Compiler Project

We define here a programming language called **C-Minus** (or C−, for short), which is a suitable language for a compiler project, which is more complex than the TINY language in that it includes functions and arrays. It is essentially a subset of C, but is missing some important pieces, hence its name. This appendix consists of five sections. In the first, we list the lexical conventions of the language, including a description of the tokens of the language. In the second, we give a BNF description of each language construct, together with an English description of the associated semantics. In the third section, we give two sample programs in C−. In the fourth, we describe a Tiny Machine runtime environment for C−. The last section describes a number of programming projects using C− and TM, suitable for a compiler course.

A.1 LEXICAL CONVENTIONS OF C−

1. The keywords of the language are the following:

```
else if int return void while
```

All keywords are reserved, and must be written in lowercase.

2. Special symbols are the following:

```
+ - * / < <= > >= == != = ; , ( ) [ ] { } /* */
```

3. Other tokens are ***ID*** and ***NUM***, defined by the following regular expressions:

```
ID = letter letter*
NUM = digit digit*
letter = a|..|z|A|..|Z
digit = 0|..|9
```

   Lower- and uppercase letters are distinct.
4. White space consists of blanks, newlines, and tabs. White space is ignored except that it must separate ***ID***'s, ***NUM***'s, and keywords.
5. Comments are surrounded by the usual C notations `/*...*/`. Comments can be placed anywhere white space can appear (that is, comments cannot be placed within tokens) and may include more than one line. Comments may not be nested.

A.2 SYNTAX AND SEMANTICS OF C—

A BNF grammar for C− is as follows:

1. *program* → *declaration-list*
2. *declaration-list* → *declaration-list declaration* | *declaration*
3. *declaration* → *var-declaration* | *fun-declaration*
4. *var-declaration* → *type-specifier* ***ID*** **;** | *type-specifier* ***ID*** **[** ***NUM*** **] ;**
5. *type-specifier* → **int** | **void**
6. *fun-declaration* → *type-specifier* ***ID*** **(** *params* **)** *compound-stmt*
7. *params* → *param-list* | **void**
8. *param-list* → *param-list* **,** *param* | *param*
9. *param* → *type-specifier* ***ID*** | *type-specifier* ***ID*** **[ ]**
10. *compound-stmt* → **{** *local-declarations statement-list* **}**
11. *local-declarations* → *local-declarations var-declaration* | *empty*
12. *statement-list* → *statement-list statement* | *empty*
13. *statement* → *expression-stmt* | *compound-stmt* | *selection-stmt*
    | *iteration-stmt* | *return-stmt*
14. *expession-stmt* → *expression* **;** | **;**
15. *selection-stmt* → **if (** *expression* **)** *statement*
    | **if (** *expression* **)** *statement* **else** *statement*
16. *iteration-stmt* → **while (** *expression* **)** *statement*
17. *return-stmt* → **return ;** | **return** *expression* **;**
18. *expression* → *var* **=** *expression* | *simple-expression*
19. *var* → ***ID*** | ***ID*** **[** *expression* **]**
20. *simple-expression* → *additive-expression relop additive-expression*
    | *additive-expression*
21. *relop* → **<=** | **<** | **>** | **>=** | **==** | **!=**
22. *additive-expression* → *additive-expression addop term* | *term*
23. *addop* → **+** | **-**
24. *term* → *term mulop factor* | *factor*
25. *mulop* → ***** | **/**
26. *factor* → **(** *expression* **)** | *var* | *call* | ***NUM***

27. *call* → `ID` `(` *args* `)`
28. *args* → *arg-list* | *empty*
29. *arg-list* → *arg-list* `,` *expression* | *expression*

For each of these grammar rules we give a short explanation of the associated semantics.

