Enigma Machine Simulator

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April 2024

# Abstract

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# Introduction

The Enigma Cypher Machine (*Enigma I)* is most well-known for its usage and eventual breaking, during World War 2 (WW2). The machine used several mechanical rotors, a reflector and a plugboard to redirect electrical signals, scrambling a plaintext message into cyphertext. Whilst most have heard of the machine, either from studies of cryptography or through history, many do not understand how the machine functions and its significance. By creating an accurate simulation and visual tool to demonstrate the inner workings of Enigma, the aim of this project was to offer a deeper insight into the functionality, significance, but also the weaknesses of the machine.

There already exists a handful of examples of Enigma simulations which tend to offer a skeuomorphic approach to modelling the machine. The challenge of this project was to create a tool that provides a complete experience of Enigma, including an accurate recreation supported by multiple application. This project began a thorough investigation into *Enigma I* to understand the inner workings of the machine and to compile this research into a simpler, abstracted model using Java. Both a multi-platform command line interface (CLI) and a multi-platform graphical user interface (GUI) were developed to allow the user to interact with the model, the former offering a step-by-step visualisation of the encryption of a message. To complete the project, a second model was developed called “EnigmaPlus” which aims to correct the two key cryptographic weaknesses of the machine. The results regarding the accuracy of the models, as well as the outcome of the CLI and GUI, are presented in this report. Additionally, these results are evaluated through comparison to similar products and other metrics.

## Aims and Objectives

The following list adapted from the original project description, however there are some additional objectives that were self-proposed. For each task, a criterion was determined to assess the success of each task’s implementation.

|  |  |
| --- | --- |
| Aim / Objective | Criteria for Success |
| Create a Java package to accurately simulate the Enigma machine. | The Java package should conform to good software engineering practises to provide an accurate simulation of Enigma machine. In addition, the system should allow for Enigma to be fully configurable. |
| Create a new “EnigmaPlus” model, existing within the Enigma package, that improves upon the weaknesses of the original machine. | The EnigmaPlus model should reside within the Enigma package, functioning similarly to the original machine but with better security. |
| Create a Command Line Interface (CLI) allowing basic interaction with the Enigma model | The user should be able to fully configure Enigma before either encoding or decoding a message. |
| Create a Graphical User Interface (GUI) allowing interactions with both Enigma and EnigmaPlus, providing a visualisation tool for both models | The user should be able to fully configure Enigma and EnigmaPlus before either encoding or decoding a message. The visualisation tool should provide an abstracted and informative representation of both model’s encryption steps.  In addition, the design of the GUI should be aesthetically pleasing. |
| Support multiple platforms | Both the CLI and GUI should be compatible with Windows/MacOS/Linux |

TODO : Give overview of the structure of the report

# History & Background

## History of the Machine

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The Enigma cypher is one of the most famous cipher machines (Enigma n.d.) due to its role in WW2 and the work undertaken at Bletchley Park to create the Turing-Welchman Bombe and crack the code. The Enigma was used extensively by the German forces to transmit coded messages for more secure communication. Whilst most people refer to this machine as “The Enigma”, Enigma is a brand name for a series of cypher machines (Enigma n.d.). The one used most in WW2 was *Enigma I* and was the key focus of this project.

To use the Enigma machine, it had to be configured to an exact setting so that the machine could be correctly decoded by the intended parties. These settings were distributed to the German forces each month in a code book, containing each day’s settings.

## Design of the Machine

The Enigma Machine was a rotor-based machine and worked using a hybrid of mechanics and electrical signals. *Enigma I* contained 5 key components that worked together to produce cyphertext: the keyboard, lampboard, the rotors, the reflector, and the plugboard. The inclusion of all these components aimed to make the machine as unpredictable as possible whilst also generating a large key-length of roughly 67 bits (nearly 159 quintillion different settings see Equation 6) (van Manen and Robertsson 2016).

The use of the machine was a simple process. A user would receive a message along with a list of settings denoting the choice of rotors and their respective settings, the plugboard settings and a choice of reflector. Each time a key was pressed on the keyboard, a light on the lampboard would illuminate as demonstrated in Owen’s animation (Owen 2021) and the user would write down the corresponding letter. Due to the symmetric design of the Enigma machine, as long as two people had the same settings then they could simply input the cyphertext into the machine and receive the plaintext and vice versa. However, this design choice was overlooked and compromised the Enigma’s security (see section 3.4) (Thimbleby 2016).

An old machine on a glass table

Description automatically generated

Figure A photo of Enigma I showing the plugboard, keyboard and lampboard. Only a small portion of the rotors are visible, and the reflector is hidden. Photo taken by author at Science Museum London (Science Museum n.d.)

### Keyboard & Lampboard

The keyboard and lampboard were the key user interfaces for Enigma. The former was comprised of the 26-letter alphabet omitting any special or numeric characters. Each key on the keyboard could be pressed which would cause a ratchet mechanism to move a lever (pawl) to step the rotors (Hamer 1997). The lampboard was a copy of the keyboard but instead of keys, there were small glass panels which would allow the bulbs underneath to shine through. These panels were also printed with the 26-letter alphabet and upon a keypress, any given lamp could light up to show the plaintext character’s corresponding cyphertext.

### Rotors

The rotors were the heart of the Enigma machine and were responsible for most of its unique properties. They were metal ratchet discs with 26 different positions representing each letter of the alphabet. Each position had a corresponding metal contact (Owen 2021) on both sides of the disk to allow electrical current to flow through the rotor. Inside the rotor, fixed wires were implemented which directed the current from one contact to another, thereby encoding the input.

Rotors also exhibited another property; each rotor had a notch at a fixed position on the ratchet which would allow the levers (pawls) mentioned earlier to ‘step’ the rotor (Hamer 1997). This stepping caused the rotor to rotate by one position. In the machine, three rotors were placed in series to allow current to pass through all three, causing a letter to be scrambled three times from one key press. Once a rotor reached its turnover position (the character shown to the user once the notch position is lined up to the pawl, the latter is not seen by the user of the machine), the rotor to left of the turnover rotor would step. The right-most rotor would step every key press and the middle rotor would step with a period of 25 (Grime 2013) (Smart 2016). This is due to a quirk of the machine known as double stepping, where the middle rotor would also step when it reached its own turnover position as demonstrated by Hamer (Hamer 1997). The left-most rotor would step with a period of 262. This rotational property of the machine allowed for the final encoding for a given letter to change each keypress.

The Enigma rotors could be swapped around and placed in any order in the three slots available. Usually, users were given a box containing 5 different rotors the choice of which to use formed part of the Enigma’s key. Table 1 depicts the 5 rotors that were included with *Enigma I* demonstrating their internal wiring as well as the location of the notch. For example, *Rotor I* will map A to E and B to K provided the rotor is in rest position (Position A and Ring setting A).

|  |  |  |  |
| --- | --- | --- | --- |
| Rotor | Encoding (Position A - Ring setting A) ABCDEFGHIJKLMNOPQRSTUVWXYZ | Notch | Turnover |
| I | EKMFLGDQVZNTOWYHXUSPAIBRCJ | Y | Q |
| II | AJDKSIRUXBLHWTMCQGZNPYFVOE | M | E |
| III | BDFHJLCPRTXVZNYEIWGAKMUSQO | D | V |
| IV | ESOVPZJAYQUIRHXLNFTGKDCMWB | R | J |
| V | VZBRGITYUPSDNHLXAWMJQOFECK | H | Z |

Table 1 "Enigma I" rotor encodings (Enigma wiring n.d.)

Finally, the rotors had an additional setting known as the ring setting. This allowed the internal wires and ratchet to be shifted independently from the letter ring, allowing the notch position to move relative to the letter ring. Whilst generally, the ring setting formed part of the key, it is important to note that it had marginal impact on the strength of the cypher, only affecting the turnover position of the adjacent rotor (How does the Enigma machine work? n.d.).

Much of the complexity of the Enigma was due to these rotors. Alone, with an *Enigma I* model, there were 1054560 different ways to configure the rotors (see Equation 1)

Equation Permutations for rotors (excluding ring setting)

### Reflector

The reflector was a similar component to that of the rotors and together formed the subsystem where most of the letter scrambling takes place. The main differences regarding the reflector are that it does not rotate, and the current does not pass through but rather is ‘reflected’, travelling back in the opposite direction through a different metal contact.

The design of the reflector was to enable the whole machine to be reciprocal, combining encryption and decryption into one operation. This, along with the fact that the reflector could not encode a letter to itself (the design of the rotor prevented the current being passed back through the same metal contact) were crucial flaws exploited (Thimbleby 2016) by the team at Bletchley Park to crack the code during WW2.

The Enigma machine came with a reflector which could be replaced with others but generally remained the same. The three reflectors that were available with the *Enigma I* were UKW-A, UKW-B and UKW-C as shown in Table 2. The encodings demonstrate the inner wiring of each reflector, for example UKW-A maps A to the letter E.

|  |  |
| --- | --- |
| Reflector | Encoding ABCDEFGHIJKLMNOPQRSTUVWXYZ |
| UKW-A | EJMZALYXVBWFCRQUONTSPIKHGD |
| UKW-B | YRUHQSLDPXNGOKMIEBFZCWVJAT |
| UKW-C | FVPJIAOYEDRZXWGCTKUQSBNMHL |

Table "Enigma I" reflector encodings (Enigma wiring n.d.)

### Plugboard

The plugboard formed the final part of the Enigma’s encryption key and was located at the front of the machine. It displayed another representation of the 26-letter alphabet, each of which had a plug socket. These sockets, and the cables that came with the machine, allowed two letters to be connected to each other on the plugboard. This created yet another scrambling of the letter, such that if socket A and socket E were connected then any current passing through the plugboard in wire A, would be directed to wire E and vice versa. Any letter left unconnected to another would result in the plugboard having no effect for that letter. The plugboards letter swapping effect only occurred twice in each encryption, once at the start of the encryption (after the keypress) and once at the end (before the lamp on the lampboard lights up).



Figure A front-facing photo of the Enigma I plugboard with cables in place (Enigma n.d.)

## Enigma Machine and Abstraction

TODO : Give open paragraph

### Enigma’s Encryption

Often the best way to understand the mechanisms of Enigma is to focus on a single letter’s encryption. As mentioned in section 3.2, the user begins with configuring the Enigma’s settings. Upon a keypress on the keyboard, the rightmost rotor will rotate. Depending on the current rotation, the other rotors may also step. Then, an electrical signal will be induced passing through the plugboard towards the rotors. Depending on the plugboard settings, this input signal may be scrambled. This electrical signal then passes through rotors right-to-left with the signal being redirected at each rotor. The output of the left-most rotor is then transmitted to the reflector where the signal’s direction is reversed and redirected to the contact of a different letter. The signal then passes through all three rotors for a final time, this time from left-to-right, before passing through the plugboard again. Finally, the signal is transmitted to the lampboard where the cyphertext is displayed. Any plaintext letter can be scrambled up to nine times before the cyphertext is displayed.

By representing each of the components of the Enigma as a transformation as demonstrated by Rejewski (Rejewski 1980), such that represents the plugboard, represents the rotor in the left, middle or right position and represents the reflector, an equation, such as Equation 2, can be formulated to describe Enigma’s encryption steps. It is important to note that due to the plugboard’s symmetry, .

Equation The encryption steps of Enigma I

### Abstractions

The Enigma machine is complex. With numerous components working together in both mechanical and electrical forms, it can prove difficult to predict the outcome of an encryption. This section aims to abstract each component into a logical model to help demonstrate the behaviour and weaknesses of the machine.

Firstly, The diagrams provided (Figures 3-7) are inspired by work from Smart (Smart 2016) and Thimbleby (Thimbleby 2016) and depict rectangles with nodes on each side to represent each letter in a truncated alphabet (A-F). The connections between these nodes represent the internal wiring of each component or, in a more logical sense, the letter-to-letter mappings of each component. These diagrams are designed such that the any letter is **input on the right** and the **output on the left** is map(x). Consequently, the left can also represent and the right-hand side represents . For example, Figure 3 shows the plugboard in which if the input on the right is “A” then the output will be map(“A”) which is “D”. The reason for representing input on the right-hand side is to better reflect the physical layout of the Enigma machine. It is important to note that, in the case of rotors, the function refers to the component in rest state (no rotational effects).

The plugboard acts as a simple cypher, either swapping the inputs and outputs of two letters or leaving the output unchanged. This means that letters connected by a cable on the physical machine are encoded to each other; in absence of a cable, no letter scrambling takes place. As shown in Figure 3, sockets on the machine that connected are represented with a connection between nodes such as A and D. Due to the plugboard symmetry, these diagrams exhibit these ‘X’ shapes.

A diagram of lines and dots

Description automatically generated

Figure A wiring diagram to show a plugboards potential encoding

The reflector acts as a substitution cypher with additional constraints being self-coding (a letter cannot be encoded to itself) and reciprocal coding (if A B, then B A) (see Equation 3). Like other components this can be represented using a wiring diagram in which the input and output both take place on the right-hand side, such as Figure 4. This diagram demonstrates an example of a reflector, where A is shown to be connected to F and vice versa such that any input into the reflector will output the letter at the connected node.

