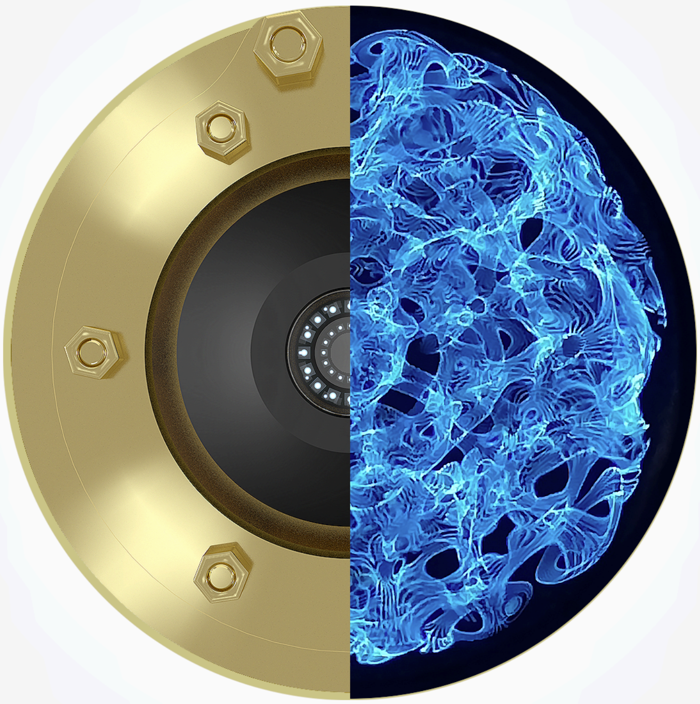

INTRODUCING BASIC ASPECTS OF QUANTUM PHYSICS THROUGH CYMATICS

GRADUATION REPORT - MARTIJN WEBER

INDUSTRIAL DESIGN ENGINEERING TU DELFT

SUPERVISORY TEAM: J.D. LOMAS & A.J.C. VAN DER HELM

Excutive Summary

Introduction

The aim of this project is to introduce aspects of quantum physics through cymatics, the study of visual wave phenomena, such as the production of patterns on a vibrating plate. Because it is aesthetically intriguing and fascinates people, it can serve as a starting point for learning wave-related aspects of quantum physics.

Context

The market of quantum computing is growing rapidly due to the rising demand of high-performance computing. By combining quantum theory and computer science, quantum computing shows great promise for future application in fields like algorithms, cryptography, machine learning and quantum simulation. Several prominent companies like Amazon, Google and IBM are well on their way in developing functional quantum computing and there has been a big increase of entrants in the market over the past decade, especially in recent years. Current investments are big and growing: the global quantum computing market size was estimated at USD 10.13 billion in 2022 and is expected to go toward USD 125 billion by 2030. Locally the Dutch government invested 615 million euros in quantum technology development through the Quantum Delta NL project in 2021 and another 60,2 million in 2023 in joint operations with France and Germany.

These investments would suggest an accompanying rise of demand for people in the fields of quantum physics and quantum computing. Data from 2021 shows that the quantum technology education infrastructure is behind on the industry. The data for instance shows that the number of outposted job vacancies in quantum technology in 2021 outnumbered the number of quantum technology master’s level graduates that year by a factor of three to one. The same research reported that 176 universities offered a quantum technology program, but only 29 universities offered a master’s degree in quantum technology. Looking at projected future investments in the quantum computing market, the current state of the quantum technology education infrastructure and it’s foreseeable shortcoming in providing a sufficiently strong workforce to answer the industry’s expansion, it can be expected that quantum education will be pressurized to conform to big change to keep up with the industry.

Project Aim and Scope

This project aims to provide a solution that will help open ways in maintaining the balance of education and industry that is needed within the quantum technology sector if the industry keeps expanding as it is currently. It hopes to deliver where currently is missing: an engaging way to interest our current youth in quantum technology before they reach university, in a way that motivates them to become one of the future quantum physicists that the industry will drastically need.

Currently basic aspects of quantum physics are difficult to convey to a younger generation in a compelling and engaging manner and the lack of existing exhibits on quantum physics in science museums, one of the places where younger generations' interest in science is fueled, only confirms this believe.

The aim of this project is to introduce basic aspects of quantum physics to a young generation through a science museum exhibit design using cymatics. The wave-like behavior in cymatics is believed to be a good starter to learn about wave-related aspects found in quantum physics.

Project Approach

To find ways to come to a successful design solution, connections between the fields of quantum and cymatics had to be made. Exploratory sessions were held to which quantum physicists from the quantum computing industry were invited, in which the examination of cymatics devices that were built for the project were examined and its relations to quantum physics and quantum computing were discussed. The collected data was analyzed and translated into design factors that were later used during the design process.

During the project several design methods were implemented. The main method used was the Vision in Product design method which formed the primary structure of the project. The strategic approach of the Vision in Product design method follows a process of deconstruction of an examined context, in this case the field of quantum computing to attain design factors that were subsequently used during the design process in a new context, approaching quantum physics and quantum computing through cymatics in a science museum exhibit environment.

Other methods applied were context mapping for data analyzation and the earlier named exploratory sessions with the quantum physicists. For the design process, a phase of conceptualization was conducted to which several concepts were developed and tested, and formulation of design visions and the use of analogies were used to come to the final science museum exhibit design.

Project Results

The data gathering and analysis resulting in the development of three concepts which were tested during a concept user test. Results and insights were used to come to a final design. In the final design museumgoers interact with cymatics through the producing of visual patterns called eigenmodes. The design uses the eigenmodes to resemble parts of a quantum computer and through interacting with the design the museumgoer can learn about basic aspects of quantum physics and quantum computing intuitively.

Introducing Basic Aspects of Quantum Physics through Cymatics

Graduation Project Report by Martijn Weber, 2023
Faculty of IDE TU Delft

Supervisory Team:
Chair: J.D. Lomas
Mentor: A.J.C van der Helm

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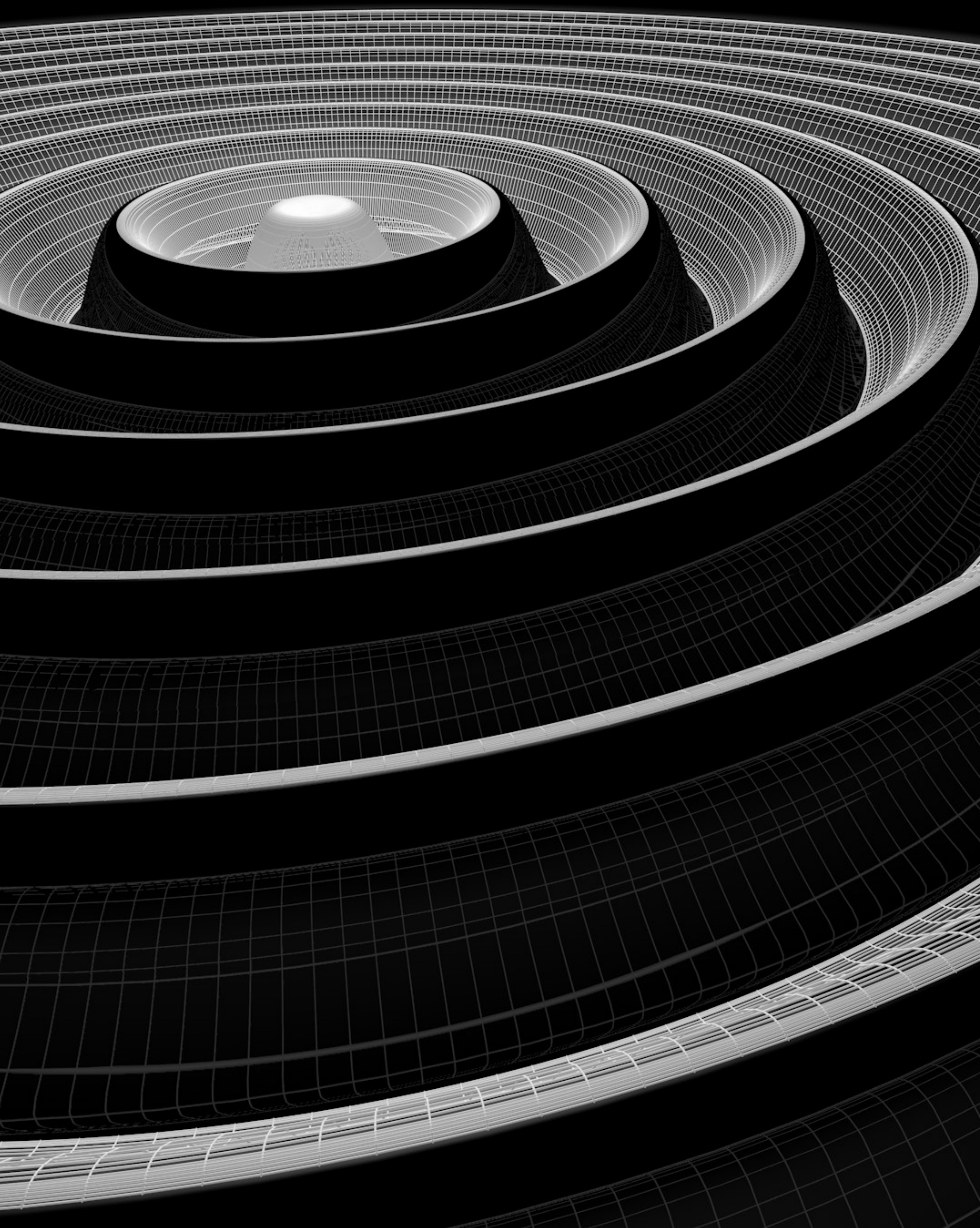

Introducing Basic Aspects of Quantum Physics through Cymatics

Introduction

The aim of this project was to introduce basic aspects of quantum physics through the use of cymatics, the study of visual wave phenomena. The goal was to find bridging connections between the topics of quantum physics, quantum computing and cymatics and use these to come to a design solution in the form of an exhibit design for a science museum. During the project a basic understanding of the topics of quantum physics, quantum computing, and cymatics was acquired and through the expertise from physicists from the research community topics and devices were examined and discussed. The project consisting of three phases comprised data gathering and analysis, exploratory sessions with experts, conceptual design and concept testing, and delivering a final design solution.

The Quantum Context

The Rise of Quantum Computing

The market of quantum computing is growing rapidly due to the rising demand of high-performance computing. By combining quantum theory and computer science, quantum computing shows great promise for future application in fields like algorithms, cryptography, machine learning and quantum simulation. Several prominent companies like Alphabet (Google), IBM, and IonQ are well on their way in developing functional quantum computing[1].

Current breakthroughs are tremendous as companies are presenting data of their quantum technology that takes quantum computing from an experimental stage of development to stages that indicate a proof of concept in terms of appliance and supremacy over classical supercomputers. IBM, being one of the leading companies in quantum technology presented a development roadmap in 2020[2] and thus far they delivered on schedule. In 2023 IBM showed with its Quantum Eagle processor composed of 127 superconducting qubits on a chip, that it was able to generate accurate results, where advanced classical computing at some point faltered, showing that we are entering a time wherein the unreliability of quantum data that quantum computing has known to be prone to, might soon be something of the past.

According to Darío Gil, Senior Vice President and Director of IBM Research, using their Eagle processor chip: “This is the first time we have seen quantum computers accurately model a physical system in nature beyond leading classical approaches,” … “To us, this milestone is a significant step in proving that today’s quantum computers are capable, scientific tools that can be used to model problems that are extremely difficult – and perhaps impossible – for classical systems, signaling that we are now entering a new era of utility for quantum computing.”[3]

In the meantime they have developed larger chips compiled of more qubits. In 2022 IBM unveiled their 433-qubit Osprey processor shown in Fig. 1 and the 1121-qubit Condor processor is planned for the end of 2023. IBM’s next step are multi-chip processors, allowing quantum communication links between the chips, with their long-term goal of developing quantum systems comprised of 10k-100k qubits after 2025. Figure 2 shows one of IBM’s vision on future large-scale quantum supercomputing. With this speed of development and accompanying results in data that show supremacy over classical systems, we could indeed be entering the age of quantum computing utility.

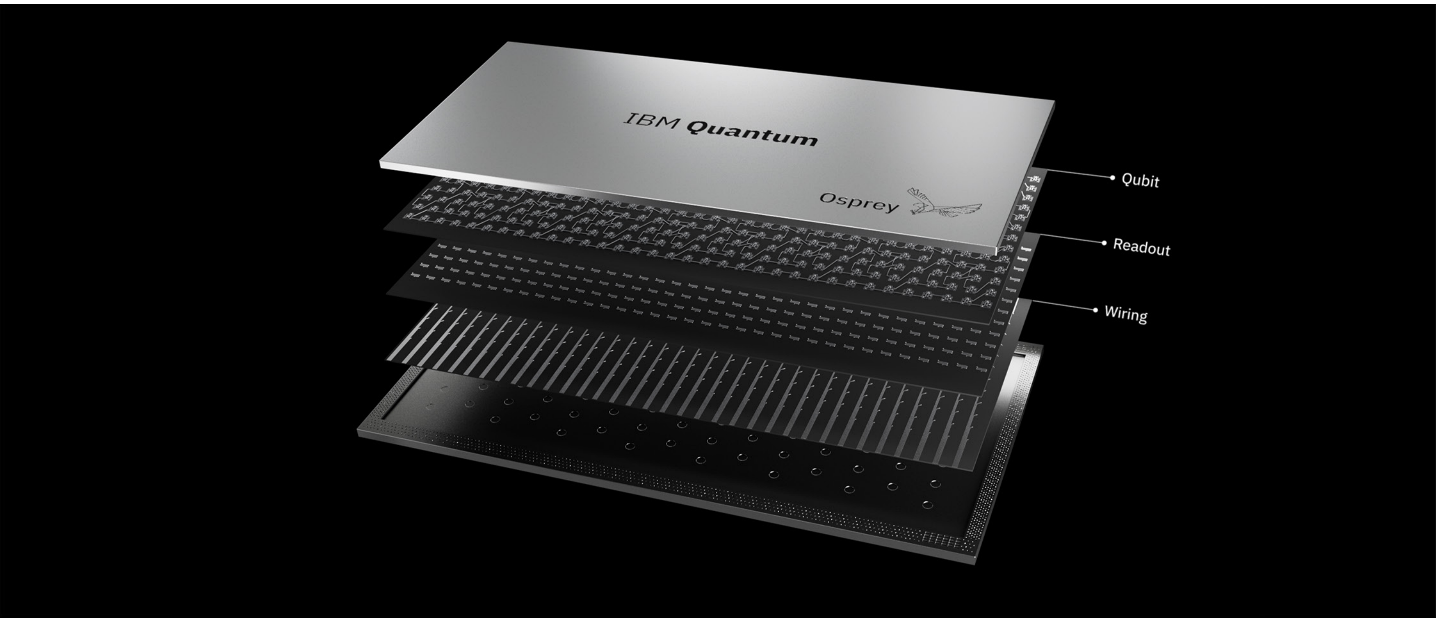

Figure 1. 433-qubit Osprey quantum chip 2022, From “*IBM Flicker account,”* by IBM research Zurich, 2023 (https://www.flickr.com/photos/ibm_research_zurich/52476814366/). Licenced under CC BY-ND 2.0 Deed

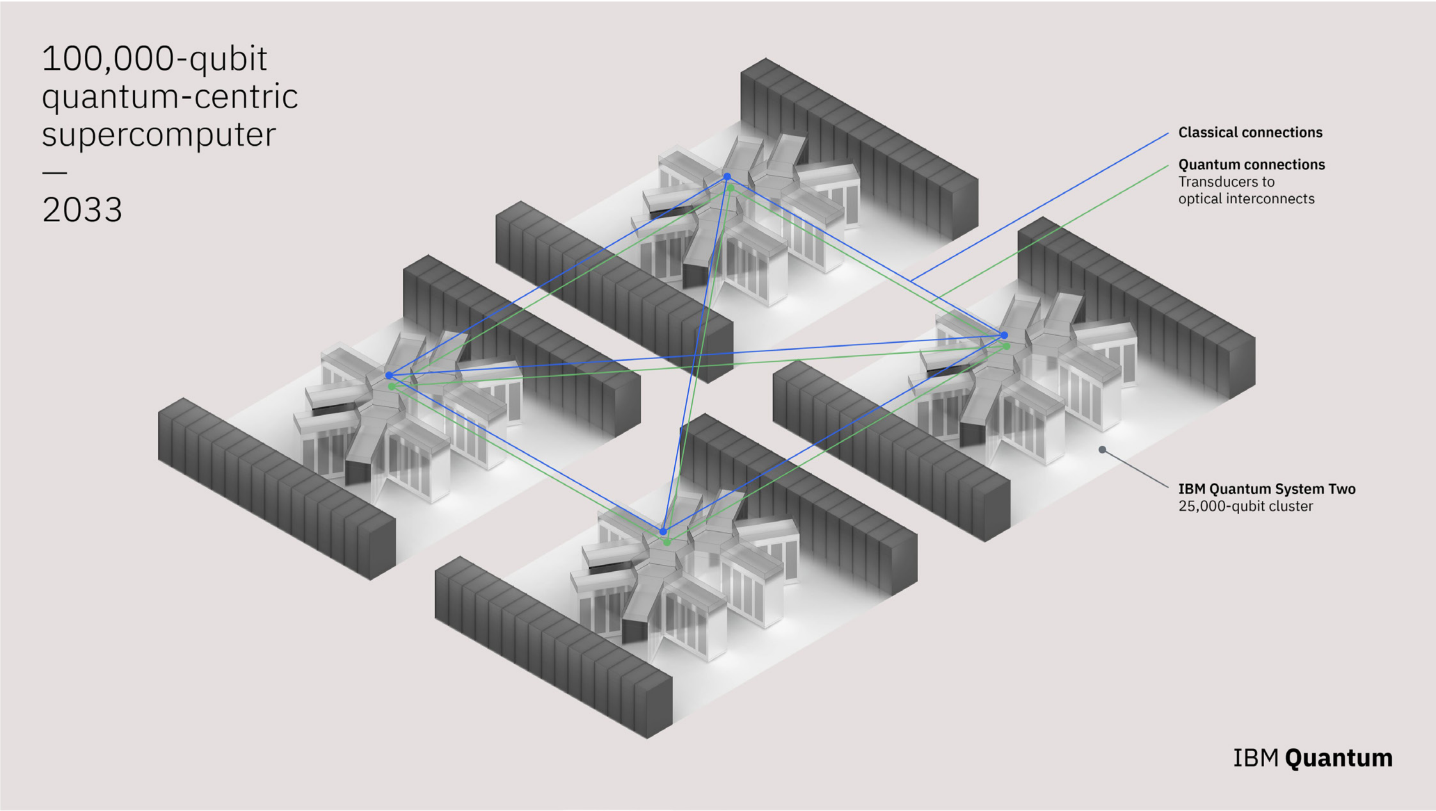

Figure 2. 100,000-qubit quantum-centric supercomputer 2033, From "*IBM Flicker account,*" by IBM research Zurich, 2023 (https://www.flickr.com/photos/ibm_research_zurich/52904644927/). Licenced under CC BY-ND 2.0

Quantum Computing Market Size Growth

Besides the previous described breakthroughs in the field of quantum technology, also the investments in the quantum computing market are big and growing: the global quantum computing market size was estimated at USD 10.13 billion in 2022 and is expected to go toward USD 125 billion by 2030[4]. Locally the Dutch government invested 615 million euros in quantum computing development through the Quantum Delta NL project in 2021 and another 60,2 million in 2023 in joint operations with France and Germany[5].

The Need for Scientists in Quantum Technology

These investments would suggest an accompanying rise of demand for people in the fields of quantum physics and quantum computing. Data from 2021 shows that the quantum technology education infrastructure is behind on the industry. The data for instance shows that the number of outposted job vacancies in quantum technology in 2021 outnumbered the number of quantum technology master's level graduates that year by a factor of three to one[6]. The same research reported that 176 universities offered a quantum technology program, but only 29 universities offered a master's degree in quantum technology. Looking at projected future investments in the quantum computing market, the current state of the quantum technology education infrastructure and it's foreseeable shortcoming in providing a sufficiently strong workforce to answer the industry's expansion, it can be expected that quantum education will be pressurized to conform to big change to keep up with the industry.

Introducing Quantum Physics

One of the aspects of quantum physics that this project mainly revolves around is the difficulty in understanding the basic principles to which the science comprises, especially when no preliminary knowledge on quantum physics or physics in general is available. An understanding of what is causing this can help formulate an approach on how to engage a younger generation in the topic. Important to note is that the project focus is more on “this is what quantum physics is about” than it is on “this is what quantum physics is”. The difficulty of understanding the principles underlying quantum physics is because many of the principles defy human intuition. Principles like quantum superposition, quantum entanglement and wave-particle duality can cause confusion when learning about quantum physics, especially for the first time. Understanding this difficulty will help understand what knowledge gap needs to be traversed minimally with the envisioned design, and as quantum physics is a difficult science to become knowledgeable in, will simultaneously help in setting boundries to the project’s investigation.

Quantum physics was examined on a level to which finding ways to reduce the difficulty gap was the primary aim and with the focus of finding a proper way to engage a younger audience in the topic. The acquiring of a basic level of understanding of quantum physics was furthermore essential for communication with experts in the field and necessary to be able to formulate design solutions that aimed in achieving the project’s design goal.

Before approaching how quantum physics could be introduced to a younger generation, an examination on how quantum physics is introduced in general was conducted first. The acquiring of a personal understanding of quantum physics already led to a clear overview on how this process could be approached. The interesting and valuable part in this was that the process of acquiring knowledge on the topic was acquired through a path other than through the educational path of university, but through other sources like scientific webpages and educational videos online, the path that is aimed for from a design perspective: a design that engages and introduces basic elements and aspects before university level is reached.

A quick search on YouTube on explaining quantum physics to young people led to the conclusion that there are sources which explain the sought after explaining of the basic principles of quantum physics to a young generation. But looking beyond the nicely edited cartoons that were used to convey the basic principles of quantum physics, the content was mostly on the same level informatively as any of the other scientific videos found on YouTube.

The Absence of Science Museum Exhibits

Searching online for existing exhibitions on quantum physics did lead to results that showed that the topic of quantum physics is exhibited. However, besides that not many instances were found, the focus of the ones that were found were foremostly on the historical part of the science, less on the theoretically side, which makes sense because of the existing difficulty gap. Most importantly was that there were no exhibits found aimed for a younger generation. Although results might have been overlooked, examination of existing exhibits was done through search engines, not only seeking locally in the Netherlands, but from a global scale. Indicated from this exploration, the conclusion was drawn that the absence of exhibits on quantum physics on the theoretical side and the absence of engaging science museum exhibits for younger generations, were mostly due to the existing difficulty gap in terms of conveying the basic principles of quantum physics and quantum computing in an engaging and compelling manner.

The Quantum Difficulty Gap: Problem, Opportunity, and Challenge

A dualistic problem arose, namely, one: that there is a difficulty gap in conveying quantum physics knowledge because of its complexity, and two: that there are sources online to be found that educate and convey the basic principles of quantum physics, yet currently, there are no engaging and compelling museum exhibits found on this topic that could get young people excited about quantum physics in the same way some of present-day scientists or physicists might have gotten excited about science back when they were young, when visiting a science museum.

Seeing the amount of media attention the topic currently receives because of its tremendous developments, and looking at its rapidly growing market size, it was concluded that the problem of the absence of science exhibits that explain these basic principles to people, especially to a younger generation, together with the expected workforce needed to comply to future demands in the industry, an opportunity had arisen with the problem, in turn leading to the challenge of this design project: engaging a young generation in this rapidly expanding science and its industry, in a way that compels them to aim for becoming one of those needed quantum physicists or engineers needed in quantum physics and quantum technology in the future.

What was hypothesized looking at the above-described contextual setting, was that the problem could have arisen from and be explained by realizing that quantum physics examines the microscopic scale, and having people experience the physical manifestation of the scientific quantum principle at hand is difficult; thus, current solutions in engaging people in topic take an approach of having people zoom in on the quantum dimension through videos that visualize the quantum principles. The challenge of this project was to try and find ways to allow people to experience wave-phenomena in the physical and perceivable dimension that could be related back to the quantum wave-related phenomena. This would help form a basic understanding of quantum physics. To generate the wave-phenomena in the physical and perceivable dimension, the design solution was looked for in cymatics, the study of visual wave-phenomena.

Approaching Quantum Physics through Cymatics

Cymatics is the study of visual wave phenomena, often a vibrating plate or liquid, acting as a medium that allows wave-like behavior, and particles, often materials like sand or salt, to enact forming of visual patterns called eigenmodes. The wave-like characteristic found in both quantum physics and cymatics was the primary factor that led to the forming of the goal of the assignment of this project: approaching quantum physics through cymatics. When studies of quantum physics and cymatics were examined and compared with an open mind, visual similarities were found and the hypothesis was made that through interacting with cymatics eigenmodes, the visual patterns created in cymatics, an intuitive understanding of wave-related aspects in quantum physics could be made.

Fig. 3 shown below shows an example of an eigenmode pattern created with one of the water cymatics setups created for this project. In this case it concerns a 56 mm petri dish filled with a layer of water that vibrated at a frequency of 43 Hz. In water cymatics there are no particles as the patterns emerge in the water medium itself. In this case the particle-behavior is visualized through the form of light reflection. The interactions between medium and particles allow an interaction of materials wherein visual patterns can manifest, creating a fascinating visual phenomenon. Besides water cymatics there are other types of cymatics that allow the emergence of visual patterns through different types of mediums when exposed to vibrations. One such example is the Chladni plate which will also be examined.

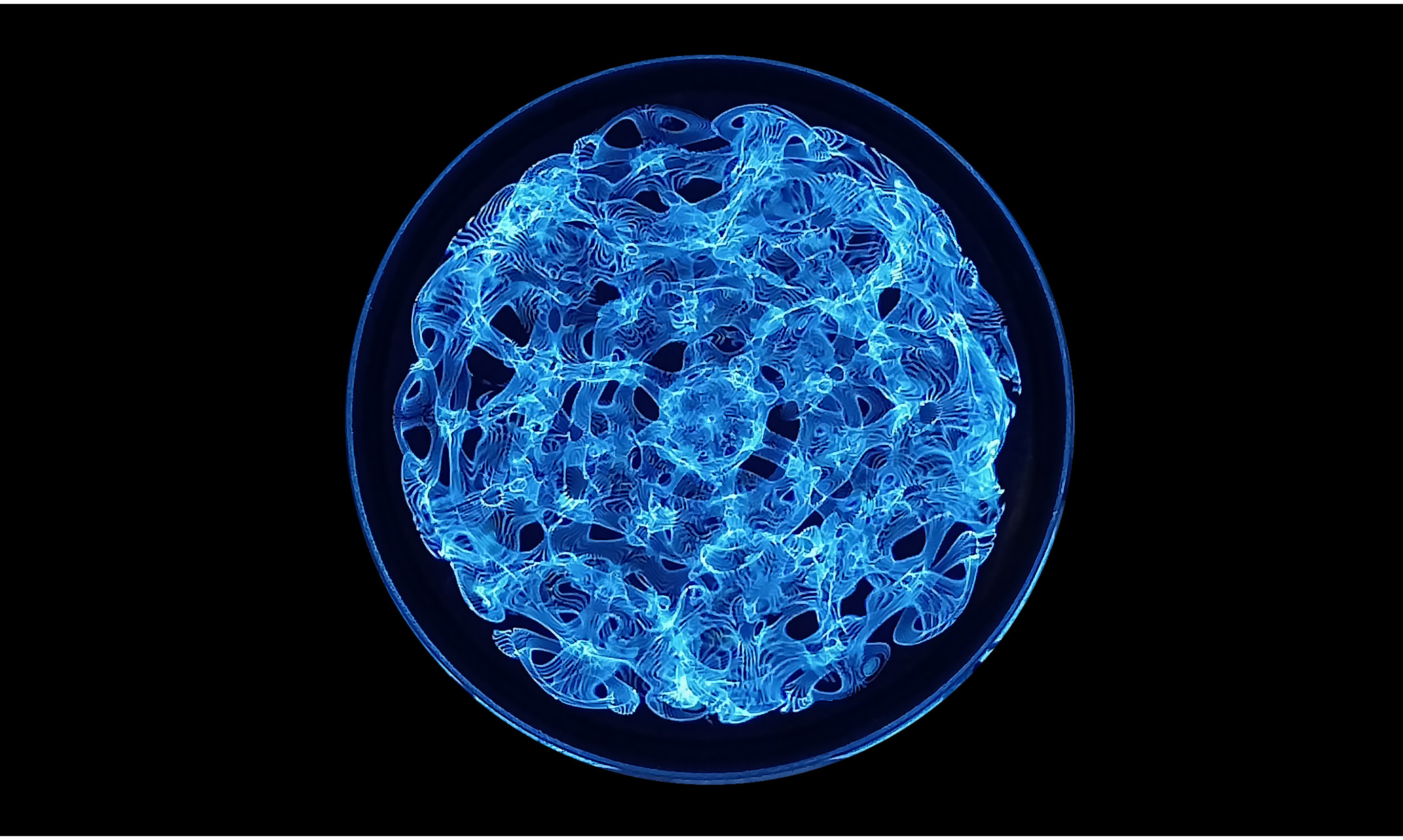

Figure 3. Water cymatics eigenmode: 43 Hz, 56 mm in diameter

Besides its wave-related characteristic another promising aspect in cymatics was that it would allow an experiential interaction in the physical and perceivable dimension. It was hypothesized that this was one of the reasons why little to no exhibits of quantum physics in science museums were found to engage a younger generation, acknowledging that quantum physics and quantum technology is not an easy to work with science when the aim is to present an exhibit design that demonstrates the real scientific phenomenon underlying the subject. This aspect is not pursued during the project as the main aim is to find the solution in cymatics. Interestingly to add to this is that simulation could allow principles of quantum physics to be demonstrated in the physical and perceivable dimension, but also this was not pursued during the project as the focus was on finding the solution in cymatics, as delivering a solution that could deliver a real manifestation of a scientific phenomenon, allowing an interaction of experiencing a real phenomenon, was thought to be superior over a simulation.

Project Aim: Engagement in Quantum Physics

The project aims to provide a solution that will help open ways to achieve maintaining the balance of education and industry that is needed within the quantum technology sector if the industry keeps expanding as it is currently. It hopes to deliver where currently is missing: an engaging way to interest our current youth in quantum technology before they reach university, in a way that motivates them to become one of the future quantum physicists that the industry will drastically need.

Currently basic aspects of quantum physics are difficult to convey to a younger generation in a compelling and engaging manner and the lack of existing exhibits on quantum physics in science museums, one of the places where younger generations' interest in science is fueled, only confirms this believe.

The aim of this project is to introduce basic aspects of quantum physics to a young generation through a science museum exhibit design wherein cymatics, the study of visual wave phenomena, will be used to approach the topic of quantum physics. The wave-like behavior in cymatics is believed to be a good starter to learn about wave-related aspects found in quantum physics. Envisioned design solution would have museumgoers interact with the visual patterns created with cymatics called eigenmodes, to achieve a basic understanding of principles that underly quantum physics, with the goal of creating further interest in the field of science.

Project Scope: Boundaries of Complexity

Because of the topic's complexity it was not the project's goal to explain quantum physics to the museumgoer in the scientific sense, but instead the focus was on finding ways to engage people in the topic through cymatics in a way that brings about further curiosity in quantum physics, quantum computing, cymatics and the wave-related aspects that were used to relate the topics to each other. Because a full knowledge conversion was not the aim, solutions were looked for by finding bridging factors that connect the topics, and analogies were explored that could be used to explain underlying principles.

As in this project's report will become clear, a design that only creates eigenmodes was found to not be sufficient in successfully conveying basic aspects of quantum physics, and a deeper level had to be explored. But as quantum physics as a science is broad and the quantum technology used in quantum computing comes in many types, a form of simplicity had to be maintained to keep a certain level of generality and accuracy at the same time, while not expanding too deeply into the level of complexity. Finding the right balance in learning about quantum physics and applying those findings in the design process was one of the challenges of the project and describes the complexity of the scope of the project.

Project Approach

Approaching Quantum Physics through Cymatics

The approach of this project to introduce basic aspects of quantum computing is through an interactive experience of cymatics in the form of a science museum exhibit. The envisioned design will guide museumgoers through an experience that resembles how quantum physicists work with their quantum systems.

Instead of working with actual quantum particles, cymatics will be used to metaphorically recreate such experience. The key to the envisioned design is to find aspects that correspond to both quantum computing and cymatics that can be used to come up with a design solution. One of the key concepts that will be explored during the project is the producing of eigenmodes with cymatics, as these visual patterns can help built an understanding of the wave functions used to do quantum calculations in quantum physics and quantum computing.

The goal is to introduce subjects like qubits, wave functions, and probability distributions and deliver an experience that simulates the work that quantum physicist and how they work with their quantum systems and how they build functioning qubits from it. Through experiencing cymatics and introducing basic aspects of quantum physics, engagement in quantum physics and quantum computing is hoped to be achieved by giving the museumgoer a simplified version of what it is to be a quantum physicist.

The goal is to stimulate young people that have a slight interest in science to apply to quantum physics and quantum computing education later in life by engaging them in the topic through an interactive experience that is mostly focused on achieving engagement through a form of experiencing phenomena and not on effectuating engagement through understanding the phenomena itself on a deeper level.

Design Goal

The goal of the envisioned design is to engage young people aged 13-30 in the topics of quantum physics and quantum computing through a science museum exhibit using cymatics. The main design problem to overcome is to find aspects that bridge the topics of quantum physics and quantum computing with the topic of cymatics, and subsequently use those aspect to come to a design solution. The goal is not to necessarily come to a design solution that will fully explain quantum physics or quantum computing. A design that will interest museumgoers in quantum physics, quantum computing, and cymatics in an engaging manner through experiencing wave phenomena will be seen as satisfactory and as an added value to the scientific context.

Project Assignment

The assignment’s approach works in two ways:

1. Investigate together with quantum physicists if simplified concepts of quantum computing can be found through the exploration of cymatics devices
2. Investigate how the results of this exploration can be used to design a compelling and engaging learning experience that introduces quantum physics to young future scientists.

Throughout the project investigations in quantum physics, quantum computing and cymatics will be conducted in order to help fill the gaps that are needed to connect and bridge the three fields and to come up with a design solution.

Using the Vision in Product Design method

During the project the Vision in Product design method (Hekkert & van Dijk, 2011)[7], in short ViP, was used from the book Vision in Design: A Guidebook for Innovators. The method's approach of splitting the design process into a deconstruction and design phase formed a structure that suited the design challenge of this project well. As shown in Fig. 4 ViP structures the process in a way wherein an past situation or context is analyzed and translated into factors that help form and build a vision to approach the designing for a future situation or context.

This approach suited this project well as knowledge had to be gained first on the topic of quantum physics to know how to approach the design process of using cymatics. In this the past context would be quantum physics and the future context would be cymatics. The special thing about this project context is that it could also be reasoned the other way around. In this case it could be said that the context of cymatics is the past context, as we are using cymatics to thereafter design for the context of quantum physics.

It is a vice-versa way of looking at the appliance of the design method, wherein both perspectives made sense and both of them contain added value in finding the right approach of tackeling the design problems. It was felt that for the project's aim of using cymatics to find bridging factors to quantum physics, and then design an exhibit using cymatics to again rebuild a connection that bridges cymatics to quantum physics, the ViP method showed great potential of structuring the process well.

The three levels of deconstruction also offered a good separation of scopes to which the design problems could be examined. Normal in ViP is that in the beginning the type of outcome of the design process is still fully open and you never know exactly what type of solution will be arrived at. In this project this was different from the beginning the producing of eigenmodes was decided to stand central, so it was clear that the outcome of the design process would incorporate a form of eigenmode production through a design using cymatics.

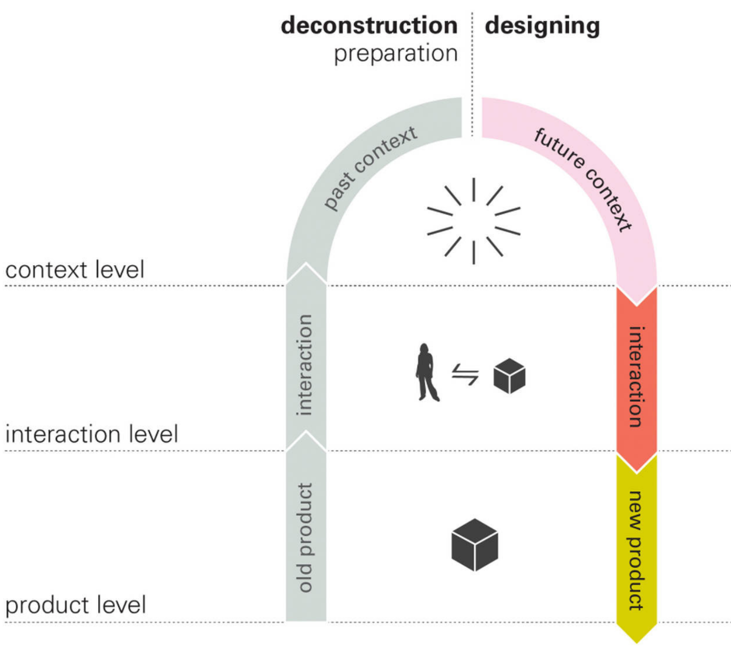

Figure 4. Three levels of description in the ViP model, From "*Vision in Design: A Guidebook for Innovators (3th ed.,p. 119),* by P.P.M. Hekkert and M.B. van Dijk, 2021, BIS Publishers

Exploratory Sessions with Quantum Physicists

To find the bridging factors needed to connect the field of cymatics to the fields of quantum physics and quantum computing, exploratory sessions with quantum physicists from the quantum computing industry were organised and conducted. For these sessions several cymatics devices were built beforehand and were improved and adapted to the sessions when investigation goals were tested and specified. During the sessions the physicists were asked to play with the cymatics devices and while during the interaction with the devices, a conversation in an interviewing manner was held on the topics of quantum computing and the method of doing quantum computing research, while along the way, while talking, links, resemblances, and overarching themes with the subject of cymatics were looked for.

Two main sessions were held and for each session a quantum physicist from a quantum technology research institute was able to join. The sessions led to interesting discussions and many connections and analogies were made with cymatics, resulting in a large collection of data to be analyzed, which were later found to be of informative and useful quality. Before the main sessions, a test session for which faculty members of IDE, relatives and friends were invited was held to test out the setups.

Phases of the Project

The project was split up in three phases: phase 1: Explore, comprising data collection and data analysis, phase 2: Conceptualize, where the insights and results were used to come to three concepts which were tested, and phase 3: design, in which the final concept was made into the final design.

Phase 1: Explore
Throughout this first phase a basic understanding on the topics of quantum physics, quantum computing, and cymatics was gathered. With the gained insights and the preliminary built devices the exploratory sessions were set up, for which first a test session called session 0 was conducted. The main goal and focus of the phase overall was gathering data that would help bridge the field of quantum physics and cymatics. Through context mapping and the appliance of the Vision in Product design method the data was analyzed.

Phase 2: Conceptualize
During the second phase the concluded results of the first phase exploration were used to approach the conceptualization of design solutions. Several design choices had to be made like determining the cymatics type and what kind of interaction would have to accompany the producing of eigenmodes in way that would satisfy and compy to the formulated design visions and findings. Multiple forms of frequency control and the overall effectiveness of the design were tested, leading to the final concept design.

Phase 3: Design
The third and final phase comprised of working towards delivering the final design solution. Based on the results and insights gained through the concept test, the interaction design was improved upon. Context intergration was done through a brief reexamination of the science museum context. Together this formed the final design.

Throughout the entire project several investigations were conducted into the topics of quantum physics and quantum computing and how they can be related to with the topic of cymatics. These investigations were conducted besides the exploratory sessions with the physicists and fulfilled the role of the finding the needed bridging factors for each phase, that could bring the separate parts of the project together. The overall investigation could be split into three parts, wherein the first part focused on gaining a basic understanding of quantum physics, quantum computing and cymatics in general, thereafter was focussed on organizing the exploratory sessions, and finally an investigation was conducted to gather knowledge on quantum computing specifically, to form analogies that were used in the interaction design to connect back to the topic of quantum physics and quantum computing. The three parts of the investigation were: the preliminary examination, the exploratory sessions, and connecting concepts.

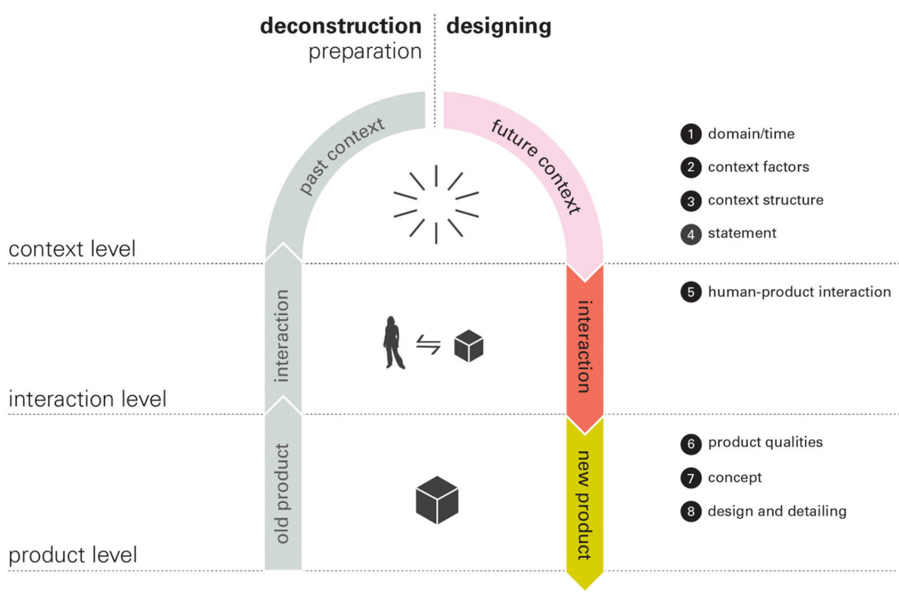

Figure 5. 8 steps of the process embedded in the ViP model, From "*Vision in Design: A Guidebook for Innovators (3th ed.,p. 133),* by P.P.M. Hekkert and M.B. van Dijk, 2021, BIS Publishers

Future Context

Exhibiting Quantum Physics in a Science Museum

Delivering an interactive exhibit design for a science museum is the goal but as the topic of quantum physics brings along a set of difficulties that make exhibiting difficult, especially in the context of a science museum that engages younger generations through short experimental experiences with science. One of the probable causes for the absence of exhibits on quantum physics with a focus on engaging a younger generation was thought to be the difficulty in exhibiting actual hands-on interactive and experiental examples of basic principles underlying quantum physics. As online courses and online videos aimed to introduce and educate are existing and cover basic explanations of said basic underlying principles, the solution to engage a young audience in the difficult topic of quantum physics in the context of a science museum needed to be found elsewhere, and for that approaching quantum physics through cymatics was thought to be a promising method of achieving the envisioned engagement as it could allow an interactive experience with a scientific phenomenon that has similarities in terms of wave behavior and could help bring about a basic understanding of quantum physics through hands-on interactive experiences.

