Code Generation for Data Processing

Lecture 2: Compiler Front-end

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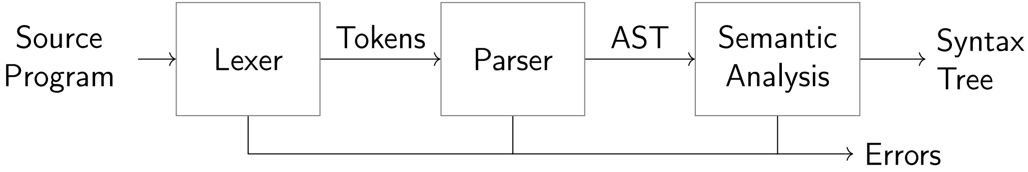
Compiler Front-end



- Typical architecture: separate lexer, parser, and context analysis
  - Allows for more efficient lexical analysis
  - Smaller components, easier to understand, etc.
- Some languages: preprocessor and macro expansion

Lexer

- Convert stream of chars to stream of words (*tokens*)
- Detect/classify identifiers, numbers, operators, ...
- Strip whitespace, comments, etc.

`a+b*c` → `ID(a) PLUS ID(b) TIMES ID(c)`

- Typically representable as regular expressions

Typical Token Kinds

- Punctuators `( ) [ ] { } ; = + += | ||`
- Identifiers `abc123 main`
- Keywords `void int __asm__`
- Numeric constants `123 0xab1 5.7e3 0x1.8p1 09.1f`
- Char constants `'a' u'œ'`
- String literals `"abc\x12\n"`
- Internal `EOF COMMENT UNKNOWN INDENT DEDENT`
  - Comments might be useful for annotations, e.g. `// fallthrough`

Lexer Implementation

```
struct Token { enum Kind { IDENT, EOF, PLUS, PLUSEQ, /*...*/ };
  std::string_view v; Kind kind; };
Token next(std::string_view v) {
  if (v.empty()) return Token{v, Token::EOF};
  if (v.starts_with("+=")) return Token{"+="sv, Token::PLUSEQ};
  if (v.starts_with("+")) return Token{"+"sv, Token::PLUS};
  switch (v[0]) {
  case '␣', '\n', '\t': return next(v.substr(1)); // skip whitespace
  case 'a' ... 'z', 'A' ... 'Z', '_': {
    Token t = // ... parse identifer, e.g. using regex
    if (auto kind = isKeyword(t.v)) return Token{*kind, t.v};
    return t;
  }
  case '0' ... '9': // ... parse number
  default: return Token{v.substr(0, 1), Token::ERROR};
  }
}
```

Lexing C??=

```
main() <%
  // yay, this is C99??/
  puts("hi␣world!");
  puts("what's␣up??!");
%>
```

Output: `what's up|`

- Trigraphs for systems with more limited encodings/char sets
- Digraphs to provide a more readable alternative...

Lexer Implementation

- Essentially a DFA (for most languages)
  - Set of regexes $\rightarrow$ NFA $\rightarrow$ DFA
- Respect whitespace/separators for operators, e.g. + and +=
- Automatic tools (e.g., flex) exist; most compilers do their own
- Keywords typically parsed as identifiers first
  - Check identifier if it is a keyword; can use perfect hashing
- Other practical problems
  - UTF-8 homoglyphs; trigraphs; pre-processing directives

Parsing

- Convert stream of tokens into (abstract) syntax tree
- Most programming languages are context-sensitive
  - Variable declarations, argument count, type match, etc.
    $\rightsquigarrow$ separated into semantic analysis

  Syntactically valid: `void foo = doesntExist / "abc";`
- Grammar usually specified as CFG

Context-Free Grammar (CFG)

