Runtime environment

Handout written by Maggie Johnson and revised by me.

Before we get into the low-level details of final code generation, we first take a look at the layout of memory and the runtime data structures for managing the stack and heap.

Data representation

Simple variables: are represented by sufficient memory locations to hold them:

char: 1 byte
integers: 2 or 4 bytes
floats: 4 to 16 bytes
booleans: 1 bit (but usually 1 byte)

If the variable is global, it will be stored in the data segment (just following the code segment in memory). If local, it is located in the activation record of the runtime stack.

Pointers: are usually represented as unsigned integers. The size of the pointer depends on the range of addresses on the machine. Currently almost all machines use 4 bytes to store an address, creating a 4GB addressable range. There is actually very little distinction between a pointer and a 4 byte unsigned integer. They both just store integers— the difference is whether the number is interpreted as a number or as an address.

One dimensional arrays: are a contiguous block of elements. The size of an array is at least equal to the size of each element multiplied by the number of elements. The elements are laid out consecutively starting with the first element and working from low-memory to high. Given the base-address of the array, the compiler can generate code to compute the address of any element as an offset from the base address:

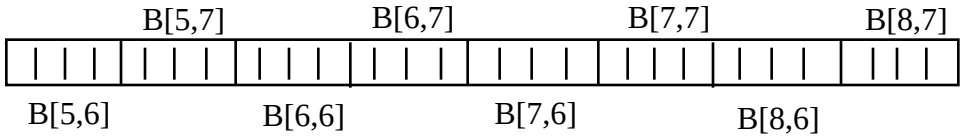
`&arr[i] = arr + 4 * i` (4-byte integers; arr = base address)

Global static arrays are stored in the data segment. Local arrays may be on stack if the language supports such a feature. What about dynamic arrays?

Multi-dimensional arrays: one of two approaches, either a true multi-dimensioned array, or an array of arrays strategy.

1) As one contiguous block. In a row-major configuration (C, Pascal), the rows are stored one after another. In a column-major (Fortran), the columns are stored one after another. For a row-major array of m rows x n columns integer array, we compute the address of an element as `&arr[i,j] = arr + 4 * (n * i + j)` or in a more general form for the array:
   `array[`L_1`..`U_1`, `L_2`..`U_2`]` (in Pascal form)
   `&arr[i, j] = arr + (sizeof T) *((i - `L_1`)*(`U_2`-`L_2`+1) + (j- `L_2`))`

   For example, the array `B[5..8, 6..7]` of integers would look like this:



(4 bytes per integer)

$L_1 = 5; U_2 = 7, L_2 = 6$

```
&B[8,6] = B + 4 * ((8-5)*(7-6+1) + (6-6)) = B + 24
```

2) As an array of arrays, i.e., we have a vector with one pointer element for each row. This is the scheme Decaf uses. Each element of the outer vector holds the address of a vector for the corresponding row. We use the following formula to find the location of the address of the ith row: B = A + 4 * i. The jth element in this vector is at byte address: B + 4 * j. How can this method be extended to arrays of more than two dimensions?

Structs: are laid out by allocating the fields sequentially in a contiguous block, working from low-memory to high. The size of a record is equal to at least the sum of the field sizes. In the example below, if integers require 4 bytes, chars 1 and doubles 4 bytes, 8 bytes, we would need at least 13 bytes with the individual fields at offsets 0, 4 and 5 bytes from the base address. Why, then, on most machines, will it reserve 16 bytes for this struct?

```
struct example {
   int index;
   char type;
   double length;
};
```

Objects: are very similar to structs, where the fields are the instance variables for the class. Methods are not stored in the object itself, but for dynamic dispatch, there may be a hidden extra pointer with each object that references shared class-wide information (often called the *vtable*) that provides information about the class methods. If the language doesn't support dynamic dispatch (or the class doesn't define any methods that require it, i.e. non-virtual in C++) there may be no need for the vtable or vptr.

Instructions: themselves are also encoded using bit patterns, usually in native word size. The different bits in the instruction encoding indicate things such as what type of instruction it is (load, store, multiply, etc.) and the registers involved to read or write from.

Storage classes

The *scope* of a variable defines the lexical areas of a program in which the variable may be referenced. The *extent* or *lifetime* refers to the different periods of time for which variable remain in existence.

global: exist throughout lifetime of entire program and can be referenced anywhere.

static: exist throughout lifetime of entire program but can only be referenced in the function (or module) in which they are declared.

local: (also called *automatic)* exist only for the duration of a call to the routine in which they are declared; a new variable is created each time the routine is entered (and destroyed on exit). They may be referenced only in the routine in which they are

declared. Locals may have even smaller scope inside an inner block within a routine (although they might "exist" for the entirety of the routine for convenience of the compiler, they can only be referenced within their block).

