Language Design

COMS W4115

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

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Fall 2003
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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

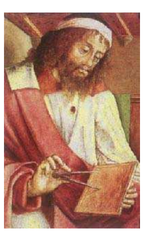
PDP-11 was byte-addressed

- 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



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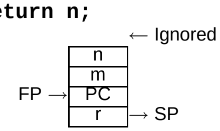
```

Automatic variable

Allocated on stack when function entered, released on return

Parameters & automatic variables accessed via frame pointer

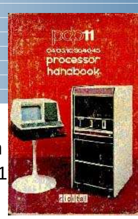
Other temporaries also stacked



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.

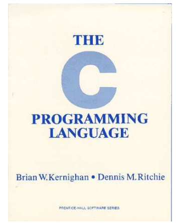
Complex addressing modes make frame-pointer-relative accesses easy.

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

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	New-style
`int f();`	`int f(int, int, double);`

Old-style:

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

New-style:

```
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:

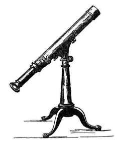
```
int a;

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