Sensemaking Sans Power: Interactive Data Visualization Using Color-Changing Ink

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Abstract—We present an approach for interactively visualizing data using color-changing inks without the need for electronic displays or computers. Color-changing inks are a family of physical inks that change their color characteristics in response to an external stimulus such as heat, UV light, water, and pressure. Visualizations created using color-changing inks can embed interactivity in printed material without external computational media. In this paper, we survey current color-changing ink technology and then use these findings to derive a framework for how it can be used to construct interactive data representations. We also enumerate the interaction techniques possible using this technology. We then show some examples of how to use color-changing ink to create interactive visualizations on paper. While obviously limited in scope to situations where no power or computing is present, or as a complement to digital displays, our findings can be employed for paper, data physicalization, and embedded visualizations.

Index Terms—Physical computing, color-changing inks, design space, data physicalization, data visualization.

1 Introduction

Despite the significant inroads made by digital media in the last few decades, paper and printed media remains a constant in the offices, living rooms, and public spaces of today's society. People consume information from a wide variety of print media such as books, newspapers, advertisement pamphlets, etc. It is estimated that 30% of all in-person transactions are still made using paper-based cash in the United States. The myth of the paperless office [1] remains just that, a myth; a study found that switching to email for all internal communications yielded an average 40% increase in paper consumption for an organization. Most data visualizations today are static representations that are either already printed or in media made for print, such as PDFs [2]

But paper is also a surprisingly good medium for data visualization. It is lightweight, durable, cheap, widely available, and unpowered and thus highly portable. With modern printing technology, it is also high resolution: it is only recently that mobile screens reached a resolution comparable to print, where 300 DPI—dots per inch—is the industry standard. In fact, typical computer screens still have not reached this level, where 200 PPI—pixels per inch—is common for a standard LCD monitor. Like electronic ink displays, paper is also *reflective*, meaning that it does not emit light but must be illuminated with ambient or direct light, which has been shown to reduce eye strain and fatigue [3] for readers. And while paper is static, it does provide interaction: a printed visualization can be turned every which way as well as moved closer or further away to enable both close study as well as larger overview. The paper can even be folded to enable comparison or masking. In fact, certain representations called hybrid images [4] use perceptual filters to blend two images into a single static one that shows different data depending on viewing distance. However, for all its benefits, paper is a largely static medium where visualizations can show only one thing and cannot respond to user interaction.

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At least, that is, until now. In this paper, we review how to use the new generation of so-called *color-changing inks* that change color depending on external stimulus—for data visualization. Examples of such stimulus include actuation by heat (thermochromic), light (photochromic), moisture (hydrochromic), or kinetic force (piezochromic). These color-changing inks have been around in the market for a while—Figure 2 shows a color-changing toy car—but has recently gained significant new capabilities. For this reason, they are particularly well suited for data visualizations because of the information-rich representations that are conveyed in a typical chart, making it possible to support Shneiderman's mantra [5] even on paper and with no need for computing or power sources. After reviewing the existing color-changing ink technology on the market, we derive a design space for the use of color-changing ink for interactive data visualization on paper. This design space incorporates methods for layering inks—both color-changing and standard static ones—to create interactive representations. We also discuss how to use color-changing inks to implement practical interaction techniques, such as masking data using standard ink and using color-changing ink to turn parts of a representation invisible.

To validate our framework and demonstrate the utility of color-changing inks for data visualization, we present a few prototypes of interactive paper-based visualizations designed with color-changing inks, including a line graph that reveals information on demand, a pie chart that dynamically switches data between day and night based on the time of the day, a visualization that changes between two views based on interaction, and a 3D topographical map that shows the animals seen at a national park based on the time of the day. Because the contribution in this paper is primarily theoretical and engineering-driven, we do not perform a user study involving human participants in this paper. However, the video accompanying this paper demonstrates all of these interactions in detail.

In summary, our paper proposes the following contributions: (*i*) a novel design framework on the use of color-changing inks for data visualization; (*ii*) a practical approach for implementing visualizations made using color-changing inks, including solutions for actuation, interaction, and data masking; and (*iii*) several example prototypes of visualizing data using color-changing inks,

Fig. 1: **Uncovering Anscombe.** Using your hand's body heat to uncover Anscombe's Quartet. Color-changing inks change their visual appearance depending on external stimulus; in this case, this ink is *thermochromic*: it changes color based on temperature.

including data-on-demand in a line graph, a pie chart displaying different data depending on the time of day, and a 3D topological map incorporating photochromic ink.

2 Related Work

Here we review the background on casual and everyday data visualization, data exploration, and data physicalization.

2.1 Data in Everyday Life

Modern day advancements in data visualization are usually catered to designing and developing tools that support analytical tasks for data professionals. Be it data analysts, data scientists, people in finance, or scientists, everyone significantly aids development in analytical tools and visualizations. But this is not the only population that makes use of visualizations to convey or perceive information. A majority of information is consumed through newspapers, information pamphlets, billboard signs, books, posters, etc, where simple visualizations help convey basic trends such as stock indices, create public awareness such as for COVID-19 data, or capture personal insights through tools such as Lifelines [6].

One example is the domain of *casual visualization* [7] for communicating data that is meaningful to a non-expert individual and not necessarily driven by a particular analytical task. Casual information visualization includes ambient information systems [8]–[11] that blend in with a user's environment while conveying information, social information visualizations such as PeopleGarden [12] that creates a graphical representation of users based on their social interaction, and artistic visualizations first described by Viegas and Wattenberg [13] that uses an artistic medium [14] to convey meaningful data. Another example of the latter is *Artefacts of the Presence Era* [15] that uses a projection-based visualization to display the audio and video captured from a museum.

2.2 Interactive Exploration

Many visualization tools are designed based on Shneiderman's visual information seeking mantra "*overview first, zoom and filter then details on demand*" [5]. Central to this mantra and data exploration in general is the role of interaction.

Becker et al. [16] explore dynamic graphical methods for data analysis that comprises manipulation (direct/indirect) and change in a response. While this is the integral idea of interaction, Yi et al. [17] propose general categories of interactions—*select, explore, reconfigure, encode, abstract/elaborate, filter and connect*—based on an extensive review of information visualization systems. Heer and Shneiderman [18] provide a formal taxonomy of tools for interactive visual dynamics—*"data and view specification, view manipulation, and process and provenance."* Thus for a visual interface to support effective data analysis, repeated interactions facilitate deriving meaningful insights. It would be interesting to explore the potential of designing interfaces that support interaction without computation for data exploration.

