Image Based Rendering: Using High Dynamic Range Photographs to Light Architectural Scenes

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Abstract

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Image Based Rendering (IBR) is a digital rendering technique that uses High Dynamic Range (HDR) photographs to light three-dimensional digital models. The HDR photographs capture lighting data and images from a physical environment: this is done by shooting a range of exposures with a digital camera and tripod. Once these exposures have been combined into a single HDR photograph using computer software, the resultant photograph can be inserted into a digital model, using the IBR method, to act as the light source and background image for the model.

While Image Based Rendering is a recently developed rendering method that is relatively well known in the area of computer graphics, it is unfamiliar to most others, has very little information available on it, has a steep learning curve, and is not specific to architectural rendering problems. The purpose of this thesis is to explore the IBR method: *i)* to identify its strengths and weaknesses, *ii)* to investigate the prescribed method, and *iii)* to explore its uses as a render and analysis tool for the architectural and lighting design communities. The original development of IBR for computer graphics is reviewed, along with its interrelations with HDR photography. HDR and IBR are explained through explicit instructions to make them more accessible and more widely used outside of the field of computer graphics.

This thesis provides the pertinent information for architectural applications and makes the methods more easily understandable and accessible within the architectural community. The rationale and methodology are discussed, and the applications are exemplified through different settings and lighting conditions.

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Chapter 1: Introduction

Three-dimensional digital models are becoming more and more common in the architectural profession as communication tools. Whether used in place of physical models or to supplement them, the digital model provides additional visual information that can easily be conveyed, such as building materials, interaction with the environment, changes through time, and lighting. Especially in initial design stages, it is common to have digital models composed of basic forms, communicating the geometry of a proposed building, but as the design process gets into more detail, the models incorporate more information. Renderings of these digital models often attempt to produce a realistic depiction of the building, as close to the visual experience of the built environment as possible.

Most currently available digital rendering engines create lighting effects based on a fabricated light source (created according to rules for that renderer) and a prescribed number of light-bounces off of materials. This is not always accurate, can be computationally expensive, and may also be misleading when used as the basis for design decisions. Digital modeling programs tend to provide a multitude of lighting options, many of which affect the lighting in unrealistic ways. The complexity and availability of unrealistic options can easily confuse the user and result in a poorly lit digital environment that does not accurately predict the final appearance of a design.

For architectural projects, the buildings are often depicted either in an empty environment, digitally inserted into a photograph of their environment, or created with a realistic 3D digital environment as part of the model. When in an empty environment, the model has basically no site context, and is difficult to imagine as something other than a stand-alone model. This effect is demonstrated in Figure 1.01. Images of models digitally inserted into their environments, using digital photo-editing programs, may look unrealistic and can occasionally be distracting, as in Figure 1.02. These first two solutions ignore the impact of site shadowing and environment inter-reflections on the model. A common solution to creating a fully integrated model is to additionally model the surrounding environment, as Figure 1.03 shows. This has the unfortunate constraint where model-building time is proportional to the detail desired, and this can be prohibitive.

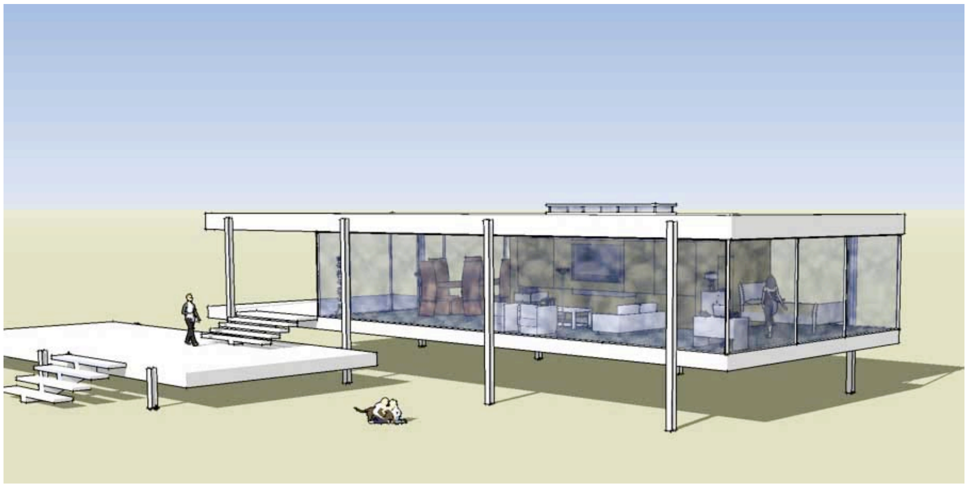


Figure 1.01: Digital model in empty environment.

Figure 1.02: Digital model inserted digitally into a photograph.

Figure 1.03: Digital model rendered complete with a modeled version of the surrounding environment.

Different rendering applications may use physically-based rendering engines, or they may use other rendering methods to approximate the visual experience. Commonly used digital techniques attempt to create photorealistic renderings using digital light sources and materials. A photorealistic rendering could be defined as an image that looks like it could possibly be a photograph, rather than a digital render. While physically-based rendering engines can create realistic images because they are based on a physical environment, it is more common to mimic or "fake" the lighting and materials, as well as the render settings, to create photorealism using a non-physically-based rendering program like Auto•des•sys FormZ [1] or Autodesk VIZ [2]. This is sometimes due to a desire to create a more dramatic rendering, but is more often because of the fact that the most commonly available rendering programs allow for many effects that would not be possible in the physical world.

Whether using a physically-based rendering program such as Radiance [3], which has been validated with physically-based modeling of material and sky conditions [4], or recreating lighting effects through careful observation and digital workarounds, most rendered images will not be an exact match of the physical environment. The inter-reflections and light diffusion caused by surrounding buildings, vegetation, and sky variability (cloud cover) cannot be recreated using modeling alone. Buildings and trees could be modeled, but the high polygon count would greatly multiply the rendering time required, and this does not address the effects of cloud cover. Some programs have daylight systems that simulate light reflections from the sky as well as direct sunlight, but again this is not always accurate, and standardized sky models are not available in all programs. One of the biggest problems with digital modeling and rendering is that the user must have detailed knowledge of the effects of lighting in a physical environment in order to mimic these effects accurately. There are a wide variety of techniques in different programs that create these effects, making it difficult to learn how to create a photorealistic rendering in a short amount of time. Even with a physically-based renderer, it is difficult to create a fully accurate lighting environment due to a steep learning curve and unavoidable approximations.

Image Based Rendering (IBR) is a recently developed digital rendering technique [5] that uses High Dynamic Range (HDR) photographs to light digital models. In the IBR method, HDR images are used to create environment maps in a digital model, in place of the sky and/or surroundings. HDR photography is a method of capturing luminance values in a scene very quickly and accurately using a digital camera [6]. These HDR maps include the lighting levels present in the environment, thus providing the light sources for the digital model. This approach removes the need to model complex environments or create accurate light effects using convoluted render tools. All of the lighting information is inherent in the HDR photo, including any light sources and light reflected from the surroundings [7].

The objective of this thesis is to explore the potential architectural applications of Image Based Rendering. The obstacles that stand in the way of this method becoming widely adopted by the architectural design community are also addressed. This method provides better visualization capabilities for designers, creating exceptionally realistic and accurate digital renderings for use in presentations. IBR is also a very useful analytical tool for studying daylighting effects in a designed space, providing accurate visual aids and light level data to accelerate and improve the design process.

The possible applications of IBR extend well beyond the range of architectural design and lighting analysis, though other applications will not be explored here. Rather, the focus is narrowed to architectural applications; various architectural examples are provided to emphasize the potential and limitations of the technique.

Chapter 2: High Dynamic Range Photography

A common problem in photography is the inability to capture both dark and bright surfaces within one image, especially in daylit interior environments. When taking a single photograph of an interior space that has a glass door or window that allows daylight into the scene, the resultant photograph rarely resembles the lighting environment that is experienced by the person in that space. Depending on the camera settings when the photograph was taken, either the interior will be underexposed or the exterior will be overexposed. If the camera is adjusted to capture the range of light in the darkened interior, as in Figure 2.01, the excessive brightness from the daylight penetrating through the glass will overexpose the film or digital sensor, resulting in an undifferentiated white patch in lieu of the outdoor view. Conversely, if the camera is adjusted to capture the full range of light in the outdoor view, as in Figure 2.02, the darkened interior will be a collection of shadows, and most of the details of the interior are lost. This problem exists because a high dynamic range of light is visible in the scene. The human visual system can adjust, but the entire range of light cannot be captured with a conventional photograph.

Figure 2.01: A conventional (single exposure) photograph that captures only the range light inside the room.

Figure 2.02: A conventional (single exposure) photograph that captures only the range of light in the exterior environment.

Figure 2.03: An HDR photograph that captures the lighting environments of both the interior and exterior.

High Dynamic Range (HDR) photography provides a feasible solution for capturing the wide range of lighting values that we experience in physical spaces. This technique, developed by Paul Debevec [6], involves the use of a digital camera to record multiple exposures of a scene. Each exposure captures a different light range. These photographs are then combined using computer software to create an HDR image, like the ones shown in Figure 2.03 and in Figure 2.04.

This HDR image can also be referred to as an environment map, a radiance map, or a luminance map. *Luminance* is a term that refers to light levels: it is a measurement of the amount of light reflected off of a surface in a specific direction. Luminance can be compared to *brightness*, in that both describe the light levels that humans can see, but luminance is a quantitative term that can describe specific values; it is represented with the units *candelas per meter squared (cd/*m^2*)*. Brightness is a qualitative descriptor that can change relative to the surrounding light levels as well as individual perceptions.

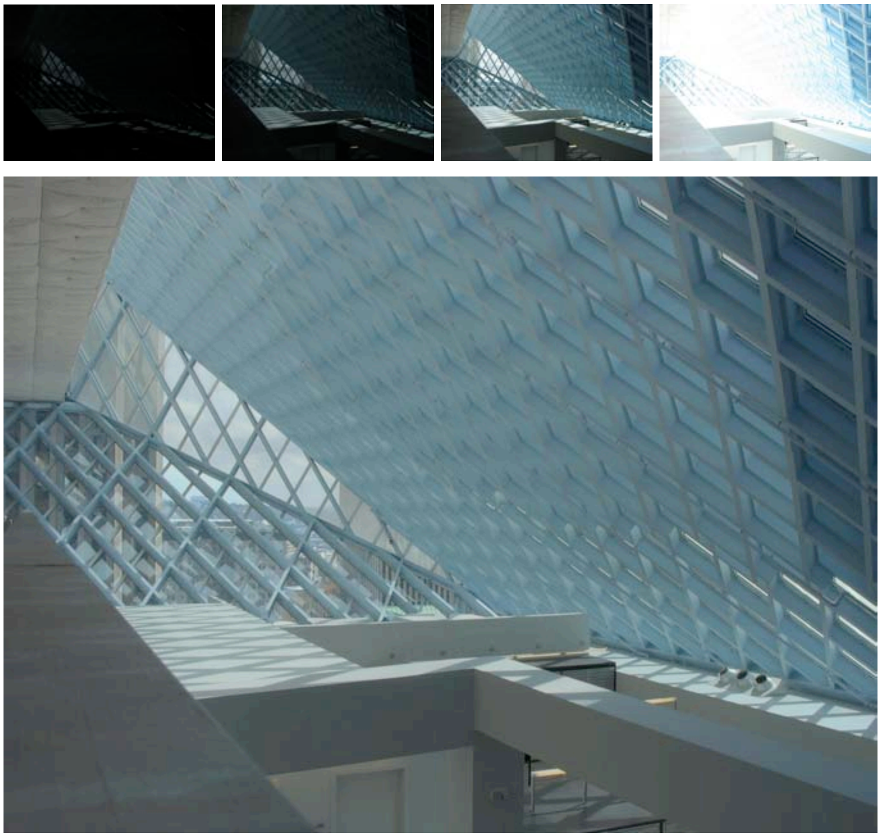


Figure 2.04: Photographs taken in the Seattle Public Library, downtown Seattle, WA. The top four images are samples of some of the exposures that were combined to create the HDR image (bottom).

2.1 DEVELOPMENT OF THE HDR PHOTOGRAPHY TECHNIQUE

Prior to the development of High Dynamic Range photography, the existing means of capturing an image depicting the visual environment of a scene was limited to conventional photography. These conventional photographs are coming to be known as Low Dynamic Range (LDR) photographs, especially when discussed in the context of HDR photography. Until quite recently, LDR photographs were most commonly captured using film cameras, but the development and subsequent commercial availability of digital cameras have made digital image capture quite common. A single photograph, whether digital or film, can only capture a small range of light values: about two orders of magnitude [8]. The range of light to which humans are capable of adapting is almost 10 orders of magnitude, which is significantly greater than the mere two orders of magnitude that can be captured with an LDR photograph [8]. High Dynamic Range photographs can encompass the entire range of light in a scene, as detected by the human visual system, rather than just a small portion of it.

In order to create an HDR image, multiple exposures of the same scene must be captured, then combined and calibrated into a single image. The common method for capturing the LDR images that will be combined into an HDR image uses a digital camera. HDR images can also be created by scanning the negatives from a film camera, but that method will not be explored here, due to the speed and ease of using the digital method [8]. Subsequent computational methods do the difficult work of calibrating the images, creating the camera response curve, and fusing multiple exposure images into an HDR image.

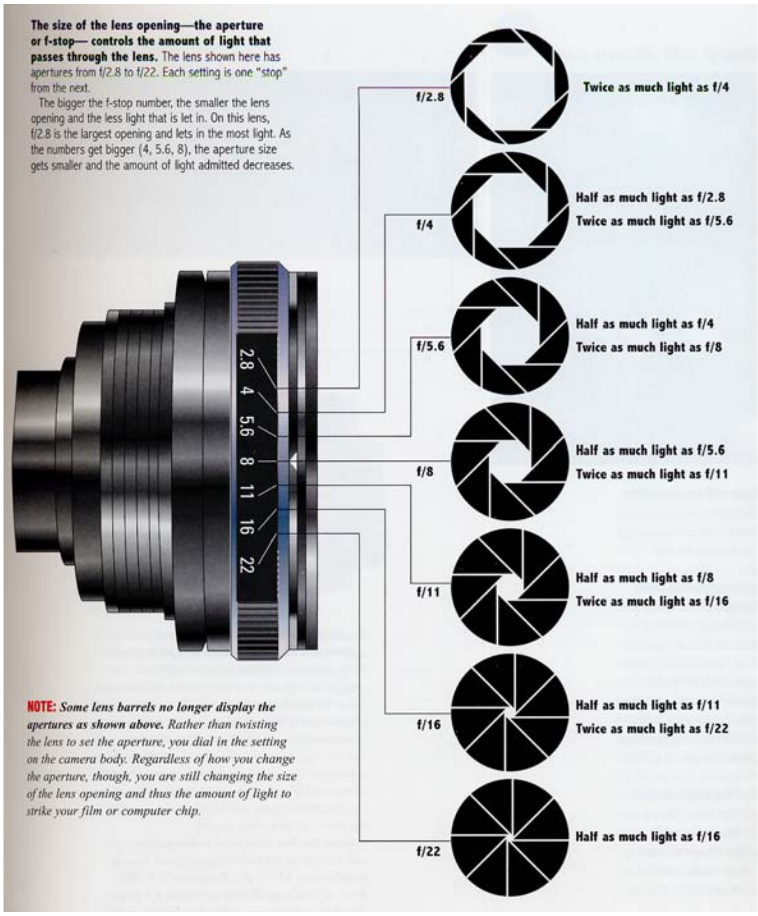
2.2 IMAGE CAPTURE PROCESS

The purpose of the HDR image capture process is to capture a range of exposures of one scene, encompassing the full range of light in the scene. For each individual image, certain pixels may be either overexposed or underexposed, but the total collection of images capture the wide range of light values from the entire scene.

The only completely necessary equipment for capturing an HDR image is a tripod and a digital camera with manual settings. However, in order to be as accurate as possible, it is best to additionally have a hand-held luminance meter and a grey reference card. The basic equipment is illustrated in Figure 2.05. The tripod will ensure that each exposure captured will be taken from the exact same position as the others. The luminance meter and reference card are tools for proper calibration of the luminance values. By placing the grey card somewhere in the scene and noting the luminance value read from it (using the luminance meter), that number could be checked later when the images are combined into a single HDR image. If a grey reference card is not available, the luminance meter can still be used to check any neutral reference area in the scene for later calibration.

Figure 2.05: Basic equipment needed to capture an HDR photograph: a tripod, digital camera, and luminance meter.

The camera, preferably set up on a tripod, must be put in the Manual Setting mode so that both the aperture size (f-stop) and exposure time can be manually adjusted. It is recommended to set the f-stop to a fixed size. The f-stop can be selected based on the desired depth of focus as well as the brightness. A large aperture creates less depth of field, allowing some near and far objects to become blurry. A small aperture creates a greater depth of field that encompasses all of the objects in the photograph, allowing objects of varying distances to remain sharp. Figure 2.06 shows the relationship between f-stop number and aperture size, while Figure 2.07 demonstrates the use of the f-stop settings to affect the depth of focus. There are two other reasons for setting a smaller aperture size: size differentiation and vignetting. Aperture size is controlled with a mechanical process. The size of the aperture may be slightly different each time a photo is taken at the same f-stop setting. Fixing the aperture size eliminates this inconsistency. Vignetting, the effect of brightness reduction at the periphery of an image, can be caused by larger aperture sizes.



The size of the lens opening—the aperture or f-stop— controls the amount of light that passes through the lens. The lens shown here has apertures from f/2.8 to f/22. Each setting is one "stop" from the next.

The bigger the f-stop number, the smaller the lens opening and the less light that is let in. On this lens, f/2.8 is the largest opening and lets in the most light. As the numbers get bigger (4, 5.6, 8), the aperture size gets smaller and the amount of light admitted decreases.

NOTE: ***Some lens barrels no longer display the apertures as shown above.*** *Rather than twisting the lens to set the aperture, you dial in the setting on the camera body. Regardless of how you change the aperture, though, you are still changing the size of the lens opening and thus the amount of light to strike your film or computer chip.*

Figure 2.06: Relationship between f-stop and aperture size. In this example, f/22 is the smallest aperture available on the camera, and f/2.8 is the largest aperture available [9].

Figure 2.07: Relationship between aperture size and depth of field [9].

Keeping the f-stop at the same setting throughout the process, the exposure time is changed for each individual photograph. A series of images is taken (e.g., eight images varying from ~1/1000th sec to 3 sec), capturing all of the luminance data in the scene. The shortest exposure time will produce the darkest image, while the longest time will produce the brightest image. To ensure that the final HDR luminance data values will be correct, there needs to be enough overlap of values between one exposure and the next. It is recommended to take 10 LDR photographs to get the full range of values necessary to combine into an HDR photograph [10].

For best results, the ISO should be set to 100. The ISO is the film speed, or equivalent for digital cameras. It is a measure of the camera's sensitivity to light. The HDR capture technique has only been validated with a 100 ISO setting [11]; it is recommended to set the ISO to 100. Most importantly, it is necessary to make sure the white balance is set so it does not change from one exposure to the next. Most digital cameras use an automatic white balance setting, adjusting all of the color values so that the brightest pixel in the frame is set to white. Some of the settings include white balance for daylight, for incandescent lighting, and for fluorescent lighting conditions; an example of these settings is shown in Figure 2.08. If it is set to automatic, the camera may adjust the white balance setting as exposure values are changed, creating different color levels for each photograph taken; therefore it should be avoided while taking the multiple exposure photographs. It is also recommended to set the white balance to daylight [11].

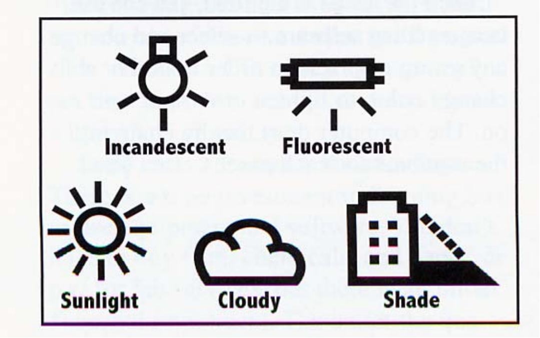


Figure 2.08: Examples of a white balance menu on a digital camera [9].

This procedure will capture images that can be combined into an HDR image. Depending on the lens used on the camera, the final image will likely only recreate the physical scene viewed in one direction. For certain applications, it may be necessary to capture a larger area of the scene, even up to a full 360˚ view; the methods for capturing these larger portions of the environment will be discussed in Chapter 4.

Once the HDR image capture process is used, the next step is to assemble the images. Some of the more complex processes have multiple iterations of each step, using the data from the assembly process to inform further calibration and sometimes using many series of image captures in the assembly process. As long as the appropriate number of exposures have been taken, in the correct manner, it is a straightforward task to complete the assembly of the single LDR photographs into an HDR image that can be used as a luminance map.

2.3 IMAGE ASSEMBLY PROCESS

In order to assemble the exposures into a single HDR photograph, software is available that has been developed specifically to complete this task. The software allows the user to choose which images are to be used, then analyzes and combines those images to create a camera response curve for the camera used and to create an HDR photograph [10].

There are many software programs available to create HDR photographs, and it is likely that many more will be developed in the future. Some of the software is freely available, while other programs must be purchased. Each program has its own strengths and weaknesses, from ease of use to quality of output to range of techniques available. This list includes Photoshop [12], Photomatix [13], Photosphere [10], FDR Tools [14], Picturenaut [15], and HDR Shop [16], among others. A user may choose to use one program exclusively or switch from one to another, taking advantage of the particular strengths of each.

The first step in the assembly process is the selection of image exposures to be combined. Digital photographs, once downloaded to the computer from the camera, have certain embedded information contained in an Exchangeable Image File (EXIF) format that can be accessed by the computer. Information about the camera itself and the camera settings used to capture each individual image are contained in the images. The image itself consists of an array of pixels, each with specific color (RGB) values from 0 to 255. When choosing which images to include for assembly into an HDR photograph, the number of white or black pixels in each image should be considered. Images that are completely overexposed (completely white) or underexposed (completely black) should be avoided.

Once the appropriate range of exposures has been chosen, the images are assembled using the camera response curve. A camera response curve is a polynomial function that models how the camera records the lighting intensity at a pixel level. The function is determined through comparison of different exposures of the same scene, taken with the same aperture size [11]. Each camera has a different camera response curve; one example is shown in Figure 2.09. As part of the first image assembly process, a new camera response curve must be created. Without the calibration achieved by the proper camera response function, the luminance data encompassed in an HDR photo would not be accurate. Therefore, it is best to use a scene with large luminance variations with gradient changes and neutral colors to create the camera response curve. The function will be more accurate with this setup, and can be saved for later use to assemble other scenes from the same camera [8].

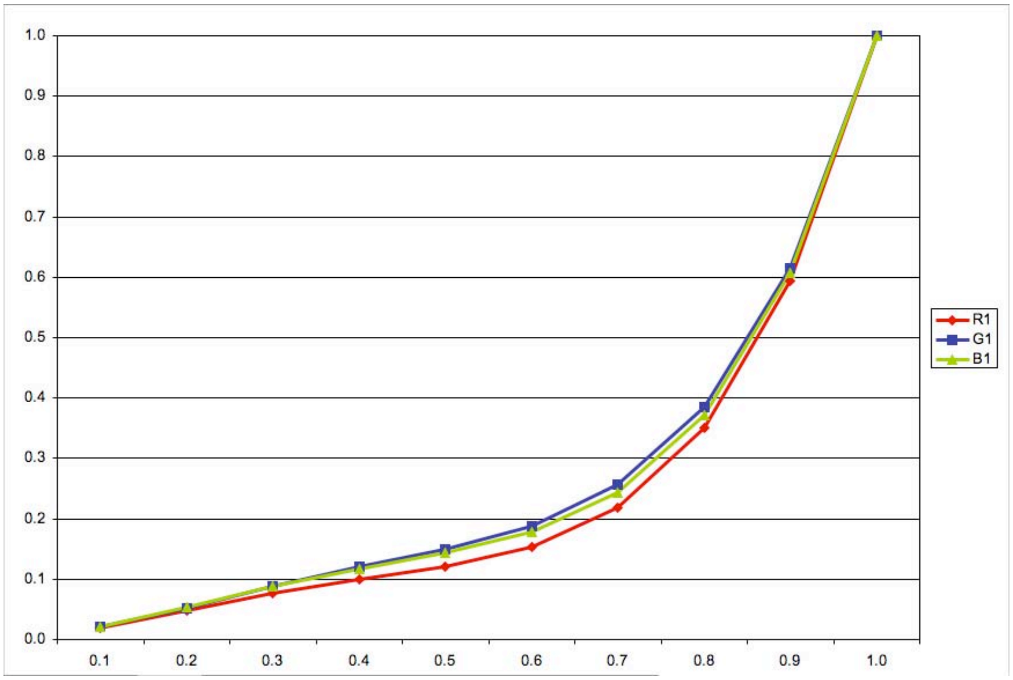


Figure 2.09: Example of a camera response curve, created through the HDR assembly process.

Using the camera response function to derive luminance values, the exposures are combined into a single image containing all of the luminance data. If changes were made to the scene between one exposure and the next, whether through camera movement or movement in the scene (e.g. wind moving tree branches, or people passing through the space), the images must be aligned and ghosts must be removed. Ghosts are images that occur in one or more exposures but are not present in the majority of the photos. In the final assembled image they seem to be transparent, as the background is visible through them from the exposures that did not contain those people or objects, as shown in Figure 2.10. Ghosts can be removed from the final image, using information only from certain exposures for that portion of the image. If the ghosts are small enough within the overall image, their removal will not significantly affect the overall lighting of the photograph [8].

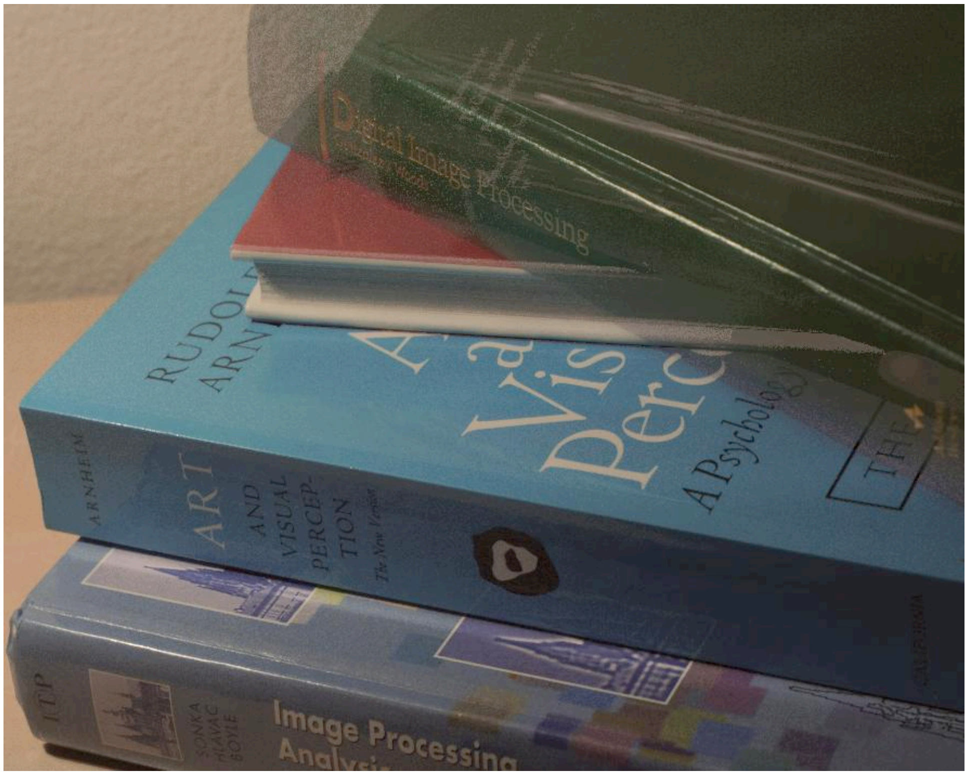
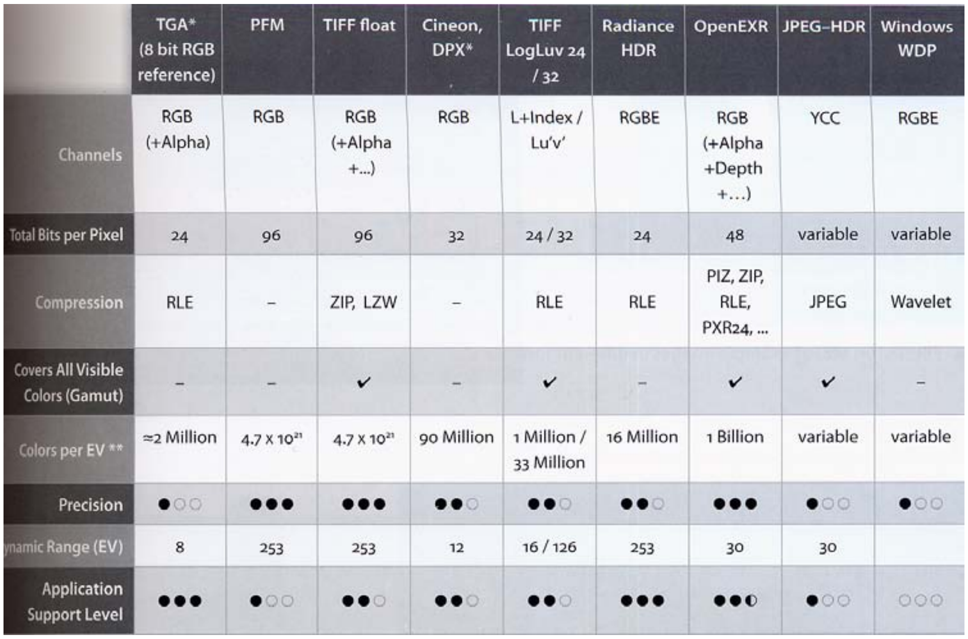


Figure 2.10: An HDR image with ghosting. The top book was moved during the image capture process, resulting in a ghost effect [17].

In the actual assembly process, each exposure is calibrated according to the camera response function and then combined into an HDR result. The pixel values are adjusted by a weighing factor to determine the luminance quantities. There are a variety of functions that have been developed to weight the pixel values, each supported by a different theory [8]. The final result is an HDR image that contains data on the luminance values of each pixel in the photograph.

2.4 HDR IMAGE FORMAT

While conventional digital photographs have information on the amount of Red, Green, and Blue (RGB) in each pixel in a range of 0 to 255, HDR images have an additional number that acts as an exponent, also from 0 to 255, expanding the range of values able to be shown for each pixel. Referring to the amount of memory used per pixel for an image, a conventional RGB image can also be called a 24-bit image. An HDR image using the RGBE encoding is a 32-bit image; an additional 8 bits are used for the exponent (E) value. This expansion of pixel values allows for the recording of a greater range of data in a 32-bit image, effectively capturing the quantities of all of the visible light in a scene. A 32-bit HDR image can contain data covering the entire range of the human visual system. Encodings other than RGBE are available for saving HDR image data, such as XYZE, IEEE RGB, and TIFFLogLuv32 [8]. Some encodings are saved in other file formats, like HDR JPG or EXR [8]. The RGBE encoding in HDR format is used for this study because it is a common format that can easily be used with a variety of software products. Figure 2.11 compares a variety of file formats, including 24-bit formats (common for LDR images) as well as 32-bit formats (for use with HDR data). Some important comparisons to consider when choosing a file format are shown below, including the Dynamic Range covered and the Applications Support Level.



	TGA* (8 bit RGB reference)	PFM	TIFF float	Cineon, DPX*	TIFF LogLuv 24 / 32	Radiance HDR	OpenEXR	JPEG–HDR	Windows WDP
Channels	RGB (+Alpha)	RGB	RGB (+Alpha +...)	RGB	L+Index / Lu'v'	RGBE	RGB (+Alpha +Depth +...)	YCC	RGBE
Total Bits per Pixel	24	96	96	32	24 / 32	24	48	variable	variable
Compression	RLE	–	ZIP, LZW	–	RLE	RLE	PIZ, ZIP, RLE, PXR24, ...	JPEG	Wavelet
Covers All Visible Colors (Gamut)	–	–	✓	–	✓	–	✓	✓	–
Colors per EV **	≈2 Million	4.7×10^{21}	4.7×10^{21}	90 Million	1 Million / 33 Million	16 Million	1 Billion	variable	variable
Precision	●○○	●●●	●●●	●●○	●●○	●●○	●●●	●○○	●○○
ynamic Range (EV)	8	253	253	12	16 / 126	253	30	30	
Application Support Level	●●●	●○○	●●○	●●○	●●○	●●●	●●◐	●○○	○○○

Figure 2.11: A chart comparing statistics of different file formats [18].

2.5 HDR DISPLAY

Similar to LDR photographs, most current display devices can only depict a range of light around two orders of magnitude [8]. Because of this limitation, the full range represented by the HDR photograph cannot be seen merely by viewing the image on the computer screen. Tone mapping is a method of compressing the light values in an image so that they can be represented in the small dynamic range of a computer screen or printed piece of paper. The application of tone mapping to an HDR image creates a separate image in an LDR format, such as JPEG. The HDR data is preserved, while the representation of its intensity is shown in the new tone mapped LDR image. There are many different tone mapping algorithms that have been developed over the years. Each of these techniques works in different ways, creating different outputs depending on the technique itself and the dynamic range of the image processed. One tone mapping equation could compress the values completely linearly, while another might compress part of the values and cut the rest off at a certain point. Other techniques have more complicated procedures and compress the extreme values significantly while leaving the median values barely compressed [8]. Each of the methods for tone mapping has different uses, creating a different look for the same image. Figure 2.12 demonstrates the effects of applying different tone mapping equations to the same HDR photograph. The goal of tone mapping HDR images is usually to recreate human perception as close as possible, or to show the most important range of light with as much differentiation as possible.

Figure 2.12: Three LDR representations of an HDR photograph. The left image has no tone mapping applied, while the center and right images have been tone mapped with different methods.

Whether the finishing step of tone mapping is used or not, a final HDR image has been created with properly aligned images, weighted pixel values, camera response function, and a result showing quantitative luminance data.

2.6 VALIDATION

The process of capturing and assembling LDR photographs into an HDR luminance map has been validated through extensive study and lab work. The validation study shows that the luminance values determined by the HDR process are within 10% of the values read by a luminance meter in the physical scene [11].

The validation study involved a commercially available digital camera, a fisheye lens, and a hand-held luminance meter. Multiple exposures were taken of various scenes and combined using Photosphere computer software. Camera response curves and luminance values were compared, examining luminance values at varying degrees of brightness. Indoor scenes with different types of electric light sources were tested, as well as outdoor scenes lit by direct sun and overcast skies. Color and grayscale targets were used as references in the photographs. The study shows that this HDR method is highly accurate for grayscale and adequately lit scenes, with increased error occurring for areas of highly saturated color and for areas that are poorly illuminated [11]. Because of the thoroughness of this study, and the favorable results, High Dynamic Range photographs can be expected to provide reasonably accurate information regarding the amount of light occurring in a scene.

2.7 HDR CAPTURE OF THE SUN

One important issue to note while exploring the HDR method is the fact that any photograph containing the disc of the sun is challenging because of the extremely high luminance values of the naked sun. It is possible that the entire image will be inaccurate, not just the area containing the sun, because the overexposed pixels could affect the luminance values determined using the assembly process [8]. The high luminance values of the sun may also damage the sensors in the camera. Methods have been developed to work around this problem of recording luminance values of the sun as an HDR image. One method uses a neutral filter on the camera, reducing the brightness of the scene so that the shortest exposure time and smallest aperture size can in fact capture the sun luminance without saturating any of the pixels in the image. The effect of this filter must be checked to calibrate the colors and luminance values of the image [19]. Other methods have also been explored for HDR capture of the sun, but all are complex [8, 19]. Further validation is necessary in this area.

2.8 APPLICATIONS OF HIGH DYNAMIC RANGE PHOTOGRAPHY

Building on the need for photographs that more accurately represent human perceptions of a scene, High Dynamic Range photography has been developed as a process of capturing the full range of light visible in a given physical scene. The data from HDR images representing quantities of light is recorded using a specific file format, so the data is always available numerically even if it cannot be visually represented.

While the processes for capturing and assembling images for an HDR photograph may vary in method and complexity, most conditions (scenes without a direct view of the sun) do allow for relatively easy completion of the HDR process by anyone who understands the process and has access to the software and equipment. Many of the software programs are freely available and the basic equipment is fairly common, making the technique available to interested parties.

The HDR technique was originally developed as a computational photography technique within the field of computer science. The ability to capture compelling photographs has gained significant interest from professionals ranging from scientific fields to entertainment industries. Many photographers have embraced the new HDR technology to create visually stunning photographs of physical scenes that could not previously be recorded by cameras [18]. Even the video game industry has begun to explore this technique in conjunction with digital rendering to improve game imagery [20]. Examples of how photographers and video game designers are beginning to take advantage of HDR technologies are shown in Figures 2.13 and 2.14, respectively.

Figure 2.13: An HDR photograph of a skyscape and town in Sweden [21].

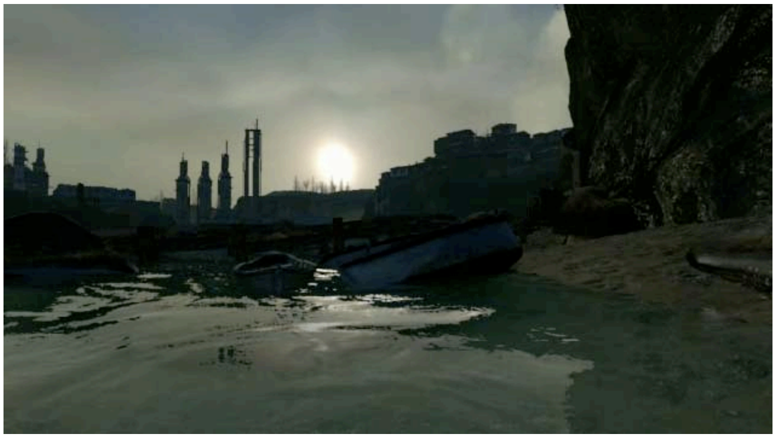


Figure 2.14: A scene from a popular video game, taking advantage of HDR techniques [20].

HDR was developed for the purpose of creating dramatic, artistic images, with no concern for accuracy. However, the images created by this technique are in fact accurate, opening the door for many other possible applications based on quantifiable luminance data. Its development provides the ability not only to match human perception with more accuracy, but also to capture a measurable quantity of the light in the scene. The faithful record of the luminance data allows HDR images to be used to analyze an existing space or lighting condition.

Despite the fact that HDR data cannot be fully displayed through conventional display devices, they can be used to create a false-color image or a tone-mapped LDR image. Tone mapping was discussed earlier in this chapter. False-color images can show the full range of light captured by the HDR method, correlating quantities of light to certain colors that can be compared using a key scale. This is a useful visualization and analysis tool, as demonstrated in Figure 2.15. Luminance values and variations can be studied for information on light distribution and possible glare issues. These kinds of studies provide quantitative data that may impact design decisions. Studies of existing buildings or building mockups, like a recent lighting and shading study for the New York Times building, can yield a vast collection of data provided by HDR capture techniques [22].

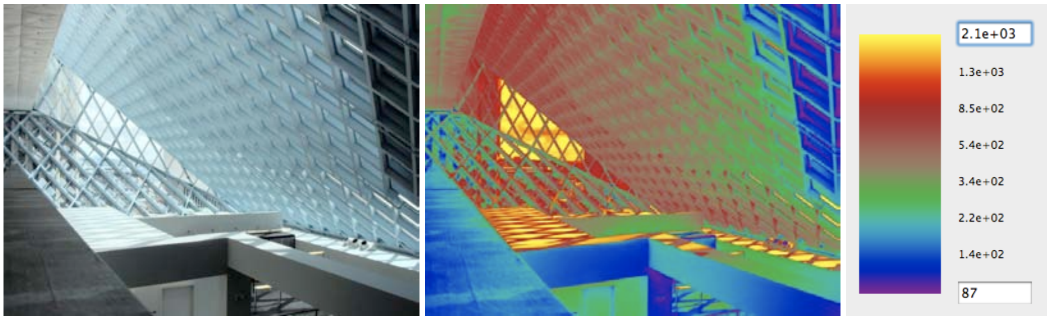


Figure 2.15: HDR photograph and corresponding false-color image taken in the Seattle Public Library, downtown Seattle, WA.

The HDR method has emerged as a photography technique that not only creates interesting and dramatic images but also can be an accurate method of capturing luminance data for an entire scene. The development of HDR photography has created opportunities for the development of many applications based on this technique. Notably, HDR images have led to the development of a new field within computer graphics where the images are used as environmental maps to light digital models with accuracy and realism that may not be matched with other rendering methods. This field is called Image Based Rendering.

Chapter 3: Image Based Rendering

Image Based Rendering (IBR) is a rendering method that uses HDR photographs to light digital models. The lighting applied to the digital scene is the information captured from a physical environment using the HDR image capture method. The captured HDR photographs cover either a 180˚ hemisphere or the full 360˚ sphere of an environment, recording the light coming from all sides and reflected from the surrounding surfaces. A physically based rendering program can use this lighting information to light a digital model; one of the earliest examples is shown in Figure 3.01. This technique results in unequivocal realism, which cannot be feasibly achieved through conventional rendering techniques.

Figure 3.01: An image created using the IBR method [23].

The realism is due to the fact that most of the physical world is illuminated by light reflected from the surrounding surfaces, as well any direct sources such as the sun, rather than solely by direct light from a source. Although physically-based rendering software computes inter-reflections in an environment along with the direct lighting, approximations and simplifications are unavoidable. IBR renderings are lit using the entire surrounding environment as a light map that encompasses the complex inter-reflections in a physical environment. The HDR luminance information stored in each pixel of the environment map is a record of the omnidirectional light coming to the camera. If an object were to be placed in that physical environment in place of the camera, it would be lit by the omnidirectional properties of the light in that environment: the same light that is captured by the HDR image. Therefore, each pixel in the HDR image represents the intensity of the lighting coming from that particular direction in the physical world, as illustrated in Figure 3.02.

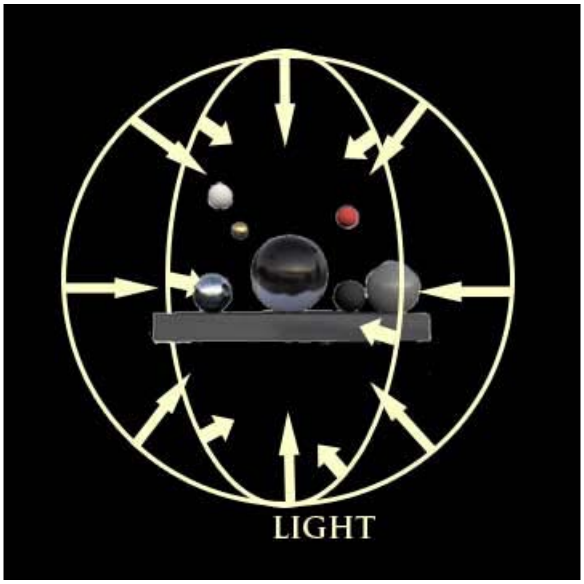


Figure 3.02: Light comes from all directions to illuminate an object when using the IBR method.

The IBR method utilizes physically-based rendering (PBR) algorithms. PBR programs create reasonably accurate renderings based on the physical behavior of light in the real world. These renderings are accurate only to the extent that the modeled geometry, material properties, light sources, and rendering algorithms are accurate. In contrast to photorealistic renders, which use simplifications that emphasize a believable appearance, PBR simulates real world conditions by creating accurate lighting effects like color bleed, reflection, and refraction. It is the addition of these sometimes subtle effects of additional light sources, inter-reflections, and shadows that create a layer of complexity, accuracy, and realism to an image [5]. IBR bypasses the necessity of digitally modeling a complex environment and then using a rendering engine to approximate the light reflecting from this environment to illuminate the model. The captured environment, with the luminance values recorded as HDR data, provides the background image as well as the light sources, leaving only the “virtual object” to be modeled. Because the captured HDR data is an accurate representation of the light in the physical scene, the resultant digital render should be an accurate representation of the lighting effects within the model.

These two properties, realism and accuracy, are intertwined in the IBR method: the image looks realistic because it is accurate. Every modeling simulation, visualization, and render is an approximation in some way. PBR programs create reasonably accurate renders because the rules for approximation are closely modeled on the rules of how light works in the physical world. Other rendering methods, using common digital modeling programs, usually create photorealistic images that are not necessarily accurate. A photorealistic image may mislead the viewer into thinking it might possibly be an image or photograph of the real physical world. Most of these methods rely on the user’s knowledge and intuition of the physical world -- lighting, materials, and the particular modeling program being used -- to create a photorealistic rendering, usually through workarounds, simplifications, and approximations. Moreover, since the photorealistic renderings are created by the user through intuition and estimation, they may be very different from the actual outcome; thus be misleading as design decision tools.

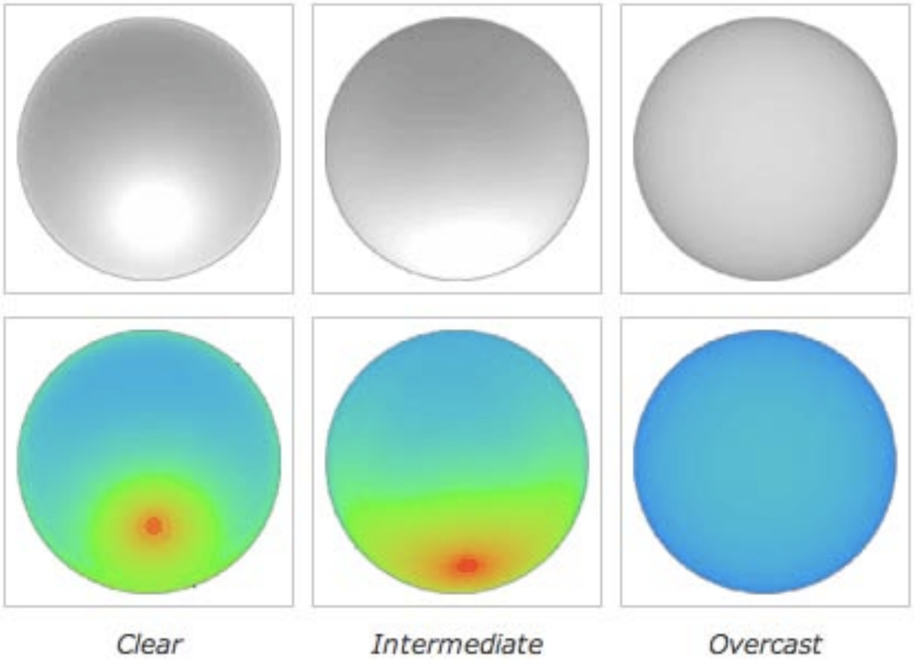


Figure 3.03: Representation of the three CIE sky models [24].

One of these approximations is the creation of the sky for use in lighting the model. Prior to the use of HDR light probes, the most accurate way to light an outdoor digital scene was to use a CIE sky model. The CIE (International Commission on Illumination) sky models are used in many rendering programs to represent clear sky days, overcast sky, and intermediate sky; representations of these three sky models are shown in Figure 3.03. These sky models are smoothed out mathematical definitions: approximations based on averaged data and created as a generalization of each type of sky condition [25]. The CIE Standard Overcast Sky, for example, is one step up from a Uniform Luminance Sky that is a sky of constant brightness. The Overcast Sky has a relative gradation from a darker horizon line to a brighter zenith, mimicking a perfectly overcast sky condition [26]. The CIE Clear Sky adds certain sky conditions like a brighter area around the disc of the sun, but does not contain any clouds or account for other atmospheric changes [26]. Another, less accurate, method of modeling daylight is merely to place a parallel light source into the digital model, simulating the direct rays of the sun. This approach does not contain the sky-light; i.e. the diffuse component of sunlight as the result of the water content and turbidity of the atmosphere. The sky is then created as a background image in the render. While the CIE skies are an improvement over this method, they still cannot encompass the range of lighting effects that can occur from varied sky conditions throughout the day and year. They also do not include any color variation that may occur, such as at dusk and dawn.

The IBR method captures much of the physical world as an HDR image, using that data and a physically-based rendering tool (Radiance [3]) to light the digital model, bypassing most of the approximations that needed to made in previous rendering methods. The sky shown in each HDR photograph is the actual sky occurring at a particular day, time, and location. It also provides accurate, and at times dramatic, recreation of intermediate or partly cloudy skies that can occur frequently but are not captured by the abstract mathematical sky models. If site specific, the HDR image can show the surrounding trees and buildings with accurate depiction of how the light reflects from them and filters through them. The surrounding environment can have a great impact on the luminous environment of any given site: an open space with no nearby obstructions will yield greatly different lighting effects than a site surrounded by trees, or one in a high density urban area. While generalizations and approximations also have their place in lighting analysis and digital rendering, the IBR method is an accurate and customizable tool that adds its own brand of useful information.

3.1 DEVELOPMENT OF IMAGE BASED RENDERING

IBR has been built upon a number of developments in the fields of photography and digital rendering. These developments include HDR photography, omnidirectional photography, environment mapping, and global illumination algorithms [5, 6, 8, 11, 19, 26, 27].