Equation An equation and additional constraints to describe the behaviour of an Enigma reflector

A diagram of a diagram

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Figure A wiring diagram to show a potential encoding for a reflector

The rotors of the machine are substitution cyphers with no additional constraints. They take an input letter and produce either the same or a different letter. Whilst a rotor can be represented using a wiring diagram, multiple diagrams are needed to convey the rotor’s rotational effects. As demonstrated in Figure 5, the image on the right depicts the same rotor displayed on the left but with a rotation of one. This causes the connections between nodes to move upwards whereas the ring setting will cause them to move downwards. This effect is easily seen with the horizontal connection between F on the left image. Once the rotor is rotated the same connection is moved upwards in the diagram to become a horizontal connection between E as shown by the image on the right. This effect can be generalised such that any input letter will be mapped to the input letter where represents the rotor’s rotation and represents the rotor’s ring setting. In addition, the output of the letter will be shifted by (see Equation 4). It is clear from these generalisations that if the rotation setting was ten and the ring setting was ten, then there would be no effect on a letter’s encryption as mentioned in 3.2.2.

Equation A function to represent the encoding behaviour of the rotor where x and x` are letters, represents the rotor’s rotation and represents the ring setting

A diagram of lines and dots

Description automatically generatedA diagram of lines and dots

Description automatically generated

Figure Two wiring diagrams to show a potential rotor encoding. The diagram on the right shows the same rotor as on the left, but with a rotation of one

By abstracting all the electrical and mechanical features of the machine, logical diagrams demonstrating the letter scrambling that takes place in the Enigma machine can be created with greater ease. The diagrams from Figures 3-5 represent each component of the machine and can be combined to create a representation of the entire Enigma machine (See Figures 6-7). These diagrams depict an Enigma machine and demonstrate how the machine works in full. It is important to note that these diagrams only show a single state, upon each key press the rotor wirings will change leading to a potentially different output for the same input.

A diagram of a network

Description automatically generated

Figure A wiring diagram representing a single state of an Enigma I machine. Input is received on the right-hand side before being scrambled by components performing a loop in the reflector. The electrical signal received back from the plugboard represents the encoded letter. The names of each rotor/reflector do not match the encodings but are given as an example.

A diagram of a network

Description automatically generated

Figure An example of an encryption/decryption taking place in an Enigma I machine. In this case A is encoded to C.

## Design Flaws & Remedies

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### Cypher Strength

At a first glance, it may seem like the Enigma machine is unbreakable and indeed the Germans shared this over-confidence (Thimbleby 2016). The Germans became complacent when operating the machine often opting to use the same three rotors and neglecting to change the reflector (Tang, Lee and Russo 2018). This led to a to a large reduction in the security of communication between operators by factors that could have been largely avoided (Thimbleby 2016).

Whilst the Enigma machine had a large key space (see Equation 6), it is not the only factor that contributes to a cypher’s strength (How does the Enigma machine work? n.d.). In fact, work from Tang, Lee and Russo (Tang, Lee and Russo 2018) suggests that the Enigma had a theoretical key space of compared to the more realistic demonstrated in Equation 6.

As suggested by Thimbleby (Thimbleby 2016), by imagining the Enigma machine without its internal components, it can be viewed a substitution cypher with different mappings from keyboard to lamp board. However, this assumes that there are no restrictions on how the mappings can be configured. As mentioned earlier in section 3.2, this was not the case for *Enigma I*. The actual number of permutations for the Enigma machine was (see Equation 5). The reduction in permutations by a factor of approximately is due to two features of the machine: self-coding and reciprocal coding (Ostwald 2023) (Thimbleby 2016).

Equation Definition of double factorial

Equation The number of settings (key space) of Enigma I assuming 10 plugboard cables are used. Ring setting is omitted as it was not changed by the Germans. Based on work from Tang, Lee and Russo (Tang, Lee and Russo 2018).

### Improving the Machine

Clearly, the most obvious solution to improve the *Enigma I* is to increase its key space with more rotors. This can be done by adding an additional slot to the machine to allow for 4 or more rotors to be in use at any one time, or even using the usual three rotor slots but having a larger collection to choose from. In fact, rotor IV and V were introduced later in 1932 (Ostwald 2023) in order to increase the key space. Other machines inspired by Enigma, such as the British Typex, were developed to utilise more than three rotors at a time, thus increasing combinatorial complexity (Ostwald 2023). Ostwald’s study (Ostwald 2023) shows numerous additional improvements that either were implemented or could have been implemented to improve the cypher key space.

Thimbleby (Thimbleby 2016) gives examples of multiple circuits that aimed to fix the Enigma’s two main weaknesses mentioned in section 3.4.1 demonstrating that the technology at the time period was capable of creating a much stronger cypher. In particular, Figure 8 demonstrates a circuit that only uses three rotors omitting both the reflector and the plugboard. By removing these two components, it avoids both self-coding and reciprocal coding by separating encoding and decoding into two distinct functions. For encoding, the current would pass from right to left, and vice versa for decoding. Whilst this model does not include the plugboard, so long as it is only applied once in an encryption, it can still be included without re-introducing the weaknesses. The removal of the reflector does reduce the key space however, this can be mitigated by simply adding another rotor in its place.

A diagram of a machine

Description automatically generated

Figure A circuit showing an Enigma style machine avoiding both self-coding and reciprocal coding. Taken from Figure 6 (Thimbleby 2016)

The design in Figure 8 mainly focusses on the electrical behaviour of the hypothetical machine however it acted as the main inspiration for “EnigmaPlus”. By representing this circuit as a wiring diagram similar to Figures 6-7, a logical model for this machine can be created as shown in Figure 9.



Figure A wiring diagram depicting "EnigmaPlus". Note that there is no reflector as well as encoding and decoding take place in opposing directions.

## Related work

Several similar products were found that simulated the Enigma machine. This project and much of the work done around *Enigma I*were inspired by these products. In addition to this, the paper written by Thimbleby (Thimbleby 2016) gave direct inspiration into the creation of “EnigmaPlus”.

“Enigma Machine Emulator” (Enigma Machine Emulator n.d.) is a webpage consisting of a short description about the Enigma machine as well as offering an interactive emulator for the Enigma machine. The emulator follows a skeuomorphic design aiming to present a flat image that resembles the real machine.

“The Enigma Machine” (Enigma Machine n.d.) presents a sleeker UI allowing the user to configure the machine as well as encode/decode their messages. The design of this webpage strays from the original look and feel of the machine, offering a new and simpler way to interact with it. Much of the design aspects of this projects were inspired by this webpage.

“Virtual Enigma” (Virtual Enigma n.d.) offers extremely immersive, interactive 3D simulation of the Enigma machine. This simulation allows full control of the machine down to each minute detail. Users can open different parts of the machine with their mouse and drag and drop rotors into place on a virtual model of the machine. The level of detail in this simulation offers an authentic experience for the user and is highly recommended for those who would like to experience the machine as a whole.

“The Enigma Machine” (MacWright n.d.) is the only similar product that I came across that offers a form of visualization to the inner workings of the machine. It represents the Enigma’s encodings as a circular wiring diagram analogous to Figures 3-7. This particular page was the inspiration for the visualiser functionality for this project.

