Syntax-Directed Translation

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Compiler Construction (CSCI-GA.2130-001) Spring 2014
NYU Courant Institute

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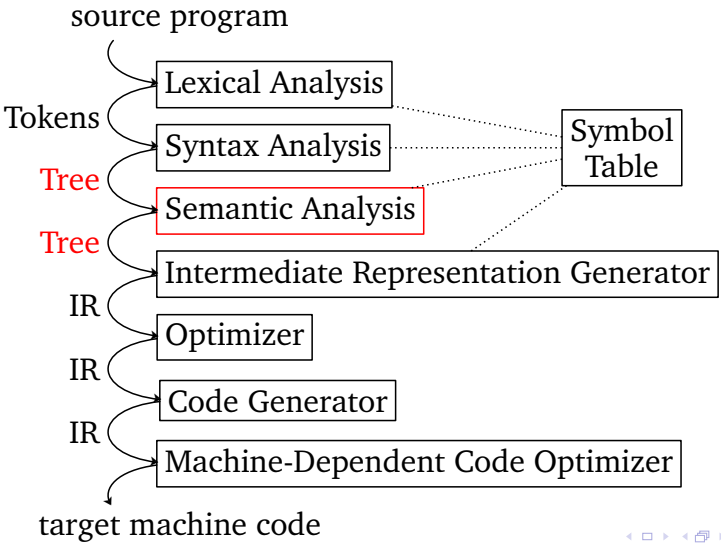
Outline

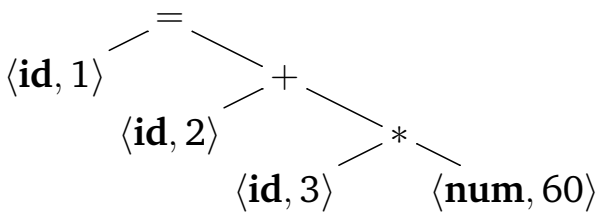
Context


source program
Lexical Analysis
Tokens
Syntax Analysis
Symbol Table
Tree
Semantic Analysis
Tree
Intermediate Representation Generator
IR
Optimizer
IR
Code Generator
IR
Machine-Dependent Code Optimizer
target machine code

From Abstract Syntax Tree (AST)

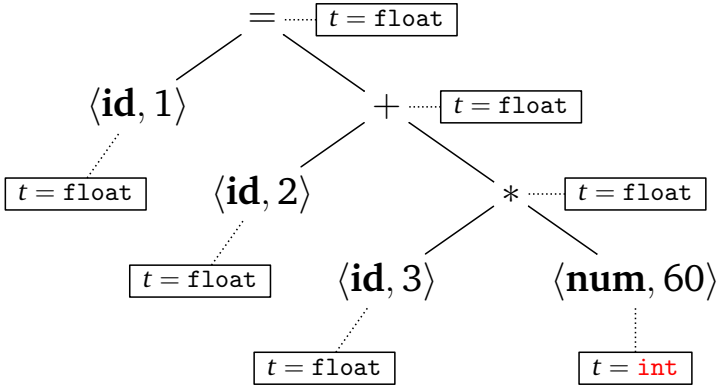
```
position = initial + rate * 60
```

parsed into *abstract syntax tree*:



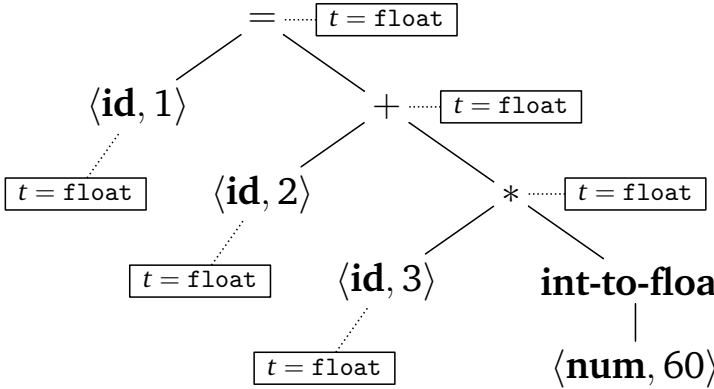
id	*lexeme*
1	`position`
2	`initial`
3	`rate`

