

# S3 Project Report

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## Sudoku OCR by Nord En Face

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## Contents

<b>1</b>	<b>Introduction</b>	<b>3</b>
<b>2</b>	<b>The members of Nord en Face</b>	<b>3</b>
2.1	Alexis Meunier . . . . .	3
2.2	Ilan Mayeux . . . . .	3
2.3	Augustin Hubert . . . . .	3
2.4	Aurélien Marques . . . . .	3
2.5	Yun LU . . . . .	4
<b>3</b>	<b>Task Distribution</b>	<b>4</b>
<b>4</b>	<b>Our steps for the project</b>	<b>5</b>
<b>5</b>	<b>Preprocessing</b>	<b>6</b>
5.1	GrayScale . . . . .	6
5.2	Normalize Brightness . . . . .	7
5.3	Level Pixel Intensity . . . . .	8
5.4	Gaussian Blur . . . . .	9
5.5	Sauvola Thresholding . . . . .	9
5.5.1	Adaptive Thresholding for Varied Luminosity . . . . .	10
5.5.2	Mitigating Dark Image Challenges . . . . .	10
5.5.3	Preserving Lines and Text in Thresholded Images . . . . .	10
5.5.4	Integration into Image Preprocessing Pipeline . . . . .	10
5.6	Filter : Erode/Dilate . . . . .	11
<b>6</b>	<b>Detection of the grid</b>	<b>12</b>
6.1	Sobel Edge Detection . . . . .	12
6.2	Hough Transform . . . . .	13
6.3	Line Filtering . . . . .	15
6.4	Grid Detection . . . . .	16
<b>7</b>	<b>Segmentation</b>	<b>17</b>
7.1	Image Rotation . . . . .	17
7.1.1	Manual rotation . . . . .	17
7.1.2	Automatic rotation . . . . .	17
7.2	Resizing . . . . .	18
7.3	The Downscale Average Box Fill Method . . . . .	18
7.3.1	Overview . . . . .	18
7.3.2	Benefits of the Downscale Average Box Fill . . . . .	18
7.3.3	Implementation and Optimization . . . . .	19
7.3.4	Comparison with Traditional Methods . . . . .	19
7.3.5	Visual Assessments . . . . .	19
7.3.6	Computational Efficiency . . . . .	19
7.4	Cropping . . . . .	20
7.5	Correct Perspective . . . . .	21
7.5.1	Computation of the correction matrix . . . . .	22
7.5.2	Creating the new Image . . . . .	22
7.6	Image splitting . . . . .	23
7.7	Extract Digit . . . . .	24

<b>8 Neural Network</b>	<b>25</b>
8.1 Theory . . . . .	25
8.2 Implementing the Network . . . . .	26
8.3 Saving and importing the Network . . . . .	28
8.4 Reading the MNIST database . . . . .	29
8.5 XOR Network . . . . .	30
8.6 Handwritten Digits Recognition Network . . . . .	31
8.7 The network... reborn . . . . .	31
8.8 Challenges in Sudoku Recognition . . . . .	32
8.8.1 Improved Results and Model Performance . . . . .	32
8.8.2 Conclusion and Continued Refinement . . . . .	32
<b>9 Sudoku solver</b>	<b>33</b>
9.1 Parsing . . . . .	33
9.2 Solver . . . . .	33
<b>10 Graphical User Interface</b>	<b>34</b>
<b>11 General Progress</b>	<b>38</b>
<b>12 Problems</b>	<b>39</b>
<b>13 Enhancements</b>	<b>39</b>
<b>14 Closing remarks</b>	<b>40</b>
<b>15 Conclusion</b>	<b>41</b>

## 1 Introduction

Our goal for this defense was to make almost everything that was asked for the second defense, with a few exceptions, such as :

- the GUI
- the digit recognition neural network
- optimizations (neural network + a bit for the solver)

We also tried to make our code very readable and quickly executable, that is why we have easily modifiable code that shows help commands and handles all the possible functions (More on those later).

We are very proud to present our progress up until now!

## 2 The members of Nord en Face

### 2.1 Alexis Meunier

I have started programming since high school and loved it ever since, but only this year have I started learning C. Even if it is more complex than other languages that I learned before such as Python, I find it much more interesting. I am enthusiastic about this project because it has deepened my knowledge of the C language, and allowed me to learn new algorithms that are very interesting and useful. I am a little disappointed in the quality and quantity of my work so far, especially compared to my peers, hence I will work more for the second defense so I can be proud of what I will have done !

### 2.2 Ilan Mayeux

I am wandering as Ilan Mayeux. A second-year Epita student from the A2 class. Previously from Le Bon Sauveur highschool, I learned precious knowledge during my scholarship and built a passion in computer science as a result. Neuron Networks and Image manipulations are subjects that I always tried to avoid. This project allows us to perfect our skills in C and discover new algorithms. In high school I learned about neuron network and image manipulation and I hardly understood. This round two is an opportunity for me to fight again. Yet it seems that I am once again not ready as my network implementation is forcing me to face logical bugs, the worst ones to solve. I hope I will manage to overcome all of that and proudly succeed with my team.

### 2.3 Augustin Hubert

Since I was young I always found myself solving puzzles or try to understand every algorithm/mechanism I encountered. Therefore I instantly loved my calculator Ti-82 stats.fr when I understood how to create programs on it. This was my first experience as a programmer on what was an assembly like language. Since then I how to code properly on python, c# and obviously as of today c. I was very enthusiastic to learn more about a low level programming language and even more so on how we are tasked to do an entire project in c. While I tried to understand what everyone was doing on this project, I focused myself on preprocessing and the grid detection. As last words I really liked working on the project so far and will try my best to finish it cleanly.

### 2.4 Aurélien Marques

I started programming a long time ago, back when I was in middle school (collège); Scratch was introduced to me by a friend, we made all the basic games such as platformers and mazes. I was then introduced by my friend Luc to C#, I really enjoyed it and the easily usable Unity made it even better. Thanks to classes and delegates, I felt like everything was possible. But then, an event changed my life: I learned about C, I instantly fell in love, the simplicity of the language, combined with the endless possibilities of C# showed me that anything was possible in code, it was beautiful.

When I saw that the OCR we had to do was in C, I was very happy and that's why I really enjoyed this project. My personal favorite was the neural network, even though I didn't work on it for a long time, it was still fairly enjoyable since it is mainly maths, and I really appreciate mathematics.

A fun fact about myself : I *really* like pasta

## 2.5 Yun LU

The one piece is easier to find than Yun's work.

## 3 Task Distribution

Tasks	Alexis	Aurélien	Augustin	Ilan	Yun
<b>Preprocessing</b>					
Gaussian Blur		✓			
Grayscaleing			✓		
Adaptive thresholding		✓	✓		
Sobel Edge Detection			✓		
<b>Grid Detection</b>					
Hough Transformation	✓	✓	✓		
Line Filtering			✓		
Square Detection/Selection			✓		
<b>Segmentation</b>					
Image Correction	✓				
Image Crop	✓				
Image Resizing	✓			✓	
Image Rotation		✓	✓		
Image Splitting	✓	✓			
<b>Neural Network</b>					
Gaussian distribution	✓				
Neural Network XOR				✓	
Neural Network Digits		✓		✓	
<b>GUI</b>					
GUI		✓			

Table 1: Final table of role divisions

## 4 Our steps for the project

To make the OCR work, we aimed for the following steps:

- (Optional in the GUI) Manual Rotation
- Get the image from a file, turn it into a SDL surface
- Grayscale the image and normalize the brightness
- Blur the image a bit (removes a bit of random noise)
- Apply adaptive thresholding (get binary values for pixels)
- Invert the colors of the image if necessary (we want a white grid over a black background)
- Erode the image ( get rid of isolated pixel)
- Apply sobel gradient (gives only the edges of an image)
- Apply hough transform (gets all lines on the image)
- Correct the perspective/rotation of the image according to the grid found
- Split the image into 81 sub images
- Extract the Digit part of each split image
- Feed the 81 images to the neural network 1 by 1
- Construct a new 9x9 matrix of numbers
- Feed this new matrix into the solver
- Construct a new image of the solved sudoku

## 5 Preprocessing

### 5.1 GrayScale

The grayscale algorithm is very simple; we loop through all the pixels on the image and apply a formula to that pixel:

$$\text{color} = 0.4 * \text{red} + 0.35 * \text{green} + 0.25 * \text{blue}$$

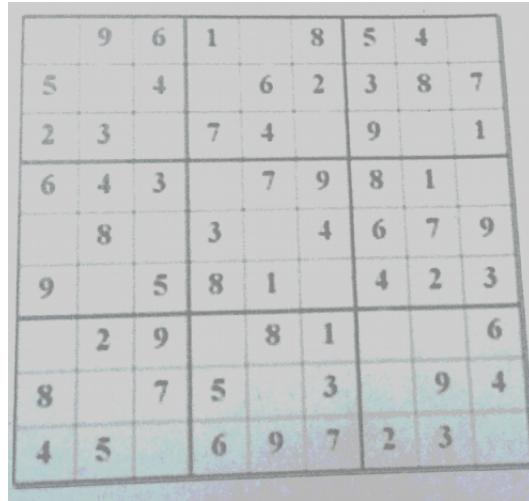


For example, we go from the top image to the bottom image using this function.

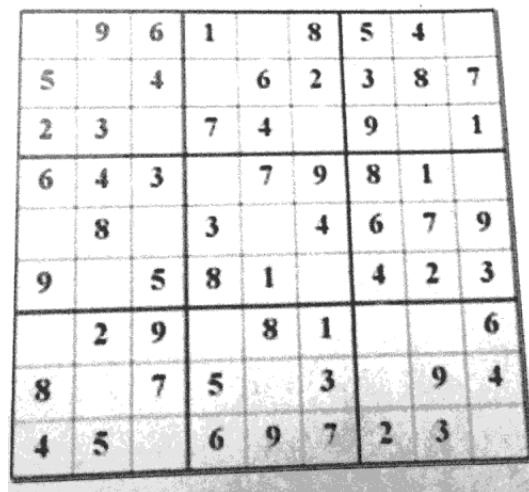
## 5.2 Normalize Brightness

The normalization function for brightness in a grayscale image is a crucial component in image processing applications. This C function is designed to take a grayscaled image as input and determine the minimum and maximum intensity values within the image. Since grayscale images have equal values for the red, blue, and green channels, the algorithm scans through the pixels to find the minimum and maximum grayscale values, ensuring they fall within the standard 0 to 255 range. Subsequently, for each pixel in the image, the function adjusts its intensity by subtracting the minimum value and then scales it using the formula  $(\text{intensity} - \text{min}) * 255 / (\text{max} - \text{min})$ . This transformation ensures that the brightness levels are normalized across the entire image, allowing for a consistent and visually appealing representation of the grayscale content.

We transform this :



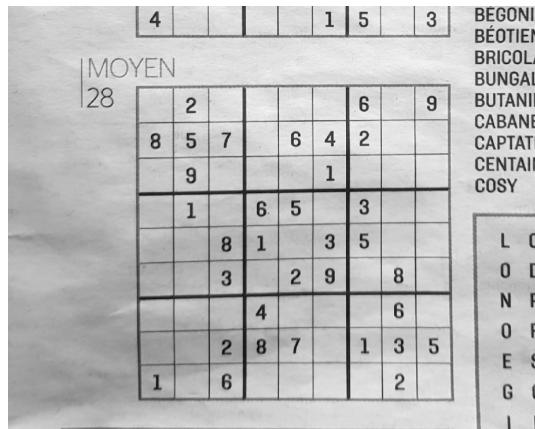
into this :



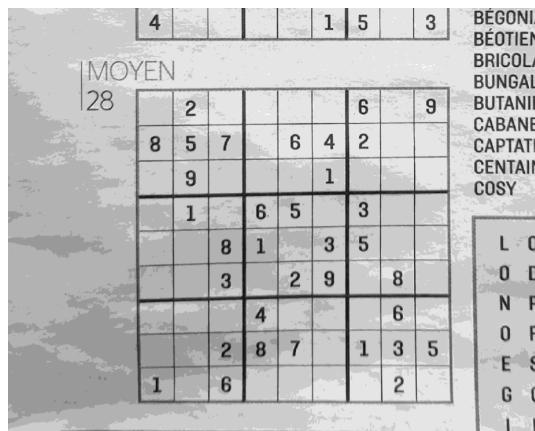
### 5.3 Level Pixel Intensity

The pixel intensity leveling function is a vital tool in image processing, particularly when dealing with images composed of a specified number of distinct colors. This C function takes the number of colors as a parameter and iterates through each pixel in the image. For each pixel, the function ensures that its intensity is clamped to the nearest multiple of (255/nbColors). This approach effectively creates distinct steps in intensity, corresponding to the different colors in the image. By clamping the pixel values to these multiples, the function introduces clear boundaries between color levels, resulting in a visually discernible and well-defined transition between different shades. This process enhances the visual representation of the image, particularly in cases where the image is composed of a limited and defined color palette.

