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Illumination Aesthetics: Light as a Creative Material within Computational Design

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Figure 1. a) an illuminated hairpin (1 led); a tactile flexible diffuser cast with small glass beads creates diffusion and shadow, b) a sun-moon light art piece (25 leds); a computationally generated reflector controls light rays to form soft and hard edges to blend colored lights, c) a dynamic tactile map of an urban center (16 leds); volumetric diffusers indicate building locations; buildings light up in succession to indicate pathways.

ABSTRACT

Recent digital fabrication tools have enabled new form-giving using a wide range of *physical* materials. However, *light as a first class creative material* has been largely ignored within the design of our electronic objects. Our work expands the illumination design space by treating light as a physical material. We introduce a digital design tool that simulates and visualizes physical light interactions with a variety of materials for creating custom luminaires. We further develop a computational design and fabrication process for creating custom secondary optics elements (SOEs), which provides additional handles for users to physically shape and redirect light to compose, fill, and evenly diffuse planar and volumetric geometries. Through a workshop study with novice electronic designers, we show how incorporating physical techniques to shape light alters how users view the role and function of LEDs and electronics. We produce example pieces that showcase how our approach expands the electronics aesthetic and discuss how viewing light as material can engender novel, expressive artifacts.

Author Keywords

New Media; displays; lighting; luminaire; digital fabrication

ACM Classification Keywords

H.5.m. Information interfaces and presentation: User Interfaces - Interaction Styles; D.2.2 Design Tools and Techniques: User interfaces

INTRODUCTION

Light is a rich, expressive medium that has enabled a tremendous amount of creativity and innovation in engineering, art, and design. This design space is quickly evolving with the introduction of smart Light Emitting Diodes (LEDs) (e.g. NeoPixels, dotStars) and electroluminescent materials (e.g. EL wire, OLED). These components are becoming easier to program, attach, and control, supporting a new ecology of devices appearing in increasingly diverse contexts and uses. However, most of these fundamental lighting elements were never intended to be used within such designs. In fact most manufactured electronic lighting components are produced for architectural lighting (39%), display backlighting (18%), and commercial signage (12%) [1]. Even worse, the most prevalent LED form-factors constrain the LED to the characteristic electronic point-light aesthetic. For many electronic projects, this limits the function of LEDs to simple status indicators. Even as the cost of the LED shrinks, the role, function, and control of LEDs in electronic devices has remained limited to blinking, flashing, and color changing via digital manipulation. The physical properties of the LED and light get omitted from the design conversation which unfortunately almost completely ignores the rich, expressive value that light can play when treated as a material.

How might we expand the different expressions of light and the LED to enable new *Illumination Aesthetics* — the expansion of light manipulation techniques to produce novel visual effects,

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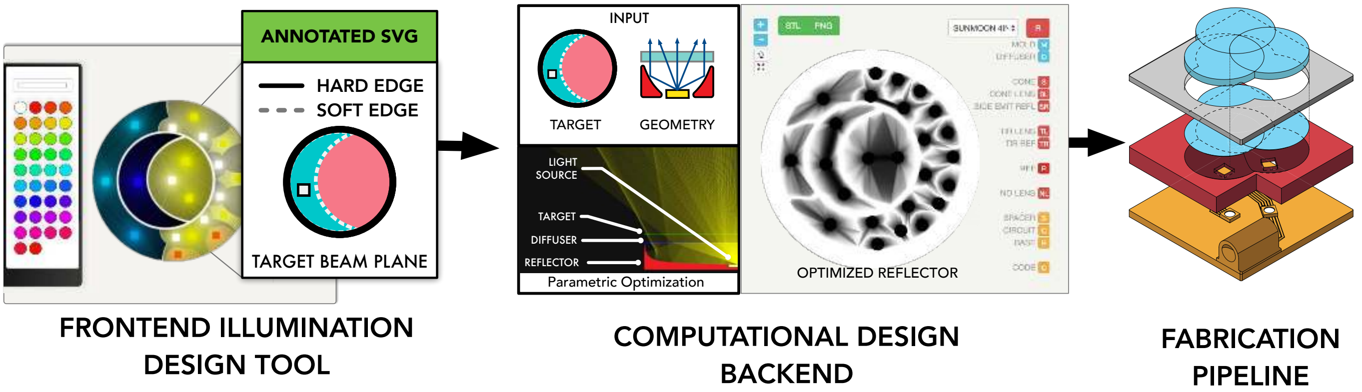

Figure 2. Luminaire Creation Pipeline. a) Given an SVG graphic, our luminaire design tool aids users with laying out LEDs, visualizing light interactions, and specifying target areas to fill with light. In the callout, an LED is specified to fill a moon-shape. b) A computational design backend generates an optimal secondary optics system to achieve the desired design using ray tracing to guide a simulated annealing search. All files for 3D printing geometries and milling circuits are produced by the backend, c) an instruction set guides the user to assemble the luminaire.

sensations, and interactions? Lighting designer Brad Hindson suggests four concepts for envisioning light as a material: light as sharp and diffuse, light as refractive and reflective, light as shadow creator, and light as dynamic element [11]. However within this expressive design landscape we lack accessible tools to readily manipulate and creatively form light.

In order to foreground light as an equal actor with other physical materials, this work develops techniques for creatively and computationally designing and fabricating secondary optics elements (SOEs). SOEs such as reflectors, diffusers, and lenses are commonly used to manipulate light emitted from a source such as an LED. Such secondary optics are commonly used in the lighting industry for applications like collimating LED rays to extend the distance a bicycle headlamp can travel, or for combining beams from multiple light sources to appear as one. However techniques for making, purchasing, or configuring appropriate materials to control light remains a tacit practice. This work aims to provide an accessible, generalizable fabrication technique for creating secondary optics to empower users to control and manipulate light and expand the electronic aesthetic.

To explore Illumination Aesthetics, we constructed a pipeline for creating luminaires — a device that produces, controls, and distributes light. The Illuminating Engineering Society (IES) [13] defines luminaires as consisting of: one or more lamps or LEDs, optical devices designed to distribute light, sockets for supplying electric power, and the mechanical components required to support or attach the housing.

Specifically, in this paper we present two contributions:

- A novel and accessible luminaire design tool for use by non-expert electronic designers to visually design, simulate, and fabricate non-trivial illumination within physical objects.
- A computational design pipeline comprising the entire physical, electronic, and optical design of materials necessary to fabricate and realize the final desired luminaire.

We evaluated the design tool in a formal user study where participants designed their own luminaire. Each of the participant's luminaires were fabricated and used to gauge perceptions of the function and aesthetic of LEDs with the expanded abilities of our technique. Furthermore, through a set of example luminaires (Figure 1), we show how this fabrication technique enables a novel set of interactive interfaces which place light as a prime citizen in design.

RELATED WORK

Diverse communities have explored the potential of light and optics for creating interactive, aesthetically pleasing, and sensing artifacts. Below, we describe work that explores light as a physical material and medium.