. . . to Annotated AST. . .



id	*lexeme*	*t*
1	position	float
2	initial	float
3	rate	float

. . . to "Fixed" AST



id	*lexeme*	*t*
1	position	float
2	initial	float
3	rate	float

Outline

Goal

From

$$expr \rightarrow expr_1 + term_2$$

to

$$\text{Code for } expr \text{ to } R = \begin{cases} \text{Code for } expr_1 \text{ to } R_1 \\ \text{Code for } term_2 \text{ to } R_2 \\ \text{Code for } R := R_1 + R_2 \end{cases}$$

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$$expr \rightarrow expr_1 + term_2$$

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$$\boxed{\text{Code for } expr \text{ to } R} = \begin{cases} \boxed{\text{Code for } expr_1 \text{ to } R_1} \\ \boxed{\text{Code for } term_2 \text{ to } R_2} \\ \boxed{\text{Code for } R := R_1 + R_2} \end{cases}$$

Syntax-Directed Definition

Define attributes:

c : code generated from non-terminal

r : register used for result of computing non-terminal

PRODUCTION	SEMANTIC RULES
$E \rightarrow E_1 + T_2$	$E_1.r = fresh; T_2.r = fresh$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"

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c : Set for *entire production* — synthesized

r : Set for *sub-production* — inherited

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r : Set for *sub-production* $\rightarrow$ inherited

Example

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \mathit{fresh\text{-}R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \mathit{fresh\text{-}R}; T_2.r = \mathit{fresh\text{-}R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
$E \rightarrow T_1$	$T_1.r = E.r; E.c = T_1.c$
$T \rightarrow$ **int**	$T.c =$ "$T.r =$ **int**.*lexeme*"

Example (text)

1+2

Example (AST)

Production	Semantic Rules
$P \rightarrow E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
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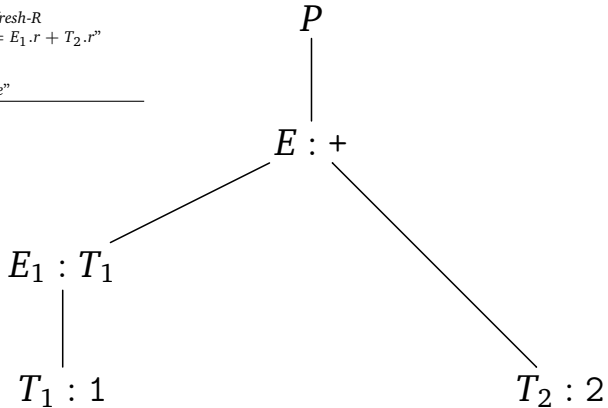

Example (attributes I)

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
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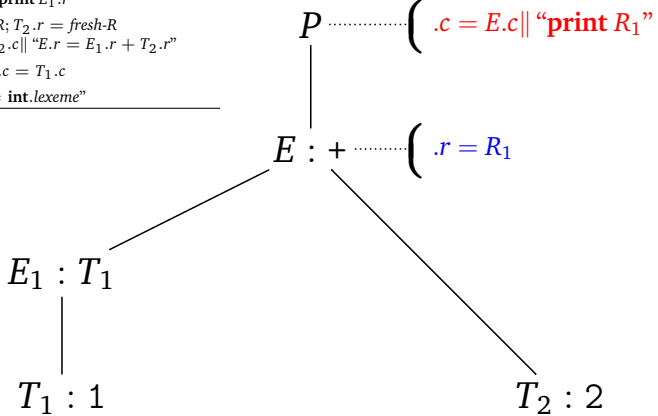
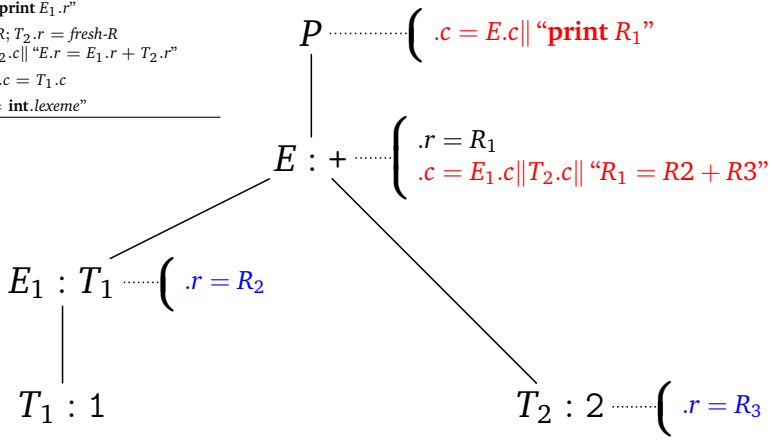


Example (attributes II)

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
$E \rightarrow T_1$	$T_1.r = E.r; E.c = T_1.c$
$T \rightarrow$ **int**	$T.c =$ "$T.r =$ **int**.*lexeme*"



Example (attributes III)

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
$E \rightarrow T_1$	$T_1.r = E.r; E.c = T_1.c$
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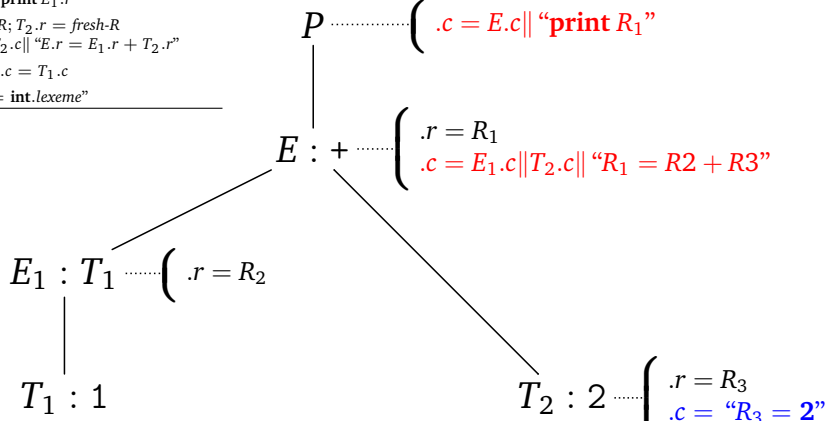
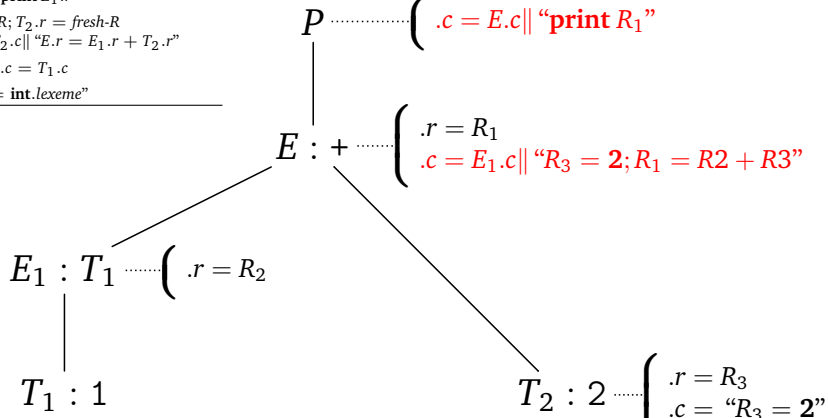


Example (attributes IV)

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
$E \rightarrow T_1$	$T_1.r = E.r; E.c = T_1.c$
$T \rightarrow$ **int**	$T.c =$ "$T.r =$ **int**.*lexeme*"



Example (attributes V)

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
$E \rightarrow T_1$	$T_1.r = E.r; E.c = T_1.c$
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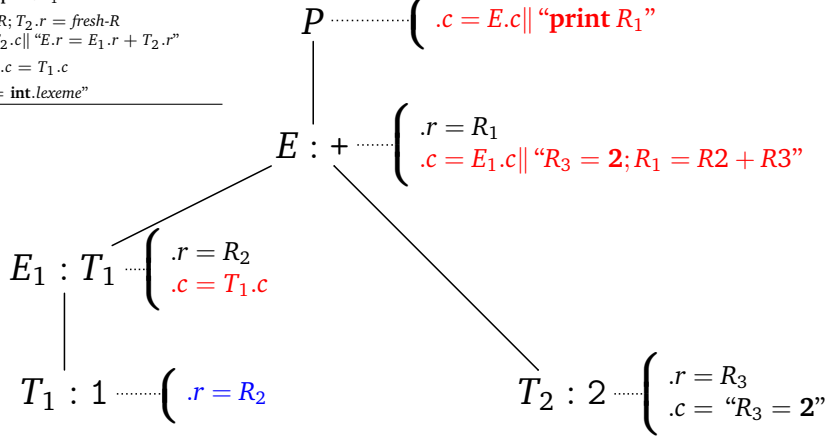

Example (attributes VI)

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
$E \rightarrow T_1$	$T_1.r = E.r; E.c = T_1.c$
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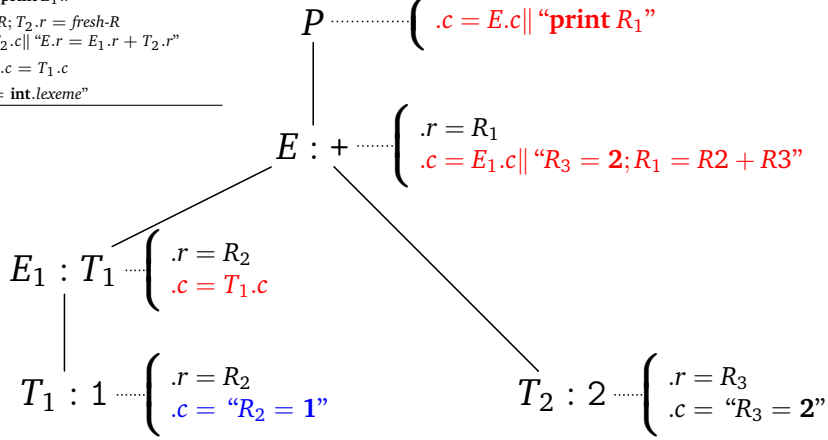

Example (attributes VII)

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
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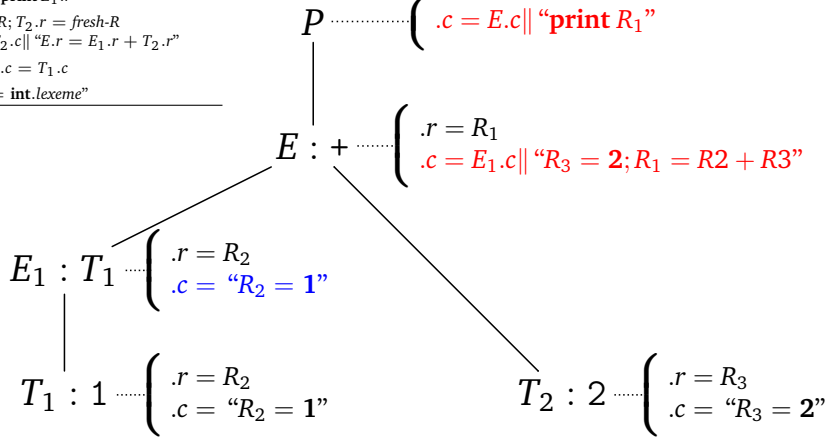

Example (attributes VIII)

PRODUCTION	SEMANTIC RULES
$P \to E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \to E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
$E \to T_1$	$T_1.r = E.r; E.c = T_1.c$
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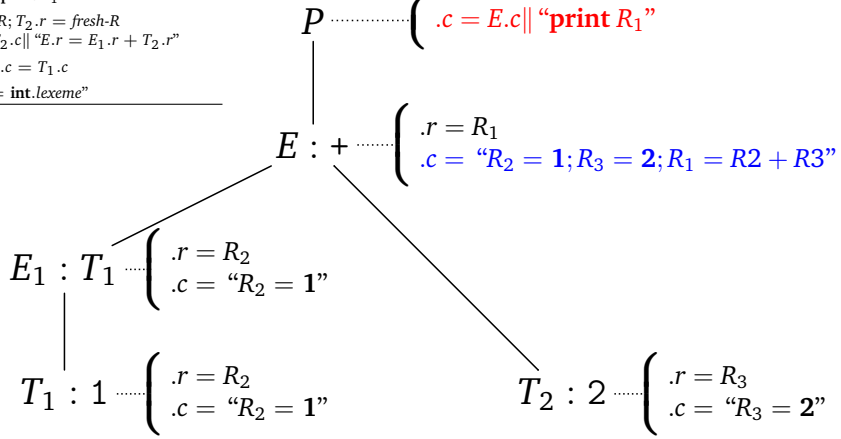

Example (attributes IX)

PRODUCTION	SEMANTIC RULES
$P \to E_1$	$E_1.r = \textit{fresh-R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \to E_1 + T_2$	$E_1.r = \textit{fresh-R}; T_2.r = \textit{fresh-R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
$E \to T_1$	$T_1.r = E.r; E.c = T_1.c$
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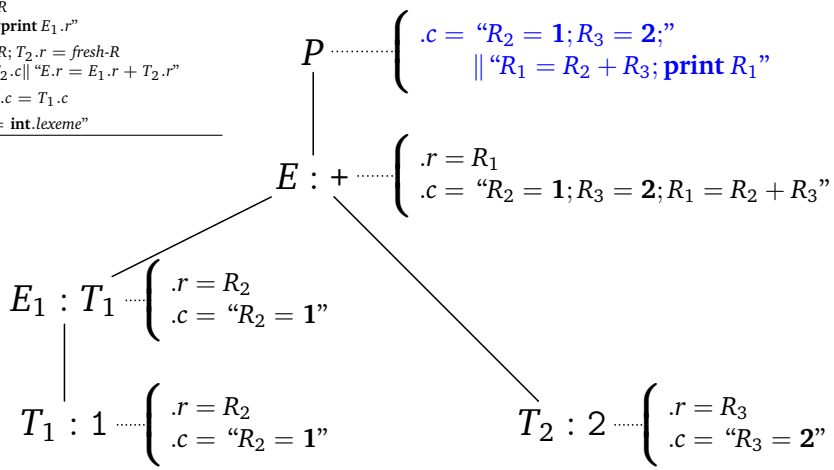
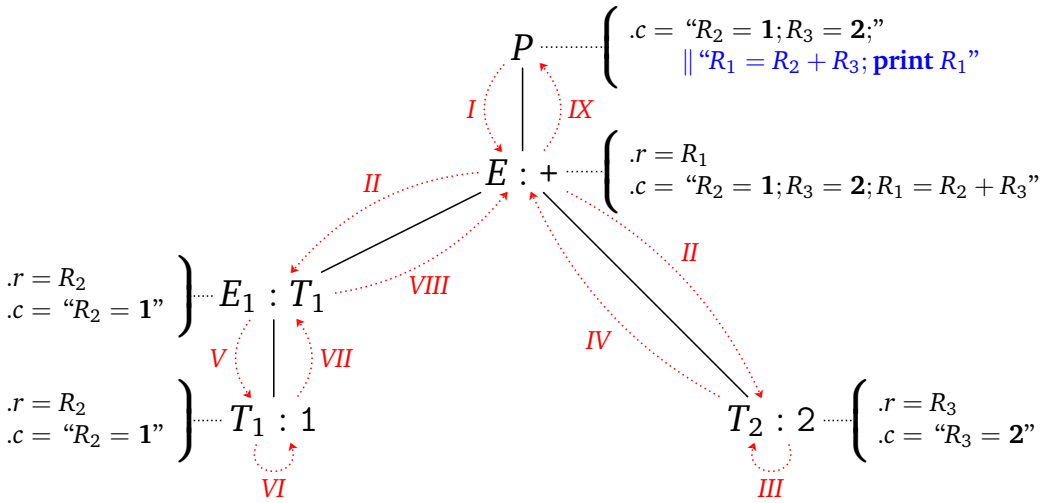


Example (attribute evaluation order)



Semantic Actions

- if we know the tree traversal mechanism left to right post-order—
- then we can replace concatenations with appending side effects.

