15-122: Principles of Imperative Computation, Spring 2020

Programming Homework 11 & 12: The C0VM

```
10 40
15 01
14 05 D2
CF
B0
```

Due: Tuesday 14th April, 2020 and
Wednesday 22nd April, 2020 by 9pm

In this assignment you will implement a virtual machine for C0, the C0VM. It has been influenced by the Java Virtual Machine (JVM) and the LLVM, a low-level virtual machine for compiler backends. We kept its definition much simpler than the JVM, following the design of C0. Bytecode verification, one of the cornerstones of the JVM design, fell victim to this simplification; in this way the machine bears a closer resemblance to the LLVM. It is a fully functional design and should be able to execute arbitrary C0 code.

The purpose of this assignment is to give you practice in writing C programs in the kind of application where C is indeed often used in practice. C is appropriate here because a virtual machine has to perform some low-level data and memory manipulation that is difficult to make simultaneously efficient and safe in a higher-level language. It should also help you gain a deeper understanding of how C0 (and, by extension, C) programs are executed.

The code handout for this assignment is on Autolab. The file `README.txt` in the code handout goes over the contents of the handout and explains how to hand the assignment in. There is a TWENTY (20) PENALTY-FREE HANDIN LIMIT for the checkpoint, and a TWENTY (20) PENALTY-FREE HANDIN LIMIT for the full assignment. Every additional handin for each will incur a small (5%) penalty (even if using a late day). Your score for each part of this assignment (checkpoint and full) will be the score of your last Autolab submission. *The checkpoint is for Tasks 1 and 2 only. This is far, far less than half the assignment.*

After the checkpoint, you can no longer earn points for Tasks 1 and 2, although the full autograder will continue to run tests against them. It will also run tests for Tasks 3 and 4, *but not for Task 5 until after the handin deadline has passed.* This means that you must do all your own testing for Task 5 and in order to earn full points you must convince yourself that you fully understand it and have tested it for correct behavior and for memory leaks where appropriate (you will see later in the writeup that certain memory leaks are unavoidable).

About this writeup The C0VM is defined in stages, and we have test programs which exercise only part of the specification. We strongly recommend that you construct your implementation following these stages and debug and test each stage (on your own *and* with the autograder) before moving on to the next. Each part has its own challenges, but each part should be relatively small and self-contained.

This document describes the structure of the C0VM first and then the instruction set (bytecodes) for the C0VM. After this, the document will describe the tasks you need to perform, step by step. Read this document very carefully as you prepare to do your work.

1 The Structure of the C0VM

Compiled code to be executed by the C0 virtual machine is represented in a byte code format, typically stored in a file ending in extension `.bc0` which we call the *bytecode file*. This file contains numerical and string constants as well as byte code for the functions defined in the C0 source. The precise form of this file is specified in Appendix A and in `lib/c0vm.h`.

1.1 The Type `c0_value`

C0 has so-called *small types* **`int`**, **`bool`**, **`char`**, **`string`**, `t[]`, and `t*`. Values of these types can be passed to or from functions and held in variables. In the C0VM, we will represent each of these types in one of two ways: the *primitive types* are represented as 32-bit signed integers (which we will abbreviate as "`w32`") and the *reference types* are represented as void pointers (which we will abbreviate as "`*`").

C0 type	C0VM type	C type
`int`	`w32`	`int32_t`
`bool`	`w32`	`int32_t`
`char`	`w32`	`int32_t`
`t[]`	`*`	`void*`
`t*`	`*`	`void*`

In `lib/c0vm.h`, we create a special type `c0_value` of C0 values. A `c0_value` can store *both* values of primitive type (which we write as `x`, `i`, or `n`) and values of reference or pointer type (which we write as `a`). We can turn primitive types into C0 values with the function `int2val`, and we can turn C0 values which we know to be primitive types back into integers with `val2int`. Similarly, `ptr2val(x)` and `val2ptr(x)` move between reference types (represented by **`void`**`*`) and C0 values. We always have `val2int(int2val(x)) == x` for any integer x and `val2ptr(ptr2val(a)) == a` for any pointer a. There's a function `val_equal(v1,v2)` which checks whether the two C0 values `v1` and `v2` are equal.

1.2 Runtime Data

The C0VM defines several types of data that are used during the execution of a program. You'll need to consider the first three of these (the operand stack, bytecode, and the program counter) to get started with Task 1.

The `execute` function you are extending in this assignment is passed a struct `bc0_file` containing all the information from the bytecode. As you read this section, you should refer to both Appendix A and `lib/c0vm.h` where this struct is described.

1.2.1 The Operand Stack (S)

The C0VM is a *stack machine*, similar in design to Clac and the JVM. This means arithmetic operations and other instructions pop their operands from an operand stack and push their result back onto the operand stack.

