G22.2130-001

Compiler Construction

Lecture 9:
Intermediate-Code Generation

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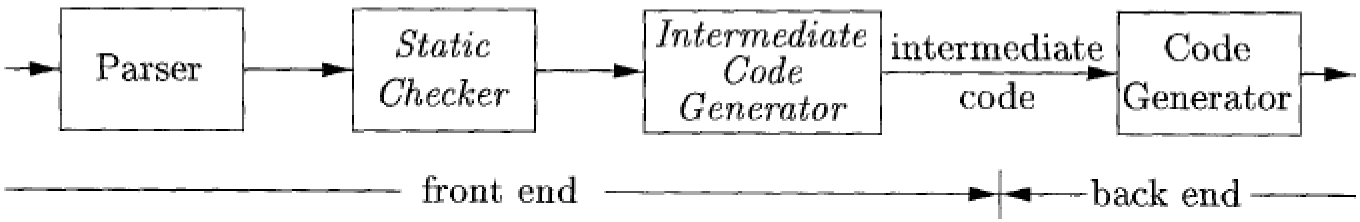
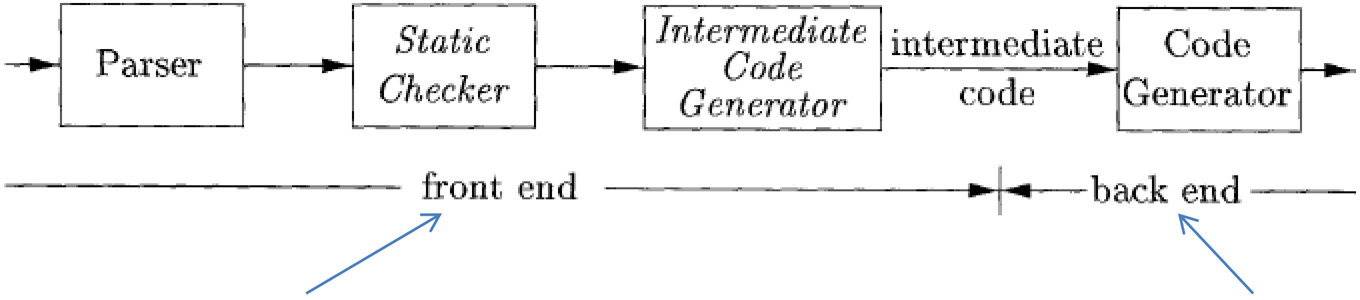
Back-end and Front-end of A Compiler

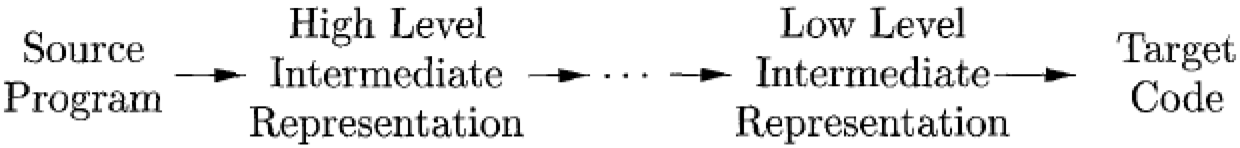


Back-end and Front-end of A Compiler



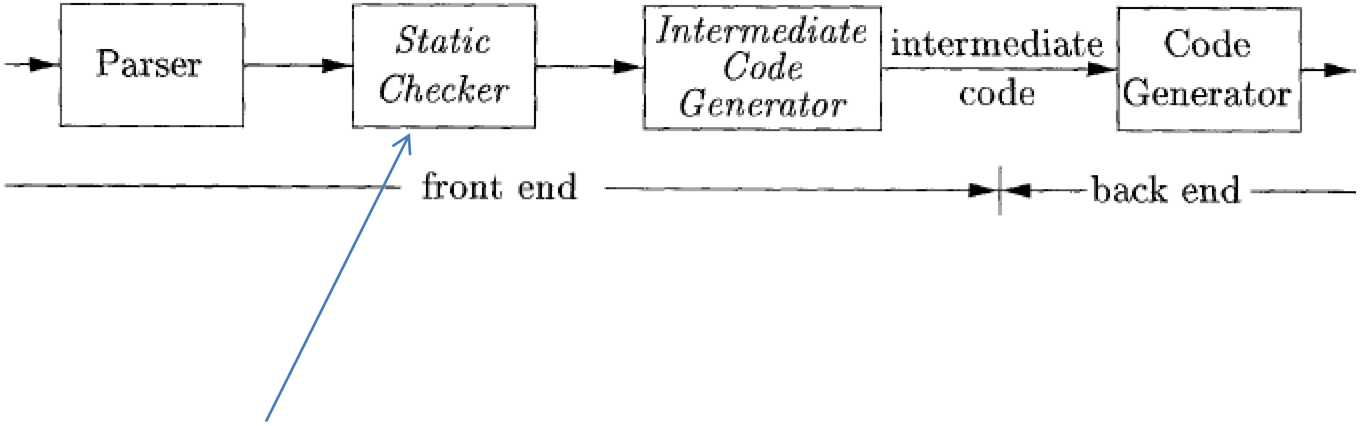
Close to source language
(e.g. syntax tree)

Close to machine language



m x n compilers can be built by writing just m front ends and n back ends

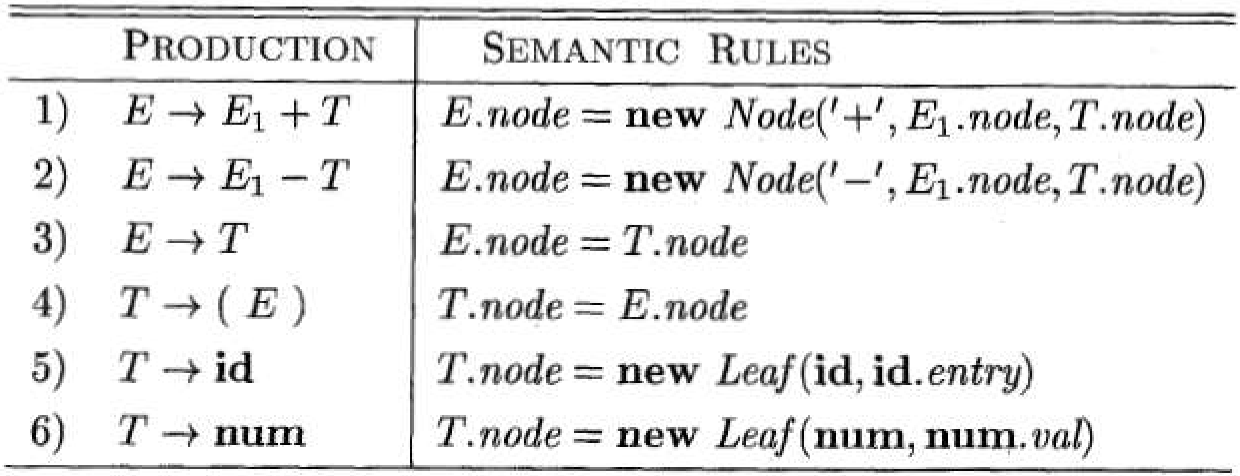
Back-end and Front-end of A Compiler



Includes:

- Type checking
- Any syntactic checks that remain after parsing (e.g. ensure *break* statement is enclosed within while-, for-, or switch statements).

