State of the Art in Artistic Editing of Appearance, Lighting, and Material

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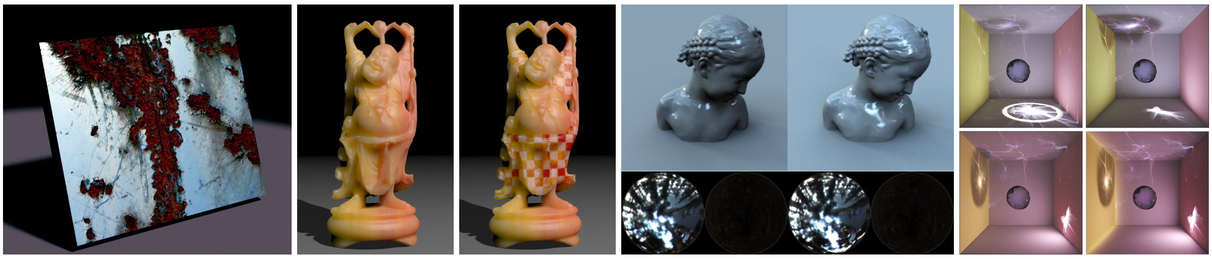

Figure 1: *Examples of artistic appearance editing (left to right): A rendering with spatially-varying reflectance and normals computed from a single image and a few input user strokes [DTPG11]; editing heterogeneous subsurface scattering acquired from a real-world material sample [STPP09]; adjusting natural environment lighting to obtain a desired shadowing and reflection appearance [Pel10]; direct manipulation of caustics and shadows with global illumination [SNM*13]. (Images taken from [DTPG11, STPP09, Pel10, SNM*13].)*

Abstract

Mimicking the appearance of the real world is a longstanding goal of computer graphics, with several important applications in the feature-film, architecture and medical industries. Images with well-designed shading are an important tool for conveying information about the world, be it the shape and function of a CAD model, or the mood of a movie sequence. However, authoring this content is often a tedious task, even if undertaken by groups of highly-trained and experienced artists. Unsurprisingly, numerous methods to facilitate and accelerate this appearance editing task have been proposed, enabling the editing of scene objects' appearances, lighting, and materials, as well as entailing the introduction of new interaction paradigms and specialized preview rendering techniques. In this STAR we provide a comprehensive survey of artistic appearance, lighting, and material editing approaches. We organize this complex and active research area in a structure tailored to academic researchers, graduate students, and industry professionals alike. In addition to editing approaches, we discuss how user interaction paradigms and rendering backends combine to form usable systems for appearance editing. We conclude with a discussion of open problems and challenges to motivate and guide future research.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism— I.3.6 [Computer Graphics]: Methodology and Techniques—Interaction techniques

1. Introduction

Synthesizing realistic images is among the longstanding goals of computer graphics, and its ambitious nature is evidenced by the advancements of our field towards realism with still a significant number of open problems. The acquisition and editing of detailed geometry, its animation, the careful modeling and reproduction of real-world material and lighting profiles, and the efficient simulation of physically accurate light transport are still in need of robust solutions. But, as our field progresses, so do its goals: while realistic image synthesis remains an important challenge, so too does the ability to *design* a (potentially realistic) image that conveys an explicit mood or information to the viewer.

One of the aspects at the core of scene design is defining the appearance of objects, which comes from the interaction of surface materials and scene lighting. Appearance design is the process by which artists edit material and lighting properties in order to achieve a desired look. In general, this is a complex and laborious process, since artists are manually solving an underconstrained inverse problem: given a desired appearance, determine the material and light settings to achieve it. In fact, even for simple scenes and highly-trained digital artists, appearance design may take several hours. Furthermore, in cases where the design goals cannot be obtained in the confines of physically accurate simulation models, more flexible artistically motivated models need to be developed. Many different approaches, ranging from physically based to purely artistic, have been proposed to intuitively edit the appearance of individual objects as well as entire scenes.

In this report we present a summary of the state of the art in artistic editing of lighting and material that includes the following topics:

- *lighting design*: the editing of lighting parameters to define a final scene appearance, which is fundamental to computer cinematography;
- *material design*: the definition of the reflectance properties of a surface or the scattering properties of materials, ranging from whole surface changes to precise adjustment in textured regions;
- *whole appearance design*: the coupled editing of the interaction between surface materials and scene lighting, when it may be difficult to segment and treat separately;
- *preview rendering*: rendering systems tailored to adapt to the more flexible demands of an appearance editing framework.

We organize prior work along two axes, defining first *what* is edited or manipulated, and second *how* these elements are edited, including the interaction paradigms they rely on. We also provide an overview guide to the methods covered in this report, providing a quick way to assess their usefulness for different practical scenarios (see Tab. 1).

2. What is Appearance Design?

The *appearance* of an image depends on complex local and global interactions of light in a virtual scene. Light emitted from light sources travels in the scene, and is subsequently reflected, transmitted or absorbed locally at the surfaces of the objects, until it finally reaches an image sensor. When participating media are present, light can also be emitted, scattered, and absorbed in the volume surrounding surfaces. This combination of global transport and local interactions repeats indefinitely until light reaches a state of equilibrium.

