# EcoPatches: Maker-Friendly Chemical-Based UV Sensing

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**Figure 1. (left) EcoPatches can printed by a maker with an inkjet printer and chemicals that can be purchased online. (right) EcoPatches can be read at a glance or interpreted with a companion smartphone app.**

## ABSTRACT

Year-round ultraviolet exposure silently causes skin damage that goes unnoticed until sunburn. Current personal wearables for monitoring UV exposure have not seen significant uptake, which may be attributed to their one-size-fits-all aesthetic or inapplicability to people with different skin tones. We present EcoPatches, inkjet-printable chemical patches that mediate a person's relationship with their environment by allowing them to create designs and formulations that resonate with them. Supporting human- and machine-interpretability for EcoPatches' visual changes means that users can glance at their EcoPatch during the day to see large exposure changes or take a picture of their EcoPatch with a smartphone app for more accurate and precise readings. We conducted an online survey to elicit visual design recommendations that support these features. We also evaluated both interpretation methods, finding that they achieved strong Pearson correlation coefficients with the EcoPatches' known exposure levels (human: 0.79, app: 0.90).

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## Author Keywords

Chemical sensing; inkjet printing; environmental sensing; mobile computing; ultraviolet radiation

## CCS Concepts

•**Human-centered computing** → *Smartphones;* •**Applied computing** → **Consumer health;** *Environmental sciences;* •**Computing methodologies** → *Computer vision;*

## INTRODUCTION

Exposure to harmful environmental factors can incur serious and lasting damage to human health. Because environmental hazards are often invisible, people tend to underestimate their risks and resist taking preventative actions until they become symptomatic. One such hazard for which this is true is ultraviolet (UV) irradiation, which some have called "the most prominent and ubiquitous physical carcinogen in our natural environment" [5]. Many devices exist for measuring UV exposure, ranging from handheld meters[1,2] to wearables like smartwatches[3], clips[4], and fingernail sensors[5]. These devices require explicit action (e.g., button press, NFC scan)

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[1] http://www.solarmeter.com.au/model65.html

[2] http://www.lsmeter.com/product/LS123new.html

[3] https://www.microsoft.com/en-us/band

[4] https://www.laroche-posay.us/my-skin-track-uv

[5] http://www.lorealusa.com/media/press-releases/2018/january/uv-sense

for users to retrieve a cumulative measurement, thus reducing the user's awareness of their exposure in real-time.

In light of this limitation, researchers and companies alike are producing wearable patches embedded with chemicals that change color when exposed to UV irradiation[6,7] [18, 22]. The patch form factor is useful because it can be worn on the skin or clothes all day long, receiving the exact same exposure as a person's skin. Despite the fact that chemical-based UV sensor patches have reached the market, they are not commonly used by the general public. Our work focuses on three possible limitations:

1. **Formulation flexibility:** Existing products have a fixed dynamic range, yet the amount of UV irradiation that damages a person's skin depends on their skin tone. Thus, there are inherent biases in the applicability of these products to a wider audience.
2. **Aesthetic flexibility:** As a wearable that must be exposed to sunlight, UV sensor patches become fashion accessories that other people can see. If a person does not like a patch's aesthetics, they will be less likely to wear it in public. Existing products are restricted to a single design, thus reducing the likelihood of pleasing all tastes.
3. **Interpretability:** A patch should be easily interpretable at a glance so that people can notice large changes throughout the day. At the same time, a patch that is easily interpretable through computer vision can help people with low color acuity or facilitate data collection on the cloud for longitudinal analysis. Human- and machine-interpretability are mutually exclusive features of many existing products.

To address these limitations and empower people to monitor how the environment affects their health, we present EcoPatches. EcoPatches are made with an inkjet printer and a UV-sensitive ink composed of chemicals available online. Because our fabrication process is tenable to makers, people can create their own sheet of EcoPatches that suit their information needs and aesthetic desires. The visual design space of EcoPatches is endless, so we conducted an online study with 84 respondents to understand people's opinions on different EcoPatch designs; we synthesize those responses into four recommendations regarding human- and machine-interpretability.

Using our recommendations, we created our own instantiation of EcoPatches and an accompanying smartphone app that analyzes them with computer vision. Doing so enabled us to conduct a quantitative comparison between the EcoPatches' human- and machine-interpretability. We found that 35 participants were able to manually interpret EcoPatches with a mean error of -0.56 ± 2.11 UVI-hrs and a Pearson correlation coefficient of 0.79. To frame the results in another way, participants were able to classify whether or not an EcoPatch reading would indicate sunburn risk for three different skin tone categories with an accuracy of 72.6%. We then took photographs of EcoPatches in 10 lighting environments and found that our companion app was able to interpret EcoPatches more accurately, achieving a mean error of -0.01 ± 1.65 UVI-hrs, a Pearson correlation coefficient of 0.90, and a sunburn risk classification accuracy of 76.9%.

The process of making EcoPatches has many different components. As such, our contribution comes in four parts:

1. The description of a fabrication process that allows makers to produce EcoPatches that suit their aesthetic and functionality preferences using a standard inkjet printer,
2. Visual design recommendations for EcoPatches elicited from 84 responses to an online survey,
3. A 35-person study that evaluates the human-interpretability of an instantiation of EcoPatches, and
4. A corresponding study that evaluates the machine-interpretability of the same EcoPatches by an app in 10 different lighting environments.

## RELATED WORK

In this section, we examine related work regarding wearable chemical sensors and UV sensing.

### Wearable Chemical Sensors

There is growing interest in chemical sensing as an alternative to handheld devices for measuring environmental and biological phenomena [16]. These sensors often rely on reactions that transduce chemical phenomena into a quantifiable electromagnetic signal. For example, Kantareddy et al. [12] created a glucose sensor by engineering an electrochemical transduction mechanism to activate a passive RFID tag; the longer the RFID tag was detected by a reader, the higher the glucose concentration in the solution. Wireless chemical sensors require power in order to transmit their data, limiting extended use.

Researchers have also engineered chemical reactions that produce visible changes in color [2]. Colormetric reactions have been embedded in fabrics [6, 11, 26, 27], pigments [13, 14], and even subdermal inks [28]. One of the most popular colorimetric mechanisms is thermochromism since reactions can be enacted passively (via the surroundings) or actively (via circuitry) [6, 11, 13, 26]. Other colorimetric reactions have been demonstrated for tracking sweat[8] and environmental pollutants[9] [13].

