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Automatic lighting design from photographic rules

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Figure 1: Our lighting setup produces realistic images for any kind of opaque surfaces, where shapes of objects are always properly conveyed.

Abstract

Lighting design is crucial in 3D scenes modeling for its ability to provide cues to understand the objects shape. However a lot of time, skills, trials and errors are required to obtain a desired result. Existing automatic lighting methods for conveying the shape of 3D objects are based either on costly optimizations or on non-realistic shading effects. Also they do not take the material information into account. In this paper, we propose a new method that automatically suggests a lighting setup to reveal the shape of a 3D model, taking into account its material and its geometric properties. Our method is independent from the rendering algorithm. It is based on lighting rules extracted from photography books, applied through a fast and simple geometric analysis. We illustrate our algorithm on objects having different shapes and materials, and we show by both visual and metric evaluation that it is comparable to optimization methods in terms of lighting setups quality. Thanks to its genericity our algorithm could be integrated in any rendering pipeline to suggest appropriate lighting.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Color, shading, shadowing, and texture—

1. Introduction

Lighting design has a strong influence on images quality both in the virtual and in the real world. Indeed the perception of the features of an object, such as its shape or its material, is strongly influenced by the lighting [CF07]. However, the need for lighting experts in films and games productions [VHK*15] proves the difficulty of the design, the main obstacles being the large number of parameters involved and the complex behavior of light. The purpose of automatic lighting design is to avoid this time consuming process, by suggesting an appropriate lighting setup for a given scene. In this paper we focus on the depiction of shape in 3D scenes which we consider as the most important feature to understand images.

Finding an appropriate lighting setup for a scene has been studied in several research works, that we can classify in two parts. On the one hand, there exists tools allowing the user to place and parameterize the lights via a graphical interface. Such approaches give control to the user on the lighting but require skills, trials and errors before obtaining the desired result. On the other hand, automatic methods have been proposed to compute a lighting setup for a given scene, avoiding to require particular skills from the user. However, either these methods rely on costly optimization frameworks, or they lack genericity since light parameters or shading type are constrained.

Our approach for automatic lighting design is inspired from handbooks of photography in which professionals describe common techniques to design lighting environments that accurately depict the shape of a subject. In this paper, we make the following contributions:

- We collect and classify lighting rules from photography books related to shape depiction and perception;
- We propose a method that uses these rules to automatically propose an appropriate lighting setup given an input object, its material and camera properties.

As opposed to previous techniques, our method does not rely on complex optimization processes. It can also be naturally integrated in any global illumination algorithm to generate realistic images.

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2. Related Work

Due to the importance of lighting in computer generated images, there has been an extensive research on lighting design. In this section, we present existing methods, classified between manual and automatic approaches.

2.1. Manual Lighting Design

The first way to set the illumination of a scene is direct lighting design, in which the lights are placed and parameterized by hand, then adjusted after visual evaluation until satisfaction. This method is used in computer generated movies and games productions using dedicated lighting and preview tools [Bir13] but also in studio photography with real lights [HBF07]. It gives a large freedom in the design but requires a large amount of work and lighting skills.

Inverse lighting design approaches have been proposed in order to reduce the complexity and time of the task. Such methods usually provide intuitive interfaces where the radiance can be painted directly on the objects surfaces [SDS*93, PBMF07], possibly with interactive previews [OMIS06]. These tools are more intuitive than designing the lighting by hand. However, they rely on costly computations to find the lighting parameters and still require a lot of trials and errors from users before reaching the desired result. To increase the usability of such methods, Pellacini *et al.* [Pel10] give direct control to the user on more specific lighting features, such as shadows and highlights.

El-Nasr and Horshwill [ENH04] and Zupko *et al.* [ZEN08] proposed a method to suggest lighting setups during interaction. Like us they rely on lighting rules extracted from photography and cinematography, but focus on the depiction of style rather than shape. Their work is dedicated to lighting artists that define the lighting style by either an objective function [ENH04] or an example image [ZEN08]. Halle and Meng [HM03] introduced a method inspired by photographic, cinematographic and theatric lighting. We classify their method as manual since it only suggests a setup with default parameters, without taking the scene into account, and lets the user adjust it.

