Week 04: Dynamic Data Structures

Memory

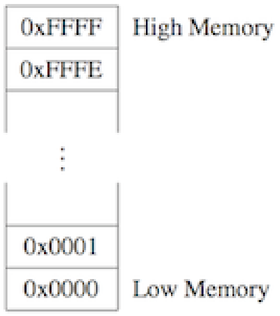
1/68

Reminder:

Computer memory … large array of consecutive data cells or bytes

- `char` … 1 byte
- `int,float` … 4 bytes
- `double` … 8 bytes
- *`any_type *`* … 4 bytes (on CSE lab computers)

Memory addresses shown in Hexadecimal notation



C execution: Memory

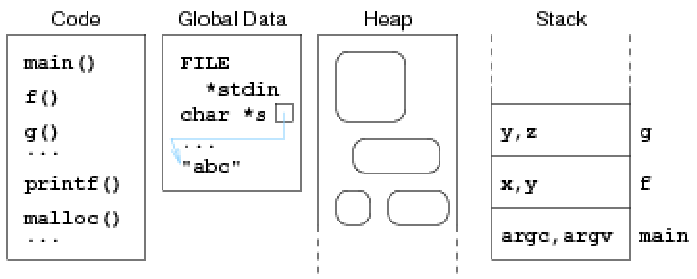
2/68

An executing C program partitions memory into:

- *code* … fixed-size, read-only region
  - contains the machine code instructions for the program
- *global data* .. fixed-size, read-write region
  - contain global variables and constant strings
- *heap* … very large, read-write region
  - contains dynamic data structures created by `malloc()` (see later)
- *stack* … dynamically-allocated data (function local vars)
  - consists of frames, one for each currently active function
  - each frame contains local variables and house-keeping info

... C execution: Memory

3/68



Exercise #1: Memory Regions

4/68

```
int numbers[] = { 40, 20, 30 };

void insertionSort(int array[], int n) {
   int i, j;
   for (i = 1; i < n; i++) {
      int element = array[i];
         while (j >= 0 && array[j] > element) {
         array[j+1] = array[j];
         j--;
      }
      array[j+1] = element;
   }
```

```
}

int main(void) {
   insertionSort(numbers, 3);
   return 0;
}
```

Which memory region are the following objects located in?

1. `insertionSort()`
2. `numbers[0]`
3. `n`
4. `array[0]`
5. `element`

---

1. code
2. global
3. stack
4. global
5. stack

Dynamic Data Structures

Dynamic Memory Allocation

So far, we have considered *static* memory allocation

- all objects completely defined at compile-time
- sizes of all objects are known to compiler

Examples:

```
int   x;      // 4 bytes containing a 32-bit integer value
char *cp;     // 4 bytes (on CSE machines)
              //   containing address of a char
typedef struct {float x; float y;} Point;
Point p;      // 8 bytes containing two 32-bit float values
char  s[20]; // array containing space for 20 1-byte chars
```

... Dynamic Memory Allocation

In many applications, fixed-size data is ok.

In many other applications, we need flexibility.

Examples:

```
char name[MAXNAME];    // how long is a name?
char item[MAXITEMS];   // how high can the stack grow?
char dictionary[MAXWORDS][MAXWORDLENGTH];
                     // how many words are there?
                     // how long is each word?
```

With fixed-size data, we need to guess sizes ("large enough").

... Dynamic Memory Allocation

Fixed-size memory allocation:

- allocate as much space as we might ever possibly need

Dynamic memory allocation:

- allocate as much space as we actually need
- determine size based on inputs

But how to do this in C?

- all data allocation methods so far are "static"
  - however, stack data (when calling a function) is created dynamically (size is known)

Dynamic Data Example

Problem:

- read integer data from standard input (keyboard)
- first number tells how many numbers follow
- rest of numbers are read into a vector
- subsequent computation uses vector (e.g. sorts it)

Example input: `6 25 -1 999 42 -16 64`

How to define the vector?

... Dynamic Data Example

Suggestion #1: allocate a large vector; use only part of it

```
#define MAXELEMS 1000

// how many elements in the vector
int numberOfElems;
scanf("%d", &numberOfElems);
assert(numberOfElems <= MAXELEMS);

// declare vector and fill with user input
int i, vector[MAXELEMS];
for (i = 0; i < numberOfElems; i++)
   scanf("%d", &vector[i]);
```

Works ok, unless too many numbers; usually wastes space.

Recall that `assert()` terminates program with standard error message if test fails.

... Dynamic Data Example

Suggestion #2: create vector after count read in

```
#include <stdlib.h>

// how many elements in the vector
int numberOfElems;
scanf("%d", &numberOfElems);
```

```
// declare vector and fill with user input
int i, *vector;
size_t numberOfBytes;
numberOfBytes = numberOfElems * sizeof(int);

vector = malloc(numberOfBytes);
assert(vector != NULL);

for (i = 0; i < numberOfElems; i++)
   scanf("%d", &vector[i]);
```

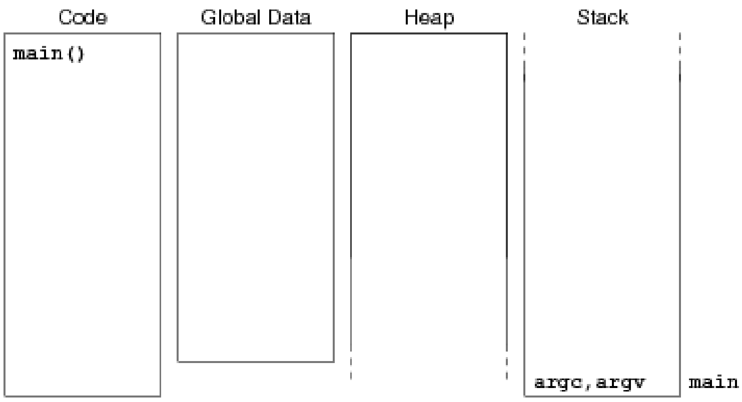
Works unless the *heap* is already full (very unlikely)

Reminder: because of pointer/array connection `&vector[i] == vector+i`

13/68

The `malloc()` function

Recall memory usage within C programs:



14/68

... The `malloc()` function

`malloc()` function interface

```
void *malloc(size_t n);
```

What the function does:

- attempts to reserve a block of `n` bytes in the *heap*
- returns the address of the start of this block
- if insufficient space left in the heap, returns `NULL`

Note: `size_t` is essentially an `unsigned int`

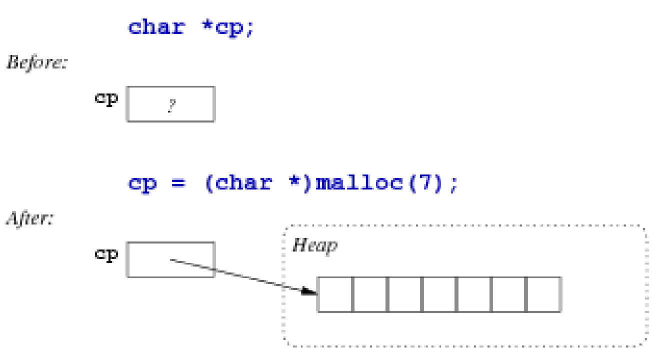
- but has specialised interpretation of applying to memory sizes measured in bytes

---

15/68

... The `malloc()` function

Example use of `malloc`:



... The `malloc()` function

16/68

Things to note about `void *malloc(size_t)`:

- it is defined as part of `stdlib.h`
- its parameter is a size in units of *bytes*
- its return value is a *generic* pointer `(void *)`
- the return value must *always* be checked (may be `NULL`)

Required size is determined by *#Elements* `*` `sizeof(`*ElementType*`)`

Exercise #2: Dynamic Memory Allocation

17/68

Write code to

1. create space for 1,000 speeding tickets (cf. Lecture Week 1)
2. create a dynamic $m \times n$-matrix of floating point numbers, given m and n

How many bytes need to be reserved in each case?

---

1. Speeding tickets:

```
typedef struct {
        int day, month, year; } DateT;
typedef struct {
        int hour, minute; } TimeT;
typedef struct {
        char plate[7]; DateT d; TimeT t; } TicketT;
```

```
TicketT *tickets = malloc(1000 * sizeof(TicketT));
assert(tickets != NULL);
```

28,000 bytes allocated

2. Matrix:

```
float **matrix = malloc(m * sizeof(float *));
assert(matrix != NULL);
int i;
for (i = 0; i < m; i++) {
   matrix[i] = malloc(n * sizeof(float));
   assert(matrix[i] != NULL);
}
```

$4m + 4 \cdot mn$ bytes allocated

Exercise #3: Memory Regions

Which memory region is `tickets` located in? What about `*tickets`?

---

1. `tickets` is a variable located in the stack
2. `*tickets` is in the heap (after **`malloc`**'ing memory)

... The `malloc()` function

`malloc()` returns a pointer to a data object of some kind.

Things to note about objects allocated by `malloc()`:

- they exist until explicitly removed (program-controlled lifetime)
- they are *accessible* while some variable references them
- if no active variable references an object, it is *garbage*

The function `free()` releases objects allocated by `malloc()`

... The `malloc()` function

Usage of `malloc()` should always be guarded:

```
int *vector, length, i;
…
vector = malloc(length*sizeof(int));
// but malloc() might fail to allocate
assert(vector != NULL);
// now we know it's safe to use vector[]
for (i = 0; i < length; i++) {
        … vector[i] …
}
```

Alternatively:

```
int *vector, length, i;
…
vector = malloc(length*sizeof(int));
// but malloc() might fail to allocate
if (vector == NULL) {
        fprintf(stderr, "Out of memory\n");
        exit(1);
}
// now we know its safe to use vector[]
for (i = 0; i < length; i++) {
        … vector[i] …
}
```

- `fprintf(stderr, …)` outputs text to a stream called **`stderr`** (the screen, by default)
- `exit(`*v*`)` terminates the program with return value *v*

Memory Management

`void free(void *ptr)`

- releases a block of memory allocated by `malloc()`
- `*ptr` is a dynamically allocated object

- if `*ptr` was not `malloc()`'d, chaos will follow

Things to note:

- the contents of the memory block are not changed
- all pointers to the block still exist, but are not valid
- the memory may be re-used as soon as it is `free()`'d

... Memory Management

Warning! Warning! Warning! Warning!

Careless use of `malloc()` / `free()` / pointers

- can mess up the data in the heap
- so that later `malloc()` or `free()` cause run-time errors
- possibly well after the original error occurred

Such errors are very difficult to track down and debug.

Must be very careful with your use of `malloc()` / `free()` / pointers.

... Memory Management

If an uninitialised or otherwise invalid pointer is used, or an array is accessed with a negative or out-of-bounds index, one of a number of things might happen:

- program aborts immediately with a "`segmentation fault`"
- a mysterious failure much later in the execution of the program
- incorrect results, but no obvious failure
- correct results, but maybe not always, and maybe not when executed on another day, or another machine

The first is the most desirable, but cannot be relied on.

... Memory Management

Given a pointer variable:

- you can check whether its value is `NULL`
- you can (maybe) check that it is an address
- you **cannot** check whether it is a valid address

... Memory Management

Typical usage pattern for dynamically allocated objects:

```
// single dynamic object e.g. struct
Type *ptr = malloc(sizeof(Type));
assert(ptr != NULL);
… use object referenced by ptr e.g. ptr->name …
free(ptr);

// dynamic array with "nelems" elements
int nelems = NumberOfElements;
ElemType *arr = malloc(nelems*sizeof(ElemType));
assert(arr != NULL);
```

```
… use array referenced by arr e.g. arr[4] …
free(arr);
```

Memory Leaks

Well-behaved programs do the following:

- allocate a new object via `malloc()`
- use the object for as long as needed
- `free()` the object when no longer needed

A program which does not `free()` each object before the last reference to it is lost contains a *memory leak*.

Such programs may eventually exhaust available heapspace.

Exercise #4: Dynamic Arrays

Write a C-program that

- prompts the user to input a positive number n
- allocates memory for two n-dimensional floating point vectors **a** and **b**
- prompts the user to input $2n$ numbers to initialise these vectors
- computes and outputs the inner product of **a** and **b**
- frees the allocated memory

Sidetrack: Standard I/O Streams, Redirects

Standard file streams:

- **`stdin`** … standard input, by default: keyboard
- **`stdout`** … standard output, by default: screen
- **`stderr`** … standard error, by default: screen

- `fprintf(stdout, …)` has the same effect as `printf(…)`
- `fprintf(stderr, …)` often used to print error messages

Executing a C program causes `main(…)` to be invoked

- with `stdin`, `stdout`, `stderr` already open for use

... Sidetrack: Standard I/O Streams, Redirects

The streams `stdin`, `stdout`, `stderr` can be *redirected*

- redirecting `stdin`

  ```
  prompt$ myprog < input.data
  ```

- redirecting `stdout`

  ```
  prompt$ myprog > output.data
  ```

- redirecting `stderr`

  ```
  prompt$ myprog 2> error.data
  ```

Abstract Data Structures: ADTs

Abstract Data Types

Reminder: An *abstract data type* is …

- an approach to implementing data types
- separates *interface* from *implementation*
- users of the ADT see only the interface
- builders of the ADT provide an implementation

E.g. does a client want/need to know how a Stack is implemented?

- ADO = *a*bstract *d*ata *o*bject (e.g. a single stack)
- ADT = *a*bstract *d*ata *t*ype (e.g. stack data type)

... Abstract Data Types

ADT *interface* provides

- an *opaque* user-view of the data structure (e.g. `stack *`)
- function signatures (prototypes) for all operations
- semantics of operations (via documentation)
- a contract between ADT and its clients

ADT *implementation* gives

- concrete definition of the data structure
- function implementations for all operations
- … including for *creation* and *destruction* of instances of the data structure

ADTs are important because …

- facilitate decomposition of complex programs
- make implementation changes invisible to clients
- improve readability and structuring of software

Stack as ADT

Interface (in `stack.h`)

```
// provides an opaque view of ADT
typedef struct StackRep *stack;

// set up empty stack
stack newStack();
// remove unwanted stack
void dropStack(stack);
// check whether stack is empty
int StackIsEmpty(stack);
// insert an int on top of stack
void StackPush(stack, int);
// remove int from top of stack
int StackPop(stack);
```

ADT *`stack`* defined as a *pointer* to an *unspecified* struct named `StackRep`

Sidetrack: Defining Structures

Structures can be defined in two different styles:

```
typedef struct { int day, month, year; } DateT;
// which would be used as
DateT somedate;

// or

struct date { int day, month, year; };
// which would be used as
struct date anotherdate;
```

The definitions produce objects with identical structures.

It is possible to combine both styles:

```
typedef struct date { int day, month, year; } DateT;
// which could be used as
DateT       date1, *dateptr1;
struct date date2, *dateptr2;
```

Static/Dynamic Sequences

Previously we have used an *array* to implement a stack

- fixed size collection of heterogeneous elements
- can be accessed via index or via "moving" pointer

The "fixed size" aspect is a potential problem:

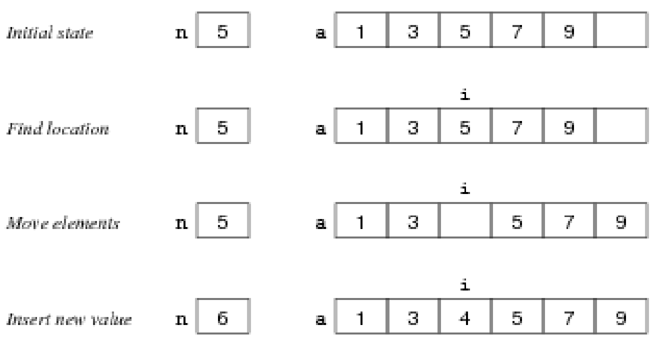
- how big to make the (dynamic) array? (big ... just in case)
- what to do if it fills up?

The rigid sequence is another problems:

- inserting/deleting an item in middle of array

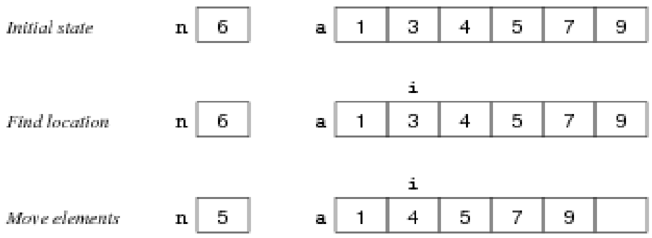
... Static/Dynamic Sequences

Inserting a value into a sorted array (`insert(a,&n,4)`):



... Static/Dynamic Sequences

Deleting a value from a sorted array (`delete(a,&n,3)`):

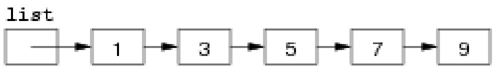


40/68

Dynamic Sequences

The problems with using arrays can be solved by

- allocating elements individually
- linking them together as a "chain"



Benefits:

- insertion/deletion have minimal effect on list overall
- only use as much space as needed for values

41/68

Self-referential Structures

To realise a "chain of elements", need a *node* containing

- a value
- a link to the next node

In C, we can define such nodes as:

```
typedef struct node {
   int data;
   struct node *next;
} NodeT;
```

42/68

... Self-referential Structures

Note that the following definition does not work:

```
typedef struct {
   int data;
   NodeT *next;
} NodeT;
```

Because `NodeT` is not yet known (to the compiler) when we try to use it to define the type of the `next` field.

The following is also illegal in C:

```
struct node {
   int data;
   struct node recursive;
};
```

Because the size of the structure would have to satisfy `sizeof(struct node) = sizeof(int) + sizeof(struct node) = ∞`.

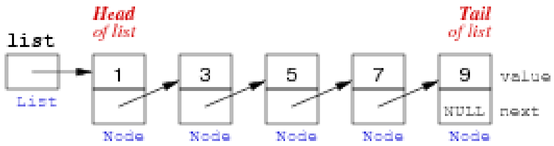
Linked Lists in C

Linked Lists

44/68

To represent a chained (linked) list of nodes:

- we need a pointer to the first node
- each node contains a pointer to the next node
- the `next` pointer in the last node is `NULL`



... Linked Lists

45/68

Linked lists are more flexible than arrays:

- values do not have to be adjacent in memory
- values can be rearranged simply by altering pointers
- the number of values can change dynamically
- values can be added or removed in any order

Disadvantages:

- it is not difficult to get pointer manipulations wrong
- each value also requires storage for `next` pointer

Memory Storage for Linked Lists

46/68

Linked list nodes are typically located in the heap

- because nodes are dynamically created

Variables containing pointers to list nodes

- are likely to be local variables (in the stack)

Pointers to the start of lists are often

- passed as parameters to function
- returned as function results

... Memory Storage for Linked Lists

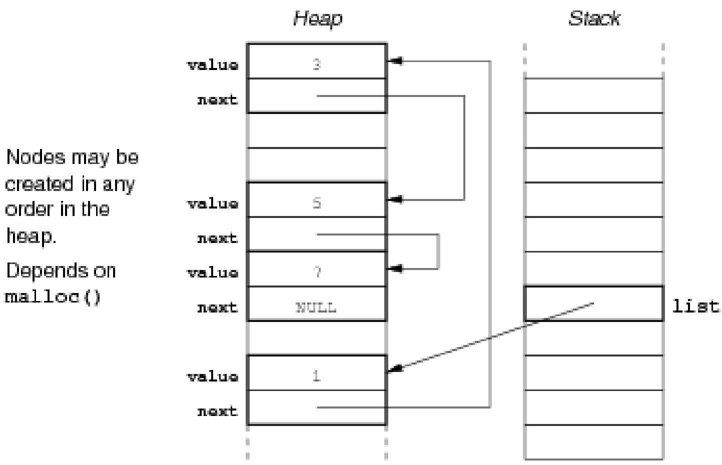
47/68

Create a new list node:

```
NodeT *makeNode(int v) {
   NodeT *new = malloc(sizeof(NodeT));
   assert(new != NULL);
   new->data = v;       // initialise data
   new->next = NULL;    // initialise link to next node
   return new;          // return pointer to new node
}
```

... Memory Storage for Linked Lists

48/68



Exercise #5: Creating a linked list

49/68

Write C-code to create a linked list of three nodes with values 1, 42 and 9024.

```
NodeT *list = makeNode(1);
list->next  = makeNode(42);
list->next->next = makeNode(9024);
```

Iteration over Linked Lists

51/68

When manipulating list elements

- typically have pointer `p` to current node (`NodeT *p`)
- to access the data in current node: `p->data`
- to get pointer to next node: `p->next`

To iterate over a linked list:

- set `p` to point at first node (head)
- examine node pointed to by `p`
- change `p` to point to next node
- stop when `p` reaches end of list (`NULL`)

... Iteration over Linked Lists

52/68

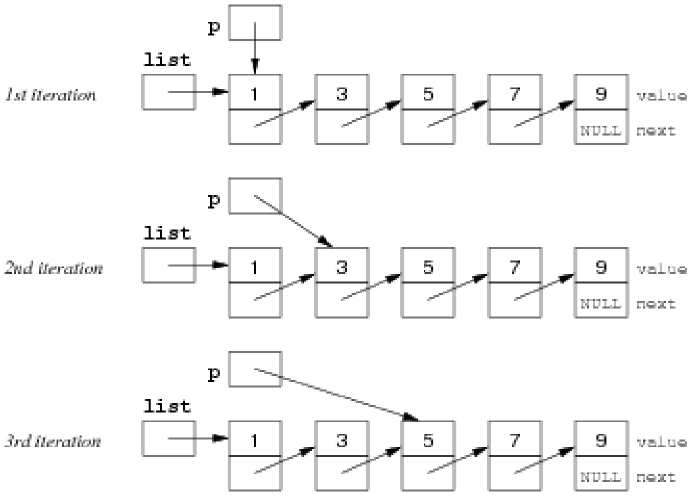
Standard method for scanning all elements in a linked list:

```
NodeT *list;  // pointer to first Node in list
NodeT *p;     // pointer to "current" Node in list

p = list;
while (p != NULL) {
        … do something with p->data …
        p = p->next;
}

// which is frequently written as
```

```
for (p = list; p != NULL; p = p->next) {
        … do something with p->data …
}
```

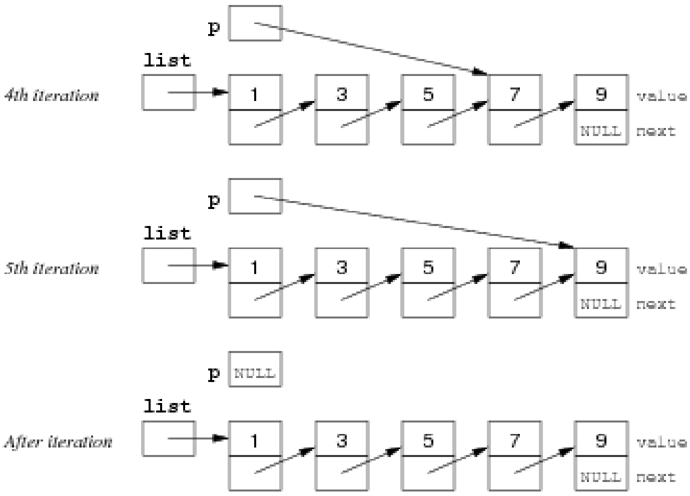
... Iteration over Linked Lists

53/68



... Iteration over Linked Lists

54/68



... Iteration over Linked Lists

55/68

Check if list contains an element:

```
int inLL(NodeT *list, int d) {
   NodeT *p;
   for (p = list; p != NULL; p = p->next)
      if (p->data == d)      // element found
         return 1;
   return 0;                 // element not in list
}
```

Print all elements:

```
void showLL(NodeT *list) {
   NodeT *p;
   for (p = list; p != NULL; p = p->next)
      printf("%6d", p->data);
}
```

Exercise #6: Traversing a linked list

What does this code do?

```
1  NodeT *p = list;
2  while (p != NULL) {
3     printf("%6d", p->data);
4     if (p->next != NULL)
5        p = p->next->next;
6     else
7        p = NULL;
8  }
```

What is the purpose of the conditional statement in line 4?

Every second list element is printed.

If `*p` happens to be the last element in the list, then `p->next->next` does not exist.
The if-statement ensures that we do not attempt to assign an invalid address to `p` in line 5.

Exercise #7: Traversing a linked list

Rewrite **`showLL()`** as a recursive function.

```
void printLL(NodeT *list) {
   if (list != NULL) {
      printf("%6d", list->data);
      printLL(list->next);
   }
}
```

Modifying a Linked List

Insert a new element at the beginning:

```
NodeT *insertLL(NodeT *list, int d) {
   NodeT *new = makeNode(d);  // create new list element
   new->next = list;          // link to beginning of list
   return new;                // new element is new head
}
```

Delete the first element:

```
NodeT *deleteHead(NodeT *list) {
   assert(list != NULL);  // ensure list is not empty
   NodeT *head = list;    // remember address of first element
   list = list->next;     // move to second element
   free(head);
   return list;           // return pointer to second element
}
```

What would happen if we didn't `free` the memory pointed to by `head`?

... Modifying a Linked List

Delete a specific element (recursive version):

```
NodeT *deleteLL(NodeT *list, int d) {
   if (list == NULL) {            // element not in list
      return list;

   } else if (list->data == d) {
      return deleteHead(list);    // delete first element

   } else {                    // delete element in tail list
      list->next = deleteLL(list->next, d);
      return list;
   }
}
```

Exercise #8: Freeing a list

Write a C-function to destroy an entire list.

Iterative version:

```
void freeLL(NodeT *list) {
   NodeT *p;

   p = list;
   while (p != NULL) {
      NodeT *temp = p->next;
      free(p);
      p = temp;
   }
}
```

Why do we need the extra variable `temp`?

Stack ADT Implementation

Linked list implementation (`stack.c`):

Remember: `stack.h` includes `typedef struct StackRep *stack;`

```
#include <stdlib.h>
#include <assert.h>
#include "stack.h"

typedef struct node {
   int data;
   struct node *next;
} NodeT;

typedef struct StackRep {
   int    height;   // #elements on stack
   NodeT *top;      // ptr to first element
} StackRep;

// set up empty stack
stack newStack() {
   stack S = malloc(sizeof(StackRep));
   S->height = 0;
   S->top = NULL;
   return S;
}

// remove unwanted stack
void dropStack(stack S) {
```

```
// check whether stack is empty
int StackIsEmpty(stack S) {
   return (S->height == 0);
}

// insert an int on top of stack
void StackPush(stack S, int v) {
   NodeT *new = malloc(sizeof(NodeT));
   assert(new != NULL);
   new->data = v;
   // insert new element at top
   new->next = S->top;
   S->top = new;
   S->height++;
}

// remove int from top of stack
int StackPop(stack S) {
   assert(S->height > 0);
```

```
    NodeT *curr = S->top;
    while (curr != NULL) {  // free the list
       NodeT *temp = curr->next;
       free(curr);
       curr = temp;
    }
    free(S);           // free the stack rep
}
```

```
    NodeT *head = S->top;
    // second list element becomes new top
    S->top = S->top->next;
    S->height--;
    // read data off first element, then free
    int d = head->data;
    free(head);
    return d;
}
```

Summary: Memory Management Functions

`void *malloc(size_t nbytes)`

- aim: allocate some memory for a data object
- attempt to allocate a block of memory of size `nbytes` in the heap
- if successful, returns a pointer to the start of the block
- if insufficient space in heap, returns `NULL`

Things to note:

- the location of the memory block within heap is random
- the initial contents of the memory block are random

... Summary: Memory Management Functions

`void free(void *ptr)`

- releases a block of memory allocated by `malloc()`
- `*ptr` is the start of a dynamically allocated object
- if `*ptr` was not `malloc()`'d, chaos will ensue

Things to note:

- the contents of the memory block are not changed
- all pointers to the block still exist, but are not valid
- the memory may be re-used as soon as it is `free()`'d

Tips for Week 4 Problem Set

Main theme: *Dynamic data structures*

- Test your understanding of memory allocation and deallocation
- Create, use and free a dynamic array (Exercise 3)
- Think about how to design and use a dynamic queue ADT (Exercise 4)
- Design and implement functions for dynamic linked lists (Exercise 5)

```
prompt$ ./llbuild
Enter an integer: 12
Enter an integer: 34
Enter an integer: 56
Enter an integer: quit
Finished. List is 12->34->56
```

- Challenge Exercise: wrack your brain — split linked list in two halves without traversing it twice

Summary

- Memory management
- Dynamic data structures
- Linked lists

- Suggested reading:
  - Moffat, Ch.10.1-10.2
  - Sedgewick, Ch.3.3-3.5,4.4,4.6

Produced: 13 Aug 2018