Light as Medium

There exists a large body of work within the arts and design community that utilized light as an artistic medium, exploring material-specific optic properties to create engaging, critical work. Utilizing projected light, James Turrell influences a viewer's depth perception by simulating 3D forms on 2D spaces (*Shallow Space Constructions*) [27]. In *Exploded Views*, Jim Campbell creates three-dimensional animated shadows by controlling the intensity of several light sources suspended in a dense irregular grid [3]. Utilizing the subtle reflective properties of wood, Daniel Rozin's *Wooden Mirror* actuated a grid of small wooden "pixels" to different orientations to create changes in value and form images [25]. Eliasson's *The Weather Project* made use of light's refractive qualities, adding a fine mist to materialize moving weather formations indoors [6]. Notably, these works demonstrate a material and space-driven exploration of light.

Dynamic light has been explored in early work such as László Moholy-Nagy's *Light-Space Modulator* which spun reflective geometries to create visceral moving light installations [19]. Through long-exposure photography, the persistence of light was captured as a drawing and painting medium in influential works like Gjon Mili's *Picasso draws a centaur* [9]. Light has also been explored conceptually; most well known in this space, Dan Flavin created light objects that function as systems of investigation [7]. Pierce et al. further described other phenomenological dimensions of light in electronic objects as tied to the object, its material, and its source [23]. Our work particularly explores the design dimensions of illumination afforded through the optical manipulation of light.

Light as Interaction and Information

As an interactive medium, the active, changing nature of light affords playful, information rich interactions. Harrison et al. surveyed the design space of point lights in modern devices, notably linking common actuation behaviors ("On w/ Bright Flash") to functional evaluations ("Notification") [10]. Light has been shown to afford emotional reactions and interpretations in objects such as luminaires [12]. Design work in this space has also explored light as an active patina, assigning visual light patterns to recorded user interaction history and activity with a tabletop surface [8]. While previous work specifically looked at light that is dynamic and computationally controlled, this work foregrounds the physical design space of light and addresses the aesthetic development of illumination beyond the point-light.

Interactive Potential of Secondary optics

Although digital fabrication technology for optics is in its nascent stage, its potential for creating unique interactive experiences and objects has been explored. WonderLens, a system of magnet-embedded optical lenses coupled with magnetic sensing, demonstrated a wide range of tangible interactions with printed images [15]. In a computational design process, Papas et al. fabricated lenses with refractive geometries to hide, reveal, and obfuscate images placed directly underneath [21]. This process utilized simulated annealing to optimize facet geometries to refract light in a pre-described manner. Similarly, our work optimizes geometries to refract and reflect light to adhere to user-supplied illumination designs. Work in optics has demonstrated the large potential of materials and geometries to efficiently transport light (e.g. optic fiber), micro-array lenses to homogeneously diffuse light [26], or double-cylindrical lenses to shape light into rectangular beams [4]. Interactive objects have also been enabled by sensing changes in light through embedded optomechanics [2, 22, 28]. We see our technique working in tandem with optomechanical sensing, although we focus on expanding illumination aesthetics to enable even richer interactions.

Printed Secondary Optics

Early work in manipulating light leveraged fiber optics to transfer an image from projecters onto specific geometries using adjustable wide-angle lenses with short focal lengths [16]. Willis et al. [28] further demonstrated the feasibility of 3D printing light pipes and lenses within geometries to channel light and create novel illumination and sensing capabilities. By bundling light pipes and routing them through a structure, this technique has been shown to create screens on both spherical geometries [2] and arbitrary geometries [22]. The resolution of this display technique is largely dependent on the density of light pipes. Ultimately, each individual light pipe terminates and forms a pixel. While this allows generalizable image creation through programmatic control of the light pipe matrix, this type of screen is bound to the digital aesthetic where the expression of light is limited to pixel-based interactions and misses the opportunity to consider light as a material.

For reflective properties, Matusik et al. [18] demonstrated the feasibility of matching Bidirectional Reflectance Distribution Functions (BRDFs) with linear combinations of reflective inks. In order to expand our control of light and its visual properties, our approach builds on these printable optics techniques by exploring methods of controlling light using diverse materials in a user-centered design system. We leverage the interactive potential of secondary optics to enable users to explore a broader set of techniques to work with light.

AESTHETIC ILLUMINATION DESIGN OBJECTIVES

For novice electronic designers, the LED is often seen as an atomic design element with a rich digital design space – a key factor influencing the adoption of the LED as a staple component of electronic maker culture, art, and education.

We chose to build a design tool for making luminaires since the design space is concentrated around using light in its purest state. This is in contrast to interactive devices that prioritize a different set of interaction goals centered around user experience. The LED is also a principle entry point into electronics design for many users; by making this experience more expressive, we see a pathway for users to gain a deeper familiarity with materials and broaden participation in STEM.

From our personal experience teaching electronic device design and our survey of online project tutorials, the most common techniques for manipulating physical light from LEDs are using the device housing as a diffuser, shielding the light with a material, or even placing the LEDs on the non-user facing side of a device so as to create an ambient glow. We focus this work on expanding physical manipulation of light with the objective of aiding a user population consisting of novice interactive device designers.

Such an objective prioritizes a material-centric workflow which we define as a process which utilizes both abstract and physical interactions with materials. Under this lens, light should be represented as a responsive element, adhering to the physics of light and convey light's interactions with different materials. Materials and techniques for manufacturing need to be inexpensive and easy-to-use. Furthermore the tool should support an iterative design process, fit into existing practice with tools used by designers, and provide enough creative freedom for users to specify minute design parameters (e.g. bolt placement, led placement, enclosure shape), but offset tedious design tasks (e.g. aligning holes, routing traces, sizing mechanical and electrical components) to the tool.

We will describe how we designed such a design tool to allow users to creatively and expressively create luminaires that treat light as a material, and then describe the implementation of a computational design backend which produces digital design files and instructions for users to digitally fabricate secondary optic elements (SOEs) and assemble luminaires.

FRONTEND LUMINAIRE DESIGN TOOL

Our luminaire design tool was designed for users familiar with vector graphics and built as a web application (Figure 2). The web application allows a user to specify high-level luminaire design specifications such as LED placement, LED color, and target areas for the LED to fill. The tool uses the paper.js

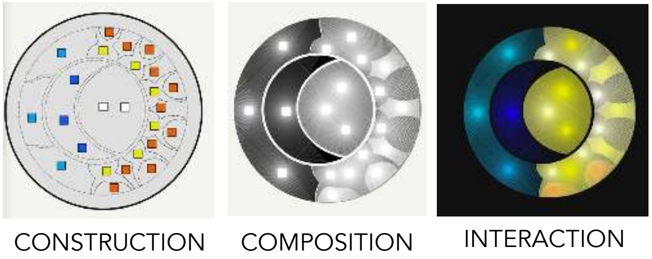

Figure 3. Illumination views. Each view can be toggled by a user when composing their design to showcase different illumination concerns. Each light source interacts with neighboring geometries and shows light interactions such as mixture and shadow creation.

vector graphics scripting framework [14] which enables common vector editing operations and backwards compatibility[1] with vector graphics applications. A computational backend, described in the next section, produces the digital fabrication files needed to fabricate the end design. An instruction set is provided to aid with post-processing and assembly.

