# The Design of C:
# A Rational Reconstruction



## Goals of this Lecture

- Help you learn about:
  - The decisions that were **available to** the designers of C
  - The decisions that were **made by** the designers of C
- Why?
  - Learning the design rationale of the C language provides a richer understanding of C itself
    - might be more interesting than simply learning the language itself
  - A power programmer knows both the programming language and its design rationale

## Goals of C

Designers wanted C to support:

- **Systems programming**
  - Development of Unix OS
  - Development of Unix programming tools

But also:

- **Applications programming**
  - Development of financial, scientific, etc. applications

**Systems** programming was the primary intended use

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## The Goals of C (cont.)

The designers of wanted C to be:

- Low-level
  - Close to assembly/machine language
  - Close to hardware

But also:

- Portable
  - Yield systems software that is easy to port to differing hardware

- These goals are conflicting
  - So compromises needed to be made

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## The Goals of C (cont.)

The designers wanted C to be:

- Easy for **people** to handle
  - Easy to understand
  - **Expressive**
    - High (functionality/sourceCodeSize) ratio

But also:

- Easy for **computers** to handle
  - Easy/fast to compile
  - Yield efficient machine language code

Commonality:

- Small/simple

- These sets of goals are also conflicting
  - Understandable and expressive; understandable and efficient

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## Design Decisions

In light of those goals…

- What design decisions did the designers of C **have**?
- What design decisions did they **make**?

Consider a few language features, from simple to complex…

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## Feature 1: Data Types

- Remember:
  - Bits can be combined into bytes
  - Our interpretation of a collection of bytes gives it meaning
    - A signed integer, an unsigned integer, a RGB color, etc.
- A **data type** is a well-defined interpretation of a set of bytes
- A high-level language should provide primitive data types
  - Facilitates abstraction
  - Facilitates manipulation via well-defined operators associated with the data types
  - Enables compiler to check for mixing of types, inappropriate use of types, etc.

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## Primitive Data Types

- Issue: What primitive data types should C provide?
- Thought process
  - C should handle:
    - **Integers**
    - **Characters**
    - Character **strings**
    - **Logical** (alias **Boolean**) data
    - **Floating-point** numbers
  - C should be small/simple
- Decisions
  - Provide **integer**, **character**, and **floating-point** data types
  - **Do not** provide a character **string** data type (More on that later)
  - **Do not** provide a **logical** data type (More on that later)

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## Integer Data Types

- Issue: What integer data types should C provide?
- Thought process
  - For flexibility, should provide integer data types of various sizes
  - For portability at **application** level, should specify size of each data type
  - For portability at **systems** level, should define integral data types in terms of **natural word size** of computer
  - Primary use will be **systems** programming

Why?

Why?

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## Integer Data Types (cont.)

- Decisions
  - Provide three integer data types: `short`, `int`, and `long`
  - Do not specify sizes; instead:
    - `int` is natural word size
    - 2 <= bytes in `short` <= bytes in `int` <= bytes in `long`
- Incidentally, on hats using gcc217
  - Natural word size: 4 bytes
  - `short`: 2 bytes
  - `int`: 4 bytes
  - `long`: 4 bytes

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## Integer Constants

- Issue: How should C represent integer constants?
- Thought process
  - People naturally use decimal
  - Systems programmers often use binary, octal, hexadecimal
- Decisions
  - Use decimal notation as default
  - Use "0" prefix to indicate octal notation
  - Use "0x" prefix to indicate hexadecimal notation
  - Do not allow binary notation; too verbose, error prone
  - Use "L" suffix to indicate `long` constant
  - Do not use a suffix to indicate `short` constant; instead must use cast
- Examples
  - `int`: `123`, `-123`, `0173`, `0x7B`
  - `long`: `123L`, `-123L`, `0173L`, `0x7BL`
  - `short`: `(short)123`, `(short)-123`, `(short)0173`, `(short)0x7B`

Was that a good decision?

Why?

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## Unsigned Integer Data Types

- Issue: Should C have both signed and unsigned integer data types?
- Thought process
  - Must represent positive and negative integers
    - Signed types are essential
  - Unsigned data can be twice as large as signed data
    - Unsigned data could be useful
  - Unsigned data are good for bit-level operations
    - Bit-level operations are common in systems programming
  - Implementing both signed and unsigned data types is complex
    - Must define behavior when an expression involves both

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## Unsigned Integer Data Types (cont.)

- Decisions
  - Provide unsigned integer types: **`unsigned short`**, **`unsigned int`**, and **`unsigned long`**
  - Conversion rules in mixed-type expressions are complex
    - Generally, mixing signed and unsigned converts signed to unsigned
    - See King book Section 7.4 for details

Do you see any potential problems?

Was providing unsigned types a good decision?

What decision did the designers of Java make?

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## Unsigned Integer Constants

- Issue: How should C represent unsigned integer constants?
- Thought process
  - "L" suffix distinguishes **`long`** from **`int`**; also could use a suffix to distinguish signed from unsigned
  - Octal or hexadecimal probably are used with bit-level operators
- Decisions
  - Default is signed
  - Use "U" suffix to indicate unsigned
  - Integers expressed in octal or hexadecimal automatically are unsigned
- Examples
  - **`unsigned int`**: **`123U`**, **`0173`**, **`0x7B`**
  - **`unsigned long`**: **`123UL`**, **`0173L`**, **`0x7BL`**
  - **`unsigned short`**: **`(short)123U`**, **`(short)0173`**, **`(short)0x7B`**

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## Character Data Types

- Issue: What character data types should C have?
- Thought process
  - The most common character codes are (were!) ASCII and EBCDIC
  - ASCII is 7-bit
  - EBCDIC is 8-bit
- Decisions
  - Provide type **`char`**
  - Type **`char`** should be one byte

Was that a good decision?

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## Character Data Types (cont.)

- Tangential Decision
  - **`char`** should be an integer type
    - Can use type **`char`** to store small integers
    - Can do arithmetic with data of type **`char`**
    - Can freely mix **`char`** and integer data
      - **`('a' + 1)`** is **`'b'`** (assuming ASCII)
      - **`('0' + 5)`** is **`'5'`** (assuming ASCII)

How does Java handle these expressions?

Was that a good decision?

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## Character Constants

- Issue: How should C represent character constants?
- Thought process
  - Could represent character constants as `int` constants, with truncation of high-order bytes
  - More readable to use single quote syntax (`'a'`, `'b'`, etc.); but then…
  - Need special way to represent the single quote character
  - Need special ways to represent non-printable characters (e.g. newline, tab, space, etc.)
- Decisions
  - Provide single quote syntax
  - Use backslash to express special characters



## Character Constants (cont.)

- Examples

| | |
|---|---|
| `'a'` | **the a character** |
| `(char)97` | the a character |
| `(char)0141` | the a character |
| `'\o141'` | the a character, octal character form |
| `'\x61'` | the a character, hexadecimal character form |
| `'\0'` | **the null character** |
| `'\a'` | bell |
| `'\b'` | backspace |
| `'\f'` | formfeed |
| `'\n'` | **newline** |
| `'\r'` | carriage return |
| `'\t'` | **horizontal tab** |
| `'\v'` | vertical tab |
| `'\\'` | backslash |
| `'\''` | single quote |

## Strings

- Issue: How should C represent strings?
- Thought process
  - String can be represented as a sequence of chars
  - How to know where char sequence ends?
    - Store length before char sequence?
    - Store special "sentinel" char after char sequence?
  - Strings are common in systems programming
  - C should be small/simple

Advantages/disadvantages?

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## Strings (cont.)

- Decisions
  - Adopt a convention
    - String consists of a sequence of chars terminated with the null (`'\0'`) character
  - Use double-quote syntax (e.g. `"abc"`, `"hello"`) to represent a string constant
  - Provide no other language features for handling strings
    - Delegate string handling to standard library functions
- Examples
  - `"abc"` is a string constant
  - `'a'` is a `char` constant
  - `"a"` is a string constant

How many bytes?

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## Logical Data Type

- Issue: How should C represent logical data?
- Thought process
  - Representing a logical value (TRUE or FALSE) requires only one **bit**
  - Smallest entity that can be addressed is one **byte**
  - Type **`char`** is one byte, so could be used to represent logical values
  - C should be small/simple

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## Logical Data Type (cont.)

- Decisions
  - Don't define a logical data type
  - Represent logical data using type **`char`**, or any integer type
  - Convention: 0 => FALSE, non-0 => TRUE
  - Convention used by:
    - Relational operators (**`<`**, **`>`**, etc.)
    - Logical operators (**`!`**, **`&&`**, **`||`**)
    - Statements (**`if`**, **`while`**, etc.)

Was that a good decision? (See the next 2 slides)

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## Logical Data Type (cont.)

- Note
  - Using integer data to represent logical data permits shortcuts

```
…
int i;
…
if (i)   /* same as (i != 0) */
   statement1;
else
   statement2;
…
```

Are such shortcuts beneficial?

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## No Logical Data Type

- Note
  - The lack of logical data type cripples compiler's ability to detect some errors

```
…
int i;
…
i = 0;
…
if (i = 5)
   statement1;
else
   statement2;
…
```

What is the problem with this code?

What is the effect of this code?

How does Java handle this code?

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# Floating-Point Data Types

- Issue: What floating-point data types should C have?
- Thought process
  - Systems programs use floating-point data infrequently
  - But some application domains (e.g. scientific) use floating-point data often
- Decisions
  - Provide three floating-point data types: **`float`**, **`double`**, and **`long double`**
  - bytes in **`float`** <= bytes in **`double`** <= bytes in **`long double`**
- Incidentally, on hats using gcc217
  - **`float`**: 4 bytes
  - **`double`**: 8 bytes
  - **`long double`**: 12 bytes



# Floating-Point Constants

- Issue: How should C represent floating-point constants?
- Thought process
  - Convenient to allow both fixed-point and scientific notation
  - Decimal is sufficient; no need for octal or hexadecimal
- Decisions
  - Any constant that contains decimal point or "E" is floating-point
  - The default floating-point type is **`double`**
  - Append "**`F`**" to indicate **`float`**
  - Append "**`L`**" to indicate **`long double`**

Why?

- Examples
  - **`double`**: **`123.456`**, **`1E-2`**, **`-1.23456E4`**
  - **`float`**: **`123.456F`**, **`1E-2F`**, **`-1.23456E4F`**
  - **`long double`**: **`123.456L`**, **`1E-2L`**, **`-1.23456E4L`**

## Feature 2: Operators

- A high-level programming language should have **operators**
- Operators combine with constants and variables to form expressions
  - E.g. x + 5
- C provides a number of arithmetic, logical, relational, bitwise and type-casting operators



## Kinds of Operators

- Issue: What kinds of operators should C have?
- Thought process
  - Should handle typical operations
  - Should handle bit-level programming ("bit fiddling")
- Decisions
  - Provide typical arithmetic operators: `+ - * / %`
  - Provide typical relational operators: `== != < <= > >=`
    - Each evaluates to 0=>FALSE or 1=>TRUE
  - Provide typical logical operators: `! && ||`
    - Each interprets 0=>FALSE, non-0=>TRUE
    - Each evaluates to 0=>FALSE or 1=>TRUE
  - Provide bitwise operators: `~ & | ^ >> <<`
  - Provide a cast operator: `(type)`

# Assignment

- 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 expressions that involve 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

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# Assignment Operator (cont.)

- Examples

```
i = 0;
  /* Assign 0 to i. Evaluate to 0.
     Discard the 0. */

i = j = 0;
  /* Assign 0 to j. Evaluate to 0.
     Assign 0 to i. Evaluate to 0.
     Discard the 0. */

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

Does the expressiveness affect clarity?

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## Increment and Decrement Operators

- Issue: Should C provide increment and decrement operators?
- Thought process
  - The construct `i = i + 1` is common
  - Special purpose increment and decrement operators would make code more expressive
  - Such operators would complicate the language and compiler
- Decisions
  - The convenience outweighs the complication
  - Provide increment and decrement operators: `++ --`

Was that a good decision?



## Special-Purpose Assignment Operators

- Issue: Should C provide special-purpose assignment operators?
- Thought process
  - Constructs such as `i = i + n` and `i = i * n` are common.
  - Special-purpose assignment operators would make code more expressive
  - Such operators would complicate the language and compiler
- Decisions
  - The convenience outweighs the complication
  - Provide special-purpose assignment operators: `+= -= *= /= ~= &= |= ^= <<= >>=`

Was that a good decision?

## Sizeof Operator

- Issue: How can programmers determine the sizes of data?
- Thought process
  - The sizes of most primitive types are unspecified
  - C must provide a way to determine the size of a given data type 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 hats using gcc217
  - **`sizeof(int)`** evaluates to 4
  - **`sizeof(i)`** evaluates to 4 (where **`i`** is a variable of type **`int`**)
  - **`sizeof(i+1)`** evaluates to 4 (where **`i`** is a variable of type **`int`**)



## 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
    - See King book
  - Sequence operator: **`,`**
    - See King book
  - Pointer-related operators: **`& *`**
    - Described later in the course
  - Structure-related operators (. ->)
    - Described later in the course

## Feature 3: Control Statements

- A programming language must provide **statements**
- Some statements must affect flow of control

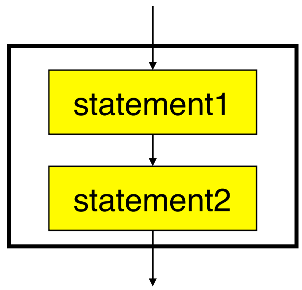


## Control Statements

- 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:

## Control Statements (cont.)

(1) Sequence

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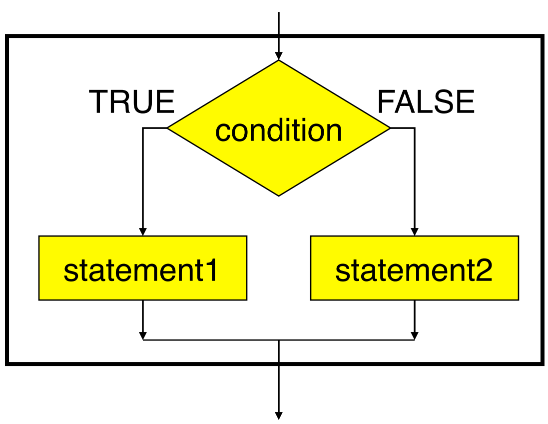
## Control Statements (cont.)

(2) Selection

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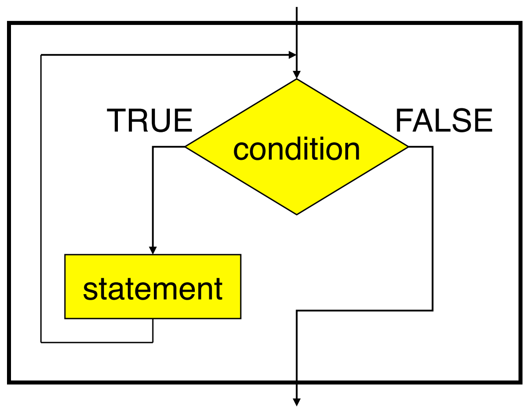
# Control Statements (cont.)

(3) Repetition

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# Control Statements (cont.)

- Thought Process (cont.)
  - **Dijkstra** argued that any algorithm **should** be expressed using only those three control structures (*GOTO Statement Considered Harmful* paper)
  - The ALGOL programming language implemented control statements accordingly

Edsgar Dijkstra

- Decisions
  - Provide statements to implement those 3 control structures
  - For convenience, provide a few extras

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## Sequence Statement

- Issue: How should C implement sequence?

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

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

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## Selection Statements

- Issue: How should C implement selection?

- Decisions
  - **if** statement, for one-path or two-path decisions

```
if (integerExpr)
   statement1;
```

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

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# Selection Statements (cont.)

- Decisions (cont.)
  - **switch** and **break** statements, for multi-path decisions

```
switch (integerExpr) {
   case integerConstant1:
      …
      break;
   case integerConstant2:
      …
      break;
   …
   default:
      …
}
```

What if these **break** statements are omitted?

Was that use of **break** a good design decision?

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# Repetition Statements

- Issue: How should C implement repetition?
- Decisions
  - **while** statement, for general repetition

```
while (integerExpr)
   statement;
```

  - **for** statement, for counting loops

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

  - **do…while** statement, for loops with test at trailing edge

```
do
   statement;
while (integerExpr);
```

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## 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
    - Can be difficult to understand; generally should avoid
  - **goto** statement and labels
    - Avoid (as per Dijkstra)

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## Feature 4: Input/Output

- A programming language must provide facilities for reading and writing data
- Alternative: A programming **environment** must provide such facilities

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## Input/Output Facilities

- Issue: Should C provide I/O facilities?
- Thought process
  - Unix provides the stream abstraction
    - A stream is a sequence of characters
  - Unix provides 3 standard streams
    - Standard input, standard output, standard error
  - C should be able to use those streams, and others
  - I/O facilities are complex
  - C should be small/simple
- Decisions
  - **Do not** provide I/O facilities in C
  - Instead provide a **standard library** containing I/O facilities
    - Constants: `EOF`
    - Data types: `FILE` (described later in course)
    - Variables: `stdin`, `stdout`, and `stderr`
    - Functions: …

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## 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"

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## 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 types beyond characters

- 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's design goals affected decisions concerning language features:
  - Data types
  - Operators
  - Control statements
  - I/O facilities
- Knowing the design goals and how they affected the design decisions can yield a rich understanding of C