Arrays

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Previously

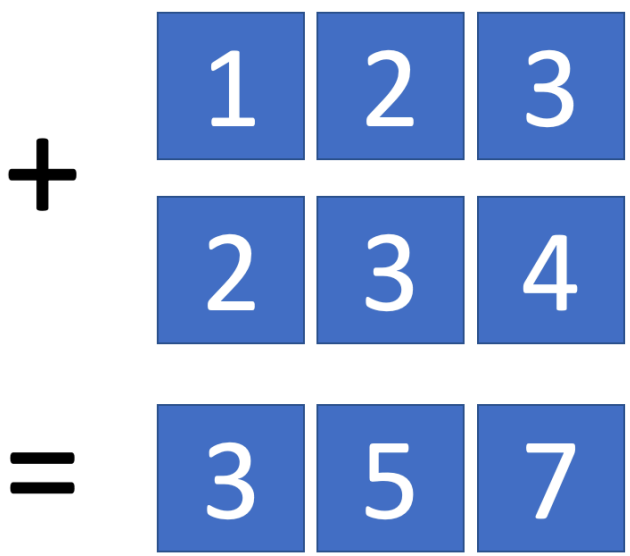
- Time Complexity
  - The number of elementary computing cycles
  - Number of loop iterations (`prime1` , `prime2` , `prime3`)
- Recursion
  - Function calls it self
  - Deposit example
- Stack Memory Layout
  - where your function and local variables are stored
  - The function being called is placed on the top of the stack

Today's Agenda

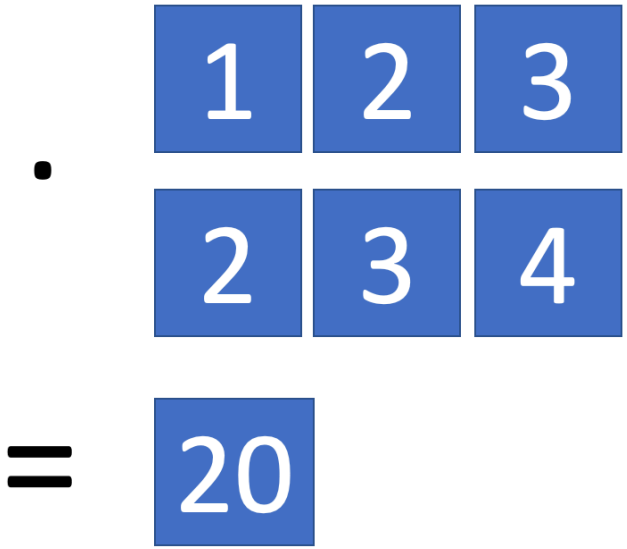
- **What is Array?**
    - How to
        - create an array?
        - access an array?
- How an array is stored in the computer memory?
- Compilation Error vs. Runtime Error.
- How to pass an array as an input argument of a function?
    - Passing by value vs Passing by reference
- How to handle matrix algebra using array?

Vector Calculation

- Vectors are a sequence of numbers.
  - $\boldsymbol{a} = [1, 2, 3]$ is a three-dimensional vector.
- Vector calculations: addition, subtraction, dot product, etc.



Vector Addition



Dot Product

Vector Calculation

- Consider the following program tries to compute the three dimensional vector addition
  - $c = a + b, a = [1, 2, 3], b = [2, 3, 4].$

```
#include <stdio.h>
void main(){
    double a1=1.0, a2=2.0, a3=3.0;
    double b1=2.0, b2=3.0, b3=4.0;
    double c1, c2, c3;
    c1 = a1+b1; c2 = a2 + b2; c3= a3 + b3;
    ...
}
```

- This program is dumb.
- What if you have a 100-dimension vector?
  - `c1 = a1 + b1; ... c100 = a100 + b100;` ?

Vector Calculation

To automate vector calculations, we need two things:

- A way to represent an element in vector via an integer index.
  - e.g. `a[i]` represents the `i`-th element of vector a.
- A loop to perform calculations on all elements in a vector

Imagine we can do something like:
(pseudo code)

```
For i from 1 to 100
    c[i] = a[i] + b[i]
```

This program is much more scalable and understandable.