From an initial vector graphic, the tool allows the user to specify whether paths block light (hard edge) or allow light to pass through (soft edge). Users can then place, remove, and relocate LED elements in a scene. Otherwise, all interactions with the design take place in an external vector graphic editor (e.g. Adobe Illustrator) in order to leverage user's knowledge of and expertise with existing graphic design tools. Depicted in Figure 3, we exposed different views to the user to prioritize different illumination aesthetic concerns. In a *construction view*, users are provided a clear view of housing elements (e.g. placement of nuts and bolts). This view allows a user to specify the shape to fill for each LED. In a *composition view*, white rays are radially emitted from each LED and interact with geometries, displaying the distribution of light in a scene as well as casting shadows when light blocking elements intersect with rays. An *interaction view* allows users to assign a unique color to track specific LED contributions in the overall illumination. Lastly, a *"lights-out"* toggle controls the background luminance to simulate a lit or unlit scene.

COMPUTATIONAL DESIGN BACKEND

To support a wide variety of luminaire designs, we built a computational backend to design custom secondary optical elements (SOEs) that diffuse, redirect, or focus light and the fixtures to appropriately configure and house them. For instance, an SOE can be designed to redirect light rays to run parallel to each other maximizing the lumens over a given area (i.e. collimating lens). Appropriately configured, this lens is the driving technology that allows bike lights to be visibile from a distance and evenly illuminate the path in front them. While such systems are readily available in consumer products, almost all manufactured SOEs shape light beams into circular areas; we expand this to include shape-optimized SOEs that can redistribute light to diffusely fill arbitrary shapes.

To leverage these new illumination capabilities, our approach intergrates these computationally designed components with fluid interactions within our design tool to allow creative control of illumination; control is separated into three different layers which house, redirect, and diffuse one or more LEDs:

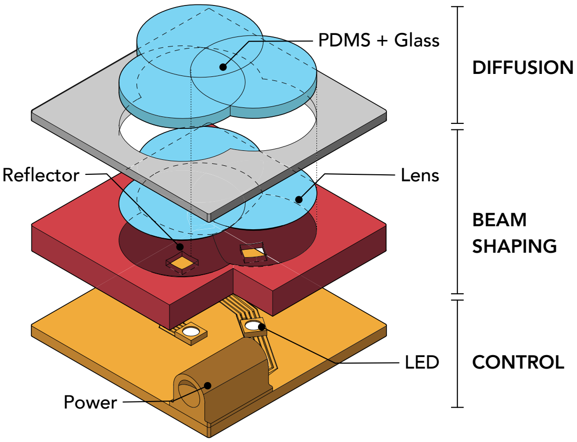

Figure 4. The luminaire consists of a light source powered through an external power supply; its rays are captured and redirected upward by a reflector, an optional lens is used to further shape the light beam; at the topmost layer, a PDMS-Glass diffuser scatters light evenly.

- **DIFFUSION** (3-5 mm): consists of materials with light scattering properties that can diffuse or produce an even distribution of light.
- **BEAM SHAPING** (10 mm): shapes light emitted from an LED using computationally-designed SOEs made with refractive or reflective materials.
- **CONTROL** (1.5 mm): composed of LEDs, a microcontroller, and a power connector on a printed circuit board (PCB).

One of the most powerful and useful parts of our approach is that it automatically generates digital design files needed to construct each layer of the luminaire. Depicted in Figure 4, these files produce a stacked assembly of components consisting of: 1) the 3D enclosure model, 2) a model to cast or print a diffuser, 3) a 3D reflector model, 4) a printed circuit board (PCB) design and microcontroller code. We can additionally specify whether the assembly functions as standalone (with a power supply and microcontroller), or as a component (with breakout pins) that can be integrated into more complex electronic designs.

Instructions are provided to assist the user with assembly, specifically: casting procedures, specifying appropriate material concentrations and estimated curing time to achieve the different effects specified in their design; printing procedures, providing assistance on the optimal parameters to set for different printing techniques (FDM/SLA); and post-processing procedures including sanding and finishing. In the following section, we describe how the diffuser, beam-shaping, and control layers are designed, fabricated, and evaluated to build custom luminaires.

DIFFUSER DESIGN

The purpose of a diffuser in a secondary optics system is to scatter light uniformly to control the luminous intensity of LEDs. A desirable quality of a diffuser is to optimize the amount of light transmitted through the diffuser (referred to as transparency). Haze, or the measure of scattered light

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[1] Backwards compatability with custom paper.js applications and SVG editors was enabled by encoding application-specifc data in the SVG `data` attribute as a `JSON` string.

due to imperfections on the surface of the diffuser, is also commonly used to describe diffusers. Frosting surfaces, a standard technique for diffusing light, produces non-smooth micro-geometries that scatter light. While this is a effective technique for hard materials like acrylic, it also restricts interactions to a limited range of haptics. Our approach described below uses silicone doped with refractive materials to create flexible, tactile diffusers. In our evaluation section, we show how our diffusers outperform standard diffusing techniques.

Flexible diffusers

We introduce a technique for fabricating flexible diffusers for 2D geometries. These diffusers are cast from 3D printed molds using translucent platinum-cured PDMS (silicone) doped with high-refraction glass beads[2](Cole, 150 Micron). This silicone mixture is maker-friendly: it cures quickly in about 2 hours, is particularly forgiving in the demolding processs even with complex molds, and its low viscosity is useful for injection molding. Furthermore, glass beads are readily available in different sizes (from 0.1 mm to 3.0 mm) and can be used to produce different light textures. Figure 1 luminaires were fabricated with 840 micron beads, while Figure 9 were fabricated with 150 micron beads.

To find the optimal mixture ratios, we doped disks (⌀ 30mm x 3mm) with concentrations from 0% to 50%[3] glass by mass mixtures in 5% increments. We extracted luminosity plots from photographs, and found that 40% glass by mass produced the highest diffusion and transmission rates. We leveraged this property to fabricate several tactile and volumetric diffusers (Figure 1a,c), which produce visually-pleasing light effects.

While a good diffuser is a key component to a successful luminaire, its effectiveness relies on the shape of the light beam itself. For this reason, diffusers such as frosted acrylic require a large distance between the diffuser and light source to light up larger areas (see Figure 5, SPACER).

BEAM SHAPER DESIGN

To better control the shape of the light beam, or the distribution of light emitting from one or more light sources, we utilized computationally designed reflectors and lenses. Our approach uses a custom ray tracer to simulate how a beam is manipulated by these geometries. The process first extracts an entropy metric that describes how well a geometry shapes a beam to a desired output to guide a stochastic search through the parametric space of the geometry until an optimal geometry is found. The resulting geometry is then fabricated for use in a luminaire.

