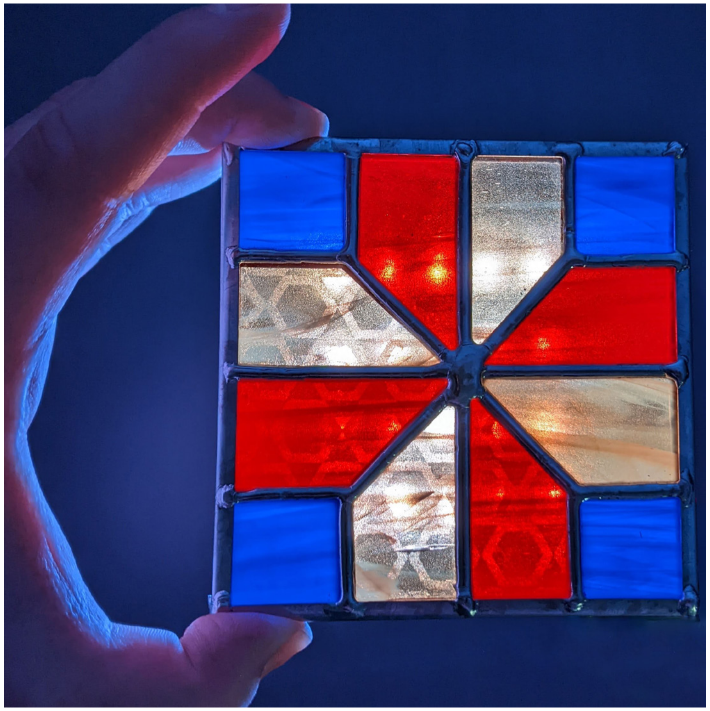

INTERACTIVE STAINED-GLASS: Exploring a new design space of traditional hybrid crafts for novel fabrication methods

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ABSTRACT
Stained-glass is a craft with a wealth of opportunities that blends seamlessly into our everyday environments. Despite sharing similar tools and materials with other types of hybrid crafting, authentic stained glass is underexplored in HCI. We introduce stained-glass to TUI researchers, explain the fabrication process thoroughly (using the traditional methods of both copper foil and lead came), and explore its potential as a conductive substrate for interactivity. We contribute fabrication techniques to support various circuit connection traces, light diffusion methods, interactivities, and aesthetic qualities. We also introduce three potential applications as proof of method validity in different contexts. We follow this with a discussion on experiential outcomes and the importance of creative practices in the development of interactive artefacts.

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tangible interfaces; glass, DIY making; prototyping; materiality.

CSS Concepts
- Human-centered computing~Human computer interaction (HCI)

INTRODUCTION
The ubiquitous computing paradigm [1][65] is built upon profound technologies that phase in and out of focus when necessary [66]. Tangible User Interface (TUI) research has been exploring a wide variety of materials to expand the palette of what can be used to make computational everyday things, such as wood, textiles, and plastics [19]. These materials help create devices that look like they belong both within our real-world environments and in relation to other objects in those spaces [44]. Most digital devices and platforms are designed to grab our attention and become our primary focus despite our finite human capacity to divide mental resources across different activities [4]. However, many of our non-computational daily interactions with the world happen in the background, or in the periphery, and can shift to the centre of attention when desired [4][24]. Computational design could blend seamlessly into our lives and fit within our routines instead of interrupting them. The natural progression of the display would thus be to become a part of the periphery and to shift to the foreground, or the centre of attention, only when necessary [5].

Hybrid crafts blend traditional crafts and tools with computational materials to create new modes of making computers [13][64]. Within the maker movement, hybrid crafts expand the backgrounds and skills that can be used for making interactive things (such as stitching and painting) to bring computational making to new audiences [6][54], and enable individuals to express themselves aesthetically by designing in a more hands-on manner [13] [25][51].

Among the ways that we can make with technology, the craft of stained-glass is underexplored despite its ability to leverage the vast amount of previous research in HCI on ambient lighting displays. There are several opportunities unique to stained-glass that make it an exciting area for hybrid craft research. Intersecting tools and materials leverage the skills of stained-glass practitioners, who are familiar with processes such as soldering and corresponding safety procedures [63]. There is also a new generation of stained-glass practitioners pushing the field into territories beyond the large stained-glass windows that many are familiar with. Stained-glass is now regularly found in interior accessories and small-scale decorative items, which makes it more accessible to DIY crafters and makers.

In this pictorial, we show how stained-glass expands upon previous research in ambient displays, while also mapping out the design space of stained-glass for HCI audiences. We contribute a summary of the procedures, terms, and design decisions involved with making stained-glass alongside opportunities for designing interactions. We then demonstrate a few applications for interactive stained-glass and provide recommendations on next steps for this burgeoning area of hybrid craft research.

RELATED WORK

While stained-glass in HCI is underexplored, existing literature describes making interactive everyday things with various fabrication techniques while leveraging the natural properties of the materials used. To gain a deeper understanding of the effects of this materiality and interactivity, we also discuss literature on calm and slow technologies supporting richer user experiences involving self-reflection, self-expression, and self-awareness.

Making interactive everyday things

Within HCI literature, there is a growing interest in incorporating interactivity on, or within, inert everyday materials [48], surfaces [44], and objects [26]. Our previous work on interactive interiors (interioraction [44]) and decor (decoraction [43]) motivated the experimentation of a new material to embed interactivity seemlessly within everyday things. For example, paper circuits have been widely researched as both a practical avenue for rapid prototyping [60] and as a playful educational fabrication method for beginners [35][53]. Incorporating interactivity in 3D-printed artefacts has also been explored using conductive filaments or copper tape as touch-sensitive electrodes [17]. Similarly, other studies used conductive threads [28] [69], e-textiles [27][31][52], chromogenic pigments [27] [67], and custom fibre-optics [68] to unlock interactions on previously inert materials. Gold-embroidered fabrics can additionally be made to be interactive by virtue of gold's naturally conductive properties [30] and everyday things like watches can be fabricated by leveraging the inner reflectivity of clear acrylic [10], a method which was explored with glass during initial experimentation for this pictorial but was deemed unsuitable for stained-glass.

