Penumbra: A Presence-Responsive Mirror Using Polarized Light for Embodied Reflection

Kushagra Barnwal[1], Soumya Agarwal[2], Abhimanyu[3], Ananta Singh[4]
Supervised by Prof. Jayesh Pillai and Prof. Venkatesh Rajamanickam
[1]IDC, IIT Bombay, Bombay, India

Abstract

Penumbra is a light-responsive mirror that reflects human presence without revealing identity. Built using a grid of rotating polarizing disks, it modulates light in real-time to form silhouettes of nearby bodies. Unlike digital displays, it captures nothing and stores nothing. Its design draws from tangible interaction principles and leverages optical behavior to offer an alternative kind of interface—quiet, responsive, and ephemeral. This paper outlines Penumbra's conceptual framework, technical structure, and potential applications across architecture, education, and sensory environments. By grounding feedback in physical material rather than data, Penumbra proposes a shift in how presence can be acknowledged.

CCS Concepts

• **Human-centered computing** → **Virtual reality**; *Interaction paradigms*; *User interface design*; • **Computing methodologies** → Simulation and modeling; • **Applied computing** → Media arts.

Keywords

Virtual Reality (VR), Way-finding, Narrative-Driven Experiences, Immersive Storytelling, Spatial Cognition, Cognitive Load, Adaptive Navigation, Spatial Scale

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Figure 1: Visitors experiencing Penumbra

1 Introduction

Interaction design today faces a dilemma. As digital systems become more responsive, they often demand increasingly detailed personal data—face scans, biometric markers, continuous tracking. This shift raises critical questions about the trade-offs between responsiveness and privacy. Must interaction require exposure? Must systems that respond to presence also identify the person present?

We began exploring alternatives grounded not in data collection, but in material responsiveness. Our central question became: what if we could design an interface that acknowledged a body's presence without recording who it was? One that responded not with content or information, but with a simple material change—something that sensed without surveillance.

This direction led us to the affordances of polarized light. Polarizing filters, when rotated against each other, can modulate light from transparent to opaque. By mechanizing this rotation, we could create physical pixels that respond in real time to bodily presence—not through a display, but through the behavior of light itself. The choice of polarization was not arbitrary; it offered a way to construct a system where interaction could be immediate, ephemeral, and materially grounded.

The result was Penumbra: a light-responsive installation composed of rotating polarizing disks that shift in response to movement. As a person enters the space, the surface darkens where their silhouette falls. When they leave, the system resets to full brightness. Nothing is stored. Nothing is recorded.

Penumbra belongs to a wider conversation about tangible user interfaces (TUIs). Drawing from Hornecker and Buur's (2006) framework, we saw our project aligning with the four dimensions of TUIs: tangible manipulation, spatial interaction, embodied facilitation, and expressive representation. Rather than using buttons or touch, the system operates through proximity and motion. The interface is understood physically, through movement in space.

In the following sections, we outline the conceptual grounding and technical design of Penumbra, and situate it among related work in tangible interaction, optical interfaces, and non-representational design. Each section builds upon the last to show how light, material, and movement can converge into a new kind of interface—responsive, embodied, and silent.

2 Overview of Related Work

Penumbra draws from a range of precedents spanning kinetic sculpture, computational optics, and critical design. These influences helped shape the project's focus on material responsiveness, presence-driven interaction, and minimal mediation.

2.0.1 ***Mechanical Mirrors and Spatial Reflection.*** Our initial inspiration came from Daniel Rozin's mechanical mirrors (1999) (see fig 2), which use arrays of actuated materials to form low-resolution silhouettes in response to the viewer's movement. Rozin's work demonstrated how reflection can be constructed mechanically and conceptually—foregrounding spatial presence rather than identity. This approach resonated with our interest in using physical systems to evoke interaction, and seeded the idea of a presence-responsive mirror that does not rely on traditional imaging.

Figure 2: Daniel Rozin's mechanical mirrors (1999)

2.0.2 ***Polarization and Light Modulation.*** As we moved from concept to material experimentation, we explored how optical properties—specifically polarization—could serve as the core mechanism of interaction. Nayar and Narasimhan's (2003) work on polarization-based material recognition introduced us to the affordances of cross-polarized filters for selectively blocking light. By rotating polarizing films, we could physically control light transmission at the pixel level, enabling a low-resolution but expressive surface.

We also experimented with birefringent materials like cellophane, drawing from Olafur Eliasson's use of layered optics in immersive installations. These trials were not part of the final prototype, but helped inform our understanding of how color and texture could emerge from light modulation alone—without digital rendering.

2.0.3 ***Non-Capturing Interaction and Minimal Systems.*** Beyond material inspiration, Penumbra was also influenced by broader questions of data, visibility, and surveillance. Dunne and Raby's (2013) work on speculative design challenged the assumption that interactivity must involve recording or optimization. Similarly, tools like Reflectacles, which block facial recognition using reflective interference, suggested that systems could respond without identification.

Rather than concealing identity through obfuscation, Penumbra sidesteps representation entirely. It registers movement in real time, produces no stored data, and resets itself as presence fades. This position aligns with a growing discourse around ephemeral, non-archival interactivity—interfaces that acknowledge without extracting.

3 Conceptual and Theoretical Foundation

3.1 Tangible and Embodied Interaction

Our approach to Penumbra was shaped early on by the framework proposed by Hornecker and Buur (2006), which articulates four key dimensions of tangible user interfaces (TUIs): tangible manipulation, spatial interaction, embodied facilitation, and expressive representation. These categories provided a structure for how we understood and evaluated the system's behavior.

- Tangible manipulation is expressed through the physical rotation of polarizing disks. Though there is no direct touch, these components are actuated in response to bodily presence, making their modulation a tangible outcome of interaction.
- Spatial interaction is central to how Penumbra operates. Users do not interact at a fixed point; rather, their movement through space drives the system's output. Position and proximity are directly mapped onto the mirror's visual state.
- Embodied facilitation is reflected in the immediacy and legibility of the interaction. No training or instruction is needed. Users intuitively understand that the mirror responds to their motion, allowing for spontaneous engagement.
- Expressive representation is achieved through light modulation rather than symbolic visuals. The resulting silhouettes communicate presence without encoding identity, offering an ambient but legible form of feedback.

These principles align closely with Dourish's (2001) notion of embodied interaction, where meaning emerges from how users physically engage with their environment. Penumbra responds to spatial presence in real time, reinforcing the idea that bodily engagement, not symbolic command, is the basis for interaction.

3.2 Material Logic and Design Rationale

Penumbra's design centers on creating embodied interactions through physical modulation of light. We were particularly drawn to the use of polarizers because they offer a simple yet powerful mechanism for controlling visibility using mechanical rotation alone. Unlike systems that require digital displays or dynamic light sources, polarizers work by filtering existing light, enabling an ambient interface that is both low-power and materially expressive (Wiberg, 2018).

The key property of polarizers—blocking or allowing light based on their rotational alignment—allowed us to construct physical pixels that could transition between visible and invisible states. This formed the foundation of Penumbra's responsive surface. Their passive nature also aligned with our goals of designing for minimal computation and quiet operation, without sacrificing legibility or expressiveness (Nayar & Narasimhan, 2003).

This logic guided the overall material assembly: each disk in the mirror is mechanically rotated to modulate light, producing a direct visual result without symbolic translation. Interaction becomes a property of matter itself—not something processed and rendered externally (Ishii & Ullmer, 1997; Dourish, 2001).