As for this approach cymatics is used to approach the topic of quantum physics, it is important that the essence of relating the envisioned interaction back to the topic of quantum physics is important. As experiences with exhibits in science museums consist of short interactions of a playful character, one of the goals of the project is to find a way that allows relating back an interaction with cymatics to the topic of quantum physics in a short and playful manner as well. One of the aims of the project is to investigate how bridging connections between cymatics and the topics of quantum physics and quantum computing can be made as simple as possible, as this would allow such short and playful interaction. As quantum physics is a difficult science to understand to its core, direct relationships to cymatics scientifically were expected to be difficult to find, and foremostly, if found, difficult to implement in the interaction design and difficult to convey to a younger audience. One of the approaches to this challenge was through the use of analogy. It was foreseen that finding connections between the topics would be possible but conveying these connections in the short interaction of a science museum exhibit aimed for a young generation, could become difficult when extensive bridging connections are to be made to relate what is done interactivily through cymatics to the topic of quantum physics. The use of analogy was thought be a promising approach as it could allow a form of simplicity in its interactional design, wherein the bridge to connect the topics of cymatics and quantum physics could be made through a simple, yet strong analogy.

Focus on Quantum Computing

Another design choice that was made was to focus on the field of quantum computing specifically. The reason for this was because of quantum computing being the applicative side of quantum physics. As the envisioned design was foreseen to be designed around “doing” and less around “knowing”, quantum computing was thought of a better context to focus on in terms of designing an exhibit that would effectuate engagement and interest in quantum computing, and and through quantum computing simultaneously in quantum physics as well.

Stakeholders

Main Contextual Structure of Stakeholders

The main stakeholders of the project's context can be split into three groups as shown in Fig. 6, consisting of the quantum computing market, science museums and the target group young future scientists. The incentive of formulating the project's assignment was through the observed growth of the quantum computing market and its accompanying investments in quantum technology that are expected over the coming decade, that indicated a need to engage younger generation in quantum physics to account for the expected amount of quantum physicists needed in the future. As universities are currently starting to adapt to the trend of the emerging quantum computing market by offering specific programs on quantum physics and quantum computing, this project aims to deliver an exhibit design that can be used by science museums to contribute to the educational infrastructure of quantum physics and help engage in the topic at a young age.

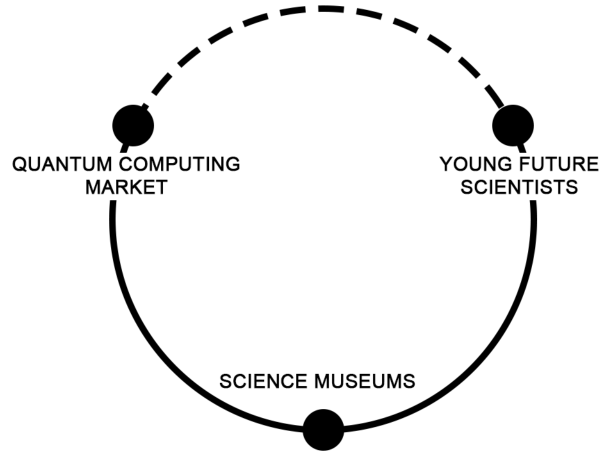

Figure 6. Overview of the main stakeholders and target group exhibiting the topics of quantum physics and quantum computing in science museums. Dotted lines indicate the necessary connections that need to be bridged.

From earlier investigation it was concluded that one of the probable reasons for absence of existing exhibits on quantum physics is because of its difficulty gap in attaining a basic understanding of the underlying principles of the science. As this project aims to do, designers can contribute in bridging this difficulty gap. From this perspective and from the perspective of this project it could be concluded that four groups of stakeholders come together when the designer is included, as shown in Fig. 7. In this overview the target group is split into two groups, for which an envisioned transition is desired: engaging museumgoers of the science museum that result in an increase of young people aiming for a future career in quantum physics and quantum computing.

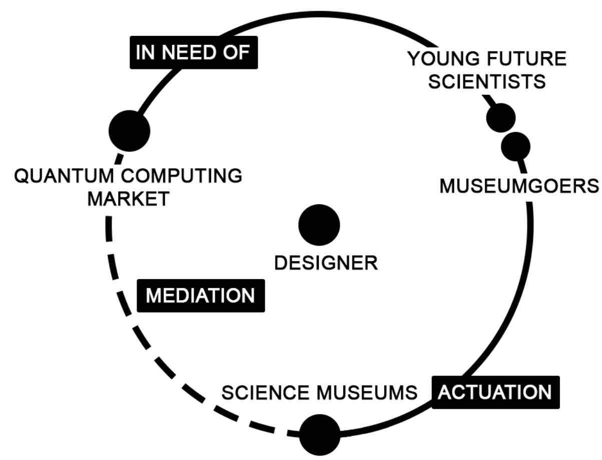

Figure 7. Overview of underlying structure of mutual relationships among the different stakeholders and their role within the structure.

In this it is the designer's role to bring together these parties through the making of an exhibiting design. These four groups make up the stakeholders, wherein the quantum computing market brings forth a need, young future scientists form the target group, the science museum acts as actuator and the designer takes the form of mediator for bringing together all groups through bringing forth a design solution.

Because of quantum physics' level of difficulty and complexity, and simultaneously aiding and respecting each stakeholder's needs, the primary aim of bringing together all parties succesfully was directed at finding a proper connection between the quantum computing market and the envisioned design first.

Bridging Quantum Physics and Cymatics: The Preliminary Examination

The Approach to Bridging Quantum Physics and Cymatics

As this project aims to examine how cymatics can be used to introduce basic aspects of quantum physics, a brief examination of each topic was conducted. The aim of this part was to gather a basic understanding of each of the topics that would help communicate with the quantum physicists during the planned exploratory sessions. As the overarching goal of the sessions was to aqcuire bridging factors and connections between the topics of quantum physics, quantum computing, and cymatics, that could used in the design process, this first examination was to form first thoughts and ideas on how connections could possibly be made, that could subsequently be tested and evaluated with the quantum physicists.

Hypothesised was that providing an experience of a physical scientific phenomenon is a good way to have museumsgoers in science museums understand the underlying principle at hand. As phenomena in quantum physics occur at the microscopic scale and embody a form of counter-intuitiveness, it was hypothesised that cymatics could allow an experience of wave related phenomena to be experienced, that when presented in the right way, could help convey basic principles of quantum physics. To be able to guide the sessions and communicate with the quantum physicists properly, a basic understanding of the topics at hand needed to be acquired first.

For this first part of the investigation of bridging the topics of quantum physics, quantum computing and cymatics, all three topics were examined on a basic level. First a brief examination of quantum physics and quantum computing in general was conducted and an examination of the history leading up to the formulation of quantum theory was conducted to investigate how current difficulties in understanding quantum physics could be understood from a historical perspective. Subsequently cymatics was examined on a basic level by focusing on two types specifically: the Chladni plate and water cymatics. Lastly one overarching theme among the different topics was then examined: superposition.

A First Brief Examination of Quantum Physics

Quantum physics is the study of matter and energy at the scale of atoms and subatomic particles. It comprises a collection of theories that arose during the first half of the twentieth century when classical physics did not hold up with what was examined. The theoretical foundation to all quantum physics is what is called quantum mechanics. As this project only touches upon the very basics of this field of physics, and its aim is not to enter the domain of theoretical quantum mechanics, the more general term quantum physics is used. One of the difficulties in this project was finding the proper scope as an industrial designer to approach the subject. One of the primary goals of the investigation was to find aspects of quantum physics that make it difficult to understand, and investigate if ways could be found to approach these subjects in a manner that would sparkle a form of intuitive understanding, without diving into the deeper theoretical layers of understanding. If these aspects could be derived and somehow be related to the visual wave phenomenon of cymatics, it was hypothesised that a bridging connection could be made to effectuate the envisioned engagement of a younger audience.

At the quantum scale, things work differently from the macroscopic scale and need different mathematics to be described. Part of the difficulty in understanding quantum physics is because many of the underlying principles work counter-intuitively. Examples of these quantum principles are wave-particle duality, quantum superposition, the uncertainty principle and quantum entanglement. From these four principles the former two were examined during the project with the above described approach and perspective as some of the aspects were thought to bear a certain level of similarity to aspects found in cymatics.

The wave-like behavior of eigenmodes produced with cymatics were perceived to hold a level of similarity to aspects of wave-particile duality. It was the Danish physicist Niels Bohr in 1913 that proposed that electrons in atoms embodied wave-like properties, and later in 1924, it was the French physicist Louis de Broglie that proposed that áll particles are associated with waves[8]. At that time, the notion was: are things particles or waves, or maybe both? Current perspective on this notion is that it depends; sometimes they are particles and sometimes they are waves, it depends on what you do with them. This is what is now known as the wave-particle duality. This should exemplify the counter-intuitiveness of quantum systems, to which the atom and the electron are also part of. Approached with an open mind, models of atomic structures show geometrical characteristics similar to the patterns produced with cymatics, sometimes quite specifically as shown in the visual comparison between Fig. 8 showing models of atomic structure and Fig. 9 showing a cymatics eigenmode pattern.

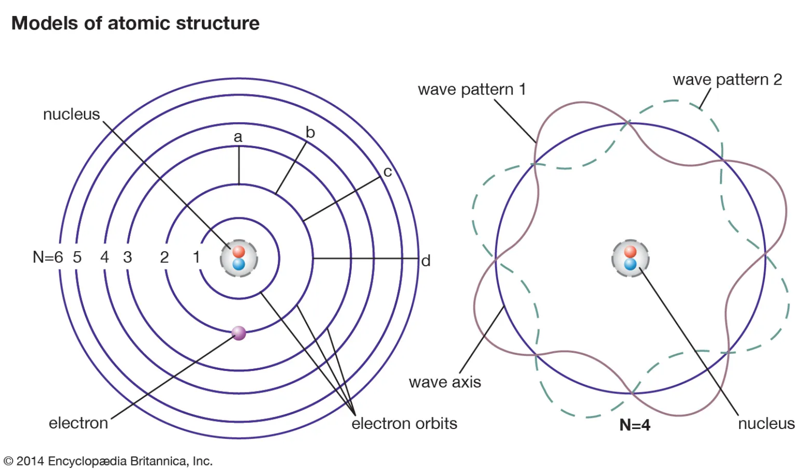

Figure 8. Bohr Theory. From "*Encyclopædia Britannica,*" by Encyclopædia Britannica, 2023 (https://www.britannica.com/science/physics-science/Quantum-mechanics#/media/1/458757/53743). Usage in line with website's "use of content".

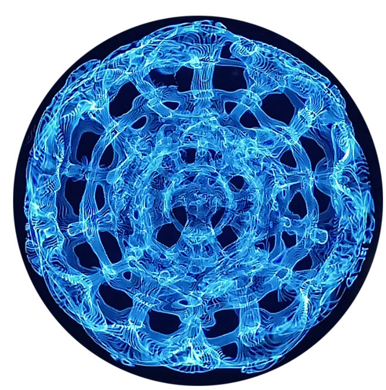

Figure 9. Water cymatics eigenmode showing comparable wave-like structuring, in comparison with Bohr models of atomic structure

The Scientific Revolution and understanding the Difficulty of Quantum Physics

One possible reason to explain why quantum physics is difficult to understand is that the mindset that flourished during the Scientific Revolution, while having revolutionary impact, and being the driving force what brought us to modern-day science and physics, did held a fallacy in terms of scientific philosophy. During the past centuries, mankind has evolved in science and technology rapidly, and this rapid evolvement has brought about a mindset that on one hand brought us to where we are now, but on the other hand also had to be challenged around the time quantum theory was formulated, as during that time it was found out that the world we live in, operates differently at the fundamental microscopic scale, the scale to which quantum physics relates, than what was previously believed during the Scientific Revolution.

One central scientific philosophy during the Scientific Revolution was Cartesian Reductionism, named after René Descartes, a mathematician, scientist, and philosopher in the seventeenth century. Descartes proposed a mechanistic conception of the world that stated that everything could be understood by reducing things into its smaller fundamental parts. Descartes' work was revolutionary and one of his famous accomplishments and contributions to science was his book "A Discourse on the Method of Correctly Conducting One's Reason and Seeking Truth in Sciences" (Descartes, 2006/1637), which was meant as an introduction to science and in which he presented his analytic method of reasoning.

Descartes held the belief of certainty of scientific knowledge and his method was designed to reach scientific truth. Although the reductionist's view in terms of the structuring of all things into smaller parts, was valuable, especially as it contributed much to modern scientific thought, it was during the twentieth century that it was discovered that many properties could not be found in the parts alone and could only emerge at the level of the system as a whole. Twentieth-century science has shown very clearly that there can be no absolute scientific truth and that all our concepts and theories always are an approximation. An excerpt from the book The Systems View of Life (Capra and Luisi, 2014) describes this as follows: "*Crucial to the contemporary understanding of science is the realization that all scientific models and theories are limited and approximate […]. Twentieth century science has shown repeatedly that all natural phenomena are ultimately interconnected, and that their essential properties, in fact, derive from their relationships to other things. Hence, in order to explain any one of them completely, we would have to understand all the others, and that is obviously impossible* (Capra and Luisi, 2014, p2)"[9].

Descartes' analytic method of reasoning was of great importance to modern scientific thought, and Cartesian Reductionism as it was named later, laid the foundation for seventeenth-century science. But it was Isaac Newton who created the pinnacle of scientific work during the Scientific Revolution: The Principia, or its full title, Mathematical Principles of Natural Philosophy, in which Newton presented his laws of motion and law of universal gravitation. Newton's work was revolutionary and was considered to be a final form of work of science for more than 200 years. In the centuries that followed new discoveries exemplified contradictions to the Newtonian model and new concepts were formulated. It were the discoveries and investigations of heat, electricity, and magnetism during the nineteenth century, and general relativity and quantum theory during the twentieth century, that ultimately led to the Newtonian model losing its role as fundamental theory of natural phenomena.

During the first three decades of the twentieth century quantum theory was formulated by an international group of physicists including Niels Bohr, Max Planck, Albert Einstein, Werner Heisenberg, Louis de Broglie, Erwin Schrödinger, Wolfgang Pauli, and Paul Dirac[9]. Investigations and experiments during this period confronted these physicists often with contradictions and paradoxes. Interestingly to add to this is a part from one of Heisenberg's books, Physics and Philosophy (Heisenberg, 1958), wherein he reflects on Cartesian Reductionism's influence on present day's difficulty of understanding quantum physics: "*This partition has penetrated deeply into the human mind during the three centuries following Descartes and it will take a long time for it to be replaced by a really different attitude towards the problem of reality* (Heisenberg, 1958, p75)"[11].

This brings us back to the starting notion of this chapter, the search for a possible reason why quantum physics is found to be difficult to understand. Present-day mindset, especially as non-scientists and non-physicists, is still built on top of a scientific paradigm that in some way must have influenced our thinking; thus, the fact that Cartesian Reductionism has had great influence on scientific thought, and in turn having science largely shaping our world and society from a Newtonian mechanistic perspective, it can be imagined how topics like quantum physics can be difficult to grasp for a normal person.

Concluding, from a design perspective and in relation to this project's design goal, it is important to take into account these different mindsets and how they relate to the past, present-time, and the future, when designing solutions that aim for reducing the difficulty gap of understanding quantum physics. Through an understanding of the past, the cause of the difficulty can be understood better, in turn helping better understand what is needed to solve the issue at hand in present-time, so the solution can strategically be designed conform to the mindset needed for the design solution to be successful in conveying an idea of the needed mindset in the future. This is of importance to the designer as incorporating this underlying perspective in the design itself, could open ways for the user of the design, to which this underlying perspective could also be valuable, in this project's case a young person whose mind is still applicable to implementing new concepts and new ways of thinking, to intuitively be exposed to the mindset that the design hopes to convey.

In the case of this project, the choice was made to approach finding aspects to design with in cymatics, because of the wave-behavior cymatics exhibits and its similarities to the wave-like characteristics found quantum physics, with the goal of creating an intuitive understanding of the wave-particle duality.

Hans Jenny, Cymatics' Pioneer

One of the most reknown researchers of cymatics and the person who coined the name was the Swiss physician and natural scientist Hans Jenny. In 1967 Jenny published his first volume of Cymatics: A Study of Wave Phenomena and Vibration (Jenny, 1967), and in 1974 the second volume was published. Both works contained large amounts of experiments on waves, vibration, and harmonic oscillation. His work focussed on the effects of vibration on liquids, powders, and liquid pastes and resulted in a large collection of cymatics experiments accompanied by large sets of photographed imagery. His method of emitting vibration was through crystals that embodied the piezoelectric effect; when excited the crystal would oscillate. With accurate control over the oscillation, this method allowed him to systematically experiment with all various forms of cymatics. It allowed him to emit low frequencies, but compared to his previous colleagues that researched vibration, he was able to reach frequencies high up to 16.000 Hz.

Jenny's words in the introduction of the first volume show how he held an extraordinary detailed and almost poetic view on life describing the essence of waves, vibration and oscillation in life on all scales imaginable.

"*Whenever we look in Nature, animate or inanimate, we see widespread evidence of periodic systems. These systems show a continuously repeated change from one set of conditions to another, opposite set. This repetition of polar phases occurs alike in systematized and patterned elements and in processes and series of events.* (Jenny, 1967, p.17)".

His perspective and interest on the phenomenon arched a broad perspective, from realm of the organic to the inorganic, from micro to macro and the implications of it in physics.

"*If an inventory were to be drawn up of periodic phenomena in the realm of the organic, it would have to include the whole scope of morphology and physiology, biology and histology. But we must not forget the inorganic world. In this field we shall merely mention some typical examples recalling known facts, with particular reference to physics. Here we encounter vibrations in a pure form, more specifically in waves.* (Jenny, 1967, p.18)".

"*What insights into vibration and periodicity have been gained in the vast range extending from the cosmic systems (rotations, pulsations, turbulences, circulations, plasma oscillations, periodicity of many kinds in both constituent elements and the whole) down to the world of atomic or even nuclear physics* (Jenny, 1967, p.18)".

Also acknowledging the implications and relevance of the phenomenon of waves, vibration, and oscillation in the quantum realm.

"*Also of interest here is the problem of matter waves (L. de Broglie). Diffraction patterns have in fact been produced by material particles (atoms and molecules) in experiments. Thus these particles also display a wave-like behavior* (Jenny, 1967, p.18)".

These few excerpts of Jenny's introduction to his work show the broadness and the scale of the phenomenon at hand. Imagining that wave phenomena are present at the fundamental level of our material world, and acknowledging current scientific and technological progressions in terms of manipulating and utilizing the realm of atoms and subatomic particles, as currently is done, one could imagine the size of impact the utilization of quantum technology can have on our society. In the field of cymatics it was Hans Jenny who pioneered with conducting and documenting a broad range of experiments using large varieties of materials. Fig. 11-15 show examples of Jenny's cymatics experiments, vibrating sand, glycerine, and mercury.

Figure 10. Hans Jenny (1904-1972). From *Cymatics: A Study of Wave Phenomena and Vibration (Revised Edition 2001, p. 6),* by Hans Jenny, 1967/2001, Basilius Presse (1967, original publisher) MACROmedia Publishing (2001, publisher revised edition).

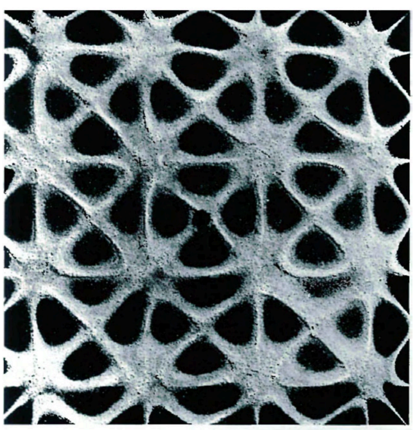

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Figure 11. 37 A sonorous figure, also by piezo-electric excitation. Square steel plate 23x23 cm, thickness 1 mm. Frequency 6700 cps. In such experiments as these, the formation of nodal lines of sand can be accurately observed. They often pile up like dunes. From *Cymatics: A Study of Wave Phenomena and Vibration (Revised Edition 2001, p. 39),* by Hans Jenny, 1967/2001, Basilius Presse (1967, original publisher) MACROmedia Publishing (2001, publisher revised edition).

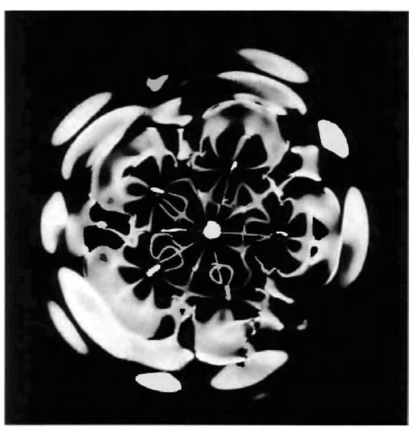

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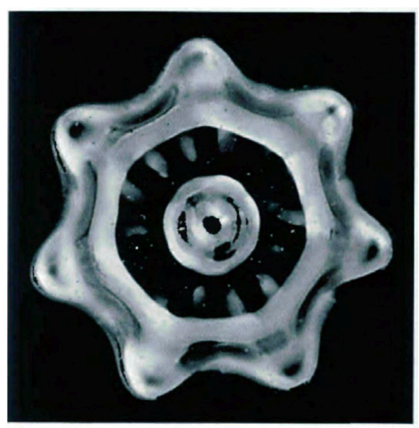
Figure 12. 44 A layer of glycerin excited by the oscillation ot a membrane. Figures can also be seen in the liquid. From *Cymatics: A Study of Wave Phenomena and Vibration (Revised Edition 2001, p6),* by Hans Jenny, 1967/2001, Basilius Presse (1967, original publisher) MACROmedia Publishing (2001, publisher revised edition).



122

Figure 13. 118-123 [only showing 122] These photographs are of vibrating mercury drops. Since high surface tension causes mercury always to seek a spherical form, the drop does not disintegrate under the action of vibration. Instead the vibration becomes visible as a change of form. These pictures thus show true spatial configurations as seen from above. [...] From *Cymatics: A Study of Wave Phenomena and Vibration (Revised Edition 2001, p6),* by Hans Jenny, 1967/2001, Basilius Presse (1967, original publisher) MACROmedia Publishing (2001, publisher revised edition).

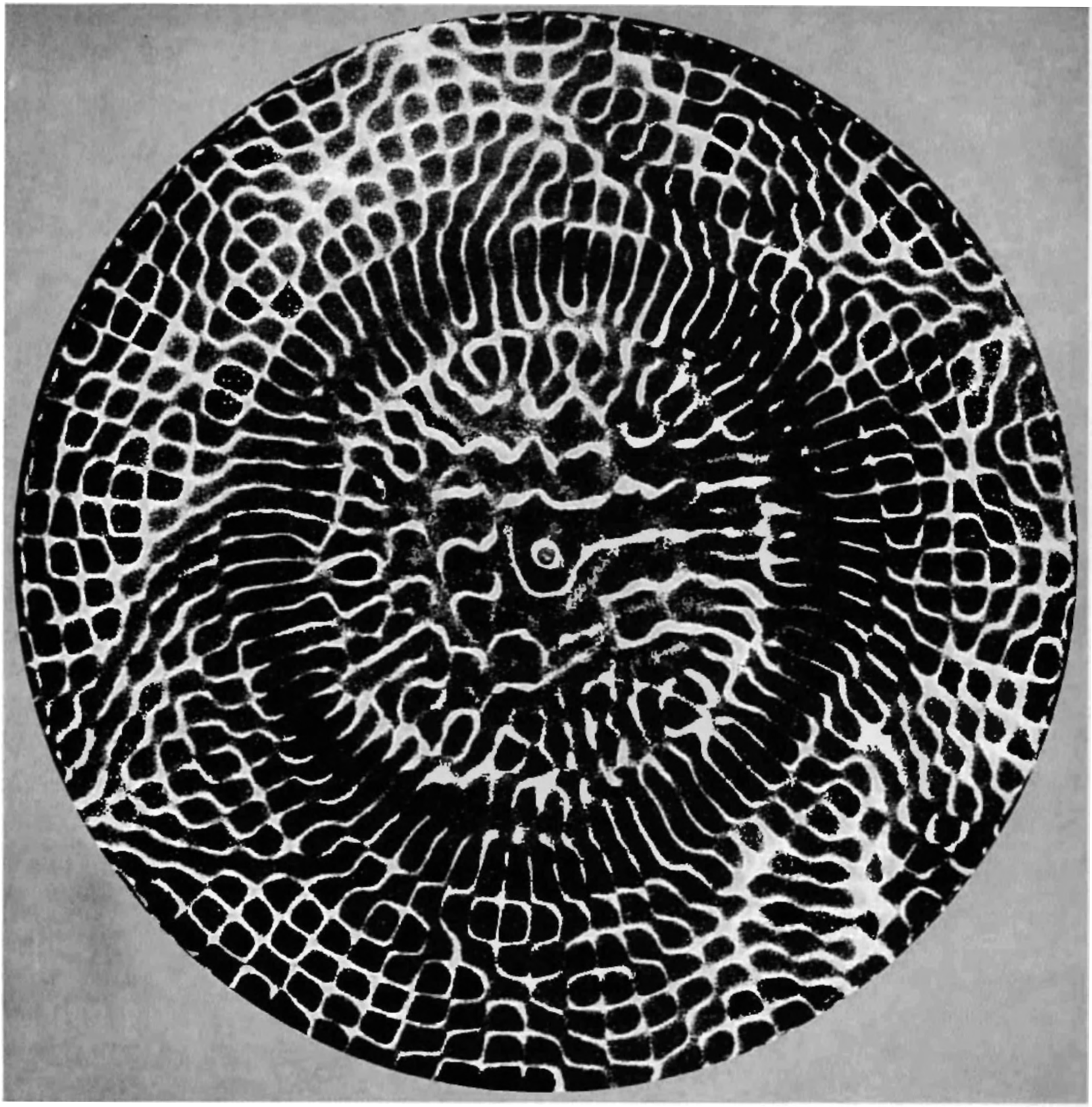


Figure 14. 41 A sonorous figure excited on a circular steel plate. Diameter 50 cm, 6250 cps. In pictures like these the patterns resulting from radial and concentric nodal lines can be studied. From *Cymatics: A Study of Wave Phenomena and Vibration (Revised Edition 2001, p. 44),* by Hans Jenny, 1967/2001, Basilius Presse (1967, original publisher) MACROmedia Publishing (2001, publisher revised edition).

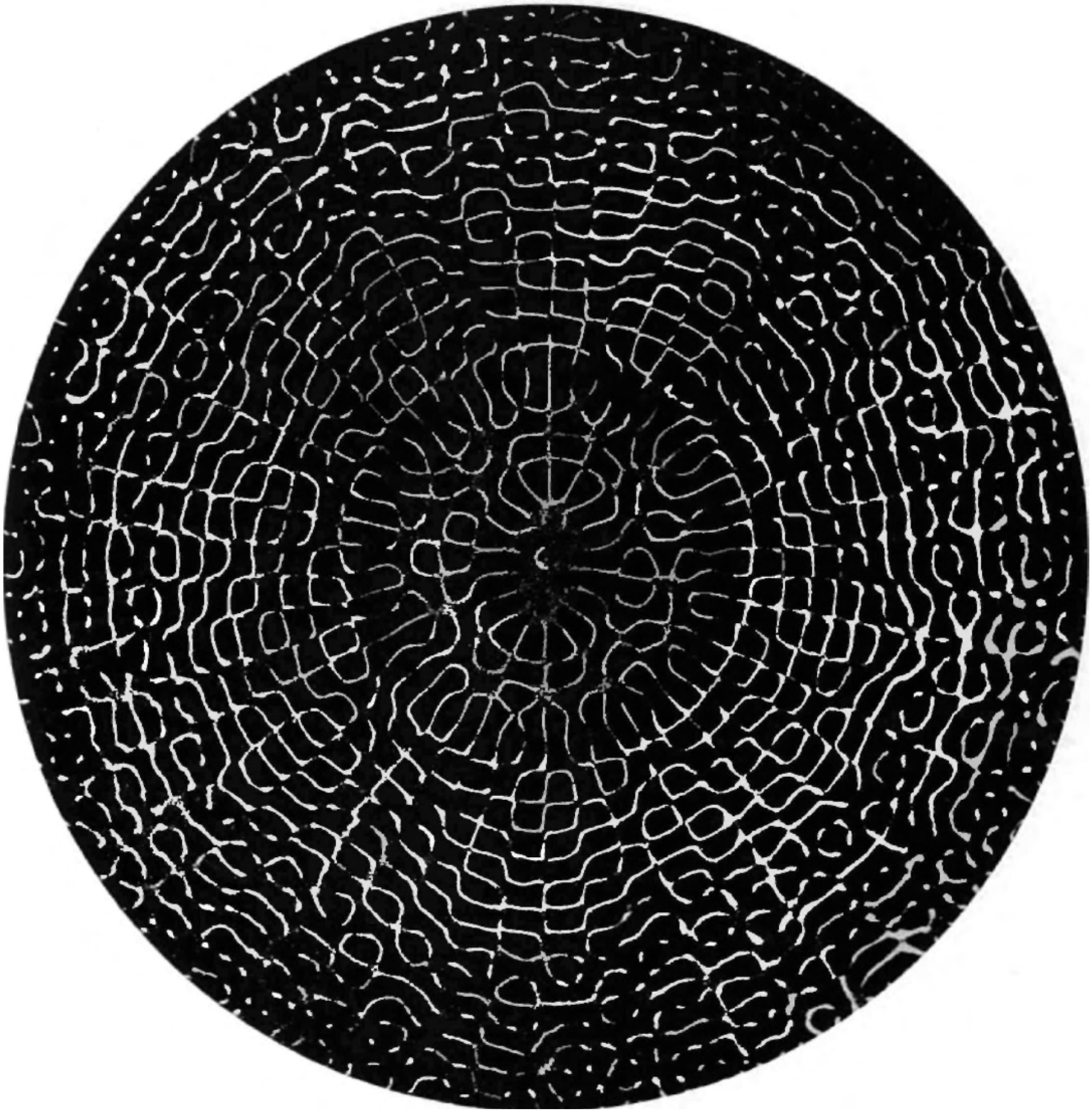


Figure 15. 42 The same plate as figure 41 except that the frequency of vibration is 16.000 cps. By using the piezoelectric method, patterns of vibration can be produced in series. The fact that the frequency is higher than in figure 41 can be inferred by the larger number of fields. From *Cymatics: A Study of Wave Phenomena and Vibration (Revised Edition 2001, p. 45),* by Hans Jenny, 1967/2001, Basilius Presse (1967, original publisher) MACROmedia Publishing (2001, publisher revised edition).

The Chladni plate and Chladni Figures

One well-known example of cymatics is the Chladni plate, named after Ernst Chladni, a German physicist and musician. Chladni is best known for research and experiments on showing various modes of vibrations on metal plates. In Chladni's book "Die Akustik" (Chladni, 1802) Chladni documented research on the emergence of visual patterns of vibrating particles on metal plates by moving a violin bow alongside the edge of the plate as shown in Fig. 16. The emergence of patterns created through such experiments are called Chladni figures or Chladni patterns and the devices used to show visual patterns of cymatics on metal plates are named after Chladni. Fig. 17 shows parts of Chladni's research documented in his book Entdeckungen über die Theorie des Klanges (Chladni, 1787). Original experiments on the phenomenon were done and documented by the English scientist, philosopher and architect Robert Hooke in the late seventeenth century who was the first to discover the phenomenon and Chladni recreated the experiments, further improved upon them and published his results in his books.

It was Mary Waller, a physics teacher in the beginning of the twentieth century that in 1932 discovered that metal plates could be vibrated by holding a solid block of carbon dioxide or "dry ice" to it. She expanded upon the works of Chladni and documented an even more detailed overview of figures that could be made through the vibrating of metal plates. She was about to publish her findings in a book right before she died. Her book Chladni Figures: A Study of Symmetry (Waller, 1961) was still published. Present-day, her systematically structured matrix of squared Chladni figures is still most refered to when it comes to Chladni figures. Her findings and resulting matrices are shown in Fig. 18 and Fig. 19 on the next page.

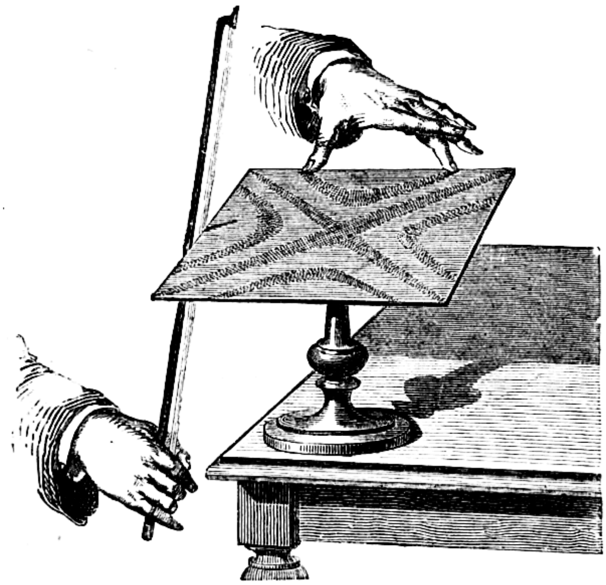


Figure 16. Striking of a Chladni plate with a violin bow. From *Elementary Lessons on Sound (p. 26),* by William Henry Stone, 1879, Macmillan and Co.. In the public domain.

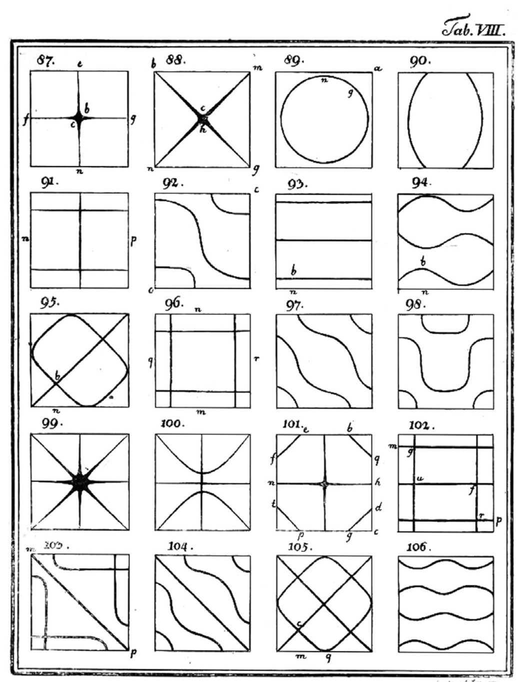


Figure 17. Tab VIII. Adapted from *Entdeckungen über die Theorie des Klanges (p. 80),* by Ernst Chladni, 1787, Weidmanns Erben und Reich. In the public domain.

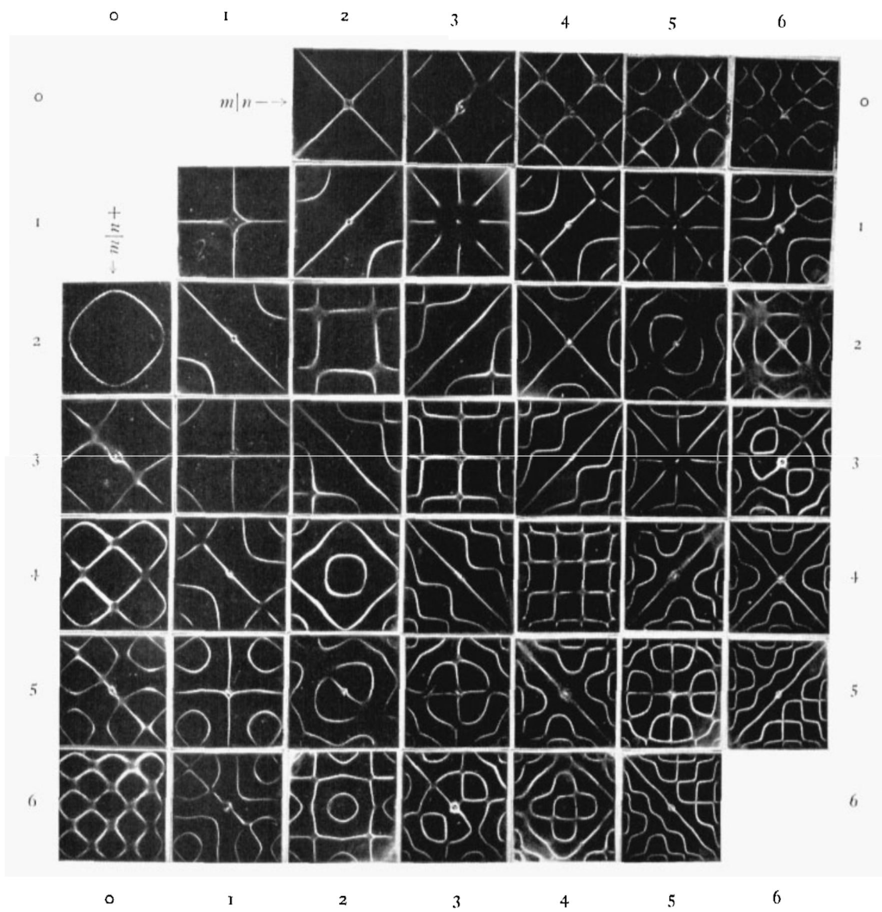


Figure 18. Normal systems of free square plate [...]. From *Vibrations in Free Square Plates: Part I. Normal Vibrating Modes* In Proceedings in the *Physical Society (Vol. 51 p. 836),* by Mary D. Waller, 1939, IOP Publishing.

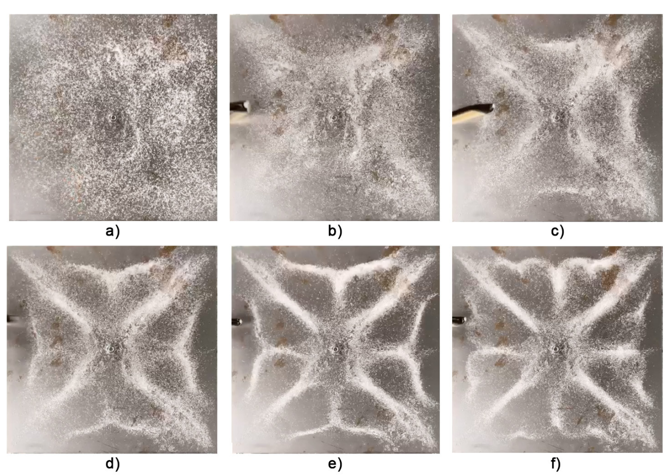


Figure 19. Sequential striking of metal plate with violin bow 245mm square, 2mm thickness, from a to f.

Chladni plate devices used in present time are electronically powered and the vibration is not caused through the striking of a violin bow on the side or blocks of solid carbon dioxide. Mechanical drivers are used able to emit high-frequency movement in the vertical direction, connecting a pin to the center of the metal plate. Modern-day laboratory equipment has allowed to map out the entire mathematical theory behind the phenomenon. The mathematical principle behind the phenomenon is linear but the data on the patterns and the corresponding patterns are variable. The reason for this is that several factors, like the size and thickness of the plate and the material from which the plate is made from, permit what patterns can be created and on which frequency they manifest. Building your own Chladni plate at home is possible and with basic materials a good Chladni plate can be build. Audio speakers are frequently used to build the mechanical driver needed for the high-frequency movement. For this project several Chladni plate devices were build, among the one shown in Fig. 20, build using a subwoofer tactile speaker.

Figure 20. Chladni plate device build for the project. 400mm square 2mm thickness steel plate mounted. Including tactile speaker and amplifier

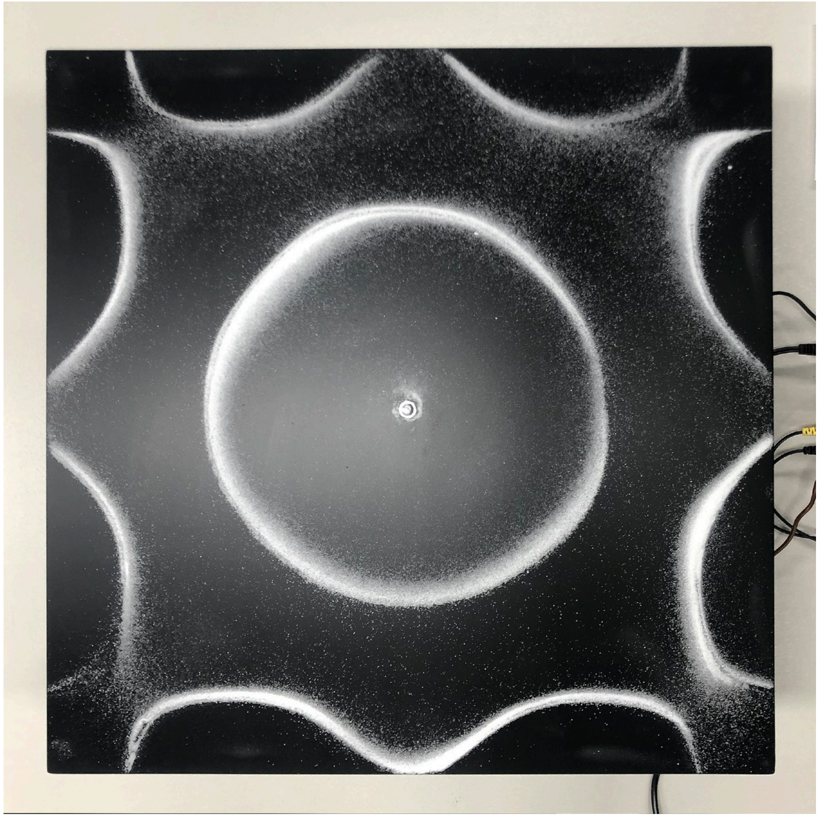


Figure 21. Chladni pattern at 280 Hz, steel 400mm square, 2mm thickness

Figure 22. Chladni pattern at 91 Hz, steel 400mm square, 2mm thickness

Water Cymatics

Another example of the creation of eigenmodes is with water cymatics. In water cymatics an amount of water, often in a circular basin, is vibrated. Installations like this, like with Chladni plate installations, often use some form of mechanical driver that allow for a high-frequency movement in the vertical direction, causing the water to vibrate. Like with the Chladni plate, the bouncing back of the waves on the edges of the system, as it is also a closed system, causes an interplay of amplitudes. The vertical displacement caused by the interplay of amplitudes forms a pattern on the surface of the water; thus, the creation of eigenmodes. The interplay of light and shadow caused by the displacement of the surface can be seen with natural lighting, but additional lighting can magnify the visual feedback, making the eigenmode more visible. In this setting the water acts as the medium that allows wave-like behavior and the visual pattern caused by the interplay of light and shadow on the vibrating surface of the water, can be seen as the particle side of the phenomenon.

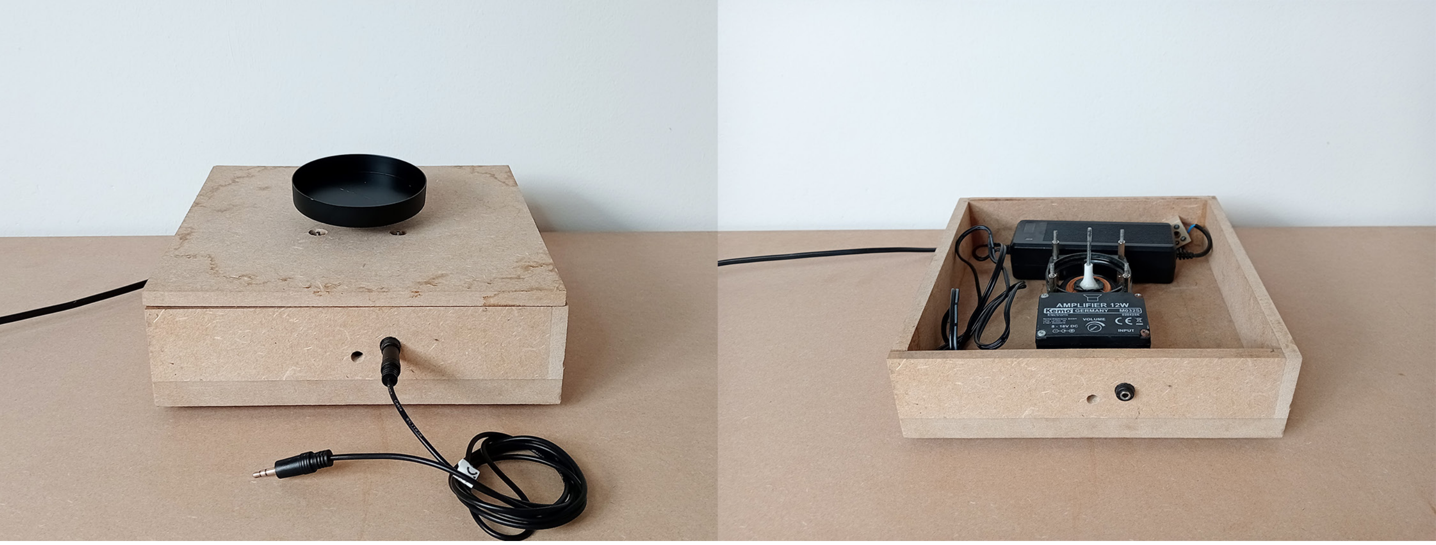


Figure 23. Water cymatics device. 85mm diameter painted black petridish mounted (left), device inside showing 10W speaker and 12W amplifier, including power adapter.

