Compiler Construction

Lecture 5: Foundations of LR parsing

Jeremy Yallop
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Lent 2023

Q: what about constructing parse trees? (We want *parsers*, not just *recognizers*.)

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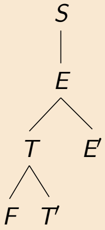

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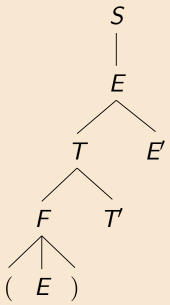

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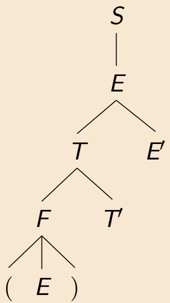

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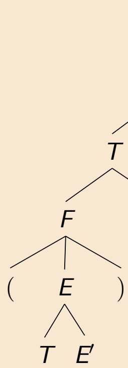

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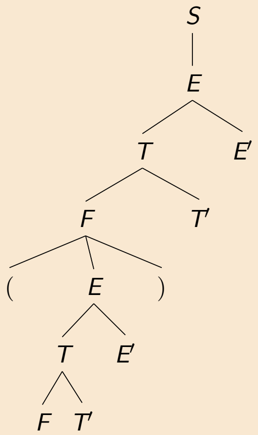

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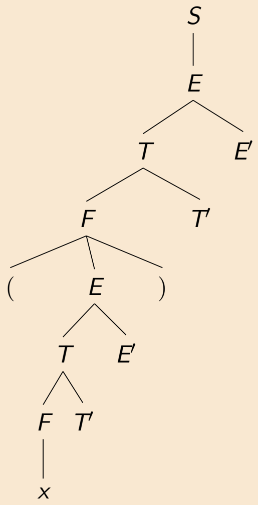

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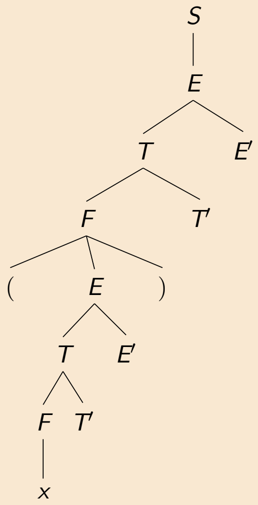

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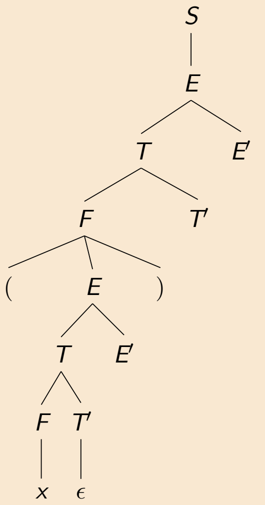

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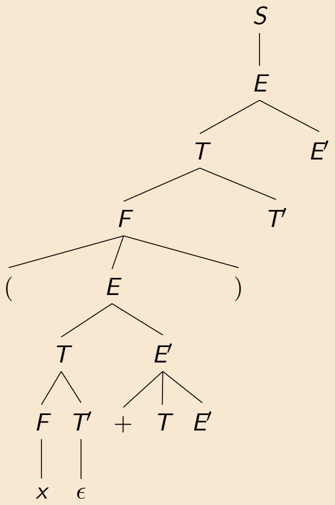

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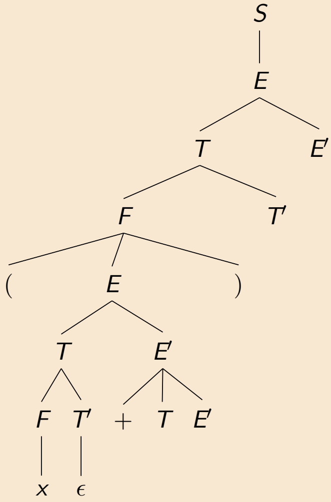

