The C Language Reference Manual

Stephen A. Edwards

Columbia University

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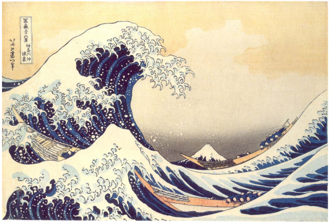


Katsushika Hokusai, *In the Hollow of a Wave off the Coast at Kanagawa*, 1827

Language Design Issues

Syntax: how programs look

- Names and reserved words
- Instruction formats
- Grouping

Semantics: what programs mean

- Model of computation: sequential, concurrent
- Control and data flow
- Types and data representation

Part I

The History of C

C History

Developed between 1969 and 1973 along with Unix

Due mostly to Dennis Ritchie

Designed for systems programming

- Operating systems
- Utility programs
- Compilers
- Filters

Evolved from B, which evolved from BCPL

BCPL

Martin Richards, Cambridge, 1967

Typeless

- Everything a machine word (n-bit integer)
- Pointers (addresses) and integers identical

Memory: undifferentiated array of words

Natural model for word-addressed machines

Local variables depend on frame-pointer-relative addressing: no dynamically-sized automatic objects

Strings awkward: Routines expand and pack bytes to/from word arrays

BCPL Example: 8 Queens

```
GET "libhdr"
GLOBAL { count:ug; all  }

LET try(ld, row, rd) BE
  TEST row=all
  THEN count := count + 1
  ELSE { LET poss = all & ~(ld | row | rd)
         WHILE poss DO
         { LET p = poss & -poss
           poss := poss - p
           try(ld+p << 1, row+p, rd+p >> 1)
         }
       }

LET start() = VALOF
{ all := 1
  FOR i = 1 TO 16 DO
  { count := 0
    try(0, 0, 0)
    writef("Number of solutions to %i2-queens is %i7*n", i, count)
    all := 2*all + 1
  }
  RESULTIS 0
}
```

C History

Original machine, a DEC PDP-11, was very small:

24K bytes of memory, 12K used for operating system

Written when computers were big, capital equipment

Group would get one, develop new language, OS

C History

Many language features designed to reduce memory

- Forward declarations required for everything
- Designed to work in one pass: must know everything
- No function nesting

PDP-11 was byte-addressed

- Now standard
- Meant BCPL's word-based model was insufficient

Euclid's Algorithm in C

```
int gcd(int m, int n)
{
  int r;
  while ((r = m % n) != 0) {
    m = n;
    n = r;
  }
  return n;
}
```

"New syle" function declaration lists number and type of arguments.

Originally only listed return type. Generated code did not care how many arguments were actually passed, and everything was a word.

Arguments are call-by-value

Euclid's Algorithm in C

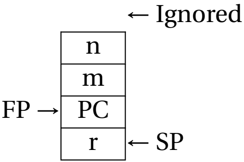
```c
int gcd(int m, int n)
{
  int r;
  while ((r = m % n) != 0) {
    m = n;
    n = r;
  }
  return n;
}
```

Automatic variable *r*

Allocated on stack when function entered, released on return

Parameters & automatic variables accessed via frame pointer

Other temporaries also stacked



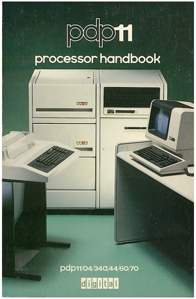
Euclid on the PDP-11

```
    .globl _gcd         GPRs: r0–r7
    .text               r7=PC, r6=SP, r5=FP
_gcd:
    jsr r5, rsave       Save SP in FP
L2: mov 4(r5), r1       r1 = n
    sxt r0              sign extend
    div 6(r5), r0       r0, r1 = m ÷ n
    mov r1, -10(r5)     r = r1 (m % n)
    jeq L3              if r == 0 goto L3
    mov 6(r5), 4(r5)    m = n
    mov -10(r5), 6(r5)  n = r
    jbr L2
L3: mov 6(r5), r0       r0 = n
    jbr L1              non-optimizing compiler
L1: jmp rretrn          return r0 (n)
```

Euclid on the PDP-11

```
    .globl _gcd
    .text
_gcd:
    jsr r5, rsave
L2: mov 4(r5), r1
    sxt r0
    div 6(r5), r0
    mov r1, -10(r5)
    jeq L3
    mov 6(r5), 4(r5)
    mov -10(r5), 6(r5)
    jbr L2
L3: mov 6(r5), r0
    jbr L1
L1: jmp rretrn
```

Very natural mapping from C into PDP-11 instructions.



Complex addressing modes make frame-pointer-relative accesses easy.

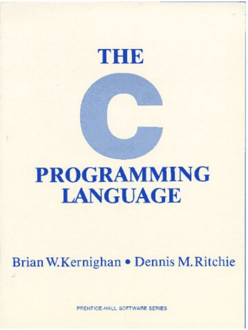
Another idiosyncrasy: registers were memory-mapped, so taking address of a variable in a register is straightforward.

Part II

The Design of C

Taken from Dennis Ritchie's *C Reference Manual*

(Appendix A of Kernighan & Ritchie)



Lexical Conventions

Identifiers (words, e.g., `foo`, `printf`)

Sequence of letters, digits, and underscores, starting with a letter or underscore

Keywords (special words, e.g., `if`, `return`)

C has fairly few: only 23 keywords. Deliberate: leaves more room for users' names

Comments (between `/*` and `*/`)

Most fall into two basic styles: start/end sequences as in C, or until end-of-line as in Java's `//`

Lexical Conventions

C is a *free-form* language where whitespace mostly serves to separate tokens. Which of these are the same?

```
1+2
1 + 2
foo bar
foobar
```

```
return this
returnthis
```

Space is significant in some language. Python uses indentation for grouping, thus these are different:

```
if x < 3:
  y = 2
  z = 3
```

```
if x < 3:
  y = 2
z = 3
```

Constants/Literals

Integers (e.g., `10`)

Should a leading – be part of an integer or not?

Characters (e.g., `'a'`)

How do you represent non-printable or `'` characters?

Floating-point numbers (e.g., `3.5e-10`)

Usually fairly complex syntax, easy to get wrong.

Strings (e.g., `"Hello"`)

How do you include a `"` in a string?

What's in a Name?

In C, each name has a storage class (where it is) and a type (what it is).

Storage classes:

1. automatic
2. static
3. external
4. register

Fundamental types:

1. `char`
2. `int`
3. `float`
4. `double`

Derived types:

1. arrays
2. functions
3. pointers
4. structures

Objects and lvalues

Object: area of memory

lvalue: refers to an object

An lvalue may appear on the left side of an assignment

```
a = 3; /* OK: a is an lvalue */
3 = a; /* 3 is not an lvalue */
```

Conversions

C defines certain automatic conversions:

- A `char` can be used as an `int`
- `int` and `char` may be converted to `float` or `double` and back. Result is undefined if it could overflow.
- Adding an integer to a pointer gives a pointer
- Subtracting two pointers to objects of the same type produces an integer

Expressions

Expressions are built from identifiers (`foo`), constants (`3`), parenthesis, and unary and binary operators.

Each operator has a precedence and an associativity

Precedence tells us

`1 * 2 + 3 * 4` means

`(1 * 2) + (3 * 4)`

Associativity tells us

`1 + 2 + 3 + 4` means

`((1 + 2) + 3) + 4`

C’s Operators in Precedence Order

```
f(r,r,...)  a[i]      p->m        s.m
!b          ~i        -i
++l         --l       l++         l--
*p          &l        (type) r    sizeof(t)
n * o       n / o     i % j
n + o       n - o
i << j      i >> j
n < o       n > o     n <= o      n >= o
r == r      r != r
i & j
i ^ j
i | j
b && c
b || c
b ? r : r
l = r       l += n    l -= n      l *= n
l /= n      l %= i    l &= i      l ^= i
l |= i      l <<= i   l >>= i
r1 , r2
```

Declarators

Declaration: string of specifiers followed by a declarator

basic type: `int`

```
static unsigned int(*f[10])(int, char*);
```

specifiers: `static unsigned int` — declarator: `(*f[10])(int, char*);`

Declarator's notation matches that of an expression: use it to return the basic type.

Largely regarded as the worst syntactic aspect of C: both pre- (pointers) and post-fix operators (arrays, functions).

Storage-Class Specifiers

`auto`	Automatic (stacked), default
`static`	Statically allocated
`extern`	Look for a declaration elsewhere
`register`	Kept in a register, not memory

C trivia: Originally, a function could only have at most three `register` variables, may only be `int` or `char`, can't use address-of operator &.

Today, `register` simply ignored. Compilers try to put most automatic variables in registers.

Type Specifiers

`int`

`char`

`float`

`double`

`struct {` *declarations* `}`

`struct` *identifier* `{` *declarations* `}`

`struct` *identifier*

Declarators

identifier	
(*declarator*)	Grouping
declarator ()	Function
declarator [*optional-constant*]	Array
* *declarator*	Pointer

C trivia: Originally, number and type of arguments to a function wasn't part of its type, thus declarator just contained `()`.

Today, ANSI C allows function and argument types, making an even bigger mess of declarators.

Declarator syntax

Is `int *f()` a pointer to a function returning an `int`, or a function that returns a pointer to an `int`?

Hint: precedence rules for declarators match those for expressions.

Parentheses resolve such ambiguities:

`int *(f())`	Function returning pointer to `int`
`int (*f)()`	Pointer to function returning `int`

Statements

expression ;
{ *statement-list* }
`if (` *expression* `)` *statement* `else` *statement*
`while (` *expression* `)` *statement*
`do` *statement* `while (` *expression* `);`
`for (` *expression* `;` *expression* `;` *expression* `)` *statement*
`switch (` *expression* `)` *statement*
`case` *constant-expression* `:`
`default:`
`break;`
`continue;`
`return` *expression* `;`
`goto` *label* `;`
label `:`

External Definitions

“A C program consists of a sequence of external definitions”

Functions, simple variables, and arrays may be defined.

“An external definition declares an identifier to have storage class `extern` and a specified type”

Function definitions

```
type-specifier declarator ( parameter-list )
type-decl-list
{
  declaration-list
  statement-list
}
```

Example:

```
int max(a, b, c)
int a, b, c;
{
   int m;
   m = (a > b) ? a : b ;
   return m > c ? m : c ;
}
```

More C trivia

The first C compilers did not check the number and type of function arguments.

The biggest change made when C was standardized was to require the type of function arguments to be defined:

Old-style

```c
int f();

int f(a, b, c)
int a, b;
double c;
{
}
```

New-style

```c
int f(int, int, double);

int f(int a, int b, double c)
{
}
```

Data Definitions

type-specifier init-declarator-list ;

declarator optional-initializer

Initializers may be constants or brace-enclosed, comma-separated constant expressions. Examples:

```
int a;

struct { int x; int y; } b = { 1, 2 };

float a, *b, c;
```

Scope Rules

Two types of scope in C:

1. Lexical scope
   Essentially, place where you don't get "undeclared identifier" errors
2. Scope of external identifiers
   When two identifiers in different files refer to the same object. E.g., a function defined in one file called from another.

Lexical Scope

Extends from declaration to terminating } or end-of-file.

```
int a;

int foo()
{
  int b;
  if (a == 0) {
    printf("A was 0");
    a = 1;
  }
  b = a; /* OK */
}

int bar()
{
  a = 3; /* OK */
  b = 2; /* Error: b out of scope */
}
```

External Scope

file1.c:

```
int foo()
{
  return 0;
}

int bar()
{
  foo(); /* OK */
}
```

file2.c:

```
int baz()
{
  foo(); /* Error */
}

extern int foo();

int baff()
{
  foo(); /* OK */
}
```

The Preprocessor

Violates the free-form nature of C: preprocessor lines *must* begin with `#`.

Program text is passed through the preprocessor before entering the compiler proper.

Define replacement text:

`# define` *identifier token-string*

Replace a line with the contents of a file:

`# include "` *filename* `"`

C's Standard Libraries

<assert.h>	Generate runtime errors	assert(a > 0)
<ctype.h>	Character classes	isalpha(c)
<errno.h>	System error numbers	errno
<float.h>	Floating-point constants	FLT_MAX
<limits.h>	Integer constants	INT_MAX
<locale.h>	Internationalization	setlocale(...)
<math.h>	Math functions	sin(x)
<setjmp.h>	Non-local goto	setjmp(jb)
<signal.h>	Signal handling	signal(SIGINT,&f)
<stdarg.h>	Variable-length arguments	va_start(ap, st)
<stddef.h>	Some standard types	size_t
<stdio.h>	File I/O, printing.	printf("%d", i)
<stdlib.h>	Miscellaneous functions	malloc(1024)
<string.h>	String manipulation	strcmp(s1, s2)
<time.h>	Time, date calculations	localtime(tm)

Language design

Language design is library design.
— Bjarne Stroustrup

Programs consist of pieces connected together.

Big challenge in language design: making it easy to put pieces together *correctly*. C examples:

- The function abstraction (local variables, etc.)
- Type checking of function arguments
- The `#include` directive