Duration: 1 lab session

For this lab exercise you should do all your work on your `ex4` branch.

The initial version of this program should be a copy of your program from the “Arrays and Memory Management” lab exercise. Copy the starting files (`arrays.c` and `makefile`) from your `ex3` branch. You should rename `arrays.c` as `lists.c` and replace `#include 'arrays.h'` with `#include 'data.h'` in `lists.c`. To copy a file you can run something like

```
git checkout ex3
cp arrays.c tmp_file
git checkout ex4
mv tmp_file lists.c
git add lists.c
```

Learning Objectives

At the end of this lab you should be able to:

- Use structs, unions, pointers, malloc and free in C;
- Explain the use of pointers and memory management in C;
- Use a simple Recursive Data Type (RDT) - lists - in C;
- Use valgrind and clang sanitiser to help debug C programs.

Introduction

Remember, you can see The GNU C Programming Tutorial for more information.

`union`

`Union` is a special data type in C which stores different variables under a single name. It is declared and accessed in similar manner as `structs`, except for the fact that all of the members in `union` are stored in the same memory location. Only one member can be in a `union` at one time. These are different from `structs` and are used to be more memory efficient.
typedef struct node {
    char name[20]; // holds the actual node content, could be any data
    struct node *next; // points to the next list node
} node;

Figure 1: Basic form of a node in a linked list.

Linked list

Here is a short video on introduction to linked list.

A linked list is a linear collection of structures chained together by pointers, while their order is not relevant to their physical memory addresses.

Linked lists are easy to be sorted by redirecting pointers, and can be updated in length dynamically. Figure ?? gives the basic form of a node in a linked list. What value should go in next at the end of the list? What would happen if we did node->next=node?

Doubly-linked list

Above is an example of a structure type in a single linked list, while there is also doubly-linked list in which each node contains pointers to the previous and to the next node. This allows easy traversal in both directions in linked lists.

Part 1

In this part you will implement a singly-linked list with different methods for insertion. You should produce a single C program lists.c for all steps of this part. You should start with the appropriately renamed arrays.c from exercise 3. See instructions at the start of this document.

Step A: Insert at start of list

Edit the program to replace the array people by a list:

• Remove all uses of nextinsert (as a variable or as a parameter) in your program. Modify the declaration of your struct to include a next pointer (i.e. to the same struct - this is why a list is a Recursive Data Structure).

• Change the declaration of people to be a pointer to your struct instead of an array, and initialise it to be empty (NULL). Your program should always keep this pointing to the start of your list. What happens if you forget to store where the start of the list is?

• Change insert so that:
    Its first parameter is a list (i.e. a pointer to your struct) instead of an array.
    It adds the malloced new person at the start of the list.
    It returns a pointer to the start of the new list as its result.

Figure ?? gives further pseudocode for this.
• Change the call to insert so that the return result is put back into the pointer to the start of the list (i.e. people).
• Change the code that frees memory. Make sure you call free after you storing where the next element in the list is. Why might this matter?

```plaintext
create a new space for the new person
(check it succeeded)
set the data for the new person
set the new person’s next link to point to the (start of the) current list
return the (start of the) new list i.e. a pointer to the new person
```

Figure 2: Pseudocode for insert

At this point you could try submitting your code and you should observe that some of the tests, but not all of them, will pass (as you haven’t added all of the functionality yet). Make sure this is the case before continuing. Importantly, use valgrind to get ride of any invalid reads or memory leaks.

**Step B: Insert at end of list**

Rename your insert function to be insert_start. Make an extra copy of it named insert_end. Modify your program to call insert_start and check that is still works as before.

Modify insert_end to insert the new struct at the end of the list. It still needs to return a pointer to the start of the list. This is only the same as a pointer to the struct that has just been inserted if the list was initially empty. Use a loop to run down the list from the start to the end each time the function is called. What is the complexity of this function? Figure ?? gives pseudocode for insert_end.

**Note:** To improve efficiency, we could keep a new pointer to the end of the list in main and pass it to insert_end, so that each time there’s no need to loop from head to tail. This improvement is optional and does not affect marking.