Figure 3.04: An HDR photograph in RGB representation (top) and false-color with scale (bottom).

The most obvious precursor to IBR is the development of High Dynamic Range photography and data capture, detailed more thoroughly in Chapter 2 and illustrated in Figure 3.04. As the IBR method depends on the use of accurate and quantifiable levels of light, HDR data is a necessity.

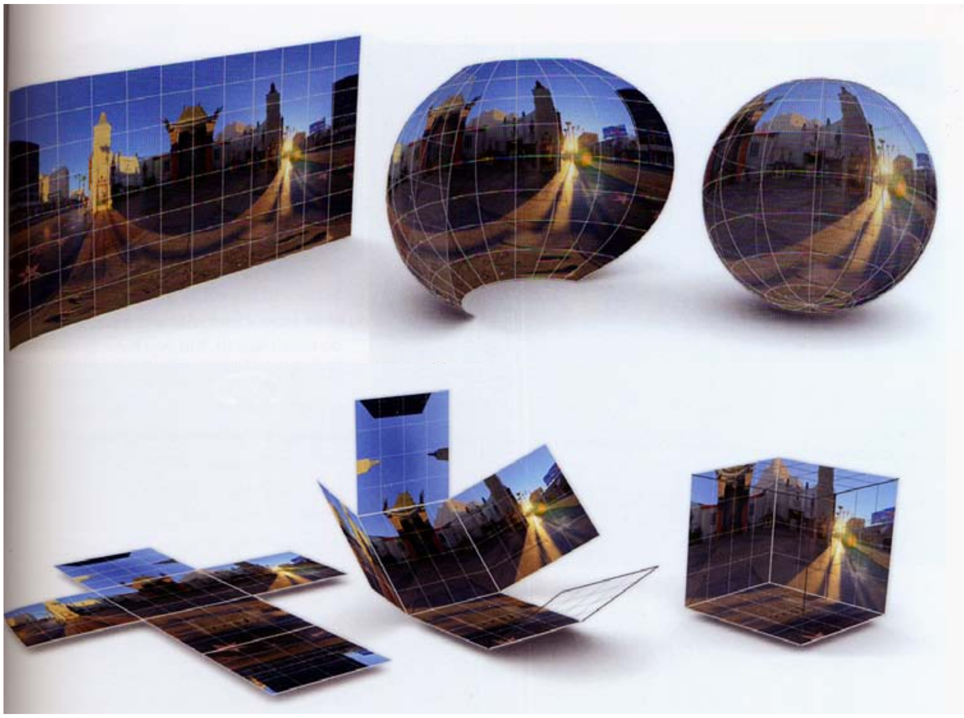


Figure 3.05: Different types of environment maps – spherical (top) and cubic (bottom) are two examples [18].

The further development of omnidirectional photography techniques, or the ability to capture environment maps for a 360˚ physical scene, was another step towards a useful IBR method [8]. Using this method, an image can be captured showing all directions as seen from one point in space. Two common types of environmental maps, spherical and cubic, are shown in Figure 3.05 as an example of wrapping methods. The type of environmental map is determined by the method by which it was captured as well as by the way it is represented as a 2D image. Different types of environmental maps each must be wrapped to a model environment in a specific way, translating the 2D image to a 3D object. When these 3D objects are used to light a model, as in the IBR method, they are referred to as *light probes*. As stated earlier, the reason image based renderings are accurate visual representations is that they include light coming from all directions as the summation of both the direct and inter-reflected light. These renderings could not be created with accuracy or realism if the surrounding environment could not be captured in its entirety to be used as a light probe.

While the surrounding environment could be captured as a series of straightforward HDR photographs (using a common lens rather than a fisheye lens), and then mapped as a cube or rectangular prism to serve as the luminance map for the digital model, that method requires much more accuracy and matching of the individual photographs to create an accurate and realistic environment. This technique is more appropriate to be used for mapping small interior environments, such as a rectangular interior space, due to the formal characteristics of mapping.

Omnidirectional photography has its own particular difficulties, but proficiency in this method is not unattainable. Once the method is learned, the resultant images are very useful for creation of image based renderings. Two common methods of capturing omnidirectional images can create satisfactory results: taking photographs of reflective spheres [7, 8, 18, 19], or using a single 180˚ fisheye image [28, 29]. A third method has been used for one study: two 180˚ hemispherical fisheye images were combined to create one 360˚ spherical environment [29]. For IBR, the environment map becomes a sphere or hemisphere that lights the digital model; this type of mapping is more appropriate for capturing the dome of the sky. The "reflective sphere" method requires post-processing combination of the photographs to create the full, unobstructed 360˚ view. However, a single 180˚ HDR photograph of the sky, captured using a fisheye lens, should also create a satisfactory IBR image if the ground plane is relatively simple and can be modeled. A vertical 180˚ image, captured with the camera facing the horizon, could be used to light interior spaces that are only affected by that half of the environment, such as a room with only one window-wall. Figure 3.06 shows this much less common use.

Figure 3.06: A small room with one window-wall illuminated by a 180˚ light probe of sky and ground. A different light probe is used for each image [29].

Environment mapping is a technique of mapping images directly onto a surface in a digital model, often used to create a background (such as the example shown in Figure 1.02); this technique is capable of creating fairly realistic renderings [8]. While the lighting may not always match up, because the environment mapped image is still on a surface that can be affected by the light in a digital model, capable use of the environment mapping technique can result in convincing renderings; it is also very efficient. In the IBR method, the luminance map is also used as the background image for the rendering. It is an improvement to the conventional environmental mapping approach because the HDR image is providing the light source in addition to acting as the background image for the rendering; the designation of the HDR image as a *light probe* differentiates it from the more generalized term of *environment map*. Figure 3.07 demonstrates the method of wrapping a 360˚ environment map to act as a light probe in a model.

Figure 3.07: Use of environment mapping to translate a 2D image of a 360˚ environment into a 3D spherical object [18].

IBR builds upon the development of global illumination algorithms that simulate the physical behavior of light. A physically-based rendering tool that is capable of processing and producing HDR images is a prerequisite to achieving the full potential of an IBR technique. Radiance Lighting Simulation and Rendering System [3] was utilized for the development of the IBR technique [5]. Global illumination utilizes a variety of algorithms, such as radiosity for diffuse inter-reflections and ray-tracing for specular reflections and photon mapping for caustic effects. These rendering algorithms are computationally expensive, but are accurate simulations of how light travels, refracts, and reflects off of surfaces. Global illumination methods must be used for IBR, since other methods use approximation and would therefore not be capable of accurately depicting the effects of the light from the luminance maps.

3.2 PROCESS OF CREATING IMAGE BASED RENDERING

The basic steps for creating an Image Based Rendering are explained as follows [7]:

- The first step in creating an image based rendering is to acquire a luminance map. A luminance map is an omnidirectional HDR image showing a 360˚ or 180˚ view of a luminous environment, also referred to as a light probe. The capture and assembly process has been outlined in Chapter 2. Alternatively, luminance maps can be downloaded from various websites [19, 30, 31].

- The second step involves the creation of the 3D model of the synthetic objects. The user defines the geometry, materials, synthetic light sources (if available) and camera viewpoints.

- A light probe is added to the digital model as a replacement of the CIE sky model. The light probe surrounds the synthetic objects, mapped onto an imaginary hemisphere or sphere for either a 180˚ or 360˚ image, respectively. Figure 3.08 illustrates how either type of image would light the scene.

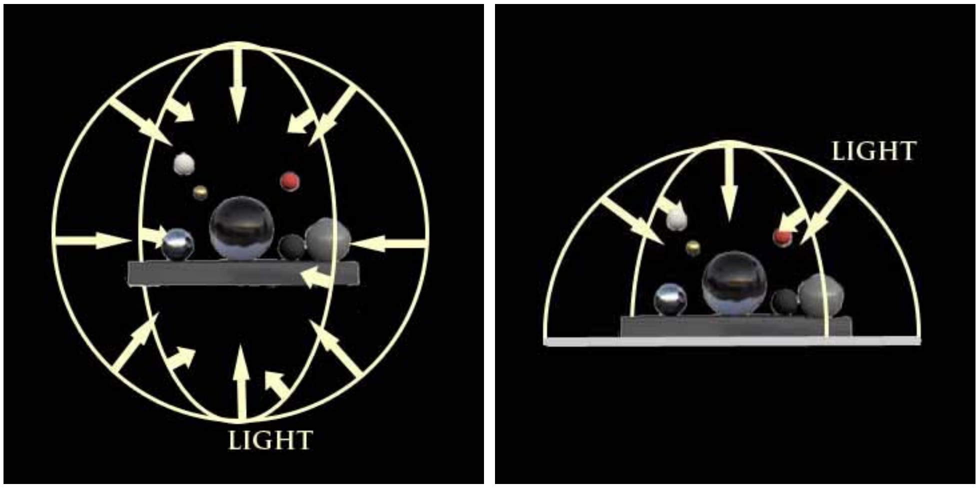


Figure 3.08: Illustration of a digital model illuminated by a 360˚ light probe (left) and by a 180˚ light probe (right).

- Finally, a rendered image can be created from the digital model and HDR luminance map. The resultant image will show a collection of objects, seemingly placed in a scene. The lighting from the HDR image will be used with PBR to create all of the reflections, shadows, and other lighting effects that make the image look realistic.

- The IBR technique creates compelling images in a quick and efficient manner under relatively diffuse light conditions. For examples, it is straightforward to produce good quality IBR images with HDR images of overcast skies. Concentrated sources, such as the sun, provide additional challenges that must be addressed [19].

Although this technique was initially demonstrated with a simple collection of objects, further studies demonstrated that the technique can realistically light larger, more complex models, with similar results [7, 12, 28, 32]. Compositing techniques can create images of the rendered model accurately inserted into a non-distorted background image with realistic lighting effects [5, 8]. Some examples of these uses are shown in Figure 3.09, illustrating more complex models, and use of compositing techniques in the image on the right.

Figure 3.09: Images created using IBR, with a more complex model (left) [32] and using compositing techniques (right) [8].

3.3 APPLICATIONS OF IMAGE BASED RENDERING

When originally developed, the IBR method found immediate applications in computer graphics and the extended area of motion picture visual effects. Digital models inserted into pre-recorded scenes need to be a close match in lighting so that they will look more realistic, and the use of IBR allows for the inclusion of the lighting inter-reflections that occur in a scene [8]. When used for computer graphics of video games, the lighting resulting from IBR similarly creates a realistic environment; with advances in computing power and speed these images will be able to be rendered in real-time [33]. In addition to the insertion of digital pieces into a previously recorded scene, IBR can also be used to create movies of fully digital environments [32] and still photographs with additional digital objects [5, 29].

IBR has the potential to influence and improve lighting and architectural presentation techniques and design decisions. Complex light interactions, such as inter-reflections and shadowing effects, are captured by the HDR environment map, as well as the effects of complex geometries such as the urban fabric and the surrounding trees. This allows design professionals to create compelling images without the need to model the surrounding environment. There is also no need, if using the IBR technique, to attempt to create photorealistic lighting effects using approximations or to painstakingly model the physical properties of light sources within the environment.

There are only a very few examples of utilization of the IBR technique for architectural visualizations and lighting analysis. As shown in Figure 3.10, a digital model of a skyscraper is modeled at night, with the effects of lighting and reflections from the surrounding buildings as they have been captured and applied using a fisheye HDR light probe [28]. A digital model of the Parthenon is dynamically lit by a series of HDR photographs in a short movie [34]; one frame is shown in Figure 3.11. Another study uses the IBR method for glare analysis, using mapped luminance values to determine possible areas of glare [29], shown in Figure 3.12.

Figure 3.10: Luminance map (left) used to light a digital model to create a rendered image (right) using IBR [28].

Figure 3.11: Rendering of the Parthenon digital model using the IBR method [34].

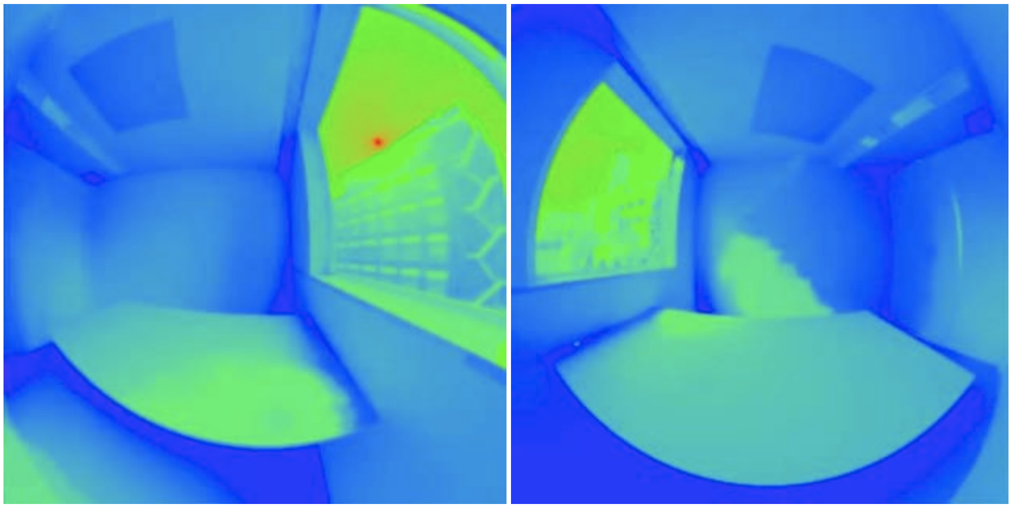


Figure 3.12: Two false-color images created for glare assessment of a room with a view, using the IBR method [29].

Despite its potential, the IBR technique is not well known among architects. In order to illustrate the potential applications of the IBR method in architecture, procedures and general guidelines are discussed in Chapter 4.

Chapter 4: Architectural Applications of Image Based Rendering

IBR, as described in the previous chapter, has tremendous potential for a variety of uses. Specifically, it has many promising usages within the field of architecture and lighting design. IBR can produce images that are visually compelling and numerically accurate. The final product is a rendered image that is a major improvement over the products of more common digital modeling and rendering programs. IBR provides scene visualizations and simulations that can be used for visual appraisal and quantitative analysis to make informed design decisions. However, the difficulty in using the script based technique and the lack of designer-friendly graphic user interfaces (GUIs) hampers the wide adoption of IBR among architectural professionals. Although a few programs (such as Ecotect [24]) provide relatively user friendly GUIs for the Radiance engine, IBR still remains accessible only to users who have some level of programming skill.

Wide range adoption of the Image Based Rendering method for architectural uses requires an explicit demonstration of the process, some adjustments to the commonly accepted IBR method, and identification of the appropriate uses of IBR for architecture and lighting design. The method needs to be explored and customized for these uses in order for it to be practical and useful in its full potential.

When originally developed for use in computer graphics, HDR photography and Image Based Rendering were merely methods of creating dramatic and realistic images; numerical accuracy was not originally a goal of either technique. The accuracy of the lighting data used in HDR has since been recognized and validated [11]. It is assumed that the lighting effects created by IBR are also quite accurate, though no formal study has yet been conducted to verify this. However, a quick, informal verification study, conducted for the purposes of this thesis, is outlined later in this chapter that supports this assumption.

It is already possible for HDR photographs to be used as lighting analysis tools for existing buildings, or for physical mock-ups of architectural designs [22]. Image based renderings using digital models of architectural designs with HDR photographs of lighting environments can be used for similar lighting analysis studies. While accurate lighting data is a useful consequence of creating these renderings, the original intent of IBR can also be utilized by architects: the creation of highly realistic and compelling renderings.

These two applications for IBR will be the main goals for any architects or lighting designers using the method. High-quality images are indispensable for architectural presentations. Numerical accuracy is necessary for evaluating the visual comfort, visual performance, and the intended visual effects of architectural lighting designs. Lighting also affects many design decisions like surface materials, building orientation, and window placement; analysis of an IBR image could influence a variety of design decisions beyond lighting. The desired goal of using the IBR method, for architects and lighting designers, would be to create reasonably accurate images that can be used both for analysis and presentation purposes. To achieve this goal, a properly calibrated HDR image must be used, the IBR process must be followed, and any errors must be recognized and nullified. Additionally, certain aspects of the IBR method must be adjusted for specific use in the architectural design field.

4.1 ADAPTATION OF IBR FOR ARCHITECTURE

Whether used for representation, analysis, or both, IBR techniques have elements that are commonly used from one application to the next. However, certain features are emphasized, and variations from the basic method are recommended here to make the method more applicable and accessible for architectural usages.

