UNIX and C Programming (COMP1000)

Lecture 6: Structs

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Textbook Reading (Hanly and Koffman)

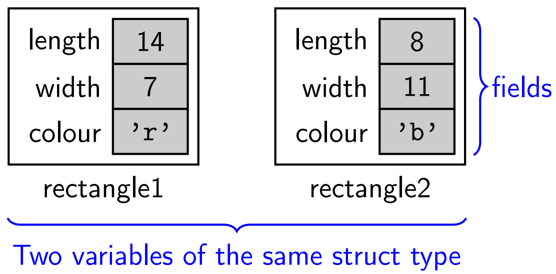
For more information, see the weekly reading list on Blackboard.

- **Chapter 10: Structure and Union Types**
  Unions (Section 10.6) are not important until lecture 9.
- **Sections 13.1 to 13.4 in Chapter 13 ("Dynamic Data Structures")**
  We're only interested in linked lists here. Other structures (sections 13.5 onwards) are beyond the scope of the unit.

Outline

Structs

- A composite datatype — a bucket of variables called "fields".
- Each field has its own name and data type.
- First, declare a struct datatype, saying what fields it contains.
- Then, declare variables of that type. Each struct variable has its own copies of those fields.



Structs vs. Arrays

- Structs and arrays both have subcomponents that behave like variables.
- Array elements:
  - Accessed by an *index* (an integer "location" in the array).
  - Have the *same* data type.
- Struct fields:
  - Accessed by name.
  - Have different data types (typically).
- Arrays are *always* accessed via pointers.
- Structs are *often* accessed via pointers, but don't have to be.

Declaration (the first way)

```
struct <tag> {
    <field declarations>
};
```

- Normally *outside* functions, and in a header file.
- Creates a new data type called "struct <tag>", where "<tag>" can be any valid identifier.
- Fields are declared like variables.
  - *Except* "=" is not allowed in the declaration.

Example

```
struct Result {
    int mark;
    char grade;
};
```


Struct Instantiation

- You can now create a struct variable (*inside* a function):

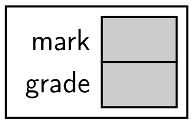
```
struct <tag> <variable-name>;
```

- "struct <tag>" is the data type.
- "<variable-name>" is the name of the variable (surprise!).

Example

Declare a variable "res" of type "struct Result":

```
int main(void)
{
    struct Result res;
    ...
}
```



res (in memory)

Instant Struct Variables (FYI)

You can also declare a struct variable directly:

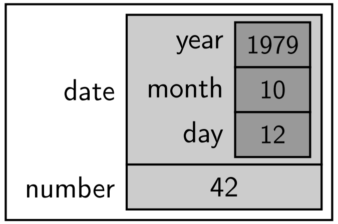
```
int main(void) {
    struct {
        int mark;
        char grade;
    } res;   /* One variable with a struct datatype. */
    ...
}
```

- The whole of "`struct{int mark; char grade;}`" is just datatype, like "`int`" itself.
- It can (in principle) appear anywhere you need a datatype.
- Above, we declare the variable "res" of that type.
- *However*... what if we need many such variables?
- Much easier to give the datatype a name!

Structs Within Structs

- Struct fields can have any data type.
- They can be structs themselves:

```
struct Answer {
    struct {
        int year;
        int month;
        int day;
    } date;
    int number;
};
```



A variable of type `struct Answer`.

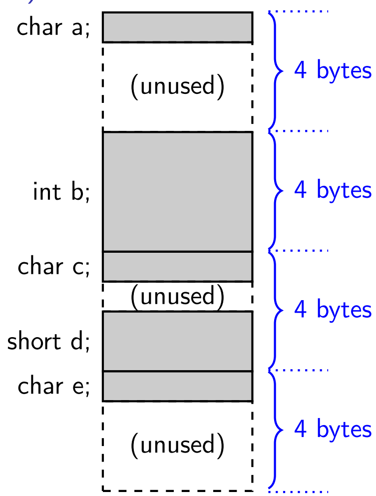
- `struct Answer` has 2 fields: `date` and `number`.
- `date` is also a struct, with 3 fields: `year`, `month` and `day`.

Alignment

- Struct fields are stored in the order of declaration.
- However, there are often gaps between them!
- The compiler tries to place fields on "word boundaries".
- A "word boundary" is a memory address that happens to be a multiple of the word size — the natural size of data processed by the CPU.
  - On a 32-bit machine, words are 4-bytes (32 bits) long.
  - On a 64-bit machine, words are 8-bytes (64 bits) long.
- The CPU can access things on word boundaries more efficiently.
- The struct is also padded at the end, if necessary, to make it a multiple of the word size.
- This behaviour is compiler-dependent. It may work different ways on different systems!

Alignment (32-Bit Example)

```
struct Example {
    char a;
    int b;
    char c;
    short d;
    char e;
};
```



Together a, b, c, d and e have 9 bytes, yet `sizeof(struct Example) == 16`.

Accessing Struct Fields

- When you have a struct variable, you can access its fields with the "." operator:

  <struct-variable>.<field-name>

- For instance:

```
struct Result res;
res.mark = 65;
```

- Note: we *cannot* simply say "`mark = 65`".
  - There could be many copies of that field, each inside a different struct variable.
  - We must say *which* mark we want; e.g. "`res.mark`".
- If the field is itself a struct, you can apply the "." operator again:

```
struct Answer ans;
ans.date.year = 1979;
```

Accessing Struct Fields — Example

Example

```
struct Result res;
int* markPtr;
char* gradePtr;

res.mark = 85;
res.grade = 'A';
printf("%d, %c\n", res.mark, res.grade);

/* Showing off with pointers. */
markPtr = &res.mark;
gradePtr = &res.grade;
printf("%d, %c\n", *markPtr, *gradePtr);
```


Struct Values

- A struct variable has a single composite value.
- You can copy an entire struct at once: `struct2 = struct1;`
- This implicitly copies all the struct's fields.
- You cannot do this with arrays.

Copying Structs — Example

Example

```
int main(void) {
    struct Result res1;
    struct Result res2;

    scanf("%d, %c", &res1.mark, &res1.grade);

    res2 = res1;   /* Copy the entire struct */

    printf("%d, %c\n", res2.mark, res2.grade);

    return 0;
}
```


Structs and Typedef

- `typedef` is often used with struct declarations.
- Otherwise, you have to type "`struct`" everywhere.

Without typedef

```
struct Result {
    int mark;
    char grade;
};

...

struct Result res;
```

With typedef

```
typedef struct {
    int mark;
    char grade;
} Result;

...

Result res;
```

(Recall: `typedef` just creates an alias. In the right-hand case, it creates an alias for "`struct{int mark; char grade;}`".)

Structs and Pointers

- If you have a pointer to a struct, you must dereference the pointer before you can access the fields.
- Due to the order of operators, you must use brackets:

```
Result* res;
...
(*res).mark = 75;
(*res).grade = 'D';
```

- Without brackets, the "." operator would take precedence:

```
*res.mark = 75;  /* Fail! This tries to
                    dereference 'res.mark'. */
```


The "->" Operator (1)

- Combines the "*" and "." operators.
- If you write "`structPtr->field`", you are:
  1. dereferencing "`structPtr`" (on the left), then
  2. accessing "`field`" (on the right).
- Exactly equivalent to "`(*structPtr).field`".
- Just syntactic sugar.

Example

```
Result* res;
...
res->mark = 75;
res->grade = 'D';
```

==

```
Result* res;
...
(*res).mark = 75;
(*res).grade = 'D';
```


The "->" Operator (2)

Don't let it confuse you:

- "->" is *only* for pointers to structs (*not* pointers in general).
- "->" does *not* "make something point to something else".
  - (You need "=" for that!)

