Week 02: Abstract Data Types

Abstract Data Objects and Types

Abstract Data Types

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A *data type* is …

- a set of *values* (atomic or structured values) e.g. *integer stacks*
- a collection of *operations* on those values e.g. *push, pop, isEmpty?*

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

... Abstract Data Types

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ADT *interface* provides

- a user-view of the data structure
- function signatures (prototypes) for all operations
- semantics of operations (via documentation)
- $\Rightarrow$ a "contract" between ADT and its clients

ADT *implementation* gives

- concrete definition of the data structures
- function implementations for all operations

... Abstract Data Types

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ADT interfaces are *opaque*

- clients *cannot* see the implementation via the interface

ADTs are important because …

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

... Abstract Data Types

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Typical operations with ADTs

- *create* a value of the type
- *modify* one variable of the type
- *combine* two values of the type

Collections

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Common ADTs …

- consist of a *collection* of *items*
- where each item may be a simple type or an ADT
- and items often have a *key* (to identify them)

Collections may be categorised by …

- *structure*:
  linear (array, linked list), branching (tree), cyclic (graph)
- *usage*:
  matrix, stack, queue, set, search-tree, dictionary, map, …

... Collections

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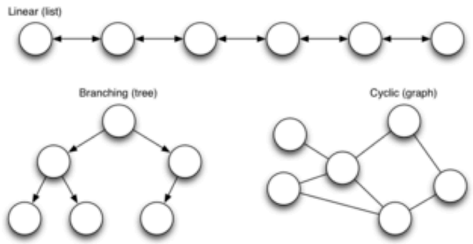
Collection structures:



... Collections

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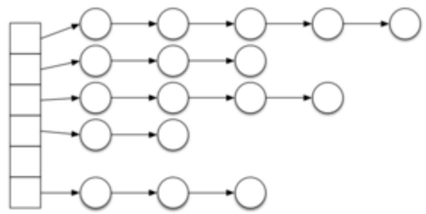
Or even a hybrid structure like:



... Collections

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For a given collection type

- many different data representations are possible

For a given operation and data representation

- several different algorithms are possible
- efficiency of algorithms may vary widely

Generally,

- there is no overall "best" representation/implementation
- cost depends on the mix of operations
  (e.g. proportion of inserts, searches, deletions, …)

ADOs and ADTs

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We want to distinguish …

- ADO = *a*bstract *d*ata *o*bject
- ADT = *a*bstract *d*ata *t*ype

Warning: Sedgewick's first few examples are ADOs, not ADTs.

Example: Abstract Stack Data Object

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Stack, aka *pushdown stack* or *LIFO data structure*

Assume (for the time being) stacks of `char` values

Operations:

- *create* an empty stack
- insert (*push*) an item onto stack
- remove (*pop*) most recently pushed item
- check whether stack *is empty*

... Example: Abstract Stack Data Object

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Example of use:

Stack	Operation	Return value
?	create	-
-	push a	-
a	push b	-
a b	push c	-
a b c	pop	c
a b	isempty	false

Exercise #1: Stack vs Queue

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Consider the previous example but with a queue instead of a stack.

Which element would have been taken out ("dequeued") first?

---

a

Stack as ADO

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Interface (a file named `Stack.h`)

```
// Stack ADO header file

void StackInit();       // set up empty stack
int  StackIsEmpty();    // check whether stack is empty
void StackPush(char);   // insert char on top of stack
char StackPop();        // remove char from top of stack
```

Note:

- no explicit reference to Stack object
- this makes it an *Abstract Data Object (ADO)*

... Stack as ADO

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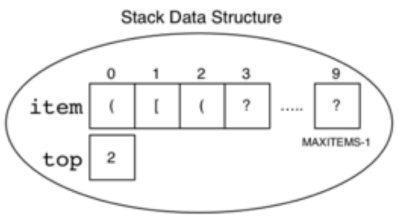
Implementation may use the following data structure:



... Stack as ADO

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Sidetrack: Character I/O Functions in C (requires `<stdio.h>`)

`int getchar(void);`

- returns character read from standard input as an `int`, or returns **`EOF`** on end of file

`int putchar(int ch);`

- writes the character `ch` to standard output
- returns the character written, or `EOF` on error

Both functions do automatic *type conversion*

- `putchar('A')` has the same effect as `putchar((int)'A')` (explicit type conversion)

... Stack as ADO

Implementation (in a file named `Stack.c`):

```
#include "Stack.h"
#include <assert.h>

#define MAXITEMS 10
static struct {
   char item[MAXITEMS];
   int  top;
} stackObject;  // defines the Data Object

// set up empty stack
void StackInit() {
   stackObject.top = -1;
}

// check whether stack is empty
int StackIsEmpty() {
   return (stackObject.top < 0);
}
```

```
// insert char on top of stack
void StackPush(char ch) {
   assert(stackObject.top < MAXITEMS-1);
   stackObject.top++;
   int i = stackObject.top;
   stackObject.item[i] = ch;
}

// remove char from top of stack
char StackPop() {
   assert(stackObject.top > -1);
   int i = stackObject.top;
   char ch = stackObject.item[i];
   stackObject.top--;
   return ch;
}
```

`assert(`*`test`*`)` terminates program with error message if *test* fails.

Exercise #2: Bracket Matching

Bracket matching … check whether all opening brackets such as '(', '[', '{' have matching closing brackets ')', ']', '}'

Which of the following expressions are balanced?

1. `(a+b) * c`
2. `a[i]+b[j]*c[k])`
3. `(a[i]+b[j])*c[k]`
4. `a(a+b]*c`
5. `void f(char a[], int n) {int i; for(i=0;i<n;i++) { a[i] = (a[i]*a[i])*(i+1); }}`
6. `a(a+b * c`

---

1. balanced
2. not balanced (case 1: an opening bracket is missing)
3. balanced
4. not balanced (case 2: closing bracket doesn't match opening bracket)
5. balanced
6. not balanced (case 3: missing closing bracket)

... Stack as ADO

Bracket matching algorithm, to be implemented as a *client* for Stack ADO:

```
#include "Stack.h"

bracketMatching(s):
|  Input  stream s of characters
|  Output TRUE if parentheses in s balanced, FALSE otherwise
|
|  for each ch in s do
|  |  if ch = open bracket then
|  |     push ch onto stack
|  |  else if ch = closing bracket then
|  |  |  if stack is empty then
|  |  |     return FALSE                    // opening bracket missing (case 1)
|  |  |  else
|  |  |     pop top of stack
|  |  |     if brackets do not match then
|  |  |        return FALSE                 // wrong closing bracket (case 2)
|  |  |     end if
|  |  |  end if
|  |  end if
|  end for
|  if stack is not empty then return FALSE  // some brackets unmatched (case 3)
|                        else return TRUE
```

... Stack as ADO

Execution trace of client on sample input:

`( [ { } ] )`

Next char	Stack	Check
-	empty	-
(	(	-
[	([	-
{	([{	-
}	([	{ vs } ✓
]	(	[vs] ✓
)	empty	(vs) ✓
eof	empty	-

Exercise #3: Bracket Matching Algorithm

Trace the algorithm on the input

```
void f(char a[], int n) {
   int i;
   for(i=0;i<n;i++) { a[i] = a[i]*a[i])*(i+1); }
}
```

Next bracket	Stack	Check
start	empty	-
(	(	-
[	([	-
]	(	✓
)	empty	✓
{	{	-
(	{ (	-
)	{	✓
{	{ {	-
[	{ { [	-
]	{ {	✓
[	{ { [	-
]	{ {	✓
[	{ { [	-
]	{ {	✓
)	{	FALSE

Compilation and Makefiles

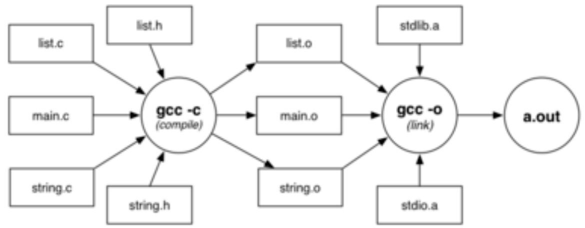
Compilers

Compilers are programs that

- convert program source code to executable form
- "executable" might be machine code or bytecode

The Gnu C compiler (**gcc**)

- applies source-to-source transformation (pre-processor)
- compiles *source code* to produce *object files*
- links object files and *libraries* to produce *executables*



... Compilers

Compilation/linking with `gcc`

```
gcc -c Stack.c
produces Stack.o, from Stack.c and Stack.h
gcc -c bracket.c
produces bracket.o, from bracket.c and Stack.h
gcc -o rbt bracket.o Stack.o
links bracket.o, Stack.o and libraries
producing executable program called rbt
```

Note that `stdio,assert` included implicitly.

gcc is a multi-purpose tool

- compiles (`-c`), links, makes executables (`-o`)

Make/Makefiles

Compilation process is complex for large systems.

How much to compile?

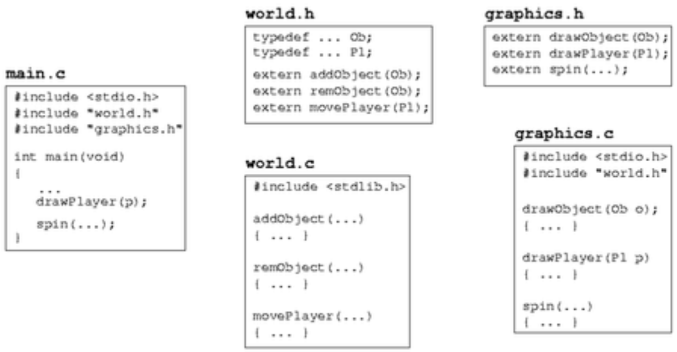
- ideally, what's changed since last compile
- practically, recompile everything, to be sure

The **make** command assists by allowing

- programmers to document *dependencies* in code
- minimal re-compilation, based on dependencies

... Make/Makefiles

Example multi-module program …



... Make/Makefiles

`make` is driven by dependencies given in a **`Makefile`**

A *dependency* specifies

```
target : source1 source2 …
        commands to build target from sources
```

e.g.

```
game : main.o graphics.o world.o
        gcc -o game main.o graphics.o world.o
```

Rule: *target* is rebuilt if older than any $source_i$

... Make/Makefiles

A **`Makefile`** for the example program:

```
game : main.o graphics.o world.o
        gcc -o game main.o graphics.o world.o

main.o : main.c graphics.h world.h
        gcc -Wall -Werror -c main.c

graphics.o : graphics.c world.h
        gcc -Wall -Werror -c graphics.c

world.o : world.c
        gcc -Wall -Werror -c world.c
```

Things to note:

- A *target* (`game`, `main.o`, …) is on a newline
  - followed by a **`:`**
  - then followed by the files that the target is dependent on
- The *action* (`gcc …`) is always on a newline
  - and must be indented with a *TAB*

... Make/Makefiles

If `make` arguments are targets, build just those targets:

```
prompt$ make world.o
gcc -Wall -Werror -c world.c
```

If no args, build first target in the `Makefile`.

```
prompt$ make
gcc -Wall -Werror -c main.c
gcc -Wall -Werror -c graphics.c
gcc -Wall -Werror -c world.c
gcc -o game main.o graphics.o world.o
```

Exercise #4: Makefile

Write a `Makefile` for the bracket matching program.

From ADOs to ADTs

Abstract Data *Objects*

- `Stack.c` provides a single abstract object **`stackObject`**

Abstract Data *Types*

- allow clients to create and manipulate arbitrarily many data objects of an abstract type
- … without revealing the implementation to a client

In C, ADTs are implemented using *pointers* and *dynamic memory allocation*

Pointers

Sidetrack: Numeral Systems

Numeral system … system for representing numbers using digits or other symbols.

- Most cultures have developed a *decimal* system (based on 10)

- For computers it is convenient to use a *binary* (base 2) or a *hexadecimal* (base 16) system

---

... Sidetrack: Numeral Systems

Decimal representation

- The base is 10; digits 0 - 9
- Example: decimal number 4705 can be interpreted as

$$4\cdot10^3 + 7\cdot10^2 + 0\cdot10^1 + 5\cdot10^0$$

- Place values:

…	1000	100	10	1
…	10^3	10^2	10^1	10^0

- Write number as 4705_{10}
  - Note use of subscript to denote base

... Sidetrack: Numeral Systems

Binary representation

- The base is 2; digits 0 and 1
- Example: binary number 1011 can be interpreted as

$$1\cdot2^3 + 0\cdot2^2 + 1\cdot2^1 + 1\cdot2^0$$

- Place values:

…	8	4	2	1
…	2^3	2^2	2^1	2^0

- Write number as 1011_2 (= 11_{10})

... Sidetrack: Numeral Systems

Hexadecimal representation

- The base is 16; digits 0,1,2,3,4,5,6,7,8,9,A,B,C,D,E,F
- Example: hexadecimal number 3AF1 can be interpreted as

$$3\cdot16^3 + 10\cdot16^2 + 15\cdot16^1 + 1\cdot16^0$$

- Place values:

…	4096	256	16	1
…	16^3	16^2	16^1	16^0

- Write number as $3AF1_{16}$ (= 15089_{10})

Exercise #5: Conversion Between Different Numeral Systems

1. Convert 101011_2 to base 10
2. Convert 74_{10} to base 2
3. Convert $2D_{16}$ to base 10
4. Convert 273_{10} to base 16

---

1. 43_{10}
2. 1001010_2
3. 45_{10}
4. 111_{16}

... Sidetrack: Numeral Systems

Conversion between binary and hexadecimal

0	1	2	3	4	5	6	7
0000	0001	0010	0011	0100	0101	0110	0111
8	9	A	B	C	D	E	F
1000	1001	1010	1011	1100	1101	1110	1111

- Binary to hexadecimal
  - Collect bits into groups of four starting from right to left
  - "pad" out left-hand side with 0's if necessary
  - Convert each group of four bits into its equivalent hexadecimal representation (given in table above)
- Hexadecimal to binary
  - Reverse the previous process
  - Convert each hex digit into equivalent 4-bit binary representation

---

Exercise #6: Conversion Between Binary and Hexadecimal

1. Convert 1011111000101001_2 to base 16
   - Hint: 1011111000101001
2. Convert 10111101011100_2 to base 16
   - Hint: 10111101011100
3. Convert $12D_{16}$ to base 2

---

1. $BE29_{16}$
2. $2F5C_{16}$
3. 100101101_2

Memory

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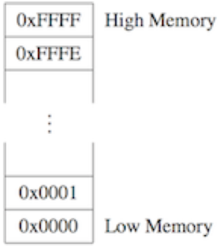
Computer memory … large array of consecutive data cells or bytes

- `char` … 1 byte `int,float` … 4 bytes `double` … 8 bytes



When a variable is declared, the operating system finds a place in memory to store the appropriate number of bytes.

If we declare a variable called `k` …

- the place where `k` is stored is denoted by `&k`
- also called the address of k

It is convenient to print memory addresses in Hexadecimal notation

... Memory

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Example:

```
int k;
int m;

printf("address of k is %p\n", &k);
printf("address of m is %p\n", &m);
```

```
address of k is BFFFFB80
address of m is BFFFFB84
```

This means that

- `k` occupies the four bytes from `BFFFFB80` to `BFFFFB83`
- `m` occupies the four bytes from `BFFFFB84` to `BFFFFB87`

Note the use of `%p` as placeholder for an address ("pointer" value)

... Memory

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When an array is declared, the elements of the array are guaranteed to be stored in consecutive memory locations:

```
int array[5];

for (i = 0; i < 5; i++) {
   printf("address of array[%d] is %p\n", i, &array[i]);
}
```

```
address of array[0] is BFFFFB60
address of array[1] is BFFFFB64
address of array[2] is BFFFFB68
address of array[3] is BFFFFB6C
address of array[4] is BFFFFB70
```

Application: Input Using `scanf()`

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Standard I/O function `scanf()` requires the *address* of a variable as argument

- `scanf()` uses a format string like `printf()`
- use `%d` to read an integer value

```
#include <stdio.h>
…
int answer;
printf("Enter your answer: ");
scanf("%d", &answer);
```

- use `%f` to read a floating point value (`%lf` for `double`)

```
float e;
printf("Enter e: ");
scanf("%f", &e);
```

- `scanf()` returns a value — the number of items read
  - use this value to determine if `scanf()` successfully read a number
    - `scanf()` could fail e.g. if the user enters letters

Exercise #7: Using `scanf`

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Write a program that

- asks the user for a number
- checks that it is positive
- applies Collatz's process (Exercise 4, Problem Set 1) to the number

Pointers

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A *pointer* …

- is a special type of variable
- storing the address (memory location) of another variable

A pointer occupies space in memory, just like any other variable of a certain type

The number of memory cells needed for a pointer depends on the computer's architecture:

- Old computer, or hand-held device with only 64KB of addressable memory:
  - 2 memory cells (i.e. 16 bits) to hold any address from `0x0000` to `0xFFFF` (= 65535)
- Desktop machine with 4GB of addressable memory

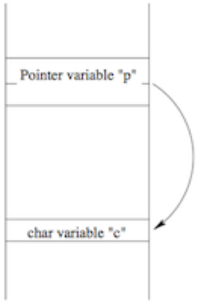
- 4 memory cells (i.e. 32 bits) to hold any address from `0x00000000` to `0xFFFFFFFF` (= 4294967295)

- Modern 64-bit computer
  - 8 memory cells (can address 2^{64} bytes, but in practice the amount of memory is limited by the CPU)

... Pointers

Suppose we have a pointer **p** that "points to" a `char` variable `c`.

Assuming that the pointer **p** requires 2 bytes to store the address of `c`, here is what the memory map might look like:



... Pointers

Now that we have assigned to p the address of variable `c` …

- need to be able to reference the data in that memory location

Operator `*` is used to access the object the pointer points to

- e.g. to change the value of `c` using the pointer p:

```
*p = 'T';  // sets the value of c to 'T'
```

The `*` operator is sometimes described as "*dereferencing*" the pointer, to access the underlying variable

---

... Pointers

Things to note:

- all pointers constrained to point to a particular type of object

```
// a potential pointer to any object of type char
char *s;

// a potential pointer to any object of type int
int *p;
```

- if pointer `p` is pointing to an integer variable `x`
  ⇒ `*p` can occur in any context that `x` could

Examples of Pointers


```
int *p; int *q; // this is how pointers are declared
int a[5];
int x = 10, y;

 p = &x;      // p now points to x
*p = 20;      // whatever p points to is now equal to 20
 y = *p;      // y is now equal to whatever p points to
 p = &a[2];   // p points to an element of array a[]
 q = p;       // q and p now point to the same thing
```

Exercise #8: Pointers

What is the output of the following program?

```
#include <stdio.h>

int main(void) {
   int *ptr1, *ptr2;
   int i = 10, j = 20;

   ptr1 = &i;
   ptr2 = &j;

   *ptr1 = *ptr1 + *ptr2;
   ptr2 = ptr1;
   *ptr2 = 2 * (*ptr2);
   printf("Val = %d\n", *ptr1 + *ptr2);
   return 0;
}
```

`Val = 120`

... Examples of Pointers

Can we write a function to "swap" two variables?

The *wrong* way:

```
void swap(int a, int b) {
   int temp = a;                    // only local "copies" of a and b will swap
   a = b;
```

```
   b = temp;
}

int main(void) {
   int a = 5, b = 7;
   swap(a, b);
   printf("a = %d, b = %d\n", a, b); // a and b still have their original values
   return 0;
}
```

... Examples of Pointers

In C, parameters are "call-by-value"

- changes made to the value of a parameter do not affect the original
- function `swap()` tries to swap the values of `a` and `b`, but fails because it only swaps the copies, not the "real" variables in `main()`

We can achieve "simulated call-by-reference" by passing pointers as parameters

- this allows the function to change the "actual" value of the variables

... Examples of Pointers

Can we write a function to "swap" two variables?

The *right* way:

```
void swap(int *p, int *q) {
   int temp = *p;             // change the actual values of a and b
   *p = *q;
   *q = temp;
}

int main(void) {
   int a = 5, b = 7;
   swap(&a, &b);
   printf("a = %d, b = %d\n", a, b);  // a and b now successfully swapped
   return 0;
}
```

Pointers and Arrays

An alternative approach to iteration through an array:

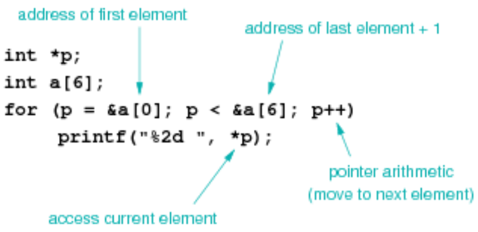
- determine the address of the first element in the array
- determine the address of the last element in the array
- set a pointer variable to refer to the first element
- use pointer arithmetic to move from element to element
- terminate loop when address exceeds that of last element

Example:

```
int a[6];
int *p = &a[0];
while (p <= &a[5]) {
    printf("%2d ", *p);
    p++;
}
```

... Pointers and Arrays

Pointer-based scan written in more typical style



Note: because of pointer/array connection `a[i] == *(a+i)`

Sidetrack: Pointer Arithmetic

A *pointer* variable holds a value which is an *address*.

C knows what type of object is being pointed to

- it knows the `sizeof` that object
- it can compute where the next/previous object is located

Example:

```
int a[6];   // address 0x1000
int *p;
p = &a[0];  // p contains 0x1000
p = p + 1;  // p now contains 0x1004
```

... Sidetrack: Pointer Arithmetic

For a pointer declared as `T *p;` (where `T` is a type)

- if the pointer initially contains address `A`
  - executing `p = p + k;` (where k is a constant)
    - changes the value in `p` to `A + k*sizeof(T)`

The value of `k` can be positive or negative.

Example:

```
int a[6];   (addr 0x1000)       char s[10];   (addr 0x2000)
int *p;     (p == ?)           char *q;      (q == ?)
p = &a[0];  (p == 0x1000)       q = &s[0];    (q == 0x2000)
p = p + 2;  (p == 0x1008)       q++;          (q == 0x2001)
```

Arrays of Strings

One common type of pointer/array combination are the *command line arguments*

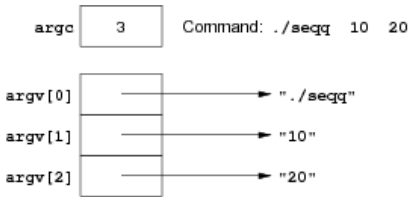
- These are 0 or more strings specified when program is run
- If you run this command in a terminal:

  ```
  prompt$ ./seqq 10 20
  ```

  then `seqq` will be given 2 command-line arguments: `"10", "20"`

... Arrays of Strings


```
prompt$ ./seqq 10 20
```



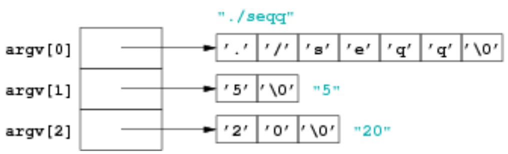
Each element of `argv[]` is

- a pointer to the start of a character array (`char *`)
  - containing a `\0`-terminated string

... Arrays of Strings

More detail on how `argv` is represented:

```
prompt$ ./seqq 5 20
```



... Arrays of Strings

`main()` needs different prototype if you want to access command-line arguments:

```
int main(int argc, char *argv[]) { ...
```

- `argc` … stores the number of command-line arguments + 1
  - `argc == 1` if no command-line arguments
- `argv[]` … stores program name + command-line arguments
  - `argv[0]` always contains the program name
  - `argv[1],argv[2],…` are the command-line arguments if supplied

`<stdlib.h>` defines useful functions to convert strings:

- `atoi(char *s)` converts string to int
- `atof(char *s)` converts string to double (can also be assigned to `float` variable)

Exercise #9: Command Line Arguments

Write a program that

- checks for a single command line argument
  - if not, outputs a usage message and exits with failure
- converts this argument to a number and checks that it is positive
- applies Collatz's process (Exercise 4, Problem Set 1) to the number

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

void collatz(int n) {
   printf("%d\n", n);
   while (n != 1) {
      if (n % 2 == 0)
         n = n / 2;
      else
         n = 3*n + 1;
      printf("%d\n", n);
   }
}

int main(int argc, char *argv[]) {
   if (argc != 2) {
      printf("Usage: %s [number]\n", argv[0]);
      return 1;
   }
   int n = atoi(argv[1]);
   if (n > 0)
      collatz(n);
   return 0;
}
```

... Arrays of Strings

`argv` can also be viewed as *double pointer* (a pointer to a pointer)

⇒ Alternative prototype for `main()`:

```
int main(int argc, char **argv) { ...
```

Can still use `argv[0]`, `argv[1]`, …

Pointers and Structures

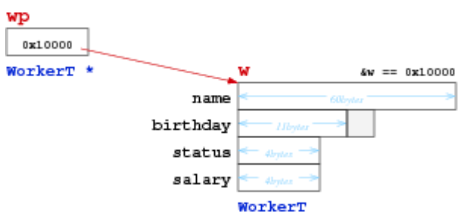
Like any object, we can get the address of a `struct` via `&`.

```
typedef char Date[11];  // e.g. "03-08-2017"
typedef struct {
    char  name[60];
    Date  birthday;
    int   status;      // e.g. 1 (≡ full time)
    float salary;
} WorkerT;

WorkerT w;  WorkerT *wp;
wp = &w;
// a problem …
*wp.salary = 125000.00;
// does not have the same effect as
w.salary = 125000.00;
// because it is interpreted as
*(wp.salary) = 125000.00;

// to achieve the correct effect, we need
(*wp).salary = 125000.00;
// a simpler alternative is normally used in C
wp->salary = 125000.00;
```

Learn this well; we will frequently use it in this course.

... Pointers and Structures

Diagram of scenario from program above:



... Pointers and Structures

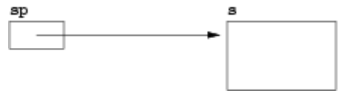
General principle …

If we have:

```
SomeStructType  s,   *sp = &s;
```

then the following are all equivalent:

```
s.SomeElem    sp->SomeElem    (*sp).SomeElem
```



Summary

- Introduction to ADOs and ADTs
- Compilation and **`Makefile`**s
- Numeral systems
- Pointers

- Suggested reading:
  - introduction to ADTs … Sedgewick, Ch.4.1-4.3
  - pointers … Moffat, Ch.6.6-6.7

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