- Terminals: basic symbols/tokens
- Non-terminals: syntactic variables
- Start symbol: non-terminal defining language
- Productions: non-terminal $\rightarrow$ series of (non-)terminals

$$
\begin{aligned}
\mathit{stmt} &\rightarrow \mathit{whileStmt} \mid \mathit{breakStmt} \mid \mathit{exprStmt} \\
\mathit{whileStmt} &\rightarrow \textbf{while}\ \textbf{(}\ \mathit{expr}\ \textbf{)}\ \mathit{stmt} \\
\mathit{breakStmt} &\rightarrow \textbf{break}\ \textbf{;} \\
\mathit{exprStmt} &\rightarrow \mathit{expr}\ \textbf{;} \\
\mathit{expr} &\rightarrow \mathit{expr} + \mathit{expr} \mid \mathit{expr}\ \textbf{*}\ \mathit{expr} \mid \mathit{expr} = \mathit{expr} \mid \textbf{(}\ \mathit{expr}\ \textbf{)} \mid \textbf{number}
\end{aligned}
$$

Hand-written Parsing – First Try

- One function per non-terminal
- Check expected structure
- Return AST node
- Need look-ahead!

```
NodePtr parseBreakStmt() {
  consume(Token::BREAK);
  consume(Token::SEMICOLON);
  return newNode(Node::BreakStmt);
}
NodePtr parseWhileStmt() {
  consume(Token::WHILE);
  consume(Token::LPAREN);
  NodePtr expr = parseExpr();
  consume(Token::RPAREN);
  NodePtr body = parseStmt();
  return newNode(Node::WhileStmt,
    {expr, body});
}
NodePtr parseStmt() {
  // whoops!
}
```

Hand-written Parsing – Second Try

- Need look-ahead to distinguish production rules
- Consequences for grammar:
  - No left-recursion
  - First n terminals must allow distinguishing rules
  - $LL(n)$ grammar; n typically 1

  $\Rightarrow$ Not all CFGs (easily) parseable (but most programming langs. are)
- Now... expressions

```
NodePtr parseBreakStmt() { /*...*/ }
NodePtr parseWhileStmt() { /*...*/ }

NodePtr parseStmt() {
  Token t = peekToken();
  if (t.kind == Token::BREAK)
    return parseBreakStmt();
  if (t.kind == Token::WHILE)
    return parseWhileStmt();
  // ...
  NodePtr expr = parseExpr();
  consume(Token::SEMICOLON);
  return newNode(Node::ExprStmt,
    {expr});
}
```

Ambiguity

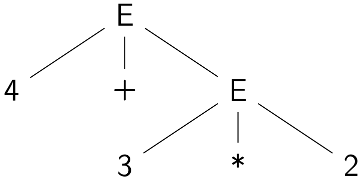
$$expr \rightarrow expr + expr \mid expr \;\mathbf{*}\; expr \mid expr = expr \mid \mathbf{(}\; expr \;\mathbf{)} \mid \mathbf{number}$$

Input: $4 + 3 * 2$

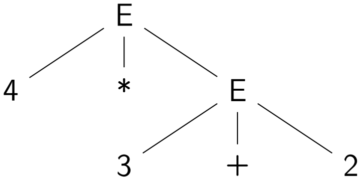
Ambiguity – Rewrite Grammar?

$$
\begin{aligned}
\textit{primary} &\rightarrow (\ \textit{expr}\ ) \mid \textbf{number} \\
\textit{expr} &\rightarrow \textit{primary} + \textit{expr} \mid \textit{primary} \ \textbf{*}\ \textit{expr} \mid \textit{primary} = \textit{expr} \mid \textit{primary}
\end{aligned}
$$

Input: $4 + 3 * 2$

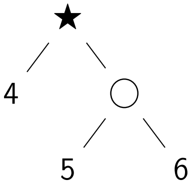


Input: $4 * 3 + 2$

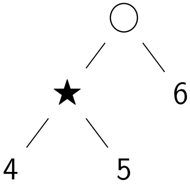


Ambiguity – Precedence

Input: $4 \bigstar 5 \bigcirc 6$



If $\mathit{prec}(\bigcirc) > \mathit{prec}(\bigstar)$ or
equal prec. and ★ is right-assoc.



If $\mathit{prec}(\bigcirc) < \mathit{prec}(\bigstar)$ or
equal prec. and ★ is left-assoc.