Parametric Models

Reflectors and lens designs were derived from commonly used SOE geometries and materials used in industry. We constructed models of each geometry as a vector graphic, parametrizing bezier curves to adhere to geometric design constraints depicted in Figure 5 and described below:

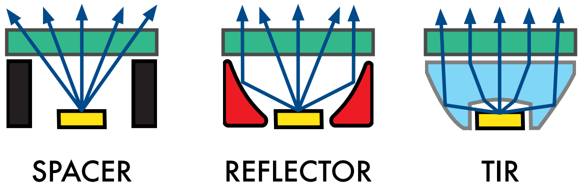

Figure 5. Secondary optics parametric models. A scene is constructed with a light source (yellow), reflective materials (red), non-reflective materials (black), refractive material (light blue), and diffusive material (green). LED light rays are modeled and traced with respect to different geometries. Three metrics, efficiency, coverage, and directionality, are used to characterize these geometries.

- SPACER. Adding a air gap between the light source and diffuse material is the most basic geometry for achieving diffusion. It is highly subject to the light source beam angle: although it works well for small diffusion targets, it requires a greater distance for large target diffusion areas limiting the range of possible applications.
- REFLECTOR. Parabolic reflectors utilize reflective geometries to bounce light towards a specific direction. They are generally inefficient, but are the most ubiquitous in lighting applications.
- TIR. If light traveling from a denser material (glass) escapes into a less dense material (air), and hits this interface at an angle greater than a critical angle, the light is reflected. This phenomena, known as Total Internal Reflection (TIR), is commonly used to efficiently transfer light (e.g. fiber optics). Lenses which utilize this phenomena typically have a cavity above the light source for rays of light to enter the lens medium at critical angles and achieve TIR (Figure 5c).

These paramterized models guide our procedure for generating SOEs for custom illumination designs.

Generating Shape-Optimized Secondary Optics

We decompose the procedure for generating shape-optimized SOEs into four stages: 1) profile extraction, 2) scene construction and ray tracing, 3) simulated annealing, and 4) geometry construction. A visual guide is depicted in Figure 2.

Input and Profile Extraction

After a user finishes their luminaire design, the tool exports an annotated SVG file. It contains the LED position information and the user-specified shape to fill, henceforth referred to as the beam plane. For each beam plane, we extract a set of cross-sections, or profiles. A circular beam plane for instance would have a single profile. Given a specific parametric model, we then compute the best geometry for each profile. In our user study, we chose to use a reflector model (Figure 5) for its relative ease to fabricate, although more complex secondary system setups and materials can be used.

Scene Construction and Ray Tracing

For each profile, we perform ray tracing by casting rays from the LED out into the materials and geometries described by the beam-shaping parametric model. This model may include diffusers, reflectors, and/or lenses. Each ray is encoded with an intensity value that diminishes based on transmission rates of materials, and adheres to light physics (Snell & Fresnel

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[2] Glass beads are commonly used in reflective street paint and signs.

[3] Mixtures with glass concentrations above 50% by mass suffered from curing issues.

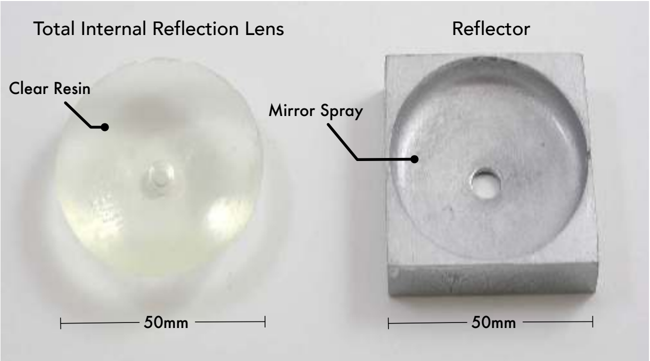

Figure 6. Fabricated reflectors. A total internal reflection (TIR) reflector printing in clear resin (left). Light enters through an air cavity above the LED and is reflected internally, spreading light throughout the lens. A parabolic reflector printing in clear resin, with a coat of mirror spray and acrylic coating (right).

Laws). We computed a metric to describe the quality of exiting light: *coverage*, or the amount of area covered by the light; *directionality*, or the deviation of the light's exiting direction to the surface normal; and *efficiency*, or the ratio of exiting intensity versus the initial intensity of all the rays. These metrics are used to select optimal geometries in a stochastic search.

Simulated Annealing

A powerful part of our technique is the use of a computational design backend engine to iteratively improve the luminaire designs within a complex higher-dimensional solution space. Using simulated annealing, we find acceptable solutions in our non-linear search space as follows: we initially generate a random geometry that satisfies the model's optical properties. Following the similated annealing metaphor, we extract an annealing factor α representing the relative temperature of the system. A "neighbor" geometry is produced by computing a neighborhood of size α around the each parameter in the model, and then choose a random position within that neighborhood. An annealing factor of 1 would span the full parametric space, while an annealing factor approaching 0 would pick a nearby parameter configuration. During each time step, we compute the energy of the system from the ray tracer light metrics which determine whether a geometry is stored as an optimal solution.

Geometry Construction

Unlike circular beam planes with a single profile curve, we require stitching together a hybrid geometry. We do this by treating each profile as an "elevation". We then make a 2.5D geometry by creating level sets which act as a heightmap. This ensures that all geometries are moldable and produce the least amount of artifacts from the printing process.

Fabrication

Once the digital modeling files are produced, they are printed using various 3D printing techniques (Figure 6). In our case, a Type A FDM printer at 0.1mm resolution was used for most luminaires. When higher quality reflection or refraction was required, a Form 1+ SLA printer at 0.025mm resolution was used with clear resin. Resolution is an important factor since ridging artifacts from stereolithography can cause low quality SOEs and uneven diffusion. Our pipeline alerts the user of luminaire quality issues when the LED density of the luminaire reaches a threshold above a reflector's efficiency. Since 3D printing with reflective materials is currently not achievable with commercial digital fabrication tools, we created reflective geometries by spraying 3D prints with a coat of Mirror Spray (Rust-Oleum 267727). This provided a low-cost approach to achieving the desired reflectance.

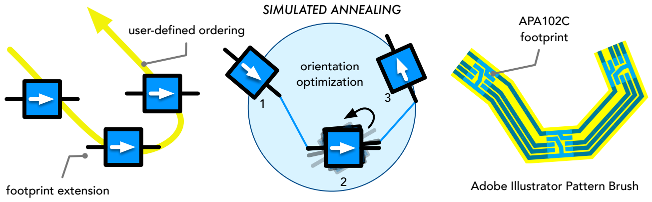

Figure 7. Trace assistance routine. a) user annotates SVG, b) positions are extracted and LED orientation is optimized, c) optimal path is extracted, d) design files produced for several processes, e) different substrates can be used to create rigid or flexible PCBs.

CONTROL LAYER DESIGN

While powering and controlling one LED is a relatively trivial task, as the number of LEDs increases, so does the circuit complexity. Such designs do not scale well since each LED requires an individual control wire or a special LED driver chip that usually enforces a matrix layout. We leverage an advancement in LED technology — dotStar (APA102C) RGB LED — that allows both simplified routing, individual RGB control of each LED, and uses the 5050 SMD package which is still large enough for hand-soldering. With the right circuit footprint, routing devolves to connecting each LED as links on a single strip.

We aid users by providing a trace-assistance mechanism which produces appropriate configurable files for PCB milling, etching, or sketching, custom to their luminaire design. This mechanism automates the PCB design process connecting LEDs using a "strip" routing algorithm. The strip can be represented as the shortest route that passes through each LED once and only once. As additional graph drawing constraints, LED orientation is unconstrained, no path overlaps can exist, and no acute turns should exist. Our trace assistance mechanism requests the user draw a path that connects all LEDs (Figure 7b). From this we obtain an ordering schema; to prevent LEDs from resting on a curve or turn, we extend the LED footprint to rest on parallel tracks (Figure 7a). To optimize LED orientation, we stochastically explore different orientations and utilize simulated annealing to find the design which minimizes overall strip length. The routine produces an editable path that allows users to add additional anchors and correct overlapping segments highlighted by our tool. Using Adobe Illustrator's Pattern Brush, we then convert this trace into the circuit footprint required by the LED specification (Figure 7c). For logical control, we add a footprint for an 8-pin socket to hold an ATTiny85 microcontroller (DIP) and a 3.1mm DC barrel jack for external power at the start of the strip. This is then milled, hand-soldered, and assembled to form the final luminaire. A certain degree of experience is needed to solder SMD LEDs; we found that once the technique is learned,

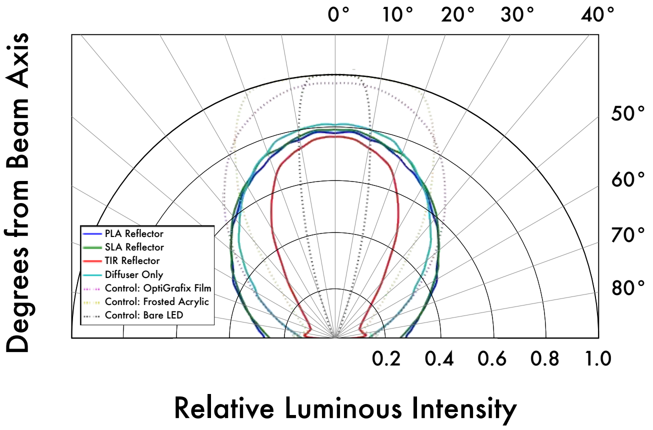

Figure 8. Polar Luminous Intensity Graph. The diagram indicates the distribution of relative luminous intensity of the luminaire. Control systems are marked with dashed lines.

one can comfortably solder 10 LEDs in 10-20 minutes. Solder paste techniques also exist which would greatly speed up and simplify the process, although the actual paste is a more hazardous material.

The hardware address of each LED is relative to the position from the microcontroller on the strip. We use this information to produce code for programming the LEDs to display user-defined colors and brightness. In particular, we translate spatial and hardware indexes, extract associated RGB values for each LED, convert the values into appropriate API command for the dotStar LED specification, and populate a code template that uses an ATTiny85 to send the appropriate signal.

EVALUATION: SECONDARY OPTICS SYSTEM

In order to quantify the effectiveness of our design tool and fabrication technique, we quantitatively evaluated our secondary optic systems against established material and diffusion techniques. We also invited 11 participants (described in the next section) to provide qualitative feedback on the overall look and feel of the diffusers and reflectors.

Setup

We constructed 7 secondary optic systems to assess luminaire quality. Each system had a circular beam plane 50 mm in diameter, positioned 10 mm above a 1 watt LED (APA102C) with a 120° viewing angle. The systems varied by the following conditions: (control) a bare uncovered LED; (control) a 3mm acrylic diffuser hand-frosted with 300 grit sandpaper; (control) two layers of 120 micron OptiGrafix Light Diffuser Film. The remaining four systems each had a 3 mm PDMS glass diffuser with: no reflector, a 0.1 mm resolution PLA reflector; a 0.005 mm resolution SLA reflector, and a 0.005 mm resolution SLA TIR reflector.

Each system was photographed in a dark room at ISO200 18mm f/11 1/100 sec; a 10 px Gaussian smoothing filter was applied to a 500 x 500 px downsampled grayscale image. A luminosity plot was constructed from the image's relative luminosity values relative to the angle from the beam axis.

Results

Figure 8 depicts the resulting luminosity plot for each system. While frosted acrylic and diffuser film do distribute luminosity (diffuse the LED), our optical systems were able to distribute more luminosity to the extreme angles (at 60°, 0.43 (PLA) compared to 0.3 (Acrylic)), and reduce glare at the beam axis (0°, 0.74 for TIR). We expect fabrication limitations to have caused lower efficiency and a bright halo in the outer regions of the TIR lens.

Participants in our study ranked the perceived diffuseness of each optical system, excluding the TIR system. Due to a small sample size, we report descriptive statistics and summarize results in Table 1:

0.005 mm SLA	**0.10 mm PLA**	**Diffuser Only**
$1.4 \pm .56$	2.1 ± 1.1	2.7 ± 0.71
OptiGrafix	**Frosted Acrylic**	**Bare LED**
3.8 ± 1.1	4.9 ± 0.3	6 ± 0

Table 1. Qualitative Ranking of Diffusement by Participants.

Notably, the system printed at the highest resolution (0.025 mm) was ranked as the most diffuse; the perceived difference between SLA and PLA printed reflectors, although quantitatively similar, was subject to stronger discrimination by participants (1.4 versus 2.1, rank). Frosted acrylic, while it only did better than an uncovered LED, had an aesthetic that many participants enjoyed. Furthermore, the tactile qualities of the PDMS-Glass diffusers were perceived as playful and interactive. Many participants desired the ability to design around these haptic features.

EVALUATION: DESIGN TOOL + LUMINAIRE

We also invited the 11 participants to design their own luminaires. The main goal of this user study was to obtain qualitative feedback on how the design tool facilitated luminaire design. We were especially interested in understanding a user's mental model of light, and what functions and aesthetic choices this understanding would afford.

Participants

We conducted the study with eleven participants who had previously used LEDs and had experience with vector graphic design. Participants were recruited from university mailing lists in Art, Architecture, and Design. The average age of participants was 22 ± 3 (7 female). Participants were selected based on self-reported expertise with vector graphic design and previous exposure working with LEDs and electronic device design. Most users reported limited experience with 3D printing or digital fabrication tools.

Procedure

Each user participated in a 1 hour workshop and 30 minute followup interview and was compensated $40. Each session resulted in a completed luminaire which was given to the user.

Workshop Each workshop consisted of an electronics background questionnaire, a showcase of luminaires, a diffuser ranking task, a design tool tutorial, and a 40 minute design task. Each participant was tasked with creating a luminaire graphic with 5-7 LEDs not to exceed a 5" x 5" area. Participants were also asked to reflect aloud on the example luminaires, the design tool, and their design process. Due to fabrication time limitations, each luminaire was fabricated by the investigators after the workshop; some degree of experience is needed to solder surface mount components, although components are relatively large ($>$5mm) and with practice easily hand-solderable. Additional steps were taken to demystify the process during the followup.

Followup After the luminaire was constructed, participants were invited back to reflect on the final design. To avoid blackboxing the process, participants were given a tour of the fabrication machines and provided an explanation of the materials and techniques involved in producing their luminaire. We asked users a series of questions regarding their experiences with the design tool, as well as the final fabricated devices.

RESULTS: DESIGN TOOL + FINAL LUMINAIRE

All participants successfully completed their designs; some designs are represented in Figure 9. We first report survey responses, then present qualitative results from participant interactions with the luminaire design tool during the workshop, and finally discuss interview responses once participants received their fabricated luminaires. We synthesize these findings into common themes and insights for future physical design tools.

Barriers of Entry to LED Design

In our survey, participants reported experience with through-hole component LEDs, while a few had interacted with addressable LED strips. The majority of users (8 of 11) had not worked with smart LEDs. Prior to being introduced to our tool, users described their projects involving LEDs in simple, binary terms. Their LEDs were used for behaviors like flashing and fading. Even for more hardware and software-proficient users, the language used to talk about light was limited to the binary “on/off”. Other difficulties included hardware-to-design translation issues, especially in more complex designs like arranging LEDs in a circle:

> **Participant 170**: I remember it being tricky to address the LEDs . . . we wanted the level of the circle to go up . . . there was endless debugging with the strips.

Users cited the cost of smart LEDs and the difficulty to program complex behaviors as the primary barriers to LED usage.

Perceptions of the LED Aesthetic

Functionally, participants reported that LEDs used in personal projects were mostly used to indicate status. Aesthetics was the principle reason limiting LEDs to this specific use case. A majority of our participants mentioned that the aesthetics of LEDs, even in strip form, were unpleasant, and physically painful: “they hurt your eyes if you look directly at [them].” Users universally criticized the “characteristic look” of LEDs and how their overpowering presence and salience in designs forced their user to focus on the mechanics of the light rather than the design or overall experience:

> **Participant 160**: You look at them and you think “those are LEDs”... I don’t like the characteristic look of LEDs. And I don’t want to look at something and go “there’s an LED inside that’s making that light up.”

Participants also described uncertainty relating to how their designs would appear in the final state, having difficulty prototyping and testing out various options:

> **Participant 169**: Sometimes LEDs just don’t look that good. It’s hard to know what they’re going to look like to the user . . . I’d love to make something that just diffused all of the lights together so that I could make a really nice transition between colors.

One participant so disliked seeing the mechanics of the LEDs that she took the opportunity to design in physical barriers to her luminaire to obfuscate the light source (Figure 9 #134), opting for an edge/rim light that emphasized the silhouette, despite the fact that our luminaires have built-in diffusers:

> **Participant 134**: [I don’t want to] have that effect of seeing that bright LED directly. I feel like [seeing the LED underneath] reveals too much about how it functions.

Many participants never considered placing anything over the LEDs to affect the production of light. Some had attempted maneuvering around the bright lights by diffusing them with opaque or semi-transperent sheets, a plastic enclosure, or prefabricated lampshades. Despite strong negative experiences, users quickly warmed to the illumination aesthetic of the showcase luminaires:

> **Participant 179**: It’s very aesthetically pleasing. And I like...the blend of colors that goes through it. It kind of reminds of seeing cities at night.

User Designs

Even in a brief workshop-style experience with limited exposure to the tool and this method of working with light, users readily generated unique light interactions. User-designed luminaires ranged from figurative to abstract (Figure 9). Several participants motivated their design decisions to elicit surprise, hiding elements in their design that would only be discoverable when power was supplied to luminaire (#**150**, #**179**, #**163**, and #**199**). Others used the design task as a sandbox, for example using a Venn diagram to explore color interactions (#**134**). Overall participant’s assessment of their experience is summarized in Table 2. In particular, participants associated their perception of creative freedom with the tool (4.3) tied to the tool incorporating software (e.g. Adobe Illustrator) and design patterns that they are already familiar with.

	Creative Freedom	**Object Quality**	**Agency**
Rating	4.3 ± 1.0	3.9 ± 1.2	4.3 ± 0.7

Table 2. Qualitative Assessment Luminaire Design Tool and Fabricated Luminaire Objects. Responses are semantically anchored on a 5-point Likert scale, positive responses = 5.

Expanded Vocabulary Mirrors New Understanding

In our tool workflow, participants had to create and annotate their design geometries in an external vector graphics editor. Once a base design was created, our tool would load their graphics and apply treatments to more clearly indicate physical and conceptual geometries. Participants did have difficulty conceptualizing these distinctions in the abstract, however direct manipulation of light sources grounded their mental model of how the design tool worked:

Figure 9. Luminaires fabricated from user designs: (top) simulated results from the luminaire design tool, (bottom) the final physical luminaire.

> **Participant 170**: I'm thinking about the way the light is going to work. I wanted to define shapes and I wanted to play with where the light was going to be placed.

One assumption we made was that participants would prioritize an arrangement of LEDs such as to produce a diffuse luminaire. However, for some, the light ray interactions became a formal element to consider. User #179 wanted to place LEDs in an arrangement that would create new shapes and forms from shadow and color interaction.

> **Participant 179**: There might be some leakage, if the [rays] intersect [geometries] at an interesting angle.

This approach exposed the positive and negative spaces that arose from the shadows created from different geometries. As users gained familiarity with the new capabilities afforded by the tool, they frequently returned to edit their base vector file, further developing their understanding of what effects their choices would have, and beginning to conceptualize light as a physical medium:

> **Participant 170**: I'm noticing the other shape that you made, these sides were different, so I could direct it to this edge, or this edge only. Instead I'm kind of diffusing it through the whole thing. I want to make one edge that encapsulates the shape but then also allows me to direct the light wherever I want.

For expert users, the largest amount of design time was spent on examining light interactions with geometries. We saw different light aesthetic concerns arise from the different simulated views. The composition view influenced more thinking around light decay/falloff.

> **Participant 169**: Also you can see a difference in the light intensity based on how concentrated the light beams are. I'm surprised that the light spreads so clearly in this [white ray view].

whereas the interaction (colored ray) view elicited more thinking about blending and LED color interactions:

> **Participant 170**: A second ago, the light was down here and it was covering more space but it wasn't really blending. So it's helpful to see that there might be some blending up here if I put the light up here...

Participants verbalized a new consideration of the physical factors of the LED. A shift in vocabulary reflected this new understanding of the aesthetic potential of light. All participants conceded they had never really thought about light interactions before, and the tool represented a new engaging type of thinking that they were eager to pursue in future designs.

Followup Reactions

In the followup, participants shared a new awareness of LEDs in their daily life. Diffusion was a particularly salient trait that began to take form in new design projects.

> **Participant 134**: I'm trying to make a tube of light ... I was thinking about what kind of considerations I have to make to get the light to spread all around.

