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# Interactions of Light with Materials – Lighting Materials and Materializing Light

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***Abstract*— Visual perception of materials is crucial for our interactions with the world around us, and understanding the optical and perceptual mechanisms behind it has applications from spectral tuning to holistic *appearance tuning*. How real materials appear optically is determined by the real light they are in and described by *ecological optics*. With formal psychophysical experiments we test the perception of their color and texture, how matte/glossy, rough/smooth, hard/soft, glittery, velvety, etcetera we perceive them to be – and how those percepts are related to the ecological optics. I will present a series of studies into light-material-interactions and material perception of computer rendered, real, and painted materials. In addition, I will present research into effects of materials on light, and how materials can be used to make spatial and form-giving qualities of light visible in empty space, using *"light probes."***

***Keywords—light, materials, appearance, interactions, design***

## I. Introduction

The appearance of materials is strongly influenced by the light in which they are seen. Fig. 1 shows a bunch of grapes, an ipod and matte and glossy birds, with for each set at left diffuse lighting and at right directed lighting. The grapes look matte and dark blue with some bloom (the whitish waxy layer on top of the grapes) at left, and glossy, much more colorful and rough at right. The ipod looks flat, sharp and matte at left, while at right it looks thicker, rounder, and the glass shiny. The birds both look matte at left and right they appear different, the lower one now showing its gloss [1]. The latter effect shows analogies to color metamery: under one type of light the materials look the same, and under another they look different. This "material appearance metamery" is caused by different spatial distributions of the light(ing) while color metamery is related to the light spectra. The effects have in common that they allow tuning of the light to optimize the appearance: spectral tuning for color appearance and distribution tuning for the appearance of other material attributes e.g. gloss, texture, translucency, softness, and shape and spatial appearance – and usually a combination of those tuning aspects is needed to optimize the desired visual aspects. In this paper I focus on these aspects and neglect other optical effects such as for instance polarization and structural colors.

So light affects material appearance. The actual light in a space, which can be described by the "light field," is actually also strongly influenced by the materials in that space [2]. Fig. 2 shows four pieces of white paper in a small box. However, they look colored (red, blue, yellow, green) due to such effects (see Fig. 5 for a view onto what is causing the colors). Reflection and interreflection effects can have an enormous impact on the light field [2], e.g. a white space and a black space lighted in the same way will differ in light density and illuminance level by easily a factor of two and light diffuseness by easily a factor of three [3][4]. This affects not just the quantity but also the spatial and form-giving qualities of the light, and thereby has a major effect on modeling and appearance of space and objects [4] and people in it [5].

Fig. 1. Examples of lighting influencing the appearance of materials and objects. For all objects the left lighting is rather diffuse (e.g. overclouded sky or diffuse light in a white room) and at right more directed (e.g. direct sunlight or a spotlight).

Fig. 2. Examples of materials or context influencing the actual light in a space. The paper squares in the box on the black background are actually white. The answer to why they look colored can be found in Fig. 4.

Moreover, if the space is finished with colored materials, the light will also get colored due to (inter)reflections, especially the light's diffuse part [6]. Instead of just analyzing illuminance levels on flat planes, it is therefore advised to put so-called 3D light probes in a space during lighting design processes, to visually assess the impact of lighting and its complex interactions with materials in a space on the space / objects / people's appearances. A light probe can be any relevant 3D convex shape, e.g. a simple sphere, or a golfbal, or a face. Such an approach will help to "see the light" and judge its qualities by the effects on the probe's appearance, which provides a quick visual tool in a practical design process [2].

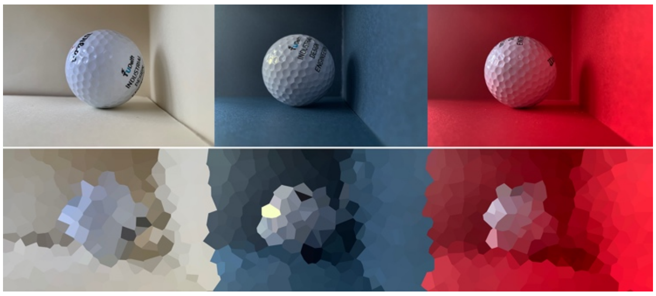

Fig. 3. Examples of a light probe put in three differently colored "spaces", under the same primary lighting (rather diffuse daylight from a cloudy sky).

Fig. 3 for example shows a golfbal in a white, dark blue and red space. Below the images the pixelated versions are shown for a quick assessment of the resulting colors, brightness and contrast variations. The right side of the probe becomes colored due to the reflections from the environment. The contrast becomes higher in the dark blue space because the light is absorbed by the environment and the interreflections in the room are strongly attenuated, causing the actual light to become less diffuse (more directed, more focus light). The white room shows the reverse effect, it shows less contrasty due to such diffuse (ambient) light. Please also note the effects on the texture gradients and modeling (how well the shape comes out), being much clearer in the dark blue than in the white room.

But how can we get a grip onto the endless variety of materials and their appearance without endless trials and errors? In this paper I propose a composition approach based on canonical modes for materials and for light, based on a large body of research done over the past decades in collaboration with many other researchers (see references). This research covered a wide spectrum from BRDF modeling to light photometry to psychophysical material and light perception studies to design methods and processes. This framework allows systematic predictions of light-material interactions and their effects on appearance [7] via testing of separate and combined modes via mixing in linear weighted combinations, e.g. analogue to a sound mixing interface [8][9].

## II. Ecological Optics

### A. Canonical modes of materials

Here I focus on opaque materials that can be described by bidirectional reflectance distribution functions [10], e.g. Lambertian reflectance (creating shading effects and giving a matte appearance), forward scattering (giving a shiny appearance for very directed forward scattering e.g. mirror reflections or a glossy appearance for broader scattering lobes), backward scattering (giving retroreflection effects), asperity scattering (e.g. by sharp edges or hairs giving surface scattering and inverse shading effects), and there are probably a dozen or so more modes. Linear combinations of such basic reflectance types can represent more complex reflectance types, which is common practice in computer graphics [11], and also used in material painting procedures [12].

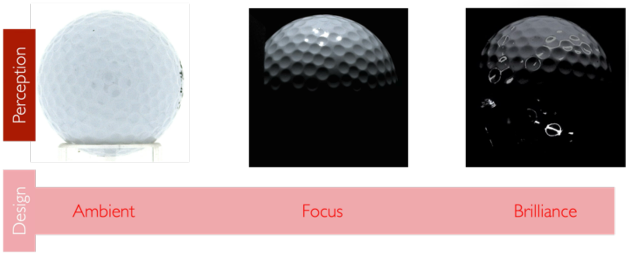


Fig. 4. The "Delft light framework", showing the basic modes ambient, focus and brilliance (from left to right) and their meaning in design and perception; the meaning in optics is not shown here but well defined and parametrized in our framework (including metrics, namely light desnity, light vector and a brilliance metric, plus the diffuseness which relates to the ratio between ambient and focus). A golfbal was used as "light probe" because it is spherical and therefore shows a hemisphere of directions in one glance, and because it has a surface structure that results in a texture gradient, giving information about the light that is additional to shading.

### B. Canonical modes of light

The light modes framework, sometimes called the Delft light framework, was based on multidisciplinary research into the physics, mathematics, perception and design of light as humans perceive it [13]. In this antropomorphic framework we found that light in all these disciplines is described with conceptually same modes which can be used for decomposing and composing light: so-called ambient, focus, and brilliance light, see Fig. 3. For these light modes we use the shortcuts of the wording of the composition framework of the famous 20th century lighting designer Richard Kelly. Interestingly, these components in my lab's research were found to be scientifically grounded in mathematics, physics, perception and design [14][13][15] and having congruent basic modes or components of light and their meaning in all these areas. Actual, often more complicated spatial light in any space can be described – and designed - by linear superpositions of those basic modes.

The basic modes represent the diffuse part of light (ambient), the directed part of light (focus) and the angular high frequencies part of light (brilliance). In design they are used for general uniform illumination of a space (ambient), putting attention and contrast in certain places or on certain objects (focus), and adding liveliness and light texture to a space (brilliance). The different modes can be simply superposed, which is physically realistic since light is additive.

The metrics associated with the modes are the light density for ambient, the light vector for the focus, and a spherical harmoncis based brilliance metric for brilliance. Zhang et al. [7] showed how these can be computed for real panoramic luminance measurements and that those can indeed be used to predict appearance effects on certain materials. Xia et al. [3], [4] developed a diffuseness metric that relates to the ratio between ambient and focus, and which is very important for modeling and contrast effects on shapes and textures. The diffuseness runs from 0 (collimated, perfectly directed light, pure focus) to 1 (spherically diffuse, pure ambient).

## III. Composing Appearance

In the proposed composition approach the materials can exist of weighted linear combinations of canonical material modes, which can be put in canonical lighting modes, which results can be superposed in weighted linearly mixtures. Such optical mixing can be used in real and virtual presentations

[9][8]. The material and lighting modes can be combined via superposition of the images representing the material modes for each of the lighting modes. In a real setup it is possible to mix in a full cue condition using a semi-transparent mirror and differential light dimming at its sides to adjust the ratio of the mixtures of the materials / objects at its sides. The mixtures show smooth transitions from one to the other material, both optically and perceptually [8], [9].

## IV. MATERIAL LIGHT INTERACTIONS

Experiments have shown that light-material interactions are systematic, that they are material-dependent, and a-symmetric [1]. Thus, what is optimal lighting for one material can be different for another material, e.g. to bring out the qualities of velvet optimally will need a different lighting than to show glittery or glossy stuff well. Also, within the sets of canonical modes here discussed observers are more sensitive to materials than to lighting variations. This asymmetry in our results is of course limited to the modes and stimuli and conditions used in our experiments, but does make sense from an ecological perspective. After all we tend to look at and interact with materials, objects, people, and usually not with light.

Moreover, using our diffuseness and brilliance metrics for natural illuminance maps we found that it was possible to predict the effects of light-material interactions on perceived qualities such as glossiness and softness [7][16].

Such methods, plus a simple technique to quickly capture the main reflectance characteristics from imaged cylinders, was also used to assess the optical and perceptual effects on textiles for ambient and focus lighting modes [17]. Since textiles provide a very rich set of possible reflectance modes they for a challenge for lighting designers in for instance fashion retail. The textile light probe set consists of a dozen textile probes that showed the largest optical and perceptual effects upon interaction with different types of light within a large set of textiles that was collected in Western Europe, and these probes can be used to tune the appearance of textiles.

## V. CONCLUSIONS AND DISCUSSION

Material-light interactions for opaque materials can be studied and predicted via a linear weighted mixing or a composition approach. The predictions were done on the basis of diffuseness and brilliance metrics, which provide strong predictors for effects on appearance in general and material appearance specifically. Materials also influence the light in a space through (inter)reflections. Since such effects are optically hard to predict in terms of distribution, spectral shifts, and effects on appearance of color, texture and modeling it is advised to probe the resulting light in renderings or real spaces using light probes to be able to assess the light qualities and its effects visually.

Future challenges for the lighting profession and research concern how to work with appearance instead of illuminance levels, and in that how to capture and progress the optical response of materials, shapes and spaces to lighting. Capturing, describing, visualizing and designing the light as a spectrally, spatially and directionally varying field we have shown is possible [18], and help to capture modeling effects on appearance [16]. Simple forms of integrating light field approaches, e.g. by cubic instead of flat light measurements, are currently being implemented in practice [5], marking the 3rd stage of the lighting profession as Cuttle coined it [19]. The next challenge needs further research into the interaction with materials, and extending beyond opaque materials. Also here the additive nature of lighting and its basic canonical modes are expected to provide a good basis for systematical approaches.

Fig. 5. The answer to Fig. 2: the upper papers on the black ground are actually white, but appear colored due to (inter)reflections from the colored papers opposite them. The optical effect is dependent on spectra of the source, of the papers, the angle between them, their size, and on the distribution of the light entering the box. The psychological effect, whether one sees the white papers as colored or not, is dependent on how strong the optical effect is and on whether one can see the colored papers or not.

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