# Bottom Up Parsing

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# LR(0) Parsing

- Build the derivation tree from the bottom
- First build the children, then connect to the parent
- Can handle left recursion
  - Which is common in real-world grammars

# LR(0) Item

An **LR(0) item** is of the form:

- $N \rightarrow \alpha . \beta$

The **dot** gives us the current location (a local view).

# LR(0) Item

An LR(0) item with the dot at the end is called **reduce** item:

- $N \rightarrow \alpha\beta.$

Otherwise, it's a **shift** item:

- $N \rightarrow .\, \alpha\beta$
- $N \rightarrow \alpha.\, \beta$

# LR(0) Item Closure Set

The **LR(0) closure set** of an LR(0) item $i$ is a set $S$ such that:

- $i \in S$
- If $A \to \alpha . N\beta \in S$ then for each rule $N \to \gamma$:
  - $N \to . \gamma \in S$

# LR(0) Item Closure Set

For example, given the following CFG:

- $S \rightarrow E\$$
- $E \rightarrow ID = X$
- $E \rightarrow \{ID\}$
- $X \rightarrow INT$

the closure set of the $S \rightarrow .E\$$ contains:

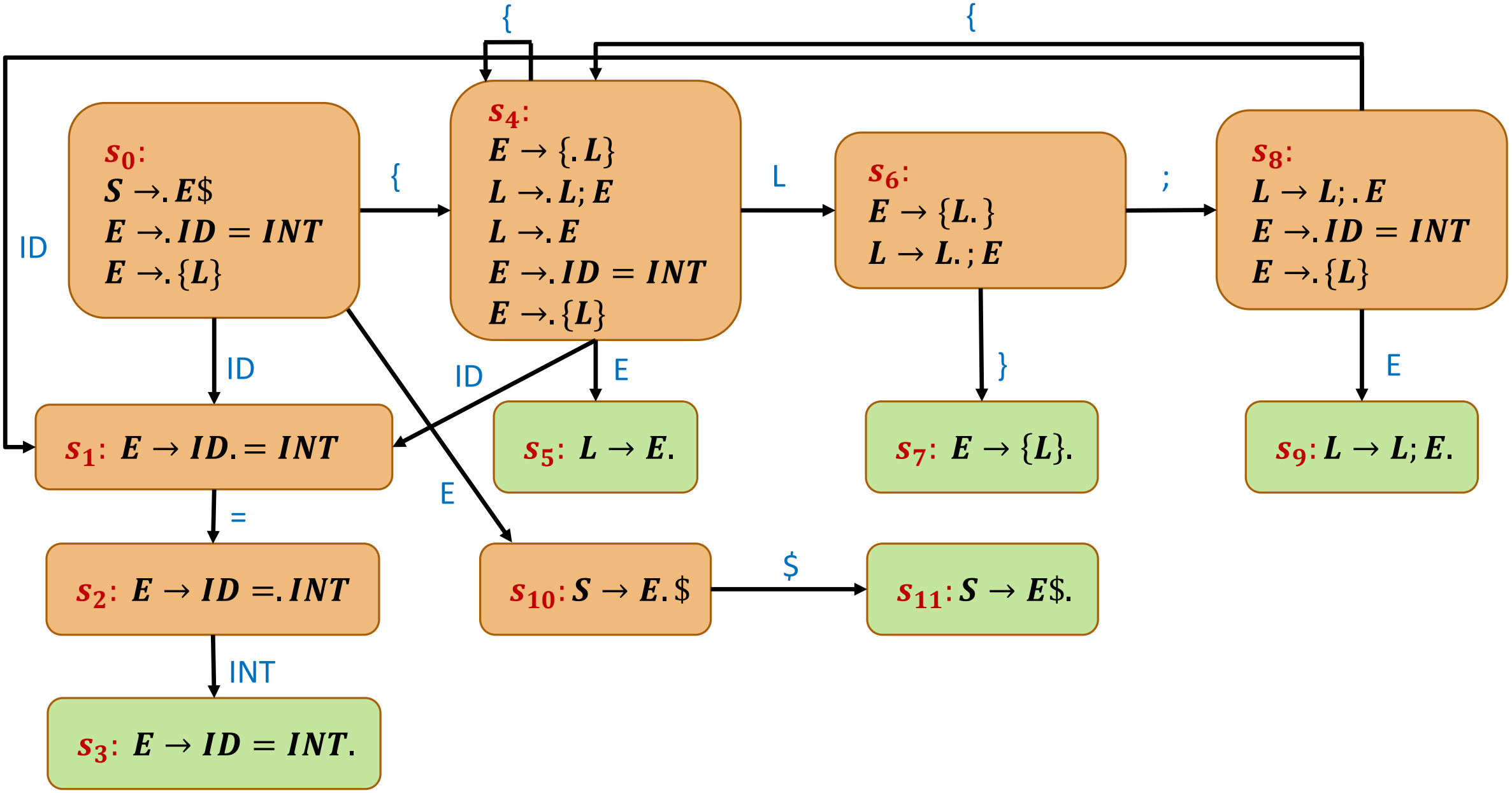
- $S \rightarrow .E\$$
- $E \rightarrow .ID = X$
- $E \rightarrow .\{ID\}$

# LR(0) Parsing

Consider the following CFG:

- $S \rightarrow E\$$
- $E \rightarrow ID = INT$
- $E \rightarrow \{L\}$
- $L \rightarrow E$
- $L \rightarrow L; E$

What will be the **transition system** of the LR(0) parser for this CFG?



{
{
$s_0$:
$S \to .E\$$
$E \to .ID = INT$
$E \to .\{L\}$
{
$s_4$:
$E \to \{.L\}$
$L \to .L; E$
$L \to .E$
$E \to .ID = INT$
$E \to .\{L\}$
L
$s_6$:
$E \to \{L.\}$
$L \to L.; E$
;
$s_8$:
$L \to L; .E$
$E \to .ID = INT$
$E \to .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \to ID. = INT$
$s_5$: $L \to E.$
$s_7$: $E \to \{L\}.$
$s_9$: $L \to L; E.$
E
=
$s_2$: $E \to ID =. INT$
$s_{10}$: $S \to E.\$$
$
$s_{11}$: $S \to E\$.$
INT
$s_3$: $E \to ID = INT.$

# LR(0) Parser

We start with the initial LR(0) item (that comes from the initial rule):

- $S \rightarrow .E\$$

The initial state is the $\epsilon$-**closure** of that item, which contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

# LR(0) Parser

We start with the initial LR(0) item (that comes from the initial rule):

- $S \rightarrow .E\$$

The initial state is the $\epsilon$-**closure** of that item, which contains:

- $S \rightarrow .E\$$
- $E \rightarrow .ID = INT$
- $E \rightarrow .\{L\}$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

$s_0$:

$S \rightarrow .E\$$

$E \rightarrow .ID = INT$

$E \rightarrow .\{L\}$

# LR(0) Parser

From $s_0$, if we recognized $ID$, then the next state will contain:

- $E \rightarrow ID.= INT$

So the next state (the $\epsilon$-closure) contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

# LR(0) Parser

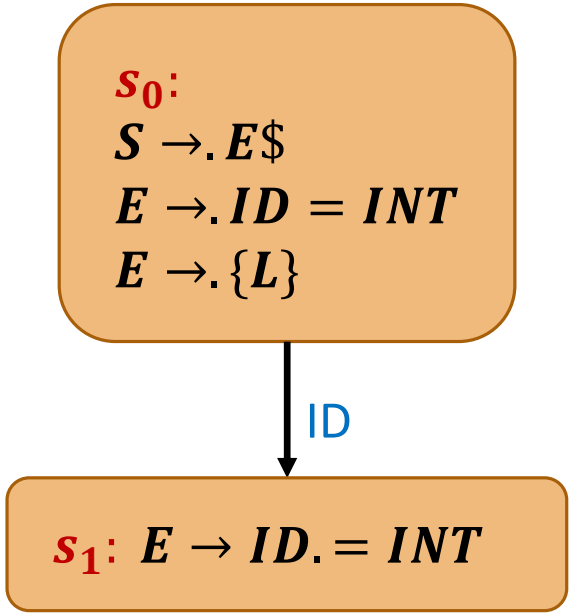
From $s_0$, if we recognized $ID$, then the next state will contain:

- $E \rightarrow ID.= INT$

So the next state (the $\epsilon$-closure) contains:

- $E \rightarrow ID.= INT$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
$s_1$: $E \rightarrow ID. = INT$

# LR(0) Parser

From $s_1$, if we recognized $=$, then the next state will contain:

- $E \rightarrow ID =.INT$

So the next state (the $\epsilon$-closure) contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

# LR(0) Parser

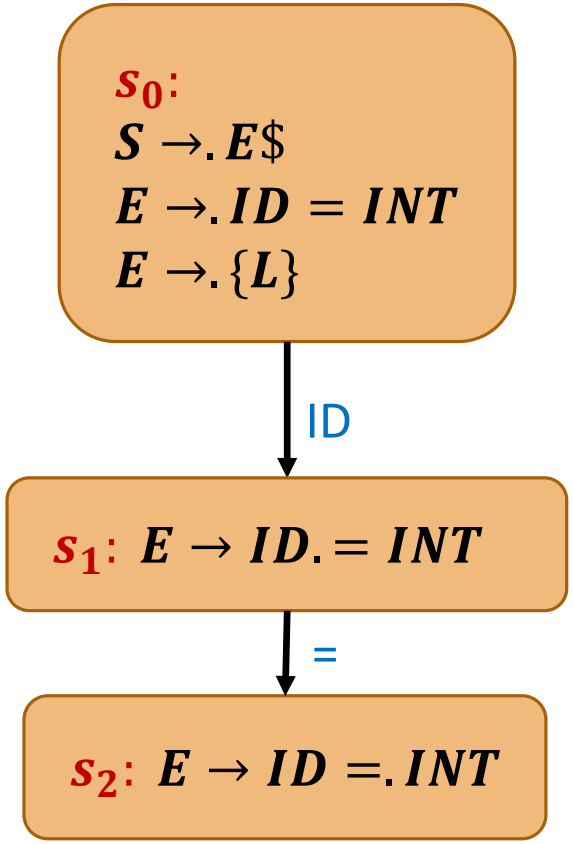
From $s_1$, if we recognized $=$, then the next state will contain:

- $E \rightarrow ID =.INT$

So the next state (the $\epsilon$-closure) contains:

- $E \rightarrow ID =.INT$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
$s_1$: $E \rightarrow ID. = INT$
=
$s_2$: $E \rightarrow ID =. INT$

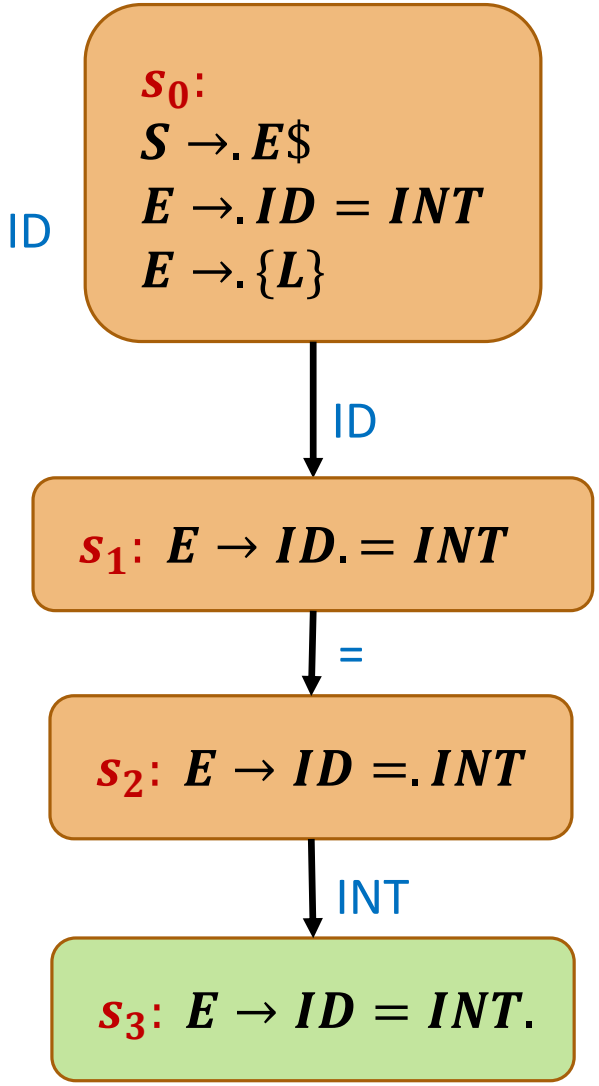
# LR(0) Parser

From $s_2$, if we recognized $INT$, then the next state will contain:

- $E \rightarrow ID = INT.$

Which is a reduce state.

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
$s_1$: $E \rightarrow ID. = INT$
=
$s_2$: $E \rightarrow ID =. INT$
INT
$s_3$: $E \rightarrow ID = INT.$

# LR(0) Parser

From $s_0$, if we recognized {, then the next state will contain:

- $E \rightarrow \{.L\}$

So the next state (the $\epsilon$-closure) contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

# LR(0) Parser

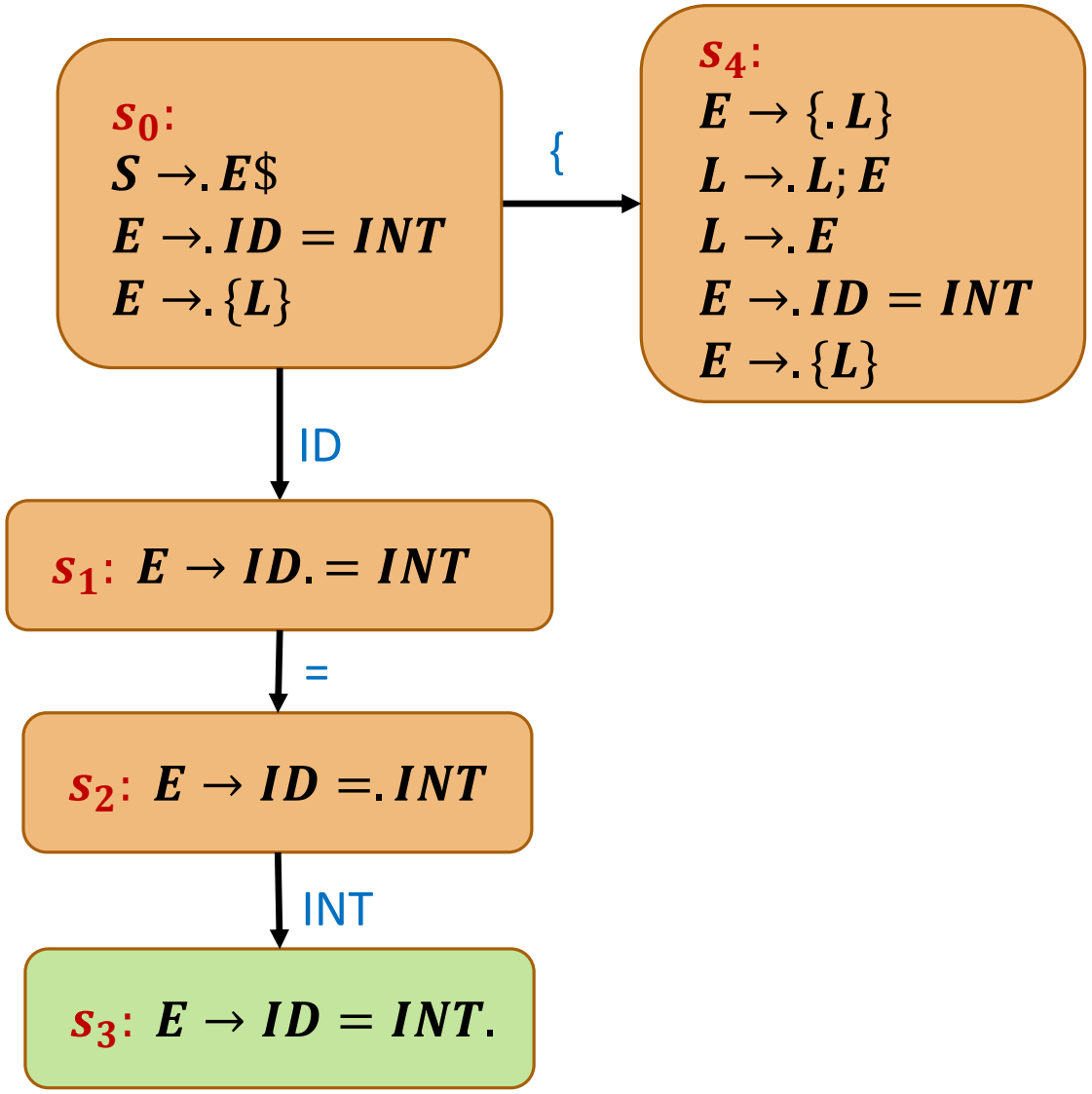
From $s_0$, if we recognized {, then the next state will contain:

- $E \rightarrow \{.L\}$

So the next state (the $\epsilon$-closure) contains:

- $E \rightarrow \{.L\}$
- $L \rightarrow .L;E$
- $L \rightarrow .E$
- $E \rightarrow .ID = INT$
- $E \rightarrow .\{L\}$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L;E$


$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
$s_1$: $E \rightarrow ID. = INT$
=
$s_2$: $E \rightarrow ID =. INT$
INT
$s_3$: $E \rightarrow ID = INT.$

# LR(0) Parser

From $s_4$, if we recognized {, then the next state will contain:

- $E \rightarrow \{.L\}$

So the next state (the $\epsilon$-closure) contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

# LR(0) Parser

From $s_4$, if we recognized {, then the next state will contain:

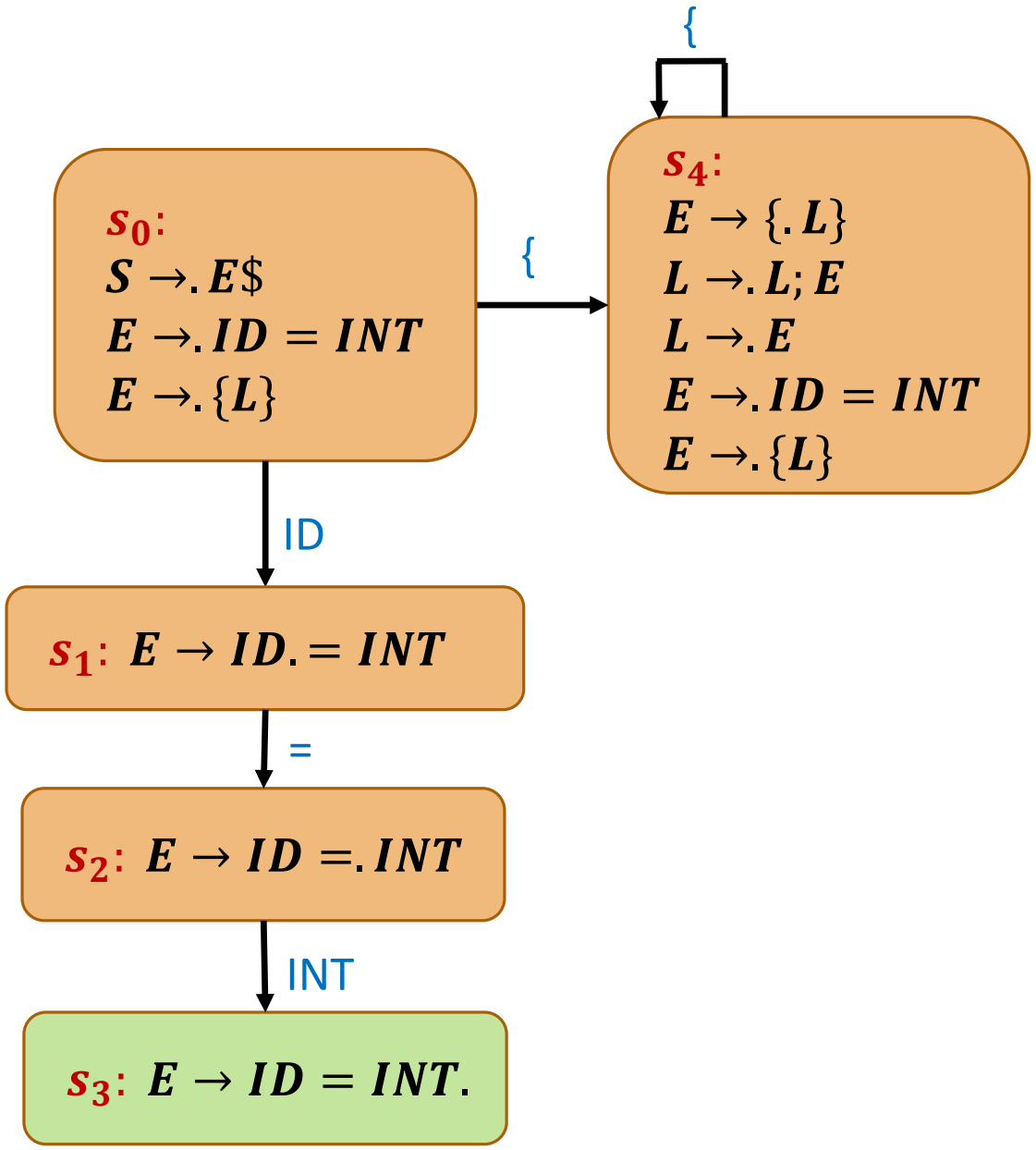
- $E \rightarrow \{.L\}$

So the next state (the $\epsilon$-closure) contains:

- $E \rightarrow \{.L\}$
- $L \rightarrow .L;E$
- $L \rightarrow .E$
- $E \rightarrow .ID = INT$
- $E \rightarrow .\{L\}$

which was already computed: $s_4$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L;E$


{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
$s_1$: $E \rightarrow ID. = INT$
=
$s_2$: $E \rightarrow ID =. INT$
INT
$s_3$: $E \rightarrow ID = INT.$

# LR(0) Parser

From $s_4$, if we recognized $ID$, then the next state will contain:

- $E \rightarrow ID.= INT$

So the next state (the $\epsilon$-closure) contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

# LR(0) Parser

From $s_4$, if we recognized $ID$, then the next state will contain:

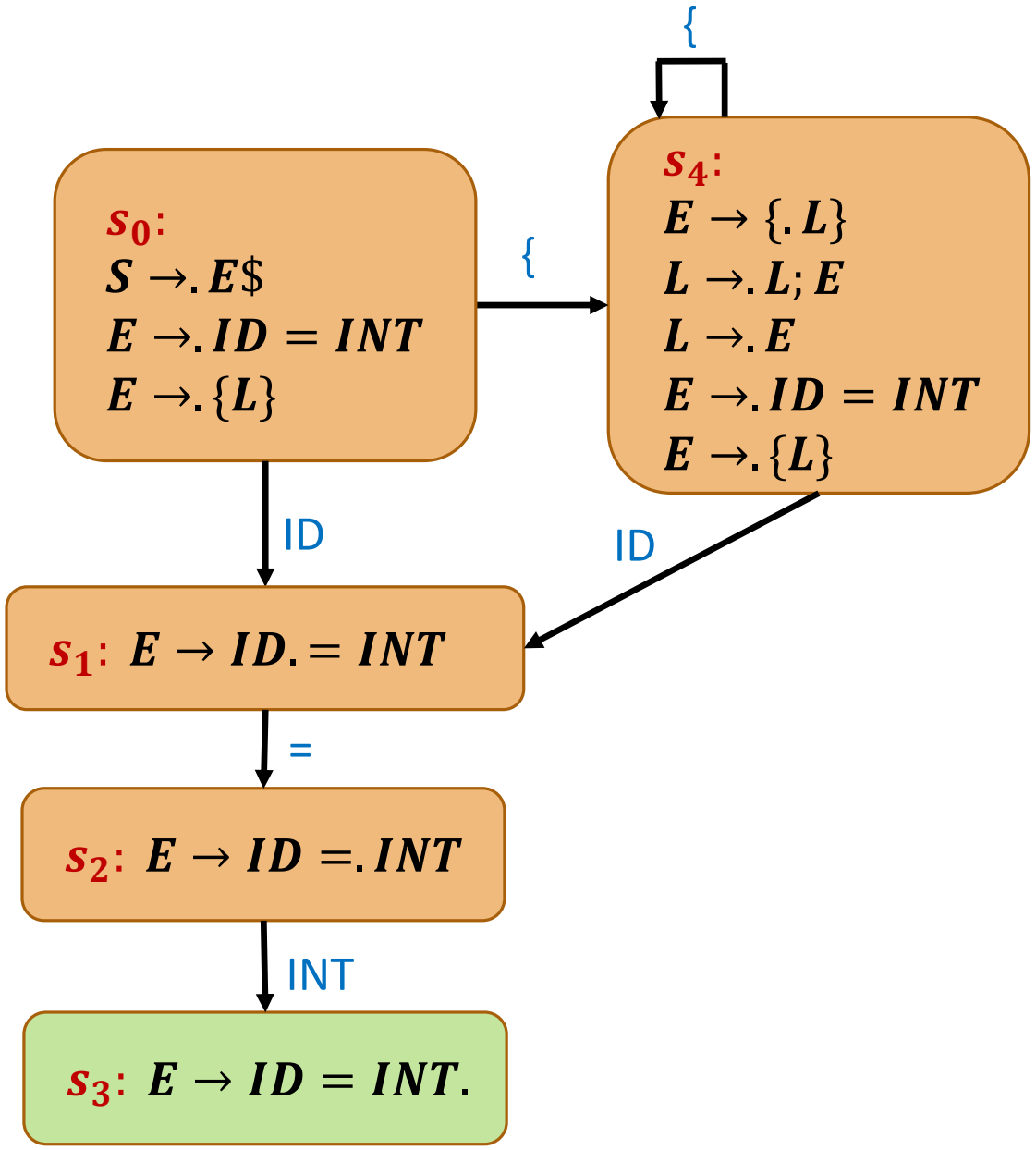
- $E \rightarrow ID. = INT$

So the next state (the $\epsilon$-closure) contains:

- $E \rightarrow ID. = INT$

which was already computed: $s_1$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
$s_1$: $E \rightarrow ID. = INT$
=
$s_2$: $E \rightarrow ID =. INT$
INT
$s_3$: $E \rightarrow ID = INT.$

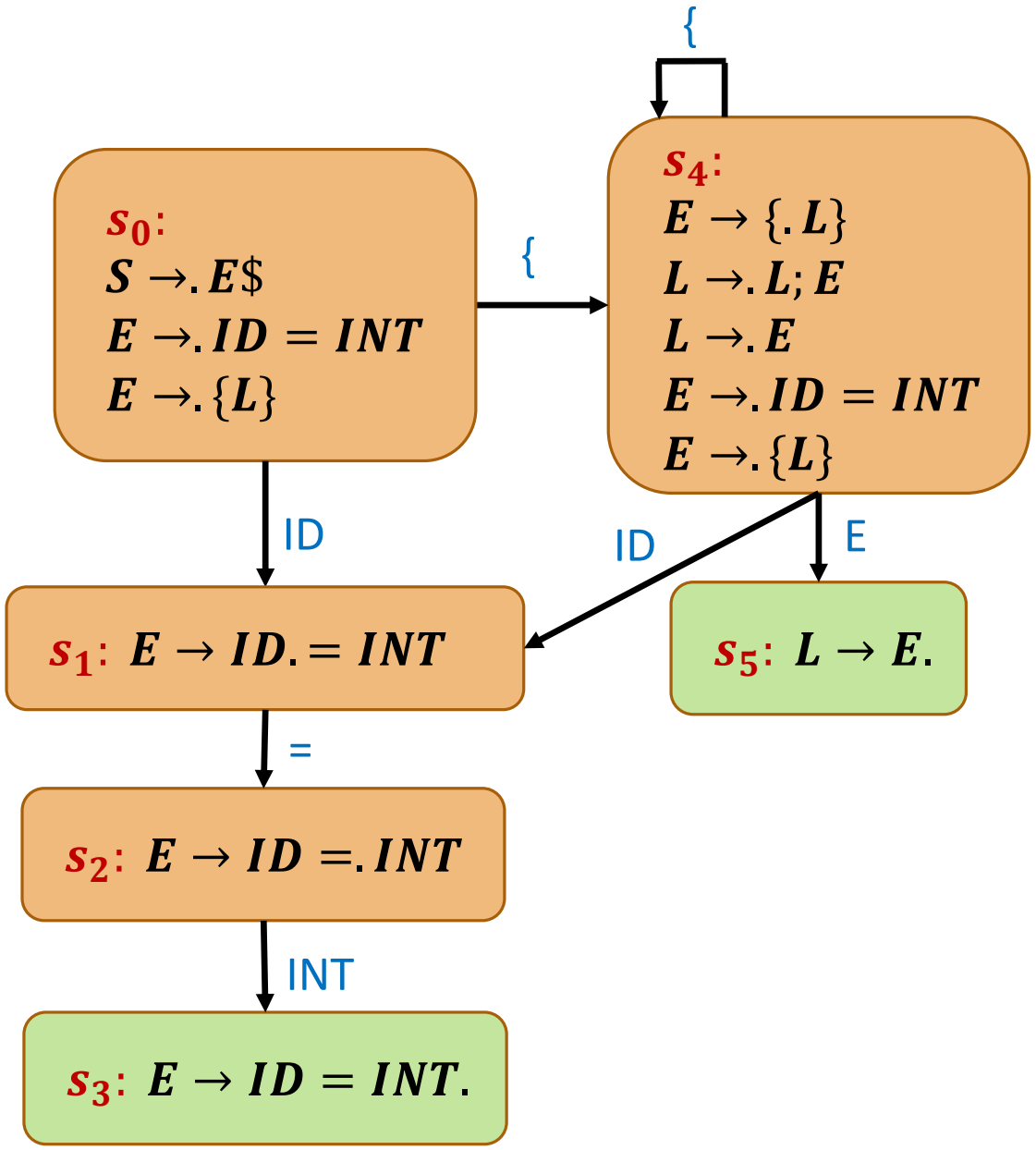
# LR(0) Parser

From $s_4$, if we recognized $E$, then the next state will contain:

- $L \rightarrow E.$

which is a reduce state.

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
=
$s_2$: $E \rightarrow ID =. INT$
INT
$s_3$: $E \rightarrow ID = INT.$

# LR(0) Parser

From $s_4$, if we recognized $L$, then the next state will contain:

- $E \rightarrow \{L.\}$
- $L \rightarrow L.;E$

So the next state (the $\epsilon$-closure) contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L;E$

# LR(0) Parser

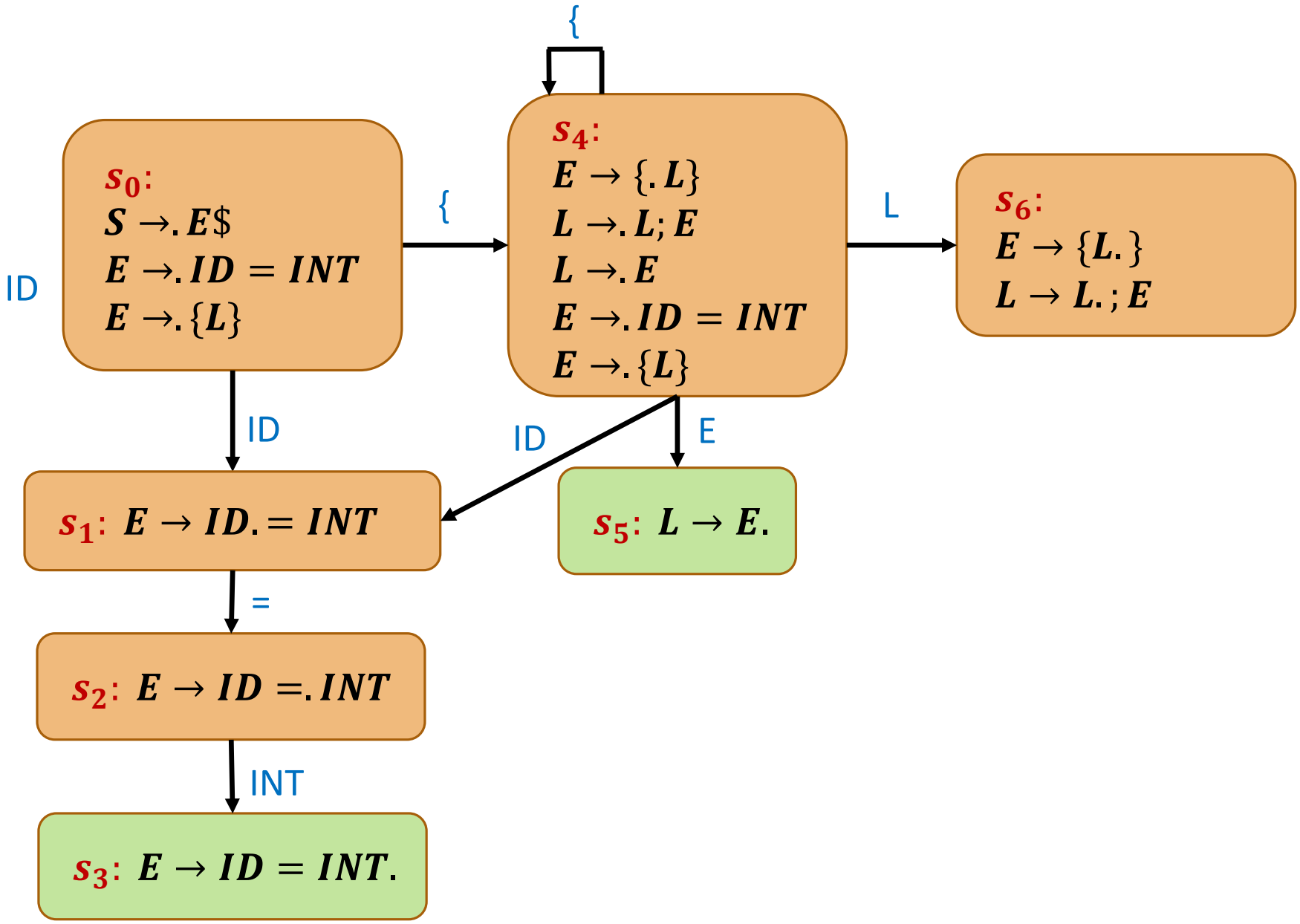
From $s_4$, if we recognized $L$, then the next state will contain:

- $E \rightarrow \{L.\}$
- $L \rightarrow L.;E$

So the next state (the $\epsilon$-closure) contains:

- $E \rightarrow \{L.\}$
- $L \rightarrow L.;E$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L;E$


{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
ID
ID
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
=
$s_2$: $E \rightarrow ID =. INT$
INT
$s_3$: $E \rightarrow ID = INT.$

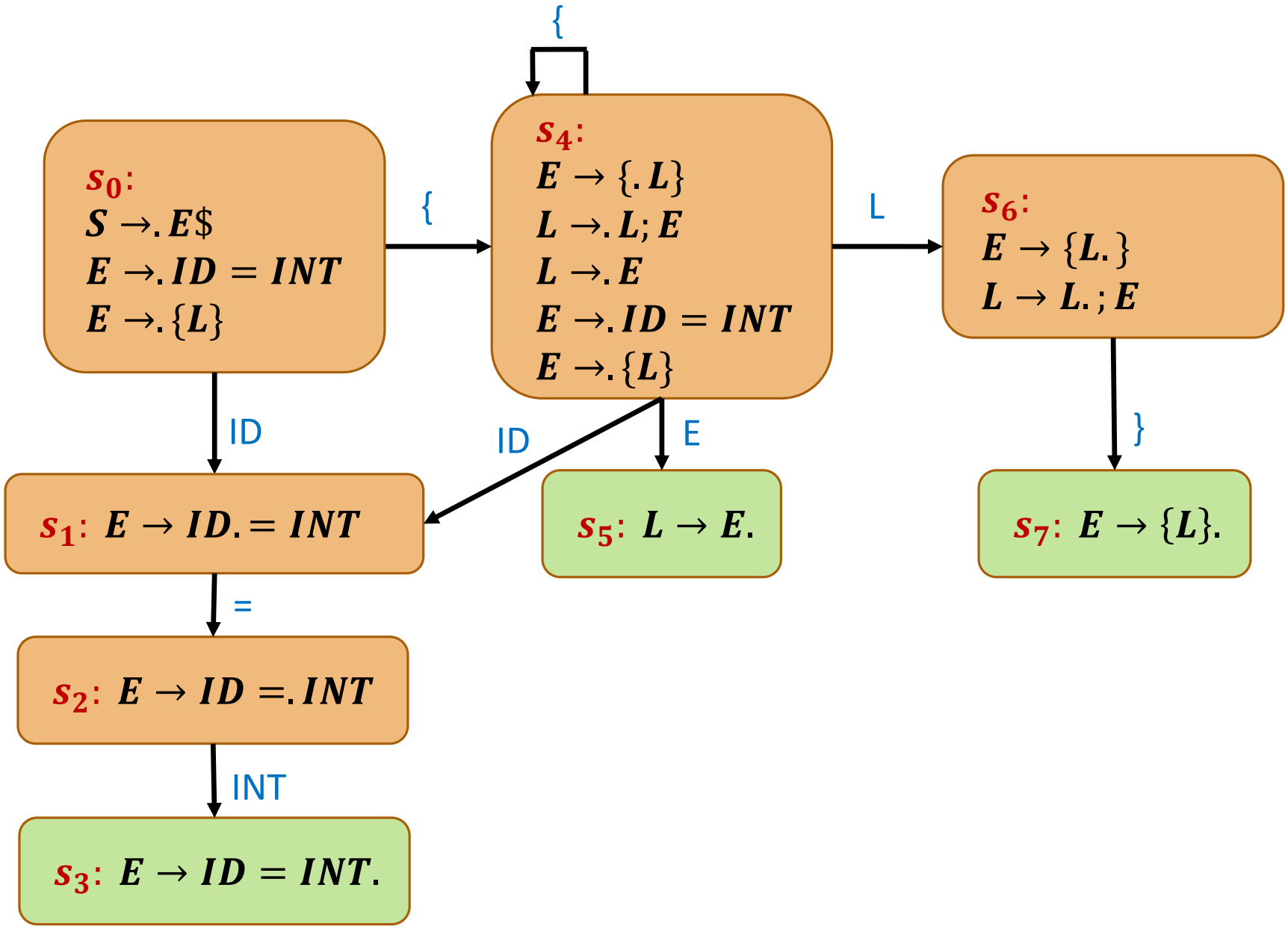
# LR(0) Parser

From $s_6$, if we recognized }, then the next state will contain:

- $E \rightarrow \{L\}.$

Which is a reduce state.

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
ID
ID
E
}
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
=
$s_2$: $E \rightarrow ID =. INT$
INT
$s_3$: $E \rightarrow ID = INT.$

# LR(0) Parser

From $s_6$, if we recognized ;, then the next state will contain:

- $L \rightarrow L; . E$

So the next state (the $\epsilon$-closure) contains:

$$S \rightarrow E\$$$
$$E \rightarrow ID = INT$$
$$E \rightarrow \{L\}$$
$$L \rightarrow E$$
$$L \rightarrow L; E$$

# LR(0) Parser

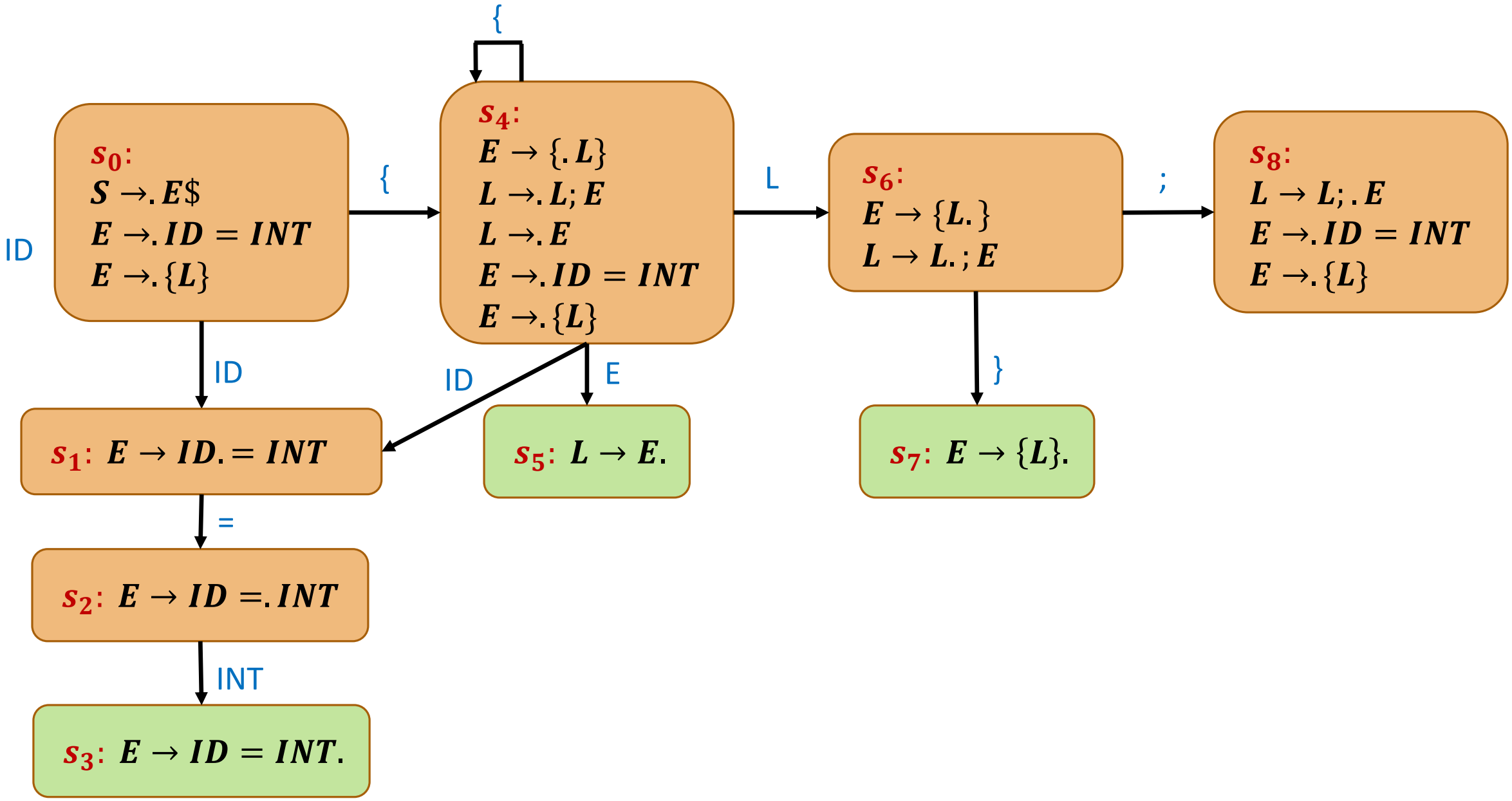
From $s_6$, if we recognized ;, then the next state will contain:

- $L \rightarrow L; . E$

So the next state (the $\epsilon$-closure) contains:

- $L \rightarrow L; . E$
- $E \rightarrow . ID = INT$
- $E \rightarrow . \{L\}$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
E
}
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
=
$s_2$: $E \rightarrow ID =. INT$
INT
$s_3$: $E \rightarrow ID = INT.$

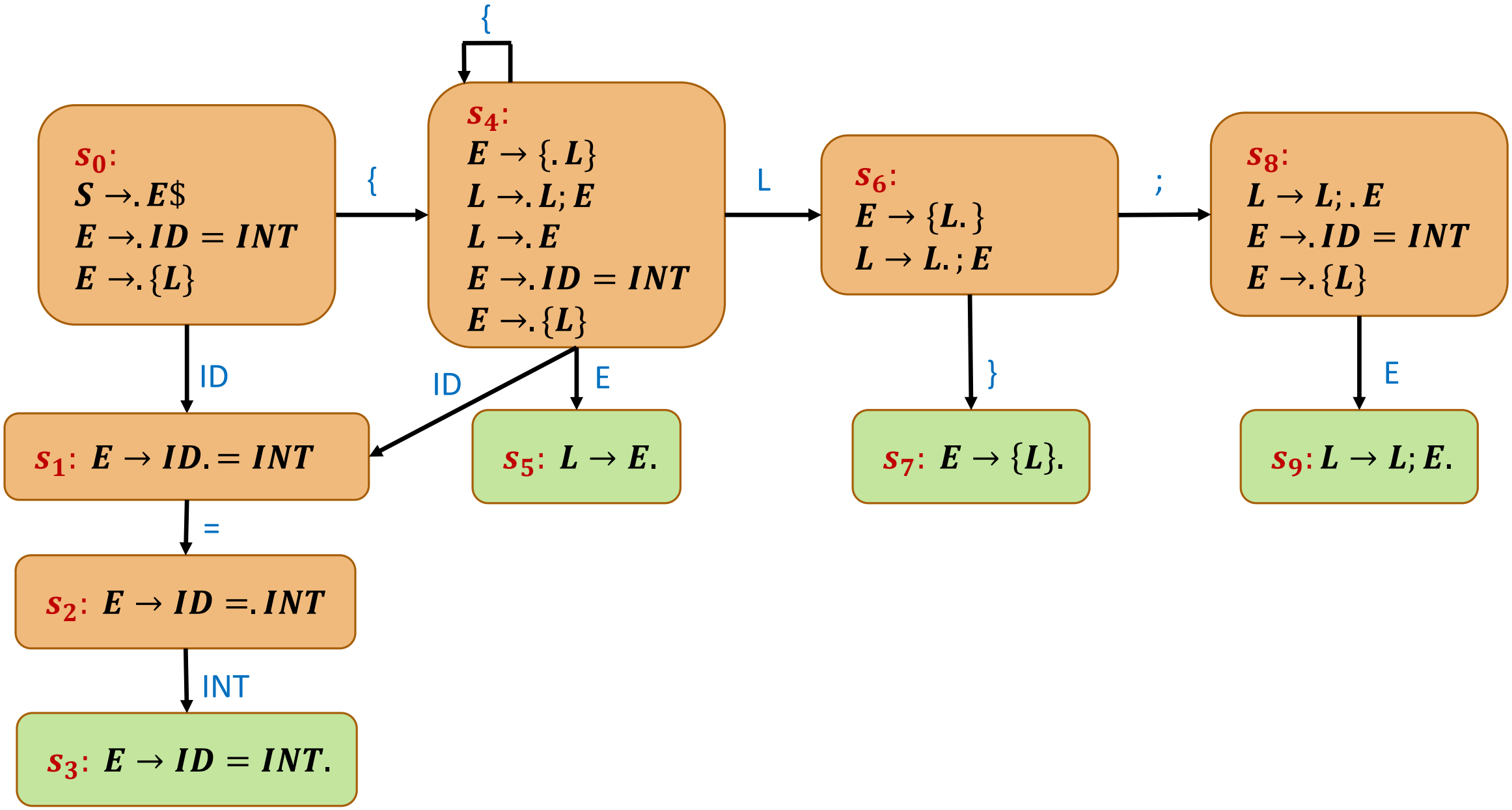
# LR(0) Parser

From $s_8$, if we recognized $E$, then the next state will contain:

- $E \rightarrow L; E.$

which is a reduce state.

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
=
$s_2$: $E \rightarrow ID = .INT$
INT
$s_3$: $E \rightarrow ID = INT.$

# LR(0) Parser

From $s_8$, if we recognized {, then the next state will contain:

- $E \rightarrow \{.L\}$

So the next state (the $\epsilon$-closure) contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

# LR(0) Parser

From $s_8$, if we recognized {, then the next state will contain:

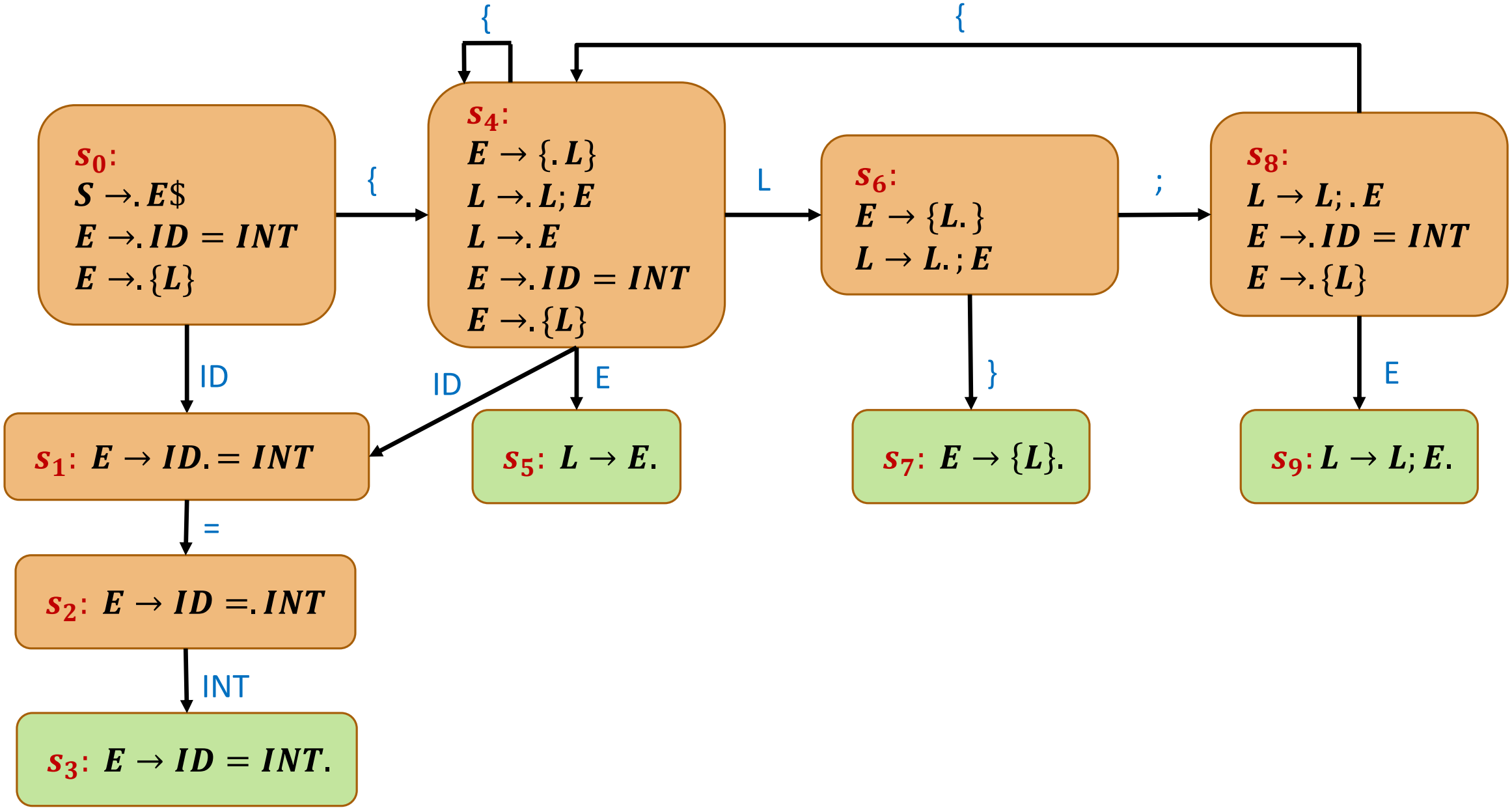
- $E \rightarrow \{.L\}$

So the next state (the $\epsilon$-closure) contains:

- $E \rightarrow \{.L\}$
- $L \rightarrow .L;E$
- $L \rightarrow .E$
- $E \rightarrow .ID = INT$
- $E \rightarrow .\{L\}$

which was already computed: $s_4$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L;E$


{
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$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
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$L \rightarrow L; .E$
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ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
=
$s_2$: $E \rightarrow ID = .INT$
INT
$s_3$: $E \rightarrow ID = INT.$

# LR(0) Parser

From $s_8$, if we recognized $ID$, then the next state will contain:

- $E \rightarrow ID.= INT$

So the next state (the $\epsilon$-closure) contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

# LR(0) Parser

From $s_8$, if we recognized $ID$, then the next state will contain:

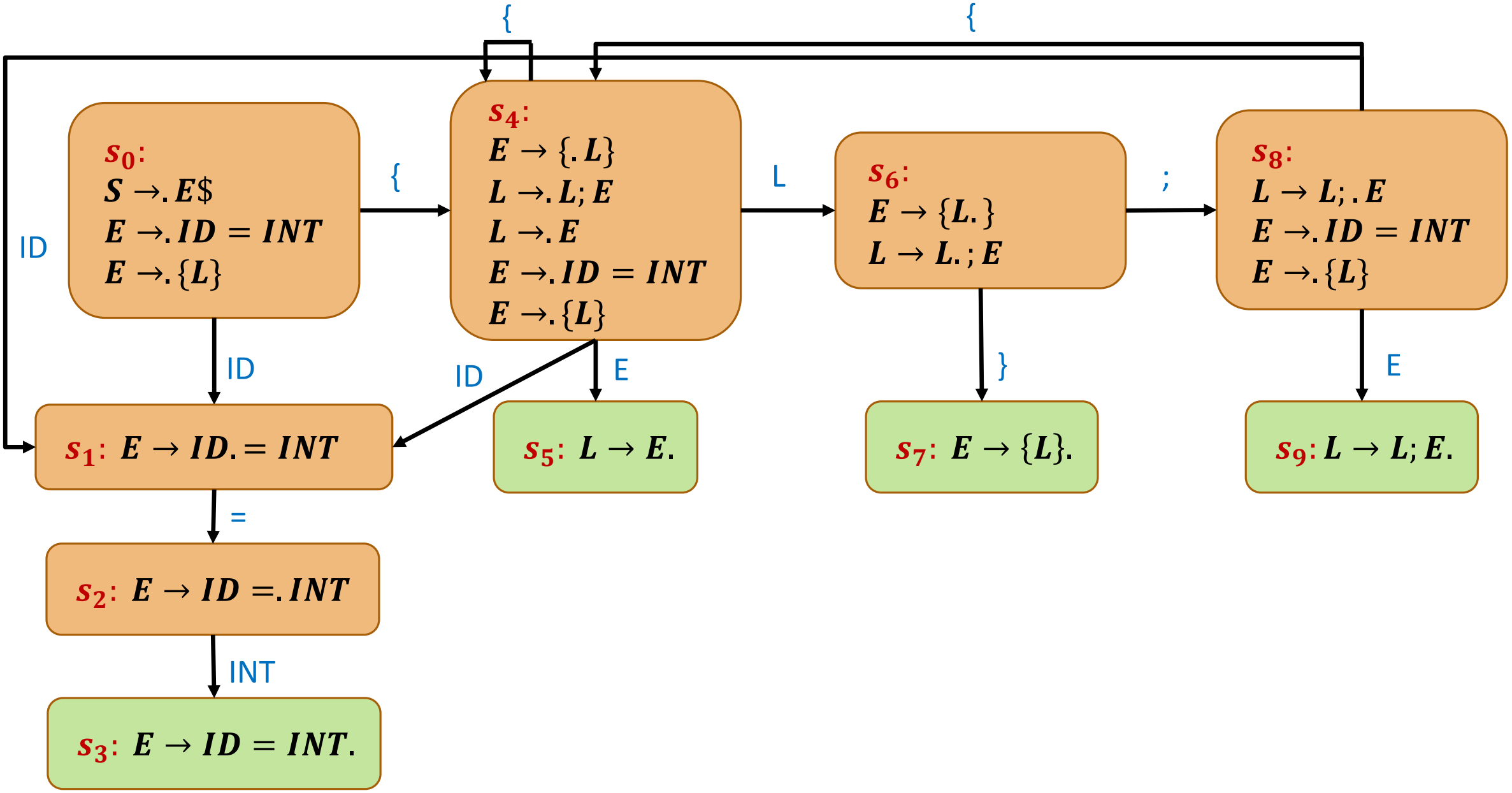
- $E \rightarrow ID.= INT$

So the next state (the $\epsilon$-closure) contains:

- $E \rightarrow ID.= INT$

which was already computed: $s_1$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


{
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$s_0$:
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$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
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$L \rightarrow L.; E$
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$s_2$: $E \rightarrow ID = .INT$
INT
$s_3$: $E \rightarrow ID = INT.$

# LR(0) Parser

From $s_0$, if we recognized $E$, then the next state will contain:

- $S \rightarrow E.\$$

So the next state (the $\epsilon$-closure) contains:

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

# LR(0) Parser

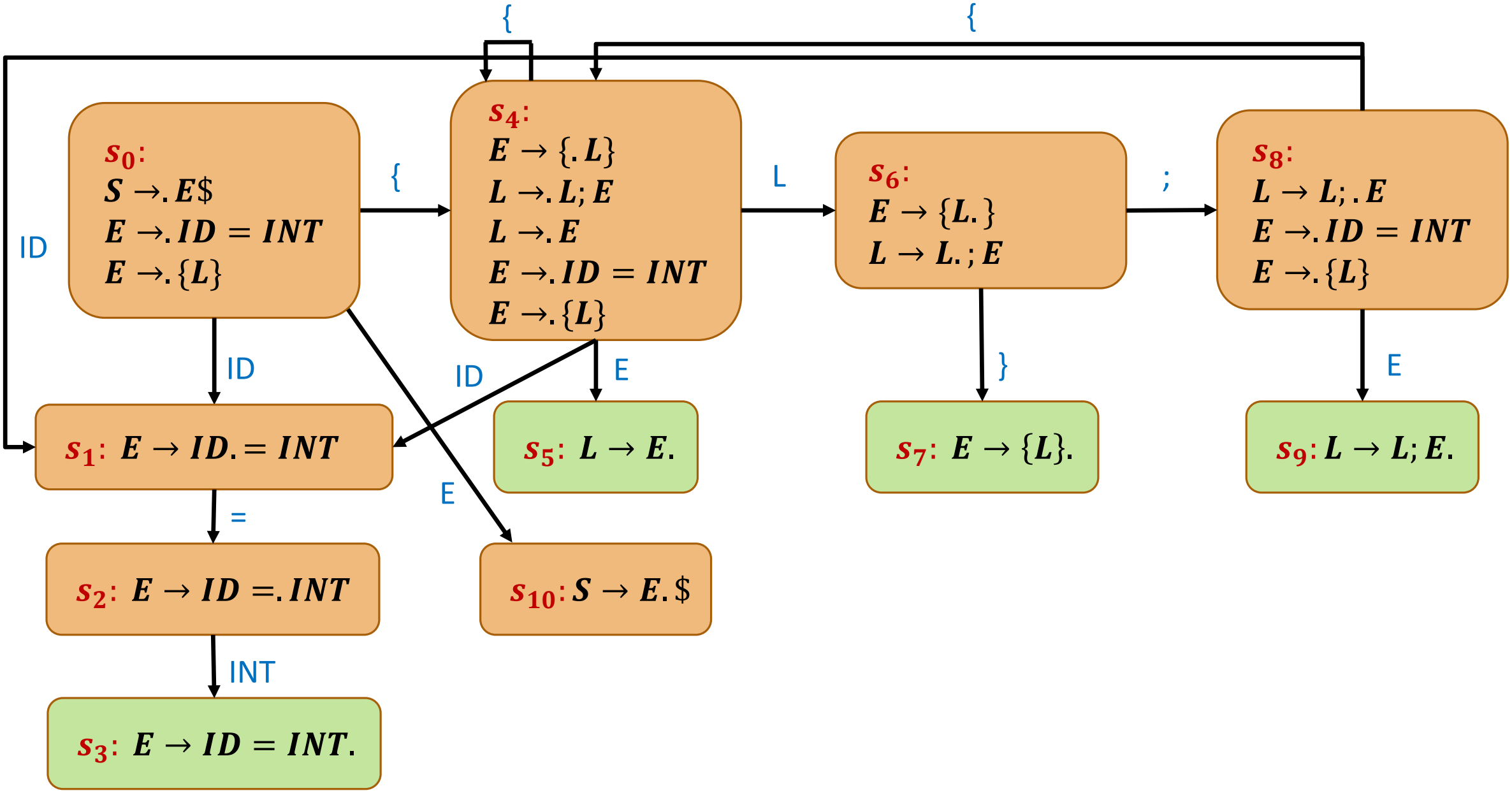
From $s_0$, if we recognized $E$, then the next state will contain:

- $S \rightarrow E.\$$

So the next state (the $\epsilon$-closure) contains:

- $S \rightarrow E.\$$

$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$


{
{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
E
=
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
INT
$s_3$: $E \rightarrow ID = INT.$

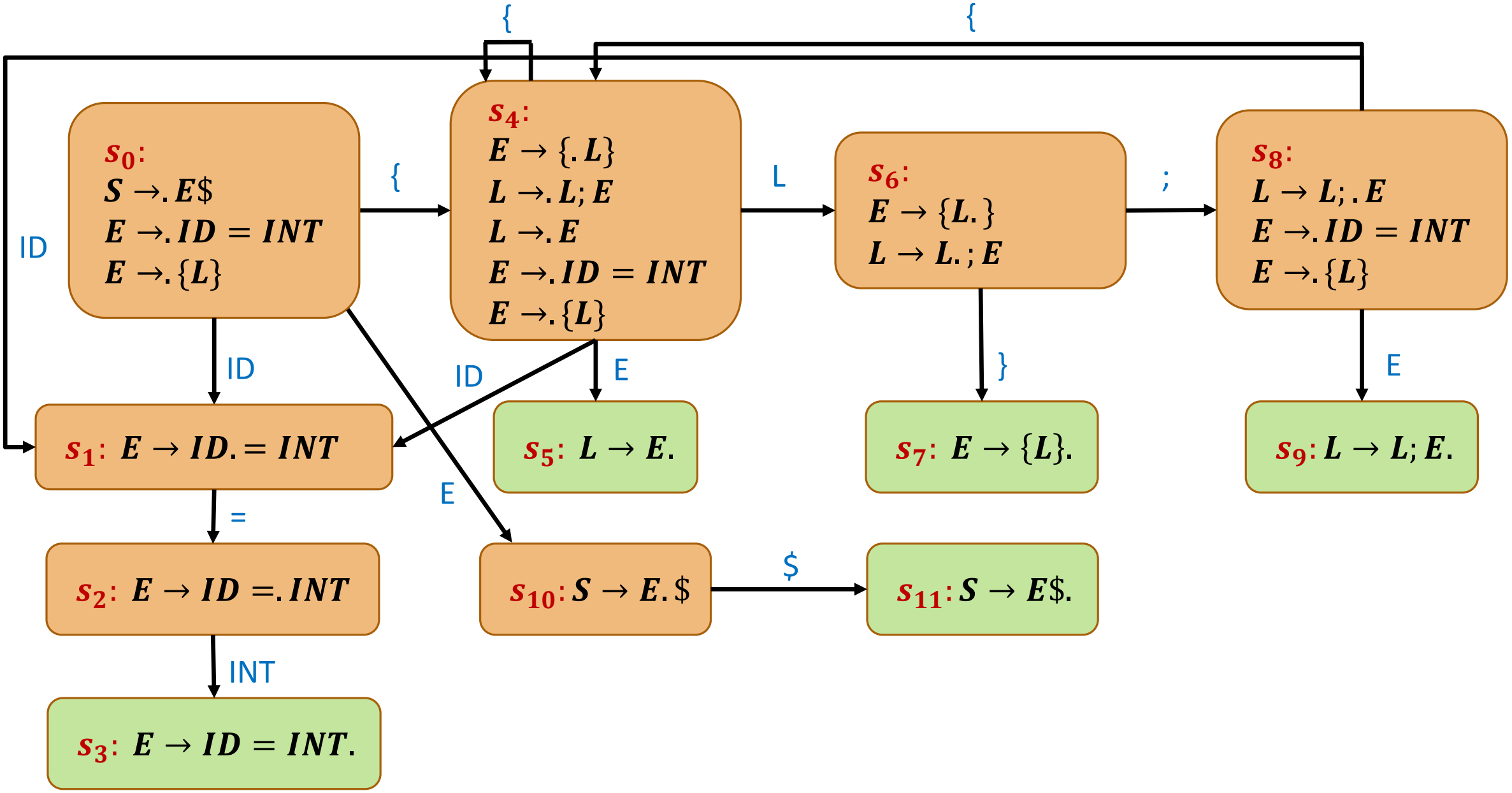
# LR(0) Parser

From $s_{10}$, if we recognized $E$, then the next state will contain:

- $S \rightarrow E\$.$

which is a reduce state.

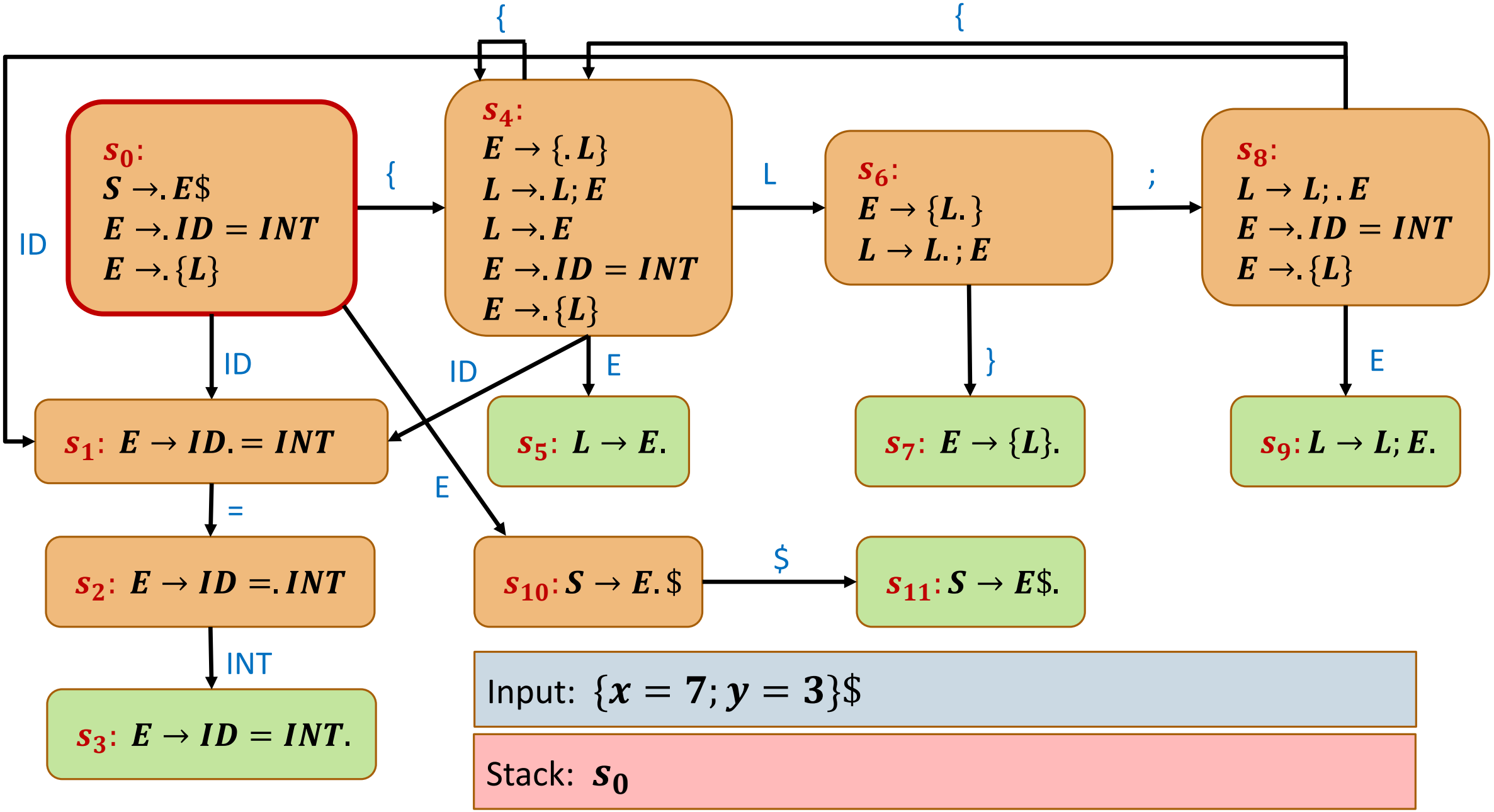
$S \rightarrow E\$$
$E \rightarrow ID = INT$
$E \rightarrow \{L\}$
$L \rightarrow E$
$L \rightarrow L; E$

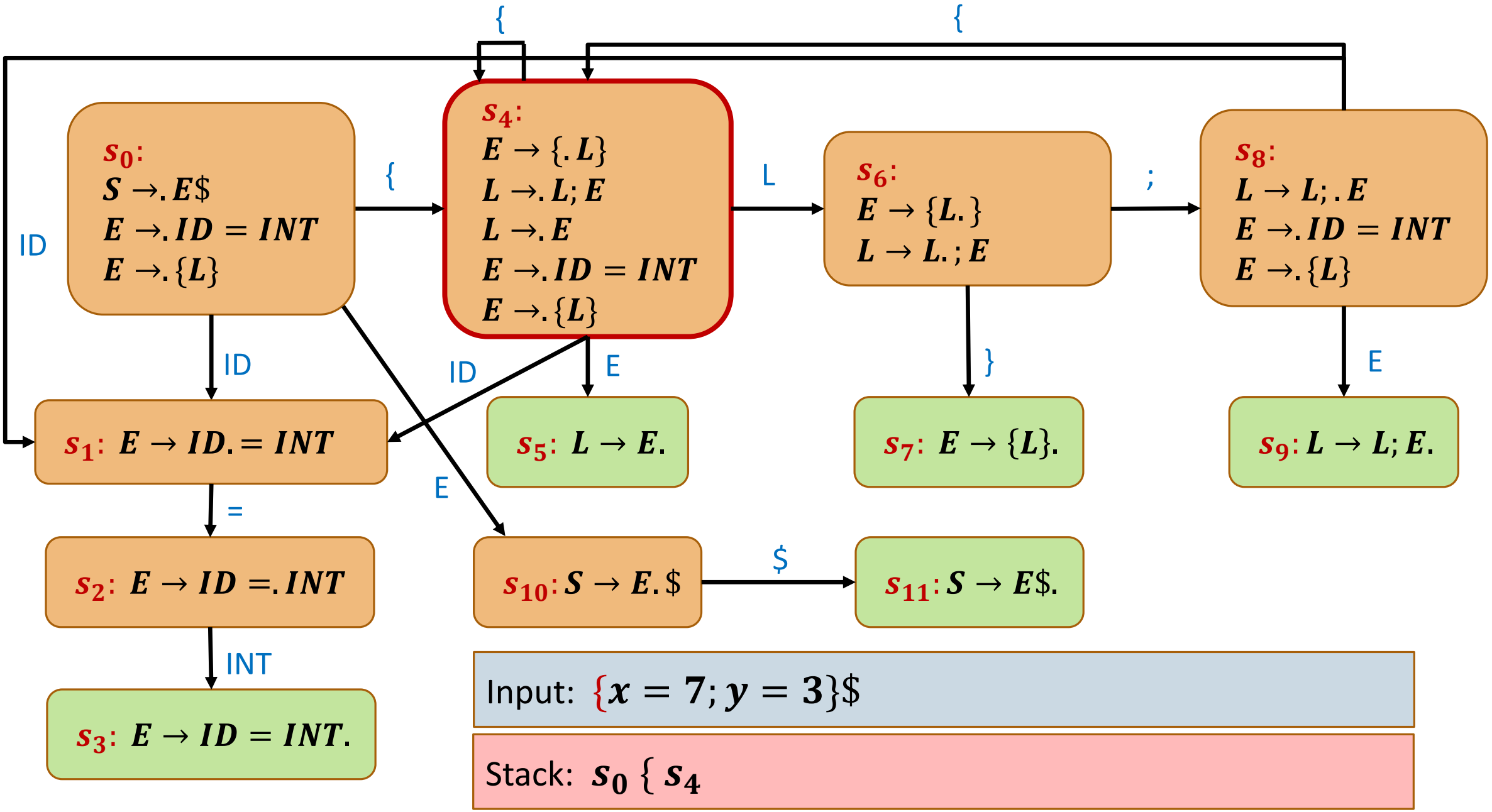

$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
$s_1$: $E \rightarrow ID. = INT$
$s_2$: $E \rightarrow ID = .INT$
$s_3$: $E \rightarrow ID = INT.$
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
$s_5$: $L \rightarrow E.$
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
$s_7$: $E \rightarrow \{L\}.$
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
$s_9$: $L \rightarrow L; E.$
$s_{10}$: $S \rightarrow E.\$$
$s_{11}$: $S \rightarrow E\$.$
{
{
ID
ID
ID
E
L
;
}
E
E
=
INT
$

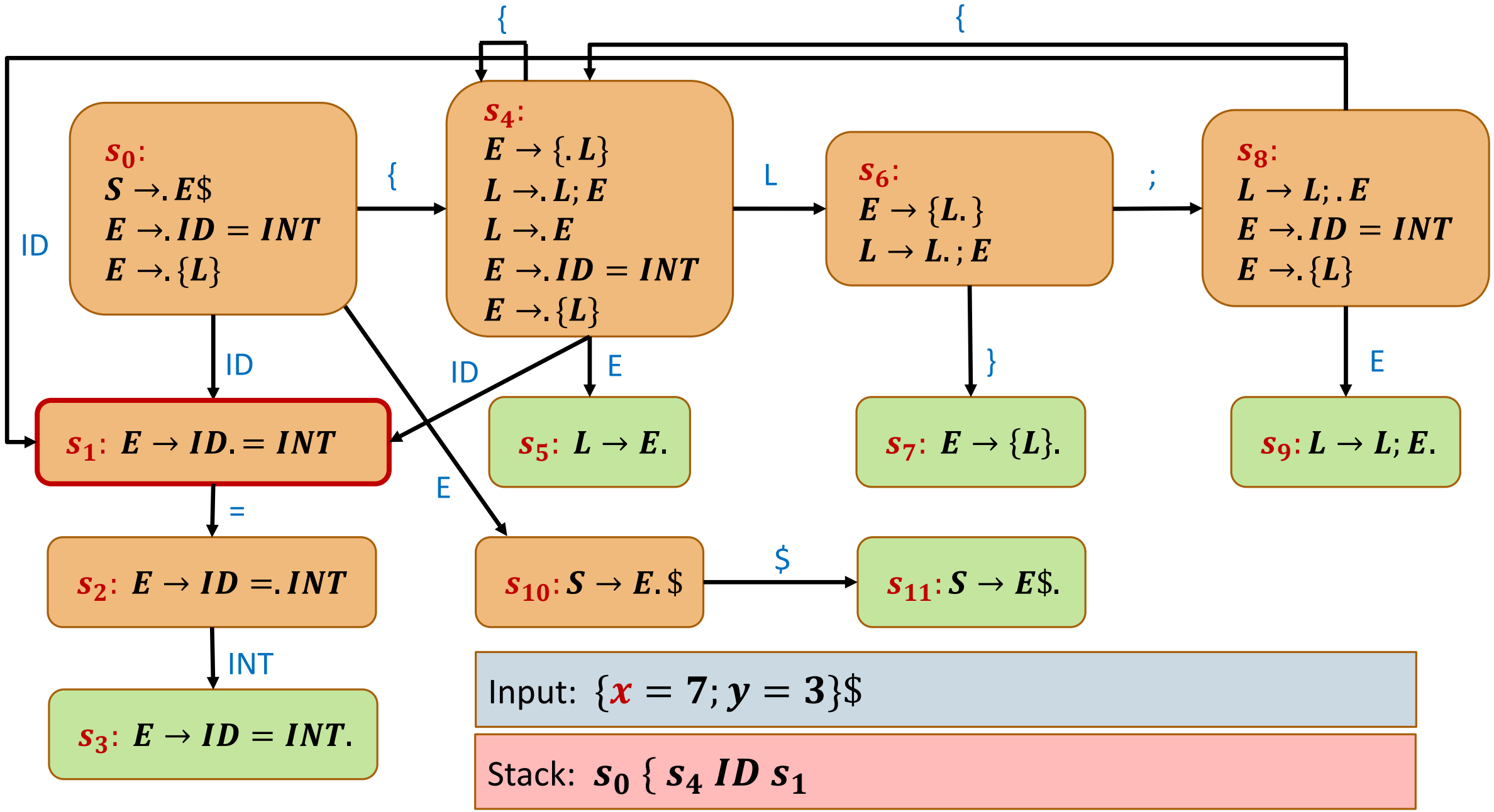
# LR(0) Parser: Running Example

What will happen with the following input:

- $\{\mathrm{x} = 7; y = 3\}\$$


{
{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
E
=
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0$


{
{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
E
=
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0\ \{\ s_4$


{
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$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
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$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
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$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
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=
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
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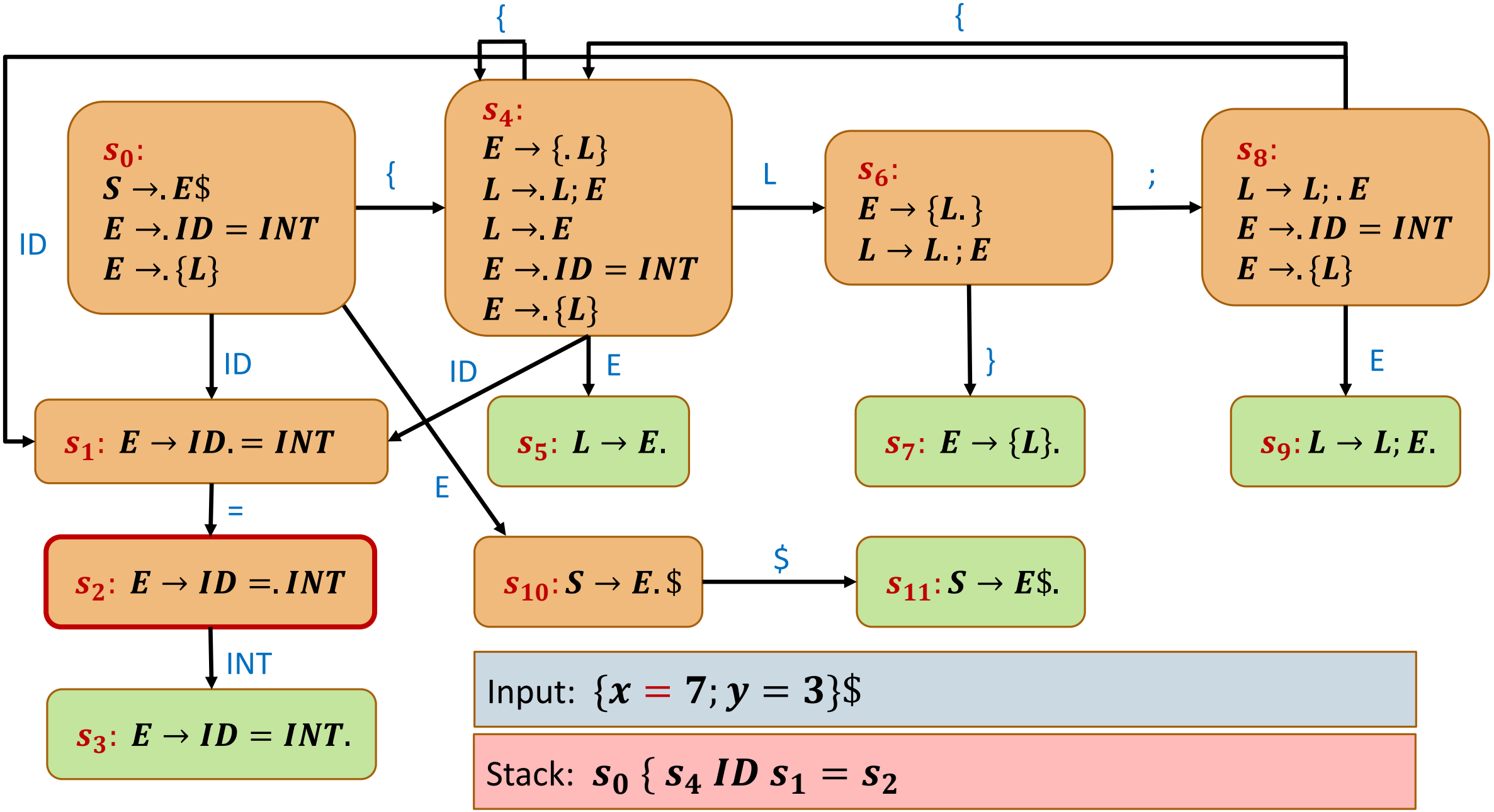
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 \; ID \; s_1$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$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
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$s_4$:
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$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
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$s_6$:
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$L \rightarrow L.; E$
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$L \rightarrow L; .E$
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ID
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$s_1$: $E \rightarrow ID. = INT$
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$s_9$: $L \rightarrow L; E.$
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$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
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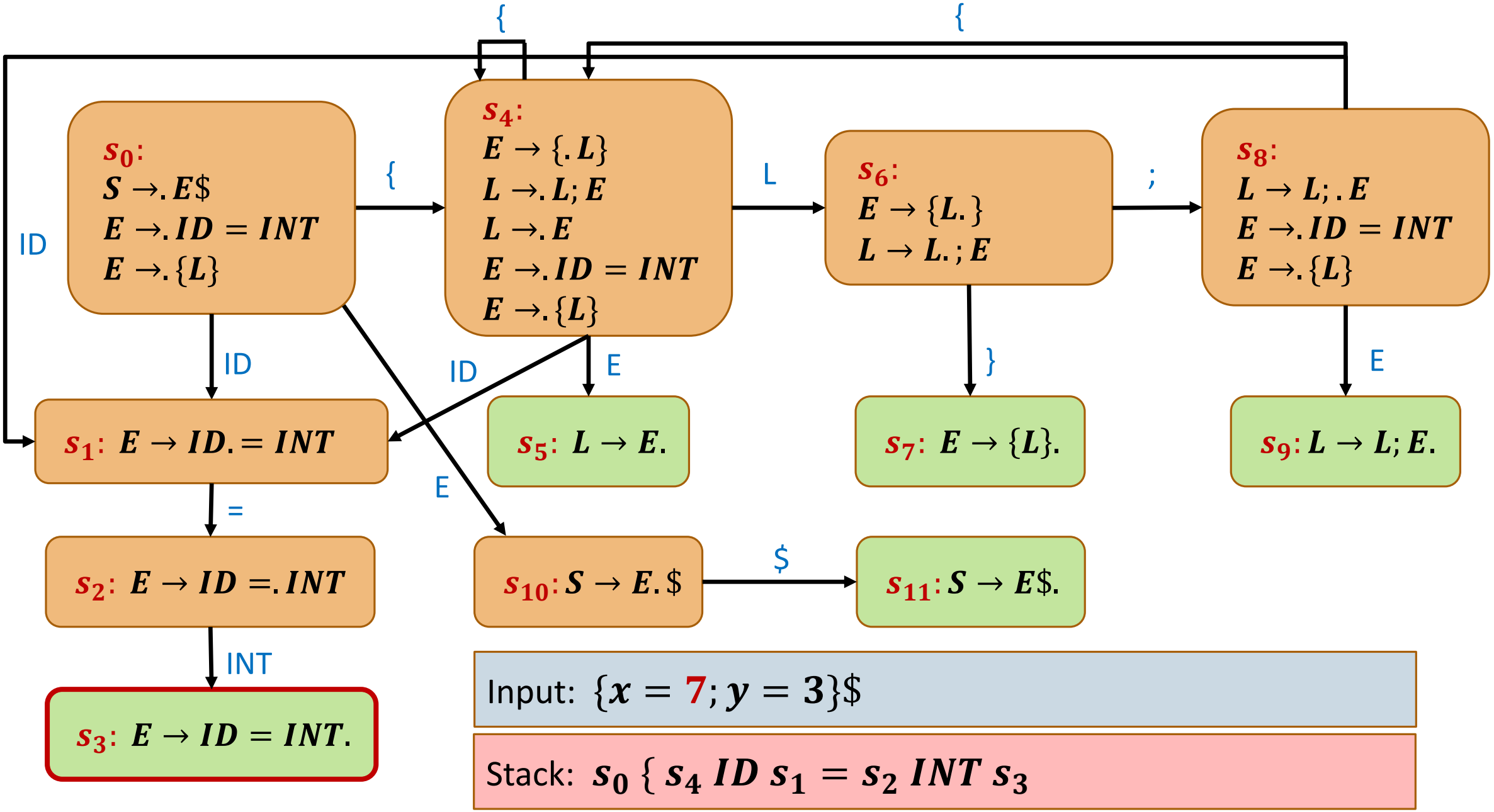
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 ID s_1 = s_2$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$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
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$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
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$s_6$:
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$E \rightarrow .\{L\}$
ID
ID
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}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
E
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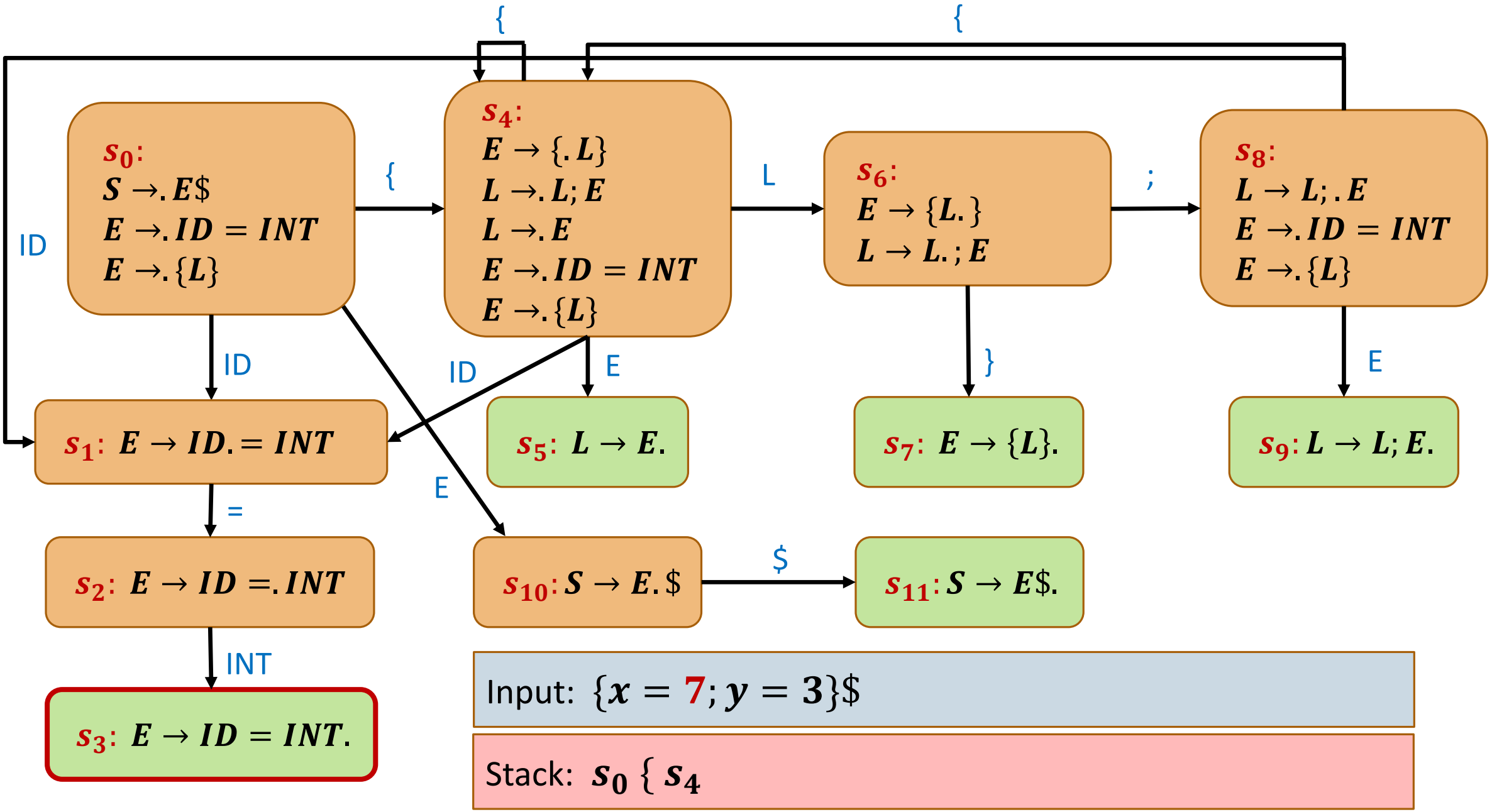
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 \; ID \; s_1 = s_2 \; INT \; s_3$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$E \rightarrow .ID = INT$
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$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
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$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
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$s_{10}$: $S \rightarrow E.\$$
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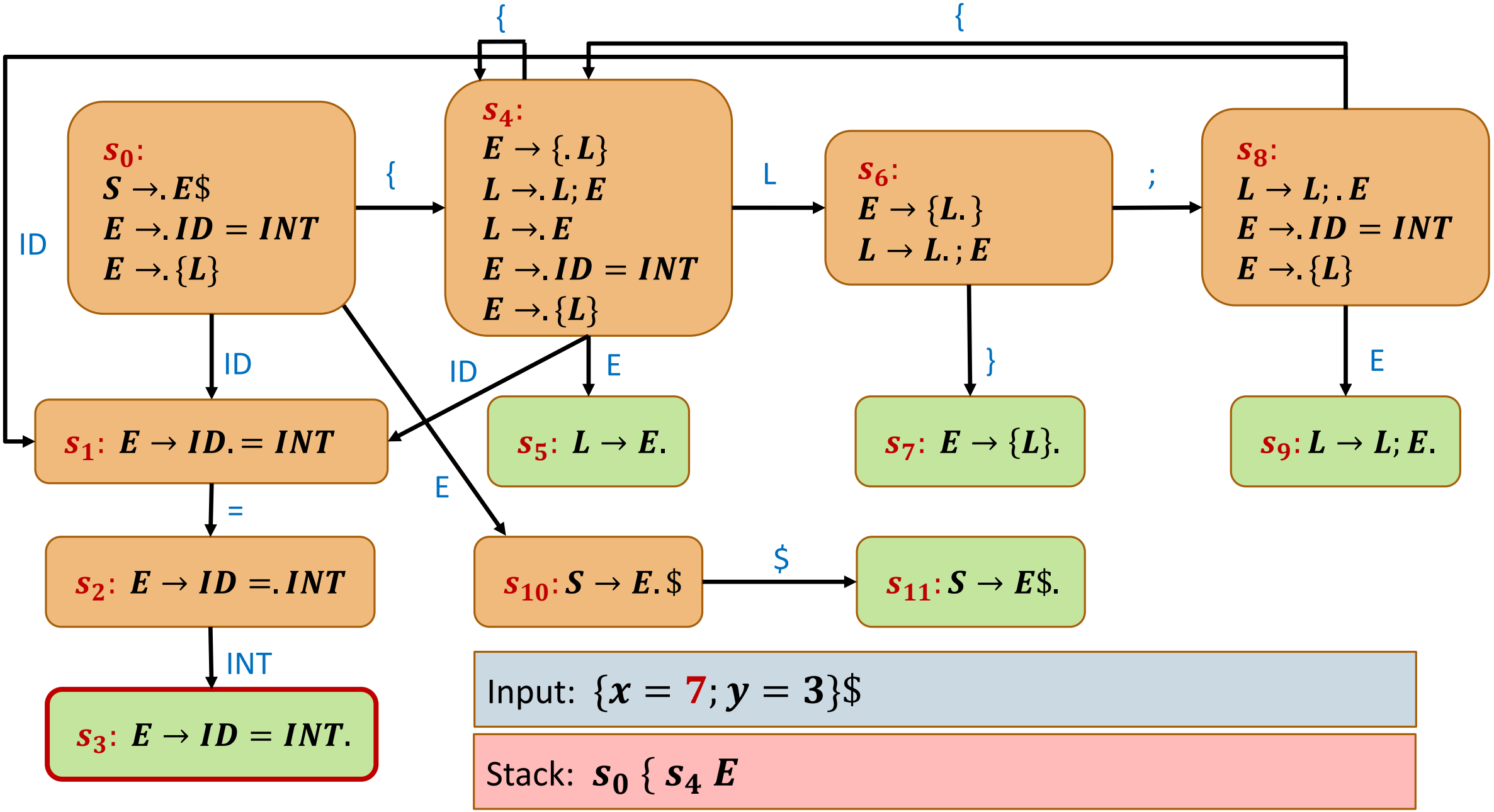
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0\ \{\ s_4$


