CSC 533: Organization of Programming Languages

Spring 2005

Background
- machine → assembly → high-level languages
- software development methodologies
- key languages

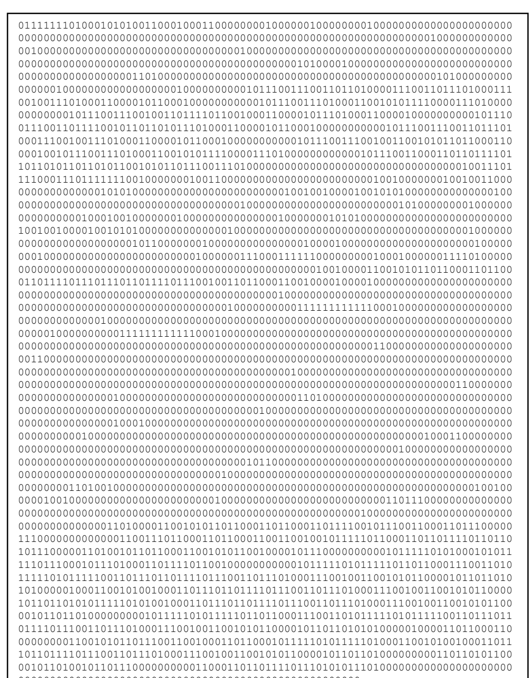
Syntax
- grammars, BNF
- derivation trees, parsing
- EBNF, syntax graphs
- parsing

Semantics
- operational, axiomatic, denotational

Evolution of programming

first computers (e.g., ENIAC) were *not* programmable
- had to be rewired/reconfigured for different computations

late 40's / early 50's: coded directly in machine language
- extremely tedious and error prone
- machine specific
- used numeric codes, absolute



Evolution of programming (cont.)

mid 1950's: assembly languages developed

- mnemonic names replaced numeric codes
- relative addressing via names and labels

a separate program *(assembler)* translated from assembly code to machine code

- still machine specific, low-level

```
.file   "hello.cpp"
gcc2_compiled.:
        .global _Q_qtod
.section ".rodata"
        .align 8
.LLC0:  .asciz  "Hello world!"
.section ".text"
        .align 4
        .global main
        .type   main,#function
        .proc   04
main:   !#PROLOGUE# 0
        save %sp,-112,%sp
        !#PROLOGUE# 1
        sethi %hi(cout),%o1
        or %o1,%lo(cout),%o0
        sethi %hi(.LLC0),%o2
        or %o2,%lo(.LLC0),%o1
        call __ls__7ostreamPCc,0
        nop
        mov %o0,%l0
        mov %l0,%o0
        sethi %hi(endl__FR7ostream),%o2
        or %o2,%lo(endl__FR7ostream),%o1
        call __ls__7ostreamPFR7ostream_R7ostream,0
        nop
        mov 0,%i0
        b .LL230
        nop
.LL230: ret
        restore
.LLfe1: .size    main,.LLfe1-main
        .ident  "GCC: (GNU) 2.7.2"
```


Evolution of programming (cont.)

late 1950's: high-level languages developed

- allowed user to program at higher level of abstraction

however, bridging the gap to low-level hardware was more difficult

- a *compiler* translated code all at once into machine code (e.g., FORTRAN, C++)
- an *interpreter* simulated execution of the code line-by-line (e.g., BASIC, Scheme)

```
// File: hello.cpp
// Author: Dave Reed
//
// This program prints "Hello world!"
//////////////////////////////////////

#include <iostream>
using namespace std;

int main()
{
    cout << "Hello world!" << endl;

    return 0;
}
```

Software development methodologies

by 70's, software costs rivaled hardware
→ new development methodologies emerged

early 70's: top-down design
- stepwise (iterative) refinement (Pascal)

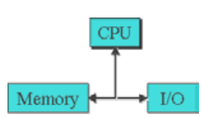
late 70's: data-oriented programming
- concentrated on the use of ADT's (Modula-2, Ada, C/C++)

early 80's: object-oriented programming
- ADT's+inheritance+dynamic binding (Smalltalk, C++, Eiffel, Java)

mid 90's: extreme programming, agile programming (???)

