# [This is CS50x]

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# Lecture 4



## Tools for debugging

- We took a look at CS50 IDE, a new web-based programming environment. We learned to use:
  - `check50` to check our work automatically
  - `debug50` and the debugger to step through our code
  - `help50` to make compilation errors more understandable
  - `printf` to print out helpful information as our program runs
  - `style50` to check the style of our code
- We also looked at how memory is used by our programs in C, and how we can allocate and free memory.

## `valgrind`

- `valgrind` is a command-line tool that we can use to run our program and see if it has any memory leaks.
  - Recall that a memory leak happens when we call `malloc` to ask the operating system for memory for our program, bu don't call `free` to mark it as free. Then, our program will use more and more memory as it runs, eventually slowing d even crashing our entire computer.
- Let's write a program called `memory.c` to experiment a little bit:

```
#include <stdlib.h>

void f(void)
{
    int *x = malloc(10 * sizeof(int));
    x[10] = 0;
}

int main(void)
{
    f();
    return 0;
}
```

- We have a function, `f`, that allocates memory for 10 integers, and using `x` as a pointer to the address of the start of t memory. Then, we try to access the 11th integer with `x[10]` (remember that pointers can act like arrays, since the me we get is contiguous, or back-to-back).
- When we run this program, we can see that it still works. It turns out, `malloc` sometimes (but not always) gives us ba little more memory than we ask for, and we might get lucky and be able to access and use memory beyond the bounds we should have.

- We can run our program with `valgrind ./memory`, and we see a lot printed out. But we do see one error message in part `Invalid read of size 4`, followed by some pointers in hexadecimal. We see `f (memory.c:15)` in the line immediate which tells us that this happened in line 15 of `memory.c` in the function `f`.
- We can also use `help50 valgrind ./memory`, which will distill the output for us, one error message at a time, and add additional clues to guide us.
- If we fix our program to access `x[9]`, then `valgrind` onluy has 1 error message for us: `40 bytes in 1 blocks are definitely lost...`. And `help50` tells us that we forgot to free memory we allocated with `malloc`, so we should call `free(x)` after we're doing using it. Now, we have 0 errors.
- Recall that we have some finite number of bytes in memory, and our operating system keeps track of which bytes are used program, which bytes are free, and indicates segmentation faults when we try to access memory that isn't allocated to our p

## Rubber duck debugging

- Rubber duck debugging is the process of explaining our code, step-by-step, to a rubber duck (or some other inanimate obje we ourselves can understand it better and hopefully realize where we might have a bug or opportunity of improvement. Ho this will be another simple, but powerful, tool for us to use.

## More from last week

- We learned, last week, that a `string` is a synonym for `char *`, a pointer to a character.
- We also learned that memory is laid out in a certain way for our program, where different regions are used to store differen of data, such as:
  - the text segment, where the machine code for our program is loaded when we start it
  - the heap, where dynamically allocated memory (memory we allocate when the program is running), stores
  - the stack, where local variables and functions, including our `main` function, live when our program is running
- We saw a `swap` function that didn't work, when values were passed in directly, since it got its own copies of those values. saw a `swap` function that took in the addresses of two variables, so those values could actually be swapped.
- Binky, from the short clip we saw, also demonstrated how we could dereference pointers and use them correctly (and incorr We need to make sure that our pointers have a valid address, before we try to dereference them.
- Finally, we saw an introduction to structs, where we can build our own data structures, with variables of our choice.