Update your program so that it takes an optional single command-line argument such that “insert_start” runs insert_start and “insert_end” runs insert_end. If no arguments are provided then the program should run insert_start.

Your code should return a non-zero return code (and a suitable message to stderr) if unrecognised/unexpected command-line options are given (this applies from now on).

Submitting now should make more tests pass. Again, check tests and valgrind before proceeding.

**Step C: Insert into sorted list**

Create a new copy of insert_end, called insert_sorted, and extend your program to take a command-line argument “insert_sorted” to call this. Now modify insert_sorted to put people into the list in (ascending) name order:

• You could just use strcmp, but instead write a similar function compare_people which, given pointers to two structs describing people, simply gets their name strings and returns the result of calling strcmp on those strings.
create a new space for the new person
(check it succeeded)
set the data for the new person
if the current list is empty (i.e. NULL)
do the same as insert_start
otherwise
use a loop to find the last item in the list (where *next* is NULL)
set the "next" link of this item to point to the new node
return the (start of the) list

Figure 3: Pseudocode for insert_end

create a new space for the new person
(check it succeeded)
set the data for the new person
if the list is empty or the new person is less than the first item
do the same as insert_start
otherwise
use a loop to find the last item that is smaller than the new person
set the new person’s *next* link to point to the next item in the list
set the *next* link of this item to point to the new person
return the (start of the) list

Figure 4: The algorithm for insert_sorted

- Modify insert_sorted so that, instead of always going to the end of the list, at each step it calls compare_people to decide whether to insert at this point in the list or to try the next person. Avoid calling compare_people when the list is empty, or when you reach the end of the list. If two people are equal then the person inserted first should appear first.

Figure ?? gives pseudocode for this. Again, submit and check.

**Step D: Parameterising the sort order**

Add an extra parameter to insert_sorted, that is itself a (pointer to a) function e.g. a function pointer. Call it compare_people. Edit your main to call insert_sorted with compare_people as the actual parameter. Check that your program still behaves as in the previous part.

Now, rename compare_people to be compare_people_by_name, and make another copy of it called compare_people_by_age. Again, edit your main to call insert_sorted with compare_people_by_name as the actual parameter and check that your program still behaves as in the previous part.

Edit compare_people_by_age to do what it says. Finally, extend your program to take a second command-line argument only when the first argument is “insert_sorted” that is either “name” or “age” (defaulting to “name” if a second option is not given). Add appropriate error-handling and ensure that the program calls insert_sorted with compare_people_by_name or compare_people_by_age appropriately.

Submit and check.
Part 2

In this part we will look at how a union data structure can be used to store different kinds of data in the same kind of variable and we will extend our list to be doubly-linked. Note that most of the marks this week are for Part 1 but still try and get as far as you can with Part 2.

Step A: Prototypes in a Header File

Copy `lists.c` to `slists.c` (standing for singly-linked lists) without removing `lists.c` (you need to keep it around for the part1 tests). Now rearrange your code so that your list functions are in `slists.c` and your main function (and its helper files e.g. `compare_people_by_name`) is in a file called `test.c`, you will need to add the people typedef and prototypes for your list functions into a new file called `slists.h` and include this in both `slists.c` and `test.c`.

If you add the following lines to your makefile

```
part2:
 $(CC) $(CFLAGS) slists . c test . c −o test
```

the command `make part2` will compile the necessary things. The resulting test program should behave in the same way as the lists program produced in part1.

If you have a duplicate symbol error then you are defining a symbol more than once – make sure you only `#include “data.h”` in `test.c`.

Before you continue make sure you understand what is going on here. Try just running `gcc test.c −o test` and you will get a linking error; what is this?

