

**Carleton University**  
**Department of Systems and Computer Engineering**  
**SYSC 2006 - Foundations of Imperative Programming**

**Lab 6 - Developing a List Collection, First Iteration**

### **Objective**

In this lab, you'll begin the development of a C module that implements a list collection that is similar to a Python `list` or a Java `ArrayList`. You'll learn how we can build useful data structures in C by using pointers to connect dynamically allocated arrays and structs.

### **Attendance/Demo**

After you finish all the exercises, call a TA, who will review your solutions, ask you to run the test harness provided on cuLearn, and assign a grade. For those who don't finish early, a TA will grade the work you've completed, starting about 30 minutes before the end of the lab period.

**Any unfinished exercises should be treated as "homework"; complete these on your own time, before your next lab.**

### **Background**

C (and C++) arrays have several limitations:

- An array's capacity is specified when the array is declared; for example, this statement declares an array that holds 10 integers: `int numbers[10];`  
This capacity is fixed when the code is compiled; there is no way to increase the array's capacity at run-time.
- C doesn't provide an operator or standard library function that returns an array's capacity. The idiom:

```
int capacity = sizeof(arr) / sizeof(arr[i]);
```

doesn't work when `arr` is a function parameter; for example, this function is incorrect:

```
/* Initialize all elements of arr to 0. */
void initialize(int arr[])
{
    int capacity = sizeof(arr) / sizeof(arr[i]); //No!
    for (int i = 0; i < capacity; i = i + 1) {
        arr[i] = 0;
    }
}
```

This technique doesn't work because parameter `arr` is not an array; it's a pointer to an array, so `sizeof(arr)` yields the size of the pointer, not the total size of the array pointed by `arr`.

- C doesn't check for out-of-bounds array indices, which means code can access memory outside the array by using an out-of-bounds index. If `numbers` is declared this way:

```
int numbers[10];
```

the expressions `numbers[-1]` or `numbers[10]` will compile without error (even though the declared capacity of the array is 10). At run-time, these expressions will not cause the program to terminate with an error, even though they access memory outside of the array.

Many modern programming languages have addressed these limitations by providing a collection known as a *list*. Java provides a class named `ArrayList` and Python has a built-in type (class) named `list`. Although C++ supports C-style arrays for backwards compatibility, many C++ programmers instead use the `vector` class that is part of the C++ Standard Template Library.

Here are the important differences between C arrays and the lists provided by many programming languages:

- A list increases its capacity as required. As you append items to a list or insert items in a list, the list will automatically grow (increase its capacity) when it becomes full.
- A list keeps track of its *length* or *size* (that is, the number of items currently stored in the list). Python has a built-in `len` function that takes one argument, a list, and returns the list's length. Java's `ArrayList` class provides a *method* (another name for a function) named `size`, which returns the number of items in the list.
- List operations will often generate a run-time error if you specify an out-of-range list index. By default, this normally results in an error message being displayed, then the program terminates.
- In Python, many common list operations are provided by built-in operators, functions and methods. Java's `ArrayList` class defines several methods that provide similar operations. Compare this with C and C++ arrays, which provide very few built-in array operations.

Over the next couple of labs, you're going to develop a C module that implements a list collection. This collection will provide many of the same features as Python's `list`, Java's `ArrayList` and C++'s `vector`, and will be a useful module to have in your "toolbox" if you end up doing a lot of C programming.

The data structure that underlies this collection is known as a *dynamic array* or *growable array*. This is an array that increases its capacity when it becomes full. C doesn't provide dynamic arrays, so you're going to learn how to build them "from scratch", using C's fixed capacity arrays.

In the first version of the list module, we won't attempt to implement all the features of Python or Java lists. Although our list will be based on a dynamically-allocated array, in this first iteration it will have fixed capacity; in other words, it won't grow when it becomes full. We're going to focus on developing functions that provide the core list operations. You'll refine and extend your module in a subsequent lab.

We'll use the following terms when working with lists:

- list *length*: the number of items currently stored in a list
- list *size*: a synonym for length
- list *capacity*: the maximum number of items that can be stored in a list

**Make sure you understand the difference between a list's length (size) and its capacity.**

## General Requirements

You have been provided with four files:

- `array_list.c` contains incomplete definitions of several functions you have to design and code;
- `array_list.h` contains the declaration of the `intlist_t` structure, as well as declarations (function prototypes) for the functions you'll implement. **Do not modify `array_list.h`.**
- `main.c` and `sput.h` implement a *test harness* (functions that will test your code, and a `main` function that calls these test functions). **Do not modify `main()` or any of the test functions.**

None of the functions you write should perform console input; i.e., contain `scanf` statements. Unless otherwise specified, none of your functions should produce console output; i.e., contain `printf` statements.

