CW2 and Revision

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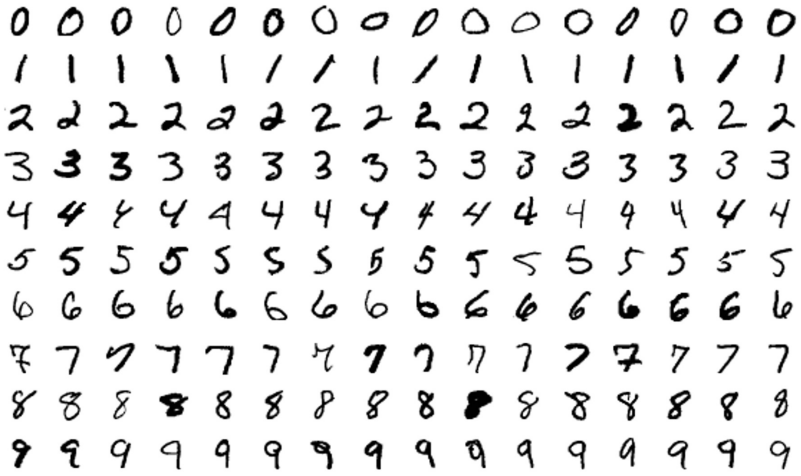
Assessed Coursework 2

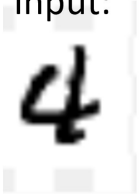
Deadline: Friday, Week 12.

Task: Given a data set (MNIST) containing images of handwritten digits, implement a simple classification algorithm (k-nearest neighbor), which labels a test image with "1", or "not 1"

Dataset:



Input:



Output:

"4"

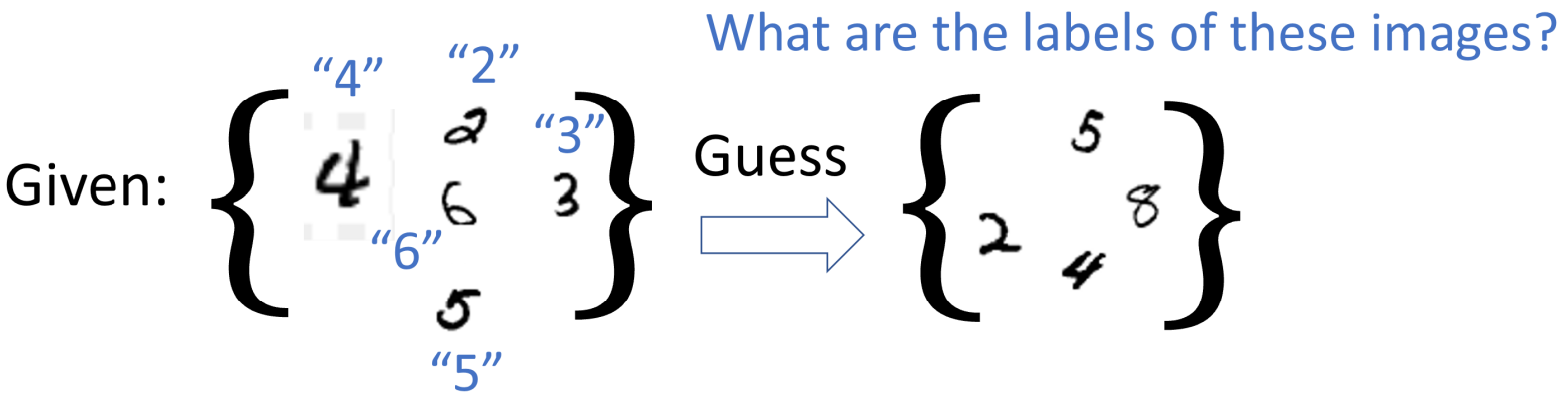
Input:

Output:

"1"

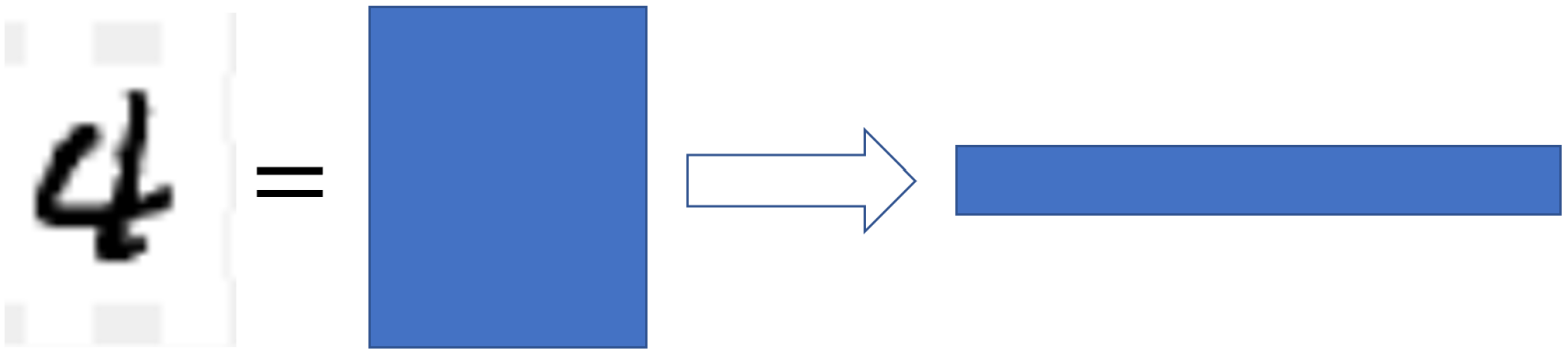
Assessed Coursework 2

- In this CW, the goal is to use images and labels in one dataset to predict labels of images in another dataset, where labels are NOT observed.