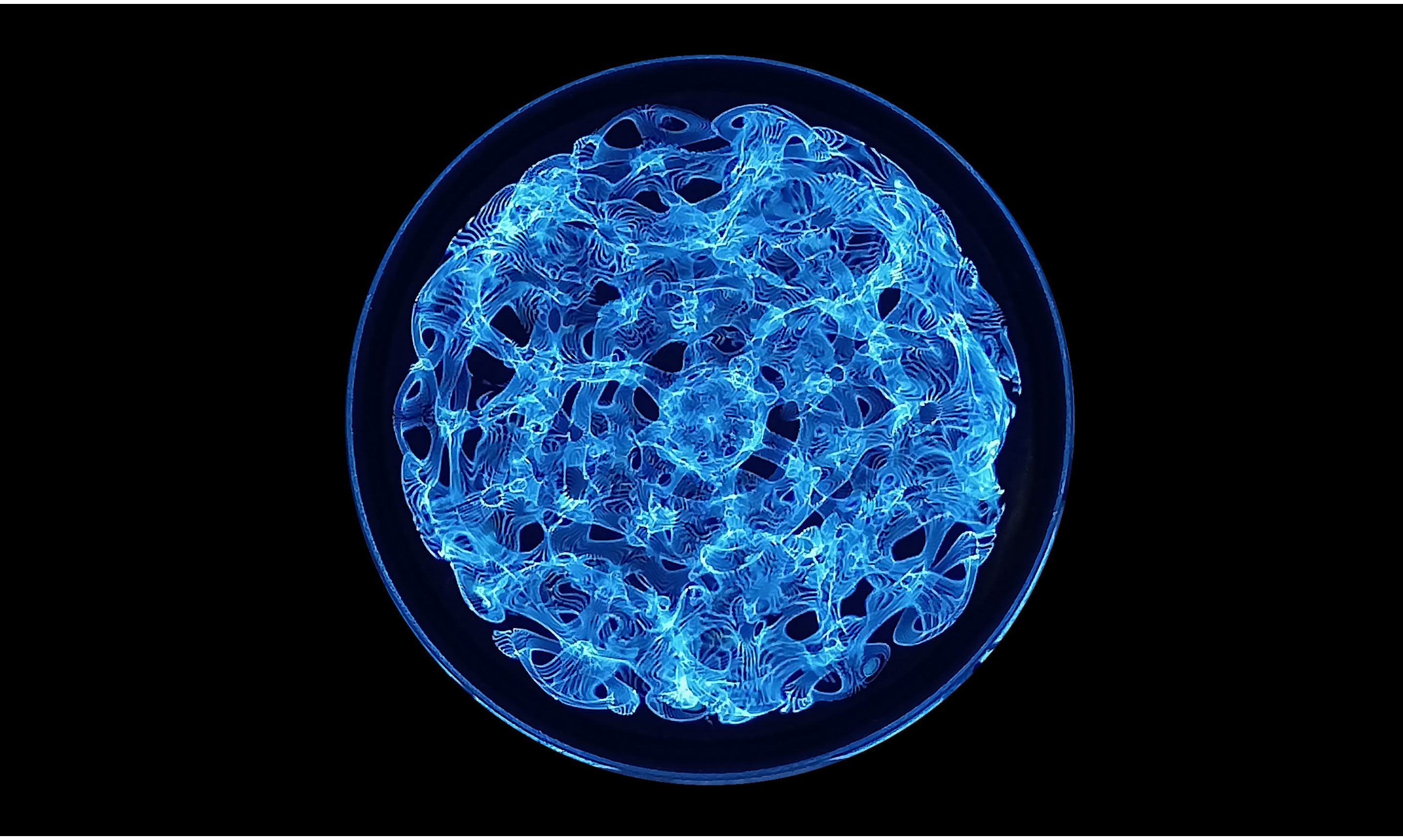


Figure 24. Water cymatics eigenmode, 43 Hz, 55mm diameter painted black petridish

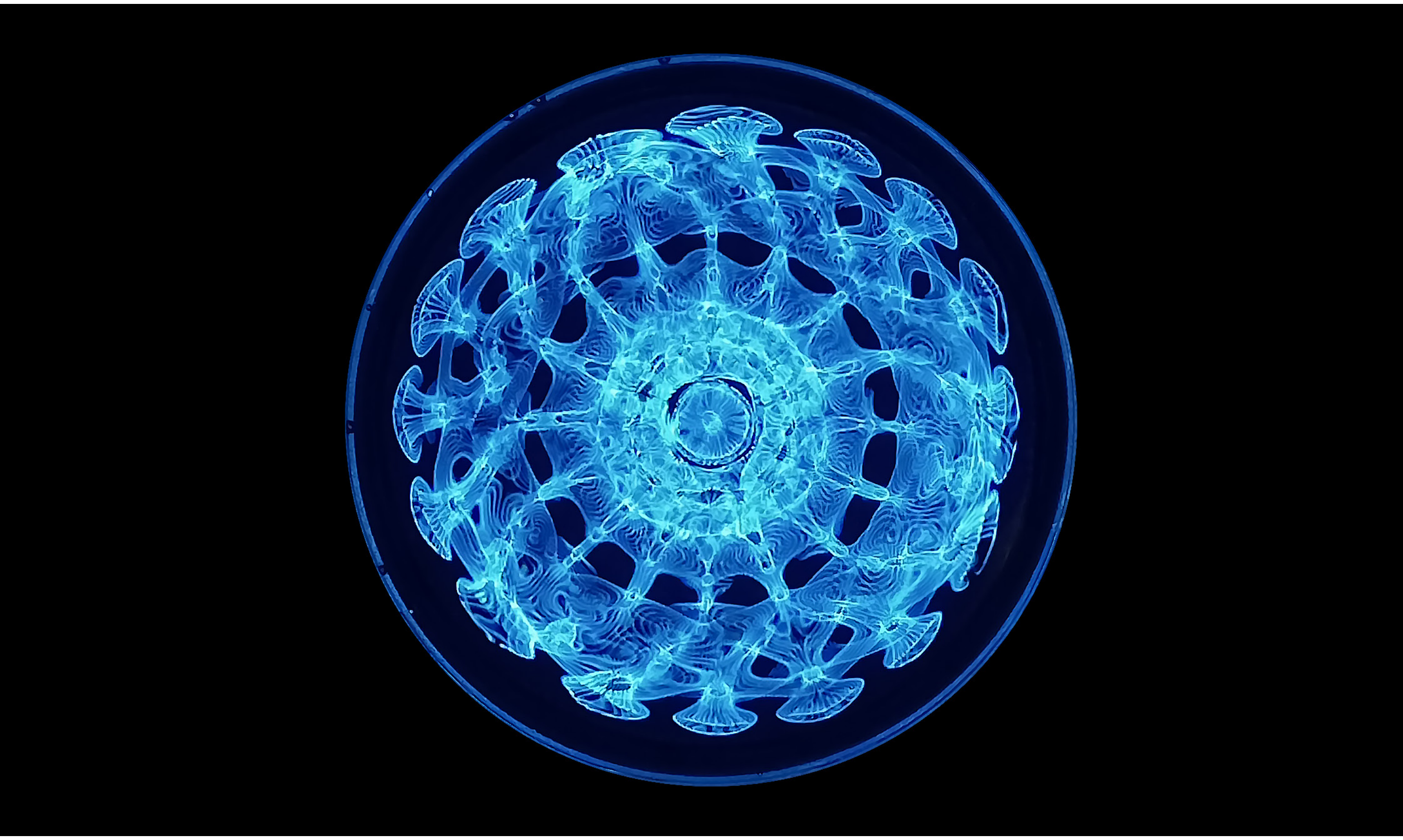


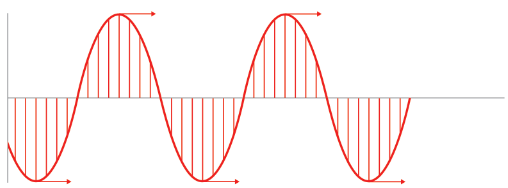
Figure 25. Water cymatics eigenmode, 55mm diameter black petridish

Standing-wave Theory, Interference and Superposition

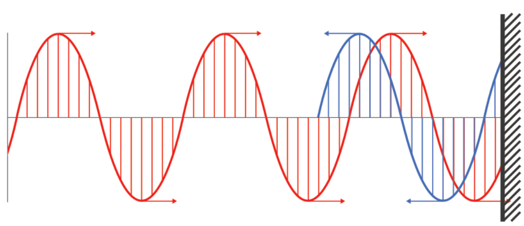
To understand how the visual patterns in cymatics called eigenmodes are produced, a brief examination of standing-wave theory was conducted. The emergence of patterns is the result of interference, a phenomenon wherein waves of opposite direction interact with each other in a way that their energies add up or cancel each other out. In Fig. 26 below this is visualized. A wave was considered travelling in one direction as shown in Fig. 26a, shown in red, where upon hitting a boundary as shown in Fig. 26b, bounced back with the same frequency and energy, shown in blue. In reality waves do not traverse through each other as shown in Fig. 26b, but instead the energies of the waves add up or cancel each other out, like shown in Fig. 26c.

When considering a continues emitted wave of constant frequency and amplitude as shown in Fig. 27, a standing wave is formed. A situation is created where the opposing waves superimpose each other, creating an alternating amplification and cancelling out of the amplitude of the compound wave. Note how as a red and blue wave move towards each other, the compound amplitude increases. The maximum points of the wave are called antinodes and the points where the energies are cancelled out are called nodes. The special thing about a standing wave is, is that the nodes stay in one place, resulting in a wave what would seem to stay in one place, but with a changing amplitude. Fig. 27a to Fig. 27e show in steps, how the red wave moving one direction and the blue wave moving in opposing direction interfere with each other over half of one cycle, visualizing the interference on different moments of time. A standing wave is considered a normal mode of vibration, a state of a dynamic system wherein all parts of the system move with the same frequency and in the same phase. Because of its closed system, cymatics also exhibits this phenomenon.

a)



b)



c)

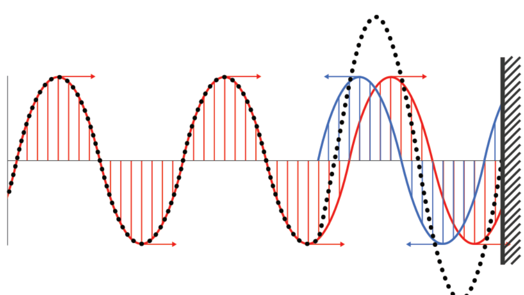


Figure 26. Wave interference; a) traveling wave, b) bounced back wave, c) waves superimposing

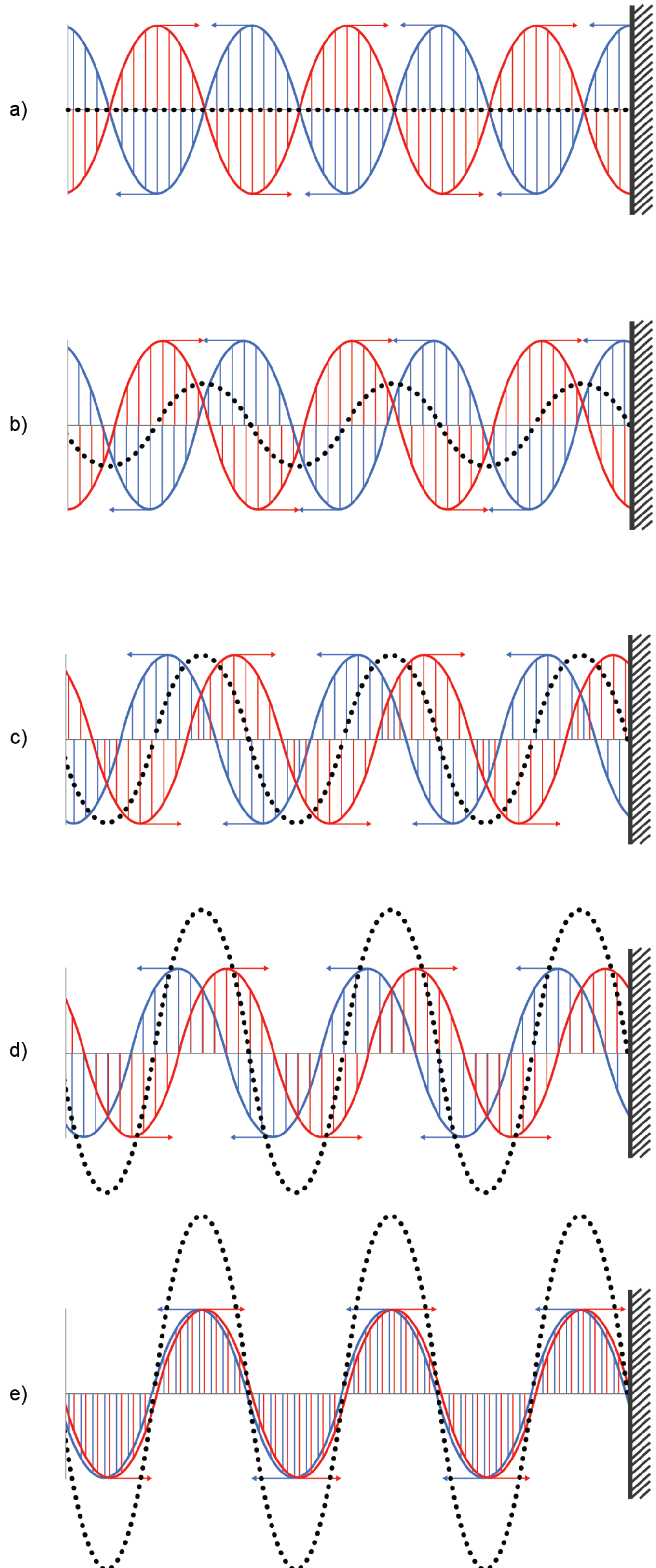
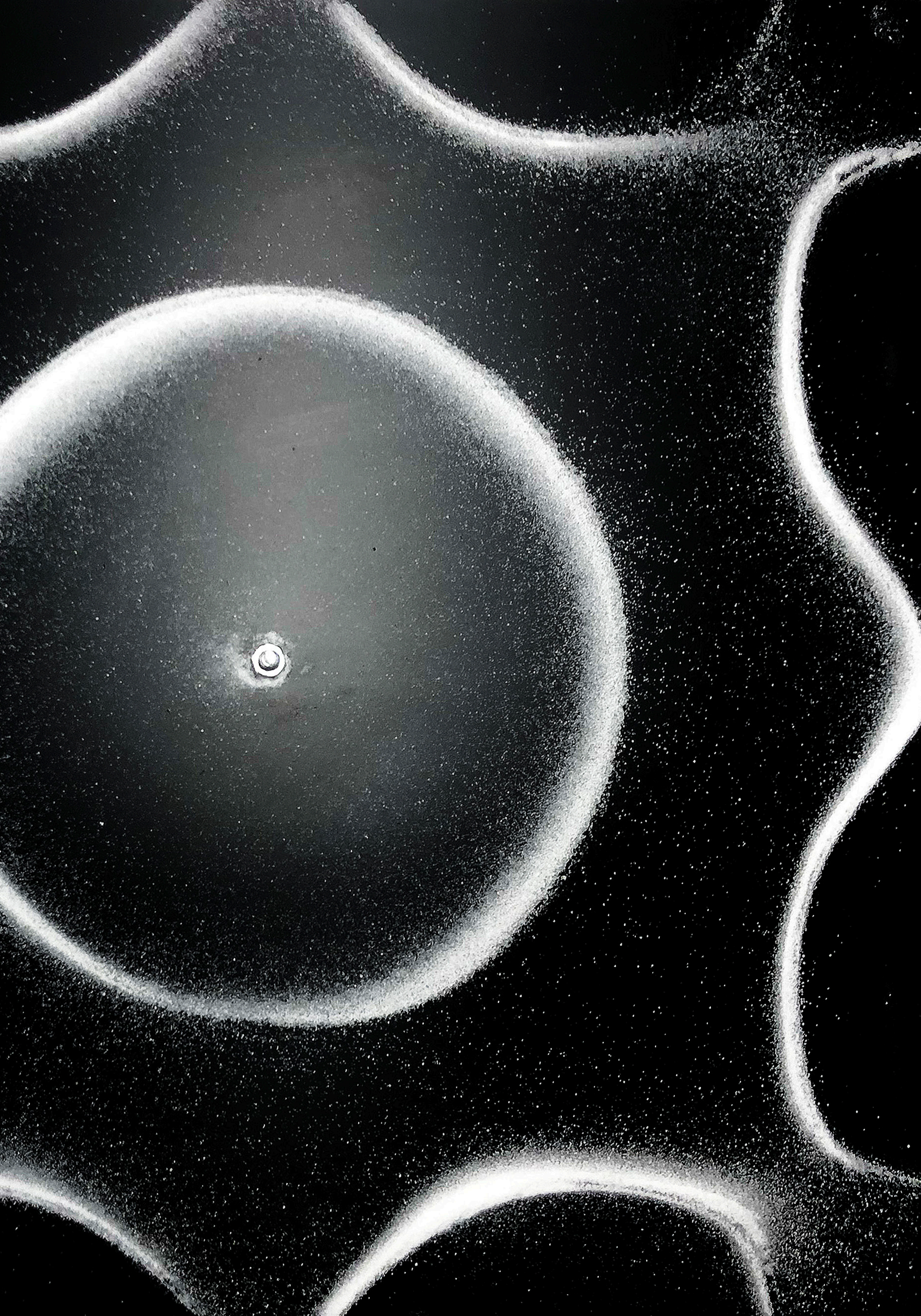


Figure 27. Chladni pattern at 280 Hz, steel 400mm square, 2mm thickness



Phase 1: Explore

Bridging Quantum Physics and Cymatics with the Expertise of Quantum Physicists

The focus of the first phase was to explore ways to bridge the topics of quantum physics, quantum computing and cymatics. During two exploratory sessions, two types of cymatics were examined together with two quantum physicists from a not called by name quantum technology research institute.

During each session ways to introduce basic aspects of quantum physics and quantum computing were investigated through the analysis of the prepared cymatics setups. One cymatics setup consisted of a Chladni plate and the second consisted of a water cymatics setup. Each setup was controlled through a MIDI controller which was connected to a software patch made especially for each setup. The software that was used was MAX MSP, a visual programming software that allowed wave function generator.

The setups were tested and evaluated through a combination of interviewing and discussion while interacting with the setups, and the overarching themes of quantum physics, quantum computing and cymatics were explored. Both sessions started with a short introductory part wherein the overall idea of the project and the goal of the session was explained.

Preparatory to the main sessions 1 and 2, a test session called session 0 was conducted for which IDE faculty members, friends and relatives were invited. To goal of this session was to familiarize with the setup, get a good feel on how to best use the reserved studio that was used for the main sessions and to make sure the main sessions would be a streamlined experience.

Applying the Vision in Product design method: Deconstructing the situation

Using the deconstruction of the ViP method (Fig. 28) as a guiding structure, with the product and interaxction level as main focus, the two cymatics setups were examined.

Product level
On the product level the cymatics devices as a standalone object were investigated with the physicists. Central to this level were the creation of eigenmodes produced by the cymatics devices. The use of eigenmodes in quantum physics and quantum computing were discussed and bridging aspects, and analogies to cymatics were looked for.

Interaction level
On the interaction level the focus was on the method of conducting quantum computing research. One goal was to try and find out how quantum computing research is conducted and if any inspiration could be drawn for the forming of design factors later to be used in the project.

Context level
During session 2 also a brief discussion was held on what characteristics in job applicants is looked for within their research institute. The goal of this was to see if aspects could be found that could be used in the later to be designed interaction design.

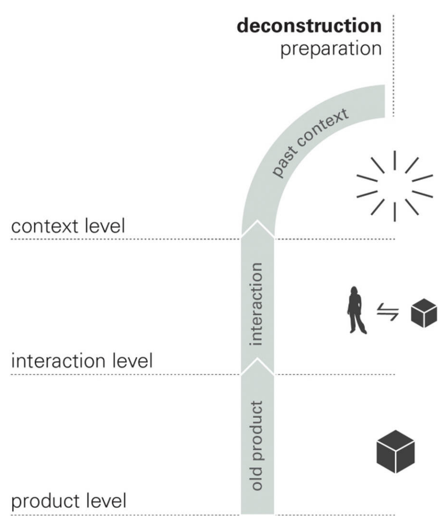


Figure 28. Adaptation from Three levels of description in the ViP model, From "*Vision in Design: A Guidebook for Innovators (3th ed.,p. 119),* by P.P.M. Hekkert and M.B. van Dijk, 2021, BIS Publishers

Session 0: Getting Familiar with the Test Setup

To make sure the main sessions would follow a well prepared and streamlined structure that would allow the gathering of enough valuable data, a preliminary session 0 conducted. The session was held in Studio Say at the faculty of Industrial Design Engineering (IDE) at the TU Delft. Session 0 allowed to get a good feel of the room and test out several ways of setting up the room logically, respectively to the setups in mind. Faculty members of IDE, relatives, and friends were invited to the session with the goal of acquiring inspiration and insights on how to approach the main sessions. An employee from a science museum was able to join the session, providing insights on the needed contextual requirements later to be used.

For the session the devices built for the Ritman Library project were used. The setups were put on separate tables, as shown in the floorplan shown in Fig. 29. Fig. 30-32 show the setups.

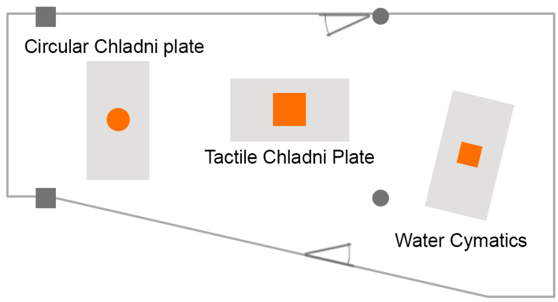


Figure 29. Floorplan of the studio and the prepared cymatics setups used during session 0.

Figure 30. Setup 1: water cymatics setup containing 88mm diameter petridish; painted mat black, filled with water. Lighted with a MOMO RGB LED ring

Figure 31. Setup 2: squared Chladni plate. Five different squared metal plates were tested, including 400mm square; 2mm thickness; steel, 400mm square; 1mm thickness; aluminium, 400mm square; 2mm thickness; brass; 240mm square; 2mm thickness; steel, 240mm; 1mm thickness aluminium, salt was used for the particles.

Figure 32. Setup 3: circular Chladni plate containing 240mm diameter; 1mm thickness; steel, salt was used for the particles.

Figure 33. Session 0 demonstration of setup 2 squared Chladni plate with IDE faculty members.

Figure 34. Session 0 demonstration of setup 1 the water cymatics setup with IDE faculty member

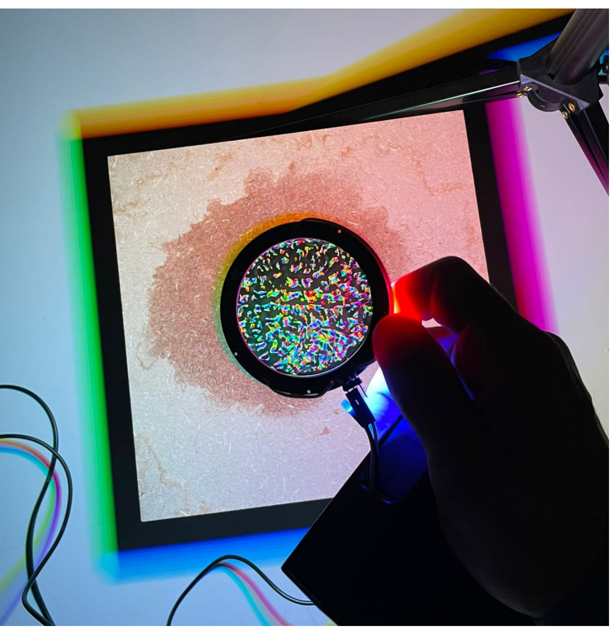


Figure 35. Topview of setup 1, the water cymatics setup, showing water vibration lighted with an 24 LED ring.

Session 0 Evaluation

Overall session 0 was a success and valuable insights were gained. The session was done over a period of several hours wherein walk-in was possible. From a positive perspective this allowed a high rate of attendance since invitees had the freedom to fit the session to their own personal schedule. The downside of having a walk-in approach was that giving introductory talks were difficult to do, with the result of the session becoming chaotic. Also taking a break in between was difficult to plan, leading to moments of mental exhaustion, especially towards the of the afternoon, to which moments occurred where I was not able to give my full attention to every discussion that arose. The insights taken from this were to have shorter scheduled blocks of interaction and to start each block with a well-prepared introduction.

Another important insight was gained from the perspective of the interaction with the devices in terms of controlling the input frequencies of the devices. The session was demonstrative, namely because the devices' input was done through a phone application, allowing little interaction with the devices from the invitees' side, besides seeing and experiencing the phenomenon.

The attendance from the science museum context was valuable in terms of validating their interest in exhibiting topics like quantum physics and quantum computing and valuable tips were shared to keep in mind during the design process to make sure the design is realizable and exposable in the context of a science museum.

It could be concluded that effectuating interest in the topic of cymatics through demonstrating the phenomenon was confirmed. The goal of introducing quantum physics through the phenomenon was regarded as ambitious. Little effort was needed to start discussion on the topic and validated the envisioned effect of fascination. The overall feedback was that people were glad that they found a moment in their planning to come by.

Bridging Quantum Physics and Cymatics: A Focus on Quantum Computing

Introduction

The main sessions, session 1 and session 2, were focused on finding insights that could bridge the topics of quantum computing and cymatics, with the goal of finding design factors that could later be used during the conceptualization phase to come to design solutions. Two not called by name quantum physicists, from here on addressed as quantum physicist 1 and quantum physicist 2, respectively to the number of the session, from the quantum technology research institute, agreed to the invitation that was send to them to help in the process of findings design factors and bridging connections between quantum physics, quantum computing, and cymatics through the exploratory sessions. The examination of cymatics devices stood central in these sessions and the physicists were notified beforehand on this notion and were giving a brief description of the goal of the project and the session specifically.

In preparation of the sessions, insights gained during session 0 were considered and adapted where needed. Instead of multiple attendees, session 1 and session 2 were held with one quantum physicist per session. This led to a situation to which the entire session could be scheduled to a specific time and over a shorter timeframe. This solved most of the negative aspects in terms of structuring and guidance in comparison to session 0. Each session started with an introduction wherein more information of the project was shared, and the goal of the session was explained. Besides informative the introduction was used as a conversation starter on the topics to be examined.

One of the important aspects in comparison to session 0 that had to be improved was increasing the amount of possible interaction with the setups. For session 1 and session 2, an interactional design was made using MIDI controllers and software. To increase the allowance of interaction within terms of regulating the frequency, a software patch was made using software called Max MSP. MIDI controllers were used to control the setup through the patch, allowing the physicist to interact with the device for examination.

Exploratory Goal

Primary in cymatics is the creation of eigenmodes. It was hypothesized that a connection could be found between the eigenmodes in cymatics and the visual representations of quantum models and data. One leading goal to find out throughout the sessions, using the expertise of the physicists, was if such connection could be made, either directly or indirectly through for example the use of analogy.

Another subject that was explored, was the method of doing quantum research. The reason for this was to try and find out if it would be possible to translate their way of conducting research into an interaction vision that could later be used for designing the interaction designs during the conceptualization.

An addition to session 2 was made, wherein there was sought after what personal characteristics and traits are looked for, from the perspective of a quantum technology research institute posting vacancies for available job opportunities. The goal of this was to see if specific traits could be found that could later be used as reference in the process of coming up with design solutions.

Levels of deconstruction using the Vision in Product design method

Above-described goals were formulated in a way corresponding to the levels of deconstruction of the Vision in Product design method, as shown in Fig. 36. Using the method's sequential structuring to structure the beforehand prepared layout of the session, led to a clear form of guidance to which the subsequent parts of the session could be held. Starting at the product level made a good way to explain the project's overall goal while at the same time starting a discussion very specifically on the examination at hand. The examination of the eigenmodes produced by the cymatics devices on the product level and its relation to quantum physics and quantum computing, framed the first part of the session clearly. In a fluid way the interaction level was incorporated automatically during the discussion and as the session furthered an analogous contextual bridge between quantum computing and cymatics was made.

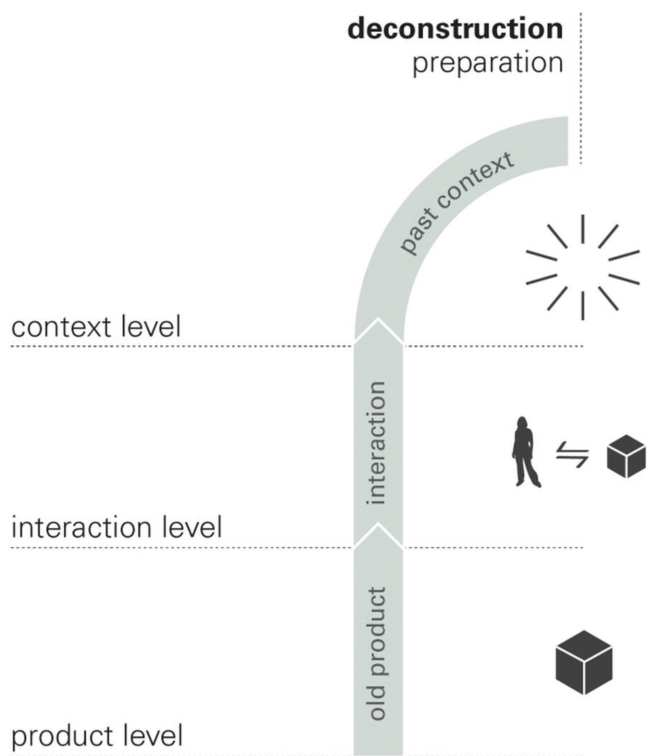


Figure 36. Adaptation from Three levels of description in the ViP model, From "*Vision in Design: A Guidebook for Innovators (3th ed.,p. 119),* by P.P.M. Hekkert and M.B. van Dijk, 2021, BIS Publishers

Session Setups: Water Cymatics and Chladni Plate

Two setups were made: one water cymatics setup controlled through an M-Audio Axion 25 MIDI keyboard, and one Chladni plate setup controlled through an Akai MPD218 MIDI controller and a computer keyboard. Instead of using two types of Chladni setups like in session 0, it was decided to only use the square shaped Chladni plate, to create a clear division of the two types of cymatics examined. For session 1 and session 2 the same setup was used. Fig. 39 shows the floorplan of the setup.

Water Cymatics setup
The water cymatics setup consisted of one steel pan filled with water, standing on top of the same type of tactile speaker used as was used in the tactile speaker Chladni plate in session 0, this time without the wooden casing but directly on top of the textile towel for dampening. The steel pan was taped to the tactile speaker. Arrays of petri dishes, varying in size and shape, were filled with water, and were positioned on each side, as additional examinations. The arrays of petri dishes were vibrated by the generated vibration of the tactile speaker, with the table acting as medium through which the frequency could traverse. One petri dish was filled with milk for the examination of a substance of a different viscosity.

Chladni plate setup
For the Chladni plate setup the tactile speaker Chladni plate device was used. Two main additions were made to this setup in comparison to the setup used in session 0. An Akai MPD218 MIDI controller and a computer keyboard were added to allow interaction with the setup through a created Max patch that could generate and change the frequency. The pads on the Akai MPD218 allowed the selection of specific frequencies and a computer keyboard was used alongside to change the frequency one Hertz at a time. A television screen was used to display the Max patch as a reference to regulate the frequency.

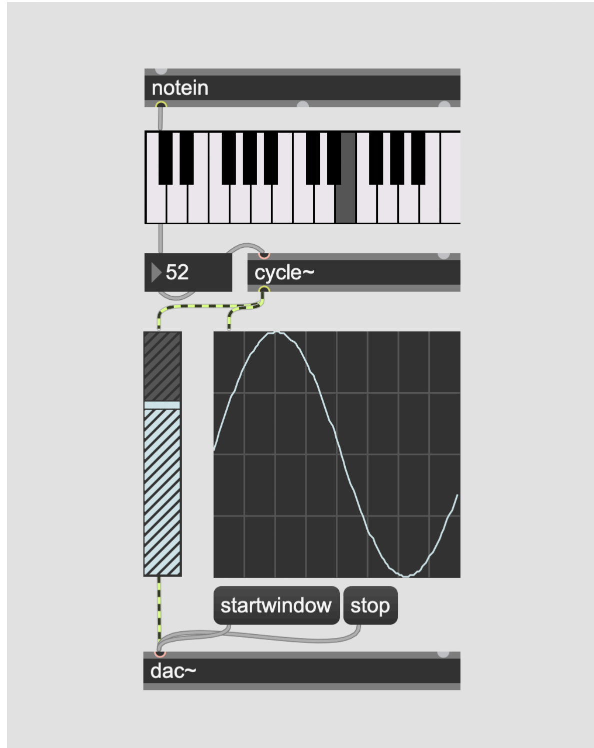


Figure 37. Water cymatics setup MAX MSP patch used for frequency control

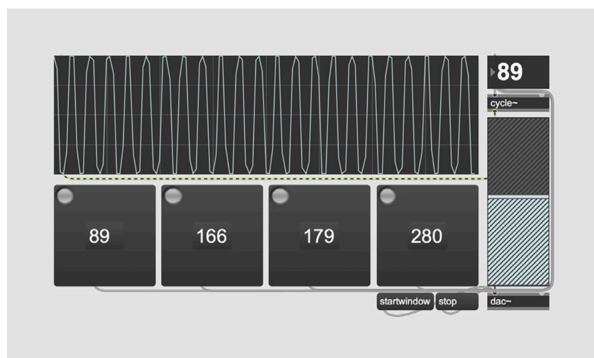


Figure 38. Chladni plate setup MAX MSP patch used for frequency control

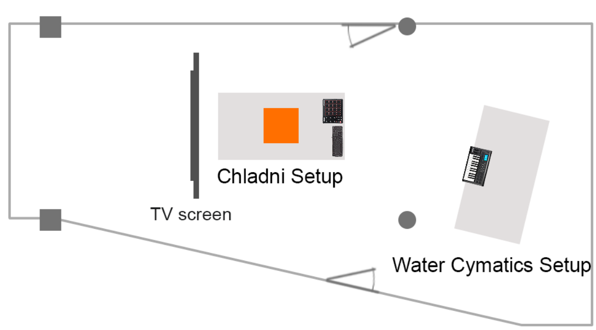


Figure 39. Floor plan containing the two cymatics setups for session 1 and session 2.

Figure 40. Water cymatics test setup in preparation for session 1 and 2

Session 1: Quantum Physicist 1

With quantum physicist 1 topics on quantum physics and quantum computing were discussed and the cymatics devices were analyzed in an interactive manner wherein the idea was to have the physicist behind the controls of the setup and hear his thoughts. Along the way discussions on several topics formed, and through the asking of specific questions in an interviewing manner, the session was guided.

During the session the focus lay mostly on product level and interaction level, following the ViP method deconstruction structure. After an introductory presentation examination of the setups began. The water cymatics setup was examined first and the Chladni plate setup followed.

An overview of the topics that were discussed can be summed up as followed:

- The fascination of understanding something and the fascination of pursuing the unknown within the fields of quantum physics and quantum computing
- The iterative process that a quantum calculation consists of
- Making changes to quantum systems, quantum quenches, and decoherency
- The superposition of quantum bits
- Relating probability distributions to their method of working with their quantum systems
- The analogous comparison of a quantum computer to a classical computer
- The importance of history in the system and its influence on the whole
- Relating quantum systems and classical systems, to each other and their relation to reality
- The value of using visual representations to visualize quantum calculation
- A comparison of open systems and closed system and their relations to probability distributions and eigenmodes

"Changes are made to a stable system by making changes to certain conditions of the system. The system then adapts to the new conditions, this takes a short moment and is called a quench. In relation to this cymatics system, the changes are made through changes of frequency, from which then also new stable situations in the system are created". (quantum physicist 1).

"In a quantum system the quantum superposition never maintains. It collapses. Changes made to the system accumulatively make up a calculation. The quantum bits that are used have a certain value, they start in zero and then changes to the system are made, with the goal of taking a zero to a one state for instance, or a superposition of 0 and 1. Every time you make changes to the system, you basically destabilize the system, but if you do that in a controlled goal-oriented manner, then every change is a step within the calculation. Done properly, these steps together can have valuable meaning". (quantum physicist 1)

"These cymatics wave patterns do have a link with quantum systems. They relate through things like wave patterns, standing waves and eigenstates. Wave patterns are found in both classical and quantum system. As these cymatics systems are classical systems, without a doubt these phenomena exist and are found in the classical world. With quantum this is a more difficult notion to state. There are aspects of quantum that exist in the classical world, and for these aspects, intuitive demonstrations could be conducted. There are also aspects of quantum that are more difficult to imagine from a classical perspective. For these aspects it could be possible that they could be described through visual representation". (quantum physicist 1).

Session 2: Quantum Physicist 2

For session 2 was conducted with quantum physicist 2, from the same quantum technology research institute. The setups that were used were the same as in session 1, but the method of approaching the discussion was changed, building on top of the knowledge gained during session 1.

In session 2 also a brief examination of the context level was done, following the deconstruction structure of the ViP method.

An overview of the topics that were discussed can be summed up as followed:

- The value of visual representations of quantum calculation
- Doing quantum research, understanding quantum systems and the manipulation of it
- The flipping of a quantum qubit
- The sensitivity in the system
- How mathematical representations relate to reality
- The analogous comparison of the water cymatics setup to their method of working with their quantum qubits, and how it relates to quantum systems and how it differs from it
- The confinement and controlling of a qubit
- Looked-for personal traits and characteristics in the field of quantum computing from the company's perspective

Primary Insights from Session 1 and 2

Session 1: most important insights:

- Again, that the visualization of quantum calculation and quantum data is valuable, and that the visual representations of eigenmodes in cymatics are similar, making the learning of eigenmodes a good method of introducing basic aspect of quantum physics and quantum computing
- A clear set of analogies between quantum computing and cymatics was obtained
- The importance of having pragmatic and exploratory mindsets in a quantum computing company

Session 2: most important insights:

- That visual representations can help in understanding and conveying quantum data and that the eigenmodes in cymatics are sometimes similar and therefor a good way to introduce basic aspects of quantum physics and quantum computing
- A clear overview was obtained on what their process is of doing quantum calculations and how they work with their quantum systems.
- That the built-up of quantum calculation is an iterative accumulation of changes made to the quantum system exploratory mindsets in a quantum computing company

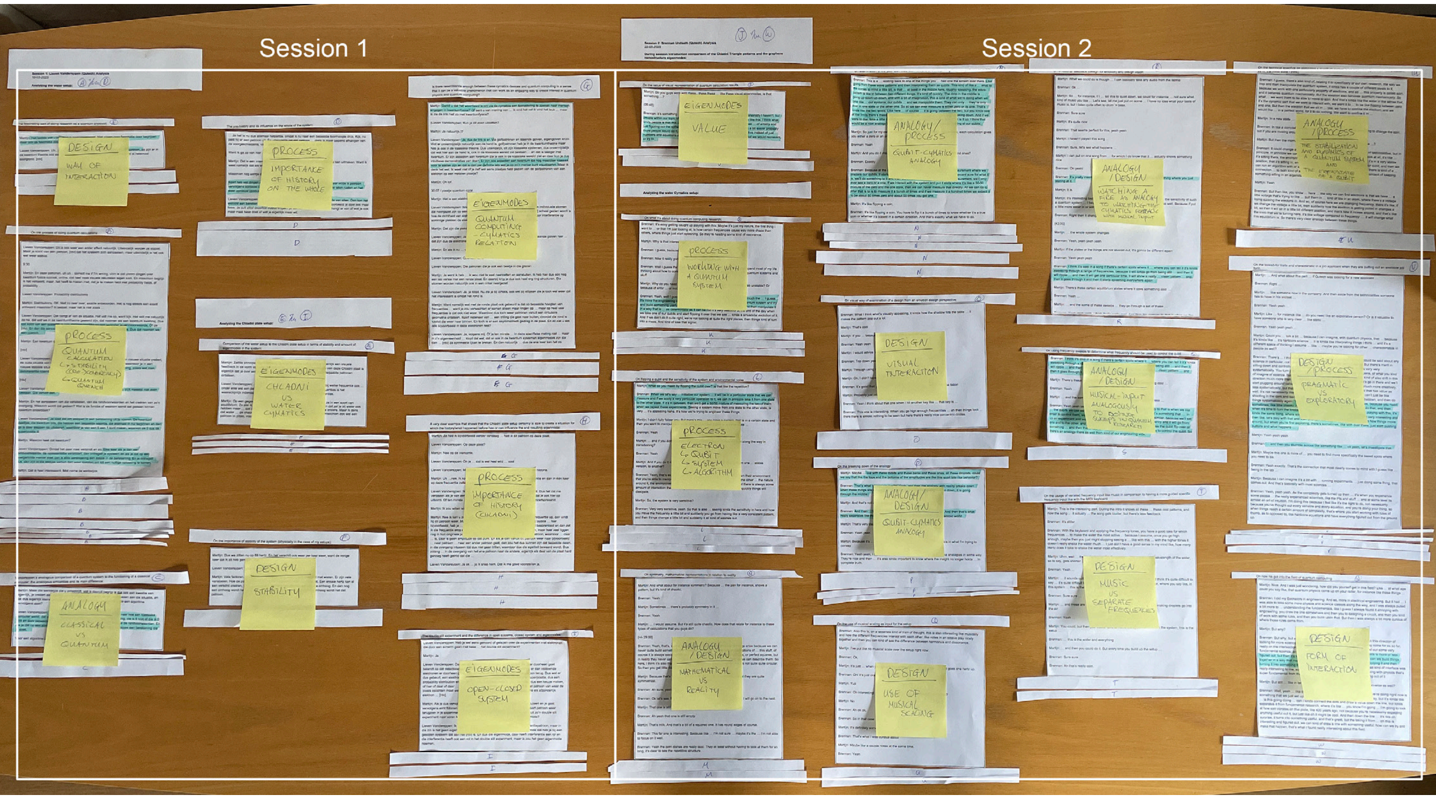


Figure 41. Laid out categorized transcript

Analysis of Sessions 1 and 2: Context Mapping

The sessions were recorded in audio form and were transferred to textual form for analyzation. A form of context mapping was applied to structure collected data in preparation of applying the Vision in Product design method.