Manual methods can be easily used by expert users to design complex lighting setups and emphasize the shape of an object. However a naive user may still have difficulties to obtain a desired result because of his lack of knowledge about the complex interactions between light, shape and materials.

2.2. Automatic Lighting Design

Automatic lighting targets non expert users and tries to automatically propose an efficient lighting setup for a given scene.

Optimization. A common way of solving the problem of automatic lighting design is to optimize the lighting setup parameters, according to an objective function that quantifies the quality of the result.

The objective function of Shacked *et al.* [SL01] quantifies the presence of features needed to understand a 3D scene in an image, for example edges or shading gradients. Like our work they are inspired by visual perception studies, however their method is not fully automatic since the user must adjust the weights associated to the terms of the function according to the scene.

Gumhold [Gum02] maximizes the quantity of information by optimizing the Shannon entropy of the luminance in the output image. His metric takes also into account the fact that too dark regions have to be avoided and regions with high curvature must be emphasized, a strategy similar to ours. Vasquez [Vaz07] computes the entropy at different image resolutions, allowing to quantify the information conveyed from fine details to global shape. Bousseau *et al.* [BCRA11] also rely on optimization and are inspired by photographic rules, but their work focus on depicting materials instead of shapes.

Optimization methods all share two main drawbacks. First, they are costly since at each step of the optimization process multiple renderings must be done for both evaluating the current lighting setup and for finding the next search direction in the space of light parameters. Second, due to the complexity of the human processes implied in shape understanding from images, it is difficult to reduce it to a mathematical function that can work for all scenes. For this reason we decided to avoid to compute an optimization but to rely on a scene analysis.

Scene Analysis. To avoid the drawbacks of a costly optimization process, the following methods rely on an analysis of the scene to suggest a lighting setup.

Lee *et al.* [LHV04, LHV06] proposed a method based on physically inconsistent lighting to enhance the perception of geometry. They segment the object in surfaces of similar curvatures, then each one is assigned to a light whose goal is to produce highlights in the direction of maximal curvature. Additional lights are used to emphasize the silhouette and to produce shadows at depth discontinuities. Their method is dependent on the illumination model, since it is designed such that each surface receives only the illumination of its light. Thus it lacks genericity and especially avoids the use of physically realistic rendering.

Finally, Zhang *et al.* [ZM13] presented a method based on a default lighting setup of three lights. The main light aims at producing a shading contrast on the surfaces. A second light is adjusted depending on the normals of the scene and compensates the hard shadows produced by the main light. A back light is used to illuminate transparent volumes, emphasizing their depth. This method is the most closely related to ours since its goal is to produce contrasts to reveal the shape. However, they only handle directional lights, avoiding to control the hardness of shadows. Moreover, their setup specifically targets volumetric rendered scenes of translucent objects, while our method focuses on opaque surfaces.

3. Photographic Lighting Rules

Photography is one of the first field where people had to properly control lights so as to reveal specific properties in a scene. Despite the fact that this is a subjective field, expert photographs know how to position lights in order to create a particular ambiance, to reveal shapes or to exaggerate shadows in a given scene. In this paper, we are interested in extracting standard photography lighting rules dedicated to convey shape through shading. This section summarizes and classifies the main lighting rules selected in photography books to reveal the shapes of objects. Note that our work focuses on opaque surfaces. We leave transparent and translucent effects for future work.

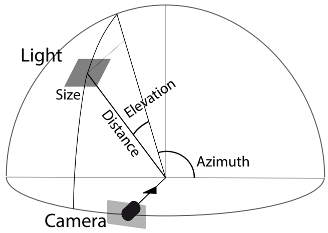


Figure 2: Coordinates system for the light position

The key idea guiding all rules stated below is to choose the light parameters that will maximize tonal variation, i.e. variation in luminance, for a given shape, material and framing. Depending on the material, the tonal variation will be obtained differently. Indeed, diffuse materials, such as paper, reflect the energy uniformly, meaning that their appearance stays similar wherever the camera is. On the contrary, specular materials, such as metal, reflect light in only a specific subset of directions based on the angle at which the light comes. Due to this difference of behavior, these two categories of materials have to be considered separately when applying lighting rules on a subject. In Sections 3.2 to 3.5 we describe how the light parameters are used to control the tonal variation for diffuse materials before discussing in Section 3.6 the case of full specular materials that need a special treatment. We start in Section 3.1 by specifying the parameters of the lights that have to be set. The lighting rules stated below form the basis of our automatic lighting method presented in sections 4 and 5.

3.1. Lights Parameters

To apply photographic lighting rules to rendering, we must use a light model that behaves as close as possible to real lamps. For that we decided to use area lights, i.e. surfaces that emit light, since it allows to control the size of the light, an important parameter as stated in section 3.4. Another advantage of using area lights is that it is a common light model in rendering [Bir13] and thus is available in any rendering tool. The parameters defining an area light are its position and orientation, the size of its emitting area and its intensity. In this work we choose to orient area lights orthogonally to the direction between the position of the light and its target, which is the center of the object bounding box.

We express the position of the lights relative to the camera frame and the object position, in coherence with the perception studies of Kleffner *et al.* [KR92] and Adams [Ada08]. Indeed, these works show that, when observing an object, the human visual system analyzes the light position in a coordinate system attached to the head rather than to the 3D scene and the gravity force direction. As shown in Figure 2, we define the light position using spherical coordinates:

- The azimuth angle, representing the angle around the subject in the picture plane;
- The elevation angle, representing the height relative to the subject above the picture plane;
- The distance to the subject.

3.2. Azimuth of Light

In photography, the term volume is used to refer to the global depth variations of a subject in the frame. When lighting a non-flat surface, photographers produce tonal variations by placing the light on one side of the object, causing a side to be illuminated and the other to be in shadow [HBF07, Chi08, Dav08]. This effect is shown on a pear in the inset image[†], where a tonal variation is obtained by positioning a light on the right side of the fruit. The azimuth of the light determines which side is lit and is chosen so as to maximize tonal variations.

3.3. Elevation of Light

While the term volume refers to depth variations of a subject at a global scale, we refer to depth variation of shapes at a local scale as geometric details. The perception of these geometric details are especially sensible to the elevation of light.

Typically a flat subject with small surface details will need a light at a grazing angle to best reveal its shape. This is equivalent to create a tonal variation for each geometric feature independently since it causes a side of the geometric features to be illuminated while the other side is in shadow [HBF07, Pra07, Dav08, Tuc09]. As illustrated on a Maya bas-relief in the inset[‡], this effect accentuates the depth perception of cavities and other geometric features, thereby revealing the shape. Note that for volumetric subjects, the elevation usually has to be increased to convey small and large features simultaneously.

3.4. Distance and Size of Lights

The distance and size of area lights change the set of directions of the light hitting the surface, and therefore have a dramatic impact on the type of shadows casted by the object onto itself. Light rays produced by a distant or a small size light will hit a surface point with almost parallel directions, thus leading to hard casted shadows with well defined edges. On the other hand light rays from a close or a large light source will hit a surface point in all possible directions, thus producing soft casted shadows with smooth edges.

To emphasize the shape of a subject, hard shadows should be preferred since it increases depth perception. However too hard shadows can distract from the subject [HBF07]. The good compromise between hard and soft shadows is essentially an aesthetic parameter, leading to a subjective choice.

3.5. Secondary light

Using a single light can produce regions that are too dark. To avoid this drawback, a common practice is to use a fill light, i.e. a secondary light which goal is to light-up these dark regions. The fill

† `https://pixabay.com` - erbs55, 2015 - under CC0 1.0
‡ `https://www.flickr.com` - Ann Wuyts, 2010 - under CC BY 2.0

light has to be correctly adjusted for not canceling the tonal variation produced by the main light. For this reason, the fill light must have an intensity less than half of the main light. To avoid interferences with the main light, the fill light should be as large as the main light, since it must produce the same smoothness of shadows.

3.6. Specular Surfaces

Purely specular materials require different rules since their apparent illumination is impacted by the camera position as well. If we apply the rule of tonal variation similarly to a diffuse object by choosing a light at a grazing angle, we have great risks that the camera will not receive enough light, leading to an almost entirely dark object. Thus, the angles that produce a reflection to the camera have to be taken into account when setting up the lighting. The idea is to fill a large part of these angles with a large light, producing highlights on surfaces. This effect is illustrated in the inset[§] where a specular statue has been lit with a large light, revealing all its details. Note that using the same large light with a diffuse material would produce an almost constant tonal value all over the object.

4. Lighting Setup for Diffuse Objects

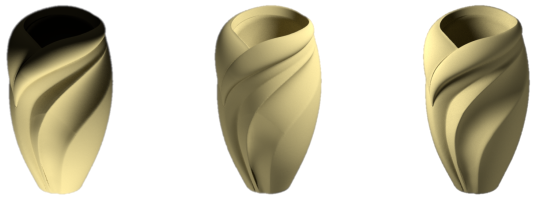
From the photographic lighting rules presented in section 3, the simplest lighting setup consists in a key light to produce tonal variation, combined with a fill light to reduce too strong shadows. Therefore, our algorithm takes as input a scene defined by a 3D model with its material and the position of the camera and computes the parameters of these two lights in order to maximize the tonal variation of the rendered image. For that we devise computation rules for each light parameter based on extracted geometric properties of the 3D model. These parameters are independent of the chosen rendering algorithm and can serve as a basis for further manual adjustment if needed.

It is important to note that geometric properties are extracted relatively to the camera in order to analyze only visible parts of the subjects. To that end, we first project geometry data into dedicated g-buffers [ST90] before computing light parameters.

4.1. Key Light

The main light of our lighting setup is the key light, whose goal is to produce tonal variation as presented in section 3. We show in this section that we can reveal both object curvatures and geometric details of surfaces by applying well-designed strategies to find the key light azimuth and elevation.

Azimuth. To suggest an appropriate azimuth for the main light, we have taken into account the visual perception studies of Ramachandran [Ram88], Kleffner [KR92] and Mamassian [MG01] about the assumptions made by the human visual system on light position. They have shown that, in the absence of direct cues, our visual system assumes the light coming from above, implying that a light



(a) $azimuth = 270°$ (b) $azimuth = 60°$ (c) $azimuth = 155°$

Figure 3: **Light azimuth.** With inappropriate angles, the light either removes significant variations (a) or flatten shape variations (b). Our computation of azimuth ensures the main variations to be clearly visible (c).

coming from below is misleading for shape perception. For this reason we always use an azimuth between $0°$ and $180°$, such that the light is positioned in the top hemisphere of the picture plane.

The photographer adjusts the position of the light according to the shape of the subject such that the tonal variation is maximized. To reproduce this rule, we analyze the projected shape of the 3D model and deduce an azimuth that maximizes the contrast along the main geometric features.

More precisely, we use the structure tensor [BVL*06] to estimate in which direction the main variations of the surface appear. The gradient of the surface depth is first obtained from the normal coordinates in image space: $\nabla d = (-n_x/n_z, -n_y/n_z)^T$. We then compute the 2×2 structure tensor $\mathcal{S}$ on the entire set of visible surface points:

$$\mathcal{S} = \sum_{i \in I} \nabla d(i) \nabla d(i)^T,$$

where I is the set of all pixels i on which the surface has been projected with a given camera in the g-buffer. The eigenvector $\mathbf{e_1}$ associated to the largest eigenvalue λ_1 extracted from $\mathcal{S}$ represents the direction in which most surface variations appear. We also take into account the anisotropy $\mathcal{A}$ of the variations to check whether $\mathbf{e_1}$ is significant or not compared to other directions:

$$\mathcal{A} = \frac{\lambda_1 - \lambda_2}{\lambda_1 + \lambda_2}.$$

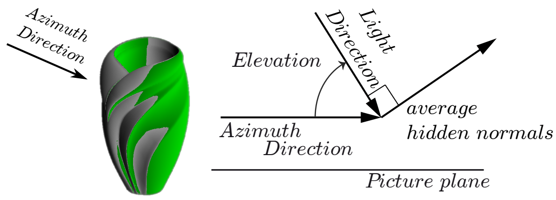
Our estimation of azimuth for the light is then given by:

$$Azimuth = \begin{cases} 120° & \text{if } \mathcal{A} < T \\ \angle \mathbf{e_1} & \text{if } \mathcal{A} > T \text{ and } 0 \leq \angle \mathbf{e_1} \leq 180° \\ \angle \mathbf{e_1} - 180° & \text{otherwise,} \end{cases} \quad (1)$$

where $\angle \mathbf{e_1} \in [0, 360]$ refers to the angle of $\mathbf{e_1}$ in our coordinate system, and T is a user-defined threshold that controls how anisotropic the surface should be to use the extracted main direction of variations. In practice, we use $T = 0.2$ for all the examples in this paper. Under this value, we consider that there is no preferred direction for the light and we use an azimuth equals to $120°$ (top-left), as specified by the studies of Mamassian [MG01].

The resulting azimuth can be seen in Figure 3(c) where tonal variations appear along the main features of the vase and consequently enhance the shape. When an inappropriate azimuth is cho-

§ https://www.flickr.com - Lamerie, 2010 - under CC BY-NC 2.0



(a) $\mathcal{H}$ (green region) (b) Elevation angle

Figure 4: **Elevation computation.** (a) The green region is the set $\mathcal{H}$ of surface points with hidden normals (equation 2). (b) The elevation is chosen such that the light direction is orthogonal to the averaged hidden normals in the picture plane.

sen as in Figure 3(b), the shape appears more flat because some features are aligned with the light and and therefore do not produce tonal variations.

Elevation. In our coordinate system, the angle of elevation defines the height of the light relative to the object. Following the concepts used in photography, we propose to compute an elevation angle that produces a grazing light according to geometric features.

For that, we initialize the light direction $\mathbf{l_o}$ with an elevation of 0° and isolate the set $\mathcal{H}$ of surface points in which the upper hemisphere does not contain this initial light direction:

$$\mathcal{H} = \{i \in I \mid \mathbf{l_o} \cdot \mathbf{n_i} > 0\}, \quad (2)$$

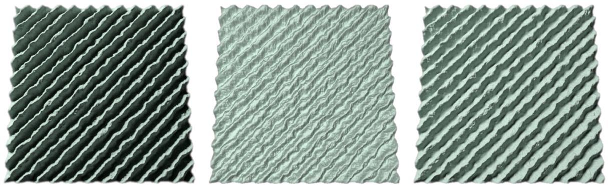
where $\mathbf{n_i}$ is the surface normal in camera space at pixel i in I. The resulting set can be seen in the green region of the vase in Figure 4(a). The final elevation is then chosen such that the light vector is orthogonal to the averaged hidden normals, as shown in Figure 4(b):

$$Elevation = 90^\circ - arccos(mean\{\mathbf{l_o} \cdot \mathbf{n_i} \mid i \in \mathcal{H}\}) * 360/2\pi. \quad (3)$$

The resulting elevation on a detailed heightfield can be seen in Figure 5. A low elevation (a) maximizes the contrast but produces too dark regions with no visible details. On the contrary, a too high elevation (b) illuminates the surface uniformly and hides important shape variations. Our estimated elevation (c) produces strong tonal variations where the whole shape is still clearly visible.

Size, Distance and Intensity. As stated in Section 3.4 the hardness of shadows is influenced by both the size and distance of the light. For instance, soft shadows can be obtained using either a close small light or a distant large light. If this cue is often a subjective choice, one has to be careful to produce not too hard or too soft shadows that would perturb the final shape appearance. Therefore, we suggest to fix the size equals to the diameter of the projected object in the picture plane and the distance to 5 times this diameter. These choices ensure that any part of the scene receive an equivalent amount of light. Then, the user can easily increase or decrease the light size to respectively obtain harder of softer shadows.