Hand-written Parsing – Expression Parsing

- Start with basic expr.:
- Number, variable, etc.
- Parenthesized expr.
  - Parse full expression
  - Next token must be)
- Unary expr: followed by expr. with higher prec.
  - - < unary - < []/->

```
NodePtr parseExpr(unsigned minPrec=0);
NodePtr parsePrimaryExpr() {
  switch (Token t = next(); t.kind) {
  case Token::IDENT:
    return makeNode(Node::IDENT, t.v);
  case Token::NUMBER: // ...
  case Token::MINUS:
    // Only exprs with high precedence
    return makeNode(Node::UMINUS,
      {parseExpr(UNARY_PREC)});
  case Token::LPAREN: // ...
  // ...
  }
}
```

Hand-written Parsing – Expression Parsing

- Only allow ops. with higher prec. on the right child
  - Right-assoc.: allow same
- Lower prec.: return + insert higher up in the tree

```
OpDesc OPS[] = { // {prec, rassoc}
  [Token::MUL] = {12, false},
  [Token::ADD] = {11, false},
  [Token::EQ] = {2, true},
  [Token::QUEST] = {3, true}, // ?:
}
```

```
NodePtr parseExpr(unsigned minPrec=1) {
  auto lhs = parsePrimaryExpr();
  while (auto op = OPS[next().kind];
         op.prec >= minPrec) {
    // ... handle (, [, ?: ...
    auto newPrec = op.rassoc ?
      op.prec : op.prec + 1;
    auto rhs = parseExpr(newPrec);
    lhs = makeNode(op.nodeKind,
      {lhs, rhs});
  }
  return lhs;
}
```

```
a = 3 * 2 + 1;        a = b + c + d = 1;        a ? 1 : b ? 2 : 3;
```

Top-down vs. Bottom-up Parsing

Top-down Parsing

- Start with top rule
- Every step: choose expansion
- LL(1) parser
  - Left-to-right, Leftmost Derivation
- “Easily” writable by hand
- Error handling rather simple
- Covers many prog. languages

Bottom-up Parsing

- Start with text
- Reduce to non-terminal
- LR(1) parser
  - Left-to-right, Rightmost Derivation
  - Strict super-set of LL(1)
- Often: uses parser generator
- Error handling more complex
- Covers nearly all prog. languages

Parser Generators

- Writing parsers by hand can be large effort
- Parser generators can simplify parser writing a lot
  - Yacc/Bison, PLY, ANTLR, ...
- Automatic generation of parser/parsing tables from CFG
  - Finds ambiguities in the grammar
  - Lexer often written by hand
- Used heavily in practice, unless error handling is important

Bison Example – part 1

```
%define api.pure full
%define api.value.type {ASTNode*}
%param { Lexer* lexer }
%code{
static int yylex(ASTNode** lvalp, Lexer* lexer);
}
%token NUMBER
%token WHILE "while"
%token BREAK "break"

// precedence and associativity
%right '='
%left '+'
%left '*'
```

Bison Example – part 2

```
%%
stmt : WHILE '(' expr ')' stmt { $$ = mkNode(WHILE, $1, $2); }
     | BREAK ';'               { $$ = mkNode(BREAK, NULL, NULL); }
     | expr ';'                { $$ = $1; }
     ;
expr : expr '+' expr           { $$ = mkNode('+', $1, $2); }
     | expr '*' expr           { $$ = mkNode('*', $1, $2); }
     | expr '=' expr           { $$ = mkNode('=', $1, $2); }
     | '(' expr ')'            { $$ = $1; }
     | NUMBER
     ;
%%
static int yylex(ASTNode** lvalp, Lexer* lexer) {
    /* return next token, or YYEOF/... */ }
```

Parsing in Practice

- Some use parser generators, e.g. Python
  some use hand-written parsers, e.g. GCC, Clang, Swift, Go
- Optimization of grammar for performance
  - Rewrite rules to reduce states, etc.
- Useful error-handling: complex!
  - Try skipping to next separator, e.g. `;` or `,`
- Programming languages are not always context-*free*
  - C: `foo* bar;`
  - May need to break separation between lexer and parser