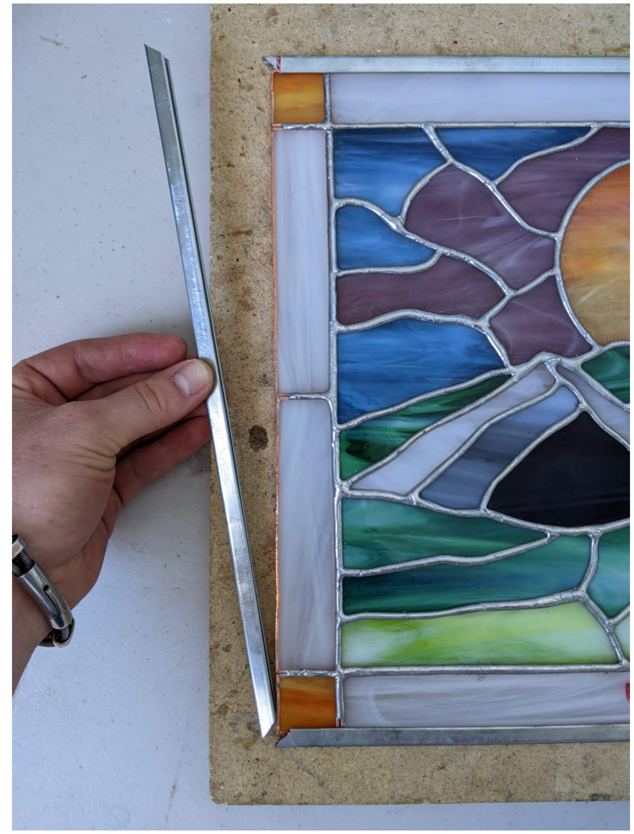
Stained-glass and HCI

Stained-glass has deep cultural roots across the world from Egyptian, Mesopotamian and Roman origins to European medieval gothic architecture dating from the 12th century. Coloured glass was developed to accommodate the massive window sizes of Western European cathedrals [7] as the metals that bind the glass pieces together act as structural reinforcers. Today, stained-glass is found in windows of churches, mosques, synagogues, temples, and in homes [57]. Although regular windows have previously been researched as peripheral displays for ambient information, there is no work to-date that explores authentic stained-glass for prototyping, interactivity, or materiality. Brown & Weiser [5] discuss the potential of office windows as agents of calm technology and Rodenstein [55] suggests windows as interactive interfaces, calling them “generally restful, both mentally and physically”. Utilizing interactive stained-glass will expand upon this research and enable artistic and aesthetic applications that, much like other elements of interactive interior design, are underexplored.

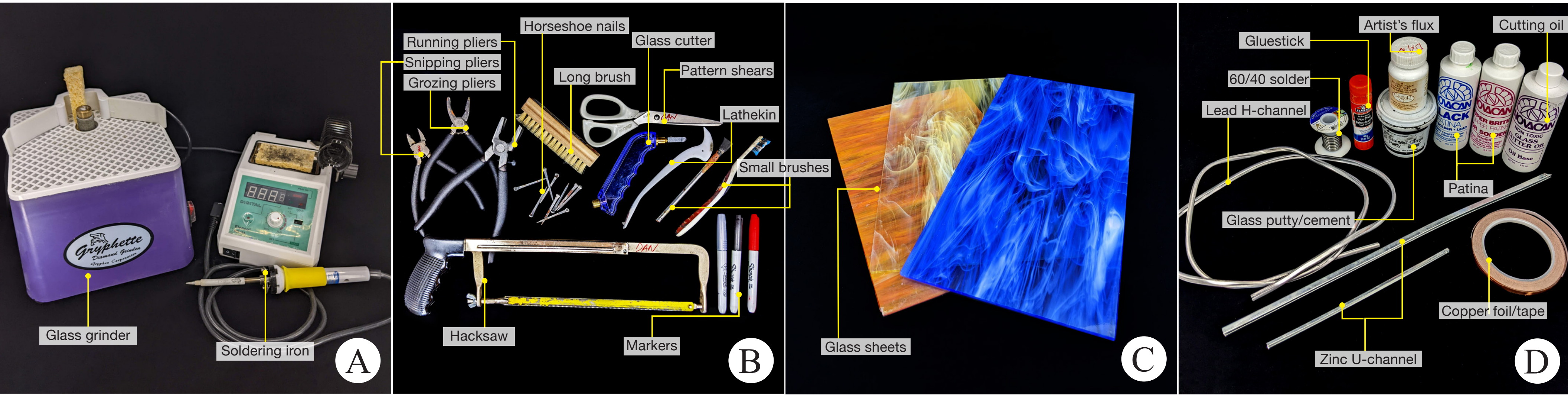
Despite the DIY nature of stained-glass [9], the notion of using it as an interactive medium has been proposed but not fully explored [38]. In research, SpectroFlexia [38] suggests designing interactive stained-glass but uses a polarizing material that changes colour in sunlight instead of using glass. In practice, Shiseido's Interactive Stained-Glass Window [71] in Tokyo, Japan, allowed pedestrians to experience the installation in their peripheries (noticing the portraits of strangers) or to actively display their own portraits. The Shiseido installation used digital screens displaying a stained-glass ‘pattern’, while the SpectroFlexia uses rotated polarized material to create a stained-glass ‘effect’.

Leveraging material properties to enable circuits

We explored fabrication methods of other DIY craft materials to gain inspiration for using stained-glass as a conductive substrate. Paper circuit techniques include hand-painting and screen-printing circuits [34][60] using conductive paints and connecting components together using conductive epoxy, superglue, cold-soldering, or conductive tape. Another application of different



conductive fluids includes creating circuit-shaped moulds to contain them, resulting in flexible, ‘flowing’ circuits [62]. Specialised equipment is not necessarily required to make paper and moulded circuits, which enables non-experts to create circuits and augment everyday things at home. While these methods are best suited for simple circuits, complicated applications are also possible by printing paper circuits or touch sensors using off-the-shelf inkjet [32][48] and toner printers [20]. Conductive inks, paints, and resin are relatively specialised, but materials as simple as copper tape/foil can be used on paper or other surfaces to create a circuit [35][54]. Coincidentally, copper foil is also used in stained-glass (a copper foil panel is pictured in the figure above).



The naturally conductive materials used in stained-glass are discussed throughout this pictorial. Other research exists that targets the use of material properties to achieve interactivity, whether it be the internal reflexivity of acrylic and fibreoptics [10][68], the carbonization properties of burnt wood [23], or the percussive feedback of everyday inert objects in the environment [39]. These works offer valuable insights into using the existing properties of materials to unlock their interactive potential.

Supporting self-reflection and self-expression

Calm technologies are foundational in supporting self-reflection and self-expression. The existing research targets integration into peoples' routines as a component of inspiring self-reflection without being overburdening [3][33][41][56] or discusses this integration as their primary goal [22][36][70]. Further research proposes various artefacts that display information in a way that encourages self-reflection on the data being presented, as opposed to the user's thoughts and actions [29][36] [41][70].

Certain proposed works may support self-reflection and thoughtful use of technology but do not invoke calmness (as this is not the intended design) [8][37][42][59][61]. Additional works focus less on artefacts and their self-reflective properties but on the act of creating an artefact as a source of self-expression and self-reflection [46] [50][58]. Related to calm technology and self-reflection is slow technology, defined as ubiquitous technology designed for reflection and mental rest as opposed to efficiency [18][47]. We aim to provide the foundations for HCI practitioners to develop self-reflective and self-expressive artefacts through the practice of augmenting traditional stained-glass with interactivity.

MATERIALS AND TOOLS

Stained-glass is a craft that can be used for low-cost prototyping as an intersection exists with the required tools and materials and what is commonly available in makerspaces. This section describes the accessible equipment, affordable tools, and commercially-available materials required to get started.

Equipment

The most common electronic equipment used to make a stained-glass panel are a glass grinder and a soldering iron (Figure A). A soldering iron for electronics can be used instead of a specialised stained-glass soldering iron if it is capable of maintaining temperatures of 300-450°C.