3.3 Affordances of Polarization

3.3.1 ***Understanding Polarized Light.*** Polarization refers to the orientation of light waves. In natural (unpolarized) light, waves oscillate in multiple planes perpendicular to the direction of propagation. A polarizing filter restricts this oscillation to a single axis, transmitting only waves aligned with its orientation (Hecht, 2002). When two polarizing films are layered and rotated relative to each other, they can either permit or block light depending on their angular alignment. At a 90° angle (cross-polarized), most of the light is blocked; when aligned, it passes through. This principle is widely used in optical imaging and display technologies (Nayar & Narasimhan, 2003), and in immersive art installations where precise control of light and shadow is critical (Eliasson, n.d.).

In our case, this physical property enabled real-time, screen-free control over visibility using material behavior rather than computation. The simplicity and immediacy of this technique allowed us to create interaction through optics alone, without translating presence into digital representation (Wiberg, 2018).

3.3.2 ***Material Exploration and Experiments.*** To understand how these filters behave under different conditions, we conducted a series of small experiments layering polarizers at varying angles as demonstrated in fig 4 , 5 . These studies helped us visualize how contrast emerges dynamically through movement and angle. We also tested the introduction of birefringent materials, such as cellophane, placed between two polarizers. This setup, though unpredictable in color outcomes, revealed the capacity of cellophane to generate spectral gradients based on viewing angle and light source.

These material tests were critical in shaping our understanding of what the medium affords—both visually and interactively—especially given the lack of accessible documentation on such optical layering in the context of interaction design.

3.3.3 ***Selected Affordances for the System.*** For this prototype, we focused on the most stable and legible affordance of polarization: binary modulation of light. Each pixel in Penumbra either allows light to pass or blocks it entirely, depending on the rotational alignment of its polarizing disk. This binary logic enabled us to create a high-contrast, silhouette-based interface that was responsive, robust under different lighting conditions. The use of passive optical materials ensured low power consumption and quiet operation, consistent with our goals for ambient, presence-based interaction.

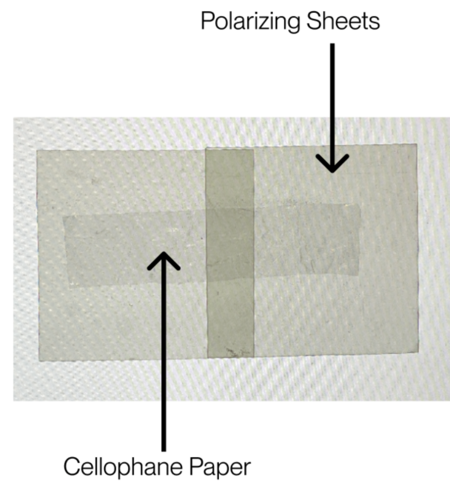
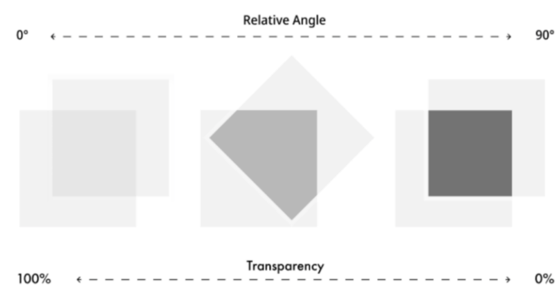


Figure 3: Placement of polarizer and cellophane sheet on screen for testing affordances of polarizing sheet



4 System Design and Technical Implementation

Penumbra's system was designed to be as minimal and transparent as possible—foregrounding material interaction over computational complexity. The design is organized into three interdependent layers: sensing, actuation, and physical structure. Each layer contributes to the project's goal of producing a seamless, ambient interaction through polarized light.

4.1 Sensing and Input Capture

Penumbra uses a basic webcam connected to a computer running a custom vision sketch written in p5.js. The system continuously captures low-resolution grayscale frames from the environment and applies a simple thresholding filter to detect regions of presence. These binary masks are mapped onto a 6×5 grid, where each cell corresponds to one disk in the mirror.