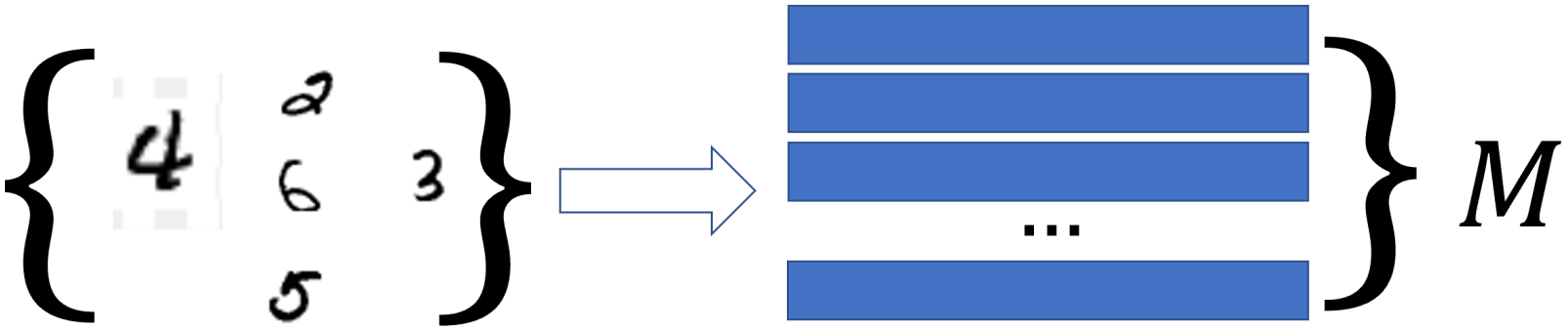
Assessed Coursework 2

- As we mentioned in previous lectures/labs, images are stored as flattened matrices (in row/col major order) in the memory.
- Each image is stored as a vector in this coursework.



Assessed Coursework 2

- In this CW, we are dealing with sets of images. Stacking all the image vectors together, you get a matrix.

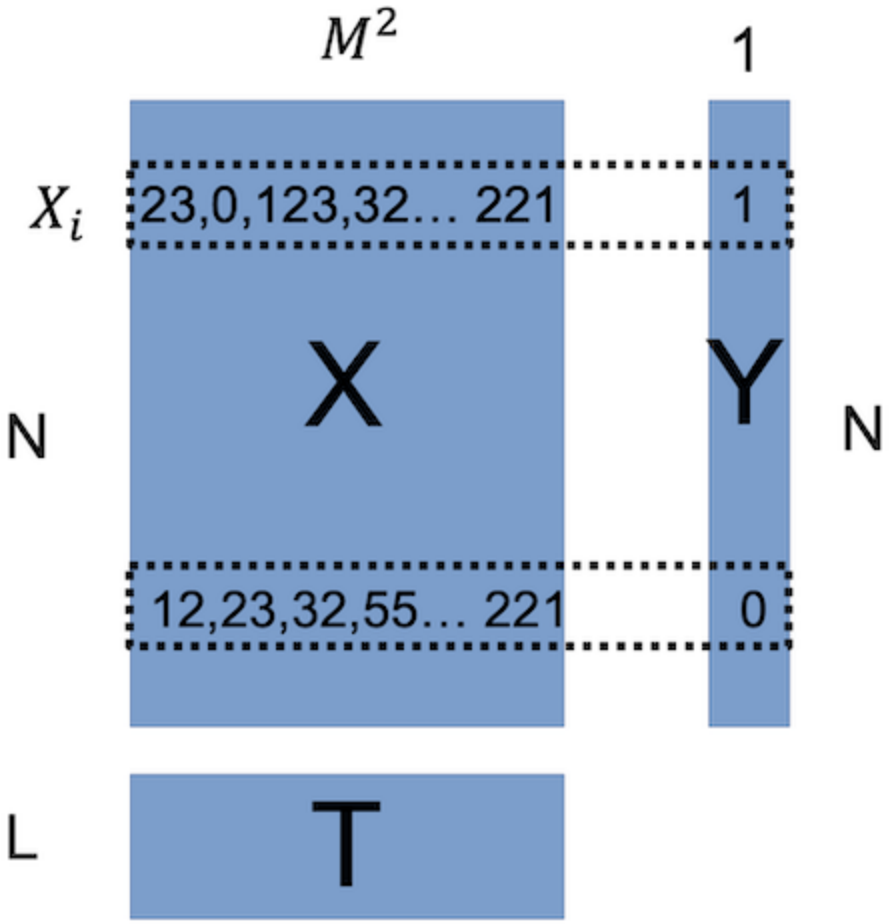


- Specifically, there are two sets of images in this CW, so they are represented by two matrices X, T.

Part I, The Data Set

- CW folder contains 3 `.matrix` files storing 3 matrices.
  - `X.matrix` stores an N by M^2 matrix X where each row is a grayscale M by M image stored in row-major order.
  - `T.matrix` stores an L by M^2 matrix T where each row is an M by M **test image** in row major order.
  - `Y.matrix` stores an N by 1 matrix Y where each row is a scalar, indicating whether the corresponding row in X is digit 1 or not.
  - X and Y together are called "training set" in machine learning, while T is the "testing set". Y is called the "labels" of X.

Part I, Data Structure



- If $Y_i = 1$, then the image X_i is a handwritten digit 1. If $Y_i \neq 1$, the image X_i is NOT a handwritten digit 1.