Given this light transport process, it is clear that both the initial *lighting* emitted from sources, as well as the local *material* interactions, play a significant role in the final appearance of a scene. As such, modifying the initial *lighting* state and/or the local *material* reflectance behaviors is a simple way to affect both the local and global appearance of the final image.

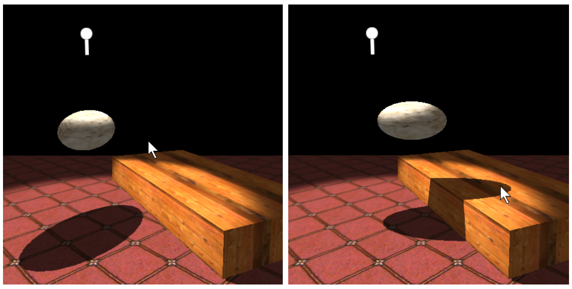

Figure 2: *Using Pellacini et al.'s interface for interactive cinematic shadow design [PTG02], users can indirectly and automatically reposition shadow-casting objects by dragging their shadow. This is an example how appearance design methods can assist the user in modifying the appearance parameters (e.g. the relative object positions) in order to achieve a desired final appearance (e.g. the shape and placement of the shadow). (Images taken from [PTG02].)*

Appearance design is a fundamental task at the tail end of digital content creation: given objects' surfaces and their relative placement in space and time, the goal of appearance design is to define the look of the final images that meets specific stylistic or artistic requirements. In general, the final image appearance relies on several controllable *appearance parameters*:

- the position, orientation, and emission profiles of light sources, ranging from simple point sources to realistic area and environment illumination;
- the camera parameters, including position, framing, aperture, lens model, shutter time, etc.;
- the materials that define the potentially spatially-varying shading response (e.g. via BRDFs, shaders, node-based networks, etc.) of each object;
- the light transport simulation algorithm and its settings.

Final images are computed by solving the *rendering equation* [Kaj86], which specifies the appearance of a point x by computing the radiance $L(c \leftarrow x)$ towards a viewer at point c as:

$$L(c \leftarrow x) = \underbrace{L_e(c \leftarrow x)}_{\text{lights \& camera}} + \int_{\mathcal{S}} \underbrace{f_r(c \leftarrow x \leftarrow y)}_{\text{materials \& camera}} \underbrace{L(x \leftarrow y)}_{\text{transport}} G(x \leftrightarrow y) dy \, , \quad (1)$$

where $L_e(c \leftarrow x)$ is the radiance emitted from light sources and $f_r(c \leftarrow x \leftarrow y)$ is the bidirectional reflectance distribution function (BRDF), that captures how the material at x

reflects incident radiance from another point y towards c. $G(x \leftrightarrow y)$ is the so-called geometry term which accounts for the mutual visibility as well as the distance and orientation of x and y. Note that the integral is over all surfaces $\mathcal{S}$ in a scene from which light may arrive at x. We could equivalently express this integral over the space of incident unit directions about x or the multi-dimensional space of light paths in the scene [Vea98]. In the equation above we ignore volume scattering dictated by the more complex *radiative transfer equation* [Cha60].

Note that the recursive definition of appearance (with L inside the integrand) means that the appearance of any point is not only the result of material-light interactions, but may also depend recursively on the appearance of all other points in a scene. Indeed, we note that the *appearance parameters* affect each term in this image formation equation. In scenes of even moderate complexity, predicting the behavior of the final appearance as any of these parameters are directly edited quickly becomes intractable for even the most skilled and experienced artists.

There have been efforts to catalog the appearance of highly diverse objects from photographs with the aid of crowdsourcing, for applications such as surface retexturing and material and image browsing [BUSB13]. From the point of view of appearance design, this can be seen as a useful database for retrieving appearances of already-existing real-world objects as a source of inspiration, but the key responsibility of actually selecting and editing (i.e. *designing*) the appearance of a specific scene remains on the artists.

In our discussion, an *appearance design approach* is a semi-automatic process for editing the final appearance of an image or animation sequence that abstracts the task of determining suitable settings of the lighting and/or material settings in a scene. Specifically, any such approach will take some higher-level input specification of the appearance edits desired by the user, and then automatically computes the lighting (Sect. 4) or material (Sect. 5) settings, or both, in order to best meet the user's requests.

2.1. Challenges & Complexity of Appearance Design

Appearance design tools inherently deal with different rendering challenges than standard rendering. In a typical renderer used for generating animations, mostly the camera, geometry, and, to some extent, lighting change, while the appearance of materials remains mostly static during a shot. Furthermore, though lighting and material may change, they have a predefined evolution during a shot. This is fundamentally different from the need to dynamically explore the entire parameter space during appearance design.

Historically, the strategy to bridge this gap has been to perform some precomputation which is then cached using more flexible intermediate representations. Typically, the system first enforces certain constraints, e.g. fixed camera, fixed lighting, or fixed materials, and caches the possible space of parameters for the remaining free variables. The choice of what is cached and its representation varies significantly across the proposed techniques, and is also highly dependent on the provided editing functionality.