The aforementioned colorimetric chemical sensors require sophisticated lab facilities to produce them, whereas EcoPatches can be made in a makerspace facility or at home. Another challenge with existing chemical sensors is that interpretability is rarely addressed. Existing sensors generally exhibit a continuous change without a mechanism for telling the user which levels should cause concern. Vega et al. [28] hint at machine-interpretability in their publication, proposing that a camera-enabled smartwatch could be used to continuously monitor and interpret one of their tattoos. As a nod towards human-interpretability, Tao et al. produced a glove that shows the word "contaminated" once exposed to *E.*

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[6] https://www.laroche-posay.us/my-uv-patch

[7] https://logicink.com/

[8] https://www.engadget.com/2019/01/06/loreal-john-rogers-my-skin-track-ph-wearable/

[9] http://aerochromics.com/

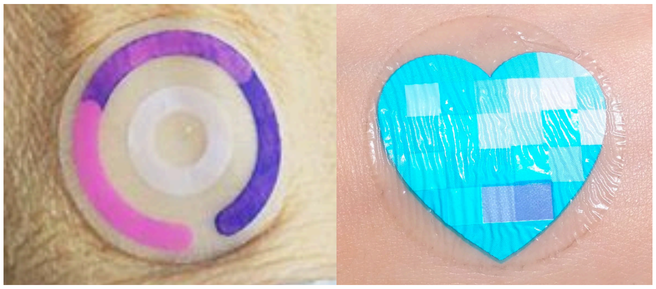

**Figure 2. (left) LogicInk's patch shows instantaneous exposure through its inner ring and cumulative exposure through its outer ring. (right) L'Oréal's My UV Patch has UV-sensitive squares interwoven with reference squares.**

*coli* [27]. EcoPatches are explicitly designed with human- and machine-interpretability in mind.

### UV Sensors

UV sensing devices come in two forms: radiometers for measuring instantaneous exposure and dosimeters for measuring cumulative exposure. Handheld dosimeter devices exist, but there has a been a recent trend of ubiquitous, lightweight, battery-free dosimeters. L'Oréal has recently announced two such sensors: My Skin Track UV[4], a clip that attaches to clothing, and UV Sense[5] [10], a sensor that can be worn on fingernails. Although these sensors continuously measure UV irradiation, cumulative measurements can only be retrieved when the wearer remembers to perform an NFC scan with their smartphone.

Chemical-based sensors that change color when exposed to UV irradiation provide continuously available measurements. Examples of such sensors have been demonstrated by academic research groups, including Liu et al. [18] and Ray et al. [22], but can also be found as commercial products (Figure 2). LogicInk's patch[7] conveys instantaneous and cumulative UV exposure using its inner and outer rings, respectively. The inner ring changes its color continuously, while the outer ring changes like a progress bar, going from purple to pink in three distinct increments. The bar fully saturates once it reaches the World Health Organization's daily recommended exposure allowance for people with fair skin. Unfortunately, information on the fabrication process or accuracy of LogicInk's patch is not publicly available. My UV Patch[6] has a corresponding publication by Shi et al. [25]. The patch is made with a custom thermoplastic polyurethane (TPU) layer and a series of custom adhesives. The patch has a design that supports machine-interpretability, consisting of ten squares for color calibration, six squares that exhibit irreversible color changes at distinct rates, and two squares that exhibit reversible color changes at distinct rates. The squares are arranged arbitrarily on the design, making it difficult to interpret them at a glance.

Unlike existing chemical-based UV sensor patches, EcoPatches do not require specialized manufacturing processes. EcoPatches can be made with off-the-shelf chemicals and equipment. EcoPatches also have the benefit of being interpretable by both humans and machines. The instantaneous exposure component of LogicInk's patch does not map to a quantitative measurement because the opacity range and scaling is hidden from the user. Furthermore, My UV Patch's complicated design necessitates a smartphone to produce a measurement. Only the cumulative exposure component of LogicInk's patch is both human- and machine-interpretable; however, the display is discretized into three segments and only has limited meaning for people with specific skin tones. To the best of our knowledge, our work is the first to present a head-to-head comparison between the human- and machine-interpretability of a chemical-based UV sensor patch that shows continuous, cumulative UV exposure.

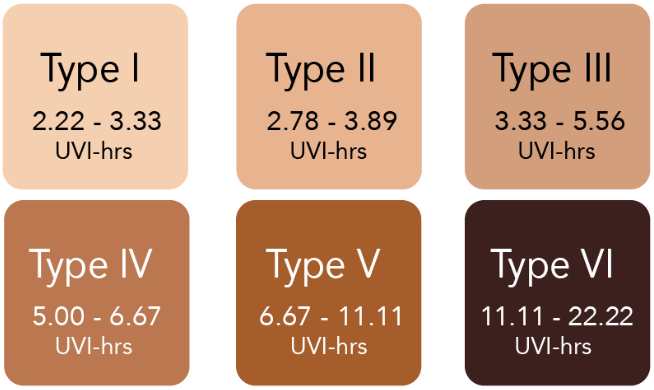

**Figure 3. Representative skin tones along the Fitzpatrick scale and the corresponding minimum dose of UV irradiation necessary to produce sunburn damage.**

## BACKGROUND ON UV SENSING

The sun emits three different types of UV radiation: UVA (315–400 nm), UVB (280–315 nm), and UVC (100–280 nm). UVC is absorbed by the ozone layer, so UVA and UVB pose the greatest threat of skin damage. UV index (UVI) is the standard measurement of instantaneous UV radiation. EcoPatches measure cumulative UV exposure, the integral of continuously changing UVI over time reported in UVI-hrs. The effective UVI to which a person is exposed is not always the same as the UVI that is reported by a weather station. Effective UVI is reduced as a person walks under shade cover from clouds, trees, and buildings. Sunscreen, skin covering, and the angle of the sun relative to the skin also impacts effective UVI.