Environment Map Type:

- The original development of the IBR method involves 360˚ views of the surrounding environment, captured as an HDR photograph, to be used as a spherical environment map. It could be an interior or an exterior photograph. This environment map acts as both a light source and a background, including surrounding objects, ground, and sky (or floor, walls, and ceiling).

- In the context of architectural renderings, a 180˚ HDR photograph of the sky for a hemispherical environment map can be used instead of the full 360˚. The underlying rationale behind this recommendation is the fact that most architectural designs will necessitate changes to the landscape of the site the building occupies. These changes would be modeled along with the building design in a digital model, abolishing the need for the ground portion of the environment map. HDR images of the actual site will capture surrounding trees and buildings, creating a custom render specific to that site. Figure 4.01

shows a site-specific example on the left. For users who cannot access the particular building site needed, or do not wish to learn the HDR process at all, a sky image captured anywhere in the same latitude may provide the basic lighting effects for the site and still create a compelling image. A sky image, with no surrounding trees or buildings, can still represent lighting conditions at the site with an accurate sun position for that latitude at the date and time when the photograph is captured. The 180˚ environment map can be captured with a fisheye lens and represented as a circular image, or can be the top half of spherical capture represented as a half-circle; these two types are compared in Figure 4.01. The only difference is the manner in which they are translated into the 3D object that lights the scene.

Figure 4.01: Two examples of 180˚ images of the sky. The left image is taken in Seattle (47˚ N, 122˚ W, May 13 2008, 6:30pm). The right image is available from [19].

HDR Capture Method:

- The image and lighting data are usually captured using the mirror-ball method, where a series of bracketed photograph exposures are taken of a reflective sphere from two angles. The equipment for this method includes a digital camera, a reflective mirror-ball, and two tripods (one to hold the sphere and one for the camera). This setup is illustrated in the left-hand image of Figure 4.02. The resulting HDR photographs are combined to create an unobstructed view of the surroundings [8, 18]. This HDR image map is then inserted into a digital model to act as the light source.

- An obvious advantage of using 180˚ fisheye images is to simplify the HDR capture process and make it more accessible. Rather than using a method that requires post-processing to combine multiple HDR images from more than one angle, a single HDR image provides sufficient data. Multiple exposures of the sky can be captured using a fisheye lens attached to a digital camera. This single set of images, once combined into a single HDR photograph, can serve as the environment map for the model. No further combining of images is involved, and only one set of bracketed exposures needs to be captured. The equipment needed includes a digital camera, a fisheye lens, and a tripod, as the image on the right illustrates in Figure 4.02.

Figure 4.02: Different setups needed for HDR image capture – 360˚ capture (left) [35] and 180˚ capture (right).

<u>Model Size and Placement:</u>

- In most examples of IBR, the digital model itself is usually small, like the orbs and pedestal seen in Figure 4.03. The center of interest can be elevated off of the model's ground plane, placing the center of interest approximately where the center of the HDR image map sphere is. This allows any downward facing views of the ground to appear realistic, so the model does not seem to be floating in space.

- Of necessity, most architectural models are much larger than the basic models used in early examples of IBR. They are also more complex, which slows down rendering time but does not affect the quality of the rendering itself. These models should contain a ground plane so that light reflected off of the ground will be properly rendered, because the 180˚ environment map of the sky will not provide that information. The modeled ground plane will also show shadows cast by the building and other objects, as shown in Figure 4.04.

Figure 4.03: A small model illuminated and rendered using IBR [23].

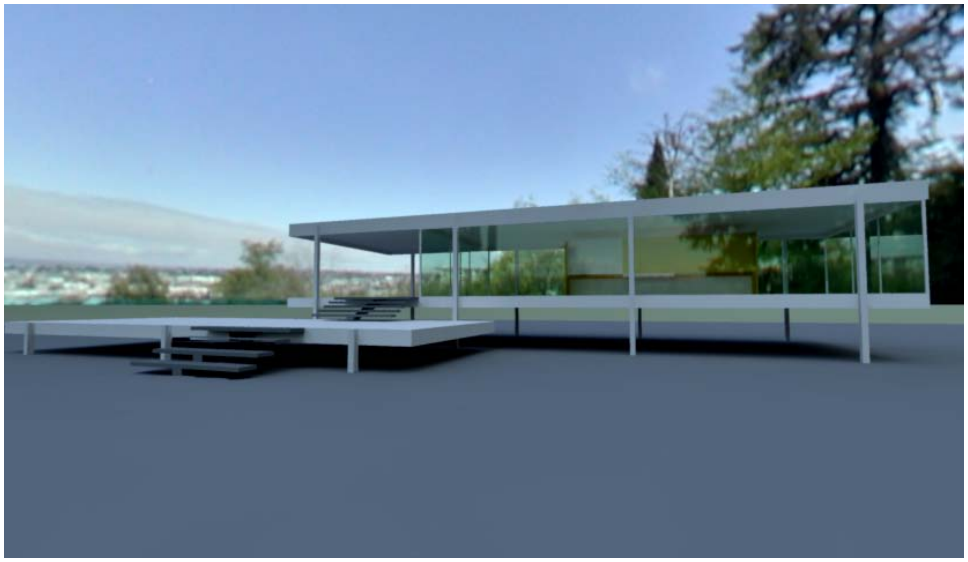


Figure 4.04: An architectural model with a ground plane, showing shadows cast by the building.

Orientation Issues:

- While it is not explicitly addressed in most current publications describing how to create an IBR image, most applications of this method require that careful attention be paid to the orientation of the digital model and that of the HDR image, making sure that the two main elements are oriented in the same way. This would be used in any computer graphics applications where a digital object is inserted into a background image of a physical scene, as seen in Figure 4.05. Most of the objects in Figure 4.05 are synthetic objects, inserted into the background photograph of a table. While some models may not need to have a specific North direction, all scenes need the basic orientation to assure that the sky or ceiling corresponds with the "up" direction of the model. This orientation is handled with an equation to translate the flat HDR image into a 3D environment map existing in the model space.

- Architectural models are built with specific orientations, where North is clearly delineated. This orientation must match up with the orientation of the environment map. For example, a building with many South-facing windows will receive direct sunlight throughout the day as the sun moves through the Southern portion of the sky. Therefore, it is important to match the orientation of the three-dimensional model and the environment map. This is accomplished with a script-based file that translates the 2D environment map into a 3D object that acts as a light probe. Examples of this file are attached in Appendix B, while the Radiance script files that use the translation equation are attached in Appendix A. The generally accepted method assumes that North is "up" in a plan view of the model (or the +y direction), each variation of the equation is based on assumptions on which way the camera was facing when the HDR image was captured, and changes can be made to accommodate a 180˚ fisheye image rather than a 360˚ capture of a sphere. Figure 4.06 illustrates the mapping of a 180˚ vertical light probe, taken with the camera facing North, onto the axes of the model space where the +y axis would correspond with the North direction.

Figure 4.05: Examples of using IBR to insert digital objects into physical scenes [5, 18].

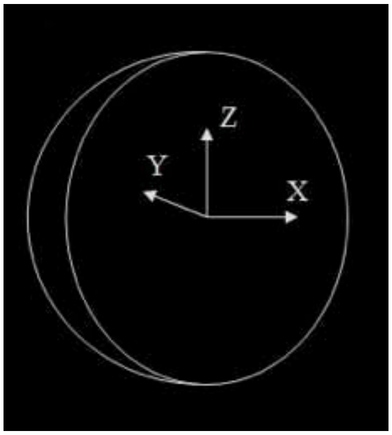


Figure 4.06: Orientation of a 180˚ light probe mapped to model space as a hemisphere [29].

4.2 EXAMPLES OF IMAGE BASED RENDERING

The potentials, limitations, and applications of the IBR method have been explored through many variations. The variations include:

- Exploration of various light probes: substitution of HDR images, including environment maps provided by others [19, 23, 30, 31], and fisheye images captured at various times and locations around Seattle, WA;
- Explorations of different digital models of varying scales;
- Alterations of ground surface definitions in the digital model;
- Exploration of the translation equation used to create the three-dimensional environment maps from the HDR images [29];

Troubleshooting tips for various issues and a list of recommended guidelines based on these explorations are provided.

The basic method for creating an image based rendering of an architectural model requires certain equipment and computer software. A variety of options have been delineated in previous chapters; this section will describe the equipment and software used only for this particular study, though many other variations are possible.

Exploration of various light probes:

The first step in the IBR process is optional: capture of an HDR image to be used as an environment map. If the specific building site is available, it is strongly recommended that the site be used for HDR image capture. This will provide much more accuracy and realism to the final IBR output, containing the actual surroundings as well as the specific lighting conditions. Multiple visits at different times of the day, year, and even at night will provide more options for presentation images as well as a more thorough set of lighting conditions to assist with analysis.

Using a digital camera, tripod, and fisheye lens, an HDR image of the sky hemisphere can be captured; the method is outlined in Section 3. If the site is not available, images can be captured from the roof of a building in the same city, providing at least the same weather conditions that would occur at the site. Once a set of exposures has been captured, they can be combined into an HDR photograph using computer software.

For this study, photographs were captured using an Olympus Camedia C-3030 ZOOM digital camera set in the Manual mode, an iPix fisheye lens with 185˚ coverage, and a camera tripod. Images were captured at various times and locations around Seattle, Washington. These HDR images were produced using the software Photosphere [10]. Additional HDR environment maps were also used, available for download online [19, 23, 30, 31], as well as a captured image of the Radiance [3] digital sky to use for verification purposes. Figure 4.07 shows a sample of the light probes that were used.

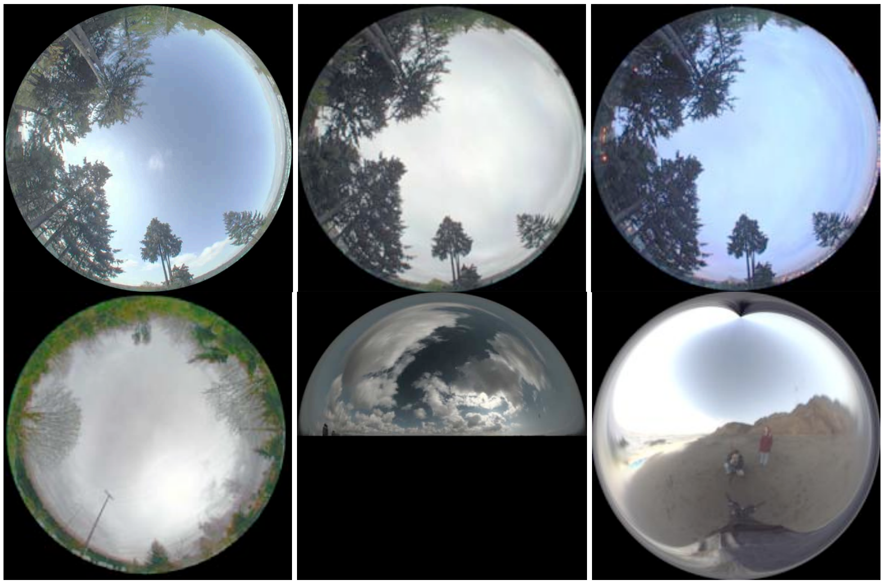


Figure 4.07: Some of the HDR environment maps used for this study. The top three images were taken at the same site in Seattle, WA, at different times and weather conditions. The bottom left photograph was taken at another location in Seattle with overcast weather. The bottom center [19] and bottom right images [31] were taken elsewhere by other photographers.

Exploration of different digital models of varying scales:

Various simple models were created in text files and using the Radiance Control Panel (RadianceCP) application through the Ecotect interface [24]. An architectural model of Ludwig Mies van der Rohe's Farnsworth House was obtained from Google Sketchup 3D Warehouse [36], edited in Ecotect [24], and exported to Radiance file format [3]. The initial phases of the study incorporated simple models to check procedural challenges and opportunities of the method, verify orientation issues, and troubleshoot. Other simple models with sphere objects were used to further explore the potentials of the IBR technique in creating compelling images with surfaces that can reflect and refract the light coming from the surrounding environment. The architectural model was used to verify the effectiveness of the recommendations to adopt the technique for architectural uses.

Using the basic IBR technique, outlined in Section 3, basic test renderings were created using the Radiance software [3]. Changes were made as the result of rendering and coding errors, substitution of HDR environment maps, and adjustment to architectural applications. Sample script-based files are attached in Appendix A. The collection of images produced by the basic and the modified IBR techniques demonstrate the uses of the method, possible errors, and specific architectural applications. Figure 4.08 contains a few samples of these images, taken from various points throughout the process of this study.

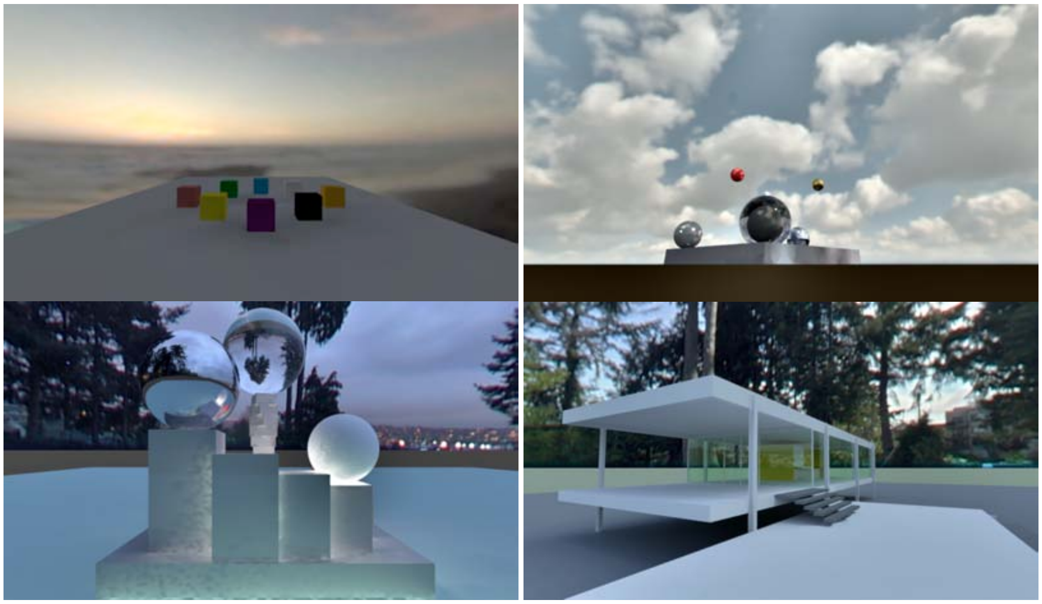


Figure 4.08: Samples of IBR images created throughout the progression of this study.

Ground surface definitions in the digital model:

Using the Radiance software for the IBR method, there are two ways to create a ground plane for digital models. A modeled ground plane can be inserted as a polygon in the model: this type of ground plane will reflect light from the HDR light probe and also show any shadows created by the other synthetic objects. A “ground glow” is an option in Radiance, which simulates a ground plane by inserting a glowing object as the lower hemisphere surrounding the model. This ground glow will not be affected in any way by the HDR light probe and will not show any cast shadows. The effects of using either or both of these ground options were explored and are further explained in the recommended guidelines later in this chapter.

Exploration of the translation equation:

The equation used to translate the HDR image into an environment map in the 3D model space is set up according to where the camera is facing to capture the HDR photograph [29]. In addition to an equation for 180˚ sky environment maps, equations for vertical HDR light probes were created, one for each direction the camera and model might be facing. This has a specialized application: an interior view of a space with windows on only one wall, as Figure 4.09 demonstrates. Samples of the translation equations used for study appear in Appendix B.

Figure 4.09: An interior view of a room with a single window (left) can be lit using a vertical light probe (right) and a customized translation equation.

4.3 RECOMMENDED GUIDELINES

Many issues associated with the IBR method surfaced during this study; some of these issues must be addressed in order to create a useful rendered image, while others may be critical depending on the context. The following guidelines are suggested for the successful use of IBR for architectural visualization purposes.

- **Equipment:** With the fisheye HDR images, it is important to use a camera that has a full-frame sensor. If the sensor is not large enough, the resultant fisheye image will be cropped and unusable as a light probe.
- **Camera Placement:** It is important to plan the location of the camera within the site during the HDR capture process. For architectural models, the center of interest should be as close to the center of the site as possible. The camera should also be placed very close

to the ground, so that the full sky hemisphere is captured all the way down to the ground plane. This is very difficult, as the photographer must stay below the lens height to remain out of the picture. Sloped sites are also difficult to deal with; the building will be occupying the entire site, but the uphill portion of the ground will appear in the environment map. Suggestions include shooting from the highest section of the site or shooting with the camera raised high enough that it does not capture the larger portion of the ground. The first option might skew the relative distance of the surrounding objects if the highest point is near the edge of the site because the center of interest has been moved. The second option cuts out some of the information on the horizon, since the model ground plane will occur at the level of the camera lens. Another option is to shoot at the center of the site at a low height, but using the viewpoint placement in the digital model and the building itself to block any anomalous effects. However, this strategy will likely create unrealistic lighting effects on the side of the building lit by the image of the uphill portion of the ground.