Relighting systems' primary function is to provide interactive editing of the lighting (while typically keeping the scene and materials static). Early examples include parameterized ray tracing [NSD94], ray trees [SS89, BP96], and the G-Buffer approach [ST90, GH00]. The Lpics [PVL*05] and Lightspeed [RKKS*07] systems also fall within this category. Direct-to-Indirect transfer techniques [HPB06, LZT*08] exploit our ability to compute direct lighting efficiently and leverage a possible precomputation to extend this to indirect illumination. Most of these methods gain efficiency by exploiting the linearity of light transport and they often capitalize on the assumption that camera movement occurs much less frequently than shading changes.

Although it may initially seem conceptually similar, material editing is inherently different than relighting. In contrast to relighting, BRDF editing is fundamentally nonlinear when global illumination is considered. In particular, editing n BRDFs in a scene with d light bounces leads to an n-variable polynomial of degree d [BAERD08]. Unfortunately, representing this explicitly is only practical for a small number of bounces. Several researchers have investigated this problem for both surface BRDFs [BAOR06, SZC*07, BAERD08], and more recently for editing participating media parameters [STPP09, HR13, ZHRB13].

Relighting, and to some extent material editing, systems have exploited a vast set of techniques developed in the precomputed radiance transfer literature [SKS02, KSS02, NRH04, NRH03, WTL04, KAMJ05, SM06, Ram09]. These techniques typically exploit the linearity of light transport and the fact that light (transport) is often sparse in a suitably chosen basis space (e.g. frequency or wavelet domain). In return for the efficiency gained through precomputation, these methods typically restrict the lighting (e.g. environment only), or material properties (e.g. diffuse only).

Although PRT techniques can provide interactive feedback when editing a specific set of parameters, once the parameter set changes, a new, expensive precomputation must be performed. For interactive design, this can lead to slow interaction times, for instance, a level designer for a game must wait for an overnight simulation to see interactive lighting changes when the scene geometry is modified. The recent Modular Radiance Transfer [LAM*11] approach addresses this challenge by trying to decouple the precomputation from the scene.

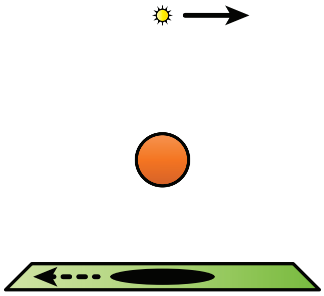

Figure 3: *Direct vs. indirect manipulation of a point light source. With direct manipulation, the user moves the light source (solid arrow) and the shadow follows accordingly (dashed arrow).* Direct interfaces *are trivial to implement but oftentimes unintuitive. With indirect/goal-based manipulation, the user moves the shadow (dashed arrow) and the system solves for the new light source position (solid arrow).*

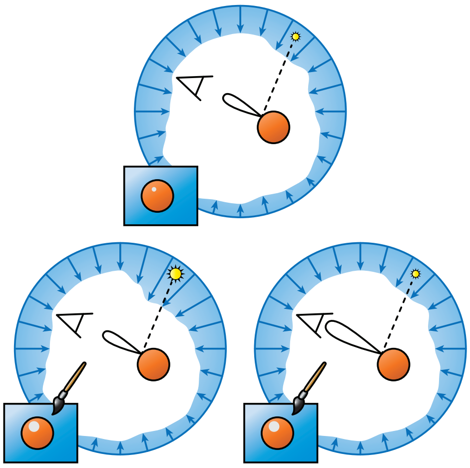

Figure 4: *Goal-based interaction. Top: the original scene illuminated by an environment map; the inset in the bottom left depicts a rendering which show a highlight. A goal-based interface allows the user to paint a new highlight. Bottom left: After painting the desired appearance, the system solves for new light parameters (e.g. a brighter area around the sun in the environment map). Bottom right: After painting the desired appearance, the system solves for new material parameters (e.g. modifying the BRDF lobe).*

3. Interaction Paradigms

Artistic editing should never be isolated from user interaction, and so we categorize according to three interaction paradigms [KP09, KPD10] (cf. Figs. 3 and 4):

- With *direct* interfaces, artists directly edit light/material parameters, such as positions and surface colors. This is the most commonly available interface in commercial software. While easy to implement, direct interfaces are neither efficient nor intuitive, since final appearance often depends unpredictably on these parameters.
- *Indirect* interfaces let users specify appearance qualifiers, e.g. shadow positions or material contrasts, and the system computes the necessary rendering parameters.
- *Goal-based* interfaces allow artists to define the rendered colors directly, for example by painting, while the system solves a complex and typically non-linear optimization to determine the rendering parameters.

The *effectiveness* of user interaction with these paradigms was investigated by Kerr and colleagues [KP09, KPD10], as well as the *selective applications* of edits for complex materials and lighting [PL07, AP08, Pel10].