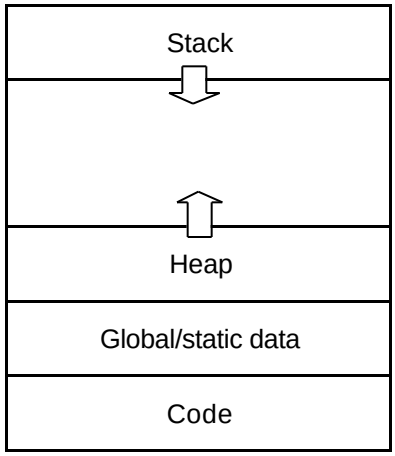
dynamic: variables that are created during program execution; usually represented by an address held in a variable of one of the above classes. Extent is the lifetime of the program (unless explicitly returned to the system); scope is the scope of the variable used to hold its address.

Both global and static variables have a single instance that persists throughout life of program and the two classes vary only in scope. The usual implementation for these is a collection of memory locations in the global/static data segment of the executable. These locations are fixed at the end of the compilation process.

Local variables only come into existence on entry to a routine and persist until its exit. To handle these we use a runtime stack that holds the values of locals. The area of memory used to hold all the locals of a routine is called the stack frame. The stack frame for the routine currently executing will be on top of the stack. The address of the current stack frame is usually held in a machine register and is called the stack or frame pointer.

Dynamic allocation of further storage during the run of a program is done by calling library functions (e.g., malloc()). This storage is obtained from memory in a different segment than the program code, global/static, or stack. Such memory is called the heap.

Here's a map depicting the *address space* of an executing program:



Runtime stack

Each active function call has its own unique stack frame. In a stack frame (activation record) we hold the following information:

1) frame pointer: pointer value of the previous stack frame so we can reset the top of stack when we exit this function. This is also sometimes called the dynamic link.
2) static link: in languages (like Pascal but not C or Decaf) that allow nested function declarations, a function may be able to access the variables of the function(s) within which it is declared. In the static link, we hold the pointer value of the stack frame in which the current function was declared.

3) return address: point in the code to which we return at the end of execution of the current function.
4) values of arguments passed to the function and locals and temporaries used in the function.

Here is what typically happens when we call a function (every machine and language is slightly different, but the same basic steps need to be done):

Before a function call, the calling routine:

1) saves any necessary registers
2) pushes the arguments onto the stack for the target call
3) set up the static link (if appropriate)
4) pushes the return address onto the stack
5) jumps to the target

During a function call, the target routine:

1) saves any necessary registers
2) sets up the new frame pointer
3) makes space for any local variables
4) does its work
5) tears down frame pointer and static link
7) restores any saved registers
8) jumps to saved return address

After a function call, the calling routine:

1) removes return address and parameters from the stack
2) restores any saved registers
3) continues executing

Parameter passing

The above description deliberately is vague on what mechanism is used for parameter-passing . Some of the common parameter-passing variants supported by various programming languages are:

Pass by value: This is the only mechanism supported by C and Decaf. Value of parameters are copied into called routine. Given the routine has its own copy, changes made to those values are not seen back in the calling function.

Pass by value-result: This interesting variant supported by languages such as Ada copies the value of the parameter into the routine, and then copies the (potentially changed) value back out. This has an effect similar to pass-by-reference, but not exactly. How could you write a test program to determine whether a language was using value-result versus reference for parameters?

Pass by reference: No copying is done, but a reference (usually implemented as a pointer) is given to the value. In addition to allowing the called routine to change the values, it is also efficient means for passing large variables (such as structs). How does this compare to explicitly passing a pointer in C?

Pass by name: This rather unusual mechanism acts somewhat like C preprocessor macros and was introduced in Algol. Rather than evaluating the parameter value, the name or expression is actually substituted into the calling sequence and each access to the parameter in the calling body re-evaulates it. This is not particularly efficient, as you might imagine.

A few other orthogonal parameter-passing features that are appear in various mainstream languages:

A read-only property such as C++ const, which allows you to use the efficient pass-by-reference mechanism only for its efficiency but not for its mutability.

Default parameters, where a routine can specify what value to use when the programmer doesn't supply one (i.e. calls routine with fewer than all parameters).

Position-independent parameters, ala Ada and LISP, allow parameters to be tagged with names rather than requiring them to be listed in some enforced arbitrary ordering.

Memory management

Typically, the program requests memory from the operating system, which usually returns it in pages. A page is a fairly large chunk anywhere from four to eight KB chucks, and sometimes even more. The program then divides up this memory on its own. There is quite a bit of research on what makes a fast allocator that minimizes fragmentation on a page. Your allocator quite likely is very smart, and keeps track of how much memory is allocated per pointer and so on.

```
a = malloc(12);   // give me 12 bytes
a = b;            // oops, lost it!
```

By now everyone has heard that Java has garbage collection, where the programmer doesn't have to free dynamically allocated memory herself. The run-time environment detects that an allocated chunk of memory can no longer be referenced by the program and disposes of the memory for her. There are several methods for implementing garbage collection. The two most common are reference counting and mark and sweep.

Automatic storage management is very convenient for the programmer, but sometimes causes problems. Why isn't garbage collection a panacea for memory management? What semantic rules are needed to for a garbage-collected language?

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