Error Handling
Syntax-Directed Translation
Recursive Descent Parsing

Lecture 6

Outline

- Extensions of CFG for parsing
  - Precedence declarations (previous slide set)
  - Error handling (slight digression)
    - I.e., what kind of error handling is available in parsers
  - Semantic actions

- Constructing a parse tree

- Recursive descent

Error Handling

- Purpose of the compiler is
  - To detect non-valid programs
    - And provide good feedback
  - To translate the valid ones
- Many kinds of possible errors (e.g. in C)

Error kind	Example	Detected by …
Lexical	… $ … (not used in C)	Lexer
Syntax	… x *% …	Parser
Semantic	… int x; y = x(3); …	Type checker
Correctness	your favorite program	Tester/User

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Syntax Error Handling

- Error handler should
  - Report errors accurately and clearly
    - Want to identify problem quickly and fix it
  - Recover from an error quickly
    - Compiler shouldn't take a long time to figure out what to do when it hits an error
  - Not slow down compilation of valid code
    - I.e., don't force good programs to pay the price for error handling

- Good error handling is not easy to achieve

Approaches to Syntax Error Recovery

- Three approaches, from simple to complex
  - Panic mode (used today)
  - Error productions (used today)
  - Automatic local or global correction
    - Idea that was pursued quite a bit in past
    - historically interesting contrast to what is done now

- Not all are supported by all parser generators

Error Recovery: Panic Mode

- Simplest, most popular method

- When an error is detected:
  - Discard tokens until one with a clear role is found
  - Continue from there

- Such tokens are called <u>synchronizing</u> tokens
  - Just tokens that have a well-known role in the language
  - Typically the statement or expression terminators

A Typical Strategy

Skip to the end of a statement or the end of a function if an error is found in a statement or function and then begin parsing either the next statement or the next function.

Syntax Error Recovery: Panic Mode (Cont.)

- Consider the erroneous expression

  (1 + + 2) + 3

- Panic-mode recovery:
  - Policy (for this particular kind of error) might be: Skip ahead to next integer and then continue

Syntax Error Recovery: Panic Mode (Cont.)

- Bison: use the special terminal error to describe how much input to skip

$$E \rightarrow \text{int} \mid E + E \mid (\ E\ ) \mid \text{error int} \mid (\ \text{error}\ )$$

Blue are "normal" options.

Red are error options

Parser is attempting to parse something (haven't seen how that works yet) and reaches a state where it expects an int, or a + or a parenthesized expression but if that isn't working out and it gets stuck, it hits panic button: throw out everything up to the next int

error matches all input up to next integer

Syntax Error Recovery: Panic Mode (Cont.)

- Bison: use the special terminal error to describe how much input to skip

$$E \rightarrow \text{int} \mid E + E \mid (\ E\ ) \mid \text{error int} \mid (\ \text{error}\ )$$

Blue are "normal" options.

Red are error options

Similarly, if it encounters an error somewhere inside a pair of matched parentheses, just throw away the whole thing and continue parsing after the closing parenthesis.

Can have these productions that involve the error token for as many different kinds of errors as you like

Syntax Error Recovery: Error Productions

- Idea: specify in the grammar known common mistakes

- Example:
  - Writing a compiler for language used by lots of mathematicians
  - They often write 5 x instead of 5 * x and complain that this generates parse errors
    - Which state that the former is not a well-formed expression
  - Solution: Add the production $E \rightarrow \ldots \mid E\ E$
    - This makes the expression well formed

Syntax Error Recovery: Error Productions

- Essentially promotes common errors to alternative syntax

- Disadvantage
  - Complicates the grammar
  - If it's used a lot grammar is going to be a lot harder to understand
- But it is used in practice!
  - E.g. gcc and other production C compilers will often warn you about things you're not supposed to do but they'll accept them anyway
  - Error productions is usually the mechanism by which this is done

- Previous mechanisms are primarily for detection. Following method actually tries to do correction!

Error Recovery: Local and Global Correction

- Idea: find a correct "nearby" program
  - I.e., programs that aren't too "different" from the original program
  - Try token insertions and deletions
    - E.g., Minimize the edit distance from bad token to newly inserted token
  - Exhaustive search (within some specified bounds)

Error Recovery: Local and Global Correction

- Disadvantages:
  - Hard to implement
    - It's actually quite complex
  - Slows down parsing of correct programs
    - Because you need to keep enough state around to manage the search or the editing
  - "Nearby" is not necessarily "the intended" program
    - Not really all that clear what "nearby" means
    - "Nearby" is not necessarily "the intended" program
    - Not all tools support it

Error Recovery: Local and Global Correction

- Best example: The PL/C compiler
  - PL: Because it's a PL1 compiler
  - C: Either "correction" or "Cornell" (where the compiler was built)
  - Well known for being willing to compile absolutely anything
    - Phone book
    - Speech from a Hamlet soliloquy
    - It would give lots of error messages
      - Many quite funny
    - But in the end it always produced a valid working PL1 program
- But, why bother?

Syntax Error Recovery: Past and Present

- When this was done (in the 1970s)
  - Slow recompilation cycle (even once a day)
    - Submit program in morning, get compiler output in the afternoon
    - With that kind of turnaround, even a single syntax error could be devastating: could lose a whole day just because of typo in a keyword
    - So having a compiler that can correct the program for you if it's a small error could save you a whole day
  - So want to find as many errors in one cycle as possible
    - And then check whether the corrections were right
    - Allow even more debugging before next round
  - Researchers could not let go of the topic

Syntax Error Recovery: Past and Present

- Present
  - Quick recompilation cycle
  - Users tend to correct one error/cycle
    - Usually the first error, since that tends to be the most reliable report from the compiler (and it needs to be fixed before others can be fixed)
  - Complex error recovery is less compelling than it was a few decades ago
  - Panic-mode seems enough

Abstract Syntax Trees

- So far a parser traces the derivation of a sequence of tokens
  - Not all that useful to the compiler because...

- The rest of the compiler needs a structural representation of the program
  - Data structure that tells it what the operations are in the program and how they're put together

- So for various reasons a parse tree isn't what we want to work on

Abstract Syntax Trees

- Abstract syntax trees
  - Like parse trees but ignore some details
    - Abstracted away some of the details
  - Abbreviated as AST
  - The core data structure used in compilers
- To be clear: We could do compilation perfectly well using a parse tree.
  - Since it is a faithful representation of program structure
  - Just inconvenient to use because of unnecessary details

Abstract Syntax Tree. (Cont.)