2.3 Hybrid Image Mechanisms

To be able to achieve interactive exploration, an interface should support ways of changing or manipulating the contents of the visual display. Hybrid images are visual representations—both powered and non-powered—whose visual content can change depending on the display angle, viewing distance, or some other outside stimulus other than a computer display. 3D multiscopy, for example, displays more than two images of an object as viewed from multiple locations by viewing the visualization from different points of view [19]. Matusik et al. [20] propose a technique to repurpose a 3D multiscopic display into a 2D display that shows different 2-dimensional content from different points of view. Similarly, researchers have also exploited the drawbacks of commonly used LCD screens to enable concurrent dual views [21]. The idea is based on the fact that LCD displays cause dimming and change in color from different angles. This can be exploited to selectively view or fade pixels to make things appear or disappear.

Novel out-of-screen displays can also be created to show multiple images with projection-based media. Izadi et al. [22] present a display that projects on the display surface while simultaneously projecting another image on a screen placed above the display surface, providing interaction capabilities for both.

Researchers have also used the idea of polarization to convey different images to multiple users all interacting with the same display [23]. Agrawala et al. [24]'s two-user Responsive Workspace use polarized goggles to interleave stereoscopic 3D images of the same scene from different viewpoints to two different users. Harrison and Hudson [25] make use of optical distortion in LCD displays to convey different images that can be seen perpendicular to the display surface when viewed obliquely.

Steganography is the technique of concealing information within another piece of information or a physical object first introduced by the book "*Steganographia*"' written in 1499 [26].

Johnson and Jajodia [27] discuss the idea of using steganography to create watermarks on images that essentially form the part of the image while still conveying an entire different meaning.

Distance-based hybrid images are a type of images that alter between views, usually two, as a function of viewing distance [28]. Isenberg et al. [29] use hybrid images to design visualizations that blend two representations—one that is viewed from a distance, and the other from a closer perspective. Physical navigation has also been used as a means of interaction with a visual display. Endert et al. [30] present a set of visual encoding interpret varying information with physical navigation/movement around the display. Ball et al. [31] study the relationship between physical and virtual navigation on user performance with large scale displays.

The screen resolution of an interface has also been used as a means of generating multiple insights from a large display, where lower resolution presents an overview and higher resolution display provides details when the user approaches the display [32]. Vogel and Balakrishnan [33] define interaction phases based on user proximity to a visualization display where by a different level of information is revealed based on the viewing distance.

Finally, spatial text visualization [34] uses the idea of spatializing text labels such that the visualization conveys spatial information from afar and provides a detailed textual description up close. Text can also be intuitively placed with word clouds to establish relationships between word cloud clusters [35]. We observe that all of the above techniques actively use computer screens or projectors to achieve interactive dynamics in the display.

2.4 Tangible and Physical Data

One way to make data widely accessible and approachable is to integrate it into our physical surroundings. Formalized in 1991, ubiquitous computing [36] is the notion of ever-present, always-on computing disappearing into the fabric of our everyday life. These ideas lead to Ishii's work on *tangible computing* [37] that bridges the digital and real-world environments to yield tangible interfaces. Many of Ishii's works use physical manifestations, such as light, movement, and touch, to convey digital data in the physical world.

With the advent of modern day technologies such as low-cost displays and augmented reality, it has become easier to integrate data into our physical environment. Vande Moere [38] was one of the first to discuss mapping abstract data to physical artifacts within a data visualization context. This work organizes the field depending on the degree of data physicality, including ambient displays, pixel sculptures, and object augmentation; the latter is the category best associated with a color-changing ink being used to augment everyday objects with data. Willett et al. [39] formalized the notion of *embedded data representations* that seamlessly integrates data into physical spaces or objects. Furthermore, physical representations of data enable exploring the dichotomy between symbolic data and the physical phenomenon that generated the data, which is not always straightforward. Interestingly, the color-changing inks explored in this paper are analog sensors responding to their environment, or what Offenhuber [40] call *autographic visualizations* (i.e., self-registering visual representations).

A recent trend has been to apply these ideas to printable visualizations. Stoppel and Bruckner propose Vol^{2}velle [41], a system for printing volume visualizations on multiple concentric circles that are assembled into revolving wheel charts that retain some interactivity. Schindler et al. [42] and Radiou et al. [43] propose and refine a workflow for creating anatomical diagrams of the human body that can be printed and even folded, and then viewed using colored filters or colored light to reveal distinct anatomical features. Finally, volograms [44] are slide-based interactive sculptures constructed from paper for representing medical data in an approachable fashion. While these ideas are all comparable to our work and all rely on papercraft materials, no existing work has specifically studied color-changing inks.

2.5 Ink-based Display Changing Mechanisms

There have been a range of display changing interfaces ranging from physical objects to printed media that that rely on color changing inks to switch between views or change colors. Photochromic Canvas [45] makes use of photochromic paint on paper coupled with a projector pen to enable users draw directly into the canvas. This also allows certain predefined custom patterns to be drawn. Similar to this, Photochromic Carpet [46] is an interactive floor where the carpet records user footprints as someone walks over it. Further extending the idea, Shader Printer [47] uses projection to paint custom prints on 3D objects printed with photochromic inks. While most of these implementations are on a 2D surface, Photochromic Sculpture [48] is based on the idea of volumetric color changing pixels that give an illusion of a 3d sculpture with changing color. ColorMod [49] is a method for changing colors of 3D printed objects even after fabrication that uses photochromic paint. This uses a projection-based technique to activate and deactivate color voxels on the printed surface. Building on this, researchers have further developed the idea of re-programmable color textures while eliminating the need for any voxel printing rather embedding CMY (Cyan, Magenta, Yellow) into a single color solution that can be sprayed and the appearance of which can be computationally controlled [50].

There has been a considerable research on the use of thermochromic inks (color based on temperature) to facilitate color change, as a simple computer-controlled heating layer can bring about this change. ChromoSkin [51] makes use of thermochromic paint in makeup as a wearable technology that changes color depending on temperature. Berzowska [52] showed the application of this technology on textiles where fabrics can change colors to yield animation. Kaiho and Wakita [53] present electronic origami that have the ability to change colors using this concept.

Researchers have also investigated fabrication technologies to develop thin and flexible color changing films [54] that are based on thermochromic ink. Anabiosis [55] in an interactive art that uses thermochromic ink that changes color when a user actuates a heating element with touch. An interesting application of photochromic inks is presented by Yamada et al. [56] where the researchers present multi color changes with thermochromic ink that are printed in a layered pattern with regular ink. These inks are actuated by infrared LEDs that generate heat upon illumination.

While display mechanisms based on color-changing ink show tremendous potential, there has to our knowledge so far been no exploration on their application to data visualization. In this paper, we thus present such an exploration.

3 Background: Color-changing Inks

Color-changing inks are a type of ink that changes color in response to external stimulus. For instance, thermochromic inks change color when heated. This is achieved by having the chemical structure of these substances change upon stimulation, resulting in a change in its reflective and absorptive characteristics, i.e., its color.

(a) Coldest (subzero freezer). (b) Cold (refrigerator). (c) Room temperature. (d) Warm (hand temperature).

Fig. 2: Color-changing ink used on a toy bus belonging to the son of one of the authors.

Depending on the type of ink, some inks have two discrete states (colors), including the intervening colors during the transition, or possibly three or more. Furthermore, the change may either be reversible and temporary or irreversible and permanent. In general, the inks that have reversible changes in color revert back to their original state when the stimulus is removed. In this paper, we make use of commercially available color-changing inks from LCR Hallcrest.[1] Inks can be divided into the following non-exhaustive list of categories based on the type of actuation stimulus:[2]

Thermochromic Ink. Thermochromic inks react to temperature (Figure 2). The threshold temperature for activation can be designed such that a color change maybe seen at a particular temperature. In general, this could be subdivided into heat-activated or cold-activated. Heat-activated inks change color when heated. When the threshold temperature is so designed that the heat from the human hand triggers a change, the inks becomes touch sensitive. Of course, this is assuming that the temperature of the environment is below the average temperature of the human hand (body). Cold-activated inks change color when cooled, such as being put in the freezer or being exposed to cold outdoor environments.

Photochromic Ink. Photochromic ink react to light to trigger a change in color (Figure 3). Most commonly, the light source is ultraviolet (UV), but other actuating wavelengths are also possible. The source of the UV light could either be from the sun or from a black light. This can be used to create surfaces that react to the presence of daylight, i.e., outdoors during a non-cloudy day.

Photoluminescent Ink. Photoluminescent inks emit a glow after being "charged" using a light source. The characteristic color of the glow depends on the type of ink. Whether the glow fades away immediately or remains for a longer period of time depends on the type of ink. The inks can respond to different wavelengths of light such as ultraviolet or infrared light based on requirement.

Solvatochromic Ink. Solvatochromic inks change color in the presence of a solvent. This change may or may not be reversible. When the solvent is water, this is called a *hydrochromic ink*.

Piezochromic Ink. Piezochromic inks change color under application of force or pressure, such as a shock, impact, or stretching. The color change is generally localized to the point of application. Again, changes can either be reversible or irreversible.

Chemochromic Ink. Chemochromic inks change color when they come in contact with a specific gas. The type of gas, i.e., its chemical composition, is unique to the ink.

1. https://www.lcrhallcrest.com/
2. https://www.olikrom.com/en/

4 Design Space: Color-changing Inks for Visualization

We are not aware of a systemic review of how to use color-changing inks to achieve unpowered interactive data visualization. In this section we present a design space exploring this area.

4.1 Marks and Channels

In data visualization, a *mark* is a geometric primitive that forms the basic graphical elements in a visual representation. *Visual channels* control the appearance of a mark [57]. A visualization consists of a 2D or 3D substrate upon which data items are mapped as marks carrying information in their visual channels. As the channels in a visualization change, the information conveyed also changes.

If we were to broadly classify the media on which visualizations are displayed, there would roughly be two main types: computer displays and print media, such as a paper or a book. While computer displays are based on the idea of *emissive* colors, i.e., displays that emit colored light, print media relies on *reflective* colors. Reflective colors are based on materials that reflect a certain type of color (and absorb others). As these are print based, dynamic changes in color are difficult because of an absence of computational paper.[3] This makes it difficult to achieve dynamic graphics using print media, such as altering any mark and channel. To display multiple levels of information, it is necessary to have multiple visualizations.

In this work, we propose leveraging the potential of color-changing inks to design marks that enable dynamically changing channels in print media visualizations. This provides a technique to alter the appearance of marks in a given visualization with an external stimulus, thereby opening up opportunities for interactive changes in print-based visualizations.

4.2 Basic Color Model

To describe the appearance of a color-changing ink under a given state, let us look at a simple system of a single layer of color-changing ink painted on a piece of paper as shown in Fig. 4. Basically, visualizations are created using color-changing inks through *alpha-composition*, i.e., with regard to the transparency of the ink. The appearance of the composition can be described in terms of the ink's visibility. When an ink disappears from a composition, it exposes the base layer. We denote its absence as the ink's complement, denoted by $i_{cc}^{\complement}$ as shown in Fig. 4(b). We denote a color-changing ink to i_{cc} for simplicity in the equations below. To describe the behavior of this composition, we may say that the ink selectively appears or disappears based on the presence or absence

3. Electronic inks are an exception, but beyond the scope of our work here.

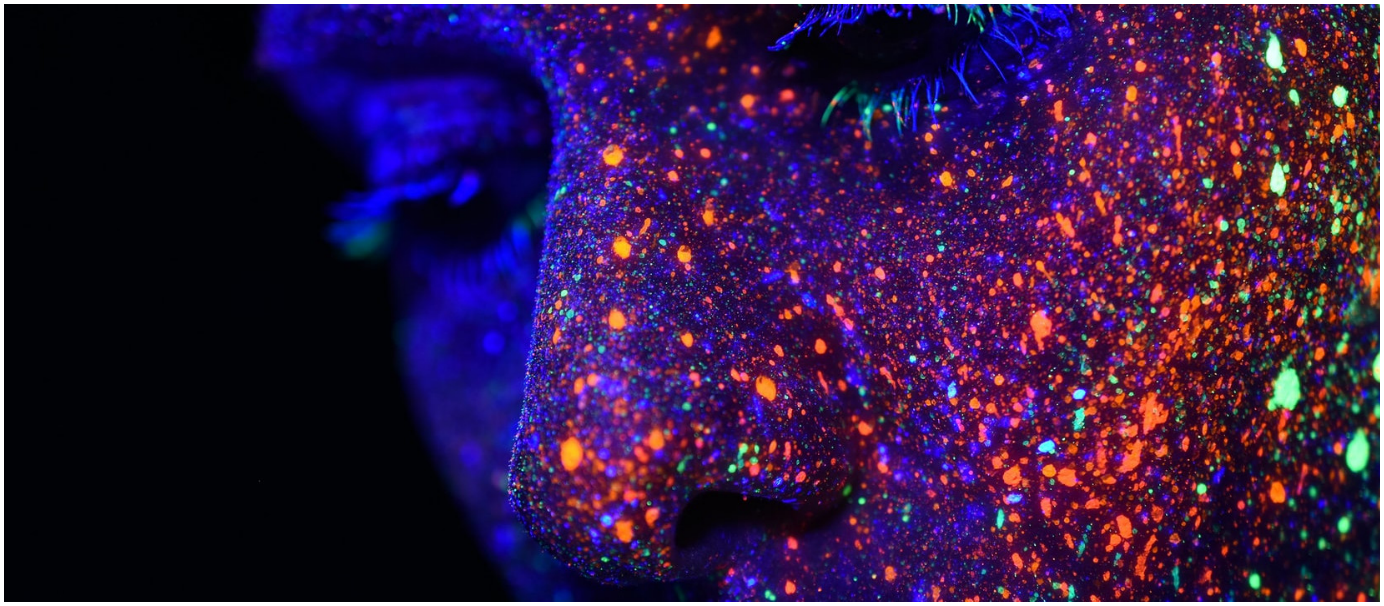


Fig. 3: **“Glow in the dark” (photoluminescent) ink.** This ink is actuated by a “black light” emitting ultraviolet (UV) light. (Photo by `@heyerlein` on Unsplash; image in the Public Domain: https://unsplash.com/photos/ndja2LJ4IcM.)

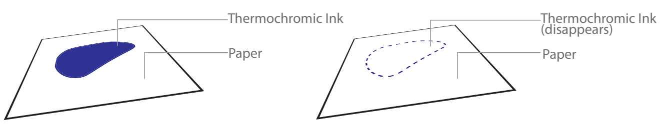


Fig. 4: **Layer of thermochromic ink on paper.** (a) (left) Ink is visible without stimulus. (b) (right) Ink is invisible when heated.

of an external stimulus, e.g., heat. This behavior is very similar to the idea of *alpha compositions* [58] used in digital images. Mathematically the composition appearance may be described as,

$$\text{composition} = \alpha_{i_{cc}} \cdot i_{cc} + (1 - \alpha_{i_{cc}}) \cdot i_{cc}^{C}; \; \textit{where } 0 \leq \alpha \leq 1 \quad (1)$$

and i_{cc} refers to the color of the ink.

As $\alpha_{i_{cc}}$ varies from 0 to 1, the composition appearance changes from the visibility of the ink to its disappearance. Here, $\alpha_{i_{cc}}$ is an intrinsic characteristic that maps the ink's behavior to its stimulus.

$$\alpha = f(\text{stimulus intensity}) \quad (2)$$

In the example composition stated above (Fig.4), $\alpha_{i_{cc}}$ may be described as,

$$\alpha_{\text{thermochromic}} \approx \begin{cases} 1, \text{heat intensity low} \\ 0, \text{heat intensity high} \end{cases} \quad (3)$$

This denotes that the thermochromic ink is visible when the stimulus (heat) is low and disappears when the stimulus(heat) is high. Color-changing inks can be classified based on this notion of α. An ink that changes completely from color to colorless will have α values 1 and 0 where as a regular ink that does not change its color will have an α value of 1.

Similarly, we can describe the behavior of a photochromic ink that appears on stimulation, i.e., under UV light, and disappears when the stimulus is removed.

$$\alpha_{\text{photochromic}} \approx \begin{cases} 0, \text{UV intensity low (absent)} \\ 1, \text{UV intensity high (present)} \end{cases} \quad (4)$$

This is a simple example of an alpha composition displaying two states i.e., the appearance and disappearance of ink.

4.2.1 Altering Marks with Alpha Compositions

Human interaction with alpha compositions limits the range of external stimuli that could be used in the interaction. Here we experimentally show the appearance and disappearance of a mark with a single external stimuli. With this as the underlying principle, we next show how we could alter channels for different marks.

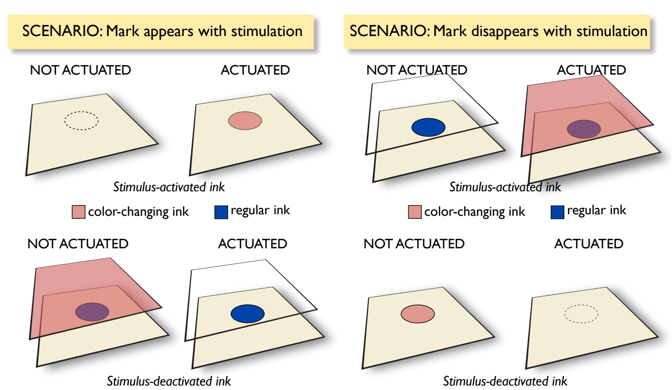


Fig. 5: **Controlling mark appearance and disappearance.** How to make marks appear (left) and disappear (right) with stimulation for different types of inks. Color-changing inks are red, regular inks are blue. Top: Stimulus-activated inks; Bottom: Stimulus-deactivated inks.

Let us consider the the setup as shown in Fig. 5 where we analyze the behavior of the composition. We consider two cases—mark appearance and disappearance—for two kinds of inks: thermochromic ink (ink disappears on stimulation) and photochromic ink (ink appears on stimulation).

Mark Appearance: The goal is to make a mark appear on a visualization when it is actuated. Fig. 5(a) shows the ways in which a mark can be made to appear upon stimulation depending on whether the ink is stimulus-activated (becomes visible with actuation) or stimulus-deactivated (becomes invisible with actuation). To make a mark appear upon stimulation with stimulus-activated ink, we paint the mark with the ink on an empty canvas as shown in Fig. 5(a) (top left). In the absence of actuation, the mark is invisible but comes to color when actuated. The approach is different with stimulation-deactivated ink. Here we mask a mark painted with regular ink on a canvas with a layer of stimulus-deactivated ink as shown in Fig. 5(a) (bottom left). When heated, the stimulation-deactivated ink layer fades and exposes the mark.

