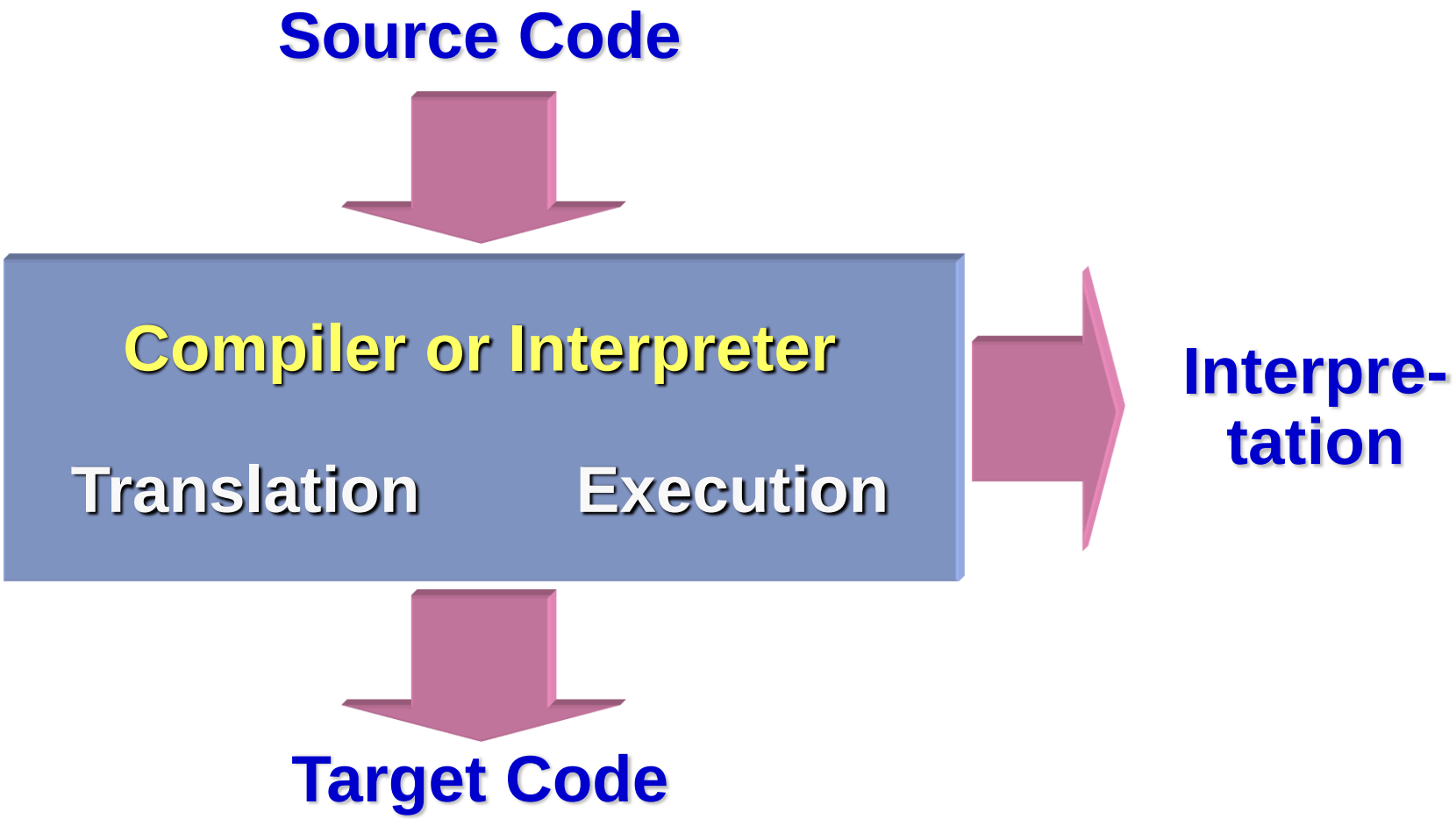
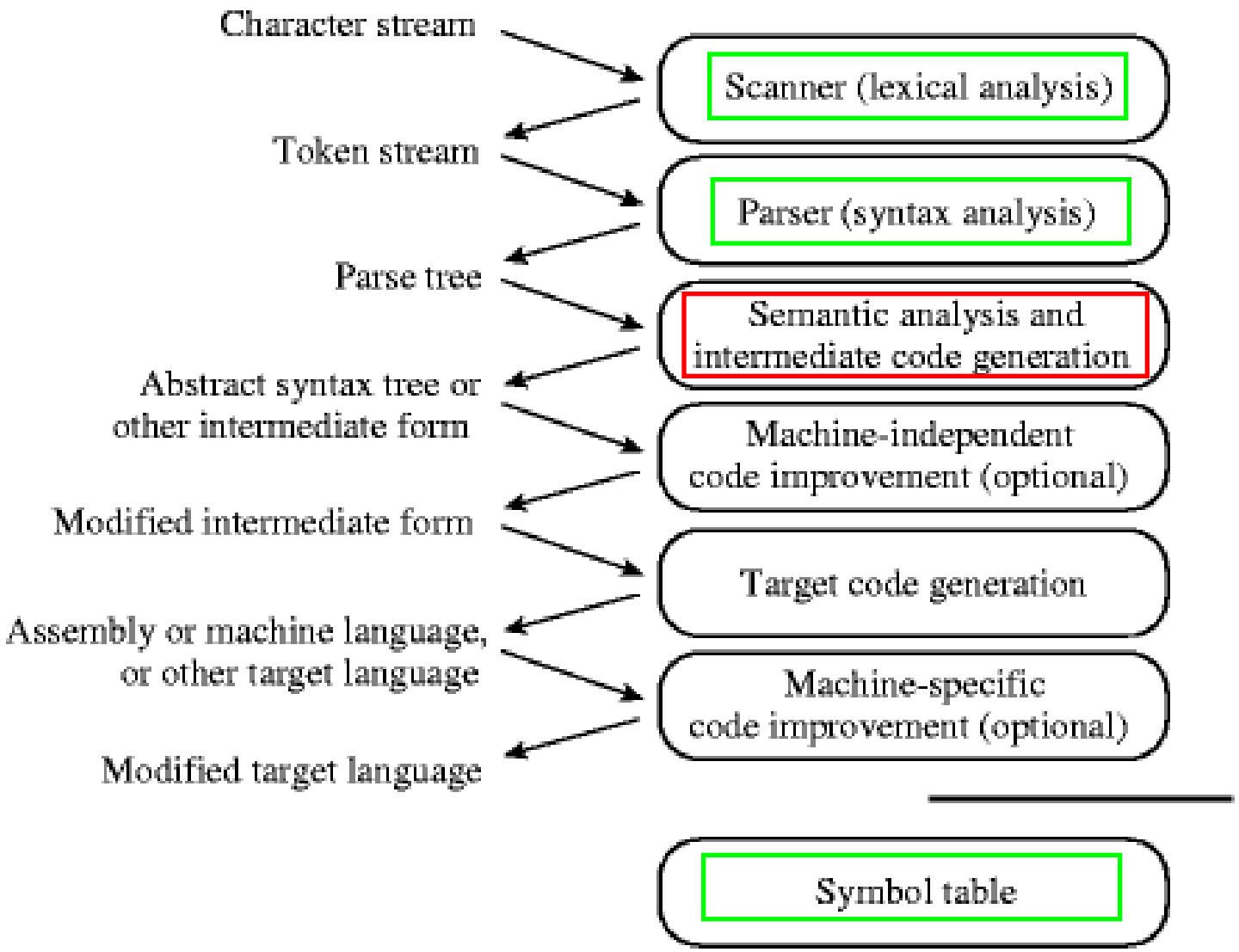
Programming Languages Advance

