C programming I

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Why program in C?

Speed!

A poorly written C program can be faster than the most efficient R or Perl program.

C, Perl, and R

C	Serious computation
Perl	Text manipulation
R	Graphics and interactive analysis

A serious statistician should be fluent in all of these languages!

How to learn a programming language

- Get a good book.
- Experiment on the computer.
- Find some good problems to work on.
- Look at others' code.
- Use the language routinely.

Suggested books

- Kernighan, Ritchie (1988) *The C Programming Language*, 2nd edition. Prentice Hall.
- Plauger (1992) *The Standard C Library*. Prentice Hall.
- Koenig (1989) *C Traps and Pitfalls*. Addison-Wesley.
- Venables, Ripley (2000) *S Programming*. Springer.
- Press et al. (1993) *Numerical Recipes in C*, 2nd ed. Cambridge Univ. Press
- Miller, Quilici (1997) *The Joy of C*, 3rd edition. Wiley.
- Reek (1997) *Pointers on C*. Addison-Wesley.
- Prata (2001) *C Primer Plus*, 4th edition. SAMS.
- van der Linden (1994) *Expert C Programming*. Prentice Hall.
- Summit (1995) *C Programming FAQs*. Addison-Wesley.
- King (1996) *C Programming: A Modern Approach*. WW Norton.
- Oualline (1997) *Practical C Programming*, 3rd edition. O'Reilly.
- Harbison, Steele (2002) *C: A Reference Manual*, 5th edition. Prentice Hall.

A first, simple program

```
/* prog1a.c */
main()
{
    double x, y;

    printf("Enter first number: ");
    scanf("%lf", &x);

    printf("Enter second number: ");
    scanf("%lf", &y);

    printf("The sum is %f\n", x+y);
}
```

Actually should be...

```
/* prog1b.c */
#include <stdio.h>       /* contains function declarations */

int main()               /* returns an integer */
{
    double x, y;

    printf("Enter first number: ");
    scanf("%lf", &x);

    printf("Enter second number: ");
    scanf("%lf", &y);

    printf("The sum is %f\n", x+y);

    return(0);           /* exit normally (no errors) */
}
```

Compiling the program

Say the program is in the file `myprog.c`.

You compile it by typing

```
gcc -o myprog myprog.c
```

or typing

```
gcc -Wall -o myprog myprog.c -lm
```

This produces an executable, `myprog`, which you can execute my just typing its name.

Note: `-Wall` results in extra warning messages; `-lm` indicates to link the math library (for stuff like `sqrt` and `sin`).

The program `lint` (see also `splint`) analyzes C programs for potential problems.

Declarations

`char` — character variable (a one-byte integer)
`int` — “natural” integer
`long` — the longest integer available
`short` — the smallest (potentially) integer

Also: `unsigned int`, `unsigned long`, `unsigned short`

`float` — (potentially) single precision
`double` — largest floating point number available

`void` — for functions which don’t return a value

All functions should be declared!

For example:

```
double myfunc(double x, double y);
long secfunc(void);
```

Arrays

Any type of object may be declared as an array.

```
double x[10];
```

The elements: `x[0]`, `x[1]`, . . . , `x[9]`

The array index is an offset in memory.

Header files

Pull in function declarations. (No executable code!)

Found in `/usr/include`
(common subdirectory `/usr/include/sys`)

For example:
`math.h` — common math functions
`stdio.h` — print functions
`stdlib.h` — general utilities

Put (at the top of the program)
```
#include <math.h>
```

Put declarations for your own functions in your own header file (e.g., `myprog.h`) and use the following:
```
#include "myprog.h"
```

Constants

integer: Just use the number (e.g., `21`)

long integer: Use an "L" after the number (e.g., `21L`)

double: Use the number with a decimal point or E-notation
(e.g. `21.` or `21.0` or `21e0`)

float: Use the number and "f" or "F". (e.g. `21f`)

character: Use single quotes (e.g. `'a'`)

special characters: `'\n'` `'\t'` `'\\'` `'\''` `'\"'`

character strings: Use double quotes (e.g., `"a string"`)