Mark Disappearance: To make a mark disappear into the background with stimulus-activated ink, we paint the mark with regular ink and layer it with stimulus-activated ink that is initially colorless as shown in Fig. 5(b) (top right). The mark is thus seen at this stage. When under actuation, the ink comes to color masking the mark and making it disappear. With stimulus-deactivated ink, we achieve mark disappearance by simply painting the mark with the stimulus-deactivated paint as shown in Fig. 5(b) (bottom right). When heated, the marks goes from color to colorless.

4.2.2 Alpha-composed Marks

Having established the idea of making a mark appear or disappear, we use this principle to alter channels for alpha-composed marks. Specifically, we choose commonly used marks: points, lines, and areas. We choose position, color, length, and area as our channels. These are some of the channels that are highly ranked in Mackinlay's ranking of visual channels [59].

Here we discuss how we alter marks as shown in Fig. 6. We use thermochromic and photochromic ink in our compositions to alter marks. Upon heating, the thermochromic ink disappears and when in sunlight the photochromic ink appears. In the table, we show two states of the compositions, the non-actuated (room temperature for thermochromic ink and no sunlight for photochromic ink) and the actuated (warm state for thermochromic ink and under sunlight for photochromic ink) state.

Position: For a point, line and area, we show a change in position along a vertical and a horizontal axis. This is based on the idea of appearance and disappearance of marks where upon actuation, the initial mark disappears and a new mark appears in a diagonal position.

Color: We show a change in color by simply letting the thermochromic ink fade away or photochromic ink appear upon actuation. This is the same idea that we used for mark appearance and disappearance.

Length: We show two cases for a change in length of the line mark—going from small to big and from big to small. We choose the line mark as a change in length isn't applicable to point and area. When the length changes from small to big, we use the idea of mark appearance where a line with a longer length appears over a line with smaller length upon actuation. When the length changes from big to small, we use the idea of mark disappearance were a line with longer length disappears from over a line with a smaller length eventually shortening it.

Area: We use the exact analogy for area as length. Here we use mark appearance and disappearance to show a change in area from either small to big or big to small.

4.3 Interaction Model

Here we describe a few possible interactions scenarios for how to use color-changing inks for interactive print visualization.

- **Thermochromic Interaction:** The transition temperature of thermochromic ink is often close to average body temperature, enabling tactile interactions with the tangible visualization to initiate a change. Another way of actuating an alpha composition with thermochromic ink is by harnessing the heat from an environment or an object. For instance, a color-changing visualization placed in a warm environment can initiate a change and this change will revert back when the temperature drops (the sun goes down or the frame is moved).
- **Photochromic Interaction:** A good interaction scenario for photochromic ink is to print visualizations that change when in direct sunlight. This can be used for outdoor visualization billboards that change during the day and revert back at night, or when manually exposed to the sun to bring about a change.

4.4 Additional Considerations

The basic color model above is relatively straightforward and forms the building block for constructing visualizations using color-changing ink. However, there are additional considerations beyond the primary alpha compositions discussed there:

- **Temporality:** Because they are based on chemical processes, most color-changing inks—even expensive ones—change state only slowly; on the order of several seconds. Change is often faster for photochromic inks, and slower for thermochromic ones, but there are no strict rules here.
- **Reversibility:** Most inks revert to their original state once they are no longer being actuated, but the reverse process is often slower due to the inertia of a physical system; e.g., paper warmed by a user's hand may cool down only slowly. Some inks are not reversible, so changes are permanent.
- **Intermediate states:** Inks are analog and will gradually change color as the actuation continues; e.g., an ink that is white at room temperature and blue at body temperature will slowly become increasingly blue as it is warmed.

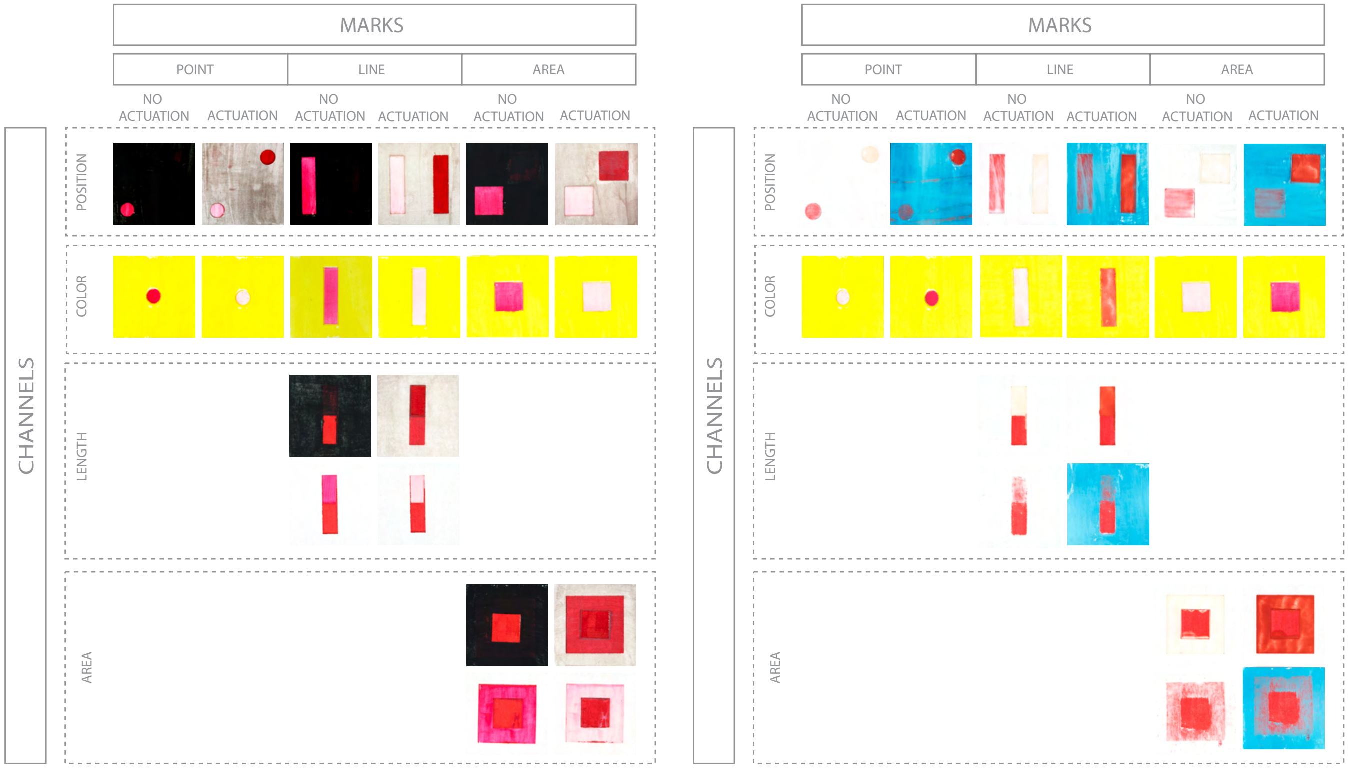
These factors may also yield inconsistencies in a visualization, especially for intermediate states during transition. For example, a mark being actuated to disappear will not do so instantly. Even final states (Figure 6) may not be perfectly matched to the background.