The C0VM is defined in terms of operand stack `S`, a stack of C0 values. Because these values are such an important part of the VM, we define stacks that only contain C0 values in

`lib/c0v_stack.h`. We recommend writing some helper functions like `push_int(S, i)` and `pop_ptr(S)` early on so that you won't have to repetitively write `c0v_push(S, int2val(i))` and `val2ptr(c0v_pop(S))` over and over.

1.2.2 Bytecode (P)

In Clac, the program instructions were strings, and they were stored in a queue of strings. In the C0VM, instructions for the current C0 function are stored in an array of (unsigned) bytes (`ubyte *P`). Each function in a compiled C0 program is represented by a struct `function_info` that is stored in the array `bc0->function_pool`. The `main()` function that you want to run first is always stored as the first struct in this array, at index 0. When you start your VM, you should initialize `P` to be the bytecode `code` stored in that struct.

You don't ever need to allocate any memory to store bytecode. Just refer to the bytecode given to the `execute` function.

1.2.3 The Program Counter (pc)

The program counter `pc` holds the address of the program instruction currently being executed. It always starts at 0 when you begin executing a function. Unless a non-local transfer of control occurs (goto, conditional branch, function call or return), the program counter is incremented by the number of bytes in the current instruction before the next instruction is fetched and interpreted.

1.2.4 Local variables (V)

Locals should be stored in a `c0_value` array. Every struct `function_info` has a field `num_vars` which specifies how big this array needs to be in order to store all the locals of that function. The four components `S`, `P`, `pc`, and `V` are everything that we need to know in order to represent the current state of any function.

1.2.5 The Call Stack

The C0VM has a call stack consisting of *frames*, each one containing local variables, a local operand stack, and a return address. The call stack grows when a function is called and shrinks when a function returns, deallocating the frame during the return.

Every frame consists of the four components that represent the current state of some function call that got interrupted in order to call another function. It contains the operand stack `S` for computing expression values, a pointer `P` to the function's byte code, a return address `pc`, which is the address of the next instruction in the interrupted function, and an array of locals `V`. At any point during the execution there is a *current frame* as well as a *calling frame*. The latter becomes the current frame when a function returns to its caller.

1.2.6 Constant Pools

Numerical constants requiring more than 8 bits and all string constants occurring in the program will be allocated in constant pools, called the *integer pool* and the *string pool*. They never change during program execution.

1.2.7 Function Pools

Functions, either C0 functions defined in a source file or library functions, are kept in pools called the *function pool* and the *native pool*, respectively. Functions in the function pool are stored with their bytecode instructions, while functions in the native pool store an index into a table of C function pointers that the C0VM implementation can dereference and invoke.

1.2.8 The Heap

At runtime, the C0 heap contains C0 strings, C0 arrays (`t[]`) and C0 cells (`t*`). C0 arrays have to store size information so that dynamic array bounds checks can be performed. You will use the C heap to implement the C0 heap: that is, you will allocate strings, arrays, and cells directly using calls to `xmalloc` and `xcalloc` as defined earlier in this course.

Since C0 is designed as a garbage-collected language, you will not be able to free space allocated on behalf of C0 unless you are willing to implement (or use) a garbage collector. We do not view this as a memory leak of the C0VM implementation. On the other hand, temporary data structures required for the C0VM's own operation should be properly freed.

This means that when you are testing your own code using `valgrind`, you must be aware of which `bc0` files should be free of `valgrind` memory leak reports and which should produce reports of memory leaks. The autograder will not penalize `valgrind` reports of memory leaks for tests that allocate space on the C0 heap.

Note that the autograder will also not penalize for memory leaks for tests that are supposed to end in a runtime error.

1.3 Runtime Errors

In order to fully capture the behavior of C0 programs, you must correctly issue errors for things like dereferencing `NULL`, indexing an array outside of its bounds, and dividing by zero. Check the C0 Language Reference for details on what kinds of errors you must handle, and then use the following provided functions (defined in `c0vm_abort.h` and `c0vm_abort.c`) to issue appropriate error messages:

```
void c0_user_error(char *err);          // for calls to error() from C0
void c0_assertion_failure(char *err);   // for failed assertions from C0
void c0_memory_error(char *err);        // for memory-related errors
void c0_arith_error(char *err);         // for arithmetic-related errors
```

For unexpected situations that arise while executing bytecode, situations which could indicate a bug in your VM, you may use the standard C library functions `abort` or `assert` to abort your program. See Section 3.3 for more details on this distinction.

2 Instruction Set

We group the instructions by type, in order of increasing complexity from the implementation point of view. We recommend implementing them in order and aborting with an appropriate message when an unimplemented instruction is encountered. Each task in this assignment corresponds to one or more sections, and tasks are summarized in Section 3.1.

