# THE PUZZLE OF ELECTROCHROMISM

## DEMONSTRATING THE OPPORTUNITIES OF EC MATERIALS IN PRODUCT DESIGN.

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# EXECUTIVE SUMMARY

Electrochromic materials exhibit a reversible color change that is triggered by an applied voltage. Controlled color change, low voltage operation and the memory effect are three unique material properties defining electrochromic materials. As a result of an electron transfer or redox reaction, the material is able to switch between its bleached (transparent) and colored state. As this color change is a chemical reaction, it only requires an applied voltage to trigger and complete the electron transfer, thus afterwards the applied potential can be removed and the material will stay in its current state; i.e. the memory effect.

Electrochromic materials are processed into a sandwich structure of thin layers that enable it to change color when a voltage is applied to it; i.e. an electrochromic device (ECD). An ECD operates through two electrodes that are connected to both the positive and negative of the voltage-source, and the two electrochromic layers. These electrochromic layers are separated by an electrolyte, that allows ion transfer, enabling change of color. Optimizing this layer structure, results into the definition of four stacking sequences, based on their vertical or co-planar stacking sequence (i.e. vertical stacking of the EC layers or merging of both EC layers in the same layer with separated electrodes) combined with the substrate used; conductive and insulating. These four stacking sequences are characterized on their transparency, shape/pattern changing abilities, coloring, design of the images displayed and interaction between the two EC layers; i.e. technical characterization.

As result of this material characterization, 'the puzzle of electrochromism' is designed. 'The puzzle of electrochromism is an edge-matching puzzle, with as goal to puzzle four geometric shapes by matching the sides of the adjacent puzzle pieces. Solving this puzzle communicates the goal of the demonstrator (i.e. the technical and experiential characterizations) to the puzzler, while emphasizing the simplicity and possibilities of integrating electrochromic materials in design. The ultimate goal is to inspire the puzzle to make use of electrochromic materials in their product designs, through exiting creativity and curiosity.

When a puzzle piece is connected to the framework, a closed loop circuit is created between the voltage source and the coin cell battery, thus the puzzle piece will change its color. When the polarity is reversed (i.e. the puzzle piece is turned 180 degrees within the horizontal plane), it immediately switches from its primary EC layer to its secondary EC layer or vice versa. All primary EC layers will form the first puzzle to be created and all secondary EC layers the secondary puzzle. Meaning, 'the puzzle of electrochromism' is not just one puzzle, but includes two different puzzles. Besides the controlled color change, the other unique material properties it demonstrates are: low voltage operation, memory effect, simplicity and transparency. All individual puzzle pieces represent a different stacking sequence, through which the shape/pattern change (i.e. single and double image display), coloring (i.e. immediate and color flow), design of the images displayed (i.e. isolated and linked) and interaction between the two EC layers (i.e. overlap, connection and separation) are demonstrated.

In the end, 'the puzzle of electrochromism' is a demonstrator making electrochromism easy understood, explainable and approachable for designers to use within their product designs; i.e. the aim of this thesis. On top of this, it is not only a good demonstrator but also a good puzzle according to the ten puzzle principles of Shell (2008).

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# PREFACE

I believe it is fascinating to see what a designer can accomplish when choosing the right material for its (product) design. As the chosen material both contributes to its technical properties but also the aesthetics and interaction, resulting into interesting opportunities and challenges within the manufacturing. In the end, a design should be optimized for both; use and production.

In my opinion, materials are under-exposed within both the bachelor and master of Industrial Design Engineering at the TU Delft, so I wanted to graduate on a project that is based on materials. To turn it around, start with the material and create the right design for it. Figure out what problems or opportunities the material can contribute to instead of starting with a problem or opportunity to be solved through (a product) design. The Material Driven Design approach, is a perfect match to what I envisioned, as the material is the core of this method. It focusses on exploring what the material is, does, expresses, elicits and makes. This will both meet my interest for materials and it challenges myself to become a kind of expert within an unknown subject; i.e. electrochromic materials.

Within the past six months, I've researched and explored all possibilities imaginable within electrochromic materials (materials that change color, triggered by an applied voltage) in the chemical lab at the Faculty of Industrial Design Engineering at the TU Delft. In the end, this resulted into a product demonstrator that is both, demonstrating the working principle of electrochromism and a good puzzle; 'the puzzle of electrochromism'. Within this product demonstrator, two of my biggest interests unite, namely: 'materials' and 'design for children'/'game design'. The target group of the design is of course not children, still a very playful puzzle is designed: as you are never too old to play!

During this process, I've experienced a lot of support from both professionals and the people close to me. Thus I want to make use of this opportunity to thank everybody who supported me throughout this process. A special thanks to my supervisory team: Kaspar Jansen, Tessa Essers and Mascha Slingerland for their guidance, knowledge, fresh eyes and mainly enthusiasm.
I sincerely hope that everybody who reads this thesis and solves 'the puzzle of electrochromism', will become as enthusiastic as I am about the possibilities electrochromic materials offer to us -designers. So, thank you for taking the time to read my thesis that finishes up my time at the faculty of Industrial Design Engineering at the TU Delft.
Most of all, enjoy and do not forget to also play with 'the puzzle of electrochromism' if you have the chance!

Resy Aarts

*Photo by Jasmijn Ponssen*

# TABLE OF CONTENTS


Glossary 10
Introduction 12

*UNDERSTANDING THE MATERIAL PHASE* *15*

Chapter 1: Electrochromism 16
1.1. Working principle of electrochromic materials 18
1.2. Material properties 20
Chapter 2: Electrochromic devices (ECDs) 22
2.1. Working principle 23
2.2. Optimizing the layer structure 28
2.3. Vertical and co-planar stacking sequences 30
2.4. Transmittance and reflectance operating ECDs 32
Chapter 3: 'Ynvisible electrochromic ink' 34
3.1. Conjugated conducting polymer 34
3.2. Unique material properties 34
3.3. 'Ynvisible electrolyte' 34
Chapter 4: Material tinkering phase 36
4.1. In general 37
4.2. Functioning ECD 39
4.3. Optimization of the layers 41
4.4. Experiment with effects 44
Chapter 5: Material benchmarking 50
Chapter 6: Material characterization 54
6.1. Technical characterization 55
6.2. Experiential characterization 58
Chapter 7: Material experience vision 60

*CREATING PRODUCT CONCEPTS PHASE* *63*

Chapter 8: Ideation 64
8.1. General ideation 65
8.2. Idea direction defenition 66
Chapter 9: Conceptualisation 68
9.1. Concept 1: Sliding puzzle 69
9.2. Concept 2: Jigsaw puzzle 69
9.3. Concept 3: Mosaic puzzle 69
9.4. Concept choice 69
Chapter 10: Proof of concept 74
10.1. Edge-matching puzzle 75
10.2. Closed loop circuit 75

*DEMONSTATOR: 'THE PUZZLE OF ELECTROCHROMISM'* *77*

Chapter 11: A puzzle as demonstrator 80
11.1. Unique material properties 81
11.2. Technical characterization 84
Chapter 12: User scenario 88
Chapter 13: A good puzzle 90
13.1. Edge matching puzzle 91
13.2. Ten puzzle principles 91
Chapter 14: Inspire other designers 94
Chapter 15: Implementation within design 96

*EVALUATION* *99*

Discussion 100
Sources 104

*APPENDICES* *107*

Appendix A: Project brief 108
Appendix B: Material driven design method 112
Appendix C: QR-codes and URL 114
Appendix D: Current applications 116
Appendix E: Production methods 120
E.1. Standard vertical ECD 120
E.2. Standard Co-planar ECD 121
Appendix F: Production: screenprinting 122
Appendix G: Material of the ECDs 124
Appendix H: All ECDs created 126
H.1. Vertical displays 126
H.2. Co-planar displays 128
Appendix I: Optimization of the layers 130
Appendix J: User research #1: questions 140
Appendix K: User research #1: conclusion and analogies 146
Appendix L: Inspirational mind-maps 150
Appendix M: Idea generation: entertaining products 154
Appendix N: Idea generation: decorative products 156
Appendix O: Idea generation: educational products 158
Appendix P: Inspirational mind-map: puzzles 160
Appendix Q: Cost calculation: 'The puzzle of electrochromism' 161

# GLOSSARY

***Active area***: the area of the primary and secondary electrochromic layer that is covered by the electrolyte; i.e. the area that is possible to change its color.

***Anodic material***: a material that changes from its bleached to colored state when it is oxidized (i.e. electron release).

***Bleached state***: the state in which the electrochromic material is transparent.

***Bleaching***: the change of an electrochromic material from its colored to bleached (transparent) state.

***Cathodic material***: a material that changes from its bleached to colored state when it is reduced (i.e. electron uptake).

***Colored state***: the state in which an electrochromic material is colored.

***Coloring***: the change of an electrochromic material from its bleached (transparent) to colored state.

***Double image display***: an ECD that switches between two colored states; i.e. two images appear and disappear in turn.

***Electrochromism***: reversible color change of a material.

***Electron***: a negatively charged atomic particle, inside an atom. (Learning, 2012)

***Ion***: an atom or a molecule with a net electric charge (positive or negative) due to the loss or gain of one or more electrons. (Learning, 2012)

***Memory effect***: the idea that an electrochromic material only requires an applied potential in order to trigger the electron-transfer or redox reaction for coloration or bleaching; i.e. the potential can be removed after the material has changed its color and will stay in its current state.

***Single image display***: an ECD that only switches between one bleached and one colored state; i.e. one image appears and disappears.

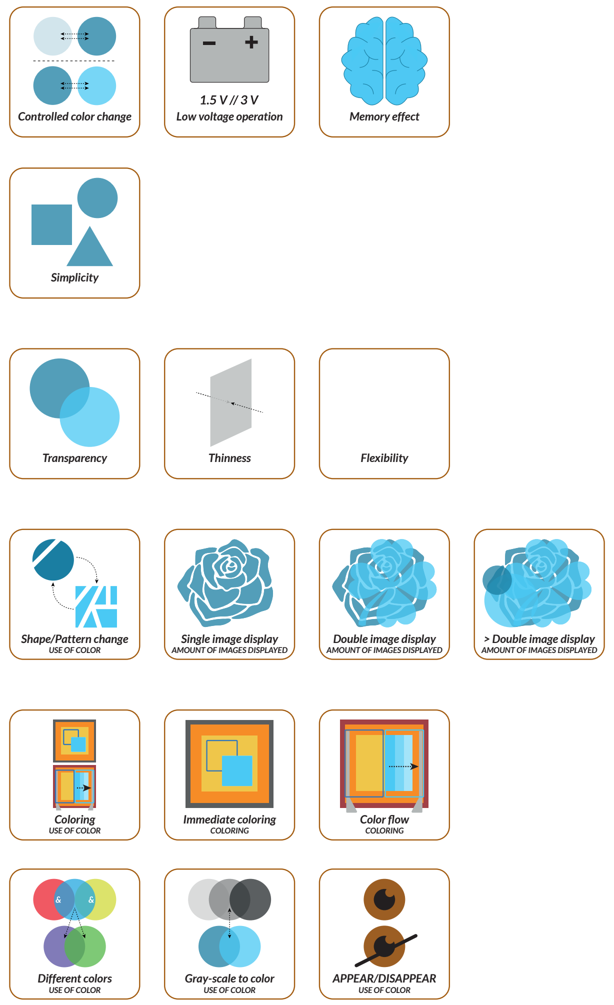
***Sky blue***: color of the Ynvisible electrochromic ink in its bleached state.

***Translucent blue***: color of the Ynvisible electrochromic ink in its colored state.

**LEGEND**

- *Insulating substrate/encapsulation*
- *Conductive substrate/encapsulation*
- *Electrode*
- *Primary electrochromic layer*
- *Secondary electrochromic layer*
- *Bi-adhesive spacer*
- *Electrolyte*

# GLOSSARY: ICONS




# INTRODUCTION

'The puzzle of electrochromism' is both, literal and figurative a puzzle about electrochromic materials (i.e. materials that exhibit electrochromism); something that is difficult to understand or explain, and a game (product demonstrator).

First of all, something that is difficult to understand or explain. Electrochromism is the phenomenon of a reversible color change in a material evoked by an applied voltage. Electrochromic materials are materials that exhibit electrochromism, enabled by the sandwich structure of thin layers it is processed in; electrochromic devices. Electrochromic devices facilitate the three unique properties that electrochromic materials are defined by: controlled color change, low voltage operation and memory effect. Besides these unique properties, this thesis will further explain and explore the technical and experiential properties of both the material and device. As these materials are relatively unknown (the only applications currently known are within glass windows and as rapid prototypes for displays, thus lots of opportunities are missed), ***the aim of this thesis is not only to make electrochromism easy understood and explainable, but also approachable for designers to use within their product designs.***
For this, the literal 'puzzle of electrochromism' is created. The 'puzzle of electrochromism' is a product demonstrator, demonstrating the working principle of electrochromic materials and their possibilities with the objective of inspiring designers to use these materials in their own designs.

## *MATERIAL DRIVEN DESIGN METHOD*

The methodology used within this thesis will be the Material Driven Design Method (MDDM) by Karana, Barati, Rognoli, & Zeeuw van der Laan (2015) (see appendix B). the material is the core of this method, as it explores what the material is, does, expresses, elicits and makes. First, it starts with the 'understanding the material phase'. Besides literature research, this phase also includes material benchmarking (position the material within a group of similar materials and their applications) and material tinkering (determine technical and experimental characterizations). At the end of the understanding the material phase, a material experience vision is drawn. A material experience vision is the "ultimate aim of the design process, which can help designers to summarize various findings under a cohesive shole and guide their decisions through the process of design" (Karana et al., 2015). This material experience vision is the start of the "creating product concepts" phase. Within this phase, ideas will be generated and eventually developed into concepts that meet the material experience vision. In the end, a product demonstrator is created that demonstrates the envisioned material experience.

## *MDDM WITHIN THIS THESIS*

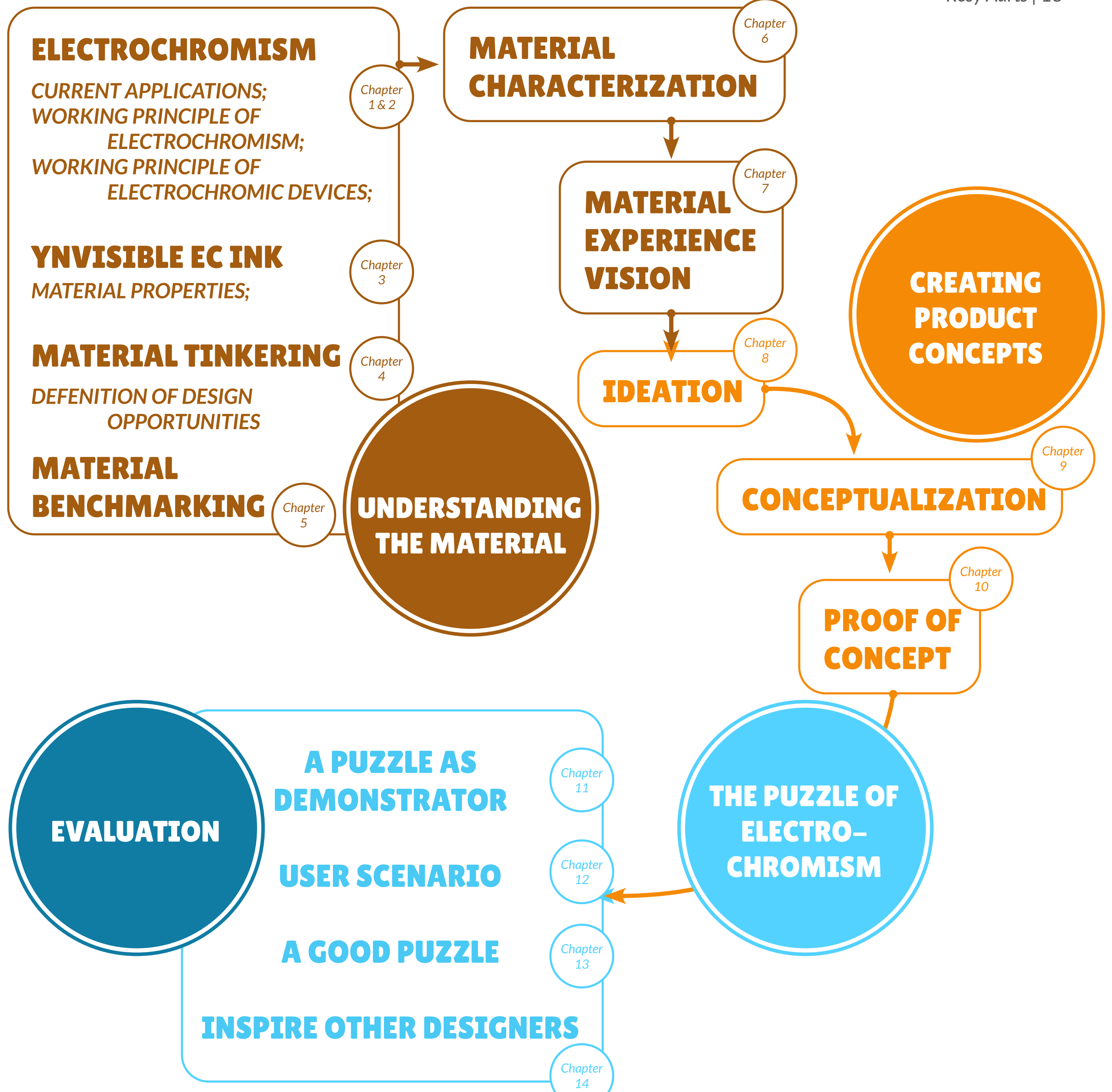
Starting with the 'understanding the material' phase. Within this thesis this phase consists of three parts: literature research, material tinkering and material benchmarking. The literature research can be further divided into the first three chapters of this thesis: 'Electrochromism (chapter 1)', 'Electrochromic devices (ECDs)' (2) and 'Ynvisible electrochromic ink' (3). Which explains the working principles of electrochromism and the corresponding electrochromic devices. On top of this, the electrochromic material used within this thesis ('Ynvisible electrochromic ink') will be further defined on its material properties. After this, with the knowledge gained from the literature research, a material tinkering phase is conducted (4). Within this phase, insights are created and design opportunities for use within product design are defined. Where finally a material benchmarking is performed. Eventually all these lead to the material characterization (6) of the 'Ynvisible electrochromic ink' and a material experience vision (7). The material experience vision will function as the starting point of the next phase: creating product concepts.

Secondly, within the 'creating product concepts' phase, ideas and concepts are created for a product demonstrator that demonstrates the material experience vision. First, ideas are generated within the ideation generation phase (chapter 8), after which three ideas are further developed into concepts (9), with finally the 'proof of concept' of the concept to be chosen (10).

After 'creating product concepts', the chosen concept is further developed into the 'puzzle of electrochromism': a product demonstrator that demonstrates the opportunities of EC materials in product design. It demonstrates both the unique material properties as well as the technical and experiential characterization of electrochromic materials, while emphasizing its simplicity and possibilities of integration in product design. With as ultimate goal to inspire designers to make use of electrochromic materials in their (product) designs. First, an overview of 'the puzzle of electrochromism' will be presented on a two-page overview. After this, the goal of the demonstrator will be explained and translated into the goal in the demonstrator (chapter 11). Within chapter 12, a user scenario of a puzzler solving 'the puzzle of electrochromism' is illustrated. Furthermore, there will be elaborated on the fact that 'the puzzle of electrochromism' is not only a good demonstrator, but also a good puzzle (13). With finally a brief explanation on the final part of the goal of the demonstrator, i.e. inspiring other designers through a small user research (14).

In the end, this thesis will be evaluated through a discussion.

Throughout this thesis, the text will be supported by QR-codes that link to videos uploaded on youtube.com, all corresponding .URLs can be found in appendix C. Besides this, icons will be used to characterize electrochromic materials in general and the 'Ynvisible electrochromic ink' specifically, an overview of these icons can be found together with the glossary on page 10 and 11.




*Structure of the Material Driven Design Method within this thesis.*

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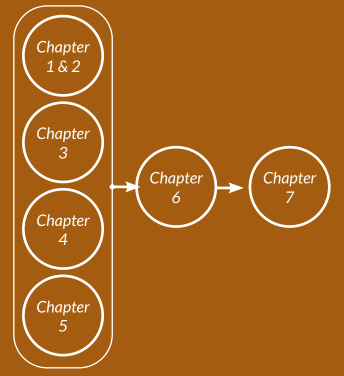
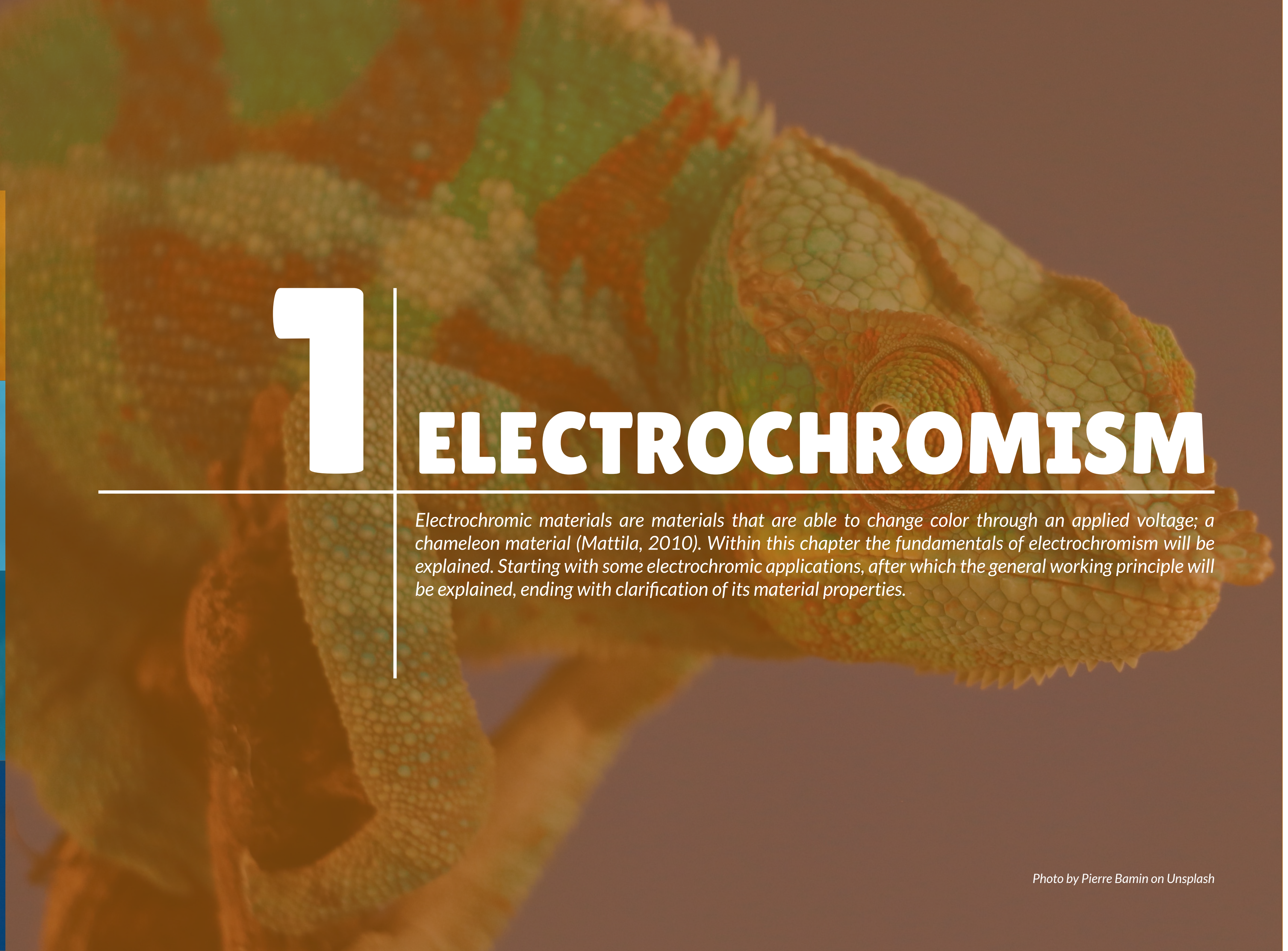
# UNDERSTANDING THE MATERIAL

*"In MMD, a designer is first expected to understand the material in hand and characterize it both technically and experientially, so as to articulate the material's unique role when applied in products." (Karana et al., 2015). Within this thesis, the understanding the material phase consists of three parts: literature research, material benchmarking and material tinkering phase.*

*First, after introducing electrochromism on the basis of some applications, the working principle of electrochromism (chapter 1) and corresponding electrochromic devices (2) will be explained through literature research. After this, the 'Ynvisible electrochromic ink' (the electrochromic material used within this thesis) will be further defined on its material properties (3). After the general understanding of electrochromism and electrochromic devices, a material tinkering phase is conducted (4). In this phase, insights are created and design opportunities for use within product design are defined. After which a material benchmarking is conducted (5). Eventually, all these lead to the material characterization (6) of the 'Ynvisible electrochromic ink' and a material experience vision (7). The material experience vision will function as the starting point of the next phase: creating product concepts.*




1. *Electrochromism*
2. *Electrochromic devices (ECDs)*
3. *'Ynvisible electrochromic ink'*
4. *Material tinkering Material*
5. *benchmarking*
6. *Material characterization*
7. *Material experience vision*



# 1 ELECTROCHROMISM

*Electrochromic materials are materials that are able to change color through an applied voltage; a chameleon material (Mattila, 2010). Within this chapter the fundamentals of electrochromism will be explained. Starting with some electrochromic applications, after which the general working principle will be explained, ending with clarification of its material properties.*

*Photo by Pierre Bamin on Unsplash*



*Figure 1.1: Chromogenics.*

*QR-code 1: SageGlass: Glass that tints on demand*

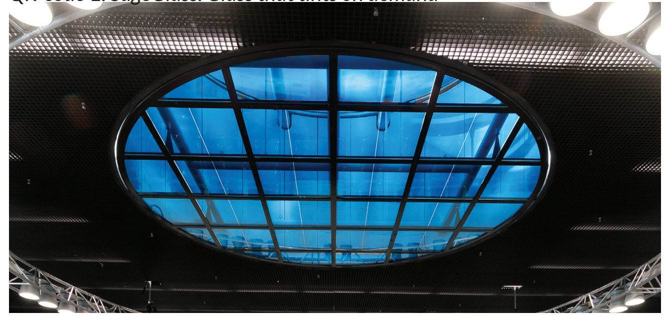


*Figure 1.2: SageGlass: Government center Utrecht. Copyright by SageGlass (2018)*

*Figure 1.3: Dimmable Aircraft Window. Copyright by GentexCorporation*

*Figure 1.4: Prototype manufacturing applications. Copyright by RdotDisplays (2021).*

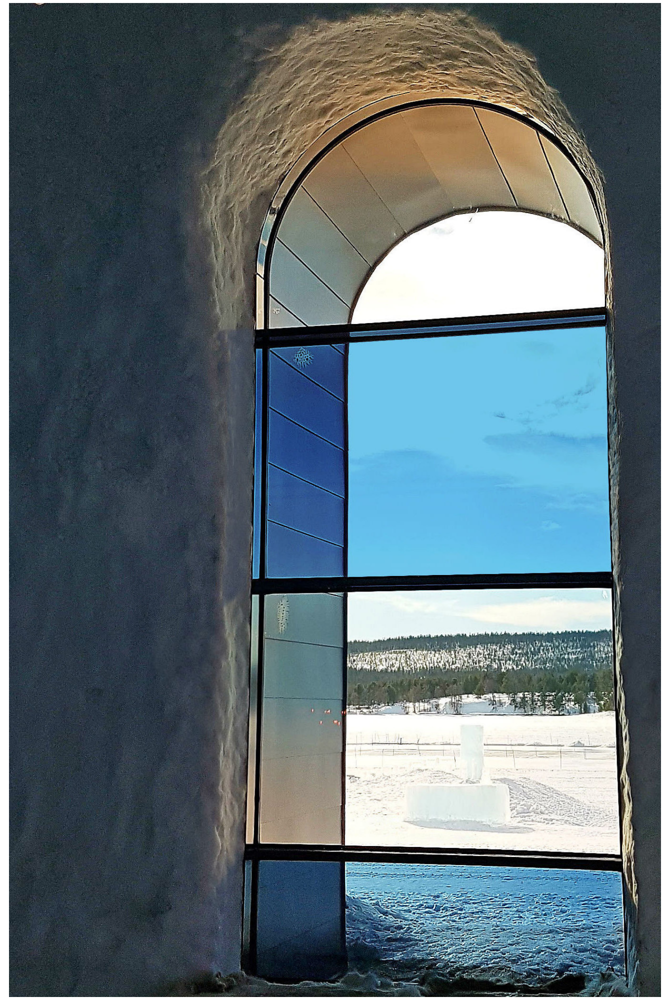


*Figure 1.5: Icehotel- Jukkasjärvi. Copyright by ChromoGenics (2021).*

Electrochromism is the phenomenon of a reversible color change in a material that is triggered by an applied voltage. As can be seen in figure 1.1 till 1.5, electrochromic materials are primarily implemented into glass; i.e. smart glass or smart windows. Besides this, a couple of applications within the automotive industry are known; i.e. self-darkening windows or anti-glare mirrors. On top of this, there are a couple of companies known that offer rapid prototypes using electrochromic materials. For further in-dept information about these applications, appendix D should be consulted. When analyzing the electrochromic phenomenon, three unique material properties can be defined: controlled color change, low voltage operation and memory effect, see figure 1.6. These three properties will be further explained within this chapter.

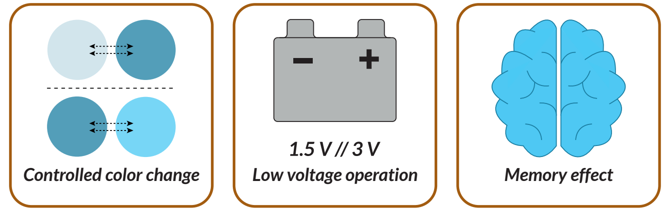



*Figure 1.6: Unique material properties of electrochromic materials.*

## 1.1. WORKING PRINCIPLE OF ELECTROCHROMIC MATERIALS

Electrochromism is a reversible change of color in a material evoked by the movement of electrical charges; i.e. an applied voltage. According to Monk et al. (1995), electrochromic materials are materials that are able to modify their ability to resonate with light of different wavelengths. As result of an electron transfer or redox reaction, in which the material undergoes reduction (uptake of an electron) or oxidation (release of an electron), the material can switch between a transparent (bleached) and colored state. Electrochromic materials are generally processed into sandwich structured ***electrochromic devices (ECDs)***, that enable the electrochromic material to change color when a voltage is applied to it. Electrochromic devices (ECDs) will be further explained in chapter 2.

Prior to explaining how this change of color exactly comes about, two commonly used terms should be classified: ions and electrons. An electron is a negatively charged atomic particle, inside an atom. And an ion is an atom or a molecule with a net electric charge (positive or negative) due to the loss or gain of one or more electrons. (Learning, 2012)

First of all, ***color***. The human eye is able to detect light in the range of 380-780 nm (i.e. visible light), which is perceived as color ("Wavelength to Colour Relationship," 2021). As can be seen in figure 1.7, different wavelengths translate to different colors. Within a molecular structure, the length of the chain over which the free double-bond electrons (pi-electrons) are able to move is directly related to this wavelength. Since complex organic molecules contain sequences containing double bonds over which electrons are able to travel (i.e. the length of the molecule chain), its color becomes visible to the human eye (Jansen, personal communication, January 1, 2021). In short, electrons that are moving over the length of the molecule chain, allows our eyes to register the corresponding color.

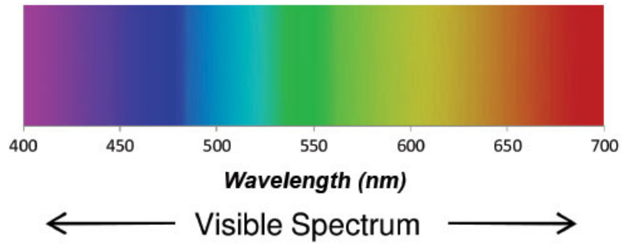
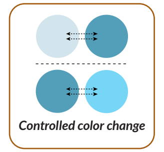


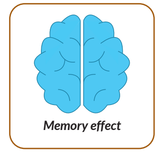

*Figure 1.7: Visible spectrum. Copyright by ORCA Grow Film, (2021)*



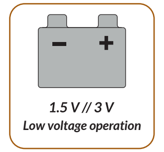

When translating this to the ***color change*** that occurs the following can be concluded: when the electrochromic material undergoes a redox reaction, ions are included into the molecule chain. The placement of these ions affects the resonance length and thus absorbs a different wavelength of light, resulting in a different color for the human eye to detect (Monk, Mortimer, & Rosseinsky, 1995)(Jansen, personal communication, December 4, 2020).



The color change of an electrochromic material occurs between the transparent (i.e. bleached) state and the colored state, see figure 1.8 (Mattila, 2010). The change from the bleached to the colored state will be referred to as ***coloring***, where from the colored state to the bleached state is ***bleaching***. As can be seen in the video (QR-code 2), the electrochromic material (square) changes from translucent blue to sky blue, triggered by the applied voltage.




As the color change of the material is induced by an electron transfer or redox reaction, a memory effect takes place. This memory effect implies that electrochromic materials only require an applied potential in order to trigger and succeed the electron-transfer or redox reaction. Meaning after the change of color (coloring or bleaching) is completed, the voltage can be removed and the coloration state of the material stays fixated. However, according to Monk et al. (1995), in practice the electrochromic device slowly decolors and regular small voltage pulses are required to maintain the current colored state; i.e. recharge.




Generally, the required voltage is between 1 and 5 V, the so called: low voltage operation, see figure 1.9. This voltage is according to Jensen et al. (2019) heavily influenced by the size of the electrochromic device, design of the image displayed and the EC material(s) used.

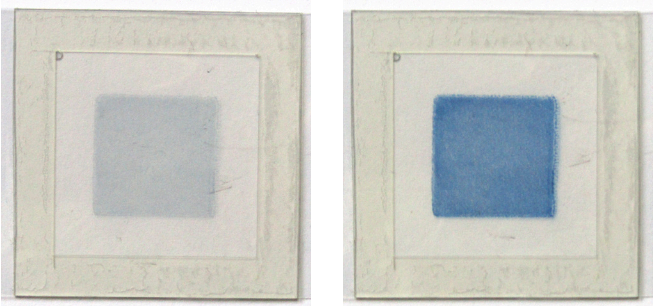


*Figure 1.8: Switching between the bleached and colored state: Bleached state (a, b) and colored state (c, d).*

*QR-code 2: Switching between the bleached and colored state.*

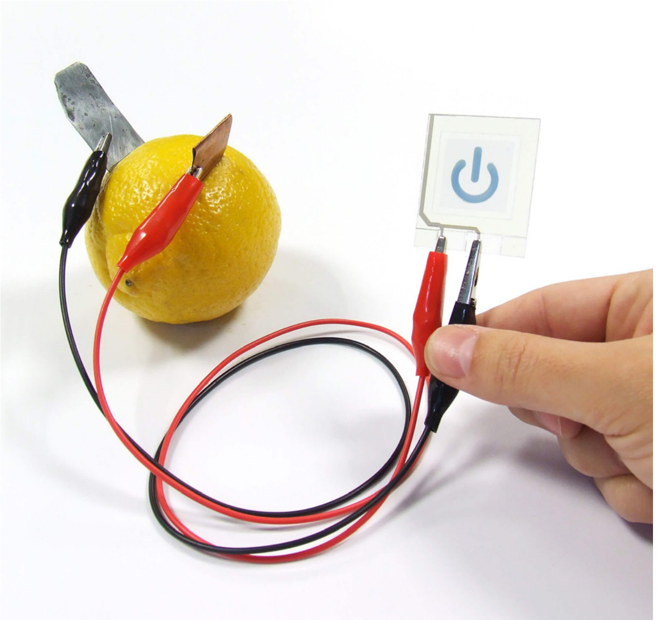


*Figure 1.9: Low voltage operation. Copyright by Ynvisible (2021)*

## 1.2. MATERIAL PROPERTIES

One of the most important material properties of electrochromic materials is the ***switching speed*** (i.e. ***response time***) of the material. This is the time required to change between bleaching and coloring, varying generally from milliseconds up to a few seconds (Monk et al., 1995). According to Monk (2007), the response time for bleaching does not equal the response time of coloring, as can be seen in the video of QR-code 2 (previous page) this time difference can be quite large. E.g. this specific electrochromic device (ECD) has a switching speed of 3.06 seconds for coloration and 0.12 seconds for bleaching. The switching speed affects are associated with the flow of ions in the electrolyte (ion transfer layer, see chapter 2.1) and thus, besides the specific EC material used, the switching speed is heavily influenced by the size of the ECD, the size of the image displayed, its film thickness, the ionic conductivity of the electrolyte and the magnitude of the applied potential. (Argun et al., 2004; Jensen, Colley, Hakkila, Pinheiro, & Lochtefeld, 2019).