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Semantic Actions (II)

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$P \rightarrow E_1$	$E_1.r = \mathit{fresh\text{-}R}$ $P.c = E_1.c \Vert$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \mathit{fresh\text{-}R}; T_2.r = \mathit{fresh\text{-}R}$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"
$E \rightarrow T_1$	$T_1.r = E.r; E.c = T_1.c$
$T \rightarrow$ **int**	$T.c =$ "$T.r =$ **int**.*lexeme*"

Semantic Actions (III)

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \mathit{fresh}\text{-}R$ $\{$ **emit** "**print** $E_1.r$" $\}$
$E \rightarrow E_1 + T_2$	$E_1.r = \mathit{fresh}\text{-}R; T_2.r = \mathit{fresh}\text{-}R$ $\{$ **emit** "$E.r = E_1.r + T_2.r$" $\}$
$E \rightarrow T_1$	$T_1.r = E.r$
$T \rightarrow$ **int**	$\{$ **emit** "$T.r =$ **int**.*lexeme*" $\}$

Outline

SDD = Grammar + Semantic (Attribute) Rules

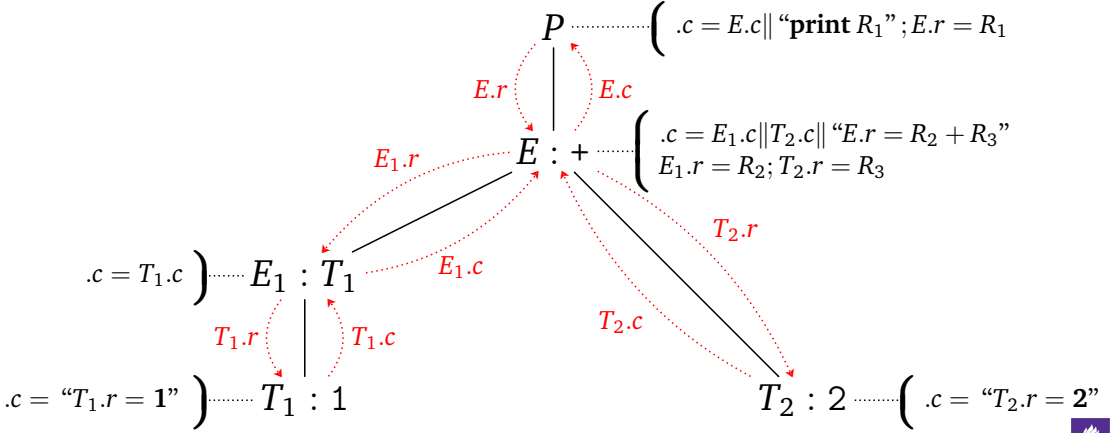
Synthesized attribute: Defined for result non-terminal of production.

Inherited attribute: Defined for (or "sent to") component non-terminals of production.

Cycles possible!

PRODUCTION	SEMANTIC RULES
$A \rightarrow B_1$	$A.s = B.i \; ; \; B.i = A.s + 1$

Dependency Graph



Good SDD Classes

S-attributed: Only synthesized attributes.

L-attributed: Each attribute is *either*

- synthesized (without restrictions), or
- inherited but for a production

$$A \to X_1 X_2 \ldots X_n$$

where inherited attributes for X_j only depends on inherited attributes for A and $X_1, \ldots, X_{j-1}$ and on synthesized attributes of $X_1, \ldots, X_{j-1}$.

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HACS-Attributed

HACS supports:

- S-attributed SDDs.
- Recursive Translation Schemes with named arguments.

For convenience the named arguments are called inherited attributes.

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- Recursive Translation Schemes with named arguments.