We transform this :



into this :



In Conclusion of these first step, a lot of function where implemented and tested to get rid as much noise as possible while keeping the grid and numbers. We ended up having only with 'Normalize Brightness' and 'Level Pixel Intensity' but there was also functions to enhance gamma and also another to augment the contrast in the image.

## 5.4 Gaussian Blur

The point of this blur is to smoothen the image, and to remove a little bit of spontaneous noise. For example, if a pixel is white and is surrounded by many black pixels, it will become essentially black (the thresholding is done after so it will remove this white pixel).

To do this, the gaussian blur works by replacing each pixel by an average of the neighbouring pixels, each of which will have a weight attached to it, depending on how far this pixel is to the pixel we are setting.

The gaussian blur function takes 2 parameters, size and sigma; size controls the size of the kernel, for example, in the image below, size = 5. Sigma is used to control the steepness of the curve; a high sigma will increase the center weights and reduce the outer ones; while a lower sigma will spread out the weights.

	1	4	7	4	1
	4	16	26	16	4
	7	26	41	26	7
	4	16	26	16	4
	1	4	7	4	1

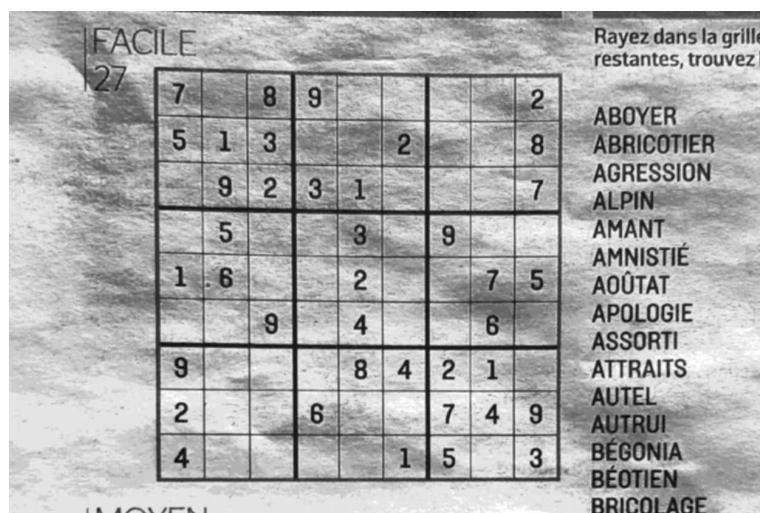
1  
273

## 5.5 Sauvola Thresholding

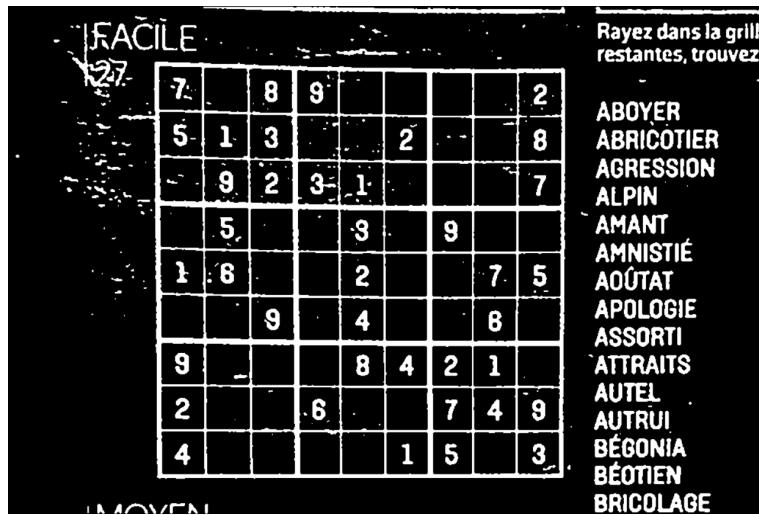
In our initial attempts at image preprocessing, we employed a basic thresholding technique that involved looping through each pixel and setting it to black if the red value was under 127, and white otherwise. While this method worked reasonably well for well-lit images, it revealed a significant limitation when applied to darker images. In such cases, the resulting thresholded image often turned nearly entirely black, leading to a loss of valuable information.

To address this issue and improve the adaptability of our image preprocessing, we turned to Sauvola thresholding, a more advanced and adaptive thresholding technique. Sauvola thresholding takes into account the local characteristics of the image, making it particularly effective in scenarios where the global thresholding approach falls short.

we've gone from :



to



### 5.5.1 Adaptive Thresholding for Varied Luminosity

Adaptive thresholding, as implemented through Sauvola's method, represents a departure from the fixed threshold used in basic thresholding. Instead of relying on a static value like 127, adaptive thresholding computes the threshold dynamically based on the average intensity of neighboring pixels. This adaptive nature ensures that the threshold adjusts to the local luminosity conditions, allowing for better preservation of details in both well-lit and dimly lit regions of the image.

### 5.5.2 Mitigating Dark Image Challenges

The primary advantage of Sauvola thresholding becomes evident when dealing with darker images that remain readable despite their reduced luminosity. Unlike basic thresholding, which tends to render dark images predominantly black, Sauvola thresholding maintains a nuanced approach. By considering the surrounding pixel intensities, it prevents the threshold from plummeting too low in darker regions, thus preserving important features and preventing the loss of crucial information.

### 5.5.3 Preserving Lines and Text in Thresholded Images

The adaptive nature of Sauvola thresholding proves beneficial not only for overall image clarity but also for preserving lines and text in the resulting thresholded images. By dynamically adjusting the threshold based on local pixel characteristics, Sauvola thresholding enhances the visibility of lines and textual elements, ensuring that crucial details remain discernible even in challenging lighting conditions.

### 5.5.4 Integration into Image Preprocessing Pipeline

Sauvola thresholding represents a pivotal component of our image preprocessing pipeline. By incorporating this adaptive thresholding method, we aim to optimize the clarity of Sudoku puzzle images, making them more conducive to subsequent digit recognition and solving processes. The adaptive nature of Sauvola thresholding aligns seamlessly with the diverse characteristics encountered in Sudoku puzzles, further contributing to the robustness of our overall solution.

**Conclusion and Future Refinements** The adoption of Sauvola thresholding in our image preprocessing stage signifies a crucial step toward addressing the challenges posed by varying luminosity in Sudoku puzzle images. The improved adaptability and nuanced thresholding offered by Sauvola's method contribute to better image quality, ultimately enhancing the effectiveness of our Sudoku solver. Moving forward, ongoing refinements may involve further optimizations of the Sauvola thresholding parameters and exploring additional techniques to bolster the overall preprocessing pipeline.

## 5.6 Filter : Erode/Dilate

Erode and dilate are morphological image processing operations commonly used for noise reduction and feature extraction. Erode works by shrinking and thinning the boundaries of objects in an image, effectively removing small details and noise. On the other hand, dilate expands the object boundaries, filling in gaps and connecting broken structures. When used in sequence, erode followed by dilate, it creates a morphological opening operation, which is effective in smoothing and cleaning up images by eliminating small unwanted elements while preserving the overall structure of larger features. This combination is often employed in image preprocessing for tasks like segmentation and object detection.

This part is fairly simple to implement, but it impacts greatly the quality of the image that can be used for later steps.

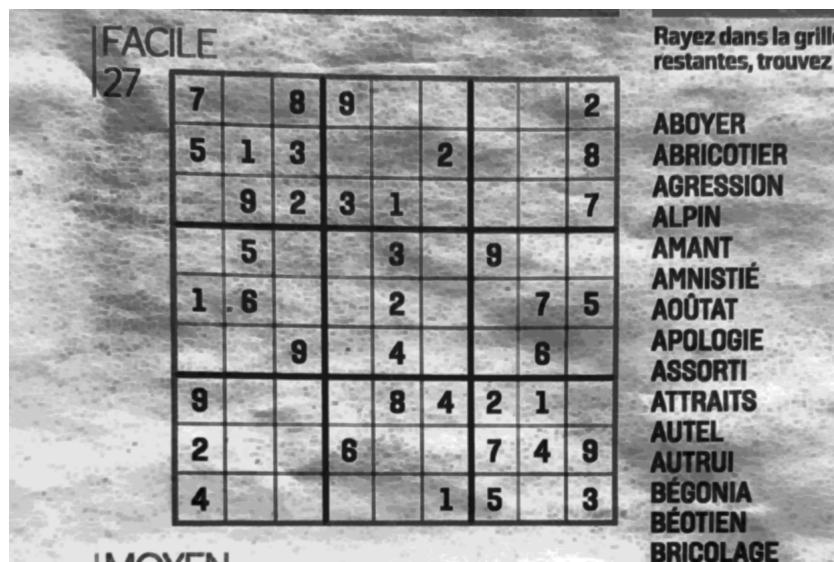


Image after Erode

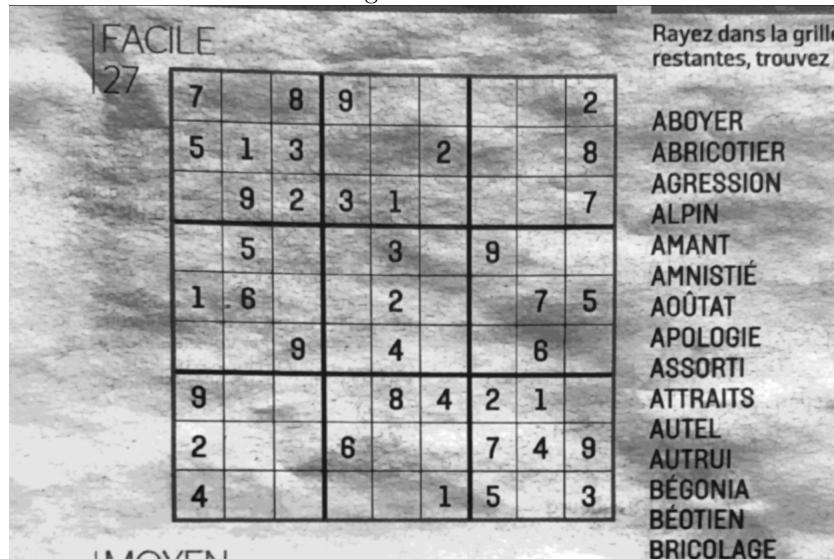


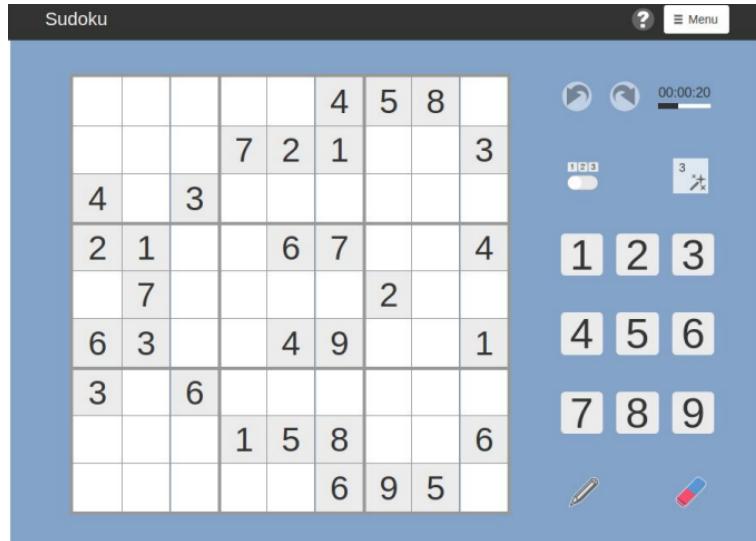
Image after Dilate

## 6 Detection of the grid

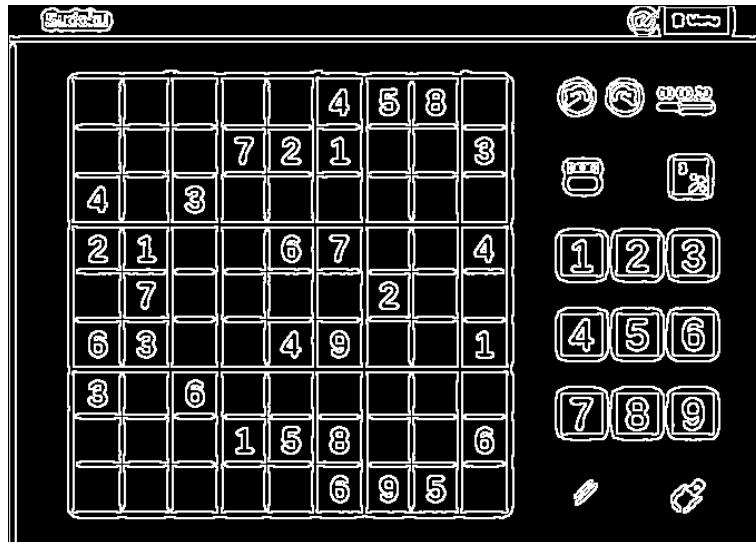
The detection of the grid was split into 3 parts, sobel, hough and the detection at the end. The goal of sobel is to find the edges of the image, hough turns those edges into lines, and then turn the lines into squares and find the best square.