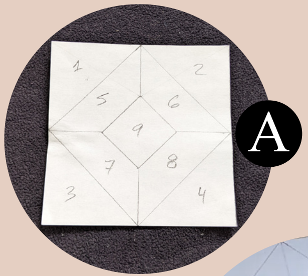
Tools

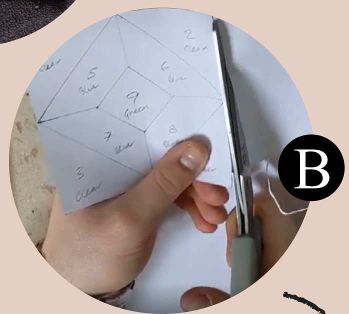
The manual tools used in stained-glass are largely non-specialised and available off-the-shelf, such as a hacksaw, brushes, markers, and horseshoe nails (Figure B). Other tools include specialised pliers, a glass cutter, lathekin (white plastic tool in Figure B used to spread lead channels and flatten copper foil on glass), and pattern shears.

Materials

Glass sheets (Figure C) are the most expensive materials in stained-glass and vary in pricing depending on their properties. Red glass, for instance, costs more than other coloured glass as it uses oxidized gold to achieve its pigmentation (£3~£4 for red glasses versus ~£2 for other glasses, per 10cm^2 sheet). Other specialised materials (Figure D) are comparatively inexpensive (zinc, lead, cutting oil, patina, artist's flux, putty). The final materials involved in making stained-glass are likely already present in makerspaces, namely copper foil/tape and 60/40 solder. The key difference between stained-glass solder and electronics solder is its larger size (3mm versus 0.6-1.5mm), though either can be used.

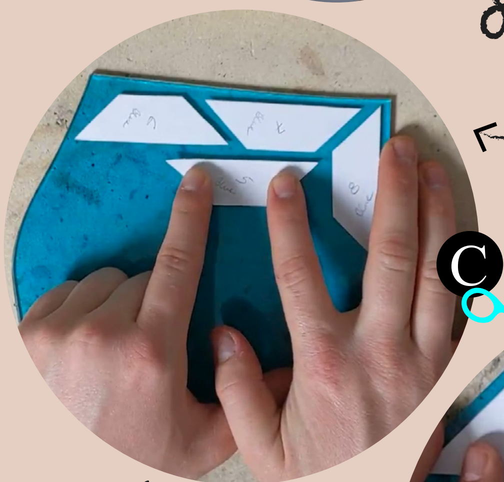
Making Stained-Glass

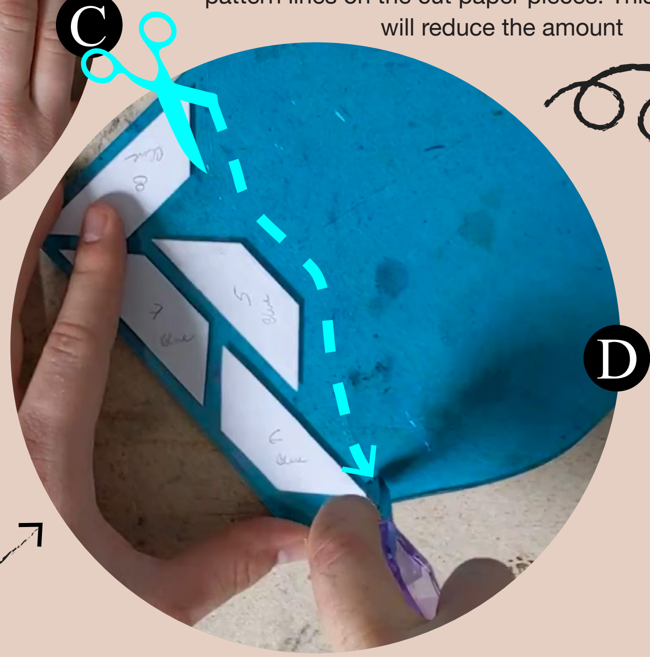


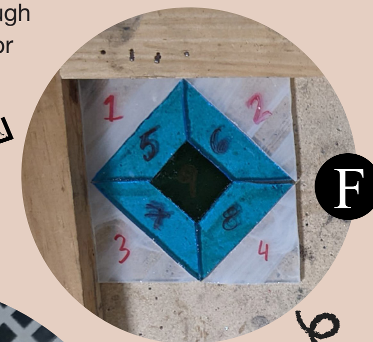


There are two primary methods for developing stained-glass. Each involves binding cut pieces of glass together using either copper foil or lead came. Copper foiling is a technique that binds glass pieces together using copper tape/foil, artist's flux, and 60/40 solder (60% tin, 40% lead). Lead caming is a technique that uses lead channels to hold glass pieces together in a stained-glass panel. The channels are then soldered together using artist's flux and 60/40 solder.

Step A: Both techniques start with the paper-sketched design. Individual pieces are numbered and labeled with their intended colours.
Step B: The pattern is then cut using either scissors or pattern shears. Pattern shears are specialised scissors with a gap in the bottom tooth for cutting away pattern lines. If using scissors, the practitioner must ensure that there are no pattern lines on the cut paper pieces. This will reduce the amount of glass that must be ground away later in this process. Lead caming in particular requires additional space between the glass pieces in which the lead channels can be inserted.
Step C: Cut paper pieces are then placed upon their respective glass sheets using a weak adhesive (glue stick).
Step D: Using the glass cutter, glass pieces are cut from their sheets by running continuous (edge-to-edge) cuts as close to the paper design pieces as possible to avoid excess glass. Moderate force should be applied when cutting glass, such that the cutting motion emits an audible hissing sound. Machines can also be used to cut glass (such as a laser cutter [12] or a glass saw) though these are typically only used for cuts that are not possible to perform by hand, such as a cross-shaped cut.
Step E: Use a glass grinder to smooth the edges and remove any excess glass after cutting.
Step F: Arrange the cut pieces into the desired pattern and clean the ground glass pieces. After transcribing the numbers of paper pieces to the glass pieces, remove the design sketch paper.
Steps G or H: The remaining steps will differ depending on if the practitioner has chosen to do lead caming or copper foiling. Both methods are explored in this pictorial as there are advantages and disadvantages to each. Figure H demonstrates a roll of copper foil, while Figure G shows a lead H-channel.







Copper Foiling

Copper foiling is a contemporary technique (developed by Louis Tiffany) known for its high strength and high versatility [57]. It is generally more **time-consuming** than lead caming but allows for more **intricate detail** work and is easier for creating 3D works such as lampshades or jewellery boxes. There are **fewer steps** involved in creating a copper foil panel and requires fewer specialised materials [40] which is why it is a **popular introductory** technique for new practitioners. Copper foiled stained-glass is not sealed and is therefore not weatherproofed.

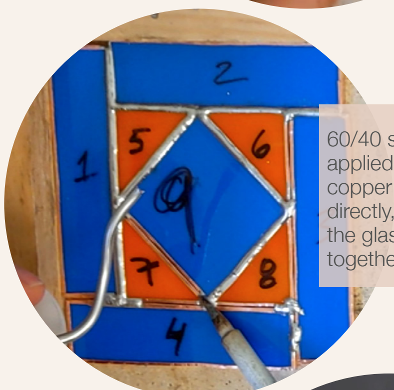
Cut and ground glass pieces are cleaned (with water) and foiled after drying. The copper tape is laid flat against the middle of the edge of the glass piece and wrapped against its perimeter. The tape is made flush against the glass using a smoothening tool such as a lathekin or a smooth piece of wood, such that the tape does not tear. Artist's flux is then applied conservatively to the copper tape (this removes oxide films and prevents the solder from balling), and the glass pieces are soldered together on both the front and back of the panel.