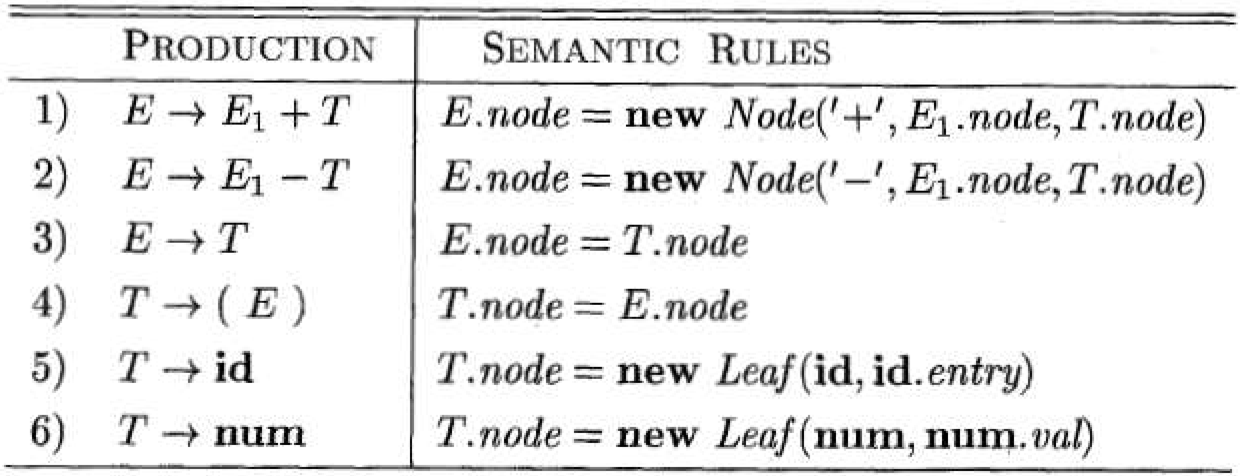
Syntax Tree



	PRODUCTION	SEMANTIC RULES
1)	$E \rightarrow E_1 + T$	$E.node = \textbf{new } Node('+', E_1.node, T.node)$
2)	$E \rightarrow E_1 - T$	$E.node = \textbf{new } Node('-', E_1.node, T.node)$
3)	$E \rightarrow T$	$E.node = T.node$
4)	$T \rightarrow (E)$	$T.node = E.node$
5)	$T \rightarrow \textbf{id}$	$T.node = \textbf{new } Leaf(\textbf{id}, \textbf{id}.entry)$
6)	$T \rightarrow \textbf{num}$	$T.node = \textbf{new } Leaf(\textbf{num}, \textbf{num}.val)$

`a + a * (b - c) + (b - c) * d`

Syntax Tree



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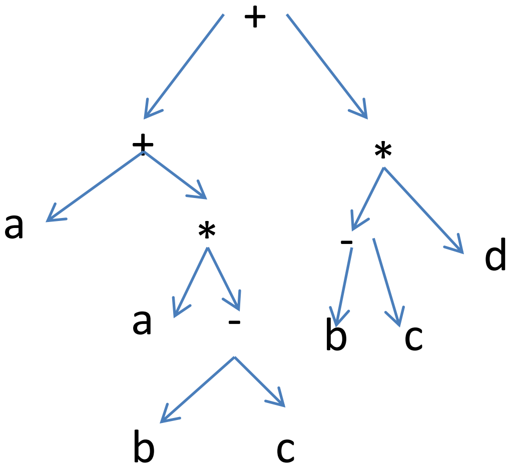

Syntax Tree

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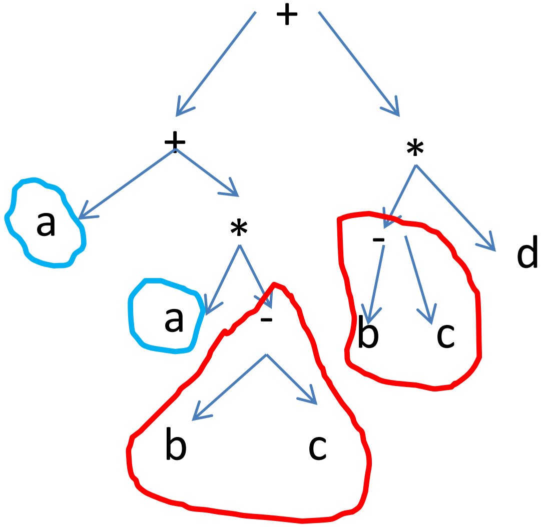
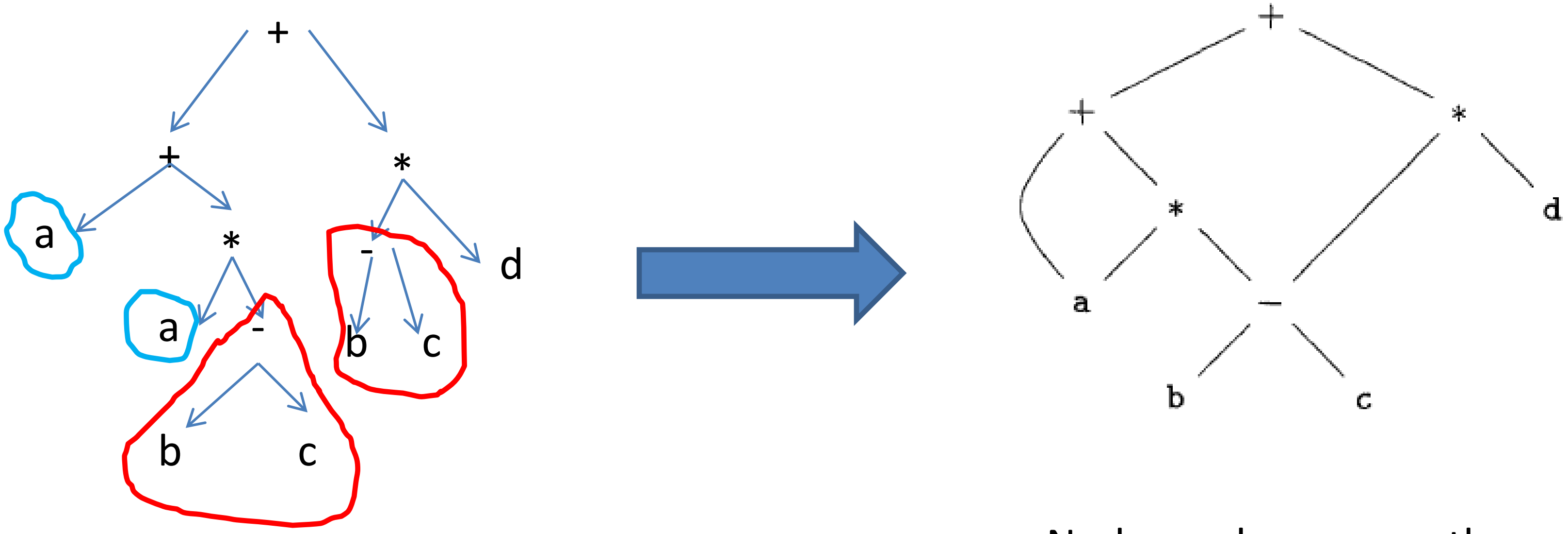
`a + a * (b - c) + (b - c) * d`



Syntax Tree



Node can have more than one parent

Directed Acyclic Graph (DAG):

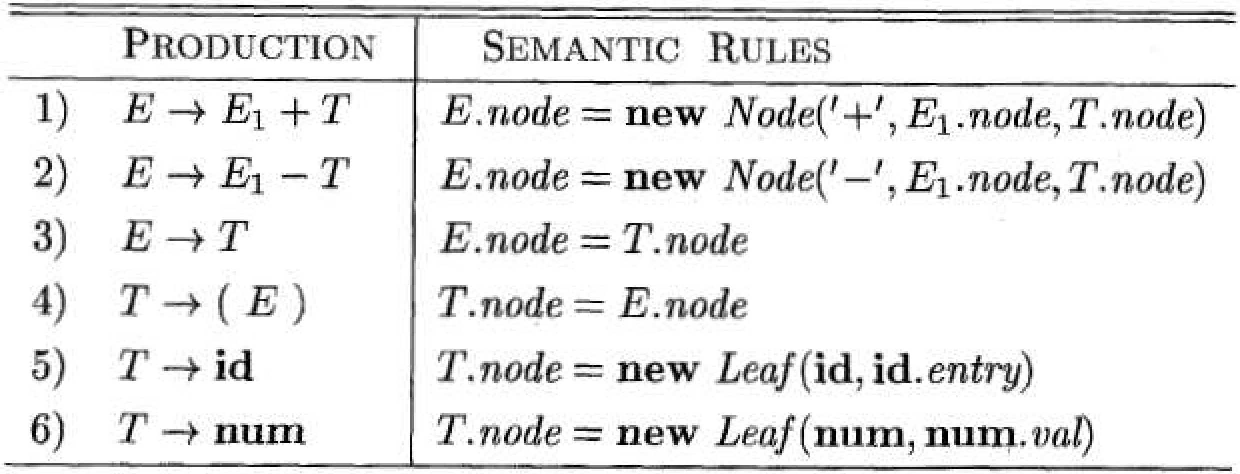
- More compact representation
- Gives clues regarding generation of efficient code

Example

Construct the DAG for:

$$((x + y) - ((x + y) * (x - y))) + ((x + y) * (x - y))$$

How to Generate DAG from Syntax-Directed Definition?



