The Design of C

"C is quirky, flawed, and an enormous success. While accidents of history surely helped, it evidently satisfied a need for a system implementation language efficient enough to displace assembly language, yet sufficiently abstract and fluent to describe algorithms and interactions in a wide variety of environments."

-- Dennis Ritchie

Goals of this Lecture

Help you learn about:

- The decisions that were made by the designers* of C
- **Why** they made those decisions

… and thereby…

- The fundamentals of C

Why?

- Learning the design rationale of the C language provides a richer understanding of C itself
- A power programmer knows both the programming language and its design rationale

* Dennis Ritchie & members of standardization committees

Goals of C

Designers wanted C to:	But also:
Support system programming	Support application programming
Be low-level	Be portable
Be easy for people to handle	Be easy for computers to handle

- Conflicting goals on multiple dimensions!
- Result: different design decisions than Java

Operators

Issue: What kinds of operators should C have?

Thought process

- Should handle typical operations
- Should handle bit-level programming ("bit twiddling")
- Should provide a mechanism for converting from one type to another

Operators

Decisions

- Provide typical arithmetic operators: **`+ - * / %`**
- Provide typical relational operators: **`== != < <= > >=`**
  - Each evaluates to 0 ⇒ FALSE, 1 ⇒ TRUE
- Provide typical logical operators: **`! && ||`**
  - Each interprets 0 ⇒ FALSE, non-0 ⇒ TRUE
  - Each evaluates to 0 ⇒ FALSE, 1 ⇒ TRUE
- Provide bitwise operators: **`~ & | ^ >> <<`**
- Provide a cast operator: **`(type)`**

Logical vs. Bitwise Ops

Logical AND (&&) vs. bitwise AND (&)

- **`2 (TRUE) && 1 (TRUE) => 1 (TRUE)`**

```
Decimal  Binary
      2  00000000 00000000 00000000 00000010
   && 1  00000000 00000000 00000000 00000001
   ----  -----------------------------------
      1  00000000 00000000 00000000 00000001
```

- **`2 (TRUE)  & 1 (TRUE) => 0 (FALSE)`**

```
Decimal  Binary
      2  00000000 00000000 00000000 00000010
    & 1  00000000 00000000 00000000 00000001
   ----  -----------------------------------
      0  00000000 00000000 00000000 00000000
```

Implication:

- Use **logical** AND to control flow of logic
- Use **bitwise** AND only when doing bit-level manipulation
- Same for OR and NOT

Assignment Operator

Issue: What about assignment?

Thought process

- Must have a way to assign a value to a variable
- Many high-level languages provide an assignment **statement**
- Would be more expressive to define an assignment **operator**
  - Performs assignment, and then *evaluates to the assigned value*
  - Allows assignment to appear within larger expressions

Decisions

- Provide assignment operator: **=**
- Define assignment operator so it changes the value of a variable, and also evaluates to that value

Assignment Operator Examples

Examples

```
i = 0;
   /* Side effect: assign 0 to i.
      Evaluate to 0.

j = i = 0; /* Assignment op has R to L associativity */
   /* Side effect: assign 0 to i.
      Evaluate to 0.
      Side effect: assign 0 to j.
      Evaluate to 0. */

while ((i = getchar()) != EOF) …
   /* Read a character.
      Side effect: assign that character to i.
      Evaluate to that character.
      Compare that character to EOF.
      Evaluate to 0 (FALSE) or 1 (TRUE). */
```

Special-Purpose Assignment

Issue: Should C provide tailored assignment operators?

Thought process

- The construct **`a = b + c`** is flexible
- The construct **`i = i + c`** is somewhat common
- The construct **`i = i + 1`** is very common
- Special-purpose operators make code more expressive
  - Might reduce some errors
  - May complicate the language and compiler

Decisions

- Introduce **`+=`** operator to do things like **`i += c`**
- Extend to **`-= *= /= ~= &= |= ^= <<= >>=`**
- Special-case increment and decrement: **`i++ i--`**
- Provide both pre- and post-inc/dec: **`x = ++i; y = i++;`**

iClicker Question

Q: What are **`i`** and **`j`** set to in the following code?

```
i = 5;
j = i++;
j += ++i;
```

A. 5, 7

B. 7, 5

C. 7, 11

D. 7, 12

E. 7, 13

sizeof Operator

Issue: How to determine the sizes of data?

Thought process

- The sizes of most primitive types are un- or under-specified
- Provide a way to find size of a given variable programmatically

Decisions

- Provide a **`sizeof`** operator
  - Applied at compile-time
  - Operand can be a **data type**
  - Operand can be an **expression**, from which the compiler infers a data type

Examples, on courselab using gcc217

- **`sizeof(int)`** evaluates to 4
- **`sizeof(i)`** evaluates to 4 (where **`i`** is a variable of type **`int`**)

iClicker Question

Q: What is the value of the following **`sizeof`** expression on the courselab machines?

```
int i = 1;

sizeof(i + 2L)
```

A. 3

B. 4

C. 8

D. 12

E. error

Other Operators

Issue: What other operators should C have?

Decisions

- Function call operator
  - Should mimic the familiar mathematical notation
  - **`function(param1, param2, …)`**
- Conditional operator: **`?:`**
  - The only ternary operator: “inline if statement”
  - Example: **`(i < j) ? i : j`** evaluates to min of **`i`** and **`j`**
  - See King book for details
- Sequence operator: **`,`**
  - See King book
- Pointer-related operators: **`& *`**
  - Described later in the course
- Structure-related operators (. ->)
  - Described later in the course

Operators Summary: C vs. Java

Java only

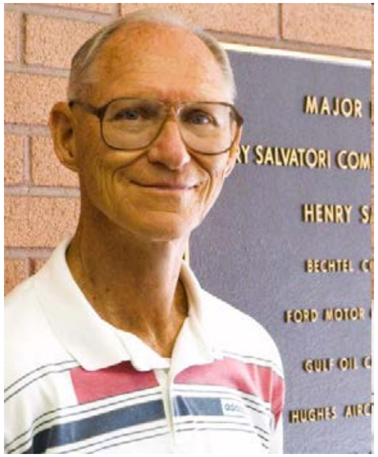
- `>>>` right shift with zero fill
- `new` create an object
- `instanceof` is left operand an object of class right operand?

C only

- `->` structure member select
- `*` dereference
- `&` address of
- `,` sequence
- `sizeof` compile-time size of

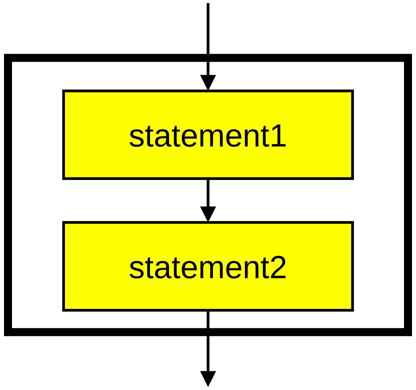
Control Statements

- **Issue: What control statements should C provide?**
- Thought process
  - **Boehm** and **Jacopini** proved that any algorithm can be expressed as the nesting of only 3 control structures:

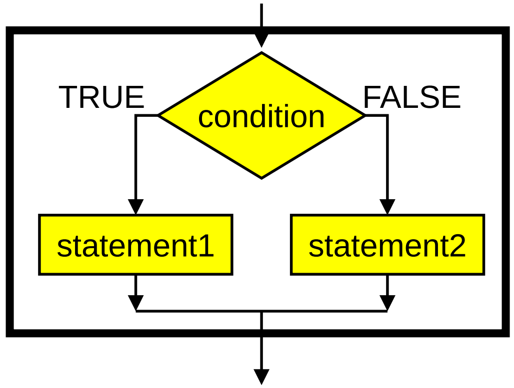


Barry Boehm

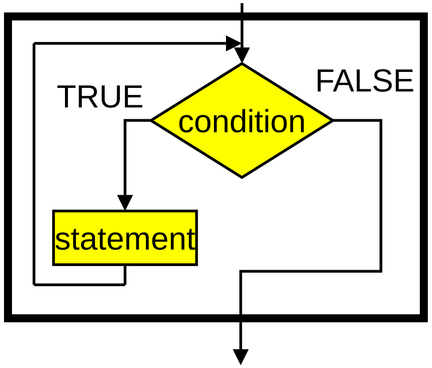
Sequence



Selection



Repetition



Control Statements (cont.)

- Thought Process (cont.)
  - **Dijkstra** argued that any algorithm **should** be expressed using only those control structures (*GOTO Statement Considered Harmful* paper)
- Decisions
  - Provide statements to implement those 3 control structures
  - For convenience, provide a few extras

Edsgar Dijkstra

Sequence Statement

Issue: How should C implement sequence?

Decision

- **Compound statement**, alias **block**

```
{
   statement1;
   statement2;
    …
}
```

Selection Statements

Issue: How should C implement selection?

Decisions

- **`if`** statement, for one-path, two-path decisions

```
if (expr)
   statement1;
```

```
if (expr)
   statement1;
else
   statement2;
```

Selection Statements

Decisions (cont.)

- **`switch`** and **`break`** statements, for multi-path decisions on a single ***`integerExpr`***

```
switch (integerExpr)
{  case integerLiteral1:
      …
      break;
   case integerLiteral2:
      …
      break;
   …
   default:
      …
}
```

What happens if you forget **`break`**?

Repetition Statements

Issue: How should C implement repetition?

Decisions

- **`while`** statement; test at leading edge

```
while (expr)
   statement;
```

- **`for`** statement; test at leading edge, increment at trailing edge

```
for (initialExpr; testExpr; incrementExpr)
   statement;
```

- **`do…while`** statement; test at trailing edge

```
do
   statement;
while (expr);
```

Other Control Statements

Issue: What other control statements should C provide?

Decisions

- **`break`** statement (revisited)
  - Breaks out of closest enclosing **`switch`** or repetition statement
- **`continue`** statement
  - Skips remainder of current loop iteration
  - Continues with next loop iteration
  - When used within **`for`**, still executes ***`incrementExpr`***
- **`goto`** statement grudgingly provided
  - Jump to specified **label**

Declaring Variables

Issue: Should C require variable declarations?

Thought process:

- Declaring variables allows compiler to check spelling
- Declaring variables allows compiler to allocate memory more efficiently

Declaring Variables

Decisions:

- Require variable declarations
- Provide **declaration statement**
- Programmer specifies type of variable (and other attributes too)

Examples

- `int i;`
- `int i, j;`
- `int i = 5;`
- `const int i = 5;  /* value of i cannot change */`
- `static int i;     /* covered later in course */`
- `extern int i;     /* covered later in course */`

Declaring Variables

Decisions (cont.):

- Unlike Java, declaration statements ***must*** appear before any other kind of statement in compound statement

```
{
   int i;
   /* Non-declaration
      stmts that use i. */
   …
   int j;
   /* Non-declaration
      stmts that use j. */
   …
}
```

Illegal in C

```
{
   int i;
   int j;
   …
   /* Non-declaration
      stmts that use i. */
   …
   /* Non-declaration
      stmts that use j. */
   …
}
```

Legal in C

Repetition Statements

Decisions (cont.)

- Similarly, cannot declare loop control variable in **`for`** statement

```
{
   …
   for (int i = 0; i < 10; i++)
      /* Do something */
   …
}
```

Illegal in C

```
{
   int i;
   …
   for (i = 0; i < 10; i++)
      /* Do something */
   …
}
```

Legal in C

Statements Summary: C vs. Java

Java only

- Declarations anywhere within block
- Declare immutable variables with **`final`**
- Conditionals of type **`boolean`**
- "Labeled" **`break`** and **`continue`**
- No **`goto`**

C only

- Declarations only at beginning block
- Declare immutable variables with **`const`**
- Conditionals of any type (checked for zero / nonzero)
- No "labeled" **`break`** and **`continue`**
- **`goto`** provided (but don't use it)

iClicker Question

Q: What does the following code print?

```
int i = 1;
switch (i++) {
   case 1: printf("%d", ++i);
   case 2: printf("%d", i++);
}
```

A. 1

B. 2

C. 3

D. 22

E. 33

I/O Facilities

Issue: Should C provide I/O facilities?

Thought process

- Unix provides the **file** abstraction
  - A file is a sequence of characters with an indication of the current position
- Unix provides 3 standard files
  - Standard input, standard output, standard error
- C should be able to use those files, and others
- I/O facilities are complex
- C should be small/simple

I/O Facilities

Decisions

- Do not provide I/O facilities in the **language**
- Instead provide I/O facilities in **standard library**
  - **Constant**: **`EOF`**
  - **Data type**: **`FILE`** (described later in course)
  - **Variables**: **`stdin`**, **`stdout`**, and **`stderr`**
  - **Functions**: …

Reading Characters

Issue: What functions should C provide for reading characters from standard input?

Thought process

- Need function to read a single character from **`stdin`**
- Function must have a way to indicate failure, that is, to indicate that no characters remain

Decisions

- Provide **`getchar()`** function
- Make return type of **`getchar()`** wider than **`char`**
  - Make it **`int`**; that's the natural word size
- Define **`getchar()`** to return **`EOF`** (a special non-character **`int`**) to indicate failure

Note

- There is no such thing as "the **`EOF`** character"

Writing Characters

Issue: What functions should C provide for writing a character to standard output?

Thought process

- Need function to write a single character to **`stdout`**

Decisions

- Provide a **`putchar()`** function
- Define **`putchar()`** to accept one parameter
  - For symmetry with **`getchar()`**, parameter should be an **`int`**

Reading Other Data Types

Issue: What functions should C provide for reading data of other primitive types?

Thought process

- Must convert external form (sequence of character codes) to internal form
- Could provide **`getshort()`**, **`getint()`**, **`getfloat()`**, etc.
- Could provide one parameterized function to read any primitive type of data

Decisions

- Provide **`scanf()`** function
- Can read any primitive type of data
- First parameter is a **format string** containing **conversion specifications**

See King book for details

Writing Other Data Types

Issue: What functions should C provide for writing data of other primitive types?

Thought process

- Must convert internal form to external form (sequence of character codes)
- Could provide **`putshort()`**, **`putint()`**, **`putfloat()`**, etc.
- Could provide one parameterized function to write any primitive type of data

Decisions

- Provide **`printf()`** function
- Can write any primitive type of data
- First parameter is a **format string** containing **conversion specifications**

See King book for details

Other I/O Facilities

Issue: What other I/O functions should C provide?

Decisions

- **`fopen()`**: Open a stream
- **`fclose()`**: Close a stream
- **`fgetc()`**: Read a character from specified stream
- **`fputc()`**: Write a character to specified stream
- **`fgets()`**: Read a line/string from specified stream
- **`fputs()`**: Write a line/string to specified stream
- **`fscanf()`**: Read data from specified stream
- **`fprintf()`**: Write data to specified stream

Described in King book, and later in the course after covering files, arrays, and strings

Summary

C design decisions and the goals that affected them

- Data types (last time)
- Operators
- Statements
- I/O facilities

Knowing the design goals and how they affected the design decisions can yield a rich understanding of C

Appendix: The Cast Operator

Cast operator has multiple meanings:

(1) Cast between integer type and floating point type:

- Compiler generates code
- At run-time, code performs conversion

f `11000001110110110000000000000000` **-27.375**

```
i = (int)f
```

i `11111111111111111111111111100101` **-27**

Appendix: The Cast Operator

(2) Cast between floating point types of different sizes:

- Compiler generates code
- At run-time, code performs conversion

```
f   11000001110110110000000000000000          -27.375

d = (double)f

d   11000000001110110110000000000000          -27.375
    00000000000000000000000000000000
```

Appendix: The Cast Operator

(3) Cast between integer types of different sizes:

- Compiler generates code
- At run-time, code performs conversion

```
i   00000000000000000000000000000010   2

c = (char)i

c   00000010   2
```

Appendix: The Cast Operator

(4) Cast between integer types of same size:

- Compiler generates no code
- Compiler views given bit-pattern in a different way

```
    i  11111111111111111111111111111110   -2

u = (unsigned int)i

    u  11111111111111111111111111111110   4294967294
```