A right-angled workspace is recommended when working with either copper foil or lead came. We employed a corkboard with an elevated wood frame, though established practitioners may opt for using layout blocks as they allow for varying shapes and sizes.

A frame can optionally be fit onto the outer edge of the panel. Zinc U-channels are used for robust, rigid frames, and lead U-channels are used for flexible frames. Once the frame is fit, it is soldered at the corners and to the panel at each intersection with interior solder points.

Copper tape is wrapped around the edges of the glass pieces.

The copper edge is made flush against the glass using a smooth tool like a lathekin.



60/40 solder is applied to the copper tape directly, binding the glass pieces together.

While it is encouraged to add a frame to foiled panels, it is not necessary. Pictured is an exposed copper tape rim around the panel.

Lead Caming

Lead caming involves **more steps** than copper foiling but has its own advantages. A practitioner might choose lead caming over copper foiling for aesthetics (such as its natural patination [14]), if the panel is meant to be **weatherproof** (though lead panels will eventually deteriorate due to exposure [15]), or if there are no intricate details in the design. Completing a lead came panel is typically **faster** than an equivalent copper foil panel, though this is also dependent on the practitioner's ability.

Some designs are inappropriate for lead caming. Designs containing tight curvature or intricate details are better suited for copper foiling, as lead channels are **not as versatile** as simply applying solder to foiled glass.

As lead is a soft metal and will warp based on environmental conditions, it must be stretched before use. Two people can pull a channel from either end using considerable force to straighten the metal, or a vice may be used instead of a second person.

A frame is not optional for lead caming as it holds the inner design together. The practitioner works from a corner outward, cutting lead as-needed and soldering the channels together after applying artist's flux.

The panel is then sealed using stained-glass putty/cement. Excess putty is cleaned using whiting (chalk powder) and a brush, and the panel is left to dry for 2-3 days. This is repeated for both sides of the lead panel.

Lead channels are cut to size as-needed.

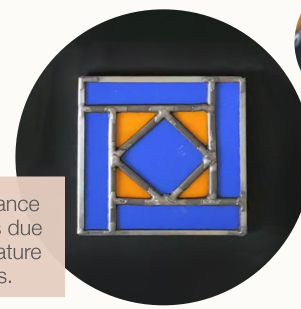
60/40 solder is applied to the lead channel joints.

7/32" lead H-channels make up the inner panel.

5/32" zinc U-channels make up the frame.

Horseshoe nails and scrap glass are used to hold lead caming panels in place during assembly.

Putty is applied in the gaps between the lead/zinc and the glass.



Thicker appearance of inner panel is due to the thicker nature of lead channels.

Conductivity

All materials in a stained-glass panel aside from the glass itself are conductive. Copper foil panels use copper tape and 60/40 solder with the option of zinc or lead frames, while lead came panels use lead channels, 60/40 solder, and the same option for a zinc/lead frame. These conductive properties can be leveraged to support embedded electrical circuits, electrical traces, and inputs/outputs.

A regular stained-glass panel has one possible trace since the frame and the inner design are touching. However, various segments of a traditional panel can be isolated during the creation of the panel to achieve multiple traces in a single panel.

We introduce four methods for running electric current through stained-glass panels to act as electric conduits. Using these novel methods, stained-glass can be used as an aesthetically pleasing conductive substrate with multiple possible applications. Our methods include: 1) embedding insulated electric wire inside a copper foil panel; 2) embedding insulated electric wire inside a lead came panel; 3) insulating the zinc frame using non-conductive adhesive (in a lead came panel); and 4) isolating the zinc frame using a non-conductive layer (in a copper foil panel).

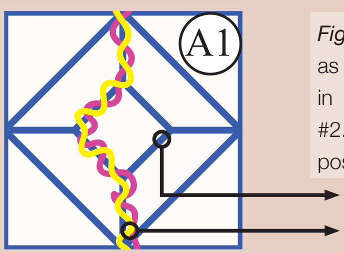


Figure A1: Using insulated wires as connection traces as described in conductivity methods #1 and #2. This figure demonstrates three possible traces.

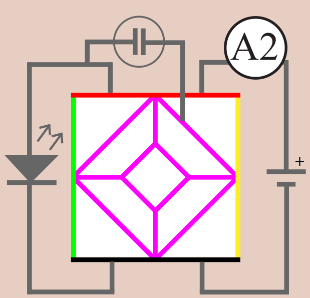
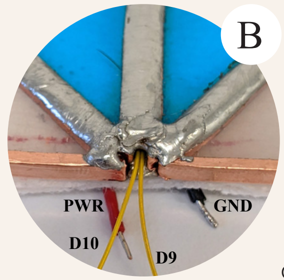
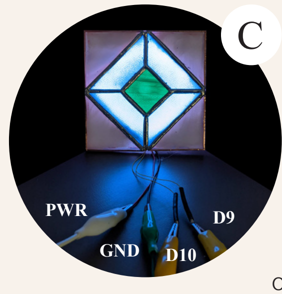


Figure A2: A simple circuit depicting a touch-sensitive panel and an LED, in line with the five possible traces for conductivity methods #3 and #4. Two traces (green, yellow) are unused.

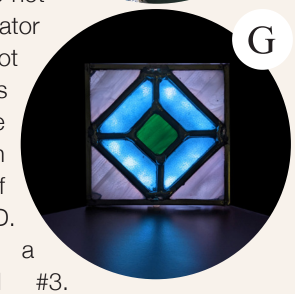
Method #1





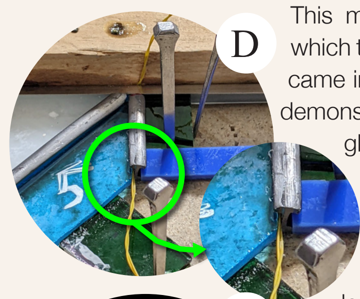
The first method leverages the slight gap between glass pieces in a copper foil panel. Using PVC-coated 30 gauge wire (yellow wires in Figure B), two isolated traces are achieved inside the inner design. The thin wires used for fitting in the panel present an obstacle in that the PVC coating melts frequently under the heated solder. By applying the solder in drops, the PVC coating does not melt as thoroughly, or at all. This is likely due to reduced exposure to the indirect heat of the soldering iron. Figure C demonstrates a panel fabricated using Method #1. Two digital pins are used to control LEDs on the left and right sides of the panel.

Method #3



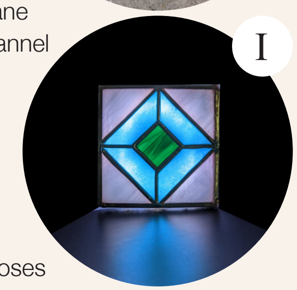
Five independent traces are achieved by applying hot glue instead of solder between the inner design and the zinc frame (see Figure F), and at the frame corners between the zinc channels. Lining the inside of the zinc channels with an insulator as in Method #4 is not necessary as the zinc channels in this method do not touch any metal. Hot glue is an insulator itself, and therefore current will not pass through it between the metals used (lead, zinc). The panel in Figure F uses the inner design's connection trace for the LED output, and 2 of 4 frame channels for PWR and GND. Figure G demonstrates a panel created using Method #3.