# Design & Implementation

The key goal of this project was to create an exact simulation of the Enigma machine and provide both a command line interface (CLI) and a graphical user interface (GUI) to interact with it, focussing on educating the user on the machine’s functionality. An additional goal of this work was to develop another model named EnigmaPlus, maintaining compatibility with the GUI as well as providing a stronger cypher than the original machine.

An overview of the development is given in this section. Figure 10 illustrates the underlying system developed throughout this project. The subsequent sections provide a detailed account of each package.

A diagram of a computer

Description automatically generated

Figure A diagram depicting the underlying packages for of this project, including Enigma, GUI, CLI, Config and Parsers

The Enigma package contains all the necessary backend functionality to accurately simulate the Enigma machine and EnigmaPlus. These models are design to encrypt any plaintext message into cyphertext and vice versa. In addition, the Enigma package also provides pre-built rotor and reflector configurations to the Parsers package. The Parsers package and Config package both aim to provide custom component creation for both the CLI and GUI. The packages also provide a means of configuring the Enigma machine exclusively for the CLI. The CLI package contains a small demo application allowing the user to quickly configure and operate the model of the Enigma machine. Independently, the GUI package provides the user with a Model-View-Controller (MVC) based graphical application, allowing the user to configure and operate the machine. In addition, the GUI provides numerous additional tools aimed at providing an informative representation of the encryption process through visualisation.

## Tools & Technology

Throughout development of this project, multiple tools and technologies were utilised to accomplish the requirements and objectives.

Java was the chosen programming language used for this project due to its native use of object-oriented programming (OOP) and its vast online support. The first of two Java packages used was JavaFX which is a graphics package specialising in user interfaces. This package was used to create the GUI, as well as provide the visualisation tool included with the GUI, due to its easy-to-use interface components and drawing capabilities. The second package was JUnit which is a testing framework that enables test cases to be created and run automatically. In this project, JUnit was used to create unit tests to validate both Enigma and EnigmaPlus and their expected outputs, supporting the development process.

Gluon Scene Builder is an external application that provides a “drag and drop” experience for GUI creation. This was used within the project to create prototypes for, and eventually implement, the GUI. The tool was chosen because it generates FXML files which are natively supported by JavaFX, creating a simpler GUI development.

The XML language is an object description language with the sole purpose of representing data. In the scope of the project, this was used to allow the user to create and store custom components as well as configure the settings of the Enigma machine.

Maven is a Java based build tool which aims to create a simpler process for the developer to build their Java project. Maven was used here to build the project as well as manage all other dependencies (such as JavaFX) to help maintain a minimal code base.

## Enigma and EnigmaPlus

TODO : Opening paragraph, Move EnigmaPlus into a final section

### Enigma

It was clear that the most elegant solution to simulating the machine was adopting object-oriented programming. By doing so, each class represents the corresponding physical component as demonstrated within Figure 11. This diagram does not include EnigmaPlus, as this was an additional requirement that was accommodated later in the development process. The diagram shows the developed Java classes for each component, which hold a composite relationship with the Enigma class. It is important to note that the UML diagram does not include any mention of the keyboard or lampboard that were covered in the background section. This is because whilst they are significant components for the physical machine, in a logical sense, they are nothing more than input and output.

A diagram of a computer

Description automatically generated

Figure UML diagram depicting the Enigma package, omitting EnigmaPlus

The components within Enigma are variations of substitution cyphers, therefore a common representation was needed for this. At first, it was thought the best way to represent the substitution cypher encodings would be with the use of hash-maps. Whilst this representation would have worked, this would have required 52 key-value pairs in the hash-map. In addition, hash-maps bring unnecessary complexity into the representation. Instead, a simple array for each component depicted as wiring, of length 26 integers, was used for the representation. In such an array, each index represents the positional encoding of a plaintext letter and the value at that index would represent the positional encoding of the cyphertext letter. This method offers greater simplicity as well as maintaining fast indexing, a process that is abundant in an encryption. For the plugboard and reflector, this representation was enough, however the rotor required a more complex representation to account for its unique properties. To achieve this, additional attributes were included in the model: reverseWiring, currentRotation, turnoverPosition and ringSetting.

In addition to the components and the machine, the Enigma package contains two factory classes: RotorFactory and ReflectorFactory. These were implemented to encapsulate all rotor and reflector instance creation. This includes creation of pre-set components, as shown in Table 1 and Table 2 from chapter 3, which were hard coded into these factory classes, as well as creation of custom components. By encapsulating this functionality, it also allows for a clean and concise method for checking additional constraints on the component’s encodings. This is especially important for the reflector, which has the most constraints.

The attributes for the Enigma model are a list of rotors, a plugboard and a reflector. This properly reflects the components of the physical machine.

The encryption process is based on two key functions: encode and rotate. The former takes a plaintext character as input and returns a cyphertext character as output whilst following the encryption steps formulated previously in Equation 2. This function only encodes one character; however, this can be simply extended to a whole message using iteration. A flowchart depicting the developed encryption process for a single character is shown in Figure 12. The flowchart shows a call to the rotate function which is presented as pseudocode in Code Block 1, before subsequently calling each components encode function (scrambling the letter) in the following order: plugboard, right rotor, middle rotor, left rotor, reflector, left rotor, middle rotor, right rotor, plugboard.

A diagram of a character

Description automatically generated

Figure A flowchart depicting the Enigma models encryption/decryption steps

FUNCTION rotate() {

doubleStepped = false

// The rare case of double stepping (the left and middle rotor rotate when the middle is at a turnover)

IF (rotors[MIDDLE\_ROTOR].isAtTurnoverPosition()) {

rotors[MIDDLE\_ROTOR].rotate()

rotors[LEFT\_ROTOR].rotate()

doubleStepped = true

}

// Rotate middle rotor if right-most rotor is at turnover

IF (rotors[RIGHT\_ROTOR].isAtTurnoverPosition() AND NOT doubleStepped) {

rotors[MIDDLE\_ROTOR].rotate()

}

// Right-most rotor rotates every key press

rotors[RIGHT\_ROTOR].rotate()

}

Code Block The Enigma's rotation mechanism demonstrated by pseudocode

### EnigmaPlus

The EnigmaPlus model was developed alongside the original machine. The readjusted structure of the Enigma package is demonstrated in Figure 13. This new UML diagram shows both EnigmaPlus and Enigma inheriting from a base class named RotorMachineBase, which was included to help reduce the amount of duplicated code within the package, as well as ensure the two models work in similar fashions.

A diagram of a machine

Description automatically generated

Figure A UML diagram showing both Enigma and EnigmaPlus

The differences between Enigma and EnigmaPlus are small but important. The encryption process of EnigmaPlus works differently, in which encoding and decoding are two distinct operations in which one is the inverse of the other. Figure 14 shows a flowchart depicting both the encode and decode function for EnigmaPlus. It can be noted that the decode function applies each components letter scrambling in the opposite order.

