

Programming Languages

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What this course is

- A study of programming language paradigms
 - ◆ Imperative
 - ◆ Functional
 - ◆ Logical
 - ◆ Object-oriented
- Tour of programming language history & roots.
- Introduction to core language design & implementation concepts.
- Exposure to languages/paradigms you may not have used before.
- Exploration of implementation issues, including performance considerations.
- Understanding and appreciation of language standards.
- Enable you to more quickly learn and understand new languages.

What this course isn't

- A learn-to-program course.
- Learn the hottest new languages
 - ◆ We study languages not because of their popularity or marketability but due to their contributions to the field.
- Become an expert in 10 new languages.
- Project-based software development course.
- A software engineering course.
- A compiler course.

Introduction

The main themes of programming language design and use:

- Paradigm (model of computation)
- Expressiveness
 - ◆ control structures
 - ◆ abstraction mechanisms
 - ◆ types and their operations
 - ◆ tools for programming in the large
- Ease of use: writeability / readability / maintainability
- Portability

Language as a tool for thought

- Role of language as a communication vehicle among programmers can be just as important as ease of writing
- All general-purpose languages are *Turing complete* (They can compute the same things)
- But languages can make expression of certain algorithms difficult or easy.
 - ◆ Try multiplying two Roman numerals
- Idioms in language A may be useful inspiration when writing in language B.

Idioms

- Copying a string `q` to `p` in C:

```
while (*p++ = *q++) ;
```

- Removing duplicates from the list `@xs` in Perl:

```
my %seen = ();  
@xs = grep { ! seen{ _ }++; } @xs;
```

- Computing the sum of numbers in list `xs` in Haskell:

```
foldr (+) 0 xs
```

Is this natural? *It is if you're used to it*

Some programming paradigms

- *Imperative (von Neumann)*: **Fortran, Pascal, C, Ada**
 - ◆ programs have mutable storage (state) modified by assignments
 - ◆ the most common and familiar paradigm
- *Functional (applicative)*: **Scheme, Lisp, ML, Haskell**
 - ◆ functions are first-class values
 - ◆ *side effects* (e.g., assignments) discouraged
- *Logical (declarative)*: **Prolog, Mercury**
 - ◆ programs are sets of assertions and rules
- *Object-Oriented*: **Simula 67, Smalltalk, C++, Ada95, Java, C#**
 - ◆ data structures and their operations are bundled together
 - ◆ inheritance
- *Quantum*: **QCL, Q, Q#, qGCL**
 - ◆ performs operations on data using quantum bits (“qubits”)
 - ◆ utilizes quantum properties such as superposition and entanglement

Choice of Languages

- Survey on the actual motivators for language choice:
 - ◆ “That’s what everybody happens to know.”
 - ◆ “It’s the hottest new language with cool features.”
- What it *should* be:
 - ◆ “It’s the best language for the job.”
 - ◆ “It contains abstractions we find useful for solving the problem.”
 - ◆ “It is the most readable language for programs in this domain.”
- Fun fact: there are over 3,000 languages in the world. Not a single one of them has been proven to decrease defect rates.

Spectrum of Languages

- High level languages are an abstraction: an interface between humans and the computer.
- There are differing levels of abstraction, known as the *program level*. (Halstead)
- Low level languages: you tell the language how to solve the problem. (**Assembly, C, Fortran**)
- High level languages: you tell the language what to do, not how to do it. (**ML, Setl, Prolog**)
- Hybrid languages: a little of both (**Ada, C++, Java, C#**)

Beginnings

- Before high level languages, programs were written in *assembly*.
 - ◆ Hardware-specific.
 - ◆ Not easily ported.
 - ◆ Repetition of the same patterns.
 - ◆ More difficult to reuse code.
 - ◆ Great effort for even simple algorithms.
 - ◆ High probability of programming error.
 - ◆ Chance of wearing out or even damaging hardware.

Beginnings

■ FORTRAN

- ◆ Invented by John Backus et al., released in 1957.
- ◆ First successful high-level programming language.
- ◆ Primary use: scientific computing and mathematics.
- ◆ Example:

$$A = C + D$$

■ COBOL

- ◆ Designed by committee, released late 1960.
- ◆ Common or Business-Oriented Language.
- ◆ Data processing, business, finance, administrative systems.
- ◆ Introduced structures.
- ◆ Example:

```
ADD C TO D GIVING A
```

Beginnings (continued)

■ ALGOL

- ◆ Invented by a group of European & American computer scientists, released in 1958.
- ◆ Popularized many PL concepts still in use today.
 - BNF
 - Compound statements using blocks
 - case statement
 - Call-by-reference
 - Concurrency
 - Orthogonality
- ◆ Was not a commercial success (e.g., no standard I/O).

```
IF Ivar > Jvar THEN Ivar ELSE Jvar FI := 3;
```

Language standards

Developed by working groups of standards bodies (ANSI, ISO).

