Compilers (in one lecture!)

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Reference Materials

1. Introduction to Compilers and Translation Engineering course notes, by H. Dietz

   https://aggregate.org/CPE380/notes.pdf

2. Mucky source code & CGI interface

   https://aggregate.org/CPE380/mucky.c

   https://aggregate.org/cgi-bin/mucky.cgi

3. Online MIPS gcc in the "Compiler Explorer"

   https://godbolt.org/

Compiling a C Program

1. Preprocessor (yeah, we skipped this before)
2. Compiler generates assembly code
3. Assembler creates binary modules
4. Linker combines needed modules into one
5. Loader is the part of the OS that loads a module into memory for execution

- Usually, HLL programmers don't see this; 1-4 invoked by `cc`, 5 when you run the program
- We will focus on step 2, with a bit of 1 & 3

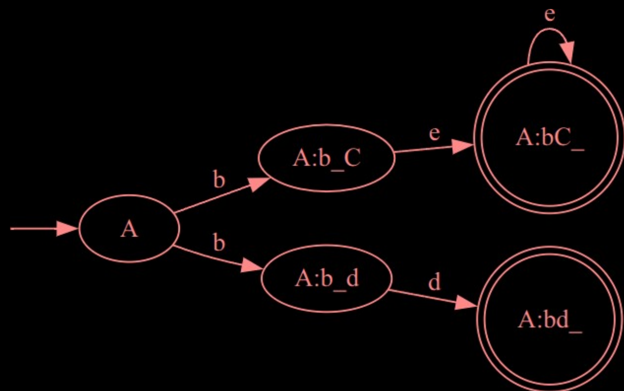
Inside a Compiler

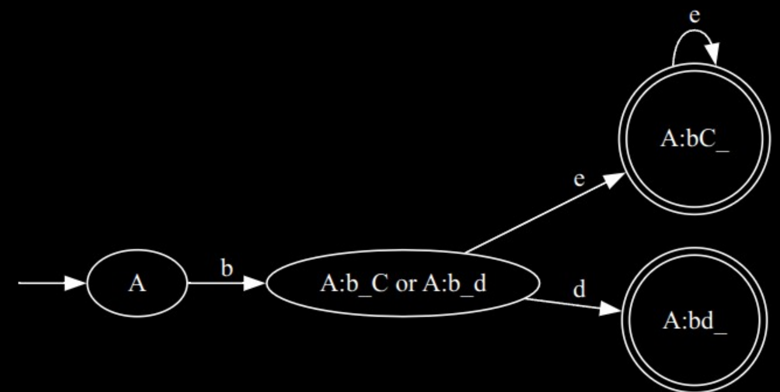
- Lexical analysis: recognizing words
  - Isthiseasytoread?
  - Is this easy to read?
- Parsing: recognizing nestable patterns
  - Like sentence diagramming in gradeschool
- Code Generation: output of translated code
  - Typically output of assembly language code
  - May be embedded in parser or complex

Lexical Analysis

- Regular patterns (aka, Type 3 Grammars)
  - Every rule like `N:t*N` or `N:t*`
  - Recognizable using FSM without a stack; NFA or DFA (Deterministic Finite Automaton)

```
A:bC
A:bd
C:eC
C:e
```



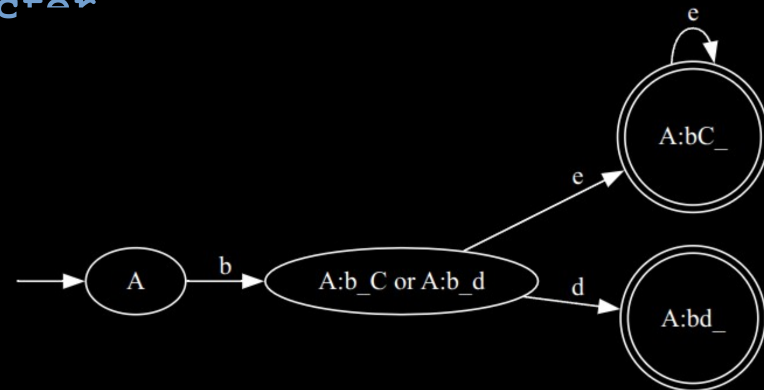


Lexical Analyzer

- Recognize next terminal
  - Always looking one character ahead
  - Lexer returns type of terminal found

```
int nextc = getchar();     // next character
int nextt;                 // next token

int lexer() {
    switch(nextc) {
    case 'b': nextc = getchar();
        switch (nextc) {
        case 'd': nextc = getchar();
            return(nextt = Abd);
        case 'e': nextc = getchar();
            while (nextc == 'e') nextc = getchar();
            return(nextt = AbC);
        }
    }
    error();
}
```