A diagram of a character

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Figure EnigmaPlus encryption and decryption flowcharts [TODO : Fix typo!]

### Model Tests

During implementation of both the Enigma and EnigmaPlus models, a suite of unit tests was developed to validate the inputs and outputs of the models. For both models, ensuring that a message can be encoded into cyphertext, as well as decoded back to the original message was essential. In addition, both models were required to be fully configurable.

Specifically for the Enigma model, the requirements also state that the model should accurately reflect the output of the real-world machine. To validate this, the output cyphertext generated by similar products was used for comparison to ensure accuracy due to the difficulty of gaining access to the real-world machine. After performing testing on the multiple similar products (Enigma Machine Emulator n.d.) (Enigma Machine n.d.), it was found that once configured in the same way (using rotors I, II and III all in rest position, the reflector choice being UKW-B and no plugboard connections), all products produced the same output (“AAAAA” encoded to “BDZGO”).

Table 3 shows an extract of a test plan that was developed and followed in order to meet the requirements mentioned in this section. It is important to note that for EnigmaPlus, the message used to test the encryption was specially chosen in order to validate the existence of self-coding. To ensure an accurate simulation of Enigma, all tests were required to pass. The results of these tests and other metrics are covered in chapter 5.

|  |  |  |  |
| --- | --- | --- | --- |
| Test Case | Description | Test Steps | Expected Result |
| Enigma/EnigmaPlus encryption + decryption test | A test to validate whether a given message can be encoded to cyphertext, and then decoded back to the original image given the same settings for the Enigma model | 1. Configure model to chosen settings  2. Encode chosen message  3. Record cyphertext  4. Decode cyphertext  5. Check output of the decryption matches original message | Input message matches the decryption output |
| Enigma accuracy test | A test to validate that the Enigma model creates the same output as other Enigma related products | 1. Encode a chosen message  2. Compare output to several examples extracted from similar products | Output of the encryption matches that of similar products |
| Enigma/EnigmaPlus configuration test | A test to validate that both Enigma and EnigmaPlus have fully configurable settings such as rotors or plugboard | 1. Setup each model with chosen settings  2. Attempt to change the rotor settings (rotation, ring, selection), reflector choice and plugboard wiring  3. Validate these changes have taken place | All components can be configured, and the respective changes take place |

Table A snippet of a test plan for validation of the Enigma and EnigmaPlus models

To implement these tests, the Java testing framework JUnit was used to create a test package with the focus of testing the components of the project. This package exists outside the scope of the overview of the project given at the beginning of this chapter. The contents of Table 3 is not exhaustive, and simply provides a snippet of the tests included in two Java test classes named EnigmaTest and EnigmaPlusTest.

### Additional Features

In addition to the models developed in this project, numerous classes were added to the Enigma package to create ease-of-use. During the development of the CLI and GUI, these features provided interesting information regarding each model. These features are not present in previous UML diagrams for simplicity.

Two static logger classes were implemented that log both Enigma and EnigmaPlus. Both models utilise these classes to provide a step-by-step outline of the encryption/decryption process. The loggers also provide information such as the current rotation at any given frame in the encryption, the effect that each component has on an input letter and all other information regarding the state of the model.

Additional functionality was needed for each model which generates a list of all wiring connections in the model at any given frame by using enumeration, where each letter of the alphabet is encrypted (without rotation applied) and the scrambling of the letter is recorded at each component. This addition allowed for a complete picture of the model to be generated at any time and was used primarily in the visualisation tool within the GUI.

## Config and Parsers

The Config and Parsers packages were implemented to create an XML based miniature database within the project. The Config package contains three files, rotor\_bank.xml, reflector\_bank.xml and enigma\_settings.xml which allows the user to configure the settings for the Enigma machine. The Parsers package contains several XML parsers to parse and store the contents of the files stored within the Config package.

As per the requirements of this project, the machine needed to be fully configurable akin to the physical machine. However, during the implementation of the Enigma package, an additional system allowing the user to configure the machine beyond the capabilities of the original machine was developed to provide a more explorative experience for the user. Both rotor\_bank.xml and reflector\_bank.xml were created to allow the user to create their own definitions of the corresponding components much like the definitions shown in Table 1 and Table 2. Code Block 2 shows an example of an entry a user could create in rotor\_bank.xml, creating a new rotor called “MyCustomRotor”. At runtime of either the CLI or GUI application, the Parsers package will then create rotor objects based on the contents of this file and store it in ComponentCache along with pre-configured components. This cache is then used in both the CLI and GUI for configuration.

<rotor\_bank>

<rotor>

<name>MyCustomRotor</name>

<encoding>ZYXWVUTSRQPONMLKJIHGFEDCBA</encoding>

<turnover\_position>E</turnover\_position>

</rotor>

...

</rotor\_bank>

Code Block rotor\_bank.xml contents showing an example custom rotor called "MyCustomRotor"

The enigma\_settings.xml file was created exclusively for the CLI for a simpler configuration experience. In addition, it also allows the use of any custom components that are stored within ComponentCache at runtime. Code Block 3 shows an example configuration of the Enigma using the custom component shown in Code Block 2.

<enigma>

<plugboard encoding="AM FI NV PS TU WZ"></plugboard>

<rotor>

<name>MyCustomRotor</name>

<ring\_setting>22</ring\_setting>

<start\_position>L</start\_position>

</rotor>

<rotor>

<name>I</name>

<ring\_setting>13</ring\_setting>

<start\_position>B</start\_position>

</rotor>

<rotor>

<name>II</name>

<ring\_setting>24</ring\_setting>

<start\_position>A</start\_position>

</rotor>

<reflector>

<name>UKW-A</name>

</reflector>

</enigma>

Code Block enigma\_settings.xml contents depicting the start settings of the machine

## CLI

As per the requirements, the CLI was to be developed as a basic and simple application which acts more like a tool rather than an educational experience. Consequently, the code that underpins this application is relatively short and simple. As previously mentioned, when using the CLI the configuration of the Enigma model takes place within the Config package, specifically enigma\_settings.xml as demonstrated in Code Block 3. Originally, a multi-faced menu approach was experimented with to allow for the user to configure the machine. However, due to the complexity of the Enigma’s key, this led to a tiresome and confusing experience during the setup of the model. The Config package approach allowed for easier editing as well as enabling the settings of the Enigma to be stored.

When the system is run, the Enigma settings are displayed to the user, to ensure that they understand the settings that were used to encrypt their message. Then, the user is prompted to enter a message before the correct cyphertext (or plaintext if this is a decryption) is displayed. Code Block 4 shows an example of the expected interaction with the CLI, showing the chosen settings being most of the text, and showing the encryption result of the message “HELLO WORLD”. The same output would be expected if the user intended to decode a message, however the input “HELLO WORLD” would be replaced with “JCUGQ KVBVF” and vice versa.