## Structs

- Let's make a file called `struct.h`:

```
typedef struct
{
    char *name;
    char *dorm;
}
student;
```

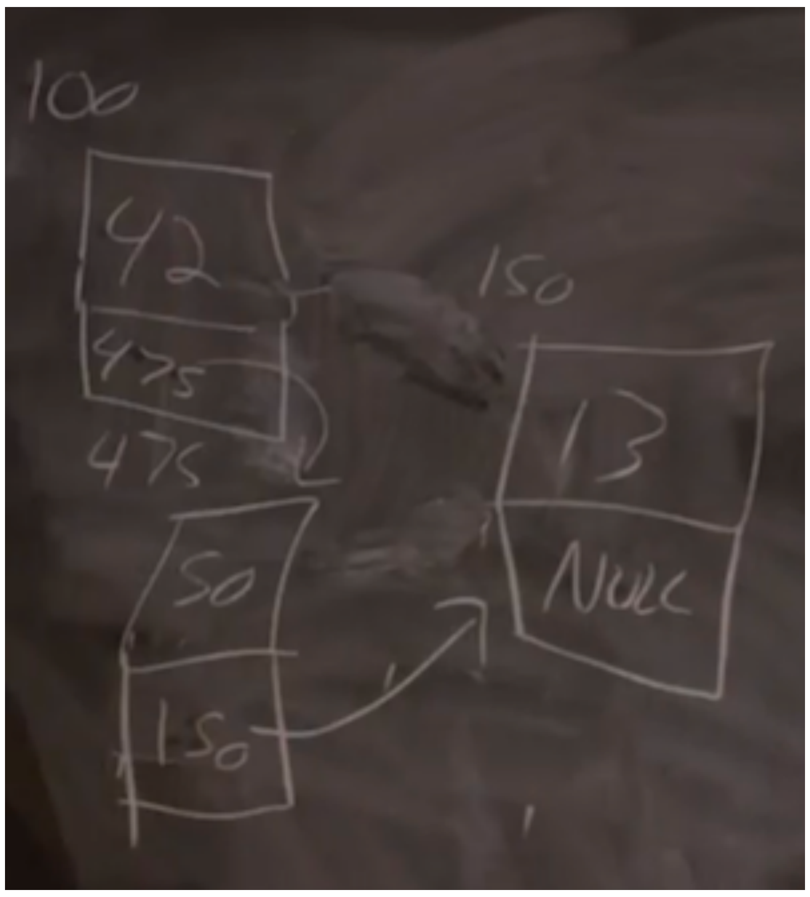
  - This is a header file, which we can share among various `.c` files.
- In `struct0.c`, we import the header file:

```
#include <cs50.h>
#include <stdio.h>
#include <string.h>

#include "struct.h"

int main(void)
{
    // Allocate space for students
    int enrollment = get_int("Enrollment: ");
    student students[enrollment];

    // Prompt for students' names and dorms
    for (int i = 0; i < enrollment; i++)
    {
        students[i].name = get_string("Name: ");
        students[i].dorm = get_string("Dorm: ");
    }

    // Print students' names and dorms
    for (int i = 0; i < enrollment; i++)
    {
        printf("%s is in %s.\n", students[i].name, students[i].dorm);
    }
}
```

  - Notice now that we have a `student` type, and an array called `students` with structs of that type.
  - Then, we can access variables inside each `student` struct with the `.` notation.
  - A `student` is like an abstraction, where we encapsulate some variables together.

## Linked Lists

- So far, arrays had to be a fixed size at the time of initialization. If we wanted to add to our array, we would have to initialize bigger array, and copy the values from the original array. But the running time of resizing an array is now $O(n)$, where $n$ is th the original array.
- We can use a function called `realloc`, which reallocates memory. We can pass in the address of our memory and the new we want, and our operating system will return a new address, where we have that much contiguous memory. It will also co array for us to the new location. But this operation will cost a linear amount of time, too, depending on how big our array is
- We can do the opposite, and ask for just enough memory for one element, like one integer, at a time. But they might be stor anywhere in the heap, so we need a way to link each element to the next, via a stored pointer.
- With this data structure, called a linked list, we lose the ability to randomly access elements. For example, we can no longe the 5th element of the list by calculating where it is, in constant time. (Since we know arrays store elements back-to-back, add 1, or 4, or the size of our element, to calculate addresses.) Instead, we have to follow each element, one at a time.
- And we create a linked list by allocating, for each element, enough memory for both the value, and a pointer to the next ele We'll call these nodes:




- We have three nodes at various addresses in memory, `100`, `150`, and `475`. Each node has the value we want to store also a pointer to the next node. The final node has a pointer of `NULL`, indicating the end of our linked list.