Architecture influences design

virtually all computers follow the *von Neumann* architecture



fetch-execute cycle: repeatedly
- fetch instructions/data from memory
- execute in CPU
- write results back to memory

imperative languages parallel this behavior
- variables (memory cells)
- assignments (changes to memory)
- sequential execution & iteration (fetch/execute cycle)

since features resemble the underlying implementation, tend to be efficient

declarative languages emphasize problem-solving approaches far-removed from the underlying hardware

e.g., Prolog (logic): specify facts & rules, interpreter performs logical inference
LISP/Scheme (functional): specify dynamic transformations to symbols & lists

tend to be more flexible and expressive, but not as efficient

FORTRAN (Formula Translator)

FORTRAN was the first* high-level language

- developed by John Backus at IBM
- designed for the IBM 704 computer, all control structures corresponded to 704 machine instructions
- 704 compiler completed in 1957

- despite some early problems, FORTRAN was immensely popular – adopted universally in 50's & 60's

- FORTRAN evolved based on experience and new programming features
  - FORTRAN II (1958)
  - FORTRAN IV (1962)
  - FORTRAN 77 (1977)
  - FORTRAN 90 (1990)

```
C
C   FORTRAN program
C   Prints "Hello world" 10 times
C
       PROGRAM HELLO
       DO 10, I=1,10
         PRINT *,'Hello world'
    10 CONTINUE
       STOP
       END
```


LISP (List Processing)

LISP is a functional language

- developed by John McCarthy at MIT
- designed for Artificial Intelligence research – needed to be symbolic, flexible, dynamic
- LISP interpreter completed in 1959

- LISP syntax is very simple but flexible, based on the λ-calculus of Church
- all memory management is dynamic and automatic – simple but inefficient

- LISP is still the dominant language in AI

- dialects of LISP have evolved
  - Scheme (1975)
  - Common LISP (1984)

```
;;; LISP program
;;; (hello N) will return a list containing
;;;   N copies of "Hello world"

(define (hello N)
  (if (zero? N)
      '()
      (cons "Hello world" (hello (- N 1)))))
```

```
> (hello 10)
("Hello world"
 "Hello world"
 "Hello world"
 "Hello world"
 "Hello world"
 "Hello world"
 "Hello world"
 "Hello world"
 "Hello world"
 "Hello world")
>
```

ALGOL (Algorithmic Language)

ALGOL was an international effort to design a universal language

- developed by joint committee of ACM and GAMM (German equivalent)
- influenced by FORTRAN, but more flexible & powerful, not machine specific

- ALGOL introduced and formalized many common language features of today
  - data type
  - compound statements
  - natural control structures
  - parameter passing modes
  - recursive routines
  - BNF for syntax (Backus & Naur)

- ALGOL evolved (58, 60, 68), but not widely adopted as a programming language
  - instead, accepted as a reference language

```
comment ALGOL 60 PROGRAM
    displays "Hello world" 10 times;
begin
  integer counter;
  for counter := 1 step 1 until 10 do
  begin
    printstring(Hello world");
  end
end
```


C → C++ → Java → JavaScript

ALGOL influenced the development of virtually all modern languages

- C (1971, Dennis Ritchie at Bell Labs)
  - designed for system programming (used to implement UNIX)
  - provided high-level constructs and low-level machine access

- C++ (1985, Bjarne Stroustrup at Bell Labs)
  - extended C to include objects
  - allowed for object-oriented programming, with most of the efficiency of C

- Java (1993, Sun Microsystems)
  - based on C++, but simpler & more reliable
  - purely object-oriented, with better support for abstraction and networking

- JavaScript (1995, Netscape)
  - Web scripting language

```
#include <stdio.h>
main() {
  for(int i = 0; i < 10; i++) {
      printf ("Hello World!\n");
  }
}
```

```
#include <iostream>
using namespace std;
int main() {
  for(int i = 0; i < 10; i++) {
      cout << "Hello World!" << endl;
  }
  return 0;
}
```

```
class HelloWorld {
  public static void main (String args[]) {
    for(int i = 0; i < 10; i++) {
        System.out.print("Hello World ");
    }
  }
}
```

```
<html>
<body>
  <script language="JavaScript">
    for(i = 0; i < 10; i++) {
        document.write("Hello World<br>");
    }
  </script>
</body>
</html>
```

Other influential languages

COBOL (1960, Dept of Defense/Grace Hopper)

- designed for business applications, features for structuring data & managing files

BASIC (1964, Kemeny & Kurtz – Dartmouth)

- designed for beginners, unstructured but popular on microcomputers in 70's

Simula 67 (1967, Nygaard & Dahl – Norwegian Computing Center)

- designed for simulations, extended ALGOL to support classes/objects

Pascal (1971, Wirth – Stanford)

- designed as a teaching language but used extensively, emphasized structured programming

Prolog (1972, Colmerauer, Roussel – Aix-Marseille, Kowalski – Edinburgh)

- logic programming language, programs stated as collection of facts & rules

Ada (1983, Dept of Defense)

- large & complex (but powerful) language, designed to be official govt. contract language

There is no silver bullet

remember: there is no *best* programming language

- each language has its own strengths and weaknesses

languages can only be judged within a particular domain or for a specific application

business applications → COBOL

artificial intelligence → LISP/Scheme or Prolog

systems programming → C

software engineering → C++ or Java or Smalltalk

Web development → Java or JavaScript or VBScript or perl

Syntax

syntax: the form of expressions, statements, and program units in a programming language

programmers & implementers need a clear, unambiguous description

formal methods for describing syntax:

- Backus-Naur Form (BNF)
  developed to describe ALGOL (originally by Backus, updated by Naur)
  allowed for clear, concise ALGOL 60 report
  (paralleled grammar work by Chomsky: BNF = context-free grammar)
- Extended BNF (EBNF)
- syntax graphs

BNF is a meta-language

a grammar is a collection of rules that define a language

- BNF rules define abstractions in terms of terminal symbols and abstractions

```
<ASSIGN> → <VAR> := <EXPRESSION>
```

- rules can be conditional using '|' to represent OR

```
<IF-STMT> → if <LOGIC-EXPR> then <STMT>
          | if <LOGIC-EXPR> then <STMT> else <STMT>
```

- arbitrarily long expressions can be defined using recursion

```
<IDENT-LIST> → <IDENTIFIER>
             | <IDENTIFIER> , <IDENT-LIST>
```

Deriving expressions from a grammar

from ALGOL 60:

```
<letter>     → a | b | c | ... | z | A | B | ... | Z
<digit>      → 0 | 1 | 2 | ... | 9
<identifier> → <letter>
              | <identifier> <letter>
              | <identifier> <digit>
```

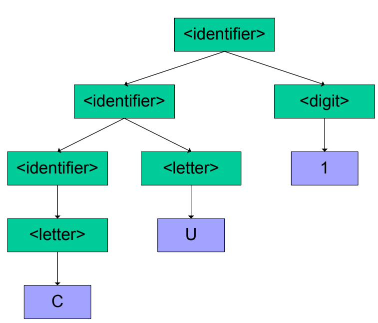
can derive language elements (i.e., substitute definitions for abstractions):

```
<identifier> → <identifier> <digit>
             → <identifier> <letter> <digit>
             → <letter> <letter> <digit>
             → C <letter> <digit>
             → CU <digit>
             → CU1
```

the above is a *leftmost* derivation (expand leftmost abstraction first)