- Consider the grammar

  $E \rightarrow \text{int} \mid (E) \mid E + E$

- And the string

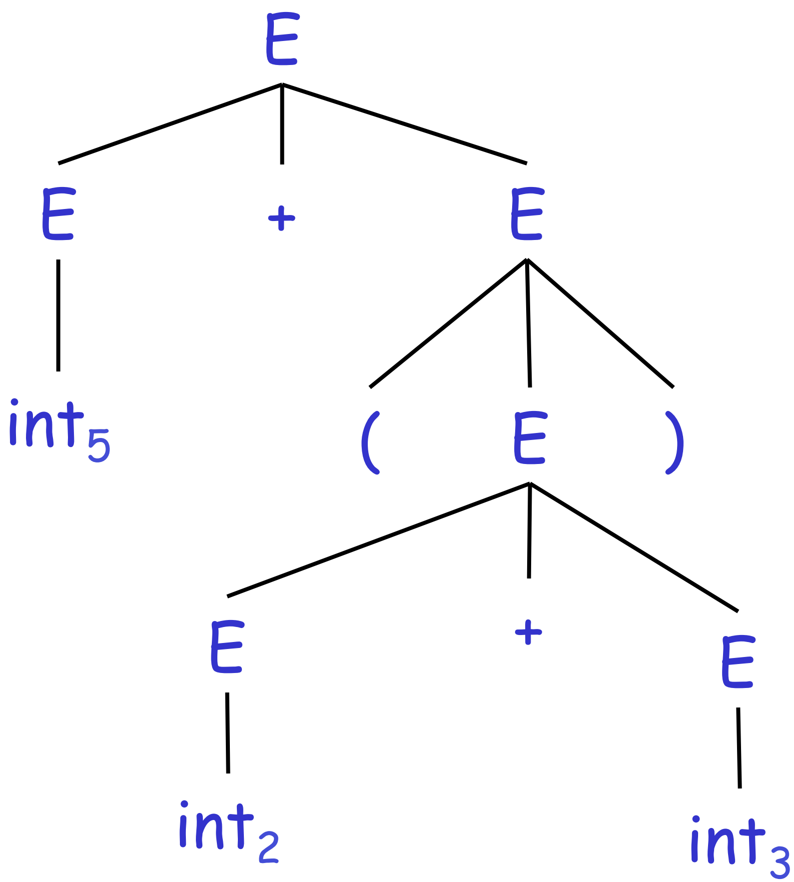
  $5 + (2 + 3)$

- After lexical analysis (a list of tokens)

  int_5 '+' '(' int_2 '+' int_3 ')'

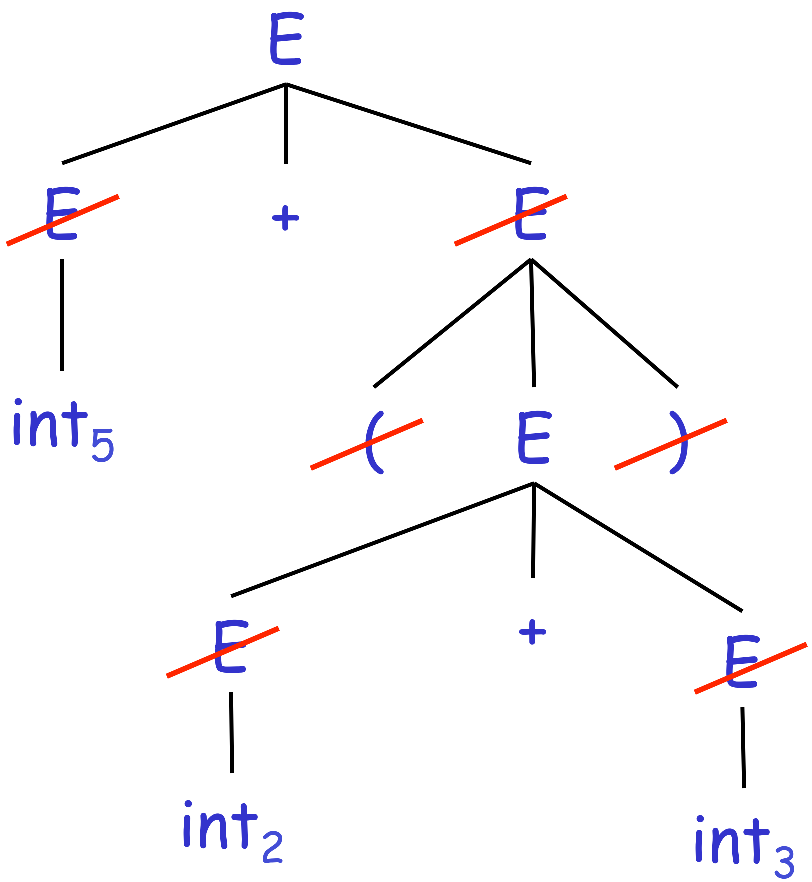
- During parsing we build a parse tree …

Example of Parse Tree



- Traces the operation of the parser
- Does capture the nesting structure
- But too much info
  - Parentheses
  - Single-successor nodes

Example of Parse Tree



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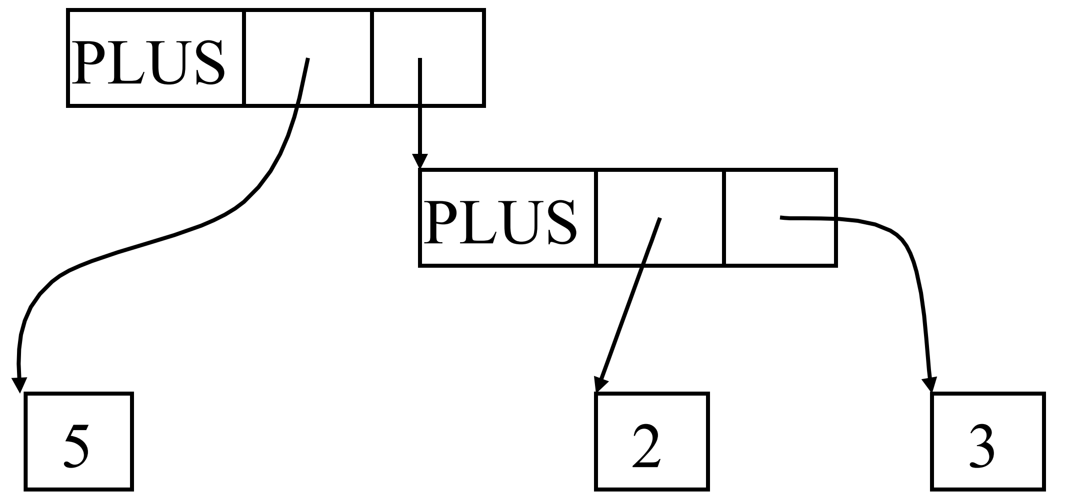
AST compresses out all the "junk" in the parse tree

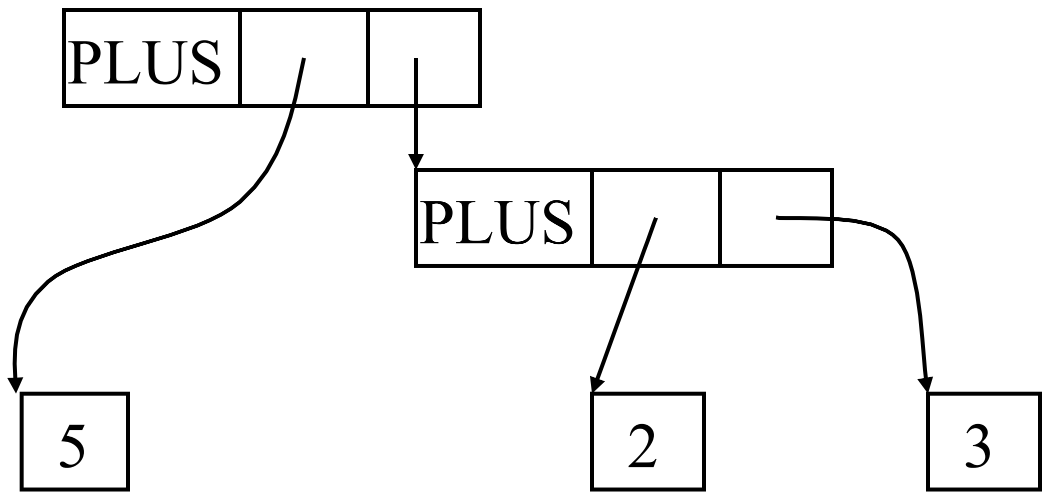
Example of Abstract Syntax Tree



- Also captures the nesting structure
  - via which plus node nested inside the other
- But abstracts from the concrete syntax