Even participants sensitive to the LED aesthetic were motivated by the diffusion of their luminaires:

> **Participant 134**: I previously hadn't even thought about incorporating LEDs, but now I'm thinking about how we might incorporate LEDs to make things more user friendly.

Expectations from the tool's simulated results and the final physical luminaire formed a hard contract with user's end perception of the tool. Notably, participants were satisfied with the fidelity of the tool to the fabricated design results of their design (3.9). Specifically, users responded positively to the texture and flexibility of the diffusers. Users were intrigued with the way the tool allowed emergent shapes to appear, and expressed interest in the construction process. Some physical luminaires failed to meet expectations:

> **Participant 179**: I can't really tell the different shapes that were initially in the design . . . besides the hard sharp boundaries. It is interesting [that] these cut off on each other a lot harder than I expected, like the yellow meeting the blue there's a sharp line of contrast – I thought there would be more of a mixing zone.

Despite this, participants reported feeling agency (4.3) to integrate their designs into more domain-specific projects upon understanding the limitations of the tool.

Renewal of Light as a Medium

Participants began to consider light as a physical medium over which they could wield control. Users emphasized blending and mixing of colors to achieve novel effects and indicated a desire to "paint with light", rather than simply add LEDs:

> **Participant 160** I've never even tried blending LED colors together so this facilitates a little more advanced thinking: I don't want to

just use LEDs separately; I want to blend them together to use color effects and make them brighter.

The tool allowed users to rapidly prototype their concepts, visualizing how the final piece would appear with the LEDs in place. Users readily incorporated soft and hard edges, mixing colors and delineated conceptual boundaries in their designs; users expressed a desire to play around with the tool more and discover new light interactions.

Participant 169: I'd play around more with hard edges and soft edges, to see if I could get some nice mixing. I'd love to see how the color is actually changing and change it with more intention.

DISCUSSION

Although this work discusses, explores, and expands the role of light in design, we see these insights and principles guiding the design of future tools for physical making.

LED as Hybrid Practice

Viewing and working with light as material presents a possible hybrid practice, or the conversation that arises from working with both digital and physical processes. This type of practice often strikes a tension largely motivated by traditional media's nearness-of-hand and digital media's distributed, fast, and random access. We see such a tension manifest in a common critique that electronics in visual design are overpowering, distracting from any other visual elements. On the other hand, this saliency has been largely leveraged by interaction designers to engage and captivate audiences. Often, this "tacking on of media" [20] limits the exploration of the physical design space to instead focus on designing through digital manipulation. This line of thinking aligned with the mental model and LED interaction patterns of participants in our workshop. This work provides an alternative viewpoint that positions a medium so closely aligned with the digital-aesthetic and provides handles to explore physical characteristics and interactions with light. The sun-moon artifact in Figure 1b demonstrates one such break in the digital aesthetic – the hard edge characteristic of graphic display; by allowing an analog mixture of light sources in the sun flames, a richer more organic aesthetic can arise. We envision this physical approach used in concert with digital exploration of smart materials.

LED Media Architectures

The demand for an expanded LED aesthetic is present and growing. As flexible electronics develop, LEDs can be integrated as tattoos on skin using maker-friendly processes [17]. In its most subversive role, low-cost LED "throwies" [24] have gained traction as urban graffiti. LEDs may also make their way into clothing and wearables should it be able to operate in a design space of ambiguity, slowness, and other physical characteristics [5]. For instance, with the wearable luminaire headpin depicted in Figure 1a, we might be able to have greater synergy with the complex texture of hair and clothing with the shadows cast by a tactile diffuser. This work supports these diversifying uses of the LED, providing handles to manipulate the LED as a material and expand the electro-aesthetic. Our fabrication technique, although bound by bed size, results in a final cost of 5" x 5" display component with 10 LEDs in the \$6-7 price range; as a standalone device, logical control and power bring the cost to \$12. Study participants all confirmed that design opportunities well deserved the cost; many cited access to fabrication facilities as the main issue to adoption. In this work, we described an approach for designing light emitted from the more ubiquitous and low-cost LED. We envision our tool as supporting a wider ecology of materials, including electroluminescence (EL) wire and panels, and organic polymer LEDs [29], to foreground the physical design of light in interactive devices, wearables, and urban architecture.

LIMITATIONS

In this work, we showed that we can generate geometries that more effectively diffuse a point light across a shape. However, our technique needs at least (5 mm) above the light source to be effective. We see our technique used in conjunction with light pipe structures that can transport light more efficiently that could reduce the footprint currently required to illuminate luminaires with large surface areas and complex geometries (i.e. twists-and-turns). Current 3D printing resolution still introduces artifacts into fabricated lenses; an efficient transfer of light would be possible with smooth surfaces, however we found aesthetically acceptable results using SLA printing techniques. As printing resolution improves, we foresee our tool as a preliminary step to designing custom non-imaging secondary optics for illumination design.

FUTURE WORK

While this work explores light's properties of diffusion, several opportunities exist for expanding Illumination Aesthetics. For instance, more advanced optics geometries such as side-emmision or phase masks can be used to finely redirect light to specific locations and produce expressive inteference patterns [30]; other techniques might incorporate motorized, high-powered, or architectural elements to produce interactive urban lighting. We touch on this with our tactile illumination map in Figure 1c, where an urban area is modelled using a 3D diffuser; buildings can be selectively illuminated to provide directions or materialize hidden energies from geophysical data feeds. While the work focuses on physical design, exploring the intersection of physical and digital control of light and other actuators could greatly expand electronic aesthetics.

CONCLUSION

In *Illumination Aesthetics*, we expanded a user's ability to physically manipulate and shape light through computational design and fabrication of secondary optics. We demonstrated that our computational design pipeline can support a wide range of geometric configurations. In our workshop study, we fabricated 11 custom luminaires designed by our participants found that our tool altered existing perceptions of the role and function of the LED in interactive objects and displays. We contribute design principles for supporting the expanding ecology of illumination design in order to fully leverage light as an expressive medium.