Array

- Array is a fundamental data structure in C programming language that **stores a sequence of elements**.
- You can declare an array using the syntax:
  - `data_type array_name[array_size];` .
  - ```
    // declares an int array with 100 elements.
    int a[100];
    ```
- `array_size` can **NOT** be a variable.
  - ```
    int c = 100;
    int b[c]; // compilation error!
    ```
  - `array_size` must be determined **compilation time**.

Accessing Array

- i-th element in an array is referred to as `array_name[i]`.
- **The first element in the array `a` is `a[0]`.**
- **The second element in the array `a` is `a[1]`.**
- and so on. This is called **zero-based indexing**.
- e.g., `a[2] = 5;` assigns 5 to **the third element** of `a`.
- The index of an element can be a variable:

```c
int a[10];
//... initialize a

int j = 5;
printf("%d\n", a[j]);
```

Use for loop with Array

- You can access elements using a loop:

```
int a[10];
for(int i = 0; i < 10; i = i+1){
    a[i] = 123; // assigning the i-th element
}
for(int i = 0; i < 10; i = i+1){
    printf("%d ", a[i]); // print the i-th element
}
```

- The structure of for loop makes it ideal for reading/writing elements in an array.

Initialize Array

- Array declaration only reserves memory space for the array. The array will not be initialized automatically.
- If you do not initialize an array yourself, **it will contain rubbish value**, similar how variable declaration is handled in C.
- You can initialize an array using the syntax:
  - `data_type array_name[] = {elements};` .
  - ```
    int a[] = {1,2,3};
    ```
  - No need to specify the `array_size` .
    ```

Vector Addition, Revisited

```
#include <stdio.h>
void main(){
    //declare and initialize array a and b.
    double a[] = {1.0, 2.0, 3.0},
           b[] = {2.0, 3.0, 4.0};
    double c[3];
    //addition
    for(int i = 0; i< 3; i=i+1){
        c[i] = a[i] + b[i];
    }
    //display each element in the array c
    for(int i = 0; i< 3; i=i+1){
        printf("%f\n", c[i]);
    }
}
```

Vector Addition, Revisited

- What is the time complexity of adding two d-element array?

Be Careful about the Length!

- What will happen if I try to access the element that does not exist?

```c
#include <stdio.h>
void main(){
    //declare and initialize array a.
    double a[] = {1.0, 2.0, 3.0};

    printf("%d\n", a[5]); // ❌ out of bounds
}
```

Be Careful about the Length!

- C compiler will **not check** if the index has exceeded the array length.
- If you try to access an array element that is clearly out of bound,
  - No error will be raised during the compilation stage.
  - However, your program will have undefined behavior (usually crash).
- Index out-of-bound is a type of runtime error 😮.

Compilation Error vs. Runtime Error

- Errors happen during compilation are called **compilation errors**.
- For example, you forget to add a semicolon after a statement:
  `printf("hello world!")`
- The compiler will raise an error saying:
  `vecadd.c:11:26: error: expected ';' before '}' token`
- The compiler will refuse to generate executable code if compilation error happens.
  - This kind of error is easy to identify and fix.

Compilation Error vs. Runtime Error

- Errors during the runtime are called **Runtime errors**.
- Your code compiles and generates an executable file.
- However, your program behaves **unexpectedly**.
- Examples of Runtime Error:
  - Division by zero
  - Loop that never ends (infinite loop)
  - Out of memory (stack overflow)
  - Index out of bounds (undefined behavior)
  - many more
- Much harder to spot and fix! Be careful about it!

Good Habits Matters!

- Having good coding habit reduces runtime errors significantly.