- Main goal: define the language.
- Pro: Discourages language “flavors” (like LISP), increases portability.
- Con: Places creative freedom in the hands of a few people.
- Major compiler manufacturers generally align to the standards.
- Defines syntactic and semantic correctness (sometimes partially).
- Enforcement is often left to individual compiler implementations.
- Undefined behavior may not be detected. Decreases portability.

Example 1 (C++):

```
int x;  
int y = x + 2; // x is undefined
```

Example 2 (C++):

```
cout << (INT_MAX+1);
```

See also: [this research paper](#)

Language libraries

The programming environment may be larger than the language.

- The predefined libraries are *indispensable* to the proper use of the language, *and its popularity*.
- The libraries are defined in the language itself, but they have to be internalized by a good programmer.

Examples:

- C++ standard template library
- Java Swing classes
- Ada I/O packages

Syntax and semantics

- Syntax refers to external representation:
 - ◆ Given some text, is it a well-formed program?
- Semantics denotes meaning:
 - ◆ Given a well-formed program, what does it mean?
 - ◆ Often depends on context (e.g. C++ keyword **const**, operator **&**).

The division is somewhat arbitrary.

- Similar looking constructs in different languages often have different meanings (e.g. **virtual**)

Compilation overview

Major phases of a compiler:

1. lexer: text \longrightarrow tokens
2. parser: tokens \longrightarrow parse tree
3. semantic analyzer: parse tree \longrightarrow abstract syntax tree
4. intermediate code generation
5. optimization (machine independent): local & global redundancy elimination, loop optimization
6. target code generation
7. optimization (machine dependent): instruction scheduling, register allocation, peephole optimization

Some languages (Java) perform some steps at compile time and others at runtime.

Grammars

A *grammar* G is a tuple (Σ, N, S, δ)

- Σ is the set of *terminal* symbols (alphabet)
- N is the set of *non-terminal* symbols
- S is the distinguished non-terminal: the root symbol
- δ is the set of rewrite rules (productions) of the form:

$$ABC \dots ::= XYZ \dots$$

where A, B, C, X, Y, Z are terminals and non terminals.

- The symbol ϵ represents the *empty string*. Epsilon transition: $A ::= \epsilon$ means “nonterminal A rewrites to no terminals or non-terminals.”
- The *language* is the set of sentences containing **only** terminal symbols that can be generated by applying the rewriting rules starting from the root symbol (let's call such sentences *strings*)

BNF for context-free grammars

(BNF = Backus-Naur Form)

Does not add expressiveness to the language—for convenience only. Some conventional abbreviations:

- alternation: $\text{Symb} ::= \text{Letter} \mid \text{Digit}$
- sequencing: $\text{Id} ::= \text{Letter Symb}$

EBNF = Extended Backus-Naur Form. Encompasses everything above, plus:

- repetition: $\text{Id} ::= \text{Letter} \{\text{Symb}\}$
or we can use a Kleene star: $\text{Id} ::= \text{Letter Symb}^*$
for one or more repetitions: $\text{Int} ::= \text{Digit}^+$
- option: $\text{Num} ::= \text{Digit}^+ [. \text{Digit}^*]$
- grouping: $\text{SignedNum} ::= ('+' | '-') \text{Num}$

Note: need convention for metasymbols – what if “|,” “[,” “],” “+,” etc. are in the language?

Partial Java Grammar

```
<typedekl>      ::= type <typedeflist>
<typedeflist>   ::= <typedef> [ <typedeflist> ]
<typedef>       ::= <typeid> = <typespec> ;
<typespec>      ::= <typeid> |
                    <arraydef> | <ptrdef> | <rangedef> |
                    <enumdef> | <recdef>

<typeid>        ::= <ident>
<arraydef>      ::= [ packed ] array '[' <rangedef> ']' of <typeid>
<ptrdef>        ::= ^ <typeid>
<rangedef>      ::= <number> .. <number>
<number>        ::= <digit> [ <number> ]
<enumdef>       ::= ( <idlist> )
<idlist>        ::= <ident> { , <ident> }
<recdef>        ::= record <vardecllist> end ;
```

The Chomsky hierarchy

■ Regular grammars (Type 3)