- In code, we might create our own struct called `node`, with an `int` and a pointer to the next `node` called `next`:

```
typedef struct node
{
    int n;
    struct node *next;
}
node;
```

  - We start this struct with `typedef struct node` so that we can refer to a `node` inside our struct.

- With some volunteers, we demonstrate how a linked list works. To store 3 values, we need 3 nodes, and a pointer, that we la "first", pointing to the first node. Each node holds a value, along with a pointer to the next node. And to add a node, we wou allocate memory for a new node, and change our pointers carefully. First, we need to find the next node that will follow the node (if we want to keep our linked list sorted). Then, our new node will point to the next node, and change the node befor point to the new node. And to find the right place for inserting a new node, we have to start with our "first" pointer, and loo values of each node as we follow the pointers in them.

- The running time of inserting a node, now, is $O(n)$, since we have to follow each node to check their values. There's more log running time, but we don't need to decide on a fixed size for our list now. And if we were to insert nodes in unsorted order, running time would be $O(1)$, since we can just add it to the front of the list. We can also keep an additional pointer to the la calling it "last", or we can even have each node store two pointers, one to the previous node and one to the next node, so w move forwards and backwards.

- Let's see how we might do this in code. First, we can store a fixed number of integers in an array:

```c
#include <cs50.h>
#include <stdio.h>

int main(void)
{
    // Prompt for number of numbers
    int capacity;
    do
    {
        capacity = get_int("Capacity: ");
    }
    while (capacity < 1);

    // Memory for numbers
    int numbers[capacity];

    // Prompt for numbers
    int size = 0;
    while (size < capacity)
    {
        // Prompt for number
        int number = get_int("Number: ");

        // Add to list
        numbers[size] = number;
        size++;
    }

    // Print numbers
    for (int i = 0; i < size; i++)
    {
        printf("%i\n", numbers[i]);
    }
}
```

    - We get a `capacity` from the user, and create an array of size `capacity`. Then, we keep adding numbers to the array we reach the capacity. Then, we print each number in the array.
    - But our program is limited to a capacity we choose initially.
- We can size an array dynamically:

```c
#include <cs50.h>
#include <stdio.h>

int main(void)
{
    // Memory for numbers
    int *numbers = NULL;
    int capacity = 0;

    // Prompt for numbers (until EOF)
    int size = 0;
    while (true)
    {
        // Prompt for number
        int number = get_int("Number: ");

        // Check for EOF
        if (number == INT_MAX)
        {
            break;
        }

        // Check whether enough space for number
        if (size == capacity)
        {
            // Allocate space for number
            int *tmp = realloc(numbers, sizeof(int) * (size + 1));
            if (!tmp)
            {
                if (numbers)
                {
                    free(numbers);
                }
                return 1;
            }
            numbers = tmp;
            capacity++;
        }

        // Add number to list
        numbers[size] = number;
        size++;
    }

    // Print numbers
    printf("\n");
    for (int i = 0; i < size; i++)
    {
        printf("%i\n", numbers[i]);
    }

    // Free memory
    if (numbers)
    {
        free(numbers);
    }
}
```

- We get one number at a time,
- First, we initialize a pointer called `numbers`, but we don't initialize it yet. We track the `capacity` of our array, as wel `size` of the array so far.
- Then, we get one number at a time from the user. `get_int` will return `INT_MAX` if we indicate EOF, or "end of file" as end to our input (control + d in the terminal), so if that happens, we can `break` out of the loop.

