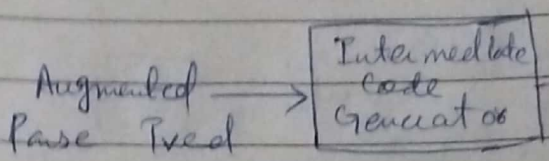
Intermediate Code Generation

Date 9-2



- Last phase of the frontend of a compiler.
- It creates an intermediate representation then the backend will generate targeted machine code.
- The choice of intermediate representation depends on compiler to compiler.
- An intermediate representation can be an actual representation or it may consist of internal data structures.
- C programming language is widely used as an intermediate form because of its flexibility with machine / low-level code.

Variants of Syntax Trees.

- Nodes in a syntax tree represents constructs in the source program, its children represents meaningful components of the construct.
- A directed acyclic graph (DAG) for an expression identifies the common subexpressions of the expression

Directed Acyclic Graphs for Expressions

- DAGs can be constructed using the same technique as for Syntax trees.
- A DAG has leaves corresponding to atomic operands & interior nodes for operators.
- Here a node can have more than one parent, if a common subexpression exists

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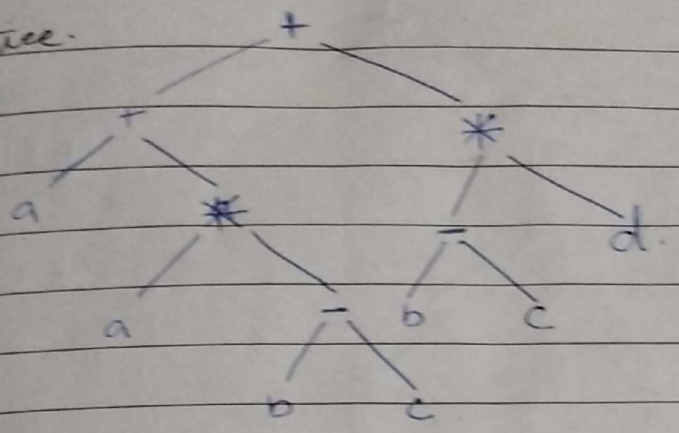
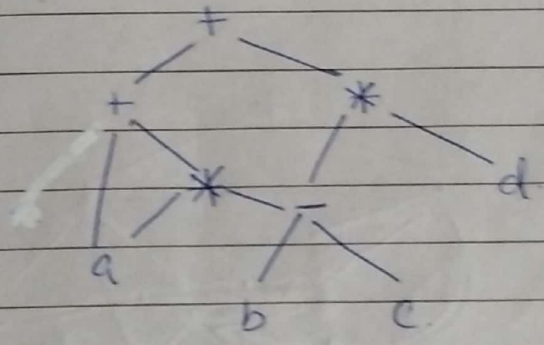
Ex: 6.1 a + a * (b - c) + (b - c) * d.

Syntax tree.



DAG.



Following are semantic rules to construct syntax trees or DAGs.

Productions	Semantic rules.
1) $E \rightarrow E_1 + T$	E.node = new Node('+', E1.node, T.node)
2) $E \rightarrow E_1 - T$	E.node = new Node('-', E1.node, T.node)
3) $E \rightarrow T$	E.node = T.node
4) $T \rightarrow (E)$	T.node = E.node.
5) $T \rightarrow id$	T.node = new Leaf(id, id.entry)
6) $T \rightarrow num$	T.node = new Leaf(num, num.val)

⇒ Node (op, left, right) → It'll first check whether there exist a node with value op & left & right child, if true, it'll returns that node, else creates a new Node.

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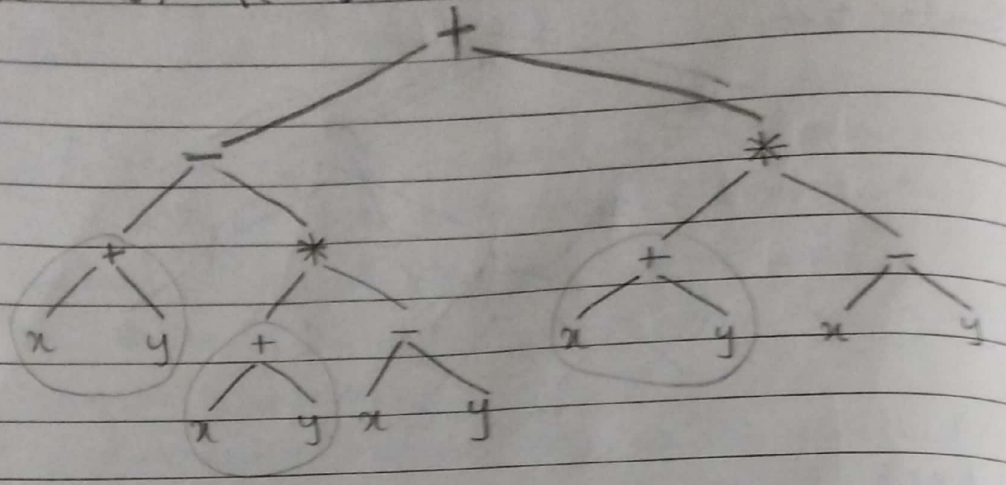
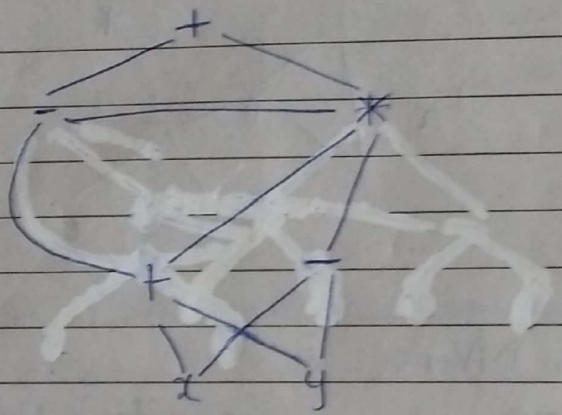
Exercise 6.1.1: Construct the DAG for the expression

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

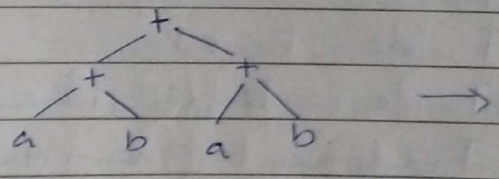


DAG



Exercise: 6.1.2: Construct a DAG ~~or identify the value numbers for the subexpressions~~ of the following expression assuming + associates from the left.

a) a + b + (a + b)



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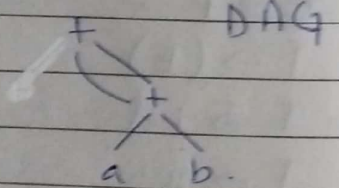
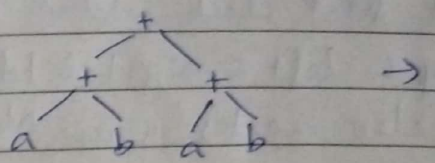
DAG



b) a + b + a + b



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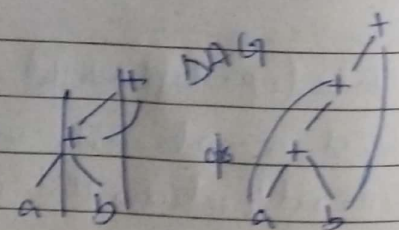
DAG



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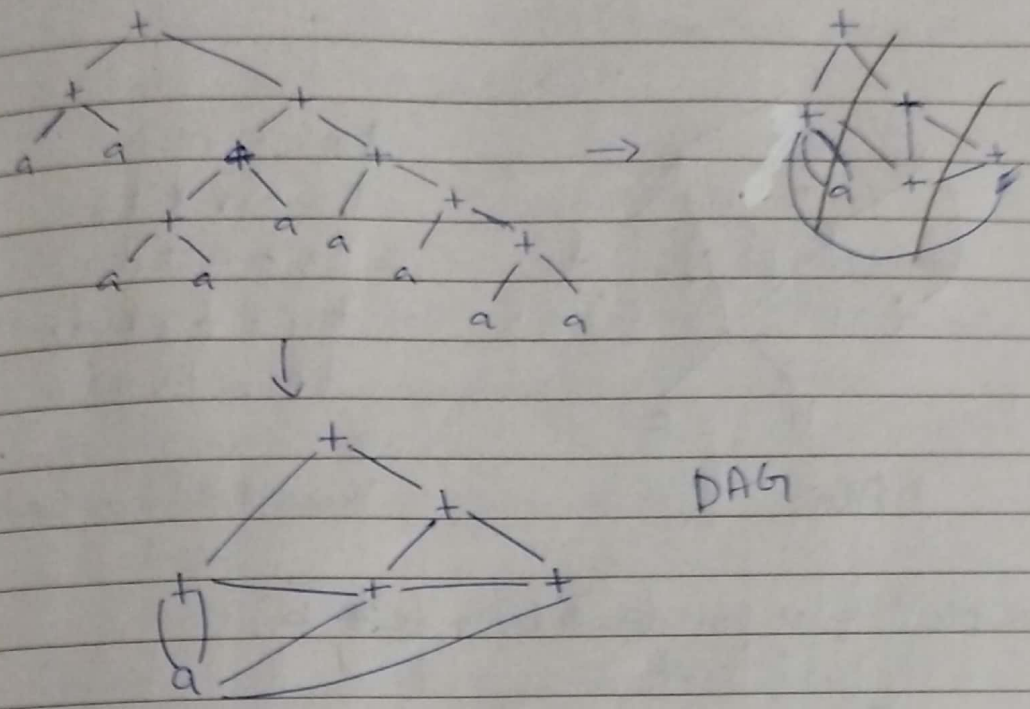
a) a+a+((a+a+a+(a+a+a+a)))



THREE ADDRESS CODE

- At most one operator on the right side of an instruction, no built up arithmetic expressions are permitted.
  ⇒ x + y * z might be translated into
  ⇒ $t_1 = y * z$
  ⇒ $t_2 = x + t_1$
- here t_1 & t_2 are temporary names generated by the compiler.
- This multi-operator arithmetic expressions & nested flow of control statements make three-address code desirable for targeted machine code.
- Three address code is a linearized representation of a syntax tree or a DAG, where the temporary names e.g. t_1 and t_2 represents intermediate nodes.

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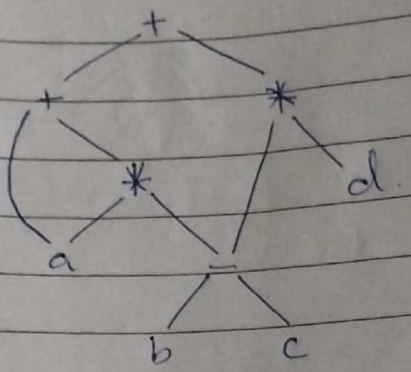
Example: $a + a * (b-c) + (b-c) * d$



DAG

$t_1 = b - c$

$t_2 = a * t_2$

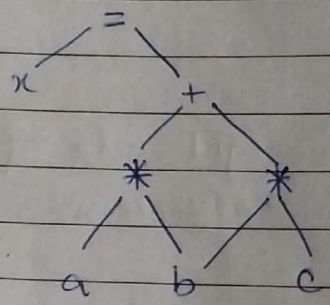
$t_3 = a + t_2$

$t_4 = t_1 * d$

$t_5 = t_3 + t_4$

Three Address Co

Example: $x = (a * b) + (c * b)$



DAG

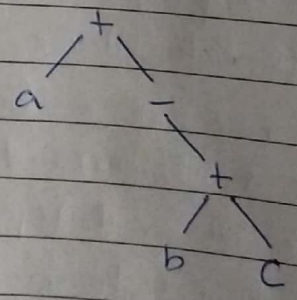
$t_1 = a * b$

$t_2 = c * b$

$x = t_1 + t_2$

Three address code.

Ex: 6.2.1: Translate the arithmetic expression $a + -(b+c)$ into a syntax tree.



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Addresses & Instructions.

- Three address code is built from two concepts: addresses and instructions.
- In object-oriented way, it corresponds to the concept of classes & subclasses.
- Three-address code can be implemented using ~~fields~~ & records. with fields for addresses & records called quadruples & tripples.
- An address can b
  1. A name (source program names)
  2. A constant
  3. A compiler-generated temporary. e.g. t_1 & t_2
- Common three-address instruction form
  1. Assignment instructions $x = y \text{ op } z$.
     op: binary, arithmetic or logical operation & x, y, z are addresses
  2. Assignment => $x = \text{op } z$, op is a unary operation such as negation, unary minus, shift etc.
  3. Copy instructions => $x = y$.
  4. Unconditional jump goto L. (L is label)
  5. Conditional jump => if x goto L.
  6. or => if x relop y goto L, relop is relational operators (>, <, == etc).
  7. Procedure calls & return statements.
     param x => for parameters.
     call p, n y = call p, n. (Procedural function calls)
     return y.
  8. Indexed copy instruction => $x = y[i]$, $x[i] = y$
  9. Addresses & pointers => $x = \&y$, $x = *y$.

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Ex: 6.5. do i = i + 1; while (a[i] < v);

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

Symbolic Labels Representation

Position Numbers Representation.

Quadruples:

- A representation is a data structure of three-address
- A quadruple (or quad) has four fields: op, arg1, arg2, and result.
- A three address instruction in quad would

x = y + z ⇒

op	arg1	arg2	result
+	y	z	x

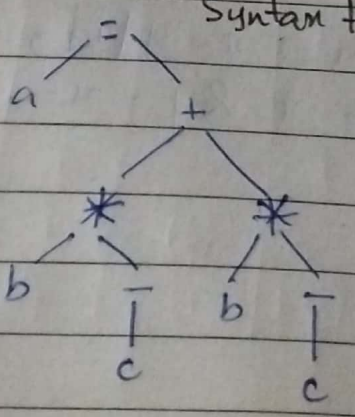
① Instructions with unary operator ⇒ x = minus y or x = y, do not use arg2. A in copy stat x = y, op is =

② Operators such as param don't use arg2 & result.

③ Conditional & Unconditional jumps, put label in result.

Ex: 6.6. a = b * -c + b * -c;

Syntax tree



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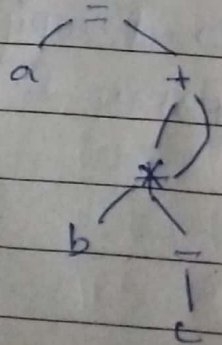

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t_1 = minus c
t_2 = b * t_1
t_3 = t_2 + t_2
a = t_3

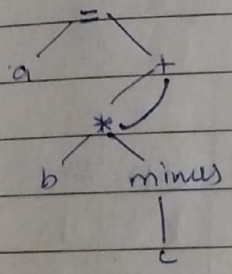
	op	arg_1	arg_2	result
0	minus	c		t_1
1	*	b	t_1	t_2
2	+	t_2	t_2	t_3
3	=	t_3		a

Three-address code Triples. Quadruple.

Triple:

- A tiple has only three fields, op, arg1, and arg2.
- Using tuples, we refer to the result of an operation x op y by its position (indexes) rather than temporary names. ~~positions~~
- Positions will be like (0). Parenthesized numbes represent pointers into the tuple data structure itself

Ex: 6.7 a = b * -c + b * -c.



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

- Triples take less space.
- Quadruples can switch statements.
- In quadruples, we store result in temporary say t, if we move that instruction, we don't have to change t.
- In tiples, result of an instruction is referred by pointer (4) if we move the instruction, the references will have to be changed.
- This problem of tiple is solved by indirect triples.

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Indirect tuples.

- Listing of pointers to tuples, rather than listing of tuples themselves
- Let's use an array instruction to list pointers to tuples in a desired order.

The indirect tuple representation of previous example:

instruction	
35	(0)
36	(1)
37	(2)
38	(3)

	op	arg1	arg2
0	minus	c	
1	*	b	(0)
2	+	(1)	(1)
3	=	a	(2)

Using indirect tuples, an instruction can be reordered ~~using~~ in instruction list.

Example: $-(a*b)+(c*d+e)$.

$t_1 = a * b$
$t_2 = -t_1$
$t_3 = c * d$
$t_4 = t_3 + e$
$t_5 = t_2 + t_4$

Three address code.

	op	arg1	arg2	result
0	*	a	b	t_1
1	-	t_1		t_2
2	*	c	d	t_3
3	+	t_3	e	t_4
4	+	t_2	t_4	t_5

Quadruple.

	op	arg1	arg2
0	*	a	b
1	-	(0)	
2	*	c	d
3	+	(2)	e
4	+	(1)	(3)

Triple

instruction		op	
101	(0)		(2)
102	(1)		(1)
103	(2)		(0)
104	(3)		(3)
105	(4)		(4)

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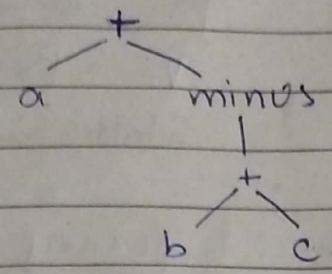
Static Single Assignment Form.

Exercise 6.2.1 : a + -(b+c)

Translate this arithmetic expression into.

(a) A syntax tree.



(b) Quadruples.

	op	arg1	arg2	result
0	+	b	c	t_1
1	-	t_1		t_2
2	+	a	t_2	t_3

(c) Triples

	op	arg1	arg2
0	+	b	c
1	-	(0)	
2	+	a	(1)

(d) Indirect Triples.

100	(0)
101	(1)
102	(2)

Static Single Assignment form. (SSA)

- An intermediate representation that provides code optimization
- There are two aspects that distinguishes SSA from three address code.

① All assignments in SSA are ~~two~~ to variables with distinct names (hence static single assignment). Each variable is defined once only but may be used multiple times. (i.e. variables cannot be repeated on L.H.S of assignment).

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Exampte:

$P = a+b$	$P_1 = a+b$
$q = p-c$	$q_1 = P_1 - c$
$P = q * d.$	$P_2 = q_1 * d$
$P = e-P$	$P_3 = e - P_2$
$q = P+q$	$q_2 = P_3 + q_2$
Three address code	Static Single assignm

minimum total variables : temporary variables.

$\{ P_1, P_2, P_3, q_1, q_2 \}$.

$+ \{ a, b, c, d, e \}$.

Total 10 variables.

Example: Consider the following three address code.

$x = a/b$	$x_1 = a / b$
$y = c+d$	$y_1 = c + d$
$y = y-x$	$y_2 = y_1 - x_1$
$x = d+y$	$x_2 = d + y_2$
$z = f+y$	$z_1 = f + y_2$
$z = z+a.$	$z_2 = z_1 + a.$

Min Temporary variables used = 6.

Min Total variables use = 6 + 5 = 11

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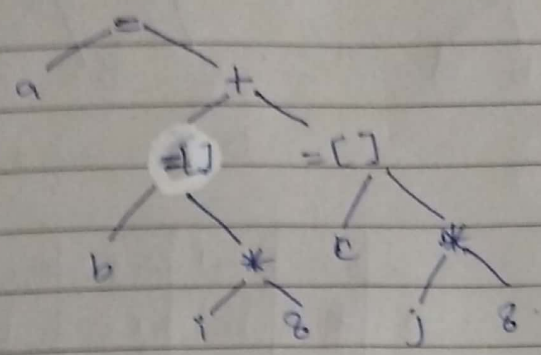
Ex16.2.2

Example: Translate the code segment into
(a) A Syntax tree (b) Quadruples (c) Triples.
(d) Indirect Triples.

(i) $a = b[i] + c[j]$.

(a) Syntax tree.



$t_1 = i * 8$.
$t_2 = b[t_1]$
$t_3 = j * 8$.
$t_4 = c[t_3]$
$t_5 = t_2 + t_4$
$a = t_5$

Three address code.

(b) Quadruple.

	op	arg1	arg2	result
0	*	i	8	t_1
1	=[]	b	t_1	t_2
2	*	j	8	t_3
3	=[]	c	t_3	t_4
4	+	t_2	t_4	t_5
5	=	t_5		a

(c) Triples

	op	arg1	arg 2
0	*	i	8
1	=[]	b	(0)
2	*	j	8
3	=[]	c	(2)
4	+	(1)	(3)
5	=	a	(4)

(d) Indirect Triples.

instructions	
100	(0)
101	(1)
102	(2)
103	(3)
104	(4)
105	(5)

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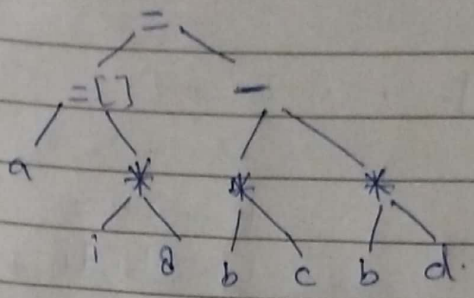
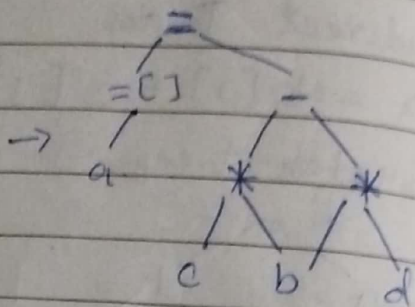
(ii) a[i] = b * c - b * d.



Syntax tree



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$t_1 = b * c$
$t_2 = b * d$.
$t_3 = t_1 - t_2$.
$t_4 = i * 8$.
$t_5 = a[t_4] = t_3$

Three address code

	op	arg1	arg2	result
0	*	b	c	t_1
1	*	b	d	t_2
2	-	t_1	t_2	t_3
3	*	i	8	t_4
4	[]=	a	t_4	t_5
5	=	t_3		t_5

Quadruples.

	op	arg1	arg2
0	*	b	c
1	*	b	d
2	-	(0)	(1)
3.	*	i	8
4.	[]=	a	(3)
5	=	( )	(2)

Triples

indirect triples

101	(0)
102	(1)
103	(2)
104	(3)
105	(4)
106	(5)

Indirect Triples.

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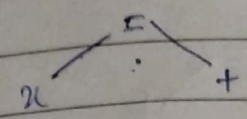
(iii) $x = f(y+1) + 2$.



f(y+1) is a function
(y+) is parameter to f.

$t_1 = y + 1$
$t_2 = f(t)$
$t_3 = t_2 + 2$
$x = t_3$.

~~Interm~~ Three address code.

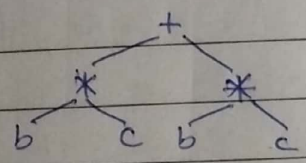
(b) Quadruples

	op	arg1	arg2	result
0	+	y	1	t_1
1	param	t_1		
2	call	f	1	t_2
3	+	t_2	2	t_3
4	=	t_3		x.

Triples.

	op	arg 1	arg 2
0	+	y	1
1	param	(0)	
2	call	f	1
3	+	(2)	2
4	=	x	(3)

① (b*c) + (b*c).



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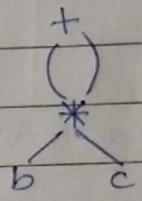


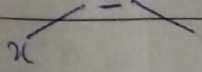
DAG

bc* bc* +

Post fix

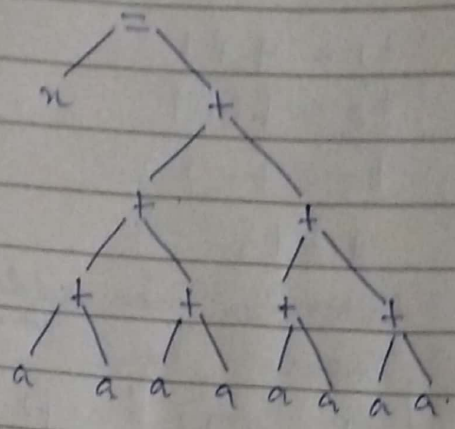
$t_1 = b * c$
$t_2 =$

Q) $x = (((a+a) + (a+a)) + ((a+a) + (a+a)))$

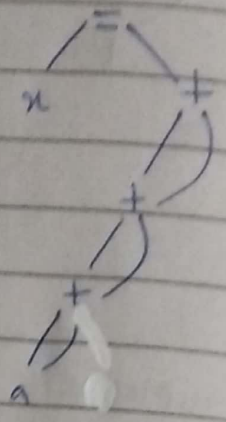


Date

Q) $x = (((a+a)+(a+a)) + (a+a)+(a+a))$



AST

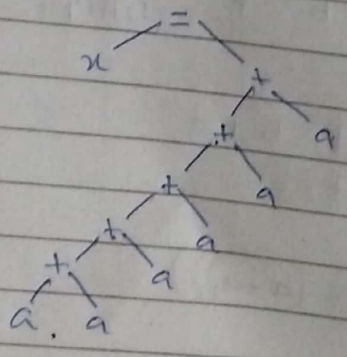


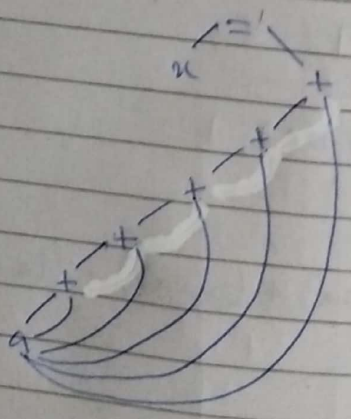
DAG.

$t_1 = a+a$
$t_2 = a+a$
$t_3 = t_1+t_2$
$t_4 = a+a$
$t_5 = a+a$
$t_6 = t_4+t_5$
$t_7 = t_3+t_6$
$x = t_7$

Three adress codes.

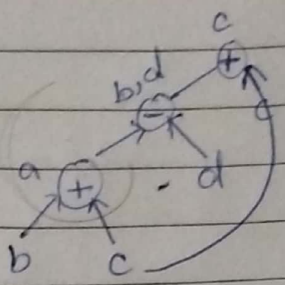
Q) $x = a+a+a+a+a+a$





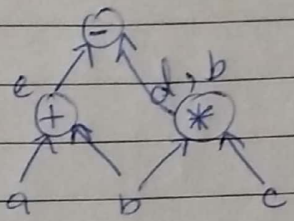
Date ____ 20 ____

Q) $a = b + c$
$b = a - d$
$c = b + c$
$d = a - d$

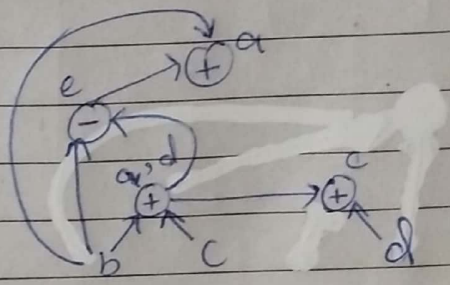


DAG.

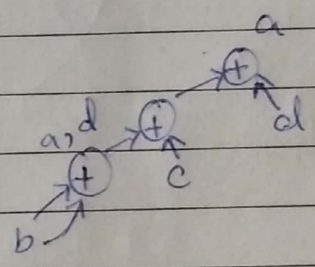
Q) $d = b * c$
$e = a + b$
$b = b * c$
$a = e - d$



Q) $a = b + c$
$c = a + d$
$d = b + c$
$e = d - b$
$a = e + b$



$a = e + b$
$= d - b + b$
$= d$
$= b + c$
$= b + a + d$
$a = b + b + c + d \rightarrow$



Q) $a = b * c$
$d = b$
$e = d * c$
$b = e$
$f = b + c$
$g = f + d$