> check_bool_expr p; stmt b1; stmt b2

  | For(e1, e2, e3, st) -> ignore (expr e1); check_bool_expr e2;
                           ignore (expr e3); stmt st

  | While(p, s) -> check_bool_expr p; stmt s
```

Statements: Return

The type of the argument to *return* must match the type of the function.

```
    | Return e ->
        let t = expr e in
        if t = func.typ then ()
        else raise (Failure ("return gives " ^ string_of_typ t ^
                    " expected " ^ string_of_typ func.typ ^ " in " ^
                    string_of_expr e))
```

Statements: Blocks

Checking a block of statements is almost `List.iter stmt sl`, but LLVM does not like code after a return:

```
int main() {
   return 1;
   print(42); /* Illegal: code after a return */
}
```

```
      | Block sl -> let rec check_block = function
          [Return _ as s] -> stmt s
         | Return _ :: _ ->
             raise (Failure "nothing may follow a return")
         | Block sl :: ss -> check_block (sl @ ss)
         | s :: ss -> stmt s ; check_block ss
         | [] -> ()
        in check_block sl
```

Bodies of check_function and check

check_function: check the statements in the body

```
    in stmt (Block func.body)  (* body of check_function *)
```

check: check each function in the program

```
  in List.iter check_function functions (* body of check *)
```

Code Generation

Assumes AST is semantically correct
Translate each AST node into LLVM IR
Construct expressions bottom-up
Construct basic blocks for control-flow statements

`http://llvm.org`
`http://llvm.org/docs/tutorial`

`http://llvm.moe` Ocaml bindings documentation

The LLVM IR

Assembly-language like: list of simple operations

Static Single-Assignment: each value (e.g., %x3) assigned exactly once

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

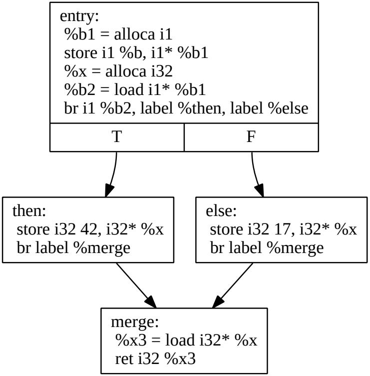
```
define i32 @add(i32 %x, i32 %y) {
entry:
  %x1 = alloca i32
  store i32 %x, i32* %x1
  %y2 = alloca i32
  store i32 %y, i32* %y2
  %x3 = load i32* %x1
  %y4 = load i32* %y2
  %tmp = add i32 %x3, %y4
  ret i32 %tmp
}
```

i32: 32-bit signed integer type
alloca: Allocate space on the stack; return a pointer
store: Write a value to an address
load: Read a value from an address
add: Add two values to produce a third
ret: Return a value to the caller

Basic Blocks

Each function consists of *basic blocks*: instruction sequence with one entry point & control-transfer at end

```
int cond(bool b) {
  int x;
  if (b) x = 42;
  else   x = 17;
  return x;
}
```



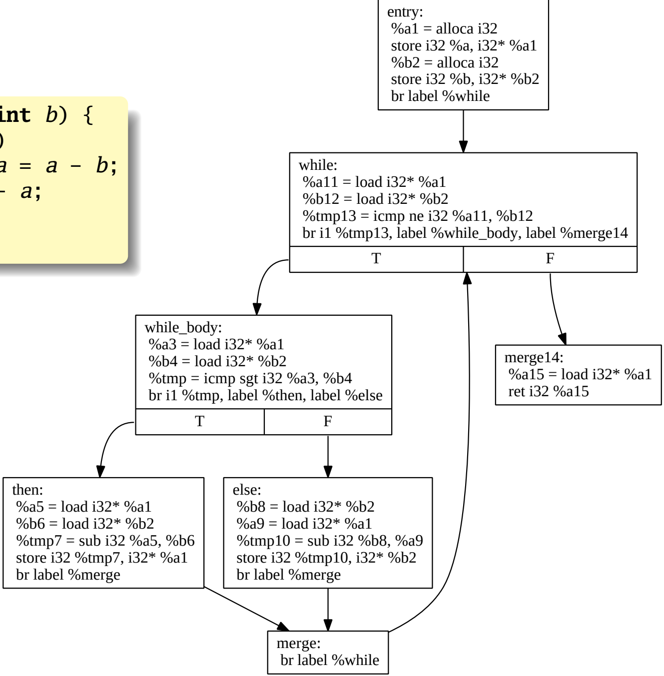
CFG for 'cond' function

