C

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Outline

Introduction

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This example comes from "The C Programming Language" by Brian Kernighan and Dennis Ritchie ("K&R")

Declarations

All variables must be declared before they can be used:

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char c = 'a';
char *s = "I am a string";
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An unqualified int is supposed to be the most efficient integral type on your machine, and is what you'd generally use unless there was some reason not to.

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CCD image data is typically created using a 16-bit A/D converter, so the natural type for a single pixel is a 2-byte integer.
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But C doesn't tell me how large an int is; I can find out (using sizeof (int)) but I don't want to have to change all my declarations when I move to a new system.
Actually, these days, I could say:

```
#include <stdint.h>
typedef uint16_t U16;
```

but even that only works if the processor actually has an unsigned 16-bit type.

Declarations

You can mix code and declarations:

```
int pwv = 0;                                   // Precipitable Water Va
/*
 * Estimate the PWV based on the altitude
 */
...;
/*
 * Given that estimate, find a better value
 */
const int pwv0 = pwv;                          /* initial estimate of p
```

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The ability to declare variables when they are first needed means that you can usually initialize them too; when possible, make them const.

Scope

A variable's *scope* is the part of the programme it may be referenced from; in C, a variable's scope is the nearest set of braces ({}), a *block*. If it isn't in a block, a variable is visible globally (i.e. it'll show up when you run nm on your object file). If this isn't what you wanted, you can:

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It is generally a good idea to declare a variable in as restricted a scope as possible (the "No Globals" rule is a special case of this one).

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If statements

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But we don't recommend it; it's too easy to write

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For loops

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CANNOT INCLUDE FILE src/for.c This only works with a compiler that supports the C99 standard (cc −−std=c99 ...) This is almost equivalent to:

```
#include <stdio.h>

int
main()
{
     int i = 0;
     while (i != 10) {
          printf("Hello world\n");
          ++i;
     }

     return 0;
}
```

Switch I

CANNOT INCLUDE FILE src/printf.c

Switch

```
$ make printf && ./printf
$ cc -g -Wall -O3 --std=c99    printf.c   -o printf
a
b
c
:
<space>
<integer>
%
<space>
d
o
n
e
<newline>
```

(N.b. The call was checkFormat("abc: %d%% done\n");)

Putting that together

CANNOT INCLUDE FILE src/switch.c

Subroutines

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That's a little clumsier — in Fortran (or python) you could have said x**2. And note the extra include file, **math.h**. In the old days you needed to link −lm too, but modern systems seem to be more forgiving.

Recursion

Subroutines may be called recursively — that is, they may call themselves, either directly or indirectly. There is no limit except the capacity of your computer. CANNOT INCLUDE FILE src/factorial.c

Recursion

That may not seem very interesting; it's easy enough to write a loop to calculate factorials.

However, consider a routine

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integrate ( float a, float b, float (*func)( float x)) 2
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However, consider a routine

`integrate(float a, float b, float (*func)(float x))` [2]

If I need to do a double integral, I can say something like:

```
static float yy;                        // current value of y

static float func(float x) {
   return sin(x)*cos(yy);
}

static float dfunc(float y) {
   yy = y;                              // pass y to func
   return integrate(0, y, func);
}

const double ans = integrate(1, 3, dfunc);
```

to calculate

Complete Example

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

double integrate(const float a, const float b, float (*func)(flo
      const int nstep = 1000;              // number of steps
      const float step = (b - a)/nstep;

      double ans = 0.0;
      float x = a;
      for (int i = 0; i != nstep; ++i) {
         ans += func(x);
         x += step;
      }

      return step*ans;
}

static float yy;                           // current value of y
```

Subroutine Arguments

Question: What does this do?

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   x *= 3;
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double x = 1;
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The solution is to pass a *pointer* to x:

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void triple(double @\color{red}*@x) {
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Fortran *always* passes arguments this way; a famous party trick when I

Prototypes

It is critically important that subroutines' callers and callees agree about the number and types of the arguments (the *signature*). C uses a *prototype* to allow the compiler to check; given

```
void triple(double *x) {
    *x *= 3;
}
```

we put the prototype `void triple(double *x);` in a header (".h") file and `#include` it in the file that defines `triple` and also whenever we call `triple`. [3]
This isn't a lot of extra work and soon becomes second nature.

[3] Most compilers these days will complain if you don't do this.

Arrays

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void foo(const int n) {
    int ids[n];
    ...
    double x = ids[n/2];
}
```

The index starts at *0* (not *1*, as in Fortran) as it specifies the distance from the start of the array.

