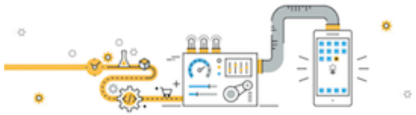
Week 1: Introduction - Elementary Data and Control Structures in C

COMP9024 19T3

Data Structures and Algorithms



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Web Site: webcms3.cse.unsw.edu.au/COMP9024/19T3/

Course Convenor

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... Course Convenor

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Course Goals

COMP9021 …

- gets you thinking like a *programmer*
- solving problems by developing programs
- expressing your ideas in the language Python

COMP9024 …

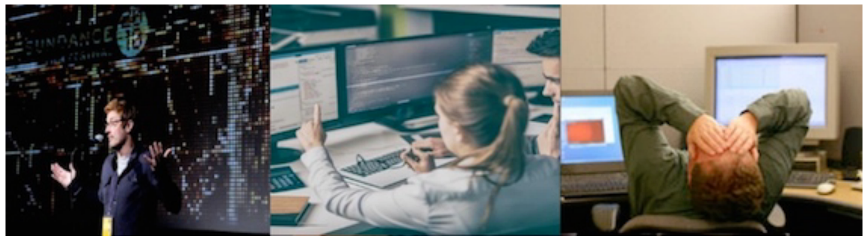
- gets you thinking like a *computer scientist*
- knowing fundamental data structures/algorithms
- able to reason about their applicability/effectiveness
- able to analyse the efficiency of programs
- able to code in C

... Course Goals

COMP9021 …

... Course Goals

COMP9024 …



Pre-conditions

At the *start* of this course you should be able to:

- produce correct programs from a specification
- understand the state-based model of computation

(variables, assignment, function parameters)
- use fundamental data structures
  (characters, numbers, strings, arrays)
- use fundamental control structures (`if`, `while`, `for`)
- know fundamental algorithms (sorting)
- fix simple bugs in incorrect programs

Post-conditions

8/108

At the *end* of this course you should be able to:

- choose/develop effective data structures (DS)
- analyse performance characteristics of algorithms
- choose/develop algorithms (A) on these DS
- package a set of DS+A as an abstract data type
- develop and maintain C programs

COMP9024 Themes

9/108

Data structures

- how to store data inside a computer for efficient use

Algorithms

- step-by-step process for solving a problem (within finite amount of space and time)

Major themes …

1. Data structures, e.g. for graphs, trees
2. A variety of algorithms, e.g. on graphs, trees, strings
3. Analysis of algorithms

For data types: alternative data structures and implementation of operations

For algorithms: complexity analysis

Access to Course Material

10/108

All course information is placed on the main course website:

- webcms3.cse.unsw.edu.au/COMP9024/19T3/

Need to login to access material, submit homework and assignment, post on the forum, view your marks

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Schedule

11/108

Week	**Lectures**	Assessment	Notes
1	Introduction, C language	—	first help lab
2	**C Practice Week**	—	
3	Analysis of algorithms	quiz	
4	Dynamic data structures	program	
5	Graph data structures	quiz	
6	Graph algorithms	program	
7	**Mid-term test (Monday)**		Large Assignment
7	Search tree data structures	quiz	|
8	Search tree algorithms	program	|
9	String algorithms, Approximation	quiz	|
10	Randomised algorithms, Review	program	| due

Credits for Material

12/108

Always give credit when you use someone else's work.

Ideas for the COMP9024 material are drawn from

- slides by John Shepherd (COMP1927 16s2), Hui Wu (COMP9024 16s2) and Alan Blair (COMP1917 14s2)
- Robert Sedgewick's and Alistair Moffat's books, Goodrich and Tamassia's Java book, Skiena and Revilla's programming challenges book

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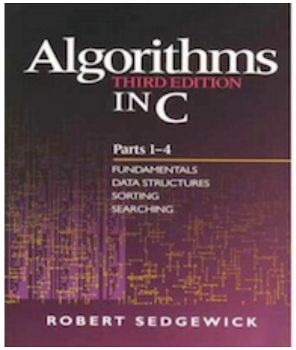
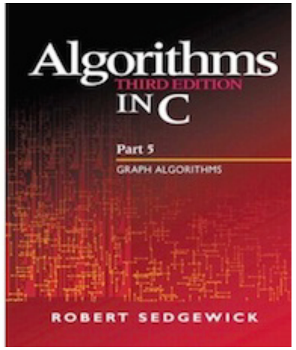
Resources

13/108

Textbook is a "double-header"

- Algorithms in C, Parts 1-4, Robert Sedgewick
- Algorithms in C, Part 5, Robert Sedgewick





Good books, useful beyond COMP9024 (but coding style …)

14/108

... Resources

Supplementary textbook:

- Alistair Moffat
  Programming, Problem Solving, and Abstraction with C
  Pearson Educational, Australia, Revised edition 2013, ISBN 978-1-48-601097-4

Also, numerous online C resources are available.

Lectures

Lectures will:

- present theory
- demonstrate problem-solving methods
- give practical demonstrations

Lectures provide an alternative view to textbook

Lecture slides will be made available before lecture

Feel free to ask questions, but No Idle Chatting

Problem Sets

The weekly homework aims to:

- clarify any problems with lecture material
- work through exercises related to lecture topics
- give practice with algorithm design skills (think before coding)

Problem sets available on web at the time of the lecture

Sample solutions will be posted in the following week

Do them yourself! and Don't fall behind!

... Problem Sets

The homework will be assessed in two different ways.

- In weeks *3, 5, 7, 9 ...*
  - you will be given a short quiz (4-5 questions)
  - with questions related to the exercises and the lecture
- In weeks *4, 6, 8, 10 ...*
  - you will be asked to submit 1 or 2 (small) programs
  - which will be auto-marked against one or more test cases

Programs and quizzes contribute 8% + 8% to overall mark.

- First homework (weeks 1-2) is programming practice and will not count
  - Deadline: Monday, 30 Sep, 11:00:00am

Large Assignment

The large assignment gives you experience applying tools/techniques
(but to a larger programming problem than the homework)

The assignment will be carried out individually.

The assignment will be released after the mid-term test and is due in week 10.

The assignment contributes 12% to overall mark.

16.67% penalty will be applied to the maximum mark for every 24 hours late after the deadline.

- 1 day late: mark is capped at 10 (83.33% of the maximum possible mark)
- 2 days late: mark is capped at 8 (66.67% of the maximum possible mark)
- 3 days late: mark is capped at 6 (50% of the maximum possible mark)
- ...

... Large Assignment

Advice on doing assignments:

They always take longer than you expect.

Don't leave them to the last minute.

Organising your time → no late penalty.

If you do leave them to the last minute:

- take the late penalty rather than copying

Plagiarism

Just Don't Do it

We get very annoyed by people who plagiarise.

... Plagiarism

Examples of Plagiarism (student.unsw.edu.au/plagiarism):

1. Copying

   Using same or similar idea *without acknowledging the source*
   This includes copying ideas from a website, internet

2. Collusion

   Presenting work as independent when produced in collusion with others
   This includes *students providing their work to another student*

Plagiarism will be checked for and punished (0 marks for assignment or, in severe cases/repeat offenders, 0 marks for course)

For COMP9024 you will need to complete an online module (self-enrolemnt, student key: `Student583`):

Working with Academic Integrity (moodle.telt.unsw.edu.au/enrol/index.php?id=33388)

- We will ask for your completion certificate if you have done the training before

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Help Lab

The *help lab*:

- aims to help you if you have difficulties with the weekly programming exercises
- … and the assignments
- non-programming exercises from problem sets may also be discussed

Fridays (Week 1-10) from 1-2pm in *CSE Drum Lab (Room B08, Bldg K17, basement)*

Attendance is entirely voluntary

Mid-term Test

1-hour online test in week 7 (*Monday, 28 Oct, at time of the lecture*).

Format:

- some multiple-choice questions
- some descriptive/analytical questions with open answers

The mid-term test contributes 12% to overall mark.

Final Exam

2-hour ~~torture~~ written exam during the exam period.

Format:

- some multiple-choice questions
- some descriptive/analytical questions

The final exam contributes 60% to overall mark.

Must score at least 25/60 in the final exam to pass the course.

... Final Exam

How to pass the mid-term test and the Final Exam:

- do the Homework *yourself*
- do the Homework *every week*
- use C Practice Week 2 to practise programming in C
- practise programming outside classes
- read the lecture notes
- read the corresponding chapters in the textbooks

Assessment Summary


```
assn1 = mark for programs/quizzes (out of 8+8)
assn2 = mark for mid-term test    (out of 12)
assn3 = mark for large assignment (out of 12)
exam  = mark for final exam       (out of 60)

if (exam >= 25)
   total = assn1 + assn2 + assn3 + exam
else
   total = exam * (100/60)
```

To pass the course, you must achieve:

- at least 25/60 for `exam`
- at least 50/100 for `total`

Summary

The goal is for you to become a better Computer Scientist

- more confident in your own ability to choose data structures
- more confident in your own ability to develop algorithms
- able to analyse and justify your choices
- producing a better end-product
- ultimately, enjoying the software design and development process

C Programming Language

Why C?

- good example of an imperative language
- gives the programmer great control
- produces fast code
- many libraries and resources
- widely used in industry (and science)

Brief History of C

- C and UNIX operating system share a complex history
- C was originally designed for and implemented on UNIX
- Dennis Ritchie was the author of C (around 1971)
- In 1973, UNIX was rewritten in C
- B (author: Ken Thompson, 1970) was the predecessor to C, but there was no A

... Brief History of C

- B was a typeless language
- C is a typed language
- In 1983, American National Standards Institute (ANSI) established a committee to clean up and standardise the language
- ANSI C standard published in 1988
  - this greatly improved source code portability
- Current standard: C11 (published in 2011)
- C is the main language for writing operating systems and compilers; and is commonly used for a variety of applications

Basic Structure of a C Program

```
// include files
// global definitions

// function definitions
function_type f(arguments) {

   // local variables

   // body of function

  return …;
}

.
.
.
.
.
.
.

// main function
int main(arguments) {

   // local variables

   // body of main function

   return 0;
}
```


Exercise #1: What does this program compute?

```
#include <stdio.h>

int f(int m, int n) {

   while (m != n) {
      if (m > n) {
         m = m-n;
      } else {
         n = n-m;
      }
   }
   return m;
}

int main(void) {

   printf("%d\n", f(30,18));
   return 0;
}
```


Example: Insertion Sort in C

Reminder — Insertion Sort algorithm:

```
insertionSort(A):
|  Input array A[0..n-1] of n elements
|
|  for all i=1..n-1 do
|  |  element=A[i], j=i-1
|  |  while j≥0 and A[j]>element do
```

```
|   |     A[j+1]=A[j]
|   |     j=j-1
|   |  end while
|   |  A[j+1]=element
|  end for
```

... Example: Insertion Sort in C


```c
#include <stdio.h> // include standard I/O library defs and functions

#define SIZE 6     // define a symbolic constant

void insertionSort(int array[], int n) {  // function headers must provide types
   int i;                                 // each variable must have a type
   for (i = 1; i < n; i++) {              // for-loop syntax
      int element = array[i];
      int j = i-1;
      while (j >= 0 && array[j] > element) {  // logical AND
         array[j+1] = array[j];
         j--;                                 // abbreviated assignment j=j-1
      }
      array[j+1] = element;                   // statements terminated by ;
   }                                          // code blocks enclosed in { }
}

int main(void) {                              // main: program starts here
   int numbers[SIZE] = { 3, 6, 5, 2, 4, 1 };  /* array declaration
                                                 and initialisation */
   int i;
   insertionSort(numbers, SIZE);
   for (i = 0; i < SIZE; i++)
      printf("%d\n", numbers[i]);             // printf defined in <stdio>

   return 0;           // return program status (here: no error) to environment
}
```

Compiling with `gcc`

C source code: `prog.c`

↓

`a.out` **(executable program)**

To compile a program `prog.c`, you type the following:

```
prompt$ gcc prog.c
```

To run the program, type:

```
prompt$ ./a.out
```

... Compiling with `gcc`

Command line options:

- The default with `gcc` is not to give you any warnings about potential problems
- Good practice is to be tough on yourself:

  ```
  prompt$ gcc -Wall prog.c
  ```

  which reports all warnings to anything it finds that is potentially wrong or non ANSI compliant

- The `-o` option tells `gcc` to place the compiled object in the named file rather than `a.out`

  ```
  prompt$ gcc -o prog prog.c
  ```

Algorithms in C

Basic Elements

Algorithms are built using

- assignments
- conditionals
- loops
- function calls/return statements

Assignments

- In C, each statement is terminated by a semicolon `;`
- Curly brackets `{ }` used to enclose statements in a block
- Usual arithmetic operators: `+, -, *, /, %`
- Usual assignment operators: `=, +=, -=, *=, /=, %=`
- The operators `++` and `--` can be used to increment a variable (add 1) or decrement a variable (subtract 1)
  - It is recommended to put the increment or decrement operator after the variable:

    ```
              // suppose k=6 initially
    k++;      // increment k by 1; afterwards, k=7
    n = k--;  // first assign k to n, then decrement k by 1
              // afterwards, k=6 but n=7
    ```

  - It is also possible (but NOT recommended) to put the operator before the variable:

    ```
              // again, suppose k=6 initially
    ++k;      // increment k by 1; afterwards, k=7
    n = --k;  // first decrement k by 1, then assign k to n
              // afterwards, k=6 and n=6
    ```

... Assignments

C assignment statements are really expressions

- they return a result: the value being assigned
- the return value is generally ignored

Frequently, assignment is used in loop continuation tests

- to combine the test with collecting the next value
- to make the expression of such loops more concise

Example: The pattern

```
v = getNextItem();
while (v != 0) {
   process(v);
   v = getNextItem();
}
```

is often written as

```
while ((v = getNextItem()) != 0) {
   process(v);
}
```

Exercise #2: What are the final values of `a` and `b`?

1.
```
a = 1; b = 5;
while (a < b) {
   a++;
   b--;
}
```

2.
```
a = 1; b = 5;
while ((a += 2) < b) {
   b--;
}
```

---

1. `a == 3, b == 3`
2. `a == 5, b == 4`

Conditionals


```
if (expression) {
   some statements;
}
```

```
if (expression) {
   some statements_1;
} else {
   some statements_2;
}
```

- `some statements` executed if, and only if, the evaluation of `expression` is non-zero
- `some statements`$_1$ executed when the evaluation of `expression` is non-zero
- `some statements`$_2$ executed when the evaluation of `expression` is zero
- Statements can be single instructions or blocks enclosed in `{ }`

... Conditionals

Indentation is very important in promoting the readability of the code

Each logical block of code is indented:

```
// Style 1
if (x)
{
   statements;
}
```

```
// Style 2 (my preference)
if (x) {
   statements;
}
```

```
// Preferred else-if style
if (expression1) {
   statements_1;
} else if (exp2) {
   statements_2;
} else if (exp3) {
   statements_3;
} else {
   statements_4;
}
```

... Conditionals

Relational and logical operators

`a > b`	`a` greater than `b`
`a >= b`	`a` greater than or equal `b`
`a < b`	`a` less than `b`
`a <= b`	`a` less than or equal `b`
`a == b`	`a` equal to `b`
`a != b`	`a` not equal to `b`
`a && b`	`a` logical and `b`
`a || b`	`a` logical or `b`
`! a`	logical not `a`

A relational or logical expression evaluates to **`1`** if true, and to **`0`** if false

---

Exercise #3: Conditionals

1. What is the output of the following program fragment?

```
if ((x > y) && !(y-x <= 0)) {
```

```
        printf("Aye\n");
    } else {
        printf("Nay\n");
    }
```

2. What is the resulting value of `x` after the following assignment?

```
x = (x >= 0) + (x < 0);
```

---

1. The condition is unsatisfiable, hence the output will always be

```
Nay
```

2. No matter what the value of `x`, one of the conditions will be true (==1) and the other false (==0)
Hence the resulting value will be `x == 1`

Sidetrack: Printing Variable Values with `printf()`

Formatted output written to standard output (e.g. screen)

`printf(format-string, expr1, expr2, …);`

`format-string` can use the following placeholders:

`%d`	decimal	`%f`	fixed-point
`%c`	character	`%s`	string
`\n`	new line	`\"`	quotation mark

Examples:

```
num = 3;
printf("The cube of %d is %d.\n", num, num*num*num);

The cube of 3 is 27.

id  = 'z';
num = 1234567;
printf("Your \"login ID\" will be in the form of %c%d.\n", id, num);

Your "login ID" will be in the form of z1234567.
```

- Can also use width and precision:

```
printf("%8.3f\n", 3.14159);

   3.142
```

Loops

C has two different "while loop" constructs

```
// while loop                  // do .. while loop
while (expression) {           do {
    some statements;              some statements;
}                              } while (expression);
```

The `do .. while` loop ensures the statements will be executed at least once

---

... Loops

The "for loop" in C

```
for (expr1; expr2; expr3) {
   some statements;
}
```

- `expr1` is evaluated before the loop starts
- `expr2` is evaluated at the beginning of each loop
  - if it is non-zero, the loop is repeated
- `expr3` is evaluated at the end of each loop

Example:

```
for (i = 1; i < 10; i++) {
   printf("%d %d\n", i, i * i);
}
```

Exercise #4: What is the output of this program?

```
int i, j;
for (i = 8; i > 1; i /= 2) {
    for (j = i; j >= 1; j--) {
        printf("%d%d\n", i, j);
    }
    putchar('\n');
}
```

```
88
87
..
81

44
..
41

22
21
```

Functions

Functions have the form

```
return-type function-name(parameters) {

     declarations

     statements

     return …;
}
```

- if *return_type* is **void** then the function does not return a value
- if *parameters* is **void** then the function has no arguments

... Functions

When a function is called:

1. memory is allocated for its parameters and local variables
2. the parameter expressions in the calling function are evaluated
3. C uses "call-by-value" parameter passing …
   - the function works only on its own local copies of the parameters, not the ones in the calling function
4. local variables need to be assigned before they are used (otherwise they will have "garbage" values)
5. function code is executed, until the first `return` statement is reached

... Functions

When a **return** statement is executed, the function terminates:

```
return expression;
```

1. the returned *expression* will be evaluated
2. all local variables and parameters will be thrown away when the function terminates
3. the calling function is free to use the returned value, or to ignore it

Example:

```
// Euclid's gcd algorithm (recursive version)
int euclid_gcd(int m, int n) {
    if (n == 0) {
        return m;
    } else {
        return euclid_gcd(n, m % n);
    }
}
```

The return statement can also be used to terminate a function of return-type `void`:

```
return;
```

Data Structures in C

Basic Data Types

- In C each variable must have a type
- C has the following generic data types:

char	character	`'A'`, `'e'`, `'#'`, …
int	integer	`2`, `17`, `-5`, …
float	floating-point number	`3.14159`, …
double	double precision floating-point	`3.14159265358979`, …

There are other types, which are variations on these

- Variable declaration must specify a data type and a name; they can be initialised when they are declared:

```
float x;
char  ch = 'A';
int   j = i;
```

Aggregate Data Types

Families of aggregate data types:

- homogeneous … all elements have same base type
  - arrays (e.g. `char s[50]`, `int v[100]`)
- heterogeneous … elements may combine different base types
  - structures

Arrays

An *array* is

- a collection of same-type variables
- arranged as a linear sequence
- accessed using an integer subscript
- for an array of size *N*, valid subscripts are 0..*N-1*

Examples:

```
int  a[20];    // array of 20 integer values/variables
char b[10];    // array of 10 character values/variables
```

... Arrays

Larger example:

```
#define MAX 20

int i;           // integer value used as index
int fact[MAX];   // array of 20 integer values

fact[0] = 1;
for (i = 1; i < MAX; i++) {
    fact[i] = i * fact[i-1];
}
```

Sidetrack: C Style

62/108

We can define a symbolic constant at the top of the file

```
#define SPEED_OF_LIGHT 299792458.0
#define ERROR_MESSAGE "Out of memory.\n"
```

Symbolic constants make the code easier to understand and maintain

`#define` *`NAME`* `replacement_text`

- The compiler's pre-processor will replace all occurrences of `NAME` with `replacement_text`
- it will **not** make the replacement if `NAME` is inside quotes ("…") or part of another name

---

... Sidetrack: C Style

63/108

UNSW Computing provides a style guide for C programs:

C Coding Style Guide (http://wiki.cse.unsw.edu.au/info/CoreCourses/StyleGuide)

Not strictly mandatory for COMP9024, but very useful guideline

- use proper layout, including indentation
- keep functions short and break into sub-functions as required
- use meaningful names (for variables, functions etc)

Style considerations that *do* matter for your COMP9024 assignments:

- use symbolic constants to avoid burying "magic numbers" in the code
- use indentation consistently (3 or 4 spaces, do *not* use TABs)
- comment your code

... Sidetrack: C Style

64/108

C has a reputation for allowing obscure code, leading to …

The International Obfuscated C Code Contest

- Run each year since 1984
- Goal is to produce
  - a working C program
  - whose appearance is obscure
  - whose functionality unfathomable
- Web site: `www.ioccc.org`
- 100's of examples of bizarre C code
  (understand these → you are a C master)

... Sidetrack: C Style

65/108

Most artistic code (Eric Marshall, 1986)

```
                                                   extern int
                                                       errno
                                                         ;char
                                                            grrr
                             ;main(                           r,
  argv, argc )            int    argc                           ,
   r        ;           char *argv[];{int                     P( );
#define x  int i,       j,cc[4];printf("      choo choo\n"      ) ;
x  ;if    (P(  !        i              )        |  cc[  !      j ]
&  P(j    )>2  ?        j              :        i  ){*  argv[i++ +!-i]
;              for    (i=              0;;    i++                   );
_exit(argv[argc- 2    / cc[1*argc]|-1<4 ]    ) ;printf("%d",P(""));}}
  P  (    a  )   char a   ;  {    a  ;   while(    a  >      "  B   "
  /* -    by E            ricM    arsh             all-      */);    }
```

... Sidetrack: C Style

66/108

Just plain obscure (Ed Lycklama, 1985)

```
#define o define
#o ___o write
#o ooo (unsigned)
#o o_o_ 1
#o _o_ char
#o _oo goto
#o _oo_ read
#o o_o for
#o o_ main
#o o__ if
#o oo_ 0
#o _o(_,__,___)(void)___o(_,__,ooo(___))
#o __o (o_o_<<((o_o_<<(o_o_<<o_o_))+(o_o_<<o_o_)))+(o_o_<<(o_o_<<(o_o_<<o_o_)))
o_(){_o_ _=oo_,__,___,____[__o];_oo ______;_____:___=__o-o_o_; _______:
_o(o_o_,____,__=(_-o_o_<___?_-o_o_:___));o_o(;__;_o(o_o_,"\b",o_o_),__--);
_o(o_o_," ",o_o_);o__(--___)_oo _______;_o(o_o_,"\n",o_o_);______:o__(_=_oo_(
oo_,____,__o))_oo _____;}
```

Strings

67/108

"String" is a special word for an array of characters

- end-of-string is denoted by `'\0'` (of type `char` and always implemented as 0)

Example:

If a character array `s[11]` contains the string `"hello"`, this is how it would look in memory:

```
  0    1    2    3    4    5    6    7    8    9    10
---------------------------------------------
| h  | e  | l  | l  | o  | \0|    |    |    |    |    |
---------------------------------------------
```


Array Initialisation

Arrays can be initialised by code, or you can specify an initial set of values in declaration.

Examples:

```
char s[6]   = {'h', 'e', 'l', 'l', 'o', '\0'};

char t[6]   = "hello";

int fib[20] = {1, 1};

int vec[]   = {5, 4, 3, 2, 1};
```

In the third case, `fib[0] == fib[1] == 1` while the initial values `fib[2] .. fib[19]` are undefined.

In the last case, C infers the array length (as if we declared `vec[5]`).

Exercise #5: What is the output of this program?

```
#include <stdio.h>

int main(void) {
   int arr[3] = {10,10,10};
   char str[] = "Art";
   int i;

   for (i = 1; i < 3; i++) {
      arr[i] = arr[i-1] + arr[i] + 1;
      str[i] = str[i+1];
   }
   printf("Array[2] = %d\n", arr[2]);
   printf("String = \"%s\"\n", str);
   return 0;
}
```

```
Array[2] = 32
String = "At"
```


Sidetrack: Reading Variable Values with `scanf()` and `atoi()`

Formatted input read from standard input (e.g. keyboard)

`scanf(`*`format-string`*`, `*`expr`*$_1$`, `*`expr`*$_2$`, …);`

Converting string into integer

`int value = atoi(`*`string`*`);`

Example:

```
#include <stdio.h>   // includes definition of BUFSIZ (usually =512) and scanf()
#include <stdlib.h>  // includes definition of atoi()

...

char str[BUFSIZ];
int n;

printf("Enter a string: ");
scanf("%s", str);
n = atoi(str);
printf("You entered: \"%s\". This converts to integer %d.\n", str, n);
```

```
Enter a string: 9024
You entered: "9024". This converts to integer 9024.
```


Arrays and Functions

When an array is passed as a parameter to a function

- the address of the start of the array is actually passed

Example:

```
int total, vec[20];
…
total = sum(vec);
```

Within the function …

- the types of elements in the array are known
- the size of the array is unknown

... Arrays and Functions

Since functions do not know how large an array is:

- pass in the size of the array as an extra parameter, or
- include a "termination value" to mark the end of the array

So, the previous example would be more likely done as:

```
int total, vec[20];
…
total = sum(vec,20);
```

Also, since the function doesn't know the array size, it can't check whether we've written an invalid subscript (e.g. in the above example 100 or 20).

Exercise #6: Arrays and Functions

Implement a function that sums up all elements in an array.

Use the *prototype*

```
int sum(int[], int)
```

```
int sum(int vec[], int dim) {
   int i, total = 0;

   for (i = 0; i < dim; i++) {
      total += vec[i];
   }
   return total;
}
```

Multi-dimensional Arrays

Examples:

`float q[2][2];`

$$\begin{bmatrix} 0.5 & 2.7 \\ 3.1 & 0.1 \end{bmatrix}$$

`int r[3][4];`

$$\begin{bmatrix} 5 & 10 & -2 & 4 \\ 0 & 2 & 4 & 8 \\ 21 & 2 & 1 & 42 \end{bmatrix}$$

Note: `q[0][1]==2.7` `r[1][3]==8` `q[1]=={3.1,0.1}`

Multi-dimensional arrays can also be initialised:

```
float q[][] = {
   { 0.5, 2.7 },
   { 3.1, 0.1 }
};
```

Sidetrack: Defining New Data Types

C allows us to define new data type (names) via `typedef`:

`typedef` *`ExistingDataType`* *`NewTypeName`*`;`

Examples:

```
typedef float Temperature;

typedef int Matrix[20][20];
```

... Sidetrack: Defining New Data Types

Reasons to use `typedef`:

- give meaningful names to value types (documentation)
  - is a given number `Temperature`, `Dollars`, `Volts`, …?
- allow for easy changes to underlying type

```
typedef float Real;
Real complex_calculation(Real a, Real b) {
        Real c = log(a+b); … return c;
}
```

- "package up" complex type definitions for easy re-use
  - many examples to follow; `Matrix` is a simple example

Structures

A *structure*

- is a collection of variables, perhaps of different types, grouped together under a single name
- helps to organise complicated data into manageable entities
- exposes the connection between data within an entity
- is defined using the `struct` keyword

Example:

```
typedef struct {
       int day;
       int month;
       int year;
} DateT;
```

... Structures

One structure can be *nested* inside another:

```
typedef struct {
        int day, month, year;
} DateT;

typedef struct {
        int hour, minute;
} TimeT;

typedef struct {
        char   plate[7];   // e.g. "DSA42X"
        double speed;
        DateT  d;
        TimeT  t;
} TicketT;
```

... Structures

Possible memory layout produced for `TicketT` object:

```
---------------------------------
| D | S | A | 4 | 2 | X | \0|   |        7 bytes + 1 padding
---------------------------------
|                          68.4 |                8 bytes
-------------------------------------------------
|             27 |              7 |          2019|    12 bytes
-------------------------------------------------
|             20 |             45 |                8 bytes
---------------------------------
```

Note: padding is needed to ensure that `plate` lies on a 4-byte boundary.

Don't normally care about internal layout, since fields are accessed by name.

... Structures

Defining a structured data type itself does not allocate any memory

We need to declare a variable in order to allocate memory

```
DateT christmas;
```

The components of the structure can be accessed using the "dot" operator

```
christmas.day   =   25;
christmas.month =   12;
christmas.year  = 2019;
```

... Structures

With the above `TicketT` type, we declare and use variables as …

```
#define NUM_TICKETS 1500

typedef struct {…} TicketT;

TicketT tickets[NUM_TICKETS];  // array of structs

// Print all speeding tickets in a readable format
for (i = 0; i < NUM_TICKETS; i++) {
    printf("%s %6.3f %d-%d-%d at %d:%d\n", tickets[i].plate,
                                           tickets[i].speed,
                                           tickets[i].d.day,
                                           tickets[i].d.month,
                                           tickets[i].d.year,
                                           tickets[i].t.hour,
                                           tickets[i].t.minute);
}
```

... Structures

A structure can be passed as a parameter to a function:

```
void print_date(DateT d) {

        printf("%d-%d-%d\n", d.day, d.month, d.year);
}

int is_leap_year(DateT d) {

        return ( ((d.year%4 == 0) && (d.year%100 != 0))
                 || (d.year%400 == 0) );
}
```

Data Abstraction

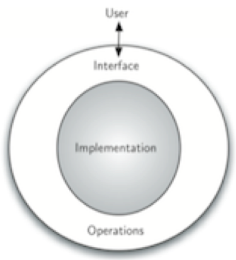
Abstract Data Types

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 a logical description of how we view the data and operations
- without regard to how they will be implemented
- creates an *encapsulation* around the data
- is a form of *information hiding*



... Abstract Data Types

Users of the ADT see only the *interface*

Builders of the ADT provide an *implementation*

ADT *interface* provides

- a user-view of the data structure
- 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 structures
- function implementations for all operations

... Abstract Data Types

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
- allow for reuse of modules in other systems

... Abstract Data Types

For a given data 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

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

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*

Applications:

- undo sequence in a text editor
- bracket matching algorithm
- …

... Example: Abstract Stack Data Object

Example of use:

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

a b c	pop	c
a b	isempty	false

Exercise #7: Stack vs Queue

93/108

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

95/108

Interface (a file named `Stack.h`)

```
// Stack ADO header file

#define MAXITEMS 10

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
```

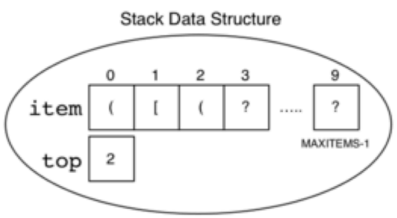
Note:

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

... Stack as ADO

96/108

Implementation may use the following data structure:



... Stack as ADO

97/108

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

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

// define the Data Structure
typedef struct {
   char item[MAXITEMS];
   int  top;
} stackRep;

// define the Data Object
static stackRep stackObject;

// 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
- `static` *`Type Var`* declares *`Var`* as *local* to `Stack.c`

Exercise #8: Bracket Matching

98/108

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

100/108

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

```
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

101/108

Execution trace of client on sample input:

```
( [ { } ] )
```

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

Exercise #9: Bracket Matching Algorithm

102/108

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

Exercise #10: Implement Bracket Matching Algorithm in C

104/108

- Use Stack ADT

  ```
  #include "Stack.h"
  ```

- *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 (keyboard: CTRL-D on Unix, CTRL-Z on Windows)

  ```
  int putchar(int ch);
  ```

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

Managing Abstract Data Types and Objects in C

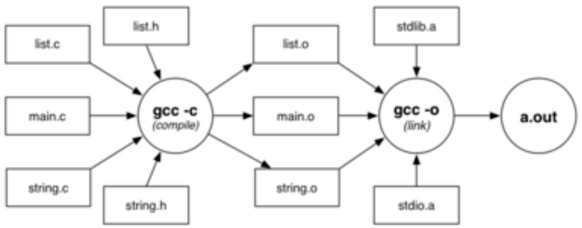
Compilers

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 brackets.c
produces brackets.o, from brackets.c and Stack.h

gcc -o rbt brackets.o Stack.o
links brackets.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`)

Summary

- Introduction to Algorithms and Data Structures
- C programming language, compiling with `gcc`
    - Basic data types (`char`, `int`, `float`)
    - Basic programming constructs (`if` … `else` conditionals, `while` loops, `for` loops)
    - Basic data structures (atomic data types, arrays, structures)
- Introduction to ADTs
    - Compilation

- Suggested reading (Moffat):
    - introduction to C … Ch. 1; Ch. 2.1-2.3, 2.5-2.6;
    - conditionals and loops … Ch. 3.1-3.3; Ch. 4.1-4.4
    - arrays … Ch. 7.1, 7.5-7.6
    - structures … Ch. 8.1
- Suggested reading (Sedgewick):
    - introduction to ADTs … Ch. 4.1-4.3

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