Strings are arrays of characters terminated by `'\0'`
– `'\0'` is the character whose value is 0
– Note that `'\0'` ≠ `'0'`

Operators

- Arithmetic operators

  Binary: `+` `-` `*` `/` `%`

  Urinary: `-` (change sign)

  Note: `pow` does exponentiation:

  `double pow(double, double)` (see `<math.h>`)

  e.g., `x3 = pow(x, 3.0);`

- Relational operators

  `>` `>=` `<` `<=` `==` `!=`

  e.g., `j = (x>3.0);` (Be careful about = versus ==)

- Logical operators

  `!` `&&` `||`

Combining logical operators

```
if(i > 10 && (x=getthat()) ) { ... }
```

Note: if `i>10` is FALSE, `getthat()` won't be called.

"Side effect": e.g., in an && statement, the thing on the right is only evaluated if the thing on the left is TRUE.

Suggestion: Use parentheses freely.

Suggestion: In using ==, <=, etc., try to ensure that both sides are of the same variable type.

Type casting

```
#include <math.h>                /* prog2.c */

int i;
double x;

i=3;

x = sqrt( (double)i );

/* NOT:     x = sqrt(i); */
```

Suggestion: If you are in doubt about how a computer will interpret a number, go ahead and use the casts; it won't slow down your program.

Increment, decrement and assignment

```
i = i + 1;     i += 1;     i++;

i = i - 1;     i -= 1;     i--;
```

Postfix version (e.g., `i++`): use the variable's value, then increment or decrement.

Prefix version (e.g., `++i`): Increment or decrement, then use the variable's (new) value.

```
if(++nobs > 10) { ... }
```
versus
```
if(nobs++ > 10) { ... }
```

Suggestion: Avoid constructions where the prefix vs. postfix version matters.

Bitwise operators

&	bitwise and
|	bitwise or
^	bitwise exclusive or
<<	left bitshift
>>	right bitshift
~	unary ones complement (1 → 0 and 0 → 1)

If-else statements

```
/*1*/    if(x > 0) x *= -1.0;

/*2*/    if(x > 0) {
              x = sqrt(x);
              y /= x;
          }


/*3*/    if(n>0) {
              for(i=0; i<n; i++)
                  if(fabs(s[i]) > 1e-8)
                      y[i] = z[i]/s[i];
          }
          else printf("n is 0\n");
```

Suggestion: Use { } freely.

while loop

```
/*1*/    while(x > y) {
             ...
         }
```

1. Evaluate expression
2. If TRUE, execute statements in the block and go back to top
3. If FALSE, skip on to the next thing.

```
/*2*/    while(1) { ... }     /* infinite loop */

/*3*/    while(x>y); {     /* an error! */
             ...
         }
```

do-while loop

```
    do {
        ...
    } while(x > y);
```

1. Execute statements.
2. Evaluate statements in the block.
3. If TRUE, go back to the top.
4. If FALSE, skip on to the next thing.

for loop

```
expr1;
while(expr2) {
    ...
    expr3;
}
```

```
for(expr1; expr2; expr3) {
    ...
}
```

1. Execute expression `expr1`.
2. Evaluate expression `expr2`.
3. If TRUE, execute the block, execute expression `expr3`, and go back to 2.
4. If FALSE, skip on to the next thing.

Example for loops

```
/*1*/    sum = 0.0;
         for(i=0; i<n; i++) sum += x[i];

/*2*/    for(i=0; i<n && sum < 100; i++)
         sum += x[i];

/*3*/    for(i=0, j=0; i<n && j<n; i++, j++) { ... }

/*4*/    for( ; i<n; i++) { ... }

/*5*/    r = unif_rand();
         for(i=0; i<n; i++) {
             if(r < p[i]) return(i+1);
             else r -= p[i];
         }
         return(n); /* this shouldn't happen */
```

break and continue

`break`: Immediately exit from a loop.