2.1 Stack Manipulation (Task 1)

There are three instructions for direct stack manipulation without regard to types.

```
0x59 dup          S, v -> S, v, v
0x57 pop          S, v -> S
0x5F swap         S, v1, v2 -> S, v2, v1
```

2.2 Arithmetic Instructions (Task 1)

Arithmetic operations in C0 are defined using modular arithmetic based on a two's complement signed representation. This does not match your implementation language (C) very well, where the result of *signed* arithmetic overflow is undefined. There are two solutions to this problem: first, because *unsigned* arithmetic overflow is defined to be modular arithmetic, you could cast `int32_t` values to `uint32_t`, perform unsigned arithmetic, then cast back. This should not be required in your implementations, however: we will compile your code with the `-fwrapv` command-line argument that forces `gcc` to treat integer arithmetic to be defined as signed two's complement arithmetic. (Remember, however, that this is not part of the C standard.)

Casting signed integers to unsigned integers and/or using the `-fwrapv` command-line argument does not do everything that is needed to ensure C0 compliance, but it goes a long way. We recommend a careful reading of the arithmetic operations in the C0 Reference, as well as the notes on casting integers in C.

For this implementation strategy to be correct, it is important to verify that our C environment does indeed use a two's complement representation and that the C type of **`int`** has 32 bits. The provided `main` function (see the file `c0vm_main.c`) performs these checks before starting the abstract machine and aborts the execution if necessary.

In the instruction table below (and for subsequent tables), we use `w32` for the type of primitive values and $*$ for the type of reference values. Each line has an opcode in hex notation, followed by the operation mnemonic, followed by the effect of the operation, first on the stack, then any other effect.

```
0x60 iadd         S, x:w32, y:w32 -> S, x+y:w32
0x7E iand         S, x:w32, y:w32 -> S, x&y:w32
0x6C idiv         S, x:w32, y:w32 -> S, x/y:w32
0x68 imul         S, x:w32, y:w32 -> S, x*y:w32
0x80 ior          S, x:w32, y:w32 -> S, x|y:w32
0x70 irem         S, x:w32, y:w32 -> S, x%y:w32
0x78 ishl         S, x:w32, y:w32 -> S, x<<y:w32
0x7A ishr         S, x:w32, y:w32 -> S, x>>y:w32
0x64 isub         S, x:w32, y:w32 -> S, x-y:w32
0x82 ixor         S, x:w32, y:w32 -> S, x^y:w32
```

Safety violations in `idiv`, `irem`, `ishr`, and `ishl` can cause run-time errors (use the provided function `c0_arith_error` to generate a message). Please refer to the C0 language specification for important details.

We have omitted negation `-x`, which the compiler can simulate with `0-x`, and bitwise negation `~x`, which the compiler can simulate with `x^(-1)`.

2.3 Constants (Tasks 1 and 2)

We can push constants onto the operand stack. There are three different forms: (1) a constant `null` which is directly coded into the instruction, (2) a small *signed* (byte-sized) constant `<b>` which is an instruction operand and must be sign-extended to 32 bits, and (3) a constant stored in the constant pool. For the latter, we distinguish constants of primitive type from those of reference type because they are stored in different pools.

The two constant loading instructions `ildc` and `aldc` take two unsigned bytes as operands, which must be combined into an unsigned integer index for the appropriate constant pool. The integer pool stores the constants directly, and the index given to `ildc` is an index into the integer pool. The string pool is one large array of character strings, each terminated by `'\0'`. The index given to `aldc` indicates the position of the first character; its address is therefore of type **`char`**`*` in C and understood by C as a string.

```
0x01 aconst_null   S -> S, null:*
0x10 bipush <b>    S -> S, x:w32     (x = (w32)b, sign extended)
0x13 ildc <c1,c2>  S -> S, x:w32     (x = int_pool[(c1<<8)|c2])
0x14 aldc <c1,c2>  S -> S, a:*       (a = &string_pool[(c1<<8)|c2])
```

You will not be able to test `aldc` in any interesting way until you implement `athrow` or `assert` (see below).

2.4 Local Variables (Task 2)

We can move data generically between local variables and the stack, because all primitive types can fit into pointers or integers and so be stored as a `c0_value`. The instruction operand `<i>` is one byte following the opcode **`0x15`** or **`0x36`** in the instruction stream. Because this is the only way to access a local variable, each function can have at most 256 local variables, which includes the function arguments.

```
0x15 vload <i>     S -> S, v                  (v = V[i])
0x36 vstore <i>    S, v -> S                  (V[i] = v)
```

2.5 Assertions and Errors (Task 2)

The instruction `athrow` implements the C0 built-in **`error`**`(s)` which aborts execution with error message `s`. In the bytecode, this error message will be at the top of the stack — it will have been put there by `aldc` if it is a literal string.