Plugboard : [AM FI NV PS TU WZ]

Reflector : UKW-A (EJMZALYXVBWFCRQUONTSPIKHGD)

Right Rotor : III

Rotation : L

Ring Setting : 22

Encoding : BDFHJLCPRTXVZNYEIWGAKMUSQO

Middle Rotor : I

Rotation : B

Ring Setting : 13

Encoding : EKMFLGDQVZNTOWYHXUSPAIBRCJ

Left Rotor : II

Rotation : A

Ring Setting : 24

Encoding : AJDKSIRUXBLHWTMCQGZNPYFVOE

Enter plaintext message:

HELLO WORLD

Cyphertext

JCUGQ KVBVF

Code Block An example of the expected interaction with the CLI

The functionality to accomplish the requirements of the CLI was achieved by creating the EnigmaSimulatorCLI runnable Java class.

## GUI

TOOD : Create opening paragraph

### GUI Design

The GUI was one of the larger requirements for this project. The goal was to create an application that could be used to configure and operate the Enigma machine as well as exhibiting an easy-to-understand user interface. As explained in section 3.5, numerous other products exist that attempt to apply skeuomorphic designs to their simulation. The UI for this project would mostly avoid reflecting a physical representation of the machine and adopt a simpler approach. This is because the Enigma machine’s layout is rather obscure. Figure 15 shows an early mock-up of the design of the GUI, which uses a top-to-bottom approach for user interaction. The idea behind this design was that the user would configure the reflector, rotors and plugboard before entering their message on an on-screen keyboard, displaying the cyphertext message below as they entered their message.

A screenshot of a computer

Description automatically generated

Figure An early mock-up design for the GUI

The rotors and the reflector are selected by drop-down menus, allowing the user to select one of the rotors stored within ComponentCache (both custom and pre-configured components). In order to stick with the simple design of the interface, it was decided that the plugboard would consist of a text field in which the user would have to enter cable pairs such as “AB CG OI” to represent the connections. The other option would be to create a clickable interface like the online Enigma emulator (Enigma Machine Emulator n.d.) however this proved difficult to implement without creating interface clutter. Finally, it was decided that the message input would consist of an on-screen keyboard, and each keypress would cause the encoded letter to appear in the “Message Display” text field.

To aid the development of the GUI, Gluon Scene Builder was used to quickly create a high-fidelity prototype of the user interface. This tool creates FXML files (a variation of XML) which can be used alongside JavaFX. Figure 16 shows this UI prototype, which exhibits a number of differences to the original design. The biggest difference is the input mechanism, which was changed from an on-screen keyboard to a simple text field. Whilst trying to build this prototype, it was decided the previously proposed on-screen keyboard would create too much clutter in the application as well as provide a significant challenge for implementation. Additionally, a large text field was added at the bottom to display a log of the encryption. This was to provide information along each step of an encryption process and later became the foundation for the visualisation.

A screenshot of a computer

Description automatically generated

Figure A high-fidelity prototype of the user interface provided with the GUI

To incorporate the EnigmaPlus model into the GUI, an additional tab was added to the top of the interface, to allow the user to switch between models. By switching models, the user is presented with a slightly different interface for the configuration of the machine. Figure 17 shows a high-fidelity prototype of the setting configuration panel for EnigmaPlus, which can be compared to that of Figure 16. The key difference between these two panels, is that EnigmaPlus does not require a reflector and an additional option allowing the user to choose whether to decode or encode the input message.

A screenshot of a computer

Description automatically generated

Figure The configuration settings for EnigmaPlus within the GUI

### Model-View-Controller Architecture

In order to create clean and easily modifiable code, the GUI follows the model-view-controller (MVC) architecture. This architecture aims to separate an applications code into three components: model, view, and controller. In the case of this project, the model is the developed Enigma/EnigmaPlus class. For the view, Gluon Scene Builder combined with minimal code could provide FXML files to define the GUI (EnigmaSimulatorApp and GUI.fxml). Finally, an additional class was created within the GUI package known as EnigmaController which handles any communication between the view and the model, thereby acting as the controller. Figure 18 shows how the MVC architecture has been applied to this project.

A diagram of a user

Description automatically generated

Figure The MVC architecture applied to this project

### Visualisation

The final requirement with the GUI was to provide the user with a visualisation of the encryption process, with the aim of educating the user about the workings of Enigma. As demonstrated in section 3.3.2, the simplest way to understand the Enigma is through abstractions, often taking the form of wiring diagrams. Therefore, a visualisation tool was developed and implemented into the GUI which generates wiring diagrams (see Figure 7) for each frame of the user’s encryptions.

The first task to complete was to integrate the visualisation tool into the already existing GUI. To accomplish this, an additional tab would be added to the bottom of the interface. Figure 19 shows another high-fidelity prototype of the GUI, this time including the “Visualisation” tab along with other changes. The idea behind this was to display the wiring diagram of the encryption in the large blank space, providing additional information above (encryption and current rotation) and allowing the user to switch frames and display additional wires not directly used in the encryption (“<” and “>” buttons along with “Show all wires” check box).

A screenshot of a computer

Description automatically generated

Figure A high-fidelity prototype of the GUI including the “Visualisation” tab

In order to draw a diagram programmatically with various shapes, a JavaFX canvas object had to be used. This object allows for shapes and lines to be drawn via a coordinate system however, all reference to any shapes created is lost. To encapsulate this functionality, two additional files called EnigmaVisualiser and EnigmaPlusVisualiser were created to control all aspects of the visualisation. The code within these classes consisted mostly of geometric calculations to generate a legible and informative diagram. The generated wiring diagrams were designed to represent Enigma like the diagrams shown in chapter 3 but instead including the entire 26 letter alphabet. Figure 20 shows a mock-up example wiring diagram depicting the minimum requirement of the visualisation. In this diagram, the red coloured lines represent current flowing right-to-left, and the blue coloured lines represent current flowing left-to-right such that the plaintext character “A” is encoded to “W”. In addition to the information presented in the figure, it was also decided that all other internal wires in the given encryption frame should be shown as well (by utilising the functionality mentioned in section 4.2.3), but this is not shown in the figure. The actual results of this visualisation tool and further discussion are expanded in chapter 5.

A diagram of a graph

Description automatically generated

Figure A mock-up example of the diagram that should be generated by the visualisation tool

# Results

This chapter presents the results of the project focussing on the accuracy of both Enigma models as well as demonstrating the finished product of both the CLI and GUI.

## Enigma and EnigmaPlus

Both the Enigma and EnigmaPlus models were required to be fully functional, where a message could be encoded and decoded using the same key. In the case of Enigma, the model also had to reflect the functionality of the real-world machine as best as possible.