  => more compact and easier to use
- An important data structure in a compiler

Example of Abstract Syntax Tree



- Consider designing algorithms to traverse this as opposed to the parse tree
  - Quite a bit easier

Semantic Actions

- Semantic actions are program fragments embedded within production bodies
  - This is what we'll use to construct ASTs
  - These actions become part of the AST
- Ex: $E \rightarrow E + T$ {print('+')}

Semantic Actions

- Ex: $E \rightarrow E + T$ {print('+')}

  - Interpretation of this particular production: When building the parse tree, any time you use this production, you end up with E having 4 children: E, +, T, and {print('+')}

  - Once AST built, perform left to right depth-first traversal and execute each action when we encounter it's leaf node
    - See example on p. 59 of text

Semantic Actions

- This is what we'll use to construct ASTs
  - Semantic actions are program fragments embedded within production bodies
- Each grammar symbol may have <u>attributes</u>
  - For terminal symbols (lexical tokens) attributes can be calculated by the lexer
- Each production may have an <u>action</u>
  - Written as: $X \to Y_1 \ldots Y_n \quad \{ \text{action} \}$
  - That can refer to or compute symbol attributes
  - Basically, you are associating rules or program fragments to productions in a grammar

Semantic Actions: An Example

- Consider the grammar

$$E \rightarrow \text{int} \mid E + E \mid (E)$$

- For each symbol X define an attribute X.val
  - For terminals, val is the associated lexeme
  - For non-terminals, val is the expression's value (and is computed from values of subexpressions)

- We annotate the grammar with actions:

$$\begin{array}{ll} E \rightarrow \text{int} & \{ E.val = \text{int}.val \} \\ \quad \mid E_1 + E_2 & \{ E.val = E_1.val + E_2.val \} \\ \quad \mid (E_1) & \{ E.val = E_1.val \} \end{array}$$

Semantic Actions: An Example (Cont.)

- String: 5 + (2 + 3)
- Tokens: int_5 '+' '(' int_2 '+' int_3 ')'

Productions	Equations
$E \rightarrow E_1 + E_2$	$E.val = E_1.val + E_2.val$
$E_1 \rightarrow int_5$	$E_1.val = int_5.val = 5$
$E_2 \rightarrow (E_3)$	$E_2.val = E_3.val$
$E_3 \rightarrow E_4 + E_5$	$E_3.val = E_4.val + E_5.val$
$E_4 \rightarrow int_2$	$E_4.val = int_2.val = 2$
$E_5 \rightarrow int_3$	$E_5.val = int_3.val = 3$

Semantic Actions: Notes

- Semantic actions specify a system of equations
  - Order of resolution is not specified

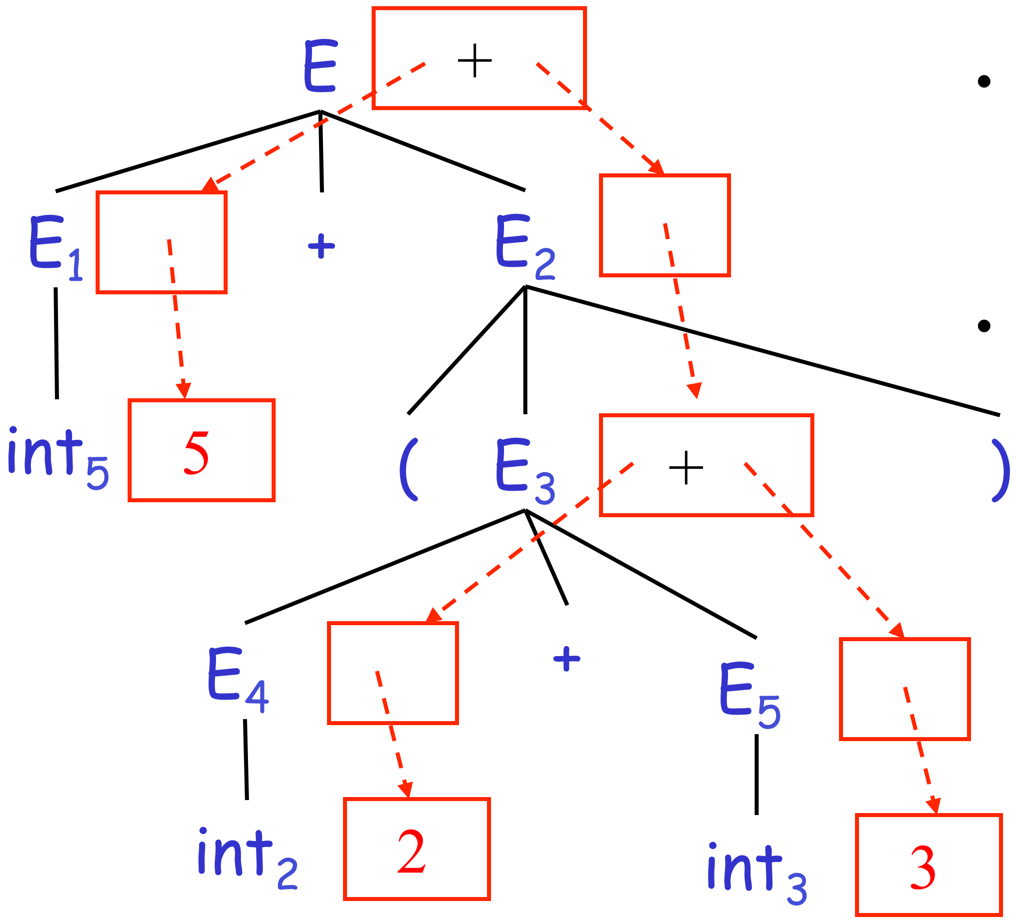
- Example:

$$E_3.val = E_4.val + E_5.val$$

  - Must compute $E_4.val$ and $E_5.val$ before $E_3.val$
  - We say that $E_3.val$ depends on $E_4.val$ and $E_5.val$