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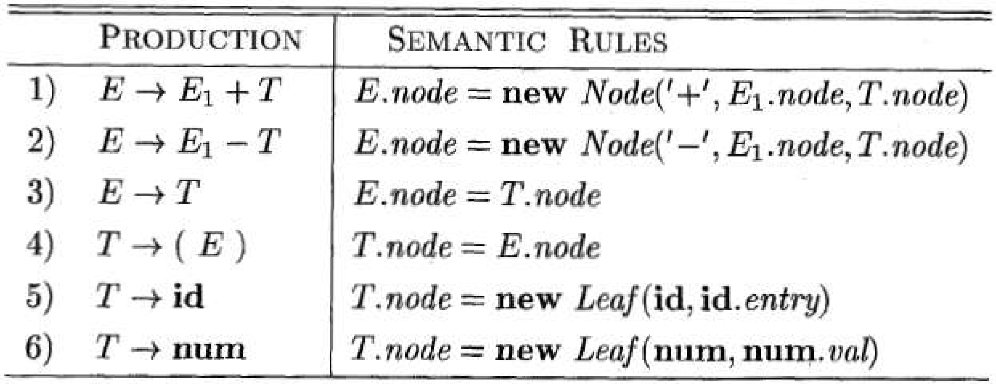
All what is needed is that functions such as ***Node*** and ***Leaf*** above check whether a node already exists. If such a node exists, a pointer is returned to that node.

How to Generate DAG from Syntax-Directed Definition?



	PRODUCTION	SEMANTIC RULES
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2)	$E \to E_1 - T$	$E.node = \mathbf{new}\ Node('-', E_1.node, T.node)$
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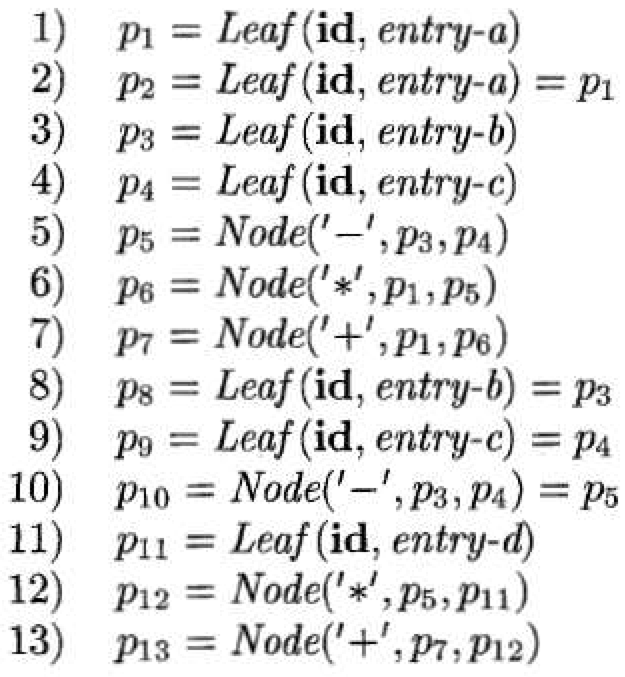
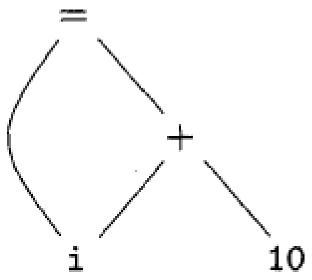
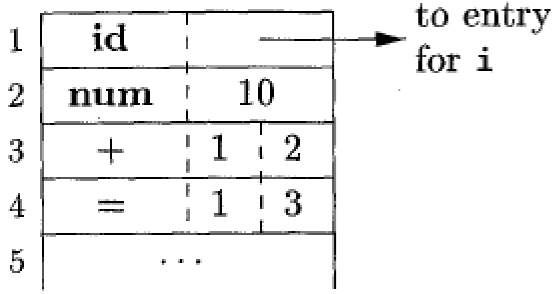


1) $p_1 = Leaf(\mathbf{id}, entry\text{-}a)$
2) $p_2 = Leaf(\mathbf{id}, entry\text{-}a) = p_1$
3) $p_3 = Leaf(\mathbf{id}, entry\text{-}b)$
4) $p_4 = Leaf(\mathbf{id}, entry\text{-}c)$
5) $p_5 = Node('-', p_3, p_4)$
6) $p_6 = Node('*', p_1, p_5)$
7) $p_7 = Node('+', p_1, p_6)$
8) $p_8 = Leaf(\mathbf{id}, entry\text{-}b) = p_3$
9) $p_9 = Leaf(\mathbf{id}, entry\text{-}c) = p_4$
10) $p_{10} = Node('-', p_3, p_4) = p_5$
11) $p_{11} = Leaf(\mathbf{id}, entry\text{-}d)$
12) $p_{12} = Node('*', p_5, p_{11})$
13) $p_{13} = Node('+', p_7, p_{12})$

`a + a * (b - c) + (b - c) * d`

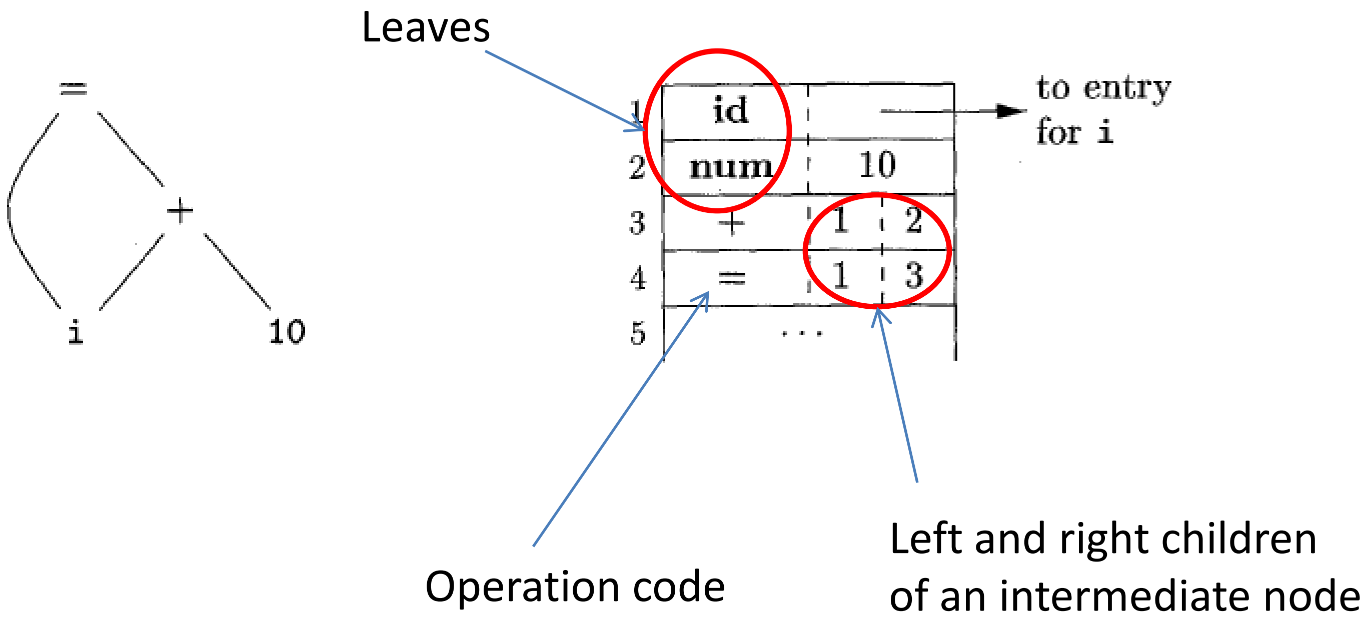
Data Structure: Array





1	**id**		
2	**num**	10	
3	+	1	2
4	=	1	3
5	. . .		

Data Structure: Array



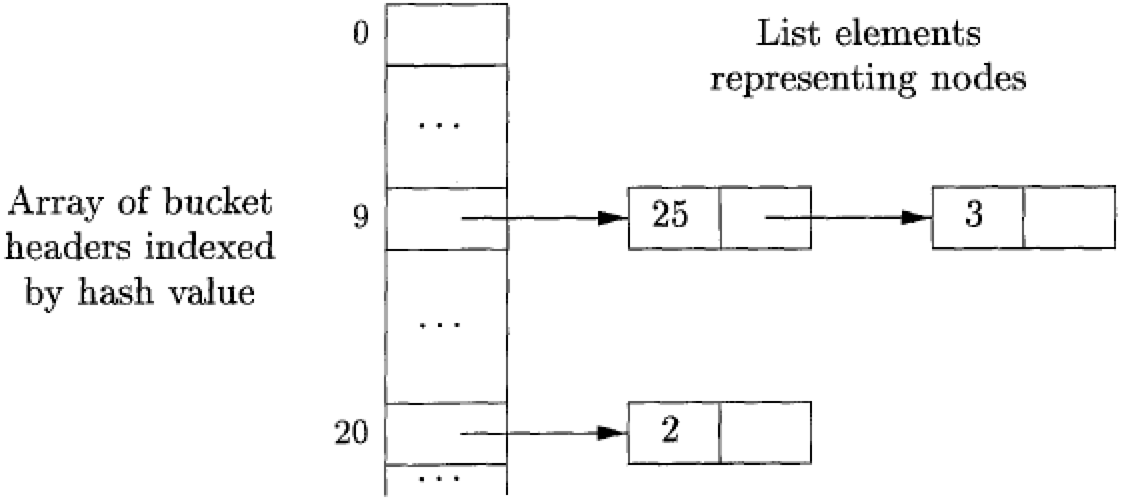
Leaves

Operation code

Left and right children of an intermediate node

Scanning the array each time a new node is needed, is not an efficient thing to do.

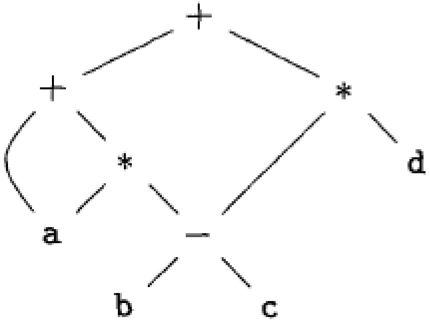
Data Structure: Hash Table

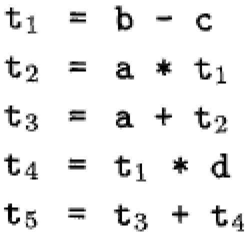


Hash function = h(op, L, R)

Three-Address Code

- Another option for intermediate presentation
- Built from two concepts:
  - addresses and instructions
- At most one operator





$t_1 = b - c$

$t_2 = a * t_1$

$t_3 = a + t_2$

$t_4 = t_1 * d$

$t_5 = t_3 + t_4$

Address

Can be one of the following:

- A name: source program name
- A constant
- Compiler-generated temporary

Instructions

Assignment instructions of the form $x = y \; op \; z$

Assignments of the form $x = op \; y$

Copy instructions of the form $x = y$

An unconditional jump `goto` L

Conditional jumps of the form `if` x `goto` L and `ifFalse` x `goto` L

Conditional jumps such as `if` $x \; relop \; y$ `goto` L

Procedure call such as p(x1, x2, …, xn) is implemented as:

`param` x_1
`param` x_2
. . .
`param` x_n
`call` p, n

Indexed copy instructions of the form $x = y[i]$ and $x[i] = y$.

Address and pointer assignments of the form $x = \& y$, $x = * y$, and $* x = y$

Example

```
do i = i+1; while (a[i] < v);
```

```
L:   t1 = i + 1
     i = t1
     t2 = i * 8
     t3 = a [ t2 ]
     if t3 < v goto L
```

OR

```
100:   t1 = i + 1
101:   i = t1
102:   t2 = i * 8
103:   t3 = a [ t2 ]
104:   if t3 < v goto 100
```

Choice of Operator Set

- Rich enough to implement the operations of the source language
- Close enough to machine instructions to simplify code generation

Data Structure

How to present these instructions in a data structure?

- Quadruples
- Triples
- Indirect triples

Data Structure: Quadruples

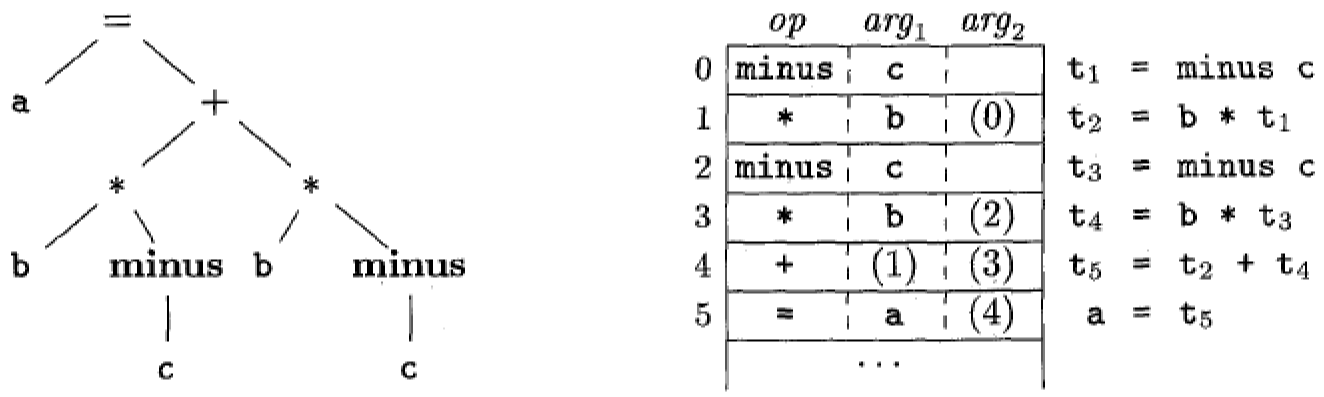
- Has four fields: op, arg1, arg2, result
- Exceptions:
  - Unary operators: no arg2
  - Operators like *param*: no arg2, no result
  - (Un)conditional jumps: target label is the result

```
t1 = minus c
t2 = b * t1
t3 = minus c
t4 = b * t3
t5 = t2 + t4
 a = t5
```

	op	arg_1	arg_2	*result*
0	minus	c		t_1
1	*	b	t_1	t_2
2	minus	c		t_3
3	*	b	t_3	t_4
4	+	t_2	t_4	t_5
5	=	t_5		a
		…		

Data Structure: Triples

- Only three fields: no *result* field
- Results referred to by its position



	op	arg_1	arg_2	
0	minus	c		t_1 = minus c
1	*	b	(0)	t_2 = b * t_1
2	minus	c		t_3 = minus c
3	*	b	(2)	t_4 = b * t_3
4	+	(1)	(3)	t_5 = t_2 + t_4
5	=	a	(4)	a = t_5
		. . .		

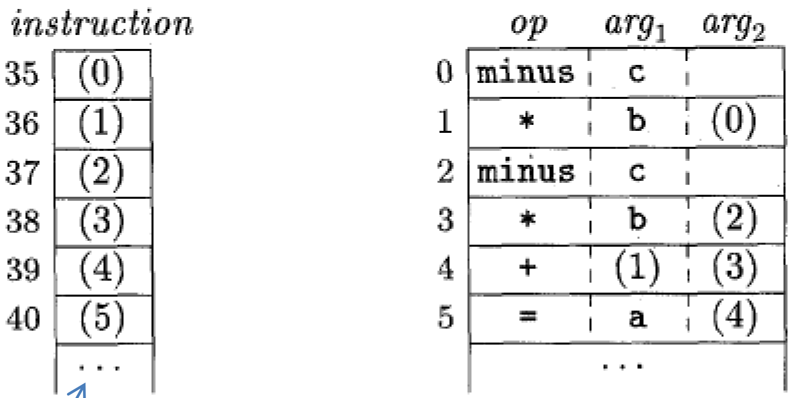
(a) Syntax tree

(b) Triples

Representations of $a + a * (b - c) + (b - c) * d$

Data Structure: Indirect Triples

- When instructions are moving around during optimizations: quadruples are better than triples.
- Indirect triples solve this problem



	instruction
35	(0)
36	(1)
37	(2)
38	(3)
39	(4)
40	(5)
	. . .

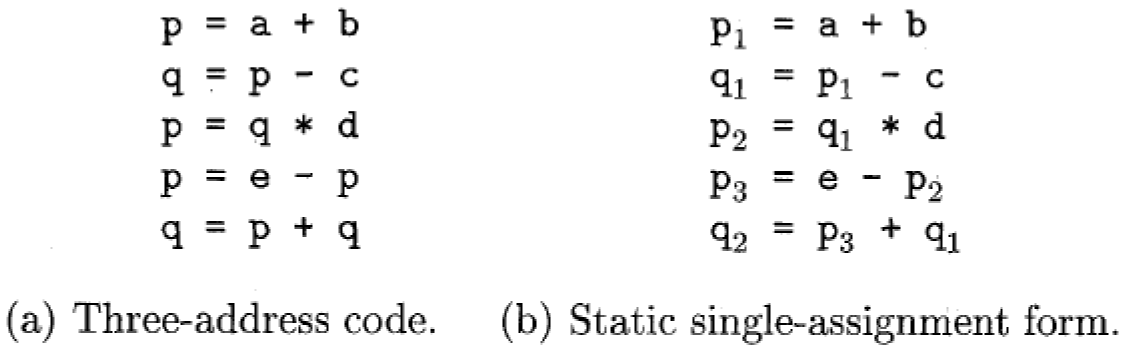
	op	arg_1	arg_2
0	minus	c	
1	*	b	(0)
2	minus	c	
3	*	b	(2)
4	+	(1)	(3)
5	=	a	(4)
		. . .	

List of pointers to triples

Optimizing complier can reorder instruction list, instead of affecting the triples themselves

Single-Static-Assignment (SSA)

- Is an intermediate presentation
- Facilitates certain code optimizations
- All assignments are to variables with distinct names



$p = a + b$
$q = p - c$
$p = q * d$
$p = e - p$
$q = p + q$

(a) Three-address code.

$p_1 = a + b$
$q_1 = p_1 - c$
$p_2 = q_1 * d$
$p_3 = e - p_2$
$q_2 = p_3 + q_1$

(b) Static single-assignment form.

Single-Static-Assignment (SSA)

Example:

```
if ( flag ) x = -1; else x = 1;
y = x * a;
```

If we use different names for X in true part and false part, then which name shall we use in the assignment of ***y = x * a*** ?

The answer is: Ø-function

if (flag) x_1 = -1; else x_2 = 1;

$x_3 = \phi(x_1, x_2)$;

Returns the value of its argument that corresponds to the control-flow path that was taken to get to the assignment statement containing the Ø-function

Example

Translate the arithmetic expression $a + -(b + c)$ into:

a) A syntax tree.

b) Quadruples.

c) Triples.

d) Indirect triples.

Types and Declarations

- Type checking: to ensure that types of operands match the type expected by operator
- Determine the storage needed
- Calculate the address of an array reference
- Insert explicit type conversion
- Choose the right version of an operator
- …

Storage Layout

- From the type, we can determine amount of storage at run time.
- At compile time, we will use this amount to assign its name a relative address.
- Type and relative address are saved in the symbol table entry of the name.
- Data with length determined only at run time saves a pointer in the symbol table.

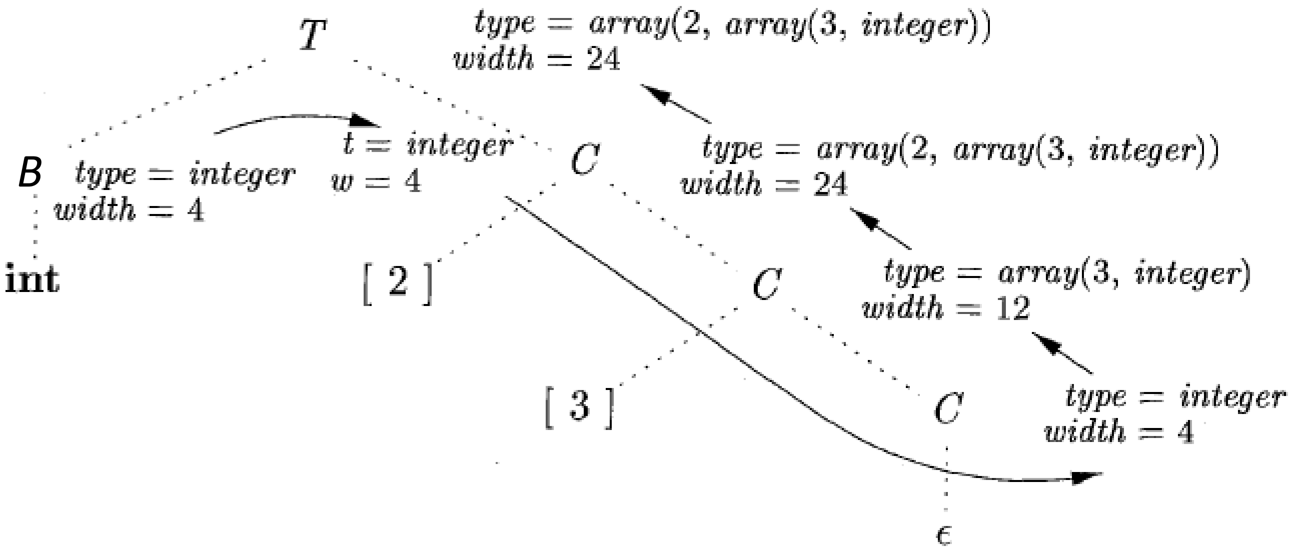
Storage Layout

- Multibyte objects are stored in consecutive bytes and given the address of the first byte
- Storage for aggregates (e.g. arrays and classes) is allocated in one contiguous block of bytes.

$$
\begin{array}{lcl}
D & \rightarrow & T\ \textbf{id}\ ;\ D \ \mid\ \epsilon \\
T & \rightarrow & B\ C \ \mid\ \textbf{record}\ '\{'\ D\ '\}' \\
B & \rightarrow & \textbf{int} \ \mid\ \textbf{float} \\
C & \rightarrow & \epsilon \ \mid\ [\ \textbf{num}\ ]\ C
\end{array}
$$

$$\begin{array}{llll}
T & \rightarrow & B & \{\ t = B.type;\ w = B.width;\ \} \\
 & & C & \\
B & \rightarrow & \textbf{int} & \{\ B.type = integer;\ B.width = 4;\ \} \\
B & \rightarrow & \textbf{float} & \{\ B.type = float;\ B.width = 8;\ \} \\
C & \rightarrow & \epsilon & \{\ C.type = t;\ C.width = w;\ \} \\
C & \rightarrow & [\ \textbf{num}\ ]\ C_1 & \{\ array(\textbf{num}.value,\ C_1.type); \\
 & & & \quad C.width = \textbf{num}.value \times C_1.width;\ \}
\end{array}$$