Semantic Analysis

Semantic Analysis
From Code Form To Program Meaning



Phases of Compilation



Specification of Programming Languages

- PLs require precise definitions (i.e. no ambiguity)
  - Language *form* (Syntax)
  - **Language *meaning* (Semantics)**
- Consequently, PLs are specified using formal notation:
  - Formal syntax
    - » Tokens
    - » Grammar
  - **Formal semantics**
    - » **Attribute Grammars (static semantics)**
    - » **Dynamic Semantics**

The Semantic Analyzer

- The principal job of the semantic analyzer is to enforce static semantic rules.
- In general, anything that requires the requires the compiler to compare things that are separate by a long distance or to count things ends up being a matter of *semantics*.
- The semantic analyzer also commonly constructs a syntax tree (usually first), and much of the information it gathers is needed by the code generator.

Attribute Grammars

- Context-Free Grammars (CFGs) are used to specify the syntax of programming languages
  - *E.g.* arithmetic expressions
- How do we tie these rules to mathematical concepts?
- *Attribute grammars* are annotated CFGs in which *annotations* are used to establish meaning relationships among symbols
  - Annotations are also known as decorations

$$
\begin{array}{lcl}
E & \longrightarrow & E \texttt{ + } T \\
E & \longrightarrow & E \texttt{ - } T \\
E & \longrightarrow & T \\
T & \longrightarrow & T \texttt{ * } F \\
T & \longrightarrow & T \texttt{ / } F \\
T & \longrightarrow & F \\
F & \longrightarrow & \texttt{- } F \\
F & \longrightarrow & \texttt{(} E \texttt{)} \\
F & \longrightarrow & \texttt{const}
\end{array}
$$

Attribute Grammars
Example

- Each grammar symbols has a set of *attributes*
  - *E.g.* the value of E_1 is the attribute E_1.val
- Each grammar rule has a set of rules over the symbol attributes
  - *Copy rules*
  - *Semantic Function rules*
    - » *E.g.* sum, quotient

1: $E_1 \longrightarrow E_2 + T$
▷ E_1.val := sum (E_2.val, T.val)

2: $E_1 \longrightarrow E_2 - T$
▷ E_1.val := difference (E_2.val, T.val)

3: $E \longrightarrow T$
▷ E.val := T.val

4: $T_1 \longrightarrow T_2 * F$
▷ T_1.val := product (T_2.val, F.val)

5: $T_1 \longrightarrow T_2 / F$
▷ T_1.val := quotient (T_2.val, F.val)

6: $T \longrightarrow F$
▷ T.val := F.val

7: $F_1 \longrightarrow - F_2$
▷ F_1.val := additive_inverse (F_2.val)