The cyclability and optical memory of an electrochromic device (ECD) are properties that are not explicitly addressed within this thesis, but nevertheless important to address. First of all, the ***cyclability*** (***cycle life***) is the loss in optical contrast (%) after a number of coloration-bleaching cycles, generally reaching up to $10^6$ cycles (Somani & Radhakrishnan, 2003); i.e. its durability.

Secondly, the ***optical memory*** (***open circuit memory***) is the time an ECD stays in its colored or bleached state after the potential is removed. The higher the optical memory, the lower the energy consumption (Zhu et al., 2014).

Besides the cyclability and optical memory of an electrochromic device (ECD), contrast ratio, coloration efficiency and write-erase efficiency are device properties of electrochromic materials that are also not explicitly addressed with this thesis. The ***contrast ratio*** (***CR***) measures the intensity of color formed electrochemically as seen by the human eye. It should be as high as possible with a minimum of 3, as <3 is almost impossible to see by the human eye. (Scrosati, 1993).

***Coloration efficiency*** is the amount of optical density change induced as a function of the amount of charge needed during an electrochemical transition (Argun et al., 2004). And finally, the ***write-erase efficiency*** is the percentage of the originally formed coloration that can be electro-bleached and should approach 100% for a successful display (Scrosati, 1993).



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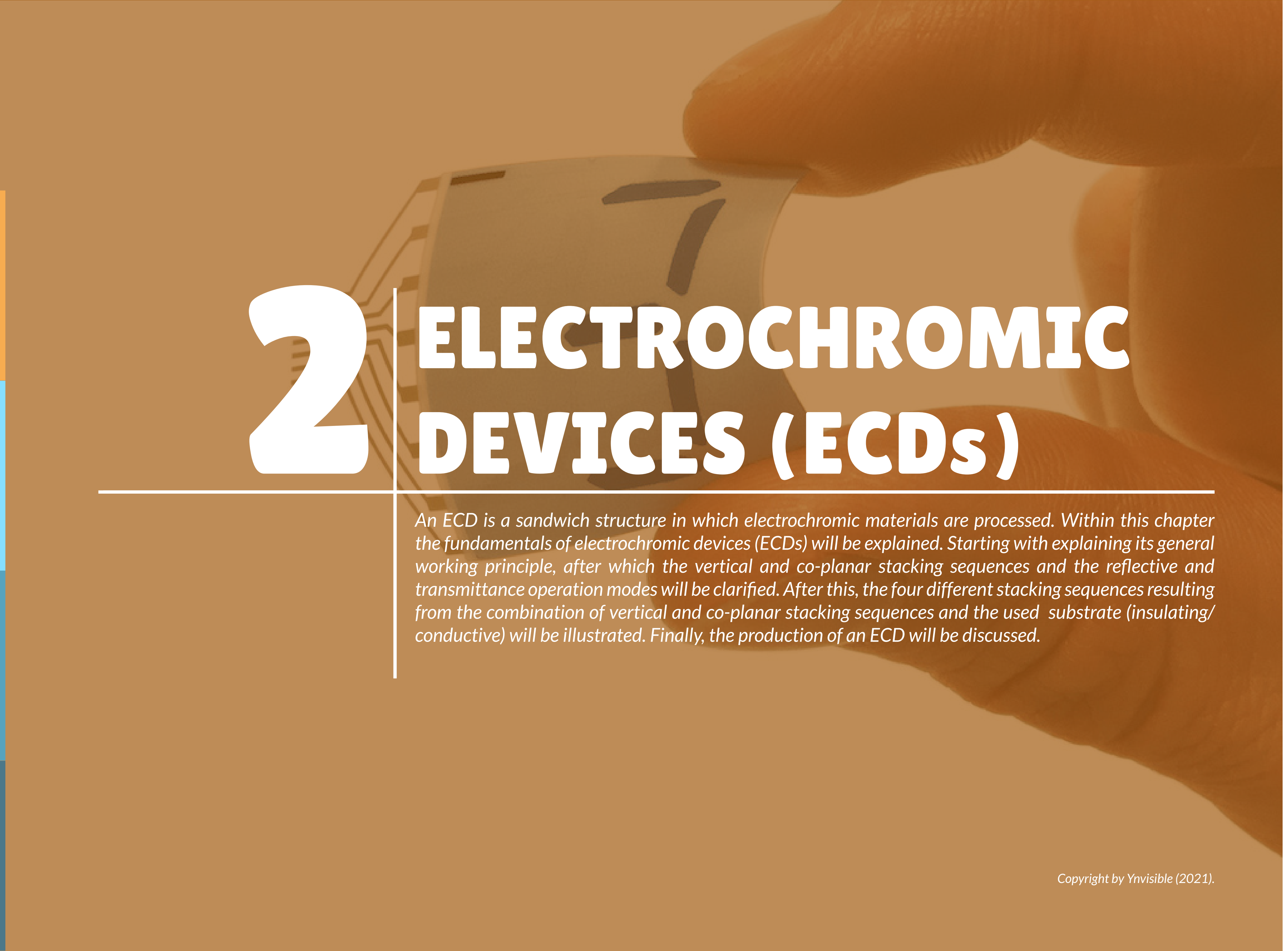

# 2 ELECTROCHROMIC DEVICES (ECDs)

*An ECD is a sandwich structure in which electrochromic materials are processed. Within this chapter the fundamentals of electrochromic devices (ECDs) will be explained. Starting with explaining its general working principle, after which the vertical and co-planar stacking sequences and the reflective and transmittance operation modes will be clarified. After this, the four different stacking sequences resulting from the combination of vertical and co-planar stacking sequences and the used substrate (insulating/ conductive) will be illustrated. Finally, the production of an ECD will be discussed.*

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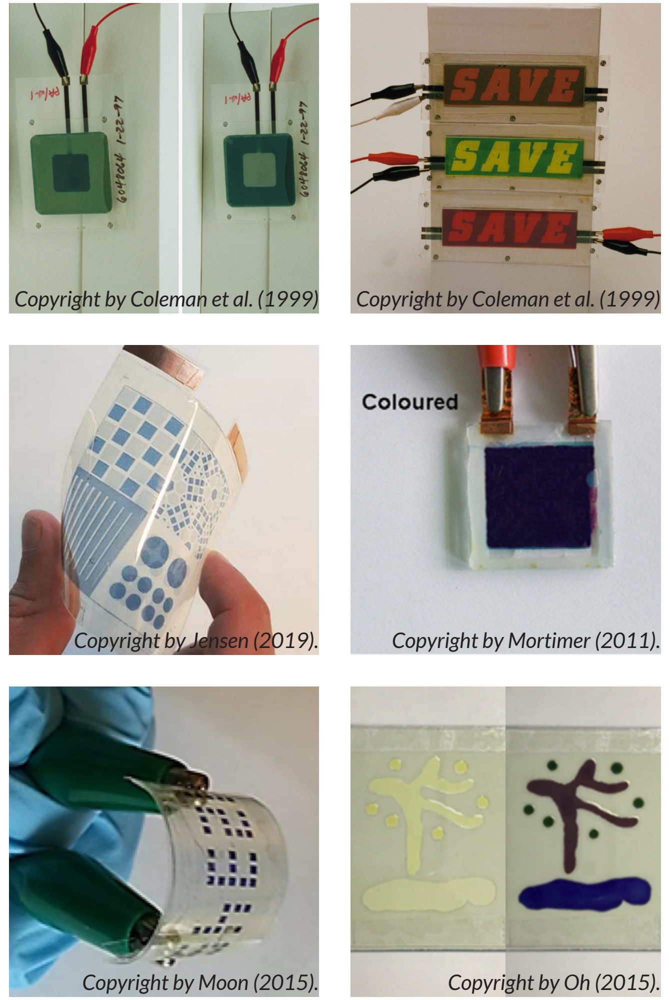
## 2.1. WORKING PRINCIPLE/ LAYERS

***An electrochromic device (ECD) is a sandwich structure of thin layers that enable the electrochromic material to change color when a voltage is applied to it.***

In figure 2.1, six examples of ECDs derived from literature are displayed. Scrosati (1993) defines it as an electrochemical battery where the cyclable energy output is revealed by a color change. This is a reasonable comparison, as both (batteries and ECDs) store and release electrical charges, where an ECD changes color when absorbing or desorbing a charged particle (Jansen, personal communication, January 1, 2021).

*Thinness* and *flexibility*, characterize electrochromic materials further; i.e. device properties. An ECD has the possibility to be thin. The thinnest ECD created within this research was of 0.48 mm (figure 2.2) and the "world's thinnest electrochromic display", on the other hand, has a thickness of about a quarter of a millimeter through comprising a pair of glass sheets into an e-reader prototype, see figure 2.3 (Mandal, 2021). This thinness creates highly flexible ECDs, see figure 2.1-c.

In general, ECDs are produced by means of screen printing, resulting into the identification of five steps: preparation, conductive layer, electrochromic layer, electrolyte and finishing. For in detail information about the production, appendices E and F should be consulted.




Copyright by Coleman et al. (1999). Copyright by Coleman et al. (1999). Copyright by Jensen (2019). Copyright by Mortimer (2011). Copyright by Moon (2015). Copyright by Oh (2015).

*Figure 2.1: ECDs.*

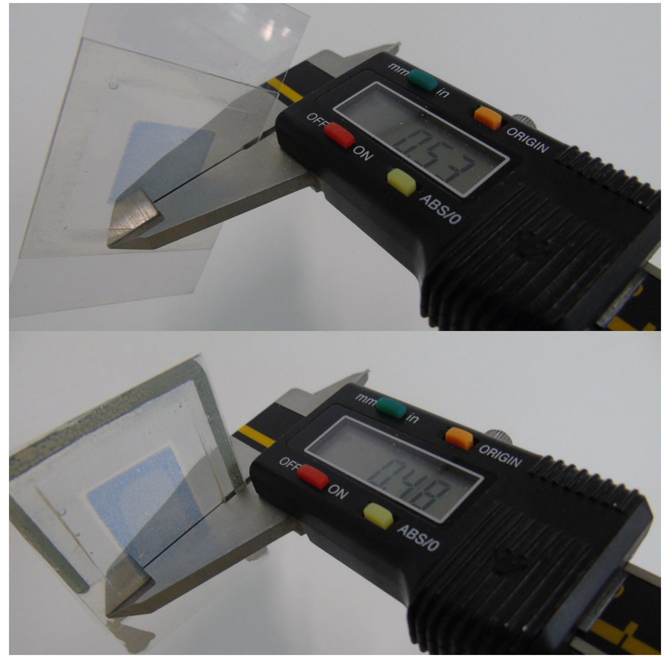


*Figure 2.2: Thinness of the ECDs created within this research.*

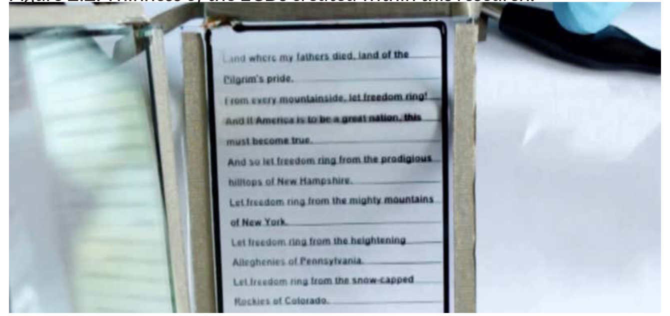


*Figure 2.3: Thinness of the "world's thinnest electrochromic display'. Copyright by Yu-Mo Zhang (2021).*

### 2.1.1. LAYERS WITHIN AN ECD

As aforesaid, the optical characteristics of the electrochromic material (i.e. controlled color change) change through the insertion or extraction of ions into the EC material. This ion insertion or extraction is enabled through the ***electrolyte*** (ion transfer layer) from the primary to the secondary ***electrochromic layer*** (and vice versa) when a voltage is applied to the two ***electrodes*** that are connected to these electrochromic layers, see figure 2.4 and 2.5. As can be seen by the dotted arrow in figure 2.4, the electrodes, electrochromic layers and the electrolyte together create a ***closed loop circuit*** between the two connections to the battery, resulting in a flow of current; thus a flow of electrons. These electrons are represented by the white spheres in figure 2.4.

These two electrodes and the electrochromic layers need to be printed on a layer that provides support to the ECD; i.e. the ***substrate*** and ***encapsulation***. As the electrolyte is a liquid gel, a ***bi-adhesive spacer*** (transparent double-sided adhesive tape) is required that connects the substrate and encapsulation and thus prevents the electrolyte from leaking. The fact that the electrolyte is a liquid gel, results into the conclusion that all ECDs that are created within this thesis are laminated ECDs (Monk, Mortimer, & Rosseinsky, 2007).

See table 2.1 for an overview of all layers and their function within an ECD and QR-code 3, for the change between the two colored states of both EC layers.

*QR-code 3: Coloring of an ECD.*

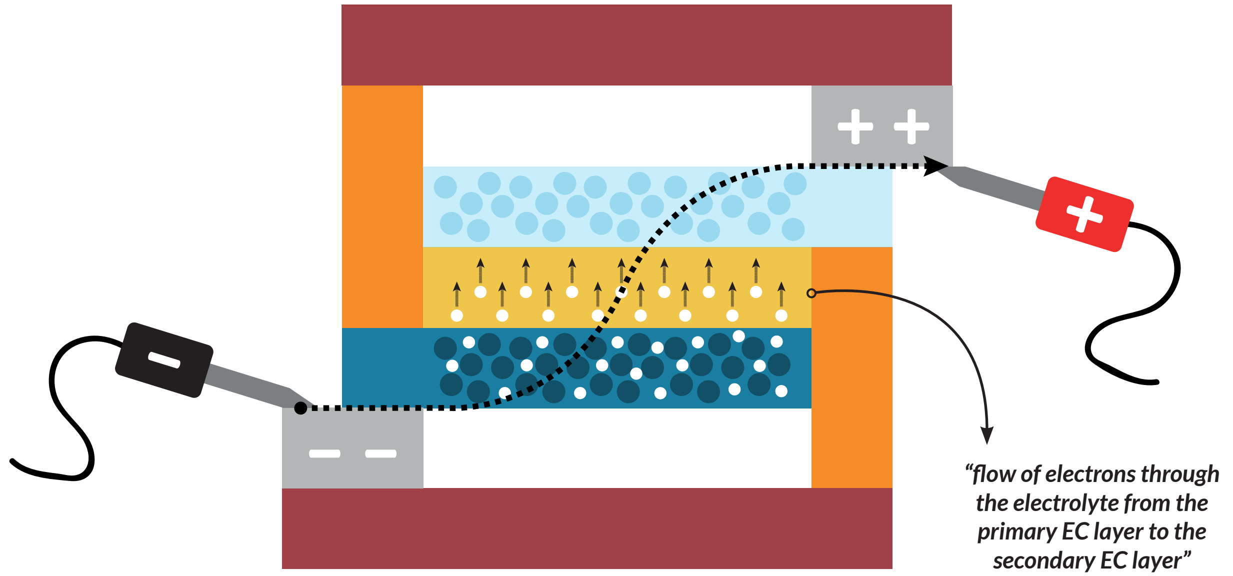



*Figure 2.4: Cross section of the electron flow in an ECD. Adjusted from (Jensen et al., 2019)*

| | |
|---|---|
| 1. ***SUBSTRATE***: back panel | Provide structural strength/solid support to the ECD. Insulate and protect the ECD. |
| 2. ***ELECTRODE (COUNTER)*** | Connected to the external power source. Electron conductor, creates together with the other conductive layer an electrical circuit required for the electron transfer. |
| 3. ***PRIMARY ELECTROCHROMIC LAYER*** | Ion storage layer. Changes color. |
| 4. ***BI-ADHESIVE SPACER*** | Connecting the encapsulation and substrate together. Prevents the electrolyte layer from leaking. |
| ***ELECTROLYTE*** | Ion transfer layer. Allowing ions to be transferred between the two electrochromic layers and separating them (to avoid a short-circuit). Active area = width x length x spacer's thickness |
| 5. ***SECONDARY ELECTROCHROMIC LAYER*** | Ion storage layer. Changes color. |
| 6. ***ELECTRODE (PRIMARY)*** | Connected to the external power source. Electron conductor, creates together with the other conductive layer an electrical circuit required for the electron transfer. |
| 7. ***ENCAPSULATION***: front panel | Provide structural strength/solid support to the ECD. Insulate and protect the ECD. |

*Table 2.1: Layer overview of a multilayer all-solid state ECD. (adjusted from: Aarts, 2020*

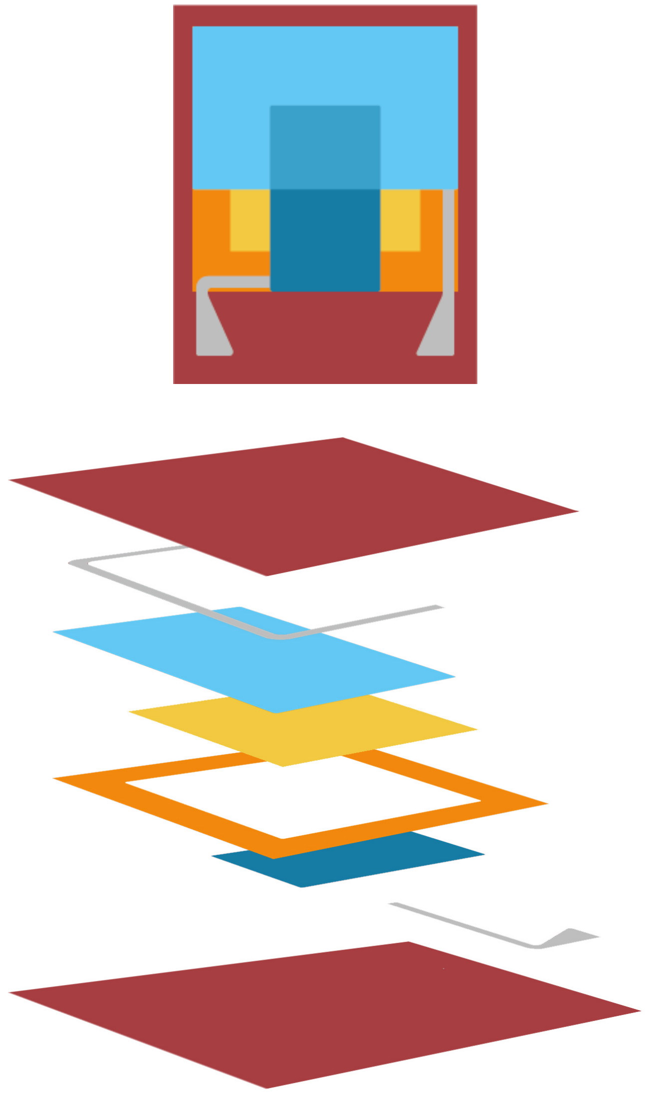


*Figure 2.5: Top view and an exploded view of an ECD.*

### 2.1.2. WORKING PRINCIPLE OF THESE LAYERS

As the different layers required for an operating ECD are clarified, the working principle of these layers will be further explained. As can be seen in figure 2.6 a so-called double image display is created. A ***double image display*** is an ECD that switches between two colored states; i.e. two images appear and disappear in turn. When looking at figure 2.6, the link between the applied potential and the layer to transfer to its colored state can be drawn.

Anodic and cathodic materials can be distinguished. An ***anodic material*** is a material that changes from its bleached to colored state when it is oxidized (i.e. electron release) and a ***cathodic material*** when it is reduced (i.e. electron uptake) (Rosa, 2015).

For example, when using an anodic coloring material (figure 2.6), the layer connected to the negative of the battery is the layer to change to its colored state, as electrons flow from the negative to the positive within a circuit, this material colors when releasing an electron. As can be seen in figure 2.6-a, the primary EC layer is connected to the negative and there is a closed loop circuit (dotted arrow) within the ECD, thus this layer colors. At the same time, as the secondary EC layer is connected to the positive and it is reduced (electron uptake from the primary EC layer), this layer is bleached (transparent). And when the potentiality is reversed (figure 2.6-b), the secondary EC layer will go to its colored state and the primary EC layer to its bleached.

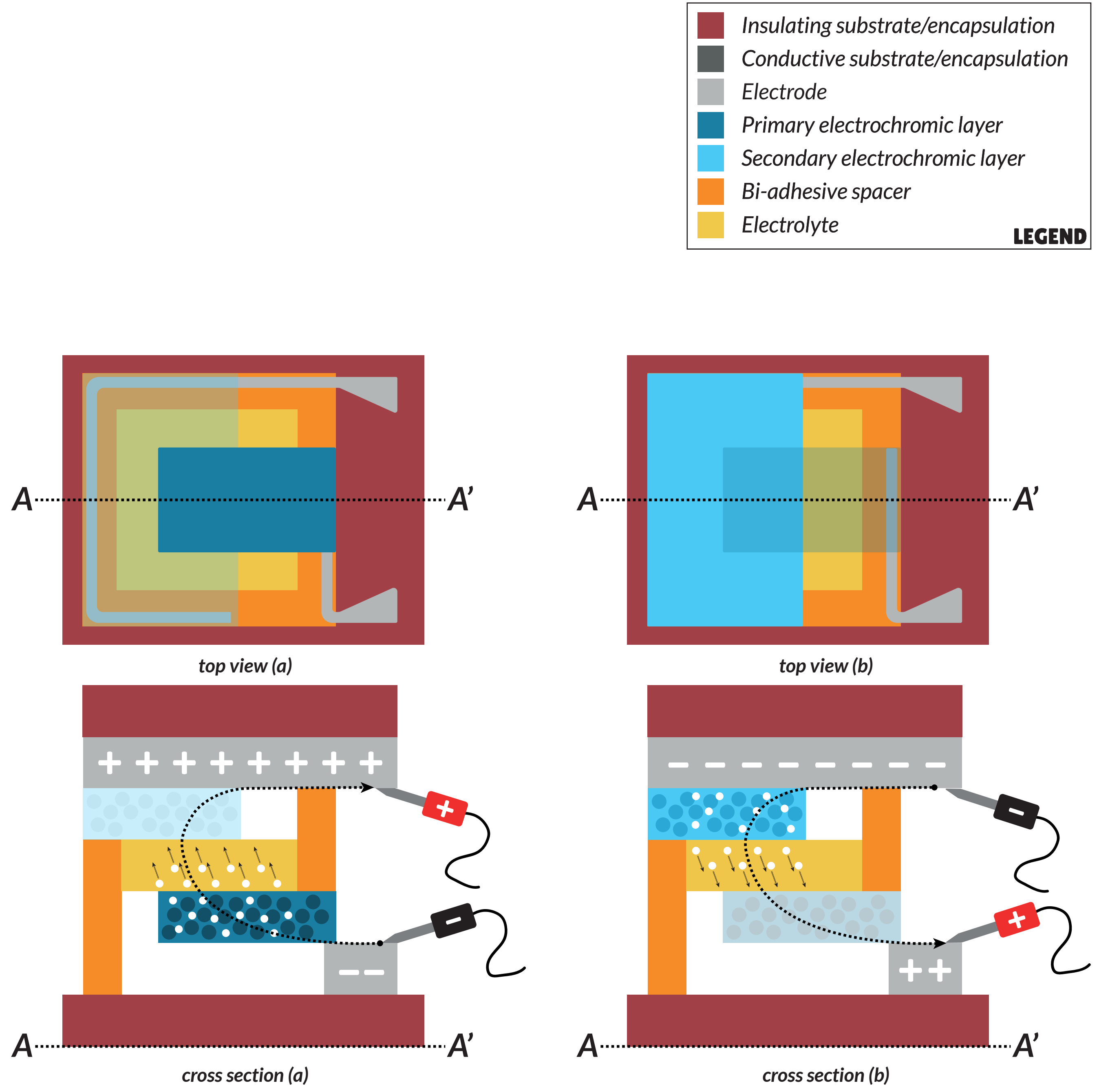



Figure 2.6: Coloring of an ECD for an anodic coloring material: Primary EC layer (a) and Secondary EC layer (b).



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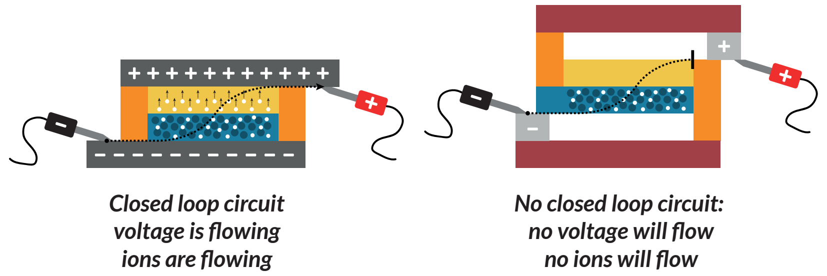



*Figure 2.7: Single image display: cross section of the flow in an ECD using a conductive substrate (a) or insulating substrate (b).*

## 2.2. OPTIMIZING THE LAYER STRUCTURE

All layers explained in table 2.1, are required for creating an operating ECD. However, there are several ways to simplify the layer structure while maintaining all functionalities. The three options that will be explained are: using a (conjugated) conductive polymer as EC material, a conductive material as substrate and creating a single image display (figure 2.9).

### 2.2.1. (CONJUGATED) CONDUCTIVE POLYMER

A (conjugated) conductive polymer is able to -as the name implies- operates as conductive layer. So for an ECD using an insulating material as substrate and encapsulation, the primary and secondary electrochromic layer can be merged with the corresponding electrode, resulting into a 5-layered ECD, see figure 2.9-a.

### 2.2.2. CONDUCTIVE MATERIAL

Using a conductive material as substrate and encapsulation, allows these layers to operate as electrodes. Resulting into a 6-layered ECD, see figure 2.9-b.

Besides simplifying the layer structure, using a conductive material also offers opportunities regarding the coloring and design of the images displayed. As can be seen in figure 2.8, using an insulating substrate results into a color flow, where a conductive substrate experiences immediate coloring. Furthermore, on the design of the images displayed, a conductive substrate results into more design freedom than an insulating substrate. As the images can be isolated from the bi-adhesive spacer frame, allowing more loose details in the image. Where for a linked image (insulating substrate) all individual parts of the image should be linked to the bi-adhesive spacer frame thus to the electrodes. As a rule of design: "all individual parts of the design should be connected to either a conductive substrate or electrode."

Besides the two differences on the design of the images displayed, another notable difference between a conductive and insulating substrate is its switching speed. As the whole substrate is conducting, the switching speed is notable faster for an ECD using a conductive substrate.

### 2.2.3. SINGLE IMAGE DISPLAY

A single image display is an ECD that only switches between one bleached and one colored state; i.e. one image appears and disappears. In order to display a single image, the secondary electrochromic layer is removed. This is only possible when using a conductive material as substrate and/or encapsulation, as a closed loop circuit is required. When removing the secondary EC layer in an ECD using an insulating substrate (figure 2.7-b), there is no closed loop circuit anymore: as the counter electrode is isolated by the bi-adhesive spacer, no voltage will flow and thus no ions will flow either. A conductive substrate (figure 2.7-a) restores the connection from the secondary EC layer to the battery, as it functions as electrode too, meaning a closed loop circuit is achieved. Thus a potential will flow through the ECD, allowing ions to flow and the color to change.

Removing the secondary EC layer forces the electrolyte also to operate as both; ion transfer and storage layer. Resulting into a 4-layerd ECD, see figure 2.9-c.

*Concluded*, using a (conjugated) conductive polymer, condutive material as substrate/encapsulation or a single image display results into optimization of the layer structure of an ECD. All simplify both, the layer structure and production process, thus making it shorter. On top of this, using an insulating or conductive substrate opens possiblities regarding the coloring or design of the images displayed that could be interesting when using ECDs within product design.

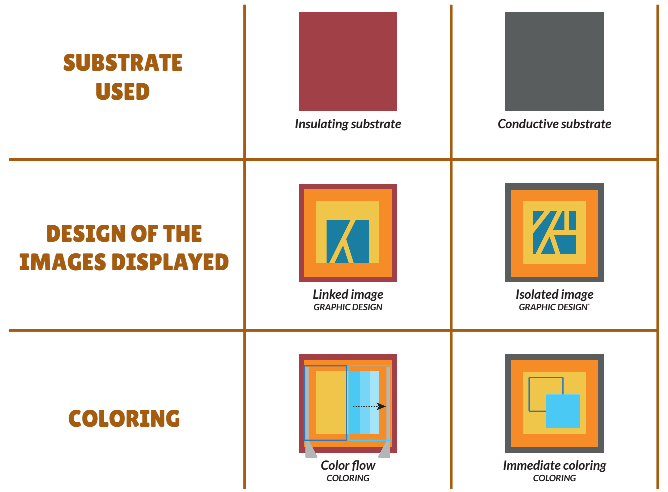
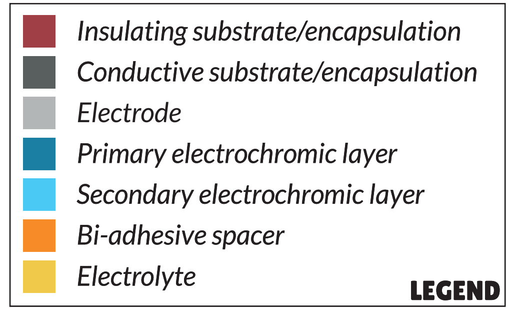
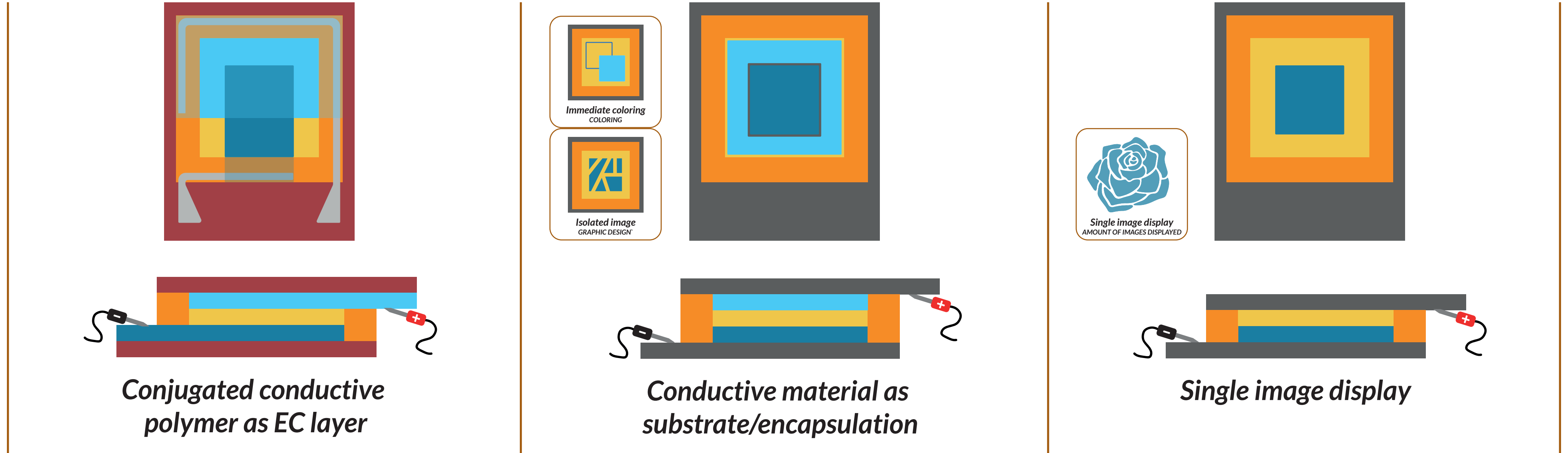



*Figure 2.8: Possibilities regarding the coloring or design of the ECD for using an insulating substrate versus a conductive substrate.*





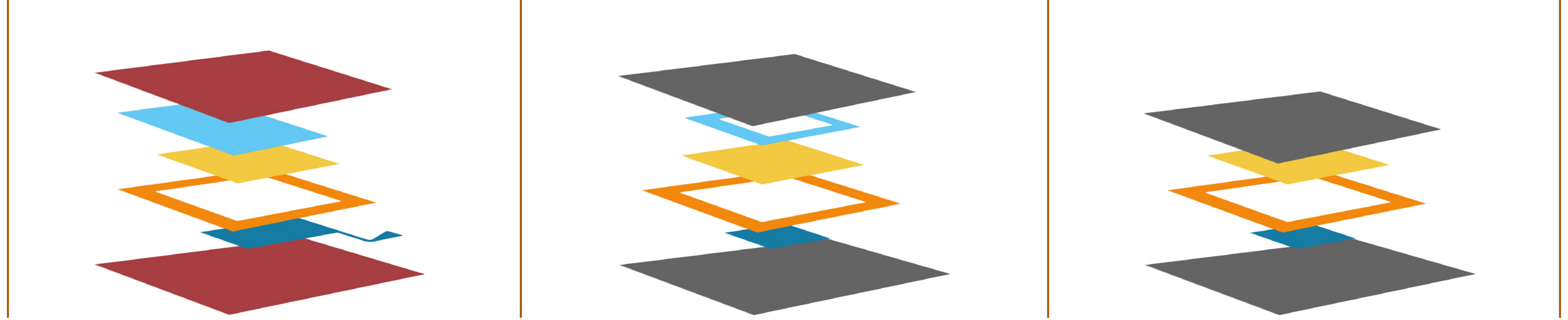
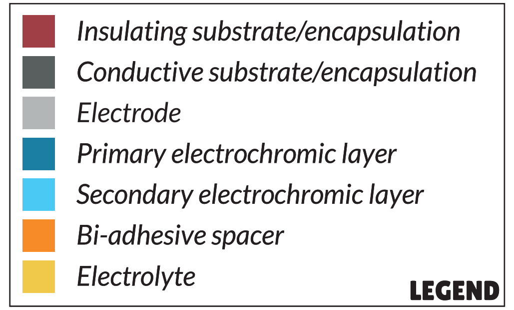



*Figure 2.9: Optimizing the layers: conjugated conductive polymer as EC layer (a), conductive material as substrate/encapsulation (b) and single image display (c). Top view, cross section and exploded view (from top to bottom).*




QR-code 4: Four stacking sequences.

## 2.3. VERTICAL AND CO-PLANAR STACKING SEQUENCES

Two types of ECDs can be distinguished: vertical and co-planar. The EC layers of a ***vertical ECD*** are stacked vertically, see figure 2.10-a. This has the advantage that the required path for the ions to travel is small, resulting in fast switching speeds and low power consumption (Brooke et al., 2017). The EC layers of a ***co-planar ECD***, are merged into the same layer (i.e. onto the substrate) with two separated electrodes, see figure 2.10-b. This results into the material restriction that only an insulating substrate can be used, as a conductive substrate would immediately lead to a short circuit. This leads to design restrictions regarding the interaction between the two EC layers, as for a vertical display they can overlap, connect or be separated, the two EC layers of a co-planar display always have to be separated to avoid a short circuit, see figure 2.10-b.

A co-planar ECD requires little higher power than a vertical ECD, as the path the ions have to travel is bigger. E.g. an ECD using the 'Ynvisible electrochromic ink' requires 1.5V for vertical stacking and 3V for co-planar stacking.