`int[2][3]`



$$
\begin{array}{lcll}
P & \rightarrow & & \{\ \mathit{offset} = 0;\ \} \\
 & & D & \\
D & \rightarrow & T\ \mathbf{id}\ \mathbf{;} & \{\ \mathit{top.put}(\mathbf{id}.\mathit{lexeme},\ T.\mathit{type},\ \mathit{offset}); \\
 & & & \quad \mathit{offset}\ =\ \mathit{offset} + T.\mathit{width};\ \} \\
 & & D_1 & \\
D & \rightarrow & \epsilon &
\end{array}
$$

To keep track of the next available relative address

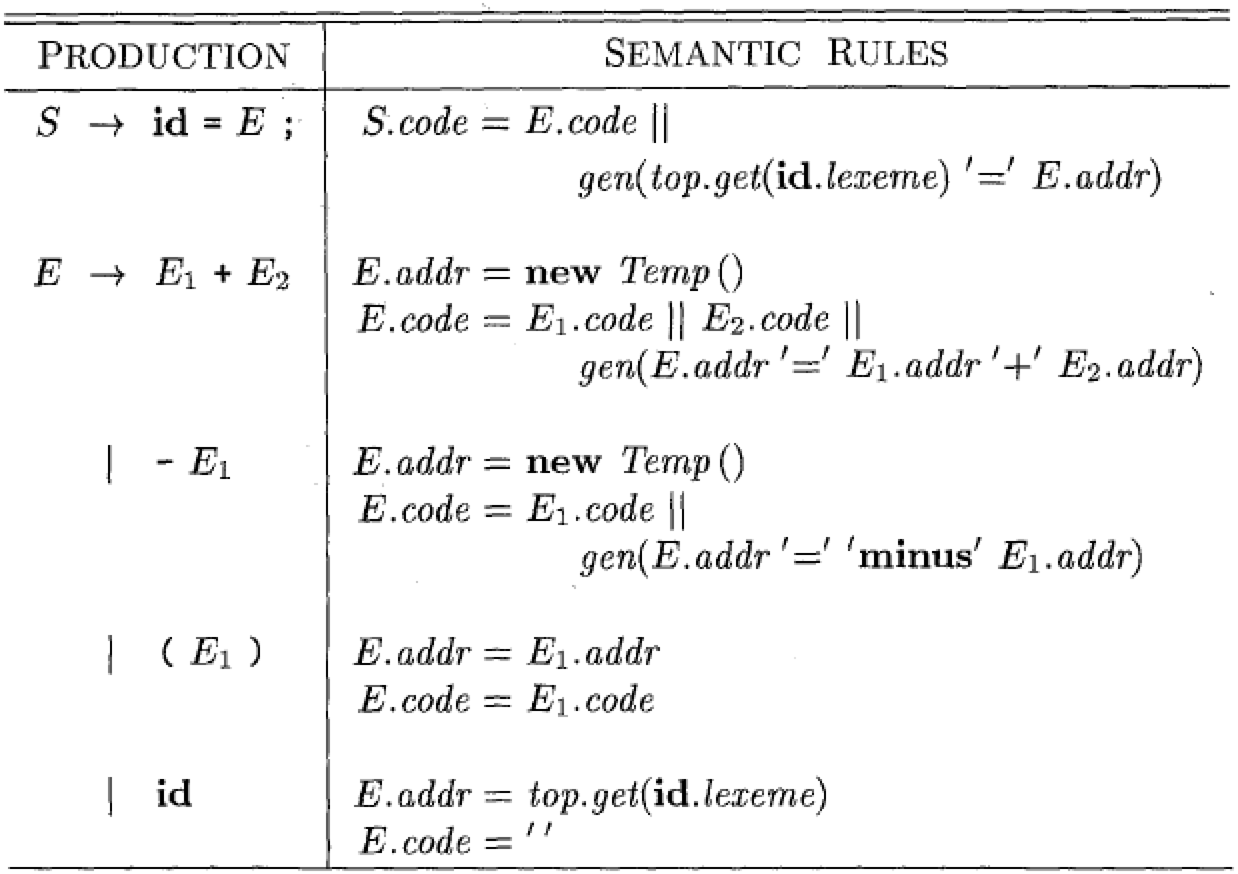
$$
\begin{array}{lll}
P & \rightarrow & \qquad\qquad \{\ \mathit{offset} = 0;\ \} \\
 & & D \\
D & \rightarrow & T\ \mathbf{id}\ ; \quad \{\ \mathit{top.put}(\mathbf{id}.\mathit{lexeme},\ T.\mathit{type},\ \mathit{offset}); \\
 & & \qquad\qquad\quad \mathit{offset}\ =\ \mathit{offset} + T.\mathit{width};\ \} \\
 & & D_1 \\
D & \rightarrow & \epsilon
\end{array}
$$

Create a symbol table entry

Translations of Statements and Expressions

Syntax-Directed Definition (SDD)

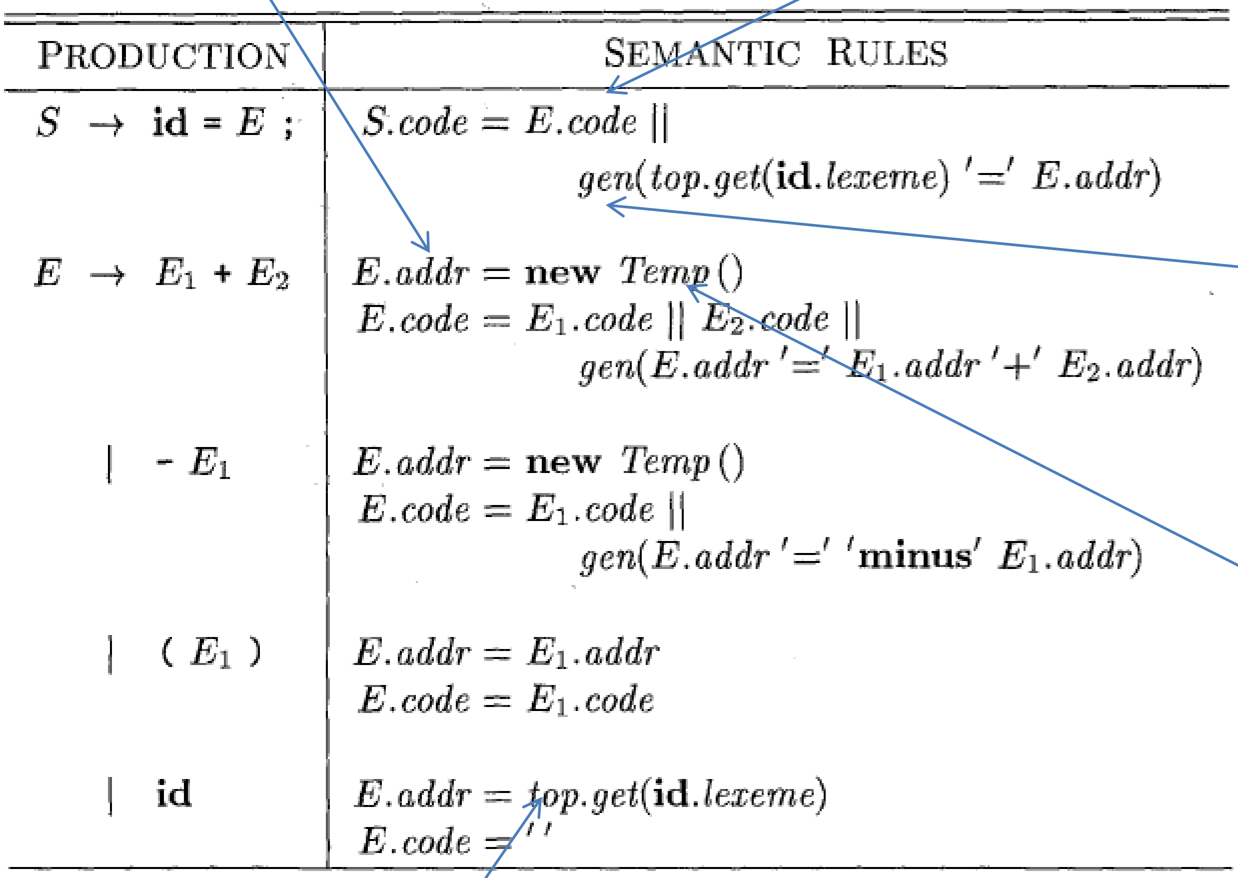
Syntax-Directed Translation (SDT)