1. *program* → *declaration-list*
2. *declaration-list* → *declaration-list declaration* | *declaration*
3. *declaration* → *var-declaration* | *fun-declaration*

A program consists of a list (or sequence) of declarations, which may be function or variable declarations, in any order. There must be at least one declaration. Semantic restrictions are as follows (these do not occur in C). All variables and functions must be declared before they are used (this avoids backpatching references). The last declaration in a program must be a function declaration of the form **`void main(void)`**. Note that C– lacks prototypes, so that no distinction is made between declarations and definitions (as in C).

4. *var-declaration* → *type-specifier* `ID` `;` | *type-specifier* `ID` `[` `NUM` `]` `;`
5. *type-specifier* → **`int`** | **`void`**

A variable declaration declares either a simple variable of integer type or an array variable whose base type is integer, and whose indices range from 0 . . `NUM`–1. Note that in C– the only basic types are integer and void. In a variable declaration, only the type specifier **`int`** can be used. **`Void`** is for function declarations (see below). Note, also, that only one variable can be declared per declaration.

6. *fun-declaration* → *type-specifier* `ID` `(` *params* `)` *compound-stmt*
7. *params* → *param-list* | **`void`**
8. *param-list* → *param-list* `,` *param* | *param*
9. *param* → *type-specifier* `ID` | *type-specifier* `ID` `[` `]`

A function declaration consists of a return type specifier, an identifier, and a comma-separated list of parameters inside parentheses, followed by a compound statement with the code for the function. If the return type of the function is **`void`**, then the function returns no value (i.e., is a procedure). Parameters of a function are either **`void`** (i.e., there are no parameters) or a list representing the function's parameters. Parameters followed by brackets are array parameters whose size can vary. Simple integer parameters are passed by value. Array parameters are passed by reference (i.e., as pointers) and must be matched by an array variable during a call. Note that there are no parameters of type "function." The parameters of a function have scope equal to the compound statement of the function declaration, and each invocation of a function has a separate set of parameters. Functions may be recursive (to the extent that declaration before use allows).

10. *compound-stmt* → `{` *local-declarations statement-list* `}`

A compound statement consists of curly brackets surrounding a set of declarations and statements. A compound statement is executed by executing the statement sequence in the order given. The local declarations have scope equal to the statement list of the compound statement and supersede any global declarations.

11. *local-declarations* → *local-declarations var-declaration* | *empty*
12. *statement-list* → *statement-list statement* | *empty*

Note that both declarations and statement lists may be empty. (The nonterminal *empty* stands for the empty string, sometimes written as ε.)

13. *statement* → *expression-stmt*
| *compound-stmt*
| *selection-stmt*
| *iteration-stmt*
| *return-stmt*
14. *expession-stmt* → *expression* **;** | **;**

An expression statement has an optional expression followed by a semicolon. Such expressions are usually evaluated for their side effects. Thus, this statement is used for assignments and function calls.

15. *selection-stmt* → **if** **(** *expression* **)** *statement*
| **if** **(** *expression* **)** *statement* **else** *statement*

The if-statement has the usual semantics: the expression is evaluated; a nonzero value causes execution of the first statement; a zero value causes execution of the second statement, if it exists. This rule results in the classical dangling else ambiguity, which is resolved in the standard way: the else part is always parsed immediately as a substructure of the current if (the "most closely nested" disambiguating rule).

16. *iteration-stmt* → **while** **(** *expression* **)** *statement*

The while-statement is the only iteration statement in C−. It is executed by repeatedly evaluating the expression and then executing the statement if the expression evaluates to a nonzero value, ending when the expression evaluates to 0.

17. *return-stmt* → **return** **;** | **return** *expression* **;**

A return statement may either return a value or not. Functions not declared **void** must return values. Functions declared **void** must not return values. A return causes transfer of control back to the caller (or termination of the program if it is inside **main**).

18. *expression* → *var* = *expression* | *simple-expression*
19. *var* → **ID** | **ID** **[** *expression* **]**

An expression is a variable reference followed by an assignment symbol (equal sign) and an expression, or just a simple expression. The assignment has the usual storage semantics: the location of the variable represented by *var* is found, then the subexpression to the right of the assignment is evaluated, and the value of the subexpression is stored at the given location. This value is also returned as the value of the entire expression. A *var* is either a simple (integer) variable or a subscripted array variable. A negative subscript causes the program to halt (unlike C). However, upper bounds of subscripts are not checked.

Vars represent a further restriction of C– from C. In C the target of an assignment must be an **l-value**, and l-values are addresses that can be obtained by many operations. In C– the only l-values are those given by the *var* syntax, and so this category is checked syntactically, instead of during type checking as in C. Thus, pointer arithmetic is forbidden in C–.

20. *simple-expression* → *additive-expression relop additive-expression*
| *additive-expression*
21. *relop* → <= | < | > | >= | == | !=

A simple expression consists of relational operators that do not associate (that is, an unparenthesized expression can only have one relational operator). The value of a simple expression is either the value of its additive expression if it contains no relational operators, or 1 if the relational operator evaluates to true, or 0 if it evaluates to false.

22. *additive-expression* → *additive-expression addop term* | *term*
23. *addop* → + | -
24. *term* → *term mulop factor* | *factor*
25. *mulop* → * | /

Additive expressions and terms represent the typical associativity and precedence of the arithmetic operators. The / symbol represents integer division; that is, any remainder is truncated.

26. *factor* → (*expression*) | *var* | *call* | *NUM*

A factor is an expression enclosed in parentheses, a variable, which evaluates to the value of its variable; a call of a function, which evaluates to the returned value of the function; or a NUM, whose value is computed by the scanner. An array variable must be subscripted, except in the case of an expression consisting of a single ID and used in a function call with an array parameter (see below).

27. *call* → *ID* (*args*)
28. *args* → *arg-list* | *empty*
29. *arg-list* → *arg-list* , *expression* | *expression*

A function call consists of an *ID* (the name of the function), followed by parentheses enclosing its arguments. Arguments are either empty or consist of a comma-separated list of expressions, representing the values to be assigned to parameters during a call. Functions must be declared before they are called, and the number of parameters in a declaration must equal the number of arguments in a call. An array parameter in a function declaration must be matched with an expression consisting of a single identifier representing an array variable.

Finally, the above rules give no input or output statement. We must include such functions in the definition of C–, since unlike C, C– has no separate compilation or linking facilities. We, therefore, consider two functions to be **predefined** in the global environment, as though they had the indicated declarations:

```
int input(void) { . . . }
void output(int x) { . . . }
```

The **input** function has no parameters and returns an integer value from the standard input device (usually the keyboard). The **output** function takes one integer parameter, whose value it prints to the standard output (usually the screen), together with a newline.

A.3 SAMPLE PROGRAMS IN C−

The following is a program that inputs two integers, computes their greatest common divisor, and prints it:

```
/* A program to perform Euclid's
   Algorithm to compute gcd. */

int gcd (int u, int v)
{ if (v == 0) return u ;
  else return gcd(v,u-u/v*v);
  /* u-u/v*v == u mod v */
}

void main(void)
{ int x; int y;
  x = input(); y = input();
  output(gcd(x,y));
}
```

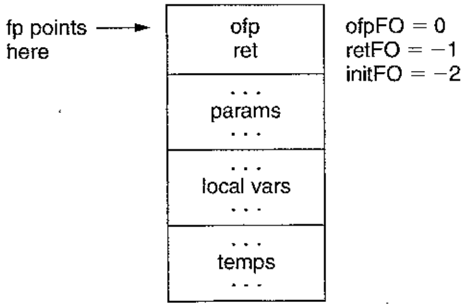
The following is a program that inputs a list of 10 integers, sorts them by selection sort, and outputs them again:

```
/* A program to perform selection sort on a 10
  element array. */

int x[10];

int minloc ( int a[], int low, int high )
{ int i; int x; int k;
  k = low;
  x = a[low];
  i = low + 1;
  while (i < high)
    { if (a[i] < x)
        { x = a[i];
          k = i; }
      i = i + 1;
    }
  return k;
}
```

```
void sort( int a[], int low, int high)
{ int i; int k;
  i = low;
  while (i < high-1)
    { int t;
      k = minloc(a,i,high);
      t = a[k];
      a[k] = a[i];
      a[i] = t;
      i = i + 1;
    }
}

void main(void)
{ int i;
  i = 0;
  while (i < 10)
    { x[i] = input();
      i = i + 1; }
  sort(x,0,10);
  i = 0;
  while (i < 10)
    { output(x[i]);
      i = i + 1; }
}
```