The instruction `assert` implements all C0 contracts and assertions. You will be able to use its full potential only after you are done with Tasks 3 and 4. For now, you can test it with programs containing simple assertions like **`assert`**`(true)` or `//@assert false;` (remember to compile the latter with the flag `-d`).

```
0xBF athrow            S, a:* -> S          (c0_user_error(a))
0xCF assert            S, x:w32, a:* -> S   (c0_assertion_failure(a) if x == 0)
```

2.6 Control Flow (Task 3)

Each instruction implicitly increments the program counter by the number of bytes making up the instruction. Control flow instructions change this by jumping to another instruction under certain conditions. The addressing is relative to the address of the branch instruction. The offset is a *signed* 16 bit integer that is given as a two-byte operand to the instruction. It must be signed so we can branch backwards in the program. Note that `if_cmpeq` and `if_cmpne` can be used to compare either integers or pointers for equality or inequality, whereas the other comparisons only make sense on integers. The `nop` "no-op" instruction has no effect.

```
0x00 nop                S -> S

0x9F if_cmpeq <o1,o2>   S, v1, v2 -> S       (pc = pc+(o1<<8|o2) if v1 == v2)
0xA0 if_cmpne <o1,o2>   S, v1, v2 -> S       (pc = pc+(o1<<8|o2) if v1 != v2)
0xA1 if_icmplt <o1,o2>  S, x:w32, y:w32 -> S (pc = pc+(o1<<8|o2) if x < y)
0xA2 if_icmpge <o1,o2>  S, x:w32, y:w32 -> S (pc = pc+(o1<<8|o2) if x >= y)
0xA3 if_icmpgt <o1,o2>  S, x:w32, y:w32 -> S (pc = pc+(o1<<8|o2) if x > y)
0xA4 if_icmple <o1,o2>  S, x:w32, y:w32 -> S (pc = pc+(o1<<8|o2) if x <= y)

0xA7 goto <o1,o2>       S -> S               (pc = pc+(o1<<8|o2))
```

2.7 Function Calls and Returns (Task 4)

Function calls come in two forms: invoking a C0 function defined in the same bytecode file and invoking a library function defined in C. In either case, generic arguments `v1` through `vn` are passed on the operand stack and consumed. The C0VM implementation must guarantee that the result `v` is pushed onto the stack when the function returns. For functions returning **`void`**, a dummy value is pushed onto the operand stack to provide a uniform interface to functions.

Function information is stored in the function pool or native pool, both of which are addressed by the instruction operand consisting of two bytes, which must be reconstituted into an *unsigned* 16 bit quantity indexing into the appropriate pool.

```
0xB8 invokestatic <c1,c2> S, v1, v2, ..., vn -> S, v
                          (function_pool[c1<<8|c2] = g, g(v1,...,vn) = v)
0xB0 return   ., v -> .   (return v to caller)
```

When invoking a C0 function (instruction `invokestatic`) we have to preserve the state of the calling function so that we can resume it later: a pointer to its bytecode, its program counter `pc` as a return address, its current local variable array V and its current operand stack S. This is the information in a *frame* which is pushed onto a global call stack. Then we set the `pc` to the beginning of the code for the called function g, allocate a new array of local variables, and initialize it with the function arguments from the old operand stack. We also create a new empty operand stack for use in the called function.

When processing a `return` instruction we restore the `pc`, the local variable array V and the operand stack S from the last frame on the call stack. We also need to arrange that the return value is popped from the current operand stack and pushed onto the operand stack

of the frame we return to. Some temporary data structures may need to be deallocated at this point.

The `main` function always has index 0 in the function pool and takes 0 arguments. After reading the file, setting up appropriate data structures, etc, your C0VM implementation should start executing byte code at the beginning of this function and at the end print the final value.

2.8 Native Function Calls (Task 4)

Native function calls have the same form as C0 function calls, but the two-byte instruction argument indexes into the native pool, rather than the function pool.

```
0xB7 invokenative <c1,c2> S, v1, v2, ..., vn -> S, v
```

The value `native_pool[c1<<8|c2]` is a struct `native_info` (defined in `lib/c0vm.h` and described in Appendix A), which contains two fields: `num_args`, the number n of arguments that should be popped off the stack, and `function_table_index`, which is an index i into a separate runtime structure, the `native_function_table` (defined in `lib/c0vm_c0ffi.h`). From that table you can retrieve the address of a function g, a pointer to a function taking an array of `c0_value` and returning a `c0_value`.

In order to call this function you have to construct an array of length n and store arguments `v1` through `vn` at indices 0 through $n-1$, and then invoke the function g on this array. The result has to be pushed back onto the operand stack.

Native function calls do not therefore involve explicitly managed stack frames. Of course, your abstract machine implementation is using the system stack, so when you call the library function, the library function also uses the system stack, rather than any stack managed explicitly by your virtual machine.

The mapping between native library functions and their indices into the native function table is given as a series of `NATIVE_*` macros in the file `c0vm_c0ffi.h`. (You will not need to use these definitions in your C0VM implementation.)

2.9 Memory Allocation, Load, and Store (Task 5)

Besides function calls, the trickiest aspect of the C0VM implementation is the management of the C0 runtime heap. Your implementation should satisfy each C0 allocation request separately by allocating a sufficient amount of space on the C runtime heap, using C pointers to implement C0VM references. Your implementation of allocation must take care to initialize all memory requested by C0 to all zeros.

```
0xBB new <s>       S -> S, a:*     (*a is now allocated, size <s>)
```

The `new <s>` instruction allocates s bytes of memory (s is an unsigned byte) and pushes the address of the newly allocated memory (a pointer) onto the stack. The data size is computed statically by the C0 compiler. For example, the C0 expression **`alloc(int)`** would translate to `new 4`, while **`alloc(struct b)`** would translate to `new n`, where n is the size of a **`struct b`** in memory in bytes, which is always known at compile time.

We read from and write to addresses in memory with the six instructions: `imload` and `imstore` for integers, `amload` and `amstore` for pointers, and `cmload` and `cmstore` for characters. For integers and pointers, we treat the value on the stack as an integer or a pointer

and store that quantity directly. For characters, we have to be a bit more careful, because characters (which may take on the values 0-127 in C0) are stored as integer values on the stack. When we read a character out of memory we have to cast it to an integer, and when we write we do the opposite, masking the given value of type `w32` to 7 bits.

```
0x2E imload    S, a:* -> S, x:w32   (x = *a, a != NULL, load 4 bytes)
0x4E imstore   S, a:*, x:w32 -> S   (*a = x, a != NULL, store 4 bytes)
0x2F amload    S, a:* -> S, b:*     (b = *a, a != NULL, load address)
0x4F amstore   S, a:*, b:* -> S     (*a = b, a != NULL, store address)
0x34 cmload    S, a:* -> S, x:w32   (x = (w32)(*a), a != NULL, load 1 byte)
0x55 cmstore   S, a:*, x:w32 -> S   (*a = x & 0x7f, a != NULL, store 1 byte)
```

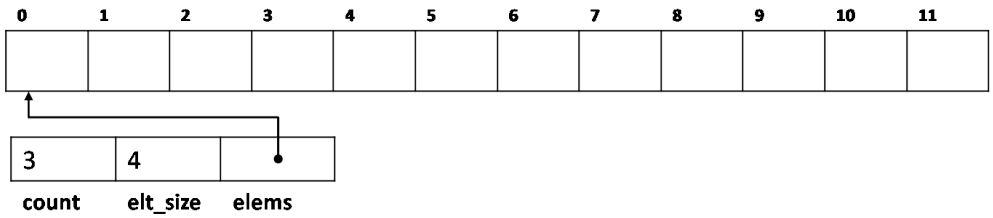
For each operation, you must check that the address a of a load or store instruction is non-NULL and raise a memory error if a is NULL.

Most of the time, when we're reading and writing from memory in our C0 program, we're not using pointers directly to read (`*p`) or write (`*p=...`). Rather, we're reading from or writing to fields of structs (`T->data=...`) or elements of arrays (`A[i]=...`). In the C0VM, these two steps are split into different VM instructions for address arithmetic and loading from or storing to a computed address. This computation then gives us the actual address of the integer, pointer, or character stored within the array or struct, which we can access with the six instructions above.

There are two kinds of offset computations: one for arrays, and one for structs. When we access a struct's field, the compiler generates a field offset f (an unsigned one-byte quantity). The `aaddf` instruction is used to add f bytes to the pointer a at the top of the stack. If the address a is NULL, you must raise a memory error by calling the provided function `c0_memory_error`.

```
0x62 aaddf <f>      S, a:* -> S, (a+f):*  (a != NULL; f field offset)
```

In order to talk about array offsets, we need to talk about how C0 arrays are represented at runtime. C0 arrays are represented as pointers to a struct[1] `c0_array_header` that has three fields. The first, `count`, is the number of elements in the array, and is determined at runtime (this is `n` in the `newarray` instruction below). The second, `elt_size`, represents the number of bytes in a single element; the compiler is able to determine this at compile time based on the type (this is `s` in the `newarray` instruction below).



The third field is `elems`, a void pointer to the beginning of the memory allocated for the actual array, which contains `n*s` bytes. The length of an array, stored in the `count` field, can be retrieved with the `arraylength` C0VM instruction. Every C0 array you encounter in the VM will be a pointer to one of these structs.[2]

[1] defined in `lib/c0vm.h`.

[2] It is possible for a C0 array to be `NULL`; the VM should treat `NULL` like an array with length 0.