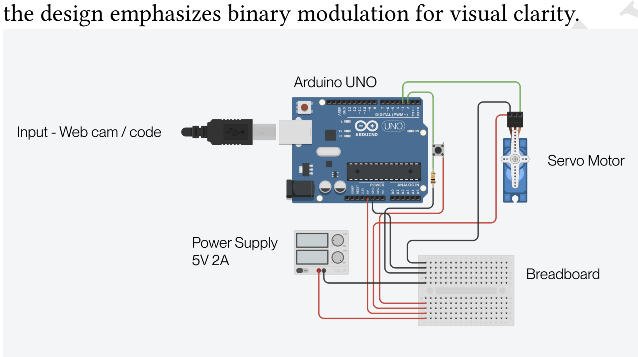
This approach keeps the sensing process lightweight, local, and easy to interpret. Since the system is only detecting changes in light and shape—rather than recognizing identity or pose—it aligns with Penumbra's core values of responsiveness without surveillance.

4.2 Processing and Communication

A webcam–computer–Arduino pipeline enables responsive actuation of Penumbra's disks. Presence data, captured and processed in real-time by a p5.js script, is transmitted via serial communication to an Arduino Uno. The Arduino controls 30 micro servo motors—each corresponding to one physical pixel—arranged in a 6×5 grid and driven using two PCA9685 PWM driver boards. This setup is illustrated in Figure 4.2, which shows the core hardware connections between input, power, and actuation.

To extend the installation's temporal behavior, a secondary mode was introduced: if no presence is detected within a predefined time window, the mirror enters an ambient "screensaver" mode. In this state, the polarizing disks move in pre-programmed mathematical patterns—such as waves, spirals, or cascades—producing gentle, continuous motion across the surface. This behavior not only maintains visual interest but reinforces Penumbra's material qualities, even when idle.

Once presence is detected in a given cell, a value is assigned to its corresponding actuator. Commands are updated only when changes occur, reducing unnecessary mechanical movement and conserving power. Each command includes a row, column, and rotation angle, which translates to either full blocking or full transparency of the pixel. Intermediate angles are not used in the current system, as the design emphasizes binary modulation for visual clarity.



4.3 Physical Pixels and Actuation

Each "pixel" in the mirror is composed of a circular polarizing disk attached to a micro servo motor. The polarizer rotates in front of a static backlit cross-polarized background. When aligned, light passes through; when rotated 90°, the pixel appears dark. This binary modulation creates a high-contrast silhouette that responds instantly to motion.

All components are mounted on a lightweight modular frame that allows for future expansion or reconfiguration. The rear polarizing film is backlit to ensure consistent contrast regardless of ambient light conditions. The servos are powered using two 5V 10A SMPS units that supply stable current across the grid.

The 6×5 configuration was selected as a practical compromise – large enough to render expressive silhouettes, yet compact enough to remain power-efficient, mechanically reliable, and easy to install. This resolution allows for presence to be registered clearly without overwhelming the viewer or the system's capabilities.

This physical setup completes the chain from sensing to visual feedback, keeping the logic simple and the behavior legible.

5 Reflections and Observations

Penumbra's development journey was as much about understanding interaction through materials as it was about system building. The final prototype revealed both strengths and limitations of the approach, offering several insights into the behavior, responsiveness, and experiential quality of the installation.

5.1 Responsiveness and Presence Detection

One of the most successful aspects of the project was the immediacy of feedback. The transition from light to shadow in response to user movement was smooth, legible, and intuitive. The low-resolution grid was sufficient to capture general body movement, and the silhouettes felt expressive without being overly detailed—aligning with the goal of reflecting presence, not identity.

The system's ability to reset itself after the user moved away reinforced the ephemerality we aimed for. Viewers found the disappearing effect particularly evocative, as it left no trace, echoing the central idea of an interface that forgets.