Part I, Loading Dataset

- The code for loading these matrices from files have been provided to you. Matrices are represented by a **matrix structure** in this coursework.

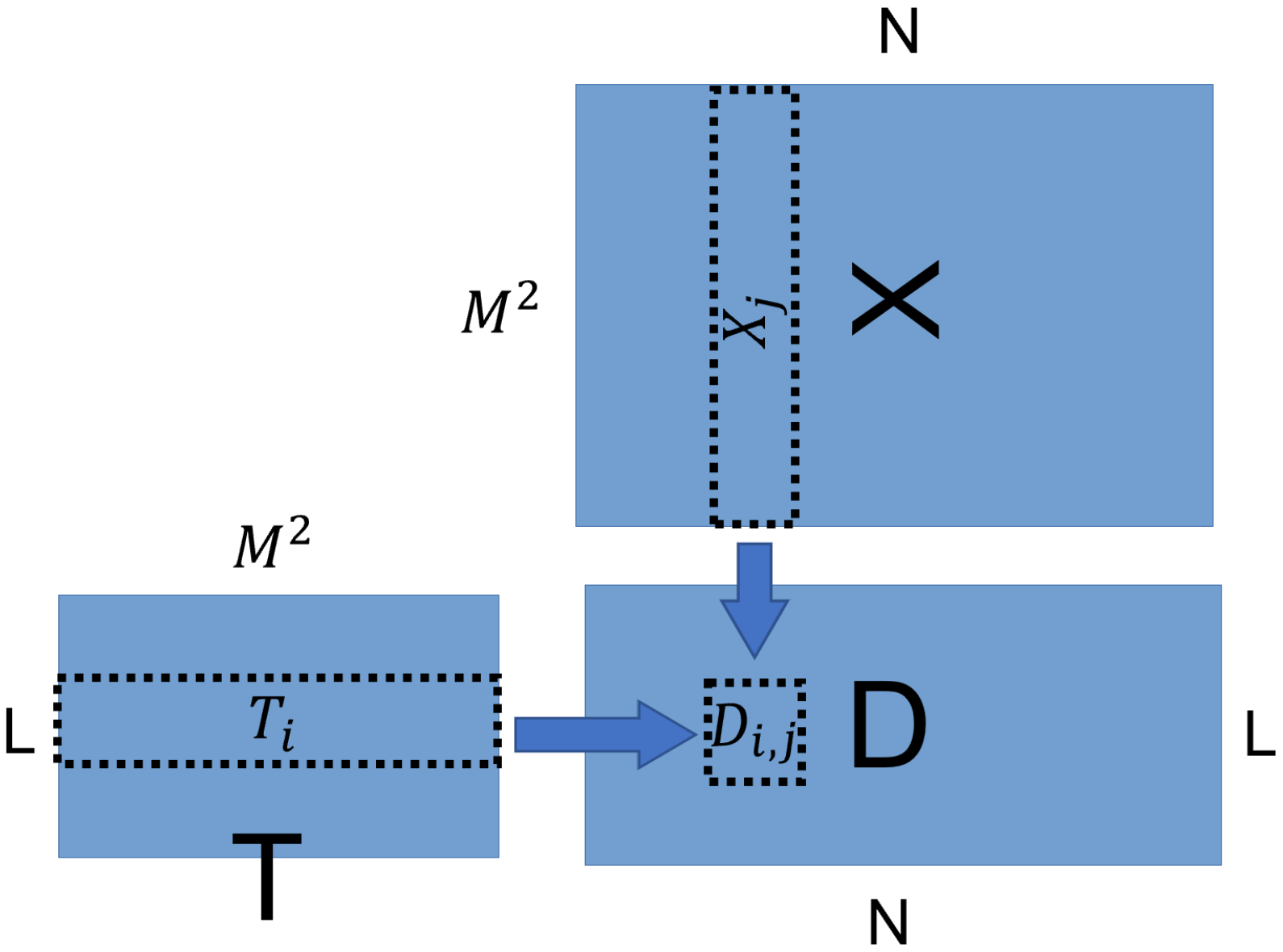
```
struct matrix
{
    int numrow; //number of rows
    int numcol; //number of columns
    int *elements; // pointer pointing to an integer array
    // storing all entries in the matrix in row major order.
};
typedef struct matrix Matrix;
// now "Matrix" is an alias of "struct matrix"
```

- By simply running the skeleton code, you should see some basic statistics of X, Y and T.
    - What are M, N and L?
    - How many images in the training set X are digit 1?

Part II Computing Distance Matrix D (40pt in total)

- Construct an L by N matrix D, where the i, j-th element $D_{ij} = \mathrm{dist2}(T_i, X_j)$
  - T_i is the i-th row of T.
  - X_j is the j-th row of X
- $\mathrm{dist2}(a, b)$ computes the squared euclidean distance between two vectors a and b with K elements.
  - $\mathrm{dist2}(a, b) := \sum_{k=1}^{K} (a_k - b_k)^2$.

Part II (Computing D)



Part II.1 (15pt) Constructing D

Before your `main` function,

1. Write a few helper functions:

```
int get_elem(Matrix M, int i, int j)
```

- returns the `i, j` th element of matrix `M`.

```
void set_elem(Matrix M, int i, int j, int value)
```

- assign `value` to the `i, j` th element of matrix `M`
  In this coursework, `i, j` are **zero-based indices**.

In your `main` function,

2. Allocate HEAP memory for D.
3. Declare and initialize a new `matrix` variable `D`.

Part II.2 Computing D (25pt)

Now, populate the matrix D with correct values.

