Lecture Notes for Lecture 8 of CS 5001 (Foundations of CS) for the Fall, 2018 session at the Northeastern University Silicon Valley Campus.

Introduction to Types and Using Typedefs to Define New Types

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Lecture 7 Review

- An array element can be addressed using either an array index or a pointer to the array element.
- Array variables point to their first element; other elements can be accessed using address arithmetic and value-of ('*') operator.
- Incrementing array pointer takes size of element type into account (e.g. adds 4 bytes for an integer array).
- 2D arrays require expensive calculation to skip over previous rows, and then skip to column (array + row * numCols + col)
- Pointers are often more efficient to access arrays by avoiding repeated address calculation if access pattern is linear.
- Arrays are passed to functions using their base pointer; compiler still allows access using array indexes in certain cases
- Most C array and string library functions have pointer parameters.

Type Definitions

What is a Data Type?

- A data type is how a programming language classifies a set of values into a common category.
- A data type also defines how values can be manipulated, and how they interact with other data types.
- The C programming language defines a set of basic data types that include **bool**, **char**, **short**, **int**, **long**, **float**, and **double**.
- Operators and functions in C provide ways to operate on its basic data types, and cast (convert) between data types.

Type Definitions

What is a Data Type?

- As we begin to build programs to solve real-world problems, we need to deal with more complex kinds of information.
- For example, a graphics program provides geometrical shapes and ways to manipulate them and to give colors to them.
- It would be useful if we could create custom data types that represent shapes and colors, and provide custom functions that operate on them.

Type Definitions

Defining Custom Data Types

- The C programming language provides a set of tools for defining custom data types and creating functions that operate on them.
- These tools fall into five categories:
  - **References** provide indirect access to values of another data type.
  - **Sequences** are indexable homogeneous collections of another data type.
  - **Aliases** provide an alternate name for another data type
  - **Enumerations** explicitly identify collections of discrete values that comprise data types.
  - **Aggregations** are heterogeneous combinations of other data types.

Type Definitions

Defining Custom Data Types

- We have already seen two of the tools that C provides for creating custom data types.
- A pointer creates a custom data type that indirectly references another data type. A pointer to integer (int *) is a data type. Its operators are address-of (&) and value-of (*).
- An array creates a custom data type that is an indexable sequences of another data type. An array of int (int[]) is a data type. Its operator ([]) accesses a value in the sequence.

Type Definitions

Aliasing a Type

- This lecture presents a tool in the C language for defining a data type as an alias for an exiting data type: *typedef*.
- Typedefs are used to simplify references to more complex data types by providing descriptive names for those types.
- Typedefs can also be used to define size-specific data types that are portable across computer platforms
- Syntax:

  typedef *existing-type new-type*

Type Definitions

Portability Typedefs

- The C language provides typedef aliases for integer storage classes in terms of basic data types.
- These typedefs provide definitions for integer types with exactly 8, 16, 32, or 64 bits, either signed or unsigned.
- Compilers define them appropriately for the operating systems and the hardware. The definitions are in <stdlib.h>
- Why use them instead of the standard types?
    - Performing calculations that require a specific integer range
    - Writing data files where sizes are required by a standard file format
    - Communicating with other systems that require specific sizes

Type Definitions

Portability Typedefs

- Here are the ones for a typical 64-bit system:

```
typedef signed char int8_t;             // 8-bit signed  (INT8_MIN ... INT8_MAX)
typedef unsigned char uint8_t;          // 8-bit unsigned  (0 ... UINT8_MAX)

typedef short int16_t;                  // 16-bit signed  (INT16_MIN ... INT16_MAX)
typedef unsigned short uint16_t;        // 16-bit unsigned  (0 … UINT16_MAX)

typedef int int32_t;                    // 32-bit signed  (INT32_MIN … INT32_MAX)
typedef unsigned int uint32_t;          // 32-bit unsigned  (0 … UINT32_MAX)

typedef long int64_t;                   // 64-bit signed  (INT64_MIN … INT64_MAX)
typedef unsigned long uint64_t;         // 64-bit unsigned  (0L … UINT64_MAX)

typedef unsigned long size_t;           //  type of array size/index
```

- Examples using size-specific typedefs

```
size_t  slen = strlen(”hello");         // length of string is of type size_t
uint8_t  pixelVal = 0x6c;               // pixel defined as a 8-bit unsigned value
uint32_t  colorVal = 0xAB0D9F27;        // RGBA color defined as 32-bit unsigned value
```

Type Definitions

Defining a Boolean Type

- Before type *bool* was introduced in C99, developers sometimes used typedef to define their own bool type:

```
typedef uint8_t bool;            // represent bool using an 8-bit unsigned int
const uint8_t true= 1;           // false defined as the inequality value (0)
const uint8_t false = 0;         // true defined as the equality value (1)

/**
  * Return bool value true if input value is even, true otherwise
  * @param val the input value
  * @return true if even, false otherwise
  */
bool isEven(int val) {
   return (val % 2 ==0) ? true: false;
}
```

Type Definitions

Defining a Tic-Tac-Toe Board Type

- Typedef can be used to define a type for a Tic-Tac-Toe board:

```
/** TTTBoard is typedef for a 3x3 array of char */
typedef char TTTBoard[3][3];

/**
 * Initialize the tic-tac-toe board.
 * @param board the tic-tac-toe board
 */
void initBoard(TTTBoard board) {  …  board[row][col] = ‘ ‘;  …  }

/** Play tic-tac-toe */
int main(void) {
    TTTBoard board;         // declare tic-tac-toe board
    initBoard(board);       // function initializes board
    …
}
```

Type Definitions

Representing Colors

- Typedefs can be used to define types that encapsulate the underlying representation.
- For example, a color can be specified using four bytes for red (R), green (G), blue (B) components, plus a byte for alpha (A) transparency.

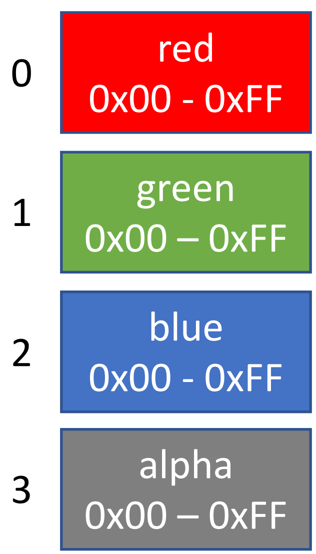
red	green	blue	alpha
0x00 - 0xFF	0x00 – 0xFF	0x00 - 0xFF	0x00 – 0xFF

RGBA image with transparent portions, on checkerboard background

Type Definitions

Representing Colors

- One way to represent a color is as an array of four uint8_t color values, with red as the lowest element 0, green as element 1, blue as element 2, and alpha as element 3.
- This order follows the OpenGL computer graphics standard.



Type Definitions

Representing Colors

```
#include <stdbool.h>
#include <stdlib.h>
#include <stdio.h>

/** Color representation for components r, g, b, a */
typedef uint8_t Color[4];

/** Create a color from r, g, b, and a components.
 * @param c the color to set
 * @param r red color component
 * @param g green color component
 * @param b blue color component
 * @param a alpha color component
 */
void makeColorFromRGBA(Color c, uint8_t r, uint8_t g, uint8_t b, uint8_t a) {
    c[0] = r;
    c[1] = g;
    c[2] = b;
    c[3] = a;
}
```

Type Definitions

Representing Colors

```
/**
 * Get red color component.
 * @param color the color
 * @return red color component
 */
uint8_t getRedOfColor(const Color c) {
	return c[0];
}

/**
 * Get green color component.
 * @param color the color
 * @return green color component
 */
uint8_t getGreenOfColor(const Color c) {
	return c[1];
}
```

Type Definitions

Representing Colors

```
/**
 * Get blue color component.
 * @param color the color
 * @return blue color component
 */
uint8_t getBlueOfColor(const Color c) {
	return c[2];
}

/**
 * Get alpha color component.
 * @param color the color
 * @return alpha color component
 */
uint8_t getAlphaOfColor(const Color c) {
	return c[3];
}
```

Type Definitions

Representing Colors

- This representation has both advantages and disadvantages.
- Advantages:
  - The representation is straight-forward and easy to work with.
- Disadvantages:
  - A Color cannot be created and returned within the makeColor() function. Instead it must be created and passed in by the caller.
  - A Color cannot easily be copied, assigned, or compared to another color using standard assignment and relational operators in the same way as a basic C type.

Type Definitions

Representing Colors

- The first disadvantage is because an array declared within a function is local to the function and no longer exists after returning from the function. It must be passed in instead.
- C does not support an array return type. Return type would have to be declared as uint8_t *.
- Consequently, the following code would not compile or run.

```
Color makeColorFromRGBA(uint8_t r, uint8_t g, uint8_t b, uint8_t a) {
    Color c;    // local uint8_t[4] array no longer exists after return
    c[0] = r;
    c[1] = g;
    c[2] = b;
    c[3] = a;
    return c;   // cannot return array from function; c is a uint8_t*
}
```

Type Definitions

Representing Colors

- The second disadvantage can be addressed by providing a makeColorFromColor() function that initializes a Color from another Color.

```
/**
 * Create a color from the components of another color
 * @param c the color to set
 * @param c2 another color
*/
void makeColorFromColor(Color c, const Color c2) {
    c[0] = c2[0];
    c[1] = c2[1];
    c[2] = c2[2];
    c[3] = c2[3];
}
```

Type Definitions

Representing Colors

- An equalsColor() function would allow comparing two colors.

```
/**
 * Determine whether two colors are equal.
 * @param color1 the first color
 * @param color2 the second color
 * @return true if the two colors are equal
 */
bool equalsColor(const Color color1, const Color color2) {
    return          color1[0] == color2[0]
                 && color1[1] == color2[1]
                 && color1[2] == color2[2]
                 && color1[3] == color2[3];
}
```

Type Definitions

Representing Colors

- Here is a main function to test our new Color data type.

```
/** Test Color data type and functions */
int main(void) {
    Color c1;
    makeColorFromRGBA(c1, 0xFF, 0xF0, 0x0F, 0x01);
    uint8_t r1 = getRedOfColor(c1);
    uint8_t g1 = getGreenOfColor(c1);
    uint8_t b1 = getBlueOfColor(c1);
    uint8_t a1 = getAlphaOfColor(c1);
    printf( “Color c1:”
            ” r: 0x%02x”        // %02x specifies 2-digit 0-padded hex field
            " g: 0x%02x"
            " b: 0x%02x"
            " a: 0x%02x\n", r1, g1, b1, a1);
```

Type Definitions

Representing Colors

- Here is a main function to test our new Color data type.

```
    Color c2;
    makeColorFromColor(c2, c1);
    uint8_t r12= getRedOfColor(c2);
    uint8_t g2 = getGreenOfColor(c2);
    uint8_t b2 = getBlueOfColor(c2);
    uint8_t a2 = getAlphaOfColor(c2);
    printf( “Color c2:”
            ” r: 0x%02x"
            " g: 0x%02x"
            " b: 0x%02x"
            " a: 0x%02x\n", r2, g2, b2, a2);

    // determine whether c1 and c2 are equal
    bool eq = equalsColor(c1,c2);
    printf("Color c1 == c2? %s", eq ? "true" : "false");
}
```

Type Definitions

Representing Colors

- Another way to represent a color is to pack the four color bytes into a uint32_t
- On a little-endian computer, the bytes are arranged like this to conform to the OpenGL graphics standard order:

31 24	23 16	15 8	7 0
alpha 0x00 – 0xFF	blue 0x00 - 0xFF	green 0x00 – 0xFF	red 0x00 - 0xFF

Type Definitions

Representing Colors

- We can use C *bit-wise operators* to build and extract the RGBA fields. Here are examples for unsigned 8-bit values.

