Princeton University

Computer Science 217: Introduction to Programming Systems

The C Programming Language

Part 2

Agenda

Data Types

Operators

Statements

I/O Facilities

Operators

Computers represent integers as bits

Arithmetic operations: +, -, *, /, etc.

Bit operations: and, or, xor, shift, etc.

Typical language design (1970s): provide *abstraction* so that one does not confuse integers with their representation

Operators

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, ≠0 ⇒ TRUE
  - Each evaluates to 0 ⇒ FALSE or 1 ⇒TRUE
- Provide bitwise operators: `~ & | ^ >> <<`
- Provide a cast operator: `(type)`

Aside: Logical vs. Bitwise Ops

Logical NOT (!) vs. bitwise NOT (~)

- `! 1 (TRUE)` ⇒ `0 (FALSE)`

```
Decimal   Binary
      1   00000000 00000000 00000000 00000001
    ! 1   00000000 00000000 00000000 00000000
```

- `~ 1 (TRUE)` ⇒ `-2 (TRUE)`

```
Decimal   Binary
      1   00000000 00000000 00000000 00000001
    ~ 1   11111111 11111111 11111111 11111110
```

Implication:

- Use **logical** NOT to control flow of logic
- Use **bitwise** NOT only when doing bit-level manipulation

Aside: 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
```

Aside: Logical vs. Bitwise Ops

Implication:

- Use **logical** AND to control flow of logic
- Use **bitwise** AND only when doing bit-level manipulation

Same for logical OR (||) and bitwise OR (|)

Assignment Operator

Typical programming language of 1970s:

Statements, Expressions

stmt ::=
    a:=exp
  | **if** exp **then** stmt **else** stmt
  | **while** exp **do** stmt
  | **begin** stmtlist **end**

stmtlist ::= stmt | stmtlist ; stmt

exp ::=
  id | exp+exp | exp−exp | −exp
  | (exp) | …

C language: assignment is an *expression!*

stmt ::=
    exp ;
  | { stmtlist }
  | **if** (exp) stmt **else** stmt
  | **while** (exp) stmt

stmtlist ::= stmt | stmtlist stmt

exp ::=
  id | exp+exp | exp−exp | −exp
  | id=exp | exp,exp | exp?exp:exp
  | (exp) | …

Assignment Operator

Decisions

- Provide assignment **operator**: **=**
    - Side effect: changes the value of a variable
    - Evaluates to the new value of the variable

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 Operators

Decisions

- Provide special-purpose assignment operators:
  `+= -= *= /= ~= &= |= ^= <<= >>=`

Examples

```
i += j  same as i = i + j

i /= j  same as i = i / j

i |= j  same as i = i | j

i >>= j same as i = i >> j
```

Special-Purpose Assignment Operators

Increment and decrement operators: **`++ --`**

- Prefix and postfix forms

Examples

```
(1) i = 5;
    j = ++i;

(2) i = 5;
    j = i++;

(3) i = 5;
    j = ++i + ++i;

(4) i = 5;
    j = i++ + i++;
```

What is the value of i? Of j?

Memory allocation

Typical programming language of 1970s:

Special program statement to allocate a new object

stmt ::=

new p

This is not so different from Java's p=new(MyClass)

Difficulties:

1. system standard allocator could be slow, or inflexible
2. What about deallocation?
   - Explicit "free" leads to bugs
   - Automatic garbage collection too expensive?

C language

Nothing built-in

- *malloc, free* functions provided in standard library
- allow programmers to roll their own allocation systems

Difficulties:

1. System standard allocator could be slow, or inflexible
   (but that's mitigated by roll-your-own)
2. Explicit "free" leads to bugs
   - Turns out, by now we know, automatic garbage collection isn't too expensive after all!

Sizeof Operator

Malloc function needs to be told how many bytes to allocate

```
struct foo {int a, b; float c;}    *p;

p = malloc(12);    /* this is correct but not portable */
```

Issue: How can programmers determine data sizes?

Rationale:

- The sizes of most primitive types are unspecified
- Sometimes programmer must know sizes of primitive types
  - E.g. when allocating memory dynamically
- Hard code data sizes ⇒ program not portable
- C must provide a way to determine the size of a given data type programmatically

Sizeof Operator

Decisions

- Provide a **`sizeof`** operator
  - Applied at compile-time
  - Operand can be a **data type**
  - Operand can be an **expression**
    - Compiler infers a data type

Examples, on CourseLab

- **`sizeof(int)`** ⇒ 4

- When i is a variable of type int…
- **`sizeof(i)`** ⇒ 4
- **`sizeof(i+1)`**
- **`sizeof(i++ * ++i – 5)`**

What is the value?

Other Operators

Issue: What other operators should C have?

Decisions

- Function call operator
  - Should mimic the familiar mathematical notation
  - **`function(arg1, arg2, …)`**
- Conditional operator: **`?:`**
  - The only ternary operator
  - See King book
- Sequence operator: **`,`**
  - See King book
- Pointer-related operators: **`& *`**
  - Address of, dereference (described in precepts)
- Structure-related operators: **`.`** **`->`**
  - Structure field select (described in precepts)

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?
- `p.f` object field select

C only

- `p.f` structure field select
- `*` dereference
- `p->f` dereference then structure member select: (*p).f
- `&` address of
- `,` sequence
- `sizeof` compile-time size of

Operators Summary: C vs. Java

Related to type `boolean`:

- **Java**: Relational and logical operators evaluate to type **`boolean`**
- **C**: Relational and logical operators evaluate to type **`int`**
- **Java**: Logical operators take operands of type **`boolean`**
- **C**: Logical operators take operands of any primitive type or memory address

Agenda

Data Types

Operators

Statements

I/O Facilities

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
```