### 6.1 Sobel Edge Detection

The sobel edge detection takes a black and white image and tries to find straight lines, this will, for example, turn this image :



into



The algorithm is similar to gaussian blur, but uses this kernel instead of a 2D gaussian curve.

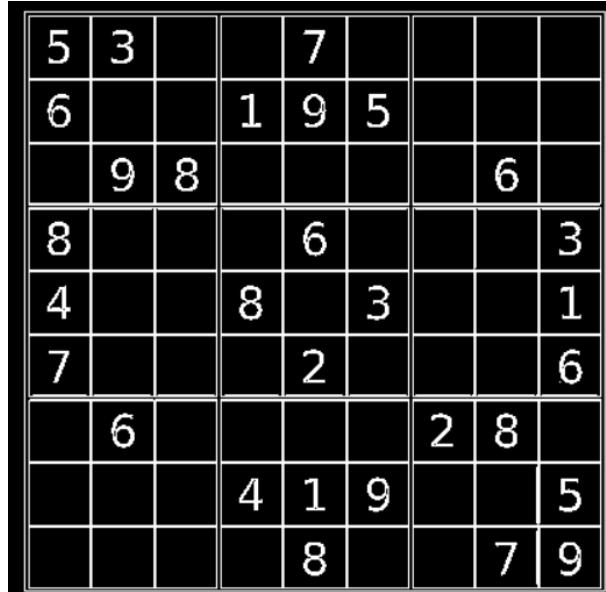
$$\begin{bmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{bmatrix}$$

The algorithm behind is trying to detect high deltas along the x and y axis in the image. Then it averages the deltas found in the x and y axis and if this value is more than 127, then the pixel of high delta is set to white.

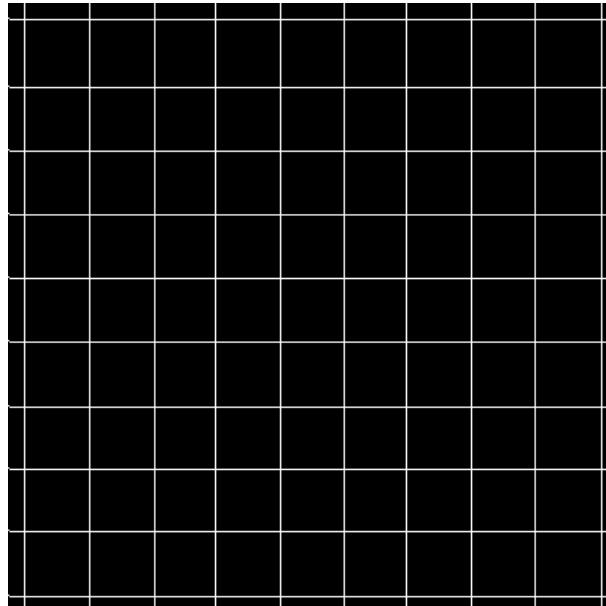
## 6.2 Hough Transform

Now comes the fun part of the grid detection, the hough transform (pronounced houg with a russian accent). This transformation is supposed to take an image and returns only lines that form this image, so for the sudoku, it will return a new image with only the grid.

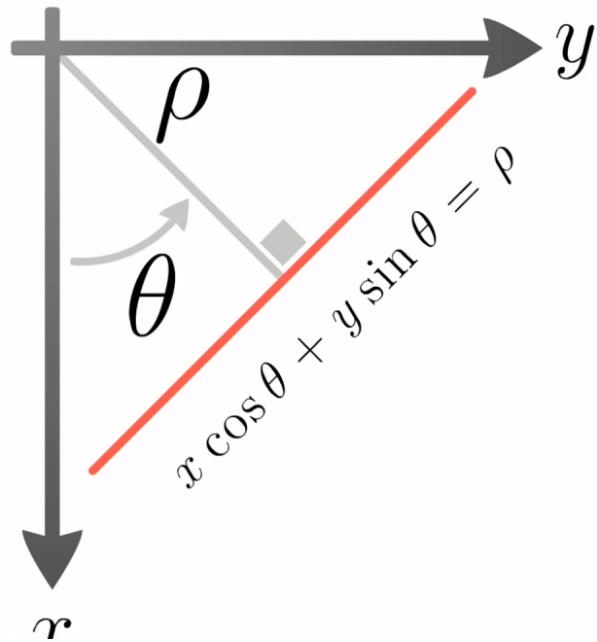
For example, it will turn an input like this :



Into this :



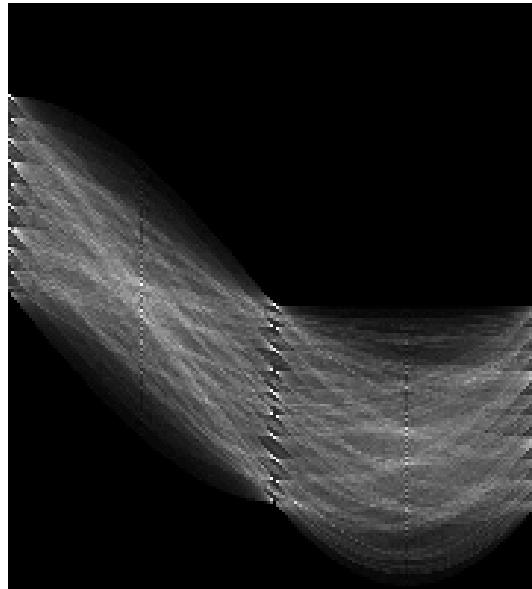
To do so, Hough uses the fact that a line, in a  $(0,x,y)$  plane, can be written as a function  $y = ax + b$  with  $a$  the slope and  $b$  the distance to the origin, which translates to  $b = -xa + y$  in a  $(0,a,b)$  plane. To find  $a$  and  $b$ , we need to use another way to express a line, which is its distance to the origin, and the angle at which it is by a perpendicular line, as can be seen in this image :



Therefore we now have a way to find each line that goes through a pixel, we then have to create an accumulator which will work as a (0,a,b) plane using a matrix. Every point of this plane represents a line in the conventional (0,x,y) plane. For example the point at coordinates (50,90) is a single line that is 50 pixels away from the origin with an angle of 90°.

Now the Function will travel through every pixel of the image, and each time a pixel is white or very close to white, it will iterate using a theta from 0 to 180 (to compute every angle), and compute a corresponding rho with the formula :  $(x * \cos(\theta) + y * \sin(\theta))$  with (x,y) the coordinates of the pixel. Doing that gives us EVERY line that goes through this point (even those we don't really care about). Then we increment the value of coordinate (rho,theta) in the accumulator.

At the end of this function, some coordinates in the accumulator have bigger values, here is the accumulator represented with every white pixel a value. The whiter the pixel the bigger the value :



This means that there are many points that have the same line going through them. Hence we found the lines we want to show, because they have the most points aligned, they will give the lines of the image as shown before.

You can think of this image as a 2D graph of a function, with the x axis being an angle going from  $-90^\circ$  to  $90^\circ$ , and the y axis being the first point hit by a ray coming out from any point, the ray is coming out at an angle x (the x axis controls the angle)

To retrieve all the important lines from the accumulator we first look for its maximum, and then gather all local maximum in the accumulator higher than a threshold being a percentage of the maximum. This will leave us with all the prominent lines in the image. As a result, the Hough Transform function gives back a linked list of line defined by a rho and a theta (lengths and angles)

It is noteworthy that due to the nature of this algorithm, it relies heavily on the input image, but is also a core part of this OCR. Meaning this function first needs close to perfect preprocessing to find a correct image with clear lines and not too much noise, but it needs to be nearly perfect itself as finding wrong lines, or not finding good lines can break the Grid detection

### 6.3 Line Filtering

Because the list of lines given by Hough Transform may vary in quality when it is used to look for quadrilateral, the list is filtered to get rid of useless lines

The first thing is that we look for each line in the list, all the lines that are similar (in angle and length), and averages them in a 'new' line. We then delete all the duplicates. This helps a lot afterwards when looking at the intersections of the lines.

To further filter out any useless lines we make an histogram of the angle of all the lines. This histogram then recompile the number of lines per angle. We then find the maximum, such angle is then considered the angle of grid. Thus all lines that are not sufficiently parallel or perpendicular to this angle are discarded.

## 6.4 Grid Detection

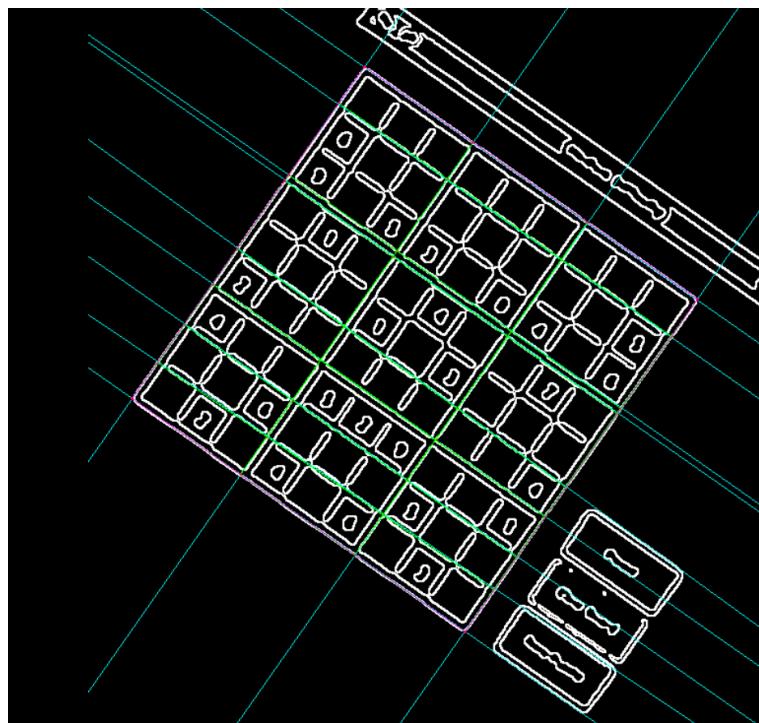
First, to detect the grid, we had to detect every square (or shape that vaguely looks like a square) in the image, only using a line list. To do that, we used 4 nested for loops, which will check for every 4 tuple of lines (without duplicates) if they form a square. If they do, we add that square into a linked list.

Once we have a quad list, we calculate a ratio for each quad according to its:

- area, (since we are looking for the largest quad)
- "squariness" of the quad (the ratio between the its smallest and biggest side )

We then pick the square which is the largest, but at the same time it must be very close to a square.

These functions took a lot of time to write, but at the end, thanks to good visualizing scripts to help test, they work pretty well.



Here the cyan represent all the lines found, the green represent all the quads found, and the magenta is the biggest square found (not very visible but it is correct!)

## 7 Segmentation

Having found our grid, the hardest part has been done, but we still need a little more work to adapt the image since we have to rotate the image to make it not sideways, that way the digit recognition would be easier and correct more often. Furthermore we need to crop the wanted Quadrilateral since it is the sudoku grid we are looking for, and we only need the grid and not outside shapes. We also need a resizing algorithm for the neural network, and a perspective correction for images that have been taken sideways or at weird angles. Lastly we need to split the image in 81 squares for each squares of the sudoku to give it to the neural network so it can find the corresponding value for the solver.