```
define i32 @cond(i1 %b) {
entry:
  %b1 = alloca i1
  store i1 %b, i1* %b1
  %x = alloca i32
  %b2 = load i1* %b1
  br i1 %b2, label %then, label %else

merge:         ; preds = %else, %then
  %x3 = load i32* %x
  ret i32 %x3

then:          ; preds = %entry
  store i32 42, i32* %x
  br label %merge

else:          ; preds = %entry
  store i32 17, i32* %x
  br label %merge
}
```

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

```
define i32 @gcd(i32 %a, i32 %b) {
entry:
  %a1 = alloca i32
  store i32 %a, i32* %a1
  %b2 = alloca i32
  store i32 %b, i32* %b2
  br label %while
while:                          ; preds = %merge, %entry
  %a11 = load i32* %a1
  %b12 = load i32* %b2
  %tmp13 = icmp ne i32 %a11, %b12
  br i1 %tmp13, label %while_body, label %merge14
while_body:                     ; preds = %while
  %a3 = load i32* %a1
  %b4 = load i32* %b2
  %tmp = icmp sgt i32 %a3, %b4
  br i1 %tmp, label %then, label %else
merge:                          ; preds = %else, %then
  br label %while
then:                           ; preds = %while_body
  %a5 = load i32* %a1
  %b6 = load i32* %b2
  %tmp7 = sub i32 %a5, %b6
  store i32 %tmp7, i32* %a1
  br label %merge
else:                           ; preds = %while_body
  %b8 = load i32* %b2
  %a9 = load i32* %a1
  %tmp10 = sub i32 %b8, %a9
  store i32 %tmp10, i32* %b2
  br label %merge
merge14:                        ; preds = %while
  %a15 = load i32* %a1
  ret i32 %a15
}
```

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



CFG for 'gcd' function

The Code Generator (codegen.ml)

Translate takes a semantically checked AST and returns an LLVM module:

```
module L = Llvm  (* LLVM VMCore interface library *)
module A = Ast   (* MicroC Abstract Syntax Tree *)

module StringMap = Map.Make(String)

let translate (globals, functions) =
  let context = L.global_context () in (* global data container *)
  let the_module = L.create_module context "MicroC" (* container *)

  and i32_t  = L.i32_type  context    (* int *)
  and i8_t   = L.i8_type   context    (* for printf format string *)
  and i1_t   = L.i1_type   context    (* bool *)
  and void_t = L.void_type context in (* void *)

  let ltype_of_typ = function  (* LLVM type for AST type *)
      A.Int  -> i32_t
    | A.Bool -> i1_t
    | A.Void -> void_t in
```

Define Global Variables

```
int i;
bool b;
int k;

int main()
{
  i = 42;
  k = 10;
```

```
@k  = global i32 0
@b  = global i1 false
@i  = global i32 0

define i32 @main() {
entry:
  store i32 42, i32* @i
  store i32 10, i32* @k
```

```
(* Initialize each global variable; remember them in a map *)
let global_vars =
  let global_var m (t, n) =
    let init = L.const_int (ltype_of_typ t) 0
    in StringMap.add n (L.define_global n init the_module) m in
  List.fold_left global_var StringMap.empty globals in
```

Declare external function *printf*

Declare *printf*, which we'll use to implement *print* and *printb*.

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

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

Define function prototypes

```
void foo() ...

int bar(int a, bool b, int c) ...

int main() ...
```

```
define void @foo() ...

define i32 @bar(i32 %a, i1 %b, i32 %c)

define i32 @main() ...
```

Build a map from function name to (LLVM function, *fdecl*)

Construct the declarations first so we can call them when we build their bodies.

```
(* Define each function (arguments and return type) *)
let function_decls =
  let function_decl m fdecl =
    let name = fdecl.A.fname
    and formal_types = Array.of_list
        (List.map (fun (t,_) -> ltype_of_typ t) fdecl.A.formals)
    in let ftype =
       L.function_type (ltype_of_typ fdecl.A.typ) formal_types in
    StringMap.add name (L.define_function name ftype the_module,
                        fdecl) m in
  List.fold_left function_decl StringMap.empty functions in
```

build_function_body

An “Instruction Builder” is the LLVM library’s object that controls where the next instruction will be inserted.

It points to some instruction in some basic block.

This is an unfortunate artifact of LLVM being written in C++.

```
(* Fill in the body of the given function *)
let build_function_body fdecl =

  let (the_function, _) =
     StringMap.find fdecl.A.fname function_decls in

  let builder =      (* Create an instruction builder *)
     L.builder_at_end context (L.entry_block the_function) in

  let int_format_str =     (* Format string for printf calls *)
      L.build_global_stringptr "%d\n" "fmt" builder in
```

```
@fmt = private unnamed_addr constant [4 x i8] c"%d\0A\00"
```

Formals and Locals

Allocate formal arguments and local variables on the stack; remember names in *local_vars* map

```
int foo(int a, bool b)
{
  int c;
  bool d;
```

```
define i32 @foo(i32 %a, i1 %b) {
entry:
  %a1 = alloca i32
  store i32 %a, i32* %a1
  %b2 = alloca i1
  store i1 %b, i1* %b2
  %c = alloca i32
  %d = alloca i1
```

```
let local_vars =
  let add_formal m (t, n) p = L.set_value_name n p;
    let local = L.build_alloca (ltype_of_typ t) n builder in
    ignore (L.build_store p local builder);
    StringMap.add n local m in

  let add_local m (t, n) =
    let local_var = L.build_alloca (ltype_of_typ t) n builder
    in StringMap.add n local_var m in

  let formals = List.fold_left2 add_formal StringMap.empty
      fdecl.A.formals (Array.to_list (L.params the_function)) in
  List.fold_left add_local formals fdecl.A.locals in
```

lookup

Look for a variable among the locals/formal arguments, then the globals. Semantic checking ensures one of the two is always found.

Used for both identifiers and assignments.

```
(* Return the value for a variable or formal argument *)
let lookup n = try StringMap.find n local_vars
               with Not_found -> StringMap.find n global_vars
in
```

Expressions

The main expression function: build instructions in the given builder that evaluate an expression; return the expression's value

```
let rec expr builder = function
    A.Literal i -> L.const_int i32_t i
  | A.BoolLit b -> L.const_int i1_t (if b then 1 else 0)
  | A.Noexpr -> L.const_int i32_t 0
  | A.Id s -> L.build_load (lookup s) s builder
  | A.Assign (s, e) -> let e' = expr builder e in
              ignore (L.build_store e' (lookup s) builder); e'
```

```
int a;

void foo(int c)
{
  a = c + 42;
}
```

```
@a = global i32 0

define void @foo(i32 %c) {
entry:
  %c1 = alloca i32
  store i32 %c, i32* %c1
  %c2 = load i32* %c1        ; read c
  %tmp = add i32 %c2, 42     ; tmp = c + 42
  store i32 %tmp, i32* @a    ; a = tmp
  ret void
}
```

Binary Operators

Evaluate left and right expressions; combine results

```
    | A.Binop (e1, op, e2) ->
        let e1' = expr builder e1
        and e2' = expr builder e2 in
        (match op with
          A.Add     -> L.build_add
        | A.Sub     -> L.build_sub
        | A.Mult    -> L.build_mul
        | A.Div     -> L.build_sdiv
        | A.And     -> L.build_and
        | A.Or      -> L.build_or
        | A.Equal   -> L.build_icmp L.Icmp.Eq
        | A.Neq     -> L.build_icmp L.Icmp.Ne
        | A.Less    -> L.build_icmp L.Icmp.Slt
        | A.Leq     -> L.build_icmp L.Icmp.Sle
        | A.Greater -> L.build_icmp L.Icmp.Sgt
        | A.Geq     -> L.build_icmp L.Icmp.Sge
        ) e1' e2' "tmp" builder
```

neg/not/print/printb

Unary operators: evaluate subexpression and compute

```
      | A.Unop(op, e) ->
          let e’ = expr builder e in
          (match op with
            A.Neg     -> L.build_neg
          | A.Not     -> L.build_not) e’ "tmp" builder
```

print/printb: Invoke `printf("%d\n", v)`

```
      | A.Call ("print", [e]) | A.Call ("printb", [e]) ->
          L.build_call printf_func
             [| int_format_str ; (expr builder e) |]
             "printf" builder
```

Function calls

Normal calls: evaluate the actual arguments and pass them to the call. *Do not name the result of void functions.*

```
      | A.Call (f, act) ->
         let (fdef, fdecl) = StringMap.find f function_decls in
         let actuals =
            List.rev (List.map (expr builder) (List.rev act)) in
         let result = (match fdecl.A.typ with A.Void -> ""
                                               | _ -> f ^ "_result") in
         L.build_call fdef (Array.of_list actuals) result builder
```

```
void foo(int a)
{
  print(a + 3);
}

int main()
{
  foo(40);
  return 0;
}
```

```
define void @foo(i32 %a) {
entry:
  %a1 = alloca i32
  store i32 %a, i32* %a1
  %a2 = load i32* %a1
  %tmp = add i32 %a2, 3
  %printf = call i32 (i8*, ...)* @printf(i8* getelementptr
    inbounds ([4 x i8]* @fmt1, i32 0, i32 0), i32 %tmp)
  ret void
}
define i32 @main() {
entry:
  call void @foo(i32 40)
  ret i32 0
}
```

Statements

Used to add a branch instruction to a basic block only of one doesn't already exist. Used by *if* and *while*

```
let add_terminal builder f =
  match L.block_terminator (L.insertion_block builder) with
    Some _ -> ()
  | None -> ignore (f builder) in
```

The main statement function: build instructions in the given builder for the statement; return the builder for where the next instruction should be placed. *Return* has an interesting expression only in non-void functions, enforced by semantic checking.

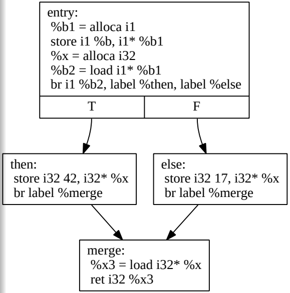
```
let rec stmt builder = function
    A.Block sl -> List.fold_left stmt builder sl

  | A.Expr e -> ignore (expr builder e); builder

  | A.Return e -> ignore (match fdecl.A.typ with
      A.Void -> L.build_ret_void builder
    | _ -> L.build_ret (expr builder e) builder); builder
```

If Statements

Build basic blocks for *then*, *else*, and *merge*—where the next statement will be placed.

```
| A.If (predicate, then_stmt, else_stmt) ->
  let bool_val = expr builder predicate in
  let merge_bb = L.append_block context
                   "merge" the_function in

  let then_bb = L.append_block context
                   "then" the_function in
  add_terminal
   (stmt (L.builder_at_end context then_bb)
         then_stmt)
   (L.build_br merge_bb);

  let else_bb = L.append_block context
                   "else" the_function in
  add_terminal
   (stmt (L.builder_at_end context else_bb)
         else_stmt)
   (L.build_br merge_bb);

  ignore (L.build_cond_br bool_val
              then_bb else_bb builder);
  L.builder_at_end context merge_bb
```

```
int cond(bool b) {
  int x;
  if (b) x = 42;
  else   x = 17;
  return x;
}
```

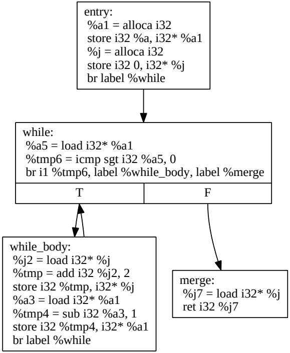


CFG for 'cond' function

While Statements

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

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

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

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

```
int foo(int a)
{
  int j;
  j = 0;
  while (a > 0) {
    j = j + 2;
    a = a - 1;
  }
  return j;
}
```



CFG for 'foo' function

For Statements

```
for ( expr1 ; expr2 ; expr3 ) {
  body;
}
```

```
expr1;
while ( expr2 ) {
   body;
   expr3;
}
```

```
      | A.For (e1, e2, e3, body) -> stmt builder
            ( A.Block [A.Expr e1 ;
                       A.While (e2, A.Block [body ;
                                             A.Expr e3]) ] )
    in
```

The End

The remainder of *build_function_body*: build the body of the function; add a *return* if control fell off the end

```
    (* Build the code for each statement in the function *)
    let builder = stmt builder (A.Block fdecl.A.body) in

    (* Add a return if the last block falls off the end *)
    add_terminal builder (match fdecl.A.typ with
        A.Void -> L.build_ret_void
      | t -> L.build_ret (L.const_int (ltype_of_typ t) 0))
  in
```

The remainder of *translate*: build the body of each function

```
  List.iter build_function_body functions;
  the_module
```

The Top-Level

microc.ml

Top-level of the MicroC compiler: scan & parse, check the AST, generate LLVM IR, dump the module

```
type action = Ast | LLVM_IR | Compile
let _ =
  let action = if Array.length Sys.argv > 1 then
    List.assoc Sys.argv.(1)
      [ ("-a", Ast); ("-l", LLVM_IR); ("-c", Compile) ]
  else Compile in

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

  Semant.check ast;

  match action with
    Ast -> print_string (Ast.string_of_program ast)

  | LLVM_IR -> print_string (Llvm.string_of_llmodule
                               (Codegen.translate ast))

  | Compile -> let m = Codegen.translate ast in
    Llvm_analysis.assert_valid_module m; (* Useful built-in check *)
    print_string (Llvm.string_of_llmodule m)
```

Source Code Statistics

File	Lines	Role
scanner.mll	45	Token rules
parser.mly	115	Context-free grammar
ast.ml	103	Abstract syntax tree & pretty printer
semant.ml	158	Semantic checking
codegen.ml	183	LLVM IR generation
microc.ml	20	Top-level
Total	624	

Type	Files	Total lines
Working .mc	34	413
Working outputs	34	105
Failing .mc	31	298
Error messages	31	31
Total	130	847