```
double a[] = {1.0, 2.0, 3.0},
       b[] = {2.0, 3.0, 4.0};
double c[3];
// after many lines of code ...
for(int i = 0; i< 999; i=i+1){ // ❌ wrong array length!
    c[i] = a[i] + b[i];
}
```

- Have "magic numbers" dotted around the code is bad for readability and sources of bugs.

Good Habits Matters!

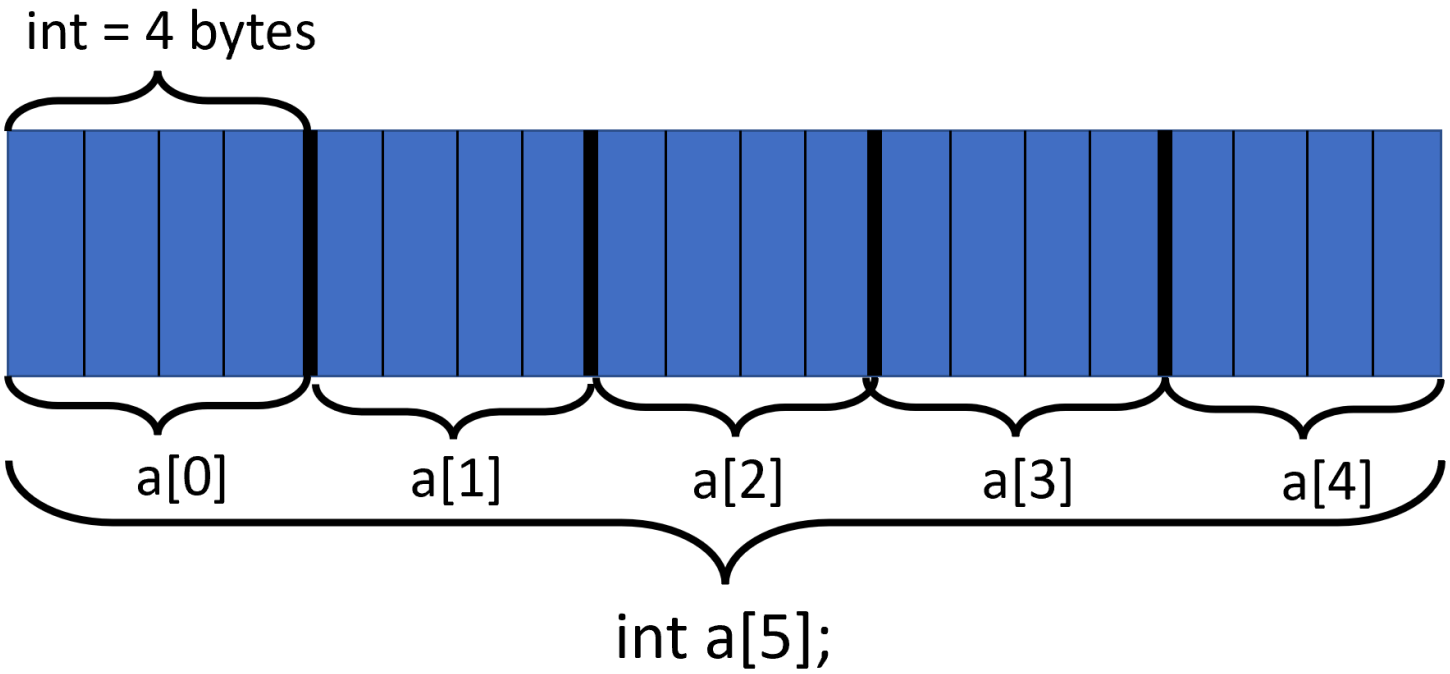
- Use a **constant** to represent the length of the array.

```
const int length = 3; // ✅ give it a meaningful name
double c[length];