8: $F \longrightarrow (E)$
▷ F.val := E.val

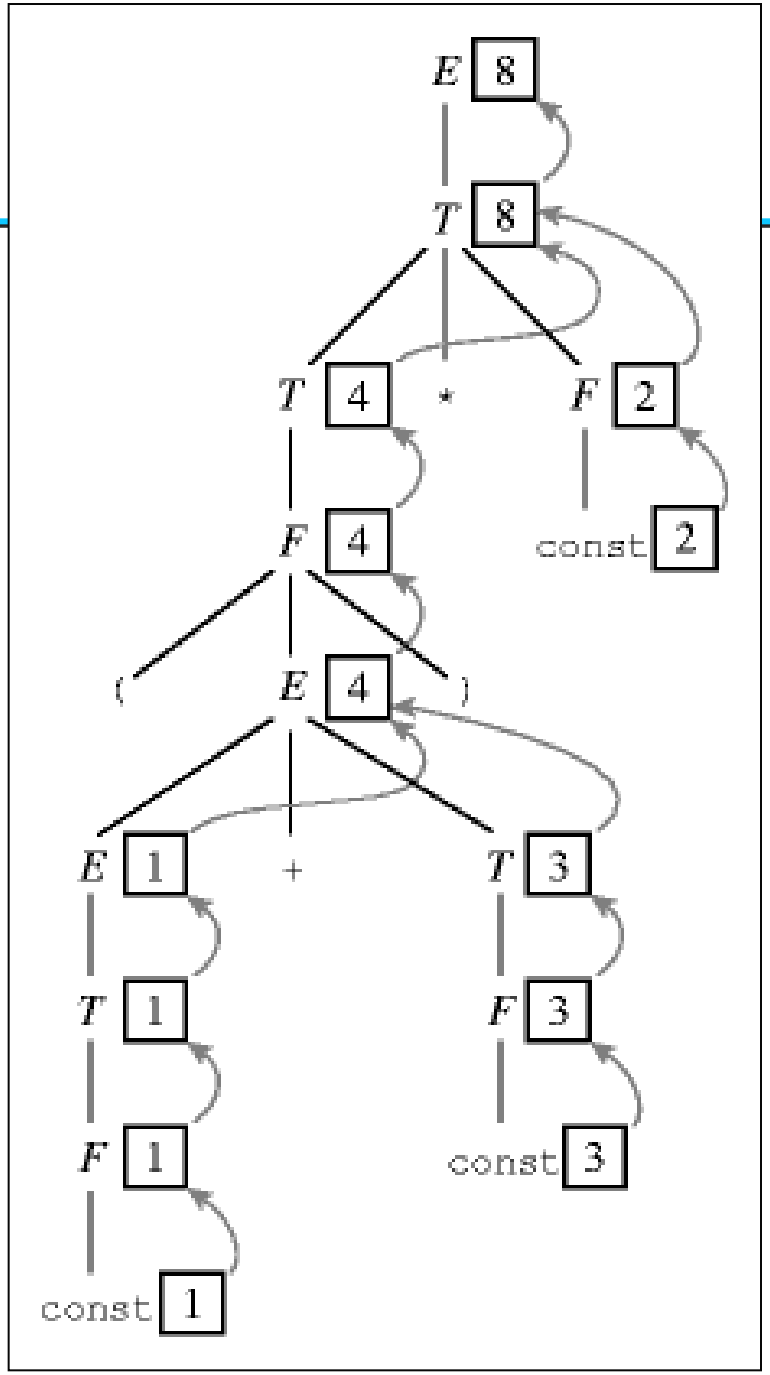
9: $F \longrightarrow$ const
▷ F.val := const.val

Attribute Flow

- Context-free grammars are not tied to an specific parsing order
  - *E.g.* Recursive descent, LR parsing
- Attribute grammars are not tied to an specific evaluation order
  - This evaluation is known as the *annotation* or *decoration* of the parse tree

Attribute Flow
Example

- The figure shows the result of annotating the parse tree for `(1+3)*2`
- Each symbols has at most one attribute shown in the corresponding box
  - Numerical value in this example
  - Operator symbols have no value
- Arrows represent *attribute flow*



Attribute Flow
Example

1: $E_1 \longrightarrow E_2$ + T
   ▷ E_1.val := sum (E_2.val, T.val)

2: $E_1 \longrightarrow E_2$ - T
   ▷ E_1.val := difference (E_2.val, T.val)

3: $E \longrightarrow T$
   ▷ E.val := T.val

4: $T_1 \longrightarrow T_2$ * F
   ▷ T_1.val := product (T_2.val, F.val)