The amount of cumulative UV exposure that leads to sunburn for an individual depends on the amount of melanin in their skin. Darker skin tones contain more melanin, making them more resistant to UV irradiation. Figure 3 shows the cumulative UV exposure levels at which people with different skin tones are likely to become sunburnt. The skin types are categorized according to the Fitzpatrick scale, a widely recognized classification scheme for human skin color [8, 9]. Figure 3 shows that as a person's skin tone becomes darker, the minimum amount of UV irradiation that leads to sunburn risk grows exponentially. At paler skin tones, a precision of $\sim$0.5 UVI-hrs is needed to separate different levels of risk; at darker skin tones, a precision of $\sim$2.0 UVI-hrs suffices. The Fitzpatrick scale highlights the need for formulation flexibility. We limit our user studies to a single formulation that covers most of the Fitzpatrick scale for the sole purpose of testing the resolution that can be achieved for a wide dynamic range. Throughout the paper, we provide guidance on how our formulation can be adjusted for different needs.

## FABRICATION

EcoPatches can be made with an inkjet printer and UV-sensitive ink composed from chemicals purchased online. If the ink maintains the same color throughout the day, users can infer that they have received little UV exposure; if the ink changes significantly, they can infer that they have been greatly exposed. To retrieve a precise cumulative UV exposure measurement from an EcoPatch, users must map the UV-sensitive ink's color to a numeric value. This mapping is facilitated through a reference color scale embedded within the EcoPatches' design. The reference color scale also supports machine-interpretability. The color of an object as perceived by a camera is a function of the object's color, ambient lighting, and the camera's sensitivity to different colors. Using the known colors within the scale, color calibration can mitigate the impacts of the latter two. Below, we describe the fabrication process a maker would go through to create their own EcoPatches. We also provide a tutorial with product links through the website Instructables[10].

### UV-Sensitive Ink

Our UV-sensitive inks are made by mixing a photoacid generator (PAG), a pH indicator dye solution, a basic buffer, and ethanol in an opaque container. Under UV irradiation, PAGs generate hydrogen ions from photon absorption. The hydrogen lowers the pH value of the solution, causing the pH indicator to change color. This color change is irreversible unless additional basic buffer is added to neutralize the hydrogen ions. Similar chemical reactions have been employed by Araki et al. for making UV-sensitive pigments [1]. However, our UV-sensitive inks are synthesized using different chemicals, and the inclusion of ethanol optimizes the ink's viscosity for inkjet printing. pH indicators are primarily used for changes in hue. However, our inks also change intensity due to photobleaching, meaning that colorblind individuals can notice changes in exposure levels.

pH is a logarithmic scale, so high pH solutions are more sensitive to changes in hydrogen ion concentration than low pH solutions. If a solution starts at pH 9, for example, changing it to pH 6 requires an increase of $9.99^{-7}$ M in hydrogen ion concentration ($10^{-6} - 10^{-9} = 9.99^{-7}$ M); applying the same concentration change at pH 6 only lowers the pH to 5.96 ($-\log_{10}[9.99^{-7} + 10^{-6}] = 5.96$). Because the number of hydrogen ions generated by a PAG is proportional to the incident UV intensity, EcoPatch inks change color quickly at low cumulative UV exposure (high pH) and slowly at a high cumulative UV exposure (low pH).

The choice of pH indicator affects both the range and discernability of colors the ink will exhibit as it accumulates UV irradiation. pH indicators that exhibit more drastic changes across smaller pH differences are generally preferred since those indicators will be more sensitive to smaller doses of irradiation. We investigated two pH indicators: phenol red, which changes from yellow to red between pH 6 and pH 8, and bromothymol blue, which changes from yellow to blue between pH 2 and pH 7. We selected phenol red for our ink formulation because it changes color across a smaller pH range; an example of an EcoPatch made with bromothymol blue is shown at the end of the paper. The ink's rate of change is dependent on its buffer concentration. Basic buffer neutralizes hydrogen ions, so increasing buffer concentration slows down the rate of pH change. In other words, inks with more buffer will undergo slower color transitions than inks with less buffer.

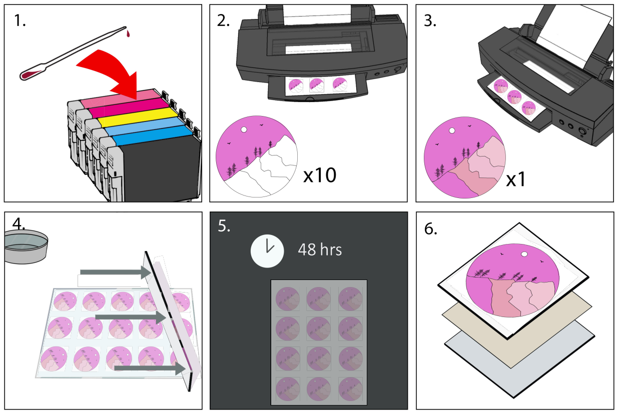

**Figure 4. The fabrication process for creating a sheet of EcoPatches: (1) UV-sensitive ink is loaded into a printer cartridge; (2) the UV-sensitive regions of the design are printed onto temporary tattoo paper 10 times; (3) the color reference regions are printed with regular inks; (4) archival resin is applied to the sheet with a squeegee; (5) the sheet is cured for 48 hours in a dark space; and (6) adhesive films are applied to the sheet.**

To create an EcoPatch that would cover most of the values associated with the Fitzpatrick scale, we evaluated an ink formulation that consists of 1 part 0.1 M diphenyliodonium chloride (PAG), 1 part 1 M sodium hydroxide (basic buffer), 10 parts phenol red (indicator dye), and 10 parts 95% ethanol. A formulation catered to people with pale skin would use less buffer to achieve a narrower dynamic range with higher resolution, whereas the opposite would be done to achieve a broader dynamic range for darker skin tones. Our ink is sensitive to broadband UV radiation but is most sensitive to UVC since its absorption peak is ∼230 nm. The fact that the ink is less sensitive to UVA and UVB allows the ink to saturate over longer periods of time.

### Printing Process

EcoPatches are made using an inkjet printer with refillable cartridges. Various printing media can be used provided that they are pH neutral and have sufficient thickness to avoid ink seepage. pH neutrality prevents the medium from reacting with the UV-sensitive ink, while thickness ensures that the ink does not cause stain or irritate skin. After testing multiple substrates—acid-free paper, temporary tattoo paper, Tyvek, DuoSkin [15], and Skintillates [19]—we settled on temporary tattoo paper with its adhesive backing still attached.

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[10] https://www.instructables.com/id/EcoPatches-Maker-Friendly-Chemical-Based-UV-Sensin

Before printing the EcoPatches, the maker must create an image file with their visual design. The image should be broken into two different layers: one for static elements and one for dynamic elements. The static elements (reference color scale, outlines, and other aesthetics) are drawn in their desired color. The dynamic elements (the UV-sensitive regions) are drawn using a single color corresponding to a printer cartridge. This way, the UV-sensitive ink can be loaded into a single cartridge when the EcoPatches are printed.

The printing process for making a sheet of EcoPatches is illustrated in Figure 4. First, the maker fills an ink cartridge with the UV-sensitive ink. The maker then loads the printer with a sheet of temporary tattoo paper. The UV-sensitive ink has a higher viscosity than regular inks, so it comes out of the cartridge at a different rate. To ensure the ink is sufficiently applied to the sheet, the maker runs the same sheet 10 times through the printer. After the UV-sensitive regions are done, the maker replaces the UV-sensitive ink cartridge with a standard ink cartridge and prints the design's static regions; only one iteration is required in this case. The sheet of EcoPatches is then kept in a dark, ventilated space for 5 minutes to let the ink dry.

The maker then mixes archival grade resin and hardener in a 1:1 ratio. After heating the mixture, the maker pours and smooths the resin over the sheet of EcoPatches. The resin provides waterproofing and chemical encapsulation. The resin also decreases UV transmittance to the ink, making the thickness of the resin layer critical for getting the correct dynamic range. Without resin, most ink formulations would saturate by 3 UVI-hrs. We achieved a resin thickness of roughly 0.5 mm using a squeegee in our makerspace. Once the maker applies resin to the sheet, the EcoPatches are left in a dark, room-temperature compartment for 48 hours to cure the resin.

As the last step, the maker applies adhesives to the back of the sheet so that the EcoPatches can be worn. Since temporary tattoo paper comes with a wet-transfer adhesive that would react with the UV-sensitive ink, we used a double-sided adhesive film and a skin-safe, single-sided adhesive film to provide an adhesive surface while isolating the ink from whatever lies underneath the EcoPatch.

### Developing a Reference Color Scale

The reference color scale for an EcoPatch depends on its UV-sensitive ink formulation and the amount of resin applied to it. Therefore, the scale is learned through a manual calibration procedure with a partially completed calibration sheet of EcoPatches and a color reference chart. The calibration sheet of EcoPatches includes the UV-sensitive ink and resin, but not the static color elements. The procedure starts with the maker exposing the calibration sheet to outdoor sunlight. As the EcoPatches change color, the maker measures the amount of cumulative UV exposure the EcoPatches receive and takes a photograph of them whenever they reach a value of interest. Cumulative exposure can be measured with either a dosimeter or a discrete integral of radiometer measurements. The maker then uses image editing software (e.g., Photoshop, GIMP) to color-correct the photographs and extract the UV-sensitive ink's color from each photograph. These colors are collated with the cumulative UV exposure measurements recorded earlier to produce a calibration mapping from color to UVI-hrs. Finally, the maker can add those colors back into their image file and reprint complete sheets of EcoPatches.

## VISUAL DESIGN

As long as an EcoPatch includes a UV-sensitive region and a reference color scale, its design flexibility is practically limitless. Nevertheless, the way an EcoPatch looks directly impacts its glanceability and human-interpretability. After iterating amongst ourselves on a number of designs, we conducted an online survey to investigate how small variations of our favorite design affected the aforementioned attributes. People would likely react differently to an EcoPatch when they first see it versus when they wear it over a period of time, but our survey focuses on the prior since that would motivate initial uptake. The insights we synthesized from this survey are situated in the design we explored, but we believe that they highlight key considerations for future EcoPatch designs.

### Design Exploration

The fact that UV exposure is a function of sunlight and cloud cover inspired us to create an EcoPatch design featuring a horizon landscape. Figure 5 shows slight variations of our initial design concept. Our UV-sensitive ink becomes brighter under exposure to UV irradiation; therefore, the sky in the landscape brightens with increased irradiation, echoing the fact that sunnier days usually lead to more UV exposure. The land below the horizon displays the reference color scale. The UV-sensitive ink changes its color continuously, but we discretized the scale into five hills for readability. Our concepts were drawn before we finalized the color range of our UV-sensitive ink formulation, but the spectrum was representative of one possibility. The designs in Figure 5 vary across three elements:

1. **Scale Direction**: Whether the reference color scale indicates higher or lower cumulative UV exposure as the hills approach the horizon
2. **Labels**: Whether text labels are included in a subset of hills to remind the user of the reference color scale's direction
3. **Holes**: Whether UV-sensitive regions are included within a subset of hills to facilitate side-by-side comparisons

### Survey

The survey had a within-subjects structure. Each participant was shown all 8 designs from Figure 5, one at a time on separate webpages in a randomized order. Each webpage included a tutorial graphic explaining which regions for the given design were UV-sensitive and how the color references were supposed to be read (in relative terms rather than with precise exposure values). For each design, we asked respondents if they found the design aesthetically pleasing, if they believed they could interpret a cumulative UV exposure measurement from the design, and if they would wear the design in public. Respondents answered the questions along 7-point Likert scales. At the end of the survey, respondents were asked to select their overall favorite design and to

