Week 01a: Introduction – Elementary Data and Control Structures in C

COMP9024 20T0

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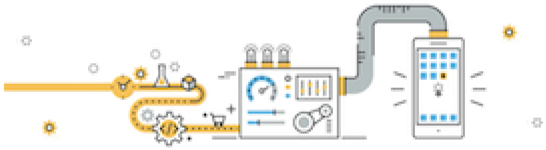
Data Structures and Algorithms



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Web Site: https://webcms3.cse.unsw.edu.au/COMP9024/20T0/

Course Convenor

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Research:	Machine Learning, Knowledge Based Systems, Artificial Intelligence

Course Goals

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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

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COMP9021 ...

... Course Goals

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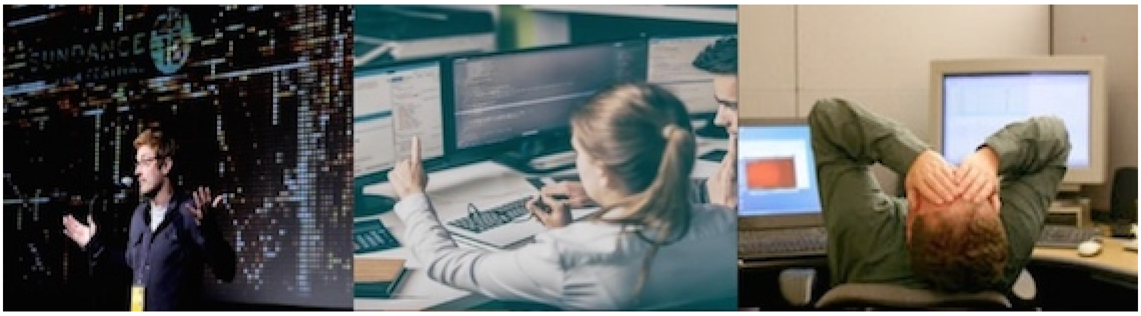
COMP9024 ...



Pre-conditions

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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

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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

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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

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All course information is placed on the main course website:

- https://webcms3.cse.unsw.edu.au/COMP9024/20T0/

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

Schedule

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Please note that the following schedule is subject to change.

Lecture Topic	Week(s)
Elementary data structures and algorithms in C	Week 1
Analysis of algorithms	Week 1–2
Dynamic data structures	Week 2
Graph data structures and algorithms	Week 2–3
Search tree data structures and algorithms	Week 3–4
Text Processing algorithms	Week 4
Ethics and Course review	Week 5

Assignment: Available at the end of week-1, due at 10am Monday 03 Feb 2020.

Credits for Material

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

The lecture slides are prepared by Michael Thielscher, and 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

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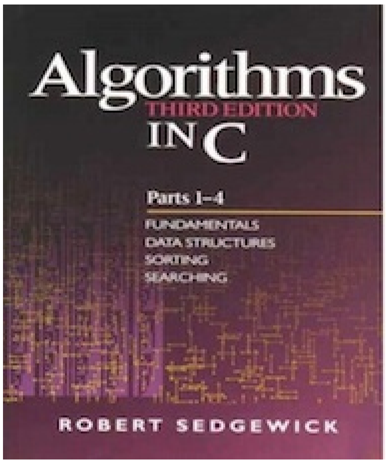
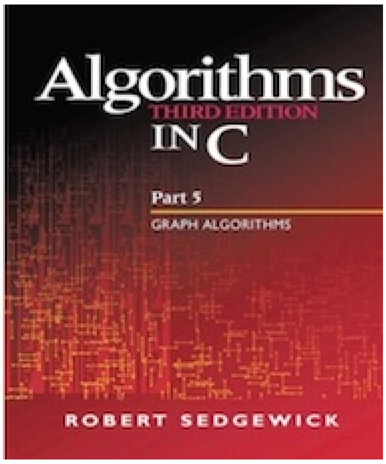
Textbook is a "double-header"

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





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

... Resources

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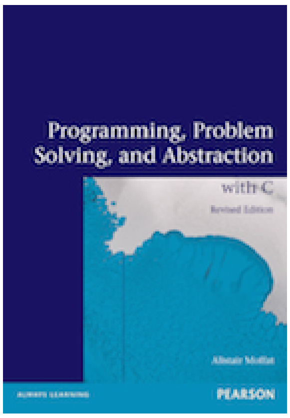
Supplementary textbook:

- 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

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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

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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!

Assignment

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The 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 later in Week-1.

The assignment contributes 30% to overall mark.

10% penalty will be applied to the maximum mark for every 24 hours late after the deadline.

- 1 day late: mark is capped at 27 (90% of the maximum possible mark)
- 2 days late: mark is capped at 24 (80% of the maximum possible mark)
- 3 days late: mark is capped at 21 (70% of the maximum possible mark)
- …

... Assignment

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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

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Just Don't Do it

We get very annoyed by people who plagiarise.

... Plagiarism

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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)

Help Sessions

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The *help Sessions*:

- 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

Time and Location – to be published later.

Attendance is entirely voluntary

Final Exam

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3-hour practical exam (in the CSE labs) during the exam period.

Format:

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

The final exam contributes 70% to overall mark.

Must score at least 35/70 in the final exam to pass the course.

... Final Exam

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How to pass the Final Exam:

- do the Homework *yourself*
- do the Homework *every week*
- practise programming outside classes
- read the lecture notes
- read the corresponding chapters in the textbooks

Assessment Summary

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```
assn  = mark for assignment (out of 30)
exam  = mark for final exam (out of 70)

if (exam >= 35)
   total = assn + exam
else
   total = exam * (100/70)
```

To pass the course, you must achieve:

- at least 35/70 for `exam`
- at least 50/100 for `total`

Summary

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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

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C Programming Language

Why C?

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- 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

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- 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

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- 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

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Basic Structure of a C Program

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```
// 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?

30/105

```
#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

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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

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```
#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`

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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`

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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

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Algorithms are built using

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

Assignments

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- 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

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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`?

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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

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

if (expression) {
   some statements1;
} else {
   some statements2;
}
```

- *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

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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) {
   statements1;
} else if (exp2) {
   statements2;
} else if (exp3) {
   statements3;
} else {
   statements4;
}
```

... Conditionals

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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

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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()`

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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

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C has two different "while loop" constructs

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

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

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

---

... Loops

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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?

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```
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

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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

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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

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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

55/105

- 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

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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

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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

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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

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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

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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

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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

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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

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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

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"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

65/105

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?

66/105

```
#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()`

68/105

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

69/105

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

70/105

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

71/105

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

73/105

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

74/105

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

75/105

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

76/105

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

77/105

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

78/105

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

79/105

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

80/105

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

81/105

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

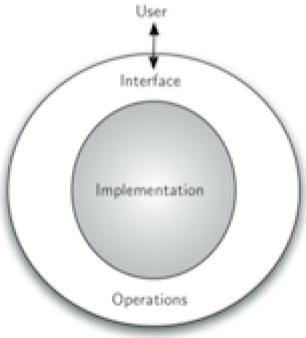
83/105

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

84/105

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

85/105

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

86/105

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

87/105

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

88/105

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

89/105

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

90/105

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

92/105

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

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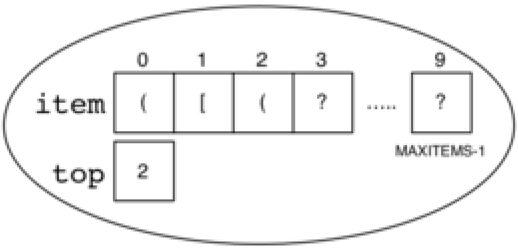
Implementation may use the following data structure:

Stack Data Structure



... Stack as ADO

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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() {
```

```
// 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;
```

```
    return (stackObject.top < 0);    }
}
```

- **`assert(test)`** terminates program with error message if *test* fails
- `static` *`Type Var`* declares *`Var`* as *local* to `Stack.c`

Exercise #8: Bracket Matching

95/105

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

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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

98/105

Execution trace of client on sample input:

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

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

Exercise #9: Bracket Matching Algorithm

99/105

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

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- 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

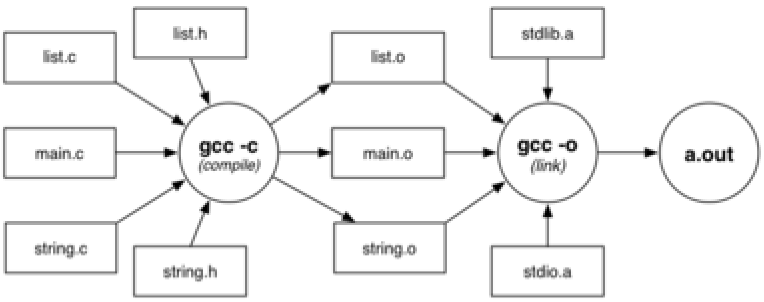
103/105

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

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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

105/105

- 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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