5: $T_1 \longrightarrow T_2$ / F
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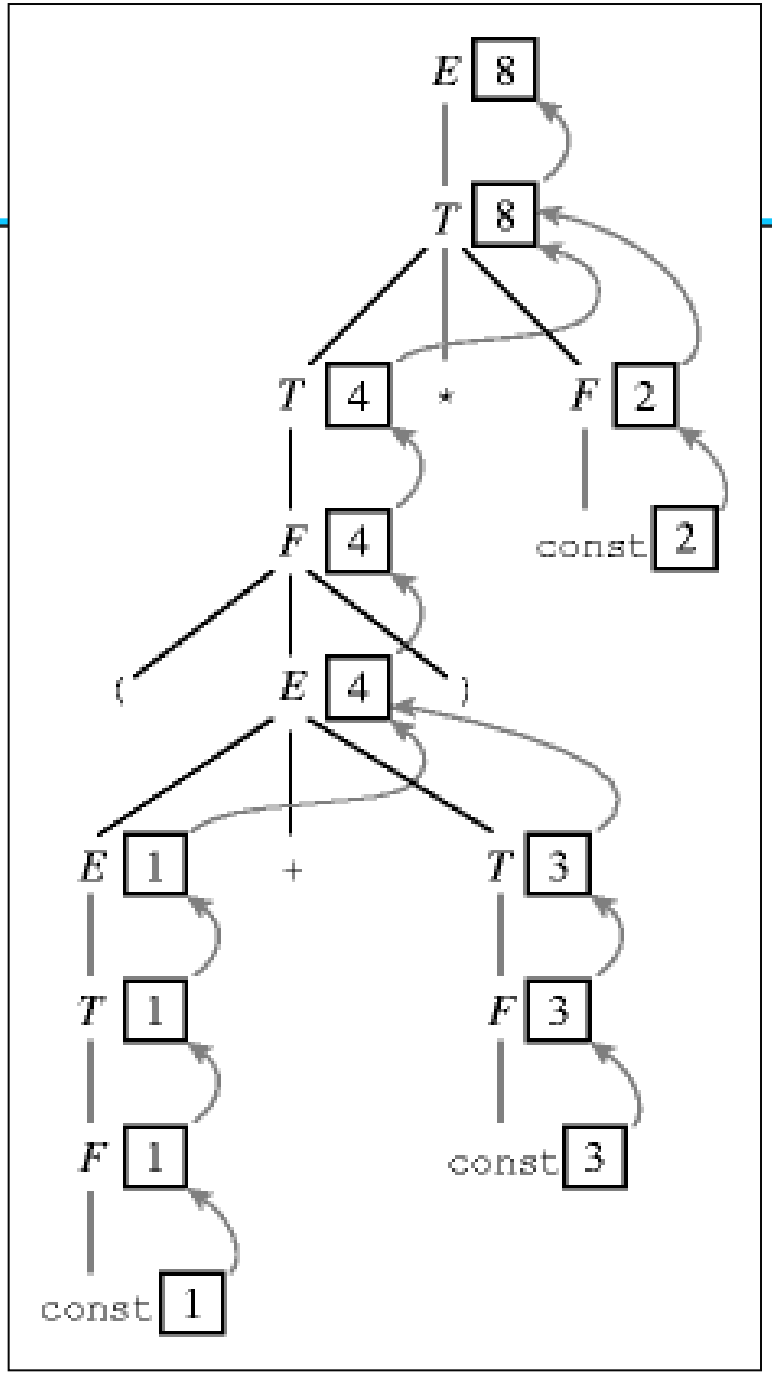

Attribute Flow
Synthetic and Inherited Attributes

- In the previous example, semantic information is pass up the parse tree
  - We call this type of attributes are called *synthetic attributes*
  - Attribute grammar with synthetic attributes only are said to be *S-attributed*
- Semantic information can also be passed down the parse tree
  - Using *inherited attributes*
  - Attribute grammar with inherited attributes only are said to be *non-S-attributed*

Attribute Flow
Inherited Attributes

- *L-attributed* grammars, such as the one on the next slide, can still be evaluated in a single left-to-right pass over the input.
- Each synthetic attribute of a LHS symbol (by definition of *synthetic*)depends only on attributes of its RHS symbols.
- Each inherited attribute of a RHS symbol (by definition of *L-attributed)* depends only on inherited attributes of the LHS symbol or on synthetic or inherited attributes of symbols to its left in the RHS.
- Top-down grammars generally require non-S-attributed flows
  - The previous annotated grammar was an S-attributed LR(1)
  - L-attributed grammars are the most general class of attribute grammars that can be evaluated during an LL parse.