for(int i = 0; i< length; i=i+1){ //✅ no magic number 3
    c[i] = a[i] + b[i];
}
```

Array's Memory Layout

- Array is stored in a **contiguous section memory**.

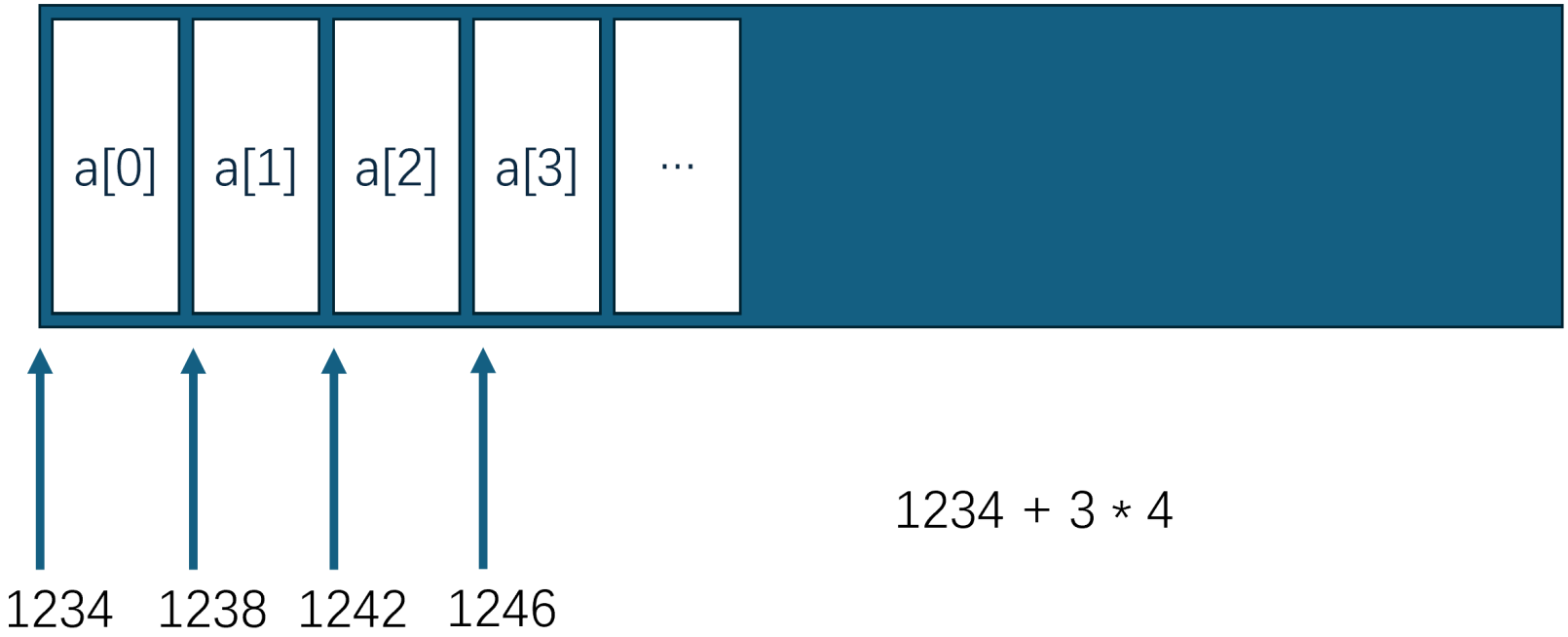


  - Recall, an integer variable takes up 4 bytes of memory.
  - No gap, highly efficient data structure.

Array's Memory Layout

- Suppose I have an array of 10 elements, stored at memory address 1234.
    - Assume each element takes up 4 bytes of memory.
    - What is the memory address of `a[3]`?
- Memory address is the starting place where data is stored.
    - If I have 10 bytes of memory, and integer variable `a` is stored from the 6th byte to the 9th byte, then the memory address of `a` is 6.

Array's Memory Layout



Increment

- Since we are going to write `i = i + 1` a lot,
- Use `i++` as a shorthand for `i = i + 1`.

```
for(int i = 0; i< 3; i++){
    printf("%f\n", c[i]);
}
// is the same as
for(int i = 0; i< 3; i = i + 1){
    printf("%f\n", c[i]);
}
```

- Similarly, `i += k` is short for `i = i + k`.

```
for(int i = 1; i< 10; i += 2){
    printf("%d\n", i);
} //prints out 1,3,5,7,9
```

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- **How to pass an array as an input argument of a function?**
    - Passing by value vs Passing by reference
- How to handle matrix algebra using array?

Array as Input Argument

- You can pass array as input variables of a function.
- Simply write `data_type array[]` inside the parenthesis following the function name.
- `array_size` is not needed.

Dot Product

- Consider a function `dot` computes the dot product between two vectors a, b: $a \cdot b = \sum_i a_i b_i$.

```
//compute dot product between a and b.
//a and b are two input arrays
double dot(double a[], double b[]){
    double s = 0;
    for(int i = 0; i< 3; i++){
        s += a[i]*b[i];
    }
    return s;
}
```

- What if you do not know the size of `a` and `b`?

Dot Product

- Pass another input argument, specifying the array length.