Derivations vs. parse trees

```
<identifier> → <identifier> <digit>
             → <identifier> <letter> <digit>
             → <letter> <letter> <digit>
             → C <letter> <digit>
             → CU <digit>
             → CU1
```



a derivation can be represented hierarchically as a *parse tree*

- internal nodes are abstractions
- leaf nodes are terminal symbols

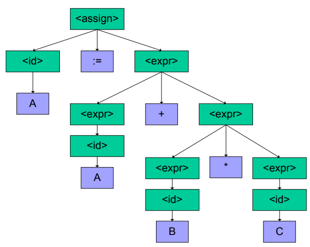
Ambiguous grammars

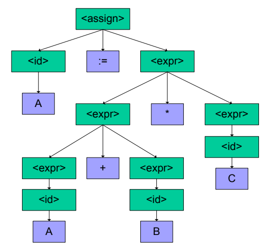
consider a grammar for simple assignments

```
<assign>   → <id> := <expr>
<id>       → A | B | C
<expr>     → <expr> + <expr>
             | <expr> * <expr>
             | ( <expr> )
             | <id>
```

A grammar is *ambiguous* if there exist sentences with 2 or more distinct parse trees

e.g., `A := A + B * C`





Ambiguity is bad!

programmer perspective

- need to know how code will behave

language implementer's perspective

- need to know how the compiler/interpreter should behave

can build concepts such as operator precedence into grammars

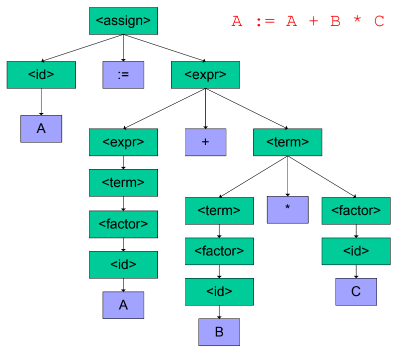
- introduce a hierarchy of rules, lower level → higher precedence

```
<assign>   → <id> := <expr>
<id>       → A | B | C
<expr>     → <expr> + <term> | <term>
<term>     → <term> * <factor> | <factor>
<factor>   → ( <expr> ) | <id>
```

higher precedence operators bind tighter, e.g., `A+B*C ≡ A+(B*C)`

Operator precedence

```
<assign>   → <id> := <expr>
<id>       → A | B | C
<expr>     → <expr> + <term> | <term>
<term>     → <term> * <factor> | <factor>
<factor>   → ( <expr> ) | <id>
```



Note: because of hierarchy,

+ must appear above * in the parse tree

*here, if tried * above, would not be able to derive + from <term>*

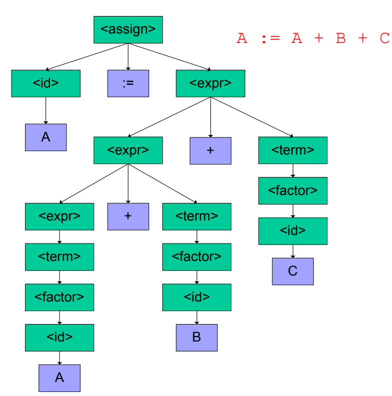
In general, lower precedence (looser bind) will appear above higher precedence operators in the parse tree

Operator associativity

similarly, can build in associativity

- left-recursive definitions → left-associative
- right-recursive definitions → right-associative

```
<assign>  → <id> := <expr>
<id>      → A | B | C
<expr>    → <expr> + <term>
            | <term>
<term>    → <term> * <factor>
            | <factor>
<factor>  → ( <expr> ) | <id>
```

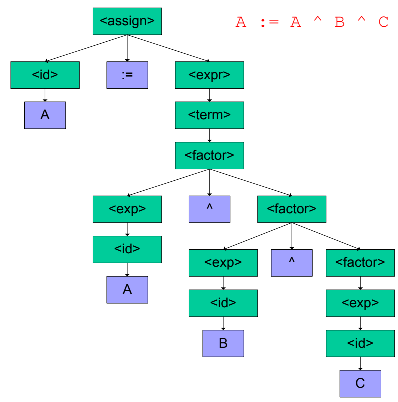


Right associativity

suppose we wanted exponentiation ^ to be right-associative

- need to add right-recursive level to the grammar hierarchy

```
<assign>  → <id> := <expr>
<id>      → A | B | C
<expr>    → <expr> + <term>
            | <term>
<term>    → <term> * <factor>
            | <factor>
<factor>  → <exp> ^ <factor>
            | <exp>
<exp>     → ( <expr> ) | <id>
```



In ALGOL 60…

```
<math expr>    → <simple math>
                 | <if clause> <simple math> else <math expr>
<if clause>    → if <boolean expr> then
<simple math>  → <term>
                 | <add op> <term>
                 | <simple math> <add op> <term>

<term>         → <factor> | <term> <mult op> <factor>
<factor>       → <primary> | <factor> ↑ <primary>

<add op>       → + | -
<mult op>      → x | / | %
<primary>      → <unsigned number> | <variable>
                 | <function designator> | ( <math expr> )
```

precedence?   associativity?