***Concluded***, the desired switching speed, voltage operation and interaction between the two EC layers will result in the choice of either a vertical or co-planar display. When combining the vertical/co-planar stacking with the substrate (insulating/conductive) used, results into the definition of four stacking sequences, see figure 2.11.

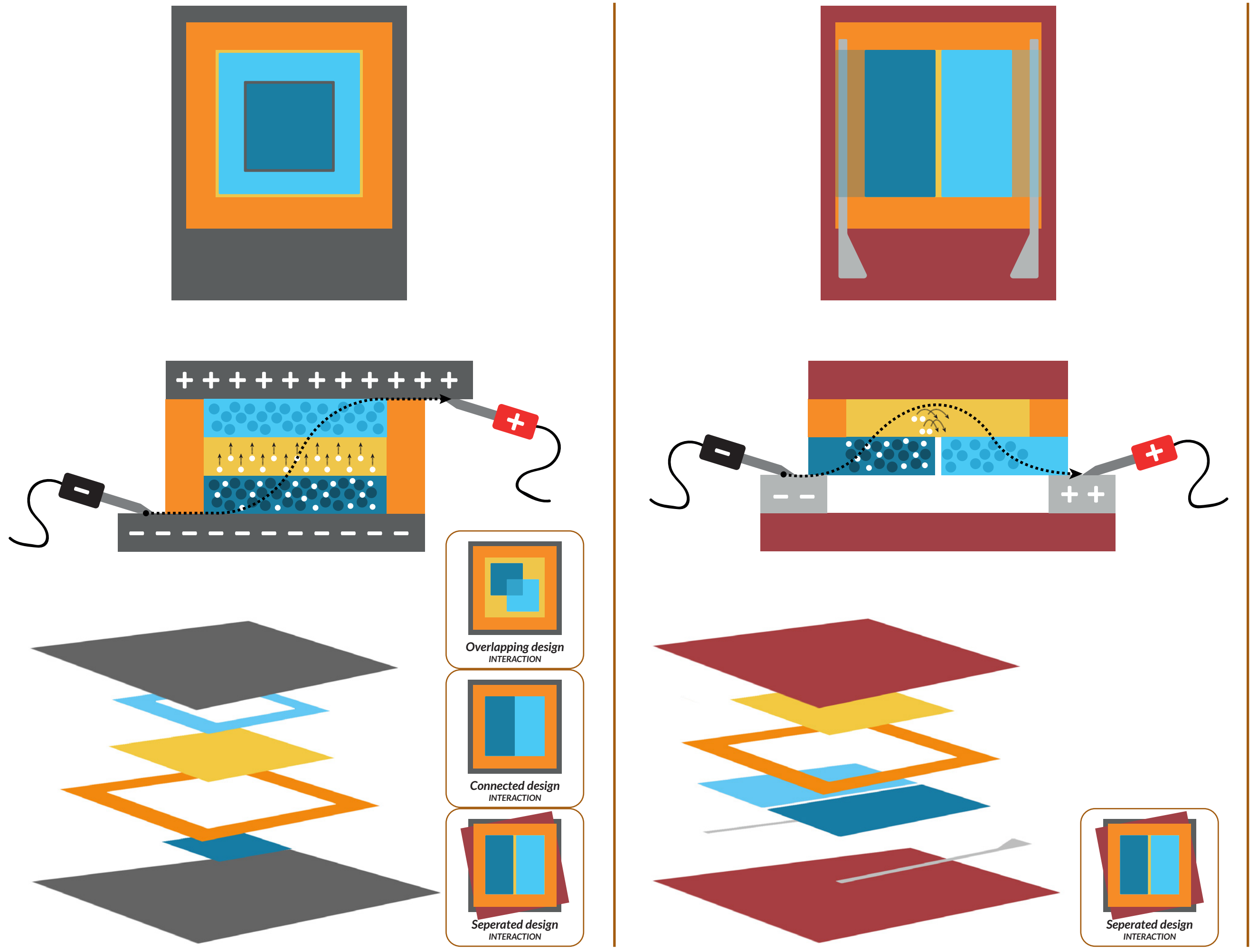



Figure 2.10: Vertical (a) and co-planar display stacking (b): cross section of electron flow (white spheres), cross-section and top-view (from top to bottom).





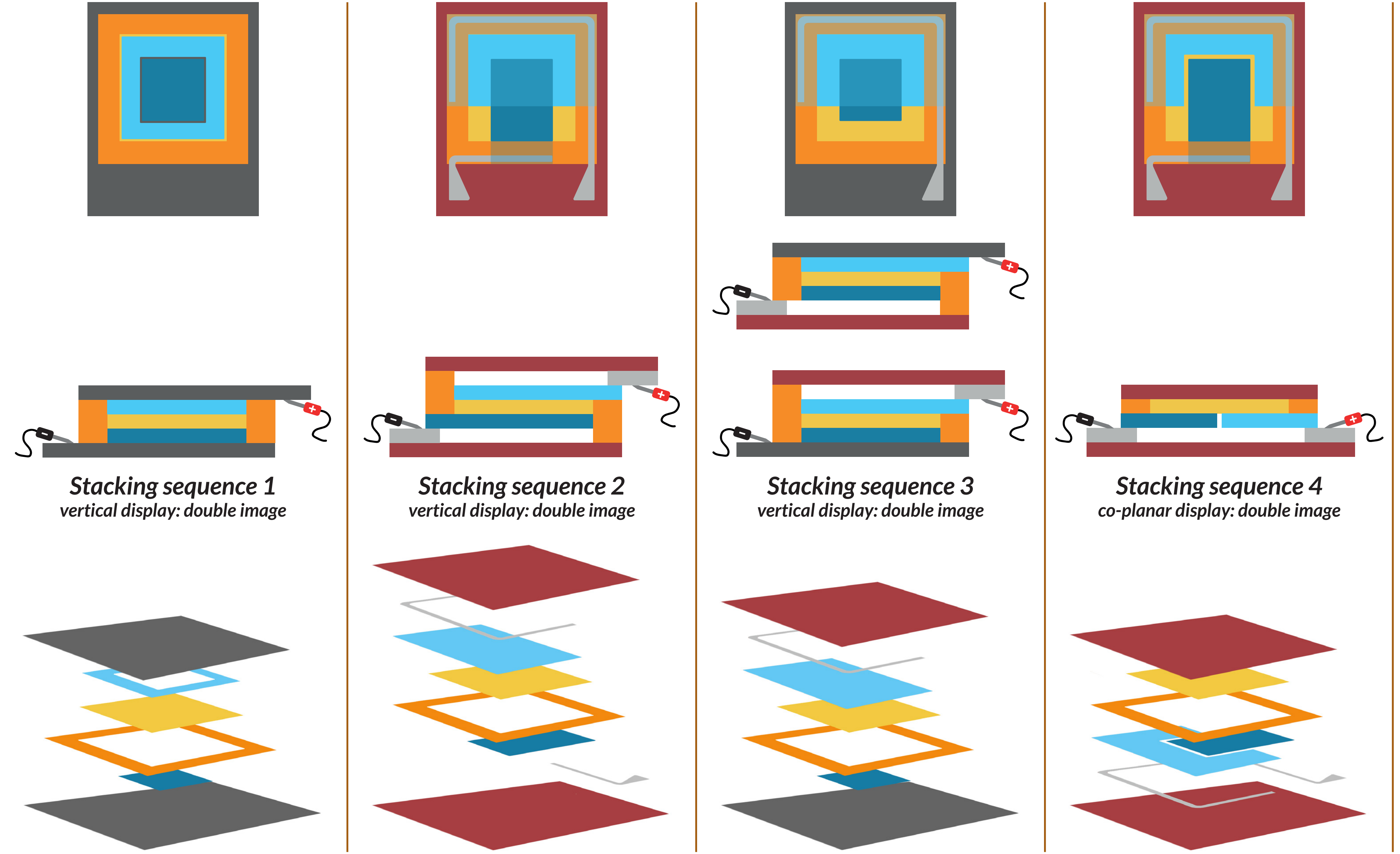



Figure 2.11: Stacking sequences: SS#1 (a), SS#2 (b), SS#3 (c) and SS#4 (d): cross section, exploded view and top view (from top to bottom).

## 2.4. TRANSMITTANCE AND REFLECTANCE OPERATING ECDs

Besides the vertical and co-planar device stacking sequences, two kinds of operation modes could be distinguished; reflective and transmittance ECDs.

The ***transmittance operation mode***, refers to the substrate used; i.e. a transparent material. The transparency of the ECD allows light to pass through, as can be seen in figure 2.12-a.

As can be seen in figure 2.12-b, within a ***reflectance operating ECD***, both electrochromic layers are positioned on top of a reflective substrate. Hereby, light will pass through these layers twice; before and after the reflection (Monk et al., 1995). This results into a higher color intensity of the ECD, theoretically double the color intensity of an ECD operating in transmittance mode. Nevertheless important to note is that, the color intensity is thus also higher in its bleached state; i.e. less transparent.

***Concluded***, when using an ECD within product design, the choice of a transmittance or reflectance mode ECD depends on the desired transparency of the material or desired color intensity.

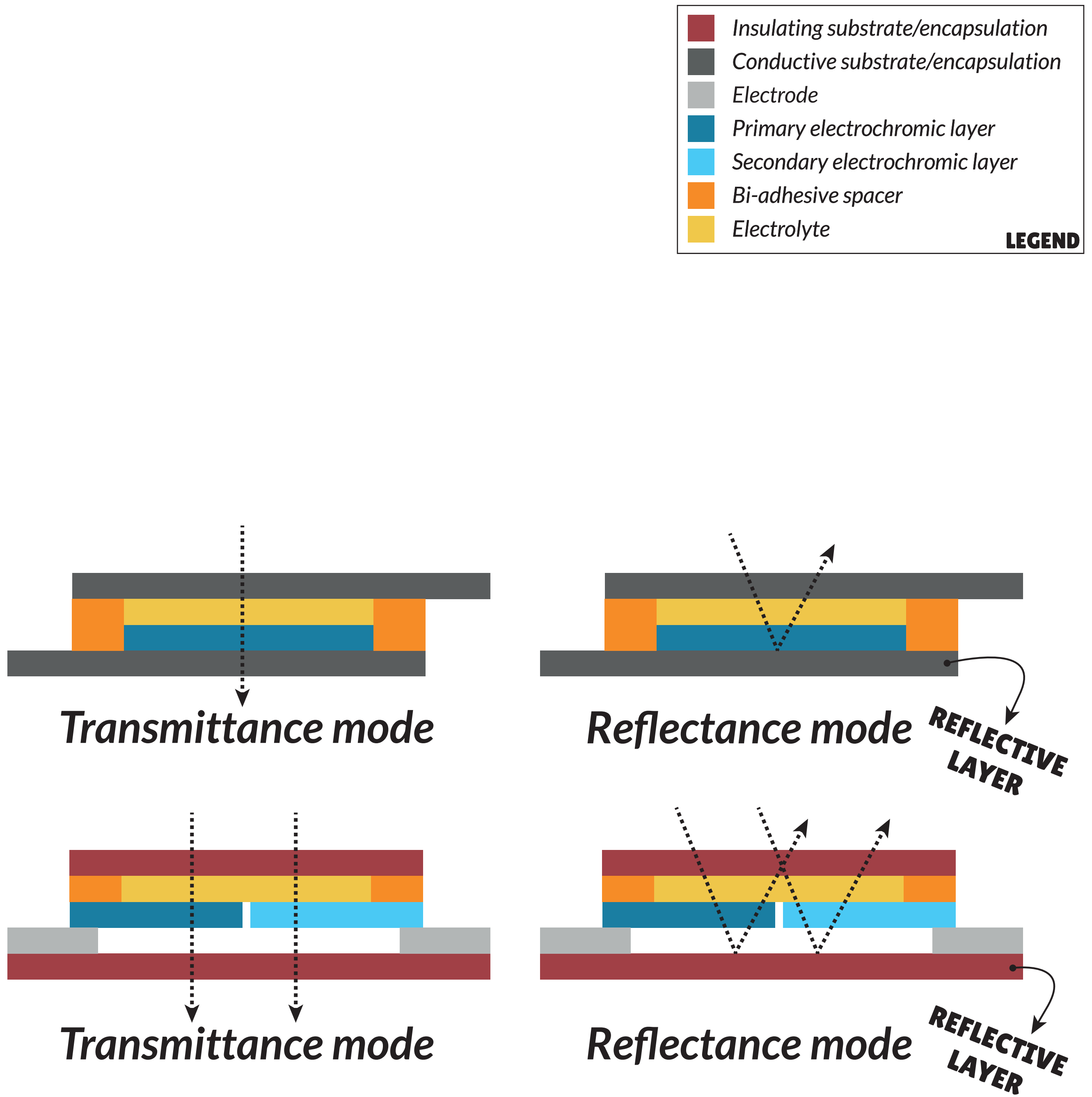



*Figure 2.12: Cross section of the transmittance (a) and reflectance (b) operation modes: vertical and co-planar ECDs (from top to bottom). Adjusted from Monk (1995).*



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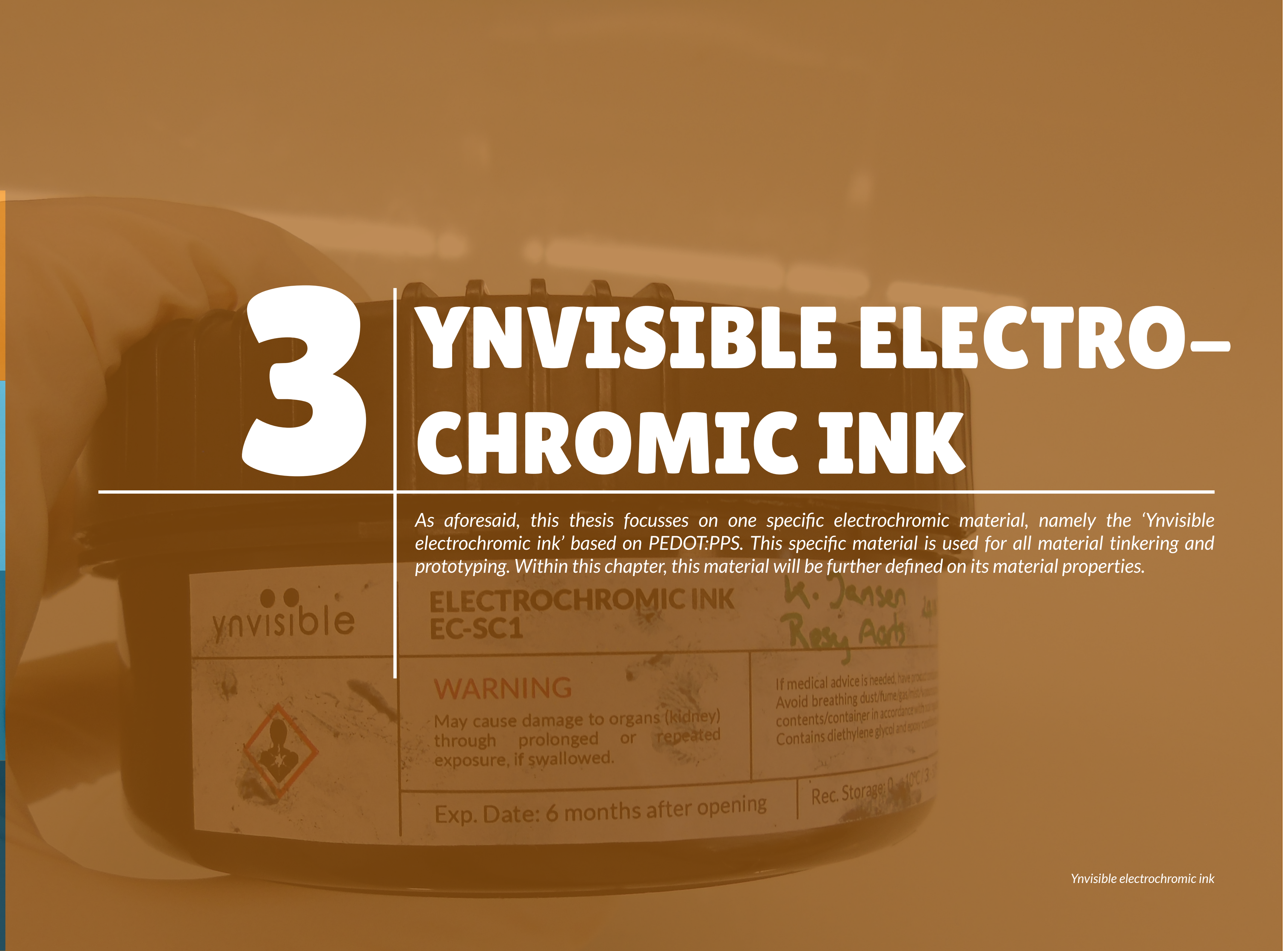



# 3 YNVISIBLE ELECTRO-CHROMIC INK

*As aforesaid, this thesis focusses on one specific electrochromic material, namely the 'Ynvisible electrochromic ink' based on PEDOT:PPS. This specific material is used for all material tinkering and prototyping. Within this chapter, this material will be further defined on its material properties.*

Ynvisible electrochromic ink

## 3.1. CONJUGATED CONDUCTING POLYMER

There are many materials known that exhibit electrochromism. These materials can be divided into inorganic and organic materials, see figure 3.1 for these materials and their subclasses. As the 'Ynvisible electrochromic ink' is based on PEDOT:PPS (Ynvisible, 2020b), it is categorized as a (conjugated) conducting polymer; a subclass of organic electrochromic materials. For further information on the other subclasses, Aarts (2020) should be consulted.

An ***(conjugated) conducting polymer*** is an organic polymer that exhibits different colors in its bleached and colored state as a result of a redox reaction. On top of this, the material is also electrical conductive. The material PEDOT:PSS specifically colors from transmissive sky blue to dark blue (Ynvisible, 2020b). According to Somani & Radhakrishnan (2003), (conjugated) conducting polymers have a volume change of a several percent when switching between the bleached and colored state.

## 3.2. UNIQUE MATERIAL PROPERTIES

When looking at the ***controlled color change***, it can be concluded that the 'Ynvisible electrochromic ink' is an ***anodic coloring material***. As explained in chapter 2.1.2., an anodic coloring material is a material that colors when it is oxidized (electron release). See figure 3.2.

By means of ***low voltage operation***, requires the 'Ynvisible electrochromic material' a power consumption of 1.5V for a vertical ECD and 3V for a co-planar ECD. As mentioned in the previous paragraph, this difference is because of the travel distance between the two EC layers. From the research of Jensen et al. (2019), it can be concluded that the switching speed of an ECD using the 'Ynvisible electrochromic ink' is less than 10 seconds, even at A4 size.

## 3.3. YNIVISBLE ELECTROLYTE

Besides the 'Ynvisible electrochromic ink', the 'Ynvisible electrolyte' ***(liquid electrolyte)*** is also used within this research. As the research focusses on electrochromic materials, the electrolyte is not further researched. According to Kraft (2019), a liquid electrolyte is an electrolyte that is based on water or polar organic liquids in which Lithium salts are dissolved. Other possibilities for an electrolyte would have been to use an electrolyte that is based on: a gel, polymer, solid polymer or solid inorganic electrolyte. However, when comparing them with a liquid electrolyte, it appeared to have the highest conductivity (Kraft, 2019). Although, the main disadvantage of a liquid electrolyte is the possibility of leakage.

***Concluded***, using a (conjugated) conducting polymer results into design opportunties regarding its electrical conductivity. Besides this, thhe fact that the 'Ynvisible electrochromic ink' is anodic coloring material, requiring an voltage of 1.5/3V and that the electrolyte used is liquid, is important background information for all experiments that will be executed.

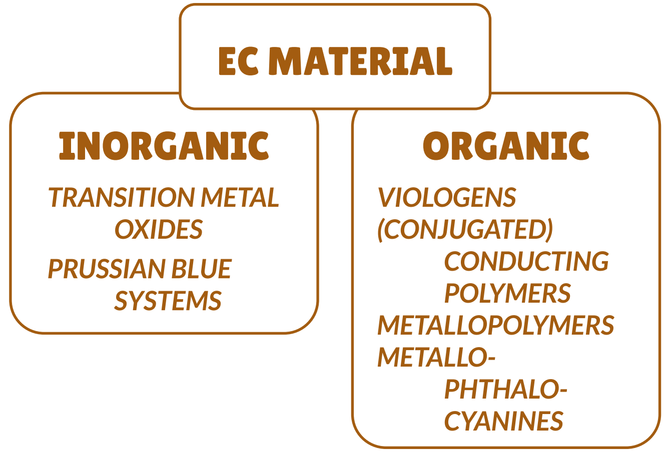



*Figure 3.1: Overview of organic and inorganic materials and their subclasses. Adjusted from Aarts (2020).*

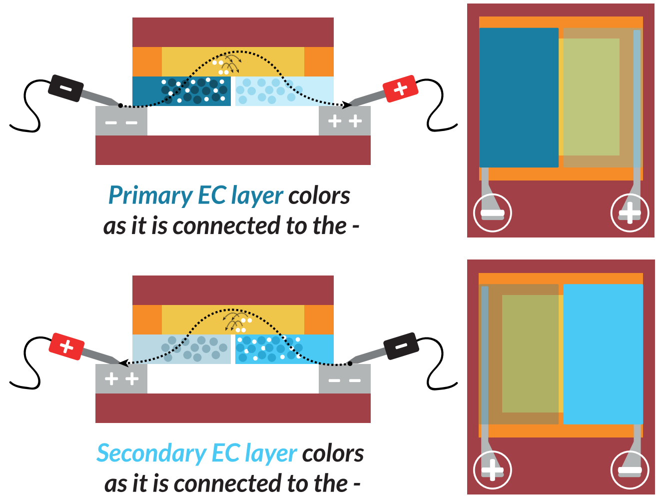



*Figure 3.2: Anodic coloring material coloration within a co-planar display; cross section of the ECD (left) and top view (right).*

# 4 MATERIAL TINKERING PHASE

*After the literature research was completed, a material tinkering phase was conducted. The goal of this phase is to: "gain insights on what the material affords, its technical/mechanical properties, as well as how it can be shaped/embodied in products"(Karana et al., 2015). On top of this, as the goal of this phase is to define the opportunity of electrochromic materials in product design, design opportunities are obtained. Three objectives were set to be accomplished through material tinkering: "Functioning ECD", "Optimization of the layers" and "Experiment with effects".*





## 4.1. IN GENERAL

Together with the literature research (electrochromism and electrochromic devices) and the material characterization of the 'Ynvisible Electrochromic Ink', the material tinkering phase will define the material characterization of the 'Ynvisible Electrochromic Ink'. This material characterization will, amongst other things, be based on the following optical properties: transparency, use of color (amount of images displayed, coloring, different colors and appear/disappear), the design of the images displayed and the interaction between the two EC layers. As the two latter can be concluded from the literature research, the important findings regarding the use of color will be displayed within this chapter.

All 201 ECDs (see appendix H for all ECDs created) are created in the chemical lab at the Faculty of Industrial Design Engineering inside a fume hood, while wearing a lab coat, safety glasses and gloves at all times. All ECDs are created by means of the production method described in appendices E and F. Besides this, the Ynvisible electrochromic ink and electrolyte are used for all prototypes. For the substrate/encapsulation, electrodes and bi-adhesive spacer different materials are tested. See appendix G for an overview of these materials.

*Figure 4.1: Applying the electrolyte within the chemical lab.*

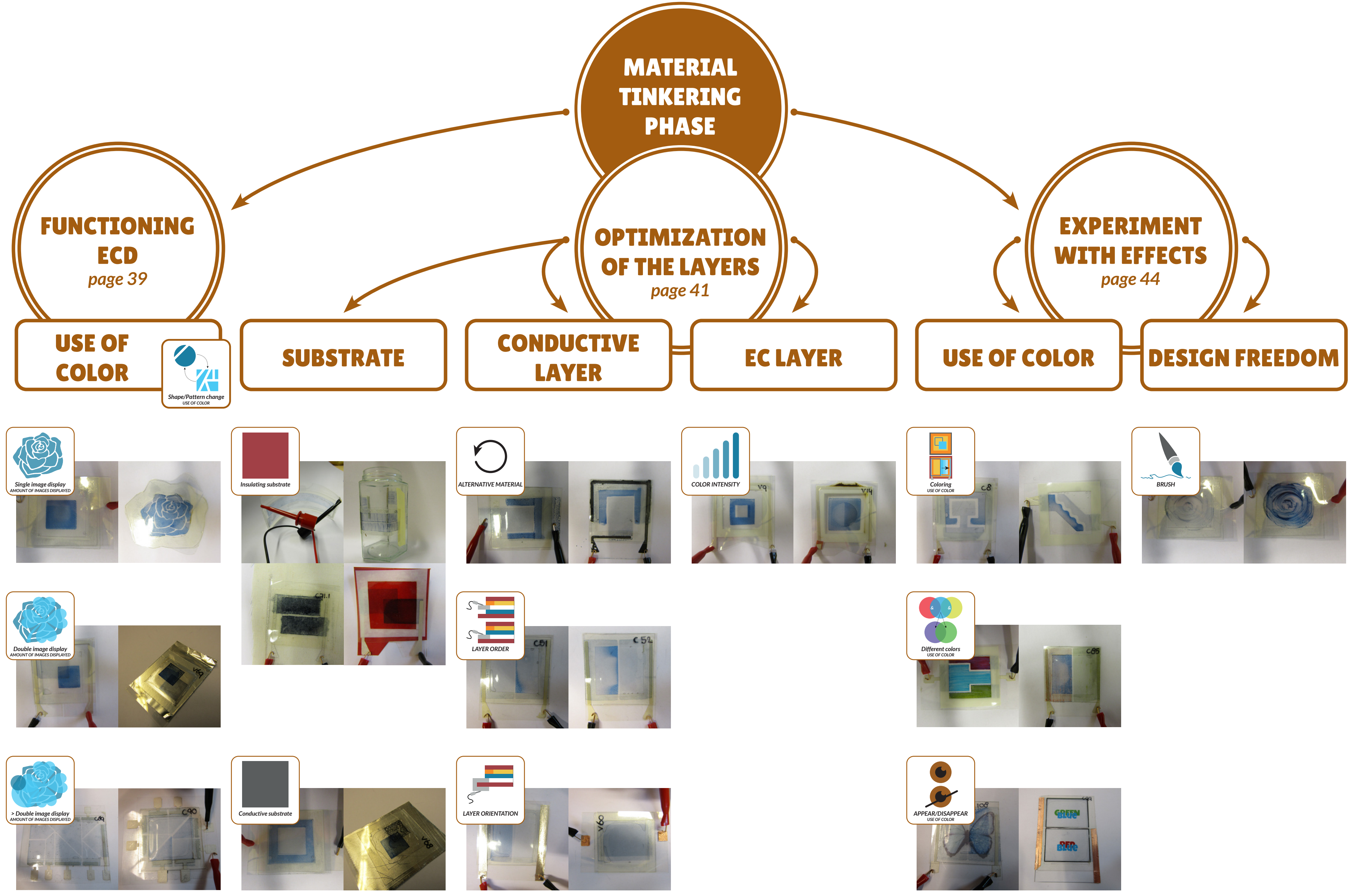



Figure 4.2: Overview of the material tinkering phase.



FUNCTIONING ECD

## 4.2. FUNCTIONING ECD

*At the start of the material tinkering phase, the objective of a functioning ECD was set. As can be seen in the overview of the material tinkering phase on the previous page (figure 4.2), this objective focusses on the amount of images displayed: e.g. single, double or >double image display.*

### 4.2.1. SINGLE IMAGE DISPLAY

A single image display is an ECD that only switches between one bleached and one colored state; i.e. one image appears and disappear, see figure 4.3. As aforesaid, a single image display can only be created when using a conductive substrate, as a closed loop circuit is created between both the connections to the battery (figure 4.4). From the material tinkering, it can be concluded that a single image display can only be created within stacking sequence 1 and partially for stacking sequence 3.

### 4.2.2. DOUBLE IMAGE DISPLAY

A double image display allows an ECD to switch between two colored states; i.e. two images appear and disappear in turn. Creating a double image display is possible within all four different stacking sequences, since ions are able to flow (figure 4.5).

The primary EC layer showed a higher color intensity than the secondary EC layer within an ECD operating in reflectance mode (figure 4.6). Where the primary EC layer is directly printed on the reflective substrate and the secondary EC layer separated from the substrate by the primary EC layer and the electrolyte.

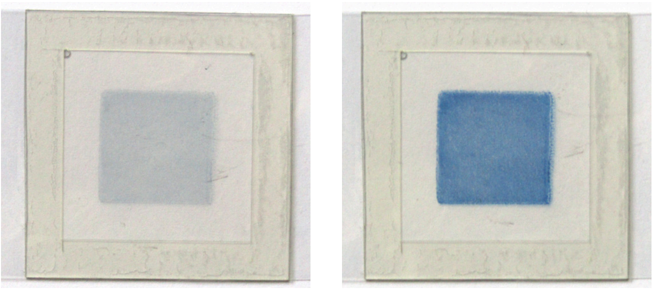


Figure 4.3: Single image ECD operating in transmittance mode (ECD-V-43): bleached (a) and colored state (b).

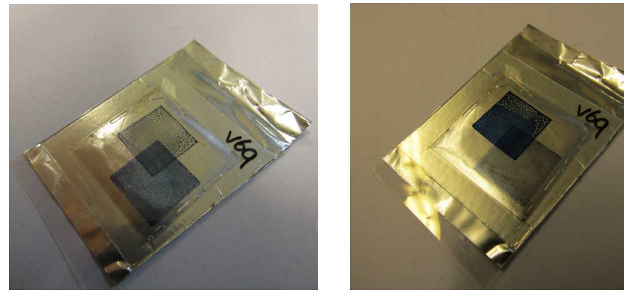


Figure 4.6: Double image display operating in reflectance mode: primary EC layer (a) and secondary EC layer (b).

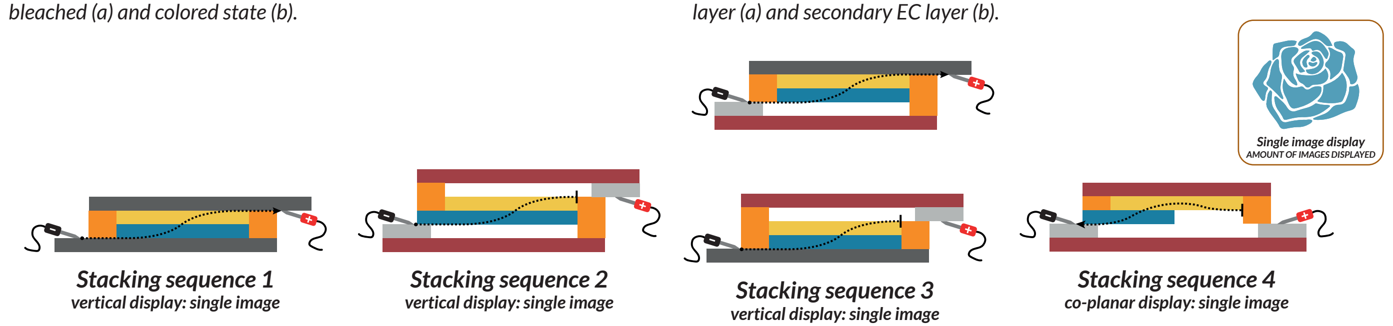



Figure 4.4: Potential flow for a single image display within the four stacking sequences.

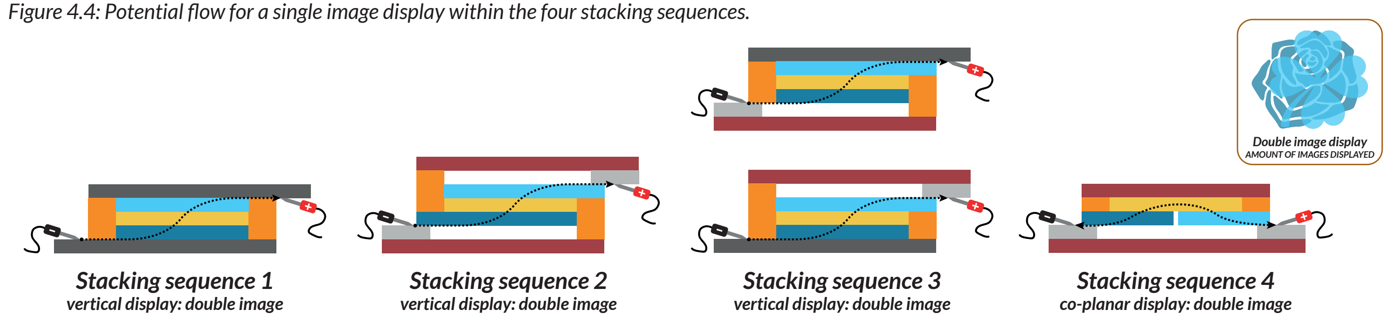



Figure 4.5: Potential flow for a double image display within the four stacking sequences.

### 4.2.3. > DOUBLE IMAGE DISPLAY

On top of a double image display, a display showing more than two images is tried to be achieved.

As can be seen in figure 4.7, four different options are researched. From this it can be concluded that the first two options (figure 4.7-a and 4.7-b) function. However, for both, no real advantage is created as both do not optimally function. The third option (figure 4.7-c), combining vertical and co-planar stacking did not work, as only one layer colored and the rest immediately were dysfunctioning.

However, the co-planar stacking with more than two layers printed on the substrate with all their own electrode (figure 4.7-d), resulted into a mosaic alike pattern where 64 different options can be created. As can be seen in figure 4.9 and QR-code 5, all individual images can be separately triggered, resulting into a nice interaction. So it can be concluded, that when more than two images are required, the co-planar stacking sequence should be used.

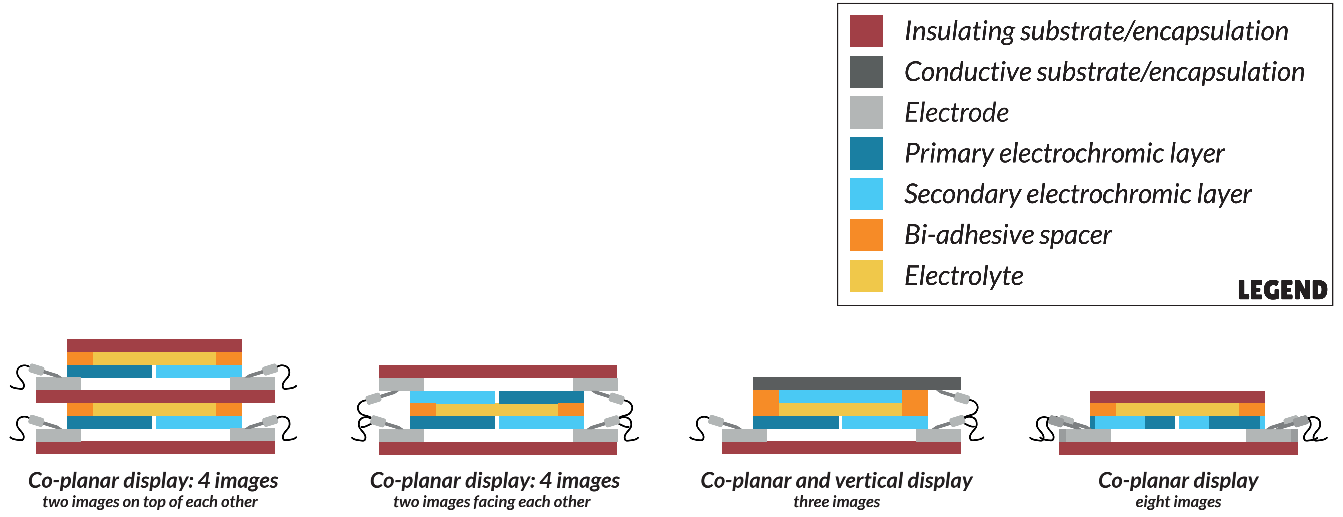



Figure 4.7: > 2 double image display.