Syntax Tree

- There is considerable variety in the extent to which parsing, semantic analysis, and intermediate code generation are interleaved.
- A *one-pass* compiler interleaves scanning, parsing, semantic analysis, and code generation in a single traversal of the input.
- A common approach interleaves construction of a syntax tree with parsing (eliminating the need to build an explicit parse tree), then follows with separate, sequential phases for semantic analysis and code generation.

Action Routines

- Automatic tools can construct a parser for a given context-free grammar
  - *E.g.* yacc
- Automatic tools can construct a semantic analyzer for an attribute grammar
  - An ad hoc techniques is to annotate the grammar with executable rules
  - These rules are known as *action routines*

Static and Dynamic Semantics

- Attribute grammars add basic semantic rules to the specification of a language
  - They specify *static semantics*
- But they are limited to the semantic form that can be checked at compile time
- Other semantic properties cannot be checked at compile time
  - They are described using *dynamic semantics*

Dynamic Semantics

- Use to formally specify the behavior of a programming language
  - Semantic-based error detection
  - Correctness proofs
- There is not a universally accepted notation
  - **Operational semantics**
    - » Executing statements that represent changes in the state of a real or simulated machine
  - **Axiomatic semantics**
    - » Using predicate calculus (pre and post-conditions)
  - **Denotational semantics**
    - » Using recursive function theory

Semantic Specification

- The most common way of *specifying* the semantics of a language is plain english
  - http://java.sun.com/docs/books/jls/first_edition/html/14.doc.html#24588
- There is a lack of formal rigor in the semantic specification of programming languages
  - Guess why

What is top-down parsing?

- Top-down parsing is a parsing-method where a sentence is parsed starting from the root of the parse tree (with the *"Start"* symbol), working recursively down to the leaves of the tree (with the terminals).
- In practice, top-down parsing algorithms are easier to understand than bottom-up algorithms.
- Not all grammars can be parsed top-down, but most context-free grammars can be parsed bottom-up.

Bottom-up Parsing

- Bottom-up parsers parse a programs from the leaves of a parse tree, collecting the pieces until the entire parse tree is built all the way to the root.
- Bottom-up parsers emulate pushdown automata:
  - requiring both a state machine (to keep track of what you are looking for in the grammar) and a stack (to keep track of what you have already read in the program).
  - making it fairly easy to automate the process of creating the parser
  - ensuring that all context-free grammars can be parsed by this method.

Bottom-up parsers as shift-reduce parsers

- Bottom-up parsers are frequently called shift-reduce parsers because of their two basic operations:
  - A shift involves moving pushing the current input token onto the stack and fetching the next input token.
  - A reduce involves popping all the variables that comprise the right-sentential form for a nonterminal and replacing them on the stack with the equivalent nonterminal that appears on the left-hand side of that production.
  - While shifting involve pushing and reducing involve popping, do not think of them as equivalent: a shift also involve advancing the input token stream and a reduce involves zero or more pops followed by a push.

Bottom-up Parsing as an Emulation of Pushdown Automata

- Most bottom-up parsers are table-driven, with the table encoding the necessary information about the grammar.
- The parser decides what action to perform based on the combination of current state and current input token.
- A state in the machine which the computer is emulating reflects both what the machine has already parsed and that which it is expect to see in the input token stream.
- Several parser generators have been created based on this theoretical machine, the best known of which is ***YACC*** (***Y***et ***A***nother ***C***ompiler ***C***ompiler), is available on many UNIX system and its public domain lookalike ***Bison***.