FabricatINK: Personal Fabrication of Bespoke Displays Using Electronic Ink from Upcycled E Readers

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Figure 1: E ink can be used in versatile ways to enable the personal fabrication of custom-shaped displays. Through a review of technical patents and a set of investigations, we uncover E ink's potential for fabricating 3D bespoke displays. We show how to harness programmable particles from broken E readers and a novel method for fabricating displays shown through 10 demonstrators: a water drop shaped display on a plant pot; a digital coffee break reminder augmenting an analog timer; a multi-segment water bottle fullness indicator; a star-chart cut out with painted on electrodes; a detachable email notification sticker to augment desktop objects; glasses with a notification icon; a necklace displaying heart-beat; a violin bow sheath for assisstive finger placement; an inkless post-it note and a smiley face badge.

ABSTRACT

Abstract: FabricatINK explores the personal fabrication of irregularly-shaped low-power displays using electronic ink (E ink). E ink is a programmable bicolour material used in traditional form-factors such as E readers. It has potential for more versatile use within the scope of personal fabrication of custom-shaped displays, and it has the promise to be the pre-eminent material choice for this purpose. We appraise technical literature to identify properties of E ink, suited to fabrication. We identify a key roadblock, universal access to E ink as a material, and we deliver a method to circumvent this by upcycling broken electronics. We subsequently present a novel fabrication method for irregularly-shaped E ink displays. We demonstrate our fabrication process and E ink's versatility through ten prototypes showing different applications and use cases. By addressing E ink as a material for display fabrication, we uncover the potential for users to create custom-shaped truly bistable displays.

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CCS CONCEPTS

• **Human-centered computing → Displays and imagers**.

KEYWORDS

Electrophoretic; E ink; E reader; Display; Prototyping; Fabrication; Free-Form Display

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1 INTRODUCTION

Electronic ink (E ink) is an electrophoretic substance made of microcapsules, within which smaller particles of different colour and charge are suspended. When an electric field is applied, the particles within move to the top or bottom, acting as programmable pigments. Despite being bicolour, E ink has many advantages, including low power consumption, bistability (maintains state without power) and functional simplicity (few layers and robustness of material). E ink microcapsules are up to 50 times smaller than the pixels in LCD screens [80].

Given the versatility of E ink, it is surprising that it is only used in prefabricated regularly-shaped displays, such as rectangular E book readers and price tags. Through personal fabrication, work in the research community has expanded the scope of display form factors with various materials [28, 40, 59]. Our work expands on this idea by introducing E ink as a promising new material to personal fabrication. E ink is not only another option for display fabrication but by benefitting from its unique properties, it has the potential to be even better suited to personal fabrication than current state-of-the-art materials. Our vision is that E ink could be sprayed, painted, printed and mixed with many different substances, like other active materials or traditional ink, to create art pieces or consumer products, of many shapes, types and scales (e.g. pens, make-up and dye).

To this end, our work demonstrates that E ink has more to offer and can be used in a more versatile way to enable the fabrication of bespoke displays, ultimately with shapes going beyond the traditional rectangle or circle. By doing so, our work contributes to two research areas which are developing rapidly:

- It expands the **diversity of materials for personal fabrication**. Within fabrication research [5, 6], fabricating displays has received significant recent attention and work has paved the way with technologies such as electroluminescent [28, 59, 78], electrochromic [10, 40], photochromic [29, 41, 62] or thermochromic [60, 79] inks. Our goal is not only to expand on these other projects by adding choice and diversity of material but to demonstrate E ink's unique strengths (e.g. bistability, high contrast, low power and high switching speeds) and its suitability and applicability to the personal fabrication of displays.
- It opens-up the **diversity of display form-factors**. Creating custom-shaped displays has become an important goal in HCI to enable displays which better fit within their settings and contexts of use. Free-form display factors have been used in numerous research areas, including Tangible User Interfaces, Organic User Interfaces or Shape Changing Interfaces, enabling end-users to interact with interactive objects with better affordances [3, 32, 36, 43, 64] as well as explored in Robotics (e.g. [65]).

We frame our contribution within Sweeney *et al.'s* [68] vision of displays as a material as a democratisation of E ink as a material for personal display fabrication. Our approach has four steps. We (1) review technical nanoscience literature and key patents, contributing a breakdown of key disparate information on E ink's strength as a material for personal fabrication. This uncovers E ink's real potential for being used in personal fabrication and its strengths as a display material in this context. It can be used in an uncased way, with the potential to be sprayed, layered onto irregular topologies and even has the potential to be integrated into truly irregular forms such as on-skin technology (Figure 1). Prompted by a lack of commercial availability, we (2) show how to extract and harness the E ink microcapsules from broken E readers and present this as a methodology in order to bypass a closed manufacturing system. We (3) perform 6 technical investigations to explore the recycled E ink's viability in the context of personal fabrication, such as the materials potential to be deposited. Lastly, we (4) present a straightforward fabrication method to create bespoke displays and validate it through 10 demonstrations (Figure 1). Our demonstrators, although limited to planar 2D shapes, on account of using recycled material, provide an archetype for the fabrication of E ink displays and act as a stepping stone to realising the potential of free-form bistable 3D displays and to inform future fabrication processes.

2 RELATED WORK

2.1 E ink displays within UIs

E ink has been used in a range of work for wearables, paper-like displays, signage and more. These works largely use E ink in pre-built display structures, with activation matrices giving regular flat rectangular or circular pixelated shapes. The closest works, Sweeney *et al.* [68] investigate the idea of autonomous pixels and demonstrate it using pre-fabricated sheets of E ink. Similarly, Grosse-Puppendahl *et al.* [26] explore the design space around E ink display put together from prefabricated display structures. This work focuses on addressing E ink, its energy neutrality and low-power updating. Through the lens of personal fabrication, FabricatINK explores E ink structures that are irregular (non-square, non-round) 2D shapes with variable layer thicknesses as well as the potential of E ink as a depositable material.

Dierk *et al.* [14] integrate pixellated E ink displays into clothing as wearable devices. They use obscuration to give the impression of irregularly-shaped displays. Dementyev *et al.* [13] introduce E ink as wireless display tags, making use of its bistable and low power properties, while emphasising the benefits of not having complex attachments to separate control elements. Klamka *et al.* [47] present an embedded notification system in the form of a bendable rectangular sleeve-integrated E ink display. DisplaySkin [7] makes use of E ink's flexibility to produce a curved wrist band display. In Watch+Strap [48], Klamka *et al.* use bendable rectangular E ink displays as a smart watch strap. Snaplet [70] uses a large rectangular flexible display to create a bracelet which Klamka et al. extend through coloured wearable E ink display pieces [46]. Lastly, Alternail [15] uses inductive electronics and produces fingernail displays with E ink outputs. These works all use regular pre-layered pixellated E ink display elements. There is significant work using prefabricated, rectangular sheets to explore E ink displays' flexibility, tangibility and paper-like properties. Flexkit [31] takes advantage of the flexibility of E ink layering structures for creating bendable displays. Gomes *et al.* [22] introduce an E ink device that deforms itself, for use as notification. Rendl *et al.* [63] augment smart phones using cases with embedded E ink displays to make the most of E ink's desirable properties. In PaperTab, Tarun *et al.* [71] use multiple A4 sheets of E ink with embedded pixelated circuitry to explore the tangibility and paper-like properties of digital information that are afforded by E ink displays when not enclosed in a rigid structure. In early stages of Papertab, E ink displays are reclaimed from E readers, as intact pixelated elements for use in its work. In Paperfold [23], Gomes *et al.* introduce paper-like folding and tearing motions to manipulate the arrangement of three prefabricated pixellated E ink displays. DisplayStacks [21] uses E ink displays to explore a paper-like stacking of digital displays. Despite the bendability demonstrated in these works they have a regular shape and addressing matrix.

2.2 Personal fabrication of displays

To our knowledge, E ink has not been analysed as a depositable material for configurable display creation within personal fabrication before. There exists significant work in this area looking at other layerable ink-based technologies. Olberding *et al.* [59] started with the use of electroluminescent (EL) for screen printing segmented displays, and Klamka *et al.* [45] applied EL to paper-like displays, classifying display types into classes of single-segment, multi-segment and matrix. These approaches simplify fabrication and open the application scope for irregularly-shaped displays. More recently, work has introduced EL displays on irregular topologies. Groeger *et al.* introduce EL displays with irregular 3D topologies through hydroprinting and Wessely *et al.* [78] introduce EL display fabrication for deformables. Wessely *et al.* [77] produce a usable fabrication pipeline for EL using spraying, while Hanton *et al.* [28] introduce a combined additive manufacturing approach for free-form EL displays through 3D printing and spraying.

Materials that are stable without electrical current for different amounts of time are also becoming increasingly popular as they allow creation of pervasive displays that require low power and independent operation. Decochrom [40, 53] promotes user-centric display fabrication through electrochromic (EC) materials. Extending this work, Colley *et al.* [10] explore the idea of unobtrusive calm computing using non-light emissive EC displays, while Jarusriboonchai *et al.* [39] explore the space of EC wearables. Zhang *et al.* [82] increase the potential for long term EC bistability (a minimum of 7% reduction in contrast over an hour). Other bistable properties are used in ColourMod [62] which introduces multicolour reprogrammable photochromic effects on objects using a voxel-based patterning, and in Photochromeleon [41] which supports recolouring objects using sprayed-on blended photochromic inks and a separate projector for colour change. Thermochromic materials can also be used for displays, as in TempTouch [60] which applies microheaters to textiles. These works demonstrate free-form display fabrication but without E ink's high contrast bistable properties.

3 A REVIEW OF E INK PRINCIPLES AND PROPERTIES

We derive information on E ink from 287 filed patents (as of September 2021, see Annex) to provide a synthesis of key information regarding E ink's properties and potential for the fabrication community.

3.1 Principles of E ink

3.1.1 Microcapsule principles and fabrication. E ink is an electrophoretic material, a subset of electrooptic materials [38]. It is comprised of coloured particles suspended in a dielectric fluid (Figure 2). The suspending fluid contains two sets of particles that are of contrasting charge and colour, such as positively charged black particles (carbon black) and negatively charged white particles (titanium oxide). Under an electric field, different coloured particles move to the surface of the fluid to create colour change. The electrophoretic composition is held within optically transparent enclosures called microcapsules which are typically around 40 microns across [80]. Microencapsulation of the suspension is necessary, as a large un-segmented volume of fluid with suspended particles would allow lateral migration of the particles. Other types of electro-optic displays exist, such as the fluid in E ink holding a colour and single suspended particles [37, 50] or other types of display such as gyricon ones relying on rotating bi-colour balls (Janus particles). Information about the manufacture of E ink microcapsules is commercially sensitive. Partial methods for microencapsulation include processes such as interfacial or insitu polymerization, in-liquid curing, coacervation or electrospraying that can be carried out in a specialist lab or factory [20, 50, 58]. A body of academic work also provide innovations on the manufacturing process [34, 84], including the use of organic material for robustness [58] as well as simplifications and increased control over output parameters [34, 52]. Due to complexity, producing the E ink material from scratch is not a viable option for a wider audience than the current manufacturers (even before IP considerations).

3.1.2 E ink display manufacturing process. An E ink display is formed of a sandwich structure with E ink layered between two electrodes (Figure 2). At least one of the electrodes is transparent for viewing the colour change. Other materials can be added to this structure such as adhesives for the E ink or an insulating layer. Electrodes belong to passive or active matrix addressing systems [8]. Note that microcapsules are not equivalent to pixels which are determined by the electrode placement. There are two steps for industrial assembly: (1) assembly of the core sandwich structure used in E ink displays, this is known as the Front Plane Laminate (FPL); (2) adhesion of the FPL to the backplane of transistors/diodes. Lecain *et al.* [49] describe the commonly used FPL as layers of transparent conductive electrode (ITO), E ink, adhesive and a release sheet on a substrate. It is produced as a continuous roll on PET [33] and cut to size before adding the backplane. E ink displays are often regularly-shaped (circular or rectangular) and pixellated with a fixed size. Custom segmented displays can be purchased but they are only available in very large quantities with significant wait times, so are only suited for integration to well established product lines [18]. This makes prototyping or designing custom-shaped

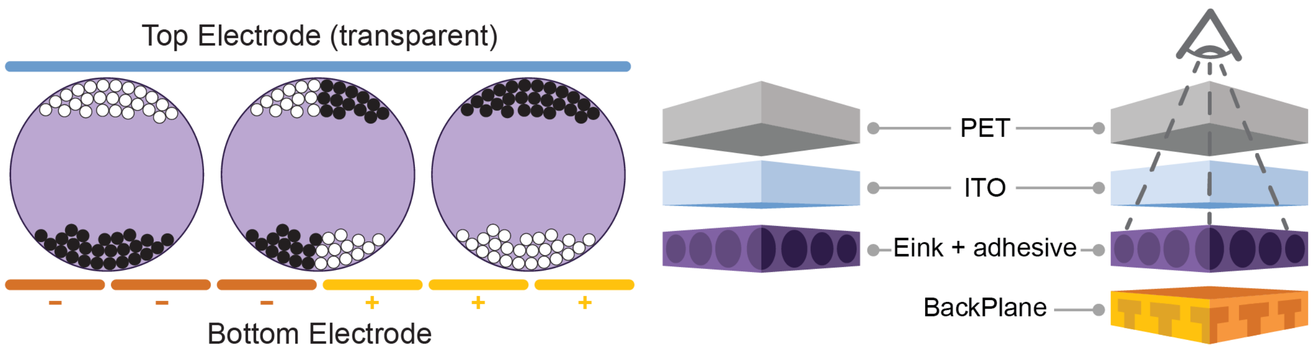

Figure 2: (left) A cross-sectional diagram of E ink microcapsules. An E ink displays works by creating an electric field over the E ink, between two electrodes on either side of the E ink microcapsules. (right) The layering structure of a typical E reader. The FPL is comprised of PET, ITO and E ink. Within an enclosed E reader, a backplane formed of an array of transistors is added to address sections of E ink. Different display types have different thicknesses and dielectric adhesive types between layers

interactive devices using E ink difficult. Further, the limit to flat structures prevents 3D and truly free-form E ink displays from being produced. Personal fabrication of E ink displays opens up this scope, particularly with the potential for E ink as a depositable material for fabrication on irregular surfaces.

3.2 E ink compared to other material choices within personal fabrication of displays

Work on the personal fabrication of displays has typically revolved around four key active materials: Electroluminescent (EL), Electrochromic (EC), Photochromic (PC) and Thermochromic (TC). Current works focus around EL and EC due to the simplicity of their direct electrical stimulation and their strengths as display materials. We beleive that E ink can also be harnessed for the personal fabrication of displays, and has the potential to not only be a fifth strong material in display fabrication but also become the preeminent material of choice. E ink as an active material has three key attributes which support its use in display fabrication:

(1) Display properties - E ink is both **high contrast** and **non-emissive** with the ability for **high switching speeds** [37] suiting potential use cases in varying light environments and with passive or active updating of information;
(2) Mechanical simplicity - E ink is well suited to fabrication due to its functional simplicity. It requires **few layers** (a minimum of 3). It also supports the potential fabrication with a **versatile layer thickness** [50, 85] as a display type that is not thin-film. Additionally it has a level of inherent **robustness** to heat, pressure and water; and
(3) Control benefits - E ink has true **bistability** with minimal fade of colours over extended periods of time (power needed only for updating information). Bistabiliy supports applications requiring low power [61] and affords the potential for unencased interactions. It is thus inherently **scalable** [12, 67, 72] as different segments can be addressed at once without the constant need for power. It also has **nuanced particle control** within microcapsules [30, 81, 85] , allowing for precise greyscale display and suiting applications with variable thicknesses.

E ink is comparable to EC material [40] for its properties of bistability, direct electrical activation and display through colour change rather than luminescence. But E ink has *true bistability* - EC is bistable but usually only in high contrast for a limited time (with significant reductions after several hours [40]). E ink retains its colour change "indefinitely" [61]. EC has relatively high contrast but implementations of it as a display material vary in their opacity [39, 53], limiting the contrast and visibility of the display, whereas the block colour change for E ink is opaque with a high contrast that diminishes little over time. E ink has high switching speed (e.g. we observed more than 10 colour changes per second on our fabricated display). A formula for its switching speed exists *et al.* [37]. As a comparison, fabricated electrochromic displays are limited to switching times of 1.1-5.1 seconds [40]. Lastly E ink's mechanical simplicity of only needing a fixed base electrode and active layer open a broader scope of ways to apply electrodes.

Compared to EL, E ink's bistability allows for (1) lower power consumption and applications that need to be detached from a power source, (2) simpler implementation of capacitive touch detection, without the need for time multiplexing [59]. E ink's non-emissive nature allows for a wider set of potential use cases in mixed light environments and lower power requirements eliminate risk of giving a user an electric shock. Additionally, although the encapsulation process could be complex, no rare materials are inherently used in the production of E ink, unlike EL which relies on processed EL phosphor. Compared to PC and TC, E ink has a simpler activation due to only requiring layered electrodes rather than external heat or light activation elements. In addition, E ink's fast switching times and precise lateral resolution are more pronounced as these are areas in which PC and TC are limited. E ink also has the inherent potential for a high level of nuanced control and grey scale display which has been explored in [30, 81, 85]. E ink can also be made of different colours [1, 16, 76] as well as being incorporated into bendable structures [33].

Additionally E ink can be suspended in other materials similar to paint and has the potential to be printed via inkjet or screen printing [74]. Chen *et al.* [8] describe the layering of an electrophoretic medium with E ink capsules in a binder that will dry to form a coherent layer. Honeyman *et al.* [33] list printing/coating techniques including spray coating, silk screen printing and inkjet printing with E ink. These sources encourage the potential of E ink as a material within display fabrication (e.g. spraying [28], hydroprinting [24] or screenprinting [59].

From this comparative assessment, we see that E ink has the potential to be the optimal material choice for the personal fabrication of displays. However, it suffers from a key draw back - universal access. In the rest of this paper (1) We provide an interim solution (our extraction method) to allow makers and researchers access to this material in a preliminary form. (2) We provide a fabrication method using E ink to prove that it has potential as a material for display fabrication. (3) Lastly we produce key demonstration applications that both validate the viability of the extraction method but also exhibit E ink's inherent strengths as a display material in a range of contexts.

4 PROCESS FOR EXTRACTING E INK

Pre-layered, enclosed E ink displays can be purchased as individual components, but only of regular rectangular or circular shape. The ink itself cannot be obtained as a layerable material, which is heavily protected by patents and isolated in industrial labs. Manufacturing techniques are extremely difficult to reproduce without professional expertise and microencapsulation facilities. However, we found that damaged E readers are easily acquirable, cheap and most are broken due to loose connections or damaged electrodes with the E ink intact. To (a) investigate the unexplored properties of E ink and (b) further examine its potential for display fabrication, we developed and optimised a way to extract intact E ink material from broken E readers (Figure 3). We used a combination of chemical and mechanical processes that we present for ease of replication. We also discuss the different extraction processes that did not work.

4.1 Step-by-step

We (a) disassemble a damaged E reader into component parts, carefully removing the lithium battery using IPA to loosen adhesive. This leaves us with the screen component of E ink sandwiched with other materials including adhesives, ITO-coated plastic, a glass sheet and a backplane of transistors. We (b) use a waterjet cutter on the screen's glass surface to split the screen into six parts. This can also be done by scoring the glass, but this takes longer. Splitting into six reduces the area of each piece and increases its perimeter allowing us to use a solvent (acetone) to dissolve the glue between the E ink and the glass. We observed this size (~4x4cm) to be most effective for producing slides with minimal damaged E ink and maximal area. The screen segments soak (c) for approximately 96 hours (±24 hours) to allow permeation of the acetone into adhesive layers. The pieces are then gently pulled apart (d), giving six slides with varying amounts of E ink on them. We define an E ink slide to be a flat piece of polyethylene terephthalate (PET) as a transparent substrate. This is covered with a layer of indium tin oxide (ITO) which is a transparent conductive electrode, and subsequently layers of adhesive and E ink [74]. This is identical to the Front Plane Laminate structure (Figure 2).

4.2 Lessons learned from failed methods

We initially tried to cut the screen with a glass cutter but we found that it damaged the E ink particles, which were then unusable. We were limited in trying conventional methods for cutting the entire E reader, as many of the materials used in the manufacture of E readers are not known, such as potentially toxic adhesives. Although information is partially protected under IP, the relevant patents suggest this is unlikely to be the case - we suggest further exploration on this. For separating the layers, we tried IPA, Acetone and water at different temperatures over different amounts of time (up to 336 hours) to calibrate the balance between loosening the adhesive and damaging the microcapsules. Prolonged exposure to strong solvents (e.g. acetone) damaged the E ink particles themselves but such a strong solvent was necessary to loosen the glue used between the layers of the E reader. If the segments of an E reader display were left too long in the solvent, or were too small, the E ink microcapsules get damaged. If they were not left long enough, then the adhesive between layers was not sufficiently loosened and so when the layers were separated, the E ink was torn into smaller sections and rendered unusable. The variability of the method (largely due to E reader damage levels) meant that even once we had optimised the process, there was up to 50% waste of E ink.

5 TECHNICAL EVALUATIONS

We carried out a series of 6 evaluative investigations to explore the properties of E ink relating to its potential in personal fabrication. We used material harnessed from our extraction process. Before summarising the evaluations, we explain how we switch the E ink on and off because our extraction process removes the sandwich structure of two opposing electrode layers that is traditionally used to activate the particles.

The slide structure, that is the output of the extraction process, has a single electrode in place with a surface of E ink exposed. We removed a small contact area of E ink to attach the single ITO electrode to the power source. We needed a way to switch the E ink without building a second permanent electrode so as to carry out investigations on the performance of microcapsules. We proceeded by using skin-contact, while conducting a (low current) charge, against the E ink as a removable surface electrode. This is the same structure as shown in Figure 2 but with the backplane being instead replaced by a finger with a charge running over the skin. By forming a temporary connection with the E ink repeatedly, we were able to observe full colour change in the microcapsules, both by eye and microscope.

We measured the quality of the microcapsules under a microscope to determine capacity for optical change. In order to measure salient factors such as the strength of materials, layer thicknesses and fatigue, it is necessary to be able to measure gradients of change in performance in order to ascertain tolerances of the material. However unlike pixels in a traditional LCD, microcapsules are irregularly-shaped, spaced and can have irregular amounts of inert material between each other, so counting active capsules is not sufficiently rigorous. To compare display strengths with each other, we measured the overall proportional difference in contrast. This allows direct measuring of deterioration and potential damage of E ink microcapsules under different circumstances.

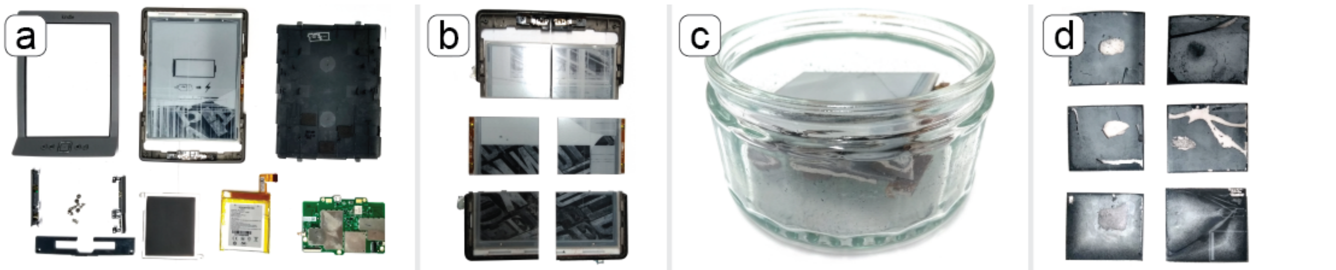

Figure 3: Extraction process: (a) Disassembly of E reader; (b) cutting using a waterjet cutter; (c) dissolving of adhesives between layers by soaking in acetone; (d) separation of layers of E ink slides for use in investigations and demonstrators.

We took images of the E ink microcapsules using a microscope [56] at a magnification of x1000 with consistent distances and lighting, for all investigations. This was magnified enough to allow clear images of each microcapsule but also to image a sufficient number of microcapsules to provide a sample distribution. We kept lighting conditions strictly consistent between samples, and used a retort stand to maintain consistent microscope position. To reduce glare, most images were taken directly (not through ITO). However, enclosed E ink was imaged through the E reader cover for investigation 1 (below). Where possible a single sheet or sample of E ink was used within investigations, in order to minimise inconsistencies between multiple different sheets from a variable extraction process.

The images produced were compared using the ImageJ [35] analysis tool following the same process in each case. We converted the images to 8-bit greyscale and analysed the shade of the slides. Each image had 307,200 pixels and we used ImageJ to measure the shade of each pixel. This gave a distribution of the shades for each image we could analyse. By looking at the black and white states of each sample (using the switching method described) we were able to compare damage to microcapsules through extraction and under other stresses.

5.1 Investigations into the extraction process

5.1.1 Investigation 1: Assessment of extracted E ink. Does extraction reduce E ink's ability to demonstrate colour contrast, compared non extracted material? We found that extracted E ink shows significant colour switching ability.

Comparison samples: We tested the extent to which our extraction process damaged the ink. We compared colour change of E ink going through our extraction process (extracted E ink) vs. E ink still within an undamaged E reader (enclosed/undamaged E ink). Two sets of 10 samples were obtained, for each of enclosed E ink and extracted E ink.

Analysis: We took images of 10 samples of E ink enclosed within an intact E reader with the microcapsules in a black state and with the microcapsules in a white state. We also took images of the 10 extracted E ink samples in black and white states. We took a range of 10 different of E ink samples from the extraction process to compensate for variability between samples. We analysed the shades of these samples in black and white states.

A sample's colour change ability can be indicated by the difference in shade measured between its black state and white state. A greater difference in average shade indicates a higher ability to show colour contrast which reduces as the material sustains damage. We define *E ink functionality* for a sample of E ink as the difference between that sample's colour change in black and white states, as a proportion of the colour change between black and white states of undamaged E ink. As such we have a metric where, 100% functionality indicates no damage and maximal ability for colour change within the sample, while 0% indicates no colour change is recorded.

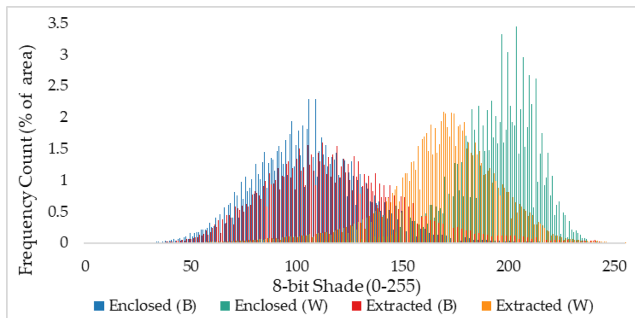

Figure 4: Distribution of average shades shown in samples of E ink that are enclosed within an E reader in both Black (B) and White (W), along with the average shades for E ink that we have extracted from an E reader in Black (B) and White (W). The distributions show the average frequency of occurrence of shades on an 8-bit scale (0-255, 0=black, 255=white), over 4 different sets of 10 samples.

Results: We took the average mean and average standard deviation for each of the 4 sets of 10 samples. On a scale of 8-bit shade from 0 (black) to 255 (white), the enclosed E ink gave μ=106.9 and σ=26.3 when in a black state and μ=193.6 and σ=18.7 when white (Figure 4). The extracted E ink gave μ=118.8 and σ=32.6 when black and μ=168.5 and σ=25.9 when white. These distributions are shown in Figure 4. The extracted samples showed an average functionality of 57.2% compared to the enclosed material, and the distributions are similar in a black state in both cases.

The low E ink functionality of extracted material suggests it sustained some fairly significant damage through extraction. Extracted distributions, having greater overlap in shades, likely implies higher rates of non-switching microcapsules. The deviation recorded for extracted materials was higher, implying that there was some amount of variation between E ink slides from the extraction process. This supports the conclusion that extracted slides work but a proportion of microcapsules are damaged. We note that although 57.2% is a low success rate, the slides themselves still show high contrast. E readers require a higher contrast to show pixellated details and gradients. Through our demonstrations below, we show the effectiveness of larger segmented patterns that are fully functional with this rate.

5.1.2 Investigation 2: Extending the extraction process. Does E ink remain functional when transfered to a different substrate? Removing E ink from slides damages a high proportion of microcapsules and only a small portion of transferred E ink microcapsules are undamaged and retain the ability to show colour change.

Comparison samples: We tested whether E ink removed from the slides and layered onto another conductive surface is functional. In this investigation we only produced a single sample of E ink, deposited on a conductive surface (Figure 5 (e,f)). We were limited in producing more comparison samples by the low yield of E ink compared to adhesives when scraped from the E ink slides. To produce the E ink as particles we submerged slides with E ink on them, that had been extracted from E readers, in warm water and scraped off the E ink. This material was then pipetted out of the water onto a blank slide of ITO. We waited for the water to evaporate in several layers until the material deposited was uniform.

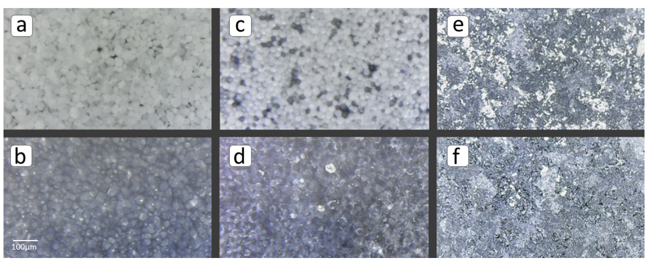

Figure 5: Microscope images of 3 samples of E ink at x1000 magnification, investigation 2: (a,b) enclosed in a functioning E reader; (c,d) post-extraction E ink slides; (e,f) E ink removed and deposited on ITO slide. (Top: white, bottom: black).

Analysis: We observed visual colour change and then compared the sample produced to the two samples: E ink extracted from an E reader and E ink still housed within a functioning E reader.

Results: Colour change was observable in the deposited E ink, although only for a minority of the area of the deposited material. Following the analysis of images taken under a microscope, for deposited E ink, we recorded μ=159.3 and σ=43.4 (white) and μ=154.7 and σ=41.9 (black), giving an *E ink functionality* measure of 5.3% for deposited material. This is a very low proportion of functioning colour change and suggests significant damage to microcapsules.A high standard deviation implies there are few microcapsules displaying significant colour change rather than many displaying little colour change. This is likely caused by obscuration by adhesive. 5.3% is a very insignificant result. We emphasise that this demonstrate the proof of concept for depositable E ink in personal fabrication and act as a stepping stone but is still to be striven for in future work, by sourcing E ink without the need for the extraction method.

5.2 Investigation into E ink's fragility

E ink could be used as a material outside of a casing with direct application of finger-pressure. We provide tests to indicate its constraints on robustness in the context of pressure and cuttability. These tests evaluate the performance of extracted E ink, with the goal of indicating the behaviour of unmarred E ink, if procured in an unenclosed form.

5.2.1 Investigation 3: E ink pressure test. To what extent are microcapsules damaged by pressure? E ink shows damage proportional to pressure.

Comparison samples: We noted that the microcapsules are easily damaged by pressure when outside the protective casing of an E reader. We recorded the colour change of a single slide of extracted E ink, repeatedly before and after it was exposed to an incrementally increasing pressure. We used a standard tabletop vice to apply force to 3 components: a digital scales, a 3D printed (PLA) truncated cone with a 10mm diameter circular sanded end (chosen as a standard approximation to fingertip), and the sample slide of E ink in between (such that force from the clamp would only be exerted through the 10mm circle). Using the vice to apply force, we measured 250g increments against the E ink from 0g to 5kg. As such, each reading was taken at increments of 7.804 kPa.

Analysis: Before applying incremental pressure we switched the sample to a black state, applied pressure, switched it to a white state and recorded an image. This meant that any damaged microcapsules would not exhibit colour change, allowing us to measure reduction in performance. We were then able to analyse this series of images for change in colour changing properties due to damage from pressure.

Results: Although we might expect a breaking point at which the microcapsules in the E ink plane start rupturing more frequently, this exploration indicates that the reduced ability to show colour change was linear to an increase in pressure (Figure 6). We observed that damage was not uniform across the sample. We attribute this to uneven pressure due to factors such as residual glue. Note that our setup had a variation of up to 0.8kPa in the pressure applied. Our results are useful in determining an indication of an upper threshold for pressure tolerance: greater than 140.5kPa appeared to damage E ink to the extent that it no longer showed significant colour change (<5%).

5.2.2 Investigation 4: Cut-ability of E ink slides. How much do different ways of cutting the E ink slides damage the E ink itself. A scalpel appears less damaging than a laser cutter or using scissors.

Comparison samples: We took separate samples of E ink slides cut in a straight line using scissors, a laser cutter and a scalpel to compare how much E ink was damaged.

Analysis: We took images of each of the samples in black and white states under the microscope to ascertain the width of damaged microcapsules, from the cut edge. Damaged microcapsules are clearly ruptured in this case and so we are able to measure range of damaged particles directly between cutting methods.

Results: Of the 3 samples, all the cuts appeared to damage a fairly consistent depth of microcapsules. The lasercutter damaged microcapsules 40-80μm away from the cut. The scalpel damaged microcapsules at a depth of 20-50μm from the cut. The scissors

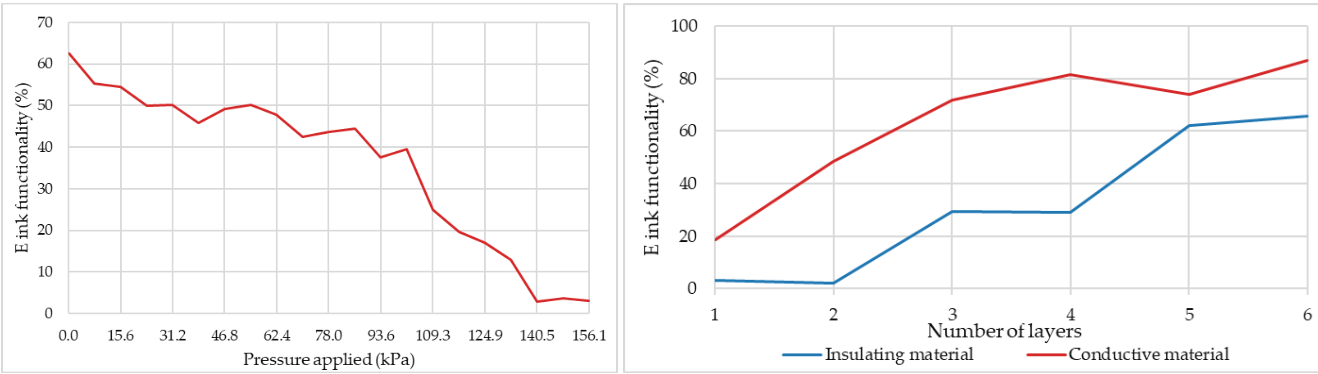

Figure 6: (left) Investigation 3: Ability for colour change in samples of E ink (shown as a percent of fully functional E ink) in reaction to increasing pressure applied. (right) Investigation 6: 8-bit shade for fabricated E ink layer structures with incrementing thicknesses of insulating layer compared to conductive electrode.

ruptured all microcapsules within 120μm of the cut but created some damage up to 500μm away. Only the scissors created significant optically noticable damage. All three cutting methods have contexts that are appropriate for their use, although these results imply that makers should limit the use of scissors for fabricating E ink displays. For completeness (and because this area is researched [9]), we include a further investigation into bendability in an annex.

5.3 Investigation into auxiliary materials for display layering

To build fabricated E ink displays from an E ink slide, many applications require a permanent second electrode. These tests are concerned with the E ink's integration with painted electrodes. We observed that the E ink layer can be porous after the extraction process, which risks short circuits between electrodes. As such, we also test the addition of an insulating layer adjacent to the E ink, between electrodes.

5.3.1 Investigation 5: Different electrode/insulating materials. Which are the optimal materials for electrodes and the insulating layer in an E ink structure? Insulating acrylic primer and conductive copper paint perform well.

Comparison samples: We compared 3 different commonly used conductive materials [25]: copper paint [55], Bare Conductive's carbon-based paint [11] and a transparent conductive polymer (PEDOT:PSS) [2]. We performed this evaluation with 3 potential intermediate layers: an insulating acrylic primer [75], a clear insulating lacquer [27] and no additional insulating layer. We created a 3x3 grid of nine 10mm square samples, to cover all nine possible material combinations, and as an approximation of fingertip size. We used a single E ink slide to further ensure consistency within the test. Insulating materials were applied by airbrush to provide consistent thicknesses.

Analysis: Before applying materials we took images of the E ink in a black state for each square as a comparison figure. We then applied the insulating and conductive materials and switched each square sequentially to white. We recorded the shade distribution of the different states in order to compare samples.

Results: Only five (of nine) combinations showed any colour change. We measured figures for the *E ink functionality* of each sample. The five combinations gave: Copper paint/no insulating layer (31.7%), Copper paint/black primer (43.1%), PEDOT:PSS/no insulating layer (39.6%), PEDOT:PSS/black primer (41.0%) and PEDOT:PSS/clear lacquer (38.5%). The combination of copper and black primer provides the most contrast in shade, although we note that the other results are similar. We also observed that the copper paint was the most robust and easily applied conductive material.

5.3.2 Investigation 6: Material layer thicknesses. Summary: How does a fabricated E ink display behave differently depending on layer thickness? Increased numbers of layers (up to 6) increase functionality for both insulating and conductive layers, however this effect tails off more quickly for conductive layers.

Comparison samples: We proceeded in two parts. First we tested the performance of E ink increasing numbers of insulating layers and a single electrode layer. We took a single slide of E ink in a black state and applied 6 1x1cm square areas with 1 to 6 layers of insulating black primer. Each layer was created using a single pass of the airbrush (30psi, 20cm perpendicular distance). We then layered a copper electrode on top of the six samples in the same way. In the second part, we layered a 1cm square with two layers of insulating primer. Materials were applied in the same way but in this case, measurements were taken with 1 to 6 layers of copper paint applied over the primer using an airbrush. Each of the two sets of 6 samples were tested on the same E ink slide to ensure internal consistency.

Analysis: We set each sample of E ink to a white state and measured shade. We compared the shade of the samples in white state for each layer thicknesses to each other to show a range of colour change. A lighter mean white value indicates a broader range of colour change. We did this for the 6 samples of insulating layers and the 6 conductive ones.

Results: We observe that the layering structure displayed strong colour contrast for a single layer of insulating material and that more layers of insulating material results in greater colour contrast for the E ink for up to 6 layers of insulating primer (Figure 6). Each layer of paint required 15-20 extra minutes to dry, providing a meaningful payoff between fabrication constraints and colour contrast when deciding on the thickness of the insulating layer. Similarly, Jacobson *et al.* [37] show that a thicker insulating layer leads to slower switching times, as another payoff against higher contrast. For the conductive material we saw a similar trend of increased performance with a higher number of layers. But after 3 coats of conductive material, the value of adding further coats appears to have diminishing returns.

6 FABRICATION OF BESPOKE DISPLAY APPLICATIONS USING UPCYCLED E INK

Building on the results of our evaluations, we present a method for fabricating displays. We present a novel way to build E ink displays through a layering process, using the extracted E ink material. This demonstrates the feasibility of E ink's use in personal fabrication. We then demonstrate the process through 10 applications showing use cases for personally fabricated E ink displays and the strengths of the material.

6.1 FabricatINK display fabrication process

The fabrication process requires starting with an E ink slide (layered PET, ITO and E ink) onto which a back electrode is constructed to control colour change. This layering reproduces the effect of the backplane common in pixellated E ink displays (Figure 2), but in a single cohesive layer, allowing for custom segmented shapes, as seen in related work with other materials [45, 53, 59].

The fabrication process we developed has four steps as shown in Figure 7. We (a) cut the E ink slides into a desired shape for the display piece. This also shapes the transparent electrode that is part of the slides. We suggest using a scalpel to avoid damage of microcapsules (investigation 4), although scissors facilitate curved edges or lasercutting allows for precise geometric shapes. We (b) layer insulating material over the E ink to control layer thickness between electrodes and provide an insulating protection of the device with regards to shorts between the electrodes. We suggest depositing the material using an airbrush, as this allows for uniform deposition over the E ink slide however a paintbrush works well as a more available alternative. Using investigation 5 we suggest applying black primer. Investigation 6 implies that we should maximise the number of layers of insulating and conductive material. In addition to ability to show colour contrast, we must take into account the balance between drying time of layers (20 minutes) and switching speeds. For insulating material we suggest 3 or more layers due to the increased performance. N.B for solvent use and airbrushing these are safe as long as they are applied in an appropriate ventilated area with PPE. Usability, availability of tools and safety of methods were chosen based on other HCI fabrication work [28, 41]. We next (c) layer the conductive electrode through which the colour change segments are defined in shape. We suggest applying two or more (investigation 6) layers of copper paint (investigation 5). Here we suggest either using an airbrush (with a lasercut stencil) for control of thickness or a paintbrush for fine control of lateral detail on the electrode. This results in the E ink and insulating layer being sandwiched between electrodes of ITO and copper paint. This stage is omitted for displays where E ink is interacted with through skin contact as described in the testing above. Lastly we (d) attach the circuity to the segmented display piece. We found success with small scale electrical clips for prototypes or wire soldered to copper tape for more permanent display elements. These latter connections were further secured with superglue and copper paint. Significant care was required to avoid peeling off the E ink layer or otherwise damaging it.

We introduce applications of E ink displays that do not require construction of a top electrode. In these cases we build on work that has mobile electrodes [57], to pass current through an external object adjacent to the display material that can then be removed. We explore this potential by combining the low current properties of E ink to allow the use of skin as an electrode, shown in the demonstrations below.

Control: For this project, the displays that were created were powered using a desktop power supply running 24V through a through a 3M DC/DC Converter [73] to give positive and negative 15V outputs for colour change along with a 0V ground. We used an array of relays so that for any display segment, one electrode functioned as the ground and the other electrode could be switched programmatically using an Arduino Nano to have a positive or negative voltage. Informal testing gave 15V as a point with sufficiently high contrast for differing layer thicknesses. Switching thresholds, greyscale control and various signal systems for E ink are extensively covered in the related work [30, 81, 85]. In further work we suggest the development of a bespoke microcontroller in conjunction with deposition methods for accurate layer thickness and greyscale control [37].

Touch detection: We carried out some basic tests to ensure that the conductive electrodes could still be used as capacitive sensors using Arduino's Capsense library [4]. Such dual use of channels has been shown to be favourable for simplicity of fabrication within other work [24, 28, 59, 78]. Due to it's bistable nature, E ink does not require constant current for maintain display output. As such, any time-multiplexing is far less complex than with electroluminescent materials, since the display inherently retains information when capacitive sensing is being implemented.

6.2 Demonstrators

Figure 1 illustrates our demonstrators. We choose diverse applications going from tangible devices, paper-based interaction and wearable technologies. In each case we indicate how the displays fabricated take advantage of some of E ink's unique properties as a display material. These scenarios emphasise the uniqueness of E ink as a display fabrication material compared to traditionally used materials. In addition, while the demonstrator uses cases are generalisable to use by a wider audience, they are prototypes and have niche use cases, that would be suitable for addressing via personal fabrication rather than the mass production of E ink display elements.

(1) **Water drop displays on a plant pot**. We present fabricated droplet-shaped displays attached to a plant pot. These individual elements act as a count down mechanism to reminder the user/maker of how many days it has been since the plant was last watered and could be combined with a water sensor or a manual input by the owner. A user could prototype this using FabricatINK and customise the segment shape to fit any purpose. We envisage fabricating additional

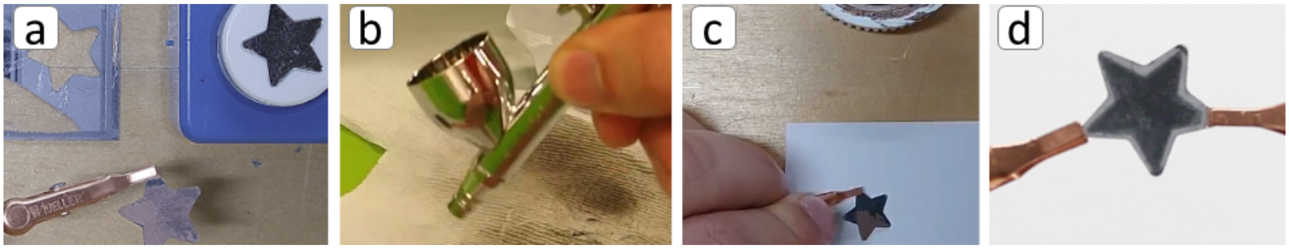

Figure 7: Fabrication process: (a) Shaping of E ink slide - here we used a star shaped stamp but alternatively a craft knife, laser cutter or scissors can be used; (b) spraying on dielectric layer (black primer) using airbrush for even coverage - a paintbrush can be used to reduce cost/skill barrier; (c) layering of conductive electrode using paint brush for optimal control; (d) attachment of circuitry.

segments depending on the species of plant. This use-case benefits from the true bistability of E ink, only needing to be powered when information is updated once a day.

(2) **Loading chevrons on a water bottle**. This is a 4-segment loading bar with a non-rectangular shape which augments a water bottle. It can be used as a count-down to encourage users to drink water, or a fullness indicator for an opaque bottle and demonstrates a multisegment fabricated display. The base electrode chevron pattern can alternatively act as an input slider to support a user inputting information such as when the bottle is filled up. It benefits from E ink's bistability to maintain information over time but also E ink's robustness to partial water damage and its ability to directly and simply support touch interaction.

(3) **Drawable post-it notes**. This is a digital post-it note allowing ink-free writing. It allows drawing by updating E ink through current conducted through the user's skin. As a user touches the pad the current on their skin completes the circuit with the base electrode of the post-it note, causing colour change where the user draws. This is possible due to E ink's true bistability holding tone changes once the finger has been removed. This is intended to be used for creating digital post-it notes for inkless writing. It can be used when carrying a pen is not practical such as a tailor holding pins and needing to mark off measurements or an engineer updating part numbers while using tools. Unenclosed E ink devices open the way for applications with external activation of display elements (e.g. SweepScreen) [57]. The unenclosed E ink has the texture of chalky paint. It is susceptible to abrasion from heavy use, but we found it to be resilient to repeated touch.

(4) **A pen sheath for writing implement**. This is a cylindrical sheath placed on a tool such as a pen. It shows touch location when a low current is applied through the user's hand as with the above demonstration. It is intended to provide visual feedback for placement of fingers for a learner without the need for any physical deposition of ink on the surface which might interfere with the learning process or damage the substrate. This application also demonstrates the bendability of the layered material. These unenclosed applications for ink-free writing are only possible through E ink as a material with its true bistability and robustness, and are not realised through any work (e.g. using electrochromic material).

(5) **Glasses with notification inside**. This shows an unobtrusive direction notification inside of a glasses frame to indicate map directions. It benefits from E ink's high contrast being able to be used in different light settings as well as its colour change being unobtrusive so as not to distract a wearer. We created a custom made single segment display that still provides sufficient information on-the-go by being arrow-shaped, and being small enough to fit on a pair of glasses. High refresh rates allow for flashing in time with car indicators and to modulate the intrusiveness of the notification. Lastly the simplicity of fabrication using E ink allows for creation of very small display types for niche applications. As a prototype, it is straightforwards for a user to replace the arrow with other segmented display symbols by fabricating such display elements.

(6) **Heart-shaped personalizable necklace**. This demonstration shows a fabricated E ink display in use as a wearable device. The necklace shows a heart beat, as a visual indication of a wearer's physiological state. We envisage this as both an aesthetic implementation of E ink but also as a way to convey information such as high-anxiety levels or the relaxation of a wearer. This particular prototype demonstrates E ink's unique properties for display fabrication through a high refresh rate while also being unobtrusive.

(7) **Gold star paper cut out**. This is a star-shaped cutout temporarily attached to a piece of paper, e.g. to serve as a reward marker on a star chart. Unlike a traditional sticker, it changes colour digitally and can be activated remotely by different users and repeated tasks such as chores where digital/remote updating could be integrated into a wider system. Here it is activated by resting in contact with painted on conductive lines on a piece of paper. Due to E ink's true bistability it doesn't need to be attached to the paper or these conductive lines after being updated while still showing the user's milestone. We see this application's ability to function without permanent electrode attachment as a step towards realising the goal of true electronic paper.

(8) **Wearable wellness badge**. This is a badge that conveys the user's mood through a smiley face. It could, for example, be used to convey a willingness to engage in social activity. It demonstrates E ink's support of touch without the need for complex time-multiplexing as well as the craft-like hand painting of an electrode allowing a wearer to directly design

their own segmented device and express through fabrication. The use of E ink as a badge benefits from light weight and visibility in bright light environments.

(9) **Coffee break notification sign on an hourglass**. The unobtrusive single segment display draws attention away from a computer screen while still providing a way of communicating digital information - here regular break times (as discussed in [10]). This demo shows that E ink can support a complex electrode pattern, in addition to the benefits of bistability and low power. It shows E ink's uniform performance when it comes to electrode thickness.

(10) **Stapler with email notification sticker**. This is a single segment display showing an email notification, with an emphasis on unobtrusiveness. It demonstrates a uses case of augmenting inanimate objects but without relying on constant updating due to bistability. In particular this demonstration can display a binary operation of on/off to indicate a singular email coming in or it can benefit from E ink's nuanced greyscale control to show a continuous scale of an inbox filling.

7 DISCUSSION

7.1 Democratisation of E ink via hacking

Limitations on independent research through patents, industrial copyright and material have the potential to be a significant roadblock to research. Specifically, disjoin between commercial and independent research settings has the potential to stop expansion and exploration into current state of the art technology developed in either setting.

At the start of this project, we carried out an extensive search for E ink as a material, ideally suspended in a fluid, including reaching out to manufacturers unsuccessfully. This has been a roadblock to the expansion of the potential of E ink beyond commercial interests. It explains the limited work that has occurred on applying E ink in fabrication. Through our analysis of patents we have also shown that alternative uses of E ink (such as inkjet printing) are known and published by manufacturers, but lack implementation as new forms of interactive systems. This indicates that the development of uses for E ink is restricted by commercial interest.

Our solution to this obstruction to research and prototyping using E ink, is to circumvent limitations by extraction or "hacking" as outlined in *Lindtner et al.'s* work [51]. We promote the use of FabricatINK as a case study, in the hacking of a material to bypass commercial constraints and an example of Tenenbaum's concept of democratised technological practises [69]. Particularly FabricatINK doesn't just use its extraction process to look at access to a material for makers, but also to develop novel uses of a material that is otherwise only available to manufacturers. The complexity of the extraction process limits democratisation to those who have some expertise in personal fabrication (e.g. reseachers or those who work in maker-spaces), in line with other work on the personal fabrication of displays [28, 59]. This work is a stepping stone for a wider audience to be able to use E ink as a layerable material beyond the extraction process.

7.2 Limitations of extraction process

Despite the beneficial aspects of being able to examine E ink using the extraction method, the process leads demonstrations and investigations to rely on potentially inconsistent qualities of material between samples. Variable damage to microcapsules has a direct impact on the replicability and reliability of the investigations. The investigations we presented (1-2) go some way towards quantifying the extraction process's reliability. The further evaluations (3-6) use the proceeds of the extraction process and establish the potential of the fabrication process. This two stage process for obtaining and then evaluating E ink's properties provides extracted material with variable quality. Similarly due to limits with the yield of extract material, we were able to carry out only small sample sizes (e.g. investigation 2).

However, there was no indication that individual working E ink microcapsules on slides that also contained damaged microcapsules (following the extraction process) behaved differently to microcapsules situated within fully intact E ink slides. We were unable to conduct a direct comparison due to a lack of access to un-encased full slides of E ink material, which was the original prompt for extraction. In investigations 1 and 2, individual sections of microcapsules were observed to behave in a manner similar to those in an intact E reader. The observed behaviour of microcapsules regarding a critical tolerance, with regards to damage and functionality, suggest that that on this scale each functional capsule behaves in a comparable way within an intact E reader or following our extraction process. The investigations would be difficult to replicate precisely with the exact same density of functioning microcapsules due to variabilities in the extraction process. However, microcapsule behaviour indicates that variability between proportions of functioning microcapsules are likely to scale appropriately and further investigations would give similar results. Therefore we suggest that the results of these investigations should be used as directives to shape further explorations. These drawbacks limit the variety of shapes and applications for our demonstrations furthering the need for E ink sources.

7.3 Improvements to the extraction process

We used approximately 30 damaged (Kindle 4) E readers. Our recycling approach provides two further favourable benefits to our fabrication process: (1) acquisition and use of damaged materials: The damaged E readers we acquired cost us an average of 4.26% of the original cost, and are easily sourced. This supports our goal of improving universal access to E ink as material but was also necessary for the quantity of E ink required for our investigations and demonstrations above; (2) no wasted materials or energy used in manufacture of new particles [44]. There is scope to improve the process to obtain purer particles and expand potential applications. We particularly identify three areas of improvement:

First, further testing and information about microcapsule composition: For example, we observe in Figure 4, that E ink microcapsules in a black state are similar between enclosed and extracted while there is a larger difference in a white state. It is unclear why this is without further information about particle ratios and behaviour. Specifically, there is significant scope for optimisation within future explorations of the times that materials were left to soak and the area into which the screens were cut if a far greater number of samples were processed. Similarly our experiments in materials (e.g. acetone), while broad were not comprehensive and further solvents could produce a higher yield of material. Second, greater information about layer structure: knowing the composition of the models of E readers can help improve our process. We did not know if rarer structures were used such as inverted FPL [33] or a double release sheet [17], or the composition of adhesives in different E readers. Lastly, we could improve our process for scaling up. Notably the E ink that we extract is limited to a PET/ITO substrate from the E reader and is limited in size. Third, alternative E ink sources could be used: as in [26] we could start with more refined display components, cutting out the need to remove the E ink from the E reader casing and potentially having a simpler layer structure. This would speed up our extraction process, requiring fewer steps but would be more expensive. We chose to use E readers because of their low cost and universal availability (in line with (1) above), with the layered structure being similar to separate E ink components. We chose Kindle 4s but in preliminary tests Sony PRS-600 and Kindle Keyboard had only marginally worse yield and other E readers as well as other solvents could be tested.

With regards to tool choice, there is a payoff between specialised equipment and available equipment that mirrors the reliability needed to improve the extraction process's yield and democratisation in using equipment that is readily available. For example, the waterjet cutter provides high accuracy, replicable, clean cuts but is not available to most makers, whereas scoring display elements is readily available but has a higher risk of damaging E ink through shattered glass and through this reducing the yield of the extraction process.

7.4 Usability of fabrication processes

Both the extraction process and fabrication process presented were developed with comparable methods to other personal display fabrication work. Tools and methods used have similar application in other related work such as material handling/mixing [24, 78] lasercutting [25], airbrushing[28, 41, 77] and hand painting [42]. As such we position the methods presented as usable by a wider audience, although not by every potential user as there is still a skill and cost threshold. We also note that this is a similar situation as has occurred in the development of 3D printing.

7.5 Insights learned for display fabrication with E ink

As discussed in the review of E ink properties, this material has many attributes well suited to fabrication (e.g. printability [74]). This opens the potential for augmenting objects with E ink, creating fully irregular 3D displays and for programmable deposition of E ink. Our extracted E ink, despite not being of manufacturing quality, showed promising performance. The direct deposition of microcapsules did not produce material that had significant contrast, although a small area of the E ink did work. This is likely due to impurities, such as residual adhesive. On the other hand, the slides from the extraction process retained a significant optical contrast and resilience to degrees of pressure, bending and cutting. The slides are robust to cutting, which is promising for personal fabrication. We also are able to identify trends for which materials and layer thicknesses maximise colour contrast through our investigations. The introduction of using electrical charge through skin to address E ink material raises questions that should be further explored in future work. Notably what are the thresholds for charge and scale with which this method can be carried out, how does finger pressure effect greyscale relative to charge and how does skin-moisture affect this innovation.

7.6 Future work and research agenda

FabricatINK's exploration into E ink through investigations and demonstrated applications is a stepping stone towards exploring E ink as a material for truly free-form displays. This goal requires significant further research, for which raw material must be sourced or manufactured. Currently we have only layed the foundations for democratisation of E ink. While the upcycling process used here allows the initial investigation and prototype development with a unique material, the limitations related to it could be discarded with a source for the material itself. We have highlighted a series of further routes that are critical to investigate for future work:

- Quantification of properties: direct comparative performance evaluations of E ink in the context of display fabrication and other comparable materials (e.g. electrochromic) should be carried out to assess more accurately where each material's strengths lie (e.g. thresholds for abrasion). Quantificcation and material availability to fabricators should be priortised to transition this work into a full democratisation of E ink.
- Physical deposition tools: Our current fabrication methods are skill-dependent and in some areas rudimentary. We suggest work on interlacing and developing interactive tools for deposition of E ink, such as an augmented air brush [19, 54, 66] or work on computational hydro-printing [24, 83]. There is also scope to extend the fabrication process to build on wider range of electrode fabrication methods that could expanded form factors or use more accessible methods (e.g. screen/inkjet printing, conductive 3D printed filament [28, 59]).
- Material extension: The extraction process has scope to be tested on other models of E reader as these could improve the E ink yield. The fabrication process could be expanded by trying multi-colour E ink.
- Software and electronics creative tools: This could be targeted at control systems (e.g. suitable microcontrollers specifically for display fabrication using E ink in HCI, extending the work of [26]) which could help improve contrast, and ways to support the process of designing custom-shaped electrodes for bistable materials. Similarly the skin based addressing of E ink in its current form could inconvenience users and further hardware to integrate this into workflows would form meaningful further work.
- Safety aspects: for the unenclosed uses of E ink presented, there is limited existing work on behaviour of E ink. Suggested methods of spraying and atomisation as well as on-skin use are potentially harmful, although unknown with E ink as a material. Further work is required into particle size, behaviour, toxicity and investigations into material composition and we hope to encourage it to be explored.

- Ethics: Care must be taken to establish processes involving ownership and responsibilities for the digital output of displays that can be layered on any surface.
- Sustainability: There are questions of sustainability with regard to unenclosed E ink being deployed in new situations and a movement towards disposable display elements. Also the impact of the extraction process (e.g. the use of solvents) and the impact E ink's production are key factors to future work on environmental imposition.

7.7 Vision

Figure 8: Our vision for the potential of E ink as a depositable material at the forefront of personal display fabrication. Through reviews of technical literature and preliminary investigations we have established the foundation for this vision for uses such as fingernail E ink display pieces, on-skin E ink tattoos, E ink Origami and E ink as a sprayable material.

E ink's potential in personal display fabrication goes beyond irregularly shaped 2D displays. We present our vision of E ink (Figure 8) as a material that can be sprayed, inkjet printed, painted and deposited in methods that have previously been used in personal display fabrication. We build this vision of depositable E ink within fabrication, on the information presented in the related patents and nanoscience literature as well as the demonstrations and investigations that we have carried out. We promote sample uses cases of E ink origami, E ink spraying, E ink on-skin tattoos and E ink nail based displays making use of the properties reported in our patent analysis, supported by our feasibility investigation of deposition E ink in Investigation 2. We further use the Investigation 5 and 6's results to support layering other materials to achieve depositable display structures using E ink if the material can be more effectively sourced. Through this vision, we see E ink as having the potential to unlock truly free-form personal display fabrication with powerful display properties.

8 CONCLUSION

This paper explores the democratisation of E ink as a material for the personal fabrication of displays. Through patent analysis and our own investigations we show that E ink has the potential to be manipulated (layered, shaped, screenprinted and sprayed) into irregular shapes in the same ways as current state-of-the-art display fabrication materials. This creates the new possibility for irregularly-shaped displays, beyond prefabricated display elements using this material. We emphasise that E ink should be at the forefront of display fabrication materials due to its inherent properties - bistability, high contrast and its addressing nature. Up until now, this has not been the case due to a lack of universal access to the material. We provide a stepping-stone solution through our extraction process that harvests E ink from upcycled E readers, to open the way for makers and researchers to work with the material. We validate the extraction process through tests and demonstrations. Using extracted E ink, we investigate E ink's properties related to personal fabrication and present a fabrication method for bespoke E ink displays. We produce a series of 10 demonstrations showing sample applications that highlight and re-emphasise both the applicability of E ink for personal fabrication but also the scope of its inherent strengths and properties. We hope this work can be an inspiration for researchers, practitioners and end-users.

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