`continue`: Jump to the next iteration of a loop

```
i=0;                              /* prog3.c */
while(1) {
    i++;
    if(i % 2) continue;
    printf("  %2d\n", i);
    if(i>10) break;
}
```

Pointers

A pointer is a variable whose value is the address of an object in memory.

Every object type (e.g., `int`, `double`) has its own separate type of pointer.

```
double *x;      /* pointer to double */
int    *y;      /* pointer to integer */

double *z, w;   /* z is pointer to double */
                /* w is a double */
```

Pointer operators

`&` Address operator

When applied to an object, returns the address of that object

`*` Dereference operator

When applied to a pointer to an object, returns the value at the address "pointed to."

```
double x;              /* prog4.c */
double *dp;

x = 12.0;
dp = &x;

printf("%g\n", *dp);
printf("%x\n", dp);   /* should put (unsigned int)dp */
```

Uses of pointers

1. Passing arguments that need to be modified.

In C, the values of arguments are passed to functions. Thus, a function usually only has access to copies of its arguments. If you send pointers as arguments, you can go to the addresses and change the values there.

```
void swap(int *a, int *b)    /* prog5.c */
{
  int temp;

  temp = *a;
  *a = *b;
  *b = temp;
}
```

Call this function as follows:

```
int i=3, j=5;

swap(&i, &j);
```

Uses of pointers

2. Pointers vs. arrays

If we declare an array

`int ix[10];`

a location in memory will be found that has enough memory assigned to it to hold 10 integers. `ix` is a pointer to that address in memory. Subscripting is just a dereference operation.

`*ix` is the same as `ix[0]`.

`*(ix+3)` is the same as `ix[3]`.

`*(ix+i)` is the same as `ix[i]`.

```
int ix[10], *ip;

ip=ix;      /* the name of an array is a pointer to */
            /* its first element */

ip += 3;    /* now ip points to the addr of ix[3] */
            /* Note: We can modify ip but not ix. */
```

Uses of pointers

3. Dynamic memory allocation

Dynamic memory allocation allows you to find the memory you need, and to associate it with a pointer, while the program is running. So there's no need for "can't have more than 10,000 observations."

`malloc` and `calloc` — allocate memory

`free` — free allocated memory

```
void *malloc(size_t size);
void *calloc(size_t number, size_t size);
void free(void *ptr);
```

Uses of pointers

3. Dynamic memory allocation: Example

```
#include <stdlib.h>                    /* prog6.c */

double *x, *y;
int n;

n=20;

x = (double *)malloc(n*sizeof(double));
y = (double *)calloc(n, sizeof(double));
if(x==NULL || y==NULL) {
  printf("Error: cannot allocate space for x and y\n");
  exit(EXIT_FAILURE);
}

free(x);
free(y);

/* Note: The values of x and y are unchanged */
```

Uses of pointers

4. 2-dimensional (and multi-dimensional) arrays

   a. Use the built-in version.

```
/* prog7a.c */
#include <stdio.h>

int i, j;
int x[3][6];    /* 3 rows and 6 columns */
                /* stored by rows */

for(i=0; i<3; i++) {
    for(j=0; j<6; j++) {
        x[i][j] = i+j;

        printf(" row=%d col=%d  addr=%u  value=%d\n",
               i, j, (unsigned int)&x[i][j], x[i][j]);
    }
}
```

Advantage:	Easy.
Disadvantages:	Pre-determined size and must be a rectangle.

Uses of pointers

4. 2-dimensional (and multi-dimensional) arrays

a. Use the built-in version.