```
//compute dot product between a and b.
//a and b are two input arrays
//len is the length of both a and b.
double dot(double a[], double b[], int len){
    double s = 0;
    for(int i = 0; i< len; i++){
        s += a[i]*b[i];
    }
    return s;
}
```

Pass by Value

Ordinarily, when you pass an input argument to a function, you are passing by value: The program will copy the value of the input to the input variable.

```
#include <stdio.h>
void hack(double s){
    s = 100; //assignment to the input variable!
}
void main(){
    double score = 40;
    hack(score);
    printf("%f %f\n", score);
    //display 40
}
```

The value of `score` is copied to the input argument `s`, thus operations on `s` has no effect on `score`.

Pass by Reference

- However, comparing to ordinary variables, the array occupies a much bigger memory space, thus pass by value can be expensive.
- In C, array is passed by reference.
    - If callee changes the array, caller's array will also be changed.

Pass by Reference, Example

```
//add all elements in an array by 1
void hack(double s[]){
    for(int i = 0; i< 4; i++){
        s[i] =100;
    }
}
void main(){
    double scores[] = {40.0, 41.0, 46.0, 48.0};
    hack(score);
    printf("%f %f %f %f\n", score[0], score[1], score[2], score[3]);
    //display 100 100 100 100, NOT 40.0, 41.0, 46.0, 48.0!!
}
```

- Careful if you do not intend to change the value of the original array.

Return an Array

- Array cannot be returned by a function.
- However, since a function can make changes to caller's array, you can pass an empty array as input argument, and the function stores results in that array.

```
//compute a+b and store the result in c
void add(double a[], double b[], double c[], int len){
    for(int i = 0; i< len; i++){
        c[i] = a[i] + b[i];
    }
}
void main(){
    double a[] = {1.0, 2.0}, b[] = {2.0, 3.0};
    double c[2];
    add(a,b,c,2);
    printf("%f %f\n", c[0], c[1]);
    //display 3 5
```

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- **How to handle matrix algebra using array?**

How to handle matrix algebra using array?

How to store and operate on matrices by using arrays?

Row Major and Column Major Order

- Matrix is a "2D object", you need to flatten it before storing it in a 1D container (such as an array).
- Row Major and Column Major Order are two methods storing a matrix in an array.
- Using zero-based indexing (indices i, j starts from 0),
- Row-major order stores a matrix as

$$A = \begin{bmatrix} A_{00}, & A_{01}, & A_{02} \\ A_{10}, & A_{11}, & A_{12} \end{bmatrix} \implies [A_{00}, A_{01}, A_{02}, A_{10}, A_{11}, A_{12}].$$

- Row major order means $A_{i,j}$ is the `i*ncol + j` -th element in the array.

Row Major and Column Major Order

- Column-major order stores a matrix as

$$A = \begin{bmatrix} A_{00}, & A_{01}, & A_{02} \\ A_{10}, & A_{11}, & A_{12} \end{bmatrix} \implies [A_{00}, A_{10}, A_{01}, A_{11}, A_{02}, A_{12}].$$

- Column Major order means $A_{i,j}$ is ?-th element in the array

Row Major and Column Major Order

- In the exam and future CWs, I will say something like:
  - "an array `A` stores a matrix $A \in \mathbb{N}^{m \times n}$, in row-major order. "
  - You should know what I mean by that!

Printing a Matrix

The code below prints out a 2 by 3 matrix stored in array A in row major order.

```
int A[] = {1, 2, 3, 4, 5, 6};

for (int i = 0; i < 2; i = i + 1){// for row i
    for (int j = 0; j < 3; j = j + 1){ // for column j
        printf("%d ", A[i*3 + j]); // print A_ij
    }
    printf("\n");
}
```

It prints out

