Compilers

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Intermediate Code Generation

Sample Exercises and Solutions

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Problem 1: Intermediate Code Generation for Three-Address Instructions – Expressions
For the assignment `x=(a+c)*(a+b)` perform the following two translations:

a. Using the SDT scheme described in class and without any effort to minimize the number of registers
b. Using the SDT scheme described in class but now using the slightly modified `newtemp` functions that attempts to reuse temporary variable as much as possible.
c. Is the number of minimal temporaries for this statement to number found by the approach in b) above? Justify.

Solution:

a. In this section we use the SDT scheme described in class which we translate the required portions below. The SDT for the assignment statement first looks up the name of the variable to see if it has been mapped to a temporary variable. It then assumes that the lookup function allocates a temporary of no temporary has been assigned. In either case the values of the location is then used to generate code that implements the assignment by using the place where the intermediate code has placed the expression E.

```
S → id = E     {
                  S.place = null;
                  p = lookup(id.name);
                  if (p != NULL) {
                     S.code = append(E.code,{gen("p = E.place")});
                  } else {
                    S.code = emptyList();
                    error;
                  }
               }
```

This SDT scheme is very similar to the SDT scheme for the assignment statement described above but does not generate the assignment instruction. Instead only creates a temporary variable where it places the valued computed for the expression.

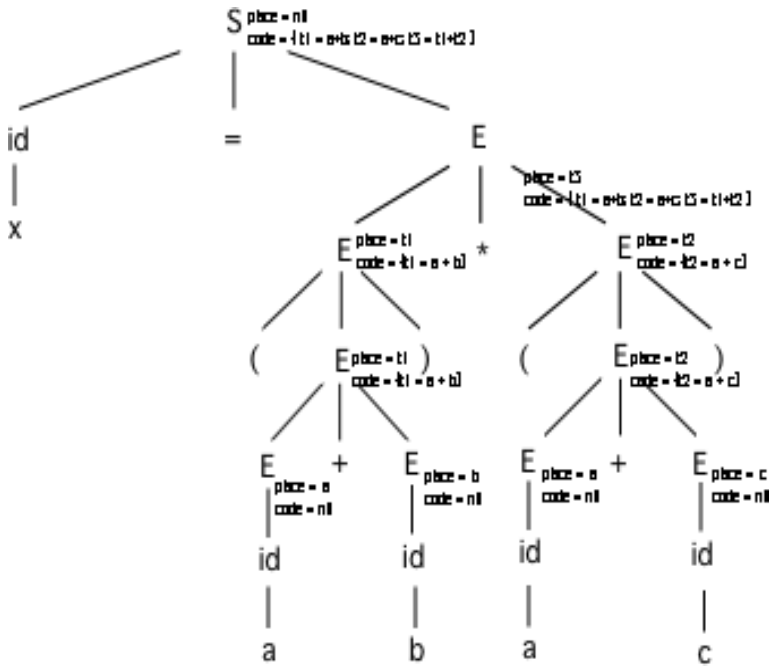
```
E → id         {
                  p = lookup(id.name);
                  if (p != NULL) {
                     E.place = p;
                  } else {
                    E.place = nil;
                    error;
                  }
                   E.code = emptyList();
               }
```

This SDT scheme generates code to evaluate the plus binary operator. It allocates a new temporary variable and then appends to the code that evaluate each of the two expressions a new instruction that uses the temporaries where the expressions E_1 and E_2 are stored and deposits the results in the newly allocated temporary variable.

```
E → E1 + E2    {
                  E.place = newtemp();
                  E.code = makelist(E1.code, E2.code, makelist(gen(E.place '=' E1.place '+' E2.place)));
               }
```

$E \rightarrow (E_1)$ {
E.place = E_1.place
E.code = E_1.code
}

For the input given in the exercises we can evaluate all the attributes with a single depth-first-search (DFS) traversal. The figure below depicts the values of the attributes for all the non-terminal symbols in the corresponding parse tree. We also present below the sequence of generated three-address instructions.



```
t1 = a + b
t2 = a + c
t3 = t1 * t2
x = t3
```

b. In this section we need to keep track of the temporary variables used at each instruction under the assumption that each definition is only used once as defined implicitly by the `newtemp` function. In this setting the generated code uses only two variables as depicted by the sequence below and where we have shown the value of the counter used internally in the `newtemp` function.

```
                     // c = 0
t1 = a + b           // c = 1
t2 = a + c           // c = 2
t1 = t1 * t2         // c = 1
x = t1               // c = 0
```

c. Yes, this is the best one can do as you need to hold the values of (a+c) and (a+b) in two registers at least before executing the multiplication. You cannot apply any of the distributive and associative arithmetic properties and thus need to have a second register at least.

Problem 2: Intermediate Code Generation for 3-Address Instructions – Boolean Expressions
For the boolean expression `a < b and c > d` perform the following two translations:

a. Using the SDT arithmetic-based scheme described in class
b. Using the short-circuit SDT evaluation scheme described in class.

State your assumptions as to the starting addresses are.

Solution:

a. For the first section of this exercise you can use the SDT where we treat each of the predicates as a simple arithmetic expression each of which will deposit its answer in a specific temporary variable. The SDT scheme is similar to the one used for the evaluation of arithmetic expressions as depicted in the code below. In this code we use an inherited attribute `nextstat` dictating the symbolic address of the code where the next statement should be located and a synthesized attribute `laststat` which indicates the symbolic address of the last generated statement. These two attributes in essence replace a global variable, which the rules could manipulate in a less pure SDT scheme. Notice the transfer of values between the attributes `laststat` and `nextstat` as the evaluation walks up the tree.

$E \rightarrow id_1$ relop id_2
```
{
   E.place = newtemp();
   E.code = gen("if id1.place relop id2.place goto E.nextstat+3;
                    E.place = 0; goto E.nextstat+2; E.place = 1;");
   E. laststat = E.nextstat+4;
}
```

$E \rightarrow E_1$ and E_2
```
{
   E.place = newtemp();
   E2.nextstat = E1.laststat
   E.code = append(E1.code, E2.code, gen("E.place = E1.place and E2.place"));
   E. laststat = E2.laststat;
}
```

Using this SDT scheme the input expression would be translated to the code below assuming an initial value of 0 to the `nextstat` attribute.

```
00: if a < b goto 03
01: t1 = 0
02: goto 04
03: t1 = 1
04: if c > d goto 07
05: t2 = 0
06: goto 08
07: t2 = 1
08: t3 = t1 and t2
```

b. For this variant of the code generation we also rely on inherited symbolic attributes, in this case `E.false` and `E.true`. These are symbolic labels for where the code will jump to in case the code evaluates to the Boolean values **false** and **true** respectively. For this SDT scheme as described in class the generated code is as shown below where `Ltrue` and `Lfalse` are symbolic labels to be define later in the code generation process.

```
00: if a < b goto 02
01: goto Lfalse
02: if c < d goto Ltrue
03: goto Lfalse
```

Problem 3: Intermediate Code Generation with Frame-Pointer

In class we saw the actions for a Syntax-Directed Translation scheme to generated code using semantic actions for a simple arithmetic expression. In this exercise you are asked to extend the semantic actions to include the explicit loading of a given scalar variable from a predefined offset of a *frame-pointer* or *FP*. The frame pointer is a specific register in the hardware processor that holds the virtual address of a section of the virtual address space where variables local to a given procedure are to be stored. As such reading the value of a scalar variable, say `a` amount to generating the sequence of three-address instructions:

```
t1 = FP + offset_a;
t2 = *t1;
```

where `offset_a` is a compiler predefined constant, say 4, and the second instruction performs an indirect loading from memory based on the address calculated in the temporary variable t1.

Assuming the frame-pointer register is correctly set up when you initiate the generation of intermediate code show the translation of the sequence of statements below indicating the following:

```
x = a * b - a * 2;
if(x < 10) then
  y = 0;
```

a) The augmented semantic actions for loading the value of a given scalar variable.
b) Using the approach for the minimization of temporary variables indicate how many temporaries would you require for executing these statements assuming the value of x is not needed after the evaluation of the conditional statement. Explain.

Solution:

a) The augmented semantic action will have instead of directly using the symbol of a scalar variable v as its address, it would insert two instructions as given by the semantic action below for a read operations

```
tn = newtemp();
emit(tn = FP + offsset_v);
tm = newtemp();
emit(tm = *tn);
```

For a write operation the semantic action would have to be modified as

```
tn = newtemp();
emit(tn = FP + offsset_v);
emit(*tn = tx);
```

where tx would be the temporary holding the value to be written to the position of the scalar variable.

Given these modifications the generated code it is depicted below where we have made no effort of reusing temporary variables and have thus assumed an infinite number of such temporaries.

```
        t1 = FP + offset_a        ; computing the address of the scalar variable a
        t2 = *t1                  ; reading the value of the scalar variable a
        t3 = t2 * 2               ; computing sub-expression (a*2)
        t4 = FP + offset_b        ; computing the address of the scalar variable b
        t5 = *t4                  ; reading the value of the scalar variable b
        t6 = t2 * t5              ; computing (a * b) as t2 still has the value of a
        t7 = t6 – t3              ; assigning (a*b) – (a*2) to temporary variable
        t8 = FP + offset_x        ; computing the address of the scalar variable x
        *t8 = t7                  ; writing value of expression back to location of scalar variable x
        if(t7 < 10) goto L1       ; condition (x < 10) evaluation
        goto L2                   ;
L1:     t9 = FP + offset_y        ; computing the address of scalar variable y
        *t9 = 0                   ; writing value of y as zero
        goto L2                   ;
L2:
```

b) Using the counter-based assignment of temporaries we arrive at the code below, which uses only three temporary variables. Note in this case a write via an address is like a read operation of the address and thus will lead to a decrease in the value of the counter used during the code generation.

```
        t1 = FP + offset_a        ; computing address of scalar variable a
        t1 = *t1                  ;
        t2 = t1 * 2               ; t2 has the value of expression (a*2)
        t3 = FP + offset_b        ; computing address of scalar variable b
        t3 = *t3                  ; t3 has the value of scalar variable b
        t3 = t1 * t3              ; t3 has the expression (a*b)
        t2 = t3 – t2              ;
        t3 = FP + offset_x        ;
        *t3 = t2                  ; writing value of expression inx
        if(t2 < 10) goto L1       ;
        goto L2                   ;
L1:     t1 = FP + offset_y        ; computing address of scalar variable x
        *t1 = 0                   ;
        goto L2                   ;
L2:
```

Problem 4: Back-patching of Loop Constructs
In class we saw the actions for a Syntax-Directed Translation scheme to generated code using the back-patching technique for a *while* loop construct. In this exercise you will develop a similar scheme for the *repeat-until* construct using the production:

S → **repeat** S **until** E;

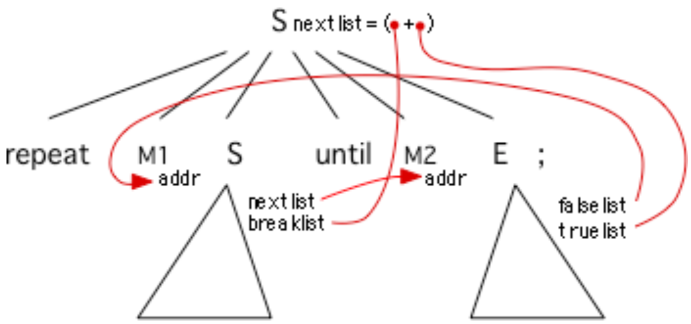
Do not forget to show the augmented production with the marker non-terminal symbols, M and possibly N along with the corresponding rules for the additional symbols. Argue for the correctness of your solution without necessarily having to show an example.

Solution:

$S \rightarrow$ repeat M_1 S_1 until M_2 E {
backpatch(S_1.nextlist, M_2.addr);
backpatch(E.falselist,M_1.addr);
S.nextlist = merge(E.truelist, S.breaklist);
}

The first back-patching command fills in the places where the control in S_1 is transferred to the next iteration, that is, to the evaluation of the conditional `E` that is given by the M_2.addr value. The second back-patching command links the places where the evaluation of `E` is false to M_1.addr that is to the top of the loop. Finally the overall construct `nextlist` consists of the location where the control for which the conditional `E` corresponds to the evaluation `E` to true as well as the location where the list of stament have a break instruction of an instruction that would cause the flow of control to evade the rest of the execution of the `repeat-until` construct.

Notice that there is no need to generate an extra `goto` statement as we had in the while-loop construct since the control can fall through the evaluation of the conditional statement. The figure below depicts the flow of the labels in the back-patching process.



Problem 5: Intermediate Code Generation
Consider the sample source code depicted below:

```
i = 0;
while (i < 10) {
  b[i] = a;
  i = i + 1;
}
```

For this code the register allocation has determined that variables `i` are allocated the physical register `r0` and the scalar variable `a` will use register `r1`. All other variables are not allocated registers but rather stay in the Activation Record throughout the computation.

a) Present a three-address instruction code for this segment of code under the assumption that all variables are live at the end of the block except variable `i`. Use the address calculation with the Frame-Pointer register (FP) where the offsets have been computed already and have symbolic names such as offset_a and offset_i.

b) Assuming variable `a` is volatile, i.e., its value can changed as a result of an external event, could you use it in a register? Why or why not?

Solution:

a) One possible translation of the code above is presented below with appropriate comments.

```
1:   r0 = 0
2:   r1 = 0
3: L1:  if r0 < 10 goto L2
4:   goto L3
5: L2:  t2 = r0 + 1
6:   t3 = a[t2]
7:   a[r0] = t3
8:   t4 = a[r0]
9:   r1 = r1 + t4
10:  t5 = r0 + 1
11:  r0 = t5
12:  goto L1
13: L3: t2 = FP + offset_i
14:  *t2 = r0 // update value of i in AR
15:  t2 = FP + offset_sum
16:  *t2 = r1 // update value of sum in AR
17:  return
```

b) Lines 8 through 9 can be replaced by the sequence below

```
8:   t4 = a[r0]
9:   putparam t4    // a[i] is second argument, goes in first
10:  putparam r1    // sum is register r1, first argument, goes last
11: r1 = call adder, 2 // function with two arguments on the stack
```

Problem 6: Attributive Grammar and Syntax-Directed Translation

In class we described a SDT translation scheme for array expressions using row-major organization. In this exercise you are asked to redo the SDT scheme for a column-major organization of the array data. Review the lectures note to understand the layout of a 2-dimensional array in column-major format. Specifically perform the following:

a. Indicate the attributes of your SDT scheme along with the auxiliary functions you are using.
b. Define a grammar and its the semantic actions for this translation.
c. Show the annotated parse tree and generated code for the assignment `x = A[y,z]` under the assumption that A is 10 x 20 array with $low_1 = low_2 = 1$ and sizeof(baseType(A)) = sizeof(int) = 4 bytes

Hint: You might have to modify the grammar so that instead of being left recursive is right recursive. Below is the grammar used for the row-major organization.

$L \rightarrow$ Elist]
Elist $\rightarrow$ $Elist_1$, E
Elist $\rightarrow$ id [E
$E \rightarrow L$
$S \rightarrow L = E$
$L \rightarrow$ id

Solution:

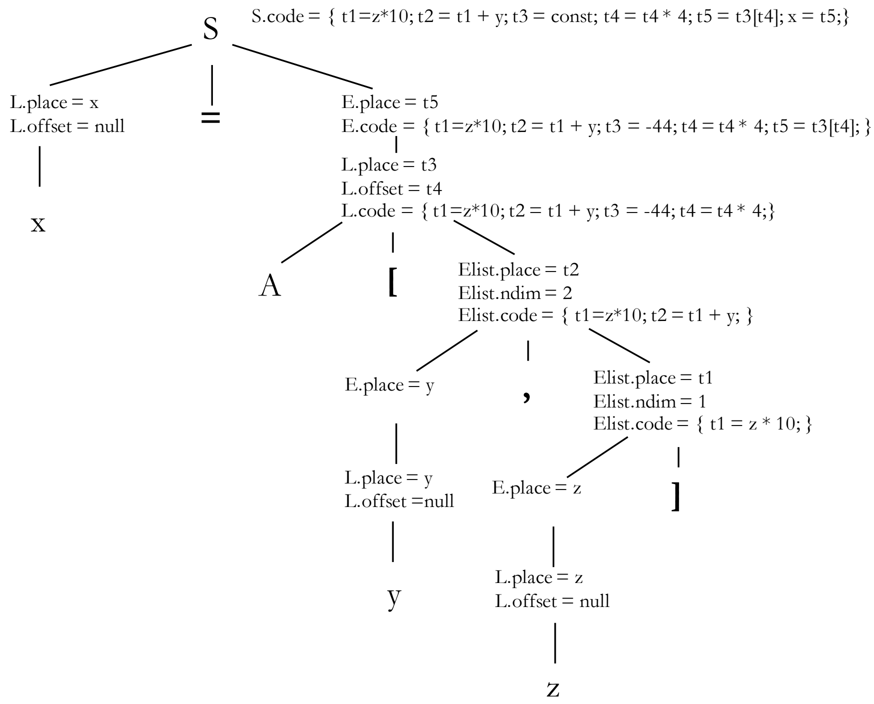
a.), b.) The basic idea is the same as in the row-major organization but rather than counting the dimensions from the left to the right we would like to count and accumulate the dimension sizes from the right to the left. This way the right-most index of the array indices is the last dimension of the rows and should be multiplied by the first dimension, in this case the size of each row. As such the revised grammar that is right-recursive would work better. Below is such a grammar to which we are associating the same **synthesized** attributed as in the row-major formulation, namely, *place*, *offset* and *ndim* as described in class.

$S \rightarrow L = E$
$E \rightarrow L$
$L \rightarrow$ id
$L \rightarrow$ id [Elist
Elist $\rightarrow$ E]
Elist $\rightarrow$ E, $Elist_1$

We also use the same auxiliary function such as `numElemDim(A, dim)` and `constTerm(Array)` as described in class. Given this grammar we define the semantic actions as described below:

```
Elist → E ]           {
                        Elist.place = E.place
                        Elist.code = E.code;
                        Elist.ndim = 1;
                      }

Elist → E , Elist1    {
                        t = newtemp();
                        m = Elist1.ndim + 1;
                        Elist.ndim = m;
                        code1 = gen(t = Elist1.place * numElemDim(m));
                        code2 = gen(t = t + E.place);
                        Elist.place = t;
                        Elist.ndim = m;
                        Elist.code = append(Elist1.code,E.code,code1,code2);
                      }

L → id [ Elist        {
                        L.place = newtemp();
                        L.offset = newtemp();
                        code1 = gen(L.place '=' constTerm(id));
                        code2 = gen(L.offset '=' Elist.place * sizeof(baseType(id)));
                        L.code = append(Elist.code,code1,code2);
                      }

E → L                 {
                        if (L.offset = NULL) then {
                          E.place = L.place;
                        } else {
                          E.place = newtemp;
                          E.code = gen(E.place = L.place[L.offset]);
                       }
                      }

S → L = E             {
                         if L.offset = NULL then
                             E.code = gen(L.place = E.place);
                         else
                            S.code = append(E.code,gen(L.place[L.offset] = E.place);
                      }

L → id                {
                         L.place = id.place;
                         L.offset = null;
                      }
```

c) For the assignment example x = A[y,z] we have the annotated parse tree shown below under the assumption that the base address for the array A is 0.



Problem 7: Intermediate Code Generation

For the assignment instruction below perform the following:

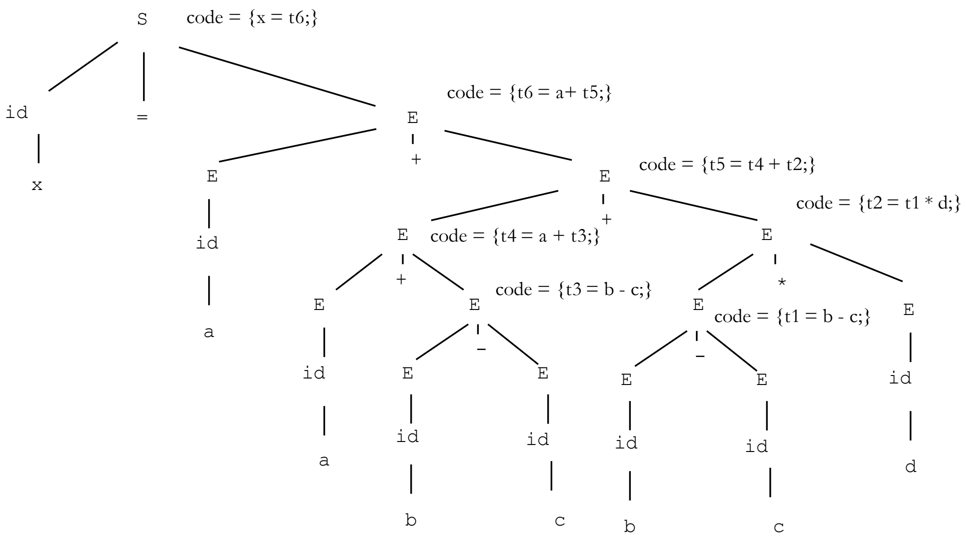
```
x = a +  (a + (b-c)) + ((b-c) * d);
```

a. Generate three-address instructions using the SDT scheme described in class and without any minimization of temporary variables.
b. Redo the code generation above but now reusing temporaries using the method described in class.
c. Argue that the solution found in b. is optimal.

Solution:

a. Below is the annotated (simplified) parse tree where we show the code that is added to the output for each node resulting the in the final three-address code sequence as follows:

```
t1 = b - c;
t2 = t1 * d;
t3 = b - c;
t4 = a + t3;
t5 = t4 + t2;
t6 = a + t5;
x  = t6;
```



b. Using the `newtemp` allocation function described in class that attempt to reuse a temporary as soon as its value is used we would get the code sequence shown below.

```
t1 = b - c;
t1 = t1 * d;  // as soon as t1 is used on the RHS it becomes available.
t2 = b - c;   // here we must use a second temp as t1 is still live.
t2 = a + t2;  // reuse of t2
t1 = t1 + t2; // reuse of t1 and t2 (both became free)
t1 = a + t1;  // reuse of t1
x  = t1;
```

c. Given that the solution above uses 2 temporaries, the best possible scenario would be for it to use a single temporary variable. In order to have a single temporary we would have to have the parse tree totally skewed towards the RHS. Even using the commutative, associative and distributive laws we cannot get this expression as a summation of basic terms. We will always need a second temporary for the computation of the product term. Not even the fact that we have a common sub-expression, the `(b-c)` factor helps out in this case. As such the next best number of temporary variables is 2, making this code optimal with respect to the number of temporary variables.

   Note that you could improve the code sequence above by recognizing the common sub-expression `(b-c)` and save the result of this subtraction in a register to be used in the addition and product with `a` and `d` respectively. The resulting code would use the same number of registers but performs one less arithmetic operation.

```
t1 = b - c;
t2 = t1 * d;
t2 = b - c;   // not needed
t1 = a + t1;
t1 = t1 + t2;
t1 = a + t1;
x  = t1;
```

Problem 8: Control-Flow Constructs

In this exercise you are going to define the SDT scheme for function calls and procedures calls. The general idea is that you need to evaluate the various arguments of the functions and procedure, generate the code that puts their values into temporary variables, push the variables onto a stack using the three-address instructions and then invoke the procedure or function with the corresponding assignment to the variable, in case of a function invocation.

To keep this exercise simple, you should assume that you already have a grammar for expressions that include function calls and procedure calls. You need to define the simple productions for these cases using the *arg_list* recursive grammar symbol as shown below. State your assumption for the attributes these additional grammar symbol needs to have to support your code generation scheme.

```
Expr    → ID ( ArgList );
ArgList →      ε
        |      Arg
        |      Arg ',' ArgList
Arg     →      Expr
Assign  →      Expr '=' Expr
```

The example below illustrates the generated code for a simple function invocation. Please recall that the arguments of the function may also be function call, so you need to be careful in the way you create temporary variable for holding the values of the various argument.

```
                                   t1= a
                                   t2 = b + 1
                                   putparam t2
x = soma(a,b+1);                   putparam t1
                                   t = call soma, 2
                                   x = t
```

Solution:

Really the only tricky part here it to save the temporary in which each parameter is to be computed into a stack so that we can pops these temporaries during the parsing and output the various `putparam` instructions with the correct identifier of the temporary. While popping you should also count the number of arguments that you need to have to issue the call instruction.

We thus define a synthesized attribute *cnt* to count the number of argument (although this would not be strictly necessary as one could do it by popping the stack until it would be empty and count at the same time the number of elements popped) and a *place* to save the temporary where a given value of an expression is saved. Also note here we are emitting the code right away as the reductions take place. For this reasons we are decoupling the assignment on a function call by having the function use a new temporary and then making the assignment to the *Expr* on the LHS of an assignment statement.

```
Expr    →  ID ( ArgList );   {   n = ArgList.cnt;
                                 t = newtemp();
                                 for(i = 0; i < n; i++){
                                   emit("putparam ",argsStack.pop());
                                 }
                                 emit("t = call ID, n");
                                 Expr.place = t;
                               }
```

```
ArgList →   ε                  { ArgList.cnt = 0; }
         |  Arg                { argsStack.push(Arg.place); ArgList.cnt ++; }
         |  Arg ‘,’ ArgList    { argsStack.push(Arg.place); ArgList.cnt ++; }

Arg     →   Expr               { Arg.place = Expr.place; }

Assign  →   Expr1 ‘=’ Expr2    { Emit(“Expr1.place = Expr2.place”); }
```