- ◆ all productions can be written in the form: $N ::= TN$
- ◆ one non-terminal on left side; at most one on right
- ◆ generally used for scanners

■ Context-free grammars (Type 2)

- ◆ all productions can be written in the form: $N ::= XYZ$
- ◆ one non-terminal on the left-hand side; mixture on right
- ◆ most major programming languages

■ Context-sensitive grammars (Type 1)

- ◆ number of symbols on the left is no greater than on the right
- ◆ no production shrinks the size of the sentential form
- ◆ used for parts of C++, but otherwise rarely used

■ Type-0 grammars

- ◆ no restrictions

Regular grammar example

A grammar for floating point numbers:

$$\text{Float} ::= \text{Digits} \mid \text{Digits} . \text{Digits}$$
$$\text{Digits} ::= \text{Digit} \mid \text{Digit Digits}$$
$$\text{Digit} ::= 0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9$$

A regular expression for floating point numbers:

$$(0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9)^+ (.(0 \mid 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6 \mid 7 \mid 8 \mid 9)^+)?$$

Perl offer some shorthands:

$$[0-9]^+(\. [0-9]^+)?$$

or

$$\backslash d^+(\. \backslash d^+)?$$

Regular expressions

Regular grammars can be used to *generate* regular languages. Regular expressions can be used to *accept* regular languages.

We say that a regular expression R denotes the language $\llbracket R \rrbracket$.

Basic regular expressions:

- ϵ denotes \emptyset
- a character x , where $x \in \Sigma$, denotes $\{x\}$
- (sequencing) a sequence of two regular expressions RS denotes $\{\alpha\beta \mid \alpha \in \llbracket R \rrbracket, \beta \in \llbracket S \rrbracket\}$
- (alternation) $R|S$ denotes $\llbracket R \rrbracket \cup \llbracket S \rrbracket$
- (Kleene star) R^* denotes the set of strings which are concatenations of zero or more strings from $\llbracket R \rrbracket$
- parentheses are used for grouping

Shorthands:

- $R^? \equiv \epsilon|R$
- $R^+ \equiv RR^*$

Regular expressions

The following are not strictly regular expressions, but rather notational conveniences:

- $\cdot \equiv \text{any } \alpha \in \Sigma$ (“any character”)
- Character classes:
 - ◆ $[abc] \equiv (a|b|c)$
 - ◆ $[\^abc] \equiv \Sigma \setminus \{a, b, c\}$
 - ◆ $[0-9] \equiv (0|1|2|3|4|5|6|7|8|9)$.
 - ◆ Similarly with a-z and A-Z.

Expressions can be *greedy* or *lazy*:

- Greedy: match as much as possible (Flex)
- Lazy: match as little as possible

Example: $f.+1$ on input string “fellow”

- Greedy: will match “fell”
- Lazy: will match “fel”

Lexical Issues

Lexical: formation of words or tokens.

- Described (mainly) by regular grammars
- Terminals are characters. Some choices:
 - ◆ character set: ASCII, Latin-1, ISO646, Unicode, etc.
 - ◆ is case significant?
- Is indentation significant?
 - ◆ Python, Occam, Haskell

Example: identifiers

$$\text{Id} ::= \text{Letter IdRest}$$
$$\text{IdRest} ::= \epsilon \mid \text{Letter IdRest} \mid \text{Digit IdRest}$$