The picture above is an array of three objects with `elt_size` of 4, perhaps a C0 integer. The third integer (array offset 2 in the C0 array) is stored in the bytes labeled 8-11. If we cast the void pointer in the `elems` field to a **`char`** pointer named `arr`, then the offset we should compute to access the third integer in the array is `&arr[2*4]` — the address 8 bytes into the block of allocated memory (array offset 2 × 4 bytes per array element; recall that a char is defined to be one byte).

```
0xBC newarray <s>  S, n:w32 -> S, a:*      (a[0..n) now allocated)
0xBE arraylength   S, a:* -> S, n:w32      (n = \length(a))
0x63 aadds         S, a:*, i:w32 -> S, (a->elems+s*i):*
                                           (a != NULL, 0 <= i < \length(a))
```

The `newarray <s>` instruction allocates memory for an array containing `n` elements at size `s`. The size is computed by the compiler, while the array size is determined at runtime because it cannot in general be known at compile time. The `aadds` instruction computes the address of an array element. The operand a on the stack must be the address of an array, and the operand i must be a valid index for this array. The C0VM must issue an error message and abort if i is not a valid index, which can be determined from the stored array length; use the provided function `c0_memory_error` to issue this error. We then use the element size s stored with the array to compute the address of the ith element. Note that one `aadds` instruction is necessary for every array access, even if we access the element at index 0. This is in contrast to structs! When we are accessing a field of a struct, we might be accessing the first field, in which case the address of the field is the same as the address of the struct.

3 Programming Tasks and Coding Advice

There are many complexities in implementing a virtual machine, especially one that is rich enough so it can execute all of C0! Fortunately, some of the complexities (such as parsing the bytecode file) are taken care of by code we are providing, but others remain. You will complete the code in `c0vm.c`.

The following are suggested strategies to help you work effectively throughout this project.

3.1 Testing

We have provided a few test cases in `tests/`, but it is more effective to write your own. Write a small file, say `test.c0` and compile it with `cc0 -b test.c0`, which will create a bytecode file `test.bc0`. Then run it with `./c0vmd test.bc0`. Compare your answers with the ones you get with `cc0 -x mytest.c0`:

```
% cc0 -x tests/iadd.c0
-2
% cc0 -b tests/iadd.c0
% ./c0vmd tests/iadd.bc0
Opcode 10 -- Stack size: 0 -- PC: 0
Opcode 10 -- Stack size: 1 -- PC: 2
Opcode 60 -- Stack size: 2 -- PC: 4
Opcode b0 -- Stack size: 1 -- PC: 5
Returning -2 from execute()
-2
```

3.2 Incremental Implementation

Implement a subset of the instruction set and test your C0VM implementation on code that only uses the subset. Generate some test cases using `cc0 -b` from simple C0 sources, or use some of the supplied examples that use limited instructions. You should recognize instructions that are valid but not in your subset and give a "*not yet implemented*" message and returning rather than aborting in the same way as for other errors. Test one stage thoroughly before moving on. After extending the machine, first make sure the old, simple examples still run correctly, a process called *regression testing*. The stages follow our discussion of the instruction set.

Task 1 (15 points) [See Sections 2.1 and 2.2]
Initialize the variables `S`, `P` and `pc` correctly in the `execute` function in the `c0vm.c` file.

Add code to handle arithmetic instructions, plus `bipush`, `swap`, and `return`. (The return instruction is mostly implemented, but needs to be checked for memory leaks.) C0 programs with only a `main` function returning an expression made of small constants can be used to test these capabilities, e.g.,

```
int main() {
  return 15 * ((1<<10) - 24) + 122;
}
```

Task 2 (10 points) [See Sections 2.3, 2.4 and 2.5]
Add code to deal with local variables, constants and assertions; you'll need to initialize the variable `V` to something better than `NULL`. C0 source files containing straight-line code using variables and large constants can be used to test these capabilities, e.g.,

```
int main() {
  int x = 15122;
  assert(true);
  int y = x * x;
  return y;
}
```

CHECKPOINT

Task 3 (7 points) [See Section 2.6]
Add code to handle `goto` and conditionals (e.g., `if_icmpge`). Now you should be able to execute loops, as in

```
int main () {
  int i; int sum = 0;
  for (i = 15; i <= 122; i++)
    sum += i;
  return sum;
}
```

Task 4 (10 points) [See Sections 2.7 and 2.8]
Add function calls (`invokestatic`, `invokenative`); you'll probably want to initialize the variable `callStack` to something better than `NULL` and use `callStack` to manage the call stack in some form. You will also need to revisit `return` (see `PROG_HINTS.txt` in the code handout). You may want to focus on ordinary C0 function calls (`invokestatic`, `return`) before moving on to native function calls (`invokenative`).

Now your `main` function can call auxiliary functions, such as the ubiquitous recursive factorial function, and library functions that print output:

```
int factorial(int n) {
  return n == 0 ? 1 : n * factorial(n-1);
}
int main () {
  printint(factorial(15));
  println(" is the factorial of 15");
  return 0;
}
```

Task 5 (8 points) [See Section 2.9]
Add the C0 heap, where arrays and structs are allocated. After this, you should be able to run arbitrary C0 code, including your own C0 assignments.