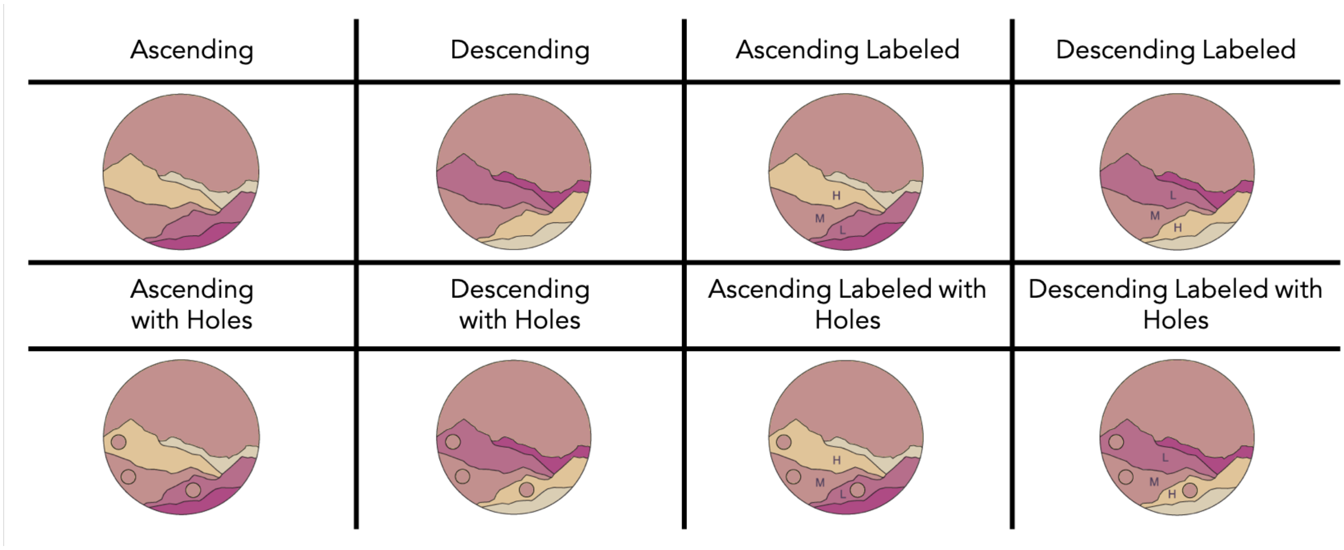

**Figure 5. The EcoPatch landscape design variations that were presented to survey respondents. The variations between them include the direction of the reference color scale, the inclusion of labels, and the inclusion of UV-sensitive holes within the references' outlines. A different color scheme was used in our actual EcoPatches, but the color range shown is possible with our UV-sensitive ink.**

provide any comments explaining their decision. The Likert-scale responses were compared across the three different design factors using the Mann-Whitney U test [21].

### Survey Findings

Respondents were recruited through email lists at a major technology company. Eighty-four people responded to the survey (40 female, 44 male). Participants' ages ranged from 21 to 62 years old (*M*=38.8, *SD*=10.0).

The *Ascending* design was the favorite amongst the eight designs, garnering 47.6% of the votes as the top-choice design; the *Descending* (16.7%) and *Ascending Labeled* (14.2%) designs were the second- and third-most favorite. We would like to note that some respondents stated that they only picked an option because they were required to do so, motivating the need for a flexible fabrication process that allows makers to create their own designs.

There were no statistically significant preferences between designs with an ascending scale versus a descending scale. Nevertheless, respondents often commented on their preference between the two. Because the mountains were arranged in a fashion that implied elevation, some respondents preferred the ascending scale because of its aesthetic connotations: "The 'reverse' versions feel counter-intuitive when considering the visual metaphor—a mountain landscape—being employed. Using the visually recognizable higher elevations of the mountains to represent lower levels of UV exposure forces me to do unnecessary mental gymnastics to convert from one scale—elevation—to another, inverse one: UV exposure" (P47). On the other hand, some people preferred the descending scale for its functionality: "I much prefer the reverse pattern because it is easy to glance at the patch and notice that an increased distance between measurement and reference corresponds to increased exposure" (P23). Respondents were not told that the color spectrum was a fixed aspect of the design, so at least a couple of people mentioned that the EcoPatch's behavior of becoming lighter over time was counter-intuitive. One person stated, "UV exposure makes human skin darken. So, my intuition is that a display like this would indicate more UV exposure via colors that get darker rather than lighter" (P84).

Respondents were clearly in favor of designs with less clutter. Designs without labels were preferred over those with labels in terms of aesthetics ($W = 45060$, $p < .001$) and wearability ($W = 48399$, $p < .005$); the same held true for designs without holes over those with holes ($W = 36270$, $p < .001$ for aesthetics; $W = 45003$, $p < .001$ for wearability). The most common complaint about the labels and holes were that they "decreased glanceability" (P11) and made the design "too busy" (P33). Although respondents were not asked to interpret the designs, some respondents stated that they were unclear about what the labels meant for their health.

Despite the negative reaction surrounding the holes, some respondents recognized their value for color comparisons: "I really like the idea that the holes will allow for more direct visual comparison, but the holes are aesthetically unappealing when the jagged 'mountain' design is less uniform and regular" (P13). Some respondents proposed their own designs where the UV-sensitive region at the top made direct contact with each of the reference scale colors. Such suggestions align with the finding that decreasing the gap between colors improves people's ability to differentiate them [3]. Example design proposals included a "[UV-sensitive] ring about the lower part of the patch for easier and more seamless comparison" (P35) or a "circle [that] is split vertically into five sections with a large horizontal area across the top" (P78). One last noteworthy comment highlights the fact that aesthetics are not only important for a person's own appreciation, but also for how they are perceived by their peers. Many commentaries on wearable displays have argued that wearables should be subtle

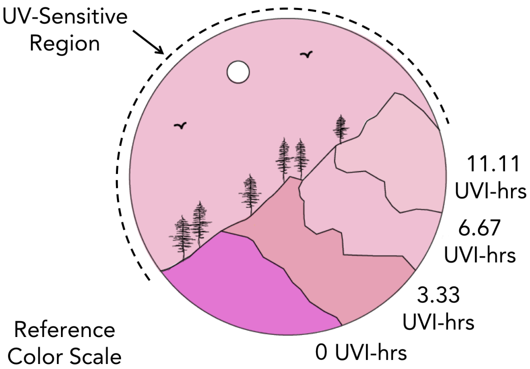

**Figure 6. The design and reference color scale of the EcoPatch that was evaluated in this work. The sky is printed with UV-sensitive ink, while the hills show the reference color scale. This image shows an EcoPatch at roughly 6.67 UVI-hrs.**

or coordinate with the wearer's outfit [6, 11, 15], but one of our respondents preferred the designs with labels for the opposite reason: "Some people wondering why I'm wearing a sticker might understand that it is a measuring device" (P30).

Given the respondents' feedback, we generated the following visual design recommendations for EcoPatches:

- **DR1.** Minimize the distance between dynamic and static regions to facilitate comparisons,
- **DR2.** Align the spatial arrangement of static regions with visual metaphors,
- **DR3.** Align the color changes of dynamic regions with visual metaphors,
- **DR4.** Avoid functional attributes that disrupt aesthetics, and
- **DR5.** Select color references that correspond to meaningful values, even if it involves a non-linear scale.

### Revised EcoPatch Visual Design

Using the respondents' feedback, we created the EcoPatch design shown in Figure 6. The color scheme of the design is representative of the UV-sensitive ink formulation we used in our evaluation. We limited our evaluation to a single design that covers most skin tones. Wider dynamic ranges tend to have lower resolutions, so testing this range allowed us to challenge the precision that could be achieved by both humans and automatic analysis.

In line with **DR5**, we selected reference colors that mapped to meaningful Fitzpatrick scale values: 3.33 UVI-hrs, the lower end of sunburn risk for skin type III; 6.67 UVI-hrs, the lower end for skin type V; and 11.11 UVI-hrs, the lower end of sunburn risk for people with skin type VI. In line with **DR1**, the reference color scale was moved so that each region touches the UV-sensitive sky. In line with **DR4**, the final design excludes extraneous functional features like labels and holes; instead, aesthetic elements like trees were added to supplement the aesthetic that some felt was too geometric. The added elements also provided local regions with unique visual keypoints that are useful for automatic detection.

## AUTOMATIC INTERPRETATION

EcoPatches are designed to be readable at a glance, but integration with a smartphone app that interprets EcoPatches on the user's behalf can assist people with low color acuity or facilitate data collection on the cloud. This section describes how computer vision is used to analyze the UV-sensitive ink's color in a variety of ambient lighting conditions. The computer vision algorithm generalizes to most designs, so a maker should not need to write any lines of code. As long as the maker annotates their design and provides an image of their EcoPatch design, the algorithm could be run on a server or on a person's smartphone.

### Design Annotation

A designer must annotate an EcoPatch template for the segmentation algorithm to know which regions serve as color references and which serve as chemical sensors. We developed software that uses GrabCut [23] to isolate specific regions in an EcoPatch image file. In short, GrabCut allows a person to separate a foreground object from the background by drawing a bounding box around the object and then correcting the automatic segmentation with touch-up strokes. This process can be repeated for each noteworthy contiguous region, after which the designer can specify the region's name and measurement value (if applicable).

### Detection and Segmentation

Many template detection algorithms involve SIFT feature matching [20]. However, patterned templates with little visual diversity do not yield a sufficient number of unique features, so we use a similar algorithm called dense SIFT [17]. The algorithm generates keypoints at regular intervals and scales—5%, 10%, 20%, and 40% of the image's width—for both the template and the photograph captured by the user. After calculating the SIFT descriptors for those keypoints, one-to-one correspondence is determined between the images within local spatial neighborhoods (roughly 1/16th of the images' areas). This constraint ensures that a feature descriptor in the bottom-right of the template cannot be compared to the top-left of the photograph. The method of least-squares is applied to the paired keypoints to calculate the $3\times3$ homographic transformation matrix that maps keypoint coordinates in the template to the photograph.

The transformation matrix is applied to the corners of the EcoPatch template image to produce a bounding box around the supposedly detected EcoPatch in the photograph. The detection is confirmed if four criteria are met by the bounding box within the photograph:

1. The angles at the box's corners are between 80°–100°,
2. The aspect ratio of the box is within 50% of the template's aspect ratio,
3. The box's width is 40–60% of the screen's width, and
4. The distance between the box's center and the screen's center is within 20% of the screen's width.

The first two criteria ensure that the EcoPatch is not skewed, while the last two criteria ensure that the EcoPatch has a reasonable scale and position.

**Figure 7. A photo of the actual EcoPatches used for the evaluation. The EcoPatches are sorted from left to right in increasing increments of 1.1 UVI-hrs. Note that the EcoPatches are covered with an additional clear layer to preserve their color for this photo.**

The template annotation can be used to further improve segmentation results. Some of the keypoint matches are likely to be erroneous, so RANSAC [7] is applied to test random subsets of matches and generate transformation matrices for each one. The best matrix is selected based on the uniformity of the color within the annotation outlines mapped onto the photograph. Color uniformity for a specific region is calculated as the standard deviation of the pixels' colors in RGB space; color uniformity for an entire EcoPatch is represented as the average of those values across all regions.

### Calibration and Interpretation

Once the different regions have been identified in the photograph, each region's color is summarized by computing a vector median in the HLS color space. A k-nearest neighbor model is then trained using the reference colors and their corresponding UV exposure measurements, where $k$ is the number of reference regions. The UV-sensitive ink's color is then input into the model to generate a UV exposure estimate. Distance between colors is calculated in the model using CIEDE2000 color error [24] rather than Euclidean distance to account for perceptual non-uniformities. Training and testing the model in-situ accounts for ambient lighting each time a new image is taken. Rather than having to determine the true color of the UV-sensitive ink, the k-nearest neighbor model compares colors directly as a human would.

## EVALUATION

Our evaluation examines both the human- and machine-interpretability of our EcoPatch instantiation in two separate studies. We first describe the preparation of the EcoPatches that were used in the study, the data collection procedures, and then the evaluation results.

### Apparatus

Both studies were conducted with the eleven EcoPatches shown in Figure 7. The EcoPatches were exposed to sunlight outdoors while a researcher recorded how much cumulative UV exposure the EcoPatches had received via discrete integration on dosimeter measurements in 5 minute increments. Every 1.1 UVI-hrs, one of the EcoPatches was covered and removed from the collection. This procedure produced a collection of EcoPatches uniformly distributed across 0-11 UVI-hrs, thus providing ground truth measurements for our analyses. The studies were conducted indoors from then on to prevent photobleaching.

