Enigma-Fusion: Connecting Digital Twin and 3D-Printed Reconstruction

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Abstract

This paper presents the design and realization of a fully functional, 3D-printed replica of the Enigma cipher machine, coupled with an interactive digital twin via a hardware–software interface. Beyond the acquisition of practical and transferable skills, the project enabled student-participants to develop a thorough understanding of the machine's mechanical operation, encryption principles, and historical relevance. The combined physical and digital system supports an illustrative and transparent demonstration of the Enigma's internal processes, making its cryptographic functionality accessible and comprehensible to a broad audience.

1 Project Framework and Conditions

The Enigma reconstruction project was carried out as a student project as part of a degree programme in computer science. The seminar component focused on the machine's historical role, as well as on the fundamentals of its cryptographic operation.

It required each student to research and present on core topics, including the Enigma's mechanical design, the principles of encryption and decryption it implements, historical context and significance, and, of course, Allied cryptanalysis efforts — most notably the work carried out at Bletchley Park. These presentations formed the academic groundwork for the practical phase (Bauer, 2000; Welchman, 2023; Bruderer, 2020).

After the seminar component, the practical one followed, which consisted of several parts. On one hand, the participants built a 3D-printed, fully working Enigma I reconstruction. On the other hand, a digital twin of the Enigma machine, EnigmaTwin, was built. Finally, the digital twin was connected to the 3D-printed Enigma machine via an interface enabling the keys from the hardware version as input to its digital twin.

An overall goal of the project was to present the final result to a wider audience in the form of a presentation and demonstration at a local science event.

2 Educational Goals and Academic Focus

A central objective was to enable the participants to develop a deep conceptual understanding of encryption mechanisms, using the Enigma machine as a historically significant and technically rich example. By studying its rotor-based cipher system, plugboard configuration, and operational procedures, the students explored how electromechanical encryption devices embody fundamental principles that still influence modern cryptography (Bauer, 2000; Bruderer, 2020).

Equally important was the historical perspective. Through their seminar work, the students examined the Enigma's decisive role in World War II, its impact on secure military communication, and the extraordinary cryptanalytic efforts at Bletchley Park that contributed to the Allied victory. This dual focus on technical function and historical consequence encouraged the participants to understand encryption not merely as a mathematical problem, but as a phenomenon with profound cultural and geopolitical implications (Welchman, 2023).

A second major objective involved strengthening practical, hands-on skills. Working with contemporary technologies such as 3D-printing introduced the students to digital fabrication processes, materials selection, tolerances, and iterative prototyping. They also practiced basic electronics and wiring techniques while assembling a functional machine. These activities required continuous experimentation, troubleshooting, and collaborative problem-solving — core competencies in computer science and engineering education.

Finally, the project was intentionally structured to foster teamwork, communication, and analytical thinking. From coordinating research for seminar presentations to planning the construction workflow, the students were required to collaborate, negotiate design choices, and reflect on their methods. In combining historical research, cryptographic theory, and modern fabrication, the project encouraged them to engage with the broader intersection of history, technology, and information security — and to appreciate how these domains inform one another (Hubwieser, 2007).

3 Reconstructed Enigma

The reconstructed Enigma is a physical reconstruction of an Enigma machine using additive manufacturing (3D-printing) for the case and selected mechanical parts. To enable correct operation, electrical functionality is required, which includes wiring and battery power, so that it can operate independently of laboratory mains power.

The build follows previous reconstructions inspired by the design of Hochschule der Medien Stuttgart which were then updated with the help of materials provided by Deutsches Museum, Munich (Wiest, 2021; Deutsches Museum, 2022). It was modified to suit available materials, safety considerations, historical accuracy, and learning objectives.

The main step is the fabrication of mechanical components of the Enigma replica through 3D-printing. The complete workflow includes file preparation, material selection and calibration. During the process, refinement of parts is an important step to ensure proper fit and durability.

In parallel, the electrical system is built. It includes the connection of micro-switches, LEDs, and rotors using wires. Additionally, the individual wiring links between letters in the rotors and the reflector are implemented. This setup creates a current circuit that can reproduce the machine's lampboard output. Verifying signal flow and debugging the circuitry forms an essential part of the later construction process.[1]

Once assembled, shown in Figure 1, the replica achieves its intended functionality: pressing a key illuminates the corresponding substituted letter, accurately reflecting the internal wiring logic of the Enigma's cryptographic mechanism.

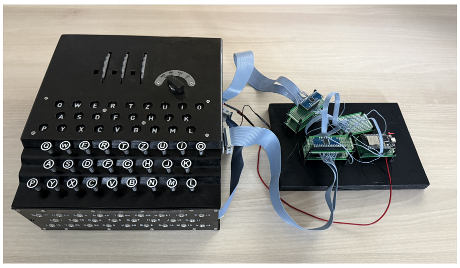

Figure 1: 3D-printed replica of the Enigma machine. On the right side is the hardware part of the interface between the replica and EnigmaTwin.

4 EnigmaTwin

EnigmaTwin is an interactive application representing a digital twin of an Enigma machine. It includes a 3D visualization with a functioning logic. This software allows viewing the machine from different angles, changing its transparency, and observing the different parts and mechanism during usage. After setting configurations, messages can be encoded or decoded using the keyboard as input. As an additional feature, the path of the current can be visualized during the encoding of a letter, allowing a better understanding of the inner mechanisms. The ability to visualize current and mechanics in an interactive way is one of the strong contributions of this paper that existing simulators do not offer (Gillow, 2021; Enigma Machine Emulator, 2019; Palloks, 2025).

Logic. The logic is the core of the program, since it is the foundation for a correct message encryption. This subsection covers the most important parts of it, providing pedagogical transparency for a possible replication of the project.

We represent the letters $a, b, \ldots, z$ by the integers $0, 1, \ldots, 25$ defining a set $\mathscr{L}$. Addition and subtraction of a letter by an integer k is performed modulo 26. Let the plugboard p, the rotors r and the reflector u be the bijective functions:

$$p : \mathscr{L} \to \mathscr{L}; r_{i,n} : \mathscr{L} \to \mathscr{L}; u : \mathscr{L} \to \mathscr{L} \qquad (1)$$

$r_{i,n}$ represents the ith rotor that has a rotation $n \in \mathscr{L}$. Plugboard p is modeled as a pair-wise mapping table including the entire set $\mathscr{L}$. A letter can be linked either to itself or to a different letter, depending on the plugging of the plugboard cables.

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[1] Before their participation, the students completed practical hands-on training in the university workshop, including soldering and the use of measurement instruments.

The rotation of the wiring n of a rotor $r_{i,n}$ combines the rotation of the digit ring, the so called ring setting $\omega \in \mathscr{L}$, and the rotation of the whole rotor $\psi \in \mathscr{L}$:

$$n = \psi - \omega \tag{2}$$

ψ is incremented every time that the rotor is rotated. The frequency of rotor rotations is determined by the rotor's position. The right rotor turns at every encryption of a new letter. The two other rotors rotate when the rotation ψ of their right neighbor equals specific values (Smart, 2016). At these rotation values, the notch of those neighbors is facing towards the back of the Enigma, allowing the pawls to rotate the rotor and its neighbor. This also realizes the double-stepping mechanism of the middle rotor.

Every rotor $r_{i,n}$ has its table t_i with unique encryption, where its values correspond to the wiring of the rotor (Bauer, 2000). Using t_i, the function of a rotor $r_{i,n}$ that corresponds to the encryption of a letter λ in the forward direction, coming from the plugboard, is defined as:

$$r_{i,n}(\lambda) = t_i(\lambda + n) - n \tag{3}$$

To calculate the output letter backwards, coming from the reflector, Equation 3 is adapted to $r^b_{i,n}$:

$$r^b_{i,n}(\lambda) = \{j - n | t_i(j) = \lambda + n\} \tag{4}$$

where $j \in \mathscr{L}$.

The reflector u is implemented as a table of encryption combinations resembling UKW-B (Bauer, 2000).

All in all, the function E that represents the whole encryption process of the Enigma is:

$$E(\lambda) = p(r^b_{\alpha,n_0}(r^b_{\beta,n_1}(r^b_{\gamma,n_2}(u(r_{\gamma,n_2}(r_{\beta,n_1}(r_{\alpha,n_0}(p(\lambda))))))))) \tag{5}$$

where λ is the input letter, and α, β and γ are three different rotors each having a rotation n_0, n_1 and n_2.

Creation and Assembly of parts. To create the digital twin, the stl files from the 3D-printed parts are incorporated. Missing parts, such as cables, screws, switches, and the battery, are designed in Blender. All parts are first assembled in Blender and then transferred to Unity for further processing. Further implementation details are provided in Section 6.

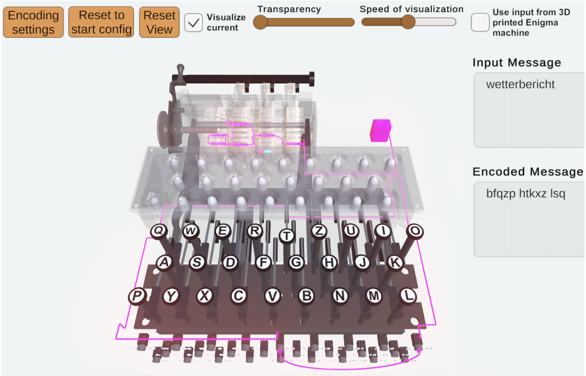
User Interface. The application also includes an interface for control. Users can zoom, rotate, and move around the Enigma using their mouse. The main view offers different features. There are two small windows showing the given input and the corresponding encryption. There are also buttons to reset the view and configurations of the Enigma. Furthermore, two check boxes enable connection to the 3D-printed Enigma or visualization of the current flow. Two sliders change the transparency of the Enigma and the speed of the current visualization. Additionally, one button opens a menu to set rotors α, β and γ, their configurations ψ and ω, and plugboard-cable combinations. Changing these settings triggers the creation of plugboard cables or animations around the rotors, as well as configurations in the logic are adjusted.

