# C Milestones

1. Originally developed by Dennis Ritchie in early 70s for use with Unix as a general *system programming language*.
2. In 1978, Kernighan and Ritchie publish *The C Programming Language*, popularly known as K&R1. C implementations based on book specification known as K&R1 C.
3. 1980 standardization by ANSI and ISO; changes include *function prototypes*. Known as C89 or C90. K&R2 describes C89.
4. 1990s standardization efforts led to C99; changes include variable-length arrays, inline functions.
5. 2000's standardization efforts led to C11; changes include multithreading support, anonymous structures and unions, `noreturn` functions.

# Distinguishing Features

- Strongly typed (compiler checks type compatibility) but allows programmer to selectively override type checking.
- Allows programmer to manipulate data at the bit-level.
- Support for directly manipulating memory addresses. This distinguishes C from higher-level programming languages where memory is abstracted out.
- Allows programmer total control over memory allocation.
- Uses a very limited macro system (compile-time text substitution).
- Higher level programming languages are often implemented by being translated into C, at least initially.

# Expressions vs Statements

- Expressions return a value which can be stored in a variable. Example of C expressions include arithmetic operators (involving operators like +, -, *, /, %), comparison expressions (with operators like ==, `!=`, <, <=, >, >=), logical expressions (involving operators like `&&`, `||`, `!` with 0 interpreted as **false**, `non-0` as **true**), bit expressions (involving operators like &, |, ~, >>, <<), assignment expressions (involving operators like =, +=, *=, etc).
- Statements do not have a value. Example of C statements are **if**, **for**, **while**, **do**, **switch**.

All programming languages have some kind of expression construct, but not all programming languages have statement constructs.

# Data

In any programming language there are two kinds of data:

**Primitive Data** Data which has no internal structure advertized by the language. In C, this includes various flavors of integers and real numbers as well as pointers (C does also allow getting at the internal structure, but this is a low-level feature).

**Composite Data** Data which is a collection of other data. In C, this includes arrays (sequence of data of the same type) and structures/unions (collections of data of possibly different types).

Ultimately, all data entities are represented as a sequence of bytes. In C, the number of bytes taken up by any data entity `x` is given by the expression `sizeof(x)`.

# C Integers

Various flavors of integers (in order of non-decreasing size):

| | |
|---|---|
| **short** | At least 2 bytes. |
| **int** | At least 2 bytes, can be 4 or 8 depending on machine. |
| **long** | At least 4 bytes, can be 8 depending on machine. |
| **long long** | At least 8 bytes. |

- Can have modifier `signed` or `unsigned`. Default is `signed`.
- If `unsigned` used without a type, then type is `int`.

# Integer Declarations with Initializers

```c
//signed by default
short answer = 42;              //signed: usually 2 bytes
int next = answer + 1;          //signed: often 4 bytes
long twice = 2 * answer;        //4 or 8 bytes
long long half = answer/2;      //at least 8 bytes
long value = 99L;               //use of a long literal

//explicitly declared unsigned
unsigned short s1 = 22;
unsigned short s2 = 1 << 15;    //ok
unsigned short s3 = 1 << 16;    //may overflow
unsigned u = 99;                //type defaults to int

short s4 = 1 << 15;             //signed: may overflow
                                //to negative
```

# Characters in C

- C does not really support characters or strings.
- A variable declared with type **char**, is declaring a 1-byte integer.
- If a variable is declared as a `char`, without a `signed` or `unsigned` modifier, then it's signed-ness is undefined.
- C does support character literals enclosed within single quotes. These integer value equal to code of character in the local character encoding (for example, `'A'` has integer value 65 in the ASCII encoding).
- Character literals support escapes as in `'\n'` newline, `'\t'` tab and `'\0'` `NUL` character.
- Since characters are merely integers, arithmetic can be performed with them as in `char c; ... c - '0'`, but the results are not portable in that they may vary with different character encodings.

# Char Declarations

Chars are always 1 byte.

```
char c1 = 'A';          //65 in ASCII
char c2 = 'B';          //66 in ASCII
char c3 = c1 + 1;       //same value as c2.
```

# C Arrays

- Arrays are a fundamental abstraction in many programming languages which abstract out the random-access property of the main memory in current computer technology.
- In C, arrays are declared using square brackets after the name of the array.

```c
int a[3];

int b[] = { 1, 2, 3 };

Employee employees[numEmployees];
```

- A C string is an array of characters terminated by a `NUL` character `'\0'`.

```c
char hello[] = "hello";   //array of 6 char's
```

- C arrays are closely related to pointers (more about that later).

# Integer Sum Program

In sum.c:

```
#include <stdio.h>

static int acc = 123;
int main()
{
  int values[] = { 2, 5, -9, };
  for (int i = 0; i < sizeof(values)/sizeof(values[0]);
        i++) {
    int value = values[i];
    acc += value;
  }
  printf("%d\n", acc);
  return 0;
}
```

# Integer Sum Program Log

Compiling:

```
$ gcc -g -Wall -std=c11 sum.c -o sum
```

- `-g` allows debugging compiled program.
- `-Wall` used for turning on reasonable warnings.
- `-std=c11` allows use of C11 features.
- `-o sum` creates executable in file `sum` (default is `a.out`).

Run using:

```
$ ./sum
121
$
```

# Integer Sum Program Discussion

- `acc` is declared outside of any function. It is loosely referred to as a *global variable*.
- Variables declared outside any function have lifetime equal to that of the entire program.
- If a variable is declared with the `static` qualifier, then it has lifetime equal to that of the entire program but is visible only to the subsequent code in the same *compilation unit* (file).
- If a variable is declared with the `extern` qualifier, then it has lifetime equal to that of the entire program and is visible to the entire program. If there is no `static` specifier, then the declaration defaults to be `extern`.
- In current programming practice, global variables are regarded as **evil** and should be avoided as far as possible. Read-only globals are not as bad as read-write globals.

# Integer Sum Program Discussion Continued

- Variables declared within a brace-delimited block are visible only within that block and (if there is no `static` qualifier) retain their value only during a single execution of that block.
- Specifically, variables declared within a function are visible only within that function and (if there is no `static` qualifier) retain their value only during a single activation of that function.
- These kind of `auto`-variables are invaluable in implementing recursive functions where multiple activations of a function are alive simultaneously.

```
int factorial(int n) {
  return (n <= 0) ? 1 : n * factorial(n - 1);
}
//factorial(4): n has values 4, 3, 2, 1, 0.
```

# Integer Sum Program Discussion Continued

- Usually, best practice is to always provide an initial value for a variable when it is declared.
- Array `values[]` is initialized with initial values enclosed within braces.
- Could also be declared as `int values[3] = { 2, 5, -9 };` but the size would be redundant.
- Best practice is to omit the size of the array and let it be determined by the length of the initializer.

# Integer Sum Program Discussion Continued

- Since the array `values[]` has 3 elements, we could have coded the **for**-loop as:

```
for (int i = 0; i < 3; i++) {
   ...
}
```

- If we decided to add another element to `values[]`, we would also need to change the loop bound to 4.
- A very important rule in programming is **Don't Repeat Yourself** (DRY). Specifically, you should avoid situations where changing one part of a program necessarily requires changing another part because the second part depends on the first part.

# Integer Sum Program Discussion Continued

- The use of the complex expression `sizeof(values)/sizeof(values[0])` avoids a DRY violation.
- The expression `sizeof(values)` gives the total number of bytes occupied by the `values[]` array and `sizeof(values[0])` gives the total number of bytes occupied by the `values[0]` element. Hence the quotient gives the number of elements in the `values[]` array.

# Integer Representation

- The C integer types can be regarded as abstract types which model a finite subset of the infinite set of all integers. These abstract types permits the usual arithmetic operations +, -, *, /, %, with results consistent with usual arithmetic (subject to size restrictions).
- However, C has operators like bitwise-and &, bitwise-or |, left-shift << and right-shift >> in which the representation of integers is no longer abstract. So it is necessary to understand the internal representation of integers.

# Decimal Positional Notation

In positional notation, the value of a digit depends on its position in the number. Specifically, a decimal integer $d_{n-1}d_{n-2}\ldots d_1 d_0$ represents the number:

$$10^{n-1} \times d_{n-1} + 10^{n-2} \times d_{n-2} + \ldots + 10^1 \times d_1 + 10^0 \times d_0$$

For example,

$$123 == 1 \times 10^2 + 2 \times 10^1 + 3 \times 10^0$$

Positional notation is a big win over additive notations like *Roman numerals* as the value of a represented number increases exponentially with the length of the representation.

# Positional Notation for a General Base

For a general base $B$ and *digits* $0, 1, \ldots B-1$ in base-$B$, the value of an $n$-digit integer $b_{n-1} b_{n-2} \ldots b_1 b_0$ in base-$B$ is given by:

$$B^{n-1} \times b_{n-1} + B^{n-2} \times b_{n-2} + \ldots + B^1 \times b_1 + B^0 \times b_0$$

For example, `0x123` (base-16) is

$$1 \times 16^2 + 2 \times 16^1 + 3 \times 16^0$$

which is 291\$, while `0123` (base-8) is

$$1 \times 8^2 + 2 \times 8^1 + 3 \times 8^0$$

which is 83.

# Common Bases used in Programming

- Decimal base is almost always the default. Example: `75`
- Base-2 binary numbers are commonly used within computers but usually too verbose for human use. Example: `01001011` binary which is `75` decimal. Not in standard C, available as gcc extension `0b01001011`.
- Base-16 commonly used as it is easy to convert to/from binary. Digits `0` .. `9` have usual meanings, `A` .. `F` (can also be lower-case) represent values 10 .. 15. An example of a C hexadecimal literal is `0x4B` (or `0x4b`) equal to decimal `75`.
- Base-8 was used earlier when word-lengths were multiples of 3 bits (PDP-8: 12-bits) but not popular currently. In C, any integer starting with a leading `0` is octal. For example, C interprets `0113` as an octal literal equal to decimal `75`. **This can be a gotcha for the unwary.**

# Representations

| Binary | Decimal | Hex | Oct |
|---|---|---|---|
| 0000 | 0 | 0x0 | 00 |
| 0001 | 1 | 0x1 | 01 |
| 0010 | 2 | 0x2 | 02 |
| 0011 | 3 | 0x3 | 03 |
| 0100 | 4 | 0x4 | 04 |
| 0101 | 5 | 0x5 | 05 |
| 0110 | 6 | 0x6 | 06 |
| 0111 | 7 | 0x7 | 07 |

# Representations Continued

| Binary | Decimal | Hex | Oct |
|---|---|---|---|
| 1000 | 8 | 0x8 | 010 |
| 1001 | 9 | 0x9 | 011 |
| 1010 | 10 | 0xA | 012 |
| 1011 | 11 | 0xB | 013 |
| 1100 | 12 | 0xC | 014 |
| 1101 | 13 | 0xD | 015 |
| 1110 | 14 | 0xE | 016 |
| 1111 | 15 | 0xF | 017 |

# Octal, Hexadecimal Conversions in C

In bases.c:

```
static void
bases(long values[], int nValues)
{
  for (int i = 0; i < nValues; i++) {
    long v = values[i];
    printf("number: %ld == 0%lo == 0X%lX == 0x%lx\n",
           v, v, v, v);
  }
}
```

In bases.c:

```
int
main()
{
  long values1[] = { 75, 123, 99 };
  long values2[] = { 075, 0x123, 0x99 };
  bases(values1, sizeof(values1)/sizeof(values1[0]));
  bases(values2, sizeof(values2)/sizeof(values2[0]));
  return 0;
}
```

# Octal, Hexadecimal Conversions in C Log

```
$ ./bases
number: 75 == 0113 == 0X4B == 0x4b
number: 123 == 0173 == 0X7B == 0x7b
number: 99 == 0143 == 0X63 == 0x63
number: 61 == 075 == 0X3D == 0x3d
number: 291 == 0443 == 0X123 == 0x123
number: 153 == 0231 == 0X99 == 0x99
$
```

# Signed Magnitude Representation of Signed Integers

*Signed magnitude* representation:

- Integer represented using a single sign bit (0 positive, 1 negative) and an unsigned magnitude.
- +75 has 8-bit signed magnitude representation 01001011; -75 has 8-bit signed magnitude representation 11001011;
- 0 has two representations: +0 00000000 and -0 10000000.
- Not used in practice, but useful when interpreting floating point representation as integers.

# Two's Complement Representation

- Two's complement is the representation used currently for representing signed integers. Given bits $b_{n-1} b_{n-2} \ldots b_1 b_0$, the MSB is used as a sign bit with weight $-2^{n-1}$. The overall value is:

$$b_{n-1} \times -2^{n-1} + b_{n-2} \times 2^{n-2} \ldots b_1 \times 2^1 + b_0 \times 2^0$$

- +75 has 8-bit 2's complement representation `01001011`; `-75` has 8-bit 2's complement representation `10110101` which is `-128 + 53`.
- To negate a 2's complement number, form its bit-complement and add 1 to the result. For example, `-75 == (~01001011 + 1) == (10110100 + 1) == 10110101`.

# Two's Complement Examples

Examples of 8-bit 2's complement numbers:

```
1000 0000 == -128
1000 0001 == -127
1000 0010 == -126
1000 0011 == -125
...
1111 1111 == -1
0000 0000 == 0
0000 0001 == 1
...
0111 1111 == 127
```

# Output Binary Representation

In out-bits.c:

```
static void out_bits(short value, FILE *out)
{
  fprintf(out, "%d == 0x%x == 0%o == 0b",
          value, value, value);
  int nBits = CHAR_BIT * sizeof(value);
  unsigned mask = 0x1 << (nBits - 1);
  for (int i = 0; i < nBits; i++) {
    char c = (mask & value) ? '1' : '0';
    mask >>= 1;
    fprintf(out, "%c", c);
    if (i % 4 == 3 && i != nBits - 1) fprintf(out, "_");
  }
  fprintf(out, "\n");
}
```

# Output Binary Representation: main()

In out-bits.c:

```
int main()
{
  short values[] = {
    0, 16, 255, 1<<(sizeof(short)*CHAR_BIT - 2), -1
  };
  for (int i = 0;
        i < sizeof(values)/sizeof(values[0]);
        i++) {
    out_bits(values[i], stdout);
  }
  return 0;
}
```

# Output Binary Representation: Log

```
./out-bits
0 == 0x0 == 00 == 0b0000_0000_0000_0000
16 == 0x10 == 020 == 0b0000_0000_0001_0000
255 == 0xff == 0377 == 0b0000_0000_1111_1111
16384 == 0x4000 == 040000 == 0b0100_0000_0000_0000
-1 == 0xffffffff == 037777777777 == 0b1111_1111_1111_1111
```

# Two's Complement Features

- Asymmetric. With n-bits, non-negative numbers range from $0 \ldots 2^{n-1} - 1$ but the negative numbers range from $-1 \ldots -2^{n-1}$. There is no positive counterpart to $-2^{n-1}$. This can result in subtle bugs.
- Each representable number has a unique representation. No multiple representations for 0. `-0 == (0xFFFFFFFF + 1) ==` 0x00000000'.
- Note that an unsigned $n$-bit number can represent values in the range $0 \ldots 2^n - 1$. So the largest unsigned number is 1 more than twice the largest positive 2's complement number. This is something to keep in mind when converting between signed and unsigned representation.

# C Integer Literals

As discussed previously, integer values can be specified in octal (leading `0`), hexadecimal (leading `0x` or `0X`) or decimal (default). However, that does not say anything about which integer type that literal corresponds to.

- `short` and `char` integers always promoted to `int` integers within expressions. Hence `short`, `char` are primarily storage types.
- A literal with `l` or `L` suffix is a long. Presence of a `long` literal within an expression will force expression to be evaluated as a `long`.

# C Integer Literals Continued

- A integer literal with a `u` or `U` suffix is unsigned. Example `1024U`.
- A integer literal with a `ll` or `LL` suffix is `long long`. Example: `1024LL`.
- The size and unsigned suffixes can be combined in either order: `1024UL` or `1024Lu` are the same.

# Bit Operators

- `&` Bitwise-and of two integers. `0x1234 & 0xF0F0` results in `0x1030`.
- `|` Bitwise-or of two integers. `0x1234 | 0xF0F0` results in `0xF2F4`.
- `^` Bitwise-xor of two integers. `0x1234 ^ 0xF0F0` results in `0xE2C4`.
- `~` Bitwise complement. `~0x1234` results in `0xEDCB`.

# Shift Operators

<< `i << n` is the value of `i` shifted to the left by `n` bits with 0 being shifted in from the right. `0x3 << 2` is `0xC`. Can be used for multiplying by powers-of-2.

>> `i >> n` is the value of `i` shifted to the right by `n` bits. If `i` is unsigned, then 0 is shifted in from the left; otherwise the sign bit is shifted in. Example: `0xC >> 2` is `0x3`.

# Bit and Shift Operator Examples

Assume `unsigned int u` and bits are numbered starting with LSB being bit 0, next bit being 1, etc.

- Bitwise operators have unintuitive precedence; always parenthesize to avoid ambiguity.
- Non-zero iff bit 0 of `u` is 0: `((u & 0x1) == 0)`.
- Non-zero iff bit 2 of `u` is 1: `((u & 0x4) != 0)`.
- Set LSB of `u` to `1` without changing other bits: `u |= 0x1`.
- Set LSB of `u` to `0` without changing other bits: `u &= ~0x1`.
- Value of 2nd hexet (bits 4 - 7) of `u`: `(u & 0xf0) >> 4` or `(u >> 4) & 0x0f`.
- Non-zero iff MSB of `u` is 1: `(u & (~0u >> 1)) != 0`. Note `u` suffix in `0u` absolutely necessary.

In count-1s-1.c:

```
int
count_ones(unsigned v)
{
  int ones = 0;
  for (unsigned i = v; i > 0; i >>= 1) {
    if (i & 1) ones++;
  }
  return ones;
}
```

In count-1s-1.c:

```
int main() {
  unsigned values[] = { 123, 32, 255 };
  for (int i = 0; i < sizeof(values)/sizeof(values[0]);
       i++) {
    unsigned v = values[i];
    printf("# of ones in %u (0x%x) is %d\n",
           v, v, count_ones(v));
  }
  return 0;
}
```

# Counting # of 1s in an int Log

```
$ ./count-1s-1
# of ones in 123 (0x7b) is 6
# of ones in 32 (0x20) is 1
# of ones in 255 (0xff) is 8
$
```

# Counting # of 1s in an `int` Discussion

- The loop starts with `i` set to the value `v` within which we want to count the number of 1-bits.
- Basic C does not have boolean type; the value 0 is treated as **false**, any non-zero value is treated as **true**. Hence `ones` is incremented if `i & 1` is non-zero; i.e., `ones` is incremented iff the least-significant bit (LSB) of `i` is 1.
- After each iteration of the loop, `i` is shifted to the right by 1 position. Thus the 1's in `i` make their way towards the LSB.
- The loop terminates when `i` is 0; i.e., there are no more 1's to count and `ones` contains the count of 1's in the original value `v`.
- The number of iterations in the loop will depend on the position of the leftmost 1 in the original value `v`.

# Counting # of 1s in an int: 2nd Attempt

In count-1s-2.c we reduce number of loop iterations to number of 1's in original value:

```
int
count_ones(unsigned v)
{
  int ones = 0;
  while (v > 0) {
    v &= v - 1;
    ones++;
  }
  return ones;
}
```

- If `v` is `101000`, then `v - 1` is `100111`. Hence `v & (v - 1)` is `100000`. By assigning this back to `v`, we knock-out the rightmost 1 in `v` in each loop iteration.
- Since we knock-out the rigthmost 1 in each loop iteration and increment `ones` on each loop iteration and terminate the loop when no 1's remain in `v`, at loop termination `ones` will contain the number of 1's in the original value of `v`.
- Note that even though the parameter value `v` is being changed within `count_ones()`, that change will not be reflected in the caller of `count_ones()`. That is because when parameters are passed in C, a copy of the actual parameter is passed. This is referred to as **call-by-value**.

# Big Endian versus Little Endian

- In what order are multi-byte quantities (like integers or floats) stored in memory?
- Two common solutions: *litte endian* versus *big endian* (details follow). Some machines can choose dynamically ("bi-endian").
- Usually not visible to programmer on an individual machine but is an issue when sending binary data between machines.
- Many current networks mandate big-endian.

# Little Endian

**Little Endian** Least significant byte stored in low address, next least significant byte stored in next higher address, .., most significant byte stored in high address. For example, if `0x01234567` stored at `0x100`:

| | | | | |
|---|---|---|---|---|
| `Address:` | `0x100` | `0x101` | `0x102` | `0x103` |
| `Value:` | `0x67` | `0x45` | `0x23` | `0x01` |

Intel machines little endian.

# Big Endian

**Big Endian** Most significant byte stored in low address, next most significant byte stored in next higher address, .., least significant byte stored in high address. For example, if `0x01234567` stored at `0x100`:

```
Address: 0x100  0x101  0x102  0x103
Value:    0x01   0x23   0x45   0x67
```

IBM, Sun big endian.

# Endian Program

In endian.c:

```
int
main()
{
  union { //memory for i and bytes overlap
    int i;
    char bytes[sizeof(int)];
  } u = { 0x123456 };
  printf("int = 0x%x\n", u.i);
  for (int i = 0; i < sizeof(int); i++) {
    printf("bytes[%d] at %p is 0x%02x\n",
           i, &u.bytes[i], u.bytes[i]);
  }
  return 0;
}
```

# Endian Program Log on x86

```
$ ./endian
int = 0x123456
bytes[0] at 0x7fff565cfe00 is 0x56
bytes[1] at 0x7fff565cfe01 is 0x34
bytes[2] at 0x7fff565cfe02 is 0x12
bytes[3] at 0x7fff565cfe03 is 0x00
$
```

# Endian Program Log on Sparc

```
bingsuns2% ./endian
int = 0x123456
bytes[0] at ffbff900 is 0x00
bytes[1] at ffbff901 is 0x12
bytes[2] at ffbff902 is 0x34
bytes[3] at ffbff903 is 0x56
bingsuns2%
```

- The members of a union are assigned at the same memory location. Hence `u.i` and `u.bytes` occupy the same memory location. This allows us to look at the individual bytes in `int i`.
- The `&` unary operator returns the address of its operand. Hence `&u.bytes[i]` returns the address of the `i`'th byte.
- Note that for x86, the most significant byte is stored at a higher address than the least significant byte. Hence x86 is a little-endian architecture.
- Note that for sparc, the least significant byte is stored at a higher address than the least significant byte. Hence sparc is a big-endian architecture.

# Signed, Unsigned Addition

- The operation of addition is the same for both signed and unsigned numbers with 2's complement.
- Consider 3 bits numbers: Unsigned: 0 to 7; Signed -4 to 3.
- Each following table shows addition of all combinations of a left operand with two right operands.
- Signed result indicated by a signed result in parentheses.
- Overflow indicated by a $*$.

Addition table for $N$ + 0b000 and $N$ + 0b001:

| **Rand1/Rand2** | $000 = 0\ (\ \ 0)$ | $001 = 1\ (+1)$ |
|---|---|---|
| $000 = 0\ (\ \ 0)$ | $000 = 0\ (\ \ 0)$ | $001 = 1\ (+1)$ |
| $001 = 1\ (+1)$ | $001 = 1\ (+1)$ | $010 = 2\ (+2)$ |
| $010 = 2\ (+2)$ | $010 = 2\ (+2)$ | $011 = 3\ (+3)$ |
| $011 = 3\ (+3)$ | $011 = 3\ (+3)$ | $100 = 4\ (-4^*)$ |
| $100 = 4\ (-4)$ | $100 = 4\ (-4)$ | $101 = 5\ (-3)$ |
| $101 = 5\ (-3)$ | $101 = 5\ (-3)$ | $110 = 6\ (-2)$ |
| $110 = 6\ (-2)$ | $110 = 6\ (-2)$ | $111 = 7\ (-1)$ |
| $111 = 7\ (-1)$ | $111 = 7\ (-1)$ | $000 = 0^*\ (\ \ 0)$ |

# Signed, Unsigned Addition Tables Continued

Addition table for $N +$ `0b010` and $N +$ `0b011`:

| **Rand1/Rand2** | $010 = 2\ (+2)$ | $011 = 3\ (+3)$ |
|---|---|---|
| $000 = 0\ (\ \ 0)$ | $010 = 2\ (+2)$ | $011 = 3\ (+3)$ |
| $001 = 1\ (+1)$ | $011 = 3\ (+3)$ | $100 = 4\ (-4^*)$ |
| $010 = 2\ (+2)$ | $100 = 4\ (-4^*)$ | $101 = 5\ (-3^*)$ |
| $011 = 3\ (+3)$ | $101 = 5\ (-3^*)$ | $110 = 6\ (-2^*)$ |
| $100 = 4\ (-4)$ | $110 = 6\ (-2)$ | $111 = 7\ (-1)$ |
| $101 = 5\ (-3)$ | $111 = 7\ (-1)$ | $000 = 0^*\ (\ \ 0)$ |
| $110 = 6\ (-2)$ | $000 = 0^*\ (\ \ 0)$ | $001 = 1^*\ (+1)$ |
| $111 = 7\ (-1)$ | $001 = 1^*\ (+1)$ | $010 = 2^*\ (+2)$ |

# Signed, Unsigned Addition Tables Continued

Addition table for $N$ + `0b100` and $N$ + `0b101`:

| **Rand1/Rand2** | $100 = 4\ (-4)$ | $101 = 5\ (-3)$ |
|---|---|---|
| $000 = 0\ (\ \ 0)$ | $100 = 4\ (-4)$ | $101 = 5\ (-3)$ |
| $001 = 1\ (+1)$ | $101 = 5\ (-3)$ | $110 = 6\ (-2)$ |
| $010 = 2\ (+2)$ | $110 = 6\ (-2)$ | $111 = 7\ (-1)$ |
| $011 = 3\ (+3)$ | $111 = 7\ (-1)$ | $000 = 0^*\ (\ \ 0)$ |
| $100 = 4\ (-4)$ | $000 = 0^*\ (\ \ 0^*)$ | $001 = 1^*\ (+1^*)$ |
| $101 = 5\ (-3)$ | $001 = 1^*\ (+1^*)$ | $010 = 2^*\ (+2^*)$ |
| $110 = 6\ (-2)$ | $010 = 2^*\ (+2^*)$ | $011 = 3^*\ (+3^*)$ |
| $111 = 7\ (-1)$ | $011 = 3^*\ (+3^*)$ | $100 = 4^*\ (-4)$ |

Addition table for $N$ + `0b110` and $N$ + `0b111`:

| **Rand1/Rand2** | $110 = 6\ (-2)$ | $111 = 7\ (-1)$ |
|---|---|---|
| $000 = 0\ (\ \ 0)$ | $110 = 6\ (-2)$ | $111 = 7\ (-1)$ |
| $001 = 1\ (+1)$ | $111 = 7\ (-1)$ | $000 = 0^*\ (\ \ 0)$ |
| $010 = 2\ (+2)$ | $000 = 0^*\ (\ \ 0)$ | $001 = 1^*\ (+1)$ |
| $011 = 3\ (+3)$ | $001 = 1^*\ (+1)$ | $010 = 2^*\ (+2)$ |
| $100 = 4\ (-4)$ | $010 = 2^*\ (+2^*)$ | $011 = 3^*\ (+3^*)$ |
| $101 = 5\ (-3)$ | $011 = 3^*\ (+3^*)$ | $100 = 4^*\ (-4)$ |
| $110 = 6\ (-2)$ | $100 = 4^*\ (-4)$ | $101 = 5^*\ (-3)$ |
| $111 = 7\ (-1)$ | $101 = 5^*\ (-3)$ | $110 = 6^*\ (-2)$ |

# Typical Ranges for Unsigned Types

```
----------+--------+--------------------------
| # bits  |  Min.  |     Max Value            |
+---------+--------+--------------------------+
|   8     |      0 |                       255|
|  16     |      0 |                    65,535|
|  32     |      0 |             4,294,967,295|
|  64     |      0 |18,446,744,073,709,551,615|
----------+--------+--------------------------
```

# Typical Ranges for Signed Types

```
+-----+--------------------------+-------------------+
|#bits|  Min. Value              |      Max Value    |
+-----+--------------------------+-------------------+
|   8 |                      -128|                127|
|  16 |                   -32,768|             32,767|
|  32 |            -2,147,483,648|      2,147,483,647|
|  64 |-9,223,372,036,854,775,808| 9,223,372,036,854,|
|     |                          |           775,807 |
+-----+--------------------------+-------------------+
```

# Finding Integer Sizes in C

In integer-sizes.c:

```c
#include <stdio.h>

int
main()
{
  //concatenation of adjacent string literals
  //%ld not portable; modern C allows %zu for sizeof()
  printf("sizeof(char) = %ld, sizeof(short) = %ld, "
         "sizeof(int) = %ld sizeof(long) = %ld, "
         "sizeof(long long) = %ld\n",
         sizeof(char), sizeof(short), sizeof(int),
         sizeof(long), sizeof(long long));
  return 0;
}
```

# Integer Sizes: Edited Log

```
sizeof(char) = 1, sizeof(short) = 2, sizeof(int) = 4
  sizeof(long) = 8, sizeof(long long) = 8
```

# Powers of $\sim 1000$

- Since $2^{10} = 1024$ which is close to 1000, $2^{20} = $ `1,048,576` which is close to 1,000,000, we can use *kilo* and *mega* notation, but need to distinguish between powers of 1000 and powers of 1024.
- Powers of 1000: normal **metric notation**: `kB`, `MB`, `GB`, etc.
- Powers of 1024: *IEC units*: `KiB`, `MiB`, `GiB`, etc.
- Write program to show quantities associated with different units.

# Kilo Powers Program Log

Note overflow for zetta and yotta.

```
#metric units
$ ./kilo-powers
1000**1 = 1 kilobyte (kB) which is 1000 bytes
1000**2 = 1 megabyte (MB) which is 1000000 bytes
1000**3 = 1 gigabyte (GB) which is 1000000000 bytes
1000**4 = 1 terabyte (TB) which is 1000000000000 bytes
1000**5 = 1 petabyte (PB) which is 1000000000000000 bytes
1000**6 = 1 exabyte (EB) which is 1000000000000000000 bytes
1000**7 = 1 zettabyte (ZB) which is 3875820019684212736 bytes
1000**8 = 1 yottabyte (YB) which is 2003764205206896640 bytes
```

```
#iec units
1024**1 = 1 kibibyte (KiB) which is 1024 bytes
1024**2 = 1 mebibyte (MiB) which is 1048576 bytes
1024**3 = 1 gibibyte (GiB) which is 1073741824 bytes
1024**4 = 1 tebibyte (TiB) which is 1099511627776 bytes
1024**5 = 1 pebibyte (PiB) which is 1125899906842624 bytes
1024**6 = 1 exbibyte (EiB) which is 1152921504606846976 bytes
1024**7 = 1 zebibyte (ZiB) which is 0 bytes
1024**8 = 1 yobibyte (YiB) which is 0 bytes

$
```

# Kilo Powers Program: Type Declaration

In kilo-powers.c:

```c
/** Package unit-name and its abbreviation. */
typedef struct {
  const char *name;
  const char *abbr;
} Unit;
```

# Kilo Powers Program: Metric Data

```
static Unit metricUnits[] = {
  { "kilobyte", "kB" },
  { "megabyte", "MB" },
  { "gigabyte", "GB" },
  { "terabyte", "TB" },
  { "petabyte", "PB" },
  { "exabyte", "EB" },
  { "zettabyte", "ZB" },
  { "yottabyte", "YB" },
};
```

# Kilo Powers Program: IEC Data

```c
static Unit iecUnits[] = {
  { "kibibyte", "KiB" },
  { "mebibyte", "MiB" },
  { "gibibyte", "GiB" },
  { "tebibyte", "TiB" },
  { "pebibyte", "PiB" },
  { "exbibyte", "EiB" },
  { "zebibyte", "ZiB" },
  { "yobibyte", "YiB" },
};
```

# Kilo Powers Program: Guts

```c
static void
outUnits(unsigned base, Unit units[], int nUnits,
         FILE *out)
{
  unsigned long long v = 1;
  for (int i = 0; i < nUnits; i++) {
    v *= base;
    fprintf(out, "%d**%d = 1 %s (%s) "
            "which is %llu bytes\n",
            base, i + 1, units[i].name,
            units[i].abbr, v);
  }
  fprintf(out, "\n");
}
```

# Kilo Powers Program main() Function

```
int
main()
{
  outUnits(1000u, metricUnits,
           sizeof(metricUnits)/sizeof(metricUnits[0]),
           stdout);
  outUnits(1024u, iecUnits,
           sizeof(iecUnits)/sizeof(iecUnits[0]),
           stdout);
  return 0;
}
```

# Kilo Powers Program Discussion

- A C `struct` allows packaging related data together.
- In C, `typedef` defines a name for some type. So the program uses the name `Unit` to refer to a particular `struct` type.
- Note the use of the `u` suffix on `1000u` and `1024u` to pass an unsigned base value to `outUnits()`.
- IEC units have not really caught on. In practice, GB may mean "gigabyte" or "gibibyte", depending on context. In commercial contexts, memory sizes are often stated in IEC units, disk sizes in metric units but no guarantees.

# Booleans

- Basic C does not have any **boolean** type.
- C99 introduced `stdbool.h` header with suitable definitions for `true` and `false`.
- Comparison operators <, <=, >, >=, ==, != return result 1 for *true* and 0 for *false*.
- Logical operators &&, ||, ! treat 0 as *false*, all non-0 values as *true*.
- C has a single **falsy value**: 0. All values other than 0 are **truthy**.

An expression which compares two numeric expressions is known as a *relational expression*.

`==`, (`!=`) Returns 1 iff two expressions are equal (not-equal), 0 otherwise. **Do not use with floating point types**:

- **Example**: `if (i != 0) b = x/i;`.
- Watch out for incorrect use of =. For example, `if (i = 0) b = 1 else b = x/i;` will always divide by `i` because of use of = instead of == in comparison. Some programmers protect for this case by writing `if (0 == i)` which will cause a compilation error if written incorrectly as `if (0 = i)`.

<, (>) Returns 1 iff the left-hand expression is less-than (greater-than) the right-hand expression, 0 otherwise. **Example**: `for (int i = 0; i < 10; i++) { ... }`.

<=, (>=) Returns 1 iff the left-hand expression is less-than-or-equal-to (greater-than-or-equal-to) the right-hand expression, 0 otherwise. **Example**: `for (int i = 9; i >= 0; i--) { ... }`.

Can also use on right-hand-side of assignment as in: `int aLT10 = (a < 10);`.

# Short-Circuit Logical Operators

The operators || (logical-or) and && (logical-and) evaluate operands from left-to-right, but stop ("short-circuit") the evaluation immediately once the result is known for sure; i.e. they may not evaluate their 2nd operand if the result is determined by the value of the first operand.

*A* || *B* If expression *A* evaluates to non-zero, then return 1 without ever evaluating expression *B*. Otherwise return 0 if *B* too evaluates to 0, otherwise return 1.

- **Example**: In `if (x == 0 || y/x > 10) { }`, short-circuit property of || avoids division-by-0 error.

# Short-Circuit Logical Operators Continued

$A$ && $B$ If expression $A$ evaluates to 0, then return 0 without ever evaluating expression $B$. Otherwise return 1 if $B$ too evaluates to non-zero, otherwise return 0.

- **Example**: Search for first element of `a[n]` which is equal to `key`: `for (int i = 0; i < n && a[i] != key; i++) { ... }`
- Note that because of short-circuit evaluation, when `i == n` code does not examine `a[i]` at all, thus avoiding an index-out-of-bounds error.

# Logical Not

`!` *A* Return 0 if *A* is non-zero, 1 when *A* is 0.

- Can avoid using `!` by applying DeMorgan's law: example, instead of `!(x <= 10 || y == 5)` use `(x > 10 && y != 5)`, but use `!` if it is clearer in a particular context.
- Idiom `!!x` can be used to convert from `x` which may not be strictly 0 or 1 to a strict 0 or 1 value.

# Logical Operators versus Bitwise Operators

- Do not confuse bit-wise operators `&`, `|`, `^`, `~` with logical operators `&&`, `||`, `!` which operate on pseudo-boolean values.
- Logical operators `&&` and `||` have short-circuit semantics and may not evaluate their 2nd operand; bitwise-operators `&` and `|` always evaluate both operands.
- Assignment operators `&=`, `|=` and `^=` refer to the bitwise operators. No assignment operators for logical operators `&&` and `||`.

# If-then-else Expressions

`x = (cond) ? expr1 : expr2` equivalent to

```
if (cond)
  x = expr1
else
  x = expr2;
```

- Note it is possible to chain conditions together as in `x = (cond1) ? expr1 : (cond2) ? expr2 : expr3` which is equivalent to `x = (cond1) ? expr1 : ((cond2) ? expr2 : expr3)`, but can easily turn ugly.
- I tend to overuse this in my code compared to normal practice.

# Sum of Integer Command-Line Arguments Log

Not particularly robust in checking for errors:

```
$ gcc -g -Wall -Wextra -std=c11 sum-args.c -o sum-args

$ ./sum-args 22 -3 5
24

#silently ignore garbage at end of values
$ ./sum-args 22 -3x 5
24

#silently ignore totally garbage values
$ ./sum-args 22 -3x 5 garbage 3
27
$
```

# Sum of Integer Command-Line Arguments

In sum-args.c:

```
/** Output sum of integer command-line arguments on stdout. */
int
main(int argc, const char *argv[])
{
  int sum = 0;
  for (int i = 1; i < argc; i++) {
    sum += atoi(argv[i]);
  }
  printf("%d\n", sum);
  return 0;
}
```

# Sum of Integer Command-Line Arguments Discussion

- Recollect that a C string is a array of `char` terminated by a `NUL` character `'\0'`.
- First argument to `main()` `argc` gives the number of command-line arguments including the name of the program.
- The notation `char` **str* can be regarded as declaring *str* to be a string (strictly speaking, is is declaring *str* to be a pointer to a `char`).
- Hence `const char *argv[]` declares `argv` to be an array of strings; the `const` means that the strings cannot be changed.

# Sum of Integer Command-Line Arguments Discussion Continued

- `atoi()` is a function declared in included file `<stdlib.h>` which converts a string (which should contain only characters corresponding to decimal digits) to the internal representation of a C integer.
- `\n` is an escape sequence used within C-strings to denote a newline character.
- The first argument for `printf()` should be a C-string denoting a C string. % characters are used as escape sequences within a format string to introduce format specifiers used to print the next corresponding argument.

# More Robust Sum Program: Log

```
$ gcc -g -Wall -Wextra -std=c11 robust-sum.c \
      -o robust-sum

$ ./robust-sum 22 -3 5
24

#produce error message for bad arguments
$ ./robust-sum 22 -3x 5
bad argument -3x not integer: ignored
27

#produce error message for bad arguments
$ ./robust-sum 22 -3x 5 garbage 3
bad argument -3x not integer: ignored
bad argument garbage not integer: ignored
30
$
```

# A More Robust Program to Sum Arguments

In robust-sum.c:

```
/** Output sum of integer command-line arguments on stdout. */
int
main(int argc, const char *argv[])
{
  int sum = 0;
  for (int i = 1; i < argc; i++) {
    char *p;
    int n = strtol(argv[i], &p, 10);
    if (*p == '\0') {
      sum += n;
    }
```

# A More Robust Program to Sum Arguments Continued

```
        else {
            fprintf(stderr,
                    "bad argument %s not integer: ignored\n",
                    argv[i]);
        }
    }
    printf("%d\n", sum);
    return 0;
}
```

# Arrays

- A C array basically just represents the address of an area of memory; i.e., a C array is basically a pointer.
- It follows that a C array does not track the number of elements it has. The programmer needs to track the number of elements in the array. Some alternatives:
  - Have another variable which explicitly stores the number of elements in the array.
  - Mark the end of the array using some kind of **sentinel value**; i.e. a value which cannot occur as a legal value in the data stored in the array. For example, if an array stores only non-negative integers, then -1 could be used as a sentinel.
  - The number of elements in the array is known ahead of time as some fixed value (like say 27) and all code is written assuming that size. **Usually a bad idea**.

# When Arrays are Pointers

Peter Van Der Linden in *Deep C Secrets*:

- The use of an array name in an **expression** (not declaration) which is not an operand of `sizeof()` is treated by the compiler as a pointer to the first element of the array.
- A subscript is always equivalent to an offset from a pointer.
- An array name in the declaration of a function parameter is treated by the compiler as a pointer to the first element of the array. This is because arrays are passed by reference for efficiency reasons (all non-array data are passed by value).

# Pointers and Arrays

- Only operations for an array are getting its size using `sizeof()` or obtaining a pointer to element 0 of the array. All other array ops are really pointer ops.
- `a[i]` is equivalent to `*(a + i)` which is equivalent to `*(i + a)` which is equivalent to `i[a]`.
- When used within an expression, an array is equivalent to a pointer to its first element.

```
int a[10], i;      //a is array of 10 int's; i is int.
a[i];              //i'th element of a.
*(a + i);          //also i'th element of a.
*(i + a);          //also i'th element of a.
i[a];              //also i'th element of a.
```

# Array of char and Pointer to char Are Different

- `char *msg = "hello";`:

  ```
  msg: [ ... ] ----> ['h'|'e'|'l'|'l'|'o'|'\0']
  ```

  - **sizeof**(`msg`) will be the size of a pointer (i.e. a memory address). Typically, this is 4 or 8.
  - To compute the address of `msg[i]`, the compiler will need to produce code to add the value of `i` to the value stored at memory location `msg`.

# Array of char and Pointer to char Are Different Continued

- `char msg[] = "hello";`

  `msg: ['h'|'e'|'l'|'l'|'o'|'\0']`

  - `sizeof(msg)` will be 6.
  - To compute the address of `msg[i]`, the compiler will need to produce code to add the value of `i` to the address of `msg`.
- It is wrong to have one file define `char msg[] = "hello";` and another file declare `extern char *msg;` as the compiler will generate different access code.

# Multi-Dimensional Arrays

- C has only 1-dimensional arrays.
- Elements of arrays can themselves be arrays, which permits array notation like `a[i][j]` for multiple dimensions for `static` and `auto` (but not dynamically `malloc()`'d) arrays.
- When declaring (not defining) a multi-dimensional array, first (leftmost) dimension can be unspecified as in `a[][10][3]`.
- Impossible to have multi-dimensional array as function parameters without all but the leftmost dimension specified. So `int a[][]` is not allowed as a function parameter.

# Declarations versus Definitions

- A **declaration** provides information about an entity like a variable or function.
- A **definition** provides a definite value for that entity.
- An entity can have multiple declarations as long as they are consistent.
- There can only be a single definition for an entity.
- Often there is only a single statement which combines both a declaration with a definition.

# Declarations vs Definitions Example

```
//declare function which takes unspecified parameters
void quadratic_roots();

//second consistent declaration
//parameter names optional in declaration
void quadratic_roots(double, double b, double c,
                     double *, double *);
```

## Declarations vs Definitions Example

```
//function definition
void quadratic_roots(
  //parameter definitions/declarations
  double a, double b, double c,
  double *root1, double *root2)
{
  double discr; //uninitialized variable definition
  discr = b*b - 4*a*c;
  assert(discr >= 0);
  double sqroot = sqrt(discr); //definition with init
  *root1 = (-b + sqroot) / (2 * a);
  *root2 = (-b - sqroot) / (2 * a);
}
```

# Pointer Sum Annotated Log

```
# 12 + 13 + -12
$ ./ptr-sum 12 13 -0xc
13

$ ./ptr-sum
0

# 64 + -171 + ** + **
$ ./ptr-sum 0100 -0xAb 12C 099
-107
$
```

# Pointer Sum

In ptr-sum.c:

```c
/** Sum numeric strings [*start, *end), silently ignoring
 *  any strings which are not valid C integer literals.
 */
long
ptr_sum(const char **start, const char **end)
{
  long sum = 0;
  for (const char **p = start; p != end; p++) {
    char *endP;
    long v = strtol(*p, &endP, 0); //0: c-syntax ints
    if (*endP == '\0') sum += v;
  }
  return sum;
}
```

# Pointer Sum Continued

```
int
main(int argc, const char *argv[])
{
  printf("%ld\n", ptr_sum(&argv[1], &argv[argc]));
  return 0;
}
```

# Pointer Sum Discussion

- `strtol()` needs to return a pointer to the first non-legal character found in the integer string pointed to by its first argument.
- Since return value is being used to return the value of the integer, this pointer must be returned using a function parameter.
- Since the actual arguments passed to a function are **copies** of the value passed by the caller a function cannot affect the value of a parameter in its caller.
- The only way to have a function return a value via an argument is to have the caller pass a pointer to that value and have the function return the value using the pointer.
- Since `strtol()` needs to return a pointer via its argument, the second parameter is passed as pointer to a pointer, i.e. `&endP`.
- Declaration of `strtol()` is `long strtol(const char *str, char **end, int base)`.

# Pointer Sum Discussion Continued

- In `ptr_sum()`, `start` is address of first string. Since a string has type `char *`, `start` is declared `char **`.
- `end` is address one past that of the last string; i.e. `end` is an **exclusive limit**.
- `p` is initialized to `start` of type `const char **`. Hence `*p` has type `const char *` which is the string being sent as the first argument to `strtol()`
- `p++` will point to next string.
- Since `end` is an exclusive limit, the loop quits when `p == end`.

# Declaration of Command-Line Arguments in main()

- Typical declaration **const char** `*argv[]` for second argument of `main()`, declares `argv` to be an array of pointers to constant `char` (typically, constant strings) with each element containing a command-line argument string.
- `argv[1]`, `argv[2]` etc. have type of the array element: namely pointer to **const char**, i.e. **const char** `*`; Hence `&argv[1]` and `&argv[2]` have type pointer to pointer to **const char**, i.e. **const char** `**`.

# Representation of Command-Line Arguments

Given command-line `./ptr-sum 12 13 -0xc`, we have `argv` array as follows:

```
argv[0]: [      ] -----> [ '.' '/' 'p' 't' ... 'u' 'm' '\0' ]
 argv[1]: [       ] -----> [ '1' '2' '\0' ]
 argv[2]: [       ] -----> [ '1' '3' '\0' ]
 argv[3]: [       ] -----> [ '-' '0' 'x' 'c' '\0' ]
 argv[4]: [ NULL ]       #usually
```

wc.c contains a simple word-count (wc(1)) program:

```
enum { COUNT_CHARS = 7 };

static int nCTotal = 0;        /* total # of chars */
static int nWTotal = 0;        /* total # of words */
static int nLTotal = 0;        /* total # of lines */
```

```c
void
wc(const char *fName, FILE *f)
{
  int inWord = 0;
  int nC = 0, nW = 0, nL = 0;
  int c;
  //standard C idiom for reading file while checking EOF
  while ((c = fgetc(f)) != EOF) {
    nC++;
    if (c == '\n') nL++;
    if (isspace(c)) {
      inWord = 0;
    }
```

```
    else {
      if (!inWord) nW++;
      inWord = 1;
    }
  }
  if (ferror(f)) {
    fprintf(stderr, "i/o error: %s\n",
            strerror(errno));
  }
  printf("%*d %*d %*d %s\n", COUNT_CHARS, nL,
         COUNT_CHARS, nW, COUNT_CHARS, nC, fName);
  nCTotal += nC; nWTotal += nW; nLTotal += nL;
}
```

# Standard I/O Example wc(1) main() Program

```
int
main(int argc, const char *argv[])
{
    int i;
    if (argc == 1) {
        wc("", stdin);
    }
    else {
        for (i = 1; i < argc; i++) {
            FILE *in = fopen(argv[i], "r");
            if (!in) {
                fprintf(stderr, "could not read %s: %s\n",
                        argv[i], strerror(errno));
            }
```

```
        else {
          wc(argv[i], in);
          fclose(in);
        }
      } //for (i = 1; i < argc; i++)
      if (argc > 2) {
        printf("%*d %*d %*d total\n",
               COUNT_CHARS, nLTotal, COUNT_CHARS,
               nWTotal, COUNT_CHARS, nCTotal);
      }
    } //else if argc != 1
    return 0;
}
```

# wc(1) Log

```
$ which wc
/usr/bin/wc
$ wc wc.c
      62     183    1154 wc.c
$ ./wc wc.c
      62     183    1154 wc.c
$ wc wc.c buffer.c
      62     183    1154 wc.c
      14      41     278 buffer.c
      76     224    1432 total
$ wc <wc.c
      62     183    1154
$ ./wc <wc.c
      62     183    1154
$
```

# C Character I/O

```
int fgetc(FILE *stream);
int getc(FILE *stream);    //like fgetc() but may be macro
int getchar(void);         //getc(stdin)

int fputc(int c, FILE *stream);
int putc(int c, FILE *stream);   //like fputc()
                                   //but may be macro
int putchar(int c);              //putc(c, stdout)
```

# C Character I/O

- Why do functions on previous slide treat characters as `int`'s rather than `char`?
- For the output `put*()` functions, the reason is to do with compatibility with pre-ISO C where all `char`/'short' arguments were passed as `int`'s.
- But why for input? Couldn't `get*()` simply return a `char`?

# Signedness of `char`

- In C, the signedness of a plain `char` is undefined as on some platforms `char` may be signed, on others it may be unsigned.
- Can be explicit by declaring `signed char` or `unsigned char`.
- `get*()` functions return `EOF` on end-of-file or error.
- `EOF` is typically a negative number, usually -1.
- Hence `get*()` functions return `int`.

# Record I/O

```
size_t fread(void *buf, size_t recSize, size_t nRecs,
             FILE *input);
size_t fwrite(const void *buf, size_t recSize, size_t
nRecs,
              FILE *output);
```

- Can read/write `nRecs` records each having size of `recSize` bytes.
- Can be used for *serializing* binary data like `struct`'s.
- Simple-minded serialization likely problematic: binary data is inherently unportable (endian and size issues). Serialized pointers are meaningless.

# Formatted I/O

- `printf()`, `fprintf()`, `scanf()`, `fscanf()` and friends.
- Since C cannot change actual parameters, it is necessary that `scanf()` receive pointers to variables to be changed.

```c
int val;
scanf("%d", val); //WRONG
scanf("%d", &val); //correct
```

- Format specifiers for `printf()` and `scanf()` bear superficial resemblance but are different.

# Character Sets

- A character is an abstract entity representing a symbol used in writing some human language.
- Printed representation is a *glyph*.
- Represented by an integer *code* within computers.
- A *character set* could refer to an abstract set of characters, or a more concrete mapping from some character codes to glyphs.
- Many different character sets.

# ASCII

1960s: ASCII is a 7-bit code `0x00 - 0x7F` evolved from codes used for telegraph.

- 95 printable characters, 33 control characters.
- `0x00 - 0x1F` Control codes: `0x0a ^J, '\n'` *line feed*; `0x0d ^M, '\r'` *carriage return*; `0x07 ^G, '\a'` *bell*; `0x09, ^I', '\t''` *horizontal tab*; `0x08, ^H, '\b''` *backspace*; `0x0c ^L, '\f'` *form feed*; `0x1B ^[` *escape*.
- `0x20` (32): *space* character.
- `0x30 - 0x39` (48 - 57): digits.
- `0x41 - 0x5a` (65 - 90): upper-case alphabet `A - Z`. Get corresponding control-code by stripping off high bit $b_6$.
- `0x61 - 0x7a` (97 - 122): lower-case alphabet `a - z`.
- `0x7f`: *delete* character.

# ASCII Continued

- Codes not listed above are symbol or punctuation characters.
- Problems with characters like brackets `[` and `]`, and braces `{` and `}`, which were difficult to type on some keyboards (currently rare). Led to C *trigraphs*: `??x` for alternate representation of problematic characters.

# 8-Bit Character Sets

**IBM EBCDIC** Used by IBM mainframes. Non-contiguous alphabetic characters. Multiple *code pages*.

**Extended ASCII** 1980s, 1990s. Microsoft *code pages* for different languages; `ISO-8859-*` for different languages. `8859-1` Latin-1 for *Western European* languages, `8859-2` Latin-2 for *Central European* languages, .., `8859-9` Latin-5 for Turkish. Other `8859-*` variants cover most European languages, Arabic, Hebrew, Thai. Various incompatibilites.

# CJK Languages

CJK: Chinese, Japanese and Korean. CJKV: + Vietnamese. Cover main East Asian Languages. Thousands of characters required. 8 bits insufficient.

Two major approaches:

**Wide Characters** Encode characters using 16-bits (or wider).

**Mult-Byte Variable Length Encoding** Need escape sequences to shift interpretations. Need to scan string sequentially to interpret escape sequences correctly. Entire string corrupted if a single bit is corrupted. Example: *Shift JIS*.

# Unicode

Unicode *universal character set* widely used by all modern computer systems to represent international characters.

- Over 1 million code points from `0x000000` to `0x10FFFF`.
- *Basic Multilingual Plane* (BMP): code points less than `0x10000`.
- Characters often specified by name or by *code-point* as `U+xxxx`.
- Combining characters.
- Can be encoded using a fixed width (UTF-32) or variable width encoding (UTF-16 on windows, UTF-8 on unix and www).

# UTF-8 Encoding for Unicode

UTF-8 is a popular variable width encoding for Unicode which is compatible with ASCII. Used widely on WWW.

```
-------------------------+---------------------------
Unicode Range            | Encoding
-------------------------+---------------------------
U+000000000 - U+0000007F | 0xxxxxxx
U+000000080 - U+000007FF | 110xxxxx 10xxxxxx
U+000000800 - U+0000FFFF | 1110xxxx 10xxxxxx 10xxxxxx
U+000010000 - U+001FFFFF | 11110xxx 10xxxxxx 10xxxxxx
                         |          10xxxxxx
U+000200000 - U+03FFFFFF | 111110xx 10xxxxxx 10xxxxxx
                         |          10xxxxxx 10xxxxxx
U+040000000 - U+7FFFFFFF | 1111110x 10xxxxxx 10xxxxxx
                         |          10xxxxxx 10xxxxxx
                         |          10xxxxxx
-------------------------+---------------------------
```

# UTF-8 Encoding for Unicode Continued

- Single byte encodings compatible with ASCII.
- Leading number of 1s in first byte gives # of bytes in multi-byte sequences.
- 4-byte encoding sufficient to represent all Unicode characters up to `U+10FFFF`.
- Easy to synchronize from middle of string by skipping `10xxxxxx` bytes.
- Designed in 1992 by Ken Thompson on a placemat at a New Jersey diner!

# UTF-8 with C

- Must set `locale` appropriately.
- `strlen()` gives number of bytes, not number of characters.
- Routines in standard library available.

# Fractional Binary Numbers

Given a fractional binary number

$$b_m b_{m-1} \ldots b_1 b_0 . b_{-1} b_{-2} \ldots b_{-n-1} b_{-n}$$

By analogy with decimal notation, its value will be given by

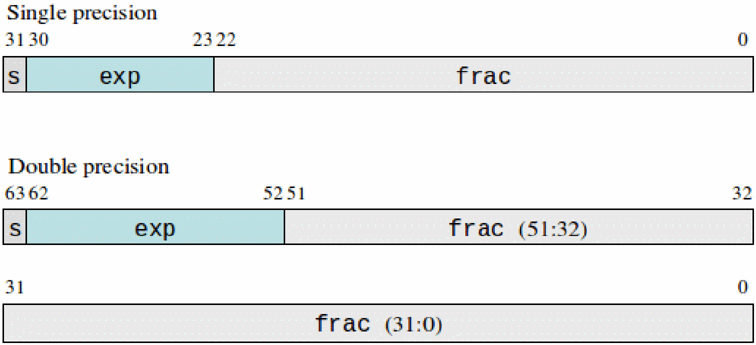
$$\sum_{i=-n}^{m} 2^i \times b_i$$

So we would have: binary `0.1` representing decimal `0.5`, binary `0.01` representing decimal `0.25` and binary `11.101` representing decimal `3.625`.

# IEEE Floating Point Representation

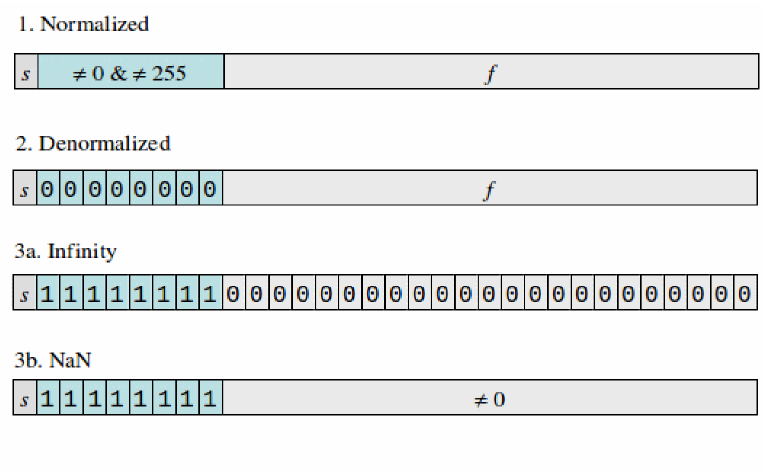
- Similar to *scientific notation* where a number is represented using a *mantissa* and an *exponent*.
- Floating point representation contains a single *sign* bit, a $k$-bit *exponent* field and a $n$-bit *mantissa* or *significand* fraction field.
- Usually, the exponent is adjusted so that the fraction field is always of the form $1.\ldots$, i.e. there is always a 1 before the binary point. Hence there is no point in storing it and we say that the fraction field is *normalized*.
- Exponent is stored with a bias.
- Reserve exponent of all 0's and all 1's for exceptional cases.

# Floating Point Formats




- Because of normalization, single precision (usually C `float`'s) only store a 23-bit fraction which actually represents 24-bits.
- Again, due to normalization double precision (usually C `double`'s) only store a 52-bit fraction which actually represents 53 bits.

# Floating Point Cases




- Denormalized numbers allow graceful underflow.
- Special values of $\pm\infty$ allows saturating arithmetic.

# Not-a-Number ('NaN')

When exponent is all 1's and fraction non-zero, we have a `NaN`.

- `NaN` indicates an invalid result like `0/0`. Can cause an exception ("signalling" `NaN`) or simply propagates as `NaN` ("quiet" `NaN`).
- `NaN` compares false with anything, including itself.

```
double x = 0/0;
x == x; //evaluates to 0.
x != x; //evaluates to 1.
x < y;  //evaluates to 0 for any y.
y < x;  //evaluates to 0 for any y.
```

# Floating Point Miscellanea

- Can be sorted by treating bit representation lexicographically or as signed-magnitude integers.
- In C, `float` literals must have trailing `f` or `F`; otherwise literal is treated as a `double`.
- The value contributed by the last bit in the fraction ("unit in last place") depends on the value of the number.

# Floating Point Parameters

- Floating point format characterized by 2 parameters:

  $N$ total number of bits.

  $k$ number of exponent bits. Biased by $2^{k-1} - 1$.

  It follows that number of bits available for storing mantissa is $m = N - k - 1$.
- IEEE single precision: $N = 32$, $k = 8$, $m = 32 - 8 - 1 = 23$. The exponent bias is $2^{8-1} - 1 = 127$. Normalized exponents in inclusive-range $[-126, 127]$.
- IEEE double precision: $N = 64$, $k = 11$, $m = 64 - 11 - 1 = 52$. The exponent bias is $2^{11-1} - 1 = 1023$. Normalized exponents in inclusive-range $[-1022, 1023]$.

# Floating Point Values

- Given a non-exceptional floating point number (exponent field is not all 0's and not all 1's), it's value is:

$$(-1)^s \times M \times 2^e$$

  where $s$ is the value of the sign-bit, $M$ is the value of the mantissa and $e$ is the exponent value (after adjusting by the bias).
- Assuming that the value as an unsigned binary integer of the mantissa field is $m'$, for normalized numbers $M = 1 + m'/2^m$; for denormalized numbers $M = m'/2^m$.
- Assuming that the value as an unsigned binary integer of the exponent field is $e'$, for normalized numbers $e = e' - (2^{k-1} - 1)$; for denormalized numbers $e = -(2^{k-1} - 2)$.

# Floating Point Values Continued

**Normalized values** When $0 < e' < 2^k - 1$: $M = 1 + m'/2^m$ and $e = e' - (2^{k-1} - 1)$. Hence value is $(-1)^s \times (1 + m'/2^m) \times 2^{e'-(2^{k-1}-1)}$.

**Denormalized values** When $e' = 0$: $M = m'/2^m$ and $e = -(2^{k-1} - 2)$ and value is $(-1)^s \times (m'/2^m) \times 2^{-(2^{k-1}-2)}$.

**Infinities** $e' = 2^k - 1, m' = 0$. Value is $(-1)^s \times \infty$.

**NaN's** $e' = 2^k - 1, m' \neq 0$. Value is `NaN`.

# 8-Bit Float Values

Following slides list all values for a 7-bit float. Fields from MSB to LSB:

- 1-bit sign
- 3-bit exponent biased by 3.
    - Field value in [1, 6]: exponent value [-2, 3].
    - Field value 0: denormalized: exponent value -2.
    - Field value 7: Exceptional cases: Infinities + NaN.
- 3-bit fraction; for normalized numbers, implicit 1 to left of binary point.

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 0 000 000 | 0 | 0 | $+0.000000(2^{-2} \times (0+0/8))$ |
| 0 000 001 | 0 | 1 | $+0.031250(2^{-2} \times (0+1/8))$ |
| 0 000 010 | 0 | 2 | $+0.062500(2^{-2} \times (0+2/8))$ |
| 0 000 011 | 0 | 3 | $+0.093750(2^{-2} \times (0+3/8))$ |
| 0 000 100 | 0 | 4 | $+0.125000(2^{-2} \times (0+4/8))$ |
| 0 000 101 | 0 | 5 | $+0.156250(2^{-2} \times (0+5/8))$ |
| 0 000 110 | 0 | 6 | $+0.187500(2^{-2} \times (0+6/8))$ |
| 0 000 111 | 0 | 7 | $+0.218750(2^{-2} \times (0+7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 0 001 000 | 1 | 0 | $+0.250000(2^{-2} \times (1+0/8))$ |
| 0 001 001 | 1 | 1 | $+0.281250(2^{-2} \times (1+1/8))$ |
| 0 001 010 | 1 | 2 | $+0.312500(2^{-2} \times (1+2/8))$ |
| 0 001 011 | 1 | 3 | $+0.343750(2^{-2} \times (1+3/8))$ |
| 0 001 100 | 1 | 4 | $+0.375000(2^{-2} \times (1+4/8))$ |
| 0 001 101 | 1 | 5 | $+0.406250(2^{-2} \times (1+5/8))$ |
| 0 001 110 | 1 | 6 | $+0.437500(2^{-2} \times (1+6/8))$ |
| 0 001 111 | 1 | 7 | $+0.468750(2^{-2} \times (1+7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 0 010 000 | 2 | 0 | $+0.500000(2^{-1} \times (1+0/8))$ |
| 0 010 001 | 2 | 1 | $+0.562500(2^{-1} \times (1+1/8))$ |
| 0 010 010 | 2 | 2 | $+0.625000(2^{-1} \times (1+2/8))$ |
| 0 010 011 | 2 | 3 | $+0.687500(2^{-1} \times (1+3/8))$ |
| 0 010 100 | 2 | 4 | $+0.750000(2^{-1} \times (1+4/8))$ |
| 0 010 101 | 2 | 5 | $+0.812500(2^{-1} \times (1+5/8))$ |
| 0 010 110 | 2 | 6 | $+0.875000(2^{-1} \times (1+6/8))$ |
| 0 010 111 | 2 | 7 | $+0.937500(2^{-1} \times (1+7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 0 011 000 | 3 | 0 | $+1.000000(2^0 \times (1+0/8))$ |
| 0 011 001 | 3 | 1 | $+1.125000(2^0 \times (1+1/8))$ |
| 0 011 010 | 3 | 2 | $+1.250000(2^0 \times (1+2/8))$ |
| 0 011 011 | 3 | 3 | $+1.375000(2^0 \times (1+3/8))$ |
| 0 011 100 | 3 | 4 | $+1.500000(2^0 \times (1+4/8))$ |
| 0 011 101 | 3 | 5 | $+1.625000(2^0 \times (1+5/8))$ |
| 0 011 110 | 3 | 6 | $+1.750000(2^0 \times (1+6/8))$ |
| 0 011 111 | 3 | 7 | $+1.875000(2^0 \times (1+7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 0 100 000 | 4 | 0 | $+2.000000(2^1 \times (1+0/8))$ |
| 0 100 001 | 4 | 1 | $+2.250000(2^1 \times (1+1/8))$ |
| 0 100 010 | 4 | 2 | $+2.500000(2^1 \times (1+2/8))$ |
| 0 100 011 | 4 | 3 | $+2.750000(2^1 \times (1+3/8))$ |
| 0 100 100 | 4 | 4 | $+3.000000(2^1 \times (1+4/8))$ |
| 0 100 101 | 4 | 5 | $+3.250000(2^1 \times (1+5/8))$ |
| 0 100 110 | 4 | 6 | $+3.500000(2^1 \times (1+6/8))$ |
| 0 100 111 | 4 | 7 | $+3.750000(2^1 \times (1+7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 0 101 000 | 5 | 0 | $+4.000000(2^2 \times (1+0/8))$ |
| 0 101 001 | 5 | 1 | $+4.500000(2^2 \times (1+1/8))$ |
| 0 101 010 | 5 | 2 | $+5.000000(2^2 \times (1+2/8))$ |
| 0 101 011 | 5 | 3 | $+5.500000(2^2 \times (1+3/8))$ |
| 0 101 100 | 5 | 4 | $+6.000000(2^2 \times (1+4/8))$ |
| 0 101 101 | 5 | 5 | $+6.500000(2^2 \times (1+5/8))$ |
| 0 101 110 | 5 | 6 | $+7.000000(2^2 \times (1+6/8))$ |
| 0 101 111 | 5 | 7 | $+7.500000(2^2 \times (1+7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 0 110 000 | 6 | 0 | $+8.000000(2^3 \times (1 + 0/8))$ |
| 0 110 001 | 6 | 1 | $+9.000000(2^3 \times (1 + 1/8))$ |
| 0 110 010 | 6 | 2 | $+10.000000(2^3 \times (1 + 2/8))$ |
| 0 110 011 | 6 | 3 | $+11.000000(2^3 \times (1 + 3/8))$ |
| 0 110 100 | 6 | 4 | $+12.000000(2^3 \times (1 + 4/8))$ |
| 0 110 101 | 6 | 5 | $+13.000000(2^3 \times (1 + 5/8))$ |
| 0 110 110 | 6 | 6 | $+14.000000(2^3 \times (1 + 6/8))$ |
| 0 110 111 | 6 | 7 | $+15.000000(2^3 \times (1 + 7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 0 111 000 | 7 | 0 | $+infinity$ |
| 0 111 001 | 7 | 1 | $+nan$ |
| 0 111 010 | 7 | 2 | $+nan$ |
| 0 111 011 | 7 | 3 | $+nan$ |
| 0 111 100 | 7 | 4 | $+nan$ |
| 0 111 101 | 7 | 5 | $+nan$ |
| 0 111 110 | 7 | 6 | $+nan$ |
| 0 111 111 | 7 | 7 | $+nan$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 1 000 000 | 0 | 0 | $-0.000000(-2^{-2} \times (0 + 0/8))$ |
| 1 000 001 | 0 | 1 | $-0.031250(-2^{-2} \times (0 + 1/8))$ |
| 1 000 010 | 0 | 2 | $-0.062500(-2^{-2} \times (0 + 2/8))$ |
| 1 000 011 | 0 | 3 | $-0.093750(-2^{-2} \times (0 + 3/8))$ |
| 1 000 100 | 0 | 4 | $-0.125000(-2^{-2} \times (0 + 4/8))$ |
| 1 000 101 | 0 | 5 | $-0.156250(-2^{-2} \times (0 + 5/8))$ |
| 1 000 110 | 0 | 6 | $-0.187500(-2^{-2} \times (0 + 6/8))$ |
| 1 000 111 | 0 | 7 | $-0.218750(-2^{-2} \times (0 + 7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 1 001 000 | 1 | 0 | $-0.250000(-2^{-2} \times (1 + 0/8))$ |
| 1 001 001 | 1 | 1 | $-0.281250(-2^{-2} \times (1 + 1/8))$ |
| 1 001 010 | 1 | 2 | $-0.312500(-2^{-2} \times (1 + 2/8))$ |
| 1 001 011 | 1 | 3 | $-0.343750(-2^{-2} \times (1 + 3/8))$ |
| 1 001 100 | 1 | 4 | $-0.375000(-2^{-2} \times (1 + 4/8))$ |
| 1 001 101 | 1 | 5 | $-0.406250(-2^{-2} \times (1 + 5/8))$ |
| 1 001 110 | 1 | 6 | $-0.437500(-2^{-2} \times (1 + 6/8))$ |
| 1 001 111 | 1 | 7 | $-0.468750(-2^{-2} \times (1 + 7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 1 010 000 | 2 | 0 | $-0.500000(-2^{-1} \times (1 + 0/8))$ |
| 1 010 001 | 2 | 1 | $-0.562500(-2^{-1} \times (1 + 1/8))$ |
| 1 010 010 | 2 | 2 | $-0.625000(-2^{-1} \times (1 + 2/8))$ |
| 1 010 011 | 2 | 3 | $-0.687500(-2^{-1} \times (1 + 3/8))$ |
| 1 010 100 | 2 | 4 | $-0.750000(-2^{-1} \times (1 + 4/8))$ |
| 1 010 101 | 2 | 5 | $-0.812500(-2^{-1} \times (1 + 5/8))$ |
| 1 010 110 | 2 | 6 | $-0.875000(-2^{-1} \times (1 + 6/8))$ |
| 1 010 111 | 2 | 7 | $-0.937500(-2^{-1} \times (1 + 7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 1 011 000 | 3 | 0 | $-1.000000(-2^0 \times (1 + 0/8))$ |
| 1 011 001 | 3 | 1 | $-1.125000(-2^0 \times (1 + 1/8))$ |
| 1 011 010 | 3 | 2 | $-1.250000(-2^0 \times (1 + 2/8))$ |
| 1 011 011 | 3 | 3 | $-1.375000(-2^0 \times (1 + 3/8))$ |
| 1 011 100 | 3 | 4 | $-1.500000(-2^0 \times (1 + 4/8))$ |
| 1 011 101 | 3 | 5 | $-1.625000(-2^0 \times (1 + 5/8))$ |
| 1 011 110 | 3 | 6 | $-1.750000(-2^0 \times (1 + 6/8))$ |
| 1 011 111 | 3 | 7 | $-1.875000(-2^0 \times (1 + 7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 1 100 000 | 4 | 0 | $-2.000000(-2^1 \times (1+0/8))$ |
| 1 100 001 | 4 | 1 | $-2.250000(-2^1 \times (1+1/8))$ |
| 1 100 010 | 4 | 2 | $-2.500000(-2^1 \times (1+2/8))$ |
| 1 100 011 | 4 | 3 | $-2.750000(-2^1 \times (1+3/8))$ |
| 1 100 100 | 4 | 4 | $-3.000000(-2^1 \times (1+4/8))$ |
| 1 100 101 | 4 | 5 | $-3.250000(-2^1 \times (1+5/8))$ |
| 1 100 110 | 4 | 6 | $-3.500000(-2^1 \times (1+6/8))$ |
| 1 100 111 | 4 | 7 | $-3.750000(-2^1 \times (1+7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 1 101 000 | 5 | 0 | $-4.000000(-2^2 \times (1 + 0/8))$ |
| 1 101 001 | 5 | 1 | $-4.500000(-2^2 \times (1 + 1/8))$ |
| 1 101 010 | 5 | 2 | $-5.000000(-2^2 \times (1 + 2/8))$ |
| 1 101 011 | 5 | 3 | $-5.500000(-2^2 \times (1 + 3/8))$ |
| 1 101 100 | 5 | 4 | $-6.000000(-2^2 \times (1 + 4/8))$ |
| 1 101 101 | 5 | 5 | $-6.500000(-2^2 \times (1 + 5/8))$ |
| 1 101 110 | 5 | 6 | $-7.000000(-2^2 \times (1 + 6/8))$ |
| 1 101 111 | 5 | 7 | $-7.500000(-2^2 \times (1 + 7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 1 110 000 | 6 | 0 | $-8.000000(-2^3 \times (1+0/8))$ |
| 1 110 001 | 6 | 1 | $-9.000000(-2^3 \times (1+1/8))$ |
| 1 110 010 | 6 | 2 | $-10.000000(-2^3 \times (1+2/8))$ |
| 1 110 011 | 6 | 3 | $-11.000000(-2^3 \times (1+3/8))$ |
| 1 110 100 | 6 | 4 | $-12.000000(-2^3 \times (1+4/8))$ |
| 1 110 101 | 6 | 5 | $-13.000000(-2^3 \times (1+5/8))$ |
| 1 110 110 | 6 | 6 | $-14.000000(-2^3 \times (1+6/8))$ |
| 1 110 111 | 6 | 7 | $-15.000000(-2^3 \times (1+7/8))$ |

# (7-3)-Bit Float Values Continued

| Bits | Exp | Fraction | Value |
|---|---|---|---|
| 1 111 000 | 7 | 0 | $-infinity$ |
| 1 111 001 | 7 | 1 | $-nan$ |
| 1 111 010 | 7 | 2 | $-nan$ |
| 1 111 011 | 7 | 3 | $-nan$ |
| 1 111 100 | 7 | 4 | $-nan$ |
| 1 111 101 | 7 | 5 | $-nan$ |
| 1 111 110 | 7 | 6 | $-nan$ |
| 1 111 111 | 7 | 7 | $-nan$ |

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