First each session was divided into separate parts respectively to the overarching themes of the discussions held. Parts of interest were taken and a selection of texts was made. Each part was given a title conveying the subject. Subsequently each part was analyzed, and important insights were gathered in a list of bullet points.

The texts were printed, and further analysis of the data was done on paper. The parts were cut out with scissors and laid down on a table to get a clear overview. Interesting parts and possible quotations were highlighted with a marker. Each part was then categorized in one of four categories: process, design, analogy, and eigenmodes, and was summarized in keywords. The categorization was done using memos, as shown in Fig. 41.

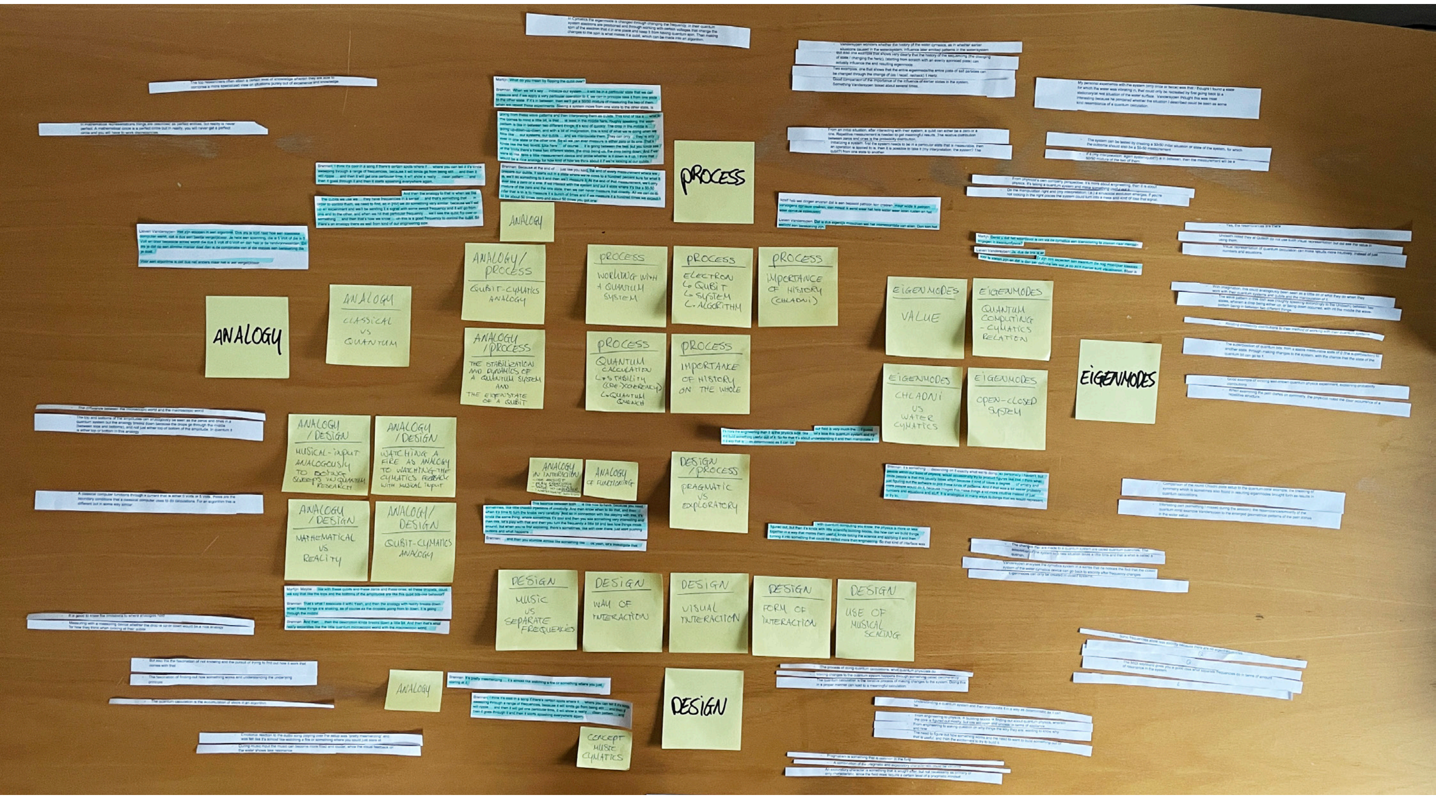


Figure 42. Ring-structure of mapped out data, containing topics (center) and insights (outer ring), and connecting texts and quotations (in between).

For the next part of analysis the memos were taken from the texts and were structured on a table. Some of the texts were put in two categories, forming combinations of categories. Afterwards the highlighted parts of the text were cut out and laid around the structuring of memos, following the structural mapping in terms of topic and categorization. Added to that were the formulated bullet points in the most outer ring, positioned accordingly to the emerging mapping in terms of meaning. The mapping of data taken together made a ring-structure of information as shown in Fig. 42, with in the center the topics, in the outer rings the insights, and in between the parts from the text and quotations were put that connect the structure of data all together.

The mapping of the data, both during the creation of the structure and the evaluation of the structure afterwards, created a good understanding of what the overall data encompassed. Together with the assessment of all collected data so far, this led to the forming of an interaction vision, for which the next part will be about.

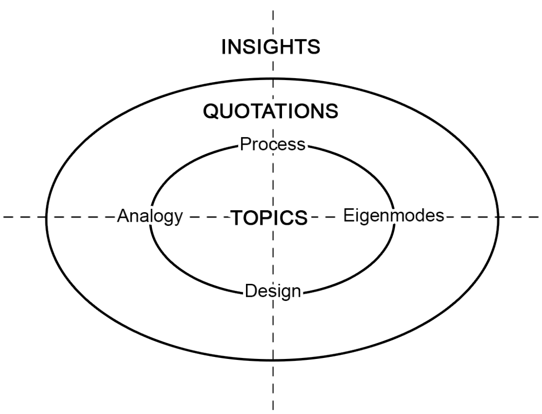


Figure 43. Schematic of ring-structure of data analysis in figure 43

Interaction Vision

"The interaction with the design should make the user feel like working like a quantum physicist."

A brief look at the photo in Fig. 44 on the right, showing the interior of one of IBM's quantum computers should give any person with a little interest in science a feeling of exhilaration. Breath-taking machines full of pipes, cables, nodes, and plates, a construction of complexity, for which the design and assembly are on a level of state-of-the-art design that is next-level, covering you in a coat of futuristic mystery, and leaving you behind with idea of looking at something from a science fiction movie, while knowing it is actual technology from the present day.

Ask someone who does not know much about quantum computing to think about quantum computing, and most likely images like the photo of IBM's quantum computer on the right will pop up in someone's mind. These types of depictions are common, and while the machines look like this, it is kind of misleading in an almost ironic way in terms of looking at the above stated interaction vision.

In short, most quantum physicist do not work directly with machines like the one shown on the right. Ironically a picture of a person sitting behind a computer, working hard writing code, would probably be a better depiction in terms of depicted the above stated interaction vision. So, what is the appropriate manner of looking at this? What is the right balance between the two described depictions? And what makes the work of a quantum physicist the type of work that quantum physicists do? And maybe most importantly, what is that feeling of above-described exhilaration, around and in the field of quantum physics and quantum computing? Because it is there, that is for sure.

To find out, a deeper look at what it means to be a quantum physicist and its relation to engaging young future scientists in the field of quantum physics and quantum computing, was conducted through another form a mapping the collected data.

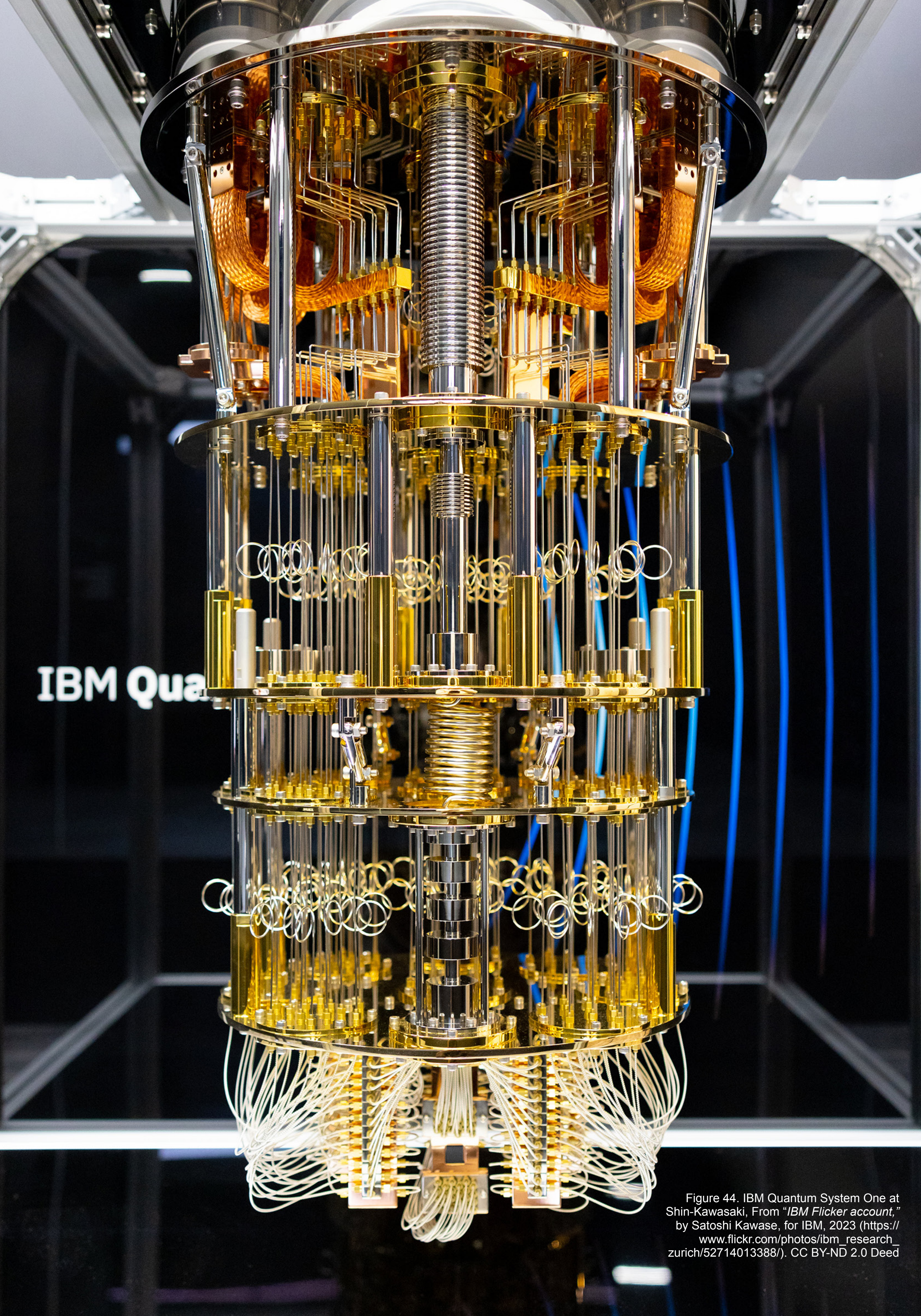


Figure 44. IBM Quantum System One at Shin-Kawasaki, From "*IBM Flicker account,*" by Satoshi Kawase, for IBM, 2023 (https://www.flickr.com/photos/ibm_research_zurich/52714013388/). CC BY-ND 2.0 Deed

Analysis of Sessions 1 and 2: Applying ViP

The previous context mapping structure led to a good forming of an interaction vision, but it had to be concluded that the mapping had a downside, namely that the items from which the mapping existed, were organized but were too much put together on topic. It was concluded that the function of finding interconnected relationships of a meaning was lost. In the following part a different mapping was constructed, that made it possible to structurally find and form the factors needed to formulate a statement. Common to the Vision in Product design method is the transition of formulation of factors on topic level to a formulation of meaning level.

Fig. 45 below depicted shows the improved mapping structure. It was made in the same four-directional structure of categorization of process, analogy, design, and eigenmodes, but the memos containing the summarization in keywords were mapped according to their meaning, and less on topic. To keep a clear overview to start from, the bullet point insights were kept out, to be used later in the process, The highlighted texts of interest and possible quotations were put in as informative referencing.

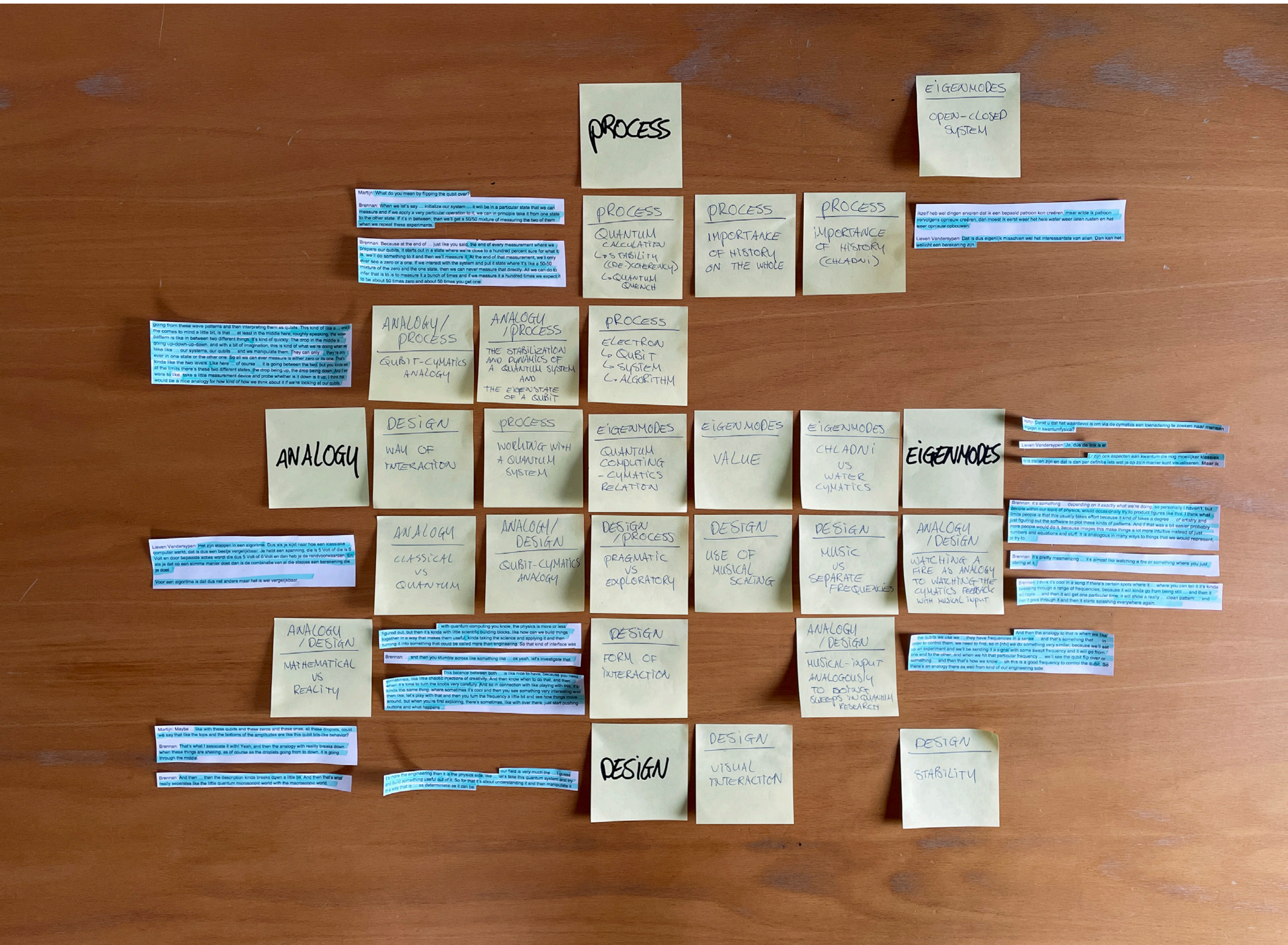


Figure 45. Restructured mapping of the data, including the four main topics and the quantum computing-cymatics relation in the center

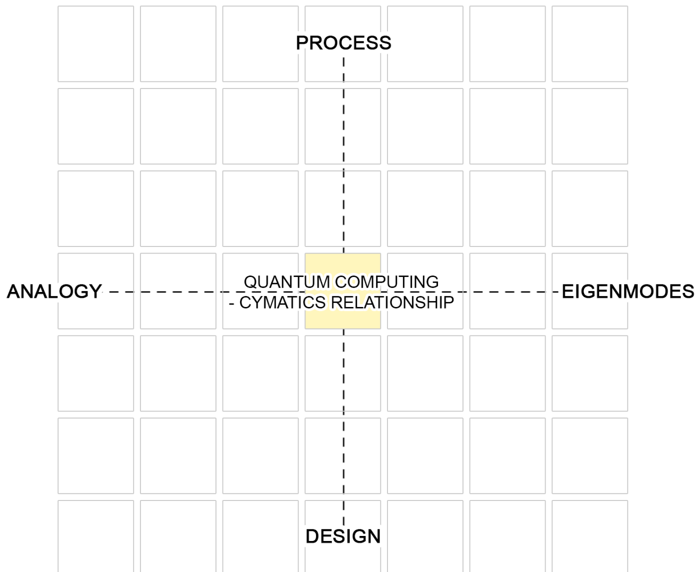


Figure 46. Schematic underlying data mapping of Fig. 46

The schematic pictured in Fig. 46 above, shows the grid to which the mapping shown on the previous page is based. Central in the schematic is the quantum computing-cymatics relationship. The mapping was used to formulate design factors needed for the design process. Through using a brainstorming method of rearranging the memos and add to that earlier gathered items of data, the factors were compiled. Below in Fig. 47, an example is shown of the forming of one of the factors. For all six forming of factors see appendix A.

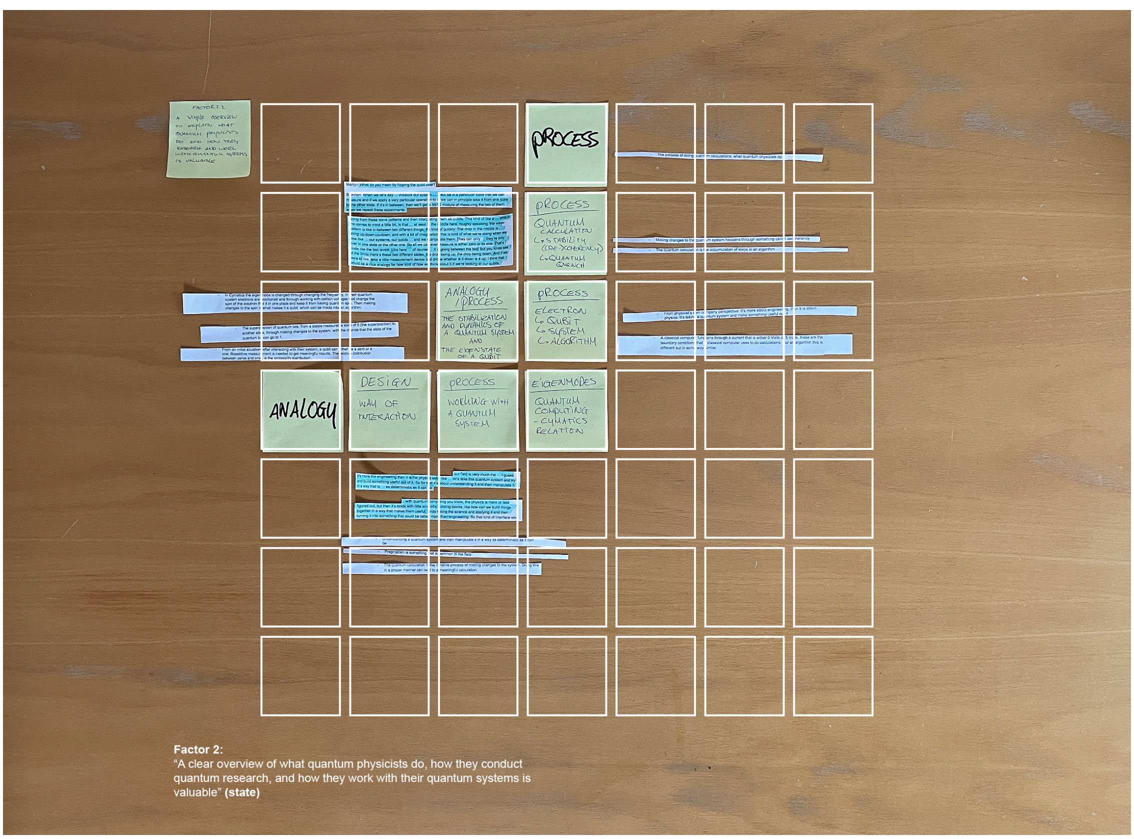


Figure 47. Example of one of the factors that was formed: "Factor 2: "A Clear overview of what quantum physicists do, how they conduct research, is valuable" (state)"

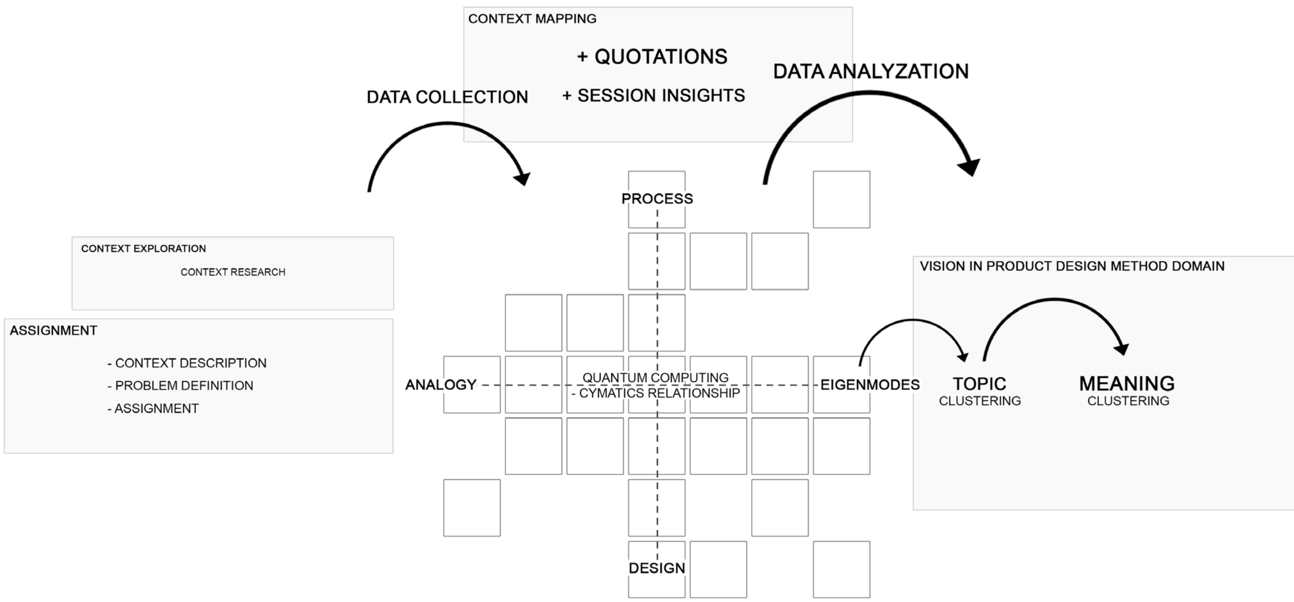


Figure 48. Diagram used for the forming of ViP factors

Formulating Factors

The example given in Fig. 47 on the previous page on the forming of factor 2, was formed through the approach of the diagram shown in Fig. 48 above. All data gathered thus far taken together, in the scope of the project's assignment were analysed through the diagrams shown in Fig. 46-48. Custom to the Vision in Product design method, is the clustering of factors on topic level and subsequently cluster on meaning level. An overview of all factors and their corresponding topics and meaning is given in the table shown in Fig. 49 on the next page.

Factor	Topic (Context mapping)	Topic	Meaning
Factor 1: “Learning about eigenmodes in Cymatics is valuable in introducing basic aspects of quantum physics and quantum computing” (state)	Analogy/Eigenmodes	Visual representation	The value of visual representation
Factor 2: “A clear overview of what quantum physicists do, how they conduct quantum research, and how they work with their quantum systems is valuable” (state)	Process/Analogy	What quantum physicists do	The need for analogy
Factor 3: “A clear analogy is needed if a successful connection is to be made between Cymatics, quantum physics and quantum computing” (state)	Process/Analogy/ Eigenmodes	Using analogy	The need for analogy
Factor 4: “For quantum computing companies to have the possibility to visualize their quantum research in terms of data visualization is valuable” (development)	Process/Eigenmodes	Visual representation	The value of visual representation
Factor 5: “Engagement in the field of quantum physics and quantum computing is needed because of projected rise of investments in the quantum computing market over the next seven years with an additional rising demand for quantum physicists in the future” (development)	Process/ Analogy/Design/ Eigenmodes	The future of quantum	The need for engagement
Factor 6: “A simple interaction design is needed to create a successful science museum exhibit” (state)	Process/Design	Using analogy	The need for engagement

Figure 49. Table containing all six formed factors, including their topic from the context mapping, the topic used in the ViP analysis, and the topic of meaning derived from the ViP analysis.

Statement

“With the envisioned design the museumgoer can create their own simplified calculation, analogous to doing a quantum computing calculation, through an interactive and playful experience using eigenmodes. Cymatics will be used to create such experience.”

The above formulated statement is based on the analyzation of the set of factors produced in the previous section. The statement was formed through a process of finding a way to combine the three main topics of meaning.

The need for engagement
Engagement is the end goal; the quantum computing market is growing rapidly and projected investments over the coming years are large. Current progress of quantum technology show signs of utility and appliance and open job applications in quantum technology show that people are needed in the field. Combined with the fact that science museums are interested and willing in exhibiting quantum physics and quantum computing and are currently not to be found in the current context of science museum, calls for more engagement in the sciences.

The value of visual representation
The central themes of the project and the overarching bridging factor to connect cymatics with the fields of quantum physics and quantum computing are the visual representation like eigenmodes and probability distributions.

The need of analogy
Lastly, the means to achieve the goal of engagement by connecting these fields in a way that is meaningful, more than just the similarities of visual representations found in each field is needed. The separate fields still differ much in core for what they are and a strong analogy needs to be added to be able to fully come to a design intervention, in the form of a science museum exhibit, that successfully achieves actual engagement in the fields of quantum physics and quantum computing.

Phase 1: Conclusion

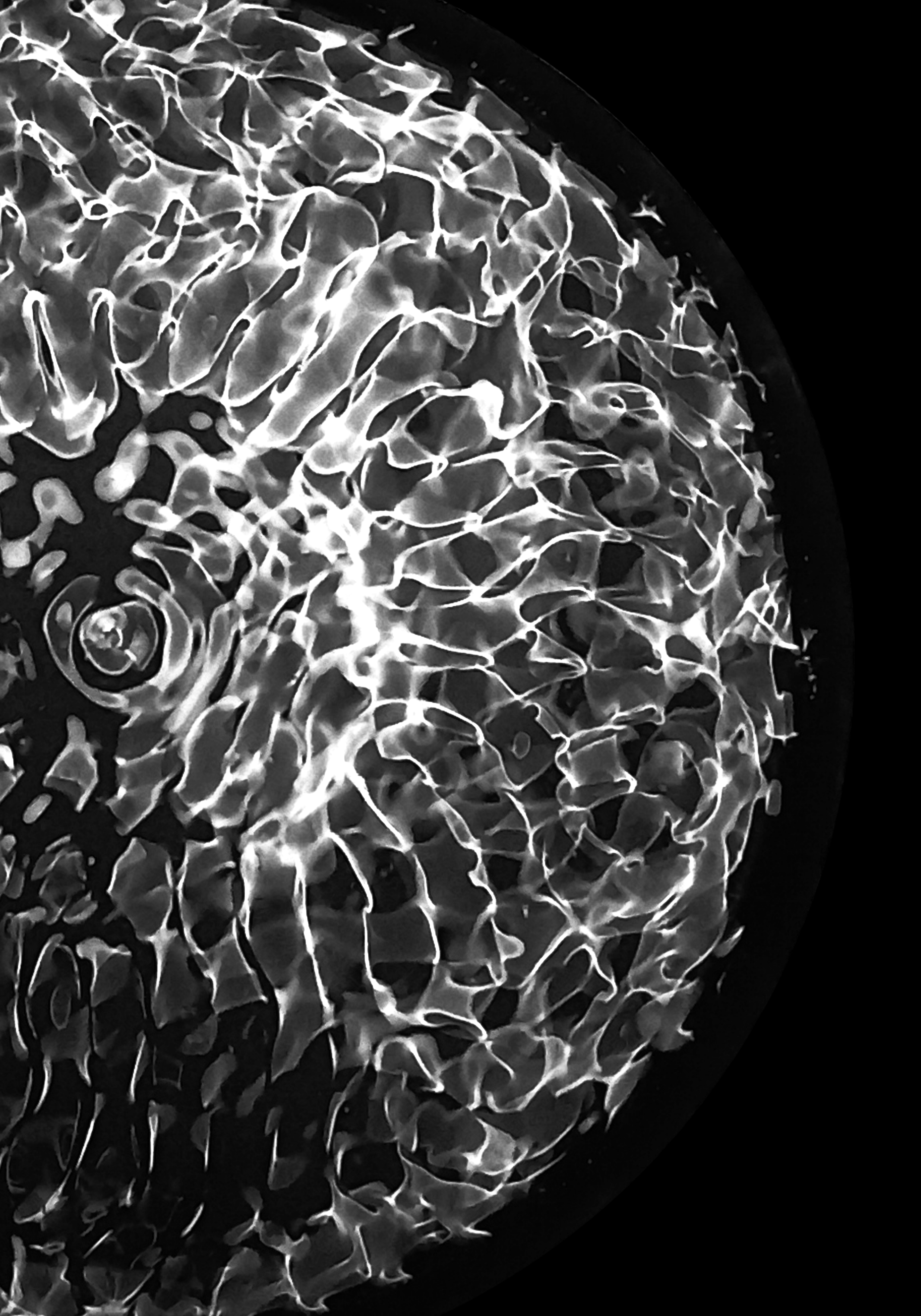
During the first phase valuable data was gathered. The exploratory sessions 1 and 2 with the quantum physicists led to the collection of valuable data and meaningful insights, which allowed for a structured and valuable data analysis. At the end of the analysis a valuable set of data was gathered, including a large set of design factors, a striking interaction vision, meaningful topics to work with, and a strong statement.

The preliminary session 0 was important as it gave insight on how to make sure that the primary sessions were structured and streamlined. It was a good way to get familiar with the studio which was used for the sessions. The approach of session 0 clearly showed what worked well and clearly showed what had to be changed for the primary sessions 1 and 2. Overall feedback from the IDE faculty members and other attendees was positive and clearly showed that excitement in cymatics could very well be effectuated through a short interaction with it. The walk-in approach stretched over a long duration made session 0 exhausting, which showed that the best approach the primary sessions was to do the sessions with each quantum physicist separately, with a fixed time block, which in hindsight was a valuable insight.

During the primary sessions 1 and 2, the feedback of the physicists on the sessions in general was positive and in terms of the project’s design goal and the aimed for design solution was understood and perceived as a valuable cause. The value of cymatics and the visual representation of eigenmodes, was perceived as an interesting approach to introduce basic aspects of quantum physics as connections could very well be made and interesting discussions emerged automatically wherein similarities and analogies between the different topics and types of cymatics were explored. In short, both physicists concluded that cymatics could indeed be helpful in engaging people in quantum physics, especially a younger audience.

The large transcripts derived from the audio recordings of sessions were extremely helpful as it allowed a structured analysis in both context mapping and in the appliance of the Vision in Product design method. The transcripts allowed for a rich form of context mapping, which was subsequently used to form the framework on which the ViP method could be applied to.

The ViP method worked well for the data analysis that followed the context mapping. Restructuring the mapping to which data was structured in allowed rich combinations of factors to be made, in turn creating valuable and meaningful clusters and topics. The method worked well in terms of deconstructing as the project was dealing with different context that had to be decomposed, bridged, and linked to each other. The striking interaction vision and strong statement that were formulated created a strong and meaningful start towards the conceptualization phase.



Phase 2: Conceptualize

Overview of the Conceptualize Phase

Primary in the conceptualization was the translating of findings from phase 1 into design aspects that could be used to make concept designs. Central in this process were the three formulated topics of meaning: the need for engagement, the value of visual representation, and the need for analogy. Through deeper analysis of the three topics, the design goal updated and a corresponding list of requirements was assembled. The type of cymatics was determined to narrow down the scope of the conceptualization and water cymatics was chosen to be the type to work with. A deeper investigation into specific details of quantum physics and quantum computing was conducted to find and establish a stronger connection between quantum physics and cymatics, which was then used to specify the interaction design. After an iterative process of finding the correct analogy to work with, the final project statement was formulated and three concepts were made, each incorporating a different form of interaction in the producing of eigenmodes. The concepts were tested through a user test and a final concept was chosen to work with for during the final design phase.

Conceptualization and Interaction Design

With the producing of eigenmodes standing central in the project's envisioned design, but as previously noted, fully bridging quantum physics and cymatics being a difficult task when the aim is to achieve this through a simple and short science museum interaction, bringing about a bridging connection between the two fields was found through the use of analogy. The goal of the interaction design was effectuating engagement in the topic and not the conveying of a full understanding of quantum physics. During this conceptualization phase the producing of eigenmodes and a fitting analogy connecting to quantum physics had to be combined to form an interaction design that could be used for the final design.

Determining the Cymatics Type

So far in the project's examination of cymatics two methods of producing eigenmodes have been explored: the Chladni plate and water cymatics. Both methods of producing eigenmodes embody a very different type of medium in which the phenomenon manifests, while the basic principles on which the particle-wave behavior is created is functionally very similar. Because of the big contrasting difference in manifestation, and the base functioning being similar, there is chosen to determine which type of cymatics will be used in the conceptualization early in the process of the conceptualization phase.

One other aspect to consider during the phase of conceptualization is whether the design should function analogously or digitally. Both analogue and digital functionality carry certain advantages and disadvantages. Another aspect to keep in mind in this process is that the appliance, whether analogously or digitally, can differ within the phases of the design process, meaning, that during conceptual testing, one or the other approach might be better, while for the final design it can be the other way around, or vice versa. This is an important aspect to bear in mind, wherein the overall approach of conceptualization and determining the final functioning of the design should be approached in a forward-looking manner, and should be, while being separate phases within the design process, be approach in a wholly manner.

Combining the two dualistic moments of choice-making described above, results in a methodological pathway shown in Fig. 50 below, resulting in four types of functioning combinations, shown in Fig. 51.

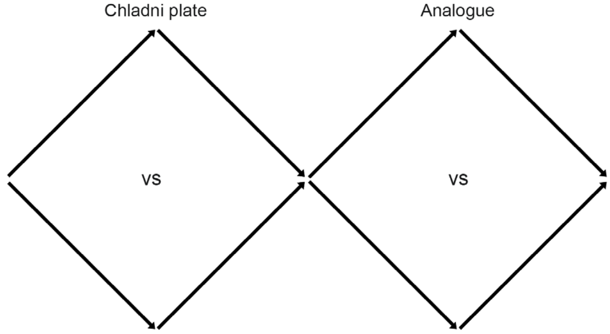


Figure 50: The methodological pathway of the two dualistic moments of choice-making, leading to the four cymatics combination types.

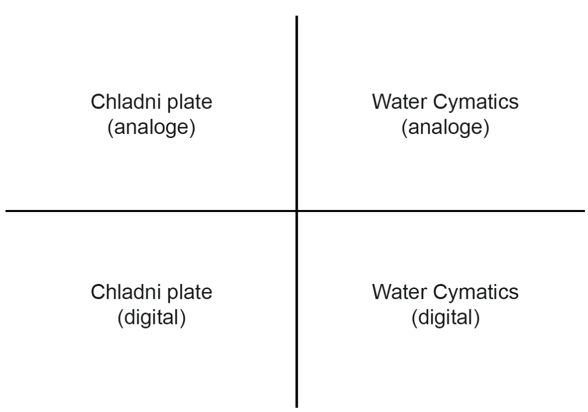


Figure 51: The four cymatics combination types

The fact there is chosen for determining the type of functioning combination type first, before the making of specific detailed concepts is a strategical design choice. It was possible to separate the aspects on which the combination types could be tested from the to be designed interactional functioning of the design. All functioning combination types could have been conceptualized to detailed form, but the choice to focus on the previous described separation of conceptual direction and interactional functioning was made strategically, bearing in mind the project's overall available timeframe and the goal of delivering a successful functioning final design. Looking back at the diamond diagram shown in Fig. 50 on the previous page, it can be noted that the at that point stated methodological pathway was traversed in a shortcut-like manner, corresponding to the same making of strategical design choices of looking ahead by looking at the design process from a wholly perspective, as described in the first paragraph of this chapter.

To determine which functioning combination type should be used for which phase of the design process, another dualistic consideration had to be made. There is chosen to start with bearing the final design in mind first, as this is the final product. As it was known that the final design would become a science museum exhibit, a brief examination of the context had to be taken into consideration. At this point of the design process, little communication had been with the contextual stakeholder, but from session 0 insights were gained from their perspective, allowing the formulation of a method of rating of the method-functioning types, without unnecessary acceleration of full involvement from the science museum as contextual stakeholder. It could be said that early involvement from the science museum should be seen as beneficial or valuable, but the choice to avoid this unless necessary, was made to keep the quantum computing-cymatics relation as primary guiding aspect at its core, without the interference of what science museums would imagine from a quantum physics exhibit. To put this last notion in perspective of positive reasoning, a reference to the primary problem definition is needed, namely that quantum physics and quantum computing are topics that are difficult to understand, and for mostly difficult to grasp when brought to the physical context. It was felt that a disclaimer on this notion was needed to keep the focus on the introduction of basic aspects of quantum computing, with the goal of creating engagement in the science to comply to the projected future demand of scientists in this field. In this the quantum physics market as main stakeholder and young future scientists as target group are seen as the primary context of reference, and science museums are regarded as the contextual stakeholder to which the goal can be achieved.

One of the shared considerations from the science museum perspective during session 0, was that the realizability of the envisioned final design in terms of maintenance and continuity was going to be important, seeing that the salt used for the Chladni plate devices was scattered all over the table the device was standing on and on the floor surrounding the setup, and that the salt had to be removed, cleaned up and refilled frequently. For the water cymatics setup same remarks could be made, since at moments water splashed on the surroundings.

Analysis of the four Cymatics Combination Types

What followed was an analysis of the four cymatics combination types for which Fig. 52 shows the outcome..

The four method-functioning types were evaluated on four aspects:

1. Eigenmode production quality and its analogous relation to visualized data in quantum computing
2. The allowance of applying an iterative method of interacting with the design
3. The viability in terms of conceptual testing from the project's perspective
4. The level of realizability in maintenance and continuity from exhibiting the design at a science museum

Out of this examination the water cymatics types rated best for both analogue and digital version and it was chosen to work with water cymatics for the rest of the project. It must be noted that the Chladni plate cymatics examined contained aspects that made relating cymatics to quantum physics and quantum computing through a Chladni plate device a better choice in correlating an exact analogy, but overall, considering all set requirements for the project, water cymatics came out as the better candidate.

In comparing the eigenmode production quality in Chladni plates and water cymatics, all four types scored well. The Chladni plate's behavior of only showing eigenmodes on very specific frequencies, while on most frequencies emitting chaos, resembles the stabilizing and destabilizing of a quantum system, and the process of finding the conditions to stabilize a qubit well. Water cymatics on the other hand, produces modes of stabilized patterns for every frequency, making less of a good analogy in this case. The reason there is chosen for water cymatics was made from a point of view wherein the interaction design and usability of the envisioned design were added to the consideration of making the choice in this comparison as well.

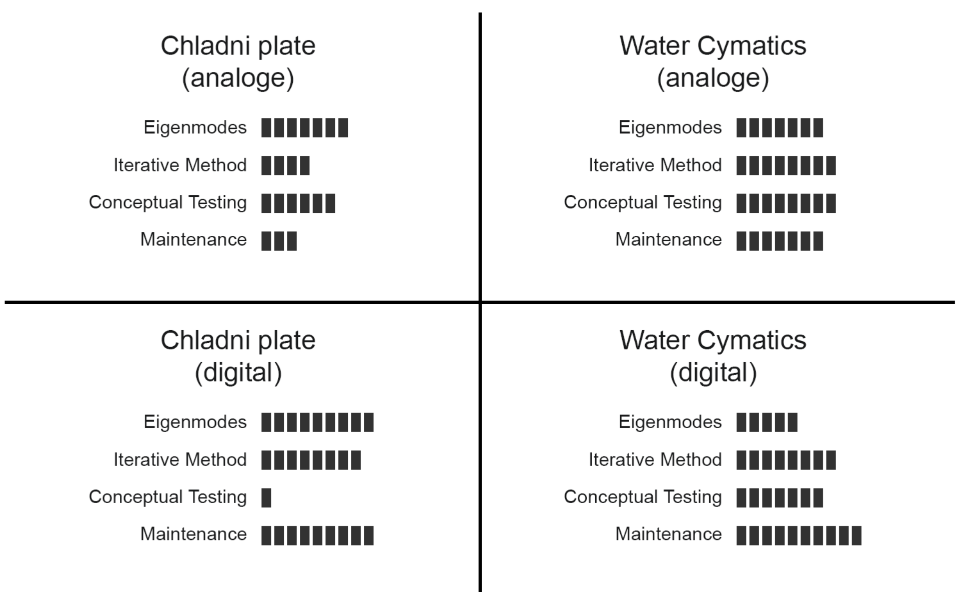


Figure 52: Showing the evaluation of the the four cymatics combination types

Before talking more about the additional consideration of interaction design aspects in the comparison, it was felt that a disclaimer or perspective on the notion of making analogous comparisons should be shared. The examination of eigenmodes creation for both Chladni plates and water cymatics in comparison with visual representations and probability distributions in quantum computing needs a disclaimer as the comparisons were made analogously. What is meant by this is that one: it requires a certain level of imagination and/or filling in, to make the analogies, which in end brings the comparison to a level of subjectivity, and two: the chance that better analogies might exist and might have been overseen.

In terms of interaction design and keeping the envisioned final design within the context of a science museum in mind, the user experience of making and interacting with the eigenmodes is important. This project's perspective is that a successful interaction with the goal of creating engagement in the fields of quantum physics and quantum computing, is achieved better through an experience that is fun and fascinating and one that follows a low entry level of interaction that is accustomed to a science museum exhibit, instead of a more deeply grounded analogy (i.e. the previous named analogy of Chladni plate cymatics in relation to the stabilization and destabilization of a quantum system) that requires a deeper and more extensive interaction to get the analogy across. With the chance of that not happening in the latter, the envisioned engagement in the fields of quantum physics and quantum computing would not be achieved.

For the allowance of applying an iterative method of interacting with the design, all four combination types are thought to score well. From looking back at the level of freedom in interaction with both setups during session 1 and 2, it can be concluded that all combination types would allow a large enough design space for designing an interaction that incorporated the iterative process of interacting with the design. For the analogue Chladni plate version it was foreseen that incorporating such interaction would be possible just as much but learning from the sessions that interaction with the device and creating eigenmodes was often time consuming, it was thought of as a less good of an option.

For conceptual testing the same notion on the time consumption in interacting with analogue Chladni plate could be said. From the perspective of the sessions, the ratio of time spend on interacting with the Chladni plate device versus the amount of interesting results in terms of produced eigenmodes and resulting discussions that came from it, in comparison with the interaction and resulting eigenmodes and discussions with the water cymatics setup, water cymatics was thought of a better type to focus for doing valuable conceptual testing. Conceptual testing for the digital Chladni plate would require a digital simulation of eigenmode production. Since this type of software was not available and was considered difficult to make, this was not considered as an option to work with.