A.4 A TINY MACHINE RUNTIME ENVIRONMENT FOR THE C− LANGUAGE

The following description assumes a knowledge of the Tiny Machine as given in Section 8.7 and an understanding of stack-based runtime environments from Chapter 7. Since C− (unlike TINY) has recursive procedures, the runtime environment must be stack based. The environment consists of a global area at the top of dMem, and the stack just below it, growing downward toward 0. Since C− contains no pointers or dynamic allocation, there is no need for a heap. The basic organization of each activation record (or stack frame) in C− is



ofpFO = 0
retFO = −1
initFO = −2

Here, fp is the **current frame pointer**, which is kept in a register for easy access. The ofp (old frame pointer) is the **control link** as discussed in Chapter 7 of the text. The constants to the right ending in FO (for frame offset) are the offsets at which each of the indicated quantities are stored. The value initFO is the offset at which the params and local vars begin their storage areas in an activation record. Since the Tiny Machine contains no stack pointer, all references to fields within an activation record will use the fp, with negative frame offsets.

For example, if we have the following C− function declaration,

```
int f(int x, int y)
{ int z;
  . . .
}
```

then **x**, **y**, and **z** must be allocated in the current frame, and the frame offset at the beginning of the generation of code for the body of **f** will be −5 (one location each for **x**, **y**, **z** and two locations for the bookkeeping information of the activation record). The offsets of **x**, **y**, and **z** are −2, −3, and −4, respectively.

Global references can be found at absolute locations in memory. Nevertheless, as with TINY, we prefer also to reference these variables by offset from a register. We do this by keeping a fixed register, which we call the gp, and which always points at the maximum address. Since the TM simulator stores this address into location 0 before execution begins, the gp can be loaded from location 0 on start-up, and the following standard prelude initializes the runtime environment:

```
0: LD gp,   0(ac)  * load gp with maxaddress
1: LDA fp,  0(gp)  * copy gp to fp
2: ST ac,   0(ac)  * clear location 0
```

Function calls also require that the beginning code location for their bodies be used in a calling sequence. We also prefer to call functions by performing a relative jump using the current value of the pc rather than an absolute jump. (This makes the code potentially relocatable.) The utility procedure **emitRAbs** in **code.h/code.c** can be used for this purpose. (It takes an absolute code location and relativizes it by using the current code generation location.)

For example, suppose we want to call a function f whose code begins at location 27, and we are currently at location 42. Then instead of generating the absolute jump

```
42: LDC pc, 27(*)
```

we would generate

```
42: LDA pc, -16(pc)
```

since 27 − (42 + 1) = −16.

The Calling Sequence A reasonable division of labor between caller and callee is to have the caller store the values of the arguments in the new frame and create the new frame, except for the storing of the return pointer in the retFO position. Instead of storing the return pointer itself, the caller leaves it in the ac register, and the callee stores it into the new frame. Thus, every function body must begin with code to store that value in the (now current) frame:

```
ST ac, retFO(fp)
```

This saves one instruction at each call site. On return, each function then loads the pc with this return address by executing the instruction

```
LD pc, retFO(fp)
```

Correspondingly, the caller computes the arguments one by one, and pushes each onto the stack in its appropriate position before pushing the new frame. The caller must also save the current fp into the frame at ofpFO before pushing the new frame. After a return from the callee, the caller then discards the new frame by loading the fp with the old fp. Thus, a call to a function of two parameters will cause the generation of the following code:

```
<code to compute first arg>
ST ac, frameoffset+initFO (fp)
<code to compute second arg>
ST ac, frameoffset+initFO-1 (fp)
ST fp, frameoffset+ofpFO (fp) * store current fp
LDA fp frameOffset(fp) * push new frame
LDA ac,1(pc) * save return in ac
LDA pc, ...(pc) * relative jump to function entry
LD fp, ofpFO(fp) * pop current frame
```

Address Computations Since both variables and subscripted arrays are allowed on the left-hand side of assignment, we must distinguish between addresses and values during compilation. For example, in the statement

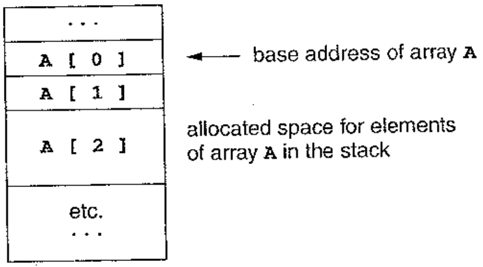
```
a[i] := a[i+1];
```

the expression **a[i]** refers to the address of **a[i]**, while the expression **a[i+1]** refers to the value of **a** at the **i+1** location. This distinction can be achieved by using an **isAddress** parameter to the **cGen** procedure. When this parameter is true, **cGen** generates code to compute the address of a variable rather than its value. In the case of a simple variable, this means adding the offset to either the gp (in the case of a global variable) or the fp (in the case of a local variable) and loading the result into the ac:

```
LDA ac, offset(fp) ** put address of local var in ac
```

In the case of an array variable, this means adding the value of the index to the base address of the array and loading the result into the ac, as described below.

Arrays Arrays are allocated on the stack beginning at the current frame offset and extending downward in memory in order of increasing subscript, as follows:



Note that array locations are computed by subtracting the index value from the base address.

When an array is passed to a function, only the base address is passed. The allocation of the area for the base elements is done only once and remains fixed for the life of the array. Function arguments do not include the actual elements of an array, only the address. Thus, array parameters become reference parameters. This causes an anomaly when array parameters are referenced inside a function, since they must be treated as having their base addresses rather than their values stored in memory. Thus, an array parameter has its base address computed using an LD operation instead of an LDA.

A.5 PROGRAMMING PROJECTS USING C– AND TM

It is not unreasonable for a one-semester compiler course to require as a project a complete compiler for the C– language, based on the TINY compiler discussed in this text (and whose listing can be found in Appendix B). This can be coordinated so that each phase of the compiler is implemented as the associated theory is studied. Alternatively, one or more parts of the C– compiler could be supplied by the instructor, and students required to complete the remaining parts. This is especially helpful when time is short (as in a quarter system) or if the students will be generating assembly code for a "real" machine, such as the Sparc or PC (which requires more detail in the code generation phase). It is less helpful to implement just one part of the C– compiler, since the interactions among the parts and the ability to test the code are then restricted. The following list of separate tasks are supplied as a convenience, with the caveat that each task may not be independent of the others and that it is probably best for all tasks to be completed in order to obtain a complete compiler-writing experience.

PROJECTS

A.1. Implement a symbol table utility suitable for the C– language. This will require a table structure that incorporates scope information, either as separate tables linked together or with a delete mechanism that operates in a stack-based fashion, as described in Chapter 6.

A.2. Implement a C– scanner, either by hand as a DFA or using Lex, as described in Chapter 2.

A.3. Design a syntax tree structure for C– suitable for generation by a parser.

A.4. Implement a C– parser (this requires a C– scanner), either by hand using recursive descent or using Yacc, as described in Chapter 4 or 5. The parser should generate a suitable syntax tree (see Project A.3).

A.5. Implement a semantic analyzer for C–. The major requirement of the analyzer, aside from gathering information in the symbol table, is to perform type checking on the use of variables and functions. Since there are no pointers or structures, and the only basic type is integer, the types that need to be treated by the type checker are void, integer, array, and function.

A.6. Implement a code generator for C–, according to the runtime environment described in the previous section.