Lecture 19. Compilers

- **The *compiler* translates a high-level language to a machine-level language**

`lcc`:	C → SPARC assembly language → … → SPARC machine code
`compile`:	arithmetic expressions → TOY instructions

- **Most compilers have the basic phases**

Lexical Analysis	source code → ‘tokens’
Syntax Analysis	tokens → abstract syntax trees
Code Generation	abstract syntax trees → machine-level code

- **A compiler is a good example of**

  Application of theoretical computer science to a practical problem

  Interaction between programming language design and computer architecture

  Building a program from independent modules — ‘software engineering’

- **For *much* more**

  Take COS 320, Compiler Design

  Read A. W. Appel, *Modern Compiler Implementation in Java*, Cambridge Univ. Press, 1997 (used in COS 320)

  Read C. W. Fraser and D. R. Hanson, *A Retargetable C Compiler: Design and Implementation*, Addison-Wesley, 1995

Lexical Analysis

- The lexical analyzer reads the source program and emits ***tokens*** or ***terminal symbols***: the ‘letters’ in the ‘alphabet’ of the programming language

  English:

  a b c d e f g h … A B C … . ; ‘ ’ ! : — - ( ) …

  C tokens:

  ```
  if else while do for int float sizeof …
  { } ; . -> + - * / % ++ -- < <= == != & ^ | ~ >= > ( ) …
  ```
  "strings"   constants   identifiers …

  Simple arithmetic expressions:

  ```
  ( ) + - *
  ```
  one-letter identifiers   one-digit constants

- A lexical analyzer usually discards white space: blanks, tabs, newlines, etc.
- Lexical analyzers can be described by and implemented with ***finite-state machines***

Syntax Analysis

- A ***context-free grammar*** specifies how tokens can be formed into valid 'sentences'

  Grammar rules or 'productions' specify how to generate all valid sentences

  1. $pgm \rightarrow expr$

2.	$expr \rightarrow expr$ + $expr$	5.	$expr \rightarrow$ ($expr$)
3.	$expr \rightarrow expr$ - $expr$	6.	$expr \rightarrow$ identifier
4.	$expr \rightarrow expr$ * $expr$	7.	$expr \rightarrow$ constant

  pgm *expr* are 'nonterminals' — they describe ***classes*** of valid sentences
  + - * ( ) identifier constant are terminals or tokens — the basic vocabulary

1	$pgm \Rightarrow expr$
3	$\Rightarrow expr$ - $expr$
5	$\Rightarrow$ ($expr$) - $expr$
4	$\Rightarrow$ ($expr$ * $expr$) - $expr$
6	$\Rightarrow$ (a * $expr$) - $expr$
5	$\Rightarrow$ (a * ($expr$)) - $expr$
2	$\Rightarrow$ (a * ($expr$ + $expr$)) - $expr$
6	$\Rightarrow$ (a * (b + $expr$)) - $expr$
7	$\Rightarrow$ (a * (b + 2)) - $expr$
5	$\Rightarrow$ (a * (b + 2)) - ($expr$)
2	$\Rightarrow$ (a * (b + 2)) - ($expr$ + $expr$)
6	$\Rightarrow$ (a * (b + 2)) - (c + $expr$)
7	$\Rightarrow$ (a * (b + 2)) - (c + 9)