- **Image Cropping:** The photographs captured using a fisheye lens will consist of a circular image on a black rectangular background. The image must be cropped as a square circumscribing the image circle, as Figure 4.10 illustrates. This can be done in a variety of programs, but the resultant image should remain in 32-bit HDR format. Uncropped fisheye images used as light probes will produce strange effects, as seen in Figure 4.11.

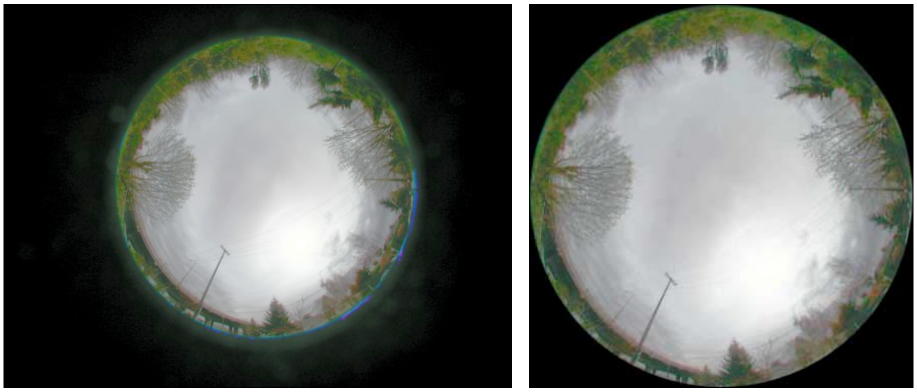


Figure 4.10: Original HDR fisheye image (left) and properly cropped image (right).

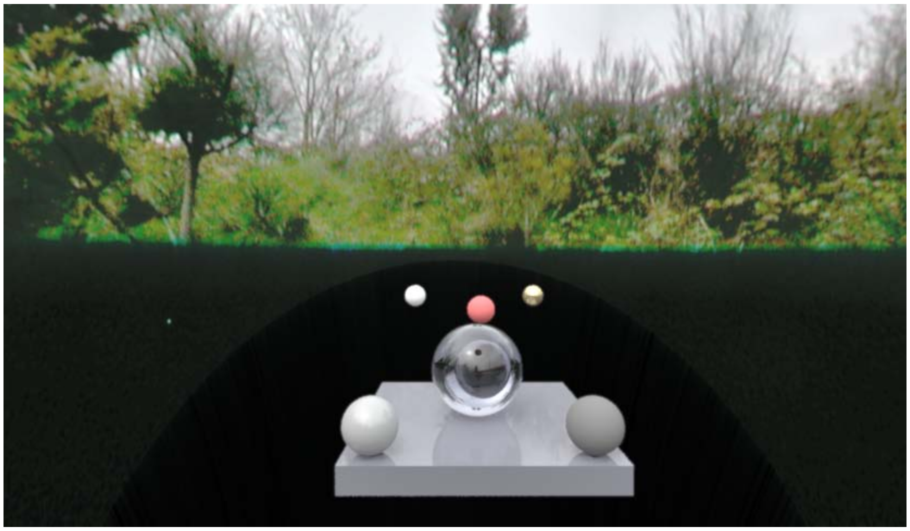


Figure 4.11: The result of using an uncropped fisheye image as a light probe.

- **HDR Image Exposure:** When a set of bracketed exposures is combined and saved as an HDR image, it is set to a certain exposure that can display the contents of the HDR image best in a LDR display device. This does not affect the luminance data, but it does affect how that data is interpreted when the HDR image is inserted as a light source using Radiance. The image exposure must be adjusted so that it is equal to 1.0 before it can be used to properly light a digital model. This can be done using picture filtering options ("*pfilt*") that is outlined in the Radiance manual [3].

- **Orientation:** The same basic translation equation can be used without editing if the same type of environment map is always used. For 180˚ images of the sky, it is easiest to orient the camera so that North is at the top of the image. Images could also be rotated until North is up. The equation must be adjusted for other rotations, 360˚ images, and images captured vertically (with the camera facing North, South, or any other orientation rather than facing the sky). Appendix B contains translation equations for various types of environment maps.

- **Materials:** Care must be taken when assigning materials to models. Unrealistic material properties will result in unrealistic and inaccurate IBR images. Physically-based modeling materials can be created in many different types (metal, plastic, glass, etc) using basic modifiers such as color (RGB), specularity, and roughness [3]. If the model is exported to

Radiance from Ecotect, the preset materials from Ecotect can first be assigned [24]. This option provides access only to the very basic material options. Various databases exist on the Internet to find user-provided definitions of more complex materials like brick or wood paneling [3, 26, 37].

- **Distance Effects:** Because of the size of the model, as well as its placement on the actual ground level of the model space, any nearby surroundings captured in the environment may seem to be farther away than they would in the physical space. This will not significantly affect the lighting effects on the model, but it affects the visual appearance of the rendered image as the environment map is also displayed as the background. This is particularly noticeable with larger models, but can also be affected by virtual camera placement, as illustrated in Figure 4.12.

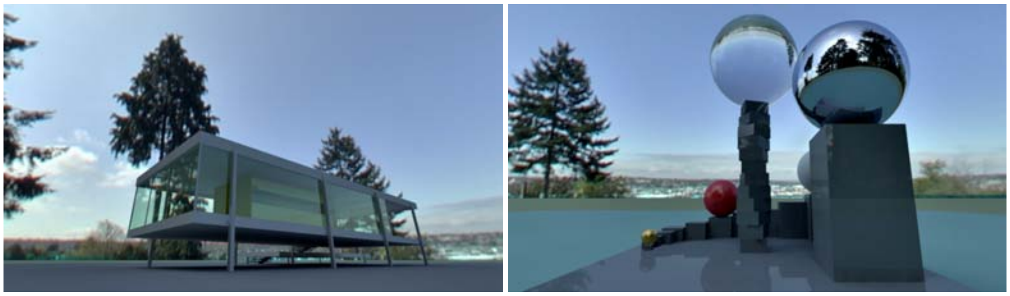


Figure 4.12: Perceived model size and relative perceived distance of the surroundings can change with camera placement.

- **Modeling of the ground properties in Radiance:** While a ground plane should be part of the digital model to provide reflected light and a canvas for shadows, the ground plane cannot reach to the edges of the mapped HDR image. The hemisphere of the HDR image will always be larger than the model, so there will always be a gap visible. If this is not addressed, the void can become very distracting, and the light reflected from the ground will be ignored in the model, as Figure 4.13 illustrates. Using the Radiance "glow" command, the other half of the sphere defined by the HDR map can be filled in as a uniform color that emits its own light. This simulates the effect of a ground plane reflecting light from the sky. It is challenging to match this glow color to ground plane color, because the latter is affected by the colors of light it is reflecting from the sky.

However, a close match would suffice to create a seamless transition between the "ground plane" and "ground hemisphere". Customizing the color of ground according to the HDR environment map being used is recommended for smooth transitions from the synthetic objects to the captured environment, as seen in Figure 4.14. Using unrealistic ground glow values (i.e. values that are too high beyond the physical properties of the actual ground surface) will result in noticeable lighting effects from below, as seen in Figure 4.15.

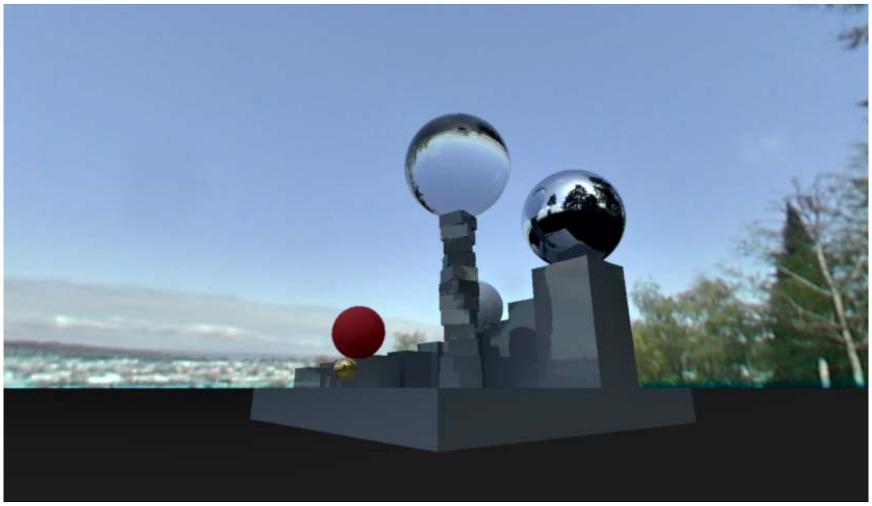


Figure 4.13: A daytime image where ground glow values are set distractingly low.

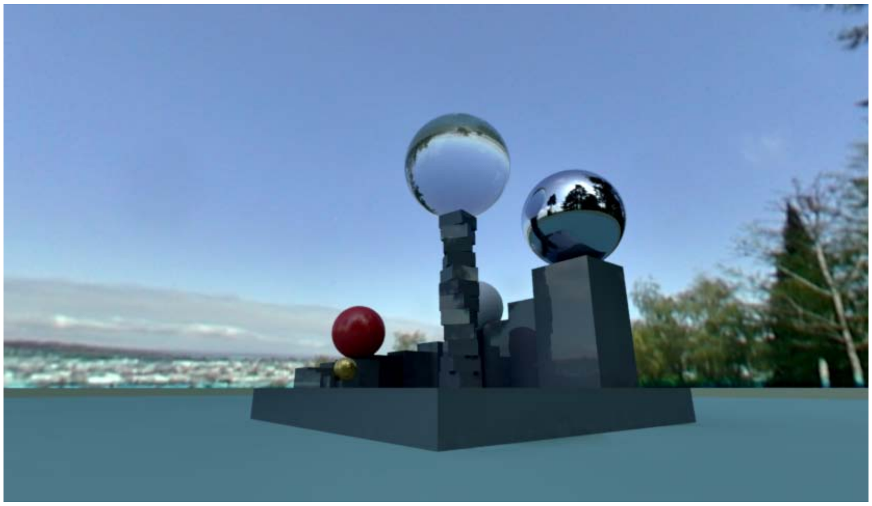


Figure 4.14: A daytime image where the modeled ground plane and the ground glow match closely.

Figure 4.15: A nighttime image where the high ground glow values overpower the light from the HDR environment map.

- **Concentrated Light Sources in Radiance:** Monte Carlo backward ray tracing methods can become problematic with concentrated light sources [26]. Rays of light are traced from the virtual camera viewpoint (specified in the model) to the objects and light sources in the scene. In addition to rays of light traveling directly to the viewpoint, light bouncing off of objects is also recorded. Inter-reflections are caused by multiple bounces of the same ray of light. The number of light rays sampled will determine the associated noise levels in a rendering. In Radiance renderings, concentrated light sources are explicitly modeled to address this problem. However, in the IBR technique, each one of the pixels in a light probe provides a separate light source for the virtual objects. Concentrated light sources in this instance begin to pose a problem, because these sources are not explicitly modeled and calculated through direct light algorithms. Using higher render settings may mitigate the effects. If the render settings are not high enough, the effects of concentrated sources look like patches of light scattered across a surface. This is illustrated in Figure 4.16, where the model is illuminated by a light probe containing some small concentrated light sources in the form of streetlights. This applies for the IBR environment maps, but not the general Radiance sky. When the concentrated source of the direct sun is used in the Radiance sky, the program accounts for that source and samples more light rays for the portion of the image. For environment maps of direct sun, blocking out the sun itself in the HDR image and placing a concentrated source at the correct position in the sky using

Radiance, with the intensity matching the recorded sun intensity, can provide a solution to this problem.

Figure 4.16: Renderings of the same IBR scene using Radiance Medium- (top) and High-Quality (bottom) render settings.

- **General Radiance Quality:** General lighting effects in Radiance, even if no concentrated sources are present, can also be affected according to the viewpoint placement and quality settings. Interior viewpoints (where the light must pass through a glass material) and close-up views (where the light greatly changes intensity over a small area of the image) usually need higher quality render settings to produce presentation-quality images when using the IBR method. Figure 4.17 compares two viewpoints of an architectural model rendered with Medium- and High-Quality settings. The improvement caused by the

High-Quality settings is merely noticeable for the exterior images, while it is markedly pronounced for the interior images.

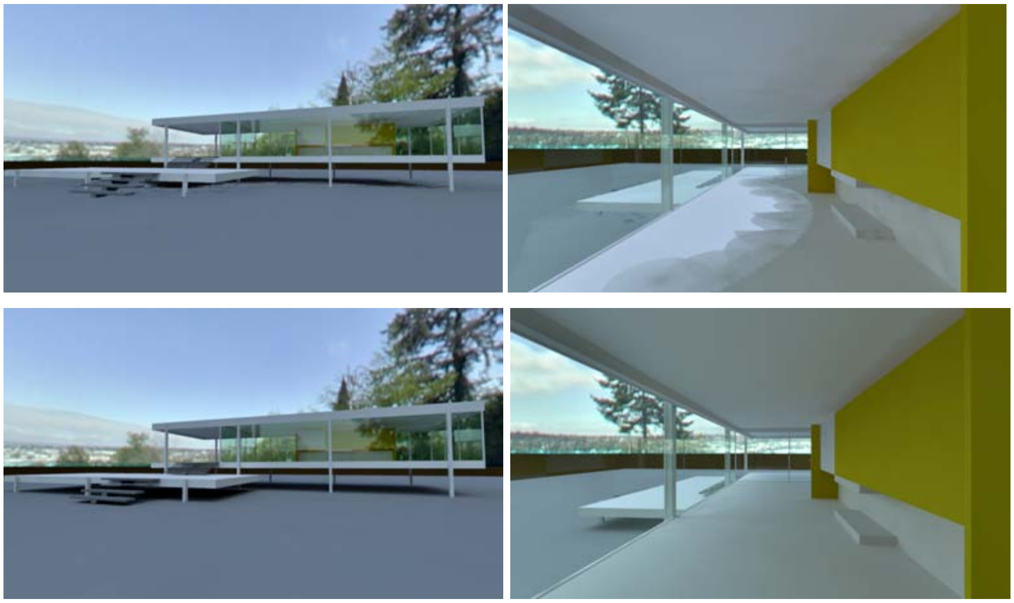


Figure 4.17: Interior and exterior views of an architectural model rendered using Medium- (top) and High-Quality (bottom) render settings.

4.4 RADIANCE SKY VERIFICATION STUDY

In order to confirm that the IBR method could be used for lighting analysis purposes, a quick verification study was conducted with the Radiance clear sky and a simple digital model. The original purpose was to verify that light probe luminance levels would be accurate, though the study also resulted in clarification of the translation equation for the environment map. Since the Radiance rendering software has been validated [4], comparison of Radiance renderings with images created using the IBR method is a reasonable method to verify the accuracy of IBR.

The Radiance software program can provide preset sky conditions, based on CIE standards [3, 25]. For this study, a light probe of the Radiance overcast sky was captured using a virtual camera that covered 360˚. The image created by Radiance was saved as a 32-bit RGBE file, containing the luminance values for the overcast sky at the chosen location, date and time: Seattle (47˚ N, 122˚ W), September 21st at noon. This image is shown in Figure 4.18.

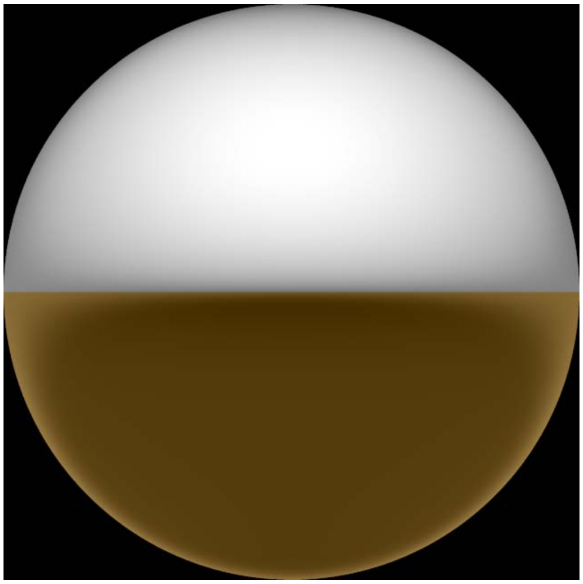


Figure 4.18: The Radiance standard overcast sky captured as a 360˚ light probe.