```
1 2 3
4 5 6
```

Time complexity

What is the time complexity of printing a matrix?

Conclusion

- Array stores sequence of objects.
- Array occupies a contiguous section of memory.
- Compilation Error vs. Runtime Error.
- Passing by value vs Passing by reference.
- Row major order and Column major order.

How Computer Stores/Displays Images?

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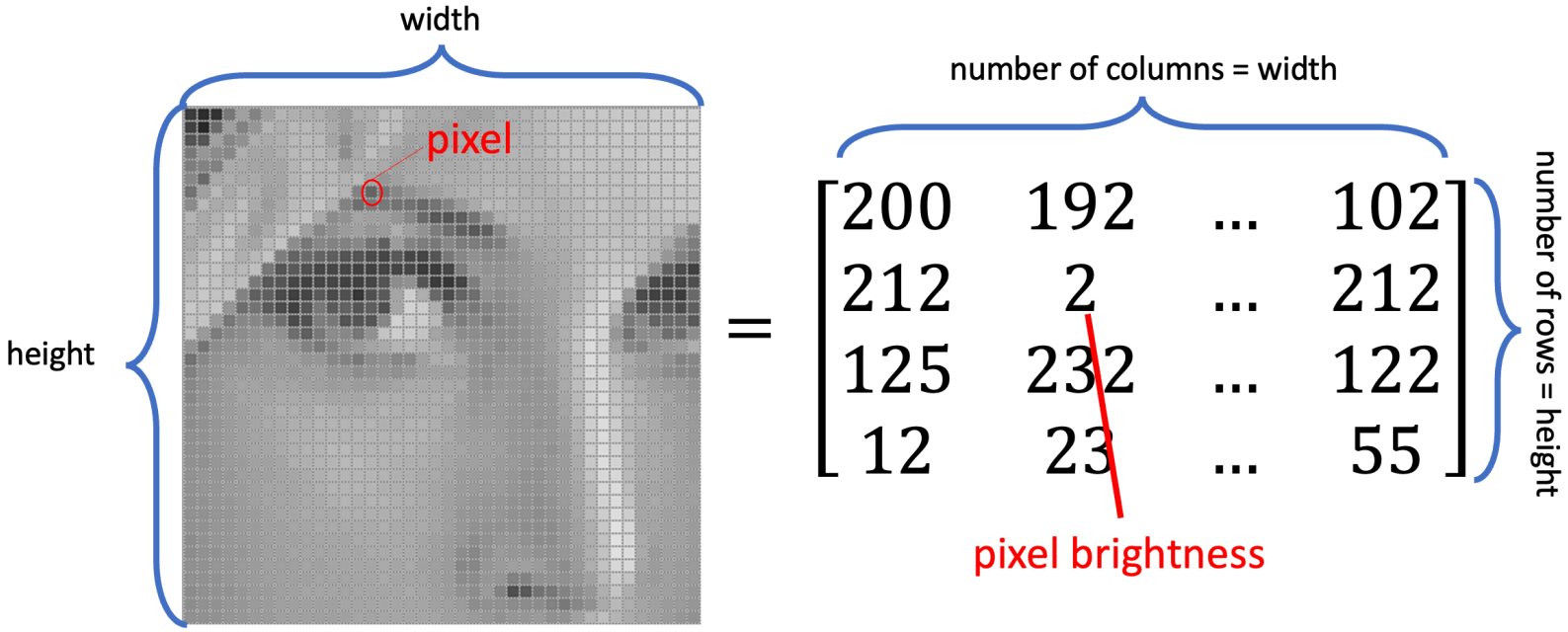
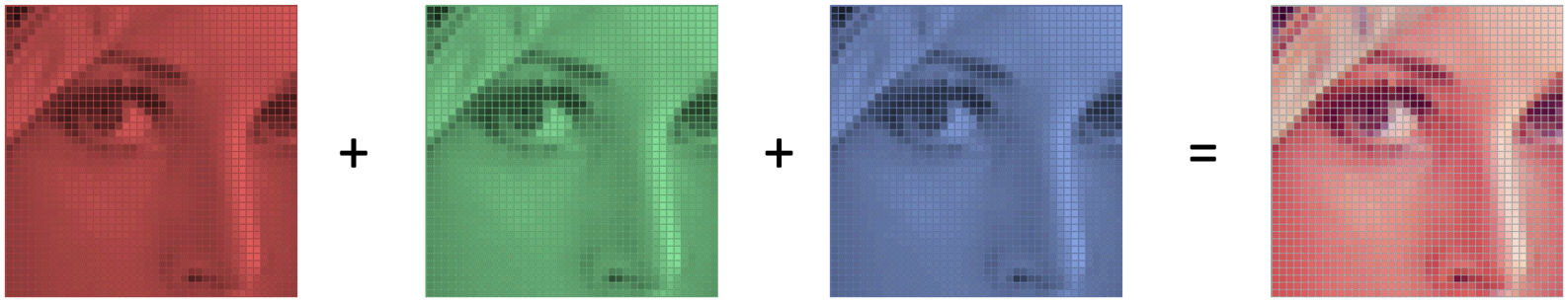
Images are Matrices



- Grayscale images are expressed as matrices in computer.
- A pixel in the image corresponds to an element in the matrix.
- Each element of the matrix indicate the brightness of a

Colored Images are Matrices too



- One colored image is expressed as **three** individual matrices:
  - Three matrices indicate brightness in Red, Green and Blue tones (RGB).
  - Computer can display a colored image by stacking three images together.

Images Files are Flattened Matrices

- **Image files** store images as a matrix in row-major order.
  - A row-major flattend matrix is

$$\begin{bmatrix} 1, & 2 \\ 3, & 4 \end{bmatrix} \implies [1, 2, 3, 4].$$

  - See Lecture 6, Task 3 for more details.
- Knowing these facts, we can build a "textual image viewer" using C programming language.

Building an Image Viewer

- Suppose you have obtained an `int` array `a` with length `M*N` and
  - It contains a flattened matrix `[12, 232, ..., 254]`
  - Let the "unflattend" matrix be $A \in \mathbb{N}^{m \times n}$.
  - Matrix A represents an image with width `N` and height `M`.
- To visualize your image, simply print out an M by N matrix replacing the integer $A_{i,j}$ with a character according to the following rules.
  - if $A_{i,j} \leq 85$, print empty space ` `.
  - if $85 < A_{i,j} \leq 170$, print character `I`.

Building an Image Viewer

Now, modify code in `image2d.c` so that it prints out the image stored in `surprise.dat` as a row-major flattened matrix.

- Hint: If you cannot see the image, try to zoom out by pressing ctrl + -
- What is the image that you see?

Homework 5.1

- Download homework files and read code in the lecture,