[2] `https://notes.eatonphil.com/parser-generators-vs-handwritten-parsers-survey-2021.html`

Parsing C++

- C++ is not context-free (inherited from C): `T * a;`
- C++ is ambiguous: `Type (a), b;`
  - Can be a declaration or a comma expression
- C++ templates are Turing-complete[3]
- C++ *parsing* is hence *undecidable*[4]
  - Template instantiation combined with C `T * a` ambiguity

[3] TL Veldhuizen. *C++ templates are Turing complete*. 2003. .

[4] J Haberman. *Parsing C++ is literally undecidable*. 2013. .

Semantic Analysis

- Syntactical correctness $\not\Rightarrow$ correct program

```
void foo = doesntExist / ++"abc";
```

- Needs context-sensitive analysis:
  - Variable existence, storage, accessibility, ...
  - Function existence, arguments, ...
  - Operator type compatibility
  - Attribute allowance
- Additional type complexity: inference, polymorphism, ...

Semantic Analysis: Scope Checking with AST Walking

- Idea: walk through AST (in DFS-order) and validate on the way
- Keep track of scope with declared variables
  - Might need to keep track of defined types separately

How to implement the scope data structure?

- For identifiers: check existence and get type
- For expressions: check types and derive result type
- For assignment: check lvalue-ness of left side

- *Might* be possible during AST creation
- Needs care with built-ins and other special constructs

Semantic Analysis and Post-Parsing Transformations

- Check for error-prone code patterns
  - Completeness of `switch`, out-of-range constants, unused variables, ...
- Check method calls, parameter types

- Duplicate code for templates
- Make implicit value conversions explicit
- Handle attributes: visibility, warnings, etc.

- Mangle names, split functions (OpenMP), ABI-specific setup, ...
- Last step: generate IR code

Parsing Performance

Is parsing/front-end performance important?

- Not necessarily: normal compilers
  - Some languages (e.g., Rust) need unbounded time *for parsing*
- Somewhat: JIT compilers
  - Start-up time is generally noticable
- Somewhat more: Developer tools
  - Imagine: waiting for seconds just for updated syntax highlighting
  - Often uses tricks like incremental updates to parse tree

Data Types

- Important part of programming languages
- Might have large variety and compatibility
  - Numbers, Strings, Arrays, Compound Types (struct/union), Enum, Templates, Functions, Pointers, ...
  - Class hierarchy, Interfaces, Abstract Classes, ...
  - Integer/float compatibility, promotion, ...
- Might have implicit conversions

Data Types: Implementing Classes

- Simple `class`/`struct`: trivial, just bunch of fields
  - Methods take (pointer to) `this` as implicit parameter
- Single inheritance: also trivial – extend struct at end

- Virtual methods: store vtable in object representation
  - vtable = table of function pointers for virtual methods
  - Each sub-class has their own vtable
- Multiple inheritance is much more involved
- Dynamic casts: needs run-time type information (RTTI)

Recommended Lectures

AD IN2227 “Compiler Constructions” covers parsing/analysis in depth

AD CIT3230000 “Programming Languages” covers dispatching/mixins/...

Compiler Front-end – Summary

- Lexer splits input into tokens
  - Essentially Regex-Matching + Keywords; rather simple
- Parser constructs (abstract) syntax tree from tokens
  - Top-down vs. bottom-up parsing
  - Typical: top-down for control flow; bottom-up for expressions
  - Respect precedence and associativity for operators
- Semantic analysis ensures meaningful program
- Some data structures are complex to implement
- Some programming languages are more difficult to parse

Compiler Front-end – Questions

- What are typical components of a compiler front-end?
- What output does the lexer produce?
- How does a parser disambiguate rules?
- What is the typical way to handle operator precedence?
- Why are not all programming languages describable using CFGs?
- How to implement classes with virtual functions?