Animations. The application features several animations that visualize the operation of the Enigma. One animation represents the illumination of the encoded letter by simulating a glowing lamp. Another animation depicts the mechanical interaction of the keyboard: when a key is pressed, the corresponding button moves downward, causing the actuator bar to rotate around its central axis. This rotation lifts the pawls, reflecting the mechanical response of the original machine. These animations are implemented using Unity's built-in animation system. In addition, the rotors are visualized through a set of dedicated animations. When a rotor is assigned to a specific position within the encryption pipeline, it is placed accordingly. Ring settings are represented by rotating the digit ring by the required offset ω. Rotating the entire rotor by a defined angle simulates the stepping mechanism.

Transparency. The cover can be made transparent with a slider. To achieve transparency, the opacity value α of the materials is decreased using Unity-specific elements called MaterialPropertyBlocks.

Plugboard cables. Setting a letter combination for the plugboard triggers the creation of a new cable. Using the positions of the two letters as start and end, a cubic Bezier curve is calculated. Subsequently, a circle is determined at discrete points of the Bezier curve using the vector between the point before and after as the normal vector. The points of all circles are then connected with triangles to form a mesh.

Visualization of the current. Inspired by an explanation video (Owen, 2021), the current can be visualized. During the visualization, all cables are set to transparent, and many parts of the Enigma have a high transparency for a better visualization. While the logic encrypts the letter, it stores the names of the different, necessary cables. Starting from the battery, the visualization uses these cables to trace each one in turn, showing the current's path. The coloring of the path is completed by iterating over the texture coordinates of the cables, and changing the colors directly in the fragment shader. The tip of the path is colored in light blue, while the remaining part of the already visualized path is colored in magenta. When the visualization passes the light bulb, it turns on. An additional blooming effect is added so that the path is better visible. This visualization allows the user to clearly see the path of the current, especially in the rotors, as shown in Figure 2.



☑ Visualize current

☐ Use input from 3D printed Enigma machine

Input Message: wetterbericht

Encoded Message: bfqzp htkxz lsq

Figure 2: EnigmaTwin with current flow visualization when a key is pressed and a plugboard cable is used. The cover is invisible.

5 Connection between Software and Hardware

Another major contribution of this paper is the connection between the 3D-printed Enigma and EnigmaTwin. To figure out the pressed key, the current has to be measured at two different positions: at the cables connecting switches and plugboard, and switches and light bulbs. Between the switches and the plugboard, current can only be measured at the cables of the input and output letter. This detail leaves only two options as the input key. When the current in the cables leading to the light bulb is measured, only the cable of the output letter shows current flow. Combining the results by a logical 'and not' determines the input.

Realization of Interface. The required hardware components are four 16:1 multiplexers and one microcontroller. The multiplexers are connected to the 52 cables from the two places where current is measured as input. Steering inputs as well as outputs are directly linked to the microcontroller. The microcontroller iterates over the inputs from the multiplexers to collect the information on which cable current flows. The logical combination of the cables is then computed by the microcontroller. If it identifies a key that is pressed, it sends this information to EnigmaTwin via WiFi. The application processes the information in real-time and uses it as new input.

6 Implementation Details

The 3D-printed parts were printed in a BambuLab X1 Carbon printer with PLA filament. The application EnigmaTwin was developed in Unity using Version 2022.3.62f2 (Unity Technologies, 2022) and missing parts were created in Blender Version 4.4 (Blender Foundation, 2024). For the interface, Arduino IDE Version 2.3.6 was used to implement the program that was transferred to the microcontroller ESP32-WROOM-32 (Arduino, 2025).

7 Conclusion

After successful completion, the outcome of this project is a fully working 3D-printed Enigma machine, which is connected via an interface with its digital twin, the EnigmaTwin. This connection allows pressing a key on the hardware Enigma and using that letter as input for the digital twin. Consequently, EnigmaTwin is an application that visualizes the inner workings and the current flow of an Enigma machine during encryption.

Among achieving different soft and practical skills, this project allowed the participants to get a deep understanding of the functionality and history of the machine. Using this result, an audience can interactively explore the encryption process from inside and outside the machine, offering an illustrative way to explain the Enigma. To ensure educational impact, EnigmaTwin has already been integrated into the seminar "History of Computing" at FAU as well as into guided tours of the ISER (Informatik Sammlung Erlangen).

Acknowledgments

The authors would like to thank Simon Wiest (HDM) for sharing his experience and results.

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