In your mind

0	1	2	3	4	5
6	7	8	9	10	11
12	13	14	15	16	17

When you declare an array as x[3][6],
x[i][j] is interpreted as x[i*6 + j]
which is the same as *(x + i*6 + j)

x

In memory

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

Uses of pointers

4. 2-dimensional (and multi-dimensional) arrays

b. Use a one-dimensional array.

```
/* prog7b.c */
#include <stdlib.h>
#include <stdio.h>
int i, j, nr=3, nc=6, *x;

x = (int *)calloc(nr*nc, sizeof(int));
if(x==NULL) { /* error */ }

for(i=0; i<nr; i++) {
    for(j=0; j<nc; j++) {
        x[i + j*nr] = i+j; /* stored by columns */

        printf(" row=%d col=%d  addr=%u  value=%d\n",
               i, j, (unsigned int)(x+i+j*nr), x[i+j*nr]);
    }
}
free(x);
```

Advantages: Dynamic memory allocation, flexible shape.

Disadvantages: Cumbersome, ugly, prone to errors.

Uses of pointers

4. 2-dimensional (and multi-dimensional) arrays

   b. Use a one-dimensional array.

In your mind

0	3	6	9	12	15
1	4	7	10	13	16
2	5	8	11	14	17

x[i + j*3] is the same as *(x + i + j*3)

x ↓

In memory

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

Uses of pointers

4. 2-dimensional (and multi-dimensional) arrays

   c. Allocate and parse a block.

```
/* prog7c.c */
#include <stdlib.h>
#include <stdio.h>
int i, j, nr=3, nc=6, **x, *temp;

/* allocate space */
temp = (int *)calloc(nr*nc, sizeof(int));
x = (int **)calloc(nr, sizeof(int *));

if(temp==NULL || x==NULL) { /* error */ }

/* make x point to the beginning of each row */
for(i=0; i<nr; i++) x[i] = temp+i*nc;

for(i=0; i<nr; i++)
    for(j=0; j<nc; j++)
        x[i][j] = i+j;

free(x);
free(temp);
```

Uses of pointers

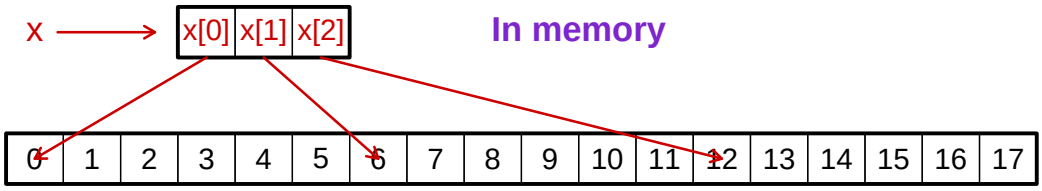
4. 2-dimensional (and multi-dimensional) arrays

   c. Allocate and parse a block: Another version.

In your mind

0	1	2	3	4	5
6	7	8	9	10	11
12	13	14	15	16	17

x[i][j] is the same as *(*(x+i) +j)



Uses of pointers

4. 2-dimensional (and multi-dimensional) arrays

   c. Allocate and parse a block: Another version.


```
#include <stdlib.h>
#include <stdio.h>
int i, j, nr=3, nc=6, **x;

/* allocate space for the pointers to each row */
x = (int **)calloc(nr, sizeof(int *));
if(x==NULL) { /* error */ }

/* allocate space for the actual matrix */
x[0] = (int *)calloc(nr*nc, sizeof(int));
if(x[0]==NULL) { /* error */ }

/* make x point to the beginning of each row */
for(i=1; i<nr; i++) x[i] = x[0]+i*nc;

for(i=0; i<nr; i++)
    for(j=0; j<nc; j++)
        x[i][j] = i+j;

free(x[0]);     /* have to do this first */
free(x);
```

Uses of pointers

4. 2-dimensional (and multi-dimensional) arrays

   c. Allocate and parse a block.

Advantages:	Dynamic memory allocation, flexible shape, referred to in natural way.
Disadvantages:	Stored by rows, a bit of work to set up, a tiny bit of extra memory required.

