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

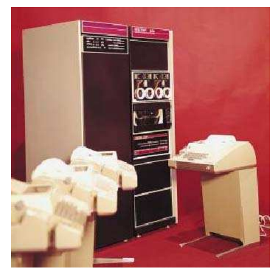
C History

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

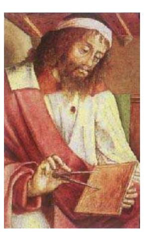
PDP-11 was byte-addressed

- 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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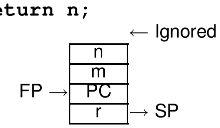
```

Automatic variable

Allocated on stack when function entered, released on return

Parameters & automatic variables accessed via frame pointer

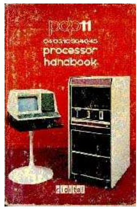
Other temporaries also stacked



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

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    .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.

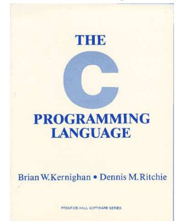
Complex addressing modes make frame-pointer-relative accesses easy.

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`			

Type Specifiers

`int`

`char`

`float`

`double`

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

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

`struct` ***identifier***

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 :

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).

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.

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"

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.

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`**

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);`

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