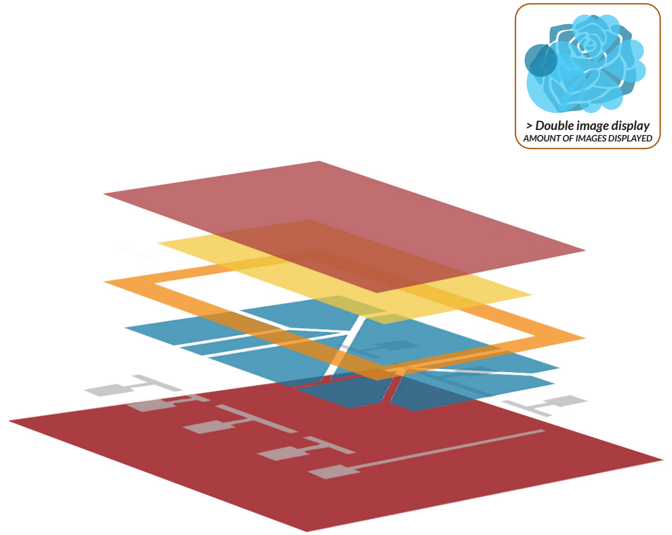



Figure 4.8: ECD-C-89: Exploded view

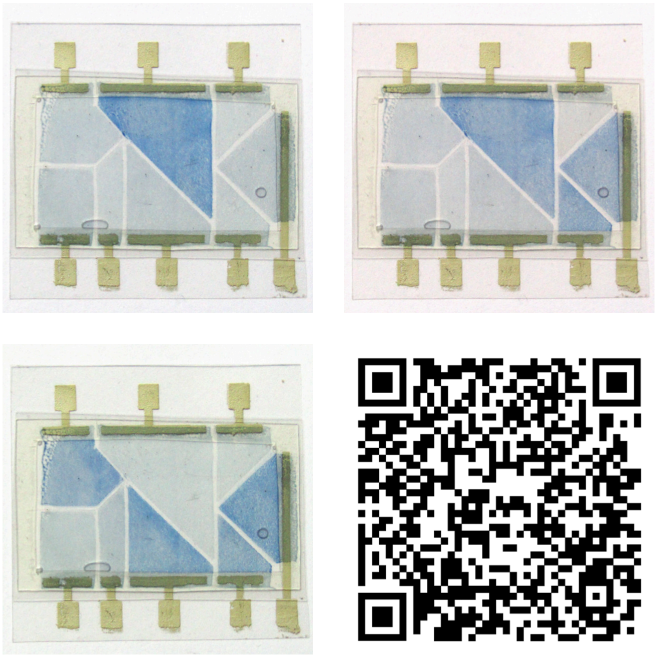


Figure 4.9: ECD-C-89: eight image display.

QR-code 5: ECD-C-89: eight image display.



OPTIMIZATION OF THE LAYERS

### 4.3. OPTIMIZATION OF THE LAYERS

*After functioning vertical and co-planar ECDs were created, optimization of the individual layers was explored. As can be seen in figure 4.2 on page 38, this objective focusses on the substrate, conductive layer and EC layer. First of all, for the substrate, both insulating and conductive materials are explored. Secondly, alternative materials are tested for the conductive layer and, the layer order and layer orientation of the conductive and EC layer are varied. Finally, the color intensity of the EC layer is optimized. For more in detail information on the different ECDs created and methods used, appendix I should be consulted.*

### 4.3.1. SUBSTRATE

Starting with the layer that provides structural strength to the ECD; i.e. the substrate. A variety of insulating and conducting material is explored, see figure 4.10 As insulating substrate, PET overhead sheets, glass (jars), textile, (colored) cardboard and magnetic paper are explored. As conductive substrate, PET coated ITO, Aluminium, Aluminium foil and conductive tape is explored.

The **PET overhead sheets** functions as an optimal material for both the substrate and encapsulation of the ECDs, no complications with adhesion of the materials occurred in the horizontal (flat) plane. However, when curving the material (see appendix I.1.1), problems with the electrolyte started to occur; i.e. it kept spreading which lead to a short circuit (figure 4.11). Presumably, the short circuit is created by the uneven spreading of the electrolyte through this curvature, leading to a connection of the primary and secondary EC layer at points where the electrolyte was swept away.

Using a **glass jar** as, resulted in problems with the adhesion of both the electrolyte and encapsulation (see appendix I.1.2). In the end, all ECDs created on all glass jars are not operating.

Screen printing the EC material on **textile** resulted in a disconnected image, as the surface showed irregularities. As it is important that all parts of the image are connected (insulating substrate) in order to make flow of ions possible, the image was fixed with a brush (figure 4.12). This resulted into a really dark image of which the change is color was barely visible. Besides this, the electrolyte also leaked through -even for the substrate that was made waterproof-. From personal communication with Lucia Gomes (Ynvisible) it appeared that the electrolyte is an aggressive solution that tends to react with some materials, which possibly explains why it leaks through the waterproof textile.

When using **cardboard**, it appeared that it absorbs the electrolyte. Leading to unevenly spreading of the electrolyte and the ECDs to not operate.

The final insulating substrate that was tested is **magnetic paper**, which appeared to be insulating instead of conducting as expected. So, none of the ECDs operated.

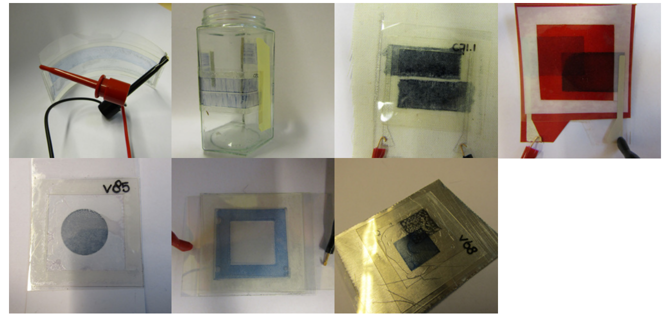



Figure 4.10: Insulating substrate (a till e) and Conductive substrate (f,g)

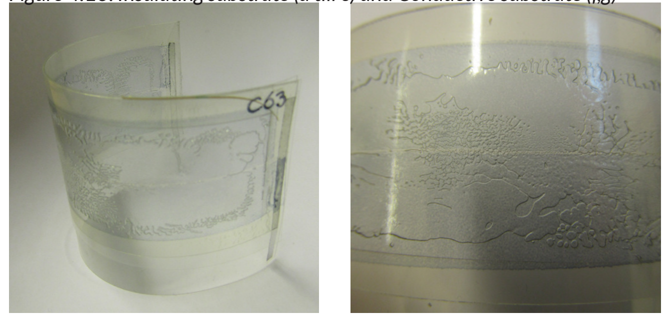



Figure 4.11: Irregularity of the electrolyte applied to a curved substrate.

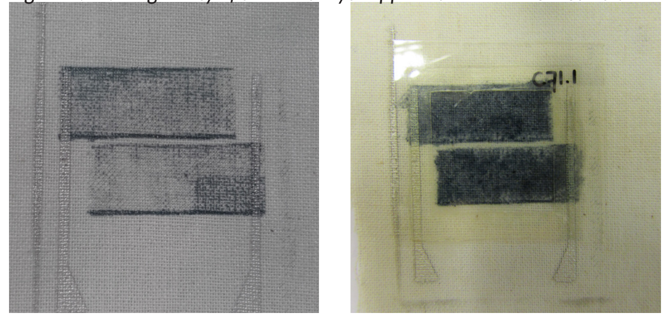
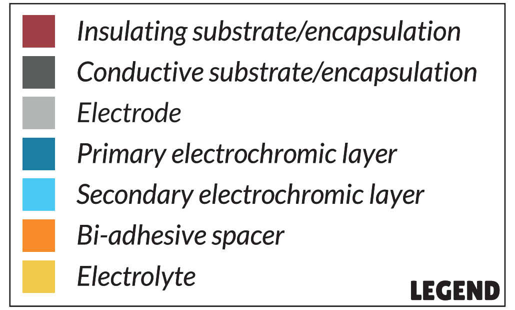



Figure 4.12: Textile as substrate: screen printing (a) and after adjustments with the brush (b)




The first conducting material explored as substrate is *ITO coated PET*. This appeared to be an optimal material for both the substrate and encapsulation of the ECDs, as no complications with adhesion of the materials occurred.

Secondly, an *Aluminum plate* was used as an (reflective) substrate. As the Aluminum plate used was not entirely smooth, problems occurred with the adhesion of both the EC material and the electrolyte.

*Aluminum foil*, on the other hand, has a more smooth surface and appeared to be an optimal material for both screen printing the EC layer on and spreading the electrolyte.

***Concluded, PET overhead sheets are the most ideal material to use when creating an ECD with an insulating substrate. Where both, ITO coated PET and Aluminium foil appeared to be good alternatives for the substrate of an ECD when using a conductive substrate.***

### 4.3.2. ElectrodeS

First, different *alternative materials* for the electrodes were tested and analyzed based on their switching speed (see appendix I.2.1). The materials researched were: 'Ynvisible EC ink', Silver paste, Conductive paint and conductive tape. No significant conclusions from these tests could be drawn, since just two ECDs were created for each material and the amount of electrolyte differs slightly; which influences the switching speed significantly. In the end, all materials met the conductivity and reasonable switching speed. Notable was, that the 'Ynvisible electrochromic ink' showed the most stable switching speed for the ECDs. When using this material as conductive layer, important is to make the tracks as wide as possible, to make sure all parts touch each other.

Secondly, the *influence of the layer order* of the electrochromic and conductive layer within a co-planar display was researched, see figure 4.13. As there was no notable difference in the switching speed or color intensity of the two displays, it can be concluded that the layer order within a co-planar display does not influence the functioning of the ECD, as long as the conductive layer is conductive at both sides.

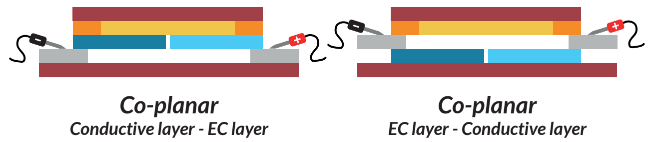



*Figure 4.13: Layer stacking sequences co-planar display.*

Besides influence of the layer order, *the orientation of the electrodes* is also researched. As can be seen in figure 4.14, conductive tape is used to redirect the connections to the power source to another plane; i.e. to the bottom of the ECD. It can be concluded that the orientation doesn't influence the functioning of the ECD, only the interaction. Notable was that the switching speed for the co-planar display was notable lower, however this could also be influenced by the irregularity of the volume of electrolyte.

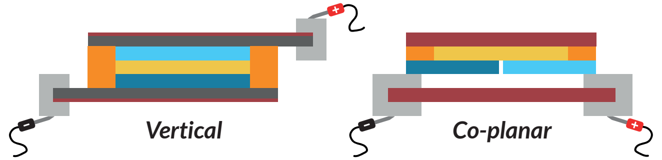



*Figure 4.14: Influence of the orientation of the plane of the conductive layer: redirecting to the bottom.*

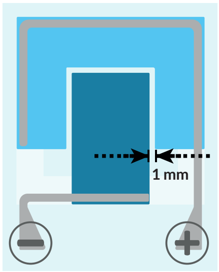


### 4.3.3. ELECTROCHROMIC LAYER

Regarding the electrochromic layer, the optimization was tried to be optimized by playing with more EC layers or overlap between the layers.

Using *more EC layers* -screen printing more EC layers within one (primary or secondary) EC layer)- influenced indeed the color intensity. "The more EC layers are screen printed, the higher the color intensity -in both the bleached and colored state- and the higher the switching speed". The disadvantage of this higher color intensity is that it is also higher within the bleached state, meaning that the image is less transparent, thus more visible already.

Creating *overlap* in the image of the primary and secondary EC layer, positively influences the color intensity. The part of the images that overlap have a higher color intensity, in both states. With the disadvantage again, that it is also more visible in the bleached state already.




ECD-C-4

*Figure 4.15: Required distance between the two EC layers: 1 mm.*

## 4.4. OPTIMIZING THE SWITCHING SPEED

As the switching speed is the most important material property that should be optimized; as low as possible, the switching speed for an ECD using an insulating substrate (stacking sequence 2 and 4) was optimized, as the switching speed is notable lower for these stacking sequences (using an insulating substrate) than the switching speed of an ECD using an conductive surface (chapter 2.2).

From the distance between the two EC layers within a co-planar ECD (see figure 4.15), it can be concluded that: ***the smaller the distance, the faster the switching speed.***

However, to avoid short circuits (merging of the two EC layers), a minimum distance of 1 mm should be taken in account, see figure 4.15 and appendix I.3. Contradictory to the 0.5 mm set within the 'Ynvisible Design Guidebook', when using manual screen printing with vinyl stickers, 0.5 mm often resulted into merging of the layers.

Furthermore, from the design of the electrodes (see figure 4.16), it can be concluded that: ***the more overlap between the EC layer and the electrodes, the faster the switching speed.***

This difference can be explained by both, the flow (move) of ions through the electrolyte or the EC layer. The flow of ions through the electrolyte is heavily influenced by certain factors such as its viscosity and the salt concentration; both could result into a slower movement of the ions through the electrolyte, thus a slower switching speed. Furthermore, the electrochromic layer. The movement of the ions through the EC material could also be slower than through the conductive layer (Jansen, personal communication, January 1, 2021).

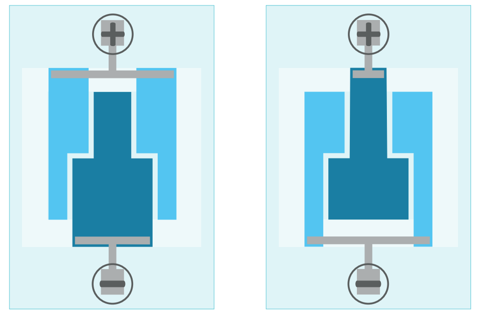


*Figure 4.16: Design of the electrodes: more overlap (a) and less overlap (b).*

**EXPERIMENT WITH EFFECTS**

## 4.5. EXPERIMENT WITH EFFECTS

*As a clear idea of the ECD and how to optimize both, its layers and materials properties is obtained, there will be experimented with effects. As can be seen in figure 4.2 on page 38, this objective focusses on use of color and design freedom. For the use of color a distinction is made between coloring (color flow), use of different colors and let something appear/disappear. All effects explored within are potentially design opportunities for the use of EC materials within product design. Also for this phase, all details on the different ECDs created and methods used, appendix I.4 should be consulted.*

### 4.5.1. USE OF COLOR: COLORING (COLOR FLOW)

When analyzing the use of the controlled color change of electrochromic materials, five different possible ways of using this aspect within product design can be distinguished: different shapes/patterns (images displayed), coloring (immediate/color flow), different colors, changing from gray-scale to color and allow something else to appear/disappear. As change of shape/pattern is analyzed within the amount of images displayed, see chapter 5.2, within this paragraph there is further experimented with the use of coloring: color flow. As within some of the preliminary experiments including co-planar ECDs, an interesting flow of color was observed. As both the options of the immediate coloring and this color flow could be leading to new design opportunities, this color flow is further investigated.

First, the influence of the **design of the EC layers** on the color flow was researched. When creating a co-planar ECD using electrodes, it appeared that a clear color flow was to be seen between the switching of the layers. As mentioned before, the layer connected to the negative of the potential is the layer to color, orientated from the layer connected to the positive, see figure 4.17. From the ECDs with different designs (figure 4.18), it seems that the specific direction is rather influenced by the parting line between the two EC layers than by the orientation of the electrodes. As can be seen in figure 4.18, 4.19, 4.20, 4.21 and QR-code 6, the color starts at the parting line between the two EC layers (the darker the color in image 4.18, the earlier it colors), and flows to its connection to the electrode (direction of the arrow) for both EC layers individually. For figure 4.18, the darker the color the earlier it colors. However, the design and orientation of the electrodes could be researched more.

*QR-code 6: Color flow within co-planar displays of figure 4.18.*

- *Insulating substrate/encapsulation*
- *Conductive substrate/encapsulation*
- *Electrode*
- *Primary electrochromic layer*
- *Secondary electrochromic layer*
- *Bi-adhesive spacer*
- *Electrolyte*

**LEGEND**

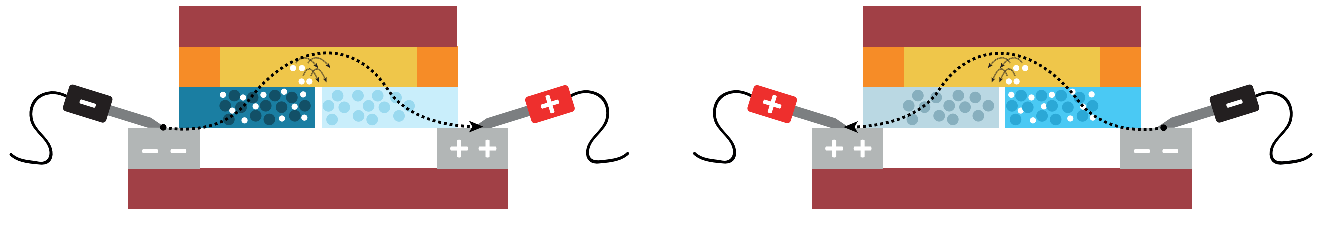



*Figure 4.17: Coloration of the primary EC layer within a co-planar display.*



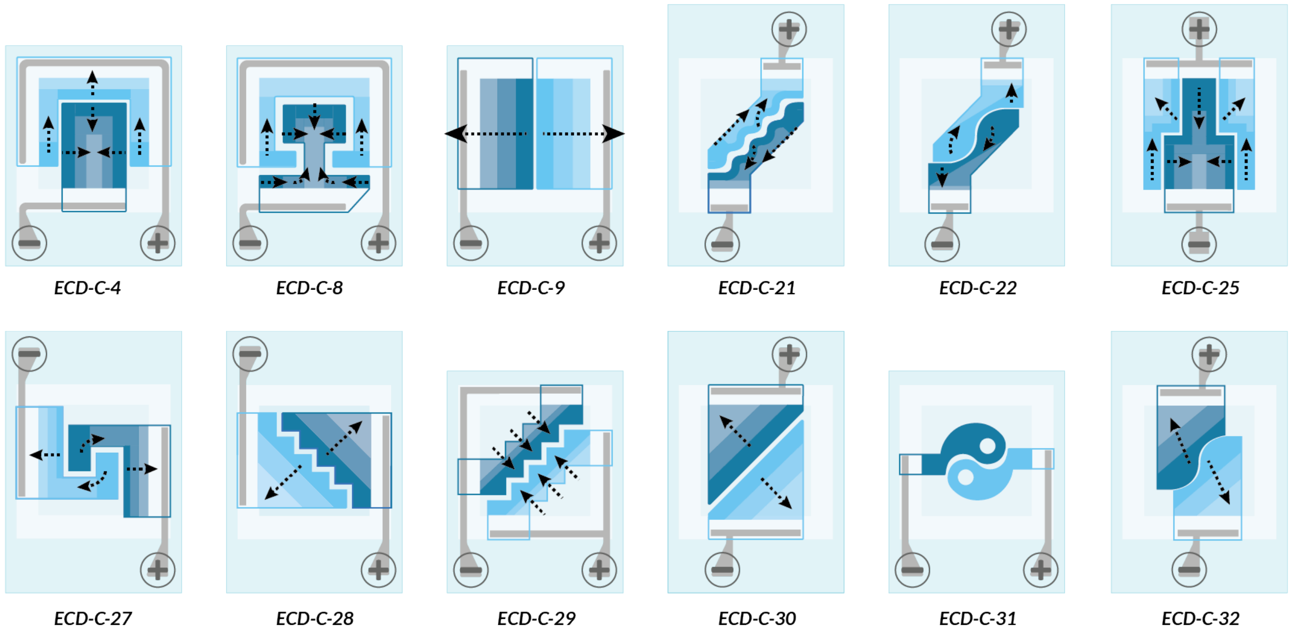



*Figure 4.18: Color flow within co-planar displays: the darker the color, the earlier it colors.*

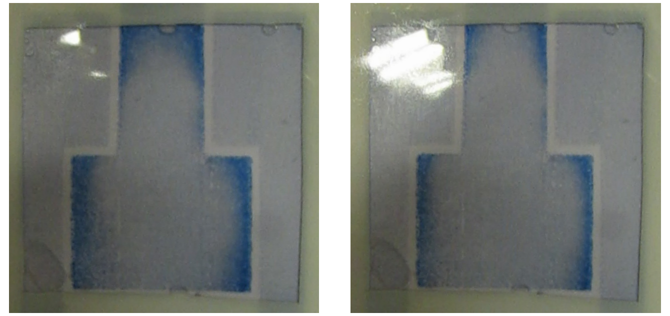


*Figure 4.20: Color flow of the primary EC layer of ECD-C-25.*

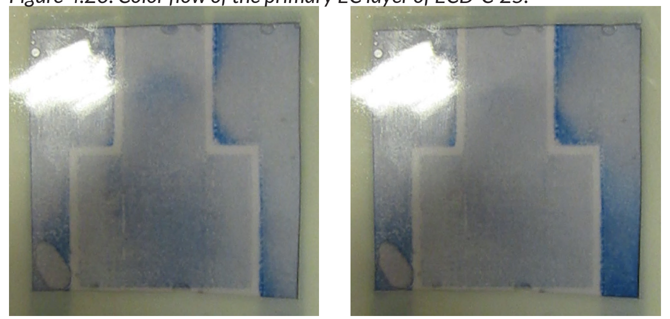


*Figure 4.21: Color flow of the secondary EC layer of ECD-C-25.*

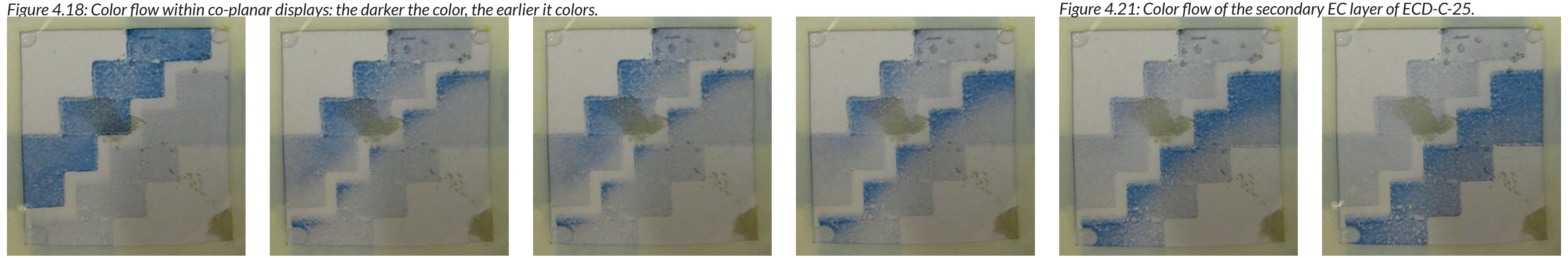


*Figure 4.19: Color flow of the secondary EC layer of ECD-C-29.*

When looking at a vertical ECD of stacking sequence 2 (insulating surface and electrodes) with overlap, this color flow is achieved too, next to immediate coloring. As can be seen in figure QR-code 7, the part of the image that overlaps between the two EC layers colors immediately, where the rest colors with the flow using the parting line between the two EC layers as orientation for this flow. From this it can be concluded that *using an insulating substrate leads to a color flow, where a conductive substrate has immediate coloring of the images (figure 2.22).*

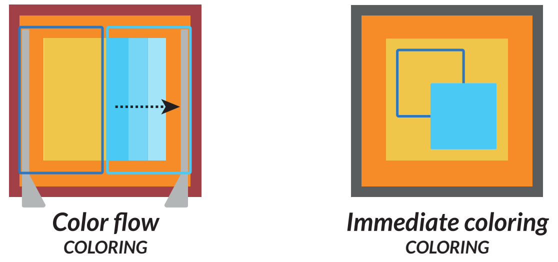


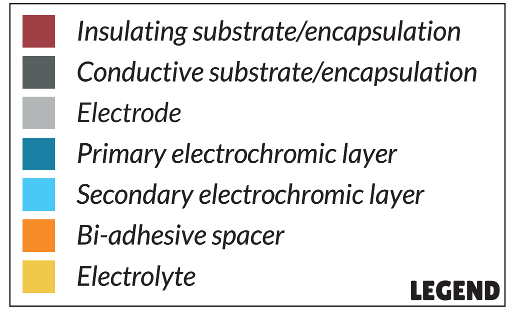

Figure 4.22: Insulating substrate: color flow (a) and conductive substrate: immediate coloring (b).

fluence of the *design of the electrodes* was also researched. As can be seen in figure 4.23, 4 different co-planar ECDs were researched with all the same active area and as variation the design of the electrodes. From these four ECDs, opposing from the assumption, it can be concluded that the design of the electrodes in the outside region does not influence the color flow (figure 4.23-b), only the switching speed; as the smaller the connection between the electrodes and the EC layers, the larger the switching speed appeared to be (as explained within chapter 4.4.1.).

QR-code 7: Vertical SS #2: immediate coloring and color flow combined.

Due to this conclusion, it was tested whether incorporating the electrodes inside the EC layer would influence the color flow, as can be seen in figure 4.24-a. However, the position of the electrodes does not influence the color flow, as the flow is clearly only influenced by the parting line of the two EC layers (figure 4.24-b).

*Concluded, the color flow of an ECD (using an insulating substrate) is heavily influenced by the parting line between the two EC layers and not by the design or orientation of the electrodes. The design of the electrodes only influences the switching speed, as the smaller the connection with the EC layer, the larger the switching speed is.*



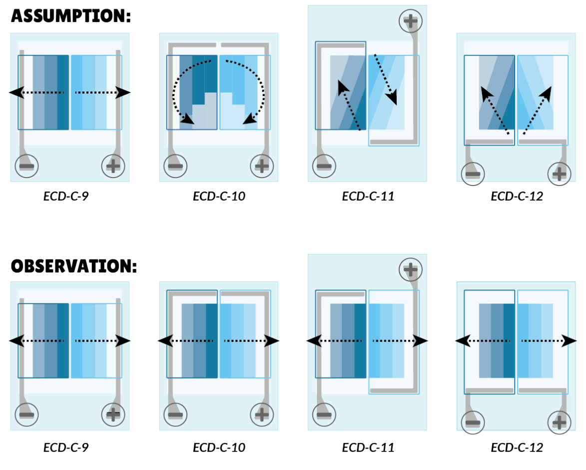




Figure 4.23: Co-planar ECD: Influence of the design of the electrodes, assumption (a) and observation (b).

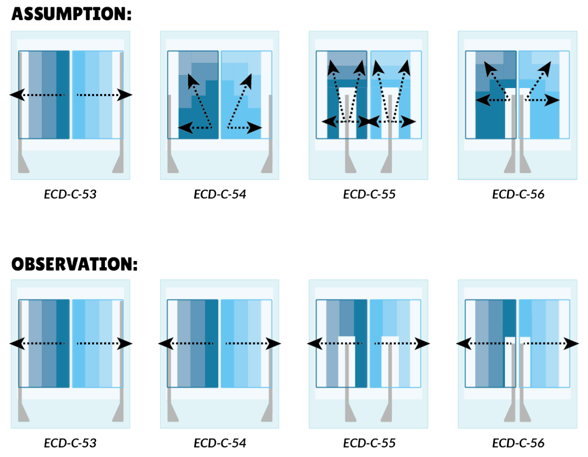



figure 4.24: Co-planar ECD: Influence of the design of the implementation of the electrodes within the EC layer, assumption (a) and observation (b).



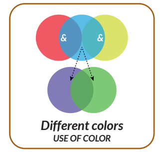
### 4.5.2. VOLTAGE FLOW

Combining the fact that the change of color within electrochromic material is induced by an applied potential with the color flow effect, left the question whether this color flow could be linked to the voltage; create a voltage flow. All eight designs created in order to create this voltage flow (see appendix I.4) showed a clear flow of color, however this flow was not related to the applied potential. Although the voltage flow could not be achieved naturally, one of the designs (ECD-C-76) showed an opportunity in order to create a programmed voltage flow, see figure 4.26; a design opportunity. As all six squares could be triggered individually (figure 4.25), they could be connected to an PCB that is programmed: the higher the voltage, the more squares will be triggered to color.

Figure 4.25: Design of ECD-C-76 with six individual squares.

Figure 4.26: ECD-C-76: All squares could be individually triggered.

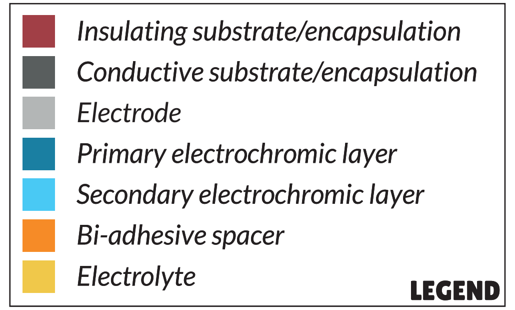
### 4.5.3. USE OF COLOR: DIFFERENT COLORS




As aforesaid, creating different colors can be defined as one of the five potential ways of using the controlled color change of electrochromic materials within product design. Within this paragraph, this will be experimented with.

As explained in chapter 1.1., the specific colors that an electrochromic material is able to change between depends on the length of the molecule chain (i.e. wavelength). Meaning, that each material represents a different color, thus when other colors are required in the design, a different material should be purchased. As electrochromic materials are relative expensive and to simplify the production, there was researched whether different colors could be obtained with one specific electrochromic material. As the Ynvisible electrochromic ink is used for all material tinkering, the starting points of this experiment are transmissive blue and sky blue.

To obtain different colors several methods are tried: create an optical illusion, use a colored substrate, use a colored surface matching the surface of the EC material and print an image on the overhead sheet. Besides this, electrochromic materials are also mixed with other materials in primary colors to create the secondary colors purple and green. The goal of all methods was to play with primary colors (blue-red-yellow), secondary colors (purple-green) and white. As blue and red mixed create purple and blue and yellow create green. By using




white, the transparency of the translucent blue was tried to be improved.

Using a ***colored substrate***, when using a colored substrate, it was expected that the color of the EC material in its colored state would be influenced by the color of the substrate; e.g. creating purple and green by using a red and yellow cardboard substrate. However, as can be seen in appendix I.4.1., there was no color mixing. Which led to the conclusion that: ***the colored substrate only influenced the color of the EC material in its darkness (i.e. contrast)."***

As using a colored substrate did not influence the color of the material as expected, the idea of the art movement of the pointillism was obtained. The assumption is made that when two colors are placed closely next to each other -or on top of each other in this case- the illusion of a mixed color will be perceived by the human eye. In order to achieve this, underneath the electrodes, a layer of acrylic paint is applied with the exact surface as the EC material print (figure 4.27). As can be seen in figure 4.28 and QR-code 8, there can be concluded that: ***if the colored layer and the EC layer have exact the same surface, it creates an illusion of color change.***

See appendix I.4.1. for more experiments regarding a painted layer underneath the EC layer. Unfortunately, this method is harder to implement in an ECD using a conductive layer, as the painted layer will then isolate the conductive layer from the EC layer.

Since using a painted layer underneath the EC material indeed created an illusion of a different color, but is creating irregularities on the surface and increasing the ease of production, using an overhead sheet with a print is researched. As can be concluded from this, there is a slight color change that could be identified as purple or green, however the intensity of the color change is larger for the painted layer underneath, as this layer is less transparent than the printed layer on the overhead sheet. Thus it can be concluded that: ***the more opaque the extra colored layer, the better the color mixing into secondary colors."***

Finally, as the Ynvisible electrochromic ink is translucent blue in its bleached state, there is tried to mix it with other (colored) materials in order to create a different color. The materials that are researched are: acrylic color paint, ecoline, coloring pigment, food coloring, aquarelle paint pigment and pastels. Consult appendix I.4.1 for all ECDs created for all individual materials.

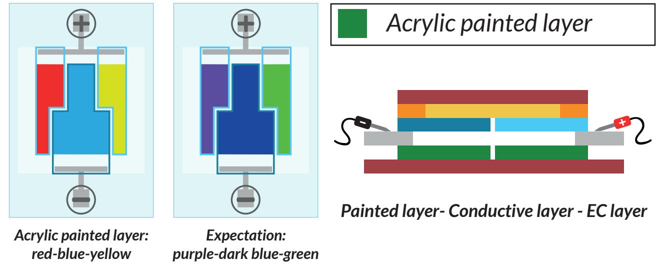



Figure 4.27: ECD-C-34: Different colors of ECD-C-34. Top view of the acrylic painted layer (a), expectation (b) and layer structure (c).

From this it could be concluded that the aquarelle pigment influences the starting color (i.e. bleached state), however not the colored state. As can be seen in figure 4.29-a and 4.29-b (next page), it starts with pastel purple and green colors in the bleached state, which color to its original bright blue color in the colored state. In figure 4.30-left, it is mixed with white aquarelle paint pigment. This changes the color to less bright blue in its colored state.

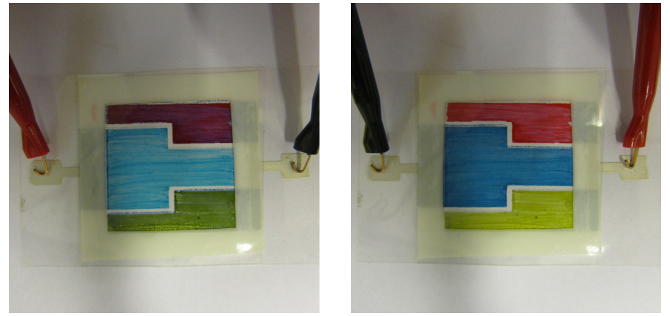


Figure 4.28: Different colors of ECD-C-34. Primary EC layer (a): purple-blue-green (a) and secondary EC layer: red-blue-yellow (b).

QR-code 8: ECD-C-34: Different colors: color change.



As the assumption is not fulfilled, another interesting aspect is to be detected: ***mixing the Ynvisible electrochromic ink with aquarelle pigment influences the color of the EC material in the bleached state in a pastel-colored way, without influencing the intensity of the sky blue color in the colored state."***

### 4.5.4. USE OF COLOR: ALLOW SOMETHING ELSE TO APPEAR/DISAPPEAR


Finally, the fifth potential way of using the controlled color change of electrochromic materials within product design is to allow something else to appear/disappear. As aforesaid, the controlled color change of electrochromic materials occur between the bleached and colored state. As color can not only be used to let an image appear, but also to cover an image to be seen, this is tried to obtain with electrochromic materials. As the printed image on the substrate is visible when the EC material is in its bleached state, its colored state is expected to cover this image. However, as can be seen in figure 4.31, the opacity of the electrochromic material is to little for letting the image of the butterfly disappear, although the image of the butterfly is already printed on an overhead sheet with an opacity of 50 and 75%. From this it can be concluded that: ***the transparency of the Ynvisible electrochromic ink is too high to allow an underlaying image to appear/disappear"***

Furthermore, allow something else to appear/disappear can also be defined as playing with the design of the images; e.g. creating an optical illusion. As can be seen in figure 4.32, this is tried to obtain with the optical illusion of two faces that create a chandelier.

### 4.5.5. CONTRAST WITHIN THE EC LAYER

All images are created by using screen printing as method. To research the effects of the EC layer itself, several images are explored by using a brush to apply the EC material. As can be seen in figure 4.33, the EC layers have uneven distribution due to irregularities in height. This resulted into an artistic, hand painted effect exploring depth and contrast in the image; i.e. creating an illusion of depth due to these contrast differences. This effect could be defined as a design possibility in order to influence the aesthetics or appearance of the design. It can be concluded that: ***an illusion of depth due to contrast differences is required, the EC layer should be manually painted."***

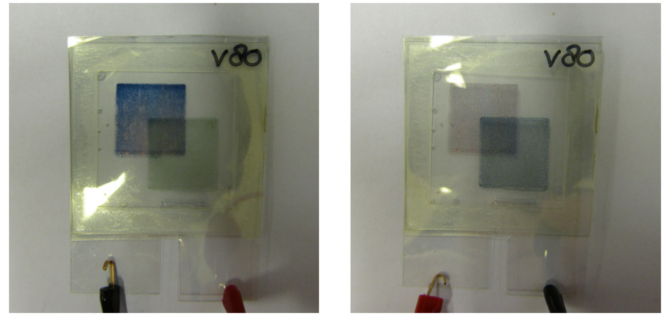


Figure 4.29: Color change: mixing with red and yellow aquarelle paint pigment: primary (a) and secondary (b) EC layer.

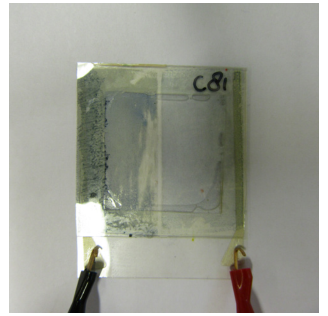


Figure 4.30: Color change: mixing with white aquarelle paint pigment.

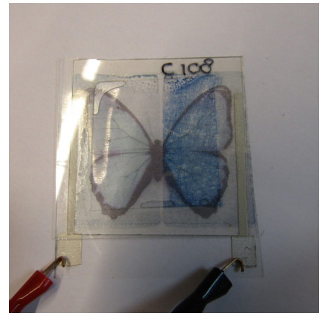


Figure 4.31: Allow something else to disappear.

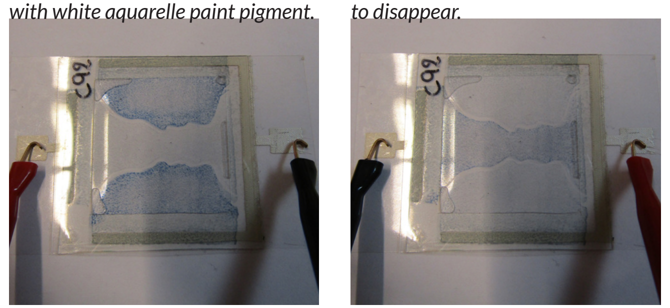


Figure 4.32: ECD-C-92: primary (a) and secondary (b) EC layer.

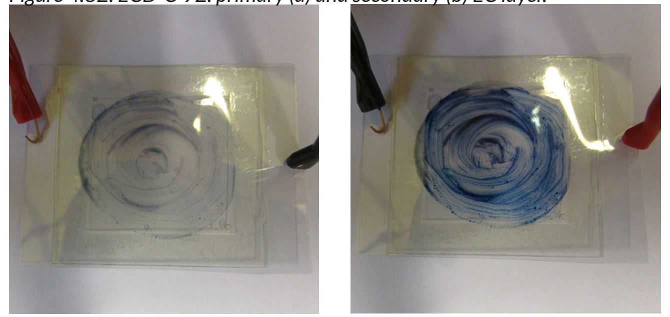


Figure 4.33: ECD-V-51: Electrochromic material applied with a brush: bleached (a) and colored (b) state.

# 5 MATERIAL BENCHMARKING

*Within this chapter the transition between the electrochromic material and its (possible) applications in product design will be made. First of all, the current applications that are already on the market will be reviewed. After which possible applications from literature research will be reviewed. Where finally, the electrochromic material will be benchmarked with other chromogenic materials.*

*Icehotel- Jukkasjärvi. Copyright by ChromoGenics (2021).*



According to Karana et al. (2015), the goal of the material benchmarking is to: "position the material amongst similar and/or alternative materials, to generate insights on potential application areas, emerging materials experiences and other emerging issues within the design domain". There is chosen to compare electrochromic materials with other chromic materials, as the application of all products using these materials focusses on a triggered color change. ***Chromic materials*** (i.e. chameleon materials) are according to Mattila (2010), materials that have a change of color that is induced by an external stimulus.

The following chromic materials phenomena can be distinguished: photochromism, thermochromism electrochromism and piezochromism. As can be seen in table 5.1, the color of ***photochromic materials*** is induced by light (e.g. UV-light, a flash light, et cetera), the color of ***thermochromic materials*** by heat and ***piezochromic materials*** by applied stress. Where electrochromism, thermochromism and piezochromism respond to a controllable input, photochromism is immediately induced by light. As the technology of piezochromism is still in development, relatively little is known of the technological characterization of this material class.

By disregarding the input needed, all four material groups have the same result: a change of color. The unique material property of its memory effect, is indeed unique when comparing with the other materials. Only photochromic materials possess a memory effect of only 30 seconds. Meaning for this comparison, the memory effect will be disregarded.

When looking at the different applications of the materials, five different product categories can be defined: informational, informational: warning, entertainment, toys and wellbeing. As can be seen in figure 5.1, thermochromic and photochromic materials are broadly implemented.

When comparing electrochromic materials to these product categories, an opportunity for implementation in the product categories: ***informational***, ***informational: warning*** and ***toys*** can be found. As electrochromic materials have an controlled color change through the applied potential, these three product categories seem viable.

| | ELECTROCHROMISM | PHOTOCHROMISM | THERMOCHROMISM | PIEZOCHROMISM |
|---|---|---|---|---|
| *External stimulus* | Potential | Light | Heat | Stress |
| *Input needed* | Low voltage operation | Immediately changing through light | Adjustable switching temperature | High pressure dependency |
| *Memory effect* | Yes | Yes, approximately 30 seconds | No | No |
| *TECHNICAL CHARACTERISTICS* | | | | |
| *Color contrast* | Depending on amount of input | Depending on amount of input | Depending on amount of input | Depending on amount of input |
| *#Colors obtainable* | Various. Depending on the wavelength of the specific material. | Various. Ability to mix with other pigments. | Various. Temperature depending. | |
| *Resolution* | Relative low | High | High | |
| *Switching time* | <16ms, 1-100ms, 10-750 ms | <1min | 1s/6s | |
| *Thermal stability* | -30 to >100 degrees | -40 to >250 degrees | -30 to <500 degrees | |
| *Light stability* | Very good | Good | Very good/good/insufficient | |
| *Transparency* | Yes | Yes | Not fully? | |
| *Flexibility* | Partially, depending on substrate and encapsulation. | Yes, depending on substrate | Yes, depending on substrate | |
| *Water resistance* | Yes, depending on substrate and encapsulation | Yes | Yes | |

*Table 5.1: Chomic materials*


Figure 5.1: Material benchmarking.

UNDERSTANDING THE MATERIAL



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# 6 MATERIAL CHARACTERIZATION

*Within this chapter, the literature research is combined with the results and insights from the material tinkering phase, resulting into a material characterization of the 'Ynvisible Electrochromic Ink'. A distinction will be made between its technical and experiential characterization. According to Karana et al. (2005), the technical characterization of a material are the inherent qualities, constraints and opportunities when applied in products. The experiential characterization, on the other hand, will be reflected on the four different experiential levels: sensorial, interpretative (meaning), affective (emotion) and performative (actions/performances).*



Prior to the characterization of the material on its technical and experiential properties, it is relevant to note the three unique material properties again as these properties define the material as being electrochromic, see figure 6.1.

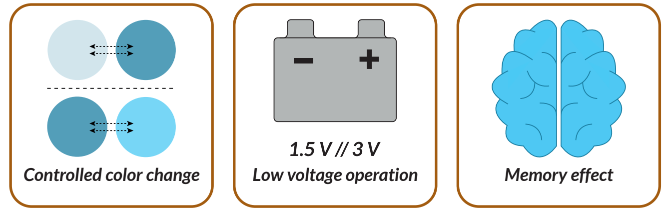



*Figure 6.1: Unique material properties of electrochromic materials.*

## 6.1. TECHNICAL CHARACTERIZATION

According to the Material Driven Design Method of Karana (2005), the technical characterization of a material starts with the ***main technical properties*** and includes the inherent qualities, constraints and opportunities for application within products. When looking at CES Edupack (2019), material properties are divided into six subcategories that are relevant within this thesis: mechanical, impact & fracture, thermal, electrical, optical and processing properties. The technical characterization of the 'Ynvisible Electrochromic ink' is based on the literature research (chapter 1 till 3), material benchmarking (chapter 4) and the material tinkering phase (chapter 5).

As electrochromic materials are processed as an ink (pigment/paste/gel) printed on a substrate within a sandwich structure of layers, all layers contribute to the technical properties of the ECD. Therefore, both the ECD as a whole and the individual layers will be taken into account.

### 6.1.1 MECHANICAL PROPERTIES

All mechanical properties of an ECD are primarily depending on the substrate and encapsulation used, as these are the layers that provide strength and support. However, independent from the substrate and encapsulation used, the bi-adhesive spacer prevents the ECD from elongation; i.e. ***elasticity***. And the electrolyte from bending substantially, as this causes the electrolyte to irregularly spread, inducing failure of the ECD; i.e. ***flexibility*** of the ECD.

### 6.1.2. IMPACT AND FRACTURE

Like the mechanical properties, the impact and fracture properties of an ECD are primarily influenced by the substrate and encapsulation used. Important to mention is the ***fracture toughness*** of the conductive layer, as when little cracks are formed in this layer, it possibly leads to dysfunction of the ECD.

### 6.1.3. THERMAL PROPERTIES

No clear information could be found regarding the thermal properties of other layers than the substrate and encapsulation, depending on the substrate and encapsulation used. Thus, no conclusions can be drawn regarding the influence of the individual layers on the thermal properties of an ECD.

### 6.1.4. ELECTRICAL PROPERTIES

The electrical resistivity and conductivity of the ECD in use is fully depending on the substrate and encapsulation used however the electrical conductivity ***inside*** the ECD is fully dependable on both the conductive layer and electrochromic layer used, as a closed loop circuit is required. As aforesaid, when using a (conjugated) conducting polymer this layer is able to function both as electrochromic and conductive layer.

### 6.1.5. OPTICAL PROPERTIES

The optical properties of an ECD are highly influenced by all layers of the ECD. Different categories within the optical properties could be distinguished: transparency, use of color, design of the images displayed and interaction between the EC layers. As can be seen in figure 6.2 (next page), all optical properties of the technical characterization are combined with their dependencies to distinguish the four stacking sequences.

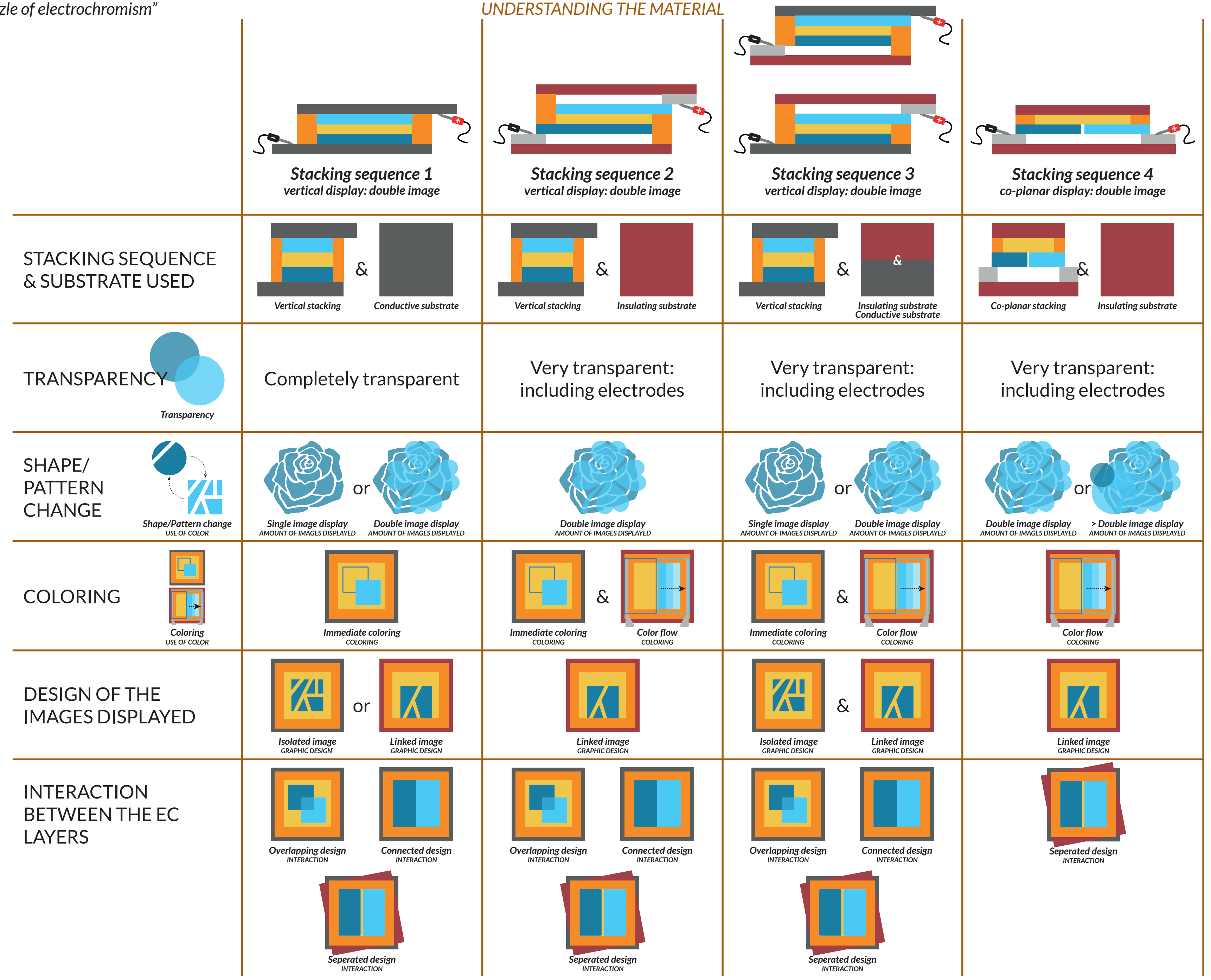
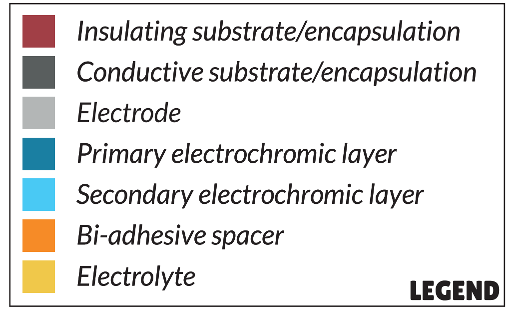
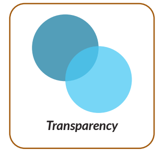



Figure 6.2: All technical characterisations are combined with their dependencies to distinguish the four stacking sequences.



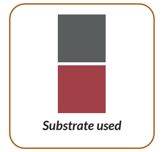


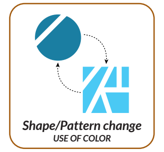

*Transparency.*
The transparency of an ECD is influenced by all layers. By CES Edupack (2019), a transparent transparency is defined as to be very good though it may be inherently tinted. As the 'Ynvisible electrochromic ink' is translucent blue in its bleached state, it can be characterized as being transparent, as well as the bi-adhesive spacer. On the other hand, the electrolyte can be defined to be of "optical quality", as it has outstanding transparency ("CES EduPack," 2019). From this, it can be concluded that the base of the ECD is to be transparent. However, the material choice for both the substrate/encapsulation and the electrodes influences this transparency heavily.

First of all, a distinction between a transmittance and reflective operation mode should be made. As aforesaid, an ECD operating in transmittance mode is fully transparent. The reflective operation mode, on the other hand, leaves opportunity for playing with colored effects. The addition of electrodes though (stacking sequence 2, 3 and 4), disrupts the transparency when another material than the 'Ynvisible Electrochromic ink' is used.

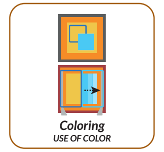
*Substrate used.*
Together with the stacking sequence (vertical or co-planar), the substrate forms the substrate the base of all optical effects created.



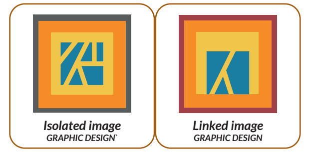

*Use of color: shape/pattern change.*
A distinction is made between a single image display, a double image display and a display displaying more than two images. A single image display is only possible when using a conductive substrate (SS#1 and partially for SS#3). Where a double image display is possible within all stacking sequences. When more than two images are required, a co-planar display (SS#4) should be used. For this, two options are to be distinguished: either placing two separate displays on top of each other (creating overlap) or by creating display where all individual images are in the same layer but connected to individual electrodes.



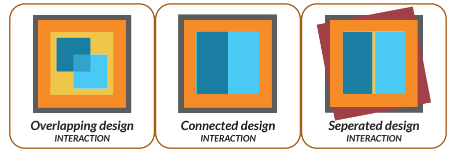

*Use of color: coloring.*
As explored in chapter 5.5.1, using an insulating substrate leads to a color flow, where both a conductive substrate and overlap experience immediate coloring of the images.




*Design of the images displayed.*
As mentioned in chapter 2.2., the design of the images displayed is highly depending on the substrate used. As in order to be able to complete the ion transfer, all parts of the design (EC layer) should be connected to either a conductive substrate or electrodes. This means that all parts of the image for a conductive substrate can be isolated; i.e. loose parts. But for an insulating substrate, that all parts of the design need to be linked to the electrodes, thus to the bi-adhesive spacer frame.




*Interaction between the EC layers.*
As mentioned in chapter 2.2, the interaction of the EC layers depends on the vertical or co-planar stacking sequence. The EC layers of a vertically stacked EC can overlap, connect or be separated. However the EC layers of a co-planar stacked ECD is limited, as both layers have to be separated to avoid a short circuit. To increase its switching speed, this separation should be as small as possible, with a minimum set at 1 mm.




*6.1.6. PROCESSING PROPERTIES*
As within this research all ECDs are created by means of manually *screen printing* using vinyl stickers as stenciling method, no further conclusions could be drawn towards other production methods. Important to note is that, using vinyl stickers as stenciling method is relative fast and easy, but also results into limitations regarding details of the image to be displayed. When a higher resolution image is required, photo emulsion should be researched to be used.

## 6.2. EXPERIENTIAL CHARACTERIZATION

As aforesaid, the experiential qualities of the material are reflected on four different experiential levels: sensorial, interpretative (meaning), affective (emotion) and performative (actions/performances). The performative level is excluded from this characterization, as the interaction (putting the voltage on the material) of the performed test is not representative, as prototypes are tested by using a lab power supply.

In order to determine the experiential characterization of the electrochromic material through user research#1, seven different comparisons of prototypes are shown to 6 participants. The full user research#1 can be found in appendix J. The showed prototypes included: a single image display versus a double image display, a screen printed image of a rose and a painted image, a reflective surface and a reflective surface with overlap, 8 different co-planar designs (these are addressed as one comparison) and a design that changes color. All displays are analyzed on the sensorial level (visual), interpretative level (meaning) and affective level (emotion).

Starting with the ***sensorial level***, seven senses are to be defined: vision, hearing, smell, taste, touch, balance and body awareness. As balance and body awareness are irrelevant for this research, they are excluded. As this thesis focusses on electrochromic materials; hearing, smell, taste and touch are also excluded as they are mainly influenced by the substrate/encapsulation used. Since a visual change is one of the main characteristics of the material, the focus is mainly on vision. As can be seen in figure 6.3, the most relevant analogies are noted from the user research#1, see appendix K for all analogies.

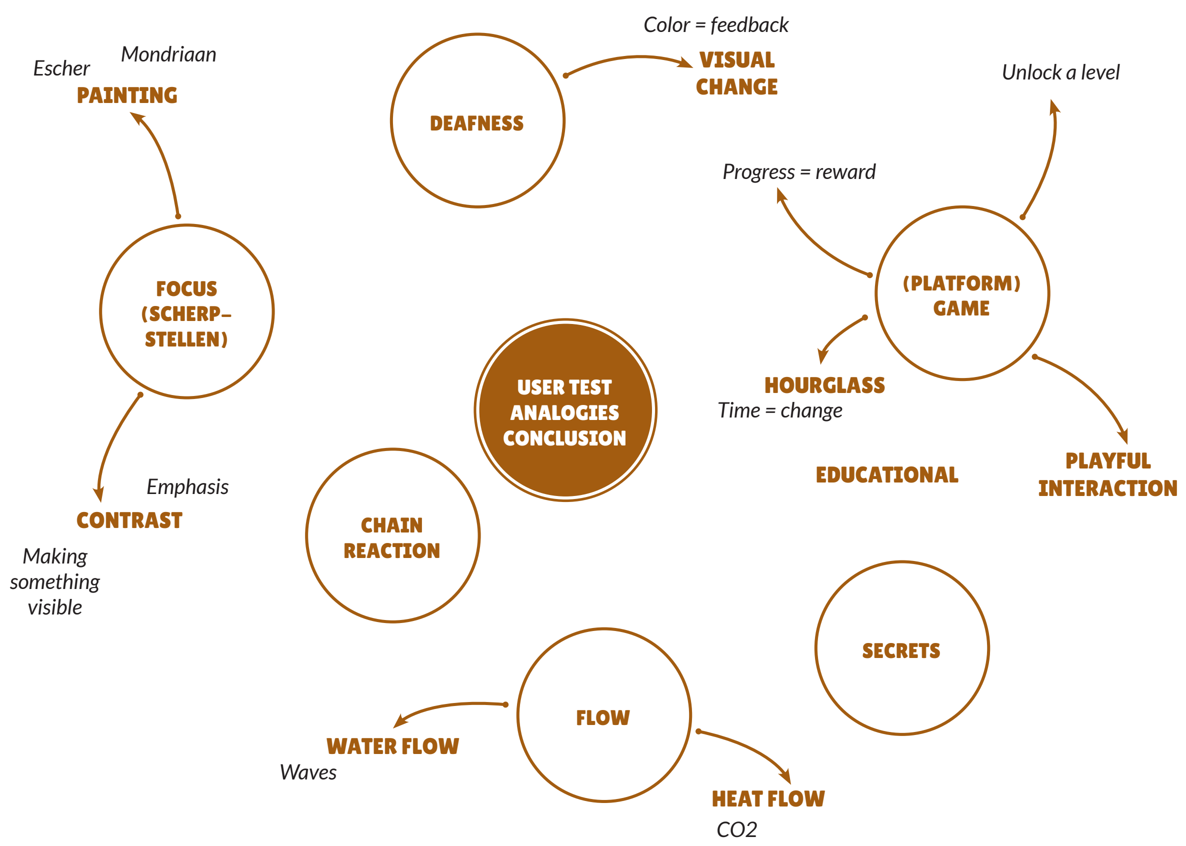



Figure 6.3: Most relevant user research#1 analogies.



For the ***interpretative level***; the meaning participants appointed to the material is analyzed. In general the material is perceived rather playful than serious, especially for the double image, co-planar and the color changing designs. When looking at whether it is rather extraordinary or average, in general it can be concluded that the material is perceived as extraordinary when more things occur; e.g. double image display. A single image display of an square and the rose are thus perceived as average, see figure 6.4. The perception of the usefulness of the material by the participants is split, only the single image display of a square (test 1.1) could be defined as an outlier. Which is an interesting example, as it is also perceived as average and serious. When looking at all the data, it could be concluded that the six participants associate serious/average designs with usefulness.
Besides analyzing the meaning users appointed to the material, the evoked emotions are analyzed too: ***affective level***. In general it can be concluded that the material evokes positive emotions, such as inspiration, amusement and satisfaction. Especially the co-planar designs made the participants feel inspired, as the color flow was surprising. Overall, the prototypes that made the participants feel inspired evoked the emotion amusement too. The single image displays of a square (test 1.1) and the rose (test 2.1) felt predictable to the users, the others were surprising.

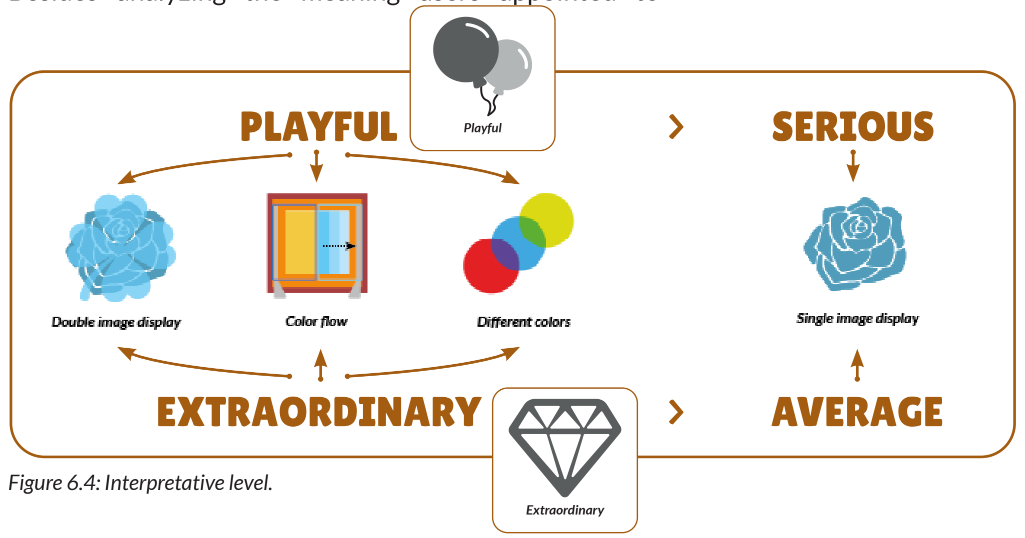



Figure 6.4: Interpretative level.

# 7 MATERIAL EXPERIENCE VISION

*Within this chapter all preliminary research and corresponding conclusions are combined into a material experience vision. Karana (2015) defines a material vision as: "the ultimate aim of the design process, which can help designers to summarize various findings under a cohesive shole and guide their decisions through the process of design".*

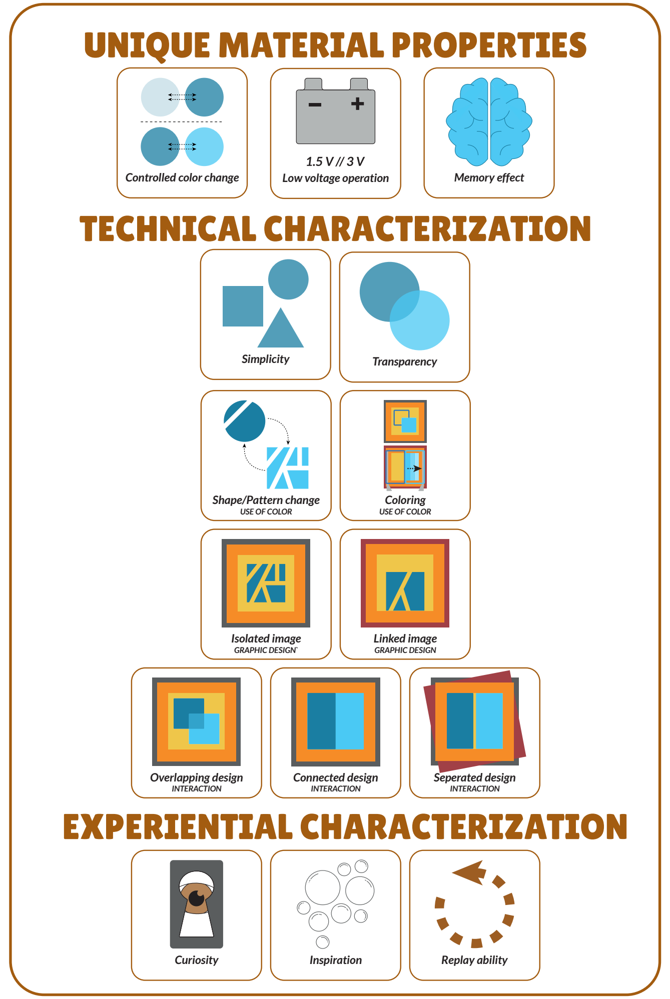
*Photo by Kelly Sikkema on Unsplash*



The three main unique properties of electrochromic materials are: ***controlled color change***, ***low voltage operation*** and the ***memory effect***. During the material tinkering phase, the material has proven to be challenging to implement as well as diverse in its (visual) properties. Ideally, the material is used within a product design that fully utilizes its technical and experiential characterization while highlighting its unique properties.

With all these possibilities and challenges, the following material experience vision is formulated, to establish what I -Resy Aarts- want to accomplish within this project:

> *"I want to design a product demonstrator that fully utilizes the **technical** and **experiential characterization** of electrochromic materials as well as highlighting its unique properties; e.g. controlled color change, low voltage operation and the memory effect. The main function of this demonstrator is to emphasize the **simplicity** and **possibilities** of integrating electrochromic materials in product designs. With as ultimate goal to **inspire designers** to make use of electrochromic materials in their (product) designs, through entice their creativity and curiosity."*




Electrochromic materials can be defined as a scenario 2 material; e.g. a relatively unknown material, accompanied by a fully developed sample (Karana et al., 2015). The opportunity for these materials is defined as to manipulate the ***sensorial qualities*** of the material. For electrochromic materials, the focus will thus be mainly on the visual (optical) qualities of the material, e.g. the technical and experiential qualities defined in the previous chapter.


Due to the fact that this is the first graduation project researching electrochromic materials for use within product design at the Emerging Materials group of the TU Delft, there is chosen to design and develop a demonstrator that highlights the simplicity of an ECD. The color change of electrochromic materials is triggered by an applied potential, meaning sensors could be used to control the color change. As integrating sensors and using an PCB to control them would complicate the interaction and perception of designers on the material, there is chosen to focus on the simplicity of integrating it, e.g. less components as possible.

I also believe that by showing the material in its simplest form as possible, designers would be more inspired than when a complicated circuit is shown, since more options are left open. The Human Experience Catalog (Desmet, 2019), states inspiration as the feeling when you suddenly have a new idea or insight, or see the world in a different light.

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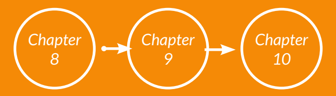
# CREATING PRODUCT CONCEPTS

*With the material experience vision as starting point, within the 'creating product concepts' phase ideas and concepts will be created for a product demonstrator that demonstrates the opportunities of EC materials in product design. It has to demonstrate both the unique material properties as well as the technical and experiential characterization of electrochromic materials, while emphasizing its simplicity and possibilities of integration in product design. With as ultimate goal to inspire designers to make use of electrochromic materials in their (product) designs.*

*First, ideas are generated within the ideation generation phase (chapter 8), after which three ideas are further developed into concepts (9), with finally the 'proof of concept' of the concept to be chosen (10).*




8. Ideation
9. Conceptualization
10. Proof of concept

# 8 IDEATION

*Within this chapter, the ideation phase will step by step be briefly discussed. First a general ideation is held within the product categories of entertaining, decorative and informational/educational products. After which, from each category one idea is further developed in order to choose an idea direction. Within this final idea direction another brainstorm is held that ultimately led to three concepts.*

*Photo by Kelly Sikkema on Unsplash*



Resulting from the material experience vision, the goal of the ideation phase was clearly defined. As the product to be designed, will function as a demonstrator, demonstrating the unique properties, technical-and-experiential characterizations of electrochromic materials in order to inspire designers to use this material in their own designs. The focus of the demonstrator will be on showing the material in its simplest form as possible.

When combining the material benchmarking (see chapter 5) with the user research analogies (see appendix K), four product categories can be defined: entertaining products, decorative products, informational/educational products and products for wellbeing. As products using electrochromic materials that are currently on the market are graded primarily within the wellbeing product category, there is chosen to focus on the other three categories within this thesis, see figure 8.1. As source of inspiration, mind-maps are created by analyzing products that are currently on the market based on the use of color, (low) voltage operation and 2D products/flat surfaces, see appendix L.

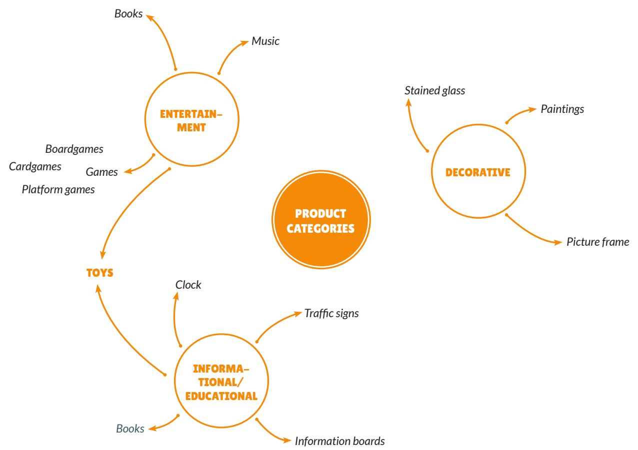



*Figure 8.1: Product categories.*

From the use of color in products in general analysis, it can be concluded that color in products is mainly used for fun, to distinguish/recognize, for educational purposes, as an indicator, in a series of products to meet personal preferences of the user or to create collectors' items or as use cue. With these objectives in mind, ideas are created within each product category, see appendix M till O.

## 8.1. GENERAL IDEATION

First of all, ***entertaining products***. Entertaining products are products that provide amusement or enjoyment to the user. Meaning, both the function (directive) as the aesthetics of the product are of importance. Within this product category, color is mainly used for fun, as personal preference/collectors' item, to distinguish/recognize or as use cue. Material is mainly used to strengthen the functioning of the product. See appendix M for the entire ideation phase.

Secondly, ***decorative products***. Decorative products serve to make something look more attractive. Rather aesthetics than function are of importance for this product category. Meaning that fun and personal preference/collectors' item are the main ways color is used within these products. See appendix N for the entire ideation phase.

Finally, ***informational/educational products***. Within this category, products are educating or enlightening the user by providing information. The function (directive) of the product is superior to the aesthetics. Color is mainly used as an indicator or warning, for educational purposes, to distinguish/recognize or as use cue. See appendix O for the entire ideation phase.

## 8.2. IDEA DIRECTION DEFENITION

Within each of these three product categories, one idea is highlighted; memory game, stained glass and a puzzle, see appendix M till O. From these three ideas, the direction of a puzzle is chosen to further develop. As a modern stained glass wouldn't function as an inspiring demonstrator since electrochromic materials are already broadly applied in windows (see chapter 4.1.1.). A memory game would be an interesting option for a demonstrator since it highlights its memory effect. However, in a memory game only single image displays (SS#1) are to be shown, meaning it would not fully demonstrate all potentialities of the material as defined in the material experience vision. For these reasons, there is chosen to further develop the idea direction of a puzzle. As both a puzzle and electrochromic materials are things that are difficult to understand or explain ("Puzzle," 2021). Besides this, both make use of the action-reaction principle; an action triggers a reaction. For electrochromic materials, the applied potential triggers a change of color. Within a puzzle, the user places a piece which allows it to see the full picture more clear. The main challenge within this direction will be to use the thickness of the bi-adhesive spacer in advantage, as each piece has an individual frame around it that is not able to color.

Within the puzzle direction a brainstorm is executed on the different possibilities of integrating electrochromic materials into a mechanical puzzle. A mechanical puzzle is a puzzle where the user manipulates the whole object or parts of it in order to solve it. See appendix P for the inspirational mind map and figure 8.3 for the brainstorm. From this brainstorm, three concepts were created, each based on a different kind of mechanical puzzle, which will be explained in the next chapter.