### Study 1: Human Readability

#### *Procedure*

Thirty-five participants were recruited through email lists at a major technology company to evaluate the readability of the EcoPatches with the naked eye. The study was conducted in three different locations in an office building with various ambient lighting conditions (230–760 lux). A researcher explained how to read an EcoPatch using an image that had the reference color scale, but no color within the UV-sensitive region. Rather than telling participants the exact correspondence between each reference color region and cumulative UV exposure measurements, the researcher told participants that each of the regions corresponded to a number 1–4. Participants were told that they could give fractional responses to any precision they deemed fit to give the most accurate response possible. A limitation of this approach is that participants reported values along a linear scale, but the EcoPatches' scales were nonlinear. This mismatch leads to an inconsistent mapping of errors between the two number systems. For example, an estimation error of 0.5 units for an EcoPatch at 2 UVI-hrs is 1.67 UVI-hrs, while the same estimation error for an EcoPatch at 10 UVI-hrs is 2.22 UVI-hrs. Nevertheless, we chose this approach since most people from pilot studies wanted to interpolate between reference color regions in a fractional manner regardless of the number system that was given to them (e.g., "halfway between the second and third region").

While the participant was being introduced to the EcoPatches, the eleven pre-exposed EcoPatches were hidden under a table. When the participant was ready to begin, the researcher randomly selected five different EcoPatches in a counterbalanced manner. One at a time, the researcher placed an EcoPatch on the table, asked the participant to estimate its measurement, and then returned it back under the table.

#### *Results*

Figure 8 shows the range of responses that were given for each EcoPatch. Across all exposure levels, people were able to read EcoPatches with a mean error of -0.56 ± 2.11 UVI-hrs. The Pearson correlation coefficient between the estimates and the actual EcoPatch exposure values was 0.79 ($p < .001$).

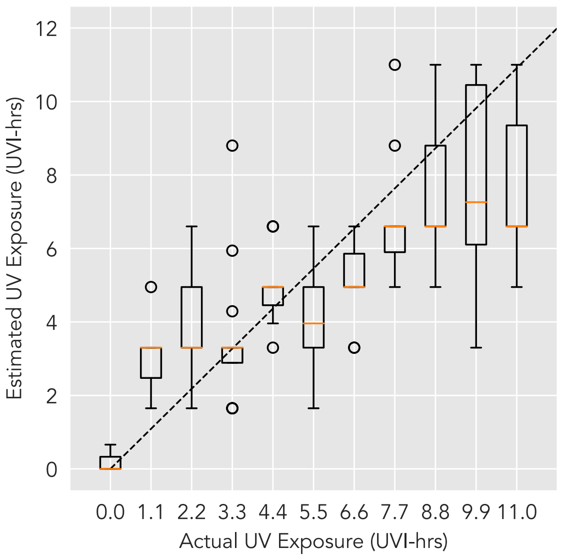

**Figure 8. The range of cumulative UV exposure estimates participants gave for the different EcoPatches. The boxes span the interquartile range (IQR), the whiskers extend to the first data point 1.5*IQR past the boxes, and the circles indicate outliers.**

The mean error is sufficient for distinguishing all sunburn risk categories, but the high standard deviation indicates that there were cases when people were 2 or 3 categories off. Participants were very precise and accurate when interpreting the EcoPatches whose color matched one of the darker reference colors (0, 3.33, and 6.67 UVI-hrs). The median estimates for the EcoPatches with colors between those references were accurate, but there was more disagreement across participants. As the EcoPatches exceeded 6.67 UVI-hrs, the estimates tapered off to roughly 7.5 UVI-hrs. This result was not unexpected because the color changes are more subtle at higher exposure levels.

Many EcoPatch users would probably not be interested in the precise value an EcoPatch shows, but rather whether they are about to exceed a minimum exposure level for sunburn risk. As such, we also analyzed our participants' estimates as a classification problem. We calculated how often participants were correct in determining whether the UV-sensitive ink was lighter or darker than each of the two intermediate reference regions: the region for skin type III (3.33 UVI-hrs) and the region for skin type V (6.67 UVI-hrs).

Participants had 96.1% sensitivity, 54.2% specificity, and 84.6% accuracy when determining sunburn risk for skin type III. Participants had a 30.6% sensitivity, 84.8% specificity, and 68% accuracy for skin type V. The overall 3-class classification accuracy (lower than skin type III, between skin type III and V, above skin type V) was 59.4%. The low sensitivity for skin type V is due to the fact that participants greatly underestimated higher EcoPatch values.

Classification accuracy can be optimized by adjusting the reference color scale's decision boundaries. Changing a decision boundary to a value not associated with the Fitzpatrick scale requires users to do extra thinking to infer the implications of their reading. Nevertheless, this analysis shows the accuracy limit of our EcoPatches in this scenario. The decision boundary for skin type III was already optimal, but lowering the decision boundary for skin type V to 4.95 UVI-hrs improved the accuracy of that decision to 89.1% (sensitivity: 98.4%, specificity: 64.6%). In doing so, the overall 3-class accuracy improved to 72.6%.

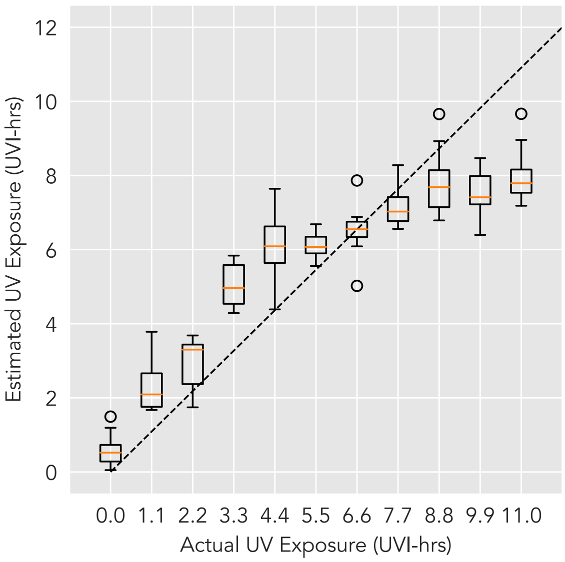

**Figure 9. The range of cumulative UV exposure estimates the companion app yielded for the different EcoPatches. The boxes span the interquartile range (IQR), the whiskers extend to the first data point 1.5*IQR past the boxes, and the circles indicate outliers.**

## Study 2: App Readability

### *Procedure*

To collect an image dataset for evaluating the machine-interpretability of EcoPatches, a companion smartphone app was developed using the computer vision algorithm described earlier. A researcher took the same set of eleven EcoPatches to ten different locations with different ambient lighting conditions (120-790 lux). The researcher placed each EcoPatch on his hand, one at a time, and took a picture of it with a smartphone. Pictures were captured with the back-facing camera of a Google Pixel 2, which has a resolution of 12.2 MP. Some effort was taken to avoid glare and shadows, but it was impossible to avoid such situations in all cases.