$s_0$:
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$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$s_{11}$: $S \rightarrow E\$.$
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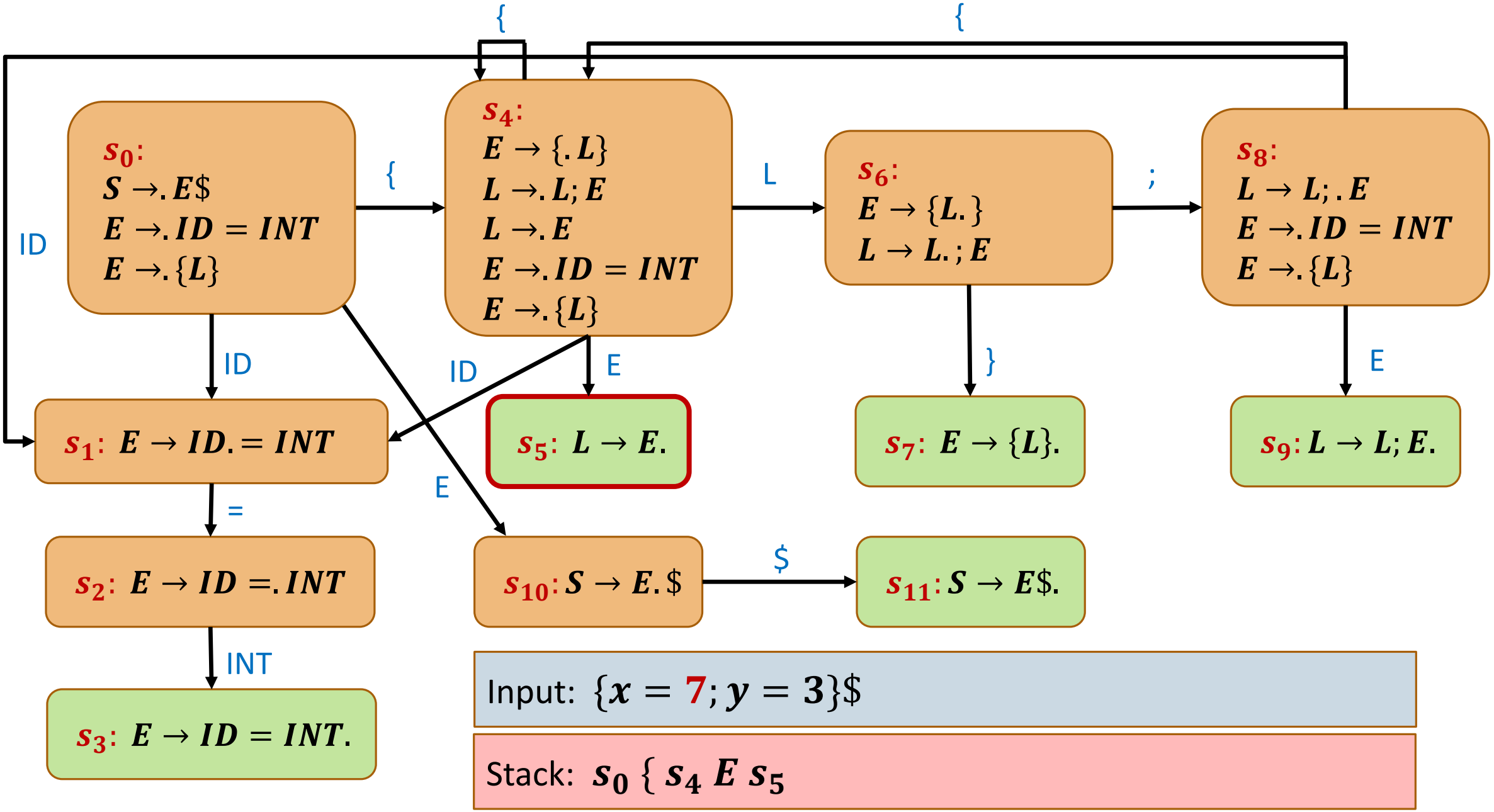
INT
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 E$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$s_0$:
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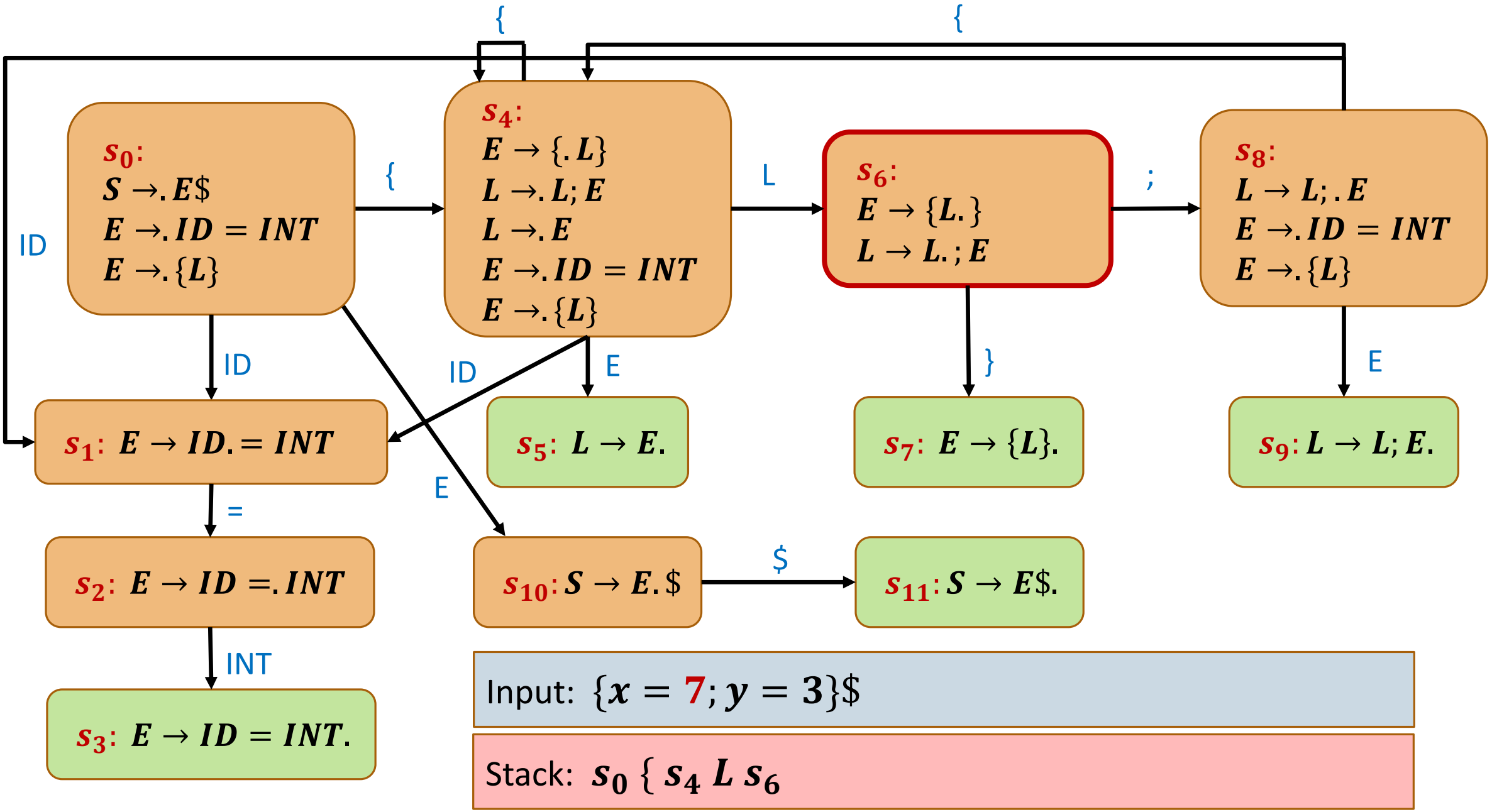
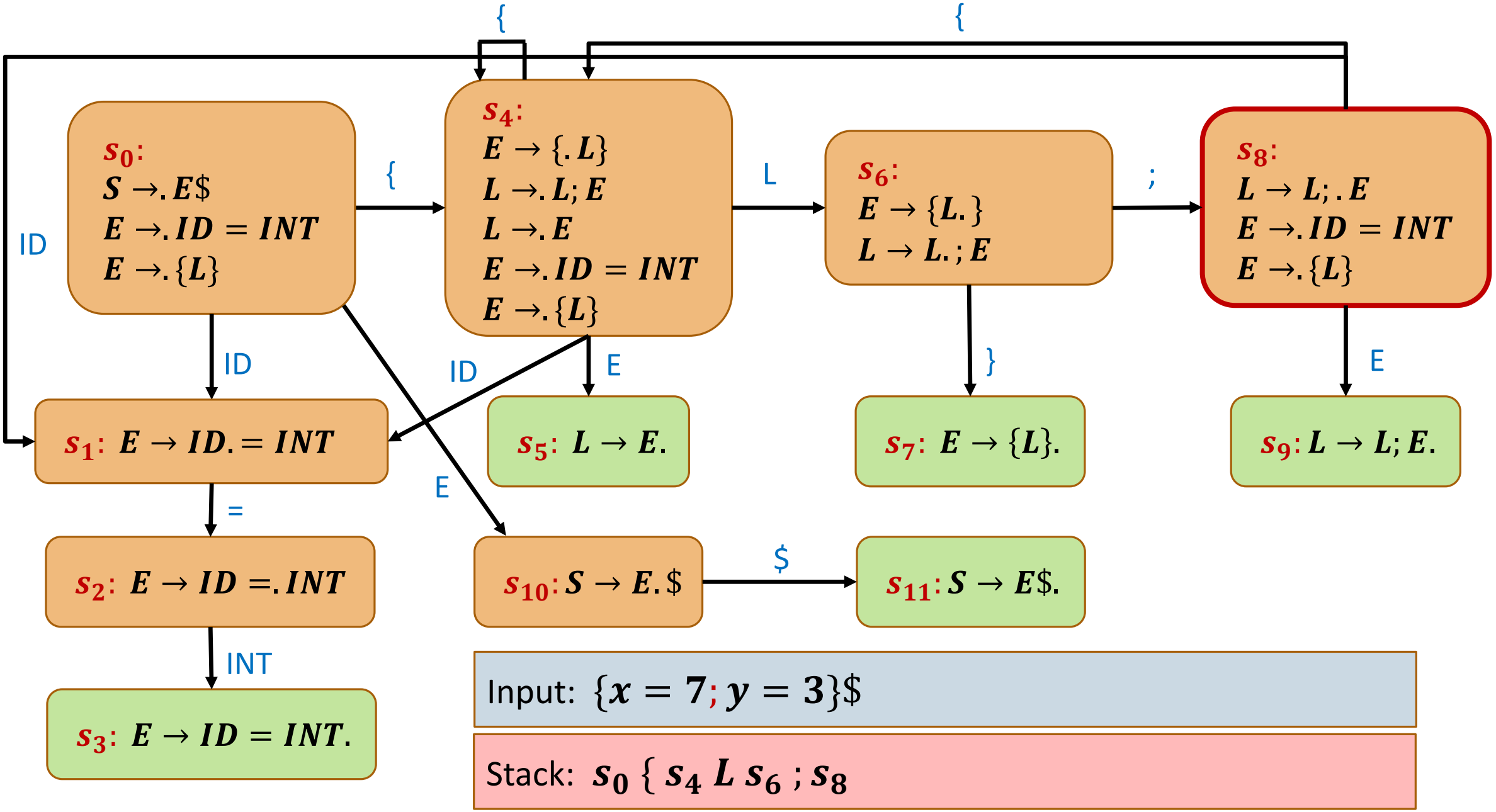
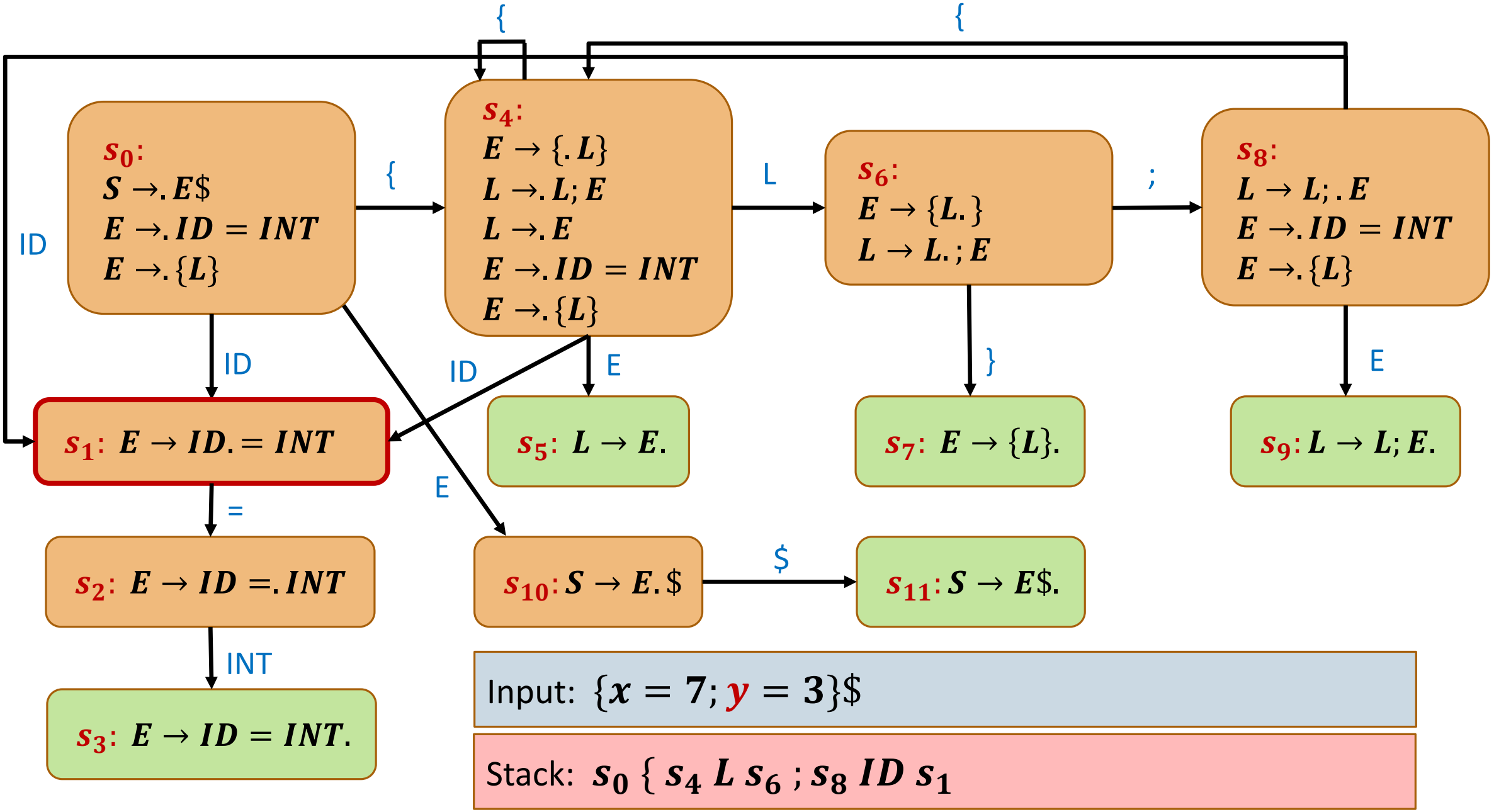
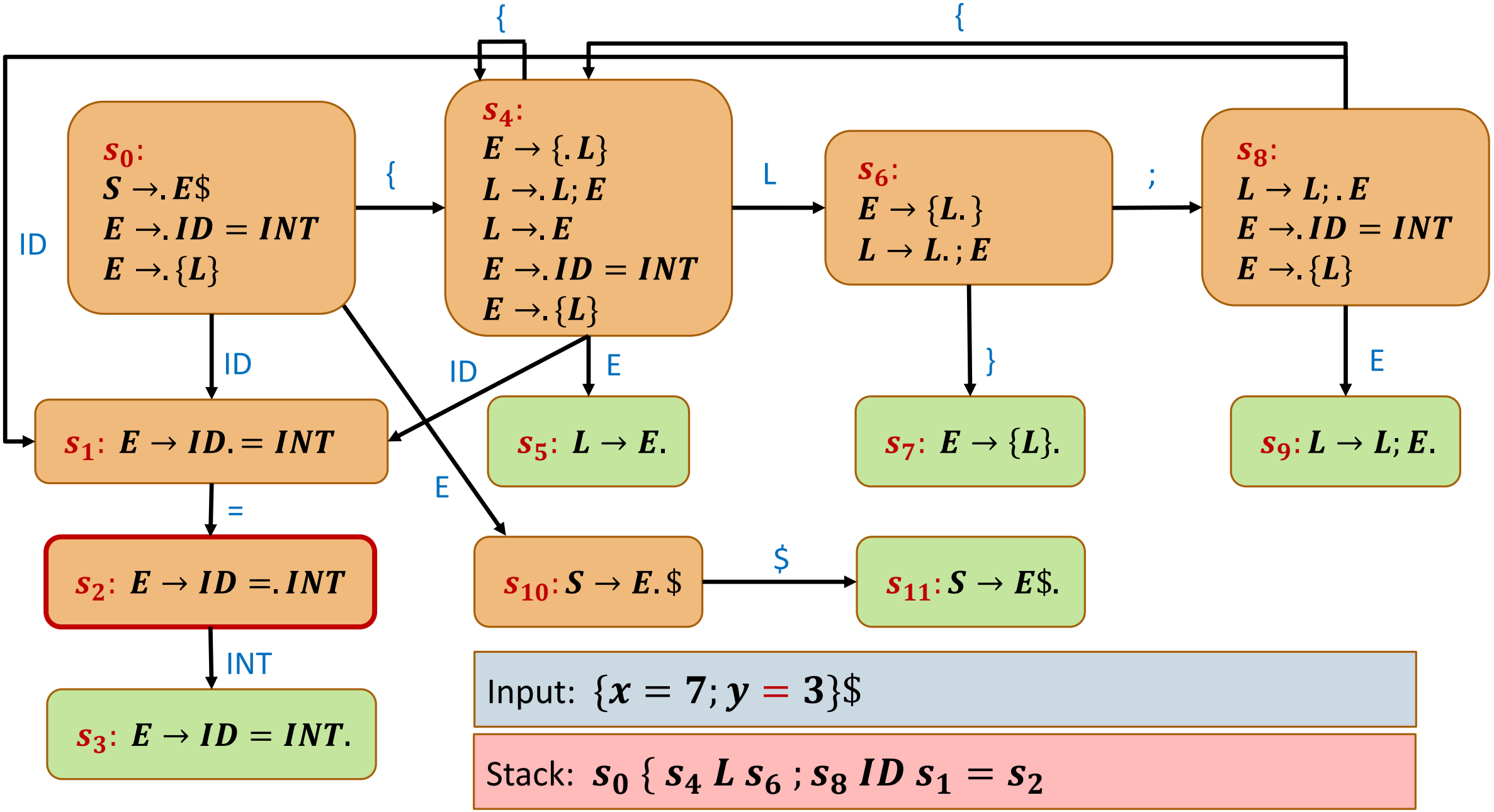
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
E
=
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 E s_5$


{
{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
E
=
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 L s_6$


{
{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
E
=
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 L s_6 ; s_8$


{
{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
=
E
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 L s_6 ; s_8 ID s_1$


{
{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
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$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
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$E \rightarrow .ID = INT$
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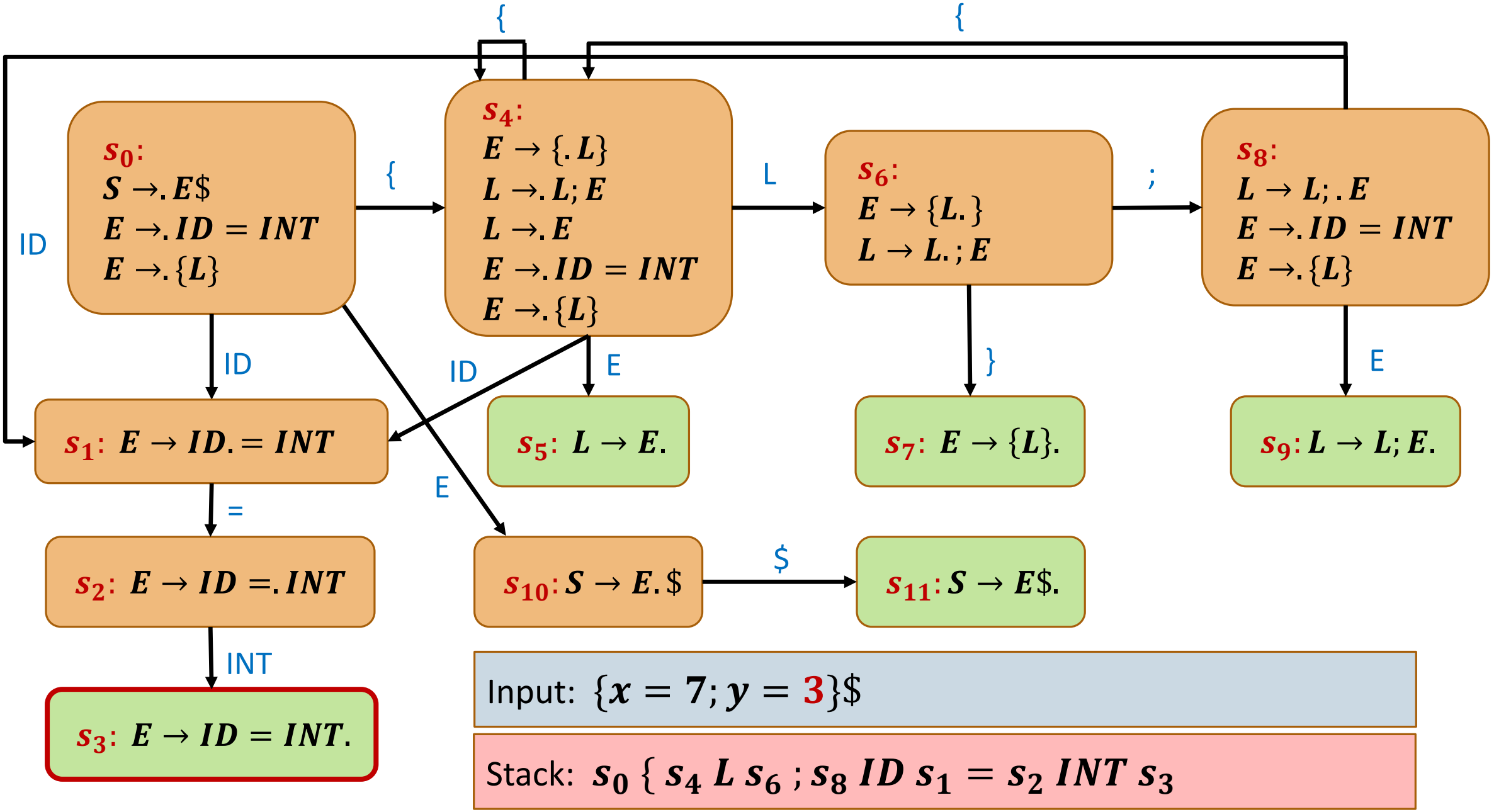
ID
ID
E
}
E
ID
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
E
=
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 L s_6 ; s_8 ID s_1 = s_2$