4.5 Multiple Ink Compositions

So far our basic color model has described alpha compositions for a single color-changing ink. However, there is significant potential in composing multiple inks. We discuss two options here.

Composing with regular ink: Common in almost all practical printable visualizations is the use of regular inks together with color-changing inks. Regular inks are often used for masking and blending, as well as to provide the non-dynamic part of a visualization. We describe these techniques in Section 4.2.1.

Composing multiple color-changing inks: Combining multiple color-changing inks allow for even more complex behavior; for example, a visualization that changes into one form when exposed to UV light, and to another form when exposed to heat. The challenge with this approach is that each of the individual alpha compositions will be designed separately and their resulting composition is hard to predict. The order of ink application may sometimes have influence, and some inks do not mix well with



(a) Thermochromic ink. (b) Photochromic ink.

Fig. 6: **Alpha composition.** Altering marks with alpha compositions.

others; for example, some photochromic inks must be applied last in order to be actuated properly. Nevertheless, composing multiple inks makes even more complex interactive behavior possible.

5 PROTOTYPES

In Section 4, we outlined how color-changing inks can be used to alter marks in a visualization. We also described some scenarios where interactions could result in an actuation of the color-changing ink. In this section, we make use of these ideas to build working prototypes to demonstrate the use of color-changing inks in building interactive visualizations and describe the scenarios of their use. Table 5 summarizes these prototypes and their components.

5.1 Interactive Newspapers

Imagine a scenario of an interactive newspaper enabled with touch-based data exploration. In Fig. 7(left) we show a line graph on a newspaper visualizing new confirmed cases of Covid-19 in the United States (green), the United Kingdom (red), and the European Union (blue) from Jan–Aug 2021 taken from *The Financial Times*. This is a fabricated picture made to show the context of a newspaper for the purposes of demonstration. The design of this visualization is based on the idea of change of color of a mark (line) that we have discussed in Section 4. The prototype makes use of thermochromic ink thus supporting touch-based interaction.

Overview. The user gains an overview about the data by glancing at the image. There is no touch interaction involved at this stage. This is shown in Fig. 7(right-top).

Filtering. To gain a deeper understanding from the data about the United States, the user may place a hand on the graph, which fades the data values from the UK and the European Union. This is the first touch interaction that results in filtering of data. The view upon interaction is shown in Fig. 7(right-middle).

Details. To further obtain details about the specific highs and lows in the data, the user may place the hand on the top bar that reveals the exact data. This is shown in Fig. 7(right-bottom)

5.2 Interactive Books

This prototype shows the metaphor of a book to demonstrate touch-based interactions. The book in Fig. 8(left) presents two of the four distributions of *Anscombe's Quartet*. Upon interaction, the distribution shown in Fig. 8(right-top) changes to the one shown in Fig. 8(right-bottom). This design makes use of thermochromic ink and is based on the idea of color change of a mark as discussed in Section 4. This enables toggling views between two datasets.

5.3 Dynamic Billboards

We explore how color-changing inks can be used to create dynamic billboards that display multiple views without the need for any computation or an electronic display. We present a prototype example displaying passenger occupant vehicle fatalities by day and night taken from the NHTSA [60] in Fig. 9 that may be used to create awareness. This is an example of how situated visualizations may be designed with color-changing ink. The prototype makes use of photochromic ink and maps day time data to day time hours (the presence of sun) and the night time data to night time hours