0 ⇒ FALSE
non-0 ⇒ TRUE

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);
```

0 ⇒ FALSE
non-0 ⇒ TRUE

Declaring Variables

Issue: Should C require variable declarations?

Rationale:

- Declaring variables allows compiler to check spelling (compile-time error messages are easier for programmer than debugging strange behavior at run time!)
- Declaring variables allows compiler to allocate memory more efficiently

Where are variables declared?

Typical 1960s language:

- Global variables

Typical 1970s language:

- Global variables
- Local variables declared just before function body

C language:

- Global variables
- Local variables can be declared at beginning of any {block}, e.g.,

```
{int i=6, j;
  j=7;
  if (i>j)
        {int x; x=i+j; return x;}
  else {int y; y=i-j; return y;}
}
```

scope of variable y ends at matching close brace

Repetition Statements

Decisions (cont.)

- Cannot declare loop control variable in **`for`** statement

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

Illegal in C
(nobody thought of
 that idea in 1970s)

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

Legal in C

Declaring Variables

Decisions (cont.):

- Declaration statements must appear before any other kind of statement in compound statement

```
{
   int i;
   /* Non-declaration
      stmts that use i. */
   i = i+1;
   int j;
   /* Non-declaration
      stmts that use j. */
   j = j+1;
}
```

Illegal in C
(nobody thought of
that idea in 1970s)

```
{
   int i;
   int j;
   …
   /* Non-declaration
      stmts that use i. */
   i = i+1;
   /* Non-declaration
      stmts that use j. */
   j = j+1;
}
```

Legal in C

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
  - Jump to specified **label**

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 */`

Computing with Expressions

Issue: How should C implement computing with expressions?

Decisions:

- Provide **expression statement**

```
expression ;
```

Computing with Expressions

Examples

```
i = 5;
   /* Side effect: assign 5 to i.
      Evaluate to 5. Discard the 5. */

j = i + 1;
   /* Side effect: assign 6 to j.
      Evaluate to 6. Discard the 6. */

printf("hello");
   /* Side effect: print hello.
      Evaluate to 5. Discard the 5. */

i + 1;
   /* Evaluate to 6. Discard the 6. */

5;
   /* Evaluate to 5. Discard the 5. */
```

Statements Summary: C vs. Java

Declaration statement:

- **Java**: Compile-time error to use a local variable before specifying its value
- **C**: Run-time error to use a local variable before specifying its value

`final` and `const`

- **Java**: Has `final` variables
- **C**: Has `const` variables

Expression statement

- **Java**: Only expressions that have a side effect can be made into expression statements
- **C**: Any expression can be made into an expression statement

Statements Summary: C vs. Java

Compound statement:

- **Java**: Declarations statements can be placed anywhere within compound statement
- **C**: Declaration statements must appear before any other type of statement within compound statement

`if` statement

- **Java**: Controlling ***`expr`*** must be of type **`boolean`**
- **C**: Controlling ***`expr`*** can be any primitive type or a memory address (0 $\Rightarrow$ FALSE, non-0 $\Rightarrow$ TRUE)

`while` statement

- **Java**: Controlling ***`expr`*** must be of type **`boolean`**
- **C**: Controlling ***`expr`*** can be any primitive type or a memory address (0 $\Rightarrow$ FALSE, non-0 $\Rightarrow$ TRUE)

Statements Summary: C vs. Java

`do`…`while` statement

- **Java**: Controlling ***`expr`*** must be of type **`boolean`**
- **C**: Controlling ***`expr`*** can be of any primitive type or a memory address (0 ⇒ FALSE, non-0 ⇒ TRUE)

`for` statement

- **Java**: Controlling ***`expr`*** must be of type **`boolean`**
- **C**: Controlling ***`expr`*** can be of any primitive type or a memory address (0 ⇒ FALSE, non-0 ⇒ TRUE)

Loop control variable

- **Java**: Can declare loop control variable in ***`initexpr`***
- **C**: Cannot declare loop control variable in ***`initexpr`***

Statements Summary: C vs. Java

`break` statement

- **Java**: Also has "labeled break" statement
- **C**: Does not have "labeled break" statement

`continue` statement

- **Java**: Also has "labeled continue" statement
- **C**: Does not have "labeled continue" statement

`goto` statement

- **Java**: Not provided
- **C**: Provided (but don't use it!)

Agenda

Data Types

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I/O Facilities

I/O Facilities

Issue: Should C provide I/O facilities?

(many languages of the 1960s / 1970s had built-in special-purpose commands for input/output)

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?

Thought process

- Need function to read a single character from **`stdin`**
  - … And indicate failure

Reading Characters

Decisions

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

Reminder

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

*actually, a macro…

Writing Characters

Issue: What functions should C provide for writing characters?

Thought process

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

Decisions

- Provide **`putchar()`** function
- Define **`putchar()`** to have **`int`** parameter
  - For symmetry with **`getchar()`**

Reading Other Data Types

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

Thought process

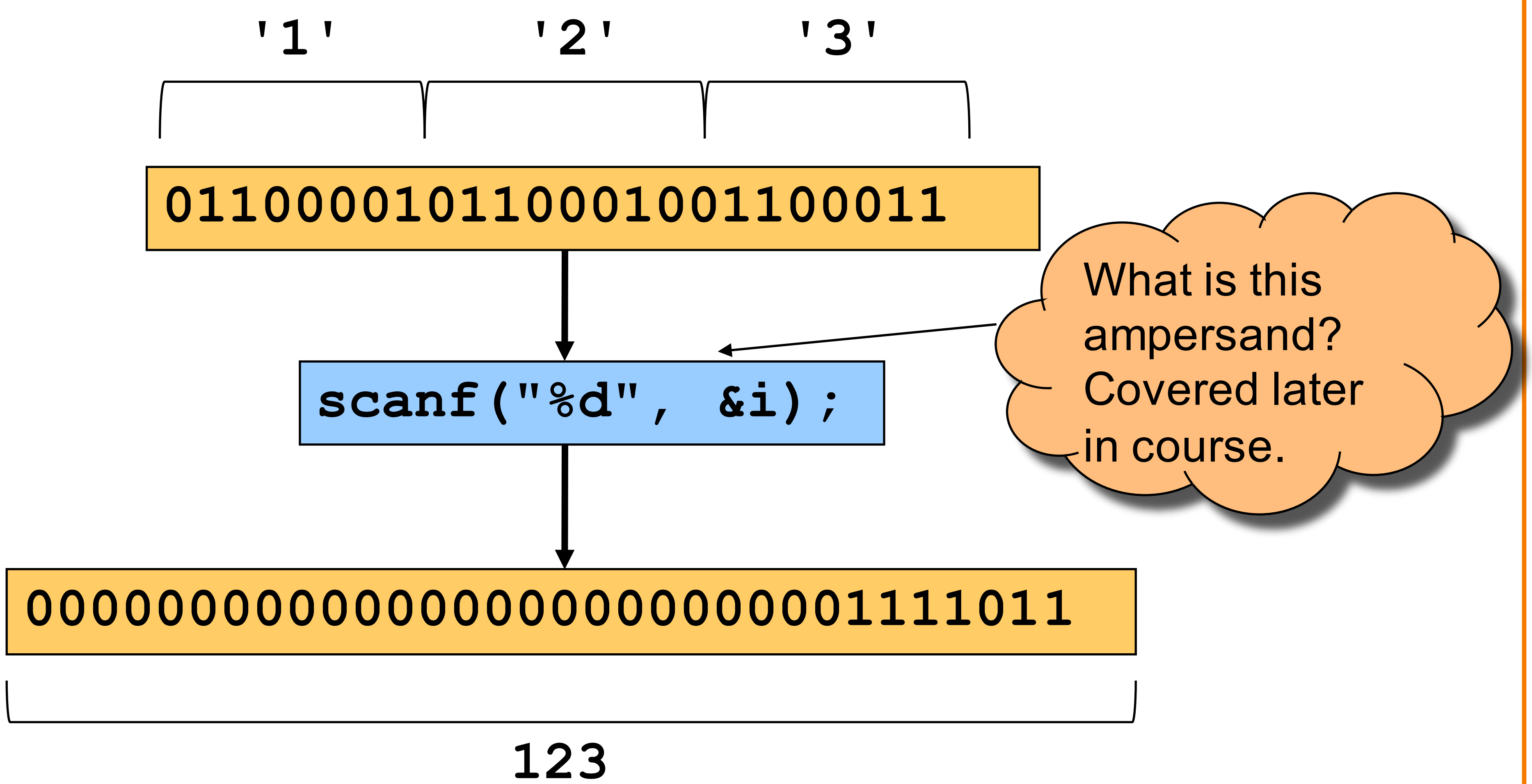
- Must convert external form (sequence of character codes) to internal form
- Could provide `getshort()`, `getint()`, `getfloat()`, etc.
- Could provide parameterized function to read any primitive type of data

Reading Other Data Types

Decisions

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

Reading Other Data Types



See King book for conversion specifications

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 parameterized function to write any primitive type of data

Writing Other Data Types

Decisions

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

Writing Other Data Types

`123`

```
00000000000000000000000001111011
```

```
printf("%d", i);
```

```
011000010110001001100011
```

`'1'` `'2'` `'3'`

See King book for conversion specifications

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
- ~~**`gets()`**: Read a line from stdin.~~ Brain-damaged, never use this!
- **`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
- 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**