You must format your C code so that it adheres to one of two commonly-used conventions for indenting blocks of code and placing braces (K&R style or BSD/Allman style). Pelles C makes it easy to do this - instructions were provided in Labs 1 and 2.

Finish each exercise (i.e., write the function and verify that it passes all of its tests) before you move on to the next one. Don't leave testing until after you've written all your functions.

## Getting Started

**Step 1:** Launch Pelles C and create a new Pelles C project named `array_list`.

- If you're using the 64-bit edition of Pelles C, the project type should be Win 64 Console program (EXE). (Although the 64-bit edition of Pelles C can build 32-bit programs, you may run into difficulties if you attempt to use the debugger to debug 32-bit programs.)
- If you're using the 32-bit edition of Pelles C, the project type should be Win32 Console program (EXE).

When you finish this step, Pelles C will create a folder named `array_list`.

**Step 2:** Download files `main.c`, `array_list.c`, `array_list.h` and `sput.h` from cuLearn. Move these files into your `array_list` folder.

**Step 3:** You must also add `main.c` and `array_list.c` to your project. To do this:

- select **Project > Add files to project...** from the menu bar.
- in the dialogue box, select `main.c`, then click **Open**. An icon labelled `main.c` will appear in the Pelles C project window.
- repeat this for `array_list.c`.

You don't need to add `array_list.h` and `sput.h` to the project. Pelles C will do this after you've added `main.c`.

**Step 4:** Build the project. It should build without any compilation or linking errors.

**Step 5:** Execute the project. The test harness (the functions in `main.c`) will report several errors as it runs, which is what we'd expect, because you haven't started working on the functions the harness tests.

**Step 6:** Open `array_list.c` in the editor and do Exercises 1 through 8.

### Exercise 1

In a recent lecture, you learned how dynamically allocate an array from the heap; for example, this code fragment allocates an array that has the capacity to hold 100 integers and stores the pointer to the array in variable `pa`. It then initializes all the array elements to 0:

```
int *pa;
pa = malloc(100 * sizeof(int)); // pa points to the first
                                // element in the array, which
                                // is in the heap

assert(pa != NULL);
for (int i = 0, i < 100; i += 1) {
    pa[i] = 0;
}
```

In another lecture, you learned how to dynamically allocate a `struct` from the heap; for example, this code fragment allocates a `struct` that stores the Cartesian coordinates of a point:

```

typedef struct {
    int x;
    int y;
} point_t;

point_t *pt;
pt = malloc(sizeof(point_t)); // pt points to the point_t
                               // struct in the heap

assert(pt != NULL);

```

The data structure that underlies our list collection will combine these two concepts. It will consist of a dynamically-allocated `struct`, and one of `struct`'s members will be a pointer to a dynamically-allocated array.

Open `array_list.h`. This file contains the declaration for a `struct` named `intlist_t`:

```

typedef struct {
    int *elems;    // Pointer to backing array.
    int capacity; // Maximum number of elements in the list.
    int size;      // Current number of elements in the list.
} intlist_t;

```

Notice that the type of member `elems` is "pointer to `int`". This member will be initialized with a pointer to an array of integers that has been allocated from the heap.

In `array_list.c` (not `array_list.h`) you have been provided with an incomplete definition of a function named `intlist_construct` that, when completed, will return a pointer to a new, empty list of integers with a specified capacity. The function prototype is:

```
intlist_t *intlist_construct(int capacity);
```

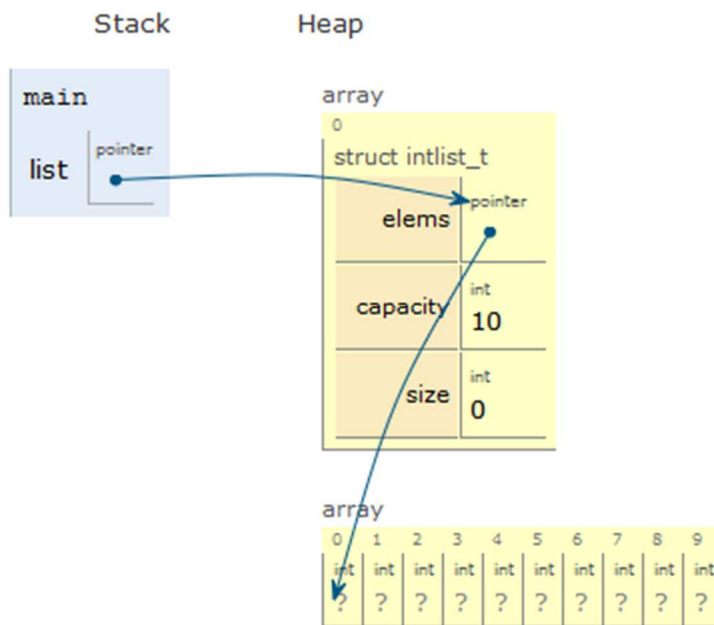
You must modify the function so that it correctly implements all of the following requirements:

- The function terminates (via `assert`) if `capacity` is less than or equal to 0.
- The function allocates two blocks of memory from the heap:
  - One block is the list's backing array; that is, a dynamically-allocated array with the specified capacity.
  - The other block is the dynamically-allocated `intlist_t` `struct`. Your `intlist_construct` function will return the pointer to this `struct`.
- The function terminates (via `assert`) if memory cannot be allocated for the `struct` or the array.
- The function initializes the `struct`'s `elems`, `capacity` and `size` members.

Suppose `main` contains this statement:

```
intlist_t *list = intlist_construct(10);
```

Here is a C Tutor diagram of the program's memory after this statement is executed:



Complete the function definition.

Build the project, correcting any compilation errors, then execute the project. The test harness will run. Review the console output and verify that your `intlist_construct` function passes all the tests in test suite #1.

We recommend that you also use C Tutor to visualize the execution of your `intlist_construct` function, step-by-step, before attempting the remaining exercises. Completing the remaining exercises will be easier if you can visualize the list data structure.

### Interlude (read this before attempting the remaining exercises)

All the functions in Exercises 2 through 8 have a parameter of type `intlist_t *`:

```
return_type fn_name(intlist_t *list, ...);
```

In other words, the first argument passed to these functions is a pointer to a list.

The function can access element `i` in the list's backing array by using this expression:

```
list->elems[i]
```

This expression might appear complicated, so let's break it into pieces:

- Parameter `list` is a pointer to the list; i.e., a pointer to an `intlist_t` struct.
- Recall that the expression `list->elems` is equivalent to `(*list).elems`; that is, we're selecting the `elems` member in the struct pointed to by `list`. Member `elems` is a

pointer to an `int`; specifically, it points to the first element in an array of integers. Therefore, the expression `list->elems` yields the pointer to the first element in the list's backing array.

- Because `elems` is a pointer to an array, we can access individual elements using the `[]` operator. So, `list->elems[i]` is element at position `i` in the array that is pointed to by `list->elems`; in other words, element `i` in the list's backing array.

## Exercise 2

File `array_list.c` contains the incomplete definition of a function named `intlist_print` that prints the integers stored in a list. The function prototype is:

```
void intlist_print(const intlist_t *list)
```

(Recall that `const` is a reserved word in C. Because parameter `list` has been declared to be `const`, if the function contains code that modifies the `intlist_t` struct that `list` points to, we'll get a compilation error.)

This function should terminate (via `assert`) if parameter `list` is `NULL`.

Complete the function definition. The required format for the output is:

```
[elem0 elem1 elem2 ... elemn-1]
```

that is, a list of integers enclosed in square brackets, with one space between each pair of values. There must be no spaces between the '[' and the first value, or between the last value and ']'.

For example, if `intlist_print` is passed a list containing 1, 5, -3 and 9, the output produced by this function should look exactly like this:

```
[1 5 -3 9]
```

If the list is empty (length 0), the output should be: `[]`.

Build your project, correcting any compilation errors, then execute the project.

Test suite #2 exercises `intlist_print`, but it cannot verify that the information printed by the function is correct. Instead, it displays what a correct implementation of `intlist_print` should print (the expected output), followed by the actual output from your function.

Review the console output, compare the expected and actual output and verify that your `intlist_print` function is correct before you start Exercise 3.

### Exercise 3

File `array_list.c` contains an incomplete definition of a function named `intlist_append` that appends an integer to the end of a list. The function prototype is:

```
_Bool intlist_append(intlist_t *list, int element)
```

This function should terminate (via `assert`) if parameter `list` is `NULL`.

Parameter `element` contains the value that will be appended to the list if the list is not full. (In other words, `element` will be stored in the list only if it has room for at least one more element.) If `element` was appended, the function should return `true`. If the function was not successful, because the list was full, it should leave the list unchanged and return `false`.

Complete the function definition.

Build the project, correcting any compilation errors, then execute the project. The test harness will run. Review the console output and verify that your `intlist_append` function passes all the tests in test suite #3.