  - `vecadd.c` : Vector Addition
  - `vecdot.c` : Vector Dot Product
  - `passingbyval.c` : Passing by Value Example
  - `passingbyref.c` : Passing by Reference Example
- Make sure you understand how to
  - Declare array and Initialize array
  - Read/Write elements of an array
  - Pass array as input to a function and
  - What is pass by value/reference.

Homework 5.2, Find Max (submit)

1. Create a new C file (file->new file... save as `max.c`)
2. In the `main` function, create an integer array and initialize it with a sequence of integers `[2,1,3,4,3]`.
    - Use the initialization syntax introduced in the lecture.
3. Write a function called `max` taking two inputs:
    - The input array
    - The length of the input array.
4. `max` returns the maximum value in the input array.
5. For example, given input `[1,2,2]`, `max` should return 2.
6. Test `max` function in `main` using the array you just created at the 2nd step and print out the maximum value.

- Hint: write pseudo code on a paper first and talk to your coursemates/TA if you are not sure where to start.

Homework 5.3, Swap (submit)

1. Write a new function **in the same file** called `swap`.
2. `swap` takes an array with length 2 as input.
3. `swap` does not return anything.
4. After `swap` function is called, the elements in the input array will be swapped.
    - If the input array is `[1,2]`, it becomes `[2,1]` after `swap` is called.
5. Test your `swap` function in `main` with the array `[1987,10]` and print out the array after swap.

Homework 5.4, Printing Matrix (submit)

1. Start a new file, called `printmat.c`.
2. In your `main` function, create an integer array `A` and initialize it with value `[1,2,3,4,5,6]`.
3. Suppose `A` is a 3 by 2 matrix stored in a row major order.

Homework 5.4, Printing Matrix (submit)

4. Write a function `print` taking 3 inputs.
    - an array storing a matrix in row major order.
    - the number of rows of the matrix.
    - the number of columns of the matrix.
5. `print` prints out the input matrix in a proper format.
6. In the `main` function, test your `print` function with the matrix `A` you have created in the second step.