- **Hint**: Compare the computation of D and the matrix multiplication. What are the similarities and what are the dissimilarities?
    - Can you modify the matrix multiplication code to compute matrix D?
- **Hint**, you can write a function

```
void pairwise_dist(Matrix T, Matrix X, Matrix D)
```

    - where D is the output, storing the outcome.
- Partial points will be given for correctly written code for computing $\mathrm{dist2}(a, b)$.

Part III.1 Guessing Labels (15%)

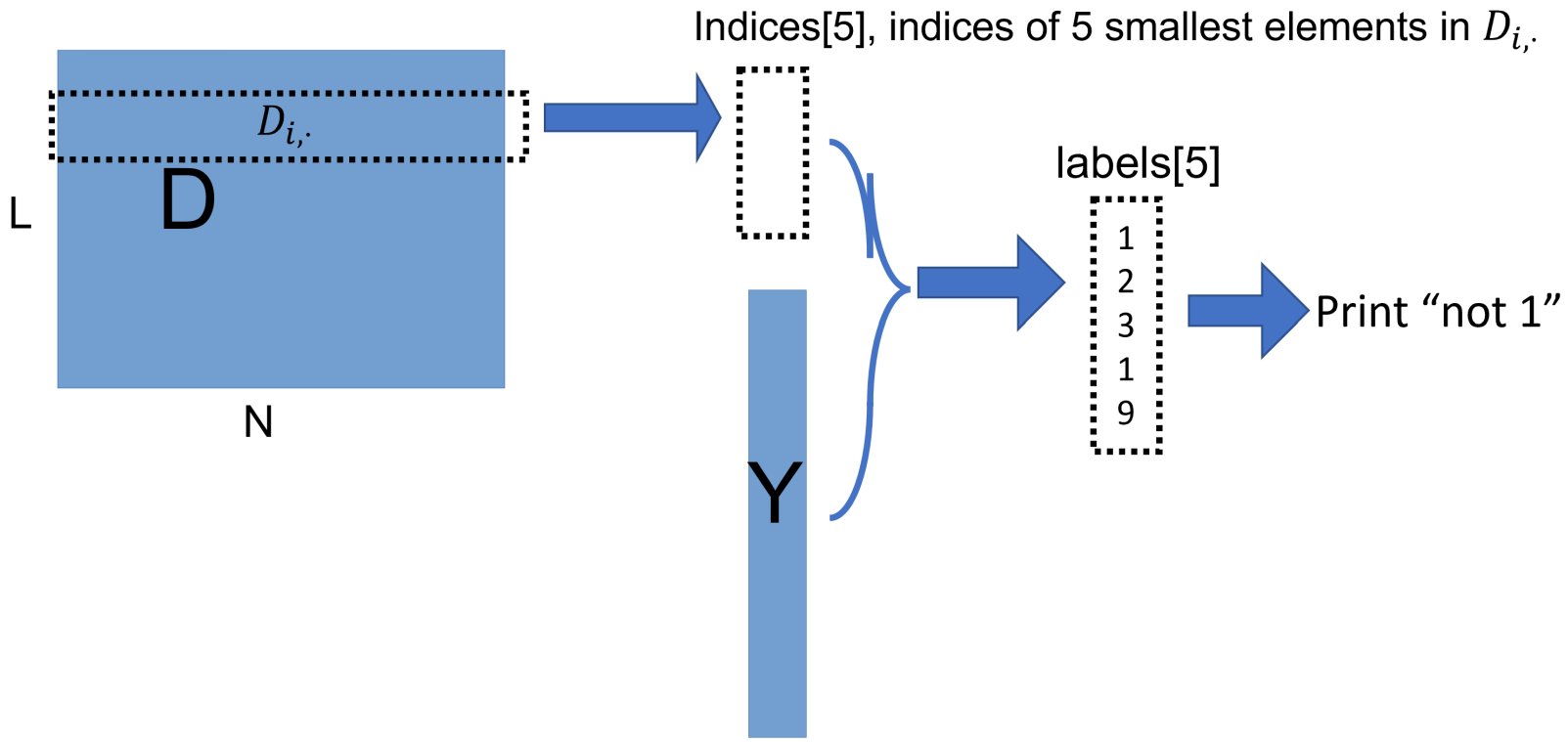
- For each row of matrix D, find **the indices** of the five smallest elements.
    - Suppose the i-th row of D is $[3, 2, 5, 1, 2, 5, 13, 46, 32]$,
    - The indices of the five smallest elements are $[3, 1, 0, 5, 6]$.

Part III.2 Guessing Labels (15%)

- Now, suppose the array `indices` contains the indices of the five smallest elements in row i of matrix D.
    - Create a new array `labels` with length 5.
    - Assign the value of $Y_{\text{indices}[k],0}$ to the k-th element in `labels`.
    - Count the number of `1` in `labels`.
    - If the count >= 3, print out `1`. Otherwise, print `not 1`.
- Repeat above for all rows in D.

Part III Guessing Labels (30pts total)

For each row in D, do:



Part III Guessing Labels

- At each row D_i, the print-out is your "guess" of the testing image T_i using 5-nearest neighbour algorithm.
    - If the print-out is `1`, it means the algorithm thinks the image T_i is a digit 1.
    - If the print-out is `not 1`, it means the algorithm thinks the image T_i is NOT a digit 1.
- After your guess, you can optionally print the image stored in T_i to the console to validate your guess.

Part III Guessing Labels

- Hint: Write a helper function

  ```
  void minimum5(int len, int a[], int indices[])
  ```

  It takes an array `a` with length `len` as input, then fills `indices[]` with the indices of the five smallest elements.

- You might want to test your functions in a separate c file to ensure that they are correctly written.