Parsers

- **A *parser* determines if a sentence can be generated by the grammar rules**

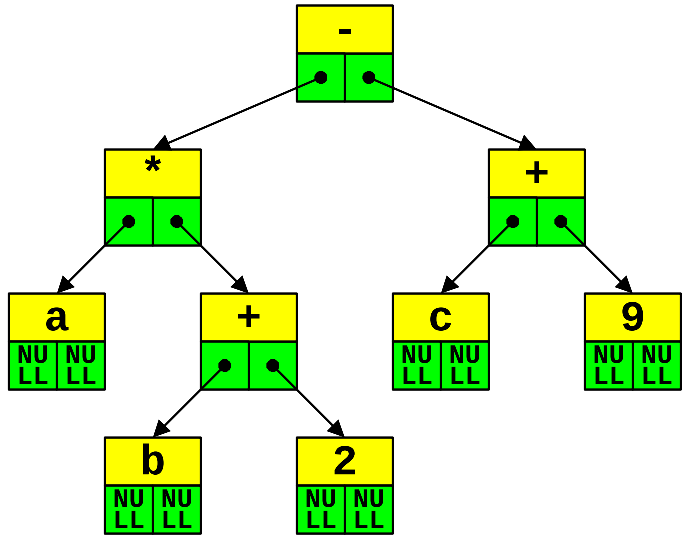
  Proves that the sentence is syntactically valid

- **A parser may also build an *abstract syntax tree* to represent the sentence**

  `(a * (b + 2)) - (c + 9)`

  Internal nodes hold terminal symbols that denote operators: + - *

  Leaf nodes hold terminal symbols that denote variables or constants: a b c 2 9



- **A 'recursive-descent' parser has a function for each nonterminal**

  'Matches' terminals in input

  Calls other nonterminal functions — including itself — to apply the rules

- **Parsers can be described by and implemented with *pushdown automata***

Code Generation

- **A *code generator* traverses the abstract syntax tree and emits code, e.g., TAL, or TOY instructions**

```
% lcc -I/u/cs126/include compile.c /u/cs126/lib/libmisc.a
% a.out 5 6 7 "(a * (b + 2)) - (c + 9)"
00:  0005
01:  0006
02:  0007
1A:  9100              R1 <- M[R0+0]
1B:  9201              R2 <- M[R0+1]
1C:  B302              R3 <- 2
1D:  1223              R2 <- R2 + R3
1E:  3112              R1 <- R1 * R2
1F:  9202              R2 <- M[R0+2]
20:  B309              R3 <- 9
21:  1223              R2 <- R2 + R3
22:  2112              R1 <- R1 - R2
23:  4102              print R1
24:  0000              halt
1A
```

- **This compiler — and only this one — bypasses assembly, linking, and loading**

```
% a.out 5 6 7 "(a * (b + 2)) - (c + 9)" | /u/cs126/toy/toy
ab2+*c9+-
Toy simulator $Revision: 1.14 $
0018
```

A Simple Compiler

- **Lexical analyzer: returns characters as tokens**

`int get(char set[])`	**returns the next token, advances the input**
`int look(void)`	**peeks at the next nonblank character**

- **Parser: returns an abstract syntax tree (AST)**

`Tree *expr(void)`	**parses an *expr*, returns its AST**
`Tree *pgm(char *string)`	**initializes lexer, parses a *pgm*, returns its AST**

```
struct tree {
    int op;
    struct tree *left, *right;
};
typedef struct tree Tree;

Tree *maketree(int op, Tree *left, Tree *right) {
    Tree *t = emalloc(sizeof (Tree));

    t->op = op;
    t->left = left; t->right = right;
    return t;
}
```

- **Code generator: emits TOY instructions**

`int codegen(Tree *t, int dst, int loc)`

emits TOY code for AST `t` starting at `loc`

Lexical Analysis

- **Globals hold the ‘state’ of lexical analysis: input and current input position**

```
char *input;      /* the "source code" */
int pos;          /* current position in input */
```

`input[pos]` holds the next character in the input

- **The next token is the next non-whitespace character, which must be in `set`**

```
int get(char set[]) {
    while (isspace(input[pos]))
        pos++;
    if (input[pos] != ’\0’ && strchr(set, input[pos]) != NULL)
        return input[pos++];
    error("syntax error: expected one of ’%s’\n", set);
    return 0;
}
```

- **The parser must peek ahead one character to determine its next action**

```
int look(void) {
    while (isspace(input[pos]))
        pos++;
    return input[pos];
}
```