Dangling else

consider the C++ grammar rule:

```
<selection stmt> → if ( <expr> ) <stmt>
                   | if ( <expr> ) <stmt> else <stmt>
```

potential problems?

```
if (x > 0)
if (x > 100)
cout << “foo” << endl;
else
cout << “bar” << endl;
```

ambiguity!

- to which ‘if’ does the ‘else’ belong?

in C++, ambiguity remains in the grammar rules

- is clarified in the English description (else matches nearest if)

Dangling else in ALGOL 60?

```
<stmt>          → <uncond stmt> | <cond stmt> | <for stmt>
<uncond stmt>   → <basic stmt> | <compound stmt>
<compound stmt>→ begin <stmt sequence> end
<cond stmt>     → <if stmt>
                  | <if stmt> else <stmt>
                  | <if clause> <for stmt>
<if stmt>       → <if clause> <uncond stmt>
<if clause>     → if <boolean expr> then
```

```
if x > y then
if y > z then
printstring("foo");
else
printstring("bar");
```

is this legal in ALGOL 60?

ambiguous?

Extended BNF (EBNF)

extensions have been introduced to increase ease of expression

- brackets denote optional features

```
<writeln> → writeln [ <item list> ]
```

- braces denote arbitrary # of repetitions (including 0)

```
<ident list> → <identifier> { , <identifier> }
```

- (|) denotes optional sub-expressions

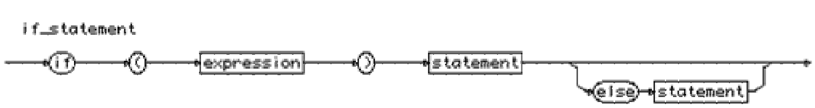
```
<for stmt> → for <var> := <expr> (to | downto) <expr> do <stmt>
```

Note: could express these in BNF, but not as easily

BNF vs. syntax graphs

see BNF Web Club for various language grammars

- each grammar rule for a language is indexed
- in addition to BNF, syntax graphs are given



- note simplicity of LISP

Syntax & parsing

grammars/syntax graphs are utilized by compiler/ writers

- before compiling/interpreting, must parse the language elements

grammars/syntax graphs provide:

1. clear and concise syntax descriptions
2. can be used as the basis for a parser
3. implementations tend to be easy to maintain due to clear modularity

parsers can be top-down or bottom-up

- *top-down* parsers build the parse tree from the root (top-level abstraction) down to the leaves (terminal symbols)

  e.g., recursive descent (LL) – simple, but limited (e.g., no left recursion)

- *bottom-up* parsers build the parse tree from the leaves(terminal symbols) up to the root (top-level abstraction)

  e.g., shift-reduce (LR)– implemented as a PDA, more complex but more general

Semantics

generally much trickier than syntax

3 common approaches

- *operational semantics:* describe meaning of a program by executing it on a machine (either real or abstract)

Pascal code
```
for i := first to last do
begin
  …
end
```

Operational semantics
```
       i = first
loop:  if i > last goto out
       …
       i = i + 1
       goto loop
out:   …
```

- *axiomatic semantics:* describe meaning using assertions about conditions, can prove properties of program using formal logic

Pascal code
```
while (x > y) do
begin
  …
end
```

Axiomatic semantics
```
while (x > y) do
begin
    ASSERT: x > y
    …
end
ASSERT: x <= y
```

- *denotational semantics:* describe meaning by constructing a detailed mathematical model of each language entity – PRECISE, BUT VERY EXACTING!