- The parser must find the order of evaluation

Dependency Graph



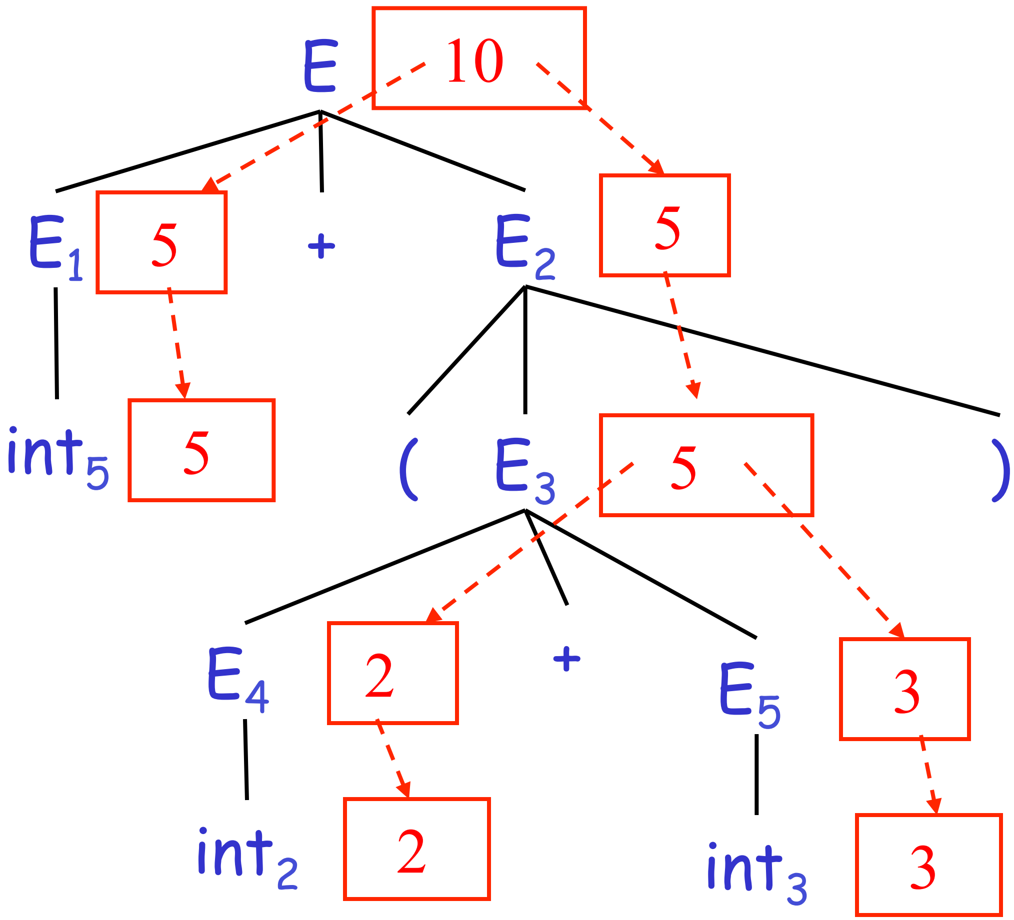
- Each node labeled E has one slot for the val attribute
- Note the dependencies

Evaluating Attributes

- An attribute must be computed after all its successors in the dependency graph have been computed
  - In previous example attributes can be computed bottom-up

- Such an order exists when there are no cycles
  - Cyclically defined attributes are not legal

Dependency Graph



Semantic Actions: Notes (Cont.)

- Synthesized attributes
  - Calculated from attributes of descendents in the parse tree
  - E.val is a synthesized attribute
  - Can always be calculated in a bottom-up order

- Grammars with only synthesized attributes are called S-attributed grammars
  - Most common case

Inherited Attributes

- Another kind of attribute

- Calculated from attributes of parent, and/or siblings, and/or self in the parse tree

- Example: a line calculator

A Line Calculator

- Each line contains an expression

  $E \rightarrow \text{int} \mid E + E$
- Each line is terminated with the = sign

  $L \rightarrow E = \mid + E =$

- In second form the value of previous line is used as starting value
- A program is a sequence of lines

  $P \rightarrow \varepsilon \mid P\ L$

Attributes for the Line Calculator

- Each E has a synthesized attribute val
  - Calculated as before
- Each L has an attribute val

$L \rightarrow E =$ { L.val = E.val }
$\quad | \; + E =$ { L.val = E.val + L.prev }

- We need the value of the previous line
- We use an inherited attribute L.prev

Attributes for the Line Calculator (Cont.)

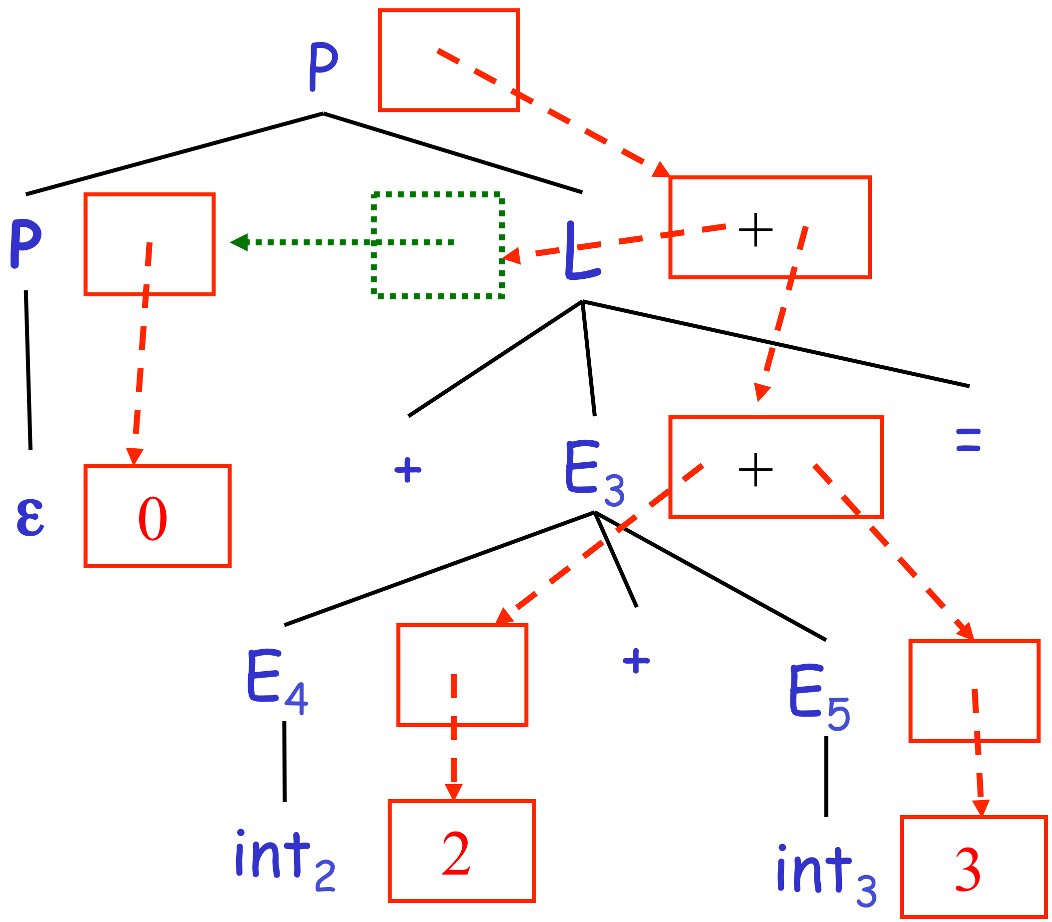
- Each P has a synthesized attribute val
  - The value of its last line

$$P \rightarrow \varepsilon \qquad \{ P.val = 0 \}$$
$$\mid \; P_1 \; L \qquad \{ P.val = L.val; \; L.prev = P_1.val \}$$

  - Each L has an inherited attribute prev
  - L.prev is inherited from sibling P_1.val

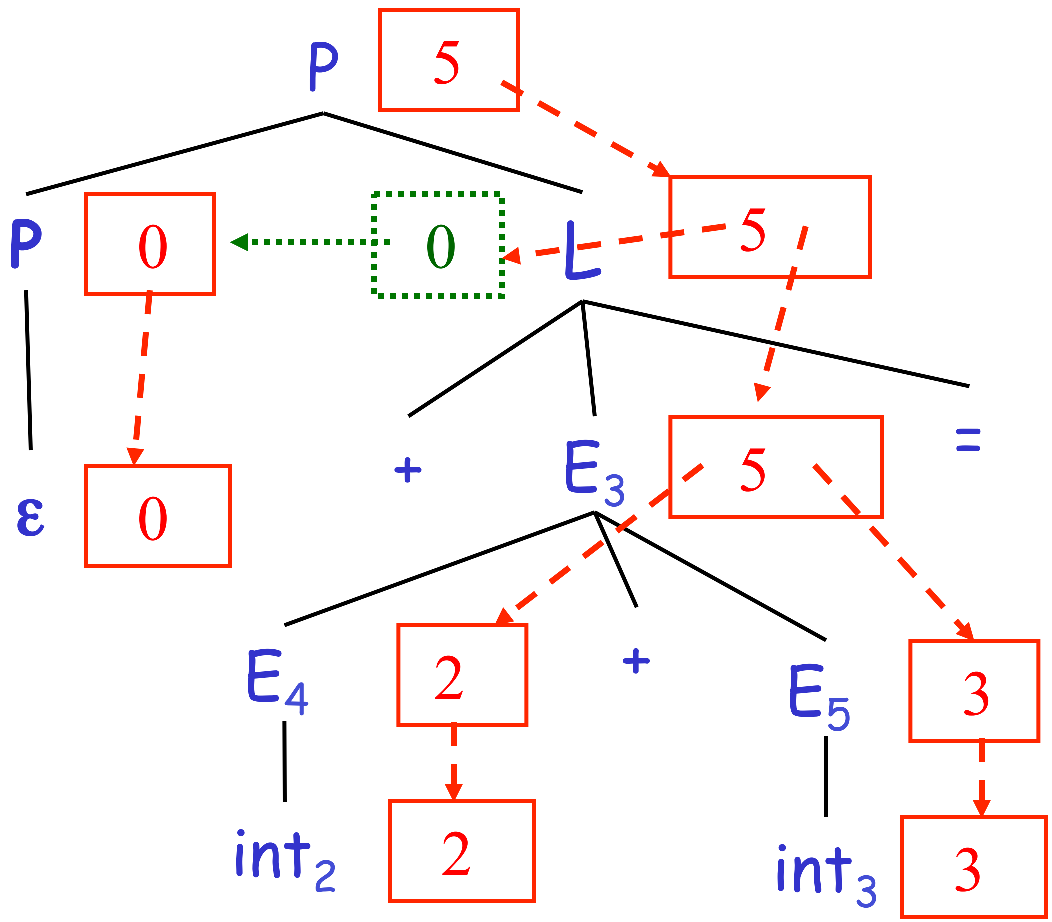
- Example …

Example of Inherited Attributes

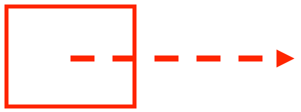


- val synthesized
- prev inherited
- All can be computed in depth-first order

Example of Inherited Attributes



- val synthesized



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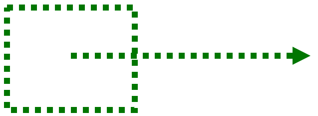


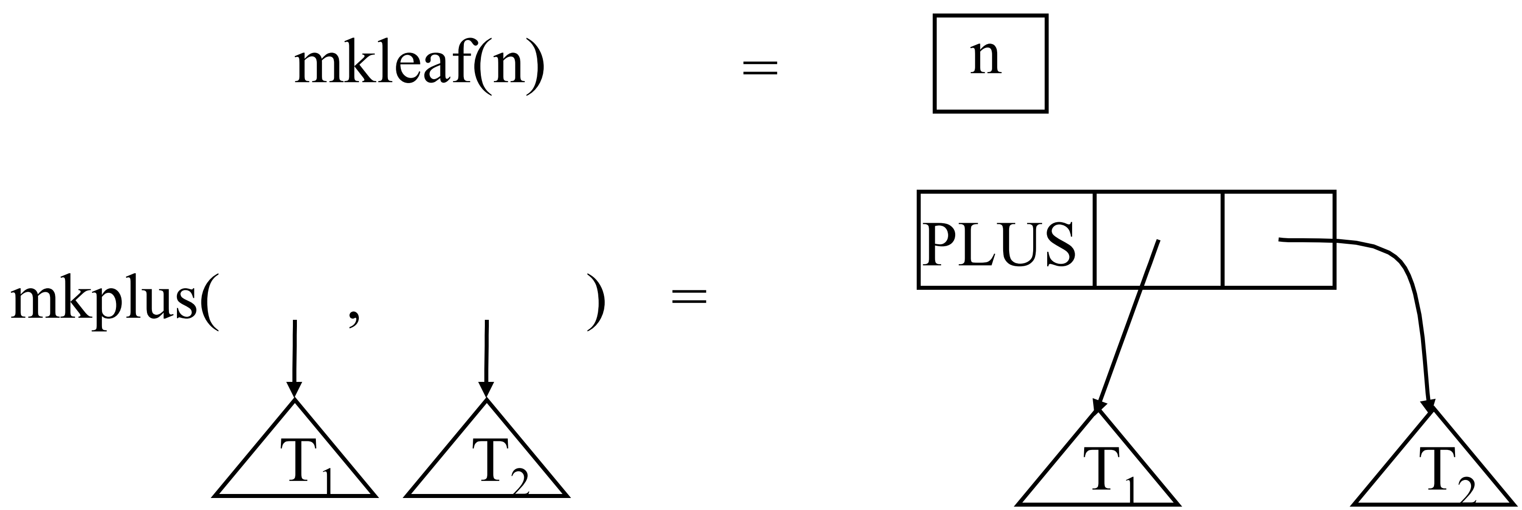
- All can be computed in depth-first order

Semantic Actions: Notes (Cont.)

- Semantic actions can be used to build ASTs
- And many other things as well
  - Also used for type checking, code generation, …
- Process is called <u>syntax-directed translation</u>
  - Substantial generalization over CFGs

Constructing An AST

- We first define the AST data type
  - Supplied by us for the project
- Consider an abstract tree type with two constructors:



Constructing a Parse Tree

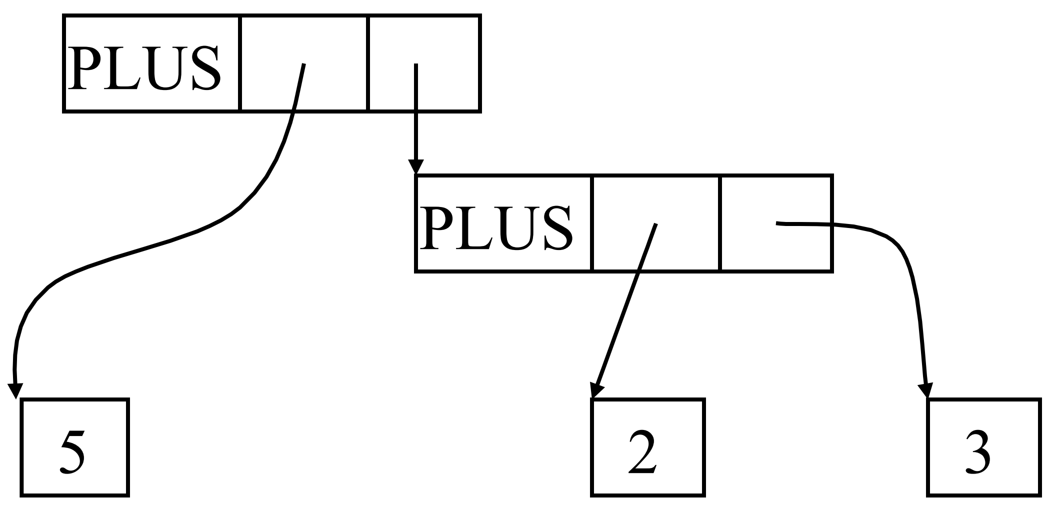
- We define a synthesized attribute ast
  - Values of ast attribute are ASTs
  - We assume that int.lexval is the value of the integer lexeme
  - Computed using semantic actions