### *Results*

Figure 9 shows the range of estimates produced by the companion app for each EcoPatch. Across all exposure levels, the app estimated EcoPatch measurements with a mean error of -0.01 ± 1.65 UVI-hrs. The Pearson correlation coefficient between the estimates and the actual EcoPatch values was 0.90 ($p < .001$). My UV Patch and its app achieve a higher correlation coefficient of 0.92 [25], but that product require sophisticated equipment that cannot be found in makerspaces.

The app yielded lower error and stronger correlation than the participants. Unlike the participants, who had varying abilities of color perception, the objective nature of the smartphone's

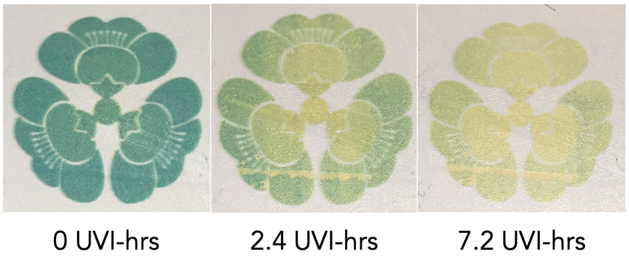

**Figure 10. An alternate EcoPatch design that radiates a color change by using three ink formulations with different sensitivities; the least sensitive ink is used on the outermost petals. The color changes from blue to yellow since bromothymol blue was used as the pH indicator.**

camera sensor led to more consistent estimates across different environments. Like the participants, however, the app underestimated higher exposure values past 6.67 UVI-hrs.

The app's stronger correlation led to better classification accuracy, as well. The app had 100% sensitivity, 79.3% specificity, and 94.2% accuracy when determining sunburn risk for skin type III. The app had a 94.4% sensitivity, 57.8% specificity, and 67.0% accuracy for skin type V. The overall 3-class classification accuracy was 83.7%.

As before, decision boundaries can be adjusted to improve accuracy. In this scenario, it is more practical to adjust decision boundaries since an algorithm can account for systematic biases and interpret the reading's implications for the user. Raising the decision boundary for skin type III to 4.29 UVI-hrs improves the accuracy of that decision to 100%. Slightly lowering the decision boundary for skin type V to 6.40 UVI-hrs improves the accuracy of that decision to 95.5% (sensitivity: 100%, specificity: 83.8%). The overall 3-class accuracy improves to 88.5% when the decision boundaries are adjusted optimally.

## DISCUSSION

In this work, we sought to design chemical-based UV sensor patches with four key properties: formulation flexibility, aesthetic flexibility, human interpretability, and machine interpretability. These properties are enabled by our novel inkjet printing process, the design recommendations that emerged from our survey, and our algorithm for automatic interpretation. Below, we discuss the limitations of our approach and possibilities for further innovation.

### Formulation Flexibility

Our manufacturing process is intended to be accessible to people without sophisticated lab spaces, allowing them to create UV-sensitive ink formulations to suit their needs. Makers can select a different pH indicator to achieve a color range other than the purple-to-pink spectrum we used. As for the ink's rate of change, a person with pale skin could create a more sensitive ink by either reducing the basic buffer concentration or the resin thickness; a person with darker skin would do the opposite. We limited our user study to a single formulation that tested the resolution limits of our ink in a meaningful manner, but we look forward to researchers creating their own formulations in the future.

Makers can also include multiple ink formulations in the same design to accommodate different tones simultaneously. Figure 10 shows a prototype of one such design without a reference color scale. The innermost petals are made with the most sensitive ink and saturate first, while the outermost petals are made with the least sensitive ink and saturate last.

### Fabrication Consistency

Because our process relies on equipment that is not laboratory-grade, there is bound to be variability between EcoPatches. In our case, variability could often be attributed to two factors: (1) irregular ink deposition due to inconsistent ink viscosity and (2) deviation in resin thickness across a sheet of EcoPatches. We considered lamination and screen printing as alternative methods to making EcoPatches [4, 29, 30]. We did not pursue lamination since it requires sophisticated equipment to make custom layering sheets. We had early success with screen printing, using custom screens for regular ink, UV-sensitive ink, and resin. We eventually pivoted to inkjet printing since screen printing has lower throughput and requires a new screen for every thickness change or design modification. Even so, makers may consider alternative fabrication methods using our UV-sensitive ink.

### Use Cases for EcoPatches

The fact that EcoPatches are both human- and machine-interpretable enables UV sensing for many different purposes. Because EcoPatches are human-interpretable, a person can glance at their EcoPatch to decide when they should move indoors to avoid damaging their skin. Because EcoPatches are machine-interpretable, a person can log their UV exposure over time to conduct experiments for their own edification. For example, a person who frequents the beach can wear an EcoPatch on one day while sitting under the shade and on another day while wearing sunscreen to learn about how much protection those measures provide. We look forward to deploying pre-made EcoPatches in the future to learn about the creative ways that people engage with a visual and accessible UV sensor.

## CONCLUSION

Although chemical-based UV sensor patches are available for purchase, they have yet to see mass consumption. We posited that the lack of flexibility (formulation and aesthetic) and the mutual exclusivity of human- and machine-readability limited the acceptability of current sensor patches, so we have presented EcoPatches as a step towards overcoming these limitations. Our inkjet printing method, visual design guidelines, and evaluation of readability demonstrate that makers can create their own EcoPatches with reasonable accuracy. Participants were able to interpret EcoPatches with a Pearson correlation coefficient of 0.79, while the computer vision algorithm built into a companion app was able to interpret EcoPatches with a Pearson correlation coefficient of 0.90. It is our hope that the HCI community expands upon our efforts to democratize chemical sensing and accelerate the growth of participatory environmental sensing.

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