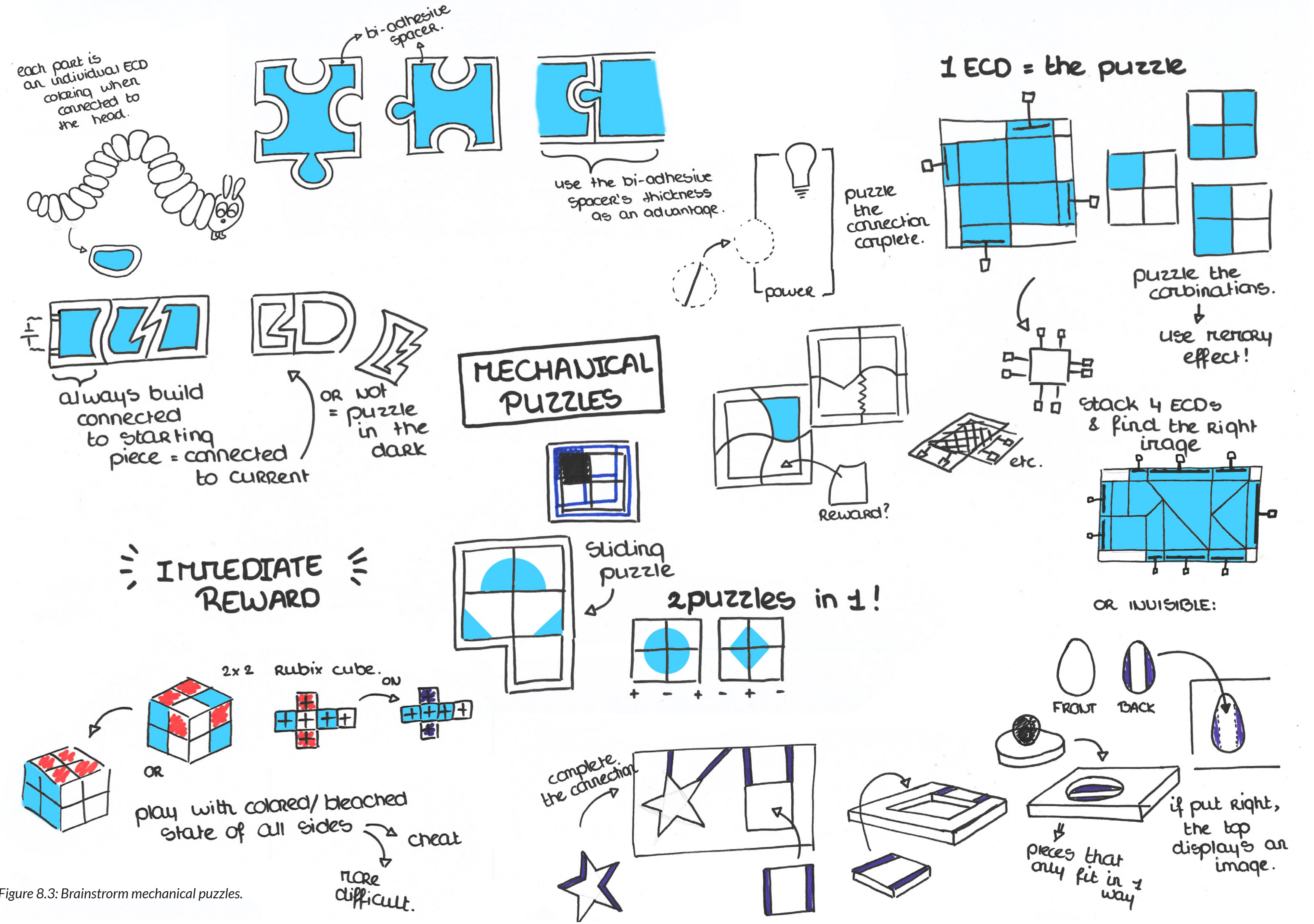



Figure 8.3: Brainstrorm mechanical puzzles.


# 9 CONCEPTUALISATION

*Within this chapter, the three concepts created from the mechanical puzzle brainstorm that is visualized in the previous chapter are explained in detail. At the end of this chapter all concepts are analyzed by a Harris Profile, which eventually led to the choice of concept 1 as demonstrator.*



## 9.1. CONCEPT 1: SLIDING PUZZLE

As can be seen in figure 9.2 (page 70), the first concept is based on a sliding puzzle. The inspiration for this was -next to sliding puzzles- also derived from the Wasgij puzzles. Wasgij puzzles are jigsaw puzzles where the user does not know what it is puzzling, as the front of the box is not the actual image it is copying. Combining these two puzzle concepts, resulted into a puzzle concept where the puzzler (designer) does not know what it is puzzling. On top of this, each puzzle piece is a double image display, that results into two puzzles that can be puzzled simultaneously by reversing the potential.

However, as the clearance between the individual pieces required for smooth operation of a sliding puzzle could interfere with the precise connection required for the conductivity, another concept is created. As can be seen in figure 9.3 (page 71), this concept is based on a jigsaw puzzle where the individual pieces not slide but rather click together by using magnets.

## 9.2. CONCEPT 2: JIGSAW PUZZLE

As can be seen in figure 9.4 (page 72), the second concept is based on jigsaw puzzles created for children. Where the child immediately receives feedback from the surroundings when it lays a piece of the puzzle on the right way. However, the memory effect is not used in a positive way, as the fun part is the immediate feedback, although when the child plays the puzzle twice in a row, the Smurf and the water stay colored, so the memory effect sabotages the whole puzzle principle.

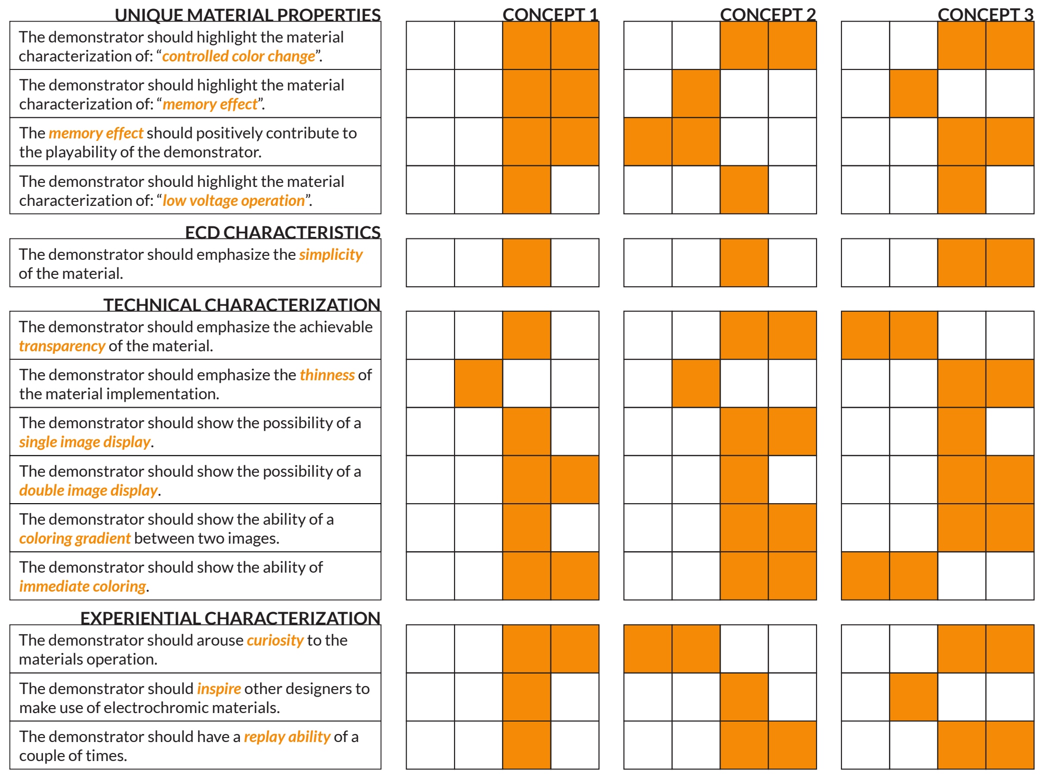



*Figure 9.1: Harris profile.*

## 9.3. CONCEPT 3: MOSAIC PUZZLE

As can be seen in figure 9.5 (page 73), the third concept is a mosaic puzzle. This concept is based on a combination between the game "Electro", the hammer tap game and a tangram puzzle. The idea is that the user either, puzzles different combinations on the corresponding cards, or makes a time dependent game of it to color a certain shape the first.

## 9.4. CONCEPT CHOICE

All concepts are analyzed using a Harris profile, see figure 9.1. By using the Harris profile, the main design requirements are ranked in order of their importance with the most important one on top (Boeijen, Daalhuizen, & Zijlstra, 2020). It is a visual method that not involves calculations.

When comparing the three Harris profiles, the second concept clearly comes third (figure 9.1). Where the first and third concept come to a close first. As both are suitable as demonstrator, within a meeting with K.M.B. Jansen and T. Essers it was decided to use both as a demonstrator for the electrochromic material. Use ECD-C-89 (concept 3) as a small demonstrator, as it is already operating and does not necessarily need the casing to be a good demonstrator. However as it only demonstrates a co-planar stacking sequence, there is chosen to further develop concept 1 into the final demonstrator, as it offers the most possibilities in demonstrating the differences between the stacking sequences (vertical/co-planar).

# Concept 1: Sliding puzzle

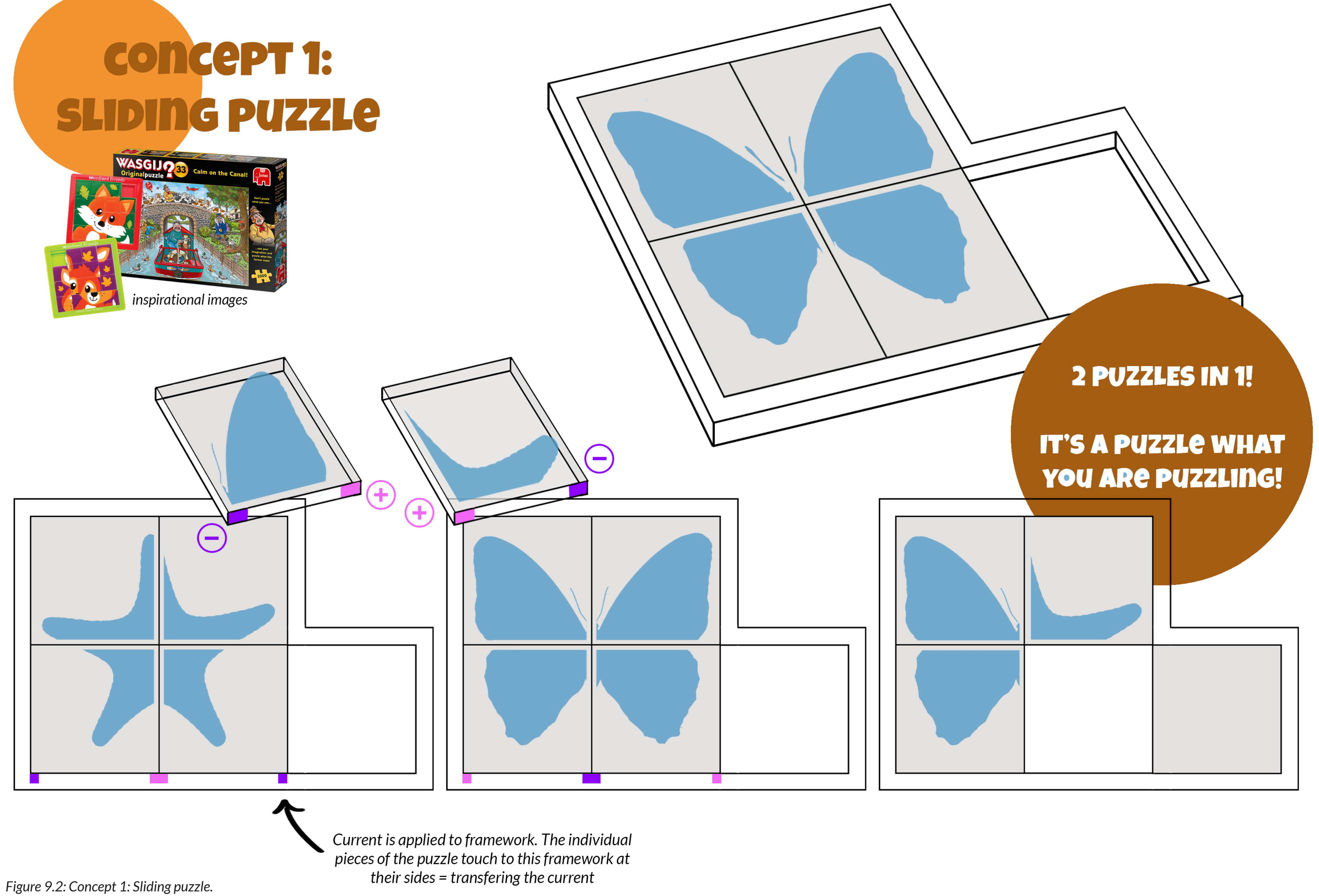



Figure 9.2: Concept 1: Sliding puzzle.



# Concept 1: Sliding puzzle 2

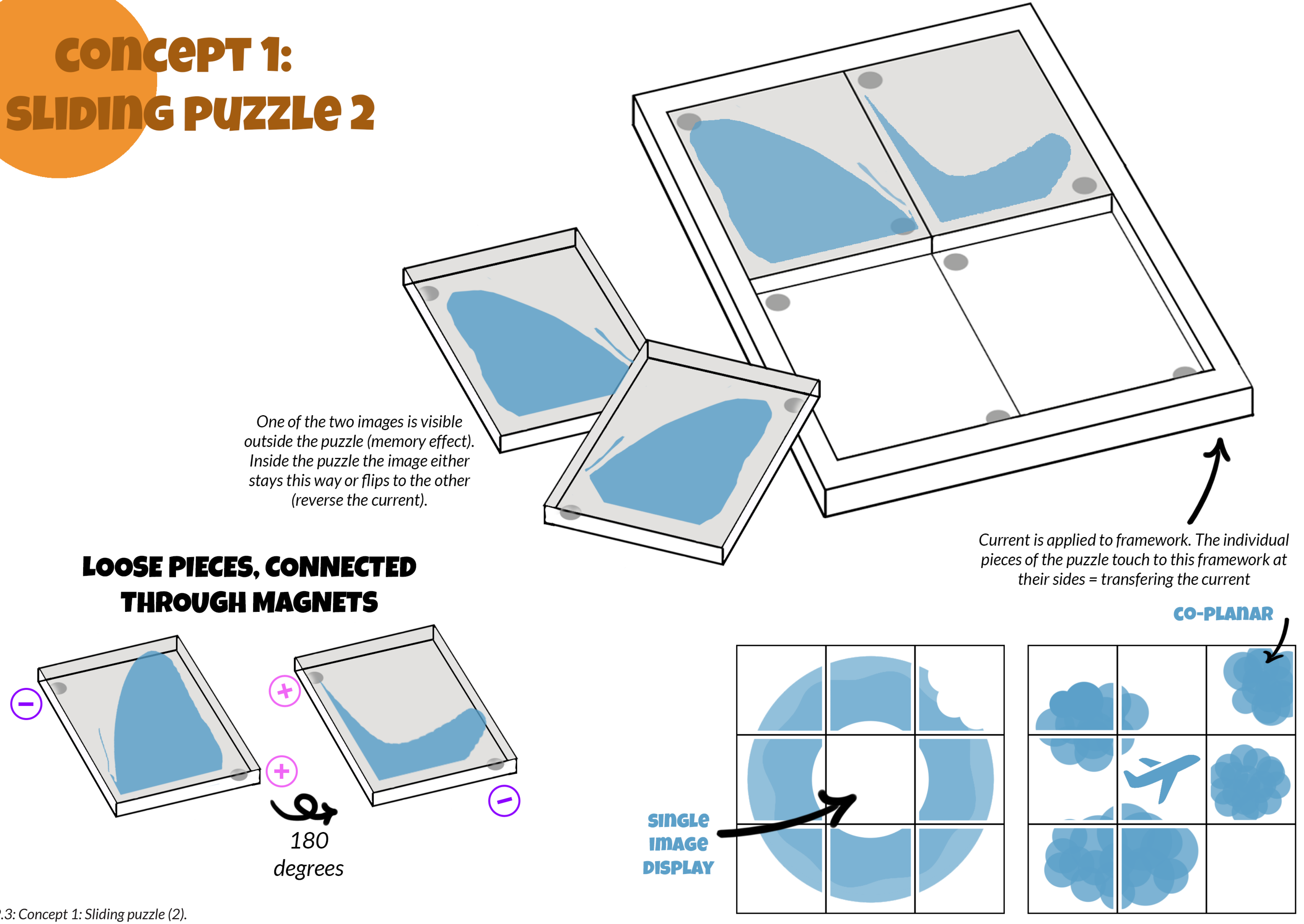



Figure 9.3: Concept 1: Sliding puzzle (2).

# Concept 2: Jigsaw puzzle

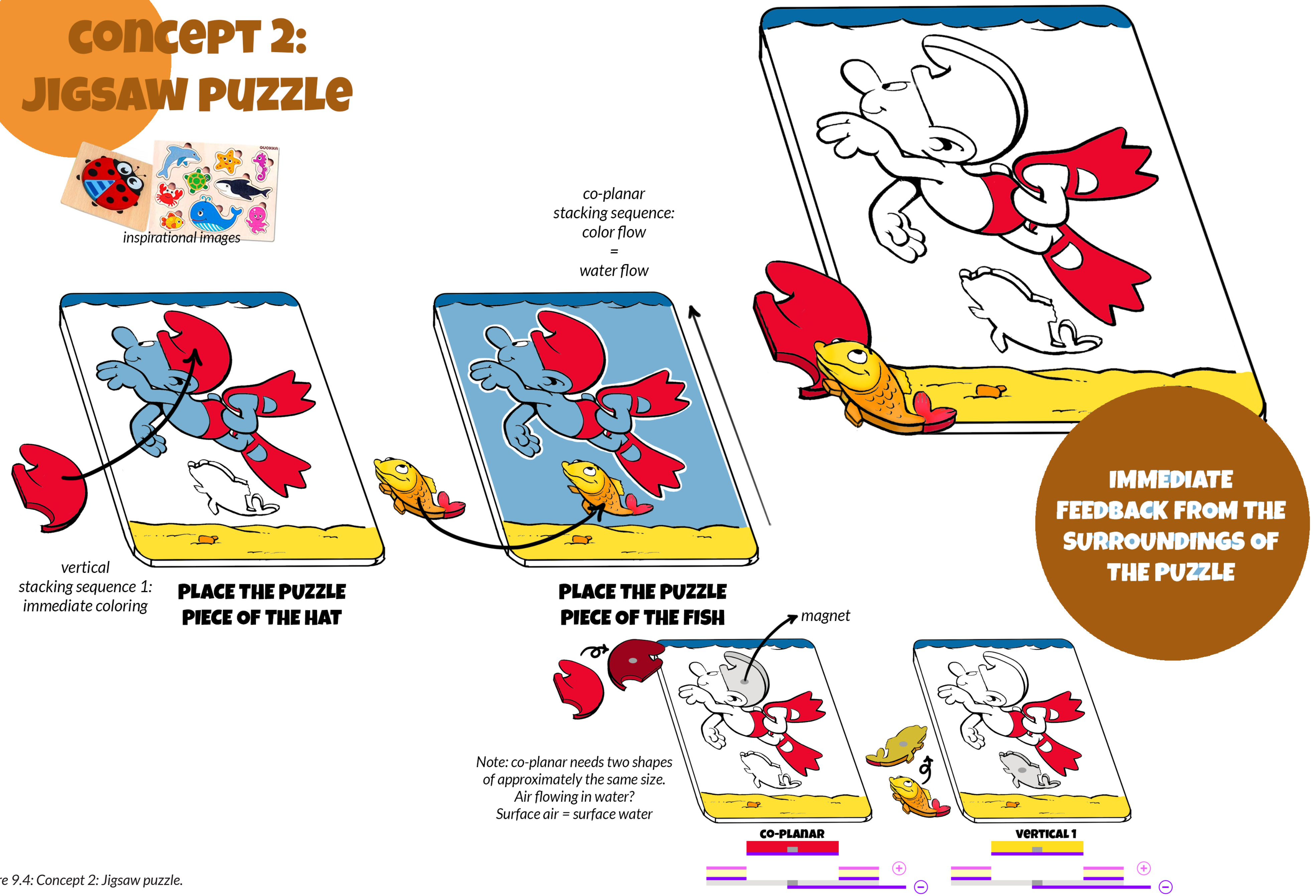



Figure 9.4: Concept 2: Jigsaw puzzle.



# Concept 3: Mosaic puzzle

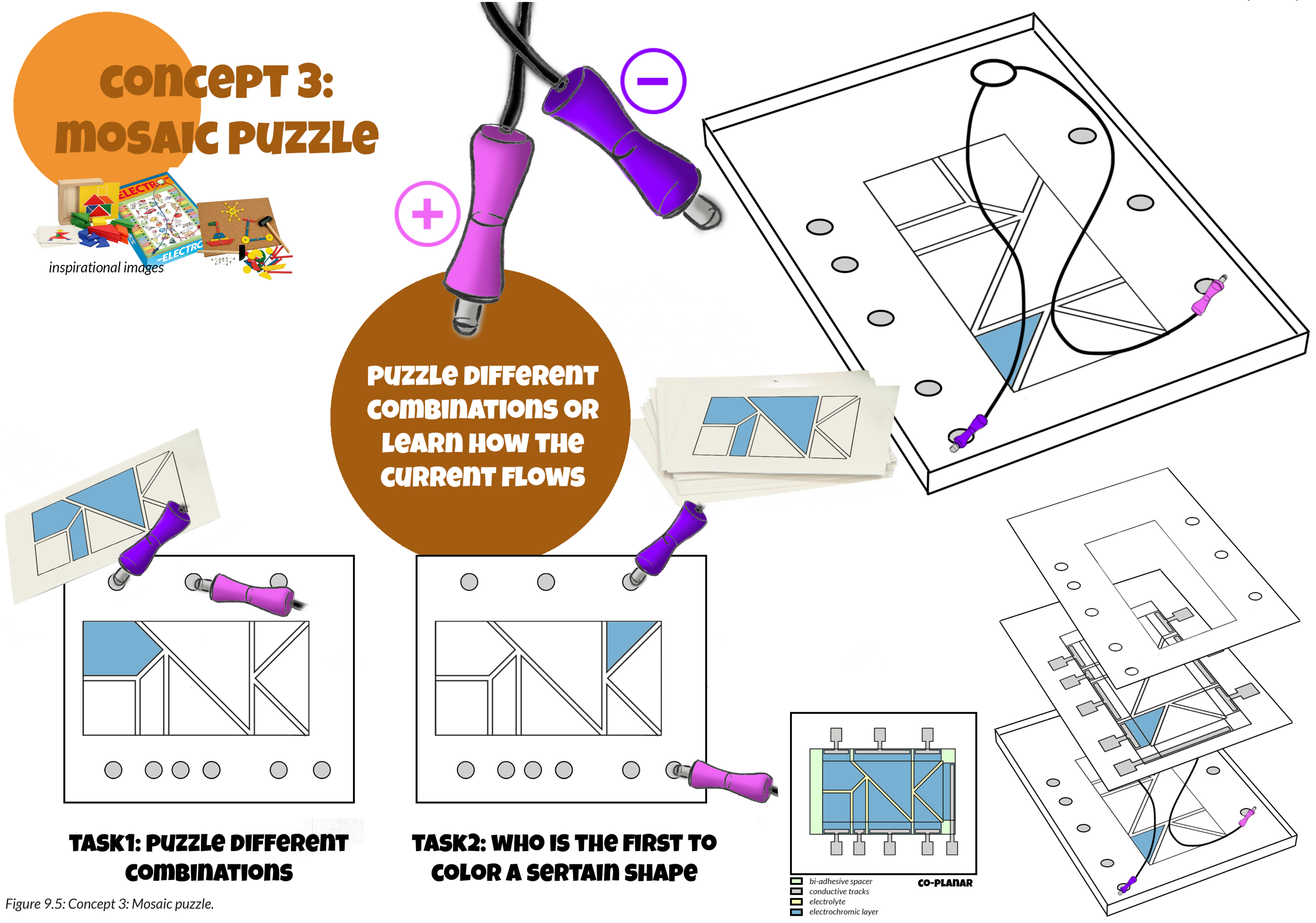
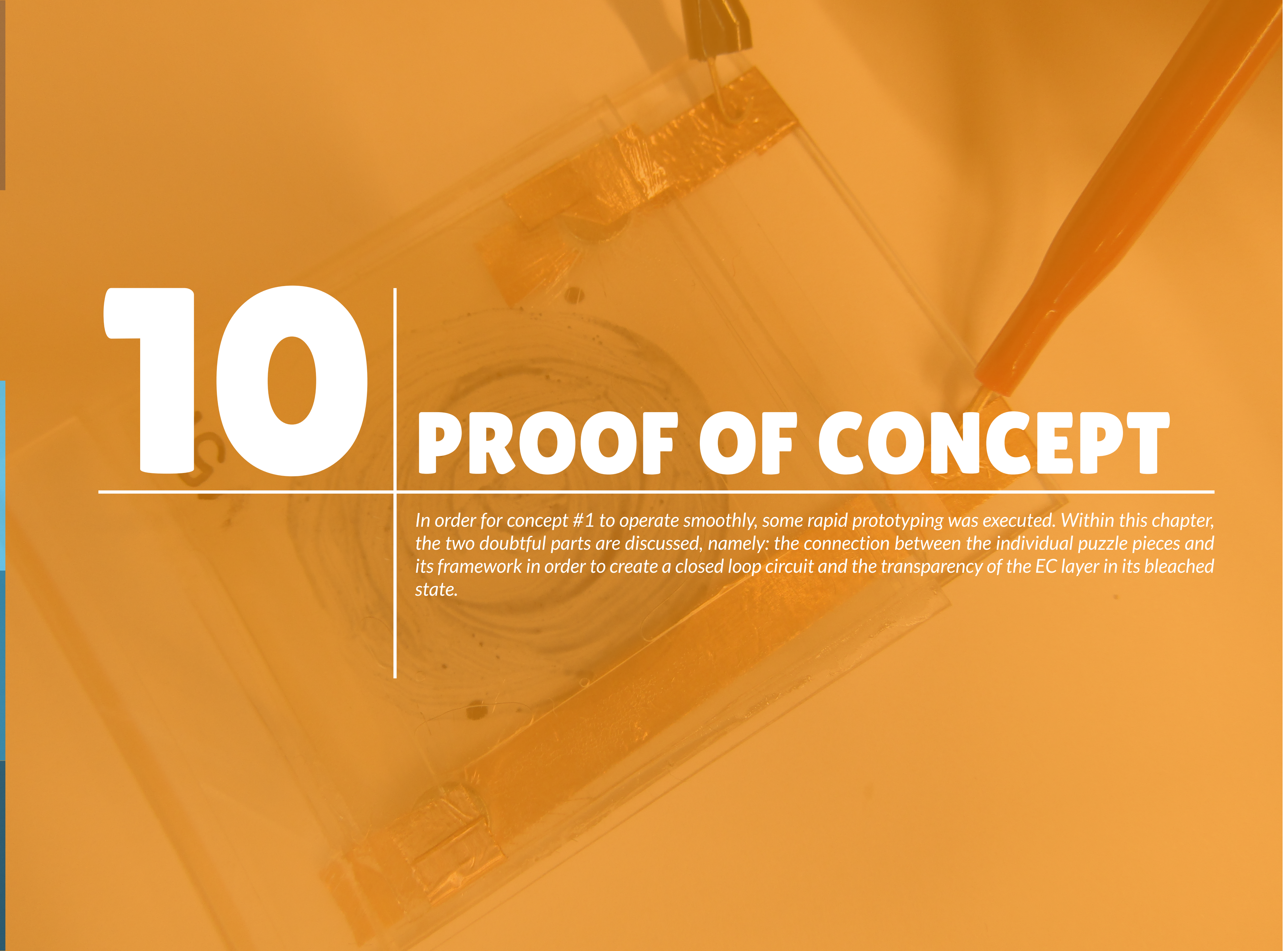



Figure 9.5: Concept 3: Mosaic puzzle.



# 10 PROOF OF CONCEPT

*In order for concept #1 to operate smoothly, some rapid prototyping was executed. Within this chapter, the two doubtful parts are discussed, namely: the connection between the individual puzzle pieces and its framework in order to create a closed loop circuit and the transparency of the EC layer in its bleached state.*



## 10.1. EDGE-MATCHING PUZZLE

First of all, there was decided to create an edge-matching puzzle (see chapter11 for further information), of which the puzzle pieces reverse their image when the piece is reversed. As can be seen in figure 10.3, a smaller version of this concept was created, using double image display of stacking sequence #1. The idea is that all four primary EC layers form puzzle #1 and all four secondary EC layers puzzle #2. But as all pieces are a square, the user does not know what the primary and secondary EC layers are; a puzzle within a puzzle.

## 10.2. CLOSED LOOP CIRCUIT

The first challenge was to create a closed loop circuit between the individual pieces and the framework. It was quickly decided to use magnets, as they are both conductive as well as they provide a strong connection.

After this, the connection point of the ECD itself had to be connected to the magnets. As the adhesive side of the copper tape is not conducting, the tape was slightly amateurish connected to the ECD, which was then glued (instant glue) on a piece of plexiglass, see figure 10.2. Yet, this connection has proven to be enough as the color change of the ECD could be triggered through the bottom of the magnets, see figure 10.4. For this, both an vertical ECD (ECD-V-51) and co-planar ECD (ECD-C-8) was used.

So, after the connection of the piece itself had proven to be sufficient, the framework had to be prototyped too. As can be seen in figure 10.5 and QR-code 9, the concept was proven to function.

Important to note is that using the instead of the instant glue, a conductive glue will be used, as the instant glue blocks the connection between the ECD and the magnet when it flows in between.

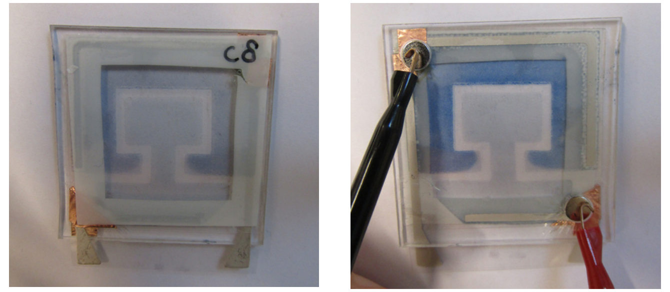



*Figure 10.4: Trigger the color change of the ECD through the bottom of the magnets.*

*Figure 10.1: Magnets.*

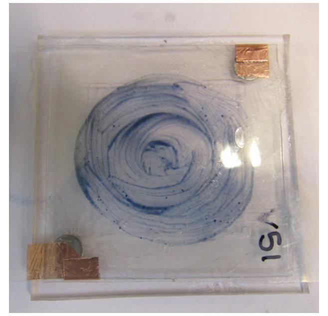



*Figure 10.2: Copper tape.*

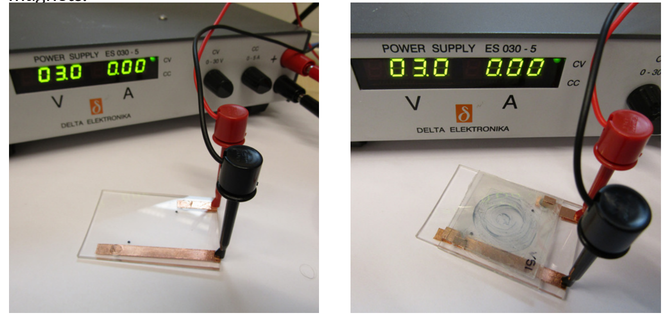



*Figure 10.5: Proof of concept.*

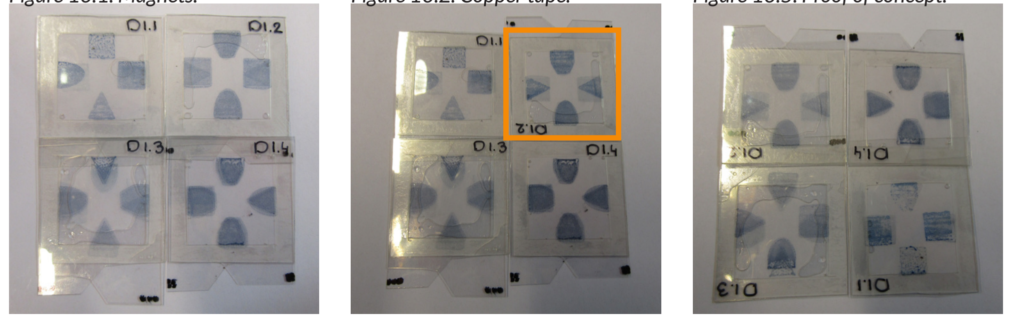



*Figure 10.3: ECD-D-1: Proof of concept puzzle idea: puzzle 1 (a), puzzling by means of turning the piece 180° (b) and puzzle 2 (c).*

*QR-code 9: Proof of concept.*

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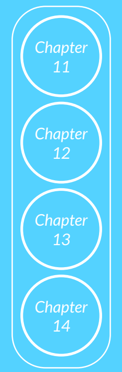
# DEMONSTATOR

## 'THE PUZZLE OF ELECTROCHROMISM'

*'The puzzle of electrochromism' is an edge-matching puzzle demonstrating the opportunities of electrochromic materials in product design. Within this phase a distinction will be made between the goal* ***of*** *the demonstrator (i.e. material experience vision (chapter 7)) and the goal* ***in*** *the demonstrator (i.e. the goal of the puzzle to be solved). The goal* ***of*** *the demonstrator is communicated to the puzzler (i.e. user) through the goal of the puzzle to be solved.*

*First, an overview of 'the puzzle of electrochromism' will be presented on a two-page overview. After this, the goal* ***of*** *the demonstrator will be explained and translated into the goal* ***in*** *the demonstrator (chapter 11). Within chapter 12, a user scenario of a puzzler solving 'the puzzle of electrochromism' is illustrated. Furthermore, in chapter 13, there will be elaborated on the fact that 'the puzzle of electrochromism' is not only a good demonstrator, but also a good puzzle. With finally in chapter 14 a brief explanation on the final part of the goal of the demonstrator, i.e. inspiring other designers through a small user research.*





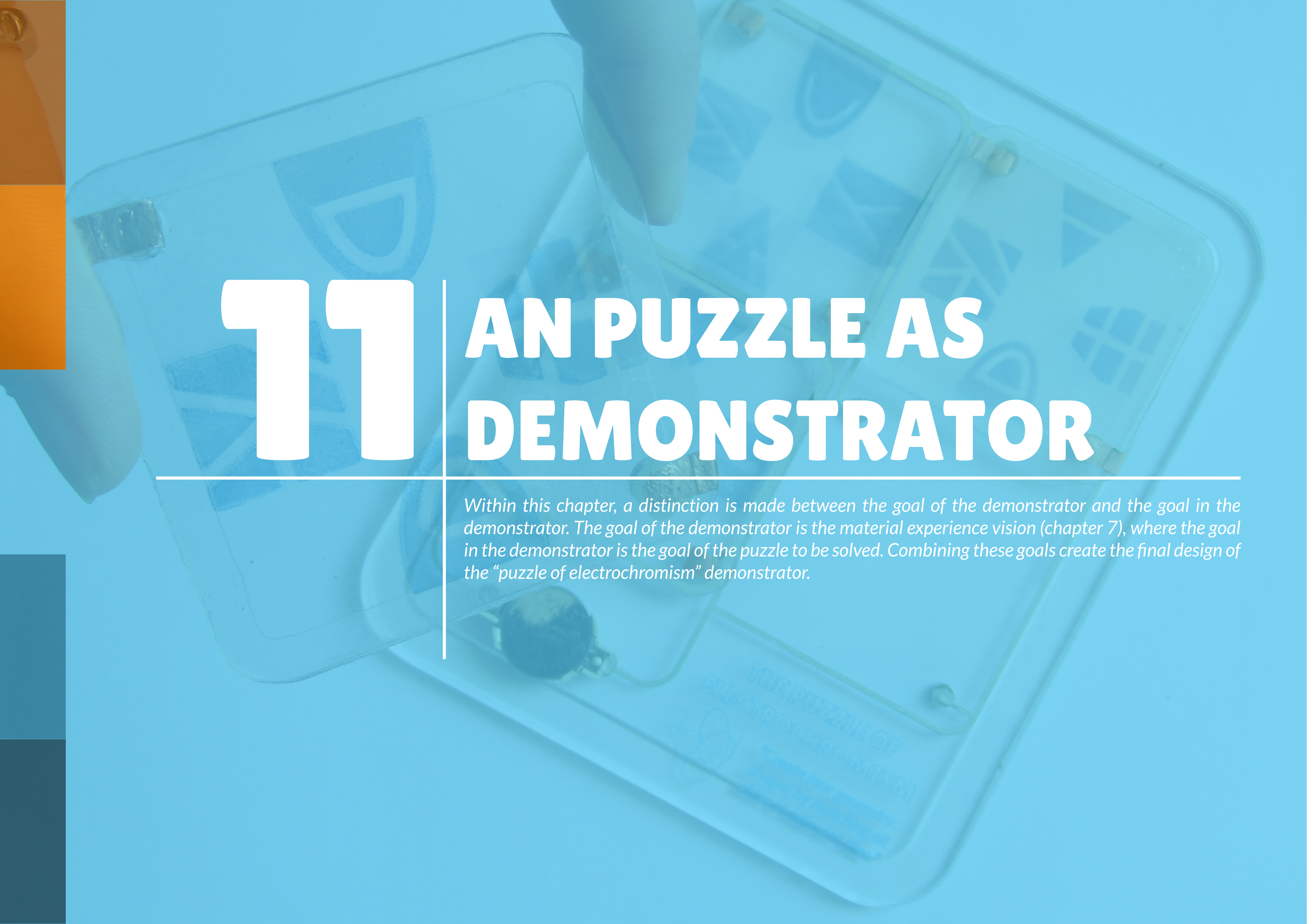
11. A puzzle as demonstrator
12. User scenario
13. A good puzzle
14. Inspire other designers


'The puzzle of electrochromism' is an edge-matching puzzle, with as goal to puzzle four geometric shapes by matching the sides of the adjacent puzzle pieces. Solving this puzzle shows the technical and experiential characterization of electrochromic materials as well as highlighting its unique properties, while emphasizing the simplicity and possibilities of integrating electrochromic materials in product design. With as ultimate goal to inspire designers to make use of electrochromic materials in their (product) designs, through exciting creativity and curiosity.



