450 COMPILERS

COMPUTER SCIENCE

News & Info

- Who's Hiring May 2016
  - https://news.ycombinator.com/item?id=11611867

- SoCal Code Camp | San Diego, CA 6/25-6/26
  - http://www.socalcodecamp.com/

Administrivia

- Lab 06
  - Due Thursday

Predictive Parsers

- Like recursive-descent but parser can "predict" which production to use
  - By looking at the next few tokens
  - No backtracking

- Predictive parsers accept LL(k) grammars
  - L means "left-to-right" scan of input
  - L means "leftmost derivation"
  - k means "predict based on k tokens of lookahead"
  - In practice, LL(1) is used

LL(1) vs Recursive Descent

- In recursive-descent,
  - At each step, many choices of production to use
  - Backtracking used to undo bad choices

- In LL(1),
  - At each step, only one choice of production
  - That is
    - When a non-terminal A is leftmost in a derivation
    - The next input symbol is t
    - There is a unique production $A \rightarrow \alpha$ to use
      - Or no production to use (an error state)

- LL(1) is a recursive descent variant without backtracking

Predictive Parsing and Left Factoring

- Recall the grammar

  $E \rightarrow T + E \mid T$

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

- Hard to predict because
  - For T two productions start with int
  - For E it is not clear how to predict

- We need to left-factor the grammar

Left-Factoring Example

- Recall the grammar

$E \rightarrow T + E \mid T$

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

- Factor out common prefixes of productions

$E \rightarrow T X$

$X \rightarrow + E \mid \varepsilon$

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

$Y \rightarrow * T \mid \varepsilon$

LL(1) Parsing Table Example

- Left-factored grammar

$E \to T\,X$ $\qquad$ $X \to +\,E \mid \varepsilon$

$T \to (\,E\,) \mid \text{int}\ Y$ $\qquad$ $Y \to *\,T \mid \varepsilon$

- The LL(1) parsing table:

next input token

	int	*	+	(	)	$
E	T X			T X		
X			+ E		ε	ε
T	int Y			(E)		
Y		* T	ε		ε	ε

leftmost non-terminal *rhs of production to use*

LL(1) Parsing Table Example

- Consider the [E, int] entry
  - "When current non-terminal is E and next input is int, use production $E \rightarrow T X$"
  - This can generate an int in the first position
- Consider the [Y,+] entry
  - "When current non-terminal is Y and current token is +, get rid of Y"
  - Y can be followed by + only if $Y \rightarrow \varepsilon$

LL(1) Parsing Tables. Errors

- Blank entries indicate error situations

- Consider the [E,*] entry
  - "There is no way to derive a string starting with * from non-terminal E"

Using Parsing Tables

- Method similar to recursive descent, except
  - For the leftmost non-terminal S
  - We look at the next input token a
  - And choose the production shown at [S,a]

- A stack records frontier of parse tree
  - Non-terminals that have yet to be expanded
  - Terminals that have yet to matched against the input
  - Top of stack = leftmost pending terminal or non-terminal

- Reject on reaching error state
- Accept on end of input & empty stack

LL(1) Parsing Algorithm

```
initialize stack = <S $> and next
repeat
   case stack of
      <X, rest>  : if T[X,*next] = Y1...Yn
                       then stack ← <Y1... Yn rest>;
                       else  error ();
      <t, rest>  : if t == *next ++
                       then  stack ← <rest>;
                       else error ();
until stack == < >
```

LL(1) Parsing Algorithm

$ marks bottom of stack

```
initialize stack = <S $> and next
repeat
   case stack of
      <X, rest>  : if T[X,*next] = Y1...Yn
                      then stack ← <Y1... Yn rest>;
                      else  error ();
      <t, rest>  : if t == *next ++
                      then  stack ← <rest>;
                      else error ();
until stack == < >
```

For non-terminal X on top of stack, lookup production

Pop X, push production rhs on stack. Note leftmost symbol of rhs is on top of the stack.

For terminal t on top of stack, check t matches next input token.

LL(1) Parsing Example

Stack	Input	Action
E $	int * int $	T X
T X $	int * int $	int Y
int Y X $	int * int $	terminal
Y X $	* int $	* T
* T X $	* int $	terminal
T X $	int $	int Y
int Y X $	int $	terminal
Y X $	$	ε
X $	$	ε
$	$	ACCEPT

Constructing Parsing Tables

- Consider non-terminal A, production $A \to \alpha$, & token t
- $T[A,t] = \alpha$ in two cases:

- If $\alpha \to^* t\ \beta$
  - α can derive a t in the first position
  - We say that $t \in First(\alpha)$

- If $A \to \alpha$ and $\alpha \to^* \varepsilon$ and $S \to^* \beta\ A\ t\ \delta$
  - Useful if stack has A, input is t, and A cannot derive t
  - In this case only option is to get rid of A (by deriving ε)
    - Can work only if t can follow A in at least one derivation
  - We say $t \in Follow(A)$

Computing First Sets

Definition

$$\text{First}(X) = \{ t \mid X \to^* t\alpha\} \cup \{\varepsilon \mid X \to^* \varepsilon\}$$

Algorithm sketch:

1. $\text{First}(t) = \{ t \}$
2. $\varepsilon \in \text{First}(X)$
   - if $X \to \varepsilon$
   - if $X \to A_1 \ldots A_n$ and $\varepsilon \in \text{First}(A_i)$ for $1 \le i \le n$
3. $\text{First}(\alpha) \subseteq \text{First}(X)$ if $X \to A_1 \ldots A_n\ \alpha$
   - and $\varepsilon \in \text{First}(A_i)$ for $1 \le i \le n$

First Sets. Example

- Recall the grammar

$$E \to T\,X \qquad\qquad X \to +\,E \mid \varepsilon$$
$$T \to (\,E\,) \mid \text{int}\ Y \qquad\qquad Y \to *\,T \mid \varepsilon$$

- First sets

$\text{First}(\,(\,) = \{\,(\,\}$ $\qquad$ $\text{First}(\,T\,) = \{\text{int},\,(\,\}$

$\text{First}(\,)\,) = \{\,)\,\}$ $\qquad$ $\text{First}(\,E\,) = \{\text{int},\,(\,\}$

$\text{First}(\,\text{int}) = \{\,\text{int}\,\}$ $\qquad$ $\text{First}(\,X\,) = \{+,\,\varepsilon\,\}$

$\text{First}(\,+\,) = \{\,+\,\}$ $\qquad$ $\text{First}(\,Y\,) = \{*,\,\varepsilon\,\}$

$\text{First}(\,*\,) = \{\,*\,\}$

Computing Follow Sets

- Definition:

  $$\text{Follow}(X) = \{ t \mid S \to^* \beta X t \delta \}$$

- Intuition
  - If $X \to A\ B$ then $\text{First}(B) \subseteq \text{Follow}(A)$ and

    $\text{Follow}(X) \subseteq \text{Follow}(B)$
    - if $B \to^* \varepsilon$ then $\text{Follow}(X) \subseteq \text{Follow}(A)$

  - If S is the start symbol then $\$ \in \text{Follow}(S)$

Computer Follow Sets continued

Algorithm sketch:

1. $\$ \in \text{Follow}(S)$
2. $\text{First}(\beta) - \{\varepsilon\} \subseteq \text{Follow}(X)$
   - For each production $A \rightarrow \alpha\ X\ \beta$
3. $\text{Follow}(A) \subseteq \text{Follow}(X)$
   - For each production $A \rightarrow \alpha\ X\ \beta$ where $\varepsilon \in \text{First}(\beta)$

Follow sets. Example

- Recall the grammar

$E \to T X$ $\quad\quad$ $X \to + E \mid \varepsilon$

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

- Follow sets

Follow(+) = { int, (} $\quad$ Follow(*) = { int, (}

Follow(( ) = { int, (} $\quad$ Follow(E) = {), $}

Follow(X) = {$,) } $\quad$ Follow(T) = {+,) , $}

Follow( )) = {+,) , $} $\quad$ Follow(Y) = {+,) , $}

Follow(int) = {*, +,) , $}

Constructing LL(1) Parsing tables

- Construct a parsing table T for CFG G

- For each production $A \rightarrow \alpha$ in G do:
  - For each terminal $t \in First(\alpha)$ do
    - $T[A, t] = \alpha$
  - If $\varepsilon \in First(\alpha)$, for each $t \in Follow(A)$ do
    - $T[A, t] = \alpha$
  - If $\varepsilon \in First(\alpha)$ and $\$ \in Follow(A)$ do
    - $T[A, \$] = \alpha$

Notes on LL(1) Parsing Tables

- If any entry is multiply defined then *G* is not LL(1)
  - If *G* is ambiguous
  - If *G* is left recursive
  - If *G* is not left-factored
  - And in other cases as well

- Most programming language CFGs are not LL(1)

Bottom-Up Parsing

- Bottom-up parsing is more general than top-down parsing
  - And just as efficient
  - Builds on ideas in top-down parsing
- Bottom-up is the preferred method
- Concepts today, algorithms next time

An Introductory Example

- Bottom-up parsers don't need left-factored grammars

- Revert to the "natural" grammar for our example:

  $E \rightarrow T + E \mid T$

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

- Consider the string: int * int + int

The Idea

Bottom-up parsing *reduces* a string to the start symbol by inverting productions:

int * int + int	T → int
int * T + int	T → int * T
T + int	T → int
T + T	E → T
T + E	E → T + E
E	

Observation

- Read the productions in reverse (from bottom to top)
- This is a rightmost derivation!

int * int + int	T → int
int * T + int	T → int * T
T + int	T → int
T + T	E → T
T + E	E → T + E
E	

Important Fact #1

Important Fact #1 about bottom-up parsing:

A bottom-up parser traces a rightmost derivation in reverse

A Bottom-up Parse

int * int + int

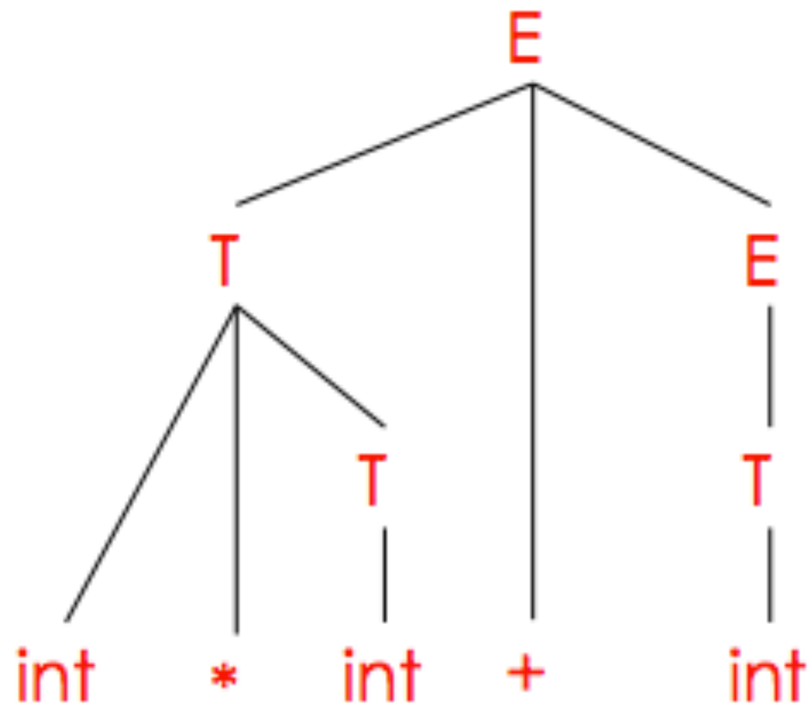
int * T + int

T + int

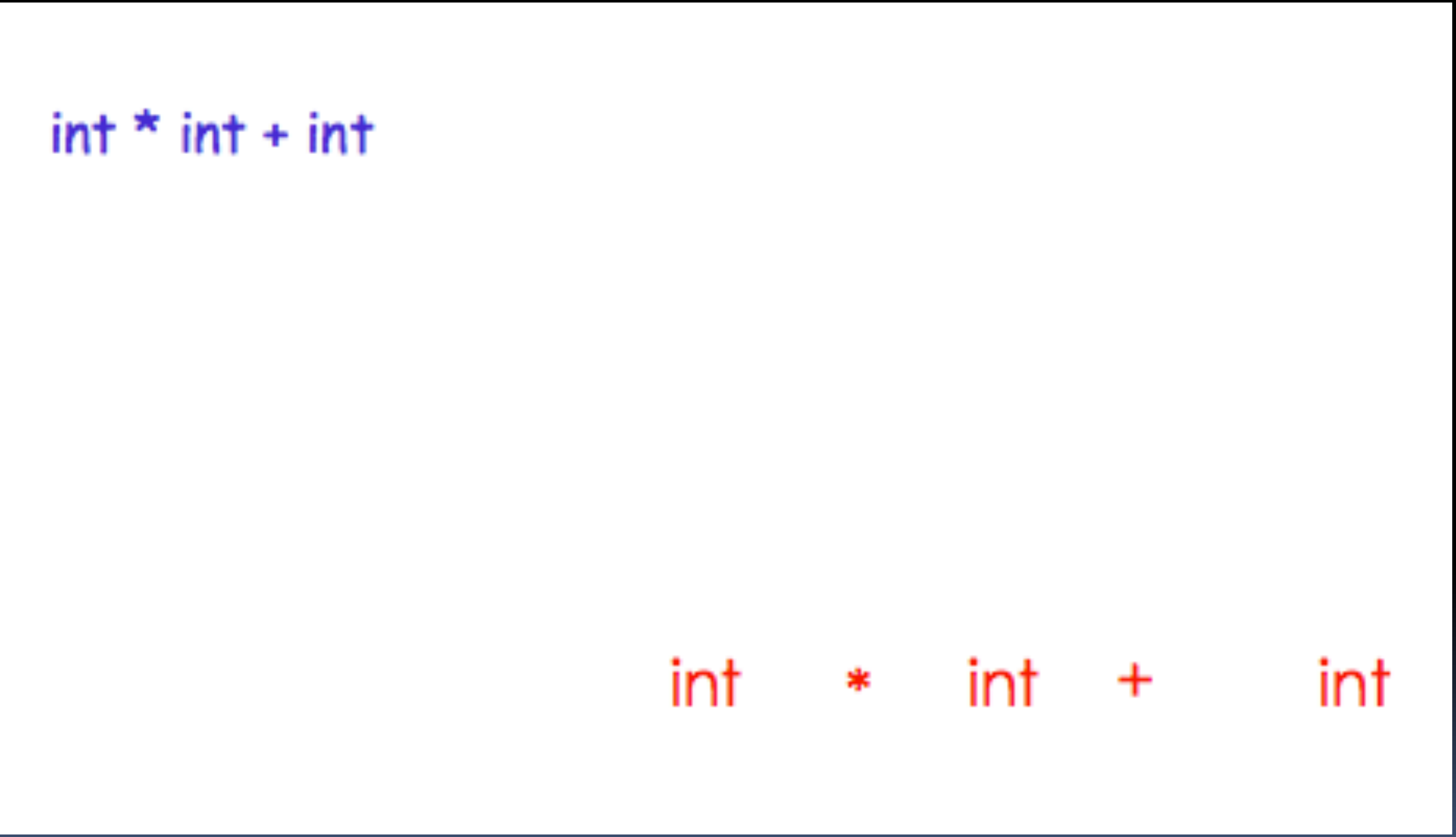
T + T

T + E

E



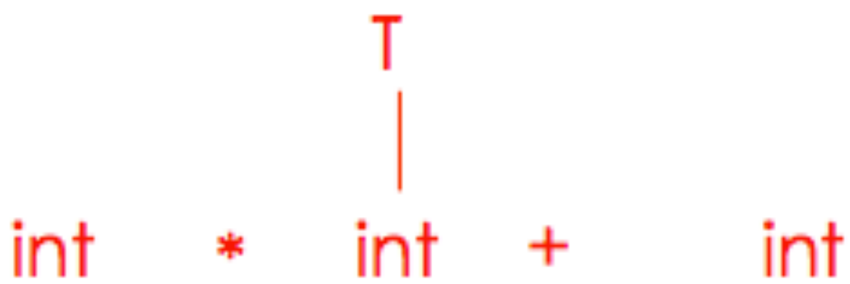
A Bottom-up Parse in Detail (1)



A Bottom-up Parse in Detail (2)

int * int + int

int * T + int

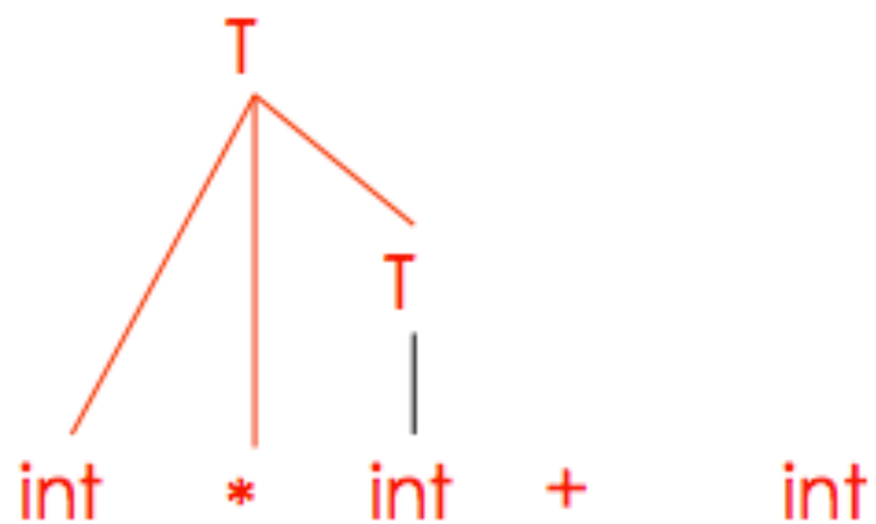


A Bottom-up Parse in Detail (3)

int * int + int

int * T + int

T + int



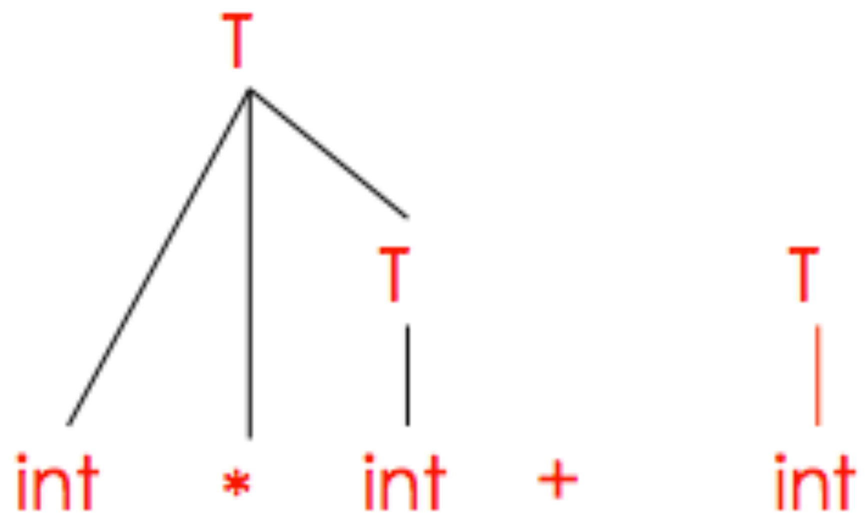
A Bottom-up Parse in Detail (4)

int * int + int

int * T + int

T + int

T + T



A Bottom-up Parse in Detail (5)

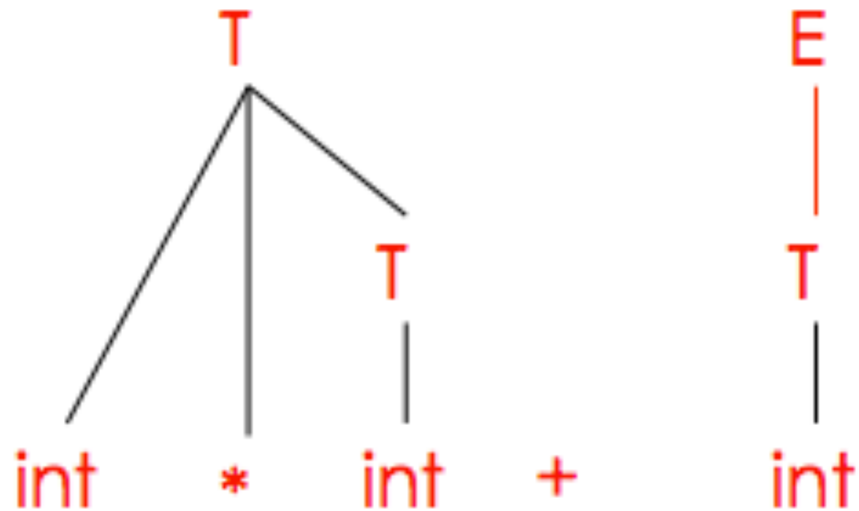
int * int + int

int * T + int

T + int

T + T

T + E



A Bottom-up Parse in Detail (6)

int * int + int

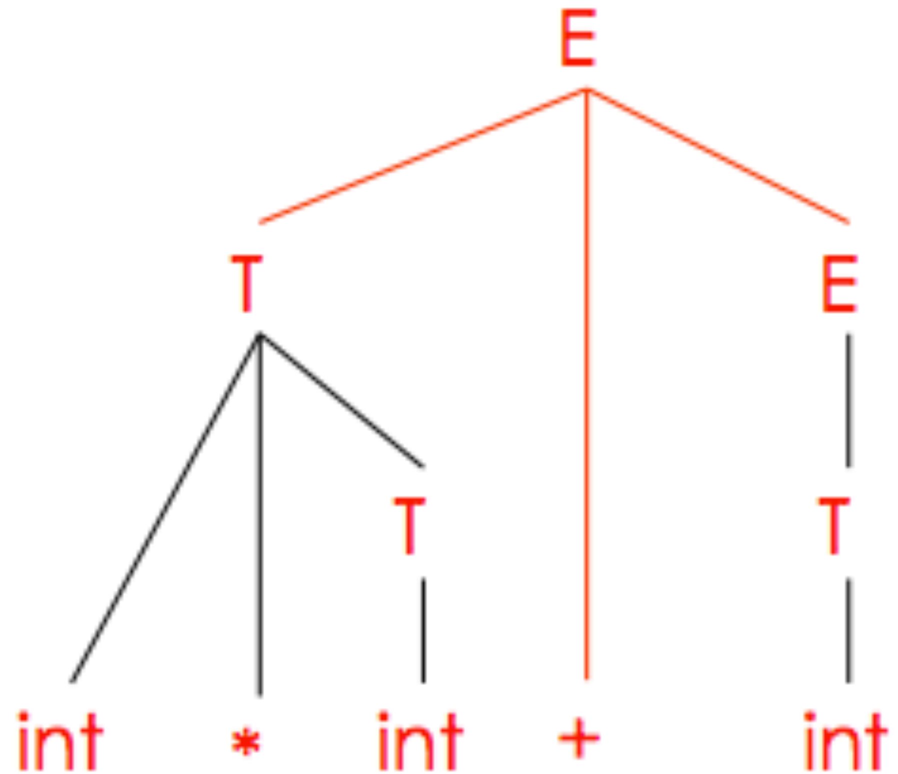
int * T + int

T + int

T + T

T + E

E



A Bottom-up Parsing Algorithm

Let I = input string
repeat
  pick a non-empty substring β of I
    where X→ β is a production
  if no such β, backtrack
  replace one β by X in I
until I = "S" (the start symbol) or all possibilities are exhausted

Where do Reductions Happen?

Important Fact #1 has an interesting consequence:

- Let $\alpha\beta\omega$ be a step of a bottom-up parse
- Assume the next reduction is by $X \rightarrow \beta$
- Then ω is a string of terminals

Why? Because $\alpha X\omega \rightarrow \alpha\beta\omega$ is a step in a right-most derivation

Notation

- Idea: Split string into two substrings
  - Right substring is as yet unexamined by parsing (a string of terminals)
  - Left substring has terminals and non-terminals
- The dividing point is marked by a $|$
  - The $|$ is not part of the string
- Initially, all input is unexamined $|x_1x_2 \ldots x_n$

Shift-Reduce Parsing

Bottom-up parsing uses only two kinds of actions:

Shift

Reduce

Shift

- *Shift:* Move | one place to the right
  - Shifts a terminal to the left string

$$ABC|xyz \Rightarrow ABCx|yz$$

Reduce

- Apply an inverse production at the right end of the left string
  - If $A \rightarrow xy$ is a production, then

$$Cbxy|ijk \Rightarrow CbA|ijk$$

The Example with Reductions Only

int * int | + int	reduce T → int
int * T | + int	reduce T → int * T
T + int |	reduce T → int
T + T |	reduce E → T
T + E |	reduce E → T + E
E |	

The Example with Shift-Reduce Parsing

|int * int + int	shift
int | * int + int	shift
int * | int + int	shift
int * int | + int	reduce T → int
int * T | + int	reduce T → int * T
T | + int	shift
T + | int	shift
T + int |	reduce T → int
T + T |	reduce E → T
T + E |	reduce E → T + E
E |	

A Shift-Reduce Parse in Detail (1)

|int * int + int

int * int + int

↑

A Shift-Reduce Parse in Detail (2)

|int * int + int

int | * int + int

int * int + int

↑

A Shift-Reduce Parse in Detail (3)

|int * int + int

int | * int + int

int * | int + int

int * int + int

↑

A Shift-Reduce Parse in Detail (4)

|int * int + int

int | * int + int

int * | int + int

int * int | + int

int * int + int

↑

A Shift-Reduce Parse in Detail (5)

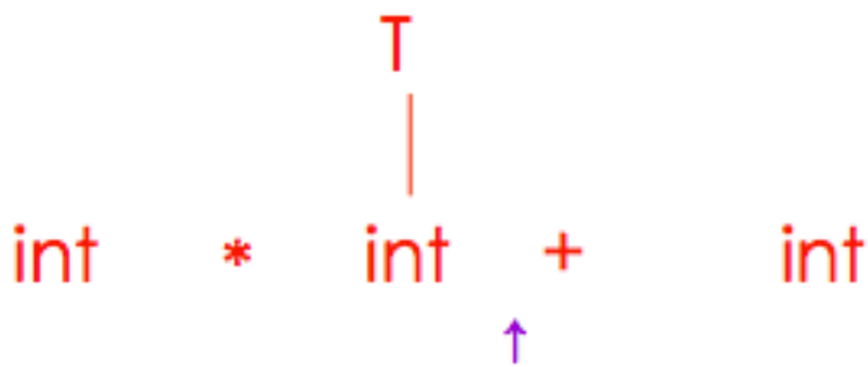
|int * int + int

int | * int + int

int * | int + int

int * int | + int

int * T | + int



A Shift-Reduce Parse in Detail (6)

|int * int + int

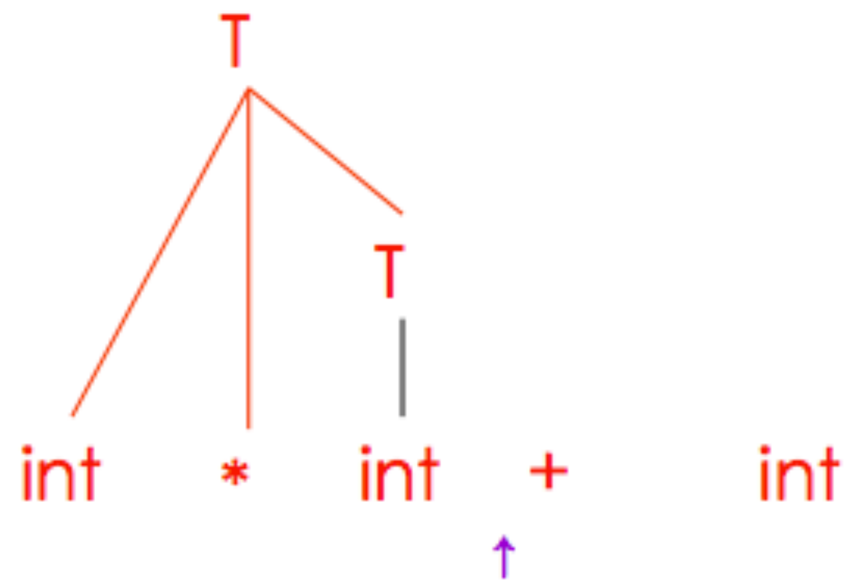
int | * int + int

int * | int + int

int * int | + int

int * T | + int

T | + int



A Shift-Reduce Parse in Detail (7)

|int * int + int

int | * int + int

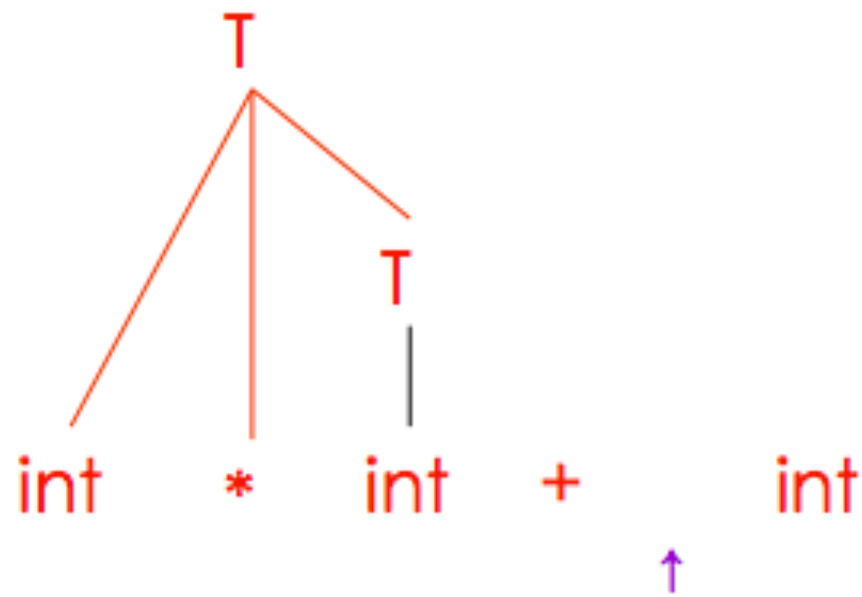
int * | int + int

int * int | + int

int * T | + int

T | + int

T + | int



A Shift-Reduce Parse in Detail (8)

|int * int + int

int | * int + int

int * | int + int

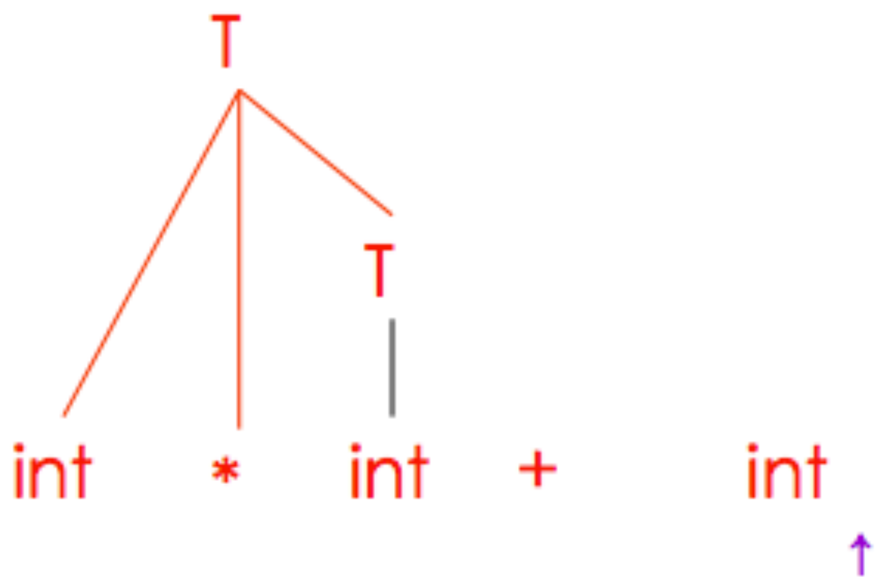
int * int | + int

int * T | + int

T | + int

T + | int

T + int |



A Shift-Reduce Parse in Detail (9)

|int * int + int

int | * int + int

int * | int + int

int * int | + int

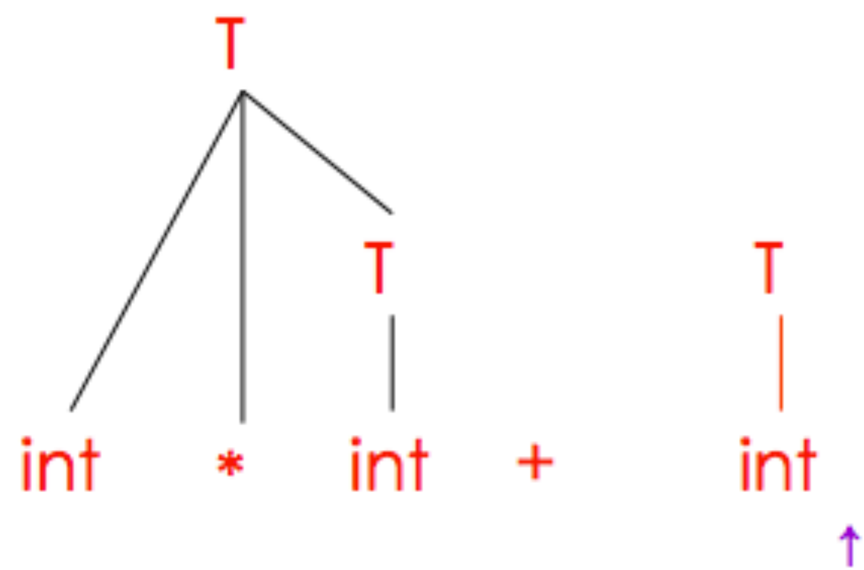
int * T | + int

T | + int

T + | int

T + int |

T + T |



A Shift-Reduce Parse in Detail (10)

|int * int + int

int | * int + int

int * | int + int

int * int | + int

int * T | + int

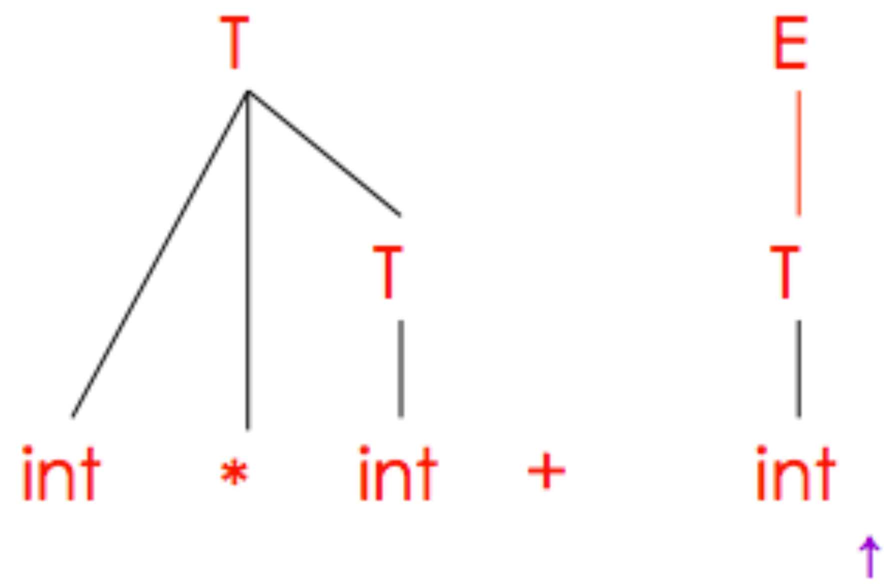
T | + int

T + | int

T + int |

T + T |

T + E |



A Shift-Reduce Parse in Detail (11)

|int * int + int

int | * int + int

int * | int + int

int * int | + int

int * T | + int

T | + int

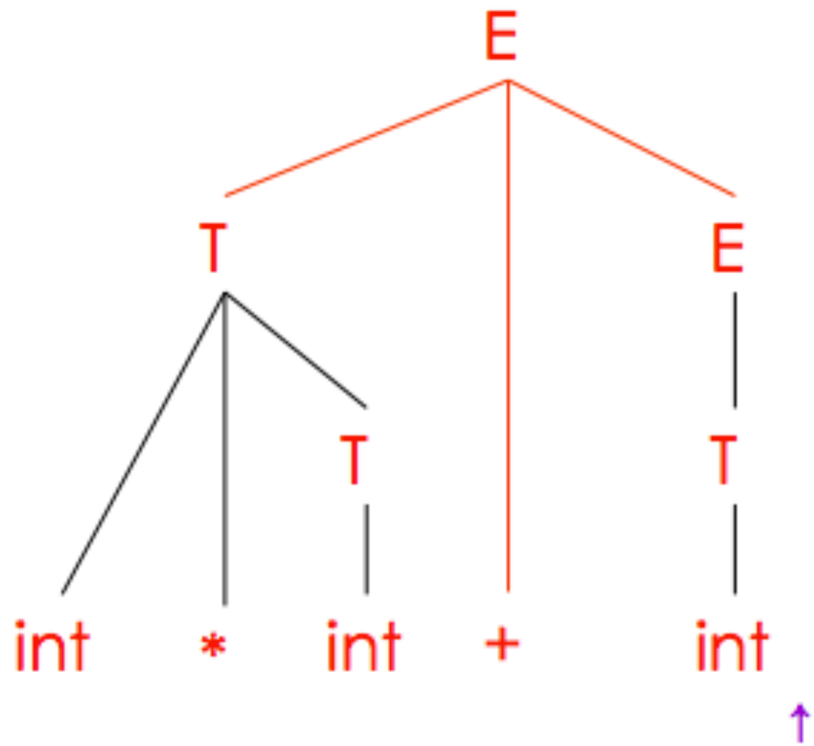
T + | int

T + int |

T + T |

T + E |

E |



The Stack

- Left string can be implemented by a stack
  - Top of the stack is the |

- Shift pushes a terminal on the stack

- Reduce pops 0 or more symbols off of the stack (production rhs) and pushes a non-terminal on the stack (production lhs)

Conflicts

- In a given state, more than one action (shift or reduce) may lead to a valid parse
- If it is legal to shift or reduce, there is a *shift-reduce* conflict
- If it is legal to reduce by two different productions, there is a *reduce-reduce* conflict
- You will see such conflicts in your project!
  - More next time . . .