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Example, Again

PRODUCTION	SEMANTIC RULES
$P \rightarrow E_1$	$E_1.r = \mathit{fresh\text{-}R}$ $P.c = E_1.c \,\|\|$ "**print** $E_1.r$"
$E \rightarrow E_1 + T_2$	$E_1.r = \mathit{fresh\text{-}R}; T_2.r = \mathit{fresh\text{-}R}$ $E.c = E_1.c \,\|\| T_2.c \,\|\|$ "$E.r = E_1.r + T_2.r$"
$E \rightarrow T_1$	$T_1.r = E.r; E.c = T_1.c$
$T \rightarrow$ **int**	$T.c =$ "$T.r =$ **int**.*lexeme*"

Grammar

$$P \to E_1 \qquad E \to E_1 + T_2 \qquad E \to T_1 \qquad T \to \textbf{int}$$

token *INTEGER* | [0−9]+ ;

sort P | ⟦ ⟨E⟩ ⟧ ;
sort E | ⟦ ⟨E⟩ + ⟨T⟩ ⟧ | ⟦ ⟨T⟩ ⟧ ;
sort T | ⟦ ⟨*INTEGER*⟩ ⟧;

Grammar

$$P \to E_1 \qquad E \to E_1 + T_2 \qquad E \to T_1 \qquad T \to \textbf{int}$$

token *INTEGER* | [0−9]+ ;

sort P | ⟦ ⟨E⟩ ⟧ ;
sort E | ⟦ ⟨E⟩ + ⟨T⟩ ⟧ | ⟦ ⟨T⟩ ⟧ ;
sort T | ⟦ ⟨*INTEGER*⟩ ⟧;

Attribute Sorts

token *REGISTER* | `'R'` (`'_'` ⟨*INTEGER*⟩)? ;

sort *Reg* | **symbol** ⟦⟨*REGISTER*⟩ ⟧;
sort *Code* | ⟦ *print* ⟨*Reg*⟩ ⟧@*1*
| ⟦ ⟨*Reg*⟩ = ⟨*Reg*⟩ + ⟨*Reg*⟩ ⟧@*1*
| ⟦ ⟨*Reg*⟩ = ⟨*INTEGER*⟩ ⟧@*1*
| ⟦ ⟨*Code*@*1*⟩ ;¶ ⟨*Code*⟩ ⟧
| ⟦⟧ ;

attribute ↓*r*(*Reg*) ;
attribute ↑*c*(*Code*) ;

Example, Again

$P \rightarrow E_1$	$E_1.r = \mathit{fresh}\text{-}R \quad P.c = E_1.c \Vert$ “**print** $E_1.r$”

Example, Again

$P \to E_1$	$E_1.r = \mathit{fresh}\text{-}R \quad P.c = E_1.c \Vert$ "**print** $E_1.r$"

sort P | **scheme** $R\_P(P)$ | **scheme** $R\_P1(P, Reg)$;

$R\_P(\llbracket\ \langle E\#1 \rangle\ \rrbracket)$
$\quad \to R\_P1(\llbracket\ \langle E\ R\_E(E\#1)\ \downarrow r(\llbracket R\_1 \rrbracket) \rangle\ \rrbracket, \llbracket R\_1 \rrbracket)$;

$R\_P1(\llbracket\ \langle E\#1\ \uparrow c(Code\#c1) \rangle\ \rrbracket, Reg\#r)$
$\quad \to \llbracket\ \langle E\#1 \rangle\ \rrbracket \uparrow c(\llbracket\ \langle Code\#c1 \rangle\ ;\ print\ \langle Reg\#r \rangle\ \rrbracket)$;

Example, Again

$E \to T_1$	$T_1.r = E.r; E.c = T_1.c$

Example, Again

$E \to T_1$	$T_1.r = E.r; E.c = T_1.c$

sort E | **scheme** $R\_E(E) \downarrow r$;

$R\_E(\llbracket \langle T\#1 \rangle \rrbracket) \downarrow r(Reg\#r)$
$\quad \to R\_E1(\llbracket \langle T\ R\_T(T\#1) \downarrow r(Reg\#r) \rangle \rrbracket)$;

| **scheme** $R\_E1(E)$;

$R\_E1(\llbracket \langle T\#1 \uparrow c(Code\#c1) \rangle \rrbracket)$
$\quad \to \llbracket \langle T\#1 \rangle \rrbracket \uparrow c(Code\#c1)$;

Example, Again

$E \rightarrow E_1 + T_2$	$E_1.r = \mathit{fresh}\text{-}R; T_2.r = \mathit{fresh}\text{-}R$ $E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"

$R\_E(\llbracket \langle E\#1 \rangle + \langle T\#2 \rangle \rrbracket) \downarrow r(Reg\#r)$
$\rightarrow R\_E2(\llbracket \langle E\ R\_E(E\#1) \downarrow r(\llbracket R\_1 \rrbracket) \rangle$
$+ \langle T\ R\_T(T\#2) \downarrow r(\llbracket R\_2 \rrbracket) \rangle \rrbracket,$
$Reg\#r, \llbracket R\_1 \rrbracket, \llbracket R\_2 \rrbracket)$;

| **scheme** $R\_E2(E, Reg, Reg, Reg)$;

$R\_E2(\llbracket \langle E\#1 \uparrow c(Code\#c1) \rangle + \langle T\#2 \uparrow c(Code\#c2) \rangle \rrbracket, Reg\#r, Reg\#r1, Reg\#r2)$
$\rightarrow \llbracket \langle E\#1 \rangle + \langle T\#2 \rangle \rrbracket$
$\uparrow c(\llbracket \langle Code\#c1 \rangle ; \langle Code\#c2 \rangle ; \langle Reg\#r \rangle = \langle Reg\#r1 \rangle + \langle Reg\#r2 \rangle \rrbracket)$;

Example, Again

$E \to E_1 + T_2$	$E_1.r = \mathit{fresh\text{-}R}; T_2.r = \mathit{fresh\text{-}R}$
	$E.c = E_1.c \Vert T_2.c \Vert$ "$E.r = E_1.r + T_2.r$"

$$
\begin{aligned}
&R\_E([\![\ \langle E\#1\rangle + \langle T\#2\rangle\ ]\!])\downarrow r(\mathit{Reg}\#r)\\
&\quad \to R\_E2([\![\ \langle E\ R\_E(E\#1)\downarrow r([\![R\_1]\!])\rangle\\
&\qquad\qquad + \langle T\ R\_T(T\#2)\downarrow r([\![R\_2]\!])\rangle\ ]\!],\\
&\qquad\quad \mathit{Reg}\#r, [\![R\_1]\!], [\![R\_2]\!])\ ;
\end{aligned}
$$

$$
\mid \textbf{scheme}\ R\_E2(E, \mathit{Reg}, \mathit{Reg}, \mathit{Reg})\ ;
$$

$$
\begin{aligned}
&R\_E2([\![\ \langle E\#1\uparrow c(\mathit{Code}\#c1)\rangle + \langle T\#2\uparrow c(\mathit{Code}\#c2)\rangle\ ]\!], \mathit{Reg}\#r, \mathit{Reg}\#r1, \mathit{Reg}\#r2)\\
&\quad \to [\![\ \langle E\#1\rangle + \langle T\#2\rangle\ ]\!]\\
&\qquad \uparrow c([\![\ \langle \mathit{Code}\#c1\rangle\ ;\ \langle \mathit{Code}\#c2\rangle\ ;\ \langle \mathit{Reg}\#r\rangle = \langle \mathit{Reg}\#r1\rangle + \langle \mathit{Reg}\#r2\rangle\ ]\!])\ ;
\end{aligned}
$$

Example, Again

$T \rightarrow \mathbf{int}$	$T.c = \text{“}T.r = \mathbf{int}.lexeme\text{”}$

sort T | **scheme** $R\_T(T) \downarrow r$;

$R\_T(\llbracket \langle INTEGER\#lexeme \rangle \rrbracket) \downarrow r(Reg\#r)$
$\rightarrow \llbracket \langle INTEGER\#lexeme \rangle \rrbracket \uparrow c(\llbracket \langle Reg\#r \rangle = \langle INTEGER\#lexeme \rangle \rrbracket)$;

Example, Again

$T \rightarrow \mathbf{int}$	$T.c = \text{“}T.r = \mathbf{int}.lexeme\text{”}$

sort T | **scheme** $R\_T(T) \downarrow r$;

$R\_T(\llbracket \langle INTEGER\#lexeme \rangle \rrbracket) \downarrow r(Reg\#r)$
$\quad \rightarrow \llbracket \langle INTEGER\#lexeme \rangle \rrbracket \uparrow c(\llbracket \langle Reg\#r \rangle = \langle INTEGER\#lexeme \rangle \rrbracket)$;

Questions?

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