*"Puzzle the **four geometric shapes** by matching all sides of the 4 puzzle pieces. However, as **electrochromism** is a reversible color change of a material, all individual pieces are able to reversibly change between two pieces belonging to **two different puzzles**. Meaning you're not only puzzling the pieces together but also which piece belongs to which puzzle! A little clue: the first puzzle includes all four different geometrical shapes, however for the second puzzle this is unknown... **Good luck!**"*


QR-code 10: 'The puzzle of electrochromism'



# 11 AN PUZZLE AS DEMONSTRATOR

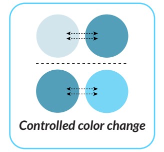
*Within this chapter, a distinction is made between the goal of the demonstrator and the goal in the demonstrator. The goal of the demonstrator is the material experience vision (chapter 7), where the goal in the demonstrator is the goal of the puzzle to be solved. Combining these goals create the final design of the "puzzle of electrochromism" demonstrator.*



Starting with the *goal in the demonstrator*, i.e. *the goal of the puzzle to be solved*. The puzzler (user) of 'the puzzle of electrochromism' has to create four geometric shapes (see figure 11.1) by matching the sides of the adjacent tiles; i.e. an edge matching puzzle. An edge matching puzzle is a puzzle with all identical shaped puzzle pieces (e.g. squares) that have to be matched at the sides of adjacent puzzle pieces, without knowing what the exact image is that has to be puzzled. For 'the puzzle of electrochromism' the final image is unknown, the puzzler only knows it has to create four geometric shapes at the sides of adjacent pieces, focusing on the outer shape, as the inner shape is allowed to differ.

The difference of the inner shape contributes to the *goal of the demonstrator*. Thus when translating the goal in the demonstrator (i.e. the goal of the puzzle) to the goal of the demonstrator: solving the puzzle shows the technical and experiential characterization of electrochromic materials as well as highlighting its unique properties, while emphasizing the simplicity and possibilities of integrating electrochromic materials in product design. With as ultimate goal to inspire designers to make use of electrochromic materials in their (product) designs, through exciting creativity and curiosity. To what extent these unique properties and technical characterization are communicated through 'the puzzle of electrochromism' will be further explained within this chapter. On its experiential characterizations will be elaborated in chapter 14.

## 11.1. UNIQUE MATERIAL PROPERTIES




*Controlled color change.* As can be seen in QR-code 10 (previous page), when a piece of the puzzle is placed on the framework, it immediately switches color. As the magnets in both the puzzle piece and the framework are attracted to each other, a closed loop circuit is created, see figure 11.3 (next page). When the polarity is reversed (i.e. the puzzle piece is turned 180° within the horizontal plane), the puzzle piece switches from its primary EC layer to its secondary EC layer or visa versa, see figure 11.2-a and 11.2-d.

As aforesaid, 'the puzzle of electrochromism' is not just one puzzle, but includes *two puzzles* using the same four puzzle pieces, see figure 11.4 (next page). The difference between the two puzzles is enabled through the polarity of the individual pieces of the puzzle: all primary EC layers together create puzzle#1 and all secondary EC layers puzzle#2 (except for puzzle piece #1, the primary EC layer of this piece belongs to both puzzles). Meaning, each time the puzzler rotates an individual puzzle piece 180° on the framework while puzzling, it immediately switches between the two puzzles. However, the puzzler has no idea what images belong to which puzzle, thus it has to figure this out through puzzling. Important to mention is that as a result of the placement of the magnets in the individual puzzle pieces and the framework, all puzzle pieces only fit in two positions in the horizontal plane. Turning a puzzle piece 180° in the vertical plane is impossible through the repulsion of the magnets.

Thus, two *puzzle variables* can be defined for each individual puzzle piece: *'position within the puzzle'* and *'whether it belongs to puzzle#1 or puzzle#2'*.

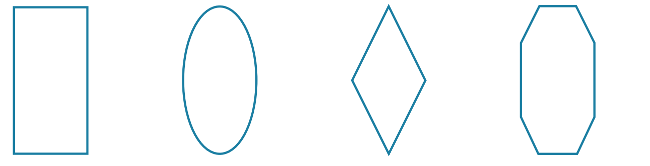



*Figure 11.1: The four geometric shapes.*

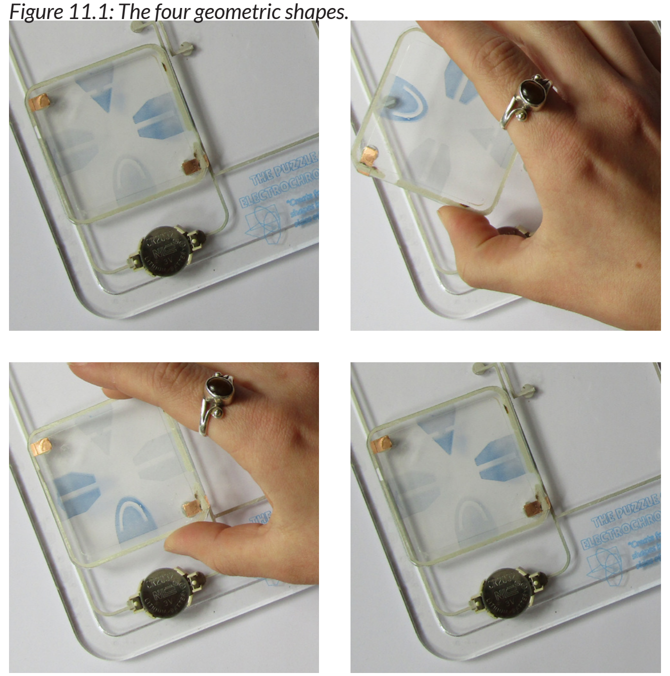


*Figure 11.2: Reversing the polarity of puzzle piece#2: primary EC layer (a), removing-turning-positioning the piece (b-c) and secondary EC layer (d).*

Copper tape
Magnets
Plexiglass
Insulating substrate/encapsulation
Conductive substrate/encapsulation
Electrode
Primary electrochromic layer
Secondary electrochromic layer
Bi-adhesive spacer
Electrolyte
LEGEND

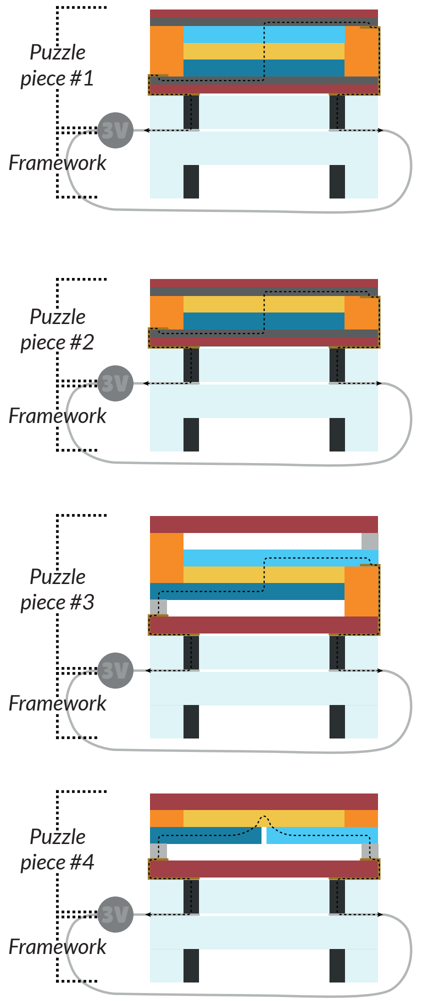



Figure 11.3: Closed loop circuit between the individual puzzle pieces and framework.

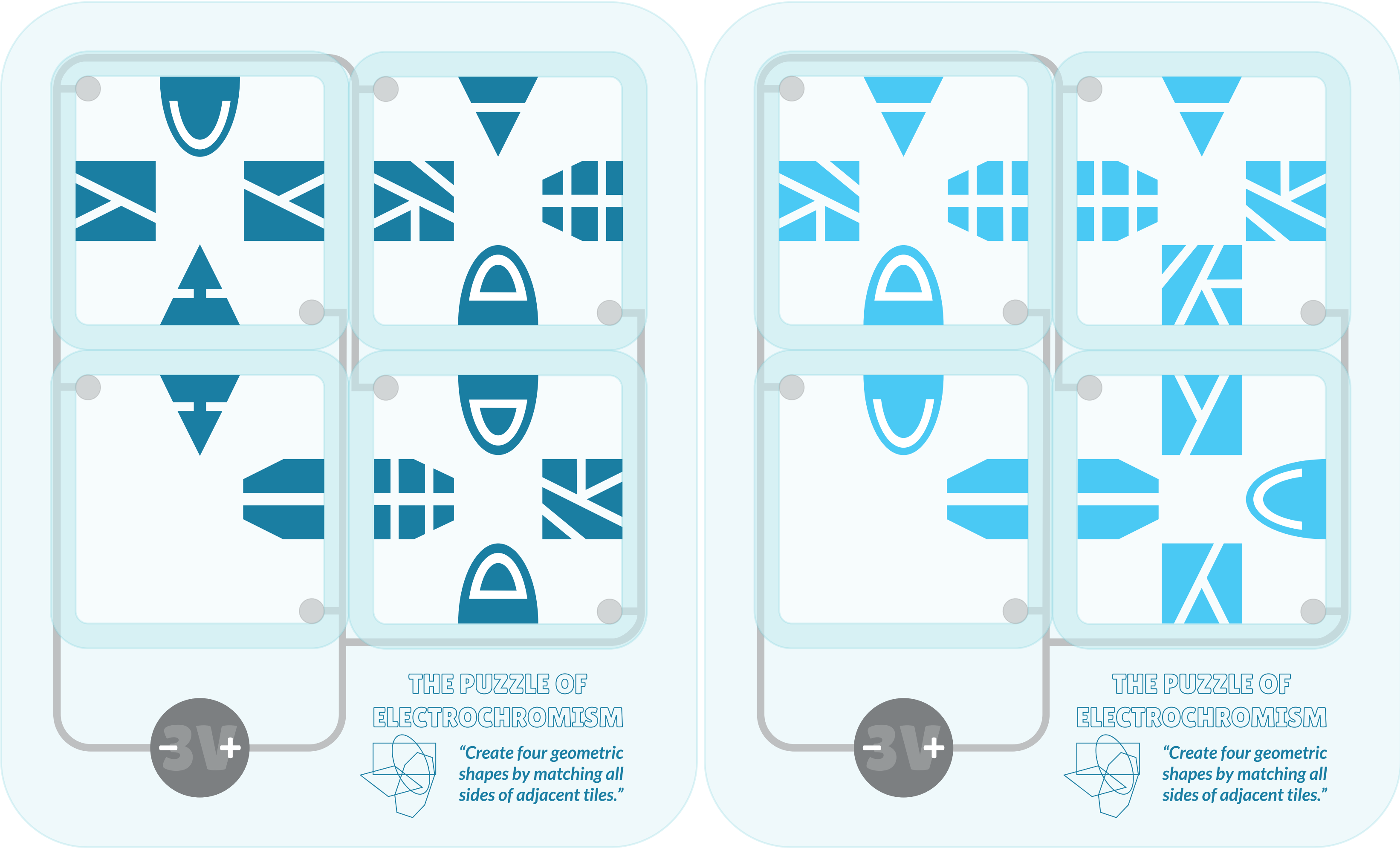
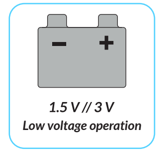
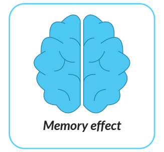



Figure 11.4: 'The puzzle of electrochromism': puzzle #1 (a) and puzzle #2 (b).

DEMONSTRATOR: 'THE PUZZLE OF ELECTROCHROMISM'


*Low voltage operation.* A battery holder for a lithium CR2032 coin cell is attached to the framework, connected to silver tracks printed on the framework (figure 11.5). Thus, when a puzzle piece is connected to the framework, the magnets of this piece create a closed loop circuit between the ECD and the framework. When the closed loop circuit is achieved, the coin cell battery with a voltage of 3V triggers the coloration of all individual pieces attached to the framework.




*Memory effect.* As explained in chapter 1.1, the memory effect is the idea that an electrochromic material only requires an applied potential in order to trigger the electron-transfer or redox reaction for coloration or bleaching; i.e. the potential can be removed after the material has changed its color and will stay in its current state. As can be seen in figure 11.6, 11.7 and 11.8, the memory effect in 'the puzzle of electrochromism' occurs in three situations: when a puzzle piece is removed from the framework while puzzling, when the battery is removed or when the 'rules of the game' sheet is placed in between the framework and puzzle pieces for storage. As an edge matching puzzle is a puzzle that is based on trial-and-error, as the puzzler does not know the image to be created, puzzle pieces will be taken on-and-off the framework regularly, thus the memory effect will be shown frequently while puzzling.

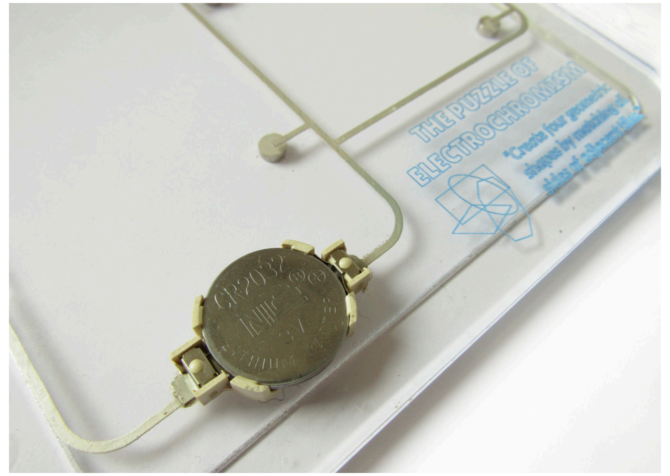


Figure 11.5: Low voltage operation: battery holder with a lithium CR2032 coin cell battery of 3V.

Figure 11.7: Memory effect: battery is removed.

Figure 11.6: Memory effect: puzzle piece is removed.

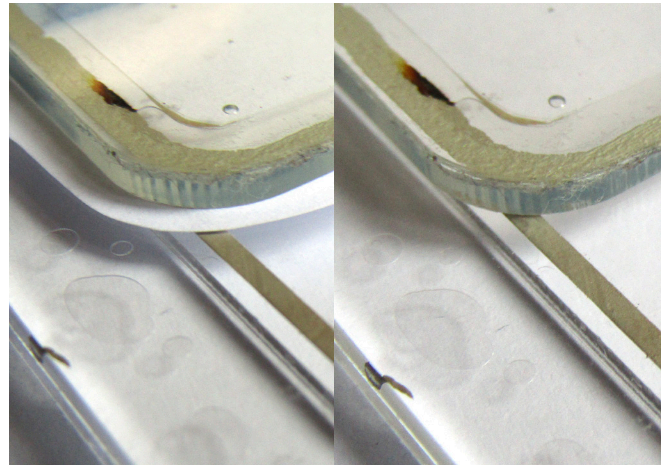
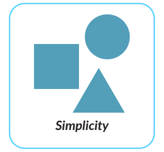


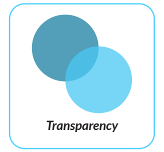
Figure 11.8: Memory effect: the game manual is placed in between the puzzle pieces and the framework for storage (a) and without (b).

## 11.2. TECHNICAL CHARACTERIZATION

### 11.2.1. 'THE PUZZLE OF ELECTROCHROMISM' IN GENERAL




*Simplicity.* As clearly stated within the material experience vision (chapter 7), the demonstrator should emphasize the simplicity of an ECD; e.g. less components as possible. As can be seen in figure 11.9, 'the puzzle of electrochromism' consists of six parts: a framework with both the silver tracks printed on and the battery holder attached to, a coin cell battery of 3V and four individual puzzle pieces. As in general all materials used are transparent, no components are hidden, thus all parts are shown in their simplest form possible.




*Transparency.* Transparency is a distinctive characteristic of an ECD operating in the transmittance operation mode and for the 'Ynvisible electrochromic ink' in its bleached state. As this transparency is rather unique for a display-kind of device, it was set as an important characteristic to be shown by the demonstrator.

All ECDs (i.e. individual puzzle pieces) are transparent, glued to Plexiglass of 2 mm (Poly(methyl methacrylate); PMMA), using 'Loca TP-1000N UV' glue to maintain this transparency. Also to provide a solid base (support) to the ECDs and the magnets. The only parts of 'the puzzle of electrochromism' that are not transparent are the silver tracks printed on the framework and puzzle piece#3 and #4 ('SunChemical Silver Paste: C2120918P1'), the copper tape (coper foil tape: 5mm) and the magnets (5x3mm nickel-plated N35).

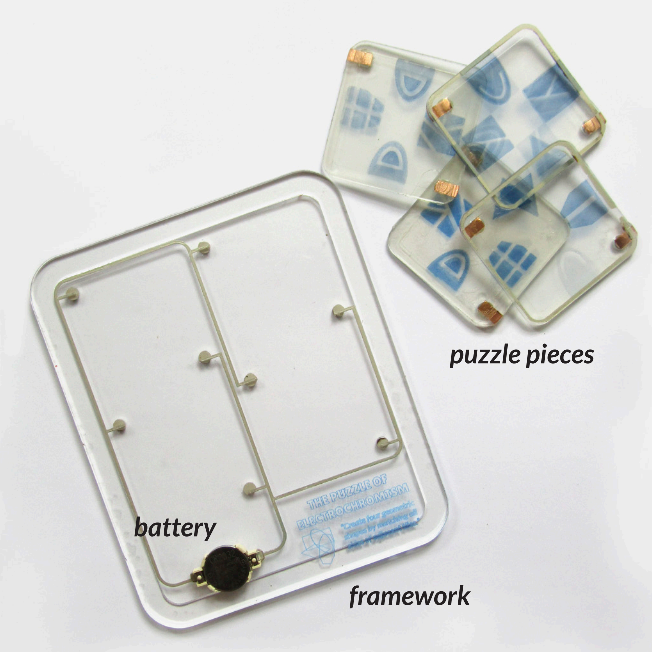



*Figure 11.9: Individual parts of 'the puzzle of electrochromism'.*

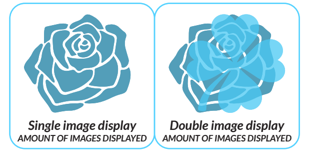


### 11.2.2. INDIVIDUAL PUZZLE PIECES

Within chapter 2.3, four different stacking sequences are defined based on the combination of the vertical or co-planar stacking sequences and the substrate used. As simplicity and transparency are not the only technical properties defined within the technical characterization (chapter 6.1), the *shape/pattern change*, *coloring*, *design of the images displayed* and the *interaction between the EC layers* for the individual puzzle pieces will be elaborated on further.

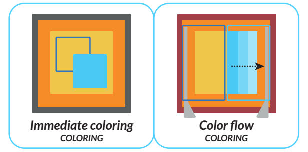
First of all, when looking at the four different stacking sequences, both *vertical* and *co-planar* stacking sequences should be demonstrated. So that not only the different switching speeds (material property: chapter 1.2) will be highlighted, but also the possibility of a single image display and a double image display and the difference in interaction between the EC layers.

Secondly, when looking at the substrate used, both *insulating* and *conductive* substrates should be demonstrated. So that both, their influence on the differences on coloring and design of the images displayed will be highlighted. In the end, both the single image and double image display option of stacking sequence#1 (SS#1), stacking sequence#2 (SS#2) and stacking sequence#4 (SS#4) are applied to the individual pieces of the puzzle. Stacking sequence#3 is excluded, as the design possibilities were not adding value to both, the goal of the demonstrator and the goal in the demonstrator (i.e. goal of the puzzle). As can be seen in figure 11.11 (page 87), single image display of SS#1 is applied to puzzle piece#1, double image display of SS#1 to puzzle piece#2, SS#2 to puzzle piece#3 and SS#4 to puzzle piece#4.



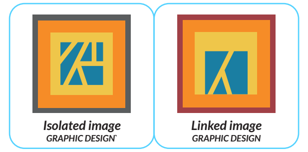

*Use of color: shape/pattern change.* First of all a *single image display* (puzzle piece #1), is as explained in chapter 4.2.1, an ECD that only switches between one bleached and one colored state; i.e. one image appears and disappears. When looking at the puzzle variables, creating a single image display not only communicates the goal of the demonstrator, but also helps with the goal in the demonstrator (i.e. goal of the puzzle). As only one image is displayed, the variable of 'whether it belongs to puzzle#1 or puzzle#1 is eliminated, as it is the same puzzle piece (i.e. image) for both puzzles.

Secondly, the other three puzzle pieces (i.e. puzzle piece #2, #3 and #4) are based on an ECD with a *double image display*. Meaning that these puzzle pieces switch between two colored states; i.e. two images appear and disappear in turn.




*Use of color: coloring.* Coloring is defined as the change of an electrochromic material from its bleached to its colored state, for which two types can be distinguished: immediate coloring and color flow. As explained in chapter 4.5.1, the type of coloring depends on the substrate used: an insulating substrate results into a color flow oriented from the parting line between the two EC layers and the image on a conductive substrate color immediately. Translating this to the four puzzle pieces: puzzle piece #1 and #2 experience immediate coloring and puzzle piece #4 a color flow. Puzzle piece #3, on the other hand, experiences both, as not only the substrate used influences the coloring, but also overlap between the two EC layers. Meaning, the parts where the images overlap experience immediate coloring and the other parts of the images a flow of color. This combination results into an interesting effect that can be defined as more of a flash, see QR-code 11.

*QR-code 11: Individual puzzle pieces*




*Design of the images displayed.* All parts of the design of the images displayed (e.g. electrochromic ink) should be connected to either a conductive substrate or electrode. As elaborated on in chapter 2.2., this results into the design restriction of 'linked images' for an ECD using an insulating substrate; all parts of the design are linked to the electrode. To highlight this within the demonstrator, a distinction between the inner shapes is made for the conductive and insulating substrate. As can be seen in figure 11.10-top, for puzzle piece #1 and #2 (conductive substrate), the design of the shapes is both isolated mutually and from the bi-adhesive frame. Puzzle piece #3 and #4 (insulating substrate), on the other hand, have a different design of the inner shape of the images displayed. All parts of this design are mutually linked and linked to the electrodes, see figure 11.10-bottom.

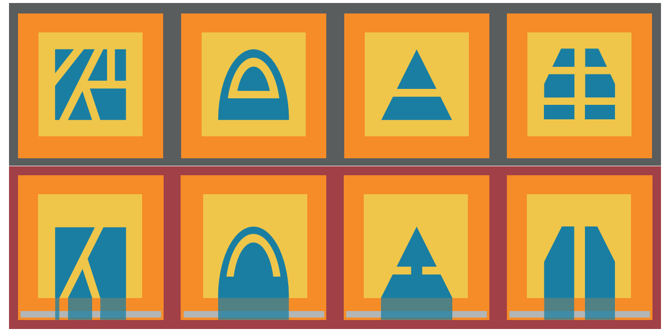
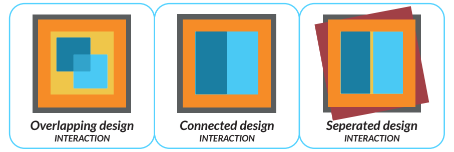


Figure 11.10: Design of the images displayed: conductive substrate (top) and insulating substrate (bottom).




*Interaction between the EC layers.* As aforesaid, vertical and co-planar stacking sequences influence the interaction between the EC layers. As within a vertical ECD the EC layers are stacked vertically, there is the possibility of an overlapping, connecting or separated design (chapter 2.3.). A co-planar ECD, on the other hand, has only the option of a separated design, as the EC layers are printed on the same substrate (i.e. in one layer). As can be seen in figure 11.11, when translating this to the puzzle, the design of puzzle piece #2 and #3 includes four different shapes at each side of the puzzle piece for both EC layers; overlap is created. Puzzle piece #4, on the other hand, includes only two shapes for each EC layer, as the designs of both EC layers have to be separated to avoid a short circuit. The co-planar stacking sequence not only communicates the goal of the demonstrator, but helps with the goal in the demonstrator (i.e. goal of the puzzle). Where puzzle piece #1 eliminated the puzzle variable of 'whether it belongs to puzzle #1 or #2' (single image display), puzzle piece #4 eliminates the puzzle variable of 'position within the puzzle'. As for both puzzles, this puzzle piece only has images at the top and right side, meaning its position within the puzzle is the bottom left corner.



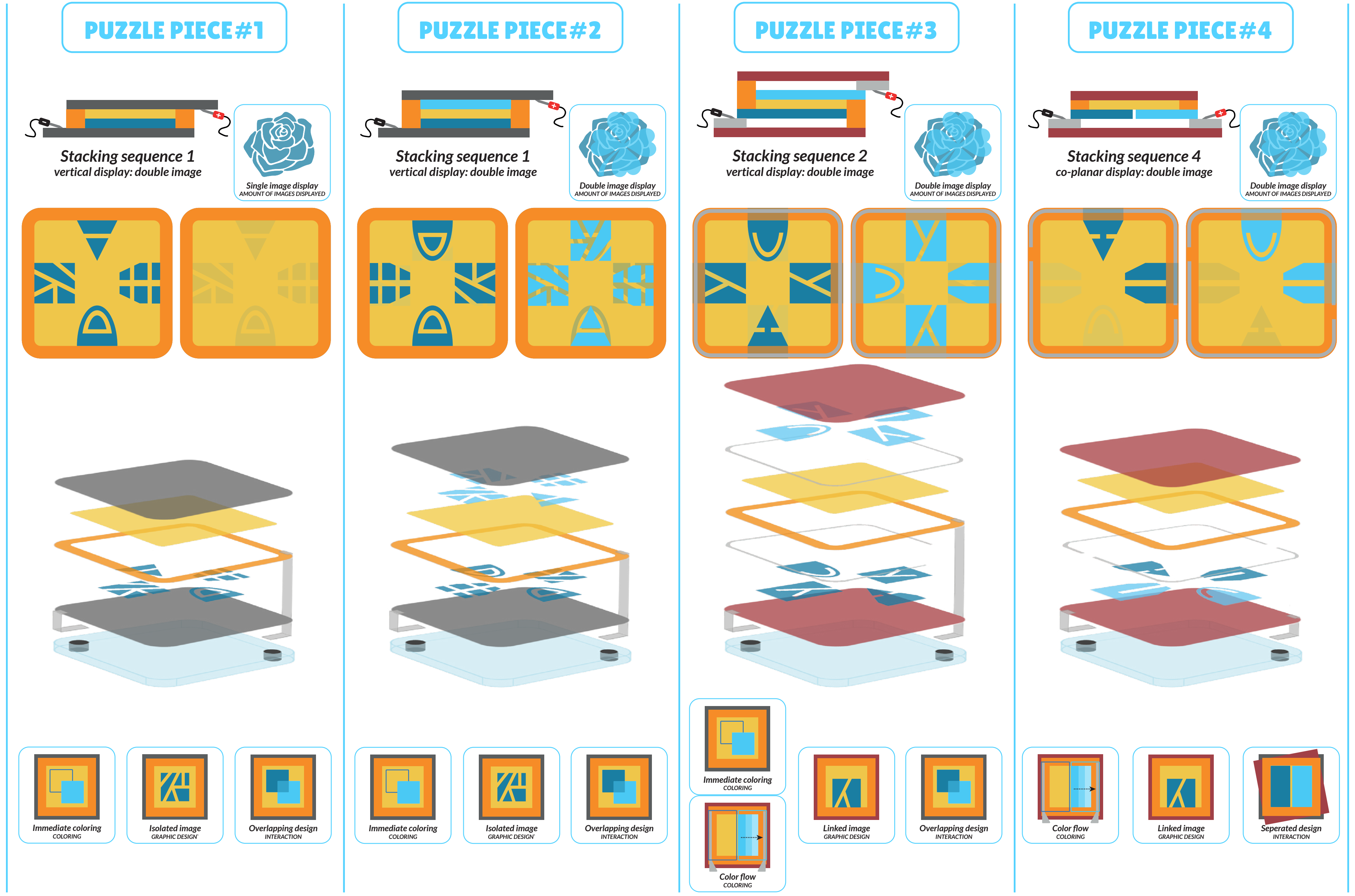
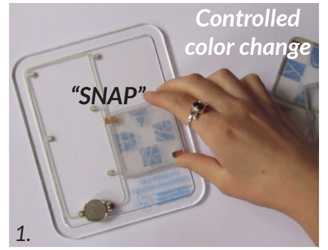



Figure 11.11: Puzzle pieces. Stacking sequence, top view, exploded view and technical properties (from top to bottom).

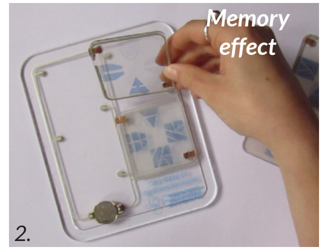
# 12 USER SCENARIO

*Within this chapter an elaborate user scenario of a puzzler solving the puzzle will be given. However not only the **goal of the puzzle** will be clarified but also the **goal of the demonstrator**, how the puzzler will experience this while puzzling.*

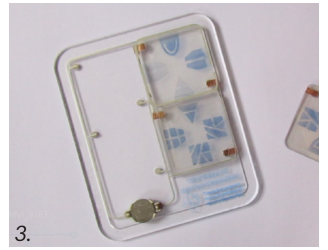
START PUZZLING WITH PUZZLE #1




1. The puzzle piece "snaps" into its place: immediate coloring.

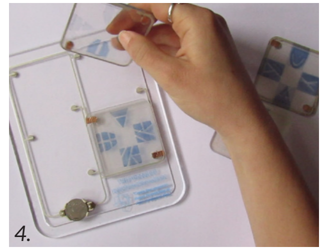



2. Puzzle the next piece by matching the shapes (rhombus).

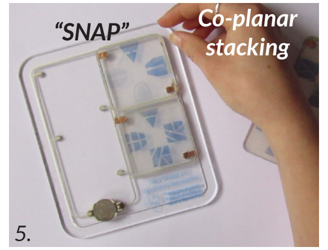


3. However, it turned 180°, so it switches the image.

*"Only two shapes.. Lets turn around and see what happens then.."*

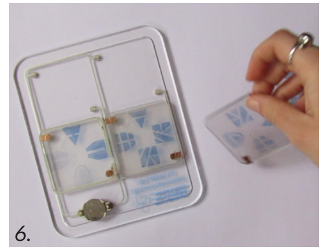


4. Turn around 180°, to see what the other image is.

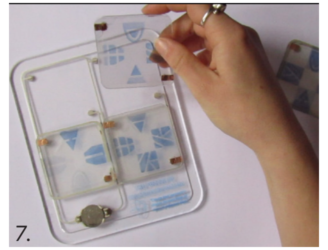



5. The puzzle piece "snaps" into its place: immediate coloring.

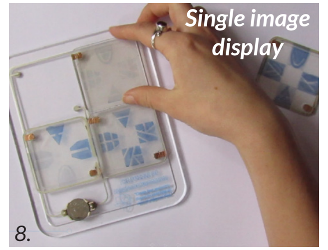
*"Both layers of the ECD only include two images, so its position must be the bottom left..!"*



6. Two puzzle pieces are matching. Try the next one!

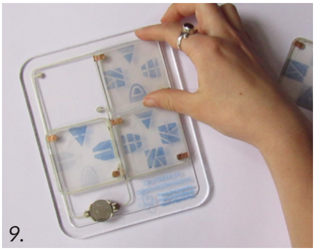


7. Puzzle the next piece by matching the shapes (rhombus).

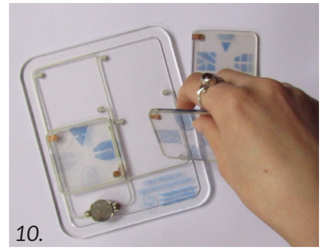



8. However, it turned 180°, so it switches the its bleached state.

*The image, it disappears.. Oh! Thus it is just this one piece for both puzzles!*

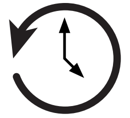


9. The primary layer of the single image does not fit anywhere...



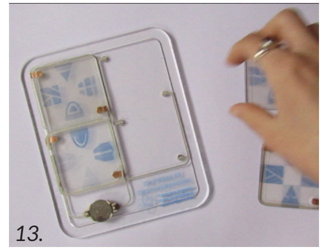
10. Remove all the pieces to start finding different positions: puzzle!

*Puzzle: try different positions for all puzzle pieces and turn them 180 180°.*



11. Puzzle #1 is solved!

12. Remove all the pieces and turn the bottom left one 180°.



13. Puzzle...

14. Puzzle...

15. Puzzle...

16. Positioning the final piece does not fit, so puzzle more...

17. Try to position the two pieces that do not match by turning them 180°.

18. Puzzle #2 is solved!

# 13 A GOOD PUZZLE

*Within this chapter the fundamentals of a good puzzle will be explained. As the goal of the demonstrator is clarified in the previous chapters, now the goal in the demonstrator will be further explained; i.e. the goal of the puzzle. As 'the puzzle of electrochromism' has not only to be a good demonstrator but also a good puzzle.*

Photo by Olav Ahrens Røtne on Unsplash



## 13.1. EDGE MATCHING PUZZLE

As both, electrochromic materials and puzzles can be defined as "things that are difficult to understand or explain" ("Puzzle," 2021), there is chosen to use a puzzle to demonstrate the working principle and characteristics of electrochromic materials. As four different stacking sequences were defined at the beginning of this thesis, a puzzle with four pieces seemed valid. As a puzzle such as a butterfly or starfish -as used within the concept design phase- would result into a far too easy puzzle to be solved, plus it is not showing all possibilities of the four stacking sequences, an edge-matching puzzle is created. According to Demaine (2007), the goal of an edge-matching puzzle is to arrange the identical shaped but differently patterned pieces (typically squares) so that the patterns match along the edges of adjacent tiles. This form of puzzling is more challenging as there is no image to guide the user, and the fact that two pieces fit together does not guarantee that they should (Demaine, 2007).

There are two types of edge-matching puzzles known; signed and unsigned. Signed edge-matching puzzles is defined by Demaine (2007) as the harder abstract form, as each edge also has a sign (+/-). Meaning that two different parts of the same pattern should be connected, e.g. the head and tail are matched. However, as this increases the complexity of the puzzle significantly and the focus should still be on the electrochromic materials, there is chosen to create an unsigned edge-matching puzzle as demonstrator.