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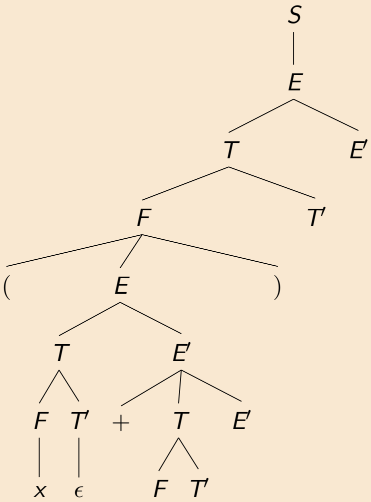

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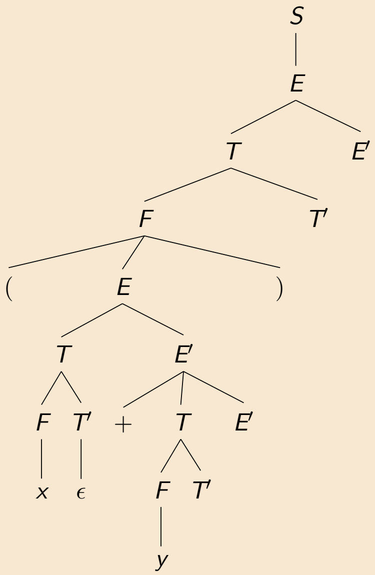

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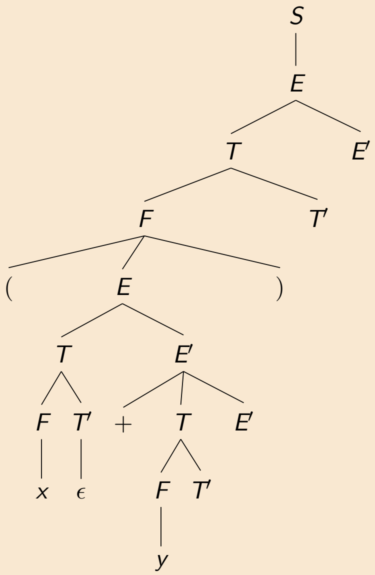

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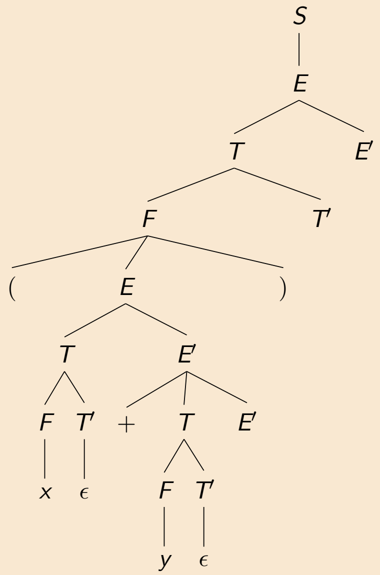

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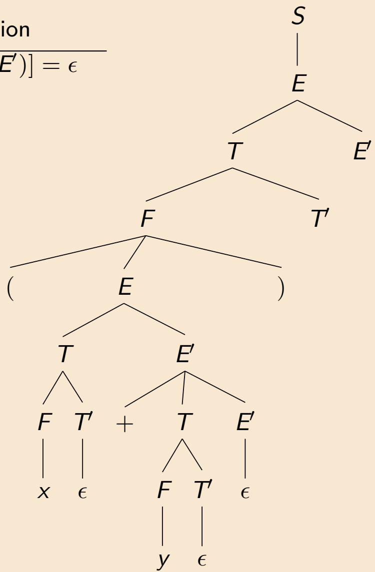

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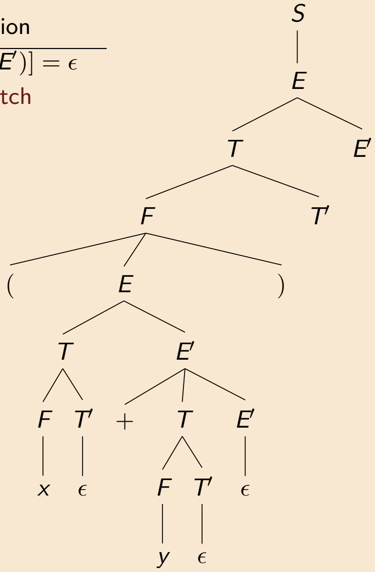

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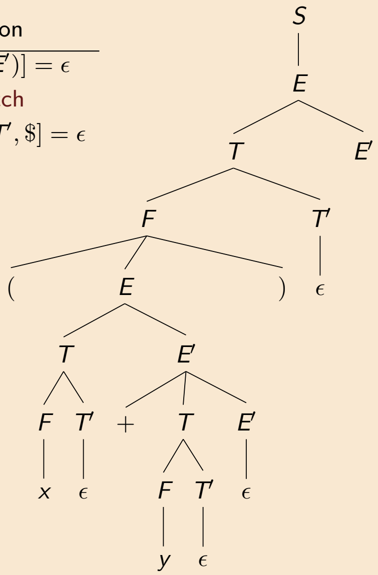

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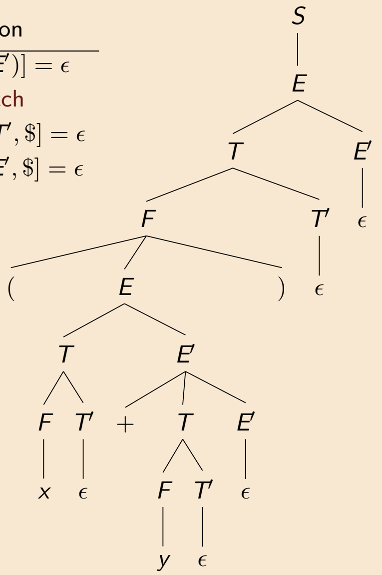

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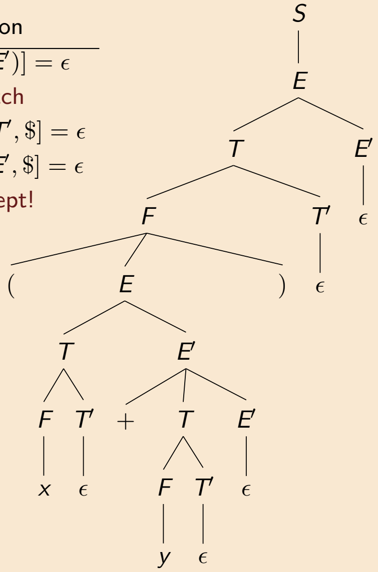
$)\$$	$E')T'E'\$$	$M[E')] = \epsilon$
$)\$$	$)T'E'\$$	match
$\$$	$T'E'\$$	$M[T', \$] = \epsilon$
$\$$	$E'\$$	$M[E', \$] = \epsilon$
$\$$	$\$$	accept!



Derivations

Recap: example grammars

G_1

$E \to E + E \mid E * E \mid (E) \mid \text{id}$

eliminate ambiguity → G_2

add S → G'_1

G_2

$E \to E + T \mid T$

$T \to T * F \mid F$

$F \to (E) \mid \text{id}$

eliminate left recursion → G_3

add S → G'_2

G_3

$E \to T\ E'$

$E' \to +\ T\ E' \mid \epsilon$

$T \to F\ T'$

$T' \to *\ F\ T' \mid \epsilon$

$F \to (\ E\ ) \mid \text{id}$

add S, \$ → G'_3

G'_1

$S \to E$

$E \to E + E \mid E * E \mid (E) \mid \text{id}$

eliminate ambiguity → G'_2

G'_2

$S \to E$

$E \to E + T \mid T$

$T \to T * F \mid F$

$F \to (E) \mid \text{id}$

eliminate left recursion → G'_3

Today's running example (G'_2)

G'_3

$S \to E\ \$$

$E \to T\ E'$

$E' \to +\ T\ E' \mid \epsilon$

$T \to F\ T'$

$T' \to *\ F\ T' \mid \epsilon$

$F \to (\ E\ ) \mid \text{id}$

Leftmost vs rightmost derivations

Leftmost derivation step:

$$wA\alpha \;\Rightarrow_{lm}\; w\beta\alpha$$

(basis of top-down (L**L**) parsing)