- If we've reached our `capacity` for the `numbers` array, we use `realloc` to reallocate enough space for an addition integer in the array. We check that `realloc` returned a pointer that isn't null, and if not, `free` the existing `numbers` we have one, and `return 1`. If we do get enough space, then we can add the new number to the array.
- Finally, we can print each number in the array, and free the array. If not, running `valgrind ./list1` will show us an

- Now let's write the same program, using a linked list:

```
#include <cs50.h>
#include <stdio.h>

typedef struct node
{
    int number;
    struct node *next;
}
node;

int main(void)
{
    // Memory for numbers
    node *numbers = NULL;

    // Prompt for numbers (until EOF)
    while (true)
    {
        // Prompt for number
        int number = get_int("number: ");

        // Check for EOF
        if (number == INT_MAX)
        {
            break;
        }
```

  - The beginning of our program is essentially the same, though we define `node` at the top of this program.

```
        // Allocate space for number
        node *n = malloc(sizeof(node));
        if (!n)
        {
            return 1;
        }

        // Add number to list
        n->number = number;
        n->next = NULL;
        if (numbers)
        {
            for (node *ptr = numbers; ptr != NULL; ptr = ptr->next)
            {
                if (!ptr->next)
                {
                    ptr->next = n;
                    break;
                }
            }
        }
        else
        {
            numbers = n;
        }
    }
```

  - Now, we allocate enough memory for a new node and point to it with a pointer `n`. If `n` was null after we called `mal` then we exit with an error. With the `->` syntax, we can follow a pointer to get a variable in a struct, so we store the ne number into the node `n` points to, along with `NULL` for the `next` pointer. (If `n` was a node and not a pointer, we w the `n.number` syntax.)

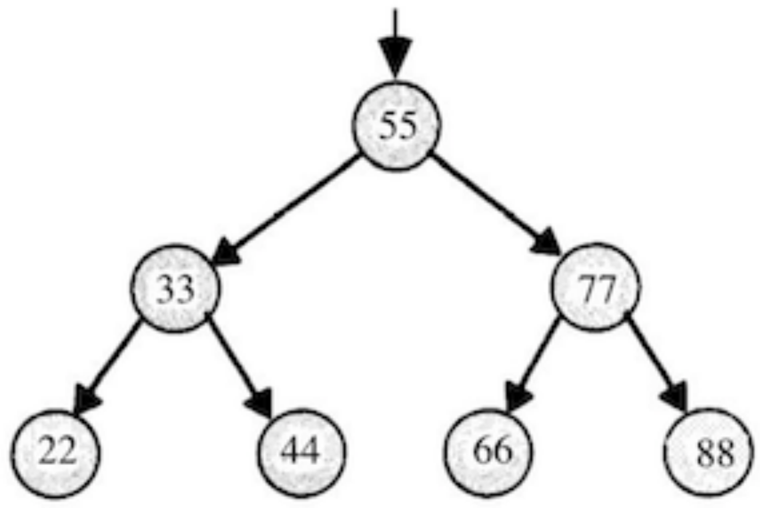
- Then, if `numbers` is a pointer, we create a temporary pointer `ptr` to follow our linked list. We start with `ptr = num` Inside our loop, if `ptr` doesn't have a `next` pointer (i.e. it's the last node in our linked list), we set the `next` pointer and break. Otherwise, our loop continues, and our temporary pointer `ptr` becomes `ptr->next`, i.e. we look at the ne
- If we didn't have an existing `numbers` pointer, we can just set it to `n`, or the start of our new list.

```
    // Print numbers
    printf("\n");
    for (node *ptr = numbers; ptr != NULL; ptr = ptr->next)
    {
        printf("%i\n", ptr->number);
    }

    // Free memory
    node *ptr = numbers;
    while (ptr != NULL)
    {
        node *next = ptr->next;
        free(ptr);
        ptr = next;
    }
}
```

- Finally, we print the numbers by following the linked list in the same way, and we also free each node as we follow its pointer.