5.2 Challenges with Alignment, Power, and Control

Beyond optical alignment and ambient light interference, one of the most critical technical challenges we faced was managing power distribution across a large number of servo motors. Early prototypes revealed issues of voltage instability, and in one instance, an accidental connection to a 12V power source instead of the intended 5V supply resulted in the burnout of 16 servo motors and a capacitor. This incident reinforced the importance of careful power regulation and led to the integration of two 5V 10A SMPS units to ensure stable and distributed power delivery.

We also encountered practical challenges related to software control and communication. Initially, the system was prototyped using TouchDesigner, which offered greater control and clearer visualization but proved to be too complex to control at scale. The integration with Arduino became increasingly complex, particularly when trying to manage real-time serial communication across many motors. These limitations ultimately led us to migrate the system logic to p5.js, which provided a more lightweight, flexible environment for data handling and gesture-driven interaction.

5.3 Emergent Reactions and Viewer Engagement

Although Penumbra was designed as an ambient interface, it often prompted exploratory behavior. Viewers moved their arms, stepped in and out of the sensing field, and tested how quickly the pixels would respond to different gestures. Some approached the installation multiple times to see whether it would respond differently based on speed or proximity. These informal interactions revealed that even without screens, instructions, or traditional feedback mechanisms, the system effectively invited playful and embodied engagement.

This observation reinforces our hypothesis that a tangible interface can rely on material behavior and spatial response to support interaction. Penumbra did not require explanation—it encouraged participation through its own responsiveness

6 Applications and Future Work

Penumbra's low-resolution format and responsive optics open up a range of future applications—extending beyond art and installation into infrastructure, well-being, and responsive architecture.

6.1 Microclimate-Controlled Greenhouses

The system's ability to modulate light through mechanical rotation has potential for adaptive shading and spectral tuning in agricultural contexts. By rotating polarizers, sunlight exposure and temperature could be controlled passively and responsively. Additionally, layered birefringent materials like cellophane may be used to selectively filter specific wavelengths of light, enabling more targeted plant growth during different phases without external electronics or LEDs.

6.2 Biofeedback Surfaces for Therapeutic Environments

Penumbra's calm, responsive behavior and lack of representational feedback make it suitable for use in therapeutic and sensory spaces; especially in trauma-sensitive or neurodivergent environments. By reflecting movement, presence, and posture without storing identity or requiring interaction, it can serve as a low-pressure biofeedback surface. Users become more aware of their motion and stillness in real time, fostering awareness without judgement.

6.3 Smart Architectural Façades

Scaled to larger dimensions, the polarizer grid system can function as a responsive façade in public or architectural settings. The system can adjust opacity based on ambient light, occupancy, or time of day, functioning as a passive climate control element. Unlike traditional responsive buildings, Penumbra requires no screens, AI, or complex sensing systems—its material design alone drives its adaptability.

These applications suggest future directions where presence, material responsiveness, and sustainability intersect to shape a new design language.

7 8. Conclusion

Penumbra proposes a materially grounded approach to interaction—one that resists capture and favors presence over representation. Through the simple rotation of polarizing filters, it renders silhouettes that appear and vanish with the body's movement, offering an interface that forgets as easily as it responds. It invites reflection not just in what it shows, but in how it shows—without screens, storage, or identity.

From its conceptual grounding in embodied interaction to its practical construction using low-tech materials, Penumbra explores how light and space can co-produce interaction. As systems continue to trend toward higher fidelity and greater data dependency, this project offers a counterpoint—one that centers simplicity, tactility, and ephemerality.

References

[1] Paul Dourish. 2001. *Where the Action Is: The Foundations of Embodied Interaction.* MIT Press.

[2] Anthony Dunne and Fiona Raby. 2013. *Speculative Everything: Design, Fiction, and Social Dreaming.* MIT Press.

[3] Olafur Eliasson. n.d.. The Weather Project. Tate Modern installation.