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REFERENCES

1. 2015. *LED Lighting in the US*. Dossier. Statista.
2. Eric Brockmeyer, Ivan Poupyrev, and Scott Hudson. 2013. PAPILLON: Designing Curved Display Surfaces with Printed Optics. In *Proceedings of ACM Symposium on User Interface Software and Technology (UIST '13)*. ACM, New York, NY, USA, 457–462. DOI: http://dx.doi.org/10.1145/2501988.2502027
3. Jim Campbell. 2011. Exploded Views. (2011).
4. Hsi-Chao Chen, Jun-Yu Lin, and Hsuan-Yi Chiu. 2013. Rectangular illumination using a secondary optics with cylindrical lens for LED street light. *Optics Express* 21, 3 (Feb. 2013), 3201. DOI: http://dx.doi.org/10.1364/OE.21.003201
5. Laura Devendorf, Joanne Lo, Noura Howell, Jung Lin Lee, Nan-Wei Gong, M. Emre Karagozler, Shiho Fukuhara, Ivan Poupyrev, Eric Paulos, and Kimiko Ryokai. 2016. "I Don't Want to Wear a Screen": Probing Perceptions of and Possibilities for Dynamic Displays on Clothing. In *Proceedings of ACM SIGCHI Human Factors in Computing Systems (CHI '16)*. ACM, New York, NY, USA, 6028–6039. DOI: http://dx.doi.org/10.1145/2858036.2858192
6. Olafur Eliasson. 2003. Olafur Eliasson the Weather Project. (2003). http://www.tate.org.uk/whats-on/exhibition/unilever-series-olafur-eliasson-weather-project/olafur-eliasson-weather-project
7. Dan Flavin. 1963. Diagonal of May 25, 1963. (1963). http://www.themodern.org/collection/Diagonal-of-May-25-1963/1126
8. William Gaver, John Bowers, Andy Boucher, Andy Law, Sarah Pennington, and Nicholas Villar. 2006. The History Tablecloth: Illuminating Domestic Activity. In *In: DIS*.
9. Gjon Mili. 1949. Picasso draws a centaur. (1949).
10. Chris Harrison, John Horstman, Gary Hsieh, and Scott Hudson. 2012. Unlocking the expressivity of point lights. In *Proceedings of ACM SIGCHI Human Factors in Computing Systems*. 1683–1692. http://dl.acm.org/citation.cfm?id=2208296
11. Brad Hindson. 2013. Light as Material – Rethinking How We Use Light. (2013).
12. Jettie Hoonhout, Lillian Jumpertz, Jon Mason, and Tom Bergman. 2013. Exploration into Lighting Dynamics for the Design of More Pleasurable Luminaires. In *Proceedings of Designing Pleasurable Products and Interfaces (DPPI '13)*. ACM, New York, NY, USA, 185–192. DOI: http://dx.doi.org/10.1145/2513506.2513526
13. Illuminating Engineering Society. 2011. Discover Lighting: An Introduction to Lighting Basics. (2011). http://www.ies.org/lighting/sources/luminaires.cfm
14. Juerg Lehni and Jonathan Puckey. 2011. Paper.js. (2011).
15. Rong-Hao Liang, Chao Shen, Yu-Chien Chan, Guan-Ting Chou, Liwei Chan, De-Nian Yang, Mike Y. Chen, and Bing-Yu Chen. 2015. WonderLens: Optical Lenses and Mirrors for Tangible Interactions on Printed Paper. In *Proceedings of ACM SIGCHI Human Factors in Computing Systems (CHI '15)*. ACM, New York, NY, USA, 1281–1284. DOI: http://dx.doi.org/10.1145/2702123.2702434
16. Gordon E. Liljegren and Eugene L. Foster. 1990. Figure with back projected image using fiber optics. (Dec. 1990). http://www.google.com/patents/US4978216 U.S. Classification 353/28, 353/74; International Classification G09F19/00, G09F19/18, G09F19/08, A63H33/22, G03B21/00, A63H3/36, G09F19/02, G03B21/62; Cooperative Classification G09F19/02, G09F19/18, G09F19/08, G09F2019/086, G09F19/00, G09F2019/088; European Classification G09F19/18, G09F19/08.
17. Joanne Lo, Doris Jung Lin Lee, Nathan Wong, David Bui, and Eric Paulos. 2016. Skintillates: Designing and Creating Epidermal Interactions. In *Proceedings of Designing Interactive Systems (DIS '16)*. ACM, New York, NY, USA, 853–864. DOI: http://dx.doi.org/10.1145/2901790.2901885
18. Wojciech Matusik, Boris Ajdin, Jinwei Gu, Jason Lawrence, Hendrik P. A. Lensch, Fabio Pellacini, and Szymon Rusinkiewicz. 2009. Printing Spatially-varying Reflectance. In *ACM SIGGRAPH Asia 2009 Papers (SIGGRAPH Asia '09)*. ACM, New York, NY, USA, 128:1–128:9. DOI: http://dx.doi.org/10.1145/1661412.1618474
19. László Moholy-Nagy. 2016. Moholy-Nagy, László: Light-Space-Modulator. (Sept. 2016). http://www.medienkunstnetz.de/works/licht-raum-modulator/
20. Michael Nitsche, Andrew Quitmeyer, Kate Farina, Samuel Zwaan, and Hye Yeon Nam. 2014. Teaching Digital Craft. In *CHI '14 Extended Abstracts on Human Factors in Computing Systems (CHI EA '14)*. ACM, 719–730. DOI: http://dx.doi.org/10.1145/2559206.2578872
21. Marios Papas, Thomas Houit, Derek Nowrouzezahrai, Markus Gross, and Wojciech Jarosz. 2012. The Magic Lens: Refractive Steganography. *ACM Trans. Graph.* 31, 6 (Nov. 2012), 186:1–186:10. DOI: http://dx.doi.org/10.1145/2366145.2366205
22. Thiago Pereira, Szymon Rusinkiewicz, and Wojciech Matusik. 2014. Computational Light Routing: 3D Printed Optical Fibers for Sensing and Display. *ACM Trans. Graph.* 33, 3 (June 2014), 24:1–24:13. DOI: http://dx.doi.org/10.1145/2602140
23. James Pierce and Eric Paulos. 2013. Electric Materialities and Interactive Technology. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, New York, NY, USA, 119–128. DOI:http://dx.doi.org/10.1145/2470654.2470672

24. Evan Roth and James Powderly. 2006. LED Throwies. (2006).

25. Daniel Rozin. 1999. Wooden Mirror. (1999).

26. Peter Schreiber, Serge Kudaev, Peter Dannberg, and Uwe D. Zeitner. 2005. Homogeneous LED-illumination using microlens arrays, Vol. 5942. 59420K–59420K–9. DOI:http://dx.doi.org/10.1117/12.618747

27. James Turrell. 1968. Shallow Space Constructions. (1968).

28. Karl Willis, Eric Brockmeyer, Scott Hudson, and Ivan Poupyrev. 2012. Printed Optics: 3D Printing of Embedded Optical Elements for Interactive Devices. In *Proceedings of ACM Symposium on User Interface Software and Technology (UIST '12)*. ACM, New York, NY, USA, 589–598. DOI: http://dx.doi.org/10.1145/2380116.2380190

29. Tomoyuki Yokota, Peter Zalar, Martin Kaltenbrunner, Hiroaki Jinno, Naoji Matsuhisa, Hiroki Kitanosako, Yutaro Tachibana, Wakako Yukita, Mari Koizumi, and Takao Someya. 2016. Ultraflexible organic photonic skin. *Science Advances* 2, 4 (2016). DOI: http://dx.doi.org/10.1126/sciadv.1501856

30. Qiang Zhou, Wenzheng Yang, Fengtao He, Razvan Stoian, Rongqing Hui, and Guanghua Cheng. 2013. Femtosecond multi-beam interference lithography based on dynamic wavefront engineering. *Optics Express* 21, 8 (April 2013), 9851. DOI: http://dx.doi.org/10.1364/OE.21.009851