Practical Image-Based Relighting and Editing with Spherical-Harmonics and Local Lights

Borom Tunwattanapong[1], Abhijeet Ghosh[2], Paul Debevec[2]

[1] University of Southern California [2] USC Institute of Creative Technologies

Abstract

We present a practical technique for image-based relighting under environmental illumination which greatly reduces the number of required photographs compared to traditional techniques, while still achieving high quality editable relighting results. The proposed method employs an optimization procedure to combine spherical harmonics, a global lighting basis, with a set of local lights. Our choice of lighting basis captures both low and high frequency components of typical surface reflectance functions while generating close approximations to the ground truth with an order of magnitude less data. This technique benefits the acquisition process by reducing the number of required photographs, while simplifying the modification of reflectance data and enabling artistic lighting edits for post-production effects. Here, we demonstrate two desirable lighting edits, modifying light intensity and angular width, employing the proposed lighting basis.

Keywords: Image-based relighting, editing, spherical harmonics, local lights.

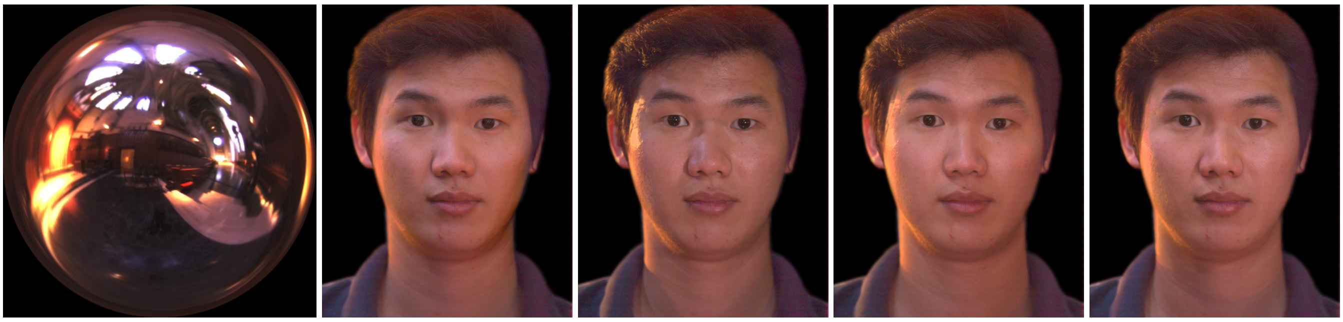
1 Introduction

Image-based relighting has been very successfully employed in production pipelines to achieve highly realistic relighting results with complex real world illumination. However, the process traditionally requires a subject to be photographed in a dense set of lighting directions and uses the linearity of light transport together with the recorded illumination of the target environment in order to relight the subject [2]. This can be a very data intensive process because such datasets typically involve photographing hundreds of lighting directions. This adds difficulty to the acquisition process and the dense data capture typically lasts long enough to only be suitable for static subjects. Once captured, it can also be difficult to modify or edit the data in post-production environments because the data is high dimensional. Adjustments may have to be made in several dimensions in order to add artistic effects to the result, which can be a cumbersome process.

In this work, we present a practical relighting technique that greatly reduces the number of images required for relighting under environmental illumination, while still achieving high quality results. We propose image-based relighting under environmental illumination by combining spherical harmonics (SH), a global lighting basis, with a set of local light sources. Spherical harmonics can efficiently capture smooth low frequency illumination [16], while local lights can efficiently capture the high frequency highlights and shadowing effects. Combining both representations of lighting, we create relighting results that include both low frequency as well as high frequency lighting effects and are a close approximation to the ground truth (see Fig. 1). Here, we employ an optimization procedure in order to solve for the weights of the combination for the SH and local lights and demonstrate good qualitative relighting results with a budget of around *only* 20 lighting conditions. Our technique benefits the acquisition process by reducing the number of required photographs by an order of magnitude compared to traditional image-based relighting, which in turn results in a much more practical data acquisition. In addition, fewer dimensions of the data potentially simplifies modification or editing of reflectance data for post-production effects, which is highly desirable given that artistic editing of lighting effects is inevitable in production pipelines. We demonstrate two types of artistic lighting edits to the relit result including intensity and angular width modulation of selected local lights that are typically desired in any post-production work-flow. To summarize, the principal contributions of this work are:

- A practical technique for image-based relighting that greatly reduces the number of required images for high quality editable relighting results.
- An optimization procedure that combines low order spherical harmonics with a set of local lights to generate a close approximation to a given environment illumination.
- An image-based approach for artistic editing of the relit result including intensity and angular width modulation of the incident illumination.

The rest of the paper is structured as follows: we first review some relevant previous work in Section 2, before describing our relighting technique in Section 3, and some possible image-based artistic edits in Section 4. Finally, we present an analysis of the technique and comparison to other lighting bases in Section 5, followed by a discussion on the merits of the technique in Section 6.