[4] Eva Hornecker and Jacob Buur. 2006. Getting a Grip on Tangible Interaction: A Framework on Physical Space and Social Interaction. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems.* 437–446. doi:10.1145/1124772.1124838

[5] Hiroshi Ishii and Brygg Ullmer. 1997. Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms. In *Proceedings of the ACM SIGCHI Conference on Human Factors in Computing Systems.* 234–241. doi:10.1145/258549.258715

[6] Shree K. Nayar and Srinivasa G. Narasimhan. 2003. Vision in Bad Weather. In *Proceedings of the IEEE International Conference on Computer Vision*, Vol. 2. 820–827. doi:10.1109/ICCV.2003.1238477

[7] Reflectacles. [n. d.]. Reflectacles Official Website. https://www.reflectacles.com/. Accessed May 2025.

[8] Daniel Rozin. 1999. Wooden Mirror. Interactive art installation.

[9] Ali Tavassoli and Jack L. Nasar. 2018. Affect and Aesthetic Preference in Street Environments: Comparing Photographs and 3D Models. *Journal of Environmental Psychology* 55 (2018), 105–115. doi:10.1016/j.jenvp.2018.01.005

[10] Mikael Wiberg. 2018. *The Materiality of Interaction: Notes on the Materials of Interaction Design.* MIT Press.

