The Design of C:
A Rational Reconstruction (cont.)

Goals of this Lecture

- Recall from last 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

  … and thereby…
  - C !
- Why?
  - Learning the design rationale of the C language provides a richer understanding of C itself
    - … and might be more interesting than simply learning the language itself !!!
  - A power programmer knows both the programming language and its design rationale

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

3

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`**

4

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

5

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

6

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`**

7

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
- Historical verdict
  - Worked fine for Latin-derived alphabets
  - Unicode required library support for "wide character" type

8

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

9

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

10

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

11

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 (1 byte)
  - `"a"` is a string constant (2 bytes – `'a'` and `'\0'`)

12

Logical Data Type

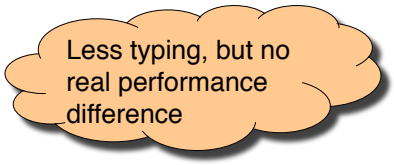
- Issue: How should C represent logical data?
- Thought process
  - Representing a logical value (TRUE or FALSE) requires only one **bit**
  - Smallest entity that can be addressed is one **byte**
  - Type **`char`** is one byte, so could be used to represent logical values
  - C should be small/simple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

13

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;
…
```

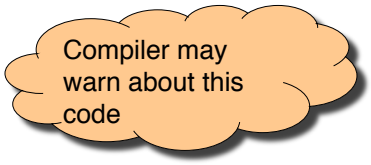


14

Logical Data Type (cont.)

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

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



15

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

16

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

17

Feature 2: 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)`**

18

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 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

19

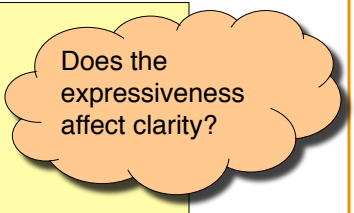
Assignment Operator (cont.)

- 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). */
```



20

Special-Purpose Operators

- Issue: Should C provide special-purpose assignment operators?
- Thought process
  - The construct `i = i + 1` is common
  - More generally, `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
  - Increment/decrement operators (not for floats/double): `++ --`
  - Provide special-purpose assignment operators: `+= -= *= /= ~= &= |= ^= <<= >>=`

21

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`**)

22

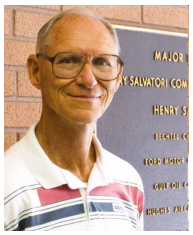
Other Operators

- 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

23

Feature 3: 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: sequence, selection, repetition



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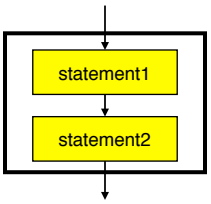

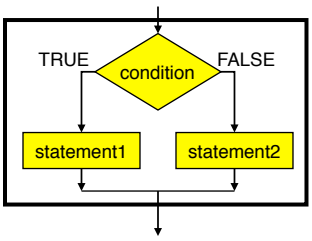

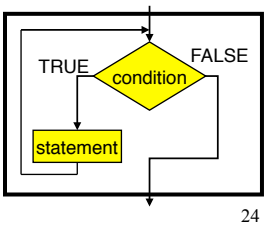

24

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

25

Sequence Statement

- Issue: How should C implement sequence?

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

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

26

Selection Statements

- Issue: How should C implement selection?
- Decisions
  - **if** statement, for one-path, two-path decisions & compound

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

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

```
if (integerExpr)
   statement1;
else {
   if (integerExpr2)
      statement2;
   else
      statement3;
}
```

```
if (integerExpr)
   statement1;
else if (integerExpr2)
   statement2;
else
   statement3;
```

27

Selection Statements (cont.)

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

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

Without **break** next case executes too

Remembering **break** is error-prone, so type it when you type **case**

28

Repetition Statements

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

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

  - **for** statement, for counting loops, zero or more times & init

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

  - **do…while** statement, for loops with test at trailing edge and **one** or more times

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

29

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 with **`for`**, still executes *incrementExpr*
    - Can be difficult to understand; generally should avoid
  - **goto** statement and labels
    - Avoid!!! (as per Dijkstra)

30

Feature 4: 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: …

31

Reading & Writing Characters

- Issue: What functions should C provide for reading & writing characters?
- Thought process
  - Need function to read a single character from `stdin` and indicate that no characters remain
- Decisions
  - Provide `getchar()` and `putchar()` functions
  - Make return type of `getchar()` wider than `char`
    - Make it `int`; that's the natural word size
    - Make `putchar()` take `int` for symmetry
  - Define `getchar()` to return `EOF` (a special non-character `int`) to indicate failure
- Note
  - There is no such thing as "the `EOF` character"

32

Reading/Writing 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 and vice-versa
  - Could provide **`getshort()`**, **`getint()`**, **`getfloat()`**, etc.
  - Could provide parameterized functions to read/write any primitive type of data
- Decisions
  - Provide **`scanf()`** / **`printf()`** functions
  - Can read/write any primitive type of data
  - First parameter is a **format string** containing **conversion specifications**
- See King book for details

33

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

34

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

35