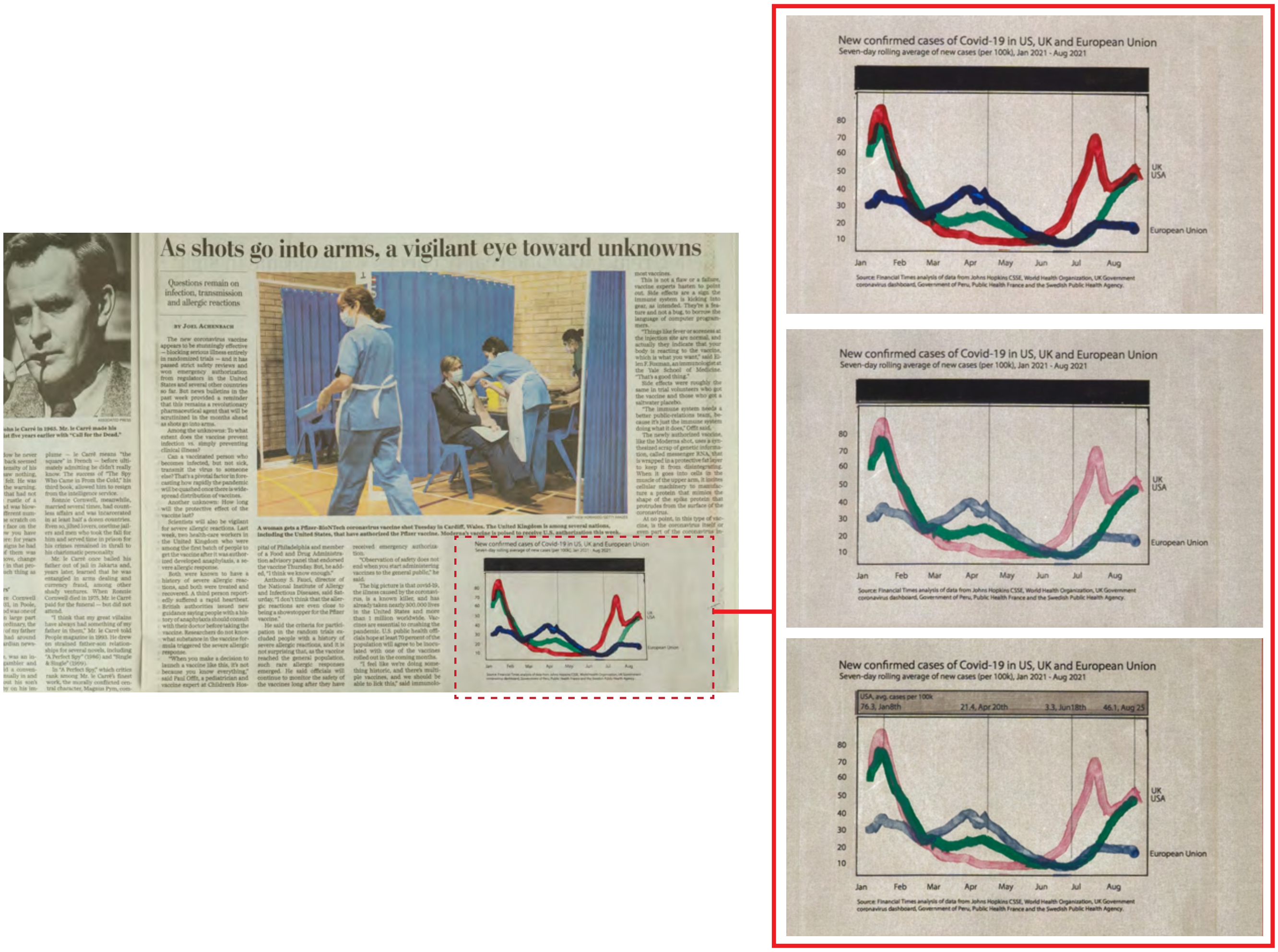


Fig. 7: **Thermochromic newspaper charts.** (left) New confirmed cases of COVID-19 in a newspaper. (right-top) Overview. (right-middle) Filtering to show U.S. data. (right-bottom) Details.

TABLE 1: **Prototype overview.** Summary of the color-changing visualization prototypes presented in this paper.

Name	Technique	Ink	Mark	Channel	Composition	Interaction
Newspaper chart (Section 5.1)	line chart	thermo	line	color	appearance	filter
Newspaper chart legend (Section 5.1)	text	thermo	text	color	appearance	details-on-demand
Book (Section 5.2)	scatterplot	thermo	point	position	disappearance	filter
Billboard (Section 5.3)	pie chart	photo	area	area	appearance	filter
Dynamic data sculpture (Section 5.4)	3D terrain	photo + thermo	glyph	color	appearance + disappearance	filter

(absence of sun). Here the assumption is that the day has clear skies with sunlight or is mildly cloudy. The night time view is shown in Fig. 9(right-top) and the day time view of the data is shown in Fig. 9(right-bottom). We use the idea of change of color of area mark in designing this prototype.

5.4 Dynamic Data Sculpture

We present an example of a dynamic data physicalization that uses color-changing inks to toggle data views. A 3D printed topographical map of the Zion National Park with the commonly spotted animals by day and night is shown in Fig .10. This data is taken from the U.S. National Park Service.[4] This is a prototype and the data is not presented to scale.

4. https://www.nps.gov/zion/

A blue color represents the animals that are visible and a white represents the animals that are not for the current part of the day. The prototype makes use of photochromic and thermochromic inks that react to the Sun's UV and heat during the day. Thus the appearance dynamically changes based on the time of the day, i.e., animals that are seen during the day appear blue during the day (as shown in Fig. 10 (top)) while animals that are seen during the night appear blue at night (as shown in Fig. 10(bottom)). We make use of the change of color of a mark in designing this prototype.

6 Discussion

Our main motivation in this paper was to explore the opportunities afforded by color-changing inks to introduce interactivity in print-based visualization. We present the scenario of limited to no

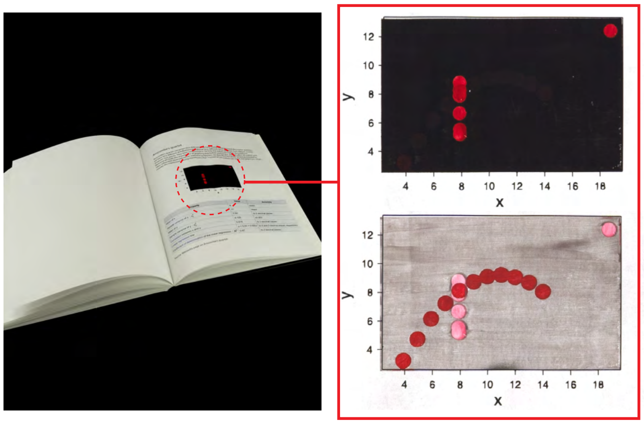


Fig. 8: **Thermochromic interactive book.** (left) Two distributions of Anscombe's Quartet shown in a book. (right-top) Distribution as seen without any interaction. (right-bottom) A new distribution appears on touch.

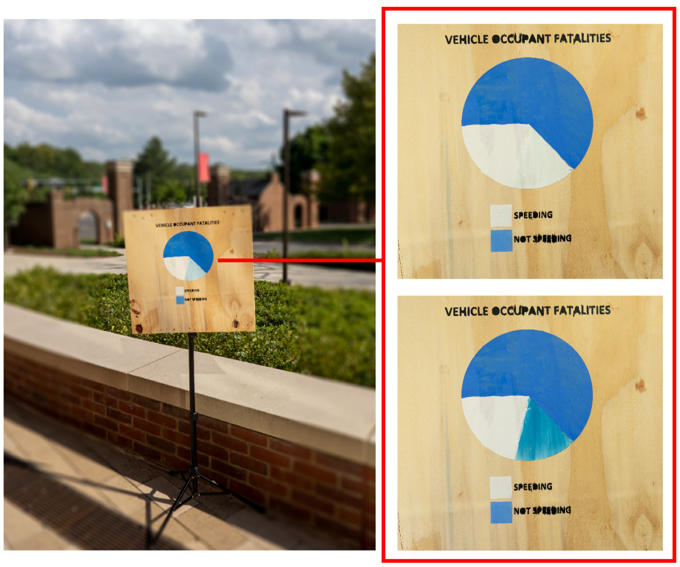


Fig. 9: **Photochromic billboard pie chart.** (left) Vehicle occupant fatalities taken from NHTSA. (right-top) Data as seen at night (no sunlight). (right-bottom) Data as seen during day (with sunlight).