Method #2



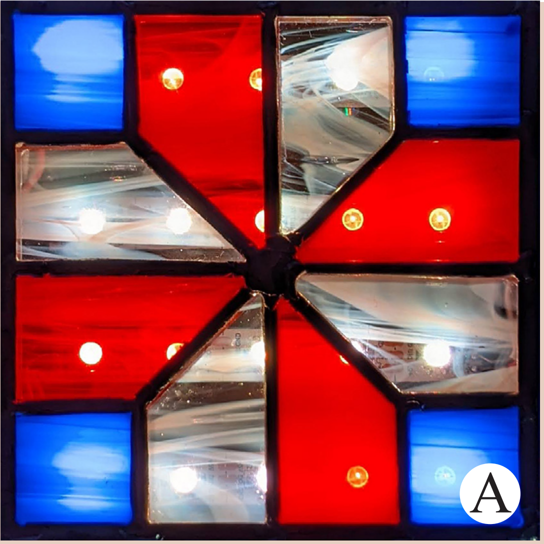
This method supports the case in which the designer needs to use lead came instead of copper foil.Figure D demonstrates the gap between the glass and the lead came where the wires are fit. As the wires are thin and difficult to manipulate, they are braided together and bonded to the lead came using a clear, low strength adhesive (clear school glue). A low strength adhesive is used to prevent permanent bonding to the lead came in the event of mistakes requiring corrections. Figure E shows a panel produced using Method #2. A single alligator clip is connected to both 30 gauge wires, requiring only one microcontroller pin.

Method #4



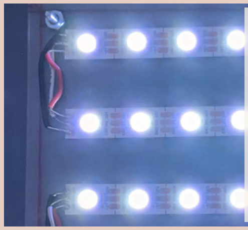
This method augments a regular copper foil panel but modifies the zinc channels for the frame. The goal is to insulate the inside of the zinc channels such that they will not establish a connection with the inner design through the copper foil along the panel's edge. A non-woven polypropylene fabric membrane is added to the inside of the zinc channel for insulation. Excess material/fabric (see Figure H) is later removed (see Figure I). The inner design's trace is used for the LED output, and 2 of 4 frame channels are used for PWR and GND respectively, leaving two connections available for other purposes (as in Method #3).

Light Diffusion



No Diffusion

Opalescent glass [57] provides limited diffusion at the test elevation of 1cm above the LED plate (see Figure A).

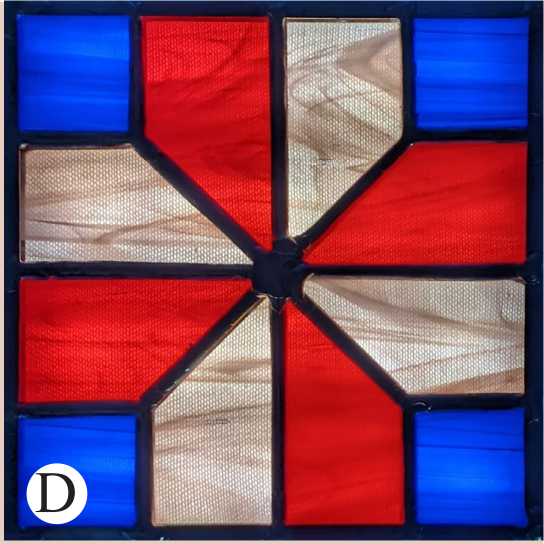


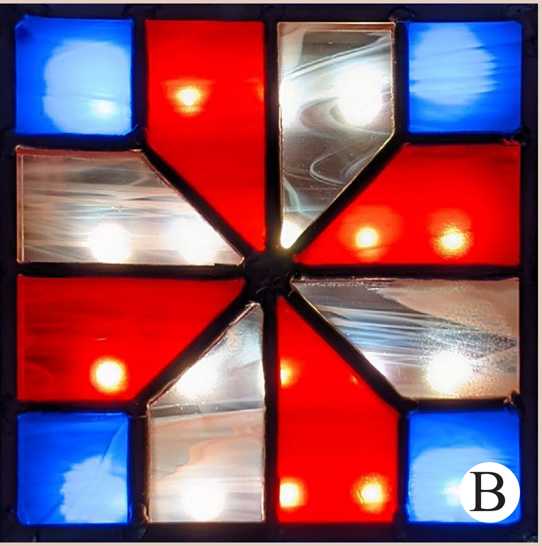
All diffusion experiments were performed using LEDs attached to an acrylic plate. Risers keep the stained-glass 1cm above the LEDs.

Cloth Membrane

Cloth diffusion is viable with a specific combination of cloth layers attached to a clear acrylic platform (see Figure D).

Layers of non-woven polypropylene fabric (4) and low-density polyester fabric (1) make up the cloth membrane diffuser.





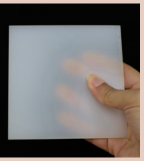
Surface Coating

Privacy window coating (i.e., aerosol glass frosting) can be applied as a surface coating for diffusion on the panel (see Figure B). It is a translucent spray paint typically used to reduce visibility through clear glass. This diffusion method does not sufficiently scatter light at a distance of 1cm (the light is visibly concentrated around the LED bulbs) despite the application of multiple layers.

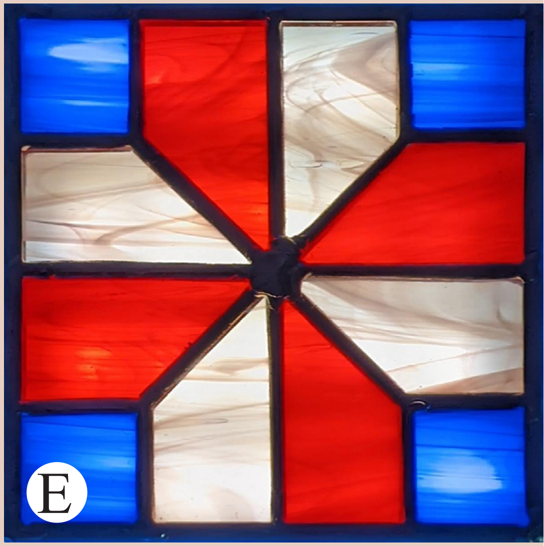
Frosted glass spray from Rust-O-Leum was used and sourced from a local hardware retailer.

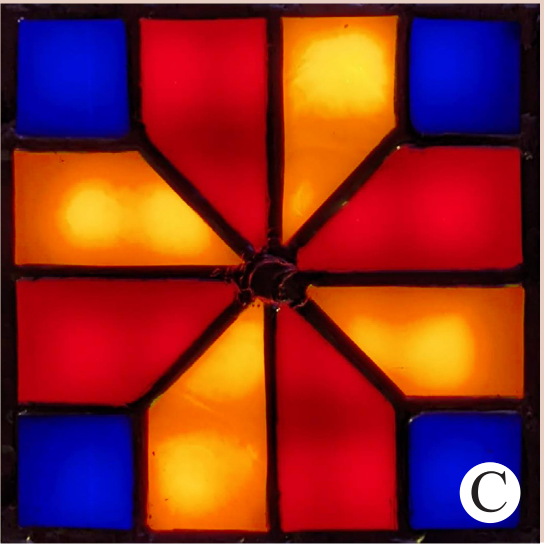
Acrylic Membrane

A 3mm lasercut acrylic layer can be sandwiched between the stained-glass panel and the LED back plate. Acrylic diffuses light successfully at a distance of 1cm (see Figure E). These results align with the use of commercial diffusers in fields such as photography and film which commonly use acrylic and cloth diffusers to create ambient light on sets.