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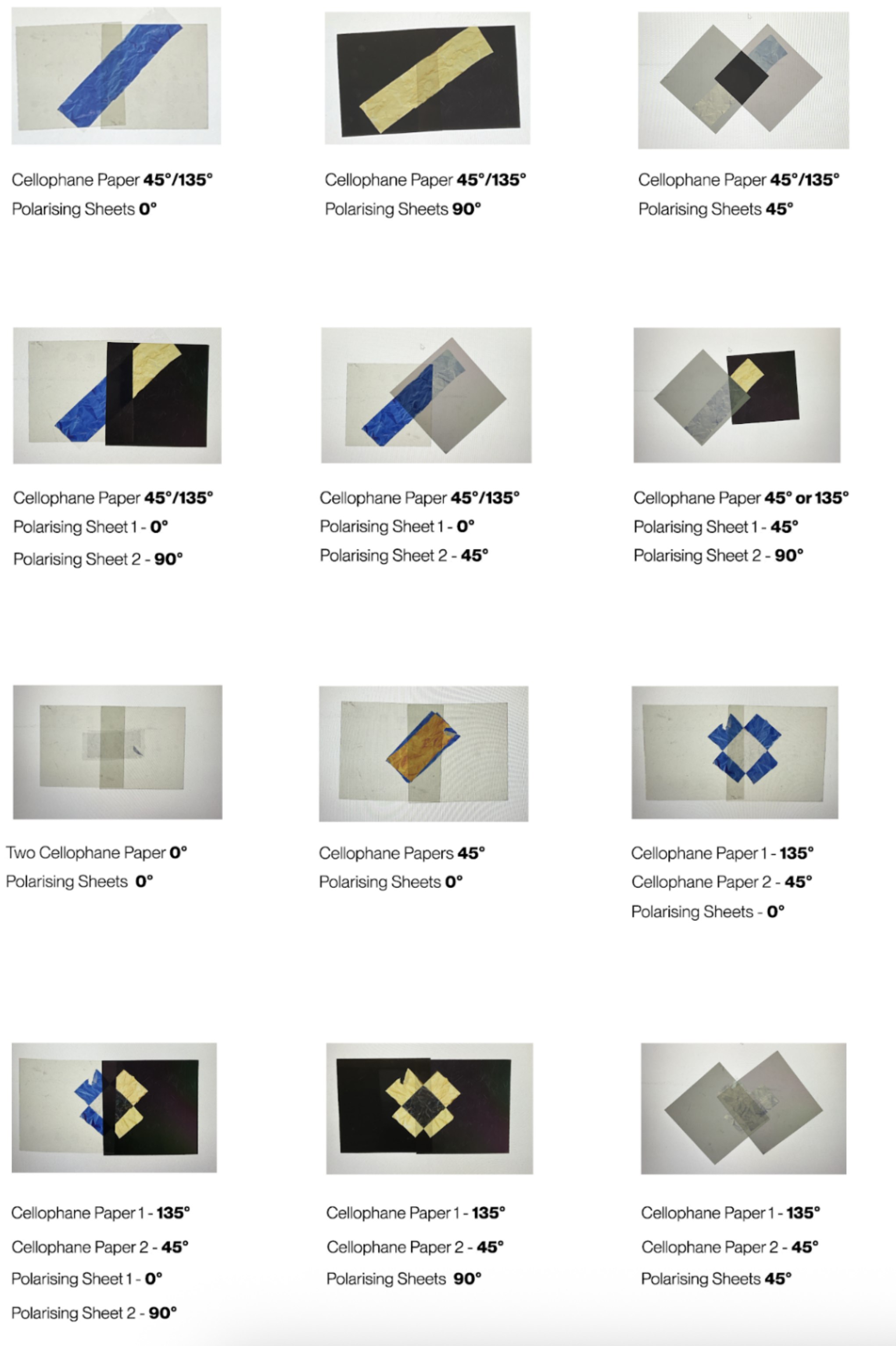
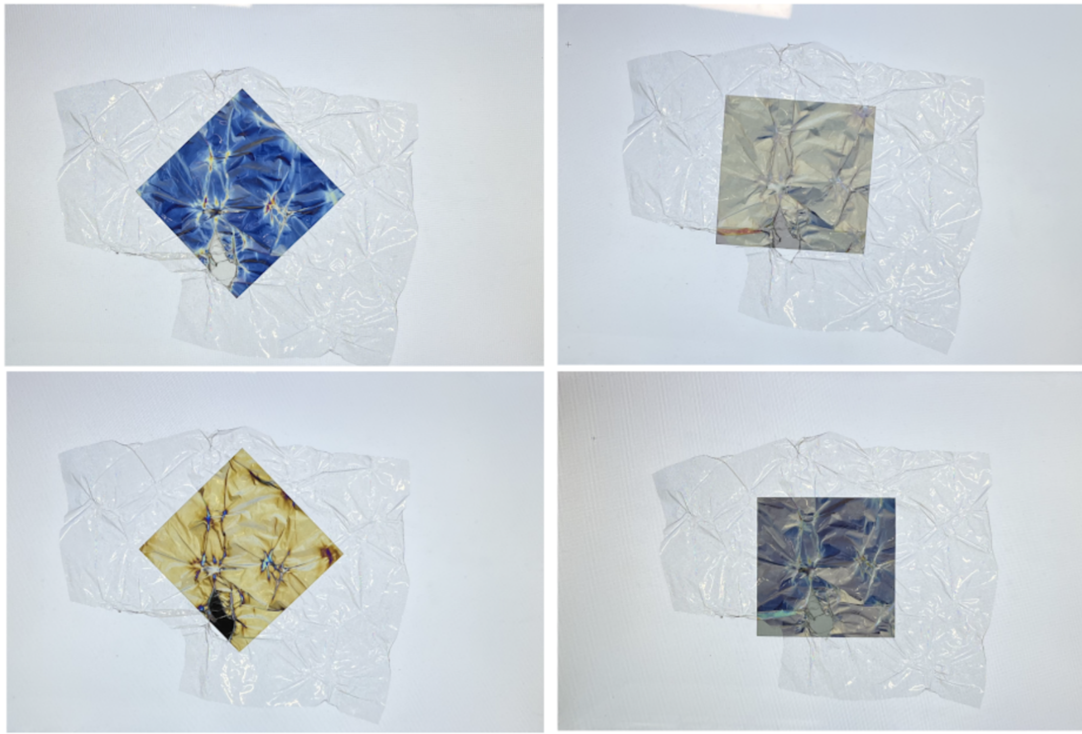


Figure 4: Affordances of a Polariser



Crumbled cellophane sheets and polarizers

Figure 5: Affordances of a Polariser