## 13.2. TEN PUZZLE PRINCIPLES

Schell (2008), defines ten puzzle principles to create good puzzles. These principles combined with the goal of the demonstrator resulted into the final design of the puzzle. All ten puzzle principles will be addressed individually in order to emphasize its effect on the puzzle.

*Puzzle principle #1: Make the goal easily understood.*

"To get people interested in your puzzle, they have to know that they are supposed to do"(Schell, 2008). When this is not immediately clear, interest will be lost. As all magnets in both the individual puzzle pieces and the framework are visible, it is expected that the idea of placing a piece on the framework is easy understandable by the puzzler. However, as this is only the action (i.e. manipulation of the puzzle) and not the actual goal, the goal of the puzzle will be displayed on the bottom right corner of the framework.

> *"Puzzle the **four geometric shapes** by matching all sides of the 4 puzzle pieces. However, as **electrochromism** is a reversible color change of a material, all individual pieces are able to reversibly change between two pieces belonging to **two different puzzles**. Meaning you're not only puzzling the pieces together but also which piece belongs to which puzzle! A little clue: the first puzzle includes all four different geometrical shapes, however for the second puzzle this is unknown… **Good luck!**"*

*Puzzle principle #2: Make it easy to get started.*

"To design a good puzzle, first build a good toy and good toys make it obvious how to manipulate them" (Schell, 2008). As stated earlier, the action of putting the individual pieces on the framework is assumed to be an easy understandable start of the puzzle; i.e. manipulation. In addition to this, puzzle piece #4 is created. As it represents stacking sequence#4 (i.e. co-planar display), only two images are shown simultaneously at the top and the right. The advantage of this, is that it is straightforward for the puzzler that the position of this piece is the bottom left corner of the puzzle, thus provides the puzzler with an easy start.

*Puzzle principle #3: Give a sense of progress.*

This puzzle principle was harder to implement into 'the puzzle of electrochromism', as the principle of an edge-matching puzzle is that only at the end -when the puzzle is solved- the user knows that all pieces are put together right. However, sense of progress is tried to be achieved by the 'small victories' the user experiences when two pieces are put together and match.

*Puzzle principle #4: Give a sense of solvability.*
This puzzle principle is also harder to implement within an edge-matching puzzle, as the solution should not be given. The aspect that abuts on to this sense of solvability is the statement that two puzzles can be created, of which one consists of the four different geometrical shapes. On top of this, a game manual is put in between the framework and the individual pieces of the puzzle for storage to interrupt the closed loop circuit, see figure 13.1. As 'the puzzle of electrochromism' has the main function of a demonstrator, the back of this game manual will provide the user with information about the individual puzzle pieces: a top view of the primary and secondary EC layer, an exploded view of the layers and the use of color and design of the image displayed, see figure 13.2-b. This will simultaneously function as a sense of solvability as all images created by the individual puzzle pieces are displayed on this.

*Puzzle principle #5: Increase difficulty gradually.*
This puzzle principle is implemented in two forms within the puzzle; in the individual puzzle pieces and the two puzzles to be solved. First of all, as aforesaid, puzzle piece #1 and puzzle piece #4 both exclude one of the two 'puzzle variables'. For puzzle piece #1, only the position within the puzzle is still unknown, as it belongs to both puzzles. And for puzzle piece #4 the variable of to which puzzle it belongs is still unknown, as its position is straightforward. Secondly, the two puzzles to be solved. As mentioned in the goal of the puzzle, puzzle #1 includes all four different geometrical shapes (e.g. rectangle, oval, rhombus and irregular octagon), where for puzzle #2 this is unknown, thus puzzle #2 is expected to be more difficult to solve than puzzle #1.

*Puzzle principle #6: Parallelism lets the player rest.*
According to Schell (2008), a danger is that when the user is unable to make progress in a puzzle, it is going to abandon the game entirely. However, "a good way to safeguard against this is to give them several different related puzzles at once" (Schell, 2008). As two puzzles are included, it is assumed that making progress with one makes it easier for the puzzler to solve the other.

*Puzzle principle #7: Pyramid structure extends interest.*
Pyramid puzzle structure is a series of small puzzles that each give some kind of clue to a larger puzzle (Schell, 2008). This puzzle principle is not included in this puzzle.

*Puzzle principle #8: Hints extend interest.*
There is chosen to not provide the user with hints, as the puzzle only consists of four pieces and there is already a clear sense of progress and solvability.

*Puzzle principle #9: Give the answer!*
The answer to the puzzle will be provided in the form of this thesis, however not with 'the puzzle of electrochromism' itself.

*Puzzle principle #10: Perceptual shifts are a double-edged sword.*
A perceptual shift is defined as "either you get it or you don't" by Schell (2008). As this puzzle does not include a perceptual shift, this puzzle principle is irrelevant.

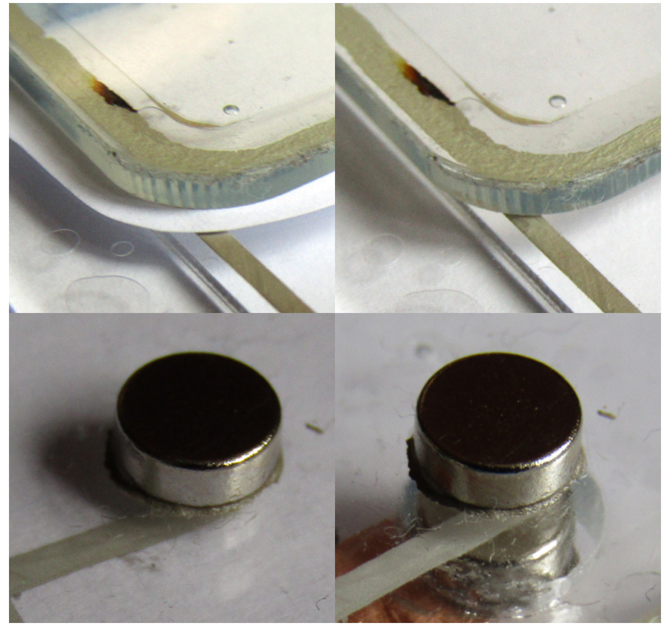


*Figure 13.1: Game manual: interrupt the closed loop circuit (a) and without game manual: closed loop circuit (b). Front of game (top) and back (bottom).*



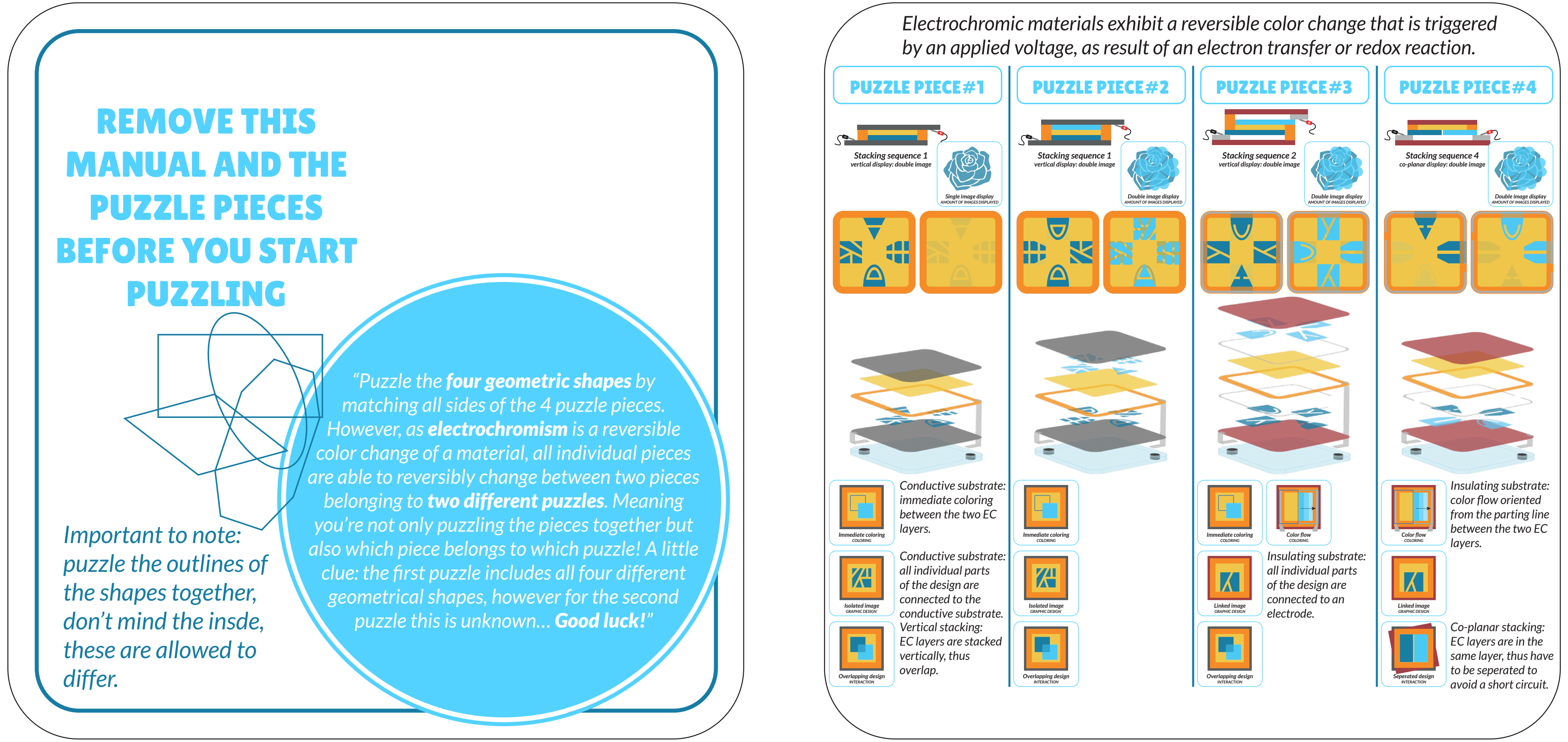



*Figure 13.2: Game manual of 'the puzzle of electrochromism': front (a) and back (b).*

# 14 INSPIRE OTHER DESIGNERS

*Within this chapter, the ultimate goal of the demonstrator will be briefly explained; i.e. inspire other designers. A small user research with is conducted where participants were asked to solve the puzzle.*

Photo by Júnior Ferreira on Unsplash



The ultimate goal of the demonstrator is to *inspire designers* to make use of electrochromic materials in their (product) designs, through exciting their creativity and curiosity. Desmet (2019) defines inspiration as the positive emotion of "the feeling when you suddenly have a new idea or insight, or see the world in a different light". According to 'Imotions' (2021), emotions can be measured by pupil dilation, skin conductance, brain activity, heart rate and facial expressions. As the techniques required are not at disposal, a small user research was conducted with the focus rather on interaction and thoughts of the participants (puzzlers).

In this, the puzzlers were asked to "solve the puzzle". No further information was provided, only when required by the puzzler, as 'the puzzle of electrochromism' should explain itself by using the game manual. Afterwards, there was room for the participant to ask questions, ending with some questions about their level of feeling inspired, extra information about electrochromic materials required and their curiosity.

*"Wow! This is cool!"*

*"It's almost magical."*

Conclusions can be drawn from this based on three characteristics: design of the demonstrator, solving the puzzle and information required about electrochromic materials.

First of all, *design of the demonstrator*. The simplicity clearly emerges from its transparent design with the battery connecter to it. One participant even clearly stated when positioning the first piece of the puzzle: "Aha! It works as a result of electricity". On top of this, the attraction and repelling of the magnets helped with solving the puzzle. The attraction was experienced as rather satisfying (*"Oooh, this is satisfying!"*), where the repelling served as use-cue. As the 'Ynvisible electrochromic ink' is transmissive sky blue in its bleached state, the image is still slightly visible. However, this was not experienced as a disadvantage, one puzzler even saw it as a big advantage: *"I secretly love the fact that you still can see a little bit what the other image is, it allows me to cheat."*

Secondly, *solving the puzzle*. The puzzlers immediately started puzzling after reading the game manual, some immediately got the goal of the puzzle, while it took a bit longer for others. However, as they tried to solve the puzzle, the goal became clear. E.g. one puzzler tried to match the empty spaces too (as is possible with games such as domino), however, as this did not help to solving the puzzle, he quickly left this idea. In the end, all puzzlers solved the puzzle in between approximately 5 and 10 minutes. The puzzling itself, was clearly experienced as slightly frustrating by some puzzlers. However, this is not necessarily a negative emotion in this context, as this frustration immediately resulted into determination.

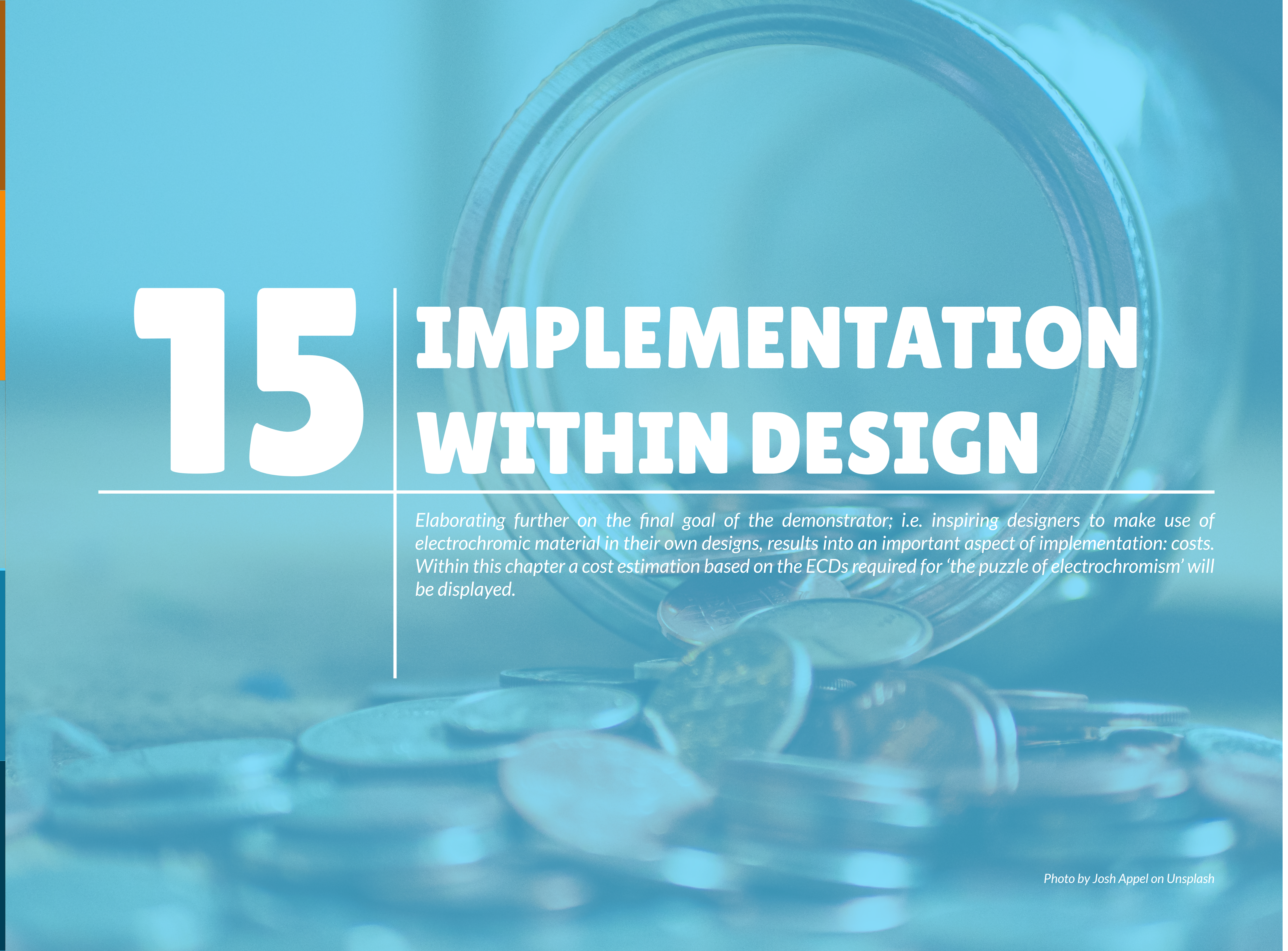
The changing aspect of the puzzle pieces resulted into an engaging interaction with the puzzle. Puzzlers were talking to the puzzle and mainly hoping they did puzzled well and waiting on the feedback. For this, one puzzler stated afterwards: *"I was puzzling controlled and slowly, I really waited for the feedback of the puzzle piece after I put it down". "It also a memory game, as I realized I have no memory of what I already tried and did turn. It can be concluded that my memory is bad.."* Some other quotes of the engagement of the puzzlers with puzzling:

*"Please, please, please, don't change.."*

*"No! Please just stay with the other image."*

*"No, no, no! Damn. Apparently I already turned this one.."*

As the goal is to make people curious to the working principle of electrochromic materials, information is included within the game manual; i.e. *information required about electrochromic materials*. The main question was: *"How does it work?"*. Besides this, other questions were also asked, such as: why do some color faster than others (coloring), and why differ the insides of the shapes? All this information is included into the game manual.



# 15 IMPLEMENTATION WITHIN DESIGN

*Elaborating further on the final goal of the demonstrator; i.e. inspiring designers to make use of electrochromic material in their own designs, results into an important aspect of implementation: costs. Within this chapter a cost estimation based on the ECDs required for 'the puzzle of electrochromism' will be displayed.*

Photo by Josh Appel on Unsplash



When encouraging designers to use electrochromic materials in their designs, a price indication cannot be excluded; as price is one of the key factors when choosing a material. Within this chapter a price estimation of the production of the ECDs of the four puzzle pieces of 'the puzzle of electrochromism' is drafted. Important to note is that only the **material costs** are included, the costs of necessarily equipment and production are excluded from this estimation.

In table 15.1, the costs of an individual piece required for the puzzle pieces are converted from the purchase costs and volume. Combining this with the amount of pieces required for one ECD results into the calculations of table 15.2. As can be seen in table 15.2, puzzle piece #1 has a material price of €2,67, puzzle piece #2 of €2,86, puzzle piece #3 of €2,94 and puzzle piece #4 of €1,74. Comparing these costs results into the conclusion that the conductive substrate and electrodes are the most expensive, resulting that puzzle piece #4 is relative cheaper than the other three as it uses only the amount of one electrode.

In the end, the total material costs of 'the puzzle of electrochromism' comes down to an amount of €20,80, see appendix Q for the cost calculation.

| ECD LAYER | | MATERIAL SPECIFICATIONS: PURCHASE [MM²] | PRICE [€] | MATERIAL SPECIFICATIONS: INDIVIDUAL PIECE [MM²] | PRICE [€] |
|---|---|---|---|---|---|
| Conductive substrate: | Indium tin oxide coated PET | 305mm x 305mm x 5 mm, 5 sheets = 93.025mm² | €122,00 | 60 mm x 60mm= 3600mm² (exact calculation) | €0,98 |
| Insulating substrate: | Overhead sheets Sigel transparent | 210mm x 297mm, 100 sheets = 62.370mm² | €19,10 | 60 mm x 60mm= 3600mm² (exact calculation) | €0,01 |
| Electrode: | SunChemical Silver Paste: C2120918P1 | 50g | €203,00 | 0,25g (rough estimation) | €1,02 |
| Electrochromic layer: | Ynvisible electrochromic ink | 200g | €150,00 | 0,25g (rough estimation) | €0,19 |
| Bi-adhesive spacer: | 3M 7961 MP double sided spacer (PET) transparent | 610mm x 914mm x 0,28mm (caliper: 0,25 mm) =557.540mm² | €14,80 | 60 mm x 60mm= 3600mm² (exact calculation) | €0,10 |
| Electrolyte: | Ynvisible electrolyte | 200g | €150,00 | 5cm x 5cm x 0,0255 cm = 0,56 ml (exact calculation | €0,42 |

*Table 15.1: Purchase costs and volume of the materials required converted into the invididual pieces required for an ECD for individual puzzle pieces.*

| PUZZLE PIECE #1 ECD LAYER | # | PRICE [€] |
|---|---|---|
| Conductive substrate | 2 | €1,96 |
| Electrochromic layer | 1 | €0,19 |
| Bi-adhesive spacer | 1 | €0,10 |
| Electrolyte | 1 | €0,42 |
| | ***Total*** | ***€2,67*** |

| PUZZLE PIECE #2 ECD LAYER | # | PRICE [€] |
|---|---|---|
| Conductive substrate | 2 | €1,96 |
| Electrochromic layer | 2 | €0,38 |
| Bi-adhesive spacer | 1 | €0,10 |
| Electrolyte | 1 | €0,42 |
| | ***Total*** | ***€2,86*** |

| PUZZLE PIECE #3 ECD LAYER | # | PRICE [€] |
|---|---|---|
| Insulating substrate | 2 | €0,02 |
| Electrode | 2 | €2,02 |
| Electrochromic layer | 2 | €0,38 |
| Bi-adhesive spacer | 1 | €0,10 |
| Electrolyte | 1 | €0,42 |
| | ***Total*** | ***€2,94*** |

| PUZZLE PIECE #4 ECD LAYER | # | PRICE [€] |
|---|---|---|
| Insulating substrate | 2 | €0,02 |
| Electrode | 1 | €1,01 |
| Electrochromic layer | 1 | €0,19 |
| Bi-adhesive spacer | 1 | €0,10 |
| Electrolyte | 1 | €0,42 |
| | ***Total*** | ***€1,74*** |

*Table 15.2: Material costs of the individual ECDs for the individual puzzle pieces.*

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# EVALUATION

# DISCUSSION

*As mentioned within the introduction, the aim of this thesis is not only to make electrochromism easy understood and explainable, but also approachable for designers: to use within their product designs. Making electrochromism easy understood and explainable is mainly the result of the literature research, material tinkering phase and material benchmarking; i.e. the 'understanding the material' phase. This information is communicated through both, this thesis and 'the puzzle of electrochromism'. Within this chapter, the limitations of the thesis will be discussed, aspects regarding future development and 'the puzzle of electrochromism'.*

There are some limitations, that are considered to be out of scope for this thesis, but nevertheless important to mention. First of all, the starting point of this thesis were the relatively unknown electrochromic materials. Electrochromic materials are to be believed of big value within product design. However, the only applications currently known are glass windows and as rapid prototypes for displays; yet lots of opportunities of this material are missed. Thus this thesis focused on making it more easy understood and explainable to be communicated to other designers, with the goal that it becomes more approachable for designers to use within their product designs. However, the underlaying question remains to be answered: "Why are these opportunities not explored yet?". The answer to this can partially be derived from literature research, as papers are written on possible (product concepts) using electrochromic materials. Especially, Nijholt (2012), Jensen et al. (2020), Lochtefeld et al. (2020), Muller et al. (2019) and, Muller, Napari et al. (2019) are worth to explore. However, in the end, none answer the question of why these opportunities are not implemented yet, which reasons could be valuable to know prior to implementing electrochromic materials in product designs yourself.

## MATERIAL PROPERTIES

As mentioned in chapter 1.2., cyclability and optical memory of electrochromic devices are properties that are not explicitly addressed within this thesis; i.e. considered to be outside the scope. The cyclability is the los in optical contrast (%) after a number of coloration-bleaching cycles. As the goal of this thesis is to implement electrochromic materials in product design, the cyclability could be of importance, as the design could be completely reliant on the cyclability of its ECD. It is recommended to further explore this and test whether the ECD created will experience loss of contrast after a -to be determined- number of cycles.

The optical memory is the time an ECD stays in its colored or bleached state after the potential is removed. The optical memory is amongst other things, highly depending on the amount of electrolyte used. As can be concluded from the material tinkering phase, the ECDs that were created without the 'Injekt F fine dosing syringe' (i.e. an estimate volume of electrolyte) had an irregular optical memory. The ECDs created with the 'Injekt F fine dosing syringe' (i.e. the right volume of electrolyte) experienced a more stable optical memory. However, as sometimes the electrolyte slipped through the bi-adhesive spacer while closing the ECD, this volume is still not precise enough to drawn conclusions based on the optical memory.



## ALTERNATIVE MATERIALS

At the start of the project, a deliberate choice was made between testing as many materials (electrochromic materials and electrolytes) as possible or to experiment with one specific material for both. As this is the first graduation project about electrochromic materials at the Emerging Material Group of the TU Delft, there was chosen to experiment with the 'Ynvisible electrochromic ink' and 'Ynvisible electrolyte'. A different electrochromic material would result into different colors for both the bleached and colored state. Thus it is important to note that a designer should not be guided by the change of color between transmissive sky blue to dark blue, as different materials have different colors. Tungsten trioxide for example switches between transmissive yellow and intense blue and Methyl viologen (MV1) between transparent and magenta (Scrosati, 1993).

The electrolyte, on the other hand, is a liquid electrolyte. According to Kraft (2019), four different types of electrolytes can be distinguished: liquid, gel, polymer and inorganic solid electrolytes. As the 'Ynvisible electrolyte' (liquid) leeks through when using textile or cardboard as substrate, when using these materials as substate, optimizing its viscosity or using a different type of electrolyte should be considered. Gel electrolytes for example have the same conductivity as a liquid electrolyte, however as polymers are added to create a more viscous solution, the possibility of leakage is reduced. Polymer electrolytes, on the other hand, have less conductivity than a liquid or gel electrolyte, but are proven to be mechanically stable and flexible. For more in-depth information about electrolytes, Kraft (2019) should be consulted.

## SUSTAINABILITY

Sustainability is currently a large topic of discussion, especially concerning overconsumption, waste flows and climate change. As designers are always creating new (extra) products for the market, it is important to not neglect this aspect of your designs; e.g. share, maintain/prolong, reuse/redistribute, refurbish/remanufacture or recycle (Ellen MacArthur Foundation). As the main topic of this thesis was to make electrochromism easy understood and explainable, and to inspire designers to make use of it in their designs, the focus was more on the technical characterization for implementation rather than for its end-of-life. When using electrochromic materials in product design, the designer should research the durability of its specific chosen material and design for the end-of-life of its product.

## MASS PRODUCTION

All prototypes within this thesis are created within the chemical lab at the 'faculty of Industrial Design Engineering' at the TU Delft. By means of manual screen printing using vinyl stickers. Companies such as 'Ynvisible' and RdotDisplays are specialized in creating rapid prototypes of ECDs. However, as the goal of this thesis was to create a product demonstrator with as main goal to inspire other designers, mass production was considered to be out of scope. The main differences between manual production and mass production is production speed (thus costs) and accuracy. As within mass production more ECDs can be produced simultaneously, the production speed will decrease, thus making it easier to implement.

## 'THE PUZZLE OF ELECTROCHROMISM'

When looking at the demonstrator designed within this thesis: 'the puzzle of electrochromism', two aspects can be brought to discussion regarding future development: voltage operation and closed loop circuit between the framework and puzzle pieces. On top of this, thinness and flexibility (device properties) are not shown within the demonstrator.

First of all, it was stated to be of importance that both vertical and co-planar stacking sequences should be demonstrated within the demonstrator (chapter 11.2). In order that the difference between the switching speeds and the possibility of a single and double image display could be shown. However, as stated in chapter 2.3, the voltage operation is another aspect that differs these stacking sequences; a co-planar ECD requires little higher power than a vertical ECD, as the path the ions have to travel is bigger. For an ECD using both the 'Ynvisible electrochromic ink' and 'Ynvisible electrolyte' this difference is 1.5V (e.g. vertical: 1.5V and co-planar:

3V). As the design of the demonstrator requires all individual puzzle pieces to be put at all (four) positions within the puzzle, it was rather impossible to make a distinction between the voltage operation of the vertical (puzzle piece #1, #2 and #3) and the co-planar (puzzle piece #4) ECDs. Thus, the influence of a higher voltage input was tested on the vertical displays (approximately 30 coloration-bleaching cycles). This resulted into the conclusion that a higher voltage created a higher contrast for the EC layer in its colored state. As the cyclability of an ECD is according to Somani (2003) generally 10^6 cycles, no conclusion could be drawn according to this. It is expected that a higher voltage input could decrease the cyclability of the ECD. Important to mention is that during testing this, some of the prototypes of puzzle piece #1 and #2 (vertical ECDs using a conductive substrate), turned yellow after the battery was connected to it for a while. As this was not continuously and happened to puzzle pieces randomly, and only half of the ECDs experienced this, it was expected that a short circuit was created between the electrolyte and the electrodes in a way not yet known. Thus, no clear conclusion could be drawn for this.

Secondly, the closed loop circuit between the framework and the individual puzzle pieces is created by magnets (chapter 11.2). Sometimes when puzzling, the connection between the puzzle pieces and the silver tracks printed on the framework are not connecting enough in order to create a closed loop circuit. Meaning it has to be adjusted manually (i.e. press with your fingers gently on the magnets). As it is the same situation as mentioned before, it is not continuously and happened to puzzle pieces randomly, it leaves the question of its cause. As it can be the either the connection between the copper tape and the ECD, between the copper tape and the magnets or between the magnets of the puzzles pieces and the silver tracks of the framework. Only, as this did not occur continuous and regularly, and has an easy fix (i.e. manual pressure), there was chosen to not further research and optimize it. Nonetheless, important to mention as it could be a point to consider for optimization within further development of 'the puzzle of electrochromism'.

Thirdly, the device properties of flexibility and thinness. As aforesaid within chapter 2.1, thinness and flexibility characterize electrochromic materials further. As the thickness of an ECD is only influenced by the thickness of the substrate/encapsulation and the bi-adhesive spacer used, it has the possibility to be really thin. However, as 'the puzzle of electrochromism' is a puzzle in which the pieces have to be taken up regularly, there was chosen to attach them to plexiglass; for both strength and support to the ECD and magnets. A consideration for the future can be made regarding the 'user manual'. As resulted from the user research, providing the solution to the puzzle would be considered not necessarily but a nice touch. This could be done by using a single image display for both puzzles (i.e. two separate ECDs) with the solution. The connection points to the battery supply, should be equal to the distance in between the silver tracks on the framework, thus the puzzler can 'reveal' the solution by pushing it on the framework manually. As this does not have to be taken up regularly and does not include magnets, it should not be attached to plexiglass but remain the ECD it is. Due to time restrictions, this is something that is not developed within this thesis, but could be considered a step to further development.



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# SOURCES


Aarts, R. (2020). "What are the characteristics and mechanics of electrochromic materials and electroch romic devices, applied to product design."

Argun, A. A., Aubert, P. H., Thompson, B. C., Schwendeman, I., Gaupp, C. L., Hwang, J., . . . Reynolds, J. R. (2004). Multicolored electrochromism polymers: Structures and devices. Chemistry of Materials, 16(23), 4401-4412. doi:10.1021/cm049669l

Boeijen, A. v., Daalhuizen, J., & Zijlstra, J. (2020). Delft Design Guide : Perspectives-Models-Approaches-Methods. Amsterdam: BIS Publishers.

Brooke, R., Mitraka, E., Sardar, S., Sandberg, M., Sawatdee, A., Berggren, M., . . . Jonsson, M. P. (2017). Infrared electrochromic conducting polymer devices. Journal of Materials Chemistry C, 5(23), 5824-5830. doi:10.1039/c7tc00257b

CES EduPack. (2019).

ChromoGenics. (2021). Technology- Electrochromic Glass. Retrieved from https://www.chromogenics.com/dynamic-glass/dynamic-glass-technology/

Coleman, J. P., Lynch, A. T., Madhukar, P., & Wagenknecht, J. H. (1999). Printed, flexible electrochromic displays using interdigitated electrodes. Solar Energy Materials and Solar Cells, 56(3-4), 395-418. doi:Doi 10.1016/S0927-0248(98)00144-5

CustomPlanet. (2021). What is screen printing? A step-by-step guide. Retrieved from https://www.customplanet.co.uk/what-is-screen-printing-step-by-step-i50#1

Demaine, E. D. D., M. L. (2007). Jigsaw puzzles, edge matching, and polyomino packing: Connections and complexity. Graphs and Combinatorics, 23, 195-208. doi:10.1007/s00373-007-0713-4

Desmet, P. F., S. . (2019). Human Experience Catalog.

Jensen, W., Colley, A., Hakkila, J., Pinheiro, C., & Lochtefeld, M. (2019). TransPrint: A Method for Fabricating Flexible Transparent Free-Form Displays. Advances in Human-Computer Interaction, 2019. doi:Artn 1340182

Karana, E., Barati, B., Rognoli, V., & Zeeuw van der Laan, A. (2015). Material Driven Design (MDD): A Method to Design for Material Experiences. International Journal of Design, 9(2), 35-54. Retrieved from <Go to ISI>://WOS:000362331300003

Kraft, A. (2019). Electrochromism: a fascinating branch of electrochemistry. Chemtexts, 5(1). doi:ARTN 1

Learning, T. (2012). Difference between ions and electrons. Retrieved from http://www.topperlearning.com/answer/what-is-difference-between-electrons-and-ions/6esegw77

Mandal, S. (2021). The world's thinnest electrochromic display can be used in future e-readers. Good E-Reader. Retrieved from https://goodereader.com/blog/tablet-slates/the-worlds-thinnest-electrochromic-display-can-be-used-in-future-e-readers

Mattila, H. R. (2010). Intelligent textiles and clothing. New Delhi; Boca Raton... [et al.]:

Oxford : Cambridge : Woodhead Publishing : The Textile Institute : CRC.

Monk, P. M. S., Mortimer, R. J., & Rosseinsky, D. R. (1995). Electrochromism fundamentals and applications.

Mortimer, R. J. (2011). Electrochromic Materials. Annual Review of Materials Research, Vol 41, 41, 241-268. doi:10.1146/annurev-matsci-062910-100344

Nijholt, A., Giusti, L., Minuto, A., & Marti, P. (2012). Smart Material Interfaces: "A Material Step to the Future". Icmi '12: Proceedings of the Acm International Conference on Multimodal Interaction, 615-616.

Oh, H., Lee, J. K., Kim, Y. M., Yun, T. Y., Jeong, U., & Moon, H. C. (2019). User-Customized, Multicolor, Transparent Electrochemical Displays Based on Oxidatively Tuned Electrochromic Ion Gels. Acs Applied Materials & Interfaces, 11(49), 45959-45968. doi:10.1021/acsami.9b15288

Puzzle. (2021). Oxford Advanced Learner's Dictionary. Retrieved from https://www.oxfordlearnersdictionaries.com/definition/english/puzzle_1?q=puzzle

Rosa, P. (2015). Minimal Computation Structures for Visual Information Applications based on Printed Electronics. (Science and Technology). New University of Lisbon,

SageGlass. (2018). What is Electrochromic Glass? Retrieved from https://www.sageglass.com/en/article/what-electrochromic-glass

Schell, J. (2008). The art of game design : a book of lenses.

Scrosati, B. (1993). Applications of electroactive polymers. Retrieved from https://link.springer.com/book/10.1007/978-0-412-41430-5

Somani, P. R., & Radhakrishnan, S. (2003). Electrochromic materials and devices: present and future. Materials Chemistry and Physics, 77(1), 117-133. doi:Pii S0254-0584(01)00575-2

Wavelength to Colour Relationship. (2021). Retrieved from https://academo.org/demos/wavelength-to-colour-relationship/

Ynvisible. (2020a). Design Guidebook: Basic Rules for Display Design. Retrieved from https://assets.website-files.com/5f7f21e12602d912658dce12/5f7f21e12602d90b658dcee3_design%20guidebook.pdf

Ynvisible. (2020b). Ink kit. Retrieved from https://www.ynvisible.com/product/ink-kit

Zhu, Y. M., Otley, M. T., Alamer, F. A., Kumar, A., Zhang, X. Z., Mamangun, D. M. D., . . . Sotzing, G. A. (2014). Electrochromic properties as a function of electrolyte on the performance of electrochromic devices consisting of a single-layer polymer. Organic Electronics, 15(7), 1378-1386. doi:10.1016/j.orgel.2014.03.038