In terms of realizability in maintenance and continuity from the perspective of exhibiting the design in a science music context, easy comparisons were able to be made. Both digital types would do well for this aspect as little maintenance would be needed to guarantee a good level of continuity. Considering the analogue types on this notion, the salt used for the analogue Chladni plate did not seem like a wise design choice, making the analogue water cymatics a more logical choice in maintenance and continuity.

Overall the water Cymatics types scored better and it was chosen to continue working with both digital and analogue. The digital type was expected to come in useful during the rest of the conceptualization phase and the analogue was foreseen as being best as a functioning final design, considering that the seeing the manifestation of the phenomenon in the physical dimension is most fascinating and engaging.

Design Goal Revisited

Through gained insights of data collection and analyzation and the specifying of the conceptualization and interaction design goals, the project's overall design goal could be expanded upon and specified more.

Old design goal:
The goal of the envisioned design is to engage young people aged 13-30 in the topics of quantum physics and quantum computing through a science museum exhibit using cymatics

Expanded design goal:
The goal of the envisioned design is to engage young people aged 13-30 in the topics of quantum physics and quantum computing through a science museum exhibit using cymatics. The interaction with cymatics should form a base analogy to quantum physics, creating a bridging connection between the two fields with the goal of effectuating engagement in quantum physics and quantum computing

List of Requirements

To make sure work during the conceptualization phase stayed concise, effectively focusing on the project's assignment, and keeping the formulated statement and factors as main guidance, a list of requirements was composed that was later during the process used as reference for making and testing the concepts.

- Through the design the user should be able to create eigenmodes.
- The design should provide the user with a clear picture of what a quantum physicist does.
- The user should be able to interact with the design, in a way that incorporates a basic level of analogy of the way quantum physicists interact with their quantum systems.
- The link between cymatics and quantum physics and quantum computing should be clear to the user in a way it makes sense that quantum physics and quantum computing are approached through the field of cymatics
- Through a short interaction with the design, without fully understanding the underlying principles to which the design is made, the user should feel a level of fascination by interacting with the design
- Engagement in the fields of quantum physics and quantum computing should emerge from interacting with the design
- It should be possible to test the design's functionality and effectiveness
- The design should be able to be successfully put in a science museum

The Need of Engagement

Out of the three topics of meaning the topic concerning “the need for engagement” overarched the project’s overall goal. The other two topics focused on visualization and analogy were found to be the means to achieve this goal. The main motive to approach the topic of quantum physics through cymatics was because of their visual characteristic similarities, and as was confirmed during the sessions with the quantum physicists, the connection is there. However, just the producing of eigenmodes alone was found to not be sufficient as a stand-alone concept and further investigation of quantum physics was necessary to understand how it could be related to the eigenmodes in cymatics specifically. Analogies were needed to bridge to two topics if connections were to be made without having the scientific expertise of a physicist. Keeping in mind the context of a science museum and the type of interactions such context would allow, together with the fact that engagement is the aim, it became clear a deeper investigation was necessary to find the correct analogy to create engagement through an understandable connection between the two fields.

The Value of Visual Representation

The presence and appliance of visual representation in both fields of quantum physics and cymatics was investigated to see how this aspect applies to each field and if analogies can be formulated that can be integrated into the interaction design. A brief examination of subatomic particles led to investigating why particles in quantum physics are described as wave functions and why visual representations can help in better understand these aspects. Subsequently this is linked back to the earlier conducted investigation of standing wave theory in cymatics and to see if any relating aspects can be found to which analogies can be formulated.

Visual Strength

Visual representation can be a good tool to help better understand data. A most simple example people will be familiar with is the two-dimensional graph in which data is presented over an x-axis and y-axis. It can help understanding data better or faster than having to read numerical data in lines of text and cross-examine the data in your head yourself. With the graph several connections can be made visually by looking at the visual representation of the data. At first glance this may seem as a simple and somewhat obvious example but when examined deeper one can recognize the strength of the example when imagining the amount effort it takes to evaluate large sets of data that are normally shown in graphs, when visual representation is not available.

The Envisioned Interaction Design

One primary aspect of the conceptualization phase was designing an interaction that suited the needs of achieving the design goal of effectuating engagement in quantum physics. Overarching themes that could connect cymatics and quantum physics and quantum computing were explored, but an exact relationship that would directly connect the separate fields, even on a basic level was still to be formulated. What was determined was that the producing of eigenmodes would stand central in the interaction design. However, to make a clear connection to quantum physics, the interaction design in its entirety would need a matching form of interaction that accompanies the interaction of producing eigenmodes make this connection. As making direct scientific connections between cymatics and quantum physics seemed to not be possible, a connecting analogy was opted as being necessary to make the envisioned connection. On the right a brief overview is given of goals and established visions that were so far established and that were used during the conceptualization

The creation of eigenmodes through cymatics

One established factor for the design is that the interaction will incorporate the producing of eigenmodes. As was concluded from the sessions, visual representation can help in understanding and conveying quantum data and experiencing the eigenmodes produced with cymatics can help better grasp these subjects. The eigenmodes are visual representations of a frequencies emitted on a specific amount of water. It is a wave-related phenomenon in the physically observable dimension that creates an experientable demonstration of wave behavior. It takes something that is normally not seen, sound and vibration, and makes it into something that is experientable, the interplay of physical waves in a substance of water. It engages to understand through a form of intuition and experiencing without relying on fully understanding underlying principles. An aspect that is aimed for to incorporate into the design.

Design Goal:
The goal of the envisioned design is to engage young people aged 13-30 in the topics of quantum physics and quantum computing through a science museum exhibit using cymatics. The interaction with cymatics should form a base analogy to quantum physics, creating a bridging connection between the two fields with the goal of effectuating engagement.

Interaction Vision:
“Interacting with the design should make the user feel like working like a quantum physicist”

Statement:
“With the envisioned design the museumgoer can create their own simplified calculation, analogous to doing a quantum computing calculation, through an interactive and playful experience using eigenmodes. Cymatics will be used to create such experience.”

The type of cymatics to work with was determined to be water cymatics. It showed, in comparison with the Chladni plate, the most promising viability in terms of allowing a short and meaningful interaction and the fact that its implementation was expected to contain less complications in terms of continuity and maintenance as a stand-alone museum exhibit.

The implementation of an iterative process

Another aspect aimed to include in the interaction design is the aspect of iteration, an aspect that characterizes quantum physics well. To do quantum research and to conduct quantum calculation, iterative steps of repeated calculation are required to achieve meaningful quantum data. These steps together form the algorithms that are used for quantum systems. This characterizing aspect of quantum physics is caused by the current state of quantum theory, wherein working with uncertainties is still a large part of the science. This is what causes the probabilistic nature of the science in its current form and iterative processes are needed to derive meaningful data. These data mostly consist of probability distributions.

A same iterative characteristic is found when examining the way quantum physicists work on quantum system. From the exploratory sessions it was learned that mathematical equations are leading in the building quantum systems but because of the sensitive nature that quantum systems hold, subsequent work on the system comprises methods of iteration wherein making small changes to the system are made until a way is found where coherency is achieved despite its sensitivity. Iterative methodology is how the probabilistic nature of quantum systems are dealt with in quantum physics and quantum computing.

With the producing of eigenmodes being at the base of the envisioned interaction design, a form of iteration is envisioned to be part of the interaction that complements the interaction of producing eigenmodes. Looking back at the formulated topics of meaning, the producing of eigenmodes fits the visual representation aspect, wherein the iterative process, because of its possible implementation analogously, could fulfill the need for analogy.

To bring it back to the formulated interaction vision, the producing of eigenmodes is the means to achieve a meaningful interaction, and the iterative process complements and completes the interaction design by adding to it an analogy of how the envisioned interaction connects to quantum physics. Together visual representation combined with a correct analogy could lead to a design that effectuates the envisioned engagement in quantum physics through a design that uses cymatics. Fig. 53 shows this process. The aim is to successfully find a combination of these factors that lets the museumgoer understand basic concepts of quantum physics intuitively without relying on conveying actual quantum theory and to provide an experience that conveys a simplistic version of what it is like to work like a quantum physicist. Bringing about an understanding of underlying principles is not the aim. The aim is to engage through experiencing intuitively.

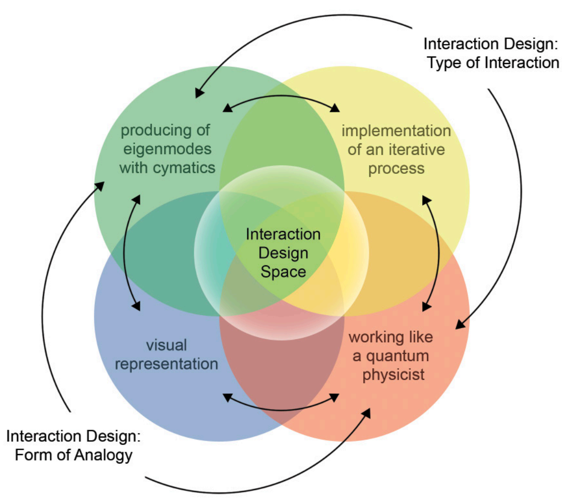


Figure 53: Schematic that was produced to approach the design process of forming the interaction design space, aimed for intergrating all envisioned design aspects to be implemented into the interaction design.

Bridging Quantum Physics and Cymatics: Connecting Concepts

Subatomic Particles as Wave Functions

To describe particle behavior, schrödinger equations are used in which the particle behavior is approached and formulated as a wave function. This allows probabilistic calculation to be carried out on the particle theoretically. Still, this does not mean that exact measurements or results can be derived from this method, for instance in terms of calculating exact positions, but it does allow the describing of the particles' behavior. Using Schrödinger equations, probabilistic calculation can be conducted on particles which result in measurements of ratios of probability. When conducted properly, these probability distributions can be visualized by plotting it graphically, allowing the visualization of a particle's behavior in the form of datasets as if it was a wave, while the particle itself, of course, being a particle. In the microscopic scale of subatomic particles the line gets blurry between whether something is a particle or a wave. This is what is called the wave-particle duality. While current quantum theory does succeed in describing these phenomena mathematically and quantum technology does indeed succeed in building functioning systems using these particles, the base of what these particles really are is still surrounding by mystery as a lot of things are still unclear. Some mathematical appliances work because the particle is approached as a particle and some mathematical appliances work because it is approached as a wave.

It allows a visual representation of characteristics like for instance the possible positions of a particle. This is called a probability distribution or probability density. In fig. 55 a set of different visualized wave function of the Hydrogen atom are shown. In these visualizations possibility of a particle being found in a certain location have been visualized. Color shows where chances are largest for the particle to be found. Also excited states of the hydrogen have been visualized in this manner, for which Fig. 54 shows an example of that. When examining the top view perspectives of the excited states of a hydrogen atom shown in Fig. 55, visual similarities to the eigenmode patterns in cymatics can be seen in terms of existing symmetries, nodes and nodal lines. Just as for the different excited states of the atom quantum numbers are assigned for their number of orbitals, nodal numbers are assigned to eigenmodes in cymatics for the number of nodal lines is contains.

Making the Unperceivable Perceivable

What in some way occurs in the previous example, where visualizing certain particle behavior become possible when the particles are described as wave functions, is that something that is difficult to perceive or to visualize, is enabled to be visualized. This is an aspect that is also brought about in cymatics as well very beautifully. In the case of cymatics, it is frequency or vibration, something that when taken in its purest form, is difficult to perceive. What cymatics does is making frequency and vibration visible. As it is a closed system of simple form, it is able to show both complex forms of interference and coherency in terms of distinguishable symmetries, nodes and nodal lines.

Approaching subatomic particles as wave functions enables the visualization of the particle's behavior. This, however, does not mean the particle itself is visualized. It allows mathematical calculation to be made which can tell things about a particle.

The visual representations used in quantum physics called probability distributions is very different than the visualizing of waves of frequency what is done in cymatics, but what these two different situations do have in common is that they both make something perceivable which is normally not perceivable. As this project aims to connect the fields of quantum physics and cymatics, finding these overarching forms of similarity is very important and valuable, as they can help formulate functioning analogies that can be used in the envisioned design. Important to note is that visual similarity does not mean things are necessarily the same and such situations can be prown to bias. As visual similarity can cause interest, it is just as important to respect their mutual distinctions and specifically emphasize the differences that distinct them. This is also the case with the importantance of knowing how an analogy is made, as it is to know where an analogy does not hold up anymore.

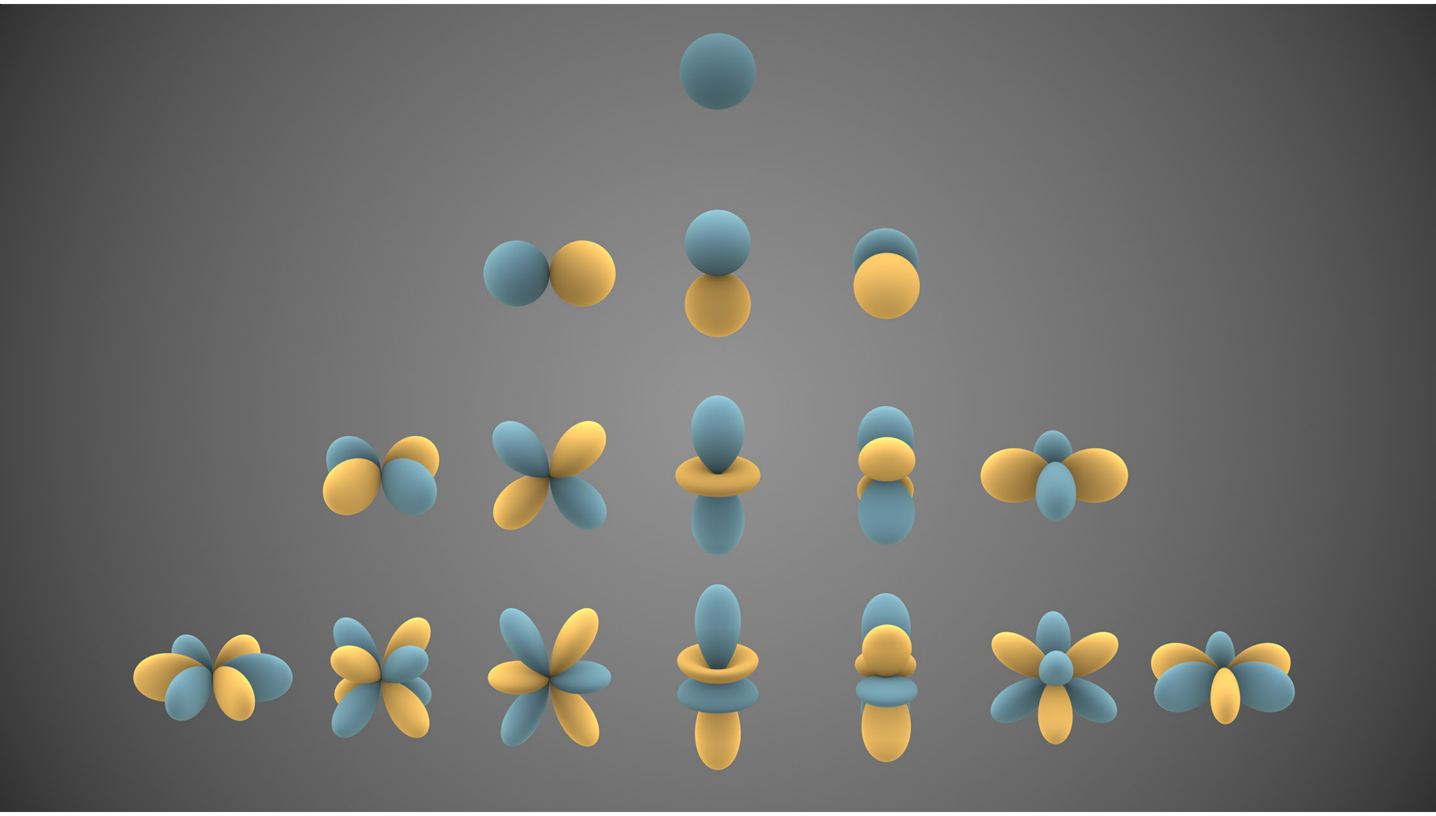


Figure 54: Visual representations of the first few real spherical harmonics. Blue portions represent regions where the function is positive, and yellow portions represent where it is negative. From “Wikipedia,” by Inigo Quilez, 2014, (https://en.wikipedia.org/wiki/Spherical_harmonics#/media/File:Spherical_Harmonics.png). Lisenced under CC BY-SA 3.0.

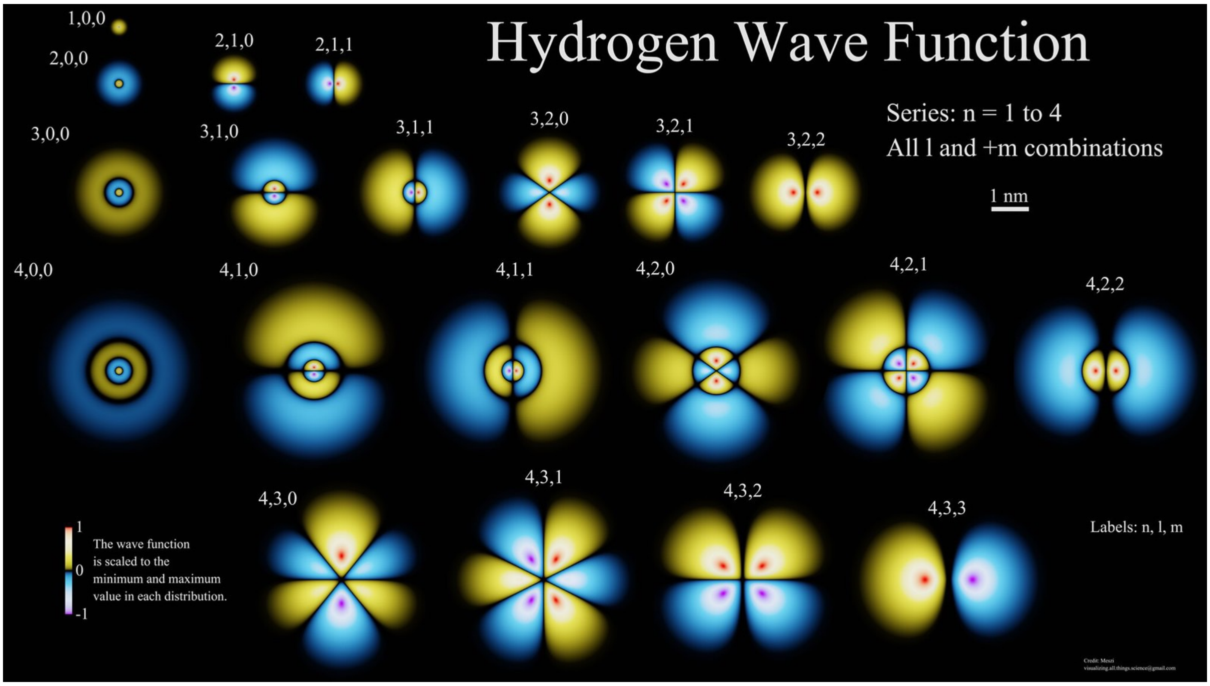


Figure 55: Hydrogen Wave Functions. From “Visualizing All Things Science Flickr account,” by Visualizing All Things Science, 2020 (https://www.flickr.com/photos/188522613@N05/49963063667/in/photostream/). Lisenced by CC BY-NC 2.0 Deed.

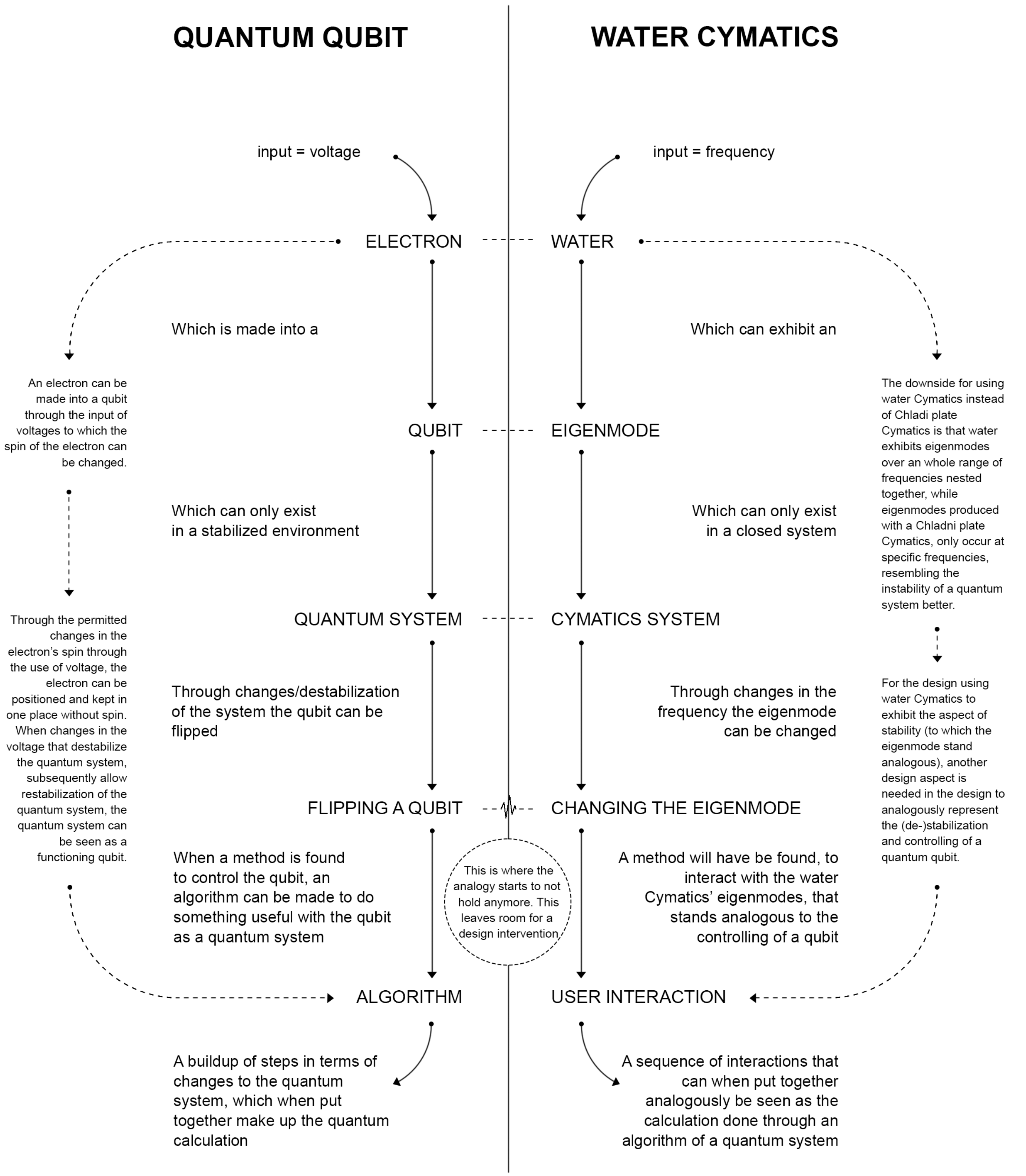


Figure 56: Showing the schematic that was constructed to produce an analogous comparison of the quantum qubit system (left) and the water cymatics system (right) showing an interpretation of what they are built up from in their most simplified form.

The Analogy of Working like a Quantum Physicist

After investigating the similarities of how visual representation applies to both fields of quantum physics and cymatics, an investigation was conducted on how a qubit in a quantum system would relate to a water cymatics system. The schematic shown in Fig. 56 shows the constructing of an analogous comparison of the two types of systems in terms of what they are built up from in their most simplistic form. The goal was to find parts of a quantum system that in some way would correspond to parts of a water cymatics system, and to find resemblances that could be used in the interaction design, in terms of what the device could build be up from, how is interacted with it, and how analogies between the interacting with cymatics can be made to interacting with quantum systems. Corresponding parts of the system were viewed as possible design spaces from which the interaction design could be designed from.

Through the middle of the schematic mutual connections of each of the levels of the two fields are shown, accompanied by a description on how the individual levels correspond to each other vertically. These correspondences were then compared to their counter parts of the other system with the goal of finding the looked-for design spaces.

Above each set of levels, the input of each system can be found. For the quantum system the input is through changes of voltage. In the case of the water Cymatics system the input is done through changes in frequency. The means of allowing interaction with the system in case of the quantum system is through what is called a quantum qubit, the part of the system that allows the computation in the quantum computing system, and one of the primary parts to which a quantum computer chip is built up from. In the water cymatics system this part is viewed as the water, as the water is the medium from which the eigenmodes emerge.

On the bottom level of each set of levels, some form of end-product in the form of sequential process can be found. For the quantum system this sequence is the algorithm that is made to do quantum calculation. For the water cymatics system, this is the location in the schematic where interaction with the cymatics systems is found and could be seen as one of the primary design spaces. The reason the design space is located here is because this is where the analogy between the quantum system and the water cymatics system started to break away from each other. What needs to be kept in mind is that this process was fully based on analogous comparison, meaning that no direct connections could be made, unless through analogy. The cause of the breaking away of the analogy was caused by the difference each system embodied through their own form of inhibiting stability. The quantum qubit is a very sensitive system and very specific containment is needed for stabilization, while in the water Cymatics, stabilization in terms of creating a stable eigenmode occurs over a broad range of frequencies in its entirety. Both types of stability were described in the outer parts of the schematic and were related back to the middle part of the schematic, where the separate levels to which the system consist of, can be found. Below the separation of the schematic focused on the breaking of analogy and the forming of the possible design space is shown, that led to the designing of the interaction that later brought back the analogy in a way, that an analogous connection and understanding between the two systems could again be made.

When a method is found to control the qubit, an algorithm can be made to do something useful with the qubit as a quantum system	A method will have to be found, to interact with the water Cymatics' eigenmodes, that stands analogous to the controlling of a qubit
ALGORITHM	INTERACTING WITH CYMATICS' EIGENMODES
A buildup of steps in terms of changes to the quantum system, which when put together make up the quantum system	A sequence of interactions that can when put together analogously be seen as the calculation done through an algorithm of a quantum system

Further investigating of the water cymatics through a test setup, new observations of the producing of eigenmodes with water cymatics led to a reformulation of the stance of stabilization of eigenmodes in water cymatics. As previously mentioned, water cymatics exhibits eigenmodes over an entire range of frequencies in its entirety. However, what was noticed was that stabilization and destabilization of the eigenmodes did occur over the range of frequencies, but it was not frequency that causes stabilization and destabilization of the system, but it was amplitude to which the frequencies were emitted onto the water. What was observed was that when emitting the frequency with too much amplitude resulted in the breaking of symmetry within the eigenmode and led to a continuous changing pattern of chaos. Also emitting a frequency of too little amplitude resulted in no producing of eigenmodes, resulting in the water remaining in a state of stillness. Further examination also led to finding out that above certain frequencies no eigenmodes were formed. This result was expected to be caused because at some point the wavelength of the frequency would be too small for waves to be formed in the water. This led to two variables to which stabilization of eigenmodes in water cymatics could be established: frequency and amplitude. It was found that with the correct combination of frequency and amplitude the resulting eigenmode could be brought to a stillstand. Other variables in the system that influenced to which combination of frequency and amplitude would allow this behavior were the size of the water basin and the amount of water that the basin contained.

What needed to be determined next was whether the interaction design would be formed around the stabilizing of the eigenmode, analogous to the stabilizing of a qubit, or that the interaction design would focus on what could be done interactively with the eigenmode when stabilization had been achieved, analogous to the algorithm performing quantum calculation.

Specifying Possible Interaction Designs

The appliance of visual representation in both quantum physics and cymatics were explored and possible design spaces containing analogous connections within both types of systems were located. To bring forth a successful interaction design the aspects of visual representation and analogy had to be brought together in a fitting manner that would allow an interaction design of interacting with a water cymatics system from which an analogous connection to quantum systems could be derived. At this point two possible directions to achieve this had formed: 1: an interaction with cymatics' eigenmodes that would stand analogous to stabilizing a qubit, and 2: an interaction with cymatics' eigenmodes that stands analogous to how a quantum algorithm performs quantum calculation. Both directions for specifying the interaction design were explored.

When a method is found to control the qubit, an algorithm can be made to do something useful with the qubit as a quantum system	An interaction with cymatics' eigenmodes that stand analogous to stabilizing a qubit	A method will have to be found, to interact with the water Cymatics' eigenmodes, that stands analogous to the controlling of a qubit
ALGORITHM	INTERACTION DESIGN	INTERACTING WITH CYMATICS' EIGENMODES
A buildup of steps in terms of changes to the quantum system, which when put together make up the quantum system	An interaction with cymatics' eigenmodes that stands analogous to how a quantum algorithm performs quantum calculation	A sequence of interactions that can when put together analogously be seen as the calculation done through an algorithm of a quantum system

The Analogy of Emulating the Quantum Algorithm

What was learned from the sessions was that a quantum calculation is comprised of a sequence of steps wherein each step enacts a change to the qubit in the quantum system. To emulate such algorithm through sequential steps of interaction as stated above, a central system of cymatics was imagined, to which changes could be made through a form of interacting with eigenmodes. In this interaction design, a sequential form of several separate interactions of the producing an eigenmode, analogous to the steps in the algorithm, and when put together, would altogether form a combined eigenmode, a visual representation, analogous to a result of a quantum calculation in the form of a probability distribution. In this interaction design the user would enact the role of algorithm and the combining of eigenmodes to create one eigenmode should be seen as the analogy to the sequential steps of changes made to a quantum system, to which the outcome is a probability distribution.

The goal was to come up with an interaction design that resembled the algorithm level of the quantum qubit system wherein the user manually operates in the way an algorithm operates automatically, to which the user will understand through this interaction, what it means to build a quantum system, what it is built up from and how its worked with. Bringing back in the aspect of stabilization in the water Cymatics, in a way that it complies again to the analogy of stabilizing a quantum qubit in a quantum system, was the focus of the next part wherein the design of the interaction to which the user interacts with the water Cymatics' eigenmodes was determined. The next part of the conceptualization will show how that interaction design came about.

The Analogy of Stabilizing a Quantum Qubit

To find inspiration for the type of changes each interaction with the cymatics system could encompass and to what form the combining of eigenmodes could resemble the stabilization and destabilization of the envisioned cymatics system, an examination of the different states a qubit can exhibit was done. Like the bit in a classical computer, a qubit can be in either a zero or a one state. The main difference classical and quantum bit is their behavior to which they exist within their system, meaning that while a classical bit can only be in one of the two states, either zero or one, a qubit can also be in a state wherein it is all possible states simultaneously. This is what is called quantum superposition. When a qubit is measured there is spoken of the collapsing of the wave-function, wherein the superposition of the qubit changes in one of the two states

Quantum systems are very sensitive to environmental noise which can lead to errors in quantum data. To be able to do meaningful calculation without any noise interference, the qubit needs to be stabilized in a way that its positioned is in a still position as much as possible, where it is unfluctuating and influenced by any environmental noise as little as possible. Environmental noise causing errors in the data is what is called decoherency.

Concept Designs

Concept Design: Three Forms of Frequency Control

For the conceptualization three concepts were produced. Three design aspects were formulated which together form the base of the interaction design for each of the concepts. Each concept was made to test out different combinations of possible interaction designs. Schematics of the separate concepts are shown in Fig. 61.

The three design aspects to which each interaction design of each concept was based on were:

1. The producing of eigenmodes to incorporate the aspect of visual representation.
2. The changing of frequency and amplitude to incorporate the aspect of working with a quantum system.
3. The combining of frequencies to incorporate the aspect of working like a quantum physicist.

The base parts of each concept consisted of:

1. A 115mm petri dish painted mat black containing 80 ml water
2. An Aura 50W 4Ω AST-2B-04 tactile speaker
3. A MDF base with attached pin to attach the petri dish to, mounted on top of the Aura tactile speaker
4. A Nobsound 1002p 100W stereo amplifier
5. A 12-inch OMMO 3200-6500K/RGB LED ring
6. An Adafruit Neopixel 24 LED ring controlled through an Arduino Nano
7. A M-Audio Axion 25 MIDI keyboard (excluding concept 3: frequency rotary dial)
8. An Akai MPD218 MIDI controller
9. A Macbook Pro running a Max MSP patch containing a wave-function generator

Concept 1: Mixing Subs, Mids, and Highs
The first concept was based around combining low frequencie, middle frequencies, and high frequencies, which could be stored under three slots. The concept was operated through an M-Audio Axion 25 MIDI keyboard, shown in Fig.58, and an Akai MPD218 MIDI controller, shown in Fig.57.

Concept 2: Making Chords
For this concept the three slots could be filled with frequencies from a range covering two octaves. Slot and frequency selection, amplitude control, and the combine function were all operated the same as in concept 1 and was also operated through the Axion 25 MIDI keyboard and the Akai MPD218 MIDI controller

Concept 3: Frequency Rotary Dial
In the third concept the three slots could be filled with frequencies selected through a rotary dial on the MPD218 MIDI controller. This concept excluded the Axion 25 MIDI keyboard. Slot selection, amplitude control, and the combine function were all operated the same as in concept 1 and concept 2.

For each concept a Max MSP patch was developed. The patches consisted of a waveform generator, a system that allowed the selecting and assigning frequencies to the slots, and a system that combined all frequencies for the combine function. A conceptual schematic of each concept is shown in Fig. 61 and an example of one Max Msp patch is shown in Fig. 62.

Figure 57: The Akai MPD218 MIDI controller used for all three concepts for slot selection and frequency and amplitude control

Figure 58: The M-Audio Axion 25 MIDI keyboard used for concept 1: Mixing Subs, Mids, and Highs and concept 2: Making Chords

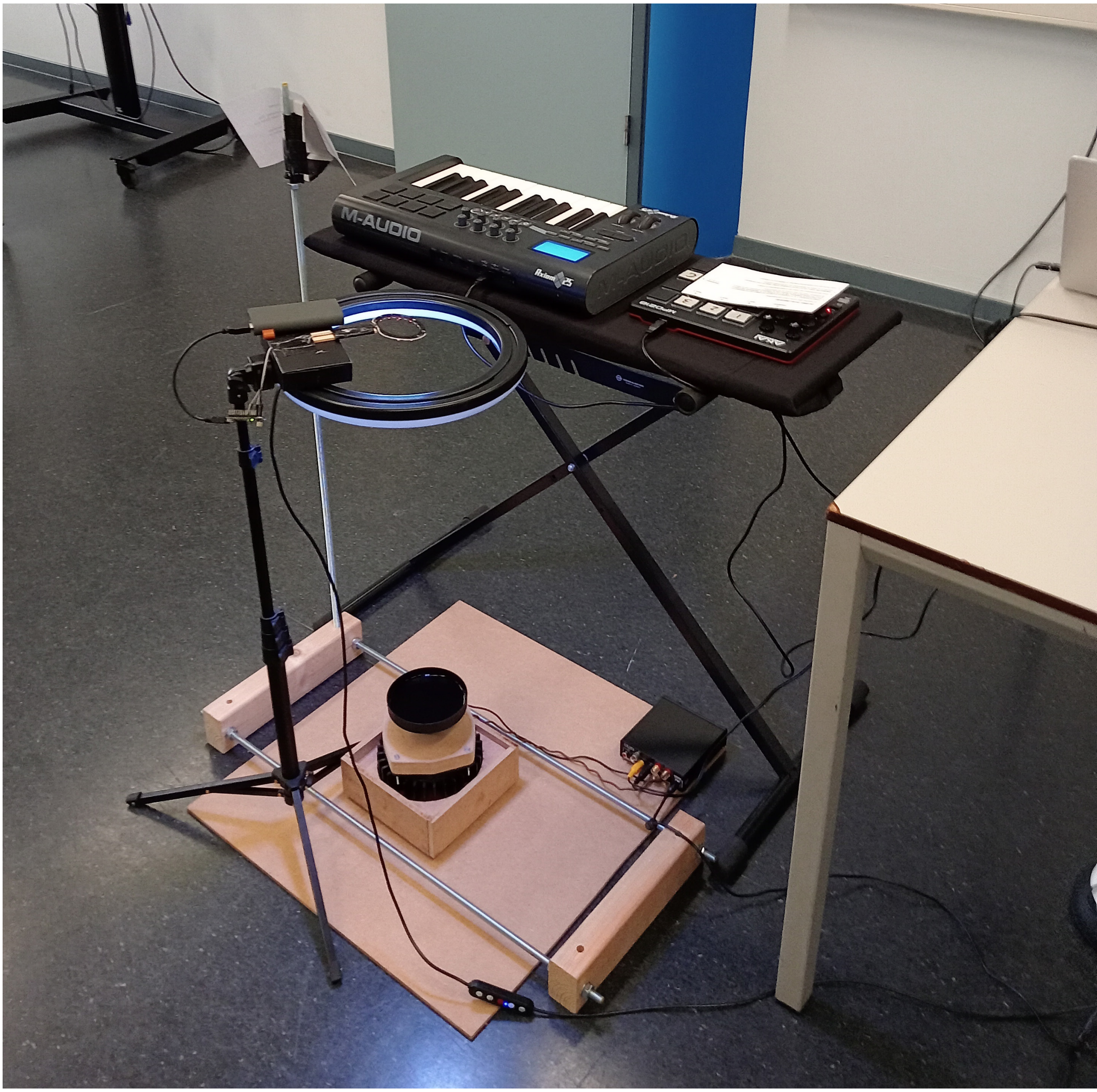


Figure 59: Overview of the concept user test setup

Figure 60: Close-up of the water basin and tactile audio speaker underneath for emitting frequencies.

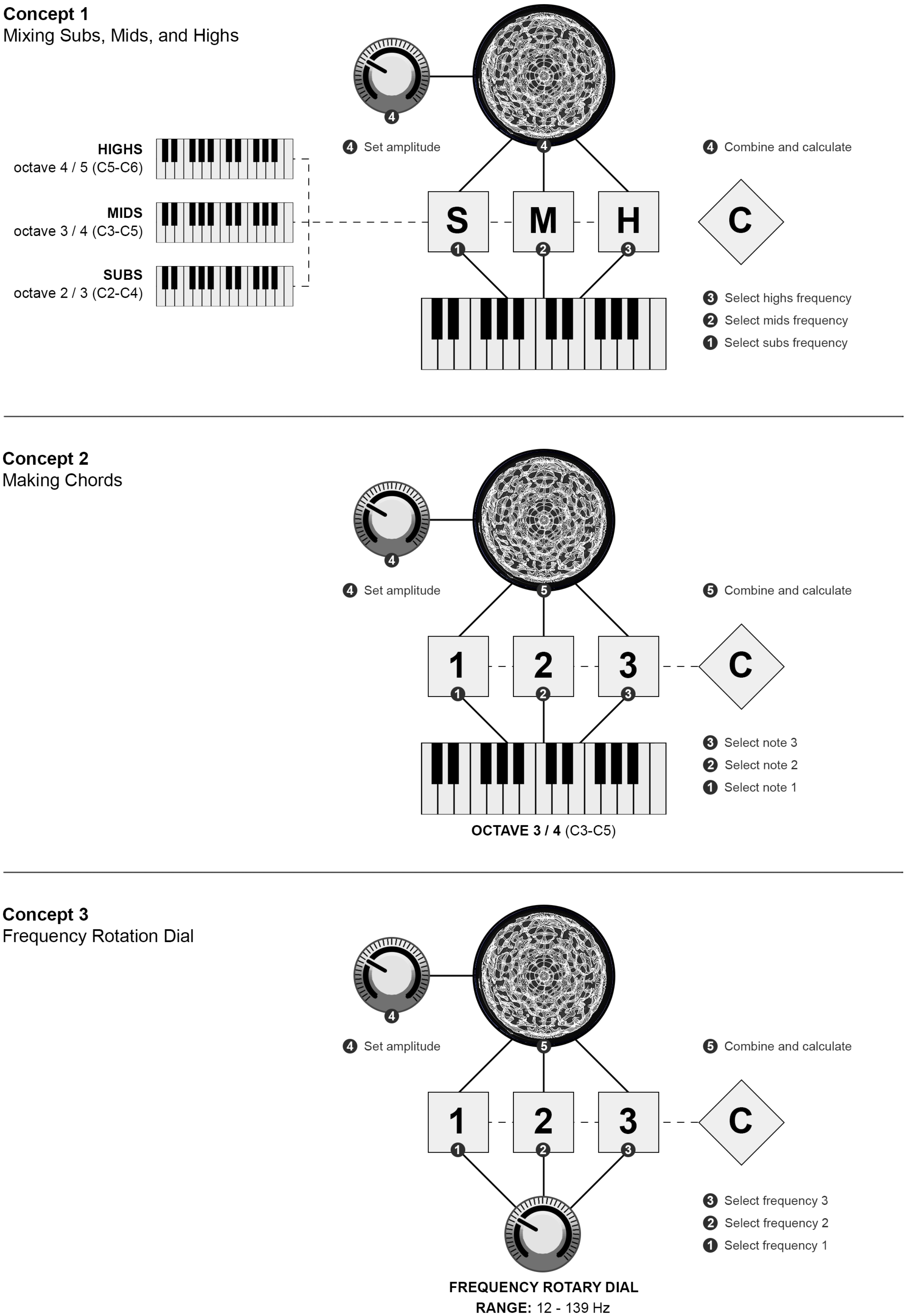


Figure 61: Showing the concept schematics of the three concepts of frequency selection and control.

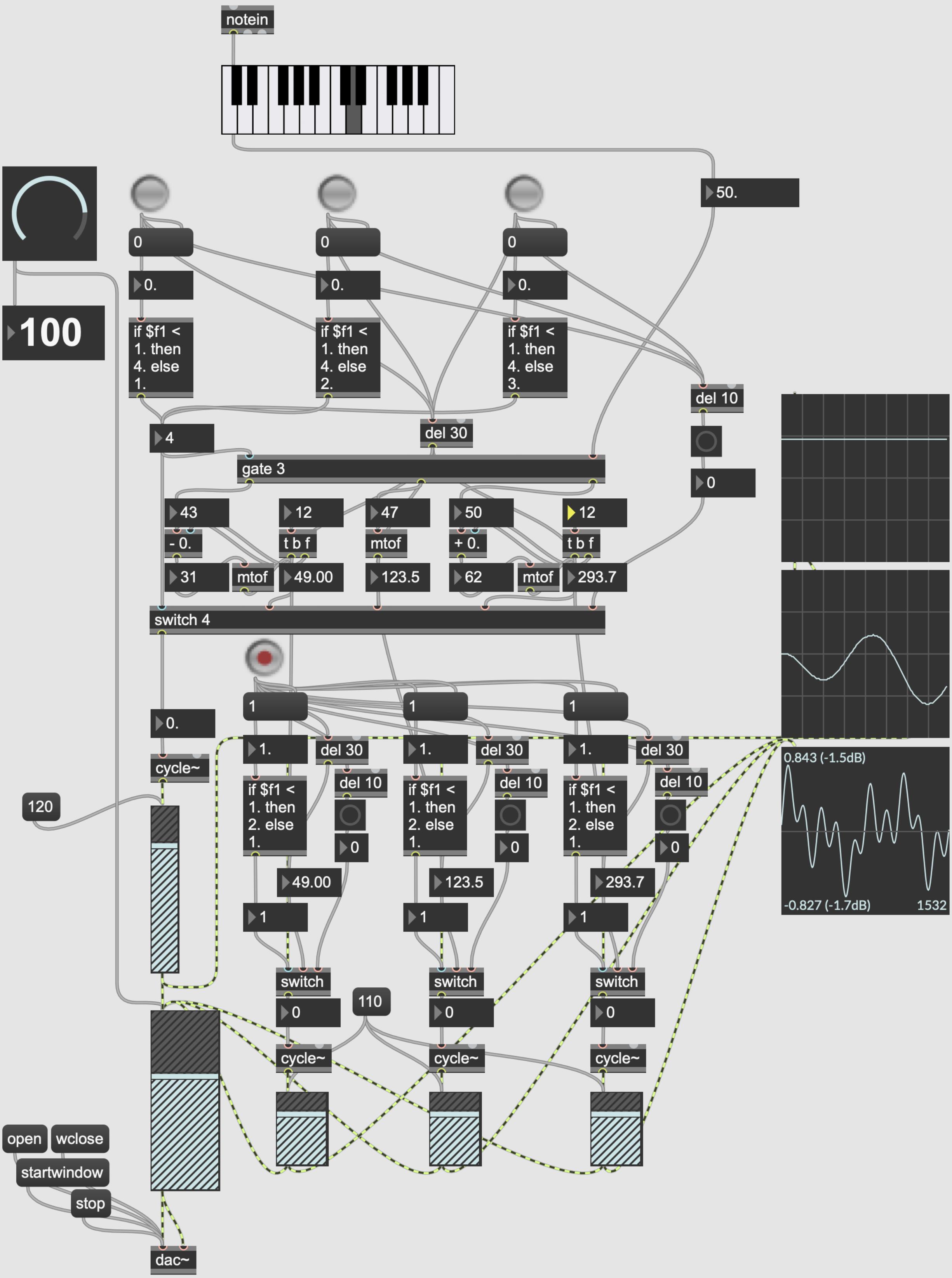


Figure 62: The Max MSP patch for concept 1: Mixing Subs, Mids, and Highs. For the schematics of all three Max MSP patches made for the concept user test see appendix B.