### 7.1 Image Rotation

#### 7.1.1 Manual rotation

To rotate an image, we first had to be sure of what we wanted to rotate. Since we are using SDL to handle images, we decided to use SDL surfaces; they are fairly easy to manipulate and hold an array of pixels (Uint32's). So, we first had to understand how to represent rotations mathematically, fortunately for us, it could be found easily on the internet :

$$x' = x \cos \theta - y \sin \theta$$

$$y' = y \cos \theta + x \sin \theta$$

So, for each pixel on the original image, we added the same pixel at the new coordinates, using theta as a parameter of the function. However, this had the downside of sometimes mapping 2 different pixels to the same new pixel. On top of that, there would be blank pixels (no pixel maps to it).

To deal with all these problems, we decided to change our view on the problem: instead of searching for the "image" of each pixel on the original image, we could search the "preimage" of each pixel on the new image. Thanks to this, every pixel was filled with a pixel from the original image, apart from the out of bounds pixels, which appear on the corners of the image (but these can be filled with black easily).

We also had some issues with angles that were too big, it was because we forgot to put an absolute value for the height and width of the rotated image, leading the image to shrink after each rotation, eventually leading to a segmentation fault. The fix was easy and it has been corrected since.

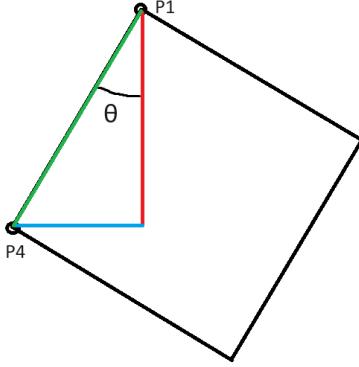
#### 7.1.2 Automatic rotation

To rotate automatically an image, we first had the following idea, we can create a function FindSkew which would give a number (int) to every image, this number would try to represent the amount of rotation it has, the higher the number, the closer to being correct it is.

Our first idea was to make a function which loops through all pixels, and if a pixel is white (filled), it checks its four neighbours; if its top or bottom neighbours are also white, then we add 2 to a global counter, if the left or right pixels are white, we remove 1.

This should try to give bigger numbers if most lines are vertical on the image. This, however, is not a very robust system since a large vertical bar (which is not part of the sudoku grid) on the sides of the image can very easily create large numbers, even though the image is rotated.

In the end, with the system not being robust enough (and after another few failed attempts at rotation), we decided to try to make the rotation work with the grid we found. After the square detection we have a quadrilateral (from the struct Quad), since we have all 4 corners, and the first corner is sure to be the top left one, we can check which rotation will have the least angle (since we assumed that the rotation would be less than 45° by default thanks to the manual rotation at the start. The rotation is then straightforward using a bit of mathematics/trigonometry.



We know that  $\cos(\Theta) = \frac{\text{adjacent}}{\text{hypotenuse}}$  which implies  $\Theta = \arccos\left(\frac{\text{adjacent}}{\text{hypotenuse}}\right) = \arccos\left(\frac{|p1.y-p4.y|}{\sqrt{|p1.y-p4.y|^2+|p1.x-p4.x|^2}}\right)$   
Now that we have a double, we can simply rotate with the value found :)

## 7.2 Resizing

The resizing algorithm is very important because the neural network only accepts 28x28 images, hence the need to resize. It wasn't really challenging, yet we had to implement 2 different algorithms.

The first algorithm was extremely simple (which is also why we needed to change it, because its simplicity brought wrong outputs with it ...).

When resizing an image, we can compute the scaling of the input image to the output image with :

$$\text{width\_scale} = \frac{\text{inputwidth}}{\text{outputwidth}} \text{ and } \text{height\_scale} = \frac{\text{inputheight}}{\text{outputheight}}$$

Now that we have the scalings, we can compute the coordinates of each pixels in the new image with the formula  $\text{newImage}[x][y] = \text{Image}[x * \text{width\_scale}][y * \text{height\_scale}]$ .

Tho as said previously, the output did work sometimes but not most of the time, leaving us with terrible outputs.

## 7.3 The Downscale Average Box Fill Method

The algorithm that has proven to be consistently reliable for our image scaling requirements is aptly named the "Downscale Average Box Fill" method. This approach diverges from traditional scaling techniques and introduces a novel strategy that not only ensures accuracy but also enhances the visual appeal of the scaled images.

### 7.3.1 Overview

At its core, the Downscale Average Box Fill method revolves around the concept of calculating the average pixel color within a designated box, offering a more refined and smoothed representation of the image during downscaling. The algorithm operates by iterating through the pixels of the output image, calculating the average color within a box of dimensions  $\text{newWidth} \times \text{newHeight}$ . This box is positioned around the current pixel, and the process continues horizontally until reaching the boundary defined by  $x + \text{newWidth} > \text{width}$ . Subsequently, the algorithm moves to the next row by incrementing  $y$  by  $\text{newWidth}$ .

### 7.3.2 Benefits of the Downscale Average Box Fill

The Downscale Average Box Fill method presents several advantages that contribute to its effectiveness and reliability in image scaling:

**Smoothing Effect:** By calculating the average pixel color within a box, the algorithm introduces a smoothing effect to the scaled images. This is particularly beneficial when dealing with high-resolution images that may exhibit jagged edges or abrupt transitions during traditional scaling.

**Artifact Reduction:** The method significantly reduces artifacts that may arise during downscaling, such as aliasing or color distortion. The averaged color values contribute to a more coherent and visually pleasing representation of the original image.

**Correctness Assurance:** Unlike some conventional scaling methods that may compromise the accuracy of pixel values, the Downscale Average Box Fill ensures correctness in the resulting image. The calculated average color serves as a robust representation of the pixel values within the specified box.

### 7.3.3 Implementation and Optimization

Implementation of the Downscale Average Box Fill involves careful consideration of the box dimensions, balancing between achieving a smoothing effect and maintaining the integrity of the original image. Additionally, optimizations can be explored to enhance computational efficiency without sacrificing the quality of the scaled images.

### 7.3.4 Comparison with Traditional Methods

To further underscore the efficacy of the Downscale Average Box Fill method, a comparative analysis with traditional scaling techniques, such as bilinear interpolation or nearest-neighbor interpolation, can be conducted. This evaluation will highlight the unique advantages and superior performance of our chosen algorithm.

To substantiate the claims regarding the Downscale Average Box Fill method's effectiveness, a series of experiments were conducted, comparing the scaled images produced by our algorithm with those generated using traditional methods. The analysis includes visual assessments, quantitative metrics, and considerations of computational efficiency.

### 7.3.5 Visual Assessments

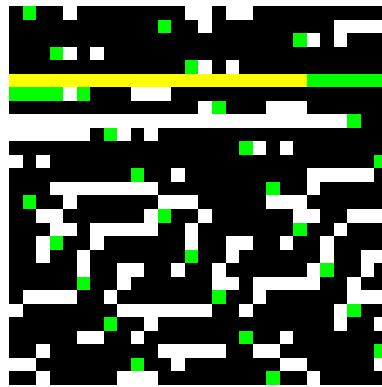
Visual comparisons between the images obtained through the Downscale Average Box Fill method and traditional scaling methods reveal the nuanced improvements achieved by our algorithm. The smoothed transitions and reduced artifacts become apparent, particularly in regions with high-frequency details or abrupt color changes.

### 7.3.6 Computational Efficiency

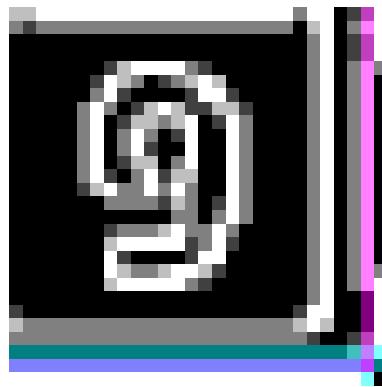
In addition to quality considerations, the computational efficiency of the Downscale Average Box Fill algorithm is evaluated. This assessment involves analyzing processing times and resource utilization, comparing them with traditional scaling methods to gauge the algorithm's practicality for real-time applications or large-scale image processing tasks.

In conclusion, the Downscale Average Box Fill method stands out as a robust and effective solution for image scaling. Its unique approach, focusing on the calculation of average pixel colors within specified boxes, results in visually pleasing and accurate scaled images. The experimental results and analyses presented in this section provide a comprehensive validation of the algorithm's performance.

we went from this :



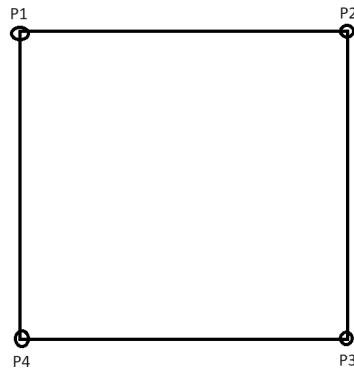
to this :



## 7.4 Cropping

Now that we have found the grid, we want to get rid of anything that is not it. Hence the use of the crop function (although we stopped using it after, more on that later).

The FindGrid() Function that we wrote returns a Quadrilateral\* with 4 points. The function was coded so that the Quadrilateral looks like that :



hence, we could use the Function to compute the angle of rotation, leaving us with a grid that is the correct way. And then the easy part was creating a new image of  $width = p2.x - p1.x$  and  $height = p4.y - p1.y$  and copying every pixel from  $p1.x$  to  $p2.x$  and  $p1.y$  to  $p4.y$ .

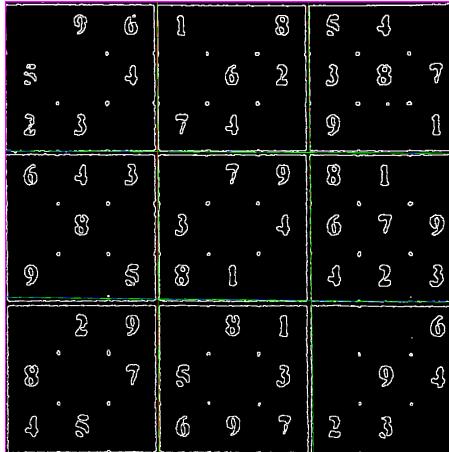
## 7.5 Correct Perspective

We mentioned previously that we didn't need the Cropping function anymore, and that is because we have found a better algorithm to do it, alongside correcting the image.

This algorithm should be able to take a skewed image and "flatten it". For example from this :



to this :



To Implement this algorithm, a lot of mathematics were needed. First we needed matrices, but we had already created a structure for them for the neural network, making it so we won a bit of time. Secondly, we had to implement functions to compute the determinant and to compute the inverse of a Matrix. Surprisingly, these functions were the hardest part to implement, given the correcting algorithm is mostly hardcoded matrices. The determinant is computed using the basic formula given by :

$$\begin{aligned}
 |A| &= \begin{vmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{vmatrix} \\
 &= A_{11} \begin{vmatrix} A_{22} & A_{23} & A_{24} \\ A_{32} & A_{33} & A_{34} \\ A_{42} & A_{43} & A_{44} \end{vmatrix} - A_{21} \begin{vmatrix} A_{12} & A_{13} & A_{14} \\ A_{32} & A_{33} & A_{34} \\ A_{42} & A_{43} & A_{44} \end{vmatrix} \\
 &\quad + A_{31} \begin{vmatrix} A_{12} & A_{13} & A_{14} \\ A_{22} & A_{23} & A_{24} \\ A_{42} & A_{43} & A_{44} \end{vmatrix} - A_{41} \begin{vmatrix} A_{12} & A_{13} & A_{14} \\ A_{22} & A_{23} & A_{24} \\ A_{32} & A_{33} & A_{34} \end{vmatrix}.
 \end{aligned}$$

Except, in our case, we're dealing with (9,9) matrices, making the computation much longer with a lot more recursive calls.

For the computation of the inverse we simply find the identity matrix by dividing the whole row by the first value different from 0, making the first value different from 0 a 1, and then subtracting Rows together, which at the end gives us the identity, and for every step we do for the first matrix, we apply it to the identity matrix which will then become the inverse of the first matrix.