Uses of pointers

4. 2-dimensional (and multi-dimensional) arrays

   d. Allocate each row or column.

```
/* prog7d.c */
#include <stdio.h>
#include <stdlib.h>
int i, j, nr=3, nc=6, **x;

/* allocate space for the pointers to each row */
x = (int **)calloc(nr, sizeof(int *));
if(x==NULL) { /* error */ }

/* allocate space for each row */
for(i=0; i<nr; i++) {
    x[i] = (int *)calloc(nc, sizeof(int));
    if(x[i]==NULL) { /* error */ }
}

for(i=0; i<nr; i++)
    for(j=0; j<nc; j++)
        x[i][j] = i+j;

for(i=0; i<nr; i++) free(x[i]);
free(x);
```

Uses of pointers

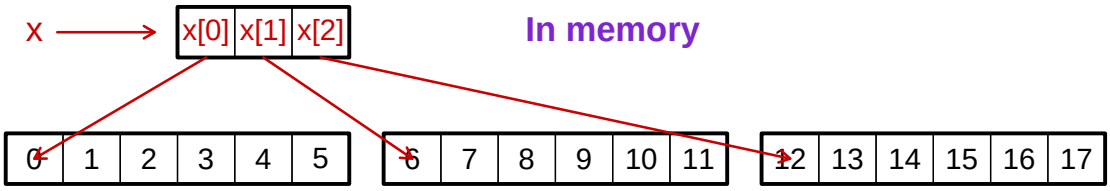
4. 2-dimensional (and multi-dimensional) arrays

   d. Allocate each row or column.

In your mind

0	1	2	3	4	5
6	7	8	9	10	11
12	13	14	15	16	17

x[i][j] is the same as *(*(x+i) +j)



Uses of pointers

4. 2-dimensional (and multi-dimensional) arrays

   d. Allocate each row or column.

Advantages: Dynamic memory allocation, flexible shape, even easier to have columns of different lengths, referred to in natural way.

Disadvantages: Stored by rows, not contiguous memory, a bit of work to set up and take down, a tiny bit of extra memory required.

Example: multi-dimensional array

```
#include <stdio.h>                /* prog8.c */
#include <stdlib.h>
int i, j, k, dim1=4, dim2=5, dim3=3;
int ***x, *temp;

temp = (int *)calloc(dim1*dim2*dim3, sizeof(int));
if(temp==NULL) { /* error */ }

x = (int ***)calloc(dim1, sizeof(int **));
if(x==NULL) { /* error */ }

for(i=0; i<dim1; i++) {
    x[i] = (int **)calloc(dim2, sizeof(int *));
    if(x[i]==NULL) { /* error */ }

    /* make things point properly */
    for(j=0; j<dim2; j++) x[i][j] = temp+(i*dim2+j)*dim3;
}

for(i=0; i<dim1; i++)
    for(j=0; j<dim2; j++)
        for(k=0; k<dim3; k++)
            x[i][j][k] = i+j+k;

for(i=0; i<dim1; i++) free(x[i]);
free(x);   free(temp);
```

Uses of pointers

5. Calling C from R

When you call a C function from R, everything is a pointer. We'll look at how to do that later.

Care with pointers

- Don’t access/modify areas of memory that you don’t have rights to.
- Be careful about going off the ends of arrays.
- Check that calloc/malloc worked.
- Free allocated memory before exiting.

printf control codes

```
#include <stdio.h>                      /* prog9.c */
double x;


printf("-->|%d|<--", 123);              -->|123|<--
printf("-->|%5d|<--", 123);             -->|  123|<--
printf("-->|%-5d|<--", 123);            -->|123  |<--


printf("-->|%s|<--", "hello");           -->|hello|<--
printf("-->|%9s|<--", "hello");          -->|    hello|<--
printf("-->|%-9s|<--", "hello");        -->|hello    |<--


x = -17.89306213;
printf("-->|%f|<--", x);                -->|-17.893062|<--
printf("-->|%7.2f|<--", x);             -->| -17.89|<--


printf("-->|%e|<--", x);                -->|-1.789306e+01|<--
printf("-->|%g|<--", x);                -->|-17.8931|<--
```