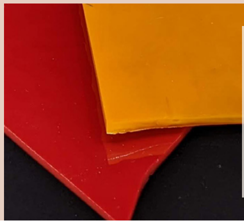
White acrylic was used for this diffusion experiment, though coloured acrylic could also be used for a different appearance.





Opaque Glass

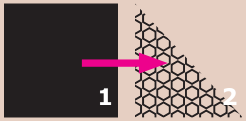
Opaque glass is coloured with a dense pigment which allows some light to pass through (see Figure C) without revealing details from the objects behind it. The LED bulbs are indistinguishable to the naked eye despite their positions being plainly visible in photography.



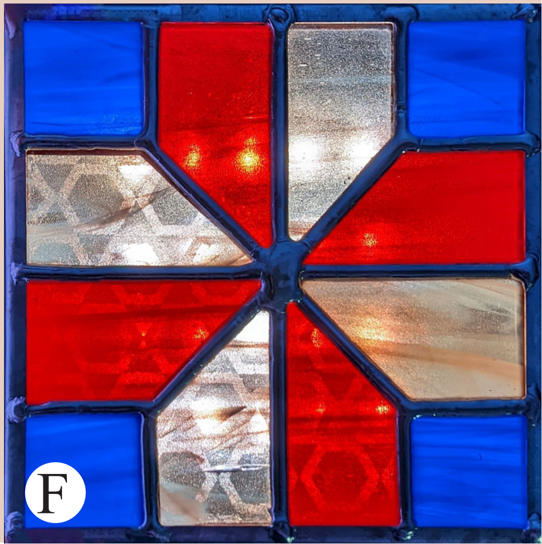
Practitioners will often mix opaque glass with other kinds of glass to achieve a certain appearance.

Machine-Assisted

The glass pieces were uniformly laser-engraved. The bottom-left pieces along the diagonal were engraved a second time with a hexagonal pattern. The pattern was not visible until a distance of 5cm from the LEDs (see Figure F), and light was not diffuse until a distance of 12cm. The surface of the glass following the pattern engraving became brittle and sharp. It is not advisable to engrave this type of glass surface twice.



Uniform (1) and pattern (2) engravings.



Aesthetic Qualities

The copper foiling and lead caming techniques have different aesthetic properties in addition to their previously discussed physical properties. The solder channels on a copper foil panel are thin and lustrous whereas lead channels are wide, muted, and robust-looking.

Copper foil panels have thinner channels with a more lustrous appearance.

Copper Foiling

Lead came panels have thicker channels with a muted and rugged appearance.

Lead Caming

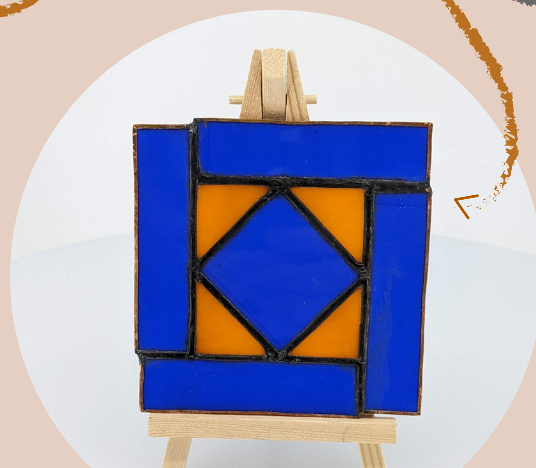
Patina

A patina is optionally applied to the channels and frame of the stained-glass panel. The patina chemically reacts with the metal, creating either a copper or black finish. Black patina chemically reacts with lead, zinc, and solder, whereas copper patina reacts only with solder. Since it is a chemical reaction, it is a permanent alteration to the panel. Lead panels typically undergo a natural patination process over time [14][16].

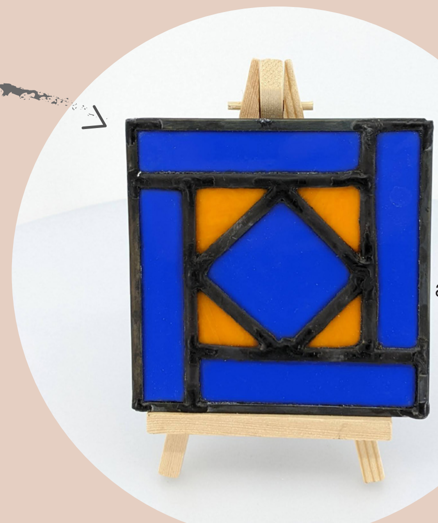
Copper patina for solder. When applied to other metals, copper patina will not set and will lead to unpredictable staining, potentially ruining the stained-glass panel.

Black patina for lead and solder. It can also be applied to zinc in a single layer (it will set unevenly otherwise). Alternatively, black patina for zinc exists.

Copper patina applied to the solder channels of a copper foil panel.

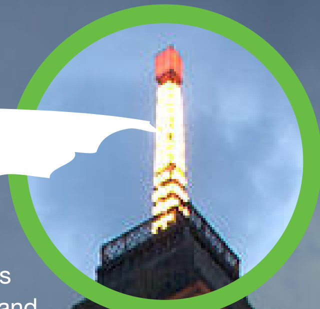


Black patina applied to the solder channels of a copper foil panel.



Black patina applied to the lead channels and zinc frame of a lead caming panel.

Interactivity



Herein we explore embedding tangible interaction into stained-glass prototypes using different input and output modalities.

Inspired by the weather beacon atop the Canada Life building [72] in Toronto, Canada, we created an application that demonstrates input and output interactions. The Canada Life beacon is composed of a diffuse cube with colour-changing actuation, sitting atop a column of light rings with photonic actuation. Various combinations of these outputs, resulting from weather data as input, communicate the forecast to pedestrians. For instance, overcast weather is indicated by a static red cube, approaching rain is indicated by a flashing red cube, a clear day is indicated by a green cube, and flashing white indicates incoming snow. Upward photonic actuations on the light column indicate rising temperatures, downward actuations indicate falling temperatures, and a steady lighting scheme indicates static temperatures. Our prototype imitates the beacon's behaviour in the form factor of a 10x10cm interactive stained-glass panel.

Input

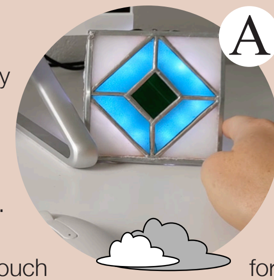
Using the aforementioned conductivity methods, we have established 5 possible connection traces for use (e.g., for capacitive touch electrodes or for microcontroller signal conduits).

Using a Sparkfun MPR121 Capacitive Touch Breakout we created several prototypes that demonstrate the fabrication and applications of touch-sensing stained-glass.