## More data structures

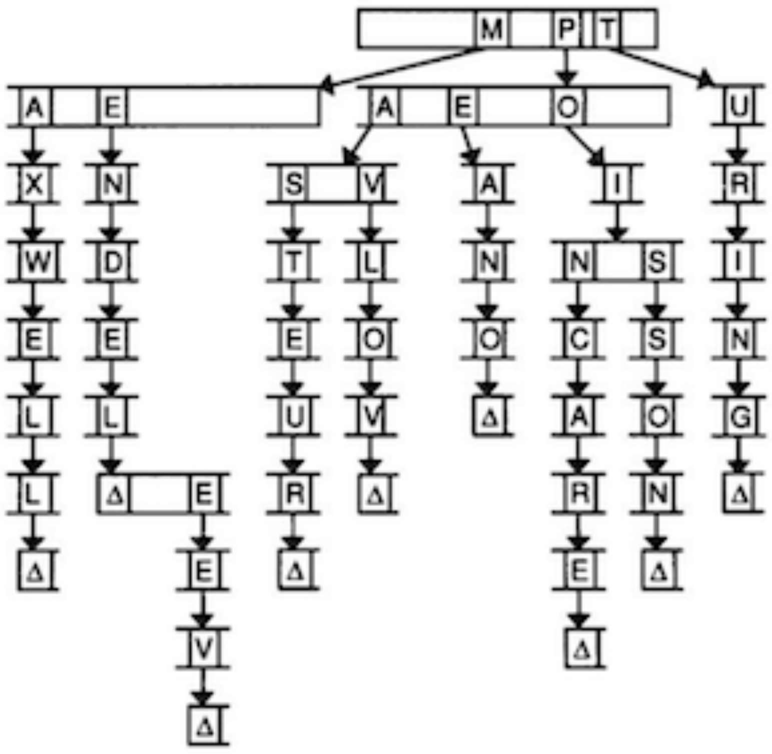
- If we had an unsorted array or linked list storing names, we would have to look through each value, one at a time.
- We, as humans, might make smaller lists where each person whose name starts with "A" will be in one list, "B" in another, ar We can represent this concept with a *hash table*, where each value to be stored is *hashed* by a *hash function*. The resulting h might be a number, and in this case might be `0` for a string that starts with `A`, `1` for a string that starts with `B`, and so the important part is that we can use that number to index into some array. The array, in turn, will have a linked list for eac of the alphabet (or more generally, a linked list for each *bucket*), and so this data structure is called a hash table.
    - Now, each linked list (in our example of strings) will only be, on average, 1/26th the size of a list with all the strings to In the worst case, all the strings will end up in the same bucket (if they happen to start with the same letter), and we v have $O(n)$ running time, like an unsorted array. We can also use a different hash function, which might distribute our el more evenly. But in the real world, our running time is likely to be much lower with a hash table. And we can even hav buckets in our hash table, so each list is an even smaller proportion.
- A *tree* is another data structure where each node points to two other nodes, one to the left (with a smaller value) and one t right (with a larger value):




- Now, we can easily do binary search, and since each node is pointing to another, we can also insert nodes into the tree moving all of them around as we would have to in an array. Recursively searching this tree would look something like:

```
typedef struct node
{
  int n;
  struct node *left;
  struct node *right;
} node;
...
bool search(int n, node *tree)
{
  if (tree == NULL)
  {
      return false;
  }
  else if (n < tree->n)
  {
      return search(n, tree->left);
  }
  else if (n > tree->n)
  {
      return search(n, tree->right);
  }
  else {
      return true;
  }
}
```

- We can use another data structure called a *trie* (pronounced like "try", and is short for "retrieval"):



  - Imagine we want to store a dictionary of words efficiently, and be able to access each one in constant time. A trie is lik but each node is an array. Each array will have each letter, A-Z, stored. For each word, the first letter will point to an arr where the next valid letter will point to another array, and so on, until we reach something indicating the end of a vali If our word isn't in the trie, then one of the arrays won't have a pointer or terminating character for our word.
- In our upcoming problem set, we'll use what we've learned about pointers and data structures to implement a spell-checki program, and gain an understanding of how something that might work at a low level.