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

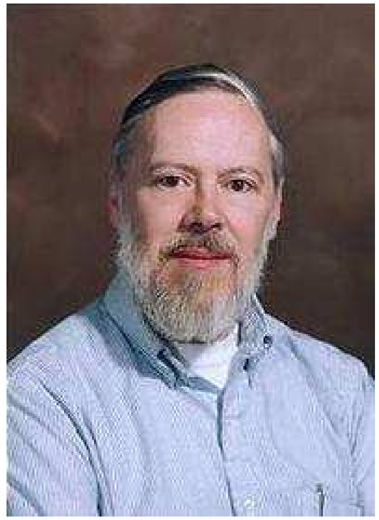
Semantics: what programs mean

- 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

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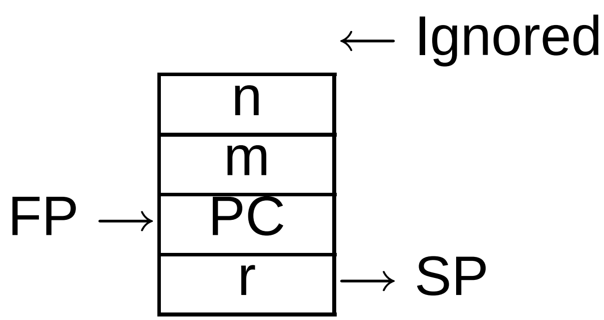


Automatic variable

Allocated on stack when function entered, released on return

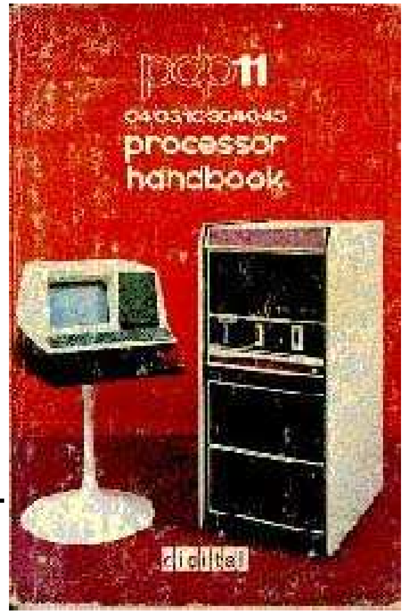
Parameters & automatic variables accessed via frame pointer

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.

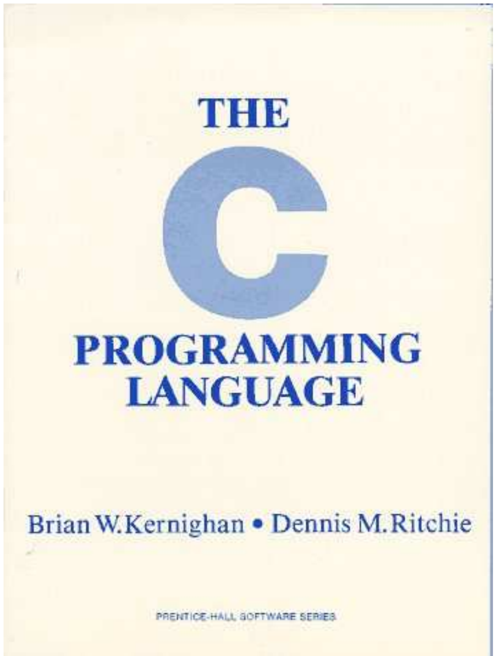
Complex addressing modes make frame-pointer-relative accesses easy.

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:	Fundamental types:	Derived types:
1. automatic	1. **`char`**	1. arrays
2. static	2. **`int`**	2. functions
3. external	3. **`float`**	3. pointers
4. register	4. **`double`**	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; **`float`**s 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

$$\underbrace{\texttt{static unsigned }\overbrace{\texttt{int}}^{\text{basic type}}}_{\text{specifiers}}\ \underbrace{\texttt{(*f[10])(int, char*)[10];}}_{\text{declarator}}$$

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 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