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printf("ID0: %d\n", ids[0]);
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printf("ID0: %d\n", ids[0]);
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This may make more sense when we discuss *pointers*.

n-D Arrays

You can also define n-D arrays:

```
U16 data[4096][2048];
...
U16 const peak = data[y][x];                // the (x, y)th pixel
```

The data is stored row-by-row so the *last* index increases fastest if we access pixels in the order in which they're stored (unlike Fortran arrays, in which the *first* index varies fastest).

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n-D arrays aren't as useful as you might think as they are passed to subroutines as *pointers*; for now all you need to know is that you **must** specify all but the first dimension when passing an n-D array to a subroutine:

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```
void debias(U16 data[][2048], const int nrow, const int ncol) {
   ...
}
```

(hmm, I seem to have typed 2048 twice; was that a good idea. . . ?)

Operator Precedence

operator	associativity
`() [] -> .`	left to right
`! ~ ++ -- - (type) * & sizeof()`	right to left
`* / %`	left to right
`+ -`	left to right
`<< >>`	left to right
`< <= > >=`	left to right
`== !=`	left to right
`&`	left to right
`^`	left to right
`|`	left to right
`&&`	left to right
`||`	left to right
`?:`	right to left
`= += -=` etc.	right to left
`,`	left to right

Macros and the C Pre-Processor (*CPP*)

C provides a simple macro processor which can be used to keep *magic numbers* out of your code[3] instead of

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writing all macros in CAPITALS is a common convention.

Conditional Compilation

In the bad old days, we wrote lots of code like:

```
#if defined(vms)
   return -1;
#elif defined(HAVE_SELECT) && !defined(USE_POLL)
   if(select(ncheck,&mask,(fd_set *)NULL,(fd_set *)NULL,
              (void *)NULL) != 0) {
        ...
   }
#else
  /* Use poll() */
#endif
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```

Fortunately, in these days of Posix (`IEEE 1003`; `ISO/IEC 9945`) there is much less need for of this sort of thing. The (or at least my) main use of the CPP is:

```
#define DEBUG 1
...
#if DEBUG
int niter = 0;
```

Good uses for macros I

One standard use for macros is to prevent header files being parsed more than once

```
#if !defined(GREET_H)
#define GREET_H
/* Lots of stuff that should be processed only once */
#endif
```

This use of a macro is known as an *include guard*.

Good uses for macros II

CANNOT INCLUDE FILE src/macros.c

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```
$ make macros && macros 1 2 3
cc -g -Wall --std=c99 macros.c -o macros
macros.c:009: Hello world!
macros.c:010: My name is macros and I was called with 3 argument
```

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Unfortunately, this code does not conform to the C99 standard (`ISO 9899:1999`):

```
$ cc -g -Wall --std=c99 --pedantic-errors macros.c -o macros
macros.c:3:29: error: ISO C does not permit named variadic macro
macros.c:7:30: error: ISO C99 requires rest arguments to be used
```

Good uses for macros II

A legal version is: CANNOT INCLUDE FILE src/macros2.c Note that we were forced to pass at least one argument (hence the "" in the first call).

Bad uses for macros I

You can use the CPP to pretend that you're writing Algol, not C

```
#define IF      if(
#define THEN    ){
#define ELSE    } else {
#define ELIF    } else if (
#define FI      ;}

IF x == 0 THEN
   printf("zero\n");
ELIF x == 1 THEN
   printf("one\n");
ELSE
   printf("many\n");
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These macros come from the original Bourne shell source code in Unix Version 7.

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double funcs(const double x) {
   static int x = 0.5;
   x = sin(x);
   return x;
}

static int i = 0;
double gunks(const double x) {
   return (x < ++i) ? 5.6 : 5.9;
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Structs

If you routinely write code like:

```
void printObjects(const int n, const int id[],
                  const float xcen[], const float ycen[],
                  const float flux[]);

#define NOBJECT 1000                          // Maximum number of obj

int id[NOBJECT];                              // Object IDs
float xcen[NOBJECT];                          // x-coordinate of centr
float ycen[NOBJECT];                          // y-coordinate of centr
float flux[NOBJECT];                          // object's flux

for (int i = 0; i < n; ++i) {
   id[i] = i;
   xcen[i] = ...;
   ycen[i] = ...;
   flux[i] = ...;
}
```

Structs

A cleaner way to write this is:

```
struct Object {
   int id;                                   // Object IDs
   float xcen;                               // x-coordinate of centr
   float ycen;                               // y-coordinate of centr
};

typedef struct Object Object;

void printObjects(const int n, const Object objs[]);

#define NOBJECT 1000                         // Maximum number of obj

Object objs[NOBJECT];                        // our objects

for (int i = 0; i < n; ++i) {
   objs[i].id = i;
   objs[i].xcen = ...;
   objs[i].ycen = ...;
```

Structs

A cleaner way to write this is:

```
struct Object {
    int id;                                   // Object IDs
    float xcen;                               // x-coordinate of centr
    float ycen;                               // y-coordinate of centr
};

typedef struct Object Object;

void printObjects(const int n, const Object objs[]);

#define NOBJECT 1000                          // Maximum number of obj

Object objs[NOBJECT];                         // our objects

for (int i = 0; i < n; ++i) {
    objs[i].id = i;
    objs[i].xcen = ...;
```

Memory Allocation

You should be a little uneasy about NOBJECT in that last example. A number of questions come to mind:

- How did I know that I only had 1000 objects?
- What would I do if I had more?
- Am I wasting space if I have less?

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- How did I know that I only had 1000 objects?
- What would I do if I had more?
- Am I wasting space if I have less?

and also

- Where is the computer putting all those IDs and positions?

Inside your job

A running program consists of a number of pieces:

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- `heap` Memory available to the programmer

All of these are mapped into a single (logical) section of RAM:

0x0	text	data	bss	heap		stack

(`0x0` is how you write a hexadecimal number in C (or C++))

Stack and Heap

It's traditional to think of the heap and stack as growing down and up respectively:

heap	$\downarrow$
stack	$\uparrow$

The Stack

What happens when I call a function? E.g.

```
double integrate(const float a, const float b, float (*func)(flo
      const int nstep = 1000;             // number of steps
      const float step = (b - a)/nstep;
      ...
      ans += func(x);
}

double ans = integrate(1, 3, dfunc);
```

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<dfunc>
3.0
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We then make space for `step` and `nstep`

???
???
<dfunc>

The Stack

We initialised `step` to `1000` and `nstep` to `(b - a)/nstep`, so:

`0.002`
`1000`
`<dfunc>`
`3.0`
`1.0`

The Stack

We initialised `step` to `1000` and `nstep` to `(b - a)/nstep`, so:

0.002
1000
<dfunc>
3.0
1.0

Within `integrate` we call `dfunc` with argument `x`; this pushes `x` (`1.0`) onto the stack:

1.0
0.002
1000
<dfunc>
3.0
1.0

The Stack

within `dfunc` we calculate `y` (`1.0`) and call integrate (0, y, func) resulting in:

0.001
1000
<func>
1.0
0.0
1.0
0.002
1000
<dfunc>
3.0
1.0

And so on.

The Stack

When `integrate` has calculated its return value, it puts it somewhere and *pops* the stack:

1.0

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1000
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And finally the outer call to `integrate` finishes, saves its value, pops the stack, and we're back where we started.

Subroutine Arguments Redux

It should now be clear that:

- A language can **only** pass variables by value if it wishes to support recursion [4]
- Variables in subroutines are irretrievably lost when the routine returns
- Uninitialized values may have any value
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The last bullet suggests a way to work around the first one: we can push the variable's *address* onto the stack and agree to use not the value on the stack, but the value stored at that location.
In C, `&x` is `x`'s address, and `*px` means "use the value stored at the address `px`"

Pointers

A variable that holds an address is called a *pointer*; there's nothing magic about it; it just happens that you can apply the $*$ operator if you want to use the value it points to.

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```
int i = 0;
int *pi = &i;
printf("i = %d, %d\n", i, *pi);
*pi = 10;
printf("i = %d, %d\n", i, *pi);
```

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If you haven't ensured that a pointer is set to a valid address, you're going to suffer. If you say

```
int *pi;
*pi = 10;
printf("i = %d\n", *pi);
```

your program may well (and should!) crash.

Arrays

By definition, given any type type

```
int i;
type p[N];
p[i] == *(p + i);
p + i == &p[i]
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In fact, whenever you refer to an array (p), it is treated as a pointer to the first element ($\&p[0]$). This is why you can't pass an `n`-D array to a subroutine.

Strings

We introduced char * as a way of spelling "string" and we can now see how it works.

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The statement `char *str = "abcdef";` is analogous to `float *x = &xx;`, and `*str` is indeed `a`.

The difference between `char *str = "abcdef";` and `char str[7] = "abcdef";` is where the data is actually stored; in the former case it's in the `data` segment, in the latter case it's on the stack.

Structs revisited

Convinced of the value of a `struct` such as

```
struct Object {
   int id;                              // Object IDs
   float xcen;                          // x-coordinate of centr
   float ycen;                          // y-coordinate of centr
};

typedef struct Object Object;
```

I wrote a convenience function:

```
Object *newObject(const int id, const float xcen, const double y
   Object obj;

   obj.id = id;
   obj.xcen = xcen;
   obj.ycen = ycen;

   return &obj;
}
```

Malloc

After some time spent in gdb, I remembered:

- Variables in subroutines are irretrievably lost when the routine returns

and that's exactly what this does:

```
Object *newObject(const int id, const float xcen, const double y
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The solution is to get a pointer to a piece of persistent memory. C provides this via a call to malloc:

```
#include <stdlib.h>

Object *newObject(const int id, const float xcen, const double y
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#define NOBJECT 1000                          // Maximum number of obj

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n = ...;
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If you don't know `n` *a priori*, look up the system call realloc . There is also calloc, but I never use it — initialising to 0x0 is a blunt weapon.

Free

As I said, malloc returns persistent memory, so it's important to return it to the system when you've finished with it:

```
for (int i = 0; i != n; ++i) {
   free(objects[i]);
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Freeing a piece of memory more than once usually has catastrophic consequences; don't do it.
Another failure mode is that sometimes malloc can't give you the memory you want. In this case it returns `0`, conventionally written `NULL`.
There is not much you can do when this happens, so a reasonable response is to abort:

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

Object *newObject(const int id, const float xcen, const double y
   Object @\color{red}*@obj = malloc(sizeof(Object));
```

struct and typedef

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struct Object {
    int id;                                     // Object IDs
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There are two reasons why you might not always want to omit the name in struct Object {...} :

- structs can contain pointers to themselves:

  ```
  typedef struct List {
      struct List *prev, *next;
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CCD Data again

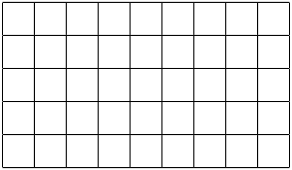
You will recall a code fragment that looked like this:

```
U16 data[4096][2048];
...
U16 const peak = data[y][x];               // the (x, y)th pixel
...
void debias(U16 data[][2048], const int nrow, const int ncol);
```

We are now in a position to do better.

CCD Data again

We need a 2-D `ncol*nrow` array of type `U16`



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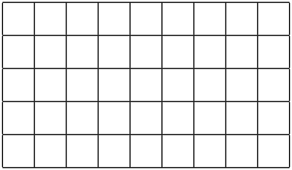
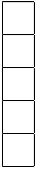


Create an 1-D array `rows` of type `U16 *` and dimension `nrow`



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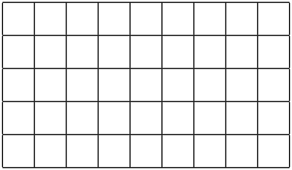

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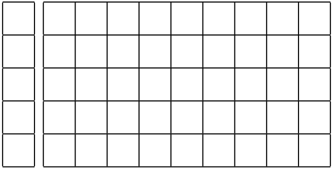

Make each element of `rows` point to the start of a row, e.g. `rows[1]` points to the first pixel in the second row of data. Then `rows[1][2]` is the value of the `(2, 1)` pixel.

CCD Data again

```
#include <stdlib.h>
#include <stdint.h>
#include <assert.h>

typedef uint16_t Pixel_t;

struct Image {
     Pixel_t **rows;
     int nrow, ncol;
};
typedef struct Image Image;

Image *newImage(const int ncol, int const nrow) {
     Image *im = malloc(sizeof(Image));   // the Image
     assert (im != NULL);

     im->rows = malloc(nrow*sizeof(Pixel_t *)); // pointers to r
     assert (im->rows != NULL);
```

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Matrices

Now we know enough to write ourselves a matrix library

```
  typedef struct Matrix {
     float **data;
     int nrow;
     int ncol;
  };

  Matrix *newMatrix(int nrow, int ncol);
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  Matrix *A = newMatrix(10, 10);
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... not until you switch to C++.

[3] In C++ you'd probably use a const variable but scoping rules are different in C, so a macro is appropriate

[4] this isn't quite true; it could pass a limited number of variables by using *registers*