Lexical Analysis Tricks

- Pronouns/identifiers change type by context
  - What is `abc`? Label, variable, function...?
  - Initially lexer says `abc` is IDENT, after parser sees `int abc;` it becomes VAR by looking-up `abc` in the symbol table
- If keywords look like identifiers, use symbol table to disambiguate: an atomic lexer
- Some languages need weird lexers...
  - Fortran `DO 10 I=1,8` vs. `DO 10 I=1.8`

Parsing

- Context-Free patterns (aka, Type 2 Grammars)
  - Every rule like **N:(t|N)***
  - Need a stack to remember position within a rule; e.g., pairing 0 or more **b**,**c** around a **d**:

A:bAc

A:d

```
int A() { // recognize an A, return 1 if successful
    switch (nextt) {
    case 'b': lex(); A(); if (nextt == 'c') lex(); /* A:bAc_ */ return(1);
    case 'd': lex(); /* A:d_ */ return(1);
    }
    return(0);
}
```

Parsing Complications

Some grammars are too hard to parse by…
so computer languages avoid such structures

- Context-Sensitive patterns (Type 1 Grammars)
  - Every rule like `αNβ:α(t|N)+β` read as `(t|N)+` becomes `N` in the context of `α`,`β`
  - In theory, pronouns/identifiers need this, but lexer + symbol table lookup suffices
- Unrestricted patterns (Type 0 Grammars)
  - Parse by nondeterministic Turing machine

Parsing Decisions

When do you decide what rule applies?

- How many tokens (terminals) of lookahead?
- LL(1) aka recursive descent
  - Read input L→R, pick rule 1 past L edge: i.e., `A:bAc` and `A:d` by looking at `b` or `d`
  - LL(k) is convenient for code generation...
- LR(0) aka shift/reduce
  - Read input L→R, pick rule at R edge: i.e., `A:bAc` and `A:d` by seeing `bAc` or `d`

Embedded Code Generation

- Simplest method embeds code generation as actions within the parser
  - `printf()` can generate assembly code
  - Place actions at the green spots:

```
A:bAc
A:d
```

```
int A() { // recognize an A, return 1 if successful
    switch (nextt) {
    case 'b': lex(); A(); if (nextt == 'c') lex(); /* A:bAc_ */ return(1);
    case 'd': lex(); /* A:d_ */ return(1);
    }
    return(0);
}
```

Grouping Expressions

- Let's generate stack code for expressions:
  - **+** has lowest priority, groups L → R
  - ***** groups R → L
  - **()** overrides grouping
  - variables can be **a**, **b**, or **c**

```
/* BNF for LR parsing */
add: add '+' mul printf("add\n");
add: mul
mul: par '*' mul printf("mul\n");
mul: par
par: '(' add ')'
par: 'a' printf("push a\n");
par: 'b' printf("push b\n");
par: 'c' printf("push c\n");
```

```
/* EBNF for LL parsing */
add: mul ('+' mul printf("add\n");)*

mul: par {'*' mul printf("mul\n");}

par: '(' add ')'
par: 'a' printf("push a\n");
par: 'b' printf("push b\n");
par: 'c' printf("push c\n");
```