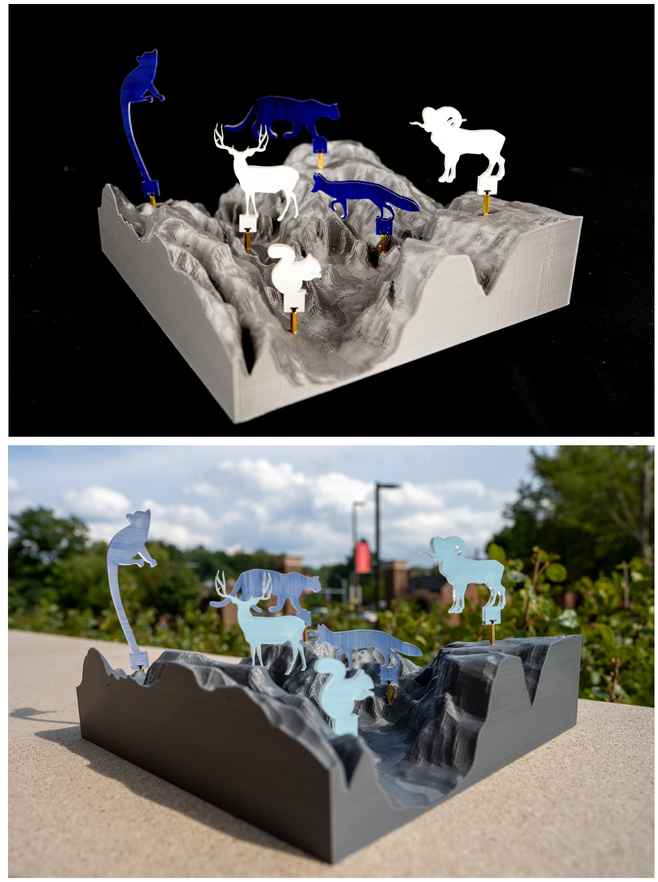


Fig. 10: **Thermochromic and photochromic digital sculpture.** A 3D printed topography of Zion National Park with the commonly seen animals based on their day and night activity. Color blue represents animals that can be seen and white represents animals that cannot. (top) Animals seen during night. (bottom) Animals seen during the day.

availability of power and computational resources, such as an outdoor or wet environment with no ready access to power.

Here we discuss some of the nuances of using color-changing ink for visualization, including the outlook and applications of the technology as well as its significant limitations.

6.1 The Outlook for Color-Changing Inks

While it is true that the present day is flooded with mobile digital displays that provide ample opportunities for visualizing data, the use of color-changing inks provides a simple low-tech cost-effective solution to displaying data interactively where otherwise one may not consider installing a computer display. Alternatively, we could easily see color-changing inks serve as a complement to regular displays, such as to expand the display area around a regular LCD screen, to display dynamic output on organic surfaces where traditional display technologies do not work, or to provide expendable display surfaces. In fact, the digital display could even provide the actuation for a photochromic ink.

Though color-changing inks have been around for a while, research and development in color-changing inks and print technology in general is making these technologies increasingly accessible for widespread use. This opens up a new window for exploration of this technology—especially the application of it to data visualization, which is a completely visual media that is highly reliant on color.

We have demonstrated a few opportunities for interactive data exploration by proposing a framework and deriving examples that we describe in a few prototypes and their scenarios of use. Unfortunately, color-changing inks are not compatible with current consumer printers, and commercial printing using them is still prohibitively expensive (all our examples in this paper were hand-drawn). This is one reason why we have not validated our designs with human participant experiments. However, we hope that our work in this paper can help motivate research and development into color-changing ink printers and designing their algorithms for computer-generated prints. This does point to opportunities for evaluation that we plan on investigating in the future.

6.2 Limitations

While we feel that our work on color-changing inks is novel, innovative, and may spark further ideas on data physicalization in the visualization community, we also want to acknowledge several limitations in our proposed framework and applications.

Some of these limitations are purely technical in nature. For example, many current color-changing inks—perhaps with the exception of the most expensive and cutting-edge ones—yield a washed-out and dull look when ideally there should be a perfect change of color to colorless or vice-versa. Furthermore, many inks yield actuation colors that are somewhat unpredictable or inconsistent, and the color is often affected by the external stimulus. Finally, as stated above, much of this technology—especially in printing—is still somewhat inaccessible due to prohibitive cost. However, we expect that most of these limitations will be addressed in time as demand grows and technology improves.

Other limitations are more fundamental in nature. Just like with any touch interaction, actuating color-changing ink through body heat or light requires the user to occlude the visualization with their hand, making reading the data impossible. The user will have to stop actuating the ink to see the actuated area. Further limitations include discoverability and learnability. While paper in general is familiar to most people, and its interactions—folding, rotating, crumpling—are common, interactive visualizations rendered on paper using color-changing inks are not. In the worst case, a color-changing ink chart may go entirely undiscovered by the reader, its data unnoticed. This is an intrinsic limitation of many "invisible" interface technologies, such as gestures, and can only be mitigated through visual indications or familiarity. Practical paper-based visualizations of this type will need instructions suggesting to the user how they can be manipulated. Such instructions will inevitably take up space on the page that otherwise could have been used for showing more data.

7 Conclusion and Future Work

We have presented a conceptual framework for the use of color-changing inks for print media visualization to allow a form of interactive data representations without power nor computation. While long pervasive for toys, stickers, print, advertisements, and even clandestine communication, such as the invisible ink used by both sides in the U.S. Revolutionary War, color-changing inks are becoming increasingly powerful. We demonstrate how this new generation of color-changing inks can be used to generate several interactive data visualizations actuated by heat or sunlight.

While our work is mostly conceptual in nature, we think that it provides yet another weapon in the data physicalization arsenal. Interactively visualizing data without power or computation is mind-boggling, and we hope to see these color-changing inks increase in sophistication in the future. Thus our work may be useful in determining how to navigate this future of data everywhere.

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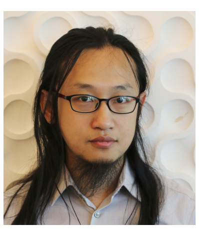

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