{
{
$s_0$:
$S \rightarrow .E\$$
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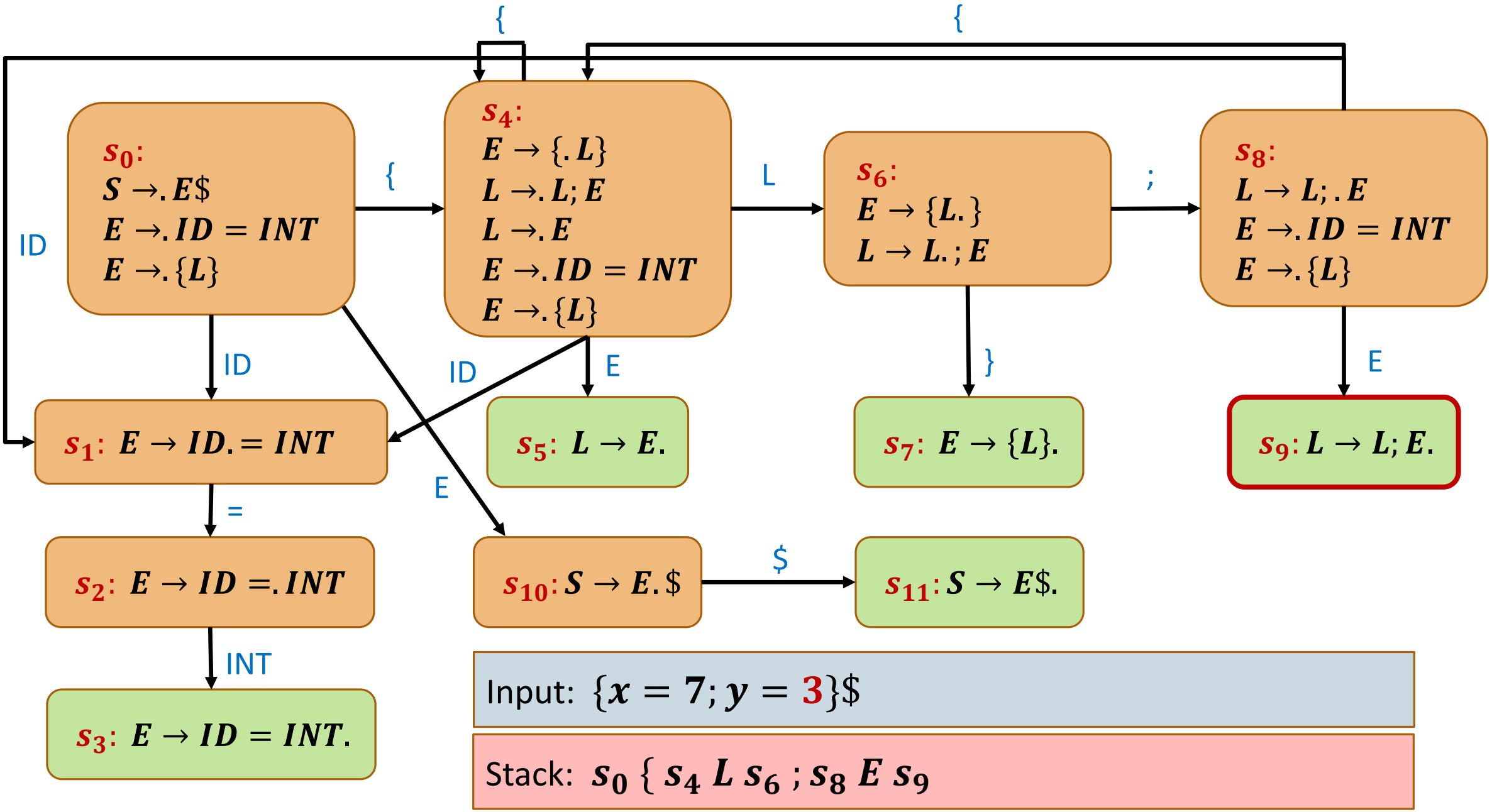
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 L s_6 ; s_8 ID s_1 = s_2 INT s_3$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$s_0$:
$S \rightarrow .E\$$
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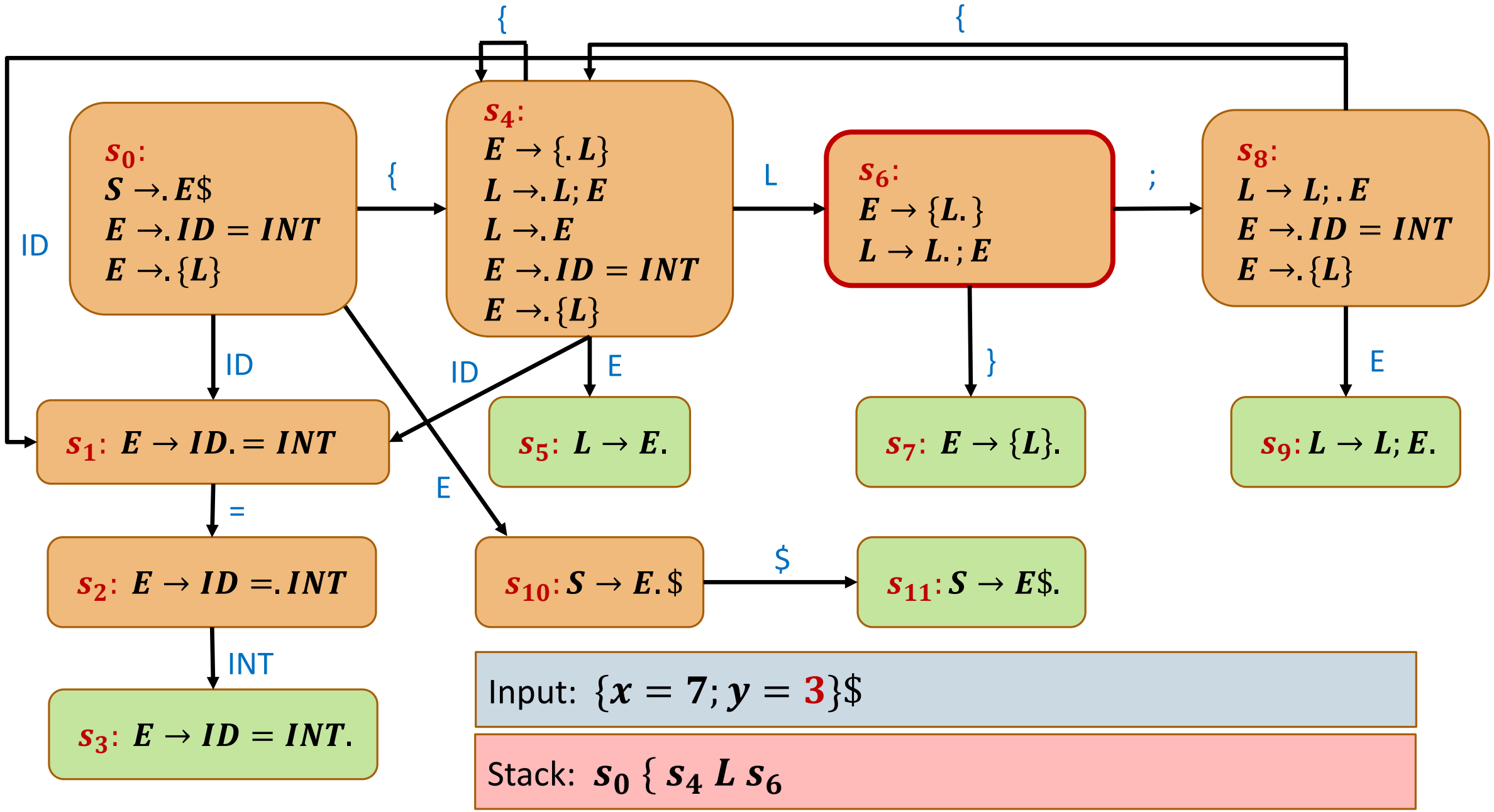
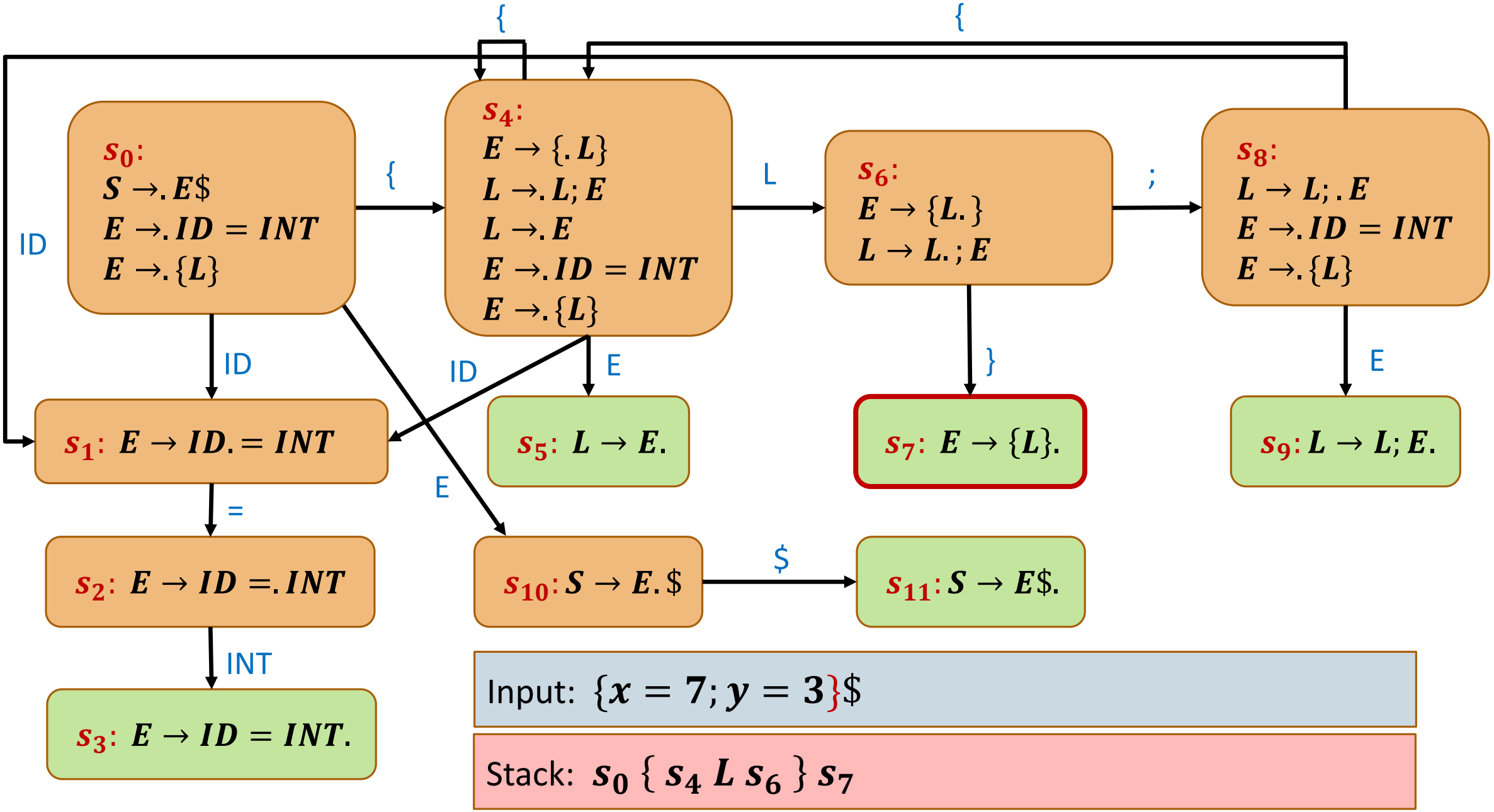
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 L s_6 ; s_8 E s_9$


{
{
$s_0$:
$S \rightarrow .E\$$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
{
$s_4$:
$E \rightarrow \{.L\}$
$L \rightarrow .L; E$
$L \rightarrow .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
L
$s_6$:
$E \rightarrow \{L.\}$
$L \rightarrow L.; E$
;
$s_8$:
$L \rightarrow L; .E$
$E \rightarrow .ID = INT$
$E \rightarrow .\{L\}$
ID
ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
$s_5$: $L \rightarrow E.$
$s_7$: $E \rightarrow \{L\}.$
$s_9$: $L \rightarrow L; E.$
E
=
$s_2$: $E \rightarrow ID = .INT$
$s_{10}$: $S \rightarrow E.\$$
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 L s_6$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$L \rightarrow L.; E$
;
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$L \rightarrow L; .E$
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ID
ID
E
}
E
$s_1$: $E \rightarrow ID. = INT$
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$s_9$: $L \rightarrow L; E.$
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$s_2$: $E \rightarrow ID = .INT$
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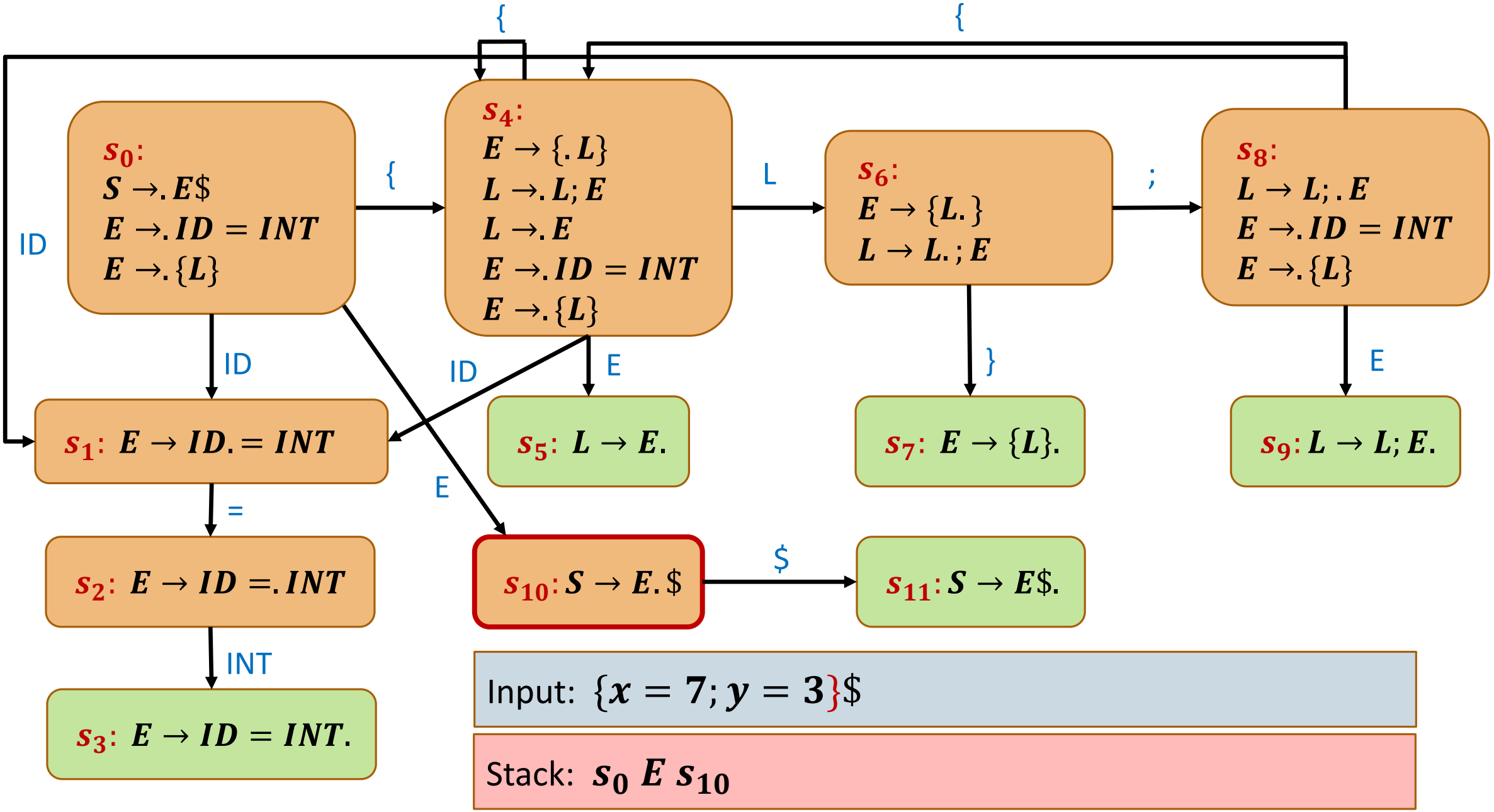
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0 \{ s_4 L s_6 \} s_7$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ID
ID
ID
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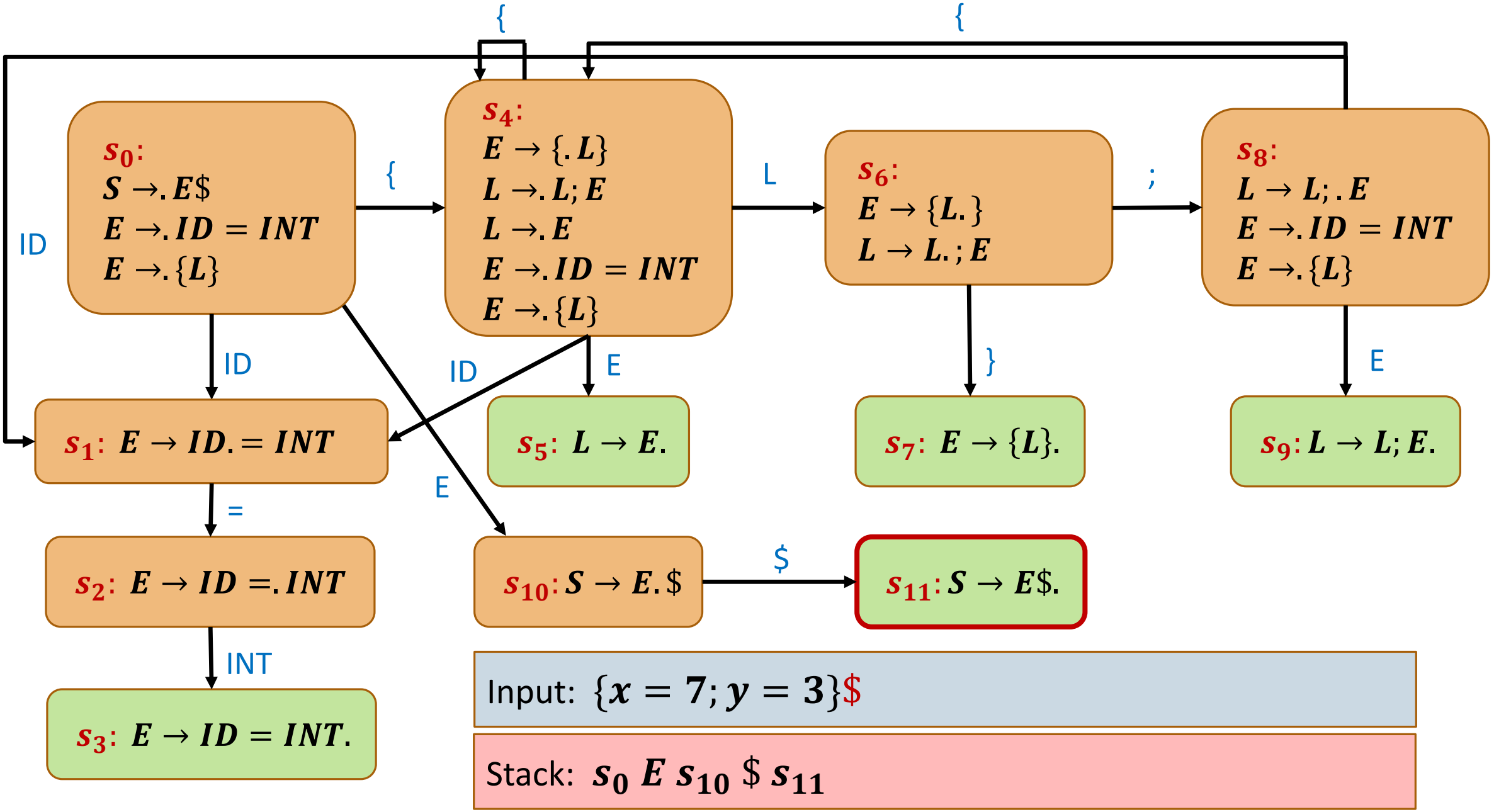
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0\ E\ s_{10}$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ID
ID
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E
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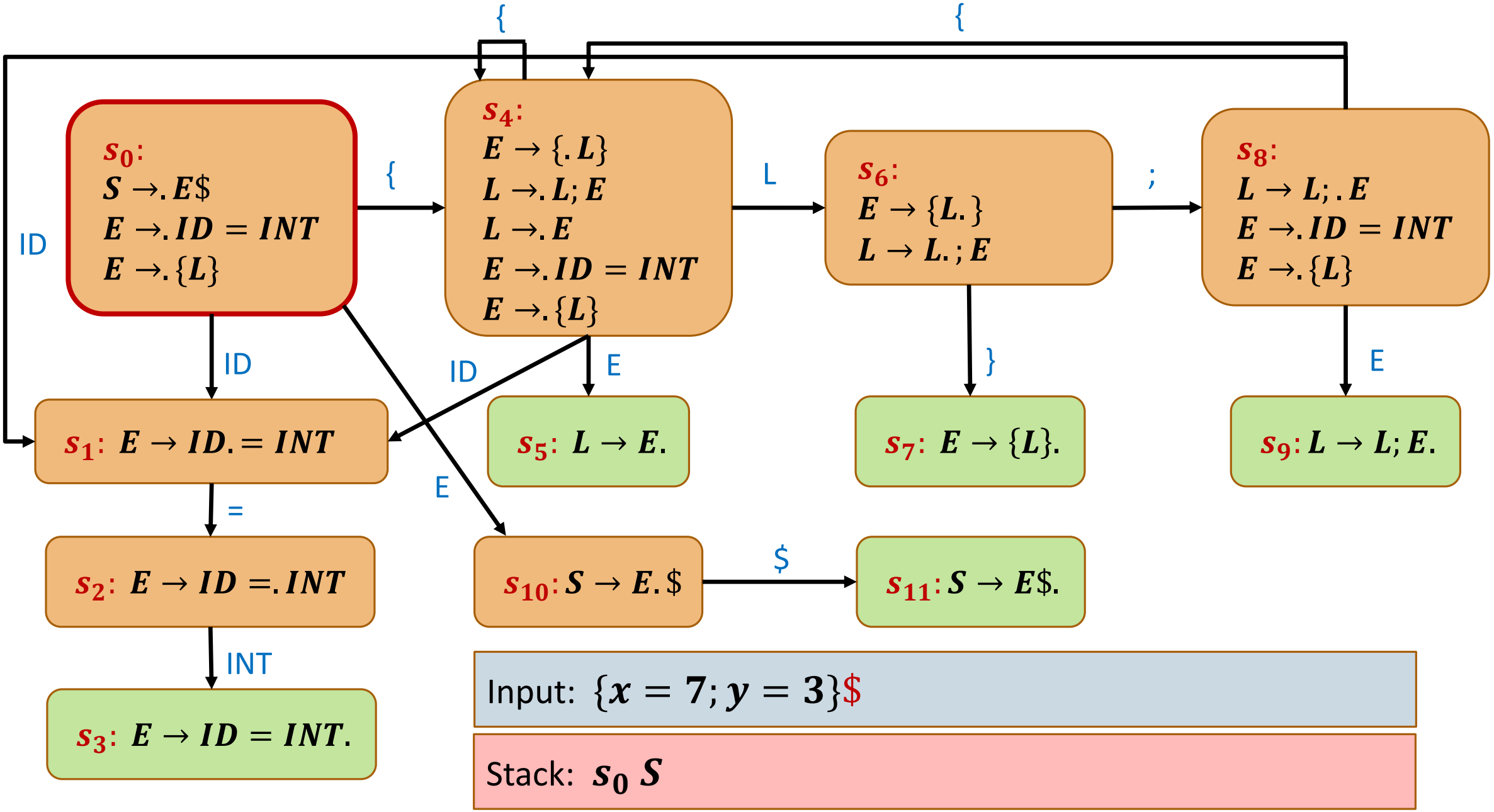
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0\ E\ s_{10}\ \$\ s_{11}$