Final Project: Marking Criteria

- Submitting correct code (10%)
    - Submitting a C file with **the correct name**.
    - Your code compiles and runs **without major error** such as **crash**, **infinite loop**.
        - It will be tested using `gcc` in the lab pack.
- Part II 40% (15% + 25%)
- Part III 30% (15% + 15%)
- Good Coding Practice (20%)
    - Good code format
    - Good variable naming scheme.
    - Apt comments

Final Project: Dos and Don'ts

- You can discuss with your classmates about general strategies but write your own code!
- Don't give your code to other students.
- Review relevant previous lab sessions before you start.
- You need to add a reference in the comments. Copy and pasting code from internet (including chatGPT) without citation is not allowed.
- You are only allowed to use standard features of C.
    - You can use `stdio.h`, `stdlib.h`, `limits.h` and `math.h`.
    - If you want to use other libraries, consult with the lecturer or TA beforehand.

Final Project: Q&A

- We will answer questions posted on the Blackboard forum or answering them during the lab sessions.
- We will inspect the forum regularly and try to respond in 24 hours.

Revision

Look back:

- TB1: C Programming Language (**done!**)
- TB2: 50/50
    - Some aspects of C++ Programming Language.
    - R Programming Language.

Revision

- Basics of Computing:
  - Foundation of Computing
  - Functions
  - Flow Control
  - Recursion and Stack Memory
- Advanced Language Features
  - Arrays
  - Pointers
  - Dynamic Memory Allocation
  - Structure and IO

Foundation

von Neumann Architecture

- **Central Processing Unit (CPU)**
  - Performs computational tasks.
  - Controls Input/Output (IO) devices.
  - Maintains data stored in the memory.
- **Memory**
  - Stores program/data being used by CPU temporarily.
- **IO Devices**
  - Hard disk
  - Display
  - Camera
  - Touch Screen, etc.

Low-level Programming Language

- **Advantages** of Low-level Programming Language:
  - gives coder total control of hardware.
  - can be efficient since it needs no translation (You talk to the computer using its native language!).
- **Disadvantages** of Low-level Programming Language:
  - can damage the hardware if the coder is not careful.
  - is difficult to learn and read (machine instructions are usually very different from human languages).
  - only works on a specific cpu architecture (e.g. x86 or ARM). Thus the code is not "portable".

High-level Programming Language

- **Advantages** of High-level Programming Languages
  - Close to human language, easy to learn/read.
  - CPU architecture independent, a.k.a., "Portable".
- **Disadvantages** of High-level Programming Languages
  - Less efficient as the code requires "translation" before it can be executed on CPU.
  - Cannot directly communicate with hardware: the coder has to interface with *the abstraction*.

Functions

Functions in Programming

- Functions are individual building blocks of your program that accomplish specific tasks.
    - Function helps you divide your code into smaller, more **manageable and readable** pieces.
    - Code in a function is only executed when its host function is "called".
    - In our "Hey Jude" example, `main` is **the caller** of `verse1` and `verse2`
- Some functions take *input arguments* from the caller.
- Some functions return *an output value* to the caller after all its code are executed.
- Some functions do not have input or output.

Your Own Function

You can write your own function and call it from `main()`:

```
...
void sayhello(){
    printf("Hello World!\n");
}
int main(){
    sayhello(); //calling "sayhello" function.
    return 0;
}
```

Data Types in C

- Some data types are:
  - `int` or `long` : integers
  - `float` or `double` : decimal numbers
  - `char` : characters
- Specifying data types tells the compiler: "reserve __ bytes of memory for this data when function is running!".
- On modern PCs (and most smartphones):
  - `int` and `float` occupies 4 bytes of memory.
  - `long` and `double` occupies 8 bytes of memory.
  - `char` occupies 1 byte of memory.

Declarations

- Variable in C is a placeholder of some value.
- The value held by a variable can be changed later.
- In C programming language, all variables must be **declared**.
- The syntax of declaration is: `data_type variable_name`.
  - Declaration: `double gravity;`
  - Declaration **with initializations**: `double m1 = 1.0;`
  - Declaration of multiple variables of the same type: `double m1, m2;`.
  - Declaration of multiple variables of the same type with initializations: `double m1 = 1.0, m2 = 2.0;`.

Flow Control

If-Else

- This simple conditional statement is called "if-else" statement and exists in many programming languages.
- If-Else statement in C is written as follows:

```
    if (condition){
        statements to be executed,
        if condition is true
        ...
    } else{
        statements to be executed,
        if condition is false
    }
```

    - If condition is true, the program bypasses all statements following `else`.
- `condition` can be logical and relational expressions.

Relational and Logical Operators

- Relational Operators
  - `>` strictly greater. `2>1` is TRUE.
  - `>=` greater or equal. `2>=3` is FALSE.
  - `==` equals to. `1 == 1` is TRUE.
    - Note, single `=` is assignment operator. It assigns the value of RHS to the variable on the LHS. Do not get confused!
  - `!=` not equal. `2 != 1` is TRUE.
- Logical Operators
  - `&&` logic AND. `1>0 && 1>-1` is TRUE.
  - `||` logic OR. `1>0 || -1>0` is TRUE.

if-else-if Ladder

```
if (condition1){
    statment1;
} else if(condition2){
    statment2;
} else if(condition3){
    statment3;
}
...
else{ //optional
    statement0;
}
```

- The program will check conditions **sequentially**.
- Once a true condition is found
    - It executes the associated statements.
    - then **bypasses the rest of the ladder**.
- If none of the conditions are true, it executes the `else` statements (if there is one).

While Loop

The simplest loop is while-loop and its syntax is:

```
while(condition){
    statements
}
```

The statements inside of the brackets will be run repeatedly as long as the `condition` is true.

```
// print out every positive integer smaller or equal than 10
int i = 1;
while(i<=10){
    printf("%d\n", i);
    i = i + 1;
}
```

Note that `i` changes every iteration.

For Loop

- For loop is another type of loop mechanism in C.

```
for(init statement; condition; update statement){
    statements to be repeated
}
```

i. It initializes a counter.

ii. Check condition,

- If it is satisfied, run statements
- If not, exit the loop.

iii. Run update statement. Go back to ii.

Nested Flow Control

Nested If-Else

- You can write conditional statement inside another conditional statement.

```
if(score >= 40){
    printf("congratulations! ");
    if(score >=70){
        printf("first class!\n");
    }else{
        printf("passed!\n");
    }
}else{
    printf("student has failed!\n");
}
```

- The code prints out
  - `student has failed!` if `score < 40`.
  - `congratulations! passed!` if `40 <=score < 70`.
  - `congratulations! first class!` if `score >= 70`.

Nested Loops

- Similarly, you can write one loop inside another loop.

```
for (int i = 1; i <= 4; i=i+1){
    // print i-th line
    for (int j = 1; j <= 4; j=j+1){
        printf("*");
    }
    printf("\n"); // change line
}
```

- It prints out a block of `*`

```
****
****
****
****
```

Early Loop Exit

- `break;`, early loop exit.
- `continue;`, early loop restart.

`return` Statement

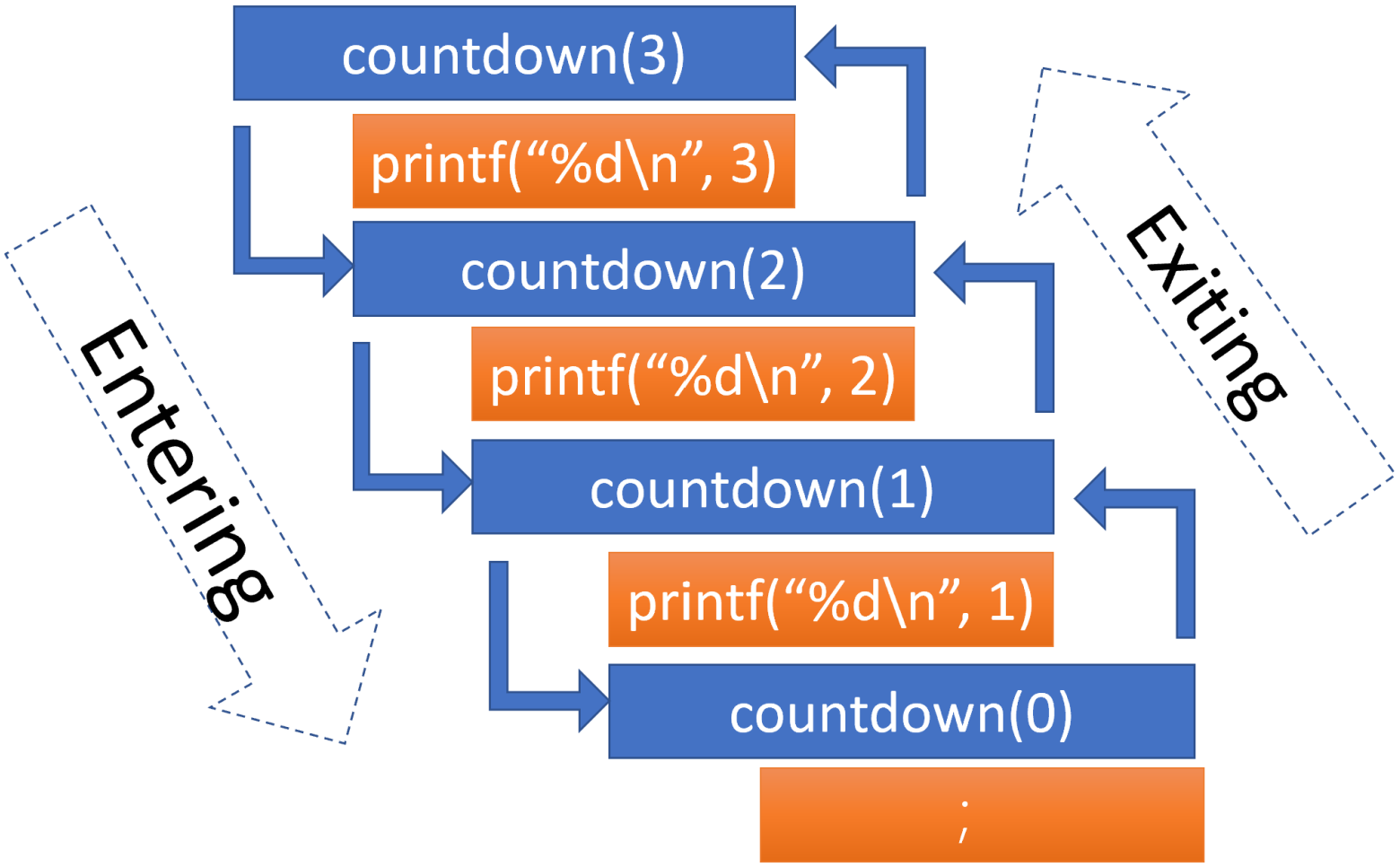
`return expression;`, will return the value of `expression`, and exit the function immediately.

Recursion and Stack Memory

Recursion

- You **cannot** define a function inside another function.
- You can **call** a function inside another function.
    - A function can call itself!

How does Recursion Work?