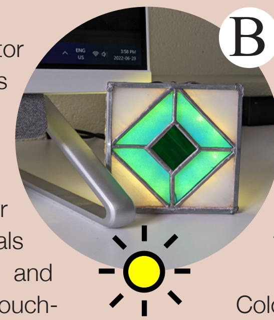
The desktop weather indicator example application employs the right and left zinc frame channels as electrodes and uses the inner design of the stained-glass panel for transporting digital signals to the LED strips. The left and right sides of the panel are touch-sensitive to adjust the brightness of the LEDs (left to dim, right to brighten).

Other types of inputs are also possible to transmit through the fabricated circuit connections in the stained-glass panel (such as sensor data input).

The desktop weather indicator example could be expanded to become an automated indoor weather station by transmitting collected sensor data from UV and humidity sensors through the panel and output through the back LED strips.

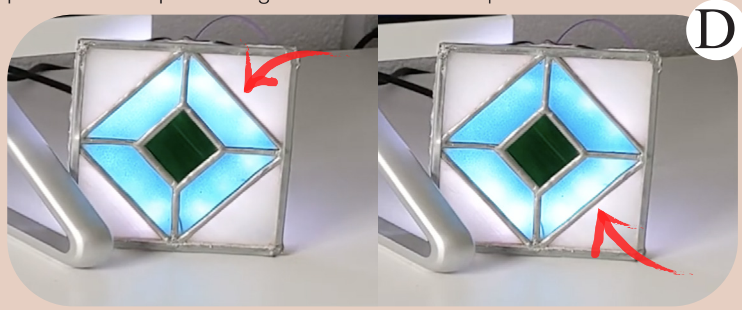


A



B

C



D

Output

Neopixel LED strips are used as a display medium as they are both digitally and physically versatile. They can be cut to-size, and linked together with wires for GND, PWR (5V) and a digital signal pin. Each LED is individually addressable both for controling brightness and changing colour.

Two types of actuations are therefore possible with these strips. Primarily, by adjusting the brightness variables in-code over time, animations can be achieved (see Figure D). In the context of the desktop weather indicator example, the animated photonic actuations emulate the upward and downward temperature fluctuations reminiscent of the behaviour of the Canada Life beacon.

Colour-changing actuation is also possible and modifies the original appearance of the stained-glass panel. Yellow light from the LEDs emitted through turquoise glass results in green light (see Figure B), indicating a sunny forecast. The yellow bleeds around the edges of the inner design and produces an additional aesthetic effect. Red light emitted through turquoise glass (see Figure C) does not change the overall colour of the panel but results in a less harsh tone indicating a storm in the forecast.

These prototyping methods open the door to numerous creative applications, including other types of output modalities, such as audio output.

Possible Applications

Illumina

Window-mounted colour-changing decorative glass panel.

The potential applications for interactive stained-glass and the augmentation of traditional, non-interactive panels are numerous. The colour-changing and photonic actuations of the LED strips provide a wealth of possibilities for ambient displays. We propose Illumina, an interactive stained-glass panel that allows natural light to pass through during the day and illuminates with customizable mood-changing colours at night.

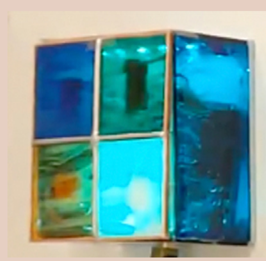
The concept of using colour in ambient display artefacts is well researched. Users involved with studies for similar artefacts have been shown to configure displayed colours based on wellbeing and routine [56], and other research proposes artefacts that are designed specifically for journaling moods using coloured light throughout the day [33]. Illumina builds on these ideas and applies them in the context of art.

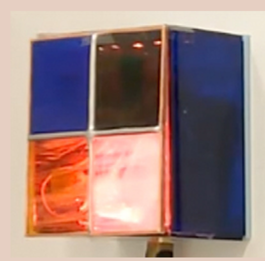
Lockthetic

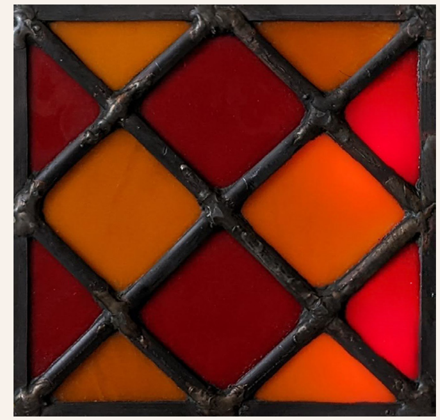
Wall-mounted touch-sensitive keypad for smart space access control.

The second proposed application is Lockthetic, an electronic door lock keypad. Different coloured segments of the 2x2 stained-glass grid correspond to a number in a numerical combination. If the colour code is incorrectly entered, Lockthetic turns red and the door remains locked. If the code is correct, Lockthetic turns green and the door will unlock.

While Lockthetic is a proof-of-concept, the same techniques can be applied for a larger, more artistic interactive stained-glass panel. The intention of Lockthetic is to demonstrate the possibility of incorporating interactive stained-glass seamlessly into everyday spaces. Instead of a keypad for a smart door lock, an interactive stained-glass panel installed in place of a door window can be used instead. Colours and shapes on an image are easier to remember [2] in contrast to the numeric combinations of traditional keypads.







Anonyglass

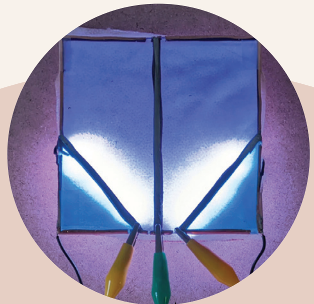
Desktop personalised and anonymous peripheral display.

The final proposed application is Anonyglass, an interactive stained-glass panel with customizable colour-changing actuations and brightness controls. Various segments of Anonyglass are illuminated at a given time to indicate a specific reminder or an anonymous message that can only be decoded/understood by the user who set it. Inspired by previous work on using colour as an anonymous message format [33] and displaying digital information using polarized materials [38], we designed Anonyglass to extend these concepts using authentic stained-glass. Anonyglass is configured such that different segments glow as a reminder for personal issues such as taking different medications on time, taking micro-breaks during working hours, or expected menstruation cycle phases.

Challenges & Limitations

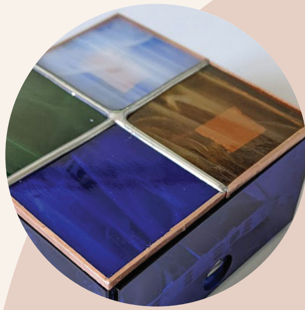
Pattern Design

Designs that accommodate multiple traces on the inner panel are too simplistic and structurally weak due to the limitation of the metallic channels not being able to touch (this would result in short circuits).



Touch Input

Turning a stained-glass panel into a single capacitive touch electrode is relatively simple, as demonstrated with the Illumina application. Making the inert glass pieces themselves touch-sensitive is more challenging. Touch electrodes can be placed behind the glass as seen with the Lockthetic application, or the glass can be coated in conductive ITO (indium tin oxide). Liquid ITO is, however, difficult to source, and the more readily available pre-coated transparent glasses, films, and plastics offer little benefit over regular electrodes.



Lead Spacing

The space available between lead H-channels and the glass pieces of a lead panel is extremely small (in this figure there is only 1mm of clearance) and must be accounted for when choosing to embed wires. As such, the use of exceptionally thin wires is suggested, like the 30 gauge wires used throughout this research. Thin wires, especially when exposed to heat, provide a whole host of challenges. Braiding the wires together and applying a weak adhesive (transparent school glue) is suggested to counteract any tensile resistance.

Insulating Zinc

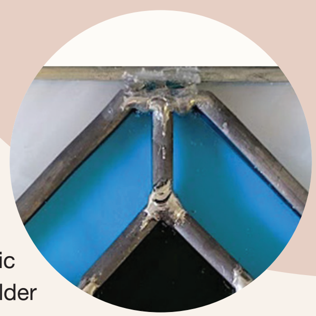
An insulator is required between the outer edge of copper foil panels and the zinc frame to allow for as many conductive traces as possible. Many insulators were tested (acrylic paint, paper, thin fabric, glue). Ultimately, non-woven polypropylene fabric worked well, though it tears easily resulting in short circuits that are difficult to debug. Weak adhesive is suggested to mitigate any tensile resistance.

Copper Spacing

Copper foil panels offer variable spacing. Glass pieces can be shifted around to accommodate multiple embedded wires. Gaps that are large enough are difficult to fill with solder, and the PVC coating on embedded wires often melts when exposed to high temperatures, which in turn causes short circuits when conductive materials come into contact with each other. Applying solder in droplets from a height of 3cm offers some protection against these undesirable effects.

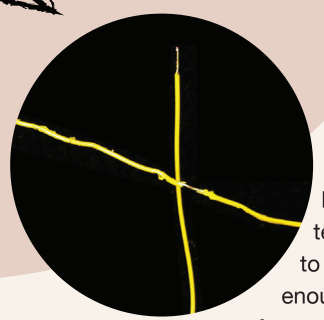
Isolating Lead

Hot glue was used instead of solder as an insulating adhesive between the zinc frames and the inner design of a lead panel to maximize the number of conductive traces (one for each side of the frame, one for the inner design). The result is unaesthetic and jarring. Hardened glue can be coloured silver to imitate solder which masks it slightly, though it is still plainly visible.



Fragile Wires

The PVC coating on the 30 gauge wires used for fitting between glass pieces melts when exposed to high temperatures, such as when applying hot solder. Heat applied to shrink tubing (used to protect fragile traces) is sometimes enough to compromise the coating. Additionally, slight force is often enough to break the wire tips that are soldered to traces. As such, silicone-coated wires are recommended.



UNPACKING EXPERIENTIAL OUTCOMES

There is value in slowness and ambiguity where technology is not prompt or immediately consumable. Modern technology often clashes with calm [5] and vies for our attention with notifications designed to extract us from the physical environment and insert us into the digital [11]. We propose a fabrication technique that aims to empower HCI designers in creating self-reflective artefacts using traditional stained-glass.

Glass materiality

The relationship between a practitioner and their materials and tools is an entangled bond [46] of cooperation that is strengthened when making manually. While glass cutting can be automated with a laser cutter or a glass saw, it is suboptimal (due to the fragility of the glass) and abstracts away the element of hands-on, tangible creativity. Stained-glass is a manual craft that benefits from handmade qualities and imperfections as a source of meaning.

Additionally, glass has tangible and aesthetic qualities that other materials do not possess. Natural light interacts with glass differently than other artificial materials such as acrylic plastic. Viewing angles become a factor to consider when experiencing stained-glass due to its streaks and textures. Natural and fabricated textures built into the glass invite touch and provide a new dimension of playfulness and tactility that would not be present in an acrylic imitation panel.

Sustainability and longevity

In long-term real world interactions, the imitation stained-glass presented in prior work [10][38] would age differently than authentic stained-glass, both physically and culturally. There is an implied permanence with glasswork that is not present with acrylic. For instance, stained-glass panels dating back to the 14^{th} century are still being preserved [15]. The ageing of stained-glass is a process that enriches the material character and charm—and therefore user experience—of the piece as the metals begin to naturally patinate [14][16]. An imitation panel made with faux-glass or plastic would not undergo the same processes, as plastics wear down differently (e.g., sun bleaching, material deterioration). The culture surrounding the wearing down of plastics is one of impermanence or transience, whereas the culture surrounding glasswork is one of permanence. It is also worth noting that the natural materials used in stained-glass are inherently more sustainable than the materials used for making plastics.

Human connection

While research proposed by Nordmoen & Mcpherson [46] highlights the relationship between the practitioner and their tools and materials, the development of many prototypes often glosses over the user and focuses more on the engineering. Artefacts developed in the realm of HCI need to support and improve the experiences of users in the world, instead of simply being neutral means to human ends [11]. Carpenter et al. take this further and advocate for less emphasis on the technology (“smart tablets, smart watches, smart water bottles” [8]) but that we embrace humanness. To be creative and to experience art is to be human; therefore, exploring the role stained-glass can play in this space is important because it speaks to this humanness and adds a layer of personal connection to interactive everyday artefacts. With stained-glass we strengthen and promote a culture of permanence involved with the creation of computational artefacts and simultaneously give meaning to the display of data.

Electrical connection

Enabling multiple electrical connections in a single stained-glass panel is challenging, both in its novelty and in its practice. Our initial experimentation attempted to create isolated circuits within the inner design (i.e., multiple electrically isolated design sections) instead of using the inner design as a single connection. These former designs were unaesthetic, difficult to create, and the resulting panels were structurally weak. To support more seamless and robust electrical connections, further experimentation involved the addition of thin insulated wires that fit in the slight gaps between glass pieces. Prior research [8] explored other traditional crafts such as the art of Kintsugi (for ceramic repair) that also uses conductive materials (i.e. gold) and proposed using them as input/output connections. Due to technical challenges, the authors of Electronic Kintsugi eventually used additional capacitive materials to achieve their results, and suggested using the inherent conductive materials of the craft as future work. By extending such research, we achieved fully-sensing interaction that is entirely embedded within traditional stained-glass fabrication. Our conductivity experiments also leveraged natural materiality as suggested by the literature [23][39]. We extended prior research [17][21] on surface-level touch interactions in Illumina and Anonyglass (proposed applications #1 and #3), where copper traces are directly interactive, supporting capacitive touch input. Inspired by Touch & Activate [49], we also explored subsurface electrodes and applied them to Lockthetic (proposed application #2).

CONCLUSION

In this work, we presented a step-by-step design process for prototyping with stained-glass. We developed novel fabrication techniques which uses stained-glass as a conduit for electrical current and explored two traditional techniques for making stained-glass in accessible and practical ways. Our experiements resulted in 5 methods for diffusing light through glass and applying aesthetic temporal interaction using patina. Our work contributes 4 methods to embed electrical current within stained-glass using either wires or the crafting materials themselves. Moreover, we suggest an array of input and output interactions and discuss 3 prototyped applications for everyday things.

The goal of this research is to expand the area of HCI focusing on interactive everyday things and hybrid craft and to promote creativity and material relationships when developing interactive artefacts. Future work will bring an application of this novel fabrication technique to users in the form of an in-situ deployment study and will aim to evaluate the user experience and sense-making of interactive stained-glass.

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