A simple model was created and rendered using the preset Radiance sky. The resultant image was then saved as a 32-bit file for later comparison of luminance values. Figure 4.19 shows this rendering on the left, in false color. Following the IBR method outlined earlier, images were then created using the saved 360˚ clear sky environment map as a light probe. This image is shown in Figure 4.19 on the right, set to same scale as the image on the left for luminance value comparison.

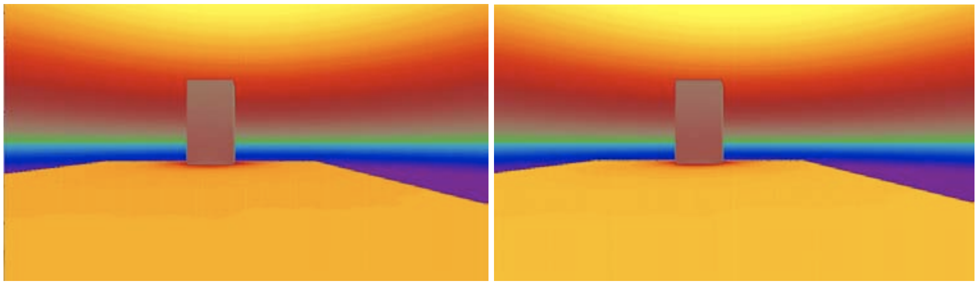


Figure 4.19: Two false-color images comparing luminance values created using the Radiance standard overcast sky (left) and the HDR light probe (right).

These two false-color images verify that the HDR light probe illuminates the model similarly to the standard Radiance sky.

4.5 FURTHER EXPLORATION

Another exploration was done to test the viability of using two 180˚ fisheye images to create a 360˚ light probe. Similar to an existing study [29], the two vertical environment maps were inserted as separate entities, as hemispherical light probes that illuminate the model from all sides. These environment maps are shown in Figure 4.20. The two corresponding translation equations were used to orient each light probe according to their original orientations, and the pre-existing virtual cameras were left in place on the model that was used.

Figure 4.20: The two environment maps used to light a model, covering a 360˚ scene.

Figure 4.21 shows the resultant images, including views of the seam between the two light probes, which is visible in the reflections and refractions of some of the spheres. The seam is apparent because of a slight vignetting effect at the edges of each probe, as well as the fact that the probe content does not line up precisely. Regardless of these minor effects, this is a quick and easy way to create a full 360˚ lighting environment. Judicious placement of the virtual camera can mitigate the visibility of these effects, as illustrated in Figure 4.22. Careful model and camera placement are needed to avoid the floating effect shown in both Figures 4.21 and 4.22. The advantage of this method for architectural applications is that the full site could be shown, and ground reflectance would be much more accurate, while the HDR capture process remains relatively simple.

Figure 4.21: Images created using the IBR method to illuminate a model with two 180˚ light probes.

Figure 4.22: A model with a camera viewpoint (left) that avoids showing the seam between the two light probes (center and right) used to illuminate it [29].

Chapter 5: Conclusions

5.1 THESIS SUMMARY

This thesis presented a framework to adapt IBR as a digital rendering technique for use in architectural and lighting design applications. IBR is a lighting and rendering method that uses HDR photographs captured from a physical environment to light a digital model, creating renderings with realism and accuracy that cannot be plausibly achieved through other rendering techniques.

The shortcomings of traditional tools are summarized Chapter 1. In Chapter 2, the HDR photography method is discussed: HDR image capture and image assembly techniques are demonstrated. Chapter 3 includes the basic IBR method, which was originally developed for use in the area of computer graphics. In Chapter 4, the IBR method has been fine-tuned in a variety of ways that make it easier to use and more specific to the field of architectural rendering.

5.2 CONTRIBUTIONS

This thesis provides a complete documentation and demonstration of the IBR technique for architectural applications. It provides the following distinct benefits:

- The information gathered in the document demonstrates the potential of the IBR technique for exceptionally realistic renderings that incorporate existing site and weather conditions at a particular location, date, and time. Use of this method negates the need to model complex environments, such as surrounding trees and buildings.
- The analytical uses of this method have been reviewed. The renderings provide an accurate visual representation that can be reliably used as the basis for design decisions. Luminance values can be represented as false-color images to study luminance distributions and to identify possible glare sources.
- Guidelines are provided for successful utilization of the IBR technique. These guidelines are the result of the review of existing studies as well as a prolonged trial-and-error based exploration of the technique. They are provided here for future users.

Simplification of the HDR capture process can be achieved by using a fisheye lens that captures 180˚ of the luminous environment, and that 180˚ light probe can then be used to light architectural models. Recommendations concerning camera placement, render settings, and digital modeling are presented to help architects use this method specifically for presentation-quality renderings. The brief Radiance sky verification study demonstrates that the luminance quantities achieved when using this method correctly are comparable to rendered Radiance light values, opening the possibility of using IBR for glare assessment as well as visual assessment of architectural lighting designs.

5.3 REMARKS

The images created using the IBR method are both accurate and visually compelling. Once the technique has been learned, dramatic rendered images can be created in a relatively short amount of time. For specific architectural applications, these rendered images can be used for presentations or for analysis. Given access to the building site, proper equipment, and a digital model, architects can create vivid images of structures placed in their specific environment and illuminated by an HDR photograph of the physical space that the building will occupy. The development of IBR and its specific application for architecture allow users to produce compelling rendered scenes with the confidence that the lighting effects shown will closely mirror the physical setting of the built project.

5.4 FUTURE WORK

Certain issues, such as the problem of concentrated light sources in Radiance, were not fully resolved in this study, though effective alternatives were explored. Further exploration of these topics would be valuable contributions to the IBR method in general, as well as for specifically architectural uses. Additional work on HDR capture of the sun and use of direct-sun light probes would make it easier to use the IBR method to show a digital model in a wider variety of naturally lit environments. Alternative solutions to the problem of concentrated light sources in the light probe, other than merely using higher-quality render settings, might also make this rendering method more viable for use with a variety of lighting conditions. Another area of study that would make IBR more accessible to the general public would be the exploration of this method with a variety of equipment and software types, rather than only the specific ones used for this study. Software development specific to the IBR method would also greatly increase the convenience and usability of this rendering technique.

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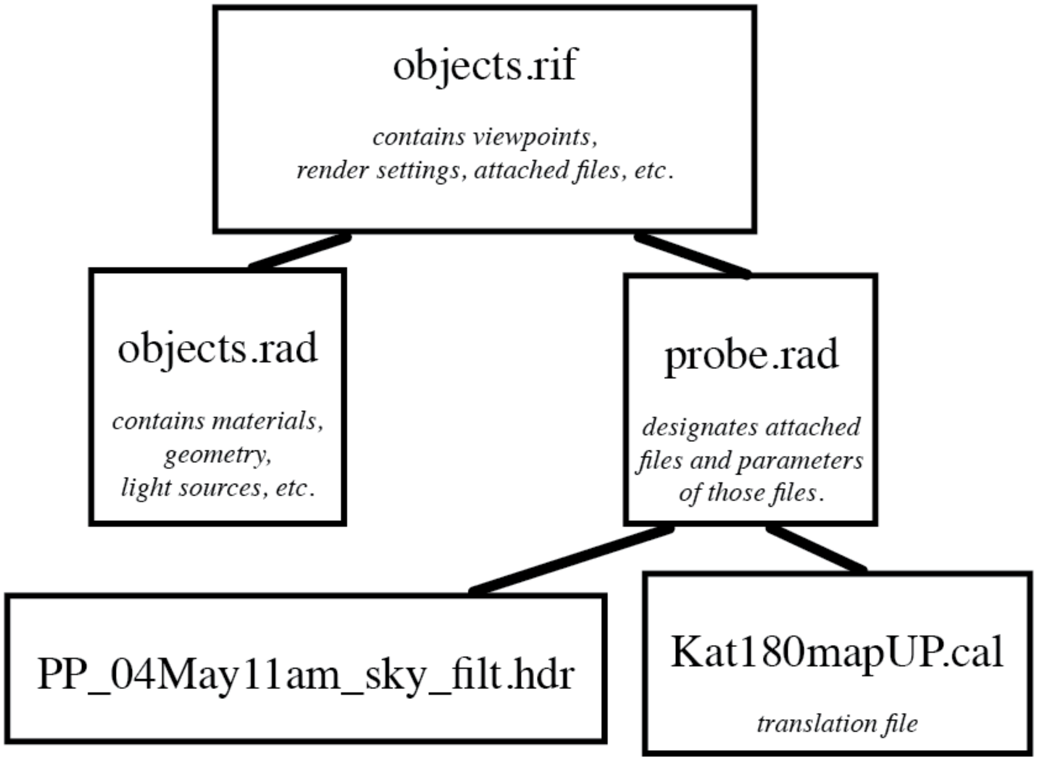
Appendix A: Sample Radiance Files

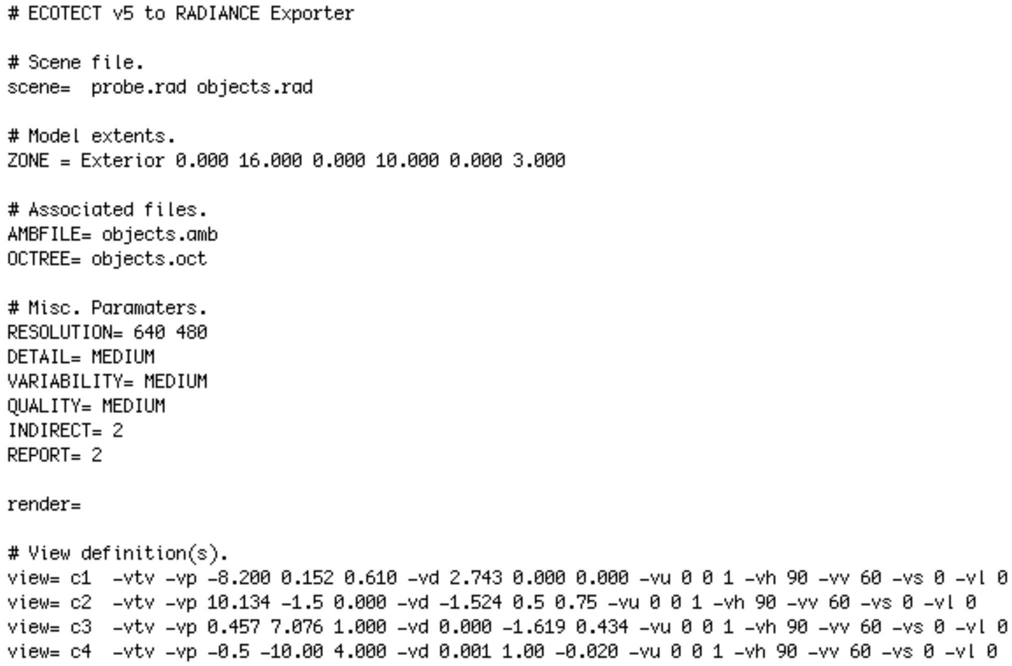
The following are samples of some of the script-based files used to create IBR renderings in Radiance.

The diagram below illustrates how the Radiance file structure works when using the IBR method. Files are designated by their extensions, such as *.rad* and *.rif*. The *.rif* file is a Radiance input file that sets the rendering parameters, including viewpoint placement, render quality, and attached *.rad* files. The *.rad* files contain model information like materials, lights, and geometry. Multiple *.rad* files can be attached to the *.rif* file, which can simplify the editing process by separating the model file from the sky or light probe file. The diagram shows the specific files and structure used for one of the renderings in this study.



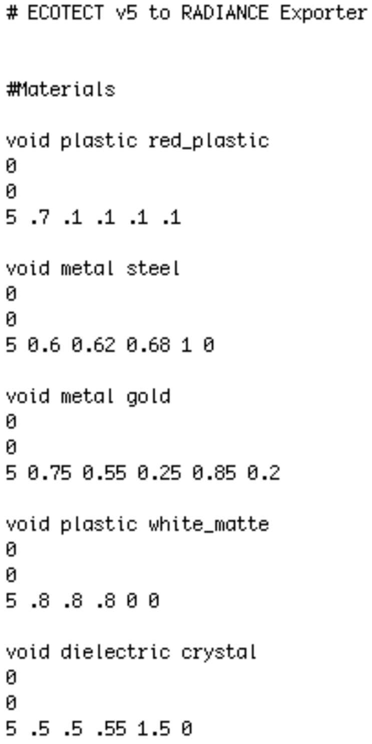
Each file is text based, and many of the *.rif* and *.rad* files used here were generated using the Ecotect export option. The files were then edited using Radiance Control Panel or a text editor to include the changes needed for renderings using the IBR method. The *.cal* translation files are further explained in Appendix B.

OBJECTS.RIF

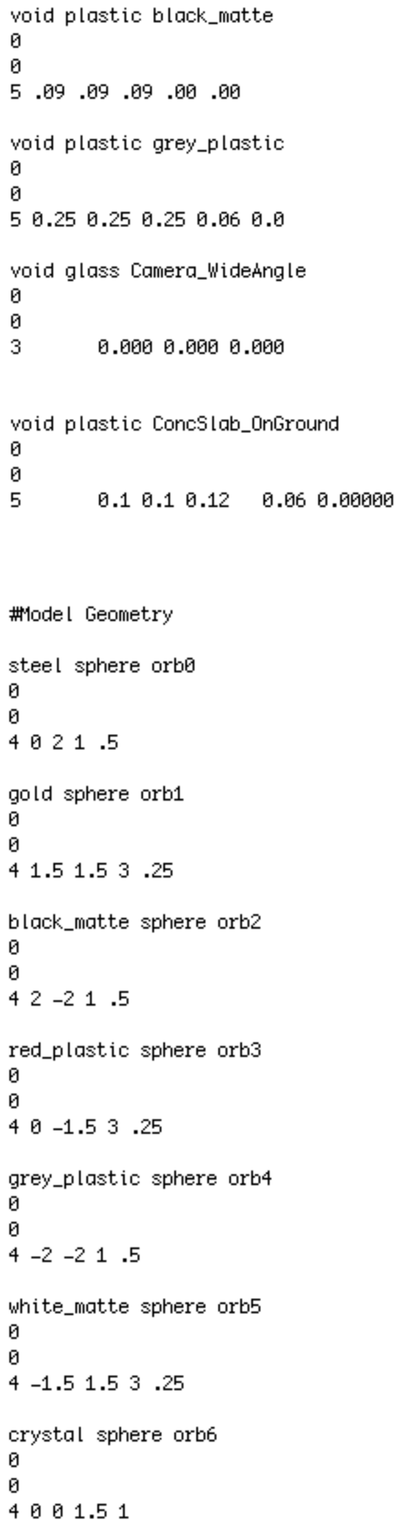


```
# ECOTECT v5 to RADIANCE Exporter

# Scene file.
scene=  probe.rad objects.rad

# Model extents.
ZONE = Exterior 0.000 16.000 0.000 10.000 0.000 3.000

# Associated files.
AMBFILE= objects.amb
OCTREE= objects.oct

# Misc. Paramaters.
RESOLUTION= 640 480
DETAIL= MEDIUM
VARIABILITY= MEDIUM
QUALITY= MEDIUM
INDIRECT= 2
REPORT= 2

render=

# View definition(s).
view= c1  -vtv -vp -8.200 0.152 0.610 -vd 2.743 0.000 0.000 -vu 0 0 1 -vh 90 -vv 60 -vs 0 -vl 0
view= c2  -vtv -vp 10.134 -1.5 0.000 -vd -1.524 0.5 0.75 -vu 0 0 1 -vh 90 -vv 60 -vs 0 -vl 0
view= c3  -vtv -vp 0.457 7.076 1.000 -vd 0.000 -1.619 0.434 -vu 0 0 1 -vh 90 -vv 60 -vs 0 -vl 0
view= c4  -vtv -vp -0.5 -10.00 4.000 -vd 0.001 1.00 -0.020 -vu 0 0 1 -vh 90 -vv 60 -vs 0 -vl 0
```