Grouping Expressions

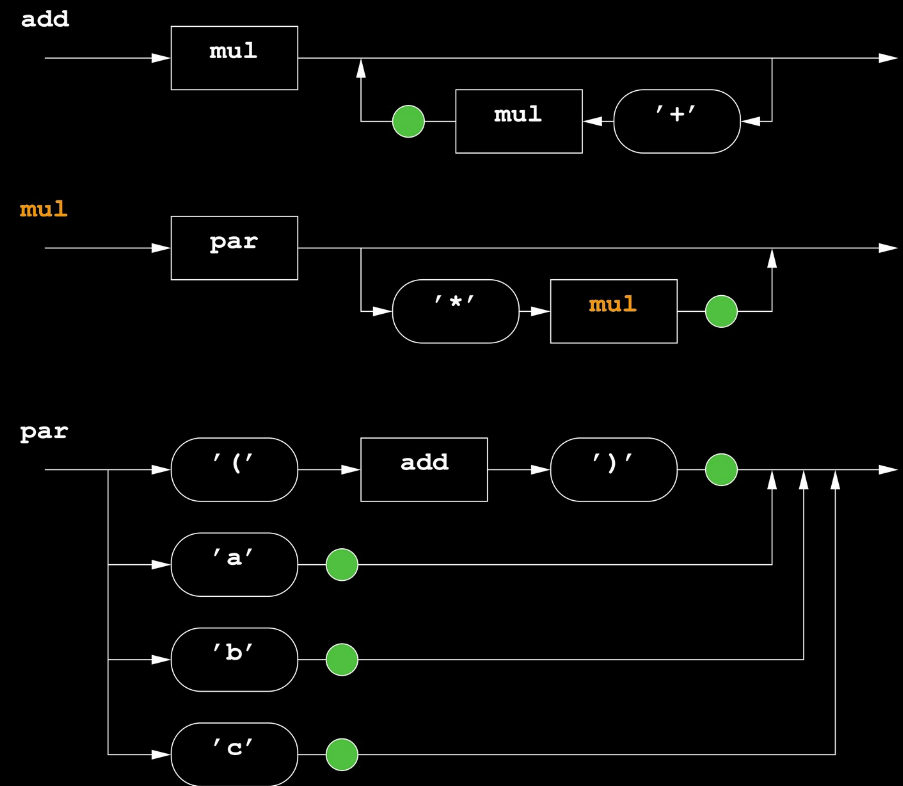
- EBNF can be rewritten as a syntax diagram

```
/* EBNF for LL parsing */
add: mul ('+' mul printf("add\n");)*


mul: par {'*' mul printf("mul\n");}



par: '(' add ')'
par: 'a' printf("push a\n");
par: 'b' printf("push b\n");
par: 'c' printf("push c\n");
```

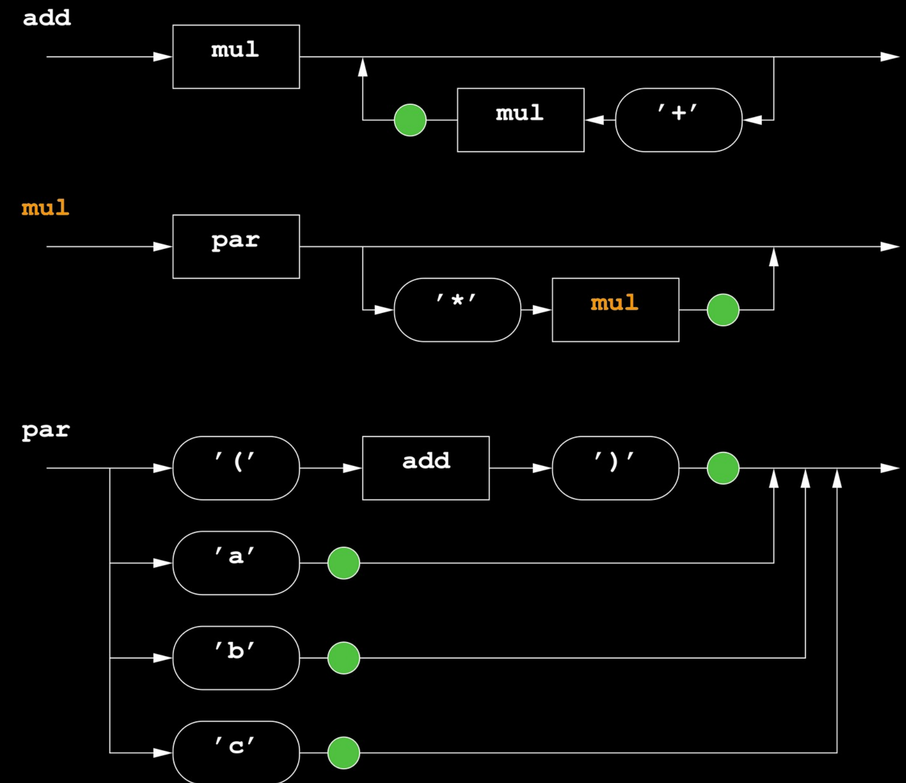


LL(1) Parser & Code Generator

```
void add() {
  mul();
  while(nextt == '+') {
    lex(); mul(); printf("add\n");
  }
}

void mul() {
  par();
  if (nextt == '*') {
    lex(); mul(); printf("mul\n");
  }
}

void par() {
  switch (nextt) {
  case '(': lex(); add(); lex(); break;
  case 'a': lex(); printf("push a\n"); break;
  case 'b': lex(); printf("push b\n"); break;
  case 'c': lex(); printf("push c\n");
  }
}
```