Allocating Structs

- Structs are often accessed via pointers, because...
- ...structs are often allocated on the heap using `malloc()`.
- You must eventually free this memory.

Example

```
Result* res = (Result*)malloc(sizeof(Result));
...
free(res);
```

(Allocates a block of memory for a single struct.)

- Of course, you don't need `malloc()` to have a pointer.
- You *do* need `malloc()` to put a struct on the heap.

Structs and Functions

- Structs can be passed by value, and even *returned* by value (unlike arrays).
- However, it's more common to pass by reference:
  - Structs are often quite large.
  - Passing/returning by value involves copying.
  - Unnecessary copying is inefficient.

Passing Structs by Value

A copy is made of the entire struct — all its fields (just as in `struct2 = struct1;`)

```
void printResult(Result res) {
    printf("%d, %c\n", res.mark, res.grade);
}

int main(void) {
    Result res;
    ...
    printResult(res);
    ...
}
```


Returning Structs

Similarly, we can return an entire struct, including all its fields:

```
Result getResult(void) {
    Result res;
    scanf("%d %c", &res.mark, &res.grade);
    return res;
}
```

Here, we're effectively returning two values, by wrapping them in a struct.

Passing Structs by Reference

More conventional — only pass a pointer (saves copying).

```
void printResult(Result* res) {
    printf("%d, %c\n", res->mark, res->grade);
}

int main(void) {
    Result res;
    res.mark = 75;
    res.grade = '7';

    printResult(&res);
    ...
}
```

Struct Initialisation

- Recall that you can initialise an array like this:

```
int array[5] = {2, 4, 6, 8, 10};
```

- You can use a similar syntax to initialise structs:

```
typedef struct {
    int mark;
    char grade;
} Result;
...
Result res = {75, 'B'};
```

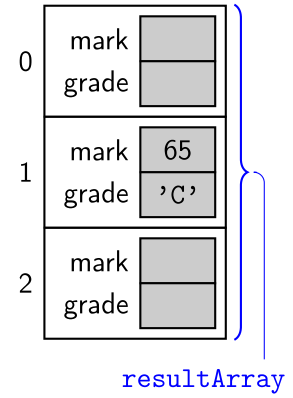
- The values are assigned to fields *in order*.
- Of course, the data types must match!

Arrays of Structs

Arrays can contain any data type, including structs:

```
typedef struct {
    int mark;
    char grade
} Result;

int main(void)
{
    Result resultArray[3];
    resultArray[1].mark = 65;
    resultArray[1].grade = 'C';
    ...
}
```



Arrays of Structs (2)

$$\underbrace{\underbrace{\underbrace{\texttt{resultArray}}_{\text{array}}\texttt{[1]}}_{\text{struct}}\texttt{.mark}}_{\text{int}}\texttt{ = 65;}$$

- "resultArray" itself is an array.
- Adding "[1]" gives us array element 1, which is a struct.
- Adding ".mark" gives us a field inside that struct.
- Notice: the more "things" we add, the more specific we get.

Structs Containing Arrays

Structs can also contain any data type, including arrays:

```
typedef struct {
    char surname[50];
    int lottoNum[6];
} Person;

int main(void)
{
    Person per = {"Blackadder",
                  {3, 14, 6, 17, 5, 2}};
    ...
    per.lottoNum[1] = 1 + per.lottoNum[2];
    ...
}
```

Structs Containing Arrays (2)

```
per.lottoNum[1] = 1 + per.lottoNum[2];
```

$\underbrace{\underbrace{\underbrace{\texttt{per}}_{\text{struct}}\texttt{.lottoNum}}_{\text{array}}\texttt{[2]}}_{\text{int}}$

- "per" itself is a struct.
- Adding ".lottoNum" gives us the lottoNum field — an array.
- Adding "[2]" indexes that array, giving us an int.

Confused?

- Pointers, arrays and structs are often combined, leading to complex cases.
- This will test whether you have understood the "*", ".", "[]" and "->" operators.
- If you truly understand them, this won't be a problem:

```
*(*var[4].fieldA)->fieldB[16][5]->fieldC = 4;
```

- You should be able to translate this into English.
- There is nothing new here. You just need to apply the rules!
- Think of this as a mathematical expression, just with different operators.

Structs and header files

- Structs are often used to pass complex data between functions.
- So, they are often declared in header files:

result.h

```
typedef struct {
    int mark;
    char grade;
} Result;

Result getResult(void);
void printResult(Result res);
```

- To call getResult() or printResult() from another file, we need both the struct and function declarations.

Problem: Duplicate #includes

result.h

```
typedef struct {
    int mark;
    char grade;
} Result;
```

unit.h

```
#include "result.h"
...
```

student.h

```
#include "result.h"
...
```

main.c

```
#include "unit.h"
#include "student.h"
...
```

- The declaration of Result is included **twice** in main.c.
- This is a compile error.

#Include Guards

- Use conditional compilation to avoid multiple declarations:

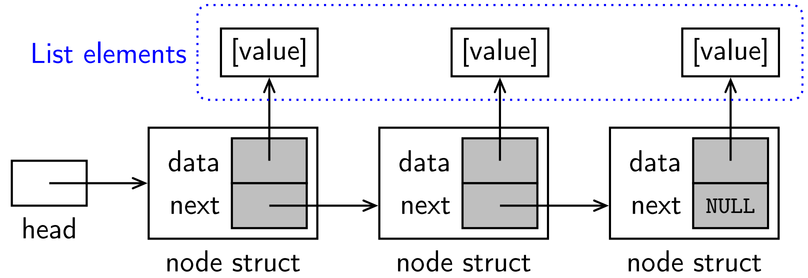
```c
#ifndef RESULT_H
#define RESULT_H

typedef struct {
    int mark;
    char grade;
} Result;
...
#endif
```

- On the first #include, the struct will be declared, along with `RESULT_H`.
- On each extra #include, `#ifndef` will skip everything.
- (You may also see the non-standard "`#pragma once`".)

Linked Lists

- A linked list is a chain of dynamically-allocated memory blocks.
- Each block — "node" — contains a pointer to the next.
- This produces a linear structure.
- Each node also contains a pointer to a value.
- These values are what we actually want to store!



Self-Referential Structs

- In C, linked lists are best implemented with structs.
- We define a struct representing the node.
- This requires some (slightly) strange syntax:

tag name

```c
typedef struct LinkedListNode {
    void* data;
    struct LinkedListNode* next;
} LinkedListNode;
```

typedef name

- Two names: the tag name and typedef name. Here, they're both the same (but they don't have to be).
- The typedef name can't be used inside the struct itself, but the tag name can.

A Closer Look

We have our Node struct, as before:

```c
typedef struct LinkedListNode {
    void* data;
    struct LinkedListNode* next;
} LinkedListNode;
```

- Many instances of this struct go into making a linked list.
- For each instance:

  `data` points to some arbitrary value (the actual contents of the linked list).

  `next` points to the next node, or `NULL` if it's the last.
- You can replace `void*` with whatever data type you like.

The Head Pointer

- Somewhere, there must be a pointer to the first node in the list — the "head".
- If this is NULL, then the list is empty.

```
int main(void)
{
    LinkedListNode* listHead = NULL;

    ... /* Create, manipulate & access the
        list using listHead. */
}
```

- An empty linked list takes up zero memory (except for the head pointer itself).

"Current" Pointers

- Say you want to traverse a linked list (i.e. access each of its values).
- You start at the head, and follow each "next" pointer in turn.
- When you're doing this, you need a "current" pointer, to keep track of the node you're currently accessing.
- When you're done with one node, you update the pointer.

```
current = head;
while(current != NULL) {
    ... /* Do something with current */
    current = (*current).next;
}
```

(Note: we could also say "`current = current->next;`".)

"Previous" Pointers

- It's also sometimes necessary to have a "previous" pointer, to keep track of the last node you visited.
- Used in conjunction with a "current" pointer.
- In general, `(*previous).next == current`.
- This is useful if you want to insert an element into the middle of a list.

```
current = head;
previous = NULL;
while(current != NULL) {
    ... /* Do something with current/previous */
    previous = current;
    current = (*current).next;
}
```


Linked List Pointer Examples

Say "`head`" and "`current`" are LinkedListNode pointers:

Expression	**Points to...**
`current`	The "current" node.
`(*current).data`	The "current" value.
`(*current).next`	The next node after the current node.
`head`	The first node.
`(*head).data`	The first value (also `head->data`).
`(*head).next`	The second node (also `head->next`).
`(*(*head).next).data`	The second value (also `head->next->data`).

A Central Linked List Struct?

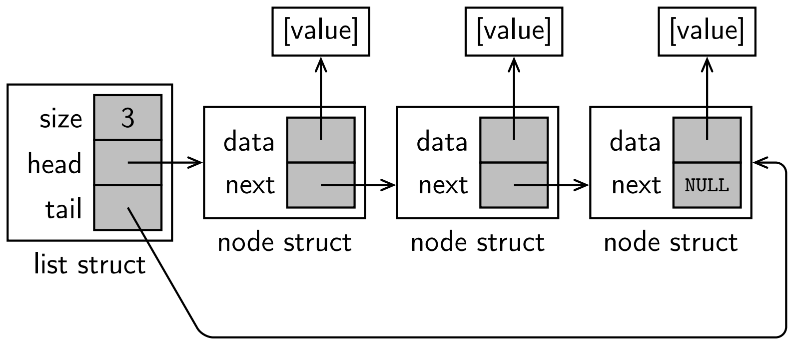
- It's often nicer to put the head pointer in its own struct:

```
typedef struct LinkedListNode {
    void* data;
    struct LinkedListNode* next;
} LinkedListNode;

typedef struct {
    LinkedListNode* head;
} LinkedList;
```

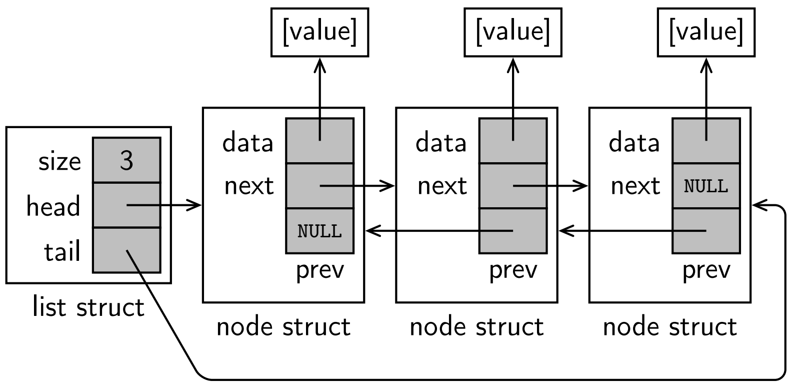
- There are other non-essential things you can store in `LinkedList`:
  - The size of the list.
  - A pointer to the *last* node — the "tail".

Linked List with a Size and Tail Pointer



- We can jump instantly to the last node.
- Updating this structure is slightly more complicated.

A Doubly Linked List



- We may decide to have a "previous" link inside each node.
- We can traverse this list forwards and backwards.

Linked List Operations

- Here's where you have to **think for yourself!**
- You can do many things with a linked list.
- This lecture will try to cover some of them.
- However, there are many *other* ways of doing the same thing.
- Treat the following slides as **examples**.

Do not...

- Memorise the following slides.
- Copy and paste from the following slides.

Do...

- Understand the linked list structure.
- Use the following slides to see how that structure works.

Linked List Operations

I mean it.

Linked List Operations

- These are some typical linked list operations:
  - creating a list;
  - populating the list;
  - traversing the list;
  - freeing the list;
  - inserting elements;
  - accessing elements;
  - deleting elements;
  - ...and many more!
- There are no standard C functions for this — you have to implement them yourself.
- These operations are usually put inside their own functions (but they could be embedded directly in other code).

Creating an Empty Linked List

To create a new, empty linked list:

- Just `malloc` the linked list struct.
- Set the `head` field to `NULL`, to indicate an empty list.

```
LinkedList* list;

list = (LinkedList*)malloc(sizeof(LinkedList));
(*list).head = NULL;
```

- Consider making a function for this!

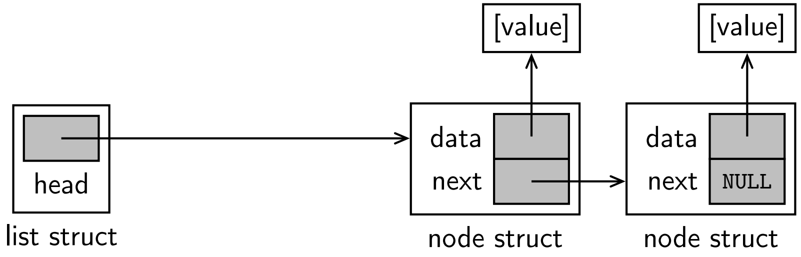
Inserting an Element at the Start

You can't do much with an empty list — we need to insert things into it:

- Create a new node (with `malloc()`).
- Point "data" to the thing we want to insert.
- Point "next" to the existing first node (which might be `NULL`)
  - Copy the value of "head", which already points there.
- Point "head" to the new node.

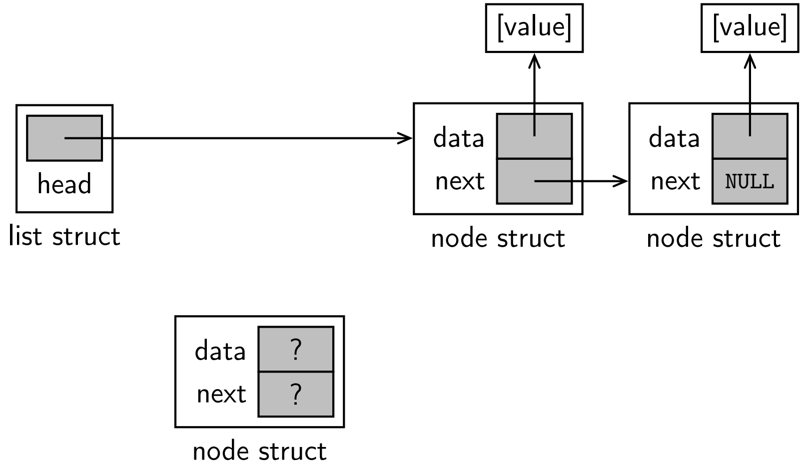
Inserting an Element at the Start

Start with an existing linked list (which could be empty).



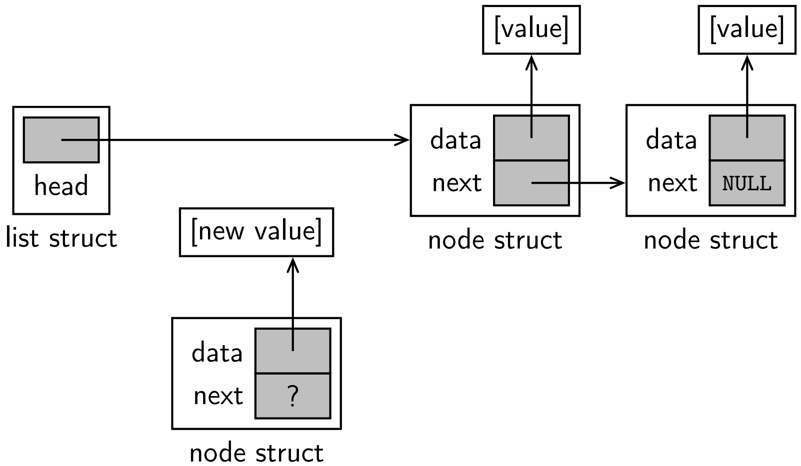
Inserting an Element at the Start

Step 1: Create a new node.



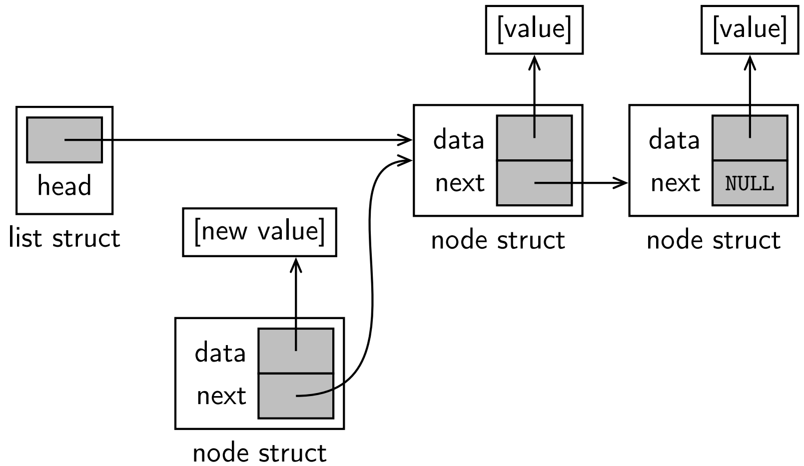
Inserting an Element at the Start

Step 2: Point "data" to the thing we want to insert.



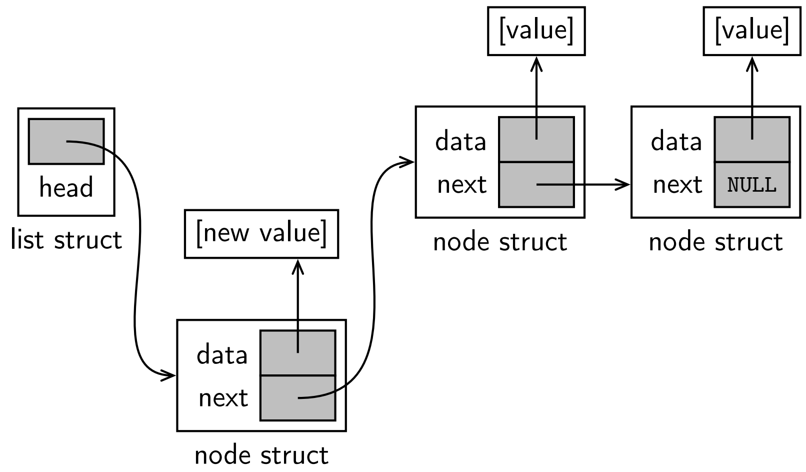
Inserting an Element at the Start

Step 3: Point "next" to the existing first node.



Inserting an Element at the Start

Step 4: Point "head" to the new node.



Inserting an Element at the Start

```
/* Create a new node */
newNode = (LListNode*)malloc(sizeof(LListNode));

/* "Data" must point to the value to be inserted */
(*newNode).data = ...;

/* "Next" must point to the existing first node */
(*newNode).next = head;

/* Now head must point to this new node */
head = newNode;
```


Filling a Linked List

- To fill/initialise a linked list, simply insert multiple elements.
- Some sort of loop might be called for.
- We could insert data from:
  - calculated values
  - user input
  - an input file
  - anything else you can think up
- Keep in mind: inserting data only at the start will cause the elements to end up in **reverse order**.
- The first thing to be inserted will end up as the last element.
- (But you can often reverse the order of insertion to compensate!)

Getting the Length of a Linked List

- Unlike arrays, the length of a linked list is stored, implicitly.
- You can find the length by counting the nodes, until you reach `NULL`:

```
int length = 0;
current = head;

while(current != NULL) {
    length++;
    current = (*current).next;
}
```

- Alternatively, you could store the length as a field inside the `LinkedList` struct.
- Update the length whenever you insert or delete an element.
- This would allow you to know the length instantly.

A Brief Diversion into Recursion

- Time to demonstrate a very useful programming principle:

```
int listLength(LinkedListNode* node) {
    int length = 0;
    if(node != NULL)
        length = 1 + listLength((*node).next);
    return length;
}
```

- This calculates the length of a linked list... without a loop.
- How?
- The function *calls itself*. Then the second copy of the function calls itself *again*, and *that* copy calls itself again, and so on.
- Each running copy of the function gets the next link in the list.
- Each copy gets the result of the next copy, and adds one.
- The first copy ends up with the total length.

Deleting the First Element

- Make a copy of the head pointer.
- Set the head pointer to the second element.
- Use the copied pointer to free the first element (and its value if you need to).

```
temp = head;
head = (*head).next;

/* Free the first value. Think carefully about
whether you actually want to do this! */
free((*temp).data);

/* Free the first node. */
free(temp);
```


Free or Return a Removed Element?

When you remove an element from the list:

- You can choose to:
  - immediately free/destroy the element itself (as well as the node); OR
  - keep the element around for some other purpose.
- You must choose! There's no "safe" answer.
- What you decide depends on the context.
- Does the list "own" its elements, or just "keep track" of them?
- (If you're using a linked list to implement a *stack*, you may not want to immediately destroy elements you pop off.)

Other Insertion/Deletion Operations

Other common operations (covered in Data Structures & Algorithms – COMP1002) include:

- Inserting and deleting the last element.
- Inserting and deleting the *n*th element.

Freeing a Linked List

- To deallocate a linked list, we must:
  - free each node; then
  - free the main list struct.
- You have to traverse the list while destroying it.
- This has to be done carefully, in a particular order.
- Very easy to create memory leaks here!
- As soon as you free a struct, you lose track of its contents, including any pointers.

Freeing a Linked List (Iteratively)

You must free all the node structs, then the linked list struct:

```
void freeLinkedList(LinkedList* list) {
    LinkedListNode *node, *nextNode;

    node = (*list).head;
    while(node != NULL) {
        nextNode = (*node).next;
        free((*node).data); /* <-- Maybe! */
        free(node);
        node = nextNode;
    }

    free(list);
}
```


Freeing a Linked List (Recursively)

```
/* Frees the whole list. */
void freeLinkedList(LinkedList* list) {
    freeNode((*list).head);
    free(list);
}

/* Frees a given node and everything after it. */
void freeNode(LinkedListNode *node) {
    if(node != NULL) {
        freeNode((*node).next); /* Recursive call. */

        free((*node).data); /* <-- Maybe! */
        free(node);
    }
}
```


Linked Lists vs. Arrays

- Linked lists and arrays serve similar purposes.
- However, they are very different structures.
- Organisation:
  - An array is a single block of memory.
  - A linked list has many small blocks.
- Speed:
  - Insertion is faster with a linked list.
  - Accessing an element is faster with an array (except for the first element).
- Memory Usage:
  - Linked lists take up more memory per element (an additional two pointers, at least).
  - Storing small elements in a linked list is very inefficient.

Coming Up

- In the next lecture, we'll talk about shell scripting.
- Test 2 is also coming up! This will cover arrays, strings, file I/O, structs and linked lists.