We've finished presenting the matrix computations, so let us explain the actual correction matrix :

### 7.5.1 Computation of the correction matrix

This algorithm will take in parameter 2 Matrices with coordinates:

$$\begin{aligned} m1 &= ((x1,y1),(x2,y2),(x3,y3),(x4,y4)) \\ m2 &= ((x1',y1'),(x2',y2'),(x3',y3'),(x4',y4')) \end{aligned}$$

with the points in m1 the four corners of the original image, and the ones in m2 the corners of the desired image. We then need the (9,9) matrix represented by :

$$\begin{bmatrix} -x_1 & -y_1 & -1 & 0 & 0 & 0 & x_1x'_1 & y_1x'_1 & x'_1 \\ 0 & 0 & 0 & -x_1 & -y_1 & -1 & x_1y'_1 & y_1y'_1 & y'_1 \\ -x_2 & -y_2 & -1 & 0 & 0 & 0 & x_2x'_2 & y_2x'_2 & x'_2 \\ 0 & 0 & 0 & -x_2 & -y_2 & -1 & x_2y'_2 & y_2y'_2 & y'_2 \\ -x_3 & -y_3 & -1 & 0 & 0 & 0 & x_3x'_3 & y_3x'_3 & x'_3 \\ 0 & 0 & 0 & -x_3 & -y_3 & -1 & x_3y'_3 & y_3y'_3 & y'_3 \\ -x_4 & -y_4 & -1 & 0 & 0 & 0 & x_4x'_4 & y_4x'_4 & x'_4 \\ 0 & 0 & 0 & -x_4 & -y_4 & -1 & x_4y'_4 & y_4y'_4 & y'_4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Let's call this matrix P. We're looking for  $PH = 0$ ; with  $h_9 = 1$  we then know that

$$PH = \begin{bmatrix} -x_1 & -y_1 & -1 & 0 & 0 & 0 & x_1x'_1 & y_1x'_1 & x'_1 \\ 0 & 0 & 0 & -x_1 & -y_1 & -1 & x_1y'_1 & y_1y'_1 & y'_1 \\ -x_2 & -y_2 & -1 & 0 & 0 & 0 & x_2x'_2 & y_2x'_2 & x'_2 \\ 0 & 0 & 0 & -x_2 & -y_2 & -1 & x_2y'_2 & y_2y'_2 & y'_2 \\ -x_3 & -y_3 & -1 & 0 & 0 & 0 & x_3x'_3 & y_3x'_3 & x'_3 \\ 0 & 0 & 0 & -x_3 & -y_3 & -1 & x_3y'_3 & y_3y'_3 & y'_3 \\ -x_4 & -y_4 & -1 & 0 & 0 & 0 & x_4x'_4 & y_4x'_4 & x'_4 \\ 0 & 0 & 0 & -x_4 & -y_4 & -1 & x_4y'_4 & y_4y'_4 & y'_4 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} h1 \\ h2 \\ h3 \\ h4 \\ h5 \\ h6 \\ h7 \\ h8 \\ h9 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$

hence  $H = P^{-1} * R$ . Thanks to the inverse Function we can compute  $P^{-1}$ , and we can return  $H^{-1}$ . This function is mostly hardcoded, especially with the huge matrix, but it was still quite hard because the implementation was very long and fastidious, and it was hard to see clearly every value, and the very first errors we had were because we had put the values wrongly because it was so hard to see.

### 7.5.2 Creating the new Image

The first step of this function is to create m1 for the first function., we then compute the distance between p1 and p2, p2 and p3, p3 and p4, p4 and p1, then we take the maximum of each distances and create a Matrix with values 0,0,max,0,0,max,max,max. We then Compute the correcting matrix from the last function with parameter m1 and the new matrix. Then comes the fun part :

Looping i from 0 to max then j from 0 to max, we create a (1,3) matrix with values i,j,1 which are the old coordinates, we then multiply the correction matrix with the matrix of the old coordinates :

$$\begin{bmatrix} \alpha' \\ \beta' \\ \gamma' \end{bmatrix} = \begin{bmatrix} \alpha_1 & \alpha_2 & \alpha_3 \\ \beta_1 & \beta_2 & \beta_3 \\ \gamma_1 & \gamma_2 & \gamma_3 \end{bmatrix} \cdot \begin{bmatrix} x_i \\ y_i \\ 1 \end{bmatrix}$$

Lastly we just need to compute the new\_x and the new\_y with  $new\_x = newCoordinates[0]/newCoordinates[2]$  and  $new\_y = newCoordinates[1]/newCoordinates[2]$ . The last step is just copying the pixel at the good indexes.

This algorithm was extremely necessary and helpful, because not only does it process the image in some sense, "flattening" an otherwise curved image, but it also crops the image where we had previously found the grid AND it rotates it. Even if the hardcoded part was extremely time consuming and otherwise unfun to write, the result is a function that allows to do 3 things at once and works mostly perfectly.

## 7.6 Image splitting

For the spitting part of this project, we had to split an image which was assumed to be of the right scale into 81 subimages, which would then get treated individually by the neural network.

This task had us struggle quite a bit since we first tried to use malloc to create a list of matrices of pixels. Unfortunately, Alexis and Aurelien started the splitting before the lecture about malloc, so we did not really understand how/when to free, how malloc really worked, and had no idea calloc and realloc existed. Our code was not very good and had many memory leaks as a consequence.

The first version (which did not work) used a pointer to 81 pointers of Uint32. It worked by iterating from 0 to 9 for an i and a j, then creating a pointer to Uint32, and iterating over a ( $h = i * height; h < (i+1) * height / 9; h += width$ ) and a ( $w = j * width / 9; w < (j+1) * width / 9; w ++$ ) and then setting the pixel of the pointer to the  $(h + w)^{th}$  pixel of the original image.

This didn't make any sense ? Well it didn't make any sense for us either, and for the computer either apparently because we got the most monstrous image known to mankind as a result. At first we tried debugging it, changing values, changing something, hoping it would miraculously give us correct images and no segmentation faults but to no avail. Well, the values are so weird, what could we hope for, we're not even sure why we did it like that. Hence, after a few weeks (after the lecture about malloc), we revisited the code to make it work (we managed to remove the use for malloc completely) without any memory leaks or issues.

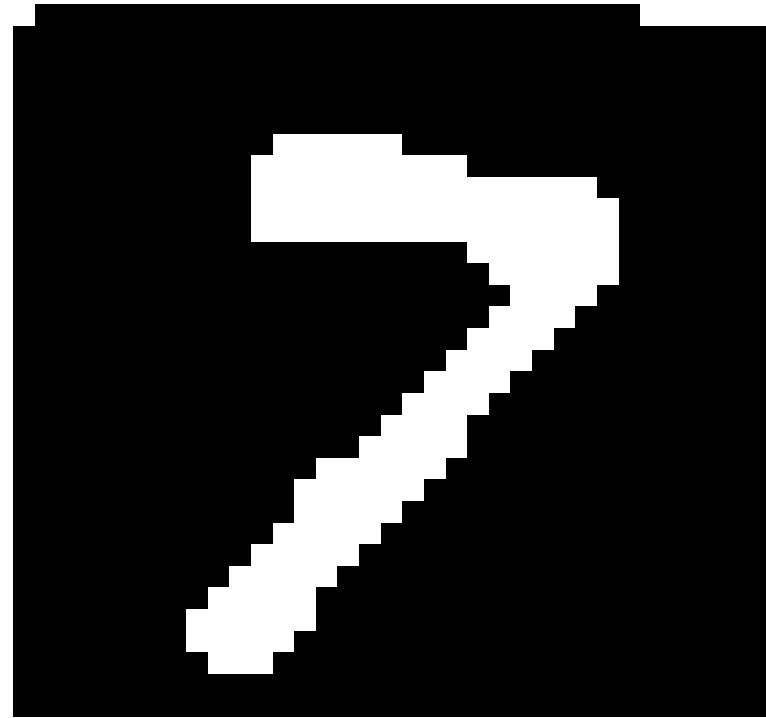
After some cleaning up, the code works with two nested loops which both loop from 0 to 9 ( $i < 9$ ), and for each of those, we loop through 1 ninth of the width and height, which makes it so we loop through the whole image, but segmented into 81 loops, we can then create new images and save them in a path, to which we add an index (path\_01 - path\_81)

## 7.7 Extract Digit

The goal of digit extraction was to turn an image like this:



Into an image like this:



To do so, we start in the middle of the image, and expand outwards, when we find a white pixel, we start the following algorithm. expand outwards, if we discovered any new white pixels, repeat if we didn't find anything new, stop there.

The issue with this algorithm is that if the number is close to the border, the whole image will be taken, but we honestly have no idea how to detect a number in a better/more robust way.

## 8 Neural Network

### 8.1 Theory

In order to recognize the digits written on the Sudoku, a neural network is necessary as handwritten digits are not all the same. The Sudoku contains digits from 0 to 9 and, fortunately, composed digits are not part of it. This means it is unnecessary to try to recognise negative numbers or numbers above 9. This simplifies a lot the problem. You may wonder why not simply write a code to "guess" what digit is written? The idea makes sense. Yet, how? Recognizing digits is something natural for us, human. But how to write a code that does that? Hard coding everything? It would most probably finish into a terrifying spaghetti code that does not work. Hence, Neuron Network is a solution to these kind of problems where written a solution is out of the scope of a mathematical representation of a problem.

A Neural Network is a structure made of neurons. A neuron is a representation that holds a bias and have weights for each input it has. When given inputs, it gives out an output. We call them perceptrons.

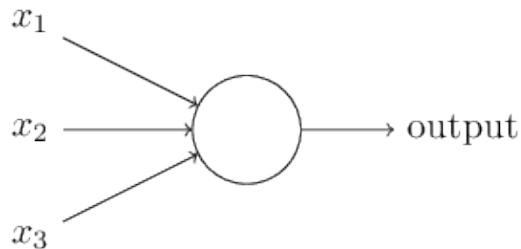


Figure 1: A perceptron with three inputs

Perceptrons alone are meaningless. It is like a brain neuron. It goes by hundreds to finally start playing a role. Hence, a neural network is composed of layers with a certain number of neurons in each. Each neuron of a layer is connected with the previous one and the next one. A neural network is travelled from left to right and, unlike the human brain, each layer is visited once. There are no loops.

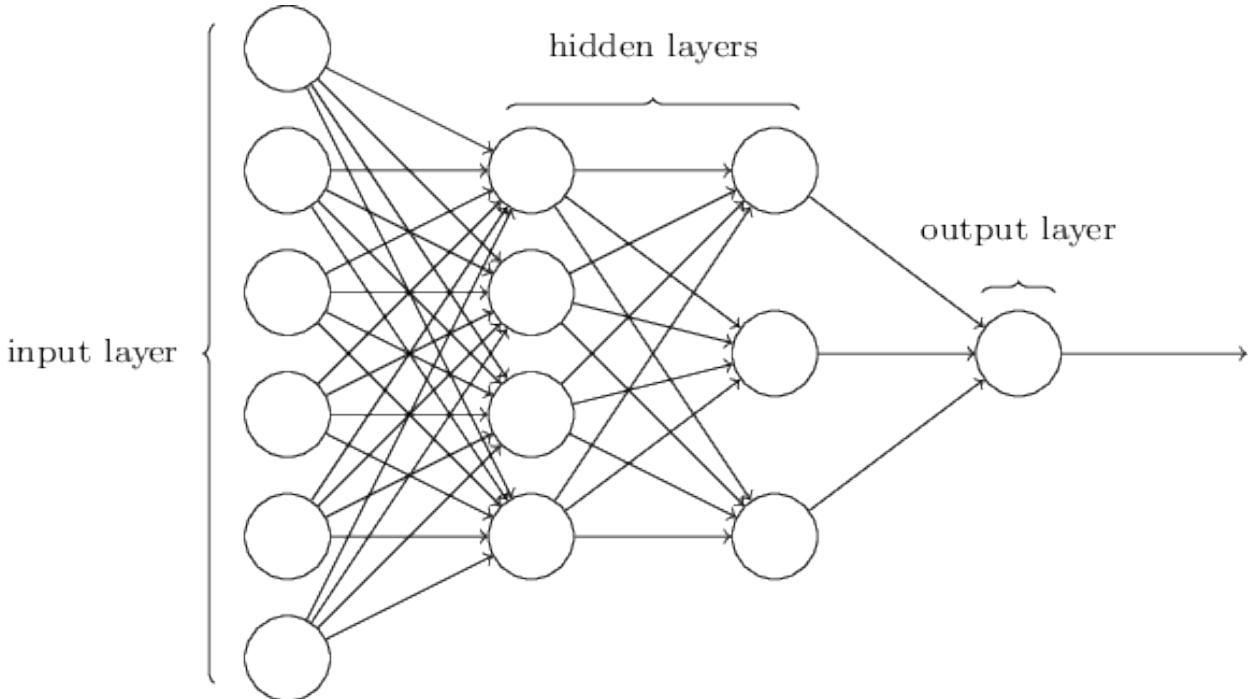


Figure 2: A neural network with four layers 6, 4, 3, 1

The input layer is what we want to feed to our network. In our case, the image to analyze It has no weights nor biases. The output layer is the answer, what digit it thinks it is. The hidden layers are intermediate layers that are here just to give more output possibilities, hence sometimes better results. Each neuron compute its output by adding the product of the input neuron and its corresponding weights and after adding the bias.