3.3 Assertions

Ideally, we would establish invariants of the bytecode that we read from a file to make sure no runtime memory or type error occurs. In the JVM this is referred to as *bytecode verification*. Unfortunately, the current bytecode format does not provide enough information to do this. Even if it did, it would be a major project in itself. So you have to fall back on dynamic checks. These checks come in two categories:

1. The usual checks on the runtime structure of your own code, verifying that pointers are not `NULL`, etc.

2. Checks that the C0 bytecode you have read in behaves properly.

Some of the checks in the second category are mandated:

(a) The C0 program must not dereference the C0 `NULL` pointer or perform pointer arithmetic on it.

(b) The C0 program must not access memory outside the bounds of a C0 array.

(c) The C0 program must not perform illegal integer division (division by 0, or the min int divided by -1).

(d) The C0 program must not shift left or right by a number < 0 or ≥ 32.

If you encounter these runtime errors, you should produce error messages using the provided functions

- `void c0_memory_error(char *err)` — for memory-related errors
- `void c0_arith_error(char *err)` — for division or shift-related errors

By calling these functions, which are declared in `c0vm_abort.h`, you make it clear that this is a runtime error in the bytecode you are executing and not a bug in your machine.

The first category of checks should in principle be redundant. For example, the `cc0` compiler should never produce a bytecode file that jumps to an invalid address. Nevertheless, bytecode written by hand or a bug in the `cc0` compiler or your VM could lead to such issues. Since C does not guarantee detection of such incorrect jumps or accesses, your code should do that using appropriate **`assert`** statements, or `ASSERT`, `REQUIRES`, and `ENSURES`. Then, if the bytecode itself or your virtual machine implementation has a bug, it will be discovered as soon as an unexpected incorrect behavior occurs. The macro annotations are recommended so that there is no undue overhead for correct code when your machine has been debugged.

3.4 Manage Your Time Well

Remember that this homework is worth **50 points**, and the last three tasks are *much* more difficult than the first two. You should plan on working on this for an hour or two every day, so you can ask for help early on if you need it. **Don't wait until the last few days!** Post general questions on Diderot (e.g., questions about the C0VM specification, wording of tasks, requirements for handin, etc).

A Bytecode File Format

The bytecode file, usually with extension `.bc0`, is produced by the `cc0` compiler when invoked with the `-b` or `--bytecode` flag. In order to allow you to easily read bytecode, and also write your own bytecode, the binary file is coded in hexadecimal form, where two-digit bytes are separated by whitespace. In addition, the file may contain comments starting with '`#`' and extending to the end of the line.

We describe the format as pseudo-structs, where we use the types described below. For multi-byte types, each byte is given separately by two hexadecimal digits, with the most significant byte first.

- `u4` — 4 byte unsigned integer
- `u2` — 2 byte unsigned integer
- `u1` — 1 byte unsigned integer
- `i4` — 4 byte signed (two's complement) integer
- `fi` — struct `function_info`, defined below
- `ni` — struct `native_info`, defined below

The size of some arrays is variable, depending on earlier fields. These are only arrays conceptually, of course. In the file, all the information is just stored as sequences of bytes separated by whitespace.

```
struct bc0_file {
  u4 magic;                          // magic number, always 0xc0c0ffee
  u2 version+arch;                   // version number and architecture
  u2 int_count;                      // number of integer constants
  i4 int_pool[int_count];            // integer constants
  u2 string_count;                   // number of characters in string pool
  u1 string_pool[string_count];      // adjacent '\0'-terminated strings
  u2 function_count;                 // number of functions
  fi function_pool[function_count];  // function info
  u2 native_count;                   // number of native (library) functions
  ni native_pool[native_count];      // native function info
};


struct function_info {
  u2 num_args;                       // number of arguments, V[0..num_args)
  u2 num_vars;                       // number of variables, V[0..num_vars)
  u2 code_length;                    // number of bytes of bytecode
  u1 code[code_length];              // bytecode
};


struct native_info {
  u2 num_args;                      // number of arguments, V[0..num_args)
  u2 function_table_index;          // index into table of library functions
};
```

We are providing code that reads bytecode files and marshals the information into similar internal C structures.