PRODUCTION	SEMANTIC RULES
$S \rightarrow \mathbf{id} = E\ ;$	$S.code = E.code \ \|\|$ $gen(top.get(\mathbf{id}.lexeme)\ '='\ E.addr)$
$E \rightarrow E_1 + E_2$	$E.addr = \mathbf{new}\ Temp\,()$ $E.code = E_1.code \ \|\|\ E_2.code \ \|\|$ $gen(E.addr\ '='\ E_1.addr\ '+'\ E_2.addr)$
$\mid\ -\ E_1$	$E.addr = \mathbf{new}\ Temp\,()$ $E.code = E_1.code \ \|\|$ $gen(E.addr\ '='\ '\mathbf{minus}'\ E_1.addr)$
$\mid\ (\ E_1\ )$	$E.addr = E_1.addr$ $E.code = E_1.code$
$\mid\ \mathbf{id}$	$E.addr = top.get(\mathbf{id}.lexeme)$ $E.code = ''$

Address holding value of E
(e.g. tmp variable, name, constant)

Three-address code of E

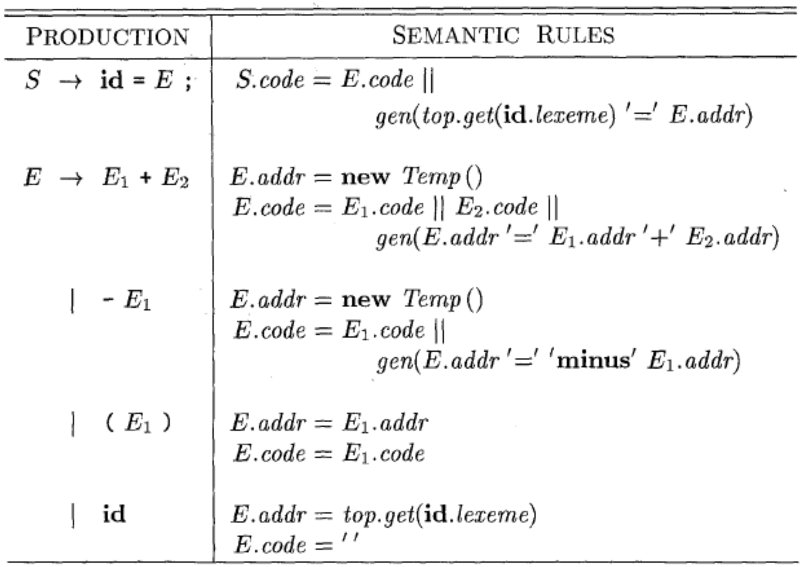


PRODUCTION	SEMANTIC RULES
$S \rightarrow \mathbf{id} = E \;;$	$S.code = E.code \;\|\|$ $gen(top.get(\mathbf{id}.lexeme)\ '='\ E.addr)$
$E \rightarrow E_1 + E_2$	$E.addr = \mathbf{new}\ Temp\,()$ $E.code = E_1.code \;\|\|\; E_2.code \;\|\|$ $gen(E.addr\ '='\ E_1.addr\ '+'\ E_2.addr)$
$\mid\ - E_1$	$E.addr = \mathbf{new}\ Temp\,()$ $E.code = E_1.code \;\|\|$ $gen(E.addr\ '='\ '\mathbf{minus}'\ E_1.addr)$
$\mid\ (\ E_1\ )$	$E.addr = E_1.addr$ $E.code = E_1.code$
$\mid\ \mathbf{id}$	$E.addr = top.get(\mathbf{id}.lexeme)$ $E.code = '\ '$

Build an instruction

Get a temporary variable

Current symbol table



PRODUCTION	SEMANTIC RULES
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$E \rightarrow E_1 + E_2$	$E.addr = \mathbf{new}\ Temp\,()$ $E.code = E_1.code \Vert E_2.code \Vert$ $gen(E.addr\ '='\ E_1.addr\ '+'\ E_2.addr)$
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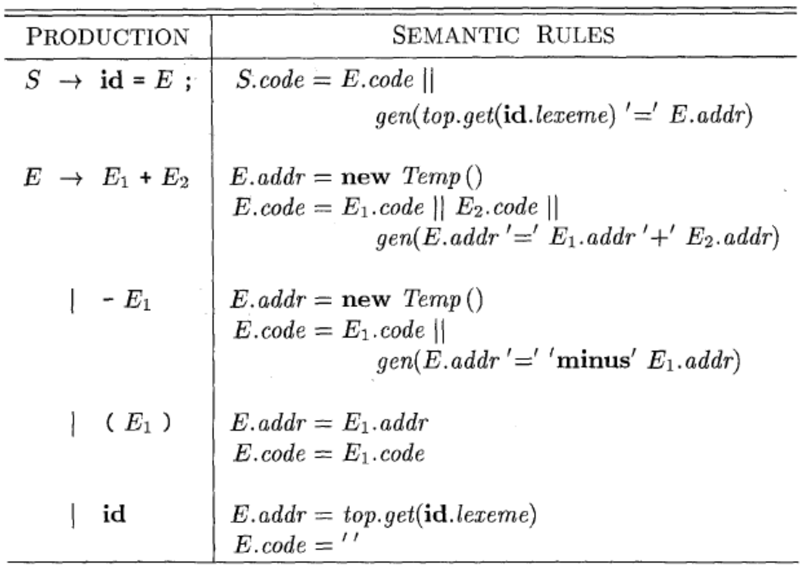
$\mid\ (\ E_1\ )$	$E.addr = E_1.addr$ $E.code = E_1.code$
$\mid\ \mathbf{id}$	$E.addr = top.get(\mathbf{id}.lexeme)$ $E.code = ''$

a = b + - c

```
t1 = minus c
t2 = b + t1
a = t2
```



PRODUCTION	SEMANTIC RULES
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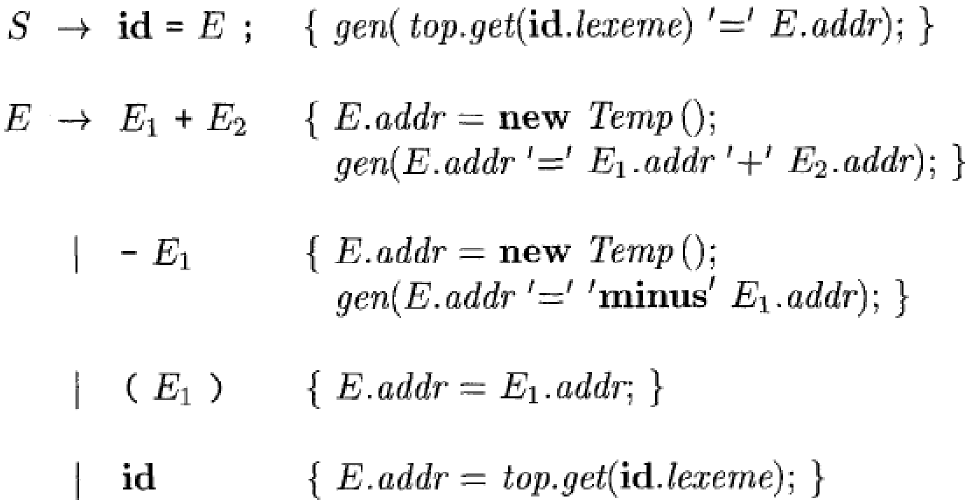
$E \rightarrow E_1 + E_2$	$E.addr = \mathbf{new}\ Temp\,()$ $E.code = E_1.code \ \Vert\ E_2.code \ \Vert$ $gen(E.addr\ '='\ E_1.addr\ '+'\ E_2.addr)$
$\mid\ -E_1$	$E.addr = \mathbf{new}\ Temp\,()$ $E.code = E_1.code \ \Vert$ $gen(E.addr\ '='\ '\mathbf{minus}'\ E_1.addr)$
$\mid\ (\ E_1\ )$	$E.addr = E_1.addr$ $E.code = E_1.code$
$\mid\ \mathbf{id}$	$E.addr = top.get(\mathbf{id}.lexeme)$ $E.code = ''$