The difficult part is to attribute each neuron the perfect weights and bias so that, in the end, it gives the expected output. This process is called the training part. We will feed the network with many inputs and compare the output with what we expected. Then, modify a little each neuron so that it gets closer to the value it should have had at each step. This process is called the backpropagation algorithm. The learning rate is what decide how much the value changes to get closer to what it should be.

In our case, this training data will be the MNSIT database. A huge database with 60 000 images containing handwritten digits images and their corresponding value and 10 000 test images to test our neuron network at each step. The images are in 28 by 28 pixels.

Since the database is using a format of 28x28, we will try to do the same to keep the consistency of our training data and test data. Hence, the pre-processing part will have to handout a resized digit image in 28x28, which means that the input layer will be made of 784 neurons. One neuron for each pixels of the image, with the value being between 0 and 1, representing the black and white degree. You may think that the output will be made of 1 neuron. However, we expect 10 different digits. We would have 4 neurons and play with the binary to decide which digit is up. But the best solution remains having 10 different neurons, and the index of the maximum output being the represented digits.

## 8.2 Implementing the Network

Implementing the network is a difficult task. We are starting from 0, only with a simple math library provided by the standard C library. To simplify and fasten the calculations, we will be working with matrices. Each layer will have a matrix of weights and biases. If  $m$  is the number of neurons in the layer  $l$  and  $n$  the number of neurons in the previous layer,  $l - 1$ , then the matrix of weights of the layer  $l$  is of size  $m \times n$  and a matrix of biases of size  $m \times 1$ .

Therefore, we need to implement many functions to simplify the usage of these matrices such as matrix multiplications, additions, transpose, etc. The first implementation chosen was simply a heap-allocated array of size  $m$  of heap-allocated array of size  $n$  to represent the matrix where a value could simply be accessed with  $[i][j]$ , with  $0 \leq i \leq m$  and  $0 \leq j \leq n$ . However, it was difficult to work with as we had to not make any mistakes with the sizes of the matrix for the operations. This is were comes the upgrade of the matrix. A structure that holds both the matrix and its size.

```
typedef struct Matrix
{
    double **matrix;
    size_t m;
    size_t n;
} Matrix;
```

This structure holds all the necessary data and could then easily be used. The other functions were simply upgrade with a version 2 that calls the version 1. For example:

```
/** 
 * Calculate matrix product
 * If A is an m * n matrix
 *      B a n * p matrix
 * then AB is a m * p matrix
 * AB is allocated in the memory
 * 1d array as 2d
 */
double **dot_2d(double **a, size_t m, size_t n, double **b, size_t p);
Matrix *dot_2d2(Matrix *a, Matrix *b);
```

It is easy to see that the second version is easier to use than the first one, 2 parameters versus 5. The same was done for the other methods which then lead to a stronger base.

With a strong helper file, we could hence start writing the network code. At first, the structures used were the following:

```
typedef struct NN_Neuron
{
    // Number of input connections to this neuron from the previous Layer
    // Also determine the number of weights
    size_t num_inputs;

    // Used to basculate the output
    double bias;

    // The array of weight from w_1 to w_n to determine the output value of the
    // neuron
    double *weights;

} NN_Neuron;

typedef struct NN_Layer
{
    size_t num_neurons;

    // array of pointers of neurons
    NN_Neuron **neurons;
} NN_Layer;

typedef struct NN_Network
{
    size_t num_layers;

    // array of pointers of layers
    NN_Layer **layers;
} NN_Network;
```

This was the one used until reaching the back-propagation algorithm part. It was starting to be difficult to handle them and the code was messy or useless transformations were made. It was however very easy to manipulate and at least, very clear. We changed and later on, moved to the one used in the book *Neural Networks and Deep Learning* by Michael Nielsen.

```
typedef struct NN_Network
{
    size_t num_layers;

    // contains the number of neurons in the respective layers
    size_t *sizes;

    // A bias for each neuron in each layer in the network
    // a matrice [layer, neuron, singleton]. Singleton is a list of length 1
    // (for matrix multiplication purpose)
    Matrix **biases2;

    // A weight for each neuron in each layer in the network
    // a matrice [layer, neuron, weights]
    Matrix **weights2;

} NN_Network;
```

This implementation uses matrices a lot. `biases2` and `weights2` are both arrays of matrices. Since the input layer has none of them, it is an array of size `num_layer - 1`. Many methods were created to manipulate this structure, such as creating it and freeing it. To create a network, you simply need to specify how many layers there are and an array that contains the number of neurons in each, input layer included. There are two main functions that have to be retained: the Feedforward and the Scalar Gradient Descent (also called SGD).

The feedforward is what will calculate the output of the network. It takes a network and an input matrix that will act as the input layer. As an output, it will give back a matrix. In our case, the input will be a matrix of size  $784 \times 1$  and the output  $10 \times 1$ . Each neuron will determine its output based on the inputs, weights and bias until reaching the end. You could then determine what digit is it by applying the "argmax" function to the output matrix, which gives back the index of the maximum in the matrix.

The Scalar Gradient Descent is the function called to train the network. It takes as parameter the given network, the training data and its size, the number of epochs, the batch size, the learning rate and the test data and its size. The training data is what was mentioned in 6.1 with the MNIST database of size 60 000. Same for the test data, the 10 000 samples. The number of epochs is the number of time the whole data-set is tested. For example, 200 epochs would be  $200 \times 60000$  samples. The mini batch size indicates how many images we test at a time. Having the results of the delta for the 60 000 samples in the memory would be too heavy. Hence we split them into mini batches and since we are dealing with an average, we can handle treating them in smaller portions. The learning rate was mentioned above. It describes how much each sample is allowed to change the weights and biases. SGD is calling other functions, such as the back-propagation algorithm we talked about in 6.1.

### 8.3 Saving and importing the Network

Having a functional neuron network is a great thing. Yet, it takes time to produce. A lot of time. Too much time for user-friendliness. And is not always giving out the best results. Hence, we would rather ship the best network we produced with the app instead of creating one at every start. This mean we need to save and load our network into files, more precisely, writing the NN\_Network structure.

First, we have to think about what kind of file we want and its goal. In our case, loading it. We won't modify it from the file as it may break everything apart or lead to unexpected behaviours. This mean that binary file is the best choice. It is unreadable and discourage its direct modification. Moreover it takes less space than writing into a readable format, useful as it can takes a lot of space with a complex network.

Secondly, in which order should we write the fields so that it is easier to read it? In fact, the answer is easily answerable but still required to be thought. The `num_layers` field would be the first to be written as everyone depends on it. The `sizes` only depends on `num_layers` so it would be written afterwards. Then, since both `weights` and `biases` depends only on `num_layers` and `sizes`, the order does not matter. We hence are written the fields in the following order: `num_layers`, `sizes`, `weights`, `biases`. To handle the matrices, we first write the sizes (rows then columns) then followed by the values in a row-wise order.

Finally, to conclude the writing process, we need to choose an identifier, a signature to our binary file and to directly inform the user that the file given is wrong and not in our format. This is where our magic number plays a part. We chose 8629. It is magic! Written beforehand the network, during the reading process, if we don't read it correctly, then we know for sure that the whole file is wrong.

In order to read our network, we simply have to do the inverse operation. First read the magic number, then the number of layers followed by the number of neurons in each layer. With that, we can allocate enough memory for the rest of the network. Continuing by reading the list of weights matrices and then the list of biases matrices. We can then close the file and return the freshly allocated neuron network.

## 8.4 Reading the MNIST database

The MNIST database isn't written in a regular format. You may even think at first it would simply be a zip file of the 70 000 examples and tests combined images. Yet, as you expect, it would have taken a LOT of space. There are a lot of unnecessary things in our example that image format carry. The MNIST database is hence composed of 4 files.

- train-images-idx3-ubyte: training set images
- train-labels-idx1-ubyte: training set labels
- t10k-images-idx3-ubyte: test set images
- t10k-labels-idx1-ubyte: test set labels

Each image has its corresponding label. The labels file are written in the following way:

Listing 1: labels-idx1-ubyte

[ offset ]	[ type ]	[ value ]	[ description ]
0000	32 bit integer	0x00000801(2049)	magic number (MSB first)
0004	32 bit integer	60000	number of items
0008	unsigned byte	??	label
0009	unsigned byte	??	label
.....			
xxxx	unsigned byte	??	label

The labels values are 0 to 9.

Listing 2: images-idx3-ubyte format

[ offset ]	[ type ]	[ value ]	[ description ]
0000	32 bit integer	0x00000803(2051)	magic number
0004	32 bit integer	60000	number of images
0008	32 bit integer	28	number of rows
0012	32 bit integer	28	number of columns
0016	unsigned byte	??	pixel
0017	unsigned byte	??	pixel
.....			
xxxx	unsigned byte	??	pixel

Pixels are organized row-wise. Pixel values are 0 to 255. 0 means background (white), 255 means foreground (black).

From these descriptions, available on <http://yann.lecun.com/exdb/mnist/>, we can determine how to read these binary files. If we want to read the 32-bit integers, we have to be careful because the bytes are written in the Most Significant bits (MSB) format while the C language is working with Least Significant Bit (LSB) format. This mean that when dealing with these numbers, we have to change the order of the bytes to get coherent values.

Thus, the difficult part is done, we simply have to read the images and their corresponding labels one by one. We can read 784 bytes and put it into the matrix since we know the dimensions. In fact, this format for the matrices is identical to the one used in the saving/loading process.

## 8.5 XOR Network

The XOR network is a basic test to determine whether or not our current model is capable of learning. The XOR function  $\oplus$  takes two inputs and gives one output. There are 4 different cases for this function:

- $0 \oplus 0 = 0$
- $0 \oplus 1 = 1$
- $1 \oplus 0 = 1$
- $1 \oplus 1 = 0$

So these four cases will be our training data. This case is different from the next one as we are working with a finite number of cases, which is easier. Since its finite, our training data is the whole set of possibilities, and our test data the same since we only have four cases.

Now the goal is to design our network. We know that the XOR function takes two inputs and so will our input layer. Concerning the output layer, similarly to the digit network, it is natural to think that it would only have 1 output neuron. However, for the same reason as the digit network, having two outputs and taking the position of the maximum as the result is the easiest way to make it learn efficiently. We will also have a single hidden layer of two neurons.

Therefore, the network will look like this:

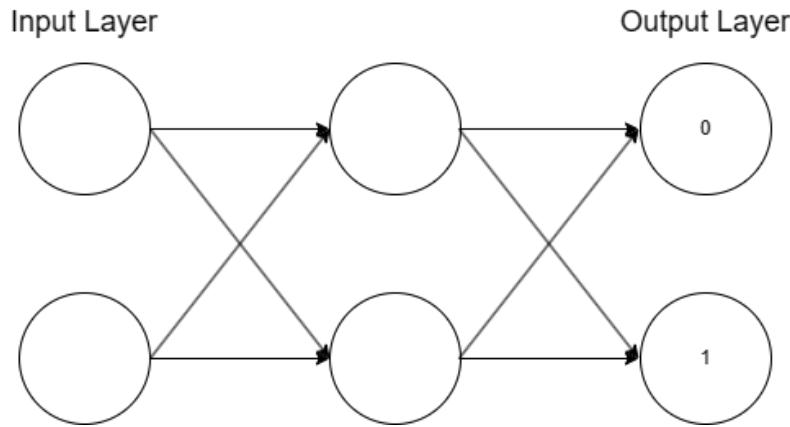


Figure 3: The chosen XOR network layout: 2 2 2

If the output element 0 has the highest value, then the result of the operation is 0. The same way for the 1, the result would be 1.

Listing 3: Teaching the network to learn the XOR function with 300 epochs.

```

=====Epoch 0/299, 75.00% (3 / 4)=====
...
=====Epoch 26/299, 50.00% (2 / 4)=====
=====Epoch 27/299, 50.00% (2 / 4)=====
=====Epoch 28/299, 25.00% (1 / 4)=====
=====Epoch 29/299, 75.00% (3 / 4)=====
...
=====Epoch 180/299, 75.00% (3 / 4)=====
=====Epoch 181/299, 75.00% (3 / 4)=====
=====Epoch 182/299, 75.00% (3 / 4)=====
=====Epoch 183/299, 100.00% (4 / 4)=====

```

## 8.6 Handwritten Digits Recognition Network

The Handwritten digits recognition network is the key to detect what digits are written on the given images. As mentioned in the theory and implementation part, we are using a 784 30 10 network and the training data given by the MNIST dataset.

Since the creation of a network is easy and that the MNSIT reader is done, to try out the current implementation of our network we simply have to put all the pieces together. However, we are facing a few issues. The first one is that the network speed was sacrificed for readability and debugging purposes. The second one is that, after starting the training and waiting 30 minutes for 30 epochs, the result reached a maximum of 70% of good answers over the 10 000 tests. This result is way too low for our final product as it means we still have over 3000 images that were not recognised correctly. The goal is to reach above 95% for the next defense but this means, trying to find out where the calculation are not going according to our plan.

## 8.7 The network... reborn

After many many hours of work by Ilan, I (Aurelien) decided to take his place as the main person on the neural network and I tried to fix the last issues with the code. Unfortunately, after a lot of work, I was not able to find the mistake, so I restarted the entire neural network. To keep it simple since I was very much limited in time, I only worked with the first chapter from the neural network website which was advised.

The initial phase of coding a neural network was akin to assembling the pieces of a complex puzzle. I started with defining the architecture, deciding on the number of layers, and selecting activation functions. However, it wasn't long before I realized that the success of my neural network was mostly due to the training data.

One of the foremost challenges I encountered was sourcing and preparing the training dataset. Neural networks work with diverse and representative data that encapsulates many scenarios (here images) the model is expected to encounter. Obtaining a dataset that could be used was fairly annoying. At first, I did not want to use the MNIST database since it seemed quite annoying to decode (it is not just 60000 images in a zip unfortunately). I decided to use another data set, composed of "only" 3000 images, and was annoyed to find that my neural network started at 20% accuracy to reach a mere 70% after 30 epochs, the reason for the low number was that the program did not have enough test cases to be accurate, except when given the EXACT image that it had seen in the data generation part. To make the network more robust, I also added noise to every image, so it would not train on similar images every time, and it would also limit the risk of the network giving flawed results when tested on an actual sudoku, since the sudokus would not be perfectly treated.

Once the dataset was in place, the next problem arrived when I had to code the training phase. Finding good parameters (ETA/learning rate, mini batch size, etc), as finding the right balance between too much of one and too little of the other proved to be very complex. The model's sensitivity to the initial weights and biases added an extra layer of complexity, requiring many iterations and tweaking.

Debugging the neural network also presented its own set of challenges. Identifying the root cause of errors, whether they were due to vanishing gradients, exploding gradients, or many other flaws, most of which I thought were impossible, demanded a deep understanding of neural networks, but I did not have nearly enough time for that during a normal day, so it ended up taking me most of my time for a few weeks. But at the end of the day it was worth it!

At the end of the day, the code very much resembles Ilan's, but a few matrix operations were made simpler, and many structs were used to create an almost python like code.

There are still a few differences, mostly in naming conventions (Network instead of NN\_Neural\_Network, column matrices instead of row matrices, etc...)

To conclude this part, I would say that I am very proud of my work, the result (90+% on the 1st epoch)

is very satisfying and works fairly well for a first neural network. This network was also made possible by the many bases Ilan had set up previously.

## 8.8 Challenges in Sudoku Recognition

When attempting to solve Sudoku puzzles using our neural network, we encountered a significant challenge despite having well-preprocessed images. Surprisingly, the obtained results were suboptimal, and the issue traced back to the training set composition. Our primary training dataset heavily relied on MNIST, a dataset known for its proficiency in recognizing handwritten digits. However, most Sudoku puzzles do not feature handwritten digits, leading to a substantial discrepancy in the network's performance.

**The Limitation of MNIST for Sudoku Recognition:** MNIST, with its focus on well-formed and standardized handwritten digits, excelled in scenarios similar to its training data. Unfortunately, this strength became a limitation when applied to Sudoku puzzles, where digits are typically presented in various fonts. The lack of diversity in the training set hampered the network's ability to generalize effectively to non-handwritten digits commonly found in Sudoku puzzles.

**Creation of a Specialized Dataset:** To address this limitation, we took a proactive step in enhancing our training set. Recognizing the need for a more varied representation of digits, we created a specialized dataset by collecting digits in various fonts. This approach aimed to simulate the diverse scenarios encountered in real-world Sudoku puzzles and ensure that the neural network could adapt to these variations.

**Diverse Font Styles for Robust Recognition:** The new dataset comprised digits in different font styles, sizes, and orientations commonly found in newspapers, magazines, or online Sudoku puzzles. By incorporating this diversity, we sought to improve the network's ability to recognize and solve Sudoku puzzles beyond the constraints of handwritten digits.

**Adapting the Network to Non-Handwritten Digits:** The process of fine-tuning the neural network involved exposing it to this augmented dataset. The network needed to learn not only the structured clarity of MNIST digits but also the intricacies of non-handwritten digits in various fonts. This adaptation was crucial for achieving a more accurate and robust performance in solving Sudoku puzzles.

### 8.8.1 Improved Results and Model Performance

The incorporation of our specialized dataset yielded notable improvements in the neural network's ability to recognize and solve Sudoku puzzles. During subsequent evaluations, the network demonstrated enhanced accuracy and efficiency, particularly when faced with the diversity of digit representations encountered in real-world Sudoku scenarios.

### 8.8.2 Conclusion and Continued Refinement

Our experience highlights the importance of a well-curated training set that aligns with the specific challenges of the task at hand. While MNIST remains a valuable resource, recognizing its limitations and supplementing it with a dataset tailored to Sudoku puzzle scenarios proved pivotal in achieving optimal results. Moving forward, ongoing efforts will focus on refining the dataset, exploring additional font styles, and continually adapting the network to ensure its effectiveness in solving Sudoku puzzles encountered in diverse settings. After these changes, the neural network was able to recognize most digits, with a few mistakes. (5 in average)

## 9 Sudoku solver

### 9.1 Parsing

The parser, designed for processing Sudoku grids stored in a text file, follows a straightforward approach to convert the file contents into a jagged array. As the parser begins its execution, it loops through the provided string obtained by reading the contents of the specified file. During this iteration, the parser populates a jagged array with values extracted from the text, using the period character ('.') to denote empty cells in the Sudoku grid. This initial phase serves to structure the Sudoku puzzle in a format that facilitates further computational manipulation.

Subsequently, the unparsing stage is equally intuitive. A character array of the appropriate length is created, and the parser iterates through the 2D array. While doing so, it dynamically assembles the corresponding string, ensuring accurate formatting with the incorporation of new lines, dots for empty cells, and spaces to delineate the Sudoku grid. The simplicity of both parsing and unparsing processes underscores the elegance of the design, providing an efficient and comprehensible solution for handling Sudoku grid representations in a text file.

### 9.2 Solver

The solver was the first part of the project that was completed, we had 2 algorithms for the solver, a first which would eliminate many possibilities off each cell, it is very optimized and efficient, but cannot solve every sudoku. For more complex sudokus, a backtracking algorithm was put into place.

The first algorithm is a collapse function, it goes through all cells and if the function has only one possibility, it sets it as the cell, and a cell is set, it calls the check function on all cells in the line/row/box.

The backtracking algorithm checks using recursion every possibility for every cell; if there is a contradiction, it leaves the recursion and removes the possibility.

Since backtracking is very expensive, we tried to optimize the code as much as we could, so the data was stored into a matrix of 9 by 9 of shorts, with each short representing everything we needed for both algorithms. The shorts were as follows (using an example here) :

Read from left to right: 00 1 0101 011010101

The first 2 bits are ignored, then the next bit is 0 if the cell is solved (only 1 possibility). The next 4 bits represent the number of possibilities (here 5 possibilities). The next 9 bits are 1 if in this cell, the bit index (from right to left, started by 1) is a valid possibility.

So here, the cell is not solved, and it can be of 5 possibilities : 1, 3, 5, 7 and 8.

In the case where the third most significant bit is 0 the short will only be just a digit of the sudoku.

This implementation permits us to keep track of which possibility has been already been searched and helps the performance for the resolution of the grid.

In case the provided grid was either unsolvable or incorrect the solver just returns an empty grid.

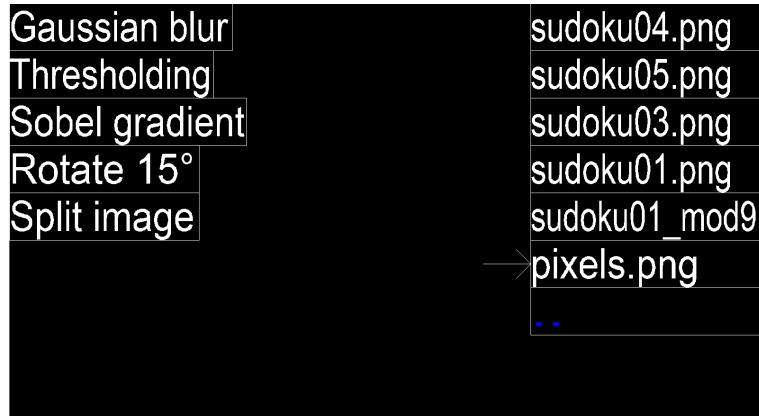
## 10 Graphical User Interface

For the first defense, our group quickly made a basic graphical user interface (GUI) using the SDL library. While functional, it was very ugly and not very practical. We had worked on SDL in the image TP from earlier this year, so we thought that SDL was the goto library for GUIs and anything image related, but as we neared completion, Ilan introduced us to GTK – a powerful library designed for creating user interfaces. We decided to integrate GTK into our project for the second defense. Using glade and the GTK TP as bases for the gui helped a lot.

The layout of our first GUI featured all the basic functions on the left and a file explorer on the right. The left panel had a list of buttons, represented by a struct with coordinates (x, y) and a function pointer called when it detected a click which was on the "box". On the right side, buttons were generated procedurally. It also had user-specific functionalities, such as a slider for manual rotation, allowing us to rectify upside-down images. On top of that, a slider facilitated the adjustment of parameters for the adaptive thresholding, although initializing it with an optimal value was very hard, especially for very bright images.

After the first defense, we had to do the GTK TP, using the new knowledge into a revamped GUI. We quickly found that creating a real gui which was user-friendly and easy to use was very hard. The design was similar to the structure of the GTK tutorial : utilizing a struct to store GUI elements and passing it through various functions, similarly to a global variable.

Some functions have specificities for the User, such as a slider for the manual rotation, which can be used to fix the rotation at the start of the process. If the image is upside down, no one but the user can fix that. After that, we also use a slider to be able to choose the parameters of the sauvola thresholding; at the start, the slider is set to a correct value, but sometimes, that value does not work correctly (usually if the image is too dark overall, or too light).

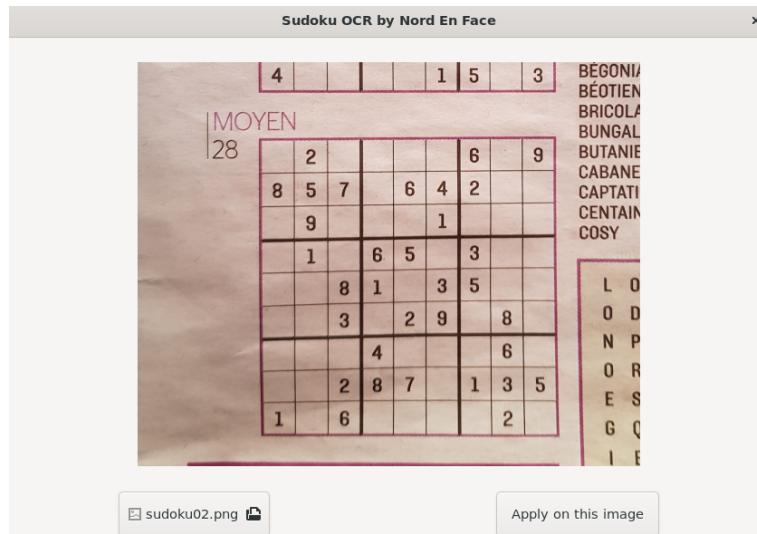


Almost immediately after the first defense, we had the GTK TP, which helped immensely to get a better understanding of GTK and glade. So we started working on the new and improved GUI. There were a few issues at first, we had to design a good looking, easy to use GUI.

