To schedule a team meeting every TEAM must indicate their availability to meet at the times indicated in this Doodle poll. Though the poll shows specific M-F dates, fill in the form with regular availability at the indicated times.

Please note that Thursday meeting times will be over Zoom. Other meeting times will be in-person in my office (343 Davis).

ONE and ONLY one person from each team must fill in the poll on behalf of the team NO LATER THAN 5:00 PM on this coming Friday 2/10. Team meetings will start next week (the week of 2/13 to 2/17).
Phases of a compiler

**Syntactic structure**

Figure 1.6, page 5 of text
Sample grammars


http://blackbox.userweb.mwn.de/Pascal-EBNF.html

https://cs.wmich.edu/~gupta/teaching/cs4850/sumII06/The%20syntax%20of%20C%20in%20Backus-Naur%20form.htm
Language Semantics

What's in language specification?

What's left up to the language implementor?
6.2.2 Evaluation Order

The order of evaluation of subexpressions within an expression is undefined. In particular, you cannot assume that the expression is evaluated left to right. For example:

```c
int x = f(2) + g(3);  // undefined whether f() or g() is called first
```

C++ Programming Language, 3rd edition.
Bjarne Stroustrup. (c) 1997. Page 122.
A compiler translates high level language statements into a much larger number of low-level statements, and then applies optimizations. The entire translation process, including optimizations, must preserve the semantics of the original high-level program.

By not specifying the order in which subexpressions are evaluated (left-to-right or right-to-left) a C++ compiler can potentially re-order the resulting low-level instructions to give a “better” result.
4.6 Sizes

Some of the aspects of C++’s fundamental types, such as the size of an int, are implementation-defined (§C.2). I point out these dependencies and often recommend avoiding them or taking steps to minimize their impact. Why should you bother? People who program on a variety of systems or use a variety of compilers care a lot because if they don’t, they are forced to waste time finding and fixing obscure bugs. People who claim they don’t care about portability usually do so because they use only a single system and feel they can afford the attitude that “the language is what my compiler implements.” This is a narrow and shortsighted view. If your program is a success, it is likely to be ported, so someone will have to find and fix problems related to implementation-dependent features. In addition, programs often need to be compiled with other compilers for the same system, and even a future release of your favorite compiler may do some things differently from the current one. It is far easier to know and limit the impact of implementation dependencies
The reason for providing more than one integer type, more than one unsigned type, and more than one floating-point type is to allow the programmer to take advantage of hardware characteristics. On many machines, there are significant differences in memory requirements, memory access times, and computation speed between the different varieties of fundamental types. If you know a machine, it is usually easy to choose, for example, the appropriate integer type for a particular variable. Writing truly portable low-level code is harder.

Sizes of C++ objects are expressed in terms of multiples of the size of a char, so by definition the size of a char is 1. The size of an object or type can be obtained using the sizeof operator (§6.2). This is what is guaranteed about sizes of fundamental types:

\[ 1 \equiv \text{sizeof(char)} \leq \text{sizeof(short)} \leq \text{sizeof(int)} \leq \text{sizeof(long)} \]
\[ 1 \leq \text{sizeof(bool)} \leq \text{sizeof(long)} \]
\[ \text{sizeof(char)} \leq \text{sizeof(wchar_t)} \leq \text{sizeof(long)} \]
\[ \text{sizeof(float)} \leq \text{sizeof(double)} \leq \text{sizeof(long long)} \]
\[ \text{sizeof(N)} = \text{sizeof(signed N)} = \text{sizeof(unsigned N)} \]

where N can be char, short int, int, or long int. In addition, it is guaranteed that a char has at least 8 bits, a short at least 16 bits, and a long at least 32 bits. A char can hold a character of the machine’s character set.
The precision of these objects depends on the machine at hand; the table below shows some representative values.

<table>
<thead>
<tr>
<th></th>
<th>DEC PDP-11 ASCII</th>
<th>Honeywell 6000 ASCII</th>
<th>IBM 370 EBCDIC</th>
<th>Interdata 8/32 ASCII</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>8 bits</td>
<td>9 bits</td>
<td>8 bits</td>
<td>8 bits</td>
</tr>
<tr>
<td>int</td>
<td>16</td>
<td>36</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>short</td>
<td>16</td>
<td>36</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>long</td>
<td>32</td>
<td>36</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>float</td>
<td>32</td>
<td>36</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>double</td>
<td>64</td>
<td>72</td>
<td>64</td>
<td>64</td>
</tr>
</tbody>
</table>

The intent is that short and long should provide different lengths of integers where practical; int will normally reflect the most "natural" size for a particular machine. As you can see, each compiler is free to interpret short and long as appropriate for its own hardware. About all you should count on is that short is no longer than long.
Review
Programming Language
Grammar Fragment

<program>  ->  <stmt-list>
<stmt-list> ->  <stmt>  |  <stmt>  ;  <stmt-list>
<stmt>  ->  <var>  =  <expr>
<var>  ->  a  |  b  |  c  |  d
<expr>  ->  <term>  +  <term>  |  <term>  -  <term>
<term>  ->  <var>  |  const

Notes:
<var>  is  defined  in  the  grammar
const  is  not  defined  in  the  grammar
A leftmost derivation of

\[ a = b + \text{const} \]

\[
\begin{align*}
<\text{program}> & \Rightarrow <\text{stmt-list}> \\
& \Rightarrow <\text{stmt}> \\
& \Rightarrow <\text{var}> = <\text{expr}> \\
& \Rightarrow a = <\text{expr}> \\
& \Rightarrow a = <\text{term}> + <\text{term}> \\
& \Rightarrow a = <\text{var}> + <\text{term}> \\
& \Rightarrow a = b + <\text{term}> \\
& \Rightarrow a = b + \text{const}
\end{align*}
\]
Parse tree

```
<program>
  |
  <stmt-list>
  |
  <stmt>
    |
    <var> = <expr>
    |
    a <term> + <term>
    |
    <var> const
    |
    b
```
Parse trees and compilation

- A compiler builds a parse tree for a program (or for different parts of a program).
- If the compiler cannot build a well-formed parse tree from a given input, it reports a compilation error.
- The parse tree serves as the basis for semantic interpretation/translation of the program.
Extended BNF

• Optional parts are placed in brackets [ ]
  \texttt{<proc\_call>} \rightarrow \texttt{ident} \ [\texttt{(<expr\_list>)}]

• Alternative parts of RHSs are placed inside parentheses and separated via vertical bars
  \texttt{<term>} \rightarrow \texttt{<term>} (+|-) \texttt{const}

• Repetitions (0 or more) are placed inside braces
  \{
  
  \}
  \texttt{<ident>} \rightarrow \texttt{letter} \ \{\texttt{letter}|\texttt{digit}\}
Comparison of BNF and EBNF

• sample grammar fragment expressed in BNF

\[
<\text{expr}> \rightarrow <\text{expr}> + <\text{term}>
\]

\[
| <\text{expr}> - <\text{term}>
\]

\[
| <\text{term}>
\]

\[
<\text{term}> \rightarrow <\text{term}> * <\text{factor}>
\]

\[
| <\text{term}> / <\text{factor}>
\]

\[
| <\text{factor}>
\]

• same grammar fragment expressed in EBNF

\[
<\text{expr}> \rightarrow <\text{term}> \{ (+ | -) <\text{term}> \}
\]

\[
<\text{term}> \rightarrow <\text{factor}> \{ (* | /) <\text{factor}> \}
Ambiguity
Ambiguity in grammars

- A grammar is ambiguous if and only if it generates a sentential form that has two or more distinct parse trees.
- Operator precedence and operator associativity are two examples of ways in which a grammar can provide unambiguous interpretation.
Operator precedence ambiguity

The following grammar is ambiguous:

<expr>  ->  <expr>  <op>  <expr>  |  const
<op>  ->  -  |  /

The grammar treats the two operators, ‘-’ and ‘/’, equivalently.
An ambiguous grammar for arithmetic expressions

\[
\begin{align*}
<\text{expr}> & \rightarrow <\text{expr}> \ <\text{op}> \ <\text{expr}> \ | \ \text{const} \\
<\text{op}> & \rightarrow / \ | \ - \\
\end{align*}
\]
Disambiguating the grammar

This grammar (fragment) is unambiguous:

<expr> -> <expr> - <term> | <term>
<term> -> <term> / const | const

The grammar treats the two operators, '-' and '/', differently.

In this grammar, '/' has higher precedence than '-'. Within a given subtree, deeper nodes are evaluated before shallower notes.
Disambiguating the grammar

- If we use the parse tree to indicate precedence levels of the operators, we can remove the ambiguity.
- The following rules give / a higher precedence than -

\[
\begin{align*}
\text{<expr> } & \rightarrow \text{ <expr> - <term> } \mid \text{ <term>} \\
\text{<term> } & \rightarrow \text{ <term> / const } \mid \text{ const}
\end{align*}
\]

```
<expr>  
  / 
<expr>  - <term>  
          /   \    
<term>  /    <term>  
         /     /     
const  const
```

Derivation of \( 2 + 5 \times 3 \) using C grammar
Recursion and parentheses

• To generate 2+3*4 or 3*4+2, the parse tree is built so that + is higher in the tree than *.
• To force an addition to be done prior to a multiplication we must use parentheses, as in (2+3)*4.
• Grammar captures this in the recursive case of an expression, as in the following grammar fragment:

\[
<\text{expr}> \rightarrow <\text{expr}> + <\text{term}> | <\text{term}>
\]
\[
<\text{term}> \rightarrow <\text{term}> * <\text{factor}> | <\text{factor}>
\]
\[
<\text{factor}> \rightarrow <\text{variable}> | <\text{constant}> | "(" <\text{expr}> ")"
\]
Given a regular language $L$ we can always construct a context free grammar $G$ such that $L = \mathcal{L}(G)$.

For every regular language $L$ there is an NFA $M = (S, \Sigma, \delta, F, s_0)$ such that $L = \mathcal{L}(M)$.

Build $G = (N, T, P, S_0)$ as follows:

- $N = \{ N_s \mid s \in S \}$
- $T = \{ t \mid t \in \Sigma \}$
- If $\delta(i, a) = j$, then add $N_i \to a N_j$ to $P$
- If $i \in F$, then add $N_i \to \varepsilon$ to $P$
- $S_0 = N_{s_0}$
(a|b)*abb

G = ( \{ A_0, A_1, A_2, A_3 \}, \{ a, b \}, \{ A_0 \rightarrow a \ A_0, A_0 \rightarrow b \ A_0, A_0 \rightarrow a \ A_1, A_1 \rightarrow b \ A_2, A_2 \rightarrow b \ A_3, A_3 \rightarrow \varepsilon \}, A_0 \)
RL \subseteq CFL

- Show that not all CF languages are regular.

- To do this we only need to demonstrate that there exists a CFL that is not regular.

- Consider \( L = \{ a^n b^n \mid n \geq 1 \} \)

- Claim: \( L \in \text{CFL}, L \notin \text{RL} \)
Proof (sketch):

\( L \in \text{CFL}: S \rightarrow aSb | ab \)

\( L \notin \text{RL} \) (by contradiction):

Assume \( L \) is regular. In this case there exists a DFA \( D = (N, \Sigma, \delta, F, s_0) \) such that \( \mathcal{L}(D) = L \).

Let \( k = |N| \). Consider \( a^ib^i \), where \( i > k \).

Suppose \( \delta(s_0, a^i) = s_r \). Since \( i > k \), not all of the states between \( s_0 \) and \( s_r \) are distinct. Hence, there are \( v \) and \( w \), \( 0 \leq v < w \leq k \) such that \( s_v = s_w \). In other words, there is a loop.

This DFA can certainly recognize \( a^ib^i \) but it can also recognize \( a^ib^i \), where \( i \neq j \), by following the loop.

"REGULAR GRAMMARS CANNOT COUNT"
public class Foo {
    public static void main(String[] args) {
        for (int i=0; i<args.length; i++) {
            if (args[i].length() < 3) { ... }
            else { ... }
        }
    }
}
Context Free Grammars and parsing

- $O(n^3)$ algorithms to parse any CFG exist
- Programming language constructs can generally be parsed in $O(n)$
Top-down & bottom-up

- A top-down parser builds a parse tree from root to the leaves
  - easier to construct by hand
- A bottom-up parser builds a parse tree from leaves to root
  - Handles a larger class of grammars
  - tools (yacc/bison) build bottom-up parsers
Our presentation
First top-down, then bottom-up

- Present top-down parsing first.
- Introduce necessary vocabulary and data structures.
- Move on to bottom-up parsing second.
The current symbol being scanned in the input is called the lookahead symbol.
Top-down parsing

- Start from grammar's start symbol
- Build parse tree so its yield matches input
- Predictive parsing: a simple form of recursive descent parsing
Basic idea:
try to build a derivation
$S \Rightarrow^* \text{input}$

$S \Rightarrow^* \alpha$

$\ldots?\ldots$

$\Rightarrow^* \text{input}$
If $\alpha \in (NUT)^*$ then $\text{FIRST}(\alpha)$ is "the set of terminals that appear as the first symbols of one or more strings of terminals generated from $\alpha$." [p. 64]

Ex: If $A \rightarrow a \beta$ then $\text{FIRST}(A) = \{a\}$

Ex. If $A \rightarrow a \beta \mid B$ then $\text{FIRST}(A) = \{a\} \cup \text{FIRST}(B)$
First sets are considered when there are two (or more) productions to expand $A \in N$: $A \rightarrow \alpha | \beta$

Predictive parsing requires that $\text{FIRST}(\alpha) \cap \text{FIRST}(\beta) = \emptyset$