4. Lighting Design

Lighting design focuses on modifying the parameters of lighting models under fixed geometry and material conditions. These models can be categorized by the complexity of effects they support, namely direct illumination and shadows from point and directional lights [PF92, PTG02], area- and image-based (direct) illumination [Pel10, OPP10], and (full) global illumination including diffuse interreflections and caustics [RTD*10, SNM*13]. Finally, some systems [NJS*11, HR13, KISE13] allow manipulation of volumetric effects. Due to high computational demands, most works have focused on direct illumination. Previous lighting design works leverage sketch-, click-and-drag, and paint-based editing concepts. Kerr and Pellacini's studies [KP09] stress that, although painting interfaces are useful in some scenarios, typical editing operations can be better achieved using *direct* and *indirect* manipulation. We follow this distinction in our discussion below.

4.1. Directly Controlled Lighting

We first focus on methods to directly control *lighting features* (not to be mistaken with direct lighting parameter control). While indirect interfaces allow artists to roughly sketch the desired appearance of lighting features and let the underlying system solve for the model parameters, sometimes more direct control over the illumination, e.g. to exactly (dis)place features, is beneficial.

A straightforward technique to directly manipulate lighting is what is commonly called "light linking" [Bar97]; here, users can select which light sources affect which objects in the scene, allowing to explicitly set shadow caster/receiver relations among them (see Fig. 5).

Apart from directly activating and deactivating light sources, the simplest and arguably most intuitive kind of direct interaction with the scene illumination normally arises from click-and-drag interfaces. For example, Ritschel et al.'s [RTD*10] *Interactive On-Surface Signal Deformation*

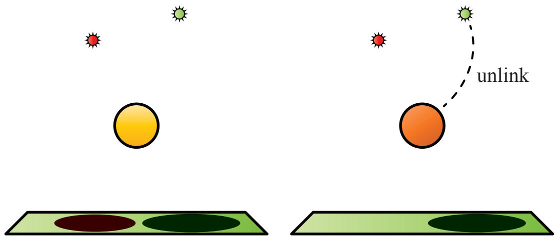

Figure 5: *Light linking. Left: Original configuration with two point light sources and two objects. Right: The green point light is unlinked from the sphere object, hence also casting no shadow onto the bottom plane anymore.*

is an object-space appearance-guided editing tool for manipulating shadows, caustics and indirect light with a custom interface that couples space warping effects for reflection and shadowing with inter-object markups for indirect light exaggeration (Fig. 6).

In designing direct user interfaces and interaction paradigms for lighting design, one important aspect is that—in contrast to materials and scene geometry—the illumination (and thus appearance) is only a by-product of the rendering process and usually not explicitly hand-authored by artists. Therefore, lighting design methods for non-trivial scenarios have to introduce abstractions and visualizations of the underlying light field, which is a five-dimensional, complex function and an effective visualization thereof is difficult [RKRD12]. That said, if the transport is limited to, e.g., a fixed viewing direction (as in cinematic lighting preview systems [PVL*05, HPB06, RKKS*07, SZC*07]) or direct lighting from a finite set of directions, then good visual mappings can be found. For example, Kerr et al. [KPD10] control spot or directional light sources using guided visualizations of the underlying user-deformable lighting volume. Another editing approach is lattice-based deformations, as in Obert et al.'s work [OPP10]. Here, a factored representation of visibility is efficiently stored in compressed matrices, enabling interactive shadow editing under environment illumination.

As industry-leading studios adopt physically based rendering (PBR) in their art generation pipelines, the usefulness of simple manipulation approaches that address effects without considering underlying PBR concepts and constraints decreases. Schmidt et al.'s path space manipulation (PSM) [SNM*13] (see Fig. 7) includes direct manipulation approaches for global illumination effects such as (multi-refracted) caustics, diffuse and glossy indirect bounces, and direct/indirect shadows. Their object-space selection interface respects the UI and interaction paradigms of the underlying DCC toolchain, and is built atop a parameterized regular expression engine in the spirit of Heckbert [Hec90]. This work is a very general approach which subsumes

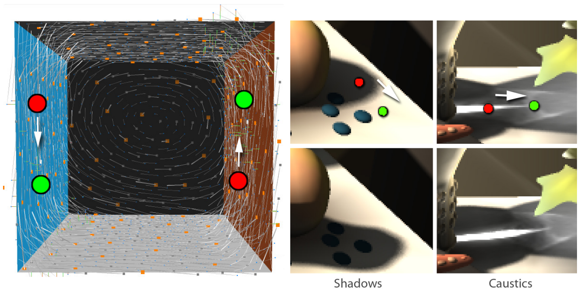

Figure 6: *Interactive On-Surface Signal Deformation [RTD*10] provides a direct interface for lighting manipulation. Users specify constraints (red and green dots) and the underlying system solves for a smooth deformation field, which can be used to accurately displace features such as shadows and caustics. (Images taken from [RTD*10].)*

previous methods, e.g. BendyLights [KPD10] or reflection editing [ROTS09], as special cases. Tabellion and Lamorlette [TL04] use shader falloff-function editing on the hue of indirect color bleeding effects, which can also achieved with PSM. Similarly, Nowrouzezahrai et al. [NJS*11] edit the underlying physical processes of volume rendering.

Lastly, goal-based approaches have also been developed using painting methods in high dynamic range [Col08] to sketch both highlights and directly paint and modify environment illumination.

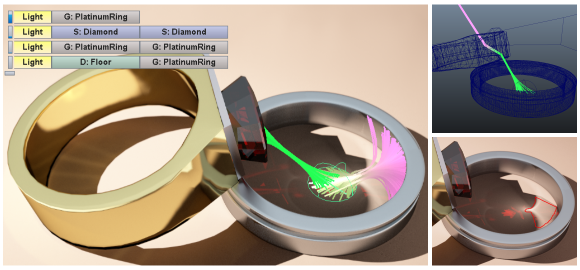

Figure 7: *Schmidt et al. [SNM*13] visualize light transport paths using edge bundling techniques. Selection of lighting features is done in a semi-automatic fashion by analyzing and ranking virtual illumination inside a user-specified region of interest. (Image taken from [SNM*13].)*

4.2. Indirectly Controlled Lighting

Another class of artist-driven lighting design tools offer an *indirect* approach to manipulating lighting parameters in order to reach a desired appearance. Such approaches allow users to indirectly affect the final appearance $L(x \to c)$ of a shot by abstracting the underlying image formation process and exposing interaction paradigms to act on these abstractions. After user manipulation of the abstracted parameters, an underlying processing system automatically determines the settings of *appearance parameters* using inverse image formation models. We overview examples of such *indirect shading and lighting* editing tools below.

Poulin and Fournier [PF92] and Pellacini et al. [PTG02] infer light positions in the context of a simple direct and local illumination model, allowing users to sketch shadow and highlight boundaries atop a final rendered shot. More complex lighting and reflectance parameters, such as light cone angles, colors and specular surface coefficients can also be automatically computed using similar image-space editing interfaces. The inverse image formation models in these works are often based on (potentially non-linear) optimization backends that search the space of *appearance parameter* settings for an appropriate solution [Bar97, CdSF99]. Recent appearance-based interfaces expose image markup techniques to allow users to identify and isolate shadow features, after which the underlying processing system infers a coupled relationship between complex all-frequency shadows and distant environment lighting (still exclusively in the context of direct illumination) [Pel10, OPP10]. Ritschel et al. [ROTS09] also expose an image-space constraint-identification interface to users, focusing on editing the reflection behavior from mirror surfaces. Their underlying system infers spatially-varying reflection directions after user input.

Several sketching-based approaches have been proposed to design complex material, reflectance, and scattering profiles. Pellacini and Lawrence [PL07] present a system where users sketch appearance constraints on the image canvas in order to infer, warp, and transfer appearance from different spatially- and temporally-varying reflectance datasets. Nowrouzezahrai et al. [NJS*11] generalize photon beam primitives [JNSJ11] to non-physical effects, allowing artist-driven sketching of heterogeneous volumetric media densities with art-parameterized shading models (see Fig. 9, left). Their system can additionally infer scattering and absorption coefficients in participating media with single-scattering from user-sketched color constraints. Dong et al. [DTPG11] present a data-driven system that automatically infers higher-dimensional appearance manifolds from a single image, given user-sketched constraints. As with An et al.'s approach [ATDP11], their system allows users to automatically warp the spatially-varying appearance of selected objects in a rendered image. Note that, as with all indirect manipulation approaches, the user is not directly exposed to the underlying behavior or *appearance parameters* of the image formation process.

In the context of indirect appearance manipulation for global illumination editing, Obert et al. [OKP*08, Obe10] expose a painting interface for artists to edit the intensity and color of indirect light. Their system additionally exposes a labeling interface, allowing users to identify indirect sender/receiver relationships (the first example of an *object-space* editing markup). With these relationships in place, indirect illumination can be exaggerated while maintaining important visual constraints necessary when generating plausible rendering results (see Fig. 8).

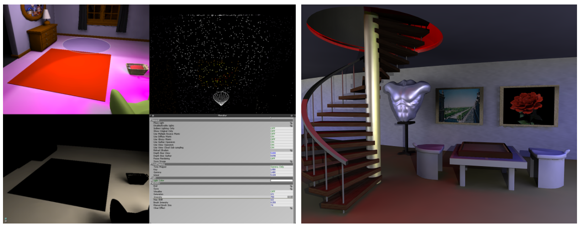

Figure 8: *Left: The user interface of iCheat [OKP*08], a method that enables editing the intensity and color of indirect, global illumination effects. Right: Example result with user-adjusted global illumination. Note that the indirect illumination on the floor matches the modified illumination inside the stairwell. (Images taken from [OKP*08].)*

5. Material Design

We refer to *material* interactions as any local interaction that manipulates the distribution of light at a surface or in a volumetric medium. Examples of materials include spatially-varying BRDFs and BSDFs that model the local reflection and transmittance profiles of a surface, the BSSRDF properties of subsurface scattering effects, the scattering properties and phase function profiles in participating media, or any combination of these properties. While these examples relate primarily to physically-accurate light transport models and simulations, non-physical or *artistic* models of local light interaction are also valid material descriptors in the context of our survey.

As with lighting design tools, material design tools and approaches enable artists to edit the final appearance of a scene. These edits, however, modify the material properties of the scene, typically assuming fixed geometry and lighting conditions. More analogues with lighting design can be drawn, as material behaviors can be edited using direct, indirect and goal-based editing paradigms. However, unlike lighting design, the literature in material design is much more recent and less established. This only recent development of more sophisticated material design approaches can be attributed to a handful of factors. Firstly, appearance modeling via material manipulation is fundamentally more difficult to formulate mathematically: while appearance changes *linearly* with respect to illumination, whether with direct- or global-illumination effects, according to well-understood mathematical models, the relationship between the final appearance and the materials in a scene is *non-linear* in general. Secondly, typical digital content creation

Figure 9: *Nonphysical, art-directed lighting and material, as used in production. Left: The flexible volumetric lighting technique of Nowrouzezahrai et al. [NJS*11] enables animated, curved light beams to visually enhance storytelling. Right: Sadeghi et al. [SPJT10] present an artist-friendly hair shading system which enables rapid modeling of desired material looks for the characters' different types of hair. (Images taken from [NJS*11, SPJT10] and ©Disney Enterprises, Inc.)*

workflows first associate materials based on the underlying "physical composition" (e.g., metal, dielectric, etc.) of an object, and only then begin light placement and manipulation in the scene; as such, lighting is more closely associated to scene setup than the materials are, and so it is also more likely to be edited in order to attain a desired appearance. A final factor that contributed to the delayed development of material design approaches relates to the relative evolution of mathematical models and simulation techniques for lighting and materials: the number of different light transport models, as well as their evolution, is much smaller than that of materials. New surface, subsurface, and volumetric material models arise more often than new methods for simulating light transport. Moreover, these material models cover a wide breadth of approaches, including basis-space reflectance models better suited to interactive shading [WRG*09], new microfacet distributions to more accurately model real-world BRDF data [WMLT07], and new volumetric distributions for accurate subsurface reflectance behavior [JAM*10]. In short, the number of material representations has increased steadily over time [DRS08, Bur12], making it difficult for any concrete material design approach to be proposed and adopted.

5.1. Material Editing Approaches

Directly editing the parameters of an underlying material model is the simplest form of material design, for example, editing the reflectance of a diffuse BRDF. Unfortunately, this approach is unintuitive as these parameters often expose too many degrees of freedom to a user and, in many cases, changes to the final appearance caused by direct parameter edits can be difficult to predict. Moreover, inconsistencies in the scale and physical interpretation of parameters between different material models further complicates intuitively controlled edits using this approach. These limitations are even more pronounced in the case of volumetric appearance editing where many physical parameters are decoupled from the final observed appearance. For example, the absorption coefficient quantifies (in a complex, scene-scale dependent fashion) the amount of light at different wavelengths that is *removed* (absorbed) during volumetric transport, instead of the amount and light that is *affected* (scattered) during transport (such as with the diffuse reflectance of a surface BRDF model) [NJS*11]. As with lighting design, more sophisticated and intuitive material design approaches allow users to specify constraints on the final targeted *appearance* before applying an underlying system to automatically determine the *material property settings* necessary to best match the requested edits.

Several model-driven approaches to material design have recently been proposed. Song et al. [STPP09] edit heterogeneous subsurface scattering on and inside surfaces, starting from the simplified diffusion model of subsurface scattering [JMLH01]. They approximate this BSSRDF model as a product of two parameterized blurring kernels, leading to a representation that is amenable to various simple parametric and image-based editing operations. Sadeghi et al. [SPJT10] present an artist-driven and controllable model for hair rendering, exposing intuitive artistic controls for generating images of hair under complex light transport scenarios (see Fig. 9, right). Their approach is built atop a high-performance rendering model that allows for rapid artist iteration. Furthermore, Sadeghi et al. explicitly alter the energy-conservation of the underlying mathematical model as many art-driven edits *require* non-physical lighting interactions (e.g., the capability of creating energy during transport) in order to obtain a desired look, even if this results in an invalidation of the underlying physical plausibility of the final edited reflectance behavior. Obert et al.'s [OKP*08] painting interface for indirect illumination exaggeration, discussed earlier in Sect. 4.2, can also be interpreted as a material design tool as the editable *transfer functions* they expose to users (indirectly) encode emitted lighting distribution or, equivalently, the reflection of the (indirect) incident lighting distributions at surfaces. Colbert's thesis [Col08] covers several approaches to material editing based on the concept of BRDF lobe (i.e. highlight) sketching under environment illumination, allowing for spatially varying BRDF editing as well as appearance matching. Colbert et al.'s BRDF-Shop [CPK06] interface allows users to sketch spatially-varying BRDF distributions for commonly used phenomenological reflectance models and, coupled with an interactive rendering tool, allows artists to very quickly visualize and manipulate simple reflectance behaviors in scenes lit by direct illumination under environment maps Khan et al. [KRFB06] use an image-based approach to estimate surrounding incident illumination given a single image, allowing the material properties of objects in an image to be edited with phenomenologically plausible results.

Data-driven and optimization techniques have also successfully been applied to the problem of material design. An and Pellacini [AP08] formulate image- and material-editing as a local search and energy minimization problem, allowing users to sketch rough appearance editing constraints and then automatically searching for patterns in the unedited dataset to warp and blend into the edited regions. Of note, they apply their approach to editing higher-dimensional spatially-varying reflectance datasets, as well as simple images and HDR map datasets. Dong et al. [DTPG11] deduce spatially-varying properties for a simple parametric reflectance model (e.g., glossiness, normal variation, and diffuse albedo), using an image-patch of a planar surface lit by a directional light source and targeted user markups in the scene. This allows them to decompose an image into a product of shading and reflectance maps that are then exposed to users in order to permit a variety of different appearance editing post-processes. An et al. [ATDP11] retarget measured material appearance by warping the reflectance behavior of a captured material according to a set of template reflectance behaviors. This approach allows users to more quickly design complex reflectance behaviors, combining the spatial variation of captured materials with the reflectance behaviors of the template materials. Kautz et al. [KBD07] edit large-scale bidirectional texture functions (BTFs) using an out-of-core system to devise new BTF data from user-specified spatially-varying micro-geometry and reflectance profiles, leveraging a data-driven analysis of existing BTF datasets during the interaction process.

Ben-Artzi et al. [BAOR06, BAERD08] express the per-pixel outgoing radiance in the reflection and rendering equations, in a fixed-view image-relighting context, as an expansion of basis elements defined according to the materials in a scene. After precomputing this extended radiance formulation, users can interactively edit the materials by reweighting the radiance expression, all while shadows and indirect illumination remain up-to-date. Sun et al. [SZC*07] similarly express outgoing radiance according to basis elements based on a library of potential materials. They instead perform the decomposition in object-space, and separately across each individual light bounce (supporting up to 2-bounces of indirect illumination), in order to additionally support interactive view manipulation. Most recently, Wu et al. [WDR11] combines micro- and macro-scale editing in a relighting framework in order to model editing across levels-of-detail, including the proper antialiasing of reflectance across scales.

Kerr and Pellacini [KP10] evaluate several material design paradigms to determine which, if any, provides a superior editing workflow for novice users. They found that manipulating BRDF parameters, either directly (e.g., varying the Phong exponent) or across perceptually mapped input spaces, outperformed image-based material design paradigms, although it is unclear whether this was due to the limitations of the underlying image-space manipulation tool they employed. Nonetheless, they clearly conclude that the type of user interface exposed to an artist for material editing can play a significant role on the utility of the underlying material design approach.

6. Rendering Challenges and Production Concerns

While solving for the light transport inside a scene at interactive rates has been tackled by many researchers (see [DK09, RDGK12, DKH*13] for recent surveys on interactive and scalable global illumination methods), their techniques are typically concerned with slightly different requirements than appearance design: dramatic changes in lighting and material are not that common and dynamism is mainly focused on geometry and camera change. Unfortunately these are exactly those components of the image formation (Eq. 1) which are usually held fixed during appearance editing.

From a rendering standpoint, two main concerns have been explored. First, appearance design should be interactive. But as scene complexity increases, it remains difficult to provide interactive feedback during light and material manipulation. This has lead to the development of various relighting engines [PVL*05, HPB06, RKKS*07]. The second main consideration has been to derive non-physical appearance models that would be inherently more controllable for artists [KPD10, NJS*11, SNM*13].

Interactive appearance design is increasingly of major interest for the special effects and animated film industries. Most major studios have adopted relighting techniques from academia, or performed their own targeted investigations. In a production environment, there are several constraints that limit the applicability of available techniques. These constraints are leading the industry in a certain direction and can be used by researchers as a guide for finding tangible future research problems.

The primary production requirement is that an appearance design tool *must* produce a preview that matches the final appearance of a shot. This preview can be noisy, consider a subset of the scene, or be lower quality in some fashion, but, given enough render time it should produce a result matching the final render. An interactive preview is of no benefit if it does not provide feedback about the final shot. This poses a significant engineering challenge, since the entire material and lighting systems (lights, textures, arbitrary shaders, etc.) available in the final renderer need to be replicated in the design tool. Some prior systems have tackled this challenge with varying degrees of automation [PVL*05, RKKS*07].

Due to this duplicate engineering burden, however, the

Figure 10: *Reiner et al. developed tools for light transport inspection and evaluated their effectiveness in comparison to straightforward approaches. From left to right, false-color rendering, spherical plots of radiance at one point in space, detecting important incident light paths, volumetric inspection, and particle flow tools. (Image taken from [RKRD12].)*

current trend has been to incorporate interactive appearance design directly into the final renderer. The shift has been towards enabling progressive updates in the final renderer (typically using ray or path tracing) with minimal need for precomputation or caches. Both the commercially available Arnold and Renderman renderers currently provide such functionality. This complexity has also inspired many studios to move towards more principled, physically based lighting and material models [Bur12]. In addition to providing vastly simplified and more intuitive models for artists—in comparison to the arbitrary shaders of the past—these systems tend to be easier to port or abstract between rendering systems due to their more rigid interfaces.

Nonetheless, these production rendering systems typically evolve slower than the pace of cutting-edge research, so studios must often make the difficult decision to either build their own separate design tools (at considerable development and maintenance effort) or to rely on updates to their core renderers. In spite of the trend for progressive final renderers, a similar challenge now exists for leveraging the full power of the GPU for interactive appearance design.

7. Open Problems & Challenges

There are two main open issues that the community should be investigating further. First, we strongly believe that fast rendering is possibly the most significant bottleneck in designing complex enough scenes. Most user studies have shown that in the presence of interactive feedback, artists are significantly more productive. Considering that appearance design is ultimately a search problem for the right parameters, this should come as no surprise. While many rendering algorithms and systems have been used in the past, we are still far away from having interactive production-quality feedback, which is what is needed to make final artistic decisions.

From an interface perspective, we believe that it still remains unclear how to control all lighting-material interactions with a unified interface that supports all lighting types, including environment maps and local area lights, together with spatially varying opaque and translucent materials. It is also challenging, and remains for future work, to convey additional information (exceeding preview renderings) about light transport and material interaction [RKRD12] (see Fig. 10). Throughout this report, we have discussed a variety of methods tailored to specific aspects of appearance design, but none encompasses all aspects concurrently. Furthermore, it remains unclear whether there is such a unified approach for appearance designs, since it often appears that different appearance parameters are manipulated more effectively with different interfaces.

Finally, in our opinion, large-scale user testing should be pursued both to validate better current interaction methods and drive more formally further research in the field.

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Table 1: *Overview of different techniques, grouped by primary goal of edits (lighting or material or combined appearance), as well as complexity of scene description (surface graphics only or participating media). For the interaction columns:* paradigm *refers to the kind of interface provided, according to Sect. 3;* scope *states whether the editing/interaction has only local effects or also includes subsequent global effects;* UI *describes what type of user interface is provided (parameters refers to traditional parameter tweaking). The* manipulation *column states which part of the scene description is being modified. Abbreviations used: Global Illumination (GI); Non-Photorealistic Rendering (NPR); Image-Based Lighting (IBL); Bidirectional Reflectance Distribution Function (BRDF); Spatially Varying BRDF (SVBRDF) = Bidirectional Texture Function (BTF); Temporally & Spatially Varying BRDF (TSVBRDF); Bidirectional Scattering Surface Reflectance Distribution Function (BSSRDF).*

		Interaction			Manipulation
Class/Method		Paradigm	Scope	UI	
Lighting					
Lights from Highlights	[PF92]	indirect	local	click & drag	direct lighting
Lighting Controls	[Bar97]	direct	local	parameters	direct lighting
Interactive Shadow Design	[PTG02]	indirect	local	click & drag; constraints	direct lighting
Lpics	[PVL*05]	direct	global	parameters	cinematic relighting
Direct-to-indirect Transfer	[HPB06]	direct	global	parameters	cinematic relighting
Lightspeed	[RKKS*07]	direct	global	parameters	cinematic relighting
Dynamic BRDF Relighting	[SZC*07]	direct	global	parameters	cinematic relighting
Goal Based Lighting Design	[CdSF99]	goal-based	global	place light sources	surface GI
Lighting with Paint	[PBMF07]	goal-based	global	painting	surface (NPR; GI)
BendyLights	[KPD10]	direct	global	manipulators	surface GI
HDR Painting	[KC07]	direct	local	painting	IBL
All-Frequency Shadow Design	[OPP10]	indirect	local	click & drag deformation	IBL shadows
envyLight	[Pel10]	indirect	global	painting; parameters	IBL
Material					
Real-time BRDF editing	[BAOR06]	direct	local	parameters; curve editing	BRDF
BRDF-Shop	[CPK06]	goal-based	local	painting	BRDF
Interactive BTF Editing	[KBD07]	direct	local	drill-down; curve editing	SVBRDF
AppWand	[PL07]	goal-based	global	constraint painting	TSVBRDF
Polynomial BRDF	[BAERD08]	direct	global	parameters	BRDF
AppGen	[DTPG11]	goal-based	global	component sketching	SVBRDF
Bi-scale Material Design	[WDR11]	direct	global	parameters; visualization	BRDF
SubEdit	[STPP09]	direct	global	masking; selection	SVBSSRDF
AppWarp	[ATDP11]	goal-based	global	template sketching	B(SS)RDF
Interactive Albedo Editing	[HR13]	direct	global	painting	heterogeneous media
Appearance (Lighting & Material)					
Image-Based Material Editing	[KRFB06]	direct	local	specify matte & material	image (photograph)
AppProp	[AP08]	goal-based	global	painting	image (photograph)
iCheat	[OKP*08]	indirect	global	painting; labeling	surface light transport
Path-Space Manipulation	[SNM*13]	direct	global	filters; manipulators	surface light transport
Reflection Editing	[ROTS09]	indirect	local	click & drag	reflected light
On-Surface Signal Deformation	[RTD*10]	direct	local	constraints; click & drag	on-surface signal
Artist-Friendly Hair Shading	[SPJT10]	direct	local	falloff curves; parameters	hair scattering
Artistic Beams	[NJS*11]	direct	local	spatial curves; shaders	heterogeneous media
Volume Stylizer	[KISE13]	indirect	global	painting	heterogeneous media