Rightmost derivation step:

$$\alpha A w \;\Rightarrow_{rm}\; \alpha\beta w$$

(basis of bottom-up (L**R**) parsing)

where

$w \in T*$

$\alpha, \beta \in (N \cup T)^*$

$A \rightarrow \beta \in P$

Bottom-up parsers perform the derivation in reverse

Rightmost derivation

$$
\begin{aligned}
S &\Rightarrow_{rm} \mathbf{E} \\
&\Rightarrow_{rm} \mathbf{T} \\
&\Rightarrow_{rm} \mathbf{F} \\
&\Rightarrow_{rm} (\mathbf{E}) \\
&\Rightarrow_{rm} (E + \mathbf{T}) \\
&\Rightarrow_{rm} (E + \mathbf{F}) \\
&\Rightarrow_{rm} (\mathbf{E} + y) \\
&\Rightarrow_{rm} (\mathbf{T} + y) \\
&\Rightarrow_{rm} (\mathbf{F} + y) \\
&\Rightarrow_{rm} (x + y)
\end{aligned}
$$

flip!

Reversed rightmost derivation

$$
\begin{aligned}
(x + y) &\Leftarrow \\
(\mathbf{F} + y) &\Leftarrow \\
(\mathbf{T} + y) &\Leftarrow \\
(\mathbf{E} + y) &\Leftarrow \\
(E + \mathbf{F}) &\Leftarrow \\
(E + \mathbf{T}) &\Leftarrow \\
(\mathbf{E}) &\Leftarrow \\
\mathbf{F} &\Leftarrow \\
\mathbf{T} &\Leftarrow \\
\mathbf{E} &\Leftarrow S
\end{aligned}
$$

parsing direction

Backwards derivation $\rightsquigarrow$ stack machine execution

$$
\begin{aligned}
(x+y) &\Leftarrow \\
(F+y) &\Leftarrow \\
(T+y) &\Leftarrow \\
(E+y) &\Leftarrow \\
(E+F) &\Leftarrow \\
(E+T) &\Leftarrow \\
(E) &\Leftarrow \\
F &\Leftarrow \\
T &\Leftarrow \\
E &\Leftarrow \quad S
\end{aligned}
$$

View reversed derivation as a stack machine →

stack	input
$\$$	$(x+y)\$$
$\$(F$	$+y)\$$
$\$(T$	$+y)\$$
$\$(E$	$+y)\$$
$\$(E+F$	$)\$$
$\$(E+T$	$)\$$
$\$(E)$	$\$$
$\$F$	$\$$
$\$T$	$\$$
$\$E$	$\$$
$\$S$	$\$$

Formalisation

LR parser configurations

An **LR parser configuration** has the form

$$\$\alpha, w\$$$

stack α

remaining input w

The configuration is **valid** when there exists a rightmost derivation of the form

$$S \Rightarrow^*_{rm} \alpha\, w$$

(NB: stacks now grow rightwards.)

LR parser reductions

Suppose

$$\alpha A x \Rightarrow_{rm} \alpha \beta B z x$$

One possible step between configurations replaces $\beta B z$ with A on top of the stack:

$$\$\alpha\beta B z, x\$ \xrightarrow[A \to \beta B z]{\text{reduce}} \$\alpha A, x\$$$

This action is called a **reduction** using production $A \to \beta B z$.

Reductions are not sufficient

Suppose we have the derivation:

$$\begin{aligned} & \alpha A x \\ \Rightarrow_{rm} \quad & \alpha\beta B z x \quad (\text{using } B \to \gamma) \\ \Rightarrow_{rm} \quad & \alpha\beta\gamma z x \quad (\text{using } A \to \beta B x) \end{aligned}$$

The reverse simulation gets stuck:

$$\begin{aligned} & \$\alpha\beta\gamma, zx\$ \\ \xrightarrow[B\to\gamma]{\text{reduce}} \quad & \$\alpha\beta B, zx\$ \\ \xrightarrow[???]{} \quad & ??? \end{aligned}$$

We have βB on top of the stack, but we want $\beta B z$ on top of the stack.

We also need *shift*

A **shift** action shifts a terminal onto the stack.

$$\begin{array}{ll} & \alpha A x \\ \Rightarrow_{rm} & \alpha\beta B z x \quad (\text{using } B \to \gamma) \\ \Rightarrow_{rm} & \alpha\beta\gamma z x \quad (\text{using } A \to \beta B x) \end{array}$$

$$\begin{array}{ll} & \$\alpha\beta\gamma, zx\$ \\ \xrightarrow[B\to\gamma]{\text{reduce}} & \$\alpha\beta B, zx\$ \\ \xrightarrow[z]{\text{shift}} & \$\alpha\beta B z, x\$ \\ \xrightarrow[A\to\beta B z]{\text{reduce}} & \$\alpha A, x\$ \end{array}$$

Q: *How do we know when to stop shifting?*
(e.g. here we don't want to shift x)

Another replay

Derivation

$$\begin{array}{ll} & \alpha BxAz \\ \Rightarrow_{rm} & \alpha Bxyz \quad (\text{using } A \to y) \\ \Rightarrow_{rm} & \alpha\gamma xyz \quad (\text{using } B \to \gamma) \end{array}$$

Our parser's possible actions:

$$\begin{array}{ll} & \$\alpha\gamma, xyz\$ \\ \xrightarrow[B\to\gamma]{\text{reduce}} & \$\alpha B, xyz\$ \\ \xrightarrow{\text{shift}} & \$\alpha Bx, yz\$ \\ \xrightarrow{\text{shift}} & \$\alpha Bxy, z\$ \\ \xrightarrow[A\to y]{\text{reduce}} & \$\alpha BxA, z\$ \end{array}$$

Again: how do we know when to reduce and when to stop shifting?

Shift & reduce

Shift and reduce are sufficient

It appears that if we have a derivation

$$S \Rightarrow^*_{rm} w$$

we can always “replay” it in reverse using shift/reduce actions:

$$\$, w\$ \rightarrow^* \$S, \$$$

i.e. **shift and reduce are sufficient**.

However, we have used the desired derivation to guide the “replay”.
When parsing there is no derivation available in advance.
So our parser is non-deterministic: it must *guess* what the future holds.

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \rightarrow E\,\$$
$E \rightarrow E + T \mid T$
$T \rightarrow T * F \mid F$
$F \rightarrow (E) \mid \text{id}$

top of stack X → next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
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$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \mathrm{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y
$\$(E + y$	$)\$$	reduce $F \to id$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x+y)\$$	shift (
$\$($	$x+y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y
$\$(E+y$	$)\$$	reduce $F \to id$

stack	input	action$[X, a]$
$\$(E+F$	$)\$$	reduce $T \to F$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y
$\$(E + y$	$)\$$	reduce $F \to id$

stack	input	action$[X, a]$
$\$(E + F$	$)\$$	reduce $T \to F$
$\$(E + T$	$)\$$	reduce $E \to E + T$

Replay parsing of $(x + y)$ using shift/reduce actions

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y
$\$(E + y$	$)\$$	reduce $F \to id$

stack	input	action$[X, a]$
$\$(E + F$	$)\$$	reduce $T \to F$
$\$(E + T$	$)\$$	reduce $E \to E + T$
$\$(E$	$)\$$	shift)

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y
$\$(E + y$	$)\$$	reduce $F \to id$

stack	input	action$[X, a]$
$\$(E + F$	$)\$$	reduce $T \to F$
$\$(E + T$	$)\$$	reduce $E \to E + T$
$\$(E$	$)\$$	shift)
$\$(E)$	$\$$	reduce $F \to (E)$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y
$\$(E + y$	$)\$$	reduce $F \to id$

stack	input	action$[X, a]$
$\$(E + F$	$)\$$	reduce $T \to F$
$\$(E + T$	$)\$$	reduce $E \to E + T$
$\$(E$	$)\$$	shift)
$\$(E)$	$\$$	reduce $F \to (E)$
$\$F$	$\$$	reduce $T \to F$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \mathrm{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y
$\$(E + y$	$)\$$	reduce $F \to id$