Then, we had to make the code work. We have a system similar to that of the GTK TP : there is a struct which is used to store all the gui elements and this struct is being passed around many functions. At the end, this is the state of the GUI.

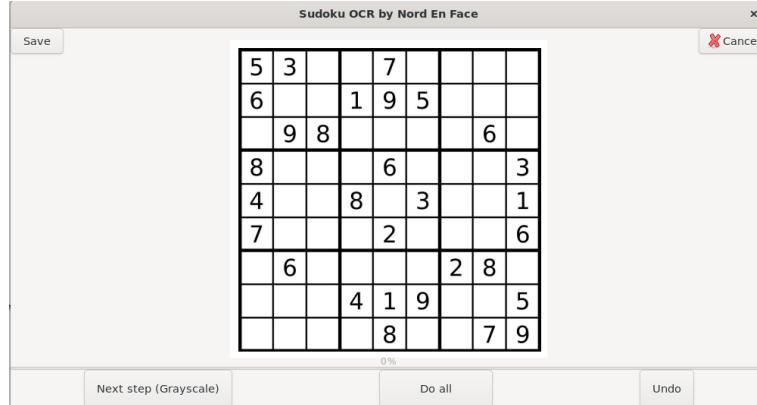


This first window is used to select a file, if a file is chosen, a second button will appear to go to the next window and the image is shown in large.



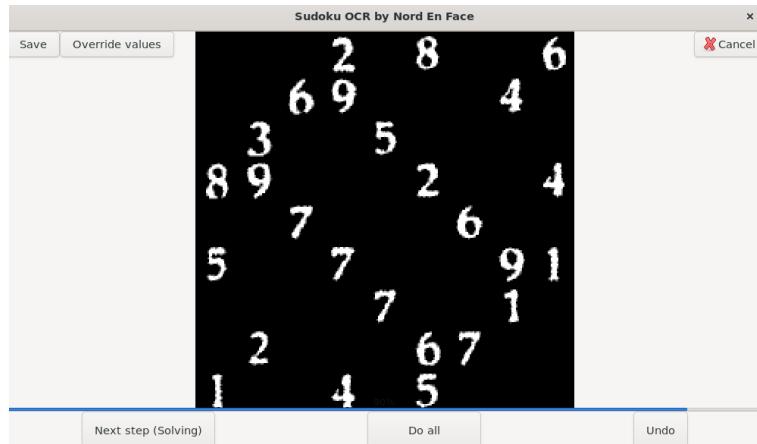
In this second window, the image is shown in the middle, and a few buttons can be seen : next step, do all, undo, cancel and save. Most of them are self explanatory but I think it's interesting to see how they work : There is a variable which represents the index of the step we are at, if we click on the next step, it saves the current image in a temp file and calculates the next image. The goal of saving many temp files are for the undo button. We don't want to recalculate everything every time we undo.

The cancel button reopens the first window to let us choose a new image.



An important step to note in the GUI is that when we split the image in 81, we will also crop out the borders off each image, and then we re concatenate all those images again into one big image. This is used to show what the GUI will feed to the neural network.

After that, we also had to implement a way to show the values found by the neural network, and if they were wrong (and they eventually will be wrong), we have to be able to manually change them. To do that, we added a button in the digits recognition step of the GUI.

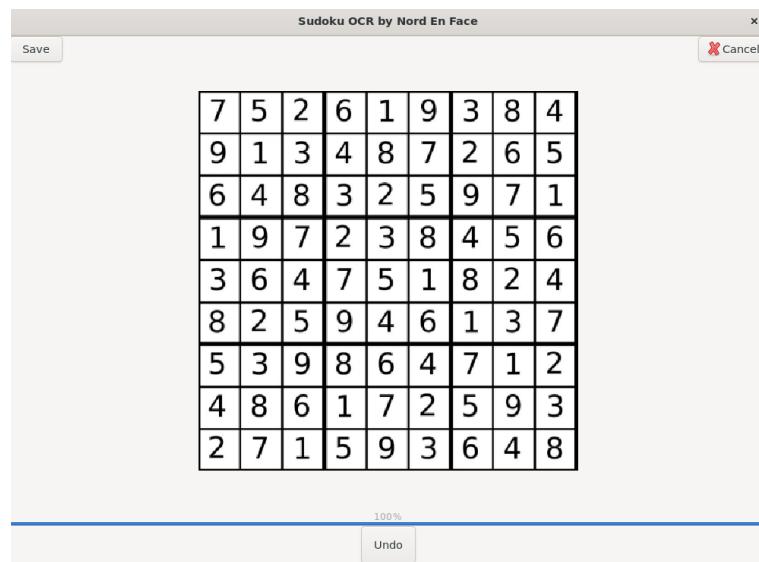


As we can see on the above image, a button can be clicked at the top left to see the output of the network. Once clicked, this window pops up:



This window lets us compare the original image (on the first window) and the neural network outputs (on the new window). Any change done on the pop-up window will automatically change the matrix used by the solver.

After all this, the GUI will show the result on a new image, which can be saved by using the save button at the top right (into the 'output.png' file)



The result with image06.jpeg

## 11 General Progress

Tasks	Percentage
<b>Preprocessing</b>	
Gaussian Blur	100%
Grayscaleing	100%
Adaptive thresholding	100%
Sobel Edge Detection	100%
<b>Grid Detection</b>	
Hough Transformation	100%
Line Filtering	100%
Square Detection/Selection	100%
<b>Segmentation</b>	
Image Resizing	100%
Image Rotation	100%
Image Splitting	100%
Image Correction	100%
<b>Neural Network</b>	
Gaussian distribution	100%
Neural Network XOR	100%
Neural Network Digits	100%
<b>GUI</b>	
GUI	100%

Table 2: First Table of role divisions

We are very happy to say that we managed to finish every single step required for this project.

## 12 Problems

Of course, the project wasn't all rainbows and daisies, we also had some problems.

Firstly we had a problem of distance, since some of us live far away from others, we didn't find any time to work next to each other. Of course we still had voice chats to talk together about what we were doing and what we had to do, but it is not the same as being in the same room, and it is far harder to code together this way.

Secondly, since the 1st defense, some code that we wrote and presented as being functional were in fact either not working properly, or they had to change/get upgraded because of other functions we wrote.

Furthermore, we decided to do some cleaning in the code since we felt it wasn't well tidied up, hence we added folders, changed the way we stored the files, and it caused several problems such as not knowing where certain files were, having to rewrite every dependencies, and having to rewrite Makefiles to include files in other folders.

This last step also caused several issues, notably making it so that a Makefile that previously worked perfectly had issues within it. Also we wanted to create a "king" Makefile, one to rule them all, this Makefile would've been the only one of the project and it would allow us to make every folder at once or one specifically. Unfortunately it was harder than anticipated and issues arose, making it so almost nothing was makeable, and we couldn't test anything, hence Ilan spent 3h trying to debug it, until we all gave up and got makefiles from old commits

## 13 Enhancements

Though the OCR works almost perfectly for most images, and all images provided for this project, we are aware of some cases where it can fail. Firstly the Neural Network has been the bane of our project. It took an extremely long time for Ilan to make it work, and after it did, it only had the correct outputs less than 90% of the time. Then for the digits, we've spent a good chunk of our time trying to enhance our percentages, unfortunately, ultimately, we've been stuck at roughly 85%, which is respectable, but not enough to accurately detect digits and have a correct Sudoku grid at the end. We've countered this issue by giving the possibility to change the digits the NN found for the solver to solve a correct grid, but it is unfortunate, and we think it is one aspect that needs the most enhancements.

Also, since our current NN does not work, we thought about making it so that if it finds a value that is not possible (i.e. two 4's in the same rows or column) it would change its value

Secondly, though we have correction function, it only works once a grid has been found, but on input images where the grid has been curved, the hough transform which is used to draw straight lines can not work, since it is a curved line and not straight. Hence we thought of something but did not have the time to add it, it would be an algorithm that would, instead of taking straight lines and stop there, would try and "concatenate" lines that are closely related, then creating a curved line :



## 14 Closing remarks

**Alexis Meunier :** In concluding this OCR project, I find myself reflecting on the journey from inception to completion. The process of developing an OCR system for Sudoku grid resolution has been both challenging and immensely rewarding. Navigating through the intricacies of image processing, algorithm design, and optimization has not only expanded my technical proficiency but has also deepened my appreciation for the intersection of computer vision and problem-solving. What I particularly enjoyed about this project was the constant problem-solving aspect, where each challenge posed an opportunity for growth.

Although, the best part, for me, was when after countless hours of failing to implement an algorithm, I would see the expected output with an image correctly processed, and it working on multiple images. The iterative nature of development allowed me to refine my algorithms and approaches, and witnessing the system successfully resolve Sudoku grids from images was truly gratifying. While grappling with occasional setbacks, I learned the value of resilience and adaptability in the face of complex technical challenges. This project has undeniably honed my skills in image processing, algorithmic design, and project management. Though the journey was demanding, the sense of accomplishment upon completion serves as a testament to the transformative power of hands-on, real-world projects in fostering professional growth. Overall, this endeavor has left me with a profound sense of achievement and a newfound confidence in tackling intricate problems in the field of computer vision.

**Aurelien Marques :** I really enjoyed this project, as it is in the C language. I just love the language too much to not love anything coded in C. I am also very interested in neural networks, so having to work on it was a blessing for me. With those 2 things combined, I can really say that this was the best project I've ever done. It is even better than the S2 project even though we were free to do anything we wanted.

This project will help me greatly for when I go to Japan with well... every member of this group (except Augustin who is going to Hiroshima and not Tokyo), where I hope to be able to pick a class in which AI is a major part. To conclude my part, I really hope we get more C projects in the future, and I hope the projects are also very grounded projects. By grounded I mean that the result is tangible easily. (a non grounded project would be something like a server/client code, in which it is hard to really see the results and debug anything)

**Augustin HUBERT :** In this project I handled mostly preprocessing. It is very visual and for that you might think it is easy (at least easier than a Neural Network) but I learned the hard way that in fact : NO! First it was not easy to get a good thresholding for each image, there was always an outlier that prevented me to pass on to the next step. And actually for most of the step of the OCR I worked on it was the same, so I had to get creative enough to create somewhat new algorithm on top of always juggling thresholds to see if it works. It really challenged me and I liked the project entirely for that. My main goal was to have the six image from the book of specifications to work until the split included. It was really vast goal including preprocessing, grid detection, and some image transformation but I did not give up and actually reached the goal I set myself ( I hope ). So to conclude, I am proud of the result I can present, and I learned a lot more about to code in c, a language that I now really appreciate for its simplicity and speed.

**Ilan Mayeux :** At first, when I arrived at Epita and learned about this project, I did not think that I would be able to produce something like that. I decided to work on the Neural Network but even after many many hours on it, I did not succeed entirely, making me a bit disappointed about my work on the Neuron networks Yet, I still enjoyed rewriting everything by myself in C, doing some image processing and linking everything together to the GUI while assuring that the code base was not crossing the dark side. I plan now on continuing my journey in C by implementing a 3d renderer with OpenGL and my fan game project. I still wish to better understand OOP in C and acquire new skills on how graphics drivers work. The next challenge awaiting us is probably the Piscine and before that, we have a new journey awaiting us in Japan.

## 15 Conclusion

To conclude this report, we are very proud of our work, and we plan to continue working on the project even when in the S4 abroad (potentially to make a better neural network, implement hexadoku, etc). We are happy to have been able to work like a group, we shared tasks, gave parts of tasks to group members who were more able on certain parts, etc.

In conclusion, our team has successfully embarked on a challenging journey to create a Sudoku OCR in C. Through hard work, dedication, and many long nights, we managed to complete the project at a scale we thought was not possible at first.

Throughout the project, we faced many challenges, namely, image preprocessing, grid recognition, and the neural network for digit recognition.

Another major issue was the lack of work of Yun, which hindered our ability to work since we had to try and get her to work, to no avail...

This project helped us a lot to learn about image processing, neural network implementations, coding in C in general, and teamwork. The last one being the most important for us; we managed to spread our tasks correctly and efficiently while giving everyone in the group a task they enjoyed.

In conclusion, our collective efforts have ended in the creation of a functional and efficient Sudoku OCR system.