$E \rightarrow \text{int}$	$E.ast = \text{mkleaf}(\text{int.lexval})$
$\mid E_1 + E_2$	$E.ast = \text{mkplus}(E_1.ast, E_2.ast)$
$\mid (E_1)$	$E.ast = E_1.ast$

Parse Tree Example

- Consider the string int_5 '+' '(' int_2 '+' int_3 ')'
- A bottom-up evaluation of the ast attribute:

  E.ast = mkplus(mkleaf(5),
                 mkplus(mkleaf(2), mkleaf(3))



Summary

- We can specify language syntax using CFG

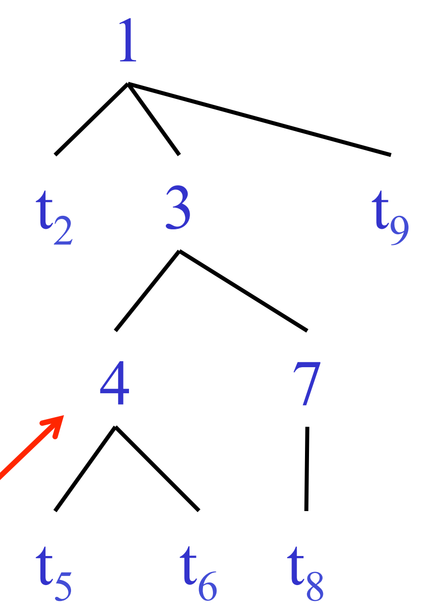
- A parser will answer whether $s \in L(G)$
  - … and will build a parse tree
  - … which we convert to an AST
  - … and pass on to the rest of the compiler

- Now, on to the actual parsing algorithms (there are a few)

Intro to Top-Down Parsing: The Idea

- The parse tree is constructed
  - From the top (i.e., starting with root node)
  - From left to right
- Terminals are seen in order of appearance in the token stream:

$t_2 \quad t_5 \quad t_6 \quad t_8 \quad t_9$



Numbers correspond to order in which nodes constructed

Intro to Top-Down Parsing: The Idea

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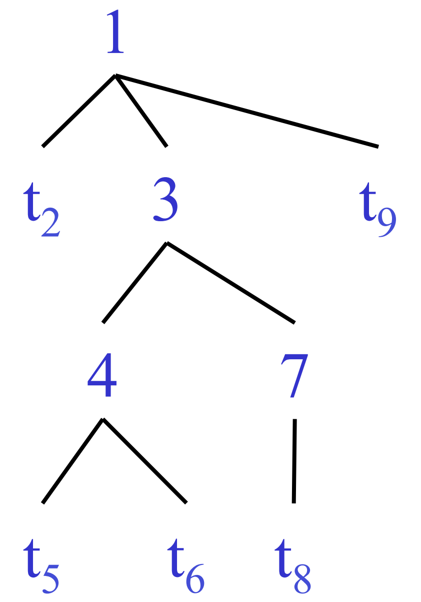

And yes, there are also bottom-up parsing algorithms

Recursive Descent Parsing

- Consider the grammar (for int expressions)

  $$E \rightarrow T \mid T + E$$

  $$T \rightarrow \text{int} \mid \text{int} * T \mid (E)$$

- Token stream is: (int_5)

- Start with top-level non-terminal E
  - Try the rules for E in order
  - There is trial-and-error involved

  And note I'm not giving pseudocode, but instead walk through the algorithm for this particular grammar

Recursive Descent: Three Components

- Grammar that we're using
- Parse tree that we're building
  - Initially just the root of the parse tree
- Input that we're processing
  - Indicated by the red arrow
  - Always points to the next terminal symbol to be read

To Repeat

- Top to bottom
- Left to Right
- As we're building the parse tree, whenever we get to a leaf (i.e., a terminal), we check whether it matches the current terminal in the input
  - If yes, then continue
  - If no, then backtrack
- But: while we are at a non-terminal, we have no way of knowing whether current track will succeed!

Recursive Descent Parsing

$E \rightarrow T \mid T + E$

$T \rightarrow int \mid int * T \mid (E)$

E

Highlighting indicates which production we're going to try

(int_5)

Recursive Descent Parsing

$E \rightarrow T \mid T + E$

$T \rightarrow \text{int} \mid \text{int} * T \mid (E)$

E

(int_5)

Recursive Descent Parsing

$E \rightarrow T \mid T + E$

$T \rightarrow \text{int} \mid \text{int} * T \mid (E)$

E

T

$(\text{ int}_5 \text{ })$

Recursive Descent Parsing

$E \rightarrow T \mid T + E$

$T \rightarrow int \mid int * T \mid (E)$

E
|
T
|
int

Mismatch: int is not "("
Backtrack …

$(\; int_5 \;)$

↑

Recursive Descent Parsing

$E \rightarrow T \mid T + E$

$T \rightarrow \text{int} \mid \text{int} * T \mid (E)$

$(\text{ int}_5 \text{ })$

$\uparrow$

Recursive Descent Parsing

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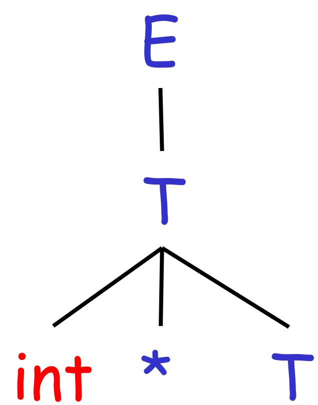

Mismatch: int is not "("

Backtrack …

$(\ int_5 \ )$

Recursive Descent Parsing

$E \rightarrow T \mid T + E$

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$$\begin{array}{c} E \\ | \\ T \end{array}$$

$(\; int_5 \;)$

$\uparrow$

Recursive Descent Parsing

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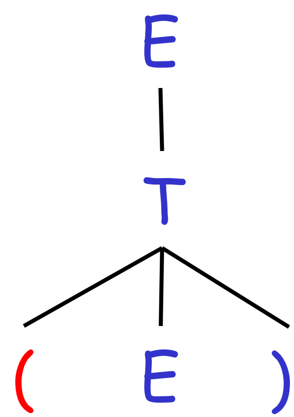

Match! Advance input.

$(\ \text{int}_5 \ )$

Recursive Descent Parsing

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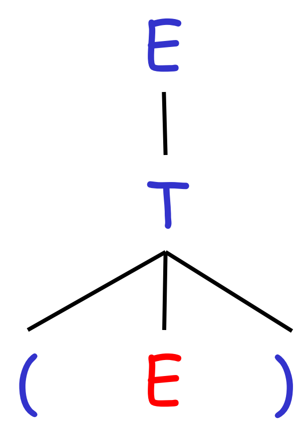

(int_5)

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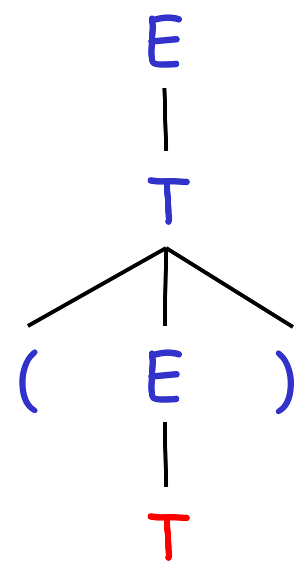

$(\; \text{int}_5 \;)$

$\uparrow$

Recursive Descent Parsing

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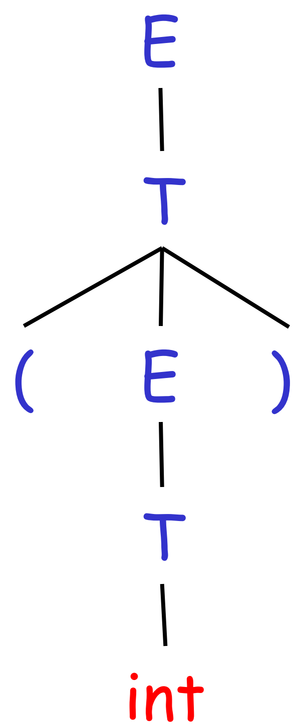

Match! Advance input.

(int_5)

Recursive Descent Parsing

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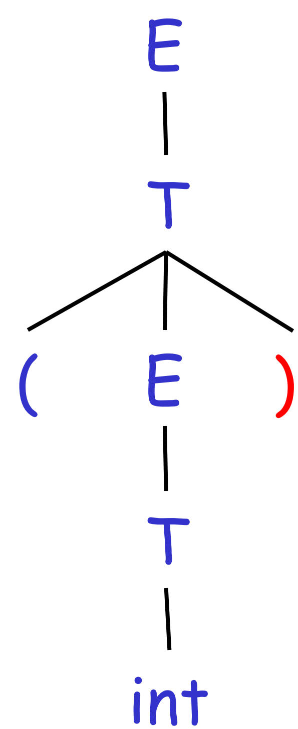

Match! Advance input.

$(\text{ int}_5 \text{ })$

Recursive Descent Parsing

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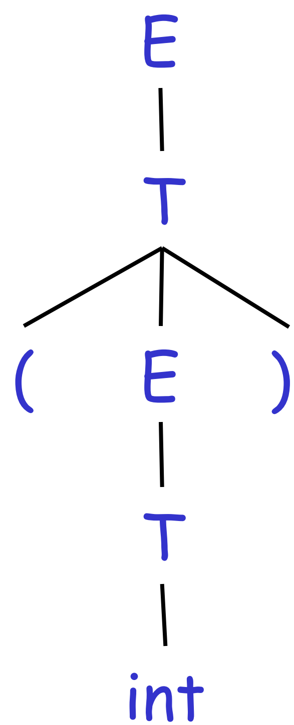

End of input, accept.

$(\ int_5 \ )$

Now for the general algorithm
But first…

A Recursive Descent Parser. Preliminaries

- Let TOKEN be the type of tokens
  - Special tokens INT, OPEN, CLOSE, PLUS, TIMES
  - E.g., TOKEN is a type, and the list above are examples of instances of that type

- Let the global next point to the next token
  - I.e., next plays the same role as the red cursor arrow

A (Limited) Recursive Descent Parser (2)

- Define boolean functions that check the token string for a match of
  - A given token terminal

    true or false

    ```
    bool term(TOKEN tok) { return *next++ == tok; }
    ```
  - Read: Is what next is pointing to equal to tok? (That is, is tok equal to the thing that next is currently pointing to in the input stream?)
    - If so, return true
    - Note: as a side effect, next is incremented **regardless of whether the match succeeded or failed!**

A (Limited) Recursive Descent Parser (2)

- Define boolean functions that check the token string for a match of
  - The nth production of S: (note: a particular production of a particular nonterminal S)

    bool S_n() { … }

  - Again, returns a bool, and only checks for the success of only one production of S
  - We'll look at "code" for that in a minute

A (Limited) Recursive Descent Parser (2)

- Define boolean functions that check the token string for a match of
  - Try all productions of S:

    ```
    bool S() { … }
    ```

Succeeds if there is ANY production of S can match the input

A (Limited) Recursive Descent Parser (2)

- So, there are two classes of functions for each nonterminal
  - One class where there is one function per production, each function able to check whether the corresponding production matches the input
  - One class that combines all the productions for a particular nonterminal and checks whether any of them can match the input

Embedded term() calls

- Note that in both of the previously mentioned classes, there are embedded term() calls.
- Why?
  - The input attempting to be matched consists of terminals
  - So only way to know if a production for a non-terminal CAN match a portion of the input is to call the term() function (on some terminal(s) in the input)
  - Thus code of both S_n and S must call term()

Who Cares?

- You should: As mentioned term() has a side effect!
  - Moves the input pointer (whether or not there is a match)

- Bottom line: When either S_n or S are called, the input pointer has been incremented (via embedded term() calls) so that it is pointing at the first terminal that was NOT matched.

Now let's see this work

A (Limited) Recursive Descent Parser (3)

- For production $E \rightarrow T$

  `bool E1() { return T(); }`
- Why?
  - E_1() is the function that deals with the first production for nonterminal E
  - It is supposed to return true if this first production can matches a given input
  - How can this production match an input?
    - Only if some production of T matches the input
    - And we have a name for the function that tries all the productions of T. It's called T().
  - So, E_1() succeeds exactly when T() succeeds

A (Limited) Recursive Descent Parser (3)

- For production $E \rightarrow T + E$

  ```
  bool E2() { return T() && term(PLUS) && E(); }
  ```

- Little more work here: Succeeds if $T + E$ can match some input. How does this happen?
  - Some production of T has to match a portion of the input AND
  - We have to find a + in the input following whatever T matched AND
  - If + has been matched, some production of E needs to match a portion of the input

A (Limited) Recursive Descent Parser (3)

- For production $E \rightarrow T + E$

  ```
  bool E2() { return T() && term(PLUS) && E(); }
  ```

- Little more work here: Succeeds if $T + E$ can match some input. How does this happen?
  - Some production of T has to match a portion of the input AND
  - We have to find a + in the input following whatever T matched AND
  - If + has been matched, some production of E needs to match a portion of the input

Note use of short circuiting && here

A (Limited) Recursive Descent Parser (3)

- For production $E \to T + E$

  bool E_2() { return T() && term(PLUS) && E(); }

- Little more work here: Succeeds if $T + E$ can match some input. How does this happen?
  - Some production of T has to match a portion of the input AND
  - We have to find a + in the input following whatever T matched AND
  - If + has been matched, some production of E needs to match a portion of the input

Note also how the side-effecting moves pointer

A (Limited) Recursive Descent Parser (3)

- For all productions of E (with backtracking)
  - Only state that we have to worry about is the next pointer,
  - Needs to be restored if we have to "undo" decisions

```
bool E() {
  TOKEN *save = next;
  return    (next = save, E1())
         || (next = save,  E2());   }
```

Note that if $E_1()$ matches, then the next pointer will have been advanced to point to the token following the portion matched by $E_1()$.

A (Limited) Recursive Descent Parser (3)

- For all productions of E (with backtracking)
  - Only state that we have to worry about is the next pointer,
  - Needs to be restored if we have to "undo" decisions

```
bool E() {
  TOKEN *save = next;
  return    (next = save, E1())
        || (next = save,  E2());   }
```

Note saved next ptr before any other "code"

Note restoring next ptr before trying E_2()

A (Limited) Recursive Descent Parser (3)

- For all productions of E (with backtracking)
  - Only state that we have to worry about is the next pointer,
  - Needs to be restored if we have to "undo" decisions

```
bool E() {
  TOKEN *save = next;
  return    (next = save, E1())
         || (next = save,  E2());   }
```

But what about this saved ptr here? Not needed, but done for uniformity

Recall Our Grammar

$E \rightarrow T \mid T + E$

$T \rightarrow \text{int} \mid \text{int} * T \mid (E)$

A (Limited) Recursive Descent Parser (4)

- Functions for non-terminal T

```
bool T1() { return term(INT); }
bool T2() { return term(INT) && term(TIMES) && T(); }
bool T3() { return term(OPEN) && E() && term(CLOSE); }

    bool T() {
      TOKEN *save = next;
      return    (next = save, T1())
             || (next = save,  T2())
             || (next = save,  T3()); }
```

Recursive Descent Parsing. Notes.

- To start the parser
  - Initialize next to point to first token
  - Invoke E()

- Notice how this simulates the example parse

- Easy to implement by hand (and people often do this)
  - But not completely general
  - Cannot backtrack once a production is successful
  - Works for grammars where at most one production can succeed for a non-terminal

Complete Example

$E \rightarrow T \mid T + E$

$T \rightarrow \text{int} \mid \text{int} * T \mid (E)$

(int)

```
bool term(TOKEN tok) { return *next++ == tok; }

bool E1() { return T(); }
bool E2() { return T() && term(PLUS) && E(); }

bool E()  {TOKEN *save = next; return    (next = save, E1())
                                      || (next = save,  E2());   }
bool T1() { return term(INT); }
bool T2() { return term(INT) && term(TIMES) && T(); }
bool T3() { return term(OPEN) && E() && term(CLOSE); }

bool T() { TOKEN *save = next;  return   (next = save, T1())
                                      || (next = save,  T2())
                                      || (next = save,  T3()); }
```

Another Example (Same Grammar)

$E \to T \mid T + E$

$T \to int \mid int * T \mid (E)$

int

```
bool term(TOKEN tok) { return *next++ == tok; }

bool E1() { return T(); }
bool E2() { return T() && term(PLUS) && E(); }

bool E()  {TOKEN *save = next; return    (next = save, E1())
                                      || (next = save,  E2());   }
bool T1() { return term(INT); }
bool T2() { return term(INT) && term(TIMES) && T(); }
bool T3() { return term(OPEN) && E() && term(CLOSE); }

bool T() { TOKEN *save = next;  return    (next = save, T1())
                                       || (next = save,  T2())
                                       || (next = save,  T3()); }
```

Still Another Example (Same Grammar)

$E \to T \mid T + E$

$T \to \text{int} \mid \text{int} * T \mid (E)$

int * int

```
bool term(TOKEN tok) { return *next++ == tok; }

bool E1() { return T(); }
bool E2() { return T() && term(PLUS) && E(); }

bool E()  {TOKEN *save = next; return    (next = save, E1())
                                         || (next = save,  E2());   }
bool T1() { return term(INT); }
bool T2() { return term(INT) && term(TIMES) && T(); }
bool T3() { return term(OPEN) && E() && term(CLOSE); }

bool T() { TOKEN *save = next;  return   (next = save, T1())
                                         || (next = save,  T2())
                                         || (next = save,  T3()); }
```

Still Another Example (Same Grammar)

$E \rightarrow T \mid T + E$

$T \rightarrow \text{int} \mid \text{int} * T \mid (E)$

int * int

```
bool term(TOKEN tok) { return *next++ == tok; }

bool E1() { return T(); }
bool E2() { return T() && term(PLUS) && E(); }

bool E()  {TOKEN *save = next; return     (next = save, E1())
                                       || (next = save,  E2());   }
bool T1() { return term(INT); }
bool T2() { return term(INT) && term(TIMES) && T(); }
bool T3() { return term(OPEN) && E() && term(CLOSE); }

bool T() { TOKEN *save = next;  return    (next = save, T1())
                                       || (next = save,  T2())
                                       || (next = save,  T3()); }
```

rejected! So what happened?

So What Happened?

- When int matched the first production for T, we said that T() was done, had matched the input.
- This caused the parse to fail because the rest of the string was not consumed.
- Once the call to T() had succeeded, there was no way to backtrack and try alternative production for T.
- To succeed, would have to be able to say that even though we found a part that matched, since the overall parse failed, that must not have been the right production to choose for T
  - Note here trying T_2() would have resulted in success

So, the Problem

- The problem is that while there is backtracking while trying to find a production that works for a given non-terminal, there is no backtracking once we have found a production that succeeds for that non-terminal.
- So once a non-terminal function commits and returns and says "I have found a way to parse part of the input using one of my productions", there is no way in this algorithm to go back and revisit that decision.

Bottom Line

- The Recursive Descent algorithm we've seen thus far is not completely general
  - It fails on some inputs on which it should succeed
- BUT, recursive descent IS a general technique
  - There are algorithms for Recursive Descent parsing that can parse any grammar (implement full language of any grammar)
  - Such algorithms have more sophisticated backtracking mechanisms than does the algorithm I've presented thus far.

So Why Show This Algorithm?

- Well, as we've seen, it's easy to implement by hand
- Also, it works on a large class of grammars
  - Any grammar where for any non-terminal at most one production can succeed.
- So, if you know by the way that you've built your grammar that the RD algorithm is only in situations where for any terminal at most one production can succeed, you're good!
- The example grammar can be rewritten to work with this algorithm via *left-factoring*

Recursive Descent: Another Issue

- Consider a simple grammar with a single production $S \rightarrow S\ a$

```
bool S1() { return S() && term(a); }
bool S() { return  S1(); }
```

- S() always goes into an infinite loop

Recall: non-empty sequence of rewrites

- A left-recursive grammar has a non-terminal S

$$S \rightarrow^{+} S\alpha \quad \text{for some } \alpha$$

- Recursive descent does not work in such cases

A Major Problem?

- Well, though it might seem so at first, the answer is that no, it’s not.

Elimination of Left Recursion

- Consider the left-recursive grammar

$$S \to S\,\alpha \mid \beta$$

- S generates all strings starting with a β and followed by a number of α
  - Note that it produces strings right to left
  - Very last thing it produces is first thing in input
- This is why it causes issues for recursive descent parsing
  - Which wants to process first part of the string first (left to right)

Elimination of Left Recursion

- Consider the left-recursive grammar

$$S \rightarrow S\ \alpha \mid \beta$$

- This gives us the idea on how to fix it: replace left-recursion with right-recursion
  - Create exactly same language

- Can rewrite using right-recursion

$$S \rightarrow \beta\ S'$$

$$S' \rightarrow \alpha\ S' \mid \varepsilon$$

More Elimination of Left-Recursion

- In general

$$S \rightarrow S\,\alpha_1 \mid \ldots \mid S\,\alpha_n \mid \beta_1 \mid \ldots \mid \beta_m$$

- All strings derived from S start with one of $\beta_1,\ldots,\beta_m$ and continue with several instances of $\alpha_1,\ldots,\alpha_n$
- Rewrite as

$$S \rightarrow \beta_1\,S' \mid \ldots \mid \beta_m\,S'$$
$$S' \rightarrow \alpha_1\,S' \mid \ldots \mid \alpha_n\,S' \mid \varepsilon$$

General Left Recursion

- The grammar

  $$S \to A\,\alpha \mid \delta$$

  $$A \to S\,\beta$$

  is also left-recursive because

  $$S \to^{+} S\,\beta\,\alpha$$

- This left-recursion can also be eliminated
  - In fact, automatically – does not require human intervention

- See Dragon Book for general algorithm
  - Section 4.3

Summary of Recursive Descent

- Simple and general parsing strategy
  - Left-recursion must be eliminated first
  - … but that can be done automatically
- Unpopular because of backtracking
  - Thought to be too inefficient
- In practice, backtracking is eliminated by restricting the grammar