B C0VM Instruction Reference

What follows is a reference for the C0VM bytecode, which is also given as part of the handout (`c0vm-ref.txt`). Every line that describes an operation has the following format:

```
0xYZ omne          S -> S' (other effect)
```

where `0xYZ` is the opcode in hex, `omne` is the operation mnemonic, and the remaining text describes the effect of the operation. The description includes the effect on the stack (e.g. transform stack `S` into stack `S'`) and any other effects (e.g. modify the program counter).

```
C0VM Instruction Reference

S = operand stack
V = local variable array, V[0..num_vars)

Instruction operands:
<i> = local variable index (unsigned)
<b> = byte (signed)
<s> = element size in bytes (unsigned)
<f> = field offset in struct in bytes (unsigned)
<c> = <c1,c2> = pool index = (c1<<8|c2) (unsigned)
<o> = <o1,o2> = pc offset = (o1<<8|o2) (signed)

Stack operands:
a : * = address ("reference")
x, i, n : w32 = 32 bit word representing an int, bool, or char ("primitive")
v = arbitrary value (v:* or v:w32)

Stack operations
0x59 dup              S, v -> S, v, v
0x57 pop              S, v -> S
0x5F swap             S, v1, v2 -> S, v2, v1

Arithmetic
0x60 iadd             S, x:w32, y:w32 -> S, x+y:w32
0x7E iand             S, x:w32, y:w32 -> S, x&y:w32
0x6C idiv             S, x:w32, y:w32 -> S, x/y:w32
0x68 imul             S, x:w32, y:w32 -> S, x*y:w32
0x80 ior              S, x:w32, y:w32 -> S, x|y:w32
0x70 irem             S, x:w32, y:w32 -> S, x%y:w32
0x78 ishl             S, x:w32, y:w32 -> S, x<<y:w32
0x7A ishr             S, x:w32, y:w32 -> S, x>>y:w32
0x64 isub             S, x:w32, y:w32 -> S, x-y:w32
0x82 ixor             S, x:w32, y:w32 -> S, x^y:w32
```

```
Local Variables
0x15 vload <i>          S -> S, v             (v = V[i])
0x36 vstore <i>         S, v -> S             (V[i] = v)

Assertions and errors
0xBF athrow             S, a:* -> S           (c0_user_error(a))
0xCF assert             S, x:w32, a:* -> S    (c0_assertion_failure(a) if x == 0)

Constants
0x01 aconst_null        S -> S, null:*
0x10 bipush <b>         S -> S, x:w32         (x = (w32)b, sign extended)
0x13 ildc <c1,c2>       S -> S, x:w32         (x = int_pool[(c1<<8)|c2])
0x14 aldc <c1,c2>       S -> S, a:*           (a = &string_pool[(c1<<8)|c2])

Control Flow
0x00 nop                S -> S
0x9F if_cmpeq <o1,o2>   S, v1, v2 -> S        (pc = pc+(o1<<8|o2) if v1 == v2)
0xA0 if_cmpne <o1,o2>   S, v1, v2 -> S        (pc = pc+(o1<<8|o2) if v1 != v2)
0xA1 if_icmplt <o1,o2>  S, x:w32, y:w32 -> S  (pc = pc+(o1<<8|o2) if x < y)
0xA2 if_icmpge <o1,o2>  S, x:w32, y:w32 -> S  (pc = pc+(o1<<8|o2) if x >= y)
0xA3 if_icmpgt <o1,o2>  S, x:w32, y:w32 -> S  (pc = pc+(o1<<8|o2) if x > y)
0xA4 if_icmple <o1,o2>  S, x:w32, y:w32 -> S  (pc = pc+(o1<<8|o2) if x <= y)
0xA7 goto <o1,o2>       S -> S                (pc = pc+(o1<<8|o2))

Functions
0xB8 invokestatic <c1,c2> S, v1, v2, ..., vn -> S, v
                              (function_pool[c1<<8|c2] => g, g(v1,...,vn) = v)
0xB0 return                .., v -> .         (return v to caller)
0xB7 invokenative <c1,c2> S, v1, v2, ..., vn -> S, v
                                (native_pool[c1<<8|c2] => g, g(v1,...,vn) = v)

Memory
0xBB new <s>          S -> S, a:*             (*a is now allocated, size <s>)
0xBC newarray <s>     S, n:w32 -> S, a:*      (a[0..n) now allocated,
                                               each array element has size <s>)
0xBE arraylength      S, a:* -> S, n:w32      (n = \length(a))
0x62 aaddf <f>        S, a:* -> S, (a+f):*    (a != NULL; f field offset in bytes)
0x63 aadds            S, a:*, i:w32 -> S, (a->elems+s*i):*
                                              (a != NULL, 0 <= i < \length(a))

0x34 cmload           S, a:* -> S, x:w32  (x = (w32)(*a), a != NULL, load 1 byte)
0x55 cmstore          S, a:*, x:w32 -> S  (*a = x & 0x7f, a != NULL, store 1 byte)
0x2E imload           S, a:* -> S, x:w32  (x = *a, a != NULL, load 4 bytes)
0x4E imstore          S, a:*, x:w32 -> S  (*a = x, a != NULL, store 4 bytes)
0x2F amload           S, a:* -> S, b:*    (b = *a, a != NULL, load address)
0x4F amstore          S, a:*, b:* -> S    (*a = b, a != NULL, store address)
```