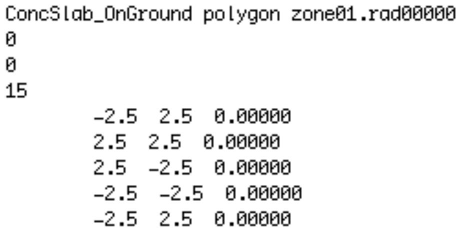
OBJECTS.RAD



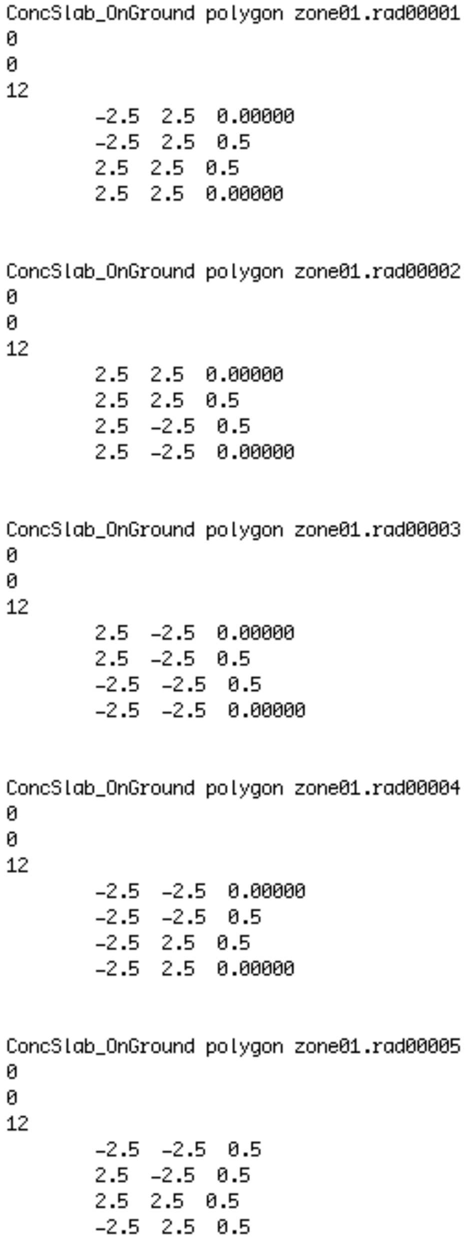
```
# ECOTECT v5 to RADIANCE Exporter


#Materials

void plastic red_plastic
0
0
5 .7 .1 .1 .1 .1

void metal steel
0
0
5 0.6 0.62 0.68 1 0

void metal gold
0
0
5 0.75 0.55 0.25 0.85 0.2

void plastic white_matte
0
0
5 .8 .8 .8 0 0

void dielectric crystal
0
0
5 .5 .5 .55 1.5 0
```



```
void plastic black_matte
0
0
5 .09 .09 .09 .00 .00

void plastic grey_plastic
0
0
5 0.25 0.25 0.25 0.06 0.0

void glass Camera_WideAngle
0
0
3       0.000 0.000 0.000


void plastic ConcSlab_OnGround
0
0
5       0.1 0.1 0.12   0.06 0.00000



#Model Geometry

steel sphere orb0
0
0
4 0 2 1 .5

gold sphere orb1
0
0
4 1.5 1.5 3 .25

black_matte sphere orb2
0
0
4 2 -2 1 .5

red_plastic sphere orb3
0
0
4 0 -1.5 3 .25

grey_plastic sphere orb4
0
0
4 -2 -2 1 .5

white_matte sphere orb5
0
0
4 -1.5 1.5 3 .25

crystal sphere orb6
0
0
4 0 0 1.5 1
```

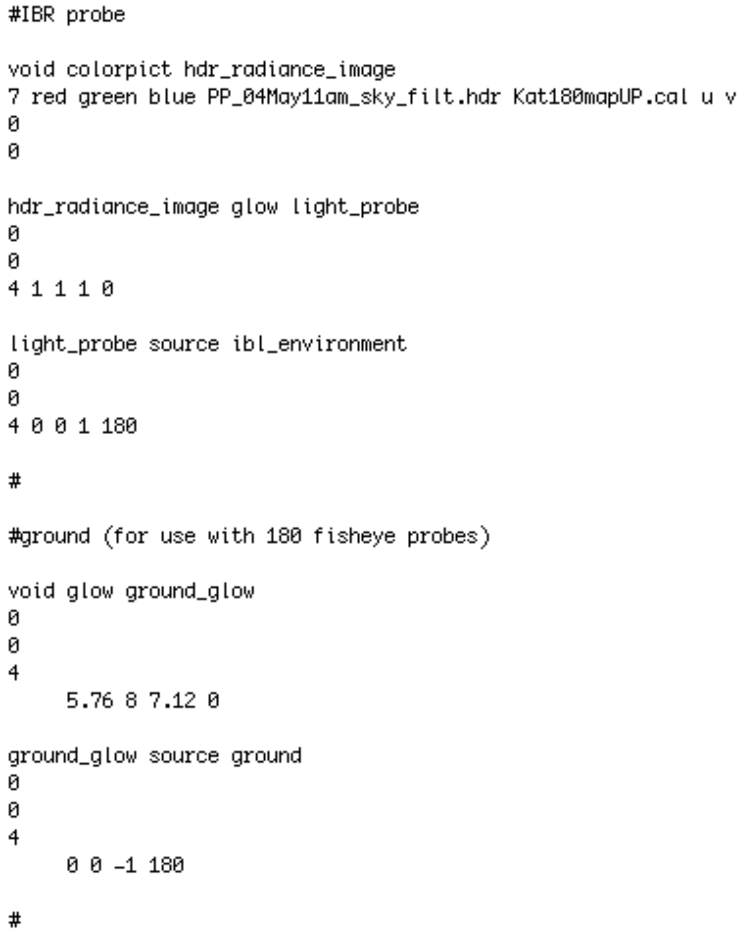


```
ConcSlab_OnGround polygon zone01.rad00000
0
0
15
        -2.5  2.5  0.00000
        2.5  2.5  0.00000
        2.5  -2.5  0.00000
        -2.5  -2.5  0.00000
        -2.5  2.5  0.00000
```



```
ConcSlab_OnGround polygon zone01.rad00001
0
0
12
        -2.5  2.5  0.00000
        -2.5  2.5  0.5
        2.5  2.5  0.5
        2.5  2.5  0.00000


ConcSlab_OnGround polygon zone01.rad00002
0
0
12
        2.5  2.5  0.00000
        2.5  2.5  0.5
        2.5  -2.5  0.5
        2.5  -2.5  0.00000


ConcSlab_OnGround polygon zone01.rad00003
0
0
12
        2.5  -2.5  0.00000
        2.5  -2.5  0.5
        -2.5  -2.5  0.5
        -2.5  -2.5  0.00000


ConcSlab_OnGround polygon zone01.rad00004
0
0
12
        -2.5  -2.5  0.00000
        -2.5  -2.5  0.5
        -2.5  2.5  0.5
        -2.5  2.5  0.00000


ConcSlab_OnGround polygon zone01.rad00005
0
0
12
        -2.5  -2.5  0.5
        2.5  -2.5  0.5
        2.5  2.5  0.5
        -2.5  2.5  0.5
```

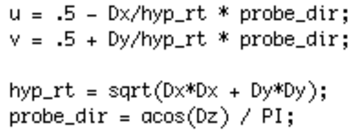
PROBE.RAD



```
#IBR probe

void colorpict hdr_radiance_image
7 red green blue PP_04May11am_sky_filt.hdr Kat180mapUP.cal u v
0
0

hdr_radiance_image glow light_probe
0
0
4 1 1 1 0

light_probe source ibl_environment
0
0
4 0 0 1 180

#

#ground (for use with 180 fisheye probes)

void glow ground_glow
0
0
4
     5.76 8 7.12 0

ground_glow source ground
0
0
4
     0 0 -1 180

#
```

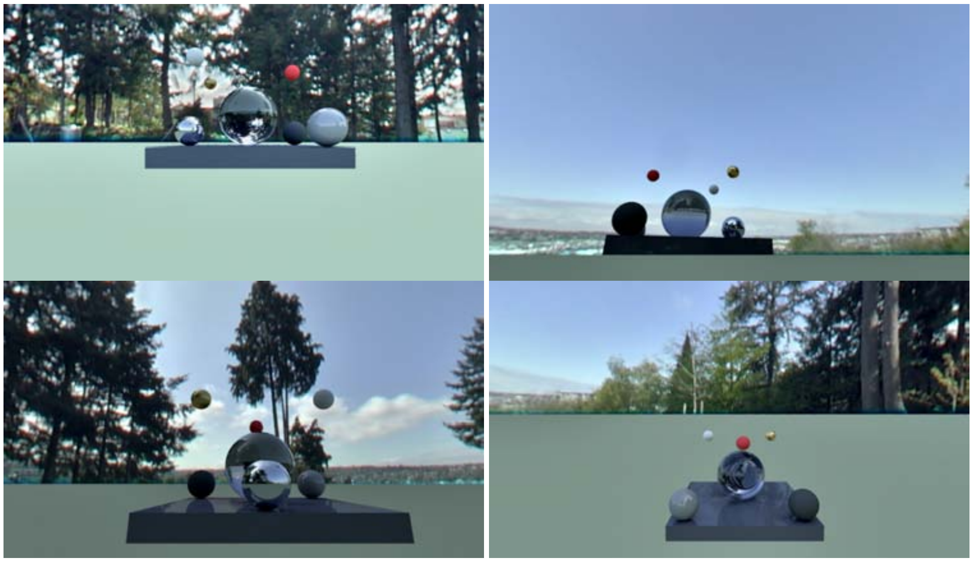
PP_04MAY11AM_SKY_FILT.HDR

KAT180MAPUP.CAL



```
u = .5 - Dx/hyp_rt * probe_dir;
v = .5 + Dy/hyp_rt * probe_dir;

hyp_rt = sqrt(Dx*Dx + Dy*Dy);
probe_dir = acos(Dz) / PI;
```

These Radiance files produce the following images:

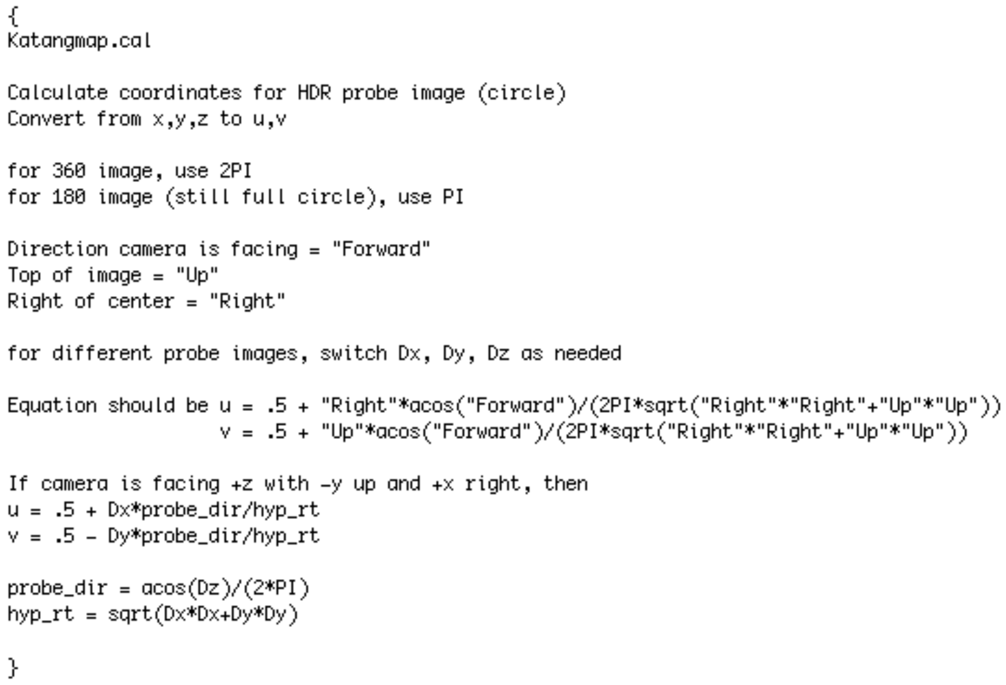


Appendix B: Sample Translation Equations

The following are samples of some of the translation equations used to convert the 2D HDR environment maps into a 3D light probe used to illuminate a model when using the IBR method. A *.cal* file is referenced in the *.rad* file of Appendix A that designates which HDR light probe is to be used to light the scene. Many variations of this equation exist; the particular organization here was devised based on the explorations of the IBR method in this study. All of these equations are based on the assumption that the North direction in the physical world corresponds with the +y axis in the digital models.

EXPLANATION

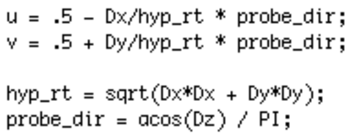
Comments (denoted by the curly brackets) explain the contents and intended use of each *.cal* file.



```
{
Katangmap.cal

Calculate coordinates for HDR probe image (circle)
Convert from x,y,z to u,v

for 360 image, use 2PI
for 180 image (still full circle), use PI

Direction camera is facing = "Forward"
Top of image = "Up"
Right of center = "Right"

for different probe images, switch Dx, Dy, Dz as needed

Equation should be u = .5 + "Right"*acos("Forward")/(2PI*sqrt("Right"*"Right"+"Up"*"Up"))
                   v = .5 + "Up"*acos("Forward")/(2PI*sqrt("Right"*"Right"+"Up"*"Up"))

If camera is facing +z with -y up and +x right, then
u = .5 + Dx*probe_dir/hyp_rt
v = .5 - Dy*probe_dir/hyp_rt

probe_dir = acos(Dz)/(2*PI)
hyp_rt = sqrt(Dx*Dx+Dy*Dy)

}
```

180˚ FISHEYE SKY PROBE

Whenever the light probe used is a 180˚ fisheye of the sky (camera pointing up), the following equation is used:

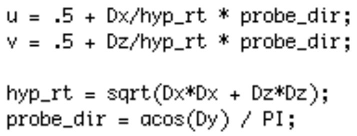


```
u = .5 - Dx/hyp_rt * probe_dir;
v = .5 + Dy/hyp_rt * probe_dir;

hyp_rt = sqrt(Dx*Dx + Dy*Dy);
probe_dir = acos(Dz) / PI;
```

This equation assumes the top of the image is North, which corresponds to the model's +y direction.

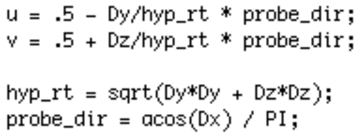
VERTICAL 180˚ PROBES

Images that are captured using the 180˚ fisheye lens facing the horizon, rather than the sky, have different equations depending on which direction the camera is facing. For North facing images the equation is as follows:



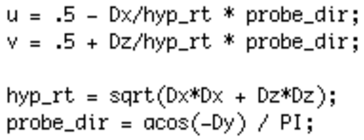
```
u = .5 + Dx/hyp_rt * probe_dir;
v = .5 + Dz/hyp_rt * probe_dir;

hyp_rt = sqrt(Dx*Dx + Dz*Dz);
probe_dir = acos(Dy) / PI;
```

For East facing images, it would be adjusted for the change in orientation:



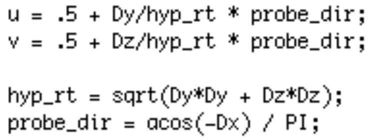
```
u = .5 - Dy/hyp_rt * probe_dir;
v = .5 + Dz/hyp_rt * probe_dir;

hyp_rt = sqrt(Dy*Dy + Dz*Dz);
probe_dir = acos(Dx) / PI;
```

Similar changes are made for South facing images:



```
u = .5 - Dx/hyp_rt * probe_dir;
v = .5 + Dz/hyp_rt * probe_dir;

hyp_rt = sqrt(Dx*Dx + Dz*Dz);
probe_dir = acos(-Dy) / PI;
```

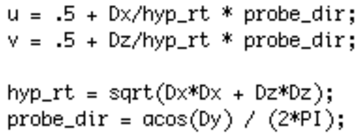
West facing images would need the following equation:



```
u = .5 + Dy/hyp_rt * probe_dir;
v = .5 + Dz/hyp_rt * probe_dir;

hyp_rt = sqrt(Dy*Dy + Dz*Dz);
probe_dir = acos(-Dx) / PI;
```

360˚ LIGHT PROBES

Light probes that capture the full 360˚ environment require a slight change in the equation. The divisor π (represented as “PI” in the equation) must become 2π (or 2*PI) when using an image that contains a 360˚ environment in the form of a 2D circle. The light probes that contain a 180˚ environment in a half-circle must also use this equation. The example here is setup up for an image where the center of the image (the direction the camera was facing) is North.



```
u = .5 + Dx/hyp_rt * probe_dir;
v = .5 + Dz/hyp_rt * probe_dir;

hyp_rt = sqrt(Dx*Dx + Dz*Dz);
probe_dir = acos(Dy) / (2*PI);
```