Missing from above grammar: limit of identifier length

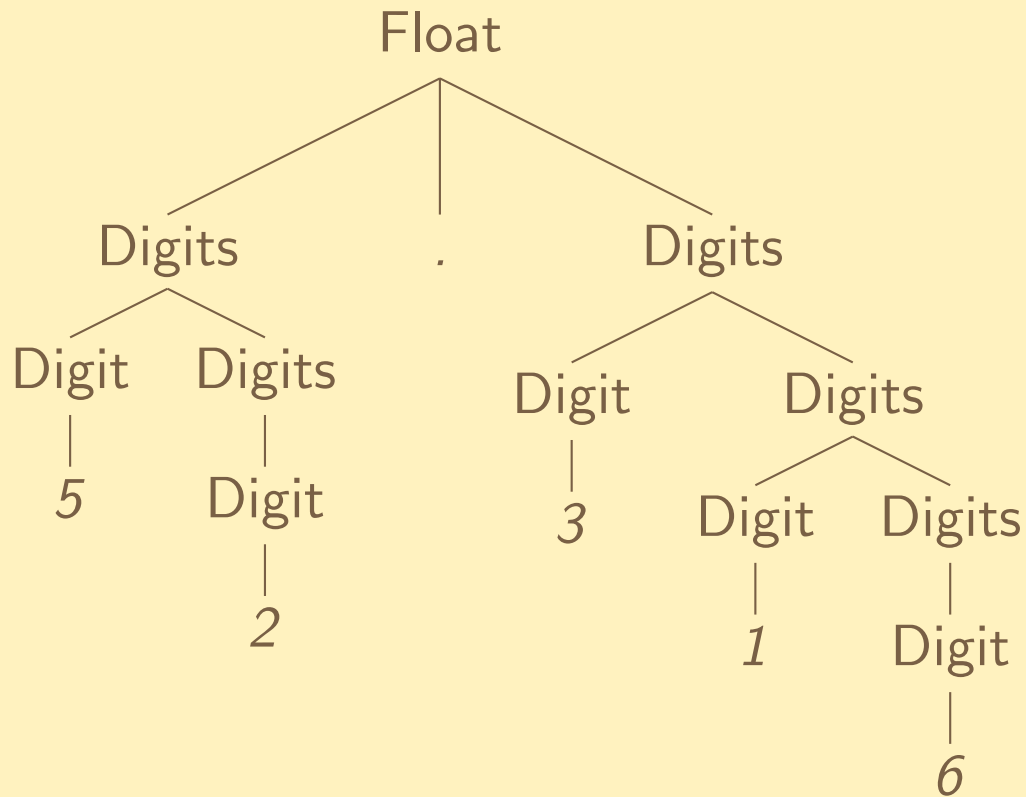
Parse trees

A parse tree describes the grammatical structure of a sentence

- root of tree is root symbol of grammar
- leaf nodes are terminal symbols
- internal nodes are non-terminal symbols
- an internal node and its descendants correspond to some production for that non terminal
- top-down tree traversal represents the process of generating the given sentence from the grammar
- construction of tree from sentence is *parsing*

Parse Tree Illustration

The parse tree for input string 52.316 on the grammar below from slide 20:



Float ::= Digits | Digits . Digits

Digits ::= Digit | Digit Digits

Digit ::= 0|1|2|3|4|5|6|7|8|9

Ambiguity

If the parse tree for a sentence is not unique, the grammar is *ambiguous*:

$$E ::= E + E \mid E * E \mid \text{Id}$$

Two possible parse trees for “A + B * C”:

- $((A + B) * C)$
- $(A + (B * C))$

One solution: rearrange grammar:

$$\begin{aligned} E &::= E + T \mid T \\ T &::= T * \text{Id} \mid \text{Id} \end{aligned}$$

Harder problems – disambiguate these (courtesy of Ada):

- $\text{function_call} ::= \text{name} (\text{expression_list})$
- $\text{indexed_component} ::= \text{name} (\text{index_list})$
- $\text{type_conversion} ::= \text{name} (\text{expression})$

Precedence

Consider the expression $5 + 2 * 3$.

- In mathematics, we say operator $*$ has *precedence* over operator $+$.
- This means evaluate the expression as: $5 + (2 * 3)$, not $(5 + 2) * 3$.
- Do not confuse precedence with order of evaluation.
 - ◆ Precedence indicates grouping.
 - ◆ Groups can be evaluated in any order.

Precedence can be specified in a couple ways:

- Write the precedence rules directly into the grammar. Rules for higher precedence operators will tend to be deeper in the parse tree than other rules. (see “calc1” example)
- Write an ambiguous grammar (i.e. make $+$ and $*$ the same level of precedence), specify operator precedence separately. Parser generators like Bison offer this as a convenience. (see “calc2” example)

Associativity

Consider the expression $5 + 2 + 3$.

We know that $5 + (2 + 3)$ yields the same mathematical result as $(5 + 2) + 3$, but $5 - (2 - 3)$ is different than $(5 - 2) - 3$.

Associativity tells the parser what to do with operators at the *same* level of precedence.

Some options:

- Use *left associativity*: $((5 + 2) + 3)$
- Use *right associativity*: $(5 + (2 + 3))$

Dangling else problem

Consider:

$$S ::= \text{if } E \text{ then } S$$
$$S ::= \text{if } E \text{ then } S \text{ else } S$$

The sentence

$$\text{if } E_1 \text{ then if } E_2 \text{ then } S_1 \text{ else } S_2$$

is ambiguous (Which then does else S_2 match?)