Memory Allocation for Functions

- When the function is being executed on the CPU, its data (such as variables declared in the function) and code are temporarily stored in the memory.
- The memory region for storing function data in the current program is called "stack".

Stack

- Stack is a data structure that the newest element is placed on top of the old elements.

Stack Memory Allocation

1. When a function is called, its data and code is added to the top of the stack.
2. CPU can only access data and code from **the top stack**.
    - It means, CPU can only access variables from the current function that is being called!
3. When a function finishes its execution, its data is removed from the stack and the space it occupies is freed for future calls of functions.

Array

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 variable_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 at the time of compilation.

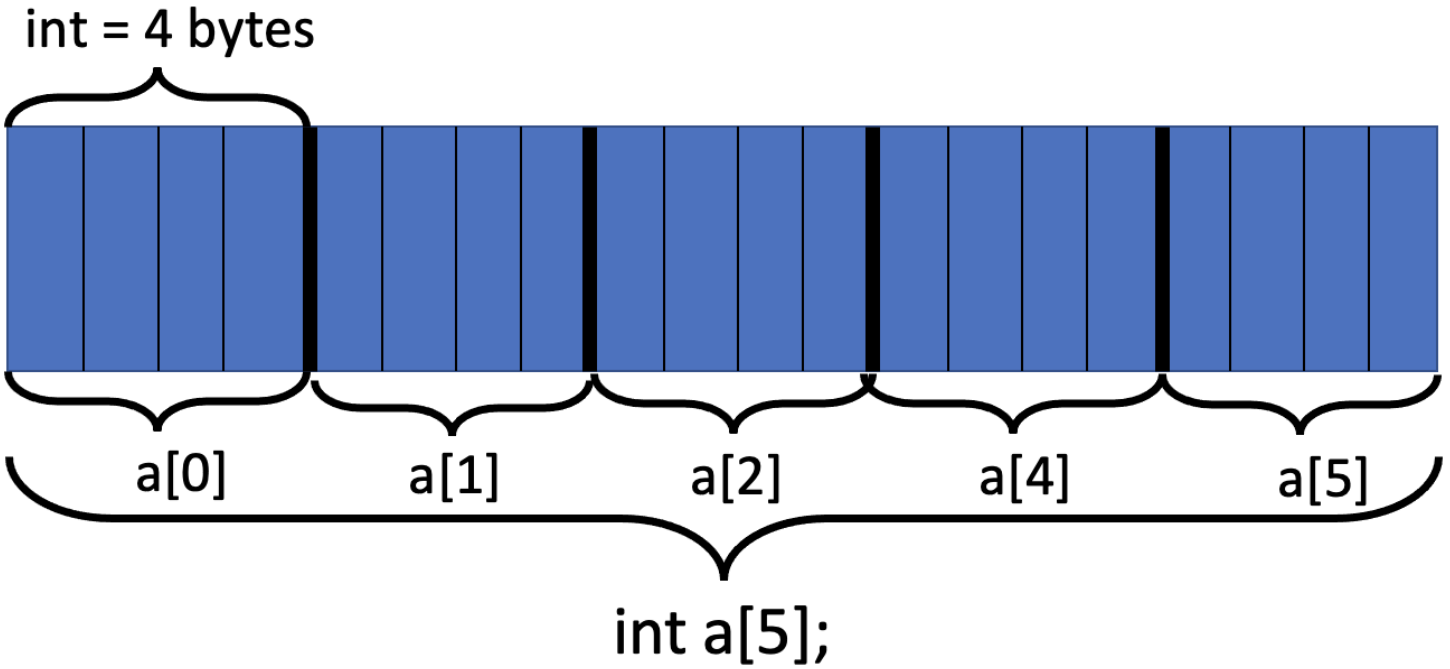
Accessing Array

- **The first element in the array is** `a[0]` .
- **The second element in the array is** `a[1]` .
- and so on.
- e.g., `a[2] = 5;` assigns 5 to **the third element** of `a` .
- You can access multiple elements using a loop:

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

Array's Memory Layout

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



Passing by Value and Passing by Reference

1. When calling a function, variables are passed to the function by creating a copy of that variable. Hence, the variable is passed by "value".
2. However, arrays are passed by reference, meaning no copies are made when passing the array.
    i. We know why in the next lecture!

Pointers

Pointer

- Pointer is a variable that **stores the address of another variable in the virtual** memory.
- Using a pointer we can access the content stored in that memory location.
    - Like index card to a book in the library.

Declare and Initialize Pointer

- A pointer itself is a variable in C, thus should be declared before use.
  - Syntax: `data_type *var_name;`
  - For example,
    - `int *pa;` declares a `int` pointer
    - `double *pb;` declares a `double` pointer.
    - `int *pa = &a;` initialize `pa` with the address of `a`.
  - `&` is the "address of" operator. `&a` gives you the virtual memory address of `a`.

`&` Operator

```c
#include <stdio.h>
void main(){
    int a = 0;
    printf("The address of a is %p.\n", &a);
    // displays "The address of a
    // is <some memory address>".
}
```

- Use `%p` to print out a pointer.

`*` Operator

- `*` is the opposite of `&`, called dereference operator.
- `*` takes the value from a certain memory address.

```
#include <stdio.h>
void main(){
    //initialize the pointer to be the address of a.
    int a = 1;
    int *pa = &a;
    int b = *pa;
    printf("My value is %d.\n", b);
    // displays "My value is 1."
}
```

Pointer and Array

In fact, in C, array name is a pointer pointing to the first element of the array!!

```c
#include <stdio.h>
void main(){
    int a[3] = {2,3,4};
    int *pa = &a[0];
    printf("%p\n", a);
    printf("%p\n", pa);
    //prints out
    // 000000c0db3ffbec,
    // 000000c0db3ffbec, the same thing.
}
```

Dynamic Memory Allocation

Stack Memory: Pros & Cons

Stack is **a highly efficient memory allocation/release mechanism**.