Concept User Test

Concept User Test Setup

For conceptual testing a user test was conducted to determine which concept could best be continued with for designing the final design. During the test the separate design aspects of producing eigenmodes, the form of interacting with the cymatics system in terms of frequency and amplitude control, and the aspect of combining frequencies to emulate the working process of a quantum physicist were tested and evaluated.

Several levels of evaluation were formulated to cover the aspects needed for the envisioned exhibit to achieve the design goal of effectuating engagement in the topic of quantum physics.

The concepts were tested on:

1. The level of knowledge conveyance
2. The quality of eigenmode producing
3. The level of intuition in interaction
4. The level of effectuated amount of engagement

For the level of knowledge conveyance a list of multiple-choice questions was made covering the importance of visual representation, the successfulness of conveying certain quantum physics principles and the successfulness of conveying the analogy of stabilization of a quantum system.

For testing the quality of eigenmode producing a preliminary investigation of possible eigenmode patterns for each concept was conducted. An overview of eigenmodes was collected covering the overall ranges of each concept. From this overview three sets compiled, each containing nine of the most appealing eigenmodes per concept and were printed on A4 paper. Participants were shown the three sets and were asked to order the sets to their appealing.

For the level of intuition of the interaction design participants were asked to fill out a form containing scales for which they were asked to rate several aspects of the interaction design in terms of how clear thing were to them. Aspects covered were the intuitiveness of operating the devices and its instructions and the textual guidance around the setup.

The level of effectuated amount of engagement was tested through a list consisting of several multiple-choice questions covering how much fun each concept was and which concept suited the context of quantum physics best.

The test ended with questions about which MIDI controller was preferred and whether the combining of frequencies contained any added value to the overall interaction design. Lastly there was room for sharing comments and thoughts.

Part of the test were the guiding and informative signs around the test setup. As the envisioned design is a science museum exhibit, museum information signs were created, printed, and put around the setup to guide the participant through the test, simulating the museum context, and along the way offering the participant background information on the analogies used to connect the cymatics system to quantum physics. These signs were used to convey information which was asked about during some of the multiple-choice questions of the questionnaire and the signs were evaluated to their level of clearness in the part of the questionnaire containing the rating scales on intuitiveness. Small depictions of the signs are shown in Fig. 65.

The test was conducted with in total four participants, covering different levels of preliminary knowledge on quantum physics, two participants with little to no knowledge on quantum physics, one participant with little knowledge on quantum physics, and one participant with an intermediate level of knowledge on quantum physics.

During the test observations were made and discussions were tried to be kept to a minimum. After the test and filling in the questionnaire, there was room to discuss the concepts further.

The questionnaire containing all the questions and full-size versions of the conceptual museum information signs can be found in the appendix C and appendix D.

Figure 63: Showing an overview of overall concept test

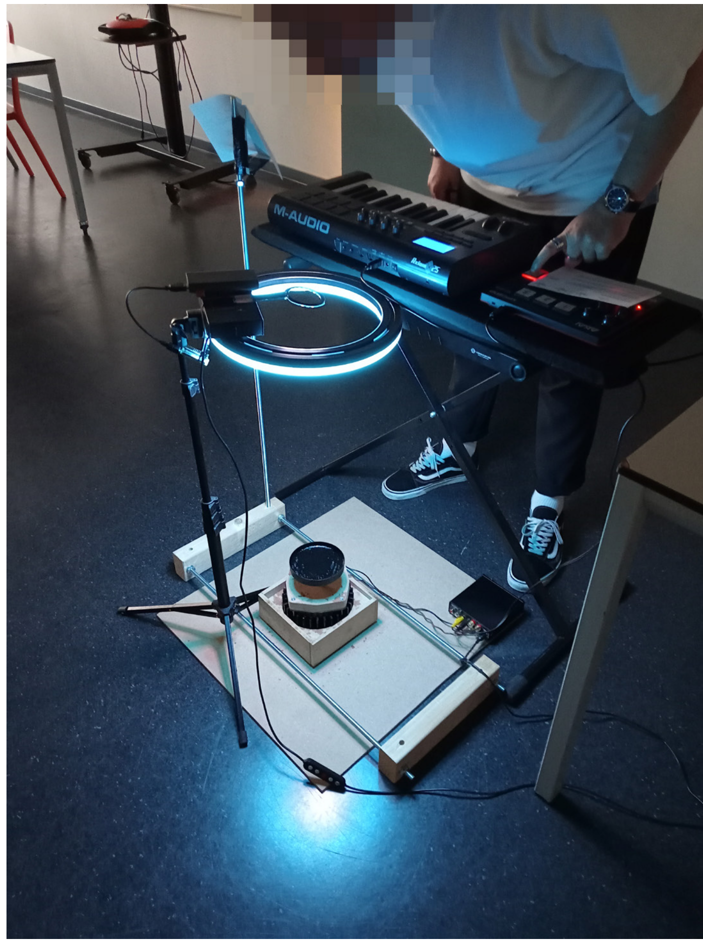


Figure 64: Showing one participant during the concept user test testing one of the concepts

To better understand quantum computing, think of this setup as an imaginary quantum computer.

The wave patterns you will be creating are part of something that is called cymatics, the study of visual wave phenomena.

Quantum physics is also all about waves!

Quantum computer chips use quantum bits called qubits instead of normal data bits found in a normal computer.

These qubits are built from elementary particles, like an electron or a proton. They are called elementary as they cannot be made into smaller parts.

The special thing about elementary particles is that they can be at several locations at the same time, making it difficult to describe them. In quantum physics this is done by doing a probability calculation that predicts where chances are largest where the particle could be located.

This prediction is described as a wave function. Below is a visual example of a very simplistic wave function. Black shows where the particle will most likely be, and white is where the chance is the smallest that the particle will be. On the right a water-like wave is visualized.

With these devices you can make your own waves.

The wave patterns that you see are called eigenmodes. The eigenmodes made in this setup resemble in the qubit found in a quantum computer.

To make qubits for quantum computing is difficult because these particles are very sensitive and it takes great effort to position and stabilize them.

Are you able to stabilize your eigenmode?

A qubit in a quantum computer can be in two states: it is a 0 or a 1, just like a data bit in a normal computer. The special thing about a qubit is that it can also be in both states at the same time. This is what is called quantum superposition.

The weird thing about a qubit is that when it's measured, the quantum superposition collapses, and it will collapse in either the 0-state or 1-state. Only before the measurement is it in both states at the same time. So only after the measurement is it a 0 or a 1, before it is both at the same time.

Do you see the resemblance with your own stabilized eigenmode? Were you able to get the water from a state of standing still (0), into a dynamic and moving eigenmode pattern (1), but were you also to the pattern to a state where it looked like it stood still? In this situation, is the water standing still or is it moving? What do you think?

Figure 65: Museum information signs used in the concept test.

Examination of Eigenmode Producing per Concept

As for each concept way frequencies were selected and the range from which frequencies could be selected were different, an examination of eigenmode producing was conducted for each concept separately. Using the concept test setup, the envisioned interaction of selecting three frequencies and subsequently combine them was conducted. For each concept three to five different combinations were made, covering the low, middle, and high ranges of the total range of possible frequencies. For concept 1 and 2, for which the MIDI keyboard was used for selection, combinations of frequencies that make chords, and combinations other than chords, were explored.

For each used frequency the influence of the amplitude was explored, resulting in several resulting patterns for one frequency. Through examination of amplitude control insights were gained on minimum required levels of amplitude to produce visual feedback and maximum levels of amplitude were localized where the water would begin to splash out of the petri dish. Also minimum and maximum levels of frequency were examined and with optimized levels of amplitude were located at 8 and 130 Hz respectively.

The process was documented through photos. Fig. 66 below shows an example of one set of frequency selection and subsequent combining, including the examination of the influence of amplitude. Fig. 67 shows an overview of the total examination of the three separate concepts. Fig. 68 shows the compiled sets of eigenmodes used during the concept test to evaluate the quality of eigenmode producing of each concept.

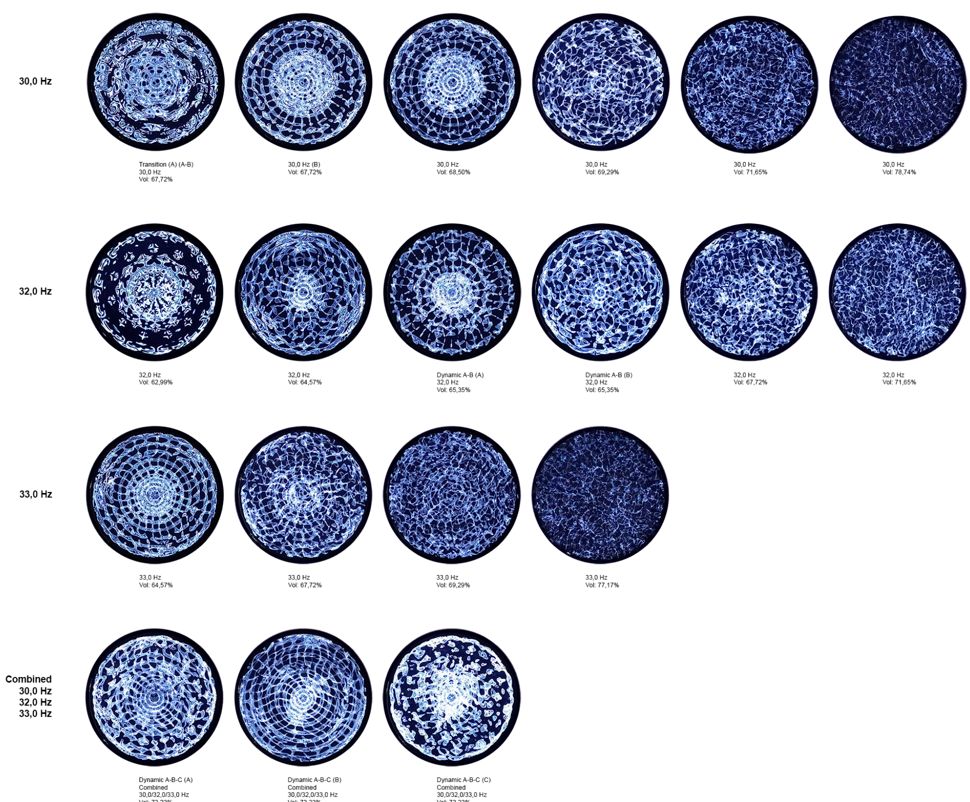


Figure 66: Showing an example of one set of frequency selection and subsequent combining, including the examination of the influence of amplitude. Taken from the examination of concept 3: Frequency Rotary Dial

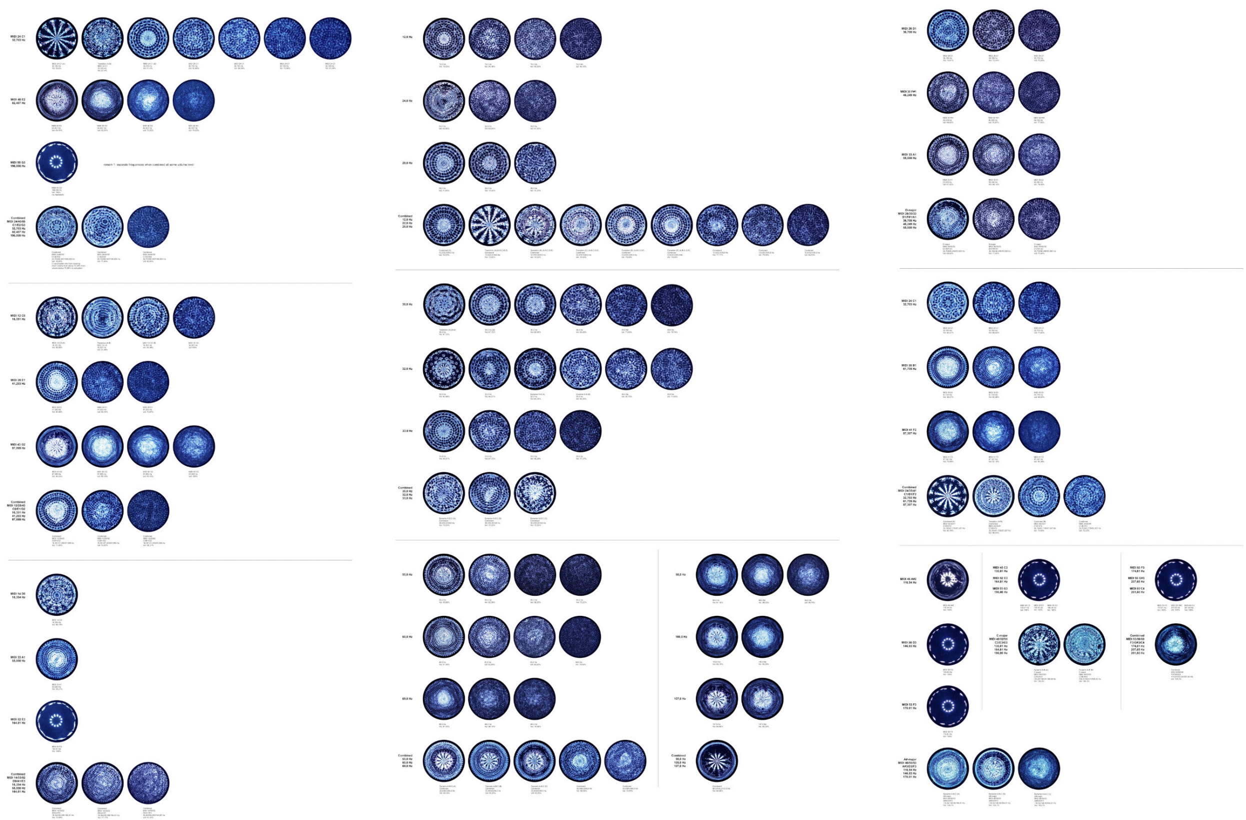


Figure 67: Showing an overview of the entire eigenmode producing per concept. With concept 1: Mixing Subs, Mids, and Highs, concept 2: Making Chords, and concept 3: Frequency Rotary Dial, in colums, respectively from left to right.

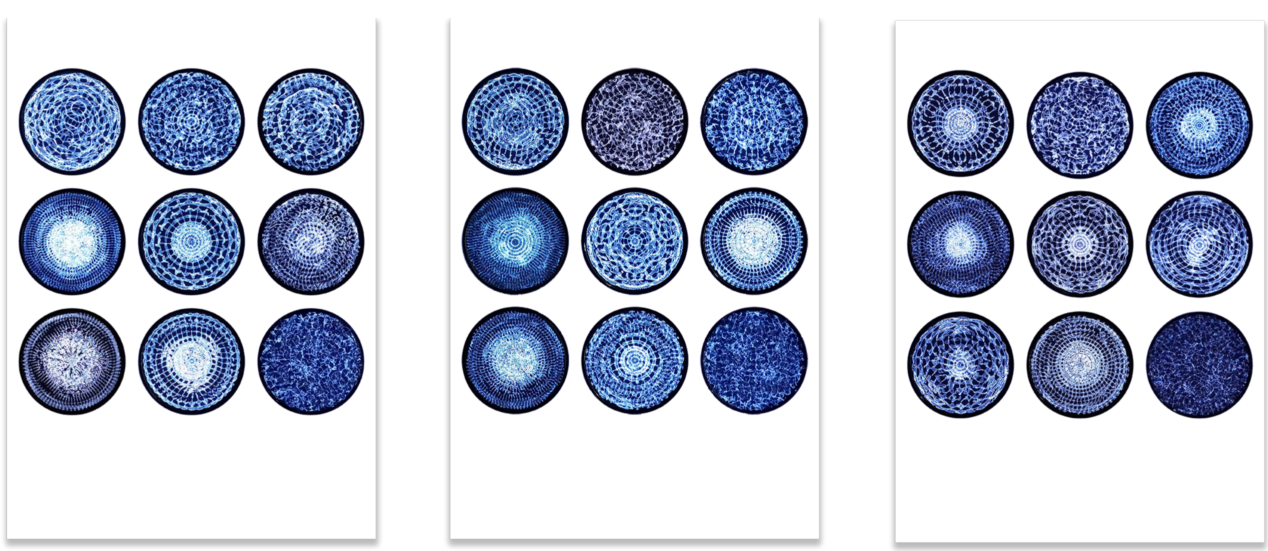


Figure 68: The three compiled sets of produced eigenmodes per concept for testing the quality of eigenmode producing in the concept user test, from left to right, concept 1 (Set A), concept 2 (Set B), concept 3 (Set C).

Concept User Test Results

The results of the questionnaire, observations and accompanying discussions with the participants, led to results on all four levels to which the concepts were to be evaluated.

Level of knowledge conveying

For this part of the concept user test the participants were asked to answer a set of six questions for which the goal was that the participants could derive the answers through interacting with the setup and reading the museum information signs. Overall it was concluded that all three concepts led to engaging the participants in the concepts of quantum physics that were implemented. Held discussion after the test showed that basic concepts of quantum physics were introduced and the results of the questions asked in the questionnaire showed that the participants were stimulated to think about and reevaluate the concepts that were explained to them throughout the interaction design and the accompanying museum information signs.

Part of the data results from the questions on knowledge conveyance were of less value as half of the participants had little to intermediate level of preliminary knowledge on the concepts of quantum physics that were implementing in the concept design, from which could be concluded that it was not necessarily the concept design that led to the answers that were given for the questions. For the participants that had no prior knowledge on quantum physics, the questions were experienced as difficult, resulting in some questions being answered correctly, and some questions were answered wrong, but as the answers given were either correct or near correct, it was concluded that some form of knowledge conveyance had taken place successfully.

Evaluating the manner to which this part of the questionnaire was set up, it could be concluded that for a small portion of the questions there was not always one specific correct answer among the multiple-choice options. This was caused because these questions were based on testing the successfulness of conveying the envisioned analogies of connecting topics of quantum physics and cymatics, and as stated earlier in this report in the chapter “Analysis of the Four Cymatics Combination Types” paragraph 3, analogous comparisons are susceptible to subjective reasoning.

Concluding for the level of knowledge conveyance, the successfulness of the questions, as interesting answers were giving, confirmed the aimed for engagement and the informativeness of the museum information signs were concluded to being satisfactory. The questionnaire can be found in appendix C.

Quality of eigenmode producing

For this part the participants were given three A4 papers, each containing a compiled set of eigenmodes produced by each concept, without the annotation to which concept they belonged, and were asked to rate them by choosing the most appealing set and second-most appealing set. Evaluation of the data was done by assigning points, wherein most-appealing sets received 1 point and second most-appealing sets received 0,5 point. The results of this part of the test were clear. All participants chose the same most appealing and second-most appealing set of eigenmodes. This clearly showed that the eigenmodes produced by concept 3: frequency rotary dial was thought to produce the most appealing eigenmodes, followed by concept 1: Mixing Subs,

Mids, and Highs, for which was thought to produce the second-most appealing eigenmodes. It could be reasoned that among all possible eigenmodes that could be produced by each concept, not all possible combinations were examined during the preliminary examination of each concept’s eigenmode producing. Conducting a full range investigation in all possible frequencies and accompanying levels of amplitude could resort to a more concise overview of which concepts succeeds best in the producing of eigenmodes that appeal to users, but as the envisioned interaction design itself comprises a short interaction, this approach was concluded to be concise and acceptable.

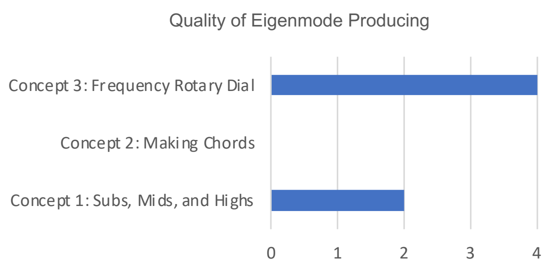


Figure 69: Data on quality of eigenmode producing per concept; most appealing and second most appealing. Most-appealing sets received 1 point, and second most-appealing sets received 0,5 point. (n=4).

Level of intuitive interaction

For this part the participants were asked to rate certain aspects of intuitiveness in interacting with the concepts by filling in rating scales going from 0-10. Questions 7, 8, and 9 from the questionnaire were focused on comparing the three different concepts in terms of intuitive interaction and questions 10, 11, and 12 were focused on the clearness of the museum information signs.

Question 7 and 8, on operating the three concepts, for which concept 3: frequency rotary dial came out best. Question 7 focused on how clear it was what the participants had to do, and question 8 focused on how they had to do this.

Question 9, on the clearness of what possible frequencies were available, on average no real differences were found among the concepts, with concept 2: Making Chords, having a slight overhand. Taking into account all data, concept 3: frequency rotary dial was concluded to fare best in terms of intuitive interaction.

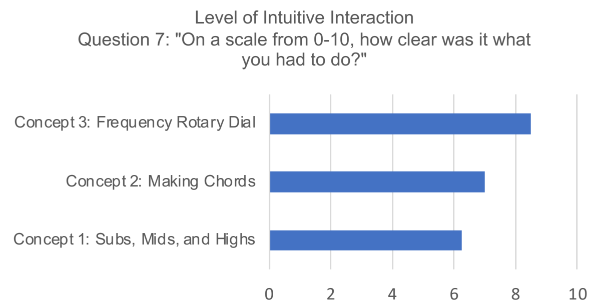


Figure 70: Data showing the results of question 7: “On a scale 0-10, how clear was it what you needed to do? (n=4)

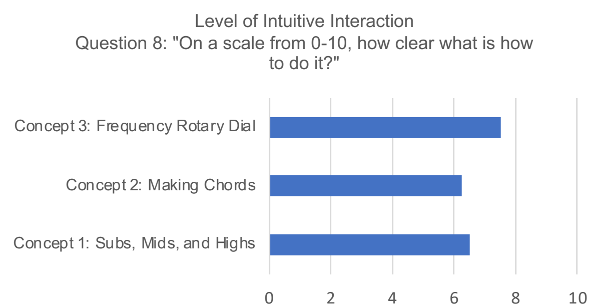


Figure 71: Data showing the results of question 8: “On a scale 0-10, how clear was it how to it? (n=4)

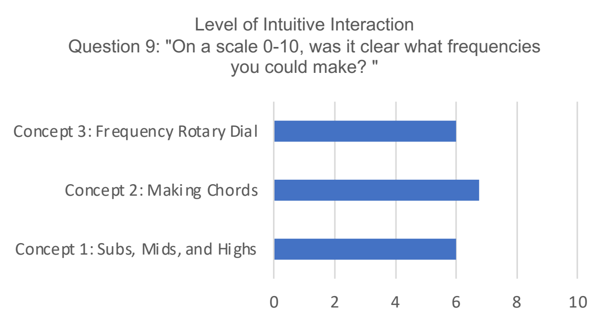


Figure 72: Data showing the results of question 7: “On a scale 0-10, how clear was it what you needed to do? (n=4)

Question 10, 11, and 12 focused on the clearness of the museum information signs and evaluate how intuitive the overall simulated science museum context was.

Question 10, on the clearness of the museum information signs in general, showed that the overall experience with the signs was good. Ratings differed with 6 being lowest rating, and 8 being the highest rating.

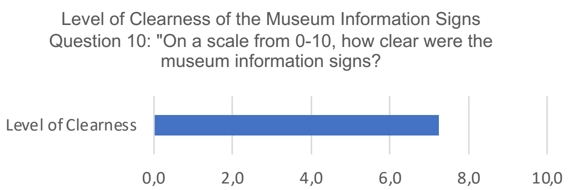


Figure 73: Data showing the results of question 10: “On a scale 0-10, how clear were the museum information signs?” (n=4)

Question 11, on the complexity of the museum information signs, showed diverse ratings. 2 out of 4 participants rating the complexity of the signs a 5, while the other 2 participants rated an 8. Interestingly to this was that this division did not occur, as could be expected, by the participants level of knowledge on quantum physics, wherein the low ratings were given by the participants with no prior knowledge of quantum physics, but that was not the case, making an interesting situation. Cross-referenced with the answers giving in the questionnaire part on knowledge conveyance given by the participant with no prior knowledge on quantum physics, led to believe that indeed the information signs were found to be informative as also in that part of the questionnaire correct answers were given.

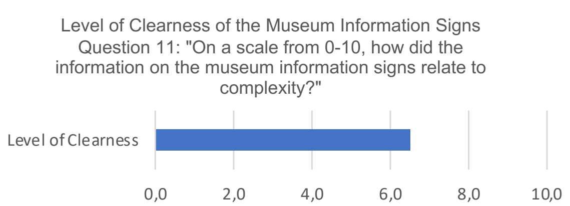


Figure 74: Data showing the results of question 11: “On a scale 0-10, how did the information on the museum information signs relate to complexity?” (n=4)

Question 12, on how the complexity of the museum information signs related to the length of the texts on the signs, overall concluded that the content of some signs was thought to be slightly too complex and the texts were thought to be slightly too long. Simultaneously it was understood that by making the texts shorter, presenting the level of complexity would not be possible as the texts were thought to be efficient in communicating the contents. For that it was concluded that the texts were good in terms of length and complexity and of good quality, while at the same time concluding that the text were experienced to be too long and too complex. The question itself started interesting discussions on the topic of finding a correct balance of text length and the conveyance of complex knowledge. As the envisioned design is aimed for a younger generation, conveying less complex theoretical knowledge could lead to a better-balanced form of texts and level of complexity.

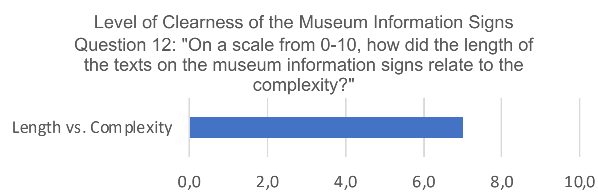


Figure 75: Data showing the results of question 12: “On a scale 0-10, how did the length of the texts on the museum information signs relate to complexity?” (n=4)

Level of effectuated engagement

This part focused on which concept was thought to be the most fun and which concept was seen as to be best suited in the context of quantum physics. The results were clear as all participants thought of concept 3: Frequency Rotary Dial, to be the most fun concept and best suited for the context of relating the interaction to quantum physics. Evaluation of the data was done by assigning points, wherein the most fun and best suited concepts received 1 point and second-most fun and second-best suited concepts received 0,5 point.

Although the Axion 25 MIDI keyboard was experienced by some of the participants as a fun interaction, the majority thought interaction through just Akai MPD218 MIDI controller would form a better experience in terms of the interaction design. Interacting with the setup with the just MPD218 controller made a clearer interaction and suited the context of quantum physics better. Although the combining of frequencies at first was exploring the setup controls was seemed as fun, ultimately the added value of combining frequencies was not seen.

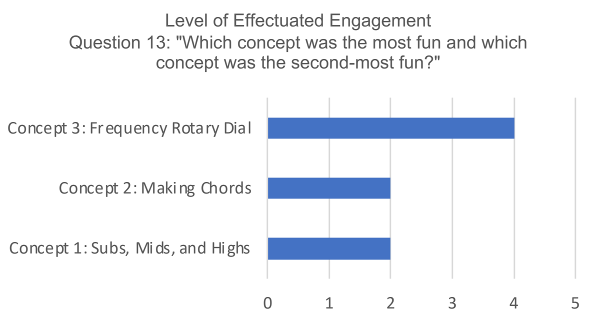


Figure 76: Data showing the results of question 13: “Which concept was the most fun, which concept was the second-most fun?” (n=4)

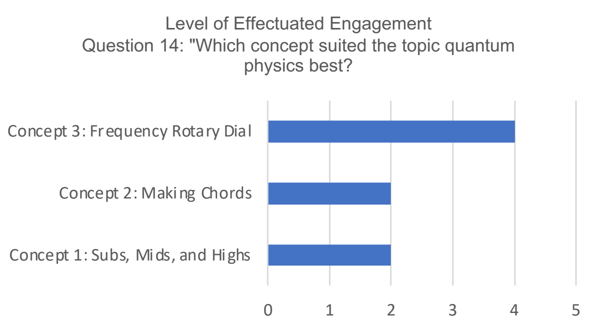


Figure 77: Data showing the results of question 14: “Which concept suited the topic quantum physics best and which concept suited the topic second-best?” (n=4)

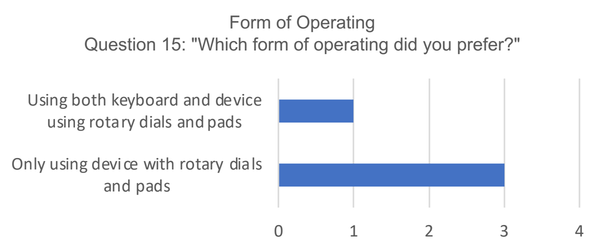


Figure 78: Data showing the results of question 12: “On a scale 0-10, how did the length of the texts on the museum information signs relate to complexity?” (n=4)

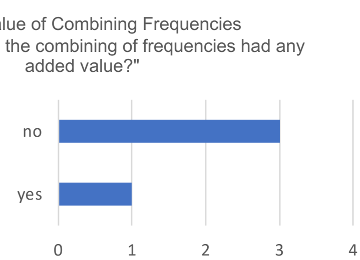


Figure 79: Data showing the results of question 12: “On a scale 0-10, how did the length of the texts on the museum information signs relate to complexity?” (n=4)

Other commentaries and observations

- A remark made by one of the participants was that having to bend over the setup too much makes your back hurt when interacting long with the setup.
- Pressing pads and keyboard keys simultaneously was observed as an intuitive action, while having no effect in terms of added functioning.
- Remarks on excitement and simultaneously worrying about water splashing out of the petri dish on high amplitudes
- Definition of the actual eigenmode was not clear and not emphasized enough
- With all four participants I had to help start interacting with the device, as first the amplitude needs to be put higher for the frequencies to be actuated. As the amplitude knob is one of the last controls intuitively was grasped for, the first experience with the setup was always that it seemed like it was not doing anything or that it was not working.
- Through observation, the overall producing of stabilized eigenmodes was too difficult. Experience with the setup was needed to understand that 1) the lower frequencies are better for making stabilized patterns and 2) to get to stabilized eigenmodes, you needed to know that you need to put the amplitude on a low level of the amplitude scaling. These aspects were thought to be too difficult to be found in a short interaction with the design.
- Question 2 on what the setup had to resemble was not clear and too much open for interpretation and subjectivity. This occurring problem was an important insight as it showed that overall it is not really clear what the setup really resembled.

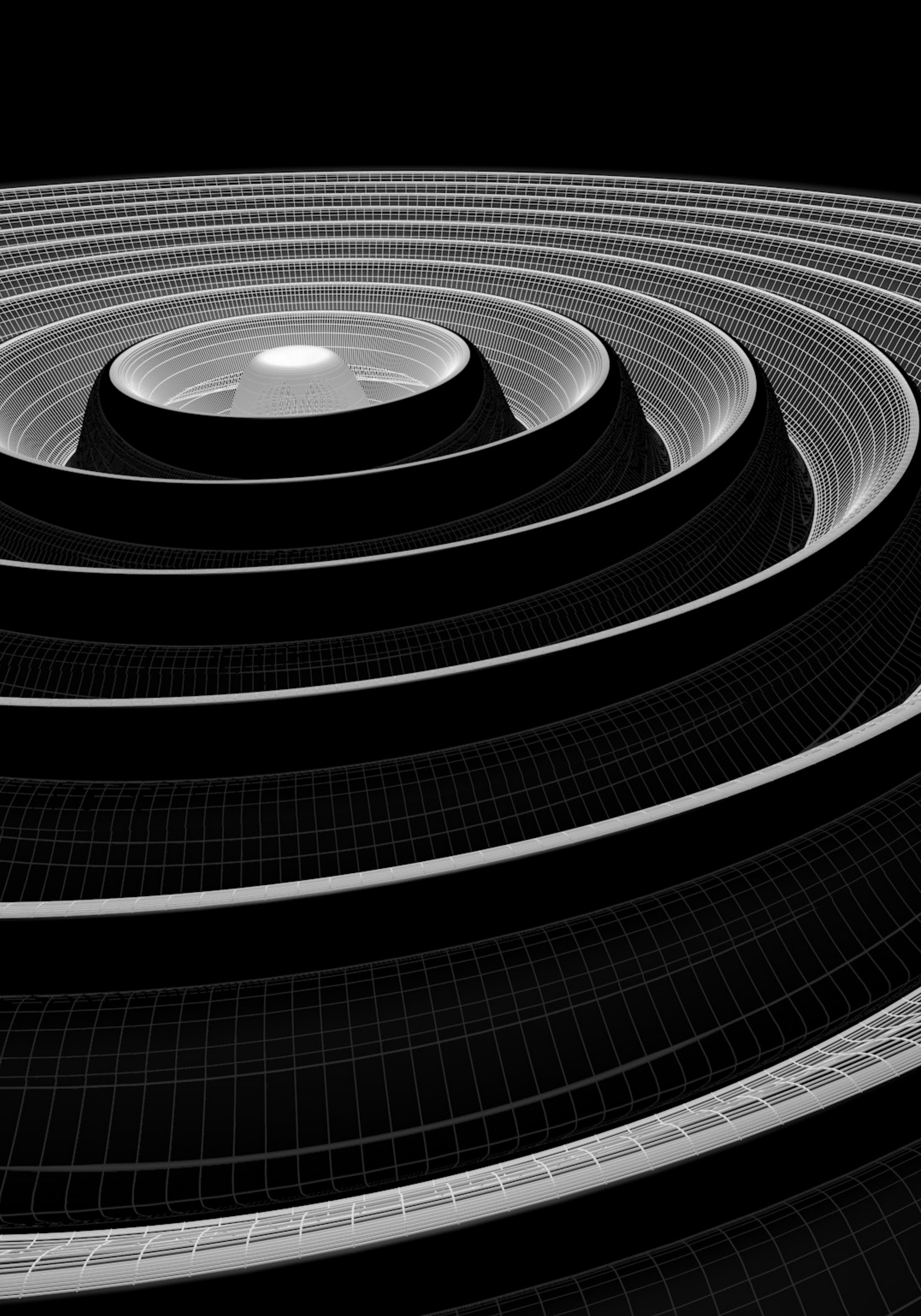
Concept User Test Discussion

The questionnaire was extensive and this led to a test that was very time consuming and resulting in having only a small group of participants. The positive side to this was that insightful data was gained, and surprisingly with only four participants, the results of the test very much were in line with each other and spoke a clear narrative. The subject and the information given throughout the interaction with the setup was thought to be complex, and most likely too complex for a science exhibit for a young audience. The part on level of knowledge conveyance could have been better. It is difficult to test actual conveyance of knowledge in the way the questionnaire was set up. The test was primarily made to have participants that had no prior knowledge of quantum physics. Having one participant with little preliminary knowledge on the topic and one participant with intermediate preliminary knowledge did allow a good comparison in how the design aim to relate cymatics to quantum physics was experienced from different levels of knowledge on the topic.

With the participant with intermediate level of knowledge of quantum physics an interesting discussion arose on the theoretical connection of the quantum physics concepts that were integrated analogously in the interaction design. The participant perceived the setup trying to convey two different types of quantum concepts, one of particles and waves, wave functions and probabilities, and one other concept on superposition and the stabilization of a qubit. She thought both concepts were clear when observed separately from each other but observing together as was one interaction design, she thought the connecting concepts among themselves were obstructing each other. Also she added, that although she liked both concepts separately, also neither of those quantum concepts had any relation to eigenmodes for what they are in definition. These remarks were in line with concerns that were foreseen towards the concept test. As the primary aim of the concept test was to investigate how the concepts together would fare in the context of usage, the test was set up the way for which the combined

Concept User Test Conclusion

Overall the concept test can be concluded to be successful. Concept 3: Frequency Rotary Dial came best out of the test and will be used as final concept to work towards the final design. Overall it scored best on most aspects. Considering the things to solve, and areas that were problematic or needed adjustment, concept 3 was seen as the best option to solve these areas. Furthermore, using only the Akai MPD218 MIDI controller, would allow a simpler interaction design. A simpler interaction design would consist of an easier way to get the user to the fully stabilize eigenmodes, using frequency and amplitude control. Incorporating a simpler interaction design might bring about a simpler analogy to convey with the design. In term this is could help in developing shorter museum information signs that could convey a very informative interaction, using simple controls, together forming a short engaging informative and foremostly fun experience with quantum physics and cymatics.



Phase 3: Design

Revisiting Design Goal and Design Visions

The design goal was to engage young people aged 13-30 in the topics of quantum physics and quantum computing through a science museum exhibit using cymatics.

The envisioned interaction design would encompass interacting with a cymatics installation that would form a base analogy to quantum physics and create a bridging connection between the two fields with the goal of effectuating engagement in quantum physics and quantum computing.

The interaction vision that was formed using the ViP method stated that the user should feel like working like a quantum physicist and that the accompanying interaction should encompass a form in which the museumgoer makes a simplified calculation that would stand analogous to the quantum calculations quantum physicists make.

Revisiting Concept Test Results

Overall all three concept design and the overarching concept design in general were concluded to be fun in terms of interaction and succesful in terms of engaging in the topics of quantum physics, quantum computing and cymatics. The background information provided through the design was, although clear and engaging for the participants, thought to be too complex for a target group that consists of a younger audience.

The conclusion that was drawn from the evaluation of all insights was that an interaction design was needed that would connect the interaction with cymatics to quantum physics through a more simple analogy. As the information on the principles of quantum physics that were implemented in the design were thought to be too extensive and too complex, the solution was found in focusing on one quantum physics specifically. As the concept designs focused on the visual representation of wave functions, quantum superposition, and the stabilization of qubits at the same time, it was chosen to focus on stabilizing qubits primarily, or more specifically, as it was changed for the final design into: working with qubits. All other aspects would still be encompassed in the design, but focusing on working with qubits primarily would allow a more simple and clear narrative. Less information signs would be required and a simpler analogy could be made that would still allow a bridge between quantum physics and cymatics to be made, but through an interaction design that would better suit a younger audience and the short interaction that matches the context of a science museum.

Final Design Approach

The final design process was split into two parts. The first part focused on forming and specifying the new final interaction design, the second part on the design appearance and aesthetics,

A new combination of interaction and analogy was formed that complied with the formulated design goals and visions and would improve upon the insights gathered from the concept test.

The new interaction design was designed around using the Akai MPD218 MIDI controller. The function of combining frequencies was left out of the design as it held little to no added value, while making the overall interaction more extensive. Instead of using only a number of pads, the entire four by four matrix of the controller was used, with every pad containing a pre-saved eigenmode pattern.

The second part consisted of redesigning the cymatics setup. The setup that was used for the concept test contained all base functionalitiet. What was done for the redesign comprised redesigning the size of the setup into a tabletop scaling and design the overal aesthetics of the device that would suit the context both in appearance and in function. The device was made to resemble the iconic chandelier design.

Final Interaction Design: The Qubit Controller

In the final interaction design the Akai MPD218 MIDI controller is used to emulate a quantum chip containing 16 qubits as shown in Fig. 80. The device is turned 90 degrees from its original usage position and is mounted with a plastic top cover. In the design each qubit is represented by a pre-determined eigenmode which can be activated by pressing down the corresponding touchpad of the controller. In this each touchpad represents a qubit. Each eigenmode consists of a combination of two variables: the frequency and the amplitude, in which the amplitude is pre-determinately set to a level that allows a stable eigenmode for that specific frequency.

The pads function as momentary switches, meaning, when no pad is pressed down, no output is generated and the device does nothing. Different eigenmodes can be generated by pressing down different pads as shown in Fig. 81. Pressing down multiple pads at the same time results in the system emitting no eigenmode, but a state of chaos similar to when the amplitude is not tuned properly to the frequency, without overloading the system.

The eigenmodes resemble qubits in the sense that the eigenmodes can be changed from one state to another through changes in frequency and amplitude. Done properly the user will be able to change one of the starting eigenmodes into another by careful tuning of the amplitude when changing the frequency, as every frequency has a corresponding level of amplitude to which the eigenmode stabilizes. When the touch pad is released, the eigenmode resets to its original values. This process is shown in Fig. 82.

Figure 80: The Akai MPD218 MIDI controller with mounted top cover, hiding the controls that are not used for the interaction design.

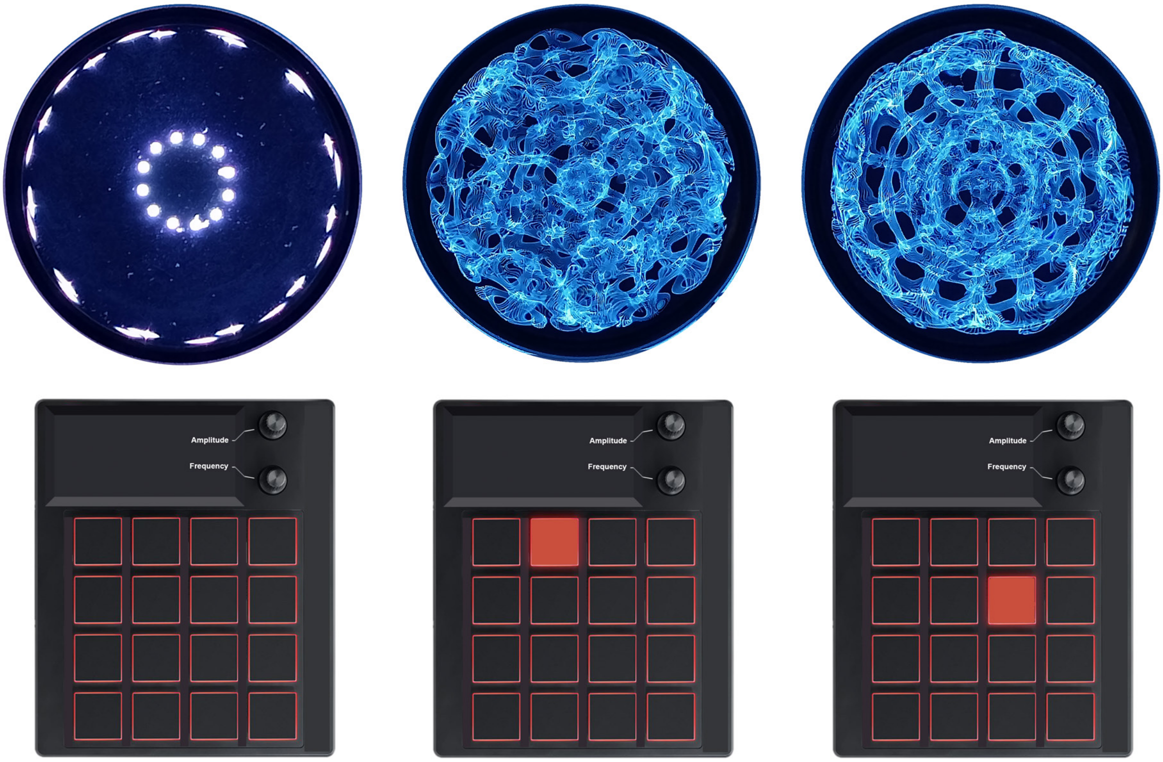


Figure 81: Each pad represents a qubit and holds a pre-determined eigenmode.

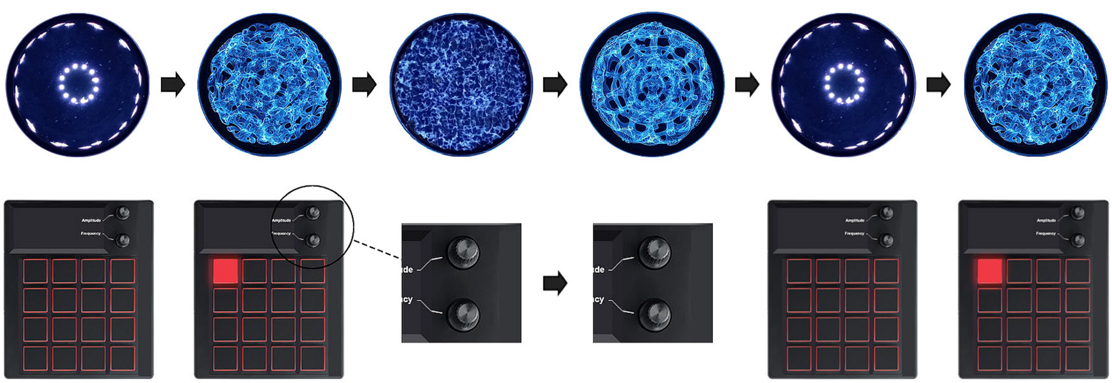


Figure 82: The user can change one eigenmode into another eigenmode through careful tuning of frequency and amplitude.

Cymatics Device Final Design

The final design for the cymatics device is shown in Fig. 83. The design is inspired by the iconic chandelier design used in many of the quantum computers developed by the big players in the quantum computer development sector. An examination on what parts these machine consist of was conducted and implemented in the design process of coming to the final appearance of the cymatics device. Besides appearance, the design also encompasses a form of functional aesthetics. By having the cymatics device look like a small quantum computer, a younger audience can be intuitively be introduced to the aimed for connection between quantum physics and cymatics.

In the final design the connection between quantum physics and cymatics is separated more than in previous concepts. In the final version the cymatics device is presented specifically as a cymatics device, and the adding of the Akai MPD218 MIDI controller as a separate add-on module, allows the interaction design specifically aimed for introducing the basic aspects of quantum physics and quantum computing that was aimed for from the project's assignment and design goal.

The functional aesthetics in terms of appearance, has a two way functioning. From using the cymatics device separately, thoughts on how it resembles a quantum computer could instigate the realization that waves are part of both quantum physics and cymatics. In this a bridging connection between the different fields could be made without any specifically indicating the connection. When combined with the Akai MPD218 MIDI controller add-on, the appearance of the cymatics device helps in understanding how it's used a simplified quantum computer simulator. Also the position of the water basin gives sense to where normally the quantum chip containing the qubits is located. The reason a quantum computer is build consisting of several layers of disks is to allow the cooling of the bottom part, which contains the quantum chip, to a precise temperature just above absolute zero, or -273,15 degrees celcius. For operation the entire chandelier of the quantum computer is put into a cryostat, a type of refrigerator that is filled for instance with liquid helium. For the vibration caused by the speaker at the bottom of the cymatics device it not necessarily needed to create such situation of stabilizing the environment, but it does allow a resembling connection to be made to why a lot of quantum computers that need to be cooled are build in the iconic chandelier form.

The separating of device and add-on module also allows a more simplified appliance of museum information signs, in the case of exhibiting in a science museum context. The device is explained through a sign that informs of it being a cymatics device and that wave patterns called eigenmodes can be produced with it. The sign next to the MPD218 controller explain how the cymatics device is used to resemble the stabilization of quantum qubits.

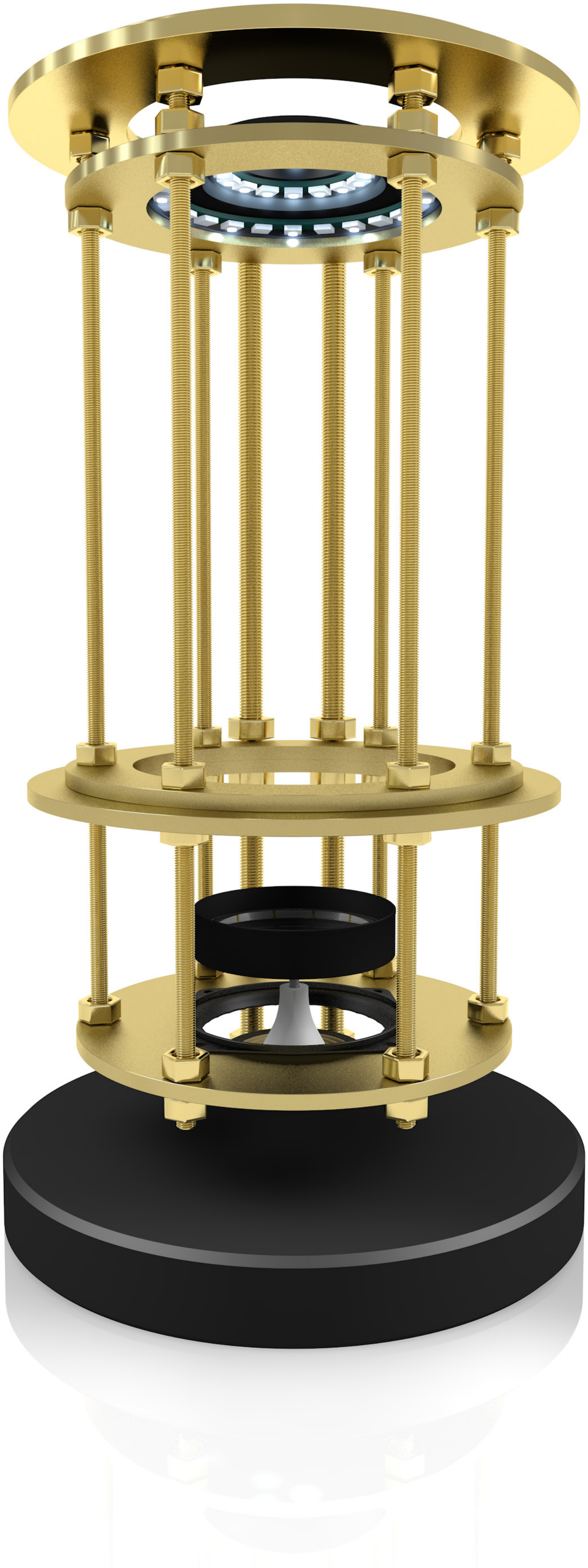


Figure 83: The final design

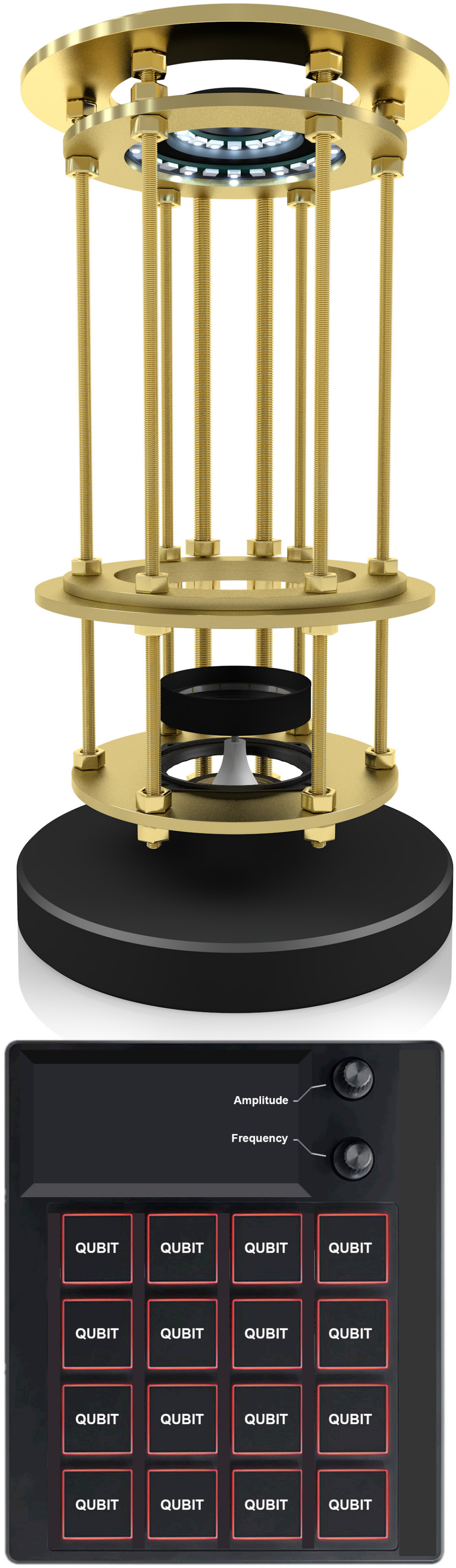


Figure 84: The final design including the Qubit Controller

Discussion

Investigating quantum physics and quantum computing was a challenging but a rewarding experience. One thing certainly is clear, quantum physics is difficult to understand. During the project several moments arose where a basic understanding was attained of what underlies the difficulty in understanding, accompanied by thought that reasoned that even without any knowledge about physics or quantum theory in specific, basic principles of quantum physics that are commonly talked about can actually be understood in a simplistic form. However, each of these moments was countered with a moments of realization that although a simple understanding can indeed be grasped, the more you start to think you understand, the more you understand how difficult it is to relate these concepts to reality.

Finding bridging connections between quantum physics, quantum computing, and cymatics was interesting but a difficult task. The key to the project's assignment, was to find simple concepts that connected difficult topics. The difficulty was in finding the right balance between finding connections by investigating the topics more deeply and focusing on making simple connection work well.

The exploratory sessions with the physicists were helpful as it gave me good specific topics to focus on. Without going to deep into any quantum theory, the physicists were able to give insight on how I should approach the project's assignment. The insights shared on how they work with their quantum systems, and how they would relate it to the cymatics setups, gave a clear direction to the project's approach as it became clear that if that could be implemented into the design solution, the envisioned engagement in the topic of quantum physics could instigated without relying too much on actual quantum theory.

Time management and documenting the findings during the project was difficult as the above described difficulty in finding the right balance in trying to understand more of actual quantum physics and quantum computing on one hand, and focusing on working out more simpler connections properly on the other hand, was difficult. In hindsight, focusing on simpler concepts could have made managing the project easier, but to know that was the right approach for sure, investigating deeply was necessary. It was a back and forth process and finding the balance in this was the difficulty. This difficulty led to a project that focused primarily on finding bridging connections between quantum physics and cymatics, and little on the science museum context and the target group. The stance on this througout the project was that making a connection between the fields of quantum physics and cymatics was primarily more important as engagement through a design that is scientifically grounded is most appealing.

Overall the project was succesful as a promising final design came forth and investigating the topics of quantum physics, quantum computing, and cymatics was interesting and rewarding experience. Further development of cymatics devices that introduce basic aspects of quantum physics is seen as promising and future involvement of science museums in this process is seen as a valuable next step.

Conclusion

The project's design goal was to find ways to introduce basic aspects of quantum physics through cymatics and the final result of the project delivers a promising combination of an interaction design that implements a simple form of analogy using qubits, in an appealing and aesthetically functioning device using cymatics. The difficulty in the project was finding the right approach towards the difficulty that quantum physics comprises. This difficulty made time management within project difficult to manage. Further cooperative design sessions with quantum physicists from could help expand upon the current design, development of cymatics devices that introduce basic aspects of quantum physics is seen as promising and future involvement of science museums is seen as a valuable next step.

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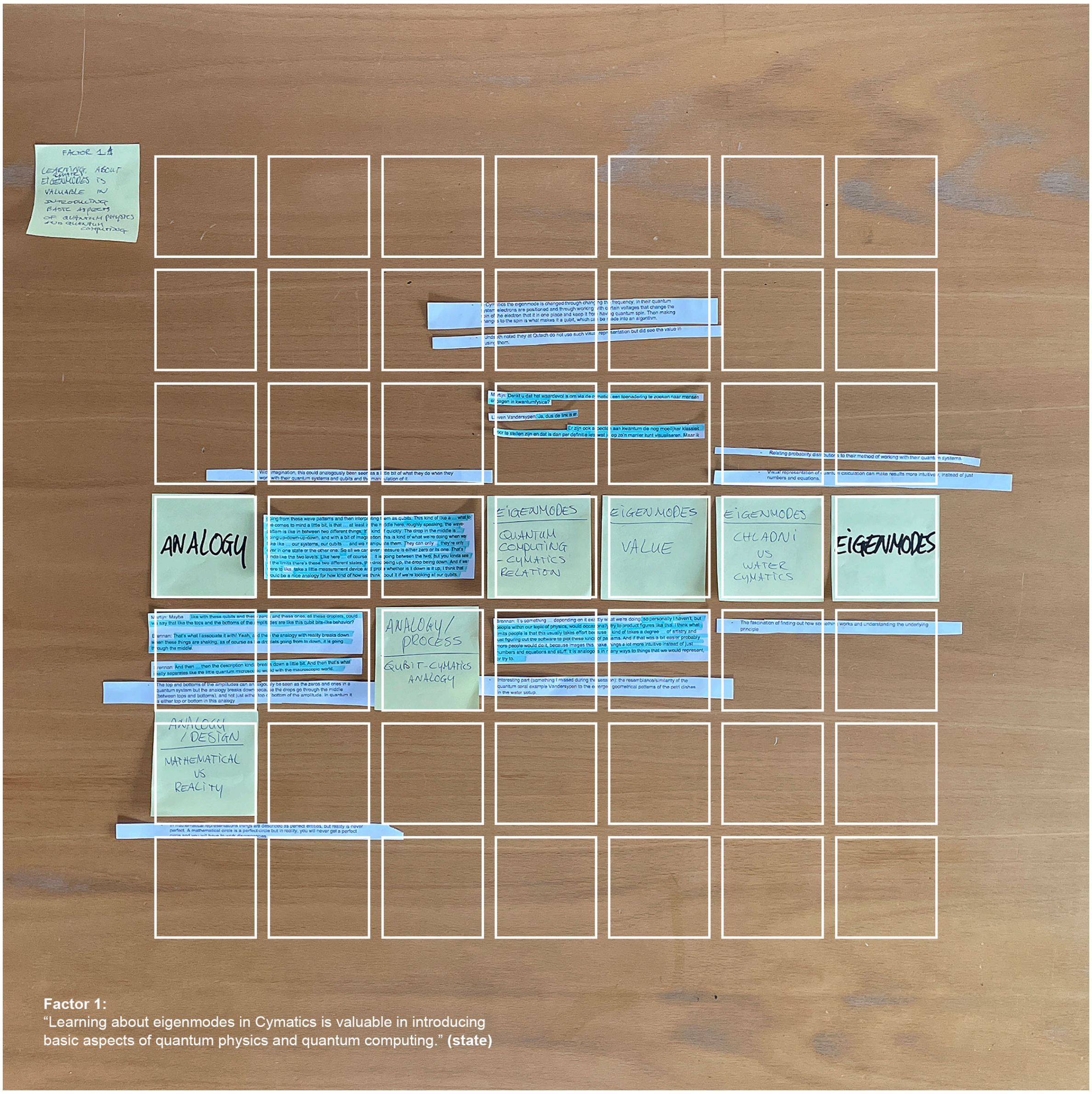
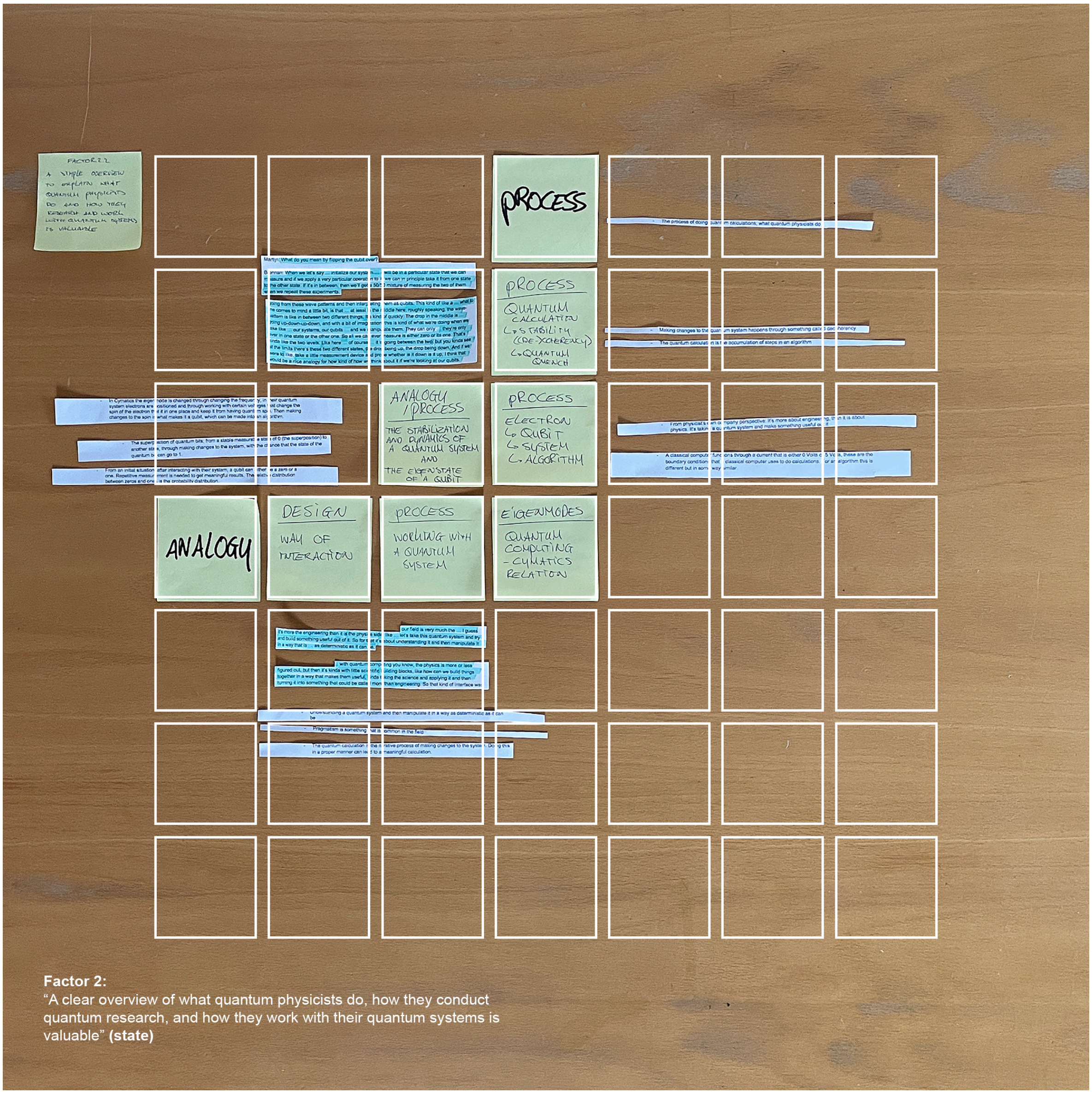
Appendix

Appendix A: Factors

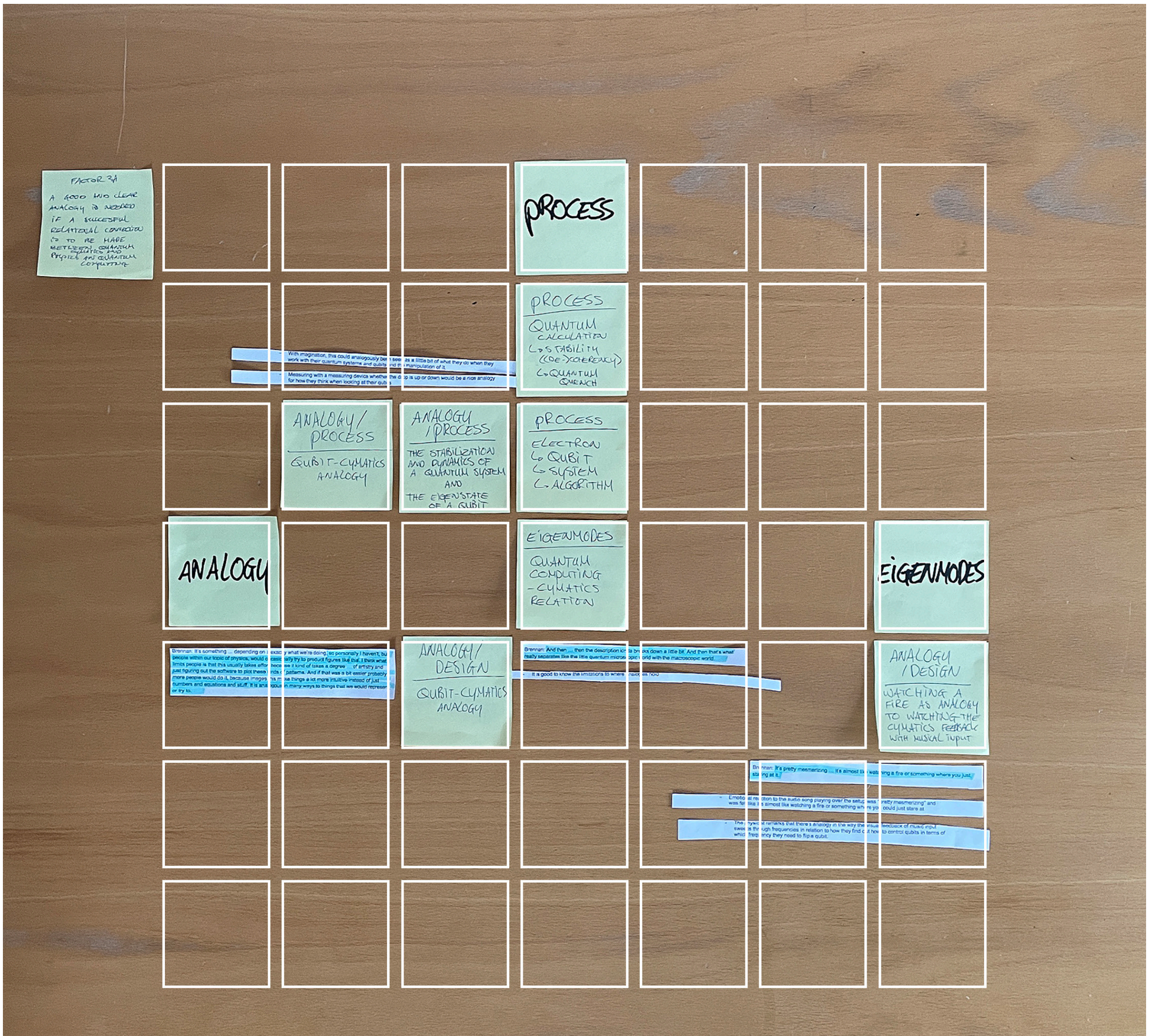
The following pages of appendix A contain the factors that were formed during the appliance of ViP. The smaller texts are deliberately not readable as the quotes among these are confidential data from the sessions with the quantum physicists.



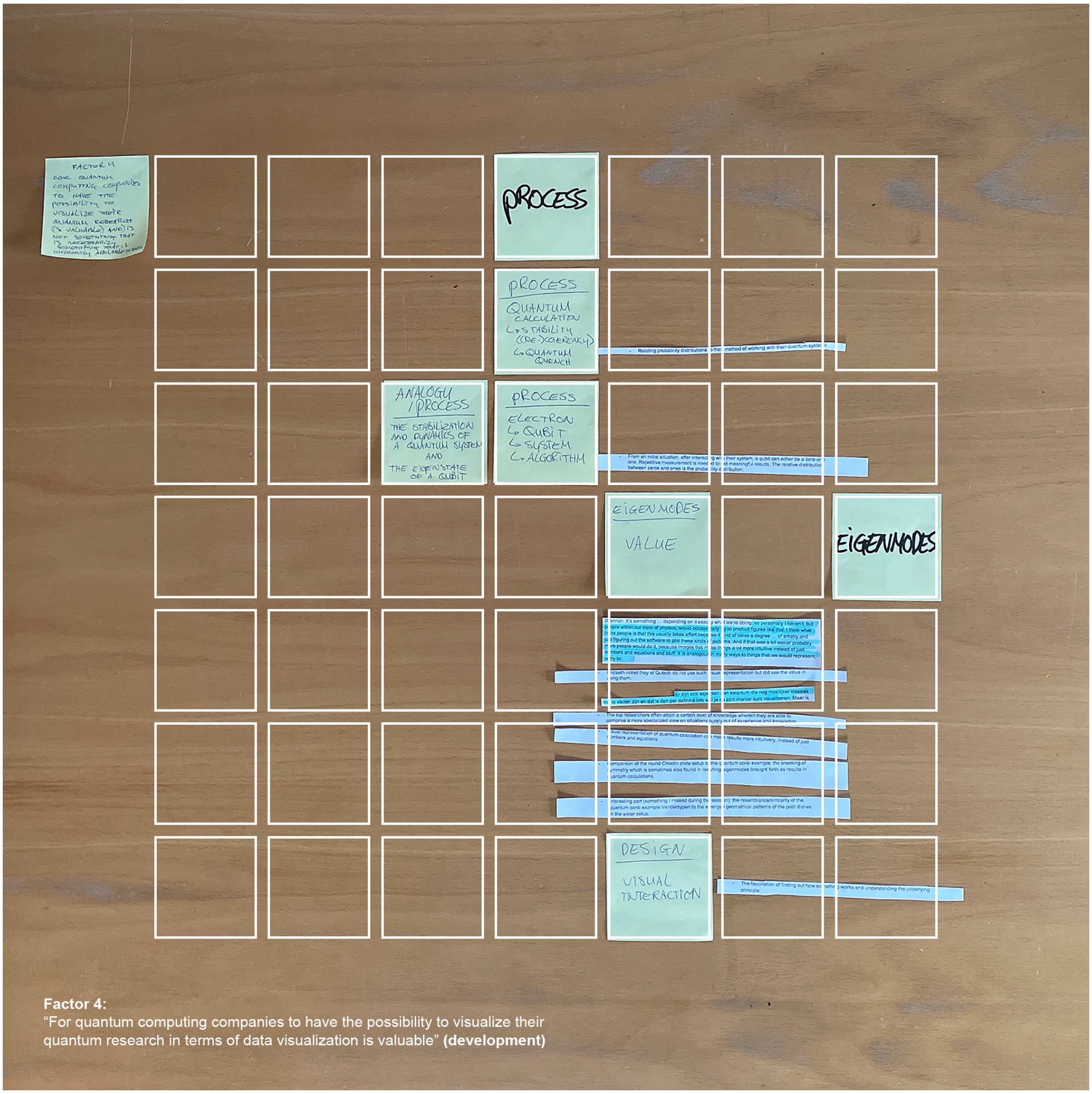
Factor 1:
“Learning about eigenmodes in Cymatics is valuable in introducing basic aspects of quantum physics and quantum computing.” **(state)**



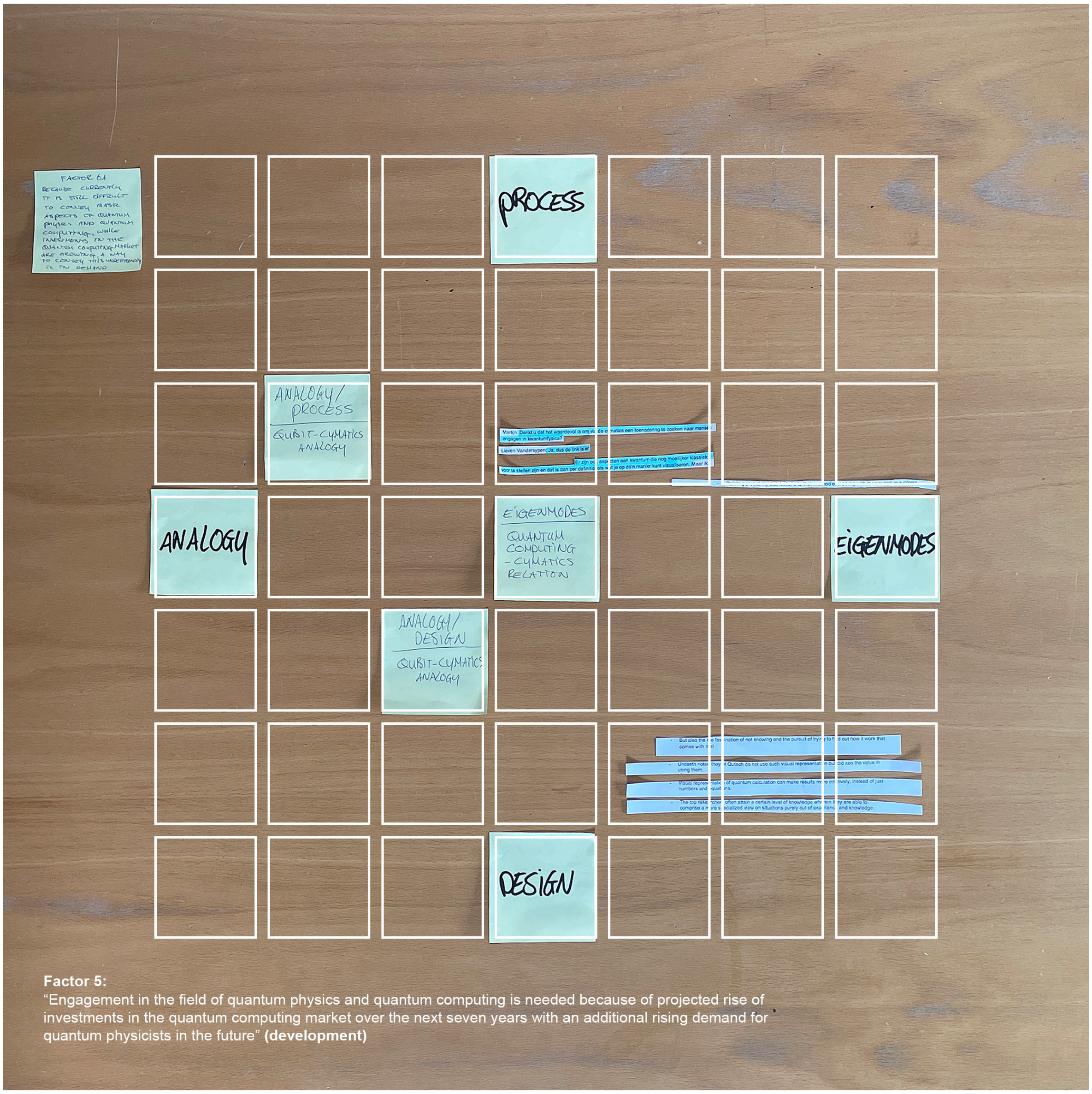
Factor 2:
"A clear overview of what quantum physicists do, how they conduct quantum research, and how they work with their quantum systems is valuable" **(state)**



Factor 3:
“A clear analogy is needed if a successful connection is to be made between Cymatics, quantum physics and quantum computing” **(state)**



Factor 4:
"For quantum computing companies to have the possibility to visualize their quantum research in terms of data visualization is valuable" **(development)**

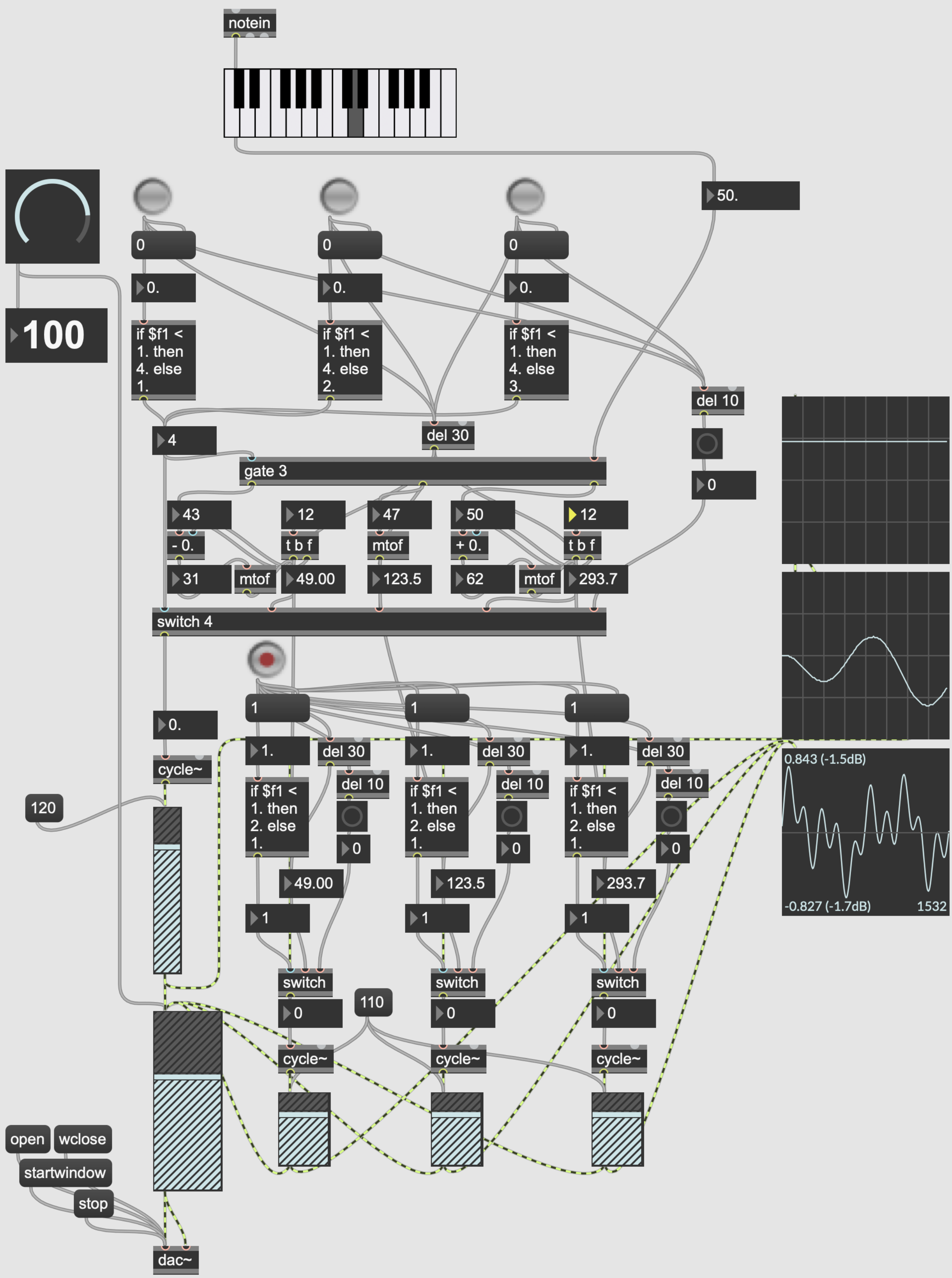


Factor 5:
“Engagement in the field of quantum physics and quantum computing is needed because of projected rise of investments in the quantum computing market over the next seven years with an additional rising demand for quantum physicists in the future” **(development)**

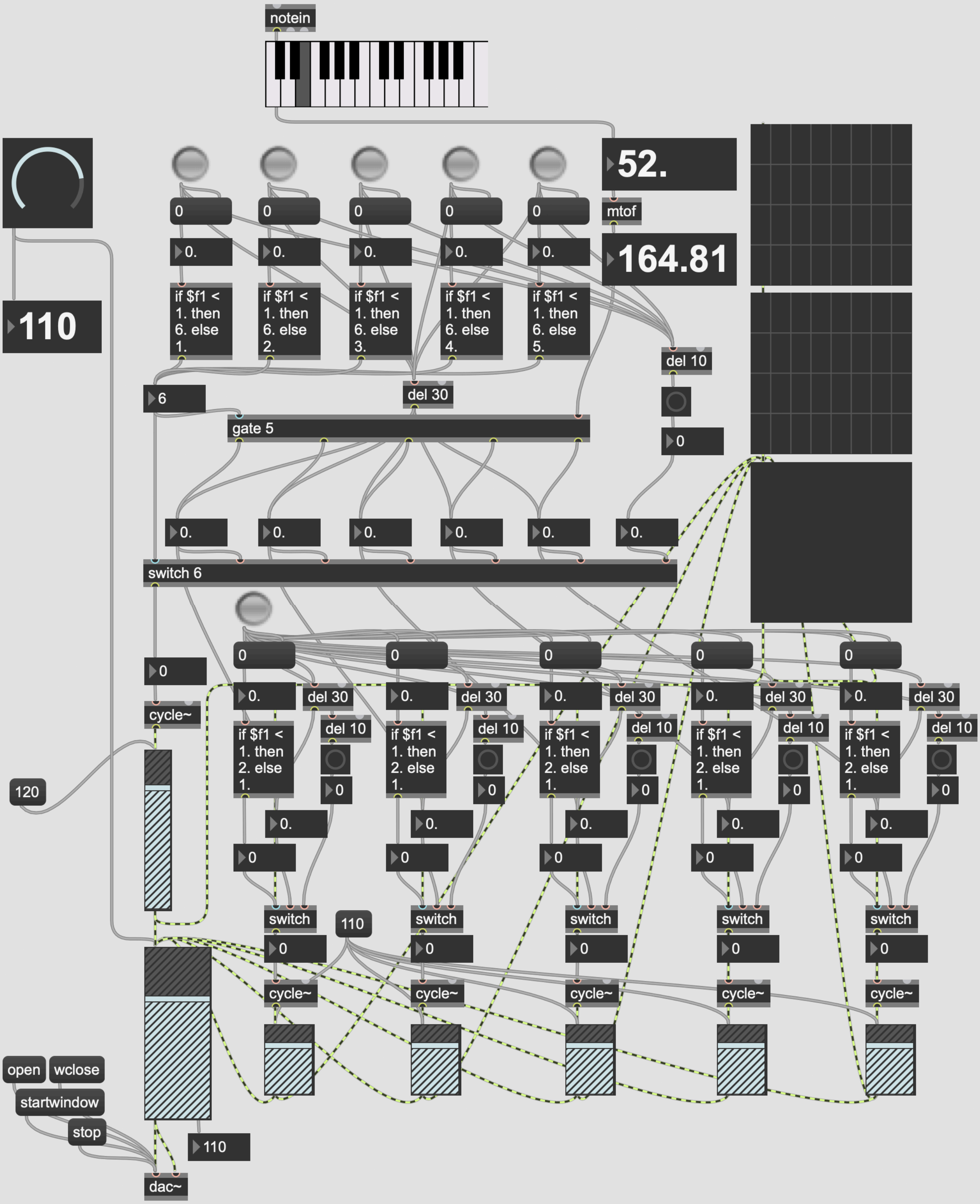
Factor 6:
"A simple interaction design is needed to create a successful science museum exhibit." **(state)**

Appendix B: Max MSP patches

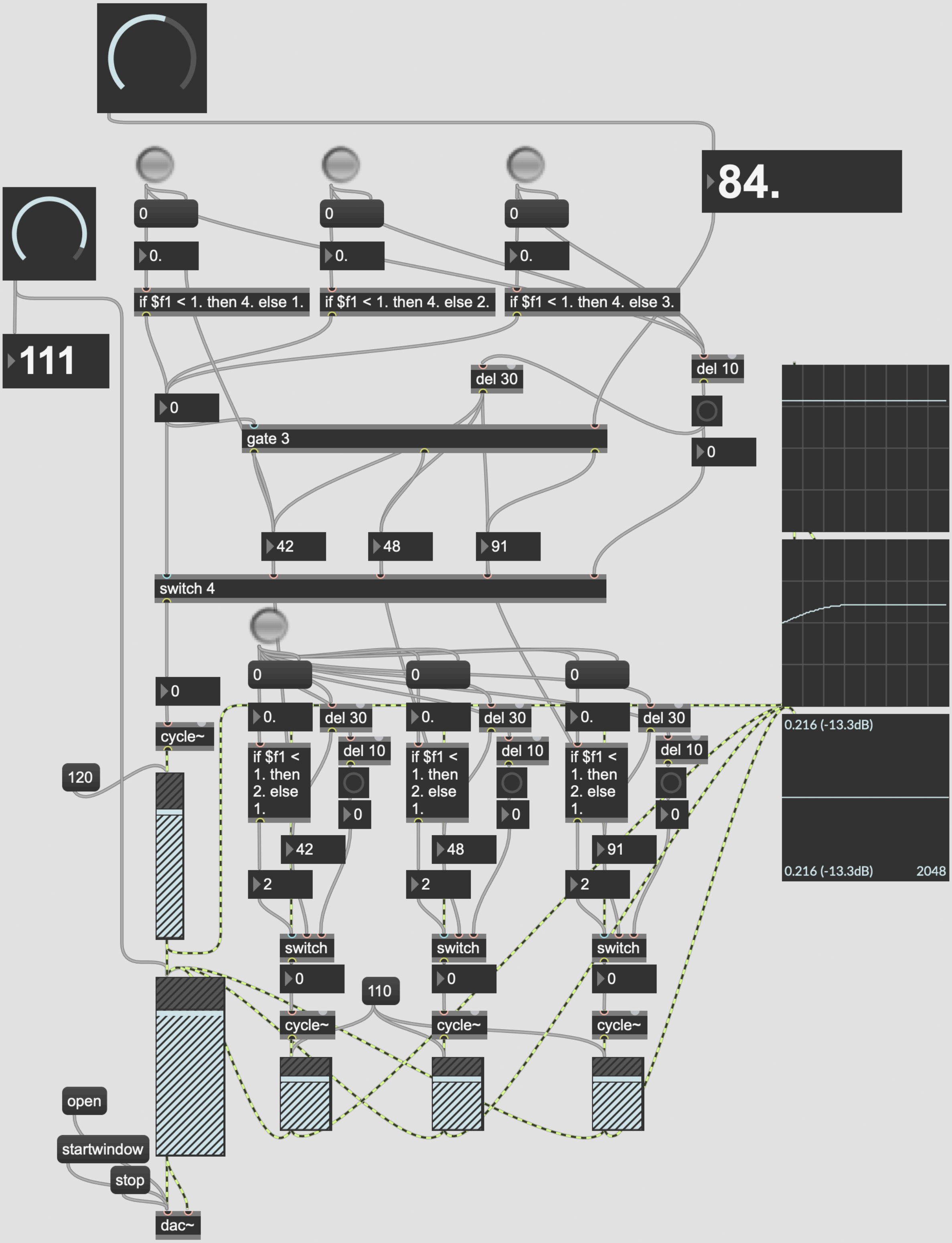
The following three pages contain the three Max MSP patches created for the concept user test.



Concept 1: Mixing Subs, Mids, and Highs



Concept 2: Making Chords



Concept 3: Rotary Frequency Dial

Appendix C

The following pages contain the questionnaire conducted during the conceptualization phase.