Figure 6 shows the influence of the light size on the hardness of shadows. When chosen too small (a), hard shadows produce strong discontinuities and may disturb the perceived shape. A too large



(a) $elevation = 5^\circ$ (b) $elevation = 80^\circ$ (c) $elevation = 43^\circ$

Figure 5: **Light elevation.** A too low elevation (a) produces strong disturbing discontinuities and shadows that may hide some details. A too high elevation (b) tends to flatten the surface with almost the same intensity everywhere. Our approach (c) estimates a proper trade-off that produces enough variations, without removing details.

light (b) rather tends to smooth all the geometric features. Our parameters of size and distance (c) allows shadows to be soft enough, without hiding shape details.

By default, we set the light intensity to a radiance of 20 units of power by unit of area. However, it is worth noting that this parameter might be arbitrarily modified since the output average luminances are mainly due to the tone mapping operator [RSSF02] applied after each rendering.

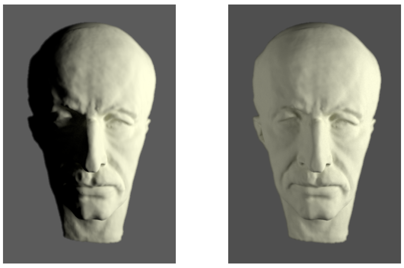
4.2. Fill Light

When using a single light, occlusions might still create very dark regions and hide geometric details. This effect is illustrated in Figure 7(a), where the key light is not sufficient to convey the right cheek. To overcome this problem we again take inspiration from photography by using a secondary light, the fill light, whose role is to illuminate the darkest regions of the scene, as explained in section 3.5. We explain here in details how to compute the parameters of such a fill light.

Position. The secondary light has to illuminate the darkest parts of the scene. Therefore we suggest an azimuth opposed to the one of the key light, i.e. we add 180° to the azimuth of the key light. To reveal the geometric details we compute the elevation using the same rule as the key light: we consider the normals opposed to the fill light to compute an angle corresponding to a grazing light, as explained in section 4.1.

(a) $size = \frac{1}{4}$ diameter (b) $size = 4$ diameter (c) $size =$ diameter

Figure 6: **Light size.** With a fixed distance of 5 diameters, too small (a) or too large (b) light sizes tend to remove or hide important shape details. Our suggestion (c) produces soft shadows while preserving main tonal variations.



(a) key light only (b) key+fill lights

Figure 7: **Fill light.** The key light only (a) might still produce dark regions. Adding a proper fill light (b) allows all features to be visible, without cancelling the variations due to the key light.

Size, Distance and Intensity. As recommended by Hunter *et al.* [HBF07], the fill light should be as large as the main light to not produce shadows with different smoothness, therefore we follow this advice and use the same distances and sizes for both lights.

However, the intensity has to be chosen carefully in order to not cancel the tonal variation created by the key light. We propose to choose the intensity of the fill light according to the variance of the normal distribution. Indeed, the key light has more chance to create dark regions when the variance of normals is high. This strategy is similar to the one used by Zhang *et al.* [ZM13]. Unlike them we compute this variance only on surface points hidden from the key light (*i.e.* $\mathcal{H}$) since the fill light should mainly affect the darkest regions.

Given I_k the intensity of the key light and $\sigma_{\mathcal{H}}$ the standard deviation of the set $\mathcal{H}$ of hidden normals defined in equation 2, the intensity of the fill light I_f is defined as:

$$I_f = \frac{\sigma_{\mathcal{H}} I_k}{2}.$$

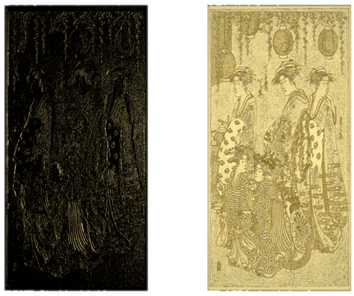
By dividing by 2, we ensure that the intensity of the fill light does not exceed half the intensity of the main light. This limit is necessary to not break the main tonal variation.

The resulting effect of the fill light can be seen in Figure 7(b), where the whole face is visible.