(a) EM (b) 20 SH lights (c) 20 local lights (d) Our technique (e) Ground truth

***Figure 1:** Face relighting comparison under the Grace cathedral environment (a). (b)* 20 *SH lights fail to capture the high frequency highlight of the bright orange alter correctly while also introducing a slight color banding artifact on the left side of the face. (c)* 20 *local lights capture the high frequency lighting effects, but do not accurately capture the low frequency lighting. (d) Our proposed technique for combining SH lighting with local lights (20 lighting conditions) captures both low frequency and high frequency lighting effects. (e) Ground truth image-based relighting consisting of* 156 *lights.*

2 Previous Work

Image-based relighting has been widely researched over the recent years in computer graphics, both in terms of acquisition techniques as well as the choice of basis for encoding of reflectance functions for relighting. We will restrict the following discussion to relighting techniques under directional lighting with no assumption of geometry or reflectance properties.

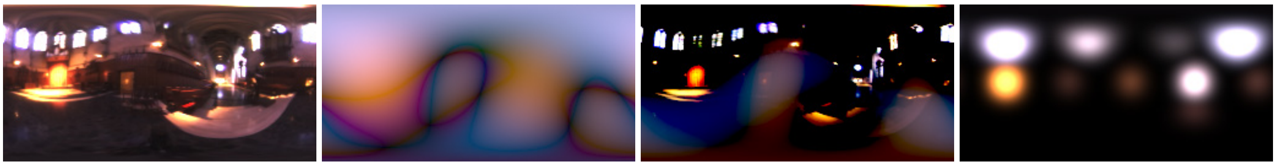
Image-based Relighting. Nimeroff et al. [11] first introduced the idea of relighting images as a linear combination of a set of basis images. Using a device called a Light Stage, Debevec et al. [2] recorded reflectance functions of a face at relatively high angular resolution and achieved very realistic relighting results with the acquired data. Subsequent versions of the apparatus improved on the acquisition time [4, 22] or generalized to a non-regular sampling of lighting directions [7]. Matusik et al. [8] extended the approach for viewpoint independent relighting. However, these approaches are data-intensive in both acquisition and storage. Additionally, inclusion and editing of the data in production pipelines requires significant effort. More recently, Peers et al. [14] proposed a reflectance transfer approach for image based relighting of facial performance. However, it is difficult to generalize the approach for relighting arbitrary objects.

Relighting Basis. Nimeroff et al. [11] proposed a set of steerable basis functions for image-based relighting and demonstrated relighting results for low frequency natural sky lighting. Spherical harmonics were first proposed by Westin et al. [23] as a basis for reflectance functions in computer graphics. Ramamoorthi and Hanrahan proposed using spherical harmonics to efficiently capture diffuse low frequency illumination [16], and extended the analysis to higher order SH for glossy and specular reflections [17]. Similar analysis has been done for relighting with pre-computed radiance transfer (PRT) [19, 5]. A significant drawback of the SH basis is Gibbs ringing or aliasing artifacts which occurs around high frequency features, such as highlights. Hence, Ng et al. [9, 10] proposed using a non-linear Haar wavelet basis for high frequency relighting. Subsequent work has proposed other non-linear representations such as spherical radial basis functions (SRBFs) [20] for even better compression of reflectance functions in a PRT context.

In this work, we demonstrate good qualitative relighting results with a budget of around *only* 20 lighting conditions. For such a restricted budget of lighting conditions, linear measurements with bases such as wavelets or SRBFs would not appropriately localize leading to a somewhat low frequency reconstruction. While a compressive sensing approach [13, 18] would seem an obvious option, even these approaches need to make direct measurements of the low frequency light transport and would not be suitable with such a small image capture budget. Recent low rank approximation techniques such as Kernel Nystrom [21] and Krylov subspace [12] methods achieve good quality results with a moderate capture budget. However, it is unclear how to practically extend these techniques from a limited projector-camera setup to relighting under full environmental illumination.

Editing. Another important consideration is the editability of the captured data as demonstrated by recent research in the area of lighting design and interfaces for editing point lights [6], as well as natural illumination [15]. SH being a global basis, does not provide a good mechanism of local lighting control which is desirable for artistic editing effects. And editing of reflectance functions based on wavelet coefficients would still be non-trivial. Instead, our proposed technique combines the efficient low frequency approximation of SH lighting with local light sources for high frequency lighting and intuitive control for artistic editing.

Our approach is similar in spirit to the work of Davidovic et al. [1] who employ visibility clustering for low-rank approximation of global effects and local lights for high rank approximation in the context of global illumination, whereas we focus on global and local control of directional lights for image-based relighting.



(a) EM (b) 9 SH (c) residual EM (d) local lights

***Figure 2:** Factorization of Grace Cathedral environmental illumination (a) into 2^{nd} order SH lighting (b) and a residual EM representing high frequency lighting (c). This residual energy is represented in our approach with a set of Gaussian local lights (d).*

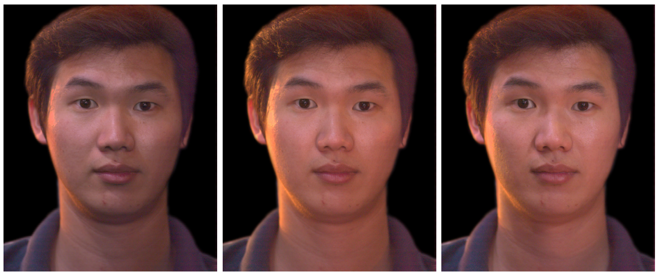
(a) Un-optimized (b) Optimized (c) Ground truth

***Figure 3:** Combination of SH lighting and local lights in the Grace cathedral environment. (a) Combination with un-optimized weights. (b) Combination with optimized weights. (c) Ground truth relighting consisting of 253 lights.*

3 Lighting Basis

In this work, we propose a practical image-based relighting approach that combines low frequency SH lighting for global contribution of environmental illumination with a set of local light sources. Building on the work of Ramamoorthi and Hanrahan [16], we employ low order SH lighting for approximating low frequency lighting. Given a total budget of N lighting conditions, we employ a fixed number of m low order SH lights and an additional set of n local lights such that $N = m+n$. We place the n local lights uniformly spaced apart on the upper hemisphere. The rationale for this is that most bright light sources tend to be located in the upper hemisphere in an environment map (EM). Our approach then proceeds as follows: we first compute an m SH reconstruction of the EM (Fig. 2, (b)). Then we generate a *residual* EM by subtracting the m SH reconstruction from the original EM (Fig. 2, (c)). The residual map normally contains the bright high frequency content of the EM. It may also contain some negative pixels from the subtraction which we clamp to zero in order to preserve the contributions of the local lights in the final combination. We then sample the residual EM into the basis of local lights in order to compute the energy of each light. In this way, the local lights account for the energy unaccounted by the SH lighting. However, direct combination of SH lighting and these local lights achieves sub-optimal relighting (see Fig. 3, (a)). Hence, we propose an optimization approach to find the optimal combination weights of SH and local lights (see Fig. 3, (b)).

Optimizing Weights. We employ an optimization procedure to find the appropriate combination weights which represents the contribution of each basis to the final relit result. Given a set of SH and local lighting basis $\beta = \{\beta_1, \beta_2, \ldots, \beta_N\}$, and an EM y,



(a) Original space (b) PCA space (c) Ground truth

***Figure 4:** Different error functions for the proposed optimization procedure. (a) Sub-optimal relighting result after 600 iterations of the optimization when using error function on the original space of the EM. (b) The optimization achieves much better convergence with the same number of iterations using error function in PCA space. (c) Ground truth relit image.*

the optimization proceeds by iteratively reducing the difference between the original EM and its reconstruction based on the weighted combination of SH and local lights. Mathematically, this can be expressed as:

$$\min_x f(x), f(x) = \|Ax - y\|_2$$

where $f(x)$ is the objective function to be minimized, x is the $N \times 1$ set of solution weights, and A is the projection of the EM y into the space spanned by the chosen lighting basis β. Each column i of the projection matrix A is given as $A[i] = c_i \cdot \beta_i, i \in [1 \ldots N]$, where $c_i = \beta_i \cdot y$.

Instead of directly solving the above optimization in the original space of the EM, we compute the error term by first projecting the EM y into Principal Component Analysis (PCA) space A' of the chosen SH and local lighting basis to obtain an $N \times 1$ feature vector y' of the EM in this PCA space. This can be formally described as:

$$\min_x f(x), f(x) = \|A'^T Ax - y'\|_2$$

where $A' = PCA(A)$, and $y' = A'^T y$.

All of the projections of SH and local lights are done using only the luminance channel. In each iteration of the optimization we calculate the distance of the target feature vector y' to the feature vector of the EM reconstructed with the combination weights of the current iteration. We initialize all the weights x to one in the first iteration. We found that employing these feature vector distances in PCA space of the chosen basis as an error function for the optimization gives rise to fewer local minima problems, faster convergence and better results than computing the optimization in the original space (see Fig. 4).

