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

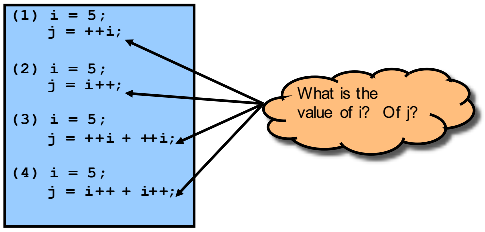
```
i += j  same as i = i + j

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

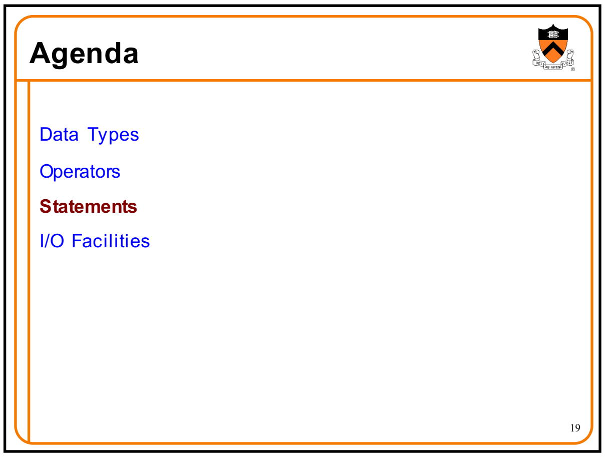
C only

• `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



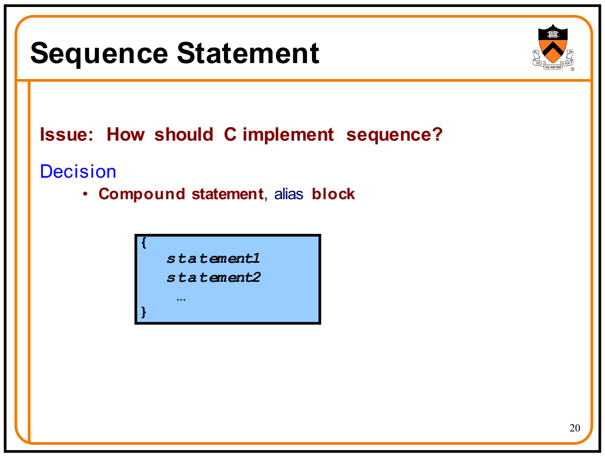
Agenda

Data Types

Operators

Statements

I/O Facilities



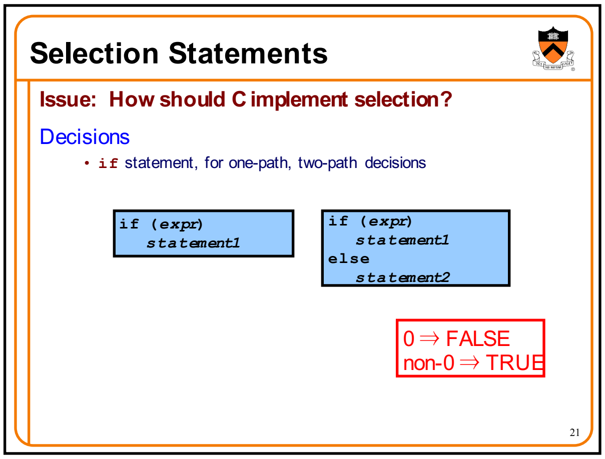
Sequence Statement

Issue: How should C implement sequence?

Decision

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

```
{
   statement1
   statement2
   …
}
```



Selection Statements

Issue: How should C implement selection?

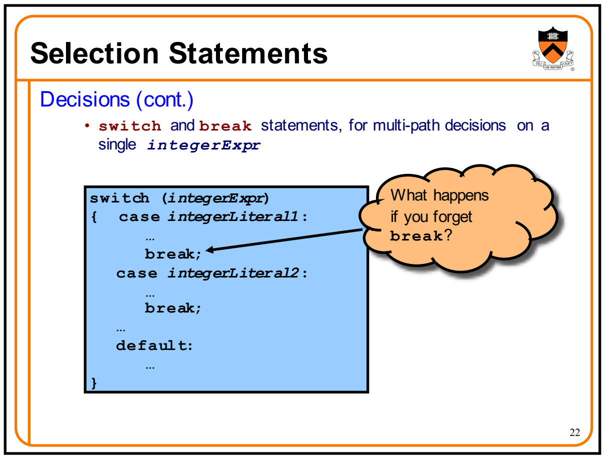
Decisions

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

```
if (expr)
   statement1
```

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

0 ⇒ FALSE
non-0 ⇒ TRUE



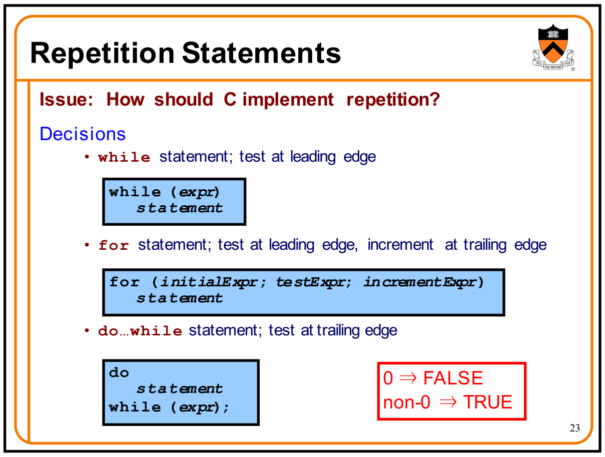
Selection Statements

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
```

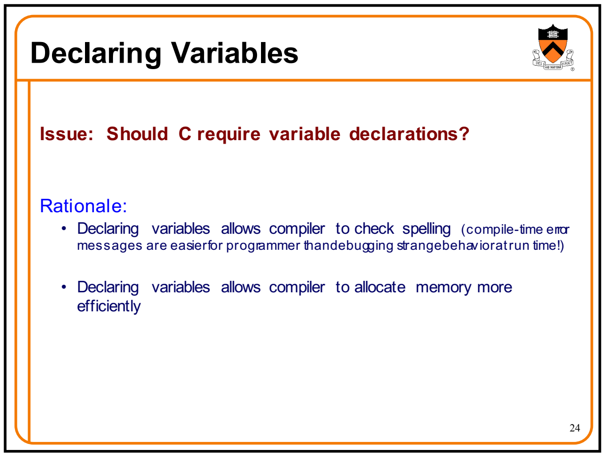
- `for` statement; test at leading edge, increment at trailing edge

```
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

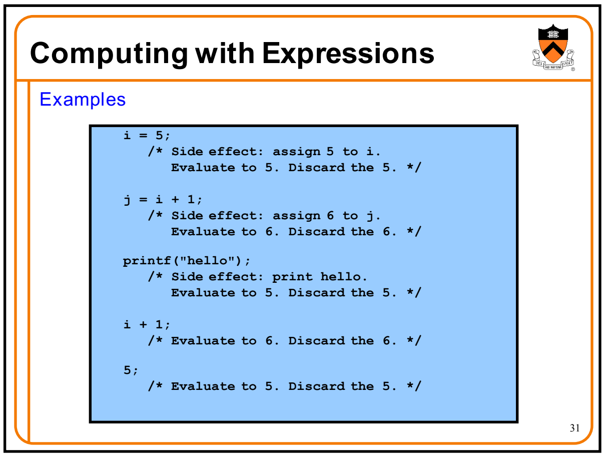
```
• int i;
• int i, j;
• int i = 5;
• const int i = 5;  /* value of i cannot change */
• static int i;     /* covered later in course */
• extern int i;     /* covered later in course */
```

Computing with Expressions

Issue: How should C implement computing with expressions?

Decisions:

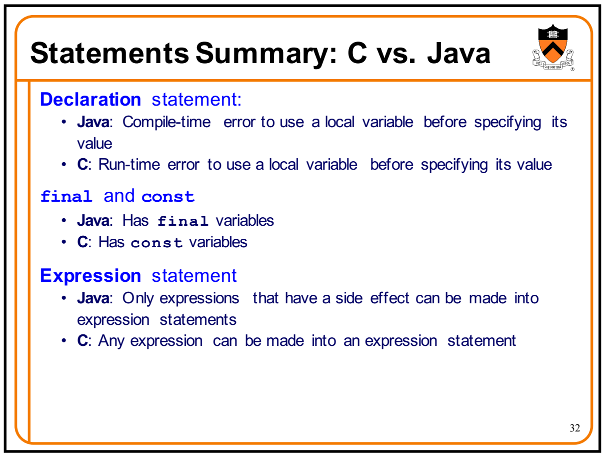
- Provide **expression statement**
  `expression ;`



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:

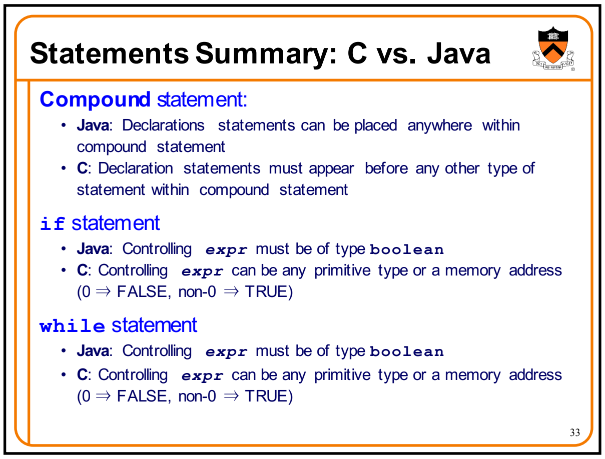
- **Java**: Compile-time error to use a local variable before specifying its value
- **C**: Run-time error to use a local variable before specifying its value

`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:

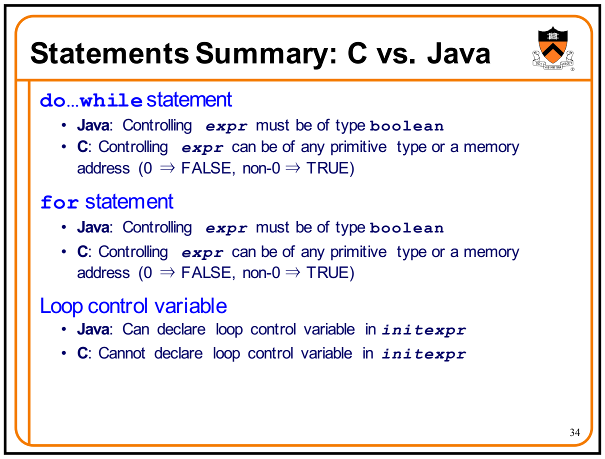
- **Java**: Declarations statements can be placed anywhere within compound statement
- **C**: Declaration statements must appear before any other type of statement within compound statement

`if` statement

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

`while` statement

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



Statements Summary: C vs. Java

`do`...`while` statement

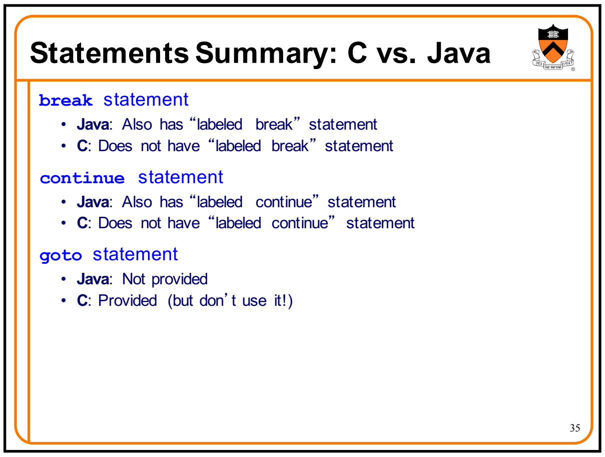
- **Java**: Controlling ***`expr`*** must be of type `boolean`
- **C**: Controlling ***`expr`*** can be of any primitive type or a memory address (0 ⇒ FALSE, non-0 ⇒ TRUE)

`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

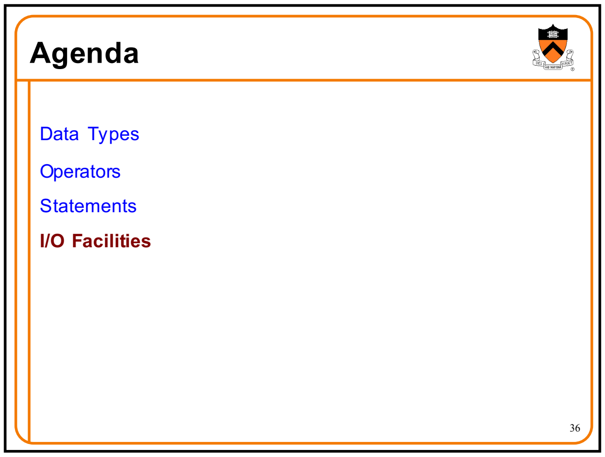
- **Java**: Also has “labeled break” statement
- **C**: Does not have “labeled break” statement

`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

Operators

Statements

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

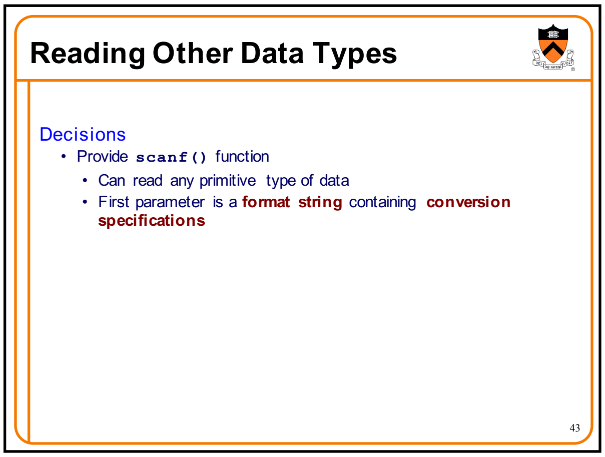
- Provide `putchar()` function
- Define `putchar()` to have `int` parameter
  - For symmetry with `getchar()`

Reading Other Data Types

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

Thought process

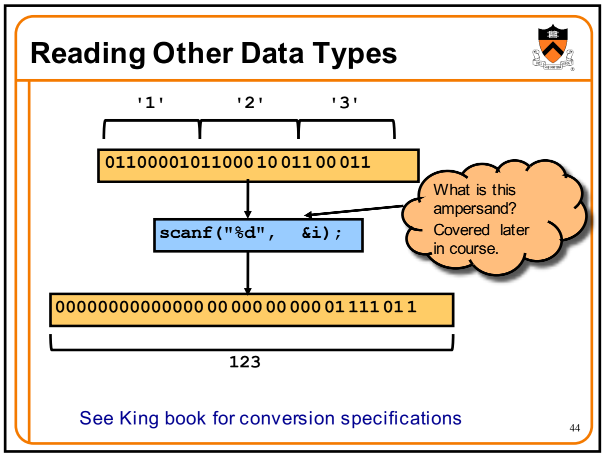
- Must convert external form (sequence of character codes) to internal form
- Could provide `getshort()`, `getint()`, `getfloat()`, etc.
- Could provide parameterized function to read any primitive type of data



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

'1' '2' '3'

011000010110001001100011

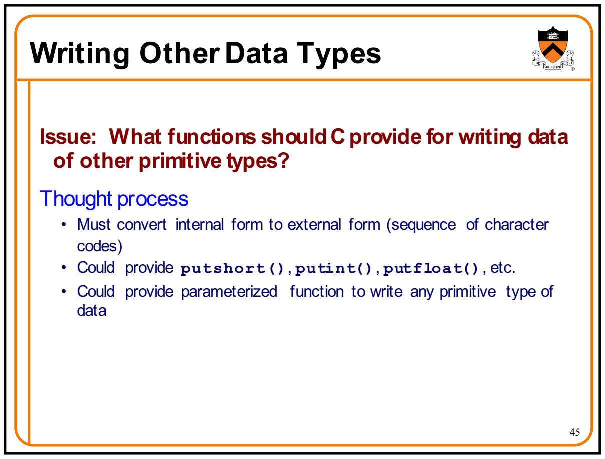
```
scanf("%d", &i);
```

What is this ampersand? Covered later in course.

00000000000000000000000001111011

123

See King book for conversion specifications

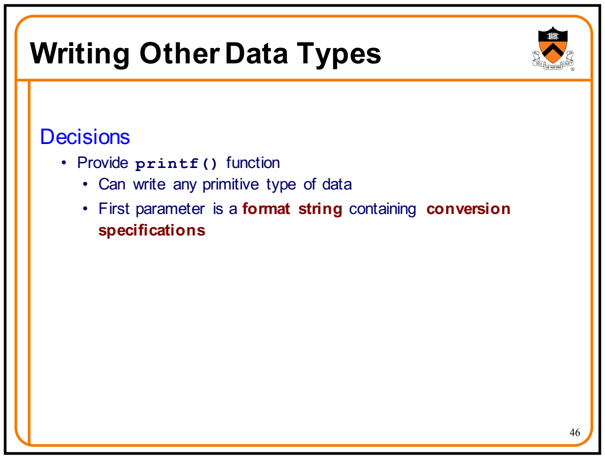


Writing Other Data Types

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

Thought process

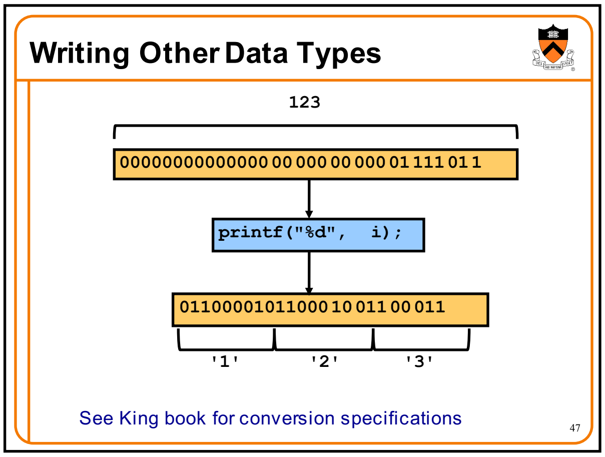
- Must convert internal form to external form (sequence of character codes)
- Could provide `putshort()`, `putint()`, `putfloat()`, etc.
- Could provide parameterized function to write any primitive type of data



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

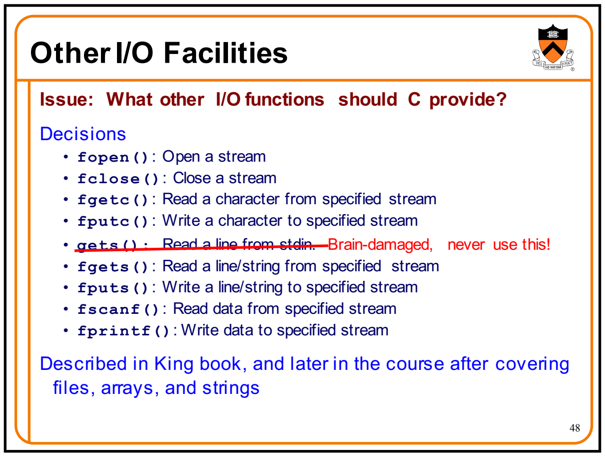
00000000000000000000000001111011

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

011000010110001001100011

'1' '2' '3'

See King book for conversion specifications



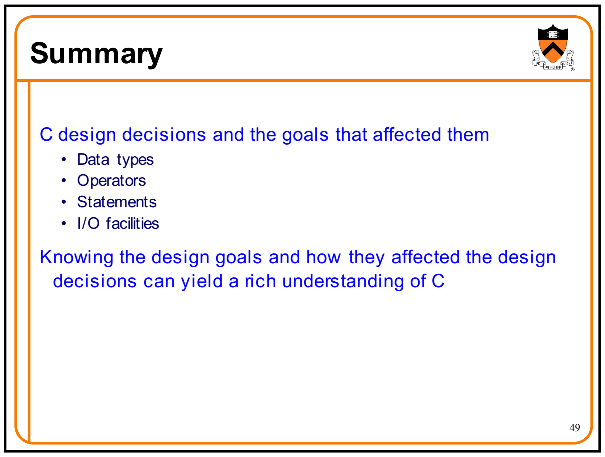
Other I/O Facilities

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

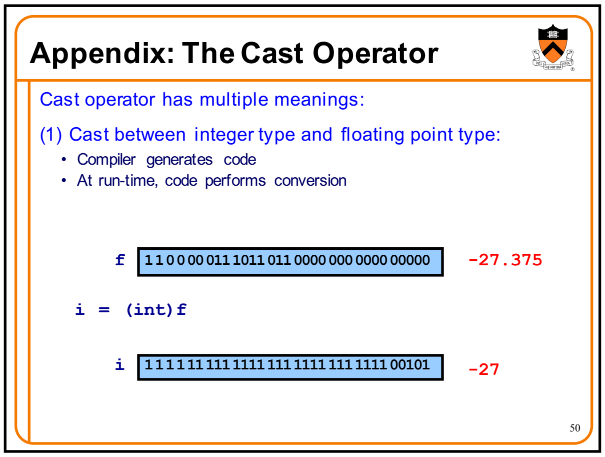


Summary

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



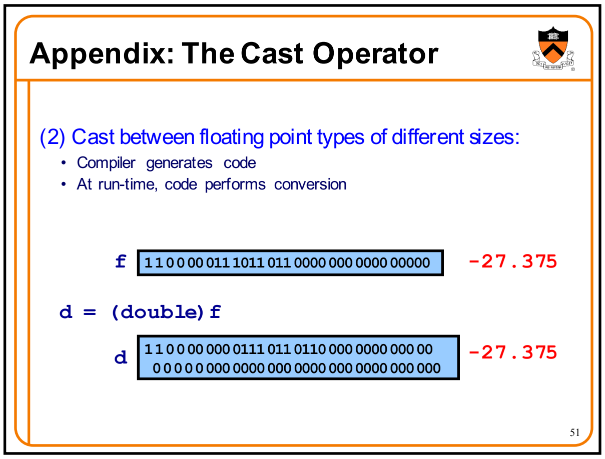
Appendix: The Cast Operator

Cast operator has multiple meanings:

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

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

```
    f  1 1 0 0 00 011 1011 011 0000 000 0000 00000   -27.375

i = (int)f

    i  1 1 1 1 11 111 1111 111 1111 111 1111 00101   -27
```

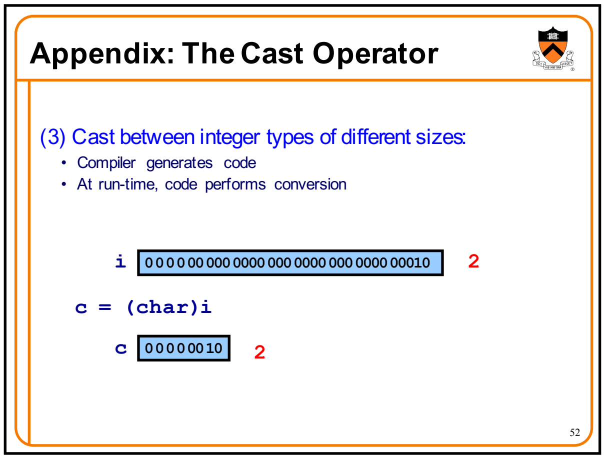


Appendix: The Cast Operator

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

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

```
    f  1 1 0 0 00 011 1011 011 0000 000 0000 00000   -27.375

d = (double)f

    d  1 1 0 0 00 000 0111 011 0110 000 0000 000 00   -27.375
        0 0 0 0 0 000 0000 000 0000 000 0000 000 000
```

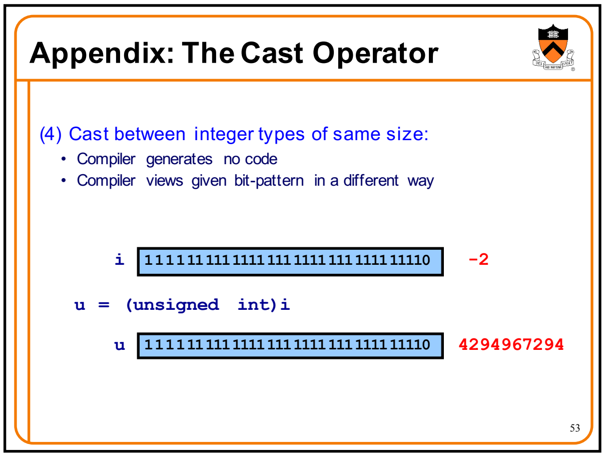


Appendix: The Cast Operator

(3) Cast between integer types of different sizes:

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

```
    i  0 0 0 0 00 000 0000 000 0000 000 0000 00010   2

c = (char)i

    c  0 0 0 0 00 10   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  1 1 1 1 11 111 1111 111 1111 111 1111 11110   -2

u = (unsigned int)i

    u  1 1 1 1 11 111 1111 111 1111 111 1111 11110   4294967294
```