{
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ID
ID
ID
E
}
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$s_1$: $E \rightarrow ID. = INT$
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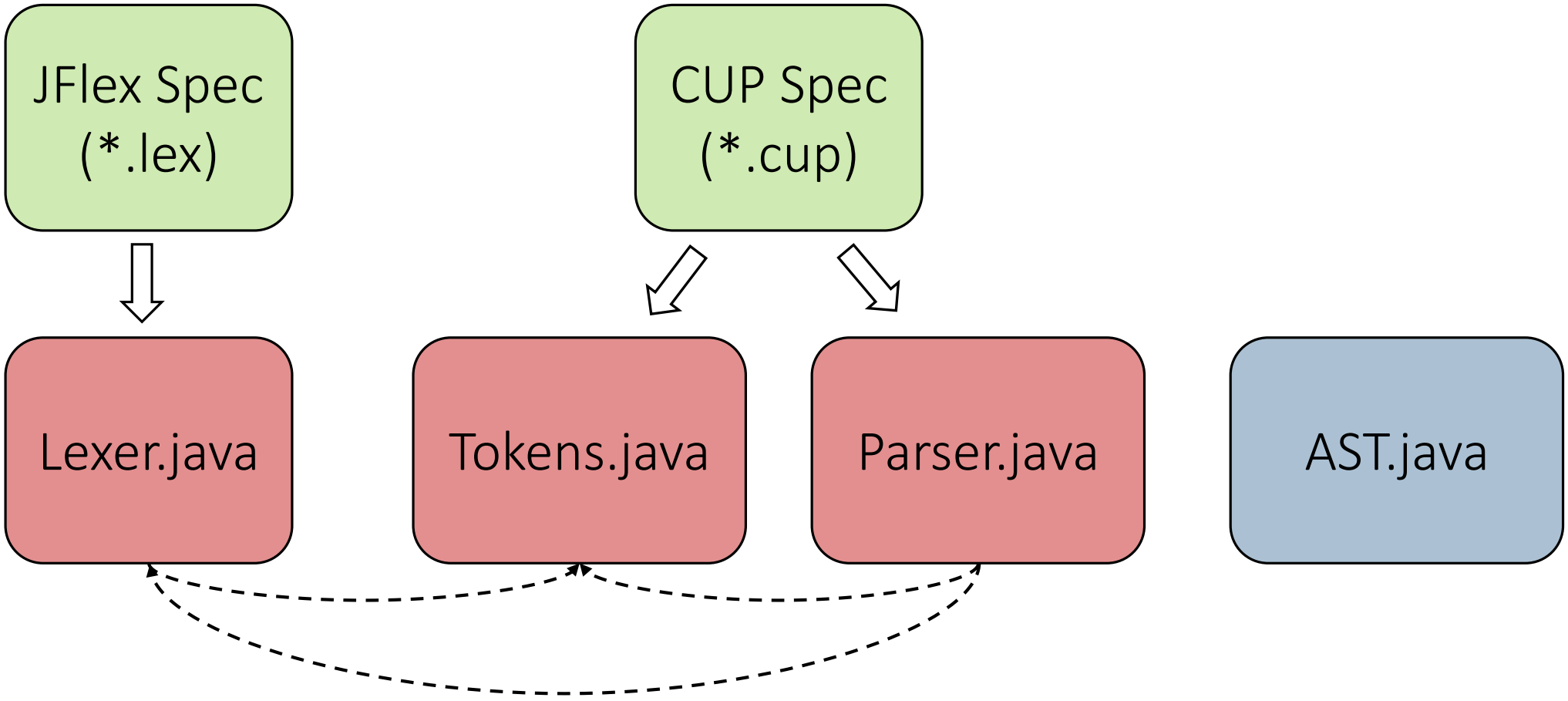
$
$s_{11}$: $S \rightarrow E\$.$
INT
$s_3$: $E \rightarrow ID = INT.$
Input: $\{x = 7; y = 3\}\$$
Stack: $s_0\ S$

# Parsing with CUP

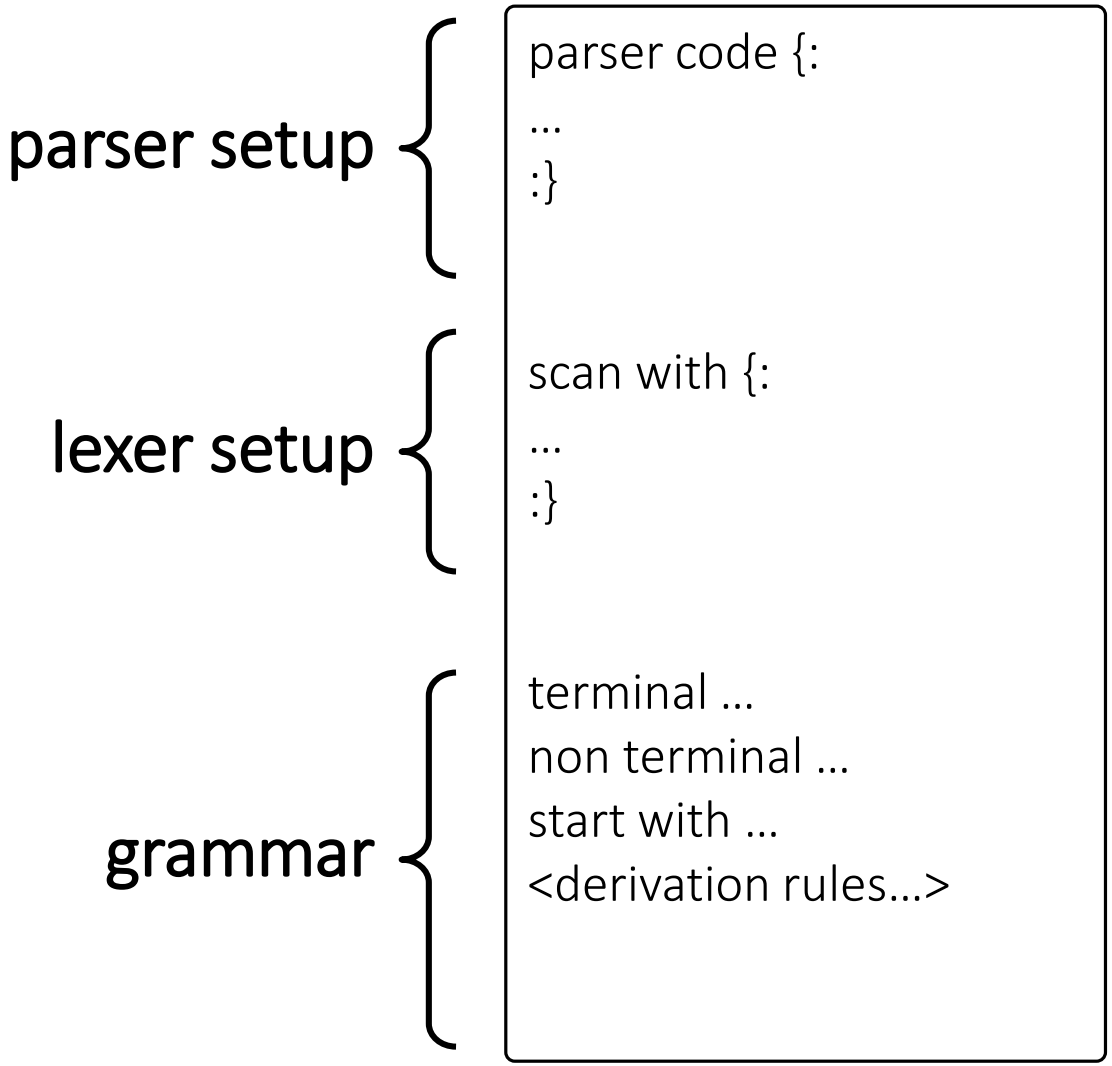
# CUP

- Given a user-specified grammar, generates an LALR parser
- Works with JFlex, which provides the parsed tokens
- Other tools:
  - Bison (for C)

# CUP/JFlex Workflow



# CUP Format


parser setup
lexer setup
grammar
parser code {:
…
:}
scan with {:
…
:}
terminal …
non terminal …
start with …
<derivation rules…>

# CUP Spec: Parser Setup

```
parser code {:
        public Lexer lexer;
        public Parser(Lexer lexer) {
                super(lexer);
                this.lexer = lexer;
        }
        public void report_error(String message, Object info) {
                System.exit(0);
        }
:}
```

# CUP Spec: Lexer Setup

```
scan with {:
        Symbol s;
        s = lexer.next_token();
        // print token…
        return s;
:};
```

# CUP Spec: Terminals

```
terminal T1;
terminal T2;
terminal T3;
terminal T4;
…
```

# CUP Spec: Non-Terminals

non terminal AST_NODE_1 E1;
non terminal AST_NODE_2 E2;
non terminal AST_NODE_3 E3;
…

# CUP Spec: Operator Precedence

```
precedence left OP1;
precedence left OP2;
precedence left OP3;
precedence left OP4;
…
```

These are token names…

# CUP Spec: Grammar

```
start with S;
S ::=
  E1:e1 E2:e2 {: RESULT = new AST_NODE_1(e1, e2);  :} |
  E3:e3       {: RESULT = new AST_NODE_2(e3);  :} ;

E1 ::= ID:id    {: RESULT = new AST_NODE_3(id);   :}

E2 ::= INT:i    {: RESULT = new AST_NODE_4(i);  :}

E3 ::= …
```

# CUP Spec: AST Nodes

- We need to **decide** which node types we have in our AST
- We need to **define** the classes for these AST nodes
- For example, for integers (INT) we can do:

```
public class AST_EXP_INT extends AST_EXP {
        public int value;
        public AST_EXP_INT(int value) {
                this.value = value;
        }
        public void PrintMe() { … }
}
```

# CUP Example

Consider the following CFG:

- $E \rightarrow INT$
- $E \rightarrow V$
- $E \rightarrow E + E$
- $E \rightarrow E\ - E$
- $V \rightarrow ID$
- $V \rightarrow V\ .ID$

# CUP Example: Terminals

```
terminal Integer INT;
terminal String ID;
terminal PLUS;
terminal MINUS;
terminal DOT;
```

# CUP Example: Non-Terminals

```
non terminal AST_EXP exp;
non terminal AST_VAR var;
```

# CUP Example: Operator Precedence

```
precedence left PLUS;
precedence left MINUS;
```

# CUP Example: Grammar

```
start with EXP;
EXP ::=
    INT:i {: RESULT = new AST_EXP_INT(i); :} |
    VAR:v {: RESULT = new AST_EXP_VAR(v); :} |
    EXP:e1 PLUS  EXP:e2 {: RESULT = new AST_EXP_BINOP(e1, e2, 0); :} |
    EXP:e1 MINUS EXP:e2 {: RESULT = new AST_EXP_BINOP(e1, e2, 1); :};
VAR ::=
    ID:name {: RESULT = new AST_VAR_SIMPLE(name); :} |
    VAR:v DOT ID:fieldName {: RESULT = new AST_VAR_FIELD(v, fieldName); :};
```

# CUP Example: AST Nodes

For the non-terminal ***VAR***:

public abstract class **AST_VAR** extends AST_Node {

}

# CUP Example: AST Nodes

For the rule ***VAR ::= ID:name***:

```
public class AST_VAR_SIMPLE extends AST_VAR {
        public String name;
        public AST_VAR_SIMPLE(String name) {
                this.name = name;
        }
}
```

# CUP Example: AST Nodes

For the rule ***VAR ::= VAR:v DOT ID:fieldName*** :

```
public class AST_VAR_FIELD extends AST_VAR {
        public AST_VAR var;
        public String fieldName;
        public AST_VAR_FIELD(AST_VAR var, String fieldName) {
                this.var = var;
                this.fieldName = fieldName;
        }
}
```

# CUP Example: AST Nodes

For the non-terminal ***EXP***:

public abstract class **AST_EXP** extends AST_Node {

}

# CUP Example: AST Nodes

For the rule ***EXP ::= INT:i***:

```
public class AST_EXP_INT extends AST_EXP {
        public int value;
        public AST_EXP_INT(int value)    {
                this.value = value;
        }
}
```

# CUP Example: AST Nodes

For the rule ***EXP ::= VAR:v***:

```
public class AST_EXP_VAR extends AST_EXP {
        public AST_VAR var;
        public AST_EXP_VAR(AST_VAR var) {
                this.var = var;
        }
}
```

# CUP Example: AST Nodes

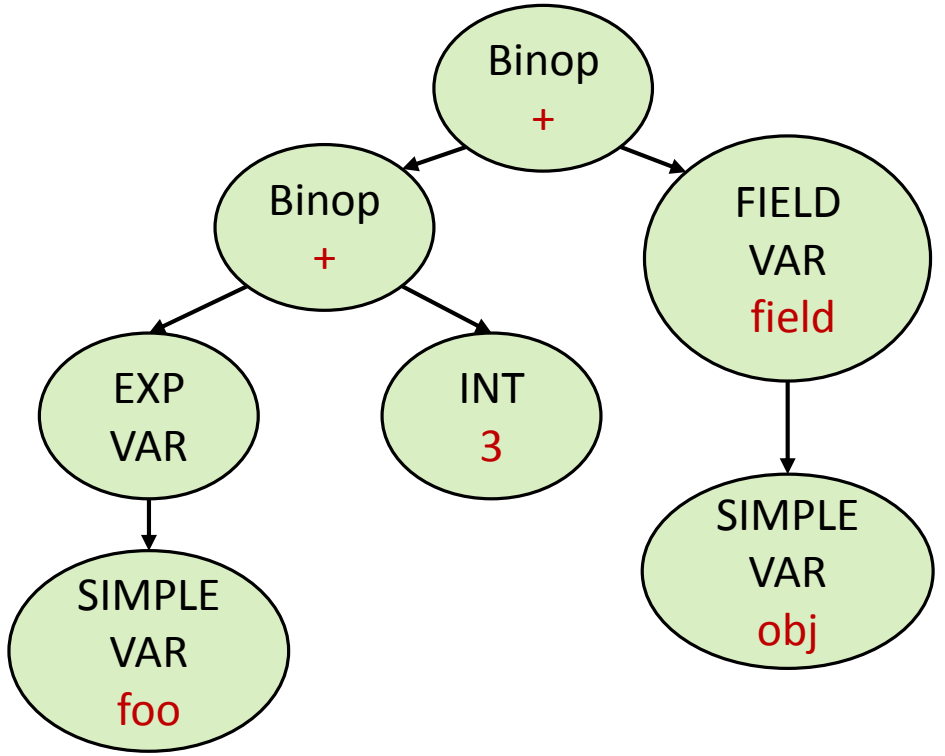
For the rule ***EXP ::= EXP:e1 <OP>  EXP:e2*** :

```
public class AST_EXP_BINOP extends AST_EXP {
        int OP;
        public AST_EXP left;
        public AST_EXP right;
        public AST_EXP_BINOP(AST_EXP left, AST_EXP right, int OP) {
                this.left = left;
                this.right = right;
                this.OP = OP;
        }
}
```

# CUP Example: AST Nodes

For the rule ***var:v DOT ID:fieldname***:

```
public class AST_VAR_FIELD extends AST_VAR {
        public AST_VAR var;
        public String fieldName;
        public AST_VAR_FIELD(AST_VAR var, String fieldName) {
                this.var = var;
                this.fieldName = fieldName;
        }
}
```

# CUP Example: Debugging

We can generate an image of the AST (using the exercise template)
For the input foo + 3 + obj.field we have: