ECE 2400 Computer Systems Programming
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T03 C Types

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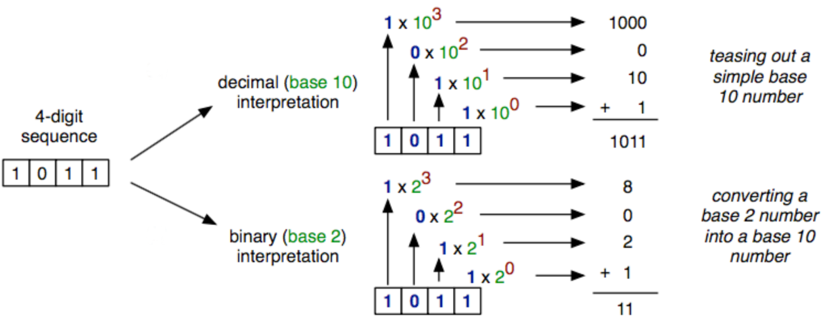
- The type of a variable specifies
  - the meaning of the variable's value
  - how the variable's value should be stored in the computer
  - what operations are allowed on the variable
- Critical to keep concept of types separate from concept of values
- C is a statically typed language, meaning that the type of a variable must be know at compile time
- Keep in mind that no matter how complex the type, everything is ultimately stored as a binary number in the computer

1. Binary and Hexadecimal Numbers

Let's review decimal, binary, and hexadecimal number representations.



Covert the following decimal number into a binary and hexadecimal number:

`300`

Covert the following binary number into a hexadecimal and decimal number:

`01101110`

2. Basic Data Types

We will primarily use the following primitive C types:

- `int`: For representing signed and unsigned integer numbers
- `char`: For representing characters
- `float/double`: For representing real numbers

2.1. `int` Type

- **Meaning?** Integer whole number
- **Stored?** 32-bit two's complement binary representation
- **Operations?** Basic integer arithmetic

```
int avg( int x, int y )
{
  int sum = x + y;
  return sum / 2;
}

int main()
{
  int a = 10;
  int b = 20;
  int c = avg( a, b );
  return 0;
}
```

Signed vs. Unsigned Integers

- By default, an `int` is short-hand for the type `signed int` which can represent both positive and negative integers
- `unsigned int` can only represent positive integers

Bits	Un-signed	Two's Comp
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	-8
1001	9	-7
1010	10	-6
1011	11	-5
1100	12	-4
1101	13	-3
1110	14	-3
1111	15	-1

```
signed   int a = 4;
signed   int b = -1;
unsigned int a = 4;
unsigned int b = 4294967295;
```

Overflow and Underflow

- Assume we have a signed 4-bit binary number
- Can store values from -8 to 7
- Adding one to 7 in a four-bit binary number = overflow
- Subtracting one from -8 in a four-bit binary number = underflow

- An `int` is a signed 32-bit binary number
- Can store values between -2,147,483,648 to 2,147,483,647
- What happens if you add one to 2,147,483,647?
- What happens if you subtract one from -2,147,483,648?

- An `unsigned int` is an unsigned 32-bit binary number
- Can store values from 0 to 4,294,967,295
- What happens if you add one to 4,294,967,295?
- What happens if you subtract one from 0?

```c
#include <stdio.h>

int main()
{
  int a = 2147483647;
  int b = a + 1;
  printf("%d (%x)\n",b,b);

  int c = -2147483648;
  int d = c - 1;
  printf("%d (%x)\n",d,d);

  unsigned int e = 4294967295;
  unsigned int f = e + 1;
  printf("%u (%x)\n",f,f);

  unsigned int g = 0;
  unsigned int h = g - 1;
  printf("%u (%x)\n",h,h);

  return 0;
}
```

http://cpp.sh/92fvq

- New format specifiers for hexadecimal (%x) and `unsigned int` (%u)

2.2. `char` Type

- **Meaning?** Character in a "word"
- **Stored?** 8-bit binary representation using ASCII standard
- **Operations?** Basic integer arithmetic

40	(	50	2	60	<	70	F	80	P	90	Z	100	d	110	n
41	)	51	3	61	=	71	G	81	Q	91	[	101	e	111	o
42	*	52	4	62	>	72	H	82	R	92	\	102	f	112	p
43	+	53	5	63	?	73	I	83	S	93	]	103	g	113	q
44	,	54	6	64	@	74	J	84	T	94	^	104	h	114	r
45	-	55	7	65	A	75	K	85	U	95	_	105	i	115	s
46	.	56	8	66	B	76	L	86	V	96	`	106	j	116	t
47	/	57	9	67	C	77	M	87	W	97	a	107	k	117	u
48	0	58	:	68	D	78	N	88	X	98	b	108	l	118	v
49	1	59	;	69	E	79	O	89	Y	99	c	109	m	119	w

```c
char a = 'e';
char b = 'c';
char c = 'e';
```

```c
#include <stdio.h>

int main()
{
  char a = 'e';
  char b = 'c';
  char c = 'e';
  printf("%c%c%c\n",a,b,c);
  return 0;
}
```

- New format specifier for `char` (`%c`)

2.3. `float/double` Type

- How can we represent real numbers?
- One option is to use *fixed-point* representation, e.g., 4-bit fixed point with 2-bit integer part and 2-bit fractional part

- Problem with fixed point is it provides a relatively small range; does not enable representing very small nor very large numbers
- An alternative is to use *floating-point* representation, where there is no fixed number of digits before and after the binary point

- C floating-point representation for `float/double` uses an IEEE standard where each number has three fields:
  sign bit (s), mantissa (m), and exponent (e)

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

- Both very small and very large numbers can be represented

Number	s	m	e	Floating-Point Representation
2.75	0	1.375	1	$(-1)^0 \times 1.375 \times 2^1$
-2.75	1	1.375	1	$(-1)^1 \times 1.375 \times 2^1$
1536	0	1.5	10	$(-1)^0 \times 1.5 \times 2^{10}$
0.1875	0	1.5	-3	$(-1)^0 \times 1.5 \times 2^{-3}$

- `float` uses 32 bits and `double` uses 64 bits to encode real numbers
- Binary encoding of the mantissa and exponent is a little more complex than a straight-forward two's complement encoding
  - The exponent is encoded using a bias, so the stored value is actually $e + 127$ (e.g., to represent 1, store $1 + 127 = 128$)
  - The integer portion of the mantissa is always assumed to be 1 so we only need to store the fractional portion of the mantissa (e.g., a mantissa of 1.375 is allowed, but a mantissa of 2.75 is not allowed)

```
float a = 2.75;
```

```
float avg( float x, float y )
{
  float sum = x + y;
  return sum / 2;
}

int main()
{
  float a = 10;
  float b = 15;
  float c = avg( a, b );
  return 0;
}
```

https://www.h-schmidt.net/FloatConverter/IEEE754.html

- There is an infinite number of values between 0 and 1
- `float`/`double` have a finite number of bits (precision)
- `float` is 32-bit and represents single-precision floating point
- `double` is 64-bit and represents double-precision floating point
- Limited bits can cause overflow/underflow, but limited precision can also cause other strange behavior

```
#include <stdio.h>

float avg( float x, float y )
{
  float sum = x + y;
  return sum / 2;
}

int main()
{
  float a = 0.2;
  float b = 0.4;
  float c = avg( a, b );
  printf(" average of %f and %f is %f\n", a, b, c );

  if ( c == 0.3 )
    printf(" the average is 0.3\n" );
  else
    printf(" the average is not 0.3\n" );

  return 0;
}
```

`http://cpp.sh/8n6buk`

- New format specifier for `float`/`double` (`%f`)
- Can also use `%m.nf` with `n` decimal places and `m` minimum width

3. Programmer-Defined Types

In addition to the default types that are included as part of the C programming language (e.g., `int`, `unsigned int`, `char`, `float`, `double`), C also enables programmers to define their own new types.

3.1. Typedefs

- A typedef actually does *not* define a new type
- A typedef simply provides a new alias for an already defined type

```
typedef type_name new_type_name;
```

- The following code is perfectly fine

```
typedef unsigned int uint_t;
uint_t a = 2;
uint_t b = 3;
unsigned int c = a + b;
```

3.2. `struct` Types

- A `struct` enables bundling multiple variables into a single entity
- A struct definition creates a new type and specifies the type and names of the variables contained within the `struct`

```
struct _complex_t
{
  double real;
  double imag;
};
typedef struct _complex_t complex_t;
```

```
typedef struct
{
  double real;
  double imag;
}
complex_t;
```

- Struct definitions are at global scope just like function definitions

- Struct declaration statement simply creates multiple variables on the stack in a single statement

```
typedef struct
{
  int x;
  int y;
}
point_t;

point_t point_add( point_t pt1,
                   point_t pt2 )
{
  point_t pt3;
  pt3.x = pt1.x + pt2.x;
  pt3.y = pt1.y + pt2.y;
  return pt3;
}

int main()
{
  point_t pt_a;
  pt_a.x = 2;
  pt_a.y = 3;

  point_t pt_b = { 4, 5 };

  point_t pt_c;
  pt_c = point_add( pt_a, pt_b );

  return 0;
}
```

3.3. enum Types

- An enum enables creating multiple named constants

```c
#include <stdio.h>

enum color_t
{
  COLOR_RED,
  COLOR_ORANGE,
  COLOR_YELLOW,
  COLOR_GREEN,
  COLOR_BLUE,
  COLOR_PURPLE
};

void print_color( color_t color )
{
  switch ( color ) {
    case COLOR_RED:    printf("red\n");    break;
    case COLOR_ORANGE: printf("orange\n"); break;
    case COLOR_YELLOW: printf("yellow\n"); break;
    case COLOR_GREEN:  printf("green\n");  break;
    case COLOR_BLUE:   printf("blue\n");   break;
    case COLOR_PURPLE: printf("purple\n"); break;
  }
}

int main()
{
  print_color( COLOR_RED  );
  print_color( COLOR_BLUE );
  return 0;
}
```

4. Working With Types

Types can offer strong static guarantees about correctness, but also need to be carefully managed.

4.1. Type Checking

- Compiler will check to ensure types are consistent
- Inconsistent types will cause a compile-time error

```
typedef struct
{
  int x;
  int y;
}
point_t;

point_t point_add( point_t pt1,
                   point_t pt2 )
{
  point_t pt3;
  pt3.x = pt1.x + pt2.x;
  pt3.y = pt1.y + pt2.y;
  return pt3;
}

int main()
{
  int a = 2;
  int b = 3;
  point_t pt_c = point_add( a, b );
  return 0;
}
```

http://cpp.sh/3ecpv

4.2. Type Inference

- Compiler uses type inference to determine type of an expression

```
int   a = 2;
int   b = 3;
int   c = a + b;          // expr (a + b) has type int
int   d = a / b;          // expr (a / b) has type int

float e = 2.0;
float f = 3.0;
float g = e + f;          // expr (e + f) has type float
float h = e / f;          // expr (e / f) has type float
```

4.3. Type Conversion

- Compiler uses type conversion if variables have different types
- Compiler must convert types so they match
- Lower precision types can be converted to higher precision types
- Higher precision types can be converted to lower precision types

```
signed   int a = 147483647;
unsigned int b = a;      // no issue

signed   int a = -1;
unsigned int b = a;      // careful! b == 4294967295

int    a = 2;
float  b = a;            // no issue, b == 2.0

float  a = 2.5;
double b = a;            // no issue, b == 2.5

float  a = 2.5;
int    b = a;            // careful!  b == 2

double a = 2.5;
float  b = a;            // ok here, but be careful!

int    a = 2;
float  b = 3;
float  c = a + b;        // expr (a + b) has type float
float  d = a / b;        // expr (a / b) has type float

unsigned int a = 2;
signed   int b = -3;
unsigned int c = a * b; // expr (e * f) has type signed int
```

- The following example illustrates automatic type conversion

```c
#include <stdio.h>

int avg( int x, int y )
{
  int sum = x + y;
  return sum / 2;
}

int main()
{
  float a = 10;
  float b = 15;
  float c = avg( a, b );
  printf(" average of %f and %f is %f\n", a, b, c );
  return 0;
}
```

http://cpp.sh/927j3

4.4. Type Casting

- Programmers can use type casting to explicitly convert types

```c
#include <stdio.h>

float avg( int x, int y )
{
  int sum = x + y;
  return ((float) sum) / 2.0;
}

int main()
{
  float a = 10;
  float b = 15;
  float c = avg( a, b );
  printf(" average of %f and %f is %f\n", a, b, c );
  return 0;
}
```

http://cpp.sh/8m7oi

- Type of LHS not part of type conversion rules ...
- ... so just specifying a return type of `float` in `avg` is not enough
- Could specify the type of `sum` to be `float` ...
- ... or use type casting to cast an `int` into a `float`