### Model Testing

The Enigma and EnigmaPlus models were developed alongside unit tests in order to provide a test suite to validate their accuracy. This suite consisted of 20 different tests which were based on examples from similar products. Both models were developed such that all 20 tests passed, ensuring that the functional requirements (demonstrated in the test plan within Table 3) of both models were met. Figure 21 shows the test coverage metrics provided by Maven, providing an indication of the robustness of the models, notably Enigma and EnigmaPlus both exhibit coverage scores over 75%.

A screenshot of a graph

Description automatically generated

Figure A table demonstrating the test coverage of the Enigma package

### Enigma Accuracy

As explained in section 4.2.3, an example encryption used in the testing was the input string “AAAAA” which was encoded into “BDZGO”. Figure 22 show a collection of screenshots demonstrating the example encryption taking place whilst using the Cryptii Enigma web application (Enigma n.d.). Figure 23 provides the input and output of the same encryption taking place using the Enigma Emulator (Enigma Machine Emulator n.d.).These two examples were then compared to the output produced by the CLI (see Figure 24 below) showing that the output of the Enigma model is a match.

A screenshot of a computer

Description automatically generatedA close-up of a computer screen

Description automatically generatedA close-up of a computer screen

Description automatically generated

Figure A collection of screenshots to show the “AAAAA” encryption using the Enigma model on Cryptii (Enigma n.d.)

A book with text on it

Description automatically generated

Figure A screenshot of the Enigma Emulator (Enigma Machine Emulator n.d.) to show the results of the “AAAAA” encryption

A screenshot of a computer program

Description automatically generated

Figure A screenshot of the CLI output showing the results of the "AAAAA" encryption

In addition to comparing similar products, a real, contemporary Enigma message was used from a collection of different messages (Enigma/Sample Messages n.d.). Due to the limited number of messages available, only one could be used for comparison. Figure 25 shows screenshots from the web page showing the message, and corresponding settings Enigma settings. Figure 26 shows a screenshot of the decryption of the message within the developed CLI. Due to arbitrary shorthand and typos, the message looks illegible, however with some additional processing, the message translates to “**FEINDLICHE INFANTERIE KOLONNE BEOBACHTET. ANFANG SUEDAUSGANG BAERWALDE ENDE DREIKM OSTWAERTS NEUSTADT**” which again translates to English as “**ENEMY INFANTRY COLUMN OBSERVED. BEGINNING SOUTH EXIT BAERWALDE END THREE KILOMETERS EAST NEUSTADT**” (Enigma/Sample Decrypts n.d.).

A white rectangular box with black text

Description automatically generated.

A black and white text

Description automatically generated

Figure A genuine message encrypted by Enigma, taken from a collection of contemporary messages (Enigma/Sample Messages n.d.)

A screenshot of a computer

Description automatically generated

Figure A screenshot of the CLI depicting the decryption of a genuine Enigma message

## CLI, GUI and Visualisation

The CLI developed for this project was designed to be simple and quick to use. As such the finished product of the CLI is close to its original design demonstrated in section 4.4. The configuration of the machine takes place within the previously mentioned enigma\_settings.xml and the output of the CLI can be seen in Figure 26 and Figure 24 shown above.

The GUI allows interactions with both Enigma and EnigmaPlus, ensuring the user can operate and configure both machines beyond their physical capabilities (see Figure 30 below, which includes “MyCustomRotor” in the drop-down menu). In addition, the application supports Windows, MacOS and Linux machines, as well as providing a visualisation tool to demonstrate the encryption process of each model. The results shown in this section follow the original design closely, with some minor additions. Most notably, the application is skinned to have a more modern aesthetic. Secondly, an additional feature has been implemented to allow the user to automatically step through the encryption, changing the wiring diagram at each step. Finally, a label called “Machine Permutations” is present, which aims to indicate the cryptographic strength of the chosen model.

Figure 27 shows an example of the GUI being used to encrypt a message displaying the visualisation at the bottom. In this particular example, the visualisation only shows the wire through which the current has passed as explained in Figure 20 from the previous chapter. This can be compared to Figure 28, which shows the same generated wiring diagram, but with all other wires also being visualised. These additional wires can be shown and hidden at any time by selecting the “Show all wires” check box. The EnigmaPlus model can be interacted with by clicking the “EnigmaPlus” tab at the top of the screen and then proceeding as usual. Figure 29 shown an example of an encryption taking place using EnigmaPlus.

A screenshot of a computer

Description automatically generated

Figure An example of the developed GUI being used for an Enigma encryption (Windows)

A screenshot of a graph

Description automatically generated

Figure A generated wiring diagram, showing all wire configurations in a given frame

A screenshot of a computer

Description automatically generated

Figure An example of the developed GUI being used to perform an EnigmaPlus encryption (Windows)

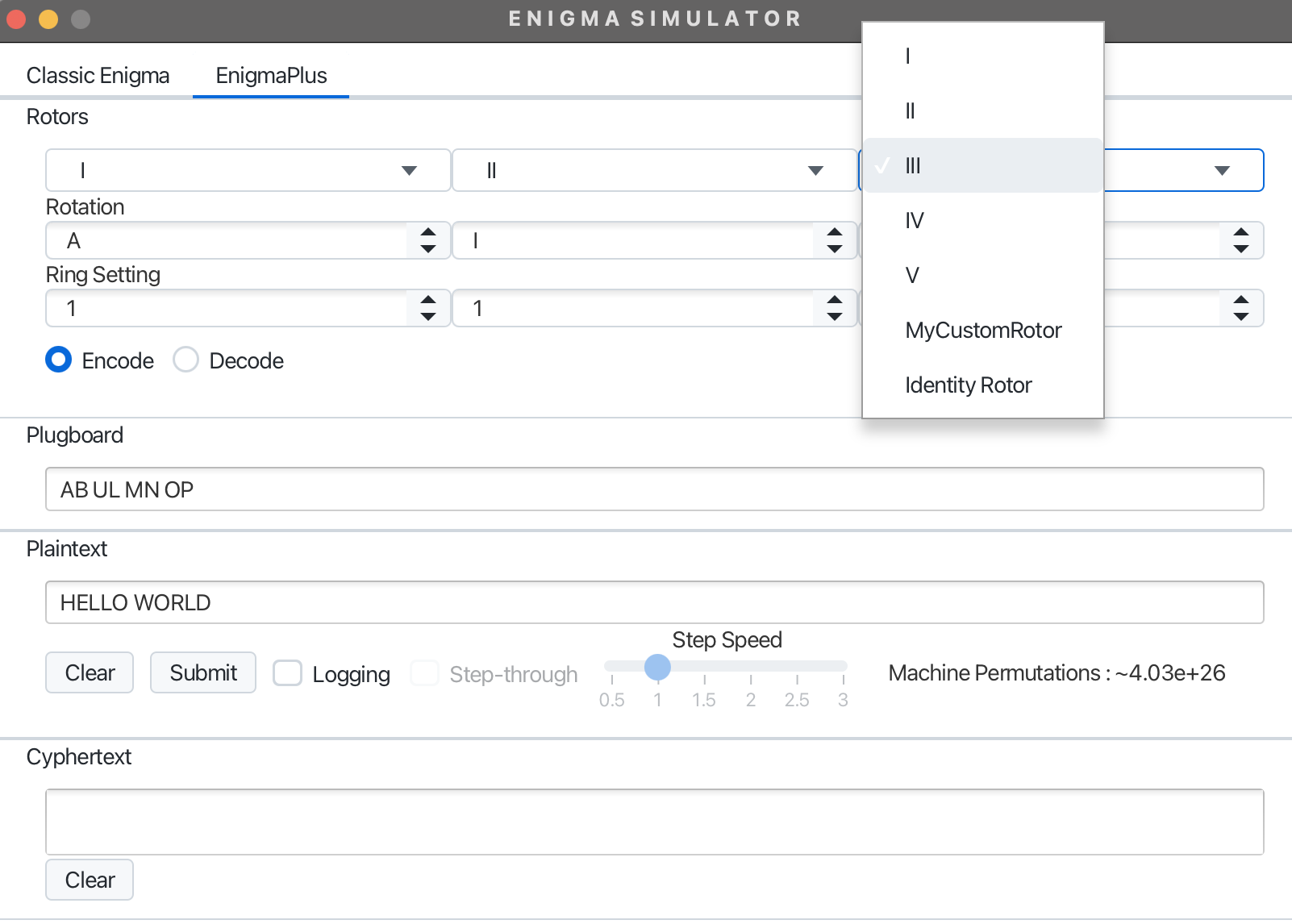


Figure A screenshot of the UI demonstrating rotor selection (MacOS)

## Additional Accomplishments

Along with the delivery of the core requirements, the development of this took place within GitHub, allowing for tasks to be planned and tracked. In addition, in some cases additional branches were used for the implementation of larger features such as the GUI. The GitHub page of this project (Brooks 2024) also contains a README file providing a brief overview of the project and instructions on how to run the program.

# Evaluation

The developed project provides a complete simulation of the Enigma machine through two different interfaces, including other features such as visualisation and EnigmaPlus. The following chapter reflects on the development process as well as the results providing a discussion of the work completed.

## Enigma Model Evaluation

The developed Enigma model performs extremely well, correctly matching the inputs and outputs of the similar products mentioned previously. In addition, the fact that genuine Enigma messages can be decrypted significantly increases the confidence that the developed model is authentic. Had it been possible, it would have been much better to compare the results to the genuine physical machine, however access to the Enigma is limited.

In terms of features, the model enables full configuration of the machine, beyond its original capabilities. However, as mentioned in the beginning of this report, the developed model simulates *Enigma I* which is only one machine belonging to the Enigma brand. Many of the machines inspired by *Enigma I* included more complicated rotor mechanisms and additional rotor slots. The model developed in this project is limited in this sense and would require significant refactoring and development to accommodate these changes.

Regarding the test results mentioned in the previous chapter, both Enigma and EnigmaPlus are well-tested, ensuring that their behaviour is correct. In addition, numerous test cases and error handling were implemented to help ensure the robustness of the two models. Despite this, there is still room for improvement regarding the test coverage as some less important functionality remains untested.

## CLI and GUI Evaluation

The CLI provides a simple tool allowing for quick configuration and message encoding. In addition, it provides helpful information to the user to demonstrate what settings are being used. Whilst simplicity was the goal for this application, it could be improved with some more interactive aspects such as generating a log of the encryption or allowing a file to be exported, reflecting a traditional setting sheet used for the physical machine.

The developed GUI exhibits a sleek aesthetic attempting to offer a simpler experience than the physical machine when operating Enigma. The design of the GUI follows a top-to-bottom approach, attempting to create a natural feel for the user. Despite the clear and uncluttered design, it does however lose some authenticity, and without being properly informed, it could introduce more confusion to the user. Other similar products such as the Enigma Emulator (Enigma Machine Emulator n.d.) offer more skeuomorphic designs, which can help the user understand the relationship between the GUI and the physical machine. This aspect was originally considered in the design however, it was decided that it would prove too complicated with the chosen technology. An additional drawback to the provided GUI design is that the input modalities vary from the physical machine. The most notable example of this is the plugboard, in which the implementation of this in the GUI avoids the use of cables or sockets.

The visualisation provided with the GUI offers an accurate, real-time abstraction of the encryption process taking place. As mentioned in section 3.3.2, by abstracting the machine into wiring diagrams the workings of Enigma become much clearer. Consequently, the visualisation feature brings significant value to a user wanting to understand how the machine works. Despite this, without the contents of this report or further research, it is not clear how to interpret the diagrams of both Enigma and EnigmaPlus. This limitation could be improved by re-designing the wiring diagrams to be more self-descriptive, potentially also including animations to support this.

## An Educational Perspective

TODO : Move to conclusion

During the development of this project, the educational value of this project was clear. The developed solution to the specification provides an interactive experience with Enigma, allowing the user to operate the machine and encourages the user to explore Enigma with the use of custom components. This provides an enriching experience for the user, without over complicating the CLI and GUI.

To further support the user’s learning, the project could provide further background. In its current form, the project is likely catered towards those who already have some knowledge of the physical machine or the similar products and want to learn more. To improve the learning experience, the additional materials could be included with the project in forms such as in-application tutorials or a guide. These materials could be aimed at multiple demographics, such as a museum, where the GUI could be presented alongside additional materials.

# Conclusion

This project is a passion driven exploration into the Enigma machine and its history. It attempts to recreate the Enigma machine in a meaningful and interesting manner to inspire others to learn about this important part of history. On a personal note, the project has also been a very significant learning experience, further developing my engineering skills as well as providing one of the biggest research projects I have taken on.

The original specification for this project only required a configurable simulation of the Enigma machine along with a simple CLI or GUI. Due to the acquired personal interest in this project, additional requirements were introduced, providing unique aspects to the project, such as EnigmaPlus, the visualisation tool and enabling further configuration to Enigma. All these requirements were met to a good standard by adopting modern software engineering practices such as OOP, MVC architecture and well tested code. The visual and interactive design for both the CLI and GUI are easy to understand, aesthetically pleasing, and fully functional, providing a complete Enigma experience.

Whilst the developed solution provides a complete set of features which are comparable to similar products, it provides other features that enhance the users understanding of Enigma. There are still numerous improvements that could be made to assist in educating the user on Enigma. The most notable improvement to be made is to allow for the user to operate, and therefore understand Enigma without the need to research additional background information.

For any future work, many of the mentioned improvements could be implemented with relative ease. In addition to this, this project naturally suggests further work regarding the events surrounding Enigma. For example, a future project could investigate the breaking of Enigma, providing an algorithm to break Enigma or even simulating the Turing-Welchman Bombe.

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