Conceptualization questionnaire, part of the graduation project “Introducing Basic Aspects of Quantum Physics through Cymatics” by Martijn Weber

Part 1:

Question 1: You will be given three A4 papers, each containing a set of nine visual patterns. Which of the three set appeals the most to you? Please make your choice by choosing the most appealing set and second-most appealing set.

Most appealing set of visual patterns:

a) Set A
b) Set B
c) Set C

Second-most appealing set of visual patterns:

a) Set A
b) Set B
c) Set C

Part 2:

Question 2: What is the device supposed to resemble?

a) A function generator
b) A quantum computer
c) A subatomic particle
d) A quantum superposition

Question 3: Why are subatomic particles described as a wave function?

a) Because during a measurement a particle collapses into either one of the two states
b) Because it is not possible to describe where each separate particle is located
c) Because as a wave function, predictions can be made on where the particle could be
d) All of the above

Question 4: How does the producing of an eigenmode in the design relate to a qubit?

a) The producing of an eigenmode resembles the stabilizing of a qubit
b) The producing of an eigenmode resembles the positioning of qubit
c) The producing of an eigenmode resembles the superposition of a qubit
d) Only answer a) and b) are correct
e) Only answer b) and c) are correct
f) Only answer a) and c) are correct
g) Answers a), b) and c) are all correct

Question 5: How was superposition resembled in the design?

a) Superposition was achieved through creating a pattern that was symmetrical
b) Superposition was achieved through creating a pattern that looked like it was standing still
c) Superposition was achieved through creating a pattern that moved dynamically

Question 6: How many possible states does a qubit have? Please write down your answer.

____

Part 3:

Question 7: Was it clear what you needed to do?

Concept 1: Combining Subs, Mids, Highs

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Concept 2: Making Chords

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Concept 3: Rotary Frequency Dial

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Question 8: Was it clear how to do it?

Concept 1: Combining Subs, Mids, Highs

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Concept 2: Making Chords

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Concept 3: Rotary Frequency Dial

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Question 9: Was it clear what frequencies you could make?

Concept 1: Combining Subs, Mids, Highs

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Concept 2: Making Chords

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Concept 3: Rotary Frequency Dial

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Question 10: How clear where the information museum signs?

Not clear at all										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Question 11: How did the information on the museum signs relate to complexity?

Much too complex										Fully clear
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Question 12: How did the lengths of the texts on the museum information boards relate to the complexity? (cross out what is not applicable)

Much too short / long										Exactly of a good length
0	1	2	3	4	5	6	7	8	9	10
O	O	O	O	O	O	O	O	O	O	O

Question 13: Which concept did you think was the most fun? Please make your choice by choosing the most and second most fun concept

Most fun concept:

a) Concept 1: Combining Subs, Mids, and Highs
b) Concept 2: Making Chords
c) Concept 3: Rotary Frequency Dial

Second most fun concept:

a) Concept 1: Combining Subs, Mids, and Highs
b) Concept 2: Making Chords
c) Concept 3: Rotary Frequency Dial

Question 14: Which concept suits the topic of quantum physics the best and which the least?

Suited the concept of quantum physics the best:

a) Concept 1: Combining Subs, Mids, and Highs
b) Concept 2: Making Chords
c) Concept 3: Rotary Frequency Dial

Suited the concept of quantum physics the least:

a) Concept 1: Combining Subs, Mids, and Highs
b) Concept 2: Making Chords
c) Concept 3: Rotary Frequency Dial

Question 15: Which type of interacting with the device did you prefer?

a) Using only the knobs and pads device
b) Using the combination of both keyboard and the knobs and pads device

Question 16: Did the combining of frequencies with the combine function have any added value according to you?

a) Yes
b) No

Room for remarks or comments that you would like share:

____

____

____

____

To better understand quantum computing, think of this setup as an imaginary quantum computer.

The wave patterns you will be creating are part of something that is called cymatics, the study of visual wave phenomena.

Quantum physics is also all about waves!

Quantum computer chips use quantum bits called qubits instead of normal data bits found in a normal computer.

These qubits are built from elementary particles, like an electron or a proton. They are called elementary as they cannot be made into smaller parts.

The special thing about elementary particles is that they can be at several locations at the same time, making it difficult to describe them. In quantum physics this is done by doing a probability calculation that predicts where chances are largest where the particle could be located.

This prediction is described as a wave function. Below is a visual example of a very simplistic wave function. Black shows where the particle will most likely be, and white is where the chance is the smallest that the particle will be. On the right a water-like wave is visualized.

With these devices you can make your own waves.

The wave patterns that you see are called eigenmodes. The eigenmodes made in this setup resemble in the qubit found in a quantum computer.

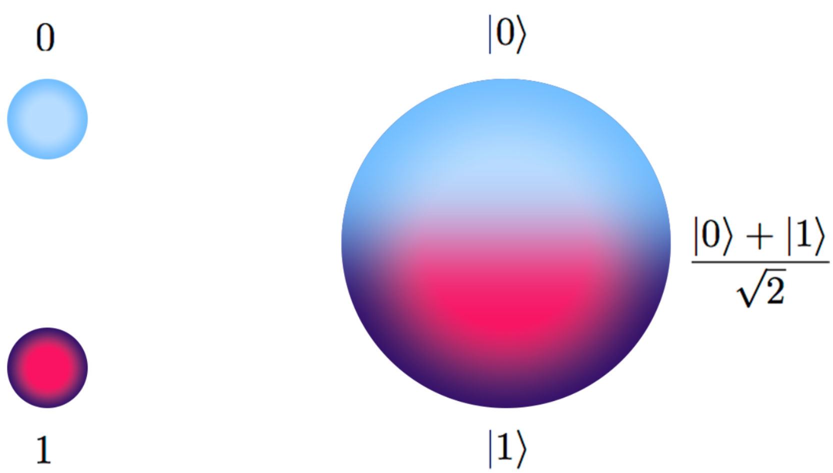
To make qubits for quantum computing is difficult because these particles are very sensitive and it takes great effort to position and stabilize them.

Are you able to stabilize your eigenmode?

A qubit in a quantum computer can be in two states: it is a 0 or a 1, just like a data bit in a normal computer. The special thing about a qubit is that it can also be in both states at the same time. This is what is called quantum superposition.

The weird thing about a qubit is that when it's measured, the quantum superposition collapses, and it will collapse in either the 0-state or 1-state. Only before the measurement is it in both states at the same time. So only after the measurement is it a 0 or a 1, before it is both at the same time.

Do you see the resemblance with your own stabilized eigenmode? Were you able to get the water from a state of standing still (0), into a dynamic and moving eigenmode pattern (1), but were you also to the pattern to a state where it looked like it stood still? In this situation, is the water standing still or is it moving? What do you think?

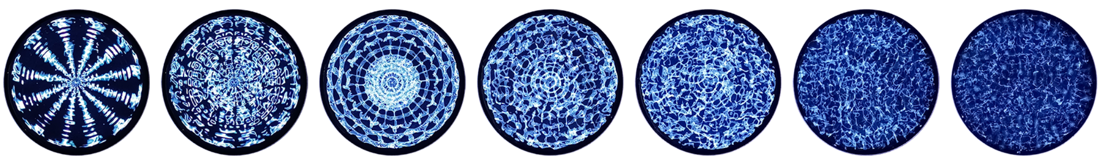


Appendix E: Eigenmode Producing Quality per Concept

The following pages contain the examination conducted on the eigenmode producing quality per concept during the conceptualization phase.

Concept 1: Mixing Subs, Mids, and Highs

MIDI 24 C1
32,703 Hz



MIDI 24 C1 (A)
32,703 Hz
Vol: 59,0%

Transition (A-B)
MIDI 24 C1
32,703 Hz
Vol: 61,4%

MIDI 24 C1 (B)
32,703 Hz
Vol: 61,4%

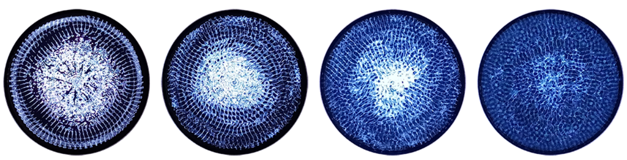
MIDI 24 C1
32,703 Hz
Vol: 62,99%

MIDI 24 C1
32,703 Hz
Vol: 64,54%

MIDI 24 C1
32,703 Hz
Vol: 70,86%

MIDI 24 C1
32,703 Hz
Vol: 81,89%

MIDI 40 E2
82,407 Hz



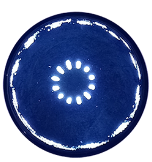
MIDI 40 E2
82,407 Hz
Vol: 63,78%

MIDI 40 E2
82,407 Hz
Vol: 65,35%

MIDI 40 E2
82,407 Hz
Vol: 73,23%

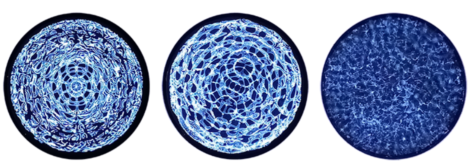
MIDI 40 E2
82,407 Hz
Vol: 79,53%

MIDI 55 G3
196,000 Hz



MIDI 55 G3
196,000 Hz
Vol: 100%
(no feedback)

Combined
MIDI 24/40/55
C1/E2/G3
32,703 Hz
82,407 Hz
196,000 Hz

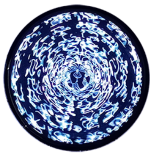


Combined
MIDI 24/40/55
C1/E2/G3
32,703/82,407/196,000 Hz
Vol: 70,08%
(!) accomplish only from lowering down volume from above 70,08% from volume below 70,08% no activation

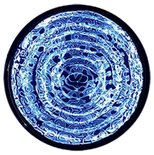
Combined
MIDI 24/40/55
C1/E2/G3
32,703/82,407/196,000 Hz
Vol: 71,65%

Combined
MIDI 24/40/55
C1/E2/G3
32,703/82,407/196,000 Hz
Vol: 90,55%

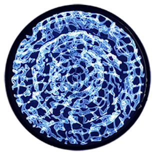
MIDI 12 C0
16,351 Hz



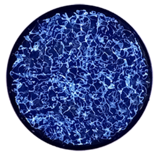
MIDI 12 C0 (A)
16,351 Hz
Vol: 88,98%



Transition (A-B)
MIDI 12 C0
16,351 Hz
Vol: 91,34%

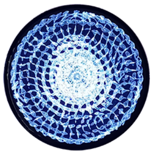


MIDI 12 C0 (B)
16,351 Hz
Vol: 91,34%

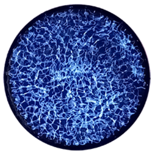


MIDI 12 C0
16,351 Hz
Vol 100%

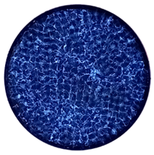
MIDI 28 E1
41,203 Hz



MIDI 28 E1
41,203 Hz
Vol: 62,99%



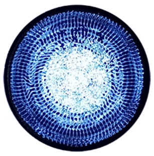
MIDI 28 E1
41,203 Hz
Vol: 66,14%



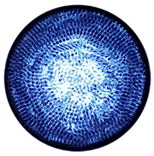
MIDI 28 E1
41,203 Hz
Vol: 70,87%

MIDI 43 G2
97,999 Hz

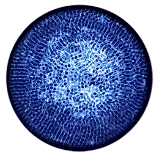
MIDI 43 G2
97,999 Hz
Vol: 84,25%



MIDI 43 G2
97,999 Hz
Vol: 88,19%

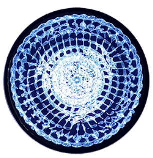


MIDI 43 G2
97,999 Hz
Vol: 92,13%

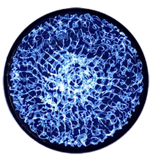


MIDI 43 G2
97,999 Hz
Vol: 100%

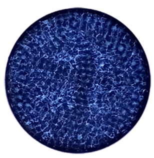
Combined
MIDI 12/28/43
C0/E1/G2
16,351 Hz
41,203 Hz
97,999 Hz



Combined
MIDI 12/28/43
C0/E1/G2
16,351/41,203/97,999 Hz
Vol: 71,65%



Combined
MIDI 12/28/43
C0/E1/G2
16,351/41,203/97,999 Hz
Vol: 74,80%

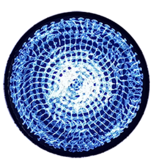


Combined
MIDI 12/28/43
C0/E1/G2
16,351/41,203/97,999 Hz
Vol: 80,31%

MIDI 14 D0
18,354 Hz

MIDI 14 D0
18,354 Hz
Vol: 88,19%

MIDI 33 A1
55,000 Hz

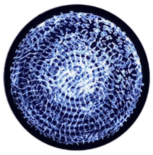


MIDI 33 A1
55,000 Hz
Vol: 58,27%

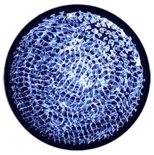
MIDI 52 E3
164,81 Hz

MIDI 52 E3
164,81 Hz
Vol: 100%

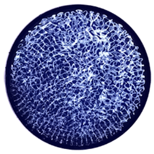
Combined
MIDI 14/33/52
D0/A1/E3
18,354 Hz
55,000 Hz
164,81 Hz



Combined
MIDI 14/33/52
D0/A1/E3
18,354/55,000/164,81 Hz
Vol: 75,59%



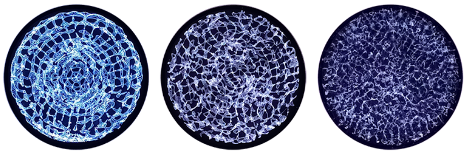
Combined
MIDI 14/33/52
D0/A1/E3
18,354/55,000/164,81 Hz
Vol: 77,17%



Combined
MIDI 14/33/52
D0/A1/E3
18,354/55,000/164,81 Hz
Vol: 81,10%

Concept 2: Making Chords

MIDI 26 D1
36,708 Hz

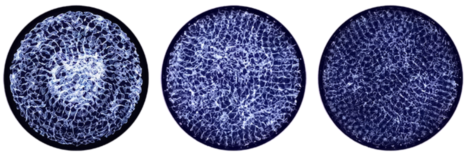


MIDI 26 D1
36,708 Hz
Vol: 70,87%

MIDI 26 D1
36,708 Hz
Vol: 72,44%

MIDI 26 D1
36,708 Hz
Vol: 75,59%

MIDI 30 F#1
46,249 Hz

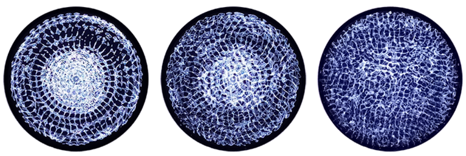


MIDI 30 F#1
46,249 Hz
Vol: 66,93%

MIDI 30 F#1
46,249 Hz
Vol: 70,87%

MIDI 30 F#1
46,249 Hz
Vol: 77,95%

MIDI 33 A1
55,000 Hz

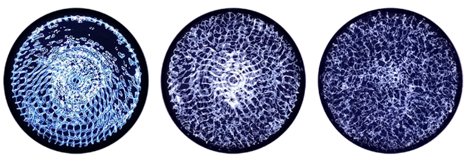


MIDI 33 A1
55,000 Hz
Vol: 61,42%

MIDI 33 A1
55,000 Hz
Vol: 66,14%

MIDI 33 A1
55,000 Hz
Vol: 74,02%

D-major
MIDI 26/30/33
D1/F#1/A1
36,708 Hz
46,249 Hz
55,000 Hz

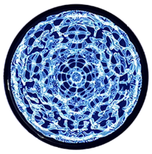


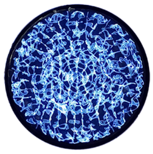
D-major
MIDI 26/30/33
D1/F#1/A1
36,708/46,249/55,000 Hz
Vol: 68,50%

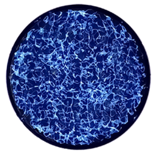
D-major
MIDI 26/30/33
D1/F#1/A1
36,708/46,249/55,000 Hz
Vol: 71,65%

D-major
MIDI 26/30/33
D1/F#1/A1
36,708/46,249/55,000 Hz
Vol: 77,95%

MIDI 24 C1
32,703 Hz

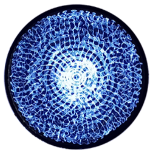

MIDI 24 C1
32,703 Hz
Vol: 64,57%

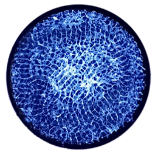

MIDI 24 C1
32,703 Hz
Vol: 66,93%


MIDI 24 C1
32,703 Hz
Vol: 71,65%

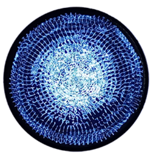
MIDI 35 B1
61,735 Hz


MIDI 35 B1
61,735 Hz
Vol: 58,27%

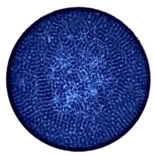

MIDI 35 B1
61,735 Hz
Vol: 62,99%


MIDI 35 B1
61,735 Hz
Vol: 66,93%

MIDI 41 F2
87,307 Hz

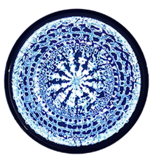

MIDI 41 F2
87,307 Hz
Vol: 75,59%

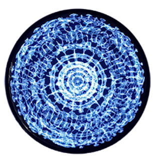

MIDI 41 F2
87,307 Hz
Vol: 81,10%

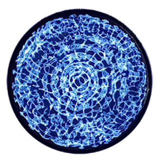

MIDI 41 F2
87,307 Hz
Vol: 91,34%

Combined
MIDI 24/35/41
C1/B1/F2
32,703 Hz
61,735 Hz
87,307 Hz


Combined (A)
MIDI 24/35/41
C1/B1/F2
32,703/61,735/87,307 Hz
Vol: 63,78%


Transition (A-B)
Combined
MIDI 24/35/41
C1/B1/F2
32,703/61,735/87,307 Hz
Vol: 66,93%

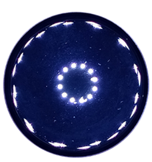

Combined (B)
MIDI 24/35/41
C1/B1/F2
32,703/61,735/87,307 Hz
Vol: 71,65%


Combined
MIDI 24/35/41
C1/B1/F2
32,703/61,735/87,307 Hz
Vol: 73,23%

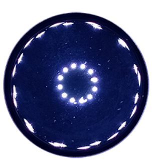
MIDI 46 A#2
116,54 Hz


MIDI 46 A#2
116,54 Hz
Vol: 100%

MIDI 50 D3
146,83 Hz


MIDI 50 D3
146,83 Hz
Vol: 100%

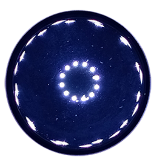
MIDI 53 F3
178,61 Hz


MIDI 53 F3
174,61 Hz
Vol: 100%

MIDI 48 C3
130,81 Hz

MIDI 52 E3
164,81 Hz

MIDI 55 G3
196,00 Hz

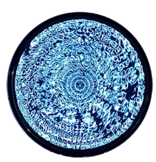

MIDI 48 C3
130,81 Hz
Vol: 100%

MIDI 52 E3
164,81 Hz
Vol: 100%

MIDI 55 G3
196,00 Hz
Vol: 100%

C-major
MIDI 48/52/55
C3/E3/G3
130,81 Hz
164,81 Hz
196,00 Hz


Dynamic A-B (A)
C-major
MIDI 48/52/55
C3/E3/G3
130,81/164,81/196,00 Hz
Vol: 106,3%


Dynamic A-B (B)
C-major
MIDI 48/52/55
C3/E3/G3
130,81/164,81/196,00 Hz
Vol: 106,3%

MIDI 53 F3
174,61 Hz

MIDI 56 G#3
207,65 Hz

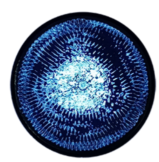
MIDI 60 C4
261,60 Hz


MIDI 53 F3
174,61 Hz
Vol: 100%

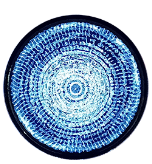
MIDI 56 G#3
207,65 Hz
Vol: 100%

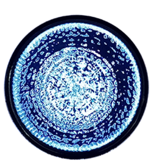
MIDI 60 C4
261,60 Hz
Vol: 100%

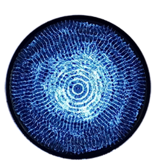
Combined
MIDI 53/56/60
F3/G#3/C4
174,61 Hz
207,65 Hz
261,60 Hz


Combined
MIDI 53/56/60
F3/G#3/C4
174,61/207,65/261,60 Hz
Vol: 105,5%

A#-major
MIDI 46/50/53
A#3/D3/F3
116,54 Hz
146,83 Hz
178,61 Hz

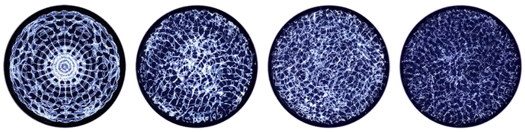

Dynamic A-B-C (A)
A#-major
MIDI 46/50/53
A#3/D3/F3
116,54/146,83/164,81 Hz
Vol: 103,1%


Dynamic A-B-C (B)
A#-major
MIDI 46/50/53
A#3/D3/F3
116,54/146,83/164,81 Hz
Vol: 103,1%


Dynamic A-B-C (C)
A#-major
MIDI 46/50/53
A#3/D3/F3
116,54/146,83/164,81 Hz
Vol: 103,1%

Concept 3: Rotary Frequency Dial

12,0 Hz



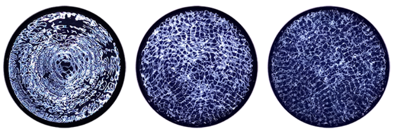
12,0 Hz
Vol: 79,53%

12,0 Hz
Vol: 83,46%

12,0 Hz
Vol: 85,83%

12,0 Hz
Vol: 90,55%

24,0 Hz

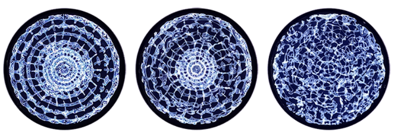


24,0 Hz
Vol: 83,46%

24,0 Hz
Vol: 85,04%

24,0 Hz
Vol: 87,40%

28,0 Hz

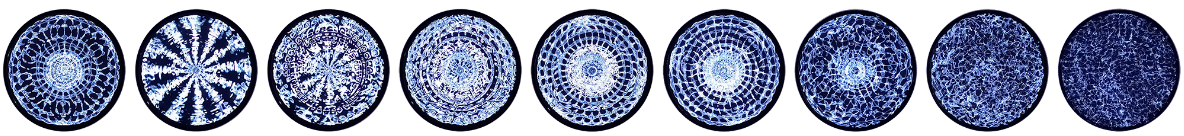


28,0 Hz
Vol: 71,65%

28,0 Hz
Vol: 72,44%

28,0 Hz
Vol: 73,23%

**Combined
12,0 Hz
22,0 Hz
28,0 Hz**



Combined (E)
12,0/22,0/28,0 Hz
Vol: 74,02%

Transition (A) (A-B-C-D-E)
Combined
12,0/22,0/28,0 Hz
Vol: 74,02%

Transition (B) (A-B-C-D-E)
Combined
12,0/22,0/28,0 Hz
Vol: 74,02%

Transition (C) (A-B-C-D-E)
Combined
12,0/22,0/28,0 Hz
Vol: 74,02%

Transition (D) (A-B-C-D-E)
Combined
12,0/22,0/28,0 Hz
Vol: 74,02%

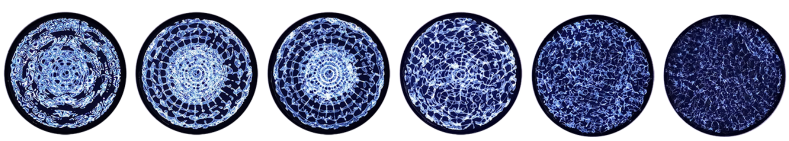
Transition (E) (A-B-C-D-E)
Combined
12,0/22,0/28,0 Hz
Vol: 74,02%

Combined
12,0/22,0/28,0 Hz
Vol: 77,17%

Combined
12,0/22,0/28,0 Hz
Vol: 79,53%

Combined
12,0/22,0/28,0 Hz
Vol: 84,25%

30,0 Hz



Transition (A) (A-B)
30,0 Hz
Vol: 67,72%

30,0 Hz (B)
Vol: 67,72%

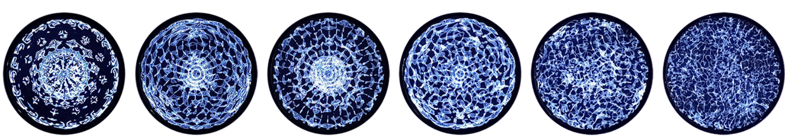
30,0 Hz
Vol: 68,50%

30,0 Hz
Vol: 69,29%

30,0 Hz
Vol: 71,65%

30,0 Hz
Vol: 78,74%

32,0 Hz



32,0 Hz
Vol: 62,99%

32,0 Hz
Vol: 64,57%

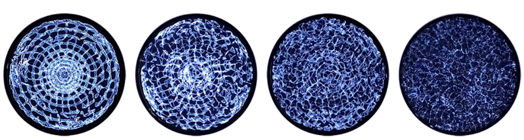
Dynamic A-B (A)
32,0 Hz
Vol: 65,35%

Dynamic A-B (B)
32,0 Hz
Vol: 65,35%

32,0 Hz
Vol: 67,72%

32,0 Hz
Vol: 71,65%

33,0 Hz



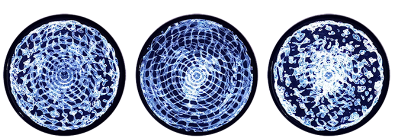
33,0 Hz
Vol: 64,57%

33,0 Hz
Vol: 67,72%

33,0 Hz
Vol: 69,29%

33,0 Hz
Vol: 77,17%

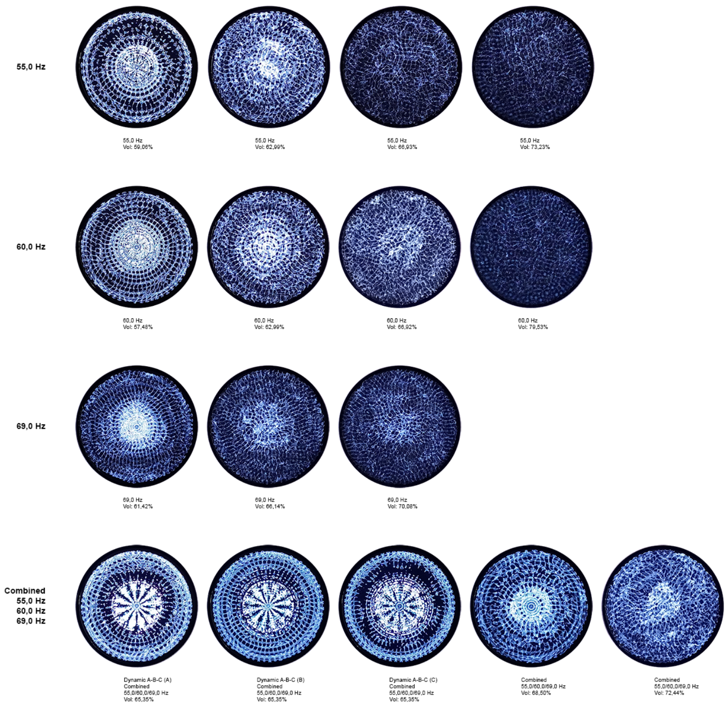
**Combined
30,0 Hz
32,0 Hz
33,0 Hz**

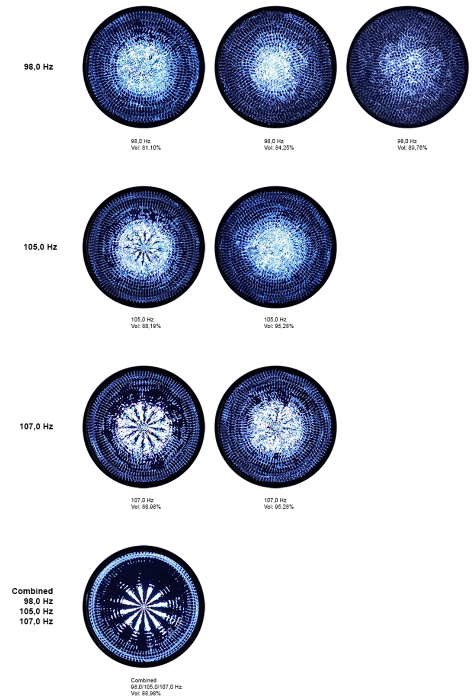


Dynamic A-B-C (A)
Combined
30,0/32,0/33,0 Hz
Vol: 73,23%

Dynamic A-B-C (B)
Combined
30,0/32,0/33,0 Hz
Vol: 73,23%

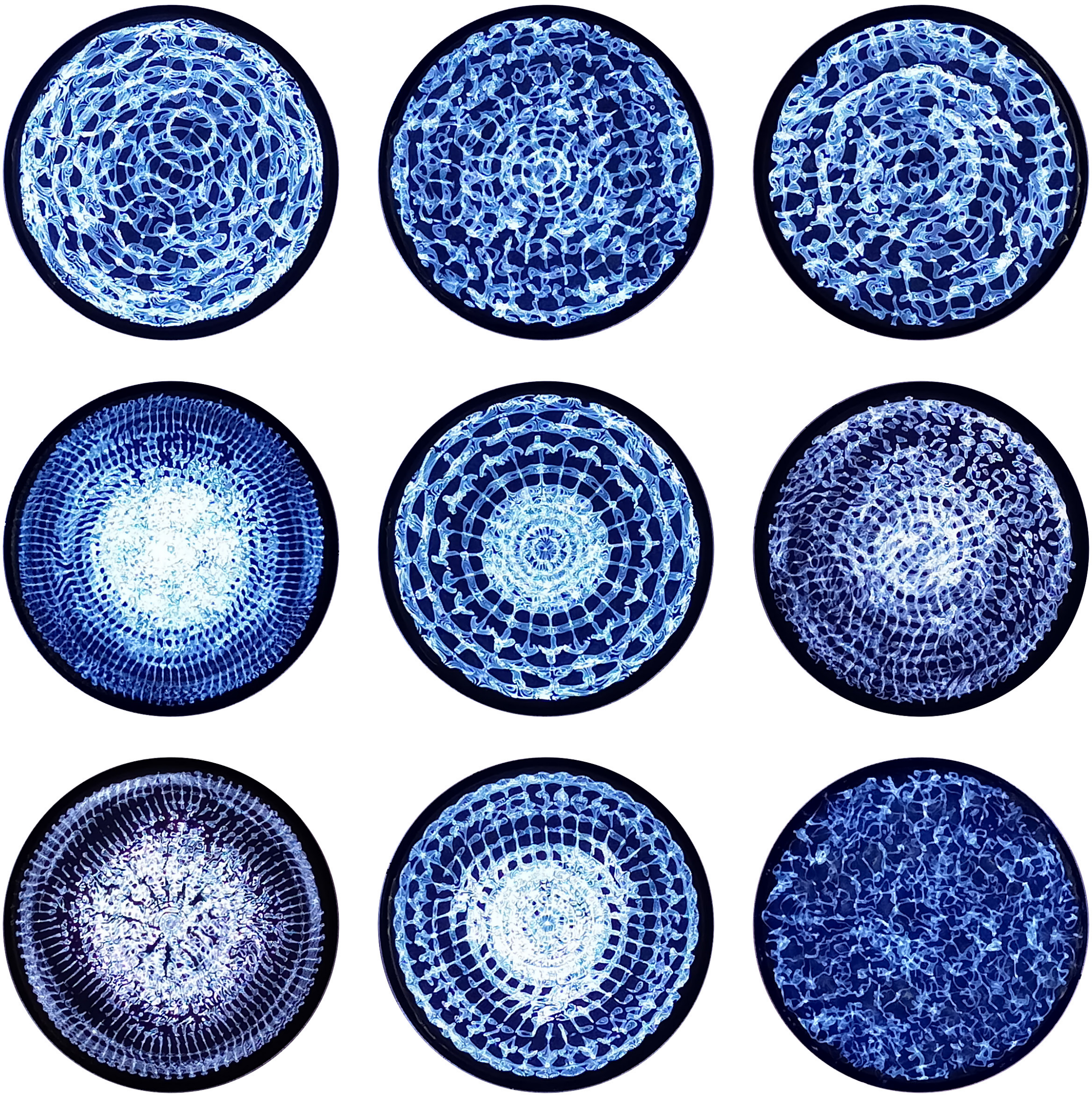
Dynamic A-B-C (C)
Combined
30,0/32,0/33,0 Hz
Vol: 73,23%

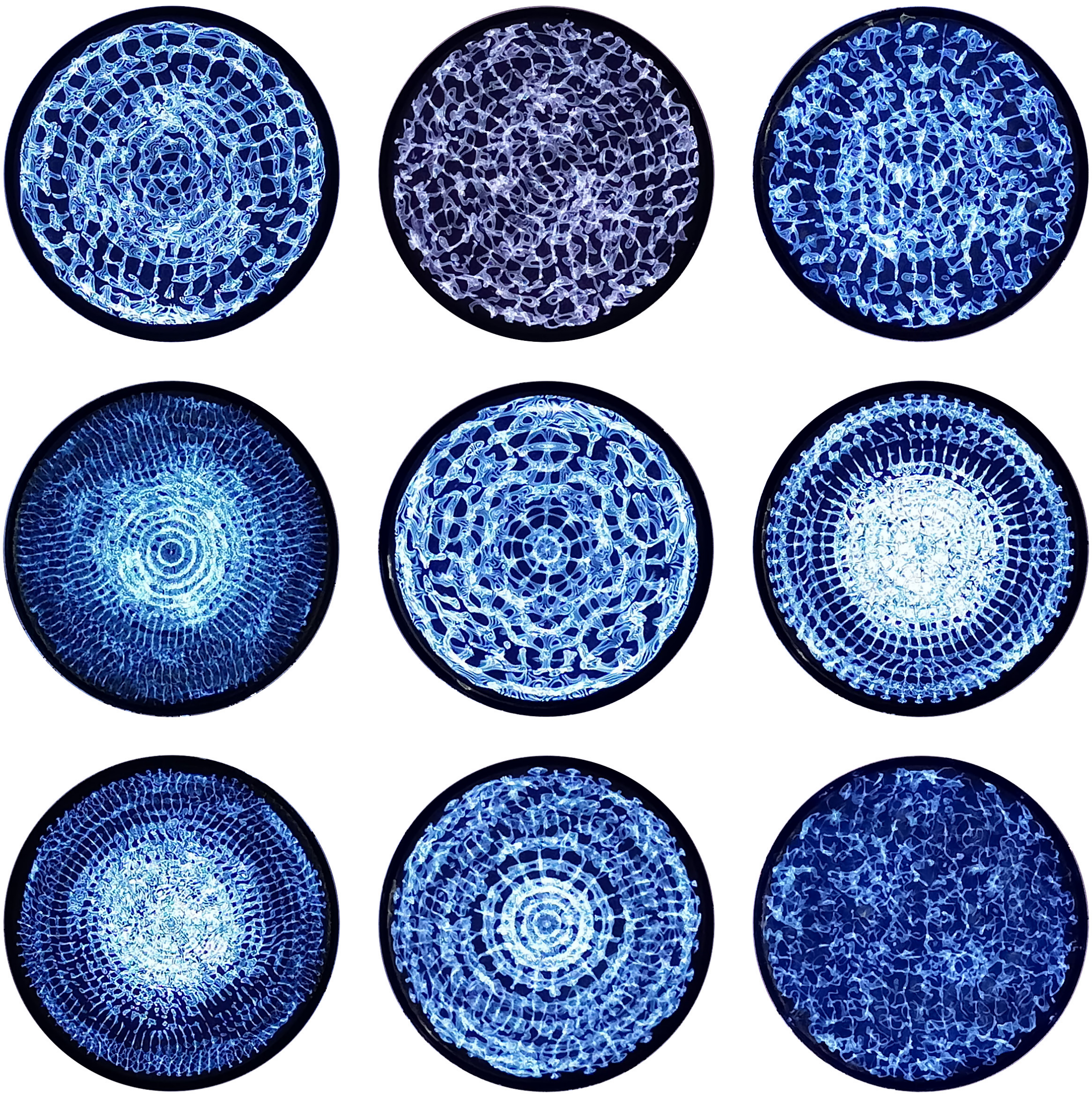

55,0 Hz
55,0 Hz
Vol: 59,06%
55,0 Hz
Vol: 62,99%
55,0 Hz
Vol: 66,93%
55,0 Hz
Vol: 73,23%
60,0 Hz
60,0 Hz
Vol: 57,48%
60,0 Hz
Vol: 62,99%
60,0 Hz
Vol: 66,92%
60,0 Hz
Vol: 79,53%
69,0 Hz
69,0 Hz
Vol: 61,42%
69,0 Hz
Vol: 66,14%
69,0 Hz
Vol: 70,08%
Combined
55,0 Hz
60,0 Hz
69,0 Hz
Dynamic A-B-C (A)
Combined
55,0/60,0/69,0 Hz
Vol: 65,35%
Dynamic A-B-C (B)
Combined
55,0/60,0/69,0 Hz
Vol: 65,35%
Dynamic A-B-C (C)
Combined
55,0/60,0/69,0 Hz
Vol: 65,35%
Combined
55,0/60,0/69,0 Hz
Vol: 68,50%
Combined
55,0/60,0/69,0 Hz
Vol: 72,44%

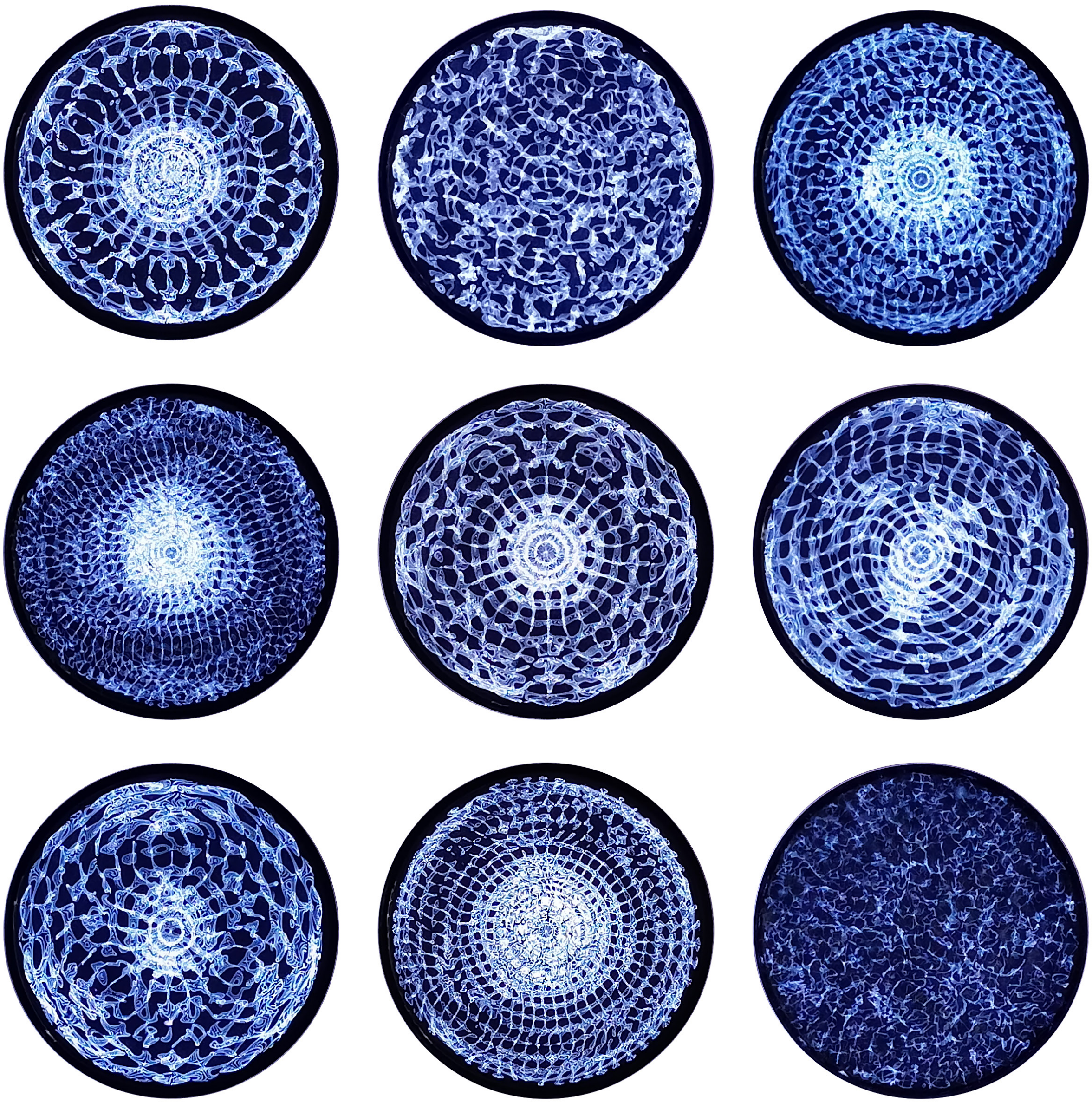

98,0 Hz
98,0 Hz
Vol: 81,10%
98,0 Hz
Vol: 84,25%
98,0 Hz
Vol: 89,76%
105,0 Hz
105,0 Hz
Vol: 88,19%
105,0 Hz
Vol: 95,28%
107,0 Hz
107,0 Hz
Vol: 88,98%
107,0 Hz
Vol: 95,28%
Combined
98,0 Hz
105,0 Hz
107,0 Hz
Combined
98,0/105,0/107,0 Hz
Vol: 88,98%

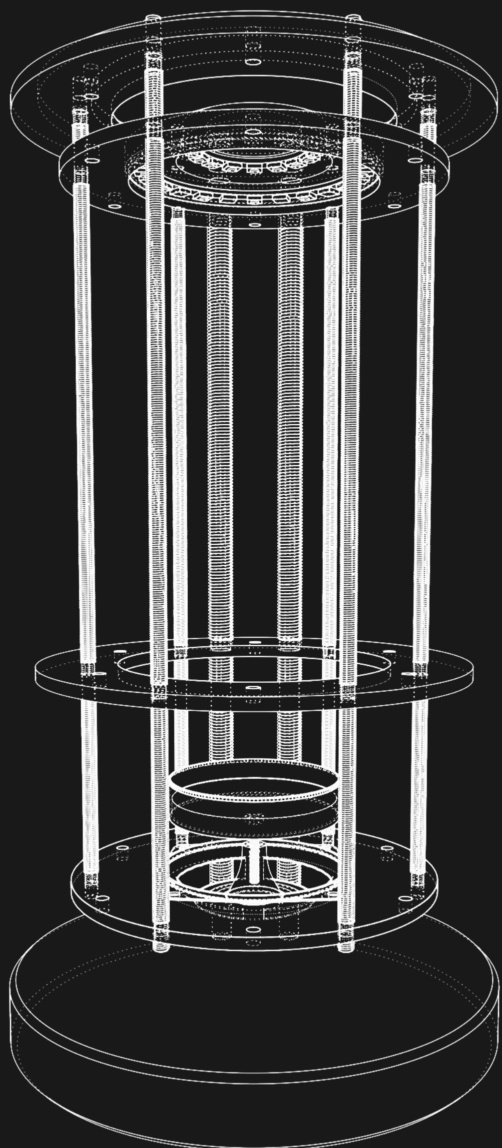
Appendix F: Three Sets of Eigenmodes per Concept

The following three sets were used assembled from the eigenmode producing quality examination to test the eigenmode producing quality of the concepts during the concept user test. Showing set A, B, C respectively.









GRADUATION REPORT - MARTIJN WEBER

INDUSTRIAL DESIGN ENGINEERING TU DELFT

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