Generating three-address code incrementally to avoid long strings manipulations

gen() does two things:

- generate three address instruction
- append it to the sequence of instructions generated so far



$S \rightarrow$	$\mathbf{id} = E\ ;$	$\{\ gen(\ top.get(\mathbf{id}.lexeme)\ '='\ E.addr);\ \}$
$E \rightarrow$	$E_1 + E_2$	$\{\ E.addr = \mathbf{new}\ Temp\,();$ $gen(E.addr\ '='\ E_1.addr\ '+'\ E_2.addr);\ \}$
$\mid$	$-\ E_1$	$\{\ E.addr = \mathbf{new}\ Temp\,();$ $gen(E.addr\ '='\ '\mathbf{minus}'\ E_1.addr);\ \}$
$\mid$	$(\ E_1\ )$	$\{\ E.addr = E_1.addr;\ \}$
$\mid$	$\mathbf{id}$	$\{\ E.addr = top.get(\mathbf{id}.lexeme);\ \}$

Arrays

- Elements of the same type
- Stored consecutively in memory
- In languages like C or Java elements are: 0, 1, …, n-1
- In some other languages:

  low, low+1, …, high

Arrays

If elements start with 0, and element width is w, then a[i] address is: $base + i \times w$
base is address of A[0]

Generalizing to two-dimensions a[i1][i2]:
w1 is width of a row and
w2 the width of an element

$base + i_1 \times w_1 + i_2 \times w_2$

or

w is width of an element, n2 is number of elements per row

$base + (i_1 \times n_2 + i_2) \times w$

Generalizing to k-dimensions: $base + i_1 \times w_1 + i_2 \times w_2 + \cdots + i_k \times w_k$

or

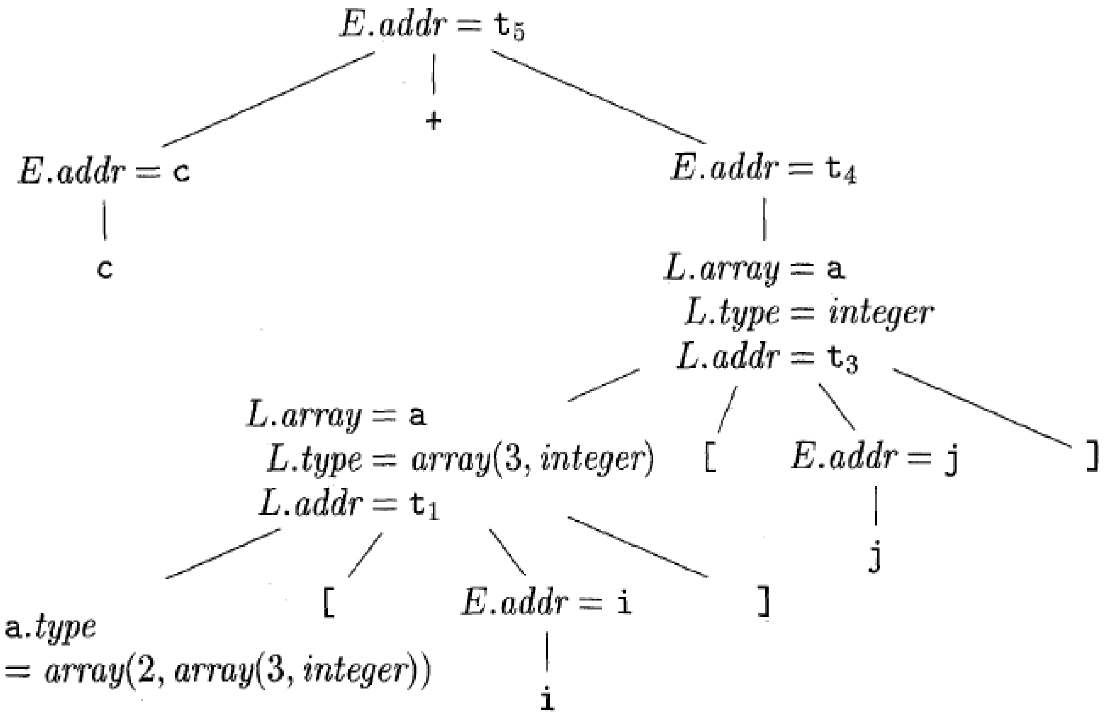
$$base + ((\cdots(i_1 \times n_2 + i_2) \times n_3 + i_3) \cdots) \times n_k + i_k) \times w$$

S	$\rightarrow$	$\textbf{id} = E\ ;$	$\{\ gen(\ top.get(\textbf{id}.lexeme)\ '='\ E.addr);\ \}$
	$\mid$	$L = E\ ;$	$\{\ gen(L.addr.base\ '['\ L.addr\ ']'\ '='\ E.addr);\ \}$
E	$\rightarrow$	$E_1 + E_2$	$\{\ E.addr = \textbf{new}\ Temp\,();$ $gen(E.addr\ '='\ E_1.addr\ '+'\ E_2.addr);\ \}$
	$\mid$	$\textbf{id}$	$\{\ E.addr = top.get(\textbf{id}.lexeme);\ \}$
	$\mid$	L	$\{\ E.addr = \textbf{new}\ Temp\,();$ $gen(E.addr\ '='\ L.array.base\ '['\ L.addr\ ']');\ \}$
L	$\rightarrow$	$\textbf{id}\ [\ E\ ]$	$\{\ L.array = top.get(\textbf{id}.lexeme);$ $L.type = L.array.type.elem;$ $L.addr = \textbf{new}\ Temp\,();$ $gen(L.addr\ '='\ E.addr\ '*'\ L.type.width);\ \}$
	$\mid$	$L_1\ [\ E\ ]$	$\{\ L.array = L_1.array;$ $L.type = L_1.type.elem;$ $t = \textbf{new}\ Temp\,();$ $L.addr = \textbf{new}\ Temp\,();$ $gen(t\ '='\ E.addr\ '*'\ L.type.width);\ \}$ $gen(L.addr\ '='\ L_1.addr\ '+'\ t);\ \}$

temporary used while computing the offset

pointer to symbol table entry

$S \rightarrow$	**id** = E ;	{ *gen(top.get(***id***.lexeme) '=' E.addr);* }
|	L = E ;	{ *gen(L.addr.base '[' L.addr ']' '=' E.ad*
$E \rightarrow$	E_1 + E_2	{ *E.addr* = **new** *Temp* (); *gen(E.addr '=' E_1.addr '+' E_2.addr);*
|	**id**	{ *E.addr = top.get(***id***.lexeme);* }
|	L	{ *E.addr* = **new** *Temp* (); *gen(E.addr '=' L.array.base '[' L.addr*
$L \rightarrow$	**id** [E]	{ *L.array = top.get(***id***.lexeme);* *L.type = L.array.type.elem;* *L.addr* = **new** *Temp* (); *gen(L.addr '=' E.addr '*' L.type.width*
|	L_1 [E]	{ *L.array* = L_1*.array;* *L.type* = L_1*.type.elem;* *t* = **new** *Temp* (); *L.addr* = **new** *Temp* (); *gen(t '=' E.addr '*' L.type.width);* } *gen(L.addr '=' L_1.addr '+' t);* }



Annotated parse tree for c + a[i][j]

A is a 2x3 array of integers

t_1 = i * 12
t_2 = j * 4
t_3 = t_1 + t_2
t_4 = a [t_3]
t_5 = c + t_4

So…

- Skim: 6.3.1, 6.3.2
- Read: Beginning of chapter 6 -> 6.4