Solutions:

- Pascal rule: else matches most recent if
- grammatical solution: different productions for balanced and unbalanced if-statements
- grammatical solution: introduce explicit end-marker

The general ambiguity problem is unsolvable

Scanners and parsers

- **Scanners** (or *tokenizers*) read input, identify, and extract small input fragments called tokens.
 - ◆ Identifiers
 - ◆ Constants
 - ◆ Keywords
 - ◆ Symbols: (,), [,], !, =, !=, etc.
- **Parsers** accept a grammar and tokens as input and attempt to construct a parse tree.
 - ◆ **LL** (or: recursive descent, predictive) parsers are depth-first, begin at the start symbol, predict the next rewrite rule, and recurse on it. Implementation: “by hand” or table-driven.
 - ◆ **LR** (or: bottom-up) parsers find LHS non-terminals that match the input tokens already seen. Normally faster in production compilers (exception: gcc). Implementation: almost always table-driven.

Relationships: **LL** \subset **LR** \subset **CF**

LL Parsers

- LL stands for: left-to-right, leftmost derivation.
- Also known as top-down, recursive descent, or predictive parsers.
- Begin at the root symbol.
- For each RHS non-terminal, decide which rewrite rule to use (if more than one).
- Ideal: only one rule to choose from. Deterministic.
- More common: multiple rules exist. Non-deterministic.
- Error: no rule exists.
- Resolving non-determinism: decide based on the next token.
- If cannot resolve based on next, “look ahead” up to k tokens.
- We refer to parsers with k look ahead as LL(k) parsers.
- Note 1: it may be possible to modify the grammar to an equivalent grammar with a smaller (or no) lookahead requirement.
- Note 2: most production LL parsers are LL(1).

Problems with LL parsing

Left recursion: a grammar is left-recursive if there exists non-terminal A such that $A \Rightarrow^+ A \alpha$ for some α . Example:

$$\begin{aligned} \text{id_list} &\Longrightarrow \text{id_list_prefix} ; \\ \text{id_list_prefix} &\Longrightarrow \text{id_list_prefix} , \text{id} \\ &\Longrightarrow \text{id} \end{aligned}$$

Common prefixes: if there exists a non-terminal A and terminal b such that there exist rules $R_1 : A \Rightarrow^* b \dots$ and $R_2 : A \Rightarrow^* b \dots$

$$\begin{aligned} \text{stmt} &\Longrightarrow \text{id} := \text{expr} \\ &\Longrightarrow \text{id} (\text{argument_list}) \end{aligned}$$

Solution to both issues: rewrite the grammar.

(Examples courtesy of Scott. See pp. 79-80 for solutions).

LR Parsers

- Stands for: left-to-right, rightmost derivation.
- Also known as bottom up or shift-reduce parsers.
- With LR parsers, the bottom of the parse tree is built first.
- If the root symbol is reachable, the parser accepts the input.
- Main data structure is a stack.
- Main operations are: **shift** and **reduce**.
- LR parsers *shift* tokens to the stack.
- Each time a token is shifted, the stack is checked to see if the tokens match the right side of a rule.
- If so, we replace the tokens on the stack with the left-hand side of the rule. This is the *reduce* step.
- If the stack is empty when the input is fully read, the input is accepted.
- If the stack is non-empty, there exist tokens with no corresponding rule: error.

Problems with LR parsing

Shift-reduce conflicts: when the choice of shifting or reducing is non-deterministic. Example:

$$\begin{aligned}\text{if_stmt} &\implies \text{IF expr THEN stmt} \\ &\implies \text{IF expr THEN stmt ELSE stmt}\end{aligned}$$

Suppose the parser has read IF expr THEN stmt (but not yet ELSE)
The parser could shift ELSE **or** reduce the above to if_stmt—there isn't enough information for it to properly choose.

Solutions: rewrite grammar (see previous slides), introduce lookahead.

Reduce-reduce conflicts: when there are multiple possible reductions (e.g. the RHS is the same). Example:

$$\begin{aligned}\text{if_stmt} &\implies \text{IF expr THEN stmt} \\ \text{if_stmt_2} &\implies \text{IF expr THEN stmt}\end{aligned}$$

Creating scanners and parsers

- **Lex** (or **Flex**) is a lexical analyzer generator.
 - ◆ Input: rules containing regular expressions.
 - ◆ Output: C code. Can be compiled into a standalone lexical analyzer or integrated into a parser.
- **Yacc** (or **Bison**) is a parser generator.
 - ◆ Input: Context-free grammar and Lex generated source code (optional).
 - ◆ Output: An LR parser.

Another popular parser generator is ANTLR (Another Tool for Language Recognition).