We employ a bounded version of FMINSEARCH function in MATLAB, which uses the Nelder-Mead simplex algorithm, to find the optimal weights x that reduce the distance between two feature vectors. Subsequently, we generate the final relit result by applying the optimized weights x to the SH and local lights with energies obtained from the initial factorization of the EM described in Fig. 2. We chose the FMINSEARCH function for the optimization over linear least squares as it enables a more general error term formulation and gave better results for more complex lighting environments. We also restrict all the m SH coefficients to share the same weight in the optimization for a total of $K = n + 1$ weights that are optimized. This further limits the dimensions for the optimization for better convergence as well as providing a single global control of the low frequency lighting in addition to a few local lights for any subsequent lighting edits. For most results presented in the paper, we set the total image capture budget to $N = 20$ lighting conditions, with $m = 9$ (2^{nd} order) SH lights and $n = 11$ local lights.

Note that an alternate possible approach for combining these SH and local lights would be orthonormalization of the space spanned by these individual lighting bases. While this approach may result in a valid relighting result, such an orthonormalization process converts the local lighting bases into bases with global support like the SH basis functions, thus negatively impacting localized lighting edits with the proposed lighting basis (Section 4).

Point vs Gaussian Lights. We compared using different types of local lights for the combination with SH lighting including point lights and narrow width Gaussians. The intuition behind using Gaussian light sources is that they result in smoother specular highlights (see Fig. 5, b) compared to point-source lights for specular scenes (see Fig. 5, a). In addition, most light sources in natural environments are extended light sources rather than true point lights. This makes the narrow Gaussian lights a more appropriate choice for the proposed combination with SH lighting (see Fig. 2, d).

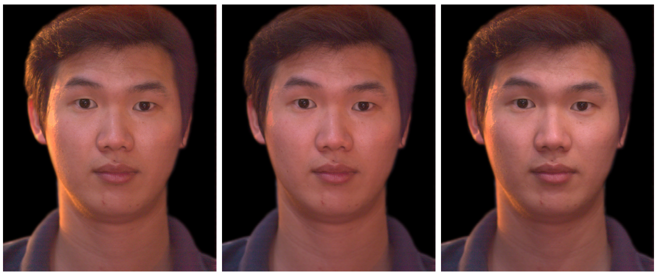
(a) Point lights (b) Gaussian lights

Figure 5: ***Comparison of local lighting in two different specular regions of the Plant dataset. (a): Point lights produce unnaturally sharp highlights. (b): Gaussian lights produce more realistic glossy highlights.***

Data Acquisition. We now briefly discuss the data acquisition and then present some results with the proposed technique in Section 5. We employ an LED sphere lighting system with 156 lights similar to [22] in order to obtain data for the face example, while using data available online from another variant of the device with greater lighting density [3] for the other examples in this paper. Such a lighting system can project spherical harmonic illumination on a subject after scaling it to the $[0, 1]$ range. This implies that we can directly capture (scaled) SH coefficients from photographing a subject under these lighting conditions. For the local lights, we capture photographs of the subject while illuminating it with banks of lights that have a sharp Gaussian fall-off in intensity. Finally, we employ traditional dense reflectance function data from photographs captured with individual lighting directions for ground truth relighting.

4 Lighting Edits

Our technique greatly reduces the number of images required for realistic relighting, which also makes post-editing of the relit result more intuitive. Our choice of basis enables direct manipulation of the combination weights as well as local light intensities, while keeping them to a manageable number for a user as argued in [6]. Figure 6 presents two examples of such direct manipulations for light intensity modulation that we can achieve with our technique. In Edit 1, we have reduced the contribution weight of the local light corresponding to the rim lighting of the orange alter in the Grace Cathedral EM. In Edit 2, we have increased the contribution weight of the local light corresponding to the bright windows above the alter, while slightly reducing the global SH contribution leading to sharper shadowing and a more dramatic look.



(a) Optimized (b) Edit 1 (c) Edit 2

***Figure 6:** Examples of lighting intensity edits in the Grace Cathedral environment. (a) Original optimized result. (b) Edit 1: The effect of the rim lighting from the orange alter has been reduced. (c) Edit 2: The effect of the sky light from the windows above the alter has been increased casting a sharper shadow under the subject's nose.*

We also present a novel image-based technique for modulating the angular width of a local light with the proposed lighting basis. For increasing the angular width of a chosen local light, we propose to interpolate between the high frequency lighting of the local light and the low frequency SH lighting using ratio images. Ratio images have been employed by Peers et al. [14] for image-based lighting transfer. In this work, we employ ratio images for artistic editing of image-based relighting. In particular, we propose to interpolate between two ratio images - one ratio representing high frequency illumination obtained by dividing the local light illumination by uniform spherical illumination (Fig. 7, top-row (b)), and another ratio representing low frequency lighting obtained by dividing a spherical linear gradient along the direction of the local light by uniform spherical illumination (Fig. 7, top-row (c)). Given that our lighting basis includes low order SH lighting scaled to [0,1], we can create a spherical linear gradient along any direction by steering the 1^{st} order SH conditions to the desired direction. Finally, we relight the subject with the interpolated ratio image after scaling it with the intensity and color of the chosen local light. An example of such an edit to the angular width of local light can be see in Fig. 7 (top-row), where the rim lighting of the orange alter has been broadened to create a softer lighting from the side.

Another lighting edit that is possible is reducing the angular width of a local light. Here, we employ the ratio image obtained by dividing the local light illumination by uniform spherical illumination and exponentiate it to effectively reduce the width of the Gaussian local light. The exponentiated ratio image is once again scaled by the intensity and color of the original local light to obtain the edited relit result. An example of such an edit to the angular width of local light can be seen in Figure 7 (bottom-row), where the width of top light corresponding to the window has be reduced with ratio image exponentiation to create a dramatic harsh lighting effect. The above lighting edits can also be seen in the accompanying video. Such artistic control of intensity and angular width modulation of lighting is very desirable in post-production work-flows where the ability to easily edit a lighting result is an important consideration besides achieving high quality relighting.

(a) Initial (b) Ratio 1 (c) Ratio 2 (d) Edited

***Figure 7:** Examples of lighting angular width modulation in the Grace Cathedral environment. (top-row) Softening of the rim light corresponding to the orange alter using interpolation between ratio images 1 and 2. (bottom-row) Sharpening of the top Gaussian local light corresponding to the window using exponentiation of ratio image 1 to obtain ratio image 2.*

5 Results

The input to our algorithm is an environment map and photographs of a subject in the chosen basis of N lighting conditions (m SH + n local lights). An advantage of the optimization procedure in our technique is that it is defined on the global lighting EM, and is hence applicable for relighting any dataset captured from any viewpoint with just a single optimization. In our implementation, the optimization procedure takes 2 minutes to converge on a dual core 2.5 GHz laptop with 4GB RAM.

Figure 1 presents the result of the optimization procedure for a subject relit in the Grace Cathedral EM. As can be seen, 20 SH lighting conditions fail to correctly capture the high frequency highlights while resulting in a slight ringing artifact on the left side of the face. The 20 local lights on the other hand fail to correctly capture the low frequency lighting correctly. Our proposed optimized combination achieves a good result for the same lighting capture budget ($N = 20$) compared to the ground truth. We present relighting results of additional datasets in the Grace Cathedral EM in Figure 13. Particularly visible here is the Gibbs ringing of SH lighting resulting in color banding artifacts (Figure 13, (a)) on specular surfaces, as well as the hot spots due to local lights on the Helmet and the sword of the Kneeling knight (Figure 13, (b)). Our proposed combination of SH and local lights achieves the best qualitative results for a similar budget of lighting conditions for these scenes. Fig. 14 presents more examples of relighting and editing with our technique in different lighting environments. Here, the edited results have been obtained with a few simple operations on selected local lights and global SH lighting. Additional EM relighting examples can

(a) 4 SH + 16 local lights (b) 9 SH + 11 local lights (c) 16 SH + 4 local lights (d) Ground truth

Figure 8: ***Relighting result for a fixed lighting budget of 20 lighting conditions. (a)*** 1^{st} ***order SH lighting with 16 local lights. (b)*** 2^{nd} ***order SH lighting with 11 local lights. (c)*** 3^{rd} ***order SH lighting with 4 local lights. (d) Ground truth relighting with 253 lights.***

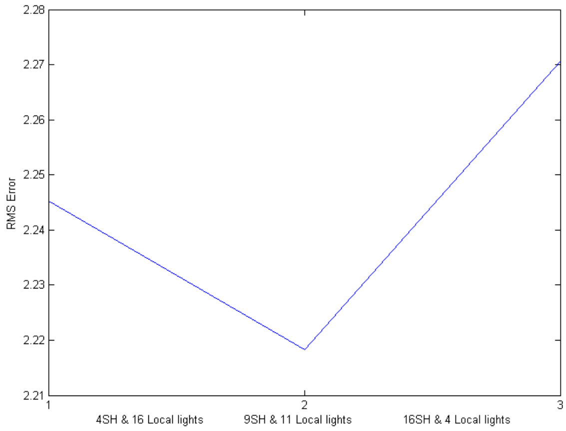


Figure 9: ***RMS error plot of approximation error for different combinations of SH and local lights.***

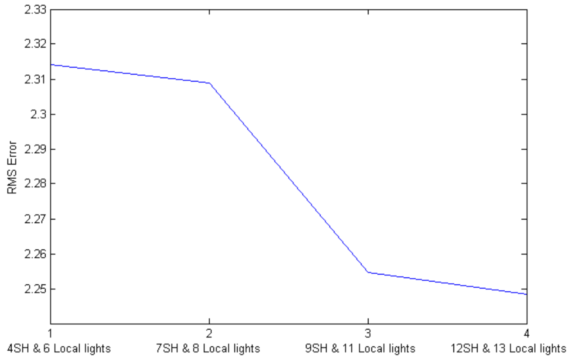


Figure 10: ***RMS error plot of approximation error for different total budget of lighting conditions.***

be found in the supplemental document. The accompanying video includes results of a lighting animation sequence where we achieve consistent results across the sequence with rotation of coefficients and weights of the SH and local lights.

In Figure 8, we analyze the optimal combination ratio of SH lighting with local lights for a fixed total budget of lighting conditions. In this example, we fixed the total number of lighting conditions $N = 20$. For this budget, we empirically found the best qualitative results to be obtained with configuration (b) with a similar number of SH ($m = 9$) and local lights ($n = 11$). Configuration (b) also resulted in a lower RMS error in the approximation of the EM compared to configurations (a) and (c) (Fig. 9).

In Figure 10, we plot the approximation error for different total budget of lighting conditions. As expected, with increase in the total number of lighting conditions N from 10 to 25, there is a decrease in the approximation error. As can be seen from the plot, a reasonable approximation of the EM can be obtained with as few as $N = 20$ lighting conditions with $m = 9$ SH lights and $n = 11$ local lights.

In Figure 11, we present relighting results for two different positions of local lights on the upper hemisphere that are slightly shifted with respect to each other. As expected, there is a slight difference in the two cases due to the discretization of high frequency lighting. However, it should be noted that despite the shift in the light positions the optimization scheme preserves the original relit result to a large extent demonstrating the robustness of the technique.

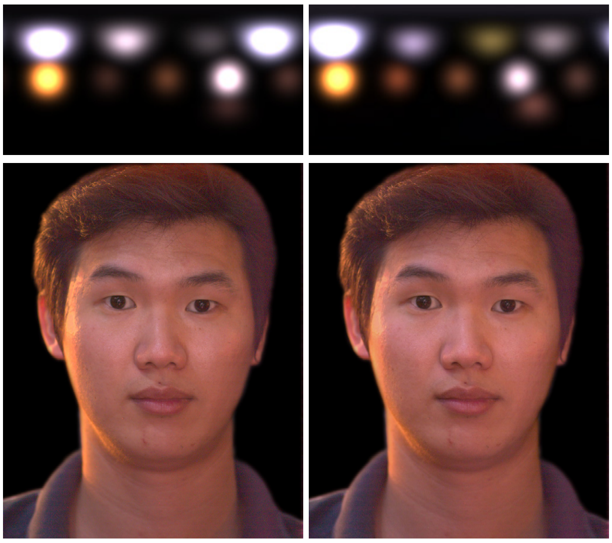
We also present combining SH lighting with local lights for an even more restricted budget of *just* 10 lighting conditions in order to test the generalization of the approach. As seen in Figure 12, our optimization procedure enables a reasonable relighting result even for such a small budget of lighting conditions (c). Here, we combine 1^{st} order SH lighting (4 images) with 6 local lights to achieve the relit result. For a similar budget of lighting conditions, the relit result suffers from low pass filtering with pure SH lighting (a), and significant low frequency bias with 10 local lights (b). This scenario would be particularly interesting for dynamic performance relighting applications where the available budget for lighting conditions is very limited even when employing high speed photography [3].

5.1 Limitation

Given that the technique relies on a small set of local lights for high frequency lighting, it may suffer from aliasing artifacts for highly specular surfaces or scenes with complex light transport. The reliance on low order SH lighting for global lighting can result in slight overestimation of low frequency lighting in the dark regions of EMs with very high dynamic range illumination. For environment maps with very low frequency illumination, our technique may not provide any advantage in relighting quality over pure SH lighting. However, the

(a) 9 SH (b) 10 local lights (c) 4 SH + 6 local lights (d) Ground truth

Figure 12: ***Generalizing our approach to fewer lighting conditions. (a)*** 2^{nd} ***order SH lighting does not preserve high frequency specular highlights. (b) 10 local lights preserve high frequency highlights but suffer from low frequency bias. (c) Combining*** 1^{st} ***order SH lighting with 6 local lights (10 lighting conditions) achieves reasonable results. (d) Ground truth relighting with 253 lights.***



(a) Distribution 1 (b) Distribution 2

Figure 11: ***Relighting result in Grace Cathedral EM for different local light positions. Top-row: Local light distributions. Bottom-row: Relit result. The light positions in (b) are slightly shifted with respect to the light positions in (a).***

proposed lighting basis should still be useful for artistic editing of the lighting in such cases. While the technique currently works for lighting animation (see accompanying video), it may lead to temporally inconsistent results for time varying illumination if the optimization is run independently for each time step. However, it should be possible to enforce temporal coherence in this scenario with temporal regularization of the optimization.

6 Conclusion

We propose a practical technique for image-based relighting that achieves very realistic results with an order of magnitude fewer images compared to traditional approaches, while enabling artistic editing of the relit result which is highly desirable for post-production effects. Our method enables control for both the global low frequency lighting as well as local directional lighting while keeping the lighting controls to a manageable number for digital artists. Our proposed relighting basis could be used as a tool for artistic editing even for dense reflectance field datasets. The technique should also benefit relighting applications with dynamic performance capture that have a very limited budget of lighting conditions. For future work, it would be interesting to extend the method for relighting with time varying illumination.

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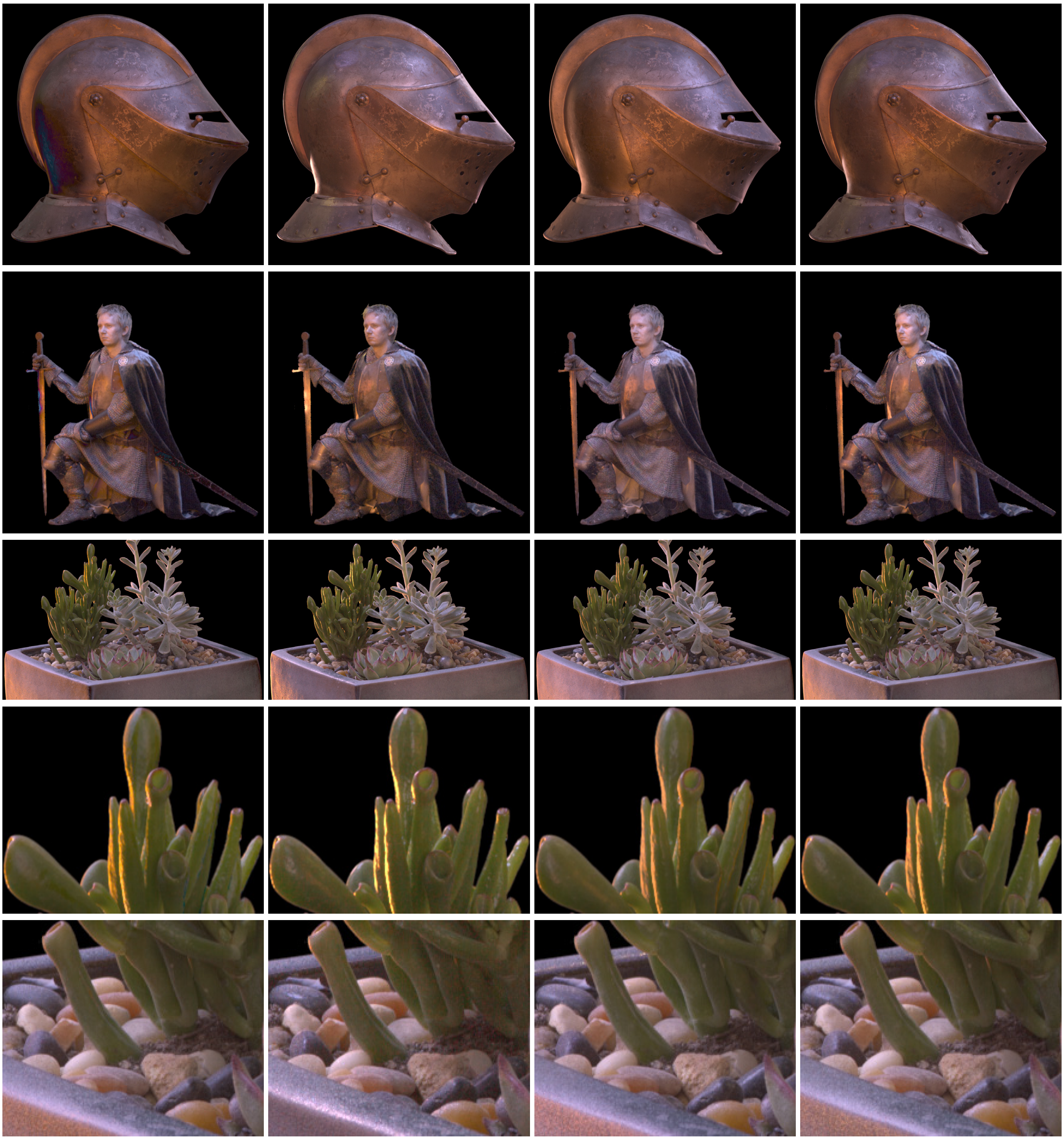
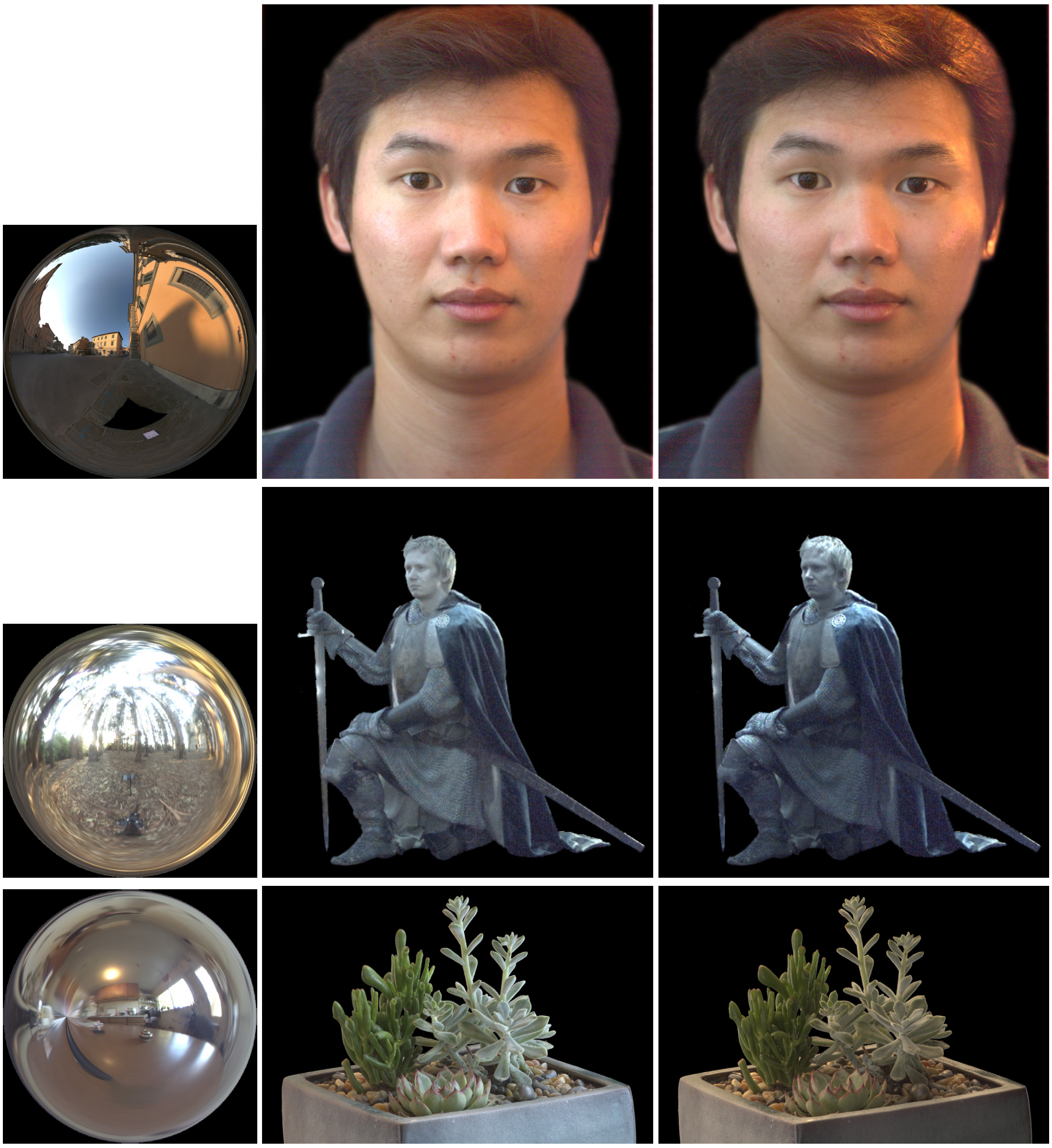


(a) 4^{th} order SH (b) 20 local lights (c) Our technique (d) Ground truth

***Figure 13:** Relighting comparison under the Grace Cathedral environment. (a) 4^{th} order SH relighting (25 lighting conditions) fails to accurately capture the high frequency highlights while also introducing color banding artifacts on specular surfaces. (b) 20 point lights capture the high frequency lighting effects, but do not accurately capture the low frequency lighting. (c) Our proposed technique for combining SH lighting with local lights (20 lighting conditions) captures both low frequency and high frequency lighting effects. (d) Ground truth image-based relighting consisting of 253 lights. Top-row: Helmet. Second-row: Kneeling knight. Bottom-three-rows: Plant.*



(a) Environment maps (b) Optimized (c) Edited

Figure 14: Relighting and editing examples in various environment maps (a). (b) Relighting result with proposed combination of SH and local lights (20 lighting conditions). (c) Edited relighting result. Top-row: Face in the Pisa EM. The orange bounce light from the wall has been sharpened while the direct skylight on the left has been diffused in (c). Center-row: Kneeling knight in Eucalyptus Grove EM. The global SH lighting has been reduced and the top sky light has been sharpened to create a more dramatic effect in (c). Bottom-row: Plant in the Kitchen EM. The direct window light from the right has been removed and the house light from the back has been intensified in (c).

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