Language Design

COMS W4115

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

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Language Design Issues

Syntax: how programs look

- Names and reserved words
- Instruction formats
- Grouping

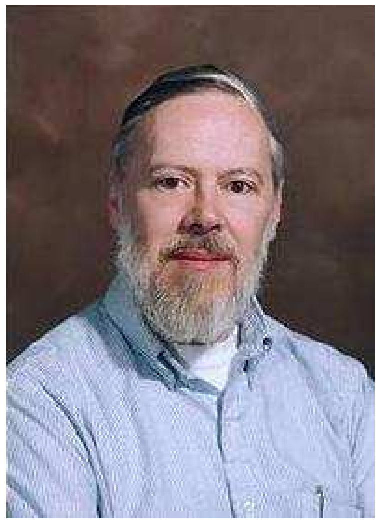
Semantics: what programs mean

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

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

C History

Original machine (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

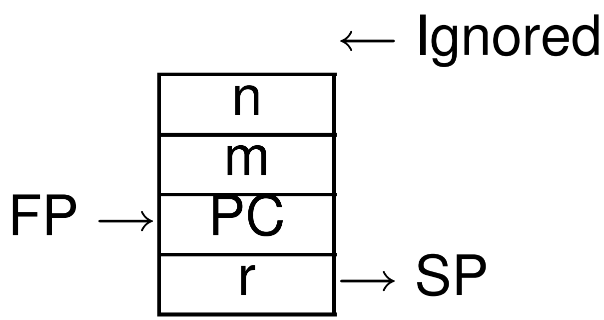
```c
int gcd(int m, int n )
{
  int r;
  while ((r = m % n) != 0) {
    m = n;
    n = r;
  }
  return n;
}
```

Automatic variable

Allocated on stack when function entered, released on return

Parameters & automatic variables accessed via frame pointer

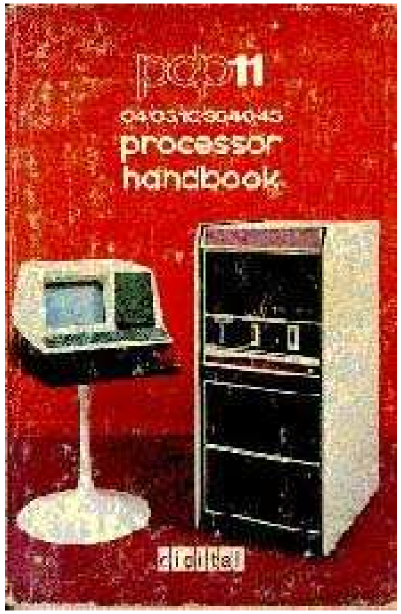
Other temporaries also stacked



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.

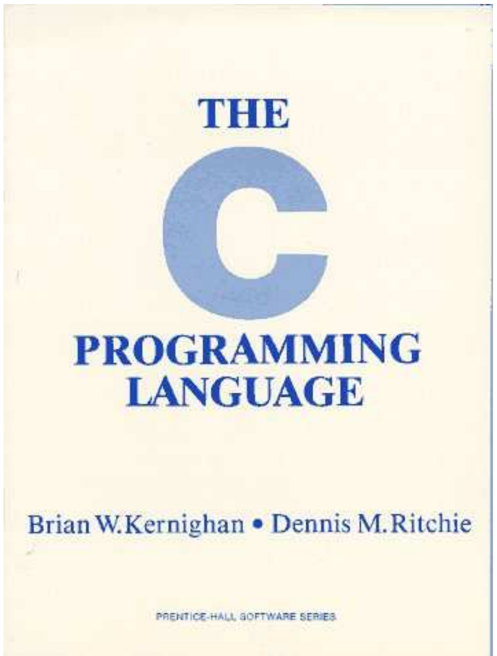
Complex addressing modes make frame-pointer-relative accesses easy.

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

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                  return this
1 + 2                returnthis
foo bar
foobar
```

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

```
if x < 3:            if x < 3:
  y = 2                y = 2
  z = 3              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`**
- Floating-point arithmetic is always done with **`double`**s; **`floats`** are automatically promoted
- **`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

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

specifiers declarator

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

```
int f();

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

New-style

```
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:

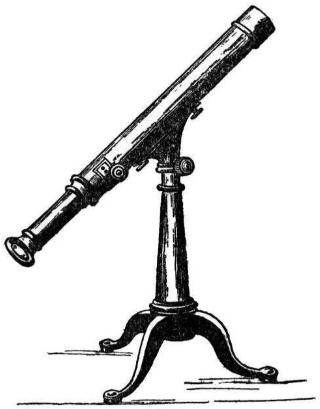
```
int a;

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 Stroustroup

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