Let’s Run It!

```
#include <stdio.h>
int nextc, nextt;
void lex(), add(), mul(), par();

void lex() {
  for (;;) switch (nextc) {
  case ' ': case '\t': case '\n':
    nextc = getchar(); break; // ignored
  case '+': case '*': case '(': case ')':
  case 'a': case 'b': case 'c':
    nextt = nextc; nextc = getchar(); return;
  default:
    nextt = '.'; return; // end of input
  }
}

void add() {
  mul();
  while(nextt == '+') {
    lex(); mul(); printf("add\n");
  }
}

void mul() {
  par();
  if (nextt == '*') {
    lex(); mul(); printf("mul\n");
  }
}

void par() {
  switch (nextt) {
  case '(': lex(); add(); lex(); break;
  case 'a': lex(); printf("push a\n"); break;
  case 'b': lex(); printf("push b\n"); break;
  case 'c': lex(); printf("push c\n");
  }
}

int main() {
  nextc = getchar(); // prime lexer
  lex();             // prime parser
  add();
  return(nextt != '.'); // ended OK?
}
```

```
$ cc comp.c -o comp
$ ./comp
a+b+c.
push a
push b
add
push c
add
$ ./comp
a+(b+c).
push a
push b
push c
add
add
$ ./comp
a*b*c.
push a
push b
push c
mul
mul
$ ./comp
(a*b)*c.
push a
push b
mul
push c
mul
```

```
$ ./comp
a+b*c.
push a
push b
push c
mul
add
$ ./comp
a*b+c.
push a
push b
mul
push c
add
$ ./comp
a*(b*a+c)+c.
push a
push b
push a
mul
push c
add
mul
push c
add
$
```

Better Code Generation

- Stack code is easy to generate...
- How do we generate better code?
  - Generate an intermediate representation (IR); e.g., ASTs (abstract syntax trees)
  - Analyze & decorate the IR
  - Apply correctness-preserving transformations
  - Walk the IR to generate code
- **It's complicated.** Nearly every data structure and algorithm has been used in compilers.

What About The Preprocessor?

- It is a very simple source-to-source translator
  - Most code passes through unchanged
  - Preprocessor directives get replaced by the translated text, usually using simple string matching and substitution
- Source-to-source translation is commonly used; e.g., C++ originally was implemented as a fancy preprocessor for C

What About The Assembler?

- Assemblers are mostly very simple compilers
- But they must handle forward references
  - A forward reference happens when you use something in a program before defining it
  - Remember `void lex(), add(), mul(), par();`?
  - Most compilers output code with forward references for the assembler to resolve:

```
          beq  $t0, $0, L
          …
L:
```

Resolving Forward References

- Before seeing `L:`, you don't know the address, but can't output `0x1100????` for `beq $t0,$0,L`
- Backpatching: remember where you left space in output and patch each value when defined
- Multi-pass resolution re-parses the source
  - Pass 1 notes locations in the symbol table
  - Pass 2 generates code
  - May need multiple Pass 1, but can handle variable-size things (e.g., branch vs. jump)

Let’s Look A “Real” Compiler

- Mucky (MIPS uCompiler from KY)
  - Accepts an undocumented C subset
  - Generated code isn’t MIPS ABI compliant

  `https://aggregate.org/cgi-bin/mucky.cgi`

- Here’s the full source code for Mucky
  - No IR; this uses embedded code generation
  - Uses CGI WWW form interface for I/O

  `https://aggregate.org/CPE380/mucky.c`

- AIK assembler is at `https://aggregate.org/AIK/`

Conclusion

- You now have a decent understanding of how compilation can be implemented!
  - Some understanding of grammars & parsing
  - Simple embedded code generation
  - Saw a complete simple compiler (Mucky)
- You know they exist, but we didn't show you:
  - Generation, analysis, & decoration of IRs
  - Optimization & automatic parallelization
  - Forward reference processing in assemblers