- You do not need to free up stack memory used by your program.
    - Operating system (OS) cleans it up for you.
- However, the amount of stack memory must be determined at the compilation time!
    - OS must know how much stack memory your program uses before your program runs!
    - Allocating memory at compilation time is called **static memory allocation**.

Dynamic Memory Allocation

- We need a mechanism to **dynamically allocate memory spaces** for variables whose sizes cannot determined before compilation.
- Memory allocation at **runtime** is called **Dynamic Memory Allocation**.
- In C programming language, variables that requires dynamic memory allocation are stored in the **heap memory** (which is a part of the virtual memory).

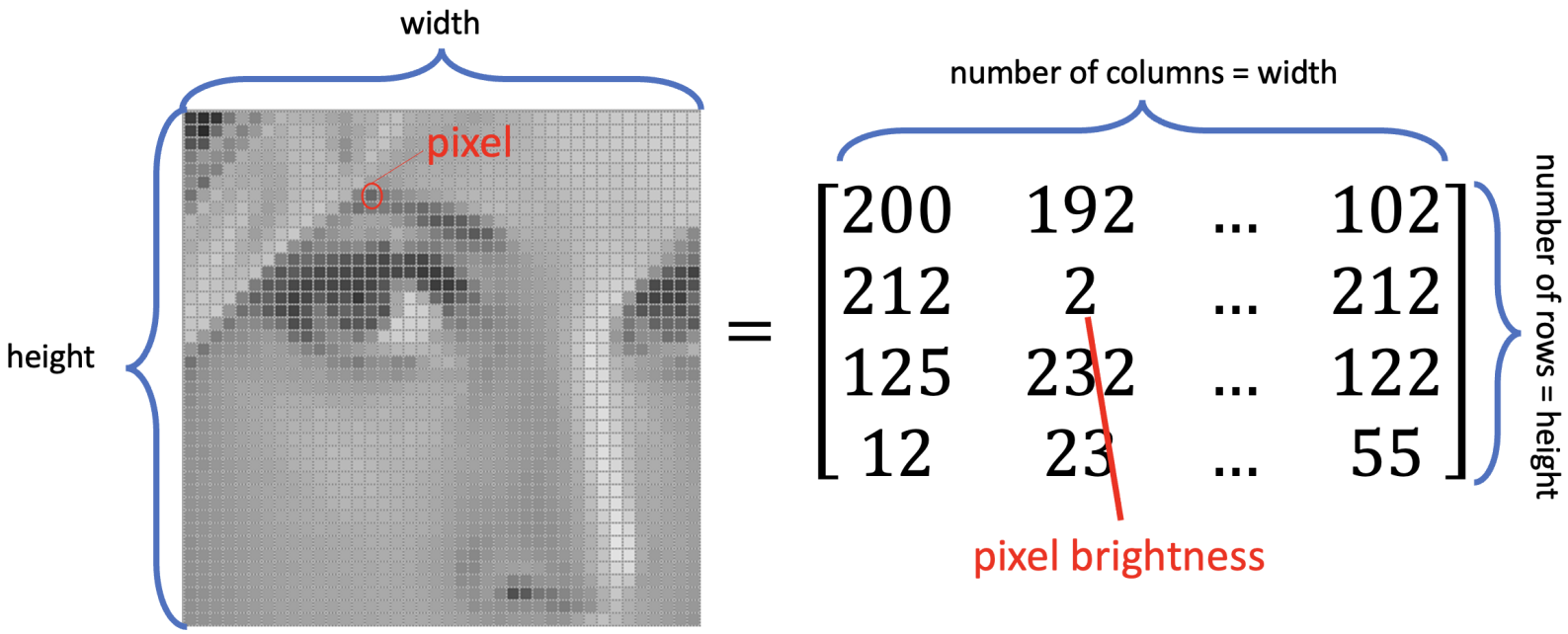
Heap Memory: Pros & Cons

- Your program can allocate heap memory to store variables while it is running.
    - The size of the allocated memory does **not** have to be known before compilation.
- However, you have to **manually allocate and free heap memory**.
    - Allocate Heap Memory, `malloc`.
    - Free Heap Memory, `free`.
    - They are provided in the **header file** `stdlib.h`.

Heap Memory Management

- `malloc`
- `free`
- `calloc`
- `realloc`

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 pixel. There are usually 256 levels of brightness, 0 is darkest while 255 is brightest.

Structure and Basic File IO

Row Major and Column Major

- Row Major and Column Major are two methods storing a matrix in an array.
- Matrix is a "2D object", you need to flatten it before storing it in a sequential container (such as an array).
- Use 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.

Grouping Variables

- Since `len1, vec1` are all variables describing the vector, we can group them together.
- Introducing a C language feature: **Structure**.
- A structure groups several related variables into **a single entity.**

Structure

- Syntax for defining a structure:

```
struct structure_name{
    data_type variable1;
    data_type variable2;
    ...
};
```

  - Do not forget the `;` at the end!

- Syntax for declaring a structured variable

```
struct structure_name struct_variablename;
```

- Syntax for referencing a sub-level variable contained in a structure variable

```
struct_variablename.variable1
```

Examples:

- Student example
- Vector example

File IOs

- `fopen`
- `fclose`
- `fgetc`
- `fputc`
- `fprintf`
- `fgets`
- `feof`