Step B: Union

In this step, you need to modify your program to know about 3 different kinds of people: students, staff, and neither:

- Use an `enum staff_or_student` to define `staff` and `student` and `neither`.
- Add a `staff_or_student` field to your `struct`.
- Note that `data.h` already contains arrays `person_type` and `info` similar to `names` and `ages`.
- Use a `union` variable named `extraInfo` to add the following extra information to your `struct`:
  - for students - a string holding their programme-name.
  - for staff - a string holding their room-number
  - for other people - no further information.
- Modify the rest of your program (e.g. to insert the appropriate data from `person_type` and `info`)
- Print the resulting list using the appropriate function from `printing.h`. This is to ensure that your person nodes are printed in the format expected by the testing tool. You may need to change the variable names from people to make it work as we have made some assumptions about what you might use.
**Step C: Doubly Linked List**

In this step, you need to create `dlists.h` and `dlists.c` by copying `slists` and changing the current single linked list into a doubly linked list, that is, to add an extra pointer in structure, pointing to the previous node.

Now update `test.c` so that it uses doubly-linked lists if the compiler flag `-DDOUBLE` is provided. You probably want to add a part2d case to your makefile to support this. Note that you can check this flag as follows.

```c
#ifdef DOUBLE
    // this code is compiled if the flag is given
#else
    // otherwise this code is compiled
#endif
```

Finally, if a doubly-linked list is used the list should be printed backwards (otherwise it should still be printed forwards). For this you may wish to keep track of the last node in the list as well as the first.

We will stop there as the lab is already quite long but we have not properly explored the advantages of doubly-linked lists (other than being able to easily print the list backwards). One thing we could have asked you to do was implement two functions that first find a particular node in the list (e.g. with a given name) and then (separately) delete that node. Why would this be easier with a doubly-linked list than a singly-linked list? **The TA will probably ask you this question during marking.**

**Marking Scheme**

Note that this may be refined to introduce extra cases reflecting special cases if required.
<table>
<thead>
<tr>
<th><strong>Are Part1 steps A and B complete, correct, and understood?</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All of the output tests pass and the student can explain the code</td>
<td>(2)</td>
</tr>
<tr>
<td>Some tests fail and/or the explanation is insufficient</td>
<td>(1)</td>
</tr>
<tr>
<td>None of the tests pass</td>
<td>(0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Are Part1 steps C and D complete, correct, and understood?</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All of the output tests pass and the student can explain the code</td>
<td>(2)</td>
</tr>
<tr>
<td>Some tests fail and/or the explanation is insufficient</td>
<td>(1)</td>
</tr>
<tr>
<td>None of the tests pass</td>
<td>(0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Does Part1 have any memory errors?</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All of the memory tests pass e.g. there are no memory leaks or invalid reads/writes</td>
<td>(2)</td>
</tr>
<tr>
<td>Some but not all of the memory tests pass</td>
<td>(1)</td>
</tr>
<tr>
<td>None of the tests pass</td>
<td>(0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Does Part1 handle incorrect input properly?</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All of the error-handling tests pass</td>
<td>(1)</td>
</tr>
<tr>
<td>Some but not all of the error-handling tests pass</td>
<td>(0.5)</td>
</tr>
<tr>
<td>None of the tests pass</td>
<td>(0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Is Part 2 complete, correct, and understood?</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>All steps have been completed correctly (tests pass) and the student understands how a union works and can describe the advantages of a doubly-linked list.</td>
<td>(2)</td>
</tr>
<tr>
<td>All steps have been completed but there are some small mistakes.</td>
<td>(1.75)</td>
</tr>
<tr>
<td>At least steps A and B have been completed correctly (tests pass).</td>
<td>(1.5)</td>
</tr>
<tr>
<td>A reasonable attempt has been made at this part but it is not finished and/or contains many mistakes</td>
<td>(1)</td>
</tr>
<tr>
<td>No submission for this part</td>
<td>(0)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Is the overall quality of all code good?</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Code is well formatted and commented with appropriate variable names</td>
<td>(1)</td>
</tr>
<tr>
<td>The code is acceptable but there are some issues</td>
<td>(0.5)</td>
</tr>
<tr>
<td>The code is not readable</td>
<td>(0)</td>
</tr>
</tbody>
</table>