5. Lighting Setup for Specular Objects

This section presents our automatic lighting setup for revealing the shape of an object having a specular material. Here the problem we have to solve is to place the light such that the camera receives a large part of the reflections produced by the object surface. The discontinuities of the shape will be visible thanks to the difference of illumination at discontinuities. Therefore we devised a different rule than for diffuse objects where a light at a grazing angle has a great chance to produce a very dark image as shown Figure 8(a).

To maximize the specular reflections, we analyze their distribution as explained now. First, each reflection vector is expressed in azimuth and elevation in the same frame as the light directions. In order to fill a sufficient part of the reflections, the position of the light is set as the mean of the azimuths and the mean of the elevations.



(a) diffuse rule (b) specular rule

Figure 8: **Specular materials.** The behavior of the light for specular materials requires different strategies for estimating the lighting setup. (a) The setup used for objects having a diffuse component leads to a complete dark image. (b) By placing the light in the set of reflected angles and choosing an appropriate size, all details are revealed.

Then the size of the light will control the range of specular reflections that will be visible. The light must be at least as large as the object to ensure that each part will receive light. However increasing the light size may be necessary to increase the visible reflections. We propose to add a quantity proportional to the standard deviation of the reflection distribution to the object size. By default we add 1 standard deviation, which produces satisfactory results for both flat and volumetric objects.

Given l the object radius, d the distance between the light and the object and σ the standard deviation of reflections, we obtain the light size L by computing (Figure 9):

$$L = l + 2d\tan(\sigma)$$

A rendering result that uses this rule on a metal surface can be seen in Figure 8(b), where all details are now visible.

6. Results

We implemented our method as a plugin in Gratin [VB15], an application dedicated to GPU programming. Object normals are projected and stored inside g-buffers [ST90] before being analyzed. The computation of light parameters is done in real-time on the GPU. Once the lighting setup obtained, we render the scene using a

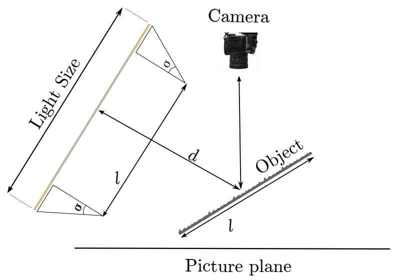


Figure 9: **Light size for specular objects.** d is the light distance, l is the object radius and σ is the standard deviation of reflection vectors.

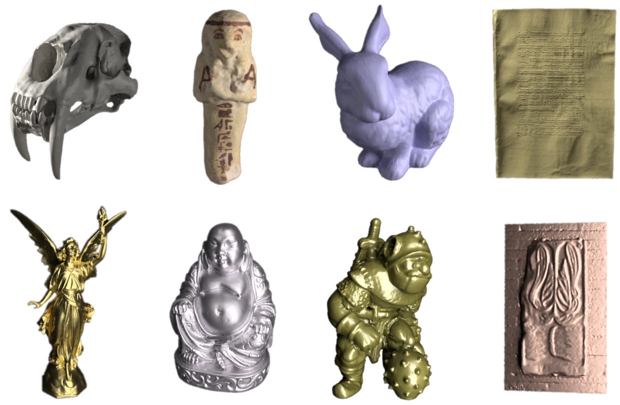


Figure 10: **Results with different shapes and materials.** The first row uses diffuse rules, the second row uses specular rules.

Model	Lee *et al.* [LHV06]	Gumhold [Gum02]	ours
Skull	2.92	3.01	2.92
Pelvis	3.00	2.93	2.87
Statue	2.86	3.00	3.03