### Exercise 4

File `array_list.c` contains an incomplete definition of a function named `intlist_capacity` that returns the capacity of a list. The function prototype is:

```
int intlist_capacity(const intlist_t *list)
```

This function should terminate (via `assert`) if parameter `list` is `NULL`.

Complete the function definition.

Build the project, correcting any compilation errors, then execute the project. The test harness will run. Review the console output and verify that your `intlist_capacity` function passes all the tests in test suite # 4.

### Exercise 5

File `array_list.c` contains an incomplete definition of a function named `intlist_size` that returns the size of a specified list. The function prototype is:

```
int intlist_size(const intlist_t *list)
```

This function should terminate (via `assert`) if parameter `list` is `NULL`.

Complete the function definition.

Build the project, correcting any compilation errors, then execute the project. The test harness will run. Review the console output and verify that your `intlist_size` function passes all the tests in test suite #5.



## Exercise 6

File `array_list.c` contains an incomplete definition of a function named `intlist_get` that returns the element located at a specified index (position) in a list. The function prototype is:

```
int intlist_get(const intlist_t *list, int index)
```

This function should terminate (via `assert`) if parameter `list` is `NULL` or if `index` is not in the range `0 .. intlist_size()-1`, inclusive.

Complete the function definition.

Build the project, correcting any compilation errors, then execute the project. The test harness will run. Review the console output and verify that your `intlist_get` function passes all the tests in test suite #6.

## Exercise 7

File `array_list.c` contains an incomplete definition of a function named `intlist_set` that stores an integer at a specified index (position) in a list. The function will return the integer that was previously stored at that index. The function prototype is:

```
int intlist_set(intlist_t *list, int index, int element)
```

This function should terminate (via `assert`) if parameter `list` is `NULL` or if `index` is not in the range `0 .. intlist_size()-1`, inclusive.

Parameter `element` contains the value that will be stored in the list.

Complete the function definition.

Build the project, correcting any compilation errors, then execute the project. The test harness will run. Review the console output and verify that your `intlist_set` function passes all the tests in test suite #7.

## Exercise 8

File `array_list.c` contains an incomplete definition of a function named `intlist_removeall` that empties a list. The function prototype is:

```
void intlist_removeall(intlist_t *list)
```

This function should terminate (via `assert`) if parameter `list` is `NULL`.

Here is a code fragment that allocates a new, empty list. It appends three integers to the list, then calls `intlist_removeall`:

```
intlist_t *my_list = intlist_construct(10); // capacity 10, size 0
_Bool success;
```

```
success = intlist_append(my_list, 2); // capacity 10, size 1
```

```
success = intlist_append(my_list, 4); // capacity 10, size 2
success = intlist_append(my_list, 6); // capacity 10, size 3
intlist_removeall(my_list); // capacity 10, size 0
```

When `intlist_removeall` returns, the list contains 0 integers.

Complete the function definition. This function should not free any of the memory that was allocated by `intlist_construct`, or call `malloc`.

Build the project, correcting any compilation errors, then execute the project. The test harness will run. Review the console output and verify that your `intlist_removeall` function passes all the tests in test suite #8.

### Wrap-up

1. Remember to have a TA review your solutions to the exercises, assign a grade and have you initial the attendance/grading sheet.
2. Remember to back up your project folder before you leave the lab; for example, copy it to a flash drive and/or a cloud-based file storage service. All files you've created on the hard disk will be deleted when you log out.
3. You'll need your `array_list` module for Lab 7. That lab assumes your module passes all the tests in the Lab 6 test harness. Remember to complete any unfinished exercises before your next lab period.

### Homework Exercise - Visualizing Program Execution

In the final exam, you will be expected to be able to draw diagrams that depict the execution of short C programs that use pointers to dynamically allocated `structs` and arrays, using the same notation as C Tutor. This exercise is intended to help you develop your code tracing/visualization skills when working with programs that allocate allocate memory from the heap.

1. The *Labs* section on cuLearn click on the link, **Open C Tutor in a new window**.
2. Copy the `intlist_t` declaration from `array_list.h` and your solutions to Exercises 1 and 3-8 into the C Tutor editor.
3. Write a short `main` function that exercises your list functions.
4. *Without using C Tutor*, trace the execution of your program. Draw memory diagrams that depict the program's activation frames just before the `return` statement in each of your list functions is executed. Use the same notation as C Tutor.
5. Use C Tutor to trace your program one statement at a time, stopping just before each `return` statement is executed. Compare your diagrams to the visualization displayed by C Tutor.