Parsing

- **The parsing functions for *expr* and *pgm* echo their grammar rules**

```
Tree *expr(void) {
    Tree *t;

    if (look() == '(') {            /* expr → ( expr ) */
        get("("); t = expr(); get(")");
    } else if (isdigit(look()))     /* expr → constant */
        t = maketree(get("0123456789"), NULL, NULL);
    else                            /* expr → identifier */
        t = maketree(get("abcdefghijklmnopqrstuvwxyz"), NULL,NULL);
    if (look() != '\0' && strchr("+-*", look()) != NULL) {
        int op = get("+-*");        /* expr → expr [+-*] expr */
        t = maketree(op, t, expr());
    }
    return t;
}

Tree *pgm(char *string) {
    Tree *t;

    input = string;             /* initialize lexical analyzer */
    pos = 0;
    t = expr();                 /* pgm → expr */
    if (look() != '\0')
        error("expected end of input\n");
    return t;
}
```

Reverse Polish Notation

- **A postorder traversal of the AST yields a *reverse Polish* rendition of the expression**

```
void postorder(Tree *t) {
    if (t != NULL) {
        postorder(t->left);
        postorder(t->right);
        fprintf(stderr, "%c", t->op);
    }
}
```

(a * (b + 2)) - (c + 9)   a b 2 + * c 9 + -

- **Reverse Polish can be *evaluated*: a *stack* holds operands and intermediate values**

	Stack→	R1	R2	R3
a b 2 + * c 9 + -	5	5		
a b 2 + * c 9 + -	5 6	5	6	
a b 2 + * c 9 + -	5 6 2	5	6	2
a b 2 + * c 9 + -	5 8	5	8	
a b 2 + * c 9 + -	40	40		
a b 2 + * c 9 + -	40 7	40	7	
a b 2 + * c 9 + -	40 7 9	40	7	9
a b 2 + * c 9 + -	40 16	40	7	16
a b 2 + * c 9 + -	24	24		

- **Instead of evaluating the expression, generate code, using *registers* for the stack**

Code Generation

- ***codegen*** **emits code to evaluate an AST into register `dst`, assuming higher numbered registers are free**

```
int codegen(Tree *t, int dst, int loc) {
    if (isalpha(t->op)) {
        int addr = t->op - 'a';
        printf("%02X: 9%X%X%X\tR%d <- M[R%d+%d]\n", loc++,
            dst, 0, addr, dst, 0, addr);
    } else if (isdigit(t->op))
        printf("%02X: B%X%02X\tR%d <- %d\n", loc++,
            dst, t->op - '0', dst, t->op - '0');
    else {
        loc = codegen(t->left, dst, loc);
        loc = codegen(t->right, dst + 1, loc);
        printf("%02X: %X%X%X%X\tR%d <- R%d %c R%d\n", loc++,
            strchr("+1-2*3", t->op)[1] - '0', dst,
            dst, dst + 1, dst, dst, t->op, dst + 1);
    }
    return loc;
}
```

Variables a..z are stored in locations 0..19_{16}

`loc` is the location counter: the address of the next instruction emitted

codegen **returns an updated value of *loc* for use by subsequent traversals**

The Main Program

- **The final touches**

  Arguments 1..`argc-2` are the initial values of the corresponding variables

  Argument `argc-1` is the 'source program'

  Starting address is $26_{10} = 1A_{16}$

```
int main(int argc, char *argv[]) {
    Tree *e;
    int i, loc = 0;

    for (i = 1; i < argc - 1; i++)
        printf("%02X: %04X\n", loc++, atoi(argv[i]));
    if (i < argc) {
        e = pgm(argv[i]);
        postorder(e);
        fprintf(stderr, "\n");
        loc = codegen(e, 1, 26);
        printf("%02X: 4102\tprint R%d\n", loc++, 1);
        printf("%02X: 0000\thalt\n", loc);
        printf("%02X\n", 26);
    }
    return 0;
}
```

  See page 19-5 for an example of use