stack	input	action$[X, a]$
$\$(E + F$	$)\$$	reduce $T \to F$
$\$(E + T$	$)\$$	reduce $E \to E + T$
$\$(E$	$)\$$	shift)
$\$(E)$	$\$$	reduce $F \to (E)$
$\$F$	$\$$	reduce $T \to F$
$\$T$	$\$$	reduce $F \to E$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \to E\,\$$
$E \to E + T \mid T$
$T \to T * F \mid F$
$F \to (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x+y)\$$	shift (
$\$($	$x+y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \to id$
$\$(F$	$+y)\$$	reduce $T \to F$
$\$(T$	$+y)\$$	reduce $E \to T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y
$\$(E+y$	$)\$$	reduce $F \to id$

stack	input	action$[X, a]$
$\$(E+F$	$)\$$	reduce $T \to F$
$\$(E+T$	$)\$$	reduce $E \to E+T$
$\$(E$	$)\$$	shift)
$\$(E)$	$\$$	reduce $F \to (E)$
$\$F$	$\$$	reduce $T \to F$
$\$T$	$\$$	reduce $F \to E$
$\$E$	$\$$	reduce $S \to E$

Replay parsing of $(x + y)$ using shift/reduce actions

$S \rightarrow E\,\$$
$E \rightarrow E + T \mid T$
$T \rightarrow T * F \mid F$
$F \rightarrow (E) \mid \text{id}$

top of stack X — next input token a

stack	input	action$[X, a]$
$\$$	$(x + y)\$$	shift (
$\$($	$x + y)\$$	shift x
$\$(x$	$+y)\$$	reduce $F \rightarrow id$
$\$(F$	$+y)\$$	reduce $T \rightarrow F$
$\$(T$	$+y)\$$	reduce $E \rightarrow T$
$\$(E$	$+y)\$$	shift $+$
$\$(E+$	$y)\$$	shift y
$\$(E + y$	$)\$$	reduce $F \rightarrow id$

stack	input	action$[X, a]$
$\$(E + F$	$)\$$	reduce $T \rightarrow F$
$\$(E + T$	$)\$$	reduce $E \rightarrow E + T$
$\$(E$	$)\$$	shift)
$\$(E)$	$\$$	reduce $F \rightarrow (E)$
$\$F$	$\$$	reduce $T \rightarrow F$
$\$T$	$\$$	reduce $F \rightarrow E$
$\$E$	$\$$	reduce $S \rightarrow E$
$\$S$	$\$$	accept!

How do we decide when to shift or reduce?

Suppose $A \to \beta\gamma$ is a production. In the configuration

$$\$\alpha\beta\gamma, x\$$$

we *might* want to reduce with $A \to \beta\gamma$.

However, if we have

$$\$\alpha\beta, x\$$$

we *might* want to continue parsing,
hoping to eventually have $\beta\gamma$ on top of the stack,
so that we can then reduce to A.

Items

LR(0) items

LR(0) items record how much of a production's RHS is already parsed.

For every grammar production

$$A \to \beta\gamma \qquad (\beta, \gamma \in (N \cup T)^*)$$

there is an LR(0) item

$$A \to \beta \bullet \gamma$$

$A \to \beta\bullet\gamma$ means: we've parsed input x derivable from β
we *might* next see input derivable from γ .

LR(0) items for G_2'

$S \to \bullet E$	$E \to \bullet E + T$	$T \to \bullet T * F$	$F \to \bullet (E)$
$S \to E \bullet$	$E \to E \bullet + T$	$T \to T \bullet * F$	$F \to (\bullet E)$
	$E \to E + \bullet T$	$T \to T * \bullet F$	$F \to (E \bullet)$
	$E \to E + T \bullet$	$T \to T * F \bullet$	$F \to (E) \bullet$
	$E \to \bullet T$	$T \to \bullet F$	$F \to \bullet \text{id}$
	$E \to T \bullet$	$T \to F \bullet$	$F \to \text{id} \bullet$

Valid LR(0) items

Definition: item $A \to \beta\bullet\gamma$ is **valid for** $\phi\beta$ if there exists a derivation

$$\begin{aligned} & S \\ \Rightarrow^*_{rm} \quad & \phi A w \\ \Rightarrow_{rm} \quad & \phi\beta\gamma w \end{aligned}$$

If

$$A \to \beta\bullet\gamma \text{ is valid for } \phi\beta$$

then

$$\text{parser can use } A \to \beta\bullet\gamma \text{ as a guide in configuration } \$\phi\beta, w\$$$

Using items as parsing guides

Suppose parser is in config $\$\phi\beta, cz\$$ and $A \to \beta \bullet c\gamma$ is valid for $\phi\beta$.
Then we *might* shift c onto the stack:

$$\$\phi\beta, cz\$ \xrightarrow{\text{shift } c} \$\phi\beta c, z\$$$

Suppose parser is in config $\$\phi\beta, z\$$ and $A \to \beta \bullet$ is valid for $\phi\beta$.
Then we *might* perform a reduction

$$\$\phi\beta, z\$ \xrightarrow[A \to \beta]{\text{reduce}} \$\phi A, z\$$$

Using items as parsing guides (continued)

Suppose parser is in valid config $\$\phi\beta, w\$$ (so $S \Rightarrow^*_{rm} \phi\beta w$).

Suppose $A \to \beta\bullet\gamma$ is valid for $\phi\beta$.

Then γ *might* capture the future of our parse (the past of the derivation).

That is, it *might* be that

$$\begin{array}{ll} & S \\ \Rightarrow^*_{rm} & \phi A x \\ \Rightarrow_{rm} & \phi\beta\gamma x \\ \Rightarrow^*_{rm} & \phi\beta y x \quad = \quad \phi\beta w \end{array}$$

If so, our parser *might* proceed like so:

$$\begin{array}{ll} & \$\phi\beta, yx\$ \quad = \quad \$\phi\beta, w\$ \\ \to^* & \$\phi\beta\gamma, x\$ \\ \xrightarrow{\text{reduce}} & \$\phi A, x\$ \end{array}$$

i.e. our parser could guess that γ will derive a prefix of the remaining input w.

Key idea

The key idea in LR parsing

Idea: Augment shift/reduce parser so that in every configuration $\$\alpha, w\$$ it can derive the set of items valid for α.

At each step parser can (non-deterministically) select an item to use as a guide.

NFA with LR(0) items as states

$$A \to \beta \bullet c\gamma \xrightarrow{\;c\;} A \to \beta c \bullet \gamma$$

$$A \to \beta \bullet B\gamma \xrightarrow{\;B\;} A \to \beta B \bullet \gamma$$

$$A \to \beta \bullet B\gamma \xrightarrow{\;\epsilon\;} B \to \bullet \alpha_i$$

Initial state is item constructed from unique starting production, e.g.:

$$q0 \quad = \quad S \to \bullet E$$

Let δ_G be the transition function of this NFA (and every state be accepting).

Theorem:

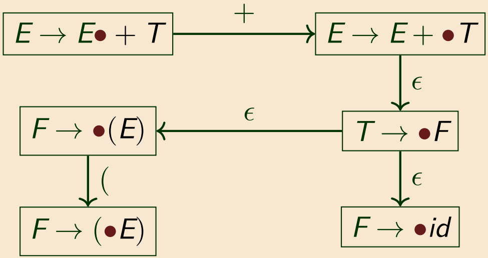
$$A \to \beta{\bullet}\gamma \in \delta_G(q_0, \phi\beta)$$

if and only if

$A \to \beta{\bullet}\gamma$ is valid for $\phi\beta$.

(NB: The set of words $\phi\beta$ is a *regular* language!)

A few NFA transitions for grammar G_2



A non-deterministic LR parsing algorithm

$c :=$ NextToken()

while true:

  $\alpha :=$ the stack

  if $A \to \beta \bullet c\gamma \in \delta_G(q_0, \alpha)$
    then SHIFT c; $c :=$ NextToken()

  if $A \to \beta \bullet \in \delta_G(q_0, \alpha)$
    then REDUCE via $A \to \beta$

  if $S \to \beta \bullet \in \delta_G(q_0, \alpha)$
    then ACCEPT (if no more input)

  if none of the above
    then ERROR

non-deterministic since multiple "if" conditions can be true and multiple items can match any condition

Next time: SLR(1) & LR(1)