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World Art and the Illumination of Virtual Space

By

Justin Harrington Underhill

A dissertation submitted in partial satisfaction of the
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in

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of the

University of California, Berkeley

Committee in charge:

Professor Whitney Davis, Chair
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Abstract

World Art and the Illumination of Virtual Space

by

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Doctor of Philosophy in History of Art

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This dissertation explores the relationship between pictures and the lighting conditions in which they were originally viewed. Using advanced rendering technology, I reconstruct the original architectural context in which a work of art was displayed and simulate the effects of variable daylight and artificial illumination on the picture's appearance. This research methodology enables me to describe the interaction between real lighting and depicted lighting relative to the picture's symbolic content. I provide a typology of these interactions (which I call "pictorialized illumination") using examples from diverse art historical traditions. In the final chapters, I analyze two case studies: Leonardo da Vinci's *Last Supper* at the refectory of Santa Maria delle Grazie in Milan, and Peter Paul Rubens's altarpiece for the church of Santa Maria in Vallicella in Rome.

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Do the digital humanities have a visual object? Is it art historical?

The term “digital humanities” has sometimes been adopted uncritically as a catchall phrase for *any* humanistic practice in which digital computation—the internet, a database, virtual reality—facilitates research. In other disciplines, such as biology, this facilitation of research by technology is taken for granted. Therefore it seems redundant to speak of “digital biology.” In biology, high-end laboratories with immense computational power now form the basis for elementary undergraduate training.

Digital humanities projects can be loosely divided into two groups: those that attempt to upload and reconfigure archival material in a database that is remotely accessible, and those that create displays of data that can be navigated in terms of its variance, optical or otherwise. To date, projects of the first kind have been the most widespread. A number of projects have utilized general-purpose database management systems to collate historical materials in the hope that increased access to a corpus will catalyze analysis of it. The transcription of the corpus that is needed to complete the database requires the most replete notational system possible because the data are often ambiguous at the syntactic or semantic level (or both). For example, the Khipu Project at Harvard University has attempted to archive the dozens of *khipu* (an undeciphered system of record-keeping among the Inca that utilized bundles of colored, knotted rope) spread across museums around the world.¹ Project administrators have devised a representation within which each interval between knots is recorded, even though it is not obvious that this information is semantically relevant. Researchers supplement this information with detailed verbal descriptions of knots and rope construction.

Art-historical pedagogy utilizes this kind of tool on a daily basis. As universities have phased out slide projectors (and associated support) from the classroom, scholars have become increasingly reliant on publically available digital scans of pictures and other art historical artifacts circulating within the public domain, as well as institutional subscriptions to specialized databases available on closed networks. Art history is currently transitioning between two well-developed imaging technologies. Until the mid-1990s, the media used to store and transmit image data were analog. Although many of the first art historians introduced to photographic technology in the 1850s (and later) eschewed it in favor of traditional printed reproductions, pointing out obvious distortions produced by the camera, the widespread distribution of commercial projection technology at the end of the nineteenth century secured the analog photograph as the principle means of representing images in academic art history for

¹ “Khipu Database Project,” Khipu Database Project, accessed September 14, 2012, <http://khipukamayuk.fas.harvard.edu/>.

the next hundred years.² Simply put, the slide projector taught late nineteenth-century audiences to overlook many of the distortions in brightness and perspective created by photography that previous generations had been acutely aware of. By the 1870s, projection technology with incandescent lighting enabling the transmission of much brighter images over much greater distances had become widespread in American and European concert and lecture halls.³ By printing from photographic negatives directly onto glass plates, projectionists created updated versions of traditional “magic” lantern shows that had been popular since the eighteenth century.

Many of the standard art-historical objections to photographic reproduction were overlooked as photographs were integrated into lectures. Compared to the human eye, photographs register a limited range of brightness. As a result, the tonal range of a painting or sculpture can appear distorted when it is photographed; the scale of light and dark is “compressed,” since bright parts of the object appear less bright and dark parts less dark. However, when a photograph is projected as illumination, the tonal range partially “decompresses.” Projection magnifies the tonal contrast of a photographic print, resulting in filtered light with a brightness range tens or hundreds of times greater than a photograph on paper.⁴

The subsequent introduction of colored 35 millimeter slides drastically reduced both the quality of the photographic image and the archival efficacy of slide libraries that used them. At a logistical level, slides were preferable to glass plates, whose size and fragility resulted in high storage and replacement costs. Cumbersome as they were, however, the integrity of glass plate slides is remarkably constant in time over use: the ink could withstand the heat generated by the projector for years before tonal values began to noticeably drift. By contrast, 35 mm. slides began formally to deteriorate as

² For a detailed account of the adoption of slides by art historians, see William Freitag, “The Lantern Slide and Art History,” *History of Photography* 8 (1984): 107-118.

³ Charles Musser, *The Emergence of Cinema: the American Screen to 1907* (Berkeley: University of California Press, 1994), 13-48.

⁴ For the use of photographic illustrations by art historians, see Wolfgang Freitag, “Early Uses of Photography in the History of Art,” *Art Journal* 39 (1979): 117-123; Eileen Fry, “From Lantern Slides to Image Presentation Systems: A Discipline in Transition,” *Indiana Libraries* 26 (2007): 15-19.

To be sure, digital projections also distort –the luminance recorded by the digital camera is compressed when it is recorded. However, we can correct these distortions computationally in digital reconstruction. In addition, a color chart can be used to calibrate the digital camera, and the digital picture can be corrected in graphics editing software like Photoshop to correct for distortions produced by the camera.

soon as they were heated, so that slide libraries often needed to make multiple slides of the same object, each of questionable value.⁵

In the space of the last two decades, the medium of art history has drastically changed yet again. Most importantly, our reproductions are now stabilized: they do not eventually decay into ghostly pastel approximations of their prototype. This is because our illustrations are stored and duplicated digitally, as configurations of discrete units of computable information (commonly known as binary digits, or bits) that cannot be reconfigured without destroying the content that they represent. Digital data cannot decay; as any computer user who has suffered a crashed system can attest, data retrieval and display on a digital computer is an “all or nothing” affair.

This technological transformation is easy to overlook, as traditional economies and discourses of picture representation and duplication have quickly accommodated it. Two generations into the digital revolution, we are used to reproducing illustrations displayed in printed or luminous media by areas of rectangular elements –visible or not—made up of pixels. The quality of the reproduction is determined by the number of bits (and therefore dependent upon the amount of memory) used to create each pixel. When I pull up a reproduction from my hard drive, the graphical user interface (GUI) retrieves a stable array of these pixels, known as a bitmap, and displays it against a backdrop of other bitmaps that helps me navigate my operating system and its associated software.

Slide libraries in universities actually had very little to do with the foundations of digital visual resource collections. Early experiments with museum database systems had provided proof of the concept that networks could effectively manage large bitmap files with retrieval protocols that could be manipulated reliably (they were “user friendly”). Because the first digital databases were limited to a closed network located at the sponsoring institution, reproductions could only be retrieved from (or entered into) the system by computers with compatible platforms (often UNIX) and the necessary telecommunications. These programs were funded as standalone projects for major museums and visual resource archives, meaning that each institution operated specialized bitmap retrieval and storage protocols, often mutually unintelligible. As a result, digital graphics could not be distributed easily outside their native networks. Even after commercial internet providers enabled the distribution of image files formatted to be viewed across multiple operating systems, the slowness of telecommunications prohibited the distribution of high-quality digital reproductions

⁵ For a discussion of the drawbacks of 35 mm. slides, see Michael Greenhalgh, “Art History,” in *A Companion to Digital Humanities*, ed. Susan Schreibman et al. (Malden, MA: Blackwell, 2007), 220-252.

unless they were compressed (in graphics exchange format, GIF) into lower-quality reproductions.⁶

When cable-based internet connections became widespread features of personal computing in the mid-1990s, users began configuring file transfer protocol (or FTP) sites for transferring image files, which at the time required specialized web architecture due to their high demands on both memory and bandwidth.⁷ Commercial art history databases followed soon after, notably Michael Greenhalgh's ARTSERVE, which began as a personal database of 300 digital images in 1994 and now consists of 190,000 images. In 2001, the Andrew W. Mellon Foundation created ARTStor, a digital image database modeled after the academic database of articles in portable document format (PDF), JSTOR. ARTStor now comprises 1.4 million digital images.

Because of its historical reliance on analog media, not to speak of the fact that most representations studied by art historians are analog, art history has largely overlooked the potential for digital technology to reorganize the way in which we understand pictorial phenomena by reconstructing their historical mode of appearance. In order to understand how the digital representation of objects could move art history beