Static, Stack-Dynamic, and Heap-Dynamic Allocation of Memory Locations for Variables and Data Structures in TinyJ, Java, C++, and Lisp

Static Allocation

Q1. What are statically allocated memory locations used for?

> **Ans**. In C++, variables that are ***not local*** to a function and also are ***not*** elements or data members of heap-dynamically allocated arrays or objects are given statically allocated memory locations, as are `static` local variables of functions and `static` variables of classes. Additionally, characters of ordinary C++ ***string literals*** are stored in statically allocated memory locations.
>
> In TinyJ, `static` variables are given statically allocated locations, and TinyJ ***string literals*** are also stored in statically allocated locations.

Q2. When are statically allocated memory locations allocated?

> **Ans**. They are allocated before program execution begins.

Q3. When are statically allocated memory locations _de_allocated?

> **Ans**. Never: The locations remain allocated for their original purposes until the program terminates.

Note: Java and Lisp are languages that do _not_ use static allocation: In these languages, memory for all variables and stored data is allocated dynamically—i.e., during program execution.

In Java, memory locations for `static` variables of a class are allocated (from a part of memory called the "method area") when that class is loaded. A typical Java VM will not load a class until that class is "used" for the first time during code execution—the class is loaded the first time one of the following occurs: an instance of the class is created; a `static` method of the class is called; a nonconstant `static` variable of the class is accessed. A Java String literal is created in heap memory the first time the Java VM loads a class in which that particular String literal occurs (except in unusual cases where an equal String has already been cached); after it is created, that String is cached in a pool of cached Strings that is maintained by the Java VM.

Stack-Dynamic Allocation

Stack-dynamic allocation allocates locations from an area of memory that is called a stack. Locations are deallocated from a stack in "last-in first-out" (more precisely, "last-allocated first-deallocated") order.

Q1. What are stack-dynamically allocated memory locations used for?

> **Ans**. (a) Conceptually, formal parameters and other local variables of a function / method are given stack-dynamically allocated memory locations.
> (b) When evaluating an expression, the values of its operand subexpressions are, conceptually, placed in stack-dynamically allocated locations, as is the value of the expression itself.
>
> Here "conceptually" means that from a programmer's perspective the program *behaves as if* the items mentioned in (a) and (b) are all given stack-dynamically allocated memory locations. But a language implementation need not give such locations to all of those items—e.g., it may put some values in processor registers, and (regarding (b)) it may not allocate any location for an operand subexpression that is a variable (which will already have a location) or is a constant.
>
> **Note**: The TinyJ VM uses two different stacks for (a) and (b). The stack used for (a) is part of the TinyJ VM's data memory; a separate stack called the **EXPRSTACK** is used for (b).

Q2. When are stack-dynamically allocated memory locations allocated?

> **Ans**. They are allocated for purpose (a) above when a function / method is called during program execution. They are allocated for purpose (b) either when the function / method that contains the expression is called or while the expression is being evaluated.

Q3. When are stack-dynamically allocated memory locations _de_allocated?

> **Ans**. The locations that are allocated when a function / method is called will be deallocated when the called function / method returns control to its caller. A location that is allocated while an expression is being evaluated to store the value of a subexpression or the expression itself will be deallocated after the value has been used.

Heap-Dynamic Allocation

Heap-dynamic allocation allocates memory locations in a part of memory that is called the heap.

Q1. What are heap-dynamically allocated memory locations used for?

> **Ans**. In Java, all Objects (including arrays) are stored in the heap. In TinyJ, arrays are stored in the heap. In C++, data items that are created using `new ...` are stored in the heap. In Lisp, we may assume all data items are stored in the heap—but an implementation of Lisp might actually store some small immutable data items (e.g., small integers) in the locations of variables whose values are those data items, and those variables' locations need not be in the heap.
>
> Data stored in the heap is accessed via variables whose locations store *references / pointers* to that data. Note that those variables' locations may well have been statically allocated or stack-dynamically allocated. However, some variables' locations are heap-dynamically allocated: The locations of indexed variables that are elements of heap-dynamically allocated arrays and instance variables of heap-dynamically allocated objects are heap-dynamically allocated as a part of those arrays / objects.

Q2. When are heap-dynamically allocated memory locations allocated?

> **Ans**. They are allocated during program execution, when creating data items that will be stored in the heap.

Q3. When are heap-dynamically allocated memory locations _de_allocated?

> **Ans**. Implementations of Java, Lisp, and many modern languages are equipped with an automatic memory management system called a *garbage collector* that will at certain times try to find and deallocate heap-dynamically allocated locations that the program is no longer able to access. But in most of these languages (including Java and Lisp) a programmer *cannot* be sure that a particular inaccessible location will actually be deallocated, and has no way to demand that particular heap-dynamically allocated locations be deallocated.
>
> In contrast, C++ and many other long-established languages allow and expect programmers to explicitly deallocate heap-dynamically allocated locations that will never again be used; `delete ...` in C++ serves this purpose. (A program is said to have suffered a *memory leak* when there are heap-dynamically allocated locations that the program is no longer able to access but which will not be deallocated before the program terminates.) When a memory location is deallocated, any pointers that still point to the deallocated location become *dangling pointers*. As deallocated locations may be reallocated for other purposes, accidental use of dangling pointers to access memory locations can create bugs that are hard to diagnose.

The TinyJ Virtual Machine's Memory

The TinyJ VM's memory consists of the *EXPRSTACK*, *data memory*, *code memory*, and some *registers*.

The **EXPRSTACK** (or *expression evaluation stack*) is used when an expression is being evaluated: Values of the expression's operand subexpressions are placed in the EXPRSTACK, and the expression's value will be in the topmost EXPRSTACK location immediately after the value has been found.

Data memory is subdivided into three areas:
1. The *statically allocated* area of data memory is used to store values of `static` TinyJ variables and characters of TinyJ string literals.
2. The *stack-dynamically allocated* area of data memory is used to store values of parameters and other local variables of TinyJ methods. This and the EXPRSTACK are the two stacks of the TinyJ VM.
3. The *heap* area of data memory is used to store TinyJ arrays.

Code memory is used to store TinyJ VM instructions for execution. Its contents will *not* change during execution of a TinyJ program. *Code memory and data memory have separate address spaces*.

Information regarding the roles of registers will be provided in the TinyJ Assignment 3 document.

Static and Stack-Dynamic Memory Allocation Rules Used by the TinyJ Compiler

Static Memory Allocation for Static TinyJ Variables

The nth `static` int or array reference variable in a TinyJ source file is given the data memory location whose address is $n-1$. (So the address of the first such variable is 0.) This rule ***does not apply to Scanner variables***: In TinyJ, Scanner variables are fictitious variables; no space is allocated to them.

Static Memory Allocation for TinyJ String Literals

The kth string literal character in the source file is placed into the data memory location whose address is $m+k$, where m is the last address allocated to a static variable. (In this respect TinyJ differs from Java: In Java, string literals are String objects and are stored in the Java VM's heap like all other Objects.)

Stack Dynamic Memory Allocation for Parameters and Other Local Variables of TinyJ Methods: Stackframes of Method Calls and How Locations Within Stackframes are Allocated

Each time a method is called during program execution, a block of contiguous data memory locations known as the call's ***stackframe*** or ***activation record*** is allocated; this block of memory locations will be deallocated when the method returns to its caller. Each formal parameter[*] of the method and each local variable declared in the method's body will be allocated a location within that stackframe—see the allocation rules below. Each location within the stackframe is referred to by its ***offset*** relative to the stackframe location at offset 0. (If in a certain stackframe the data memory address of the location at offset 0 is 73, then the data memory address of the stackframe location at offset +5 is $73 + 5 = 78$.)

Memory Allocation Rule for Local Variables Declared in TinyJ Method Bodies:

Whenever the compiler sees a declaration of a local variable (other than a Scanner variable) in the body of a method, that local variable is given the first stackframe location with offset $\geq +1$ which has NOT already been allocated to another local variable *that is still in scope*. (So, ignoring Scanner variables, the stackframe offset of the ***first*** local variable in each method's body is +1.) **EXAMPLE**:

```
int func()
{
  int a, b[], c;
  ...
  if ( ... ) {
    int d, e[];
    ...
  }
  else {
    int f, g;
    ...
    int h;
    ...
  }
  ...
  int i;
  ...
}
```

In this example: `a` gets offset 1   `b` gets offset 2   `c` gets offset 3   `d` gets offset 4   `e` gets offset 5
When `f` is declared, `d` and `e` are out of scope. So: `f` gets offset 4   `g` gets offset 5   `h` gets offset 6
When `i` is declared, `f`, `g`, and `h` are out of scope. So: `i` gets offset 4

Memory Allocation Rule[*] for Formal Parameters of TinyJ Methods:

Formal parameters are given locations with ***negative*** offsets; the *last* formal parameter of the method gets the stackframe location at offset –2, the *second-last* parameter gets the location at offset –3, etc. **EXAMPLE**: In a stackframe of any call of `int g(int p, int q[], int r)`, `r` gets offset –2, `q` gets offset –3, and `p` gets offset –4.

[*]This ***does not apply to main( )'s parameter***: In TinyJ—unlike Java—main( )'s parameter is ***not*** a real parameter. (**main( )'s stackframe has no locations with negative offsets**.)

Use of Offsets 0 and –1 [This subsection is relevant mainly to <u>TinyJ Assignment 3</u>.]

The stackframe locations at offsets 0 and –1 store information that is used to support return of control from a called method to its caller. Specifically:

In each stackframe other than main( )'s stackframe, the ***<u>dynamic/control link</u>*** is stored at offset 0. (In main( )'s stackframe, the location at offset 0 stores an implementation-dependent pointer.) In stackframes of methods other than main( ), the dynamic/control link is a pointer to the data memory location at offset 0 in the stackframe of the method's caller.

In each stackframe other than main( )'s stackframe, the ***<u>return address</u>*** is stored at offset –1. The return address is the ***code memory*** address of the next VM instruction to be executed after the current method returns control to its caller. (In main( )'s stackframe there's no location at offset –1.)

Allocation and Deallocation of Stackframes: An Example

Suppose a TinyJ program has methods `main`, `f()`, `g()`, `h()`, and this happens when it is executed:

    (1) `main()` is called
    (2) `main()` calls `f()`
    (3)   `f()` calls `g()`
    (4)   `g()` calls `h()`
    (5)   `h()` calls `f()`
    (6)   `f()` returns control to `h()`
    (7)   `h()` returns control to `g()`
    (8)   `g()` calls `f()`

Then stackframes are *allocated* in <u>data memory</u> at times (1), (2), (3), (4), (5), and (8); stackframes are *deallocated* at times (6) and (7). Thus there will be just 4 stackframes in data memory immediately after (8). Listed ***in order of increasing memory addresses***, these 4 stackframes will be:

                the stackframe of `main()` allocated for call (1)
                the stackframe of `f()` allocated for call (2)
                the stackframe of `g()` allocated for call (3)
                the stackframe of `f()` allocated for call (8)

Note that the stackframes of `h()` and `f()` allocated at times (4) and (5) would no longer exist: The stackframe of `f()` allocated at time (5) would have been deallocated at time (6), and the stackframe of `h()` allocated at time (4) would have been deallocated at time (7).

Comment on Scanner Variables

The data memory allocation rules for TinyJ variables do ***<u>not</u>*** apply to Scanner variables (such as the local variable `userInput` of `howManyRings()` in CS316ex2.java and the static variable `input` in CS316ex5.java). ***<u>No memory at all is allocated for Scanner variables</u>*** in TinyJ. A Scanner variable `x` in TinyJ can only be used in `x.nextInt()`. This is executed by reading an integer from the standard input stream `System.in` (which is usually associated with the keyboard) and returning its value. So the Scanner variable `x` is completely irrelevant. That is why TinyJ essentially ignores Scanner variables and never allocates memory for them. (In contrast, the Scanner variable `x` is ***not*** irrelevant when a ***Java*** program executes `x.nextInt()`: In Java, a Scanner object need not be associated with `System.in`—a Scanner object may, for example, be associated with any input file.) In TinyJ, the Scanner variable `x` in `x.nextInt()` is there only because we want TinyJ to be a subset of Java so that TinyJ programs will be compilable by a Java compiler.

Effects of Executing Each TinyJ Virtual Machine Instruction

"Push" and "pop" refer to the TinyJ VM's **expression evaluation stack** (the **EXPRSTACK**).

n denotes an arbitrary nonnegative integer   *addr* denotes an arbitrary code memory address
a denotes an arbitrary data memory address   *a'* denotes an arbitrary data memory address $\geq a$
s denotes an arbitrary stackframe offset in the currently executing method activation's stackframe

If an assumption made by a VM instruction is **not** satisfied when the instruction is executed (e.g., if the item popped by LOADFROMADDR is *not* a pointer), then the effects of executing the instruction are unspecified.

TinyJ VM Instruction	Effects of Executing the Instruction
STOP	Halts the machine.
NOP	Does nothing.
DISCARDVALUE	Pops an item.
PUSHNUM *n*	Pushes the nonnegative integer value *n*.
PUSHSTATADDR *a*	Pushes a pointer to the data memory location whose address is *a*.
PUSHLOCADDR *s*	Pushes a pointer to the data memory location that is at offset *s* in the currently executing method activation's stackframe.
SAVETOADDR	Pops an item *v*. Pops an item *p*, which is assumed to be a pointer to a data memory location. Stores *v* in the memory location to which *p* points.
LOADFROMADDR	Pops an item *p*, which is assumed to be a pointer to a data memory location. Pushes the value that is stored in the memory location to which *p* points.
WRITELNOP	Writes a newline to the screen.
WRITEINT	Pops an item *i*, which is assumed to be an integer. Writes the integer *i* to the screen.
WRITESTRING *a* *a'*	Assumes that the data memory locations whose addresses are $\geq a$ but $\leq a'$ contain the characters of a string literal. Writes that string literal to the screen.
READINT	Assumes the character sequence of an int will be entered on the keyboard. Reads that character sequence and computes the int value it represents. Pushes that integer value.
CHANGESIGN	Pops an item *i*, which is assumed to be an integer. Pushes the value $-i$.
NOT	Pops an item *b*, which is assumed to be a Boolean value. Pushes the Boolean value NOT *b*.
op = ADD, SUB, MUL, DIV, MOD, EQ, LT, GT, NE, GE, or LE	Pops an item *i*, which is assumed to be an integer. Pops an item *j*, which is also assumed to be an integer. Pushes the integer or Boolean value *j* **op** *i*; MOD is C++/Java's % operation.
op = AND or OR	Pops an item *b*, which is assumed to be a Boolean value. Pops an item *c*, which is also assumed to be a Boolean value. Pushes the Boolean value *c* **op** *b*.

JUMP *addr*	Loads *addr* into the program counter register.
JUMPONFALSE *addr*	Pops an item *b*, which is assumed to be a Boolean value. Loads *addr* into the program counter register if (and only if) *b* is **false**.
PASSPARAM	Allocates 1 location in the stack-dynamically allocated part of data memory. Pops an item and stores that item in the allocated location; it is expected that the item which is popped and stored will be the value of an actual argument of a method that is about to be called.
CALLSTATMETHOD *addr*	Allocates 1 location in the stack-dynamically allocated part of data memory; this location will be at offset –1 in the callee's stackframe. Stores the program counter in the allocated location; the stored address is the call's return address. Loads *addr* into the program counter register.
INITSTKFRM *n*	Allocates 1 location in the stack-dynamically allocated part of data memory; this will be at offset 0 in the current method activation's stackframe. Stores the frame pointer in the allocated location; this will serve as the stackframe's dynamic/control link pointer. Loads a pointer to the allocated location into the frame pointer register. Allocates *n* more locations in the stack-dynamically allocated part of data memory; these will be the locations at offsets 1 through *n* in the current method activation's stackframe.
RETURN *n*	Assumes *n* is the number of parameters of the currently executing method. Assumes the location at offset 0 in the currently executing method activation's stackframe contains the dynamic/control link pointer. Assumes the location at offset –1 in the currently executing method activation's stackframe contains the return address. Loads the dynamic/control link pointer into the frame pointer register. Loads the return address into the program counter register. Deallocates the data memory locations that constitute the currently executing method activation's stackframe.
HEAPALLOC	Pops an item *i*, which is assumed to be a nonnegative integer. Allocates $i+1$ contiguous locations[*] in the heap area of data memory; it is expected that the second through $i+1^{st}$ of those locations will be used to store the elements of an array of *i* elements. Stores in the first of the $i+1$ locations a pointer[†] to the first location above the $i+1$ locations; the second through $i+1^{st}$ locations will all contain 0. Pushes a pointer to the second of the $i+1$ locations.
	[*]If there isn't enough available memory in the heap area of data memory to do this, garbage collection will be performed (to deallocate any currently allocated heap locations that can no longer be accessed by the program) and then another attempt will be made to allocate $i+1$ contiguous heap locations.
	[†]ADDTOPTR uses this pointer to check for array-index-out-of-range errors. The garbage collector uses this pointer to find the ends of allocated blocks.
ADDTOPTR	Pops an item *i*, which is assumed to be a nonnegative integer. Pops an item *p*, which is assumed to be a pointer to the data memory location of the first element of an array *arr*. Pushes $p+i$ (which is a pointer to the location of the array element *arr*[*i*]), unless *arr* has $\leq i$ elements in which case an error is reported.

Example: The TinyJ Compiler of Assignment 2 should translate the following TinyJ source file into the TinyJ VM instructions shown on the next page.

```
import java.util.Scanner;

class Simple3 {

  static Scanner input = new Scanner(System.in);
  static int x, y = 10;

  public static void main(String args[])
  {
      System.out.print("Enter num: ");
      x = input.nextInt();
      f(17, y, x-y);
      System.out.println(y + f(21,22,23));
  }

  static int f (int a, int b, int c)
  {
      int v[], w;
      int u = x;

      g(c, b + u);
      System.out.print("returning from f ... ");
      return y - a % u;
  }

  static void g (int d, int e)
  {
      int z;

      y = d / e;
  }
}
```

```
Instructions Generated:

0:      PUSHSTATADDR    1           34:     INITSTKFRM      3
1:      PUSHNUM         10          35:     PUSHLOCADDR     3
2:      SAVETOADDR                  36:     PUSHSTATADDR    0
======================================  37:     LOADFROMADDR
3:      INITSTKFRM      0           38:     SAVETOADDR
4:      WRITESTRING     2    12     39:     PUSHLOCADDR     -2
5:      PUSHSTATADDR    0           40:     LOADFROMADDR
6:      READINT                     41:     PASSPARAM
7:      SAVETOADDR                  42:     PUSHLOCADDR     -3
8:      PUSHNUM         17          43:     LOADFROMADDR
9:      PASSPARAM                   44:     PUSHLOCADDR     3
10:     PUSHSTATADDR    1           45:     LOADFROMADDR
11:     LOADFROMADDR                46:     ADD
12:     PASSPARAM                   47:     PASSPARAM
13:     PUSHSTATADDR    0           48:     CALLSTATMETHOD  60
14:     LOADFROMADDR                49:     NOP
15:     PUSHSTATADDR    1           50:     WRITESTRING     13   33
16:     LOADFROMADDR                51:     PUSHSTATADDR    1
17:     SUB                         52:     LOADFROMADDR
18:     PASSPARAM                   53:     PUSHLOCADDR     -4
19:     CALLSTATMETHOD  34          54:     LOADFROMADDR
20:     DISCARDVALUE                55:     PUSHLOCADDR     3
21:     PUSHSTATADDR    1           56:     LOADFROMADDR
22:     LOADFROMADDR                57:     MOD
23:     PUSHNUM         21          58:     SUB
24:     PASSPARAM                   59:     RETURN          3
25:     PUSHNUM         22          ======================================
26:     PASSPARAM                   60:     INITSTKFRM      1
27:     PUSHNUM         23          61:     PUSHSTATADDR    1
28:     PASSPARAM                   62:     PUSHLOCADDR     -3
29:     CALLSTATMETHOD  34          63:     LOADFROMADDR
30:     ADD                         64:     PUSHLOCADDR     -2
31:     WRITEINT                    65:     LOADFROMADDR
32:     WRITELNOP                   66:     DIV
33:     STOP                        67:     SAVETOADDR
======================================  68:     RETURN          2
```

Code generated for **main**.

Code generated for **f**.

Code generated for **g**.

Code Generation Rules Used by the TinyJ Compiler

1. The generated code begins with instructions which initialize each static int and static array reference variable *that has an explicit initializer.* [**Example**: The instructions at addresses 0 – 2 in the code generated for the **Simple3** source file.]

2. For variables that do **_not_** have an explicit initializer, no initialization code is generated. Static variables that are **_not_** explicitly initialized will have a value of 0 (in the case of static **int** variables) or **null** (in the case of static array reference variables) when code execution begins: In the TinyJ VM, the data memory locations allocated to static variables all contain 0 when execution begins, and the **null** pointer is represented by 0.

3. Method bodies are translated in the order in which they appear. [**Example**: The code generated for main()'s body appears before the code generated for other methods' bodies.]

4. The code generated for each method (including main) starts with:
    > **INITSTKFRM** <total number of stackframe locations needed for local variables declared in that method's body>
    [**Example**: The instructions at addresses 3, 34, and 60.]

5. **main()**'s code ends with: **STOP** [**Example**: The instruction at address 33.]

6. The code generated for each **void** method (other than **main()**) ends with: **RETURN** *k* Here *k* is the number of formal parameters that the method has. [**Example**: The instruction at address 68.]

7. A **return** *expression;* statement in a method is translated into:
    > <code which leaves the value of *expression* on top of EXPRSTACK>
    > **RETURN** *k*
    Again, *k* is the number of formal parameters that the method has. [**Example**: The instructions generated for **return y-a%u;** at addresses 51 – 59.]

8. A method call **f(***arg₁*, *arg₂*, ..., *argₖ***)** *within an expression* is translated into:
    > <code that leaves the value of *arg₁* on top of EXPRSTACK>
    > **PASSPARAM**
    > <code that leaves the value of *arg₂* on top of EXPRSTACK>
    > **PASSPARAM**
    > ...
    > <code that leaves the value of *argₖ* on top of EXPRSTACK>
    > **PASSPARAM**
    > **CALLSTATMETHOD** <address of the first instruction in method **f()**'s code>
    [**Example**: The instructions generated for **f(21, 22, 23)** at addresses 23 – 29.]

9. A method call that is a *standalone statement* is translated in the same way as a method call within an expression, except that the **CALLSTATMETHOD** may be followed by **DISCARDVALUE**, **NOP**, or neither:

    (a) If the called method is known to return a value (either because it has already been declared to return a value, or because it has previously been called within an expression) then the **CALLSTATMETHOD** must be followed by **DISCARDVALUE** to pop the returned value off EXPRSTACK.

    (b) If the called method has already been declared as a **void** method, then no **DISCARDVALUE** instruction is generated.

    (c) If the called method has not yet been declared, and has not previously been called within an expression, then the compiler cannot tell if the method returns a value or not. In this case, the compiler essentially leaves a one-instruction gap after generating the **CALLSTATMETHOD** instruction. Later, when the compiler sees the declaration of the called method, it fills in the gap with either a **NOP** or a **DISCARDVALUE** instruction, according to whether the called method is declared to be a **void** method or a method that returns a value. [**Examples**: The instructions generated for **f(17, y, x-y)** at addresses 8 – 20, and the instructions generated for **g(c, b+u)** at addresses 39 – 49.]

How Should Your Assignment 2 Compiler Translate TinyJ Source into TinyJ VM Code?

Answer: Your compiler should perform ***recursive descent translation***.

Notation For any non-terminal node *n* in the parse tree of a TinyJ source file, let *n*.code denote *the sequence of TinyJ VM instructions that should be generated by your compiler for the corresponding sequence of tokens* (i.e., the VM instructions that should be generated for the sequence of tokens that are the leaves of the subtree whose root is the node *n*).

Example If *n* is the <statement> node in the parse tree of the above program that corresponds to the statement   y = d / e;   in the body of the method g, then
$$n.code = \text{the instructions at code memory addresses } 61 - 67$$

Example If *n* is the <expr2> node in the parse tree of the above program that corresponds to the expression d / e in the statement y = d / e;, then
$$n.code = \text{the instructions at code memory addresses } 62 - 66$$

Assuming the input file is a valid TinyJ program, when the parser of TinyJ Assignment 1 is executed there is one call of method *N*( ) for each occurrence *n* of a nonterminal <*N*> in the program's parse tree.

In Assignment 1, that call of *N*( ) reads in the corresponding sequence of tokens[*] from the input file and outputs the subtree of the parse tree whose root is *n* (and whose leaves are those tokens).

[*]with the exception of the *first* of those tokens, as `CurrentToken` should correspond to that token when *N*( ) is called.

This is still true when the recursive descent translator of TinyJ Assignment 2 is executed, ***but in Assignment 2 the same call of *N*( ) also generates *n*.code.***

If *n* is an <expr *i*> node (where *i* = 1, 2, 3, 4, 5, 6, or 7), then:
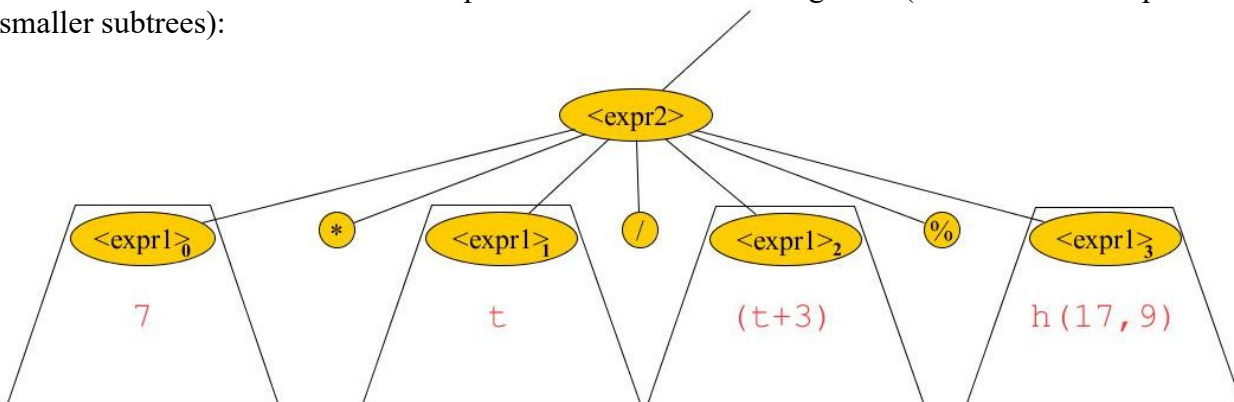   *n*.code is code that leaves the value of the corresponding expression on top of **EXPRSTACK**.
(The TinyJ VM doesn't use data registers for evaluating expressions but uses the **EXPRSTACK**.)

Example Suppose *n* is an <expr2> node that corresponds to: 7 * t / (t+3) % h(17,9)
Recalling from Assignment 1 that the EBNF rule for <expr2> is
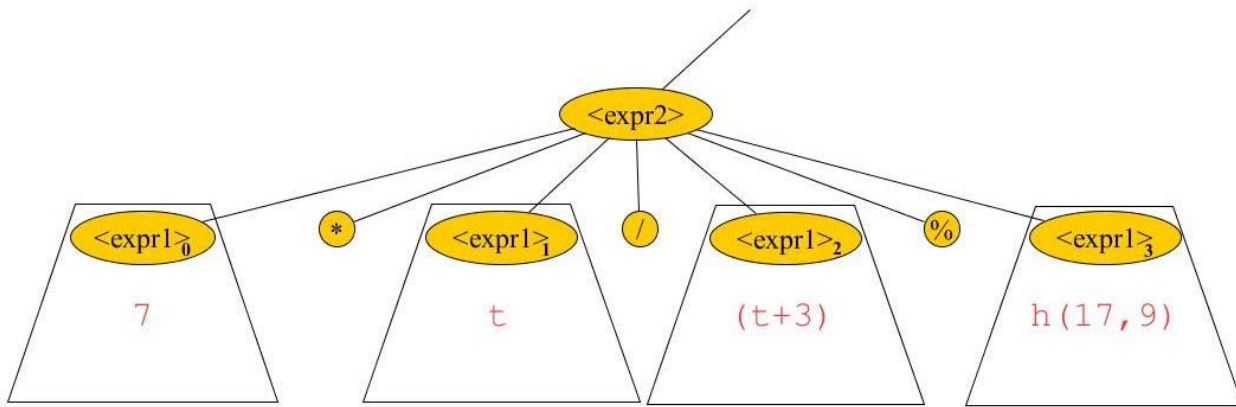$$\text{<expr2>} ::= \text{<expr1>} \{ (* | / | \%) \text{<expr1>}\}$$
we see the subtree rooted at this <expr2> node has the following form (where the four trapezoids represent smaller subtrees):

In this case,   <expr2>.code   =   <expr1>$_0$.code
                                             <expr1>$_1$.code
                                             MUL
                                             <expr1>$_2$.code
                                             DIV
                                             <expr1>$_3$.code
                                             MOD

To make this same example more concrete, assume that in `7 * t / (t+3) % h(17,9)`

       `t`   is a static variable whose address is 5.

       `h`   is a method whose VM code begins at address 91 in code memory.

Then:

<expr2>.code =	<expr1>$_0$.code ——	PUSHNUM	7
	<expr1>$_1$.code ——	PUSHSTATADDR LOADFROMADDR	5
	MUL ——	MUL	
	<expr1>$_2$.code ——	PUSHSTATADDR LOADFROMADDR PUSHNUM ADD	5 3
	DIV ——	DIV	
	<expr1>$_3$.code ——	PUSHNUM PASSPARAM PUSHNUM PASSPARAM CALLSTATMETHOD	17 9 91
	MOD ——	MOD	

How the Compiler Can Generate a VM Instruction

There is a class in the `TJasn.virtualMachine` package for each kind of instruction.

To generate an instruction, create a new instance of that class; if the instruction has one or two operands, pass these operands as arguments when invoking the constructor. Examples:

```
new WRITEINTinstr();            generates    WRITEINT
new JUMPONFALSEinstr(31);       generates    JUMPONFALSE   31
new WRITESTRINGinstr(21, 27);   generates    WRITESTRING   21  27
```

The generated instruction is put in the next available location in code memory (which is represented by the ArrayList `TJ.generatedCode`).

Each time an instruction is generated, a line that reports this is written to the output file. For example:

```
        *** Generating:  35:     PUSHLOCADDR        -3
```

How the Method `expr2()` **in Assignment 1's** `Parser.java` **was Modified to Produce the Method** `expr2()` **in Assignment 2's** `ParserAndTranslator.java`

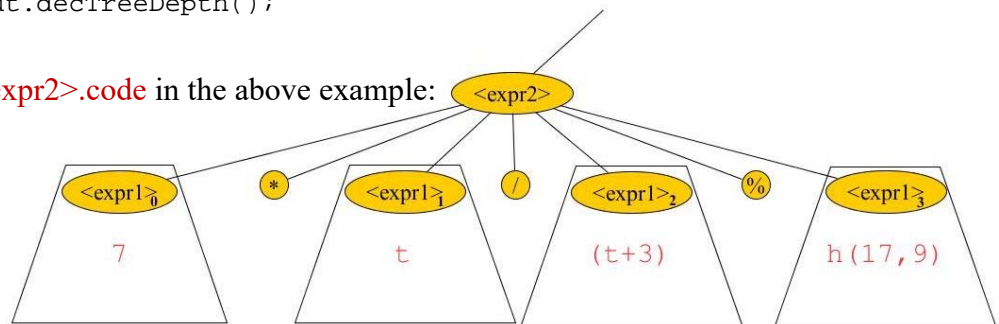Here is `expr2()` in Assignment 1's `Parser.java`, which is based on the EBNF rule

$$\langle expr2\rangle ::= \langle expr1\rangle \ \{(*\,|\,/\,|\,\%)\,\langle expr1\rangle\}$$

```
374            private static void expr2() throws SourceFileErrorException
375            {
376               TJ.output.printSymbol(NTexpr2);
377               TJ.output.incTreeDepth();
378
379               expr1();
380
381               while (   getCurrentToken() == TIMES
382                      || getCurrentToken() == DIV
383                      || getCurrentToken() == MOD) {
384
385                  nextToken();
386
387                  expr1();
388               }
389
390               TJ.output.decTreeDepth();
391            }
```

Consider the generation of $\langle expr2\rangle$.code in the above example:

Recall that
   $\langle expr2\rangle$.code = $\langle expr1\rangle_0$.code $\langle expr1\rangle_1$.code **MUL** $\langle expr1\rangle_2$.code **DIV** $\langle expr1\rangle_3$.code **MOD**

Now if we just *copy* lines 379 – 388 above into Assignment 2's `expr2()` method, execution of those lines will generate: $\langle expr1\rangle_0$.code $\langle expr1\rangle_1$.code $\langle expr1\rangle_2$.code $\langle expr1\rangle_3$.code

[Line 379 generates $\langle expr1\rangle_0$.code; line 387 generates $\langle expr1\rangle_j$.code at the *j*th iteration of the while loop!]

So, to produce a correct version of `expr2()` that generates all of $\langle expr2\rangle$.code, *we only need to add statements that generate the* **MUL**, **DIV**, *and* **MOD** *instructions*:

```
expr1();
while (   getCurrentToken() == TIMES
       || getCurrentToken() == DIV
       || getCurrentToken() == MOD) {

   Symbols op = getCurrentToken();          // ADDED

   nextToken();

   expr1();

   if (op == TIMES) new MULinstr();         // ADDED
   else if (op == DIV) new DIVinstr();      // ADDED
   else new MODinstr();                     // ADDED
}
```

After reading this page, you should be able to fill in the /* ???????? */ gaps on lines 638 through 682!

As the method `expr2()` illustrates, a good way to write a method `N()` in Assignment 2's ParserAndTranslator.java that corresponds to a nonterminal `<N>` is to start with the parsing method `N()` in Assignment 1's Parser.java and decide what (if anything) must be added for Assignment 2. Here are two more examples of this.

Example 1: Consider the method `argumentList()` in ParserAndTranslator.java. We see from p. 1 of the Assignment 1 document that the EBNF rule for `<argumentList>` is

       `<argumentList> ::= '(' [<expr3>{,<expr3>}] ')'`

Note that there may be any number of `<expr3>`'s (and possibly none at all) between the opening and closing parentheses. Based on this, and the part of Code Generation Rule 8 that relates to the list of arguments, we see that

       `<argumentList>.code =`   `<expr3>`$_1$.code
                              `PASSPARAM`
                              `<expr3>`$_2$.code
                              `PASSPARAM`
                                   .
                                   .
                                   .
                              `<expr3>`$_k$.code
                              `PASSPARAM`

where k is the number of `<expr3>`'s in the `<argumentList>`, and `<expr3>`$_i$ means the ith of those k `<expr3>`'s. Assuming you correctly filled in the gap in the method `argumentList()` in Assignment 1, if you copy just that code into the body of Assignment 2's `argumentList()` then its calls of `expr3()` will generate `<expr3>`$_1$.code, `<expr3>`$_2$.code, ... , `<expr3>`$_k$.code. To complete Assignment 2's `argumentList()` method, you would also need to insert one or more statements of the form `new PASSPARAMinstr();` in appropriate places to generate the k `PASSPARAM` instructions.

Example 2: Consider the method `outputStmt()` in ParserAndTranslator.java. We see from the EBNF rule for `<outputStmt>` that there are three cases:

 1. `<outputStmt>  ::=  System.out.print '(' <printArgument> ')' ;`

    In this case, `<outputStmt>.code = <printArgument>.code`
    where `<printArgument>.code` is the code that prints the `<printArgument>` to the screen.

 2. `<outputStmt>  ::=  System.out.println '(' ')' ;`

    In this case, `<outputStmt>.code = WRITELNOP`

 3. `<outputStmt>  ::=  System.out.println '(' <printArgument> ')' ;`

    In this case, `<outputStmt>.code = <printArgument>.code`
                              `WRITELNOP`

Assuming you correctly filled in the gap in the method `outputStmt()` in Assignment 1, if you copy just that code into the body of Assignment 2's `outputStmt()` then its calls of `printArgument()` will generate `<printArgument>.code` in cases 1 and 3. To complete Assignment 2's `outputStmt()`, you would also need to insert one or more statements of the form `new WRITELNOPinstr();` to generate the `WRITELNOP` instructions in cases 2 and 3.

Hints Relating to the Gaps on Lines 627, 723, and 593 in ParserAndTranslator.java

The Method `printArgument()` [gap on line 627]

The relevant EBNF rule is   `<printArgument>` `::=`   `CHARSTRING` | `<expr3>`

(a) In the case `<printArgument>` `::=`   `<expr3>`   the code to be generated is given by

> `<printArgument>.code = <expr3>.code`
>   WRITEINT

Assuming you correctly filled in the gap in the method `printArgument()` in Assignment 1, if you copy just that code into the body of Assignment 2's `printArgument()` then its call of `expr3()` will generate `<expr3>.code`. To complete the `printArgument()` method, you would also need to insert a   **new** `WRITEINTinstr();` statement.

(b) In the case `<printArgument>` `::=`   `CHARSTRING` the code to be generated is given by

> `<printArgument>.code = WRITESTRING a b`

where a and b are the data memory addresses of the first and last characters of the `CHARSTRING` string literal that is to be printed. The `WRITESTRING a b` instruction can be generated by   **new** `WRITESTRINGinstr(a,b);` with the appropriate addresses a and b; but how can your code find the two addresses a and b?

  The solution is provided by the lexical analyzer: When `LexicalAnalyzer.nextToken()` sets `LexicalAnalyzer.currentToken` to `CHARSTRING`, it also sets the private variables `LexicalAnalyzer.startOfString` and `LexicalAnalyzer.endOfString` to the addresses of the memory locations where the first and last characters of the `CHARSTRING` will be placed. **`LexicalAnalyzer.getStartOfString()`** and **`LexicalAnalyzer.getEndOfString()`** are public accessor methods that return the two addresses.

The Method `expr1()` [gap on line 723]

The relevant EBNF rule is

```
<expr1>    ::=    '(' <expr7> ')'  |  (+|-|!) <expr1>  |  UNSIGNEDINT  |  null
           |       new int '[' <expr3> ']' { '[' ']' }
           |       IDENTIFIER ( . nextInt '(' ')'  |  [<argumentList>]{'[' <expr3> ']'} )
```

The **null** and the `IDENTIFIER` (. **nextInt** `'(' ')'` | [`<argumentList>`]{`'[' <expr3> ']'`}) cases have been done for you in `ParserAndTranslator.java`. Here are hints for the other cases:

(a) In the case `<expr1>`   `::=`   `'(' <expr7> ')'`   the code to be generated is given by

> `<expr1>.code = <expr7>.code`

Similarly, in the case `<expr1>`   `::=`   `+ <expr1>`$_1$ the code to be generated is given by

> `<expr1>.code = <expr1>`$_1$`.code`

In these two cases, assuming you correctly completed the body of the method `expr1()` when doing Assignment 1, if you use that code as the body of Assignment 2's `expr1()` then in the first case the call of `expr7()` will generate `<expr7>.code`, and in the second case the recursive call of `expr1()` will generate `<expr1>`$_1$`.code`.

(b) In the case `<expr1>`   `::=`   `- <expr1>`$_1$ the code to be generated is given by

> `<expr1>.code = <expr1>`$_1$`.code`
>   CHANGESIGN

Similarly, in the case `<expr1>`   `::=`   `! <expr1>`$_1$ the code to be generated is given by

> `<expr1>.code = <expr1>`$_1$`.code`
>   NOT

These two cases are similar to the second case of (a), except that you need to insert a **new** `CHANGESIGNinstr();` or a **new** `NOTinstr();` statement.

(c) In the case `<expr1>` `::=` `UNSIGNEDINT` the code to be generated is given by

$$\text{<expr1>.code = PUSHNUM v}$$

where v is the numerical value of the `UNSIGNEDINT` integer literal. The `PUSHNUM v` instruction can be generated by **new** `PUSHNUMinstr(v);` with the appropriate value v; but how can your code find the value v?

The solution is provided by the lexical analyzer: When `LexicalAnalyzer.nextToken()` sets `LexicalAnalyzer.currentToken` to UNSIGNEDINT, it also sets the private variable `LexicalAnalyzer.currentValue` to the numerical value of the `UNSIGNEDINT` integer literal. **`LexicalAnalyzer.getCurrentValue()`** is a public accessor method that returns this value.

(d) In the case `<expr1>` `::=` **new int** `'['` `<expr3>` `']'` `{` `'['` `']'` `}` the code to be generated is given by

$$\text{<expr1>.code = <expr3>.code}$$
$$\text{HEAPALLOC}$$

Assuming you correctly completed the body of `expr1()` when doing Assignment 1, if you use that code as the body of Assignment 2's `expr1()` then `<expr3>.code` will be generated by a call of `expr3()`. You would need to insert a **new** `HEAPALLOCinstr();` statement.

The Method `whileStmt()` [gap on line 593]

The relevant EBNF rule is

`<whileStmt>` `::=` **while** `'('` `<expr7>` `')'` `<statement>`

and the code to be generated is given by:

$$\text{<whileStmt>.code = a: <expr7>.code}$$
$$\text{JUMPONFALSE b}$$
$$\text{<statement>.code}$$
$$\text{JUMP a}$$
$$\text{b:}$$

In `Instruction.java`, the static variable `Instruction.nextCodeAddress` is used to hold the code memory address of the **_next_** instruction to be generated. [This variable is incremented by 1 (by the constructor for the `Instruction` class) each time an instruction is generated.]

A call of `Instruction.getNextCodeAddress()` returns `Instruction.nextCodeAddress`.

Before calling `expr7()` to read the `<expr7>` expression and generate `<expr7>.code`, `whileStmt()` needs to call `Instruction.getNextCodeAddress()` and save the code memory address that is returned in an **int** local variable (which needs to be declared). This saved address will be needed as the operand a of the

$$\text{JUMP a}$$

instruction which `whileStmt()` must generate later!

`Instruction.OPERAND_NOT_YET_KNOWN` (line 13 in `Instruction.java`) is a constant integer that the compiler uses to represent an unknown operand value.

When `whileStmt()` begins to generate JUMPONFALSE b **_it does not know what the address_** b **_will be_**. So at that time `whileStmt()` should merely generate

$$\text{JUMPONFALSE \texttt{Instruction.OPERAND\_NOT\_YET\_KNOWN}}$$

and also **_save a reference_** to this JUMPONFALSE instruction in a local variable, to allow the instruction to be found again when `whileStmt()` is ready to fix up its operand:

`JUMPONFALSEinstr jInstr = new JUMPONFALSEinstr(Instruction.OPERAND_NOT_YET_KNOWN);`

`fixUpOperand()` is an important method of `OneOperandInstruction.java`: If `instr` is a reference to a one-operand VM instruction then `instr.fixUpOperand(k)` sets that instruction's operand to the integer k.

So, after generating the JUMP a instruction, `whileStmt()` can fix up the operand of the previously generated JUMPONFALSE `Instruction.OPERAND_NOT_YET_KNOWN` instruction as follows:

    jInstr.fixUpOperand(Instruction.getNextCodeAddress());

Also Study the Method `ifStmt()` [lines 555 – 85]

The above hints should provide enough information for you to complete the method `whileStmt()`. But you should also study the method `ifStmt()`, which has already been written for you and provides further examples of how `Instruction.OPERAND_NOT_YET_KNOWN`, `Instruction.getNextCodeAddress()`, and `fixUpOperand()` are used. Here the relevant EBNF rule is

    <ifStmt>   **::=**   **if** '(' <expr7> ')' <statement> **[else** <statement>**]**

and the code to be generated is as follows:

Case 1:   <ifStmt> ::=   **if** '(' <expr7> ')' <statement>$_1$

            <ifStmt>.code =   <expr7>.code
                                  JUMPONFALSE **a**
                                  <statement>$_1$.code
                        a:

Case 2:   <ifStmt> ::=   **if** '(' <expr7> ')' <statement>$_1$ **else** <statement>$_2$

            <ifStmt>.code =   <expr7>.code
                                  JUMPONFALSE **a**
                                  <statement>$_1$.code
                                  JUMP **b**
                        a: <statement>$_2$.code
                        b:

It is *possible* that there will be one or more questions on Exam 2 or the Final Exam which test your understanding of the method `ifStmt()`.

Hints Relating to the Gaps on Lines 492, 495, and 511 in ParserAndTranslator.java

Here the relevant EBNF rule is:

    <assignmentOrInvoc> ::= IDENTIFIER ({ '['<expr3>']' } = <expr3> ; | <argumentList> ;)

This rule has two cases:

> **Case 1**: `<assignmentOrInvoc> ::= IDENTIFIER { '['<expr3>']' } = <expr3> ;`
>
> **Case 2**: `<assignmentOrInvoc> ::= IDENTIFIER <argumentList> ;`

The gaps you have to fill in relate only to Case 1. In that case the code to be generated is as follows:

`<assignmentOrInvoc>`.code = `PUSHLOCADDR IDENTIFIER.stackframe_offset` **or** `PUSHSTATADDR IDENTIFIER.address`
                  `LOADFROMADDR`
                  `<expr3>`index_1.code
                  `ADDTOPTR`
                      .
                      .
                      .
                  `LOADFROMADDR`
                  `<expr3>`index_k.code
                  `ADDTOPTR`
                  `<expr3>`right_side.code
                  `SAVETOADDR`

where `<expr3>`right_side means the expression on the right side of `=`, and where the number of occurrences of

                  `LOADFROMADDR`
                  `<expr3>`index_i.code
                  `ADDTOPTR`

is equal to the *number of indexes* after the IDENTIFIER—i.e., the number of times `'['<expr3>']'` occurs. Often there are no indexes (i.e., the assignment is of the form IDENTIFIER = `<expr3>`right_side `;`). In any case the loop on lines 500–507 generates `LOADFROMADDR`, `<expr3>`index_i.code, and `ADDTOPTR` as many times as is needed. But you must fill in the ***gap on line 511*** in such a way that `<expr3>`right_side.code and `SAVETOADDR` are generated.

Note that the compiler must generate `PUSHLOCADDR IDENTIFIER.stackframe_offset` if the IDENTIFIER is a formal parameter or a local variable declared in the method's body, but it must instead generate `PUSHSTATADDR IDENTIFIER.address` if the IDENTIFIER is a static variable. To determine which of these two cases applies, and to determine the identifier's stackframe offset in the former case and its data memory address in the latter case, the compiler looks up the IDENTIFIER in the ***symbol table***. The symbol table is a table, maintained by the compiler. When a method's body is being compiled, the symbol table contains:

1. A `LocalVariableRec` object for each formal parameter of the method, and for each local variable that is declared in the method's body and is in scope at the point the compiler has reached.

2. A `ClassVariableRec` object for each static variable whose declaration has been seen by the compiler. The compiler records information about each variable / parameter in its `LocalVariableRec` or its `ClassVariableRec` object. For example, if v is a static variable then v's data memory address is stored in the `offset` field of v's `ClassVariableRec` object. Similarly, if v is a formal parameter / local variable then v's stackframe offset is stored in the `offset` field of v's `LocalVariableRec` object.

The symbol table also contains a `MethodRec` object for each method that has been declared or called in the part of the program that has been seen by the compiler. But you will ***not*** have to write any code that deals with `MethodRec` objects to complete Assignment 2.

Line 480 of ParserAndTranslator.java sets `identName` to the name of the IDENTIFIER. On line 485, `t = symTab.searchForVariable(identName);` looks in the symbol table for the IDENTIFIER's `LocalVariableRec` or `ClassVariableRec` object, and sets `t` to refer to that object. Therefore the Boolean value of `t instanceof LocalVariableRec` on line 491 will be **true** or **false** according to whether the IDENTIFIER is a local variable / formal parameter or a static variable. In the former case `t.offset` will contain IDENTIFIER.stackframe_offset; in the latter case `t.offset` will contain IDENTIFIER.address. Use `t.offset` to fill in the ***gaps on lines 492 and 495*** in such a way that `PUSHLOCADDR IDENTIFIER.stackframe_offset` is generated if the IDENTIFIER is a local variable or formal parameter, but `PUSHSTATADDR IDENTIFIER.address` is generated if the IDENTIFIER is a static variable.