Table 1: Entropy computed on the results of Figure 11

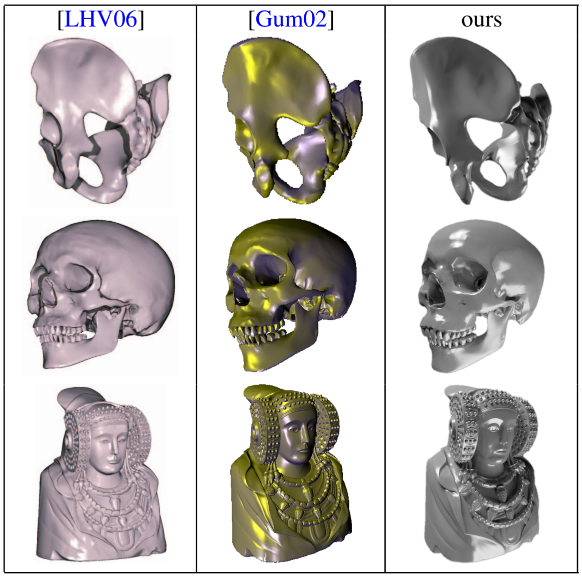


Figure 11: Comparison of the methods of Lee *et al.* [LHV06] and Gumhold [Gum02] with ours. The three models are identical and have the same material.

global illumination algorithm in Mitsuba [Jak10]. Obtained images are automatically tone mapped with the algorithm of Reinhard *et al.* [RSSF02] to make sure that most image variations appear when displayed on a screen.

6.1. Variation of Shapes and Materials

Results for different objects and materials can be seen in Figure 1. The first four objects use the diffuse rule while the last result uses the specular rules. Additional results are presented in Figure 10. Objects of the first row use the diffuse rule, while the specular rule is used for the second row.

We can note that our method reveals both volume and geometric details of the objects, whatever their shape or material. For example, the details of bas-reliefs are revealed for both diffuse and specular materials. Complex geometric details of volumes are also visible, for instance the cavities of the skull or the creases of the statue. The global shape of characters is also well conveyed, as for the bunny or the soldier.

6.2. Comparison with previous works

We compare our results with the method of Gumhold [Gum02], which optimizes the luminance entropy, and the method of Lee *et al.* [LHV06], which uses local lights and non realistic lighting. The results are obtained from the same model and the same material.

Visual comparison. As shown in Figure 11, our method does not alter the visual appearance of the material. On the contrary, Gumhold uses light colors, producing yellow reflections on surfaces, and Lee *et al.* uses a non realistic lighting model which alters the surface colors. We can note that our method reveals both the global shape and geometric details of the models. Especially, we perceive well the curvature of the pelvis bone on its left, and all its details on its right. We also reveal the volume of the collar on the statue by producing shadows and tonal variation, while it looks flatter with the other methods.

Entropy. Lighting is subjective, therefore it is difficult to find a metric to evaluate it. Following [Gum02] we propose to measure the Shannon entropy computed on the luminance histogram of images which quantifies the amount of information produced by the lighting. Note that the entropy is more a cue than a reliable evaluation of the visual quality of the lighting, since it can be high for inappropriate lighting setups as stated by Gumhold. The entropy is computed from the luminance histogram as

$$H = \sum_{i=1}^{m} p_i \, log_2 \frac{1}{p_i}$$

where m is the number of bins of the histogram and p_i is the probability of a pixel to be in the bin i. In Table 1 we compare the entropy obtained by the 3 methods on models used in Figure 11. All three methods obtain similar entropies on these models. Our method has the best entropy for the statue, since we produce more contrast on the chest. We perform the lowest entropy on the pelvis bone, since our method produces less color variation on the left part. However it does not alter the perception of curvature since there is still a tonal variation.

7. Conclusion

We introduced a method that automatically proposes an appropriate lighting setup to reveal the shape of a given input object. By relying on photographic rules and visual perception principles we estimate light parameters using a simple analysis of the projected geometry.

Our method still has limitations that we would like to improve in the future. First, Our model does not take occlusions into account when estimating the position of the light. Consequently, undesirable shadows might occur in the presence of occluders, as seen in the inset image.

Second, our method is limited to diffuse and specular objects. We would like to investigate more complex materials, such as transparent or translucent surfaces. Finally, our system could include more than two lights for depicting other shape properties. For instance, a backlight could be added, as it is often used by photographs to exaggerate silhouettes or edges.

In the future we plan to integrate our method in various applications. In 3D modeling tools, our method would allow artists to initialize a lighting environment in a scene. We could also extend our system to make it temporally coherent and thus more adapted to animated movies. Another promising idea would be to use our system in real-world applications. For instance, it could be used to propose the lighting setup of real objects in museums or in studio photography.

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