bits << count	shift bits left by count (fills with 0's from right)	$1\ 0\ 0\ 0\ \underline{1\ 0\ 0\ 1}$ << 4 $= \underline{1\ 0\ 0\ 1}\ 0\ 0\ 0\ 0$ ← left 4
bits >> count	shift bits right by count (fills with 0s from left)	$\underline{1\ 0\ 0\ 1}\ 1\ 0\ 0\ 1$ >> 4 $= 0\ 0\ 0\ 0\ \underline{1\ 0\ 0\ 1}$ → right 4

bits1 & bit2 — bits in bits1 that are also in bits2 (bits2 *masks* bits1)

	$\underline{1\ 0\ 1\ 0}\ \underline{1\ 0\ 1\ 0}$	bits1 with two 4-bit fields
&	$0\ 0\ 0\ 0\ \underline{1\ 1\ 1\ 1}$	bits2 masks lower 4 bit field in bits1
=	$0\ 0\ 0\ 0\ \underline{1\ 0\ 1\ 0}$	only lower 4 bits of bits1 retained

bits1 \| bit2 — bits that are in either bits1 *or* bits2

	$\underline{1\ 0\ 1\ 0}\ 0\ 0\ 0\ 0$	upper 4-bit field in bits1
|	$0\ 0\ 0\ 0\ \underline{1\ 0\ 1\ 0}$	lower 4-bits field in bits2
=	$\underline{1\ 0\ 1\ 0}\ \underline{1\ 0\ 1\ 0}$	combines upper, lower 4-bit fields

Type Definitions

Representing Colors

```
#include <stdbool.h>
#include <stdlib.h>
#include <stdio.h>

/** Color representation for components little-endian a b g r */
typedef  uint32_t  Color;

/**
 * Create a color from the components of another color
 * @param c the color to set
 * @return a copy of the color
 */
Color makeColorFromColor(Color c) {
    return c;   // returns uint32_t field by value
}
```

Type Definitions

Representing Colors

```
/**
 * Create a color from r, g, b, and a components
 * @param r red color component
 * @param g green color component
 * @param b blue color component
 * @param a alpha color component
 * @return color
 */
Color makeColorFromRGBA(uint8_t r, uint8_t g, uint8_t b, uint8_t a) {
    Color c = a;             // set alpha field
    c = (c << 8) | b;        // shift fields up and add b field
    c = (c << 8) | g;        // shift fields up and add g field
    c = (c << 8) | r;        // shift fields up and add r field
    return c;
}
```

Type Definitions

Representing Colors

```
/**
 * Determine whether two colors are equal.
 * @param color1 the first color
 * @param color2 the second color
 * @return true if the two colors are equal
 */
bool equalsColor(const Color color1, const Color color2) {
    return color1 == color2;  // == operator on Color (uint32_t)
}
```

Type Definitions

Representing Colors

```
/**
 * Get red color component.
 * @param color the color
 * @return red color component
 */
uint8_t getRedOfColor(Color c) {
	return c & 0xFF;     // extract r field
}

/**
 * Get green color component.
 * @param color the color
 * @return green color component
 */
uint8_t getGreenOfColor(const Color c) {
	return (c >> 8) & 0xFF;   // shift fields down 8 bits and extract g field
}
```

Type Definitions

Representing Colors

```
/**
 * Get blue color component.
 * @param color the color
 * @return blue color component
 */
uint8_t getBlueOfColor(const Color c) {
	return (c >> 16) & 0xFF;	// shift fields down 16 bits and extract g field

}

/**
 * Get alpha color component.
 * @param color the color
 * @return alpha color component
 */
uint8_t getAlphaOfColor(const Color c) {
	return (c >> 24) & 0xFF;	// shift fields down 16 bits and extract a field
}
```

Type Definitions

Defining a Boolean Type

- Here is a main function to test our new Color data type.

```
/** Test Color data type and functions */
int main(void) {
    Color c1 = makeColorFromRGBA(0xFF, 0xF0, 0x0F, 0x01);
    uint8_t r1 = getRedOfColor(c1);
    uint8_t g1 = getGreenOfColor(c1);
    uint8_t b1 = getBlueOfColor(c1);
    uint8_t a1 = getAlphaOfColor(c1);
    printf( “Color c1:”
            ” r: 0x%02x"
            " g: 0x%02x"
            " b: 0x%02x"
            " a: 0x%02x\n", r1, g1, b1, a1);
```

Type Definitions

Defining a Boolean Type

- Here is a main function to test our new Color data type.

```
    Color c2 = makeColorFromColor(c1);
    uint8_t r12= getRedOfColor(c2);
    uint8_t g2 = getGreenOfColor(c2);
    uint8_t b2 = getBlueOfColor(c2);
    uint8_t a2 = getAlphaOfColor(c2);
    printf( “Color c2:”
            ” r: 0x%02x"
            " g: 0x%02x"
            " b: 0x%02x"
            " a: 0x%02x\n", r2, g2, b2, a2);

    // determine whether c1 and c2 are equal
    bool eq = equalsColor(c1,c2);
    printf("Color c1 == c2? %s", eq ? "true" : "false");
}
```

Type Definitions

Representing Colors

- This representation has both advantages and disadvantages.
- Advantages:
  - A Color can be created and returned within the makeColor() function.
  - A Color can easily be copied, assigned, or compared to another color in the same way as a basic C type.
- Disadvantages:
  - The representation is not as straight-forward or easy to work with.

Type Definitions

Representing Colors

- Both representations share the advantage that working with Color does not depend on which typedef is used.
- A Color is created by functions that initializes its r, g, b, a appropriately, and accesses its values appropriately for the typedef.
- Color is called an *abstract data type* and its functions are said to *encapsulate* its typedef representation.
- These are important concepts that we will build on in this and future courses.

Type Definitions

Typedefs and Functions

- We saw earlier how to use pointers to scalar and array values. Now we will learn about pointers to functions.
- Here is a function that compares two ints and returns true if the first is greater than the second.

```
/**
 * Compares two int values for greater than.
 * @param val1 the first value
 * @param val2 the second value
 * @return true if val1 is greater, false otherwise
 */
bool compareGreater(int val1, int val2) {
    return val1 > val2;
}
```

Type Definitions

Typedefs and Functions

- In C, a function name is actually a const pointer to a function definition.
- Here is the declaration of a function pointer myFunct that also points to the compareGreater() function:

```
bool (*myFunct)(int, int) = compareGreater;
```

- Given a similar function compareLess(), we could also make myFunct point to that function instead:

```
myFunct = compareLess;
```

- Whichever function that myFunct points to can be called as

```
bool result = myFunct(3, 5);
```

Type Definitions

Typedefs and Functions

- We can create a typedef for the type of these comparison functions with two int parameters and return a bool.

  ```
  typedef bool (*CompareFunct)(int, int);
  ```

- This enables us to declare a pointer to a comparison function using the typedef rather than spelling out the type for each declaration.

  ```
  CompareFunct myFunct = compareGreater;
  ```

- It also makes it more convenient to pass a pointer to a comparison function to another function that uses it to perform whatever comparison is specified.

Type Definitions

Typedefs and Functions

```
/**
 * Return the value from array selected by compare function.
 * @param n the array size
 * @param array the array
 * @param compare the compare function
 * @return the selected value from the array
 */
int select(size_t n, int array[n], CompareFunct compare) {
    int val = array[0];  // initially select first element
    for (int i = 1; i < n; i++) {
        if (compare(array[i], val)) {
            val = array[i];        // select this element if compares
        }
    }
    return val;
}
```

Type Definitions

Typedefs and Functions

```
/** Test the comparison functions */
int main(void) {
    // test array for selection
    int array[] = {-7, 4, 7, 3, 2, -3};

    // select the least element in the array
    int ltVal = select(6, array, compareLess);
    printf("Least value in array is %d\n", ltVal);

    // select the greatest element in the array
    int gtVal = select(6, array, compareGreater);
    printf("Greatest value in array is %d\n", gtVal);
}
```

Output:

```
Least value in array is -7
Greatest absolute value in array is 7
```