10 types of students

There are only 10 types of students ...
- those that understand binary
- those that don’t understand binary

Decimal Representation

- Can interpret decimal number 4705 as:
  \[ 4 \times 10^3 + 7 \times 10^2 + 0 \times 10^1 + 5 \times 10^0 \]
- The *base or radix* is 10 ... digits 0 – 9
- Place values:

  \[
  \begin{array}{cccc}
  & \ldots & 1000 & 100 & 10 & 1 \\
  \ldots & 10^3 & 10^2 & 10^1 & 10^0
  \end{array}
  \]

- Write number as 4705\textsubscript{10}
  - Note use of subscript to denote base
Representation in Other Bases

- base 10 is an arbitrary choice
- can use any base
- e.g. could use base 7
- Place values:

<table>
<thead>
<tr>
<th></th>
<th>343</th>
<th>49</th>
<th>7</th>
<th>1</th>
</tr>
</thead>
</table>
  \(7^3\) | 7\(^2\) | 7\(^1\) | 7\(^0\) |

Write number as 1216\(_7\) and interpret as:
\[ 1 \times 7^3 + 2 \times 7^2 + 1 \times 7^1 + 6 \times 7^0 = \overline{454}_{10} \]

Binary Representation

- Modern computing uses binary numbers
  - because digital devices can easily produce high or low level voltages which can represent 1 or 0.
- The base or radix is 2
  - Digits 0 and 1
- Place values:

<table>
<thead>
<tr>
<th></th>
<th>8</th>
<th>4</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
</table>
  \(2^3\) | 2\(^2\) | 2\(^1\) | 2\(^0\) |

Write number as 1011\(_2\) and interpret as:
\[ 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = \overline{11}_{10} \]

Hexadecimal Representation

- Binary numbers hard for humans to read — too many digits!
- Conversion to decimal awkward and hides bit values
- Solution: write numbers in hexadecimal!
- The base or radix is 16 ... digits 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, F
- Place values:

<table>
<thead>
<tr>
<th></th>
<th>4096</th>
<th>256</th>
<th>16</th>
<th>1</th>
</tr>
</thead>
</table>
  \(16^3\) | 16\(^2\) | 16\(^1\) | 16\(^0\) |

Write number as 3AF\(_{16}\) and interpret as:
\[ 3 \times 16^3 + 10 \times 16^2 + 15 \times 16^1 + 1 \times 16^0 = \overline{15089}_{10} \]

- in C, \texttt{0x} prefix denotes hexadecimal, e.g. \texttt{0x3AF1}
Octal & Binary C constants

- Octal (based 8) representation used to be popular for binary numbers
- Similar advantages to hexadecimal
- In C a leading 0 denotes octal, e.g. 07563
- Standard C doesn’t have a way to write binary constants
- Some C compilers let you write 0b
  - OK to use 0b in experimental code but don’t use in important code

```c
printf("%d", 0x2A); // prints 42
printf("%d", 052);  // prints 42
printf("%d", 0b101010); // might compile and print 42
```

Binary Constants

In hexadecimal, each digit represents 4 bits

0x 4 8 F A B C 9 7

In octal, each digit represents 3 bits

0 1 1 0 7 6 5 3 6 2 2 7

In binary, each digit represents 1 bit

0b01001000111110101011110010010111

Binary to Hexadecimal

- Example: Convert 1011110001010012 to Hex:

- Example: Convert 101111010111002 to Hex:
Hexadecimal to Binary

- Reverse the previous process ...
- Convert each hex digit into equivalent 4-bit binary representation
- Example: Convert $A_{16}D_{16}$ to Binary:

Representing Negative Integers

- modern computers almost always use two's complement to represent integers
- positive integers and zero represented in obvious way
- negative integers represented in clever way to make arithmetic in silicon fast/simpler
- for an n-bit binary number the representation of $-b$ is $2^n - b$
- e.g. in 8-bit two's complement $-5$ is represented as $2^8 - 5 = 11111011_2$

Code example: printing all 8 bit twos complement bit patterns

- Some simple code to examine all 8 bit twos complement bit patterns.

```c
for (int i = -128; i < 128; i++) {
    printf("%4d ", i);
    print_bits(i, 8);
    printf("\n");
}
```

```
$ dcc 8_bit_twos_complement.c print_bits.c -o 8_bit_twos_complement
```

source code for print_bits.c source code for print_bits.h
### Code example: printing all 8 bit twos complement bit patterns

```
$ ./8_bit_twos_complement
-128 10000000
-127 10000001
-126 10000010
...
-3 11111101
-2 11111110
-1 11111111
  0 00000000
  1 00000001
  2 00000010
  3 00000011
...
 125 01111101
 126 01111110
 127 01111111
```

### Code example: printing bits of int

```c
#include <stdio.h>

int a = 0;
printf("Enter an int: ");
scanf("%d", &a);
// sizeof returns number of bytes, a byte has 8 bits
int n_bits = 8 * sizeof a;
print_bits(a, n_bits);
printf("\n");
```

```sh
$ dcc print_bits_of_int.c print_bits.c -o print_bits_of_int
$ ./print_bits_of_int
Enter an int: 42
00000000000000000000000000101010
$ ./print_bits_of_int
Enter an int: -42
11111111111111111111111111010110
```

```c
#include <stdio.h>

int a = 0;
printf("Enter an int: ");
scanf("%d", &a);
// sizeof returns number of bytes, a byte has 8 bits
int n_bits = 8 * sizeof a;
print_bits(a, n_bits);
printf("\n");
```

```sh
$ ./print_bits_of_int
Enter an int: 0
00000000000000000000000000000000
$ ./print_bits_of_int
Enter an int: 1
00000000000000000000000000000001
$ ./print_bits_of_int
Enter an int: -1
11111111111111111111111111111111
$ ./print_bits_of_int
Enter an int: 2147483647
01111111111111111111111111111111
$ ./print_bits_of_int
Enter an int: -2147483648
10000000000000000000000000000000
```
Many hardware operations works with bytes: 1 byte == 8 bits

C's `sizeof` gives you number of bytes used for variable or type

`sizeof variable` - returns number of bytes to store variable

`sizeof (type)` - returns number of bytes to store type

On CSE servers, C types have these sizes

- `char` = 1 byte = 8 bits, 42 is 00101010
- `short` = 2 bytes = 16 bits, 42 is 00000000000000000000000000101010
- `int` = 4 bytes = 32 bits, 42 is 00000000000000000000000000101010
- `double` = 8 bytes = 64 bits, 42 = ?

- above are common sizes but not universal on a small embedded CPU

C's `sizeof (int)` might be 2 (bytes)

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**Code example: integer_types.c - exploring integer types**

We can use `sizeof` and `limits.h` to explore the range of values which can be represented by standard C integer types on our machine...

```bash
$ gcc integer_types.c -o integer_types
$ ./integer_types
```

<table>
<thead>
<tr>
<th>Type</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>-128</td>
<td>127</td>
</tr>
<tr>
<td>signed char</td>
<td>-128</td>
<td>127</td>
</tr>
<tr>
<td>unsigned char</td>
<td>0</td>
<td>255</td>
</tr>
<tr>
<td>short</td>
<td>-32768</td>
<td>32767</td>
</tr>
<tr>
<td>unsigned short</td>
<td>0</td>
<td>65535</td>
</tr>
<tr>
<td>int</td>
<td>-2147483648</td>
<td>2147483647</td>
</tr>
<tr>
<td>unsigned int</td>
<td>0</td>
<td>4294967295</td>
</tr>
<tr>
<td>long</td>
<td>-9223372036854775808</td>
<td>9223372036854775807</td>
</tr>
<tr>
<td>unsigned long</td>
<td>0</td>
<td>18446744073709551615</td>
</tr>
<tr>
<td>long long</td>
<td>-9223372036854775808</td>
<td>9223372036854775807</td>
</tr>
<tr>
<td>unsigned long long</td>
<td>0</td>
<td>18446744073709551615</td>
</tr>
</tbody>
</table>

Source code for `integer_types.c`
#include <stdint.h>

- to get below integer types (and more) with guaranteed sizes
- we will use these heavily in COMP1521

```c
// range of values for type
// minimum maximum
int8_t i1; // -128 127
uint8_t i2; // 0 255
int16_t i3; // -32768 32767
uint16_t i4; // 0 65535
int32_t i5; // -2147483648 2147483647
uint32_t i6; // 0 4294967295
int64_t i7; // -9223372036854775808 9223372036854775807
uint64_t i8; // 0 18446744073709551615
```

Common C bug:
```
char c; // c should be declared int (int16_t would work, int is better)
while ((c = getchar()) != EOF) {
    putchar(c);
}
```

Typically `stdio.h` contains:
```
#define EOF -1
```
- most platforms: char is signed (-128..127)
  - loop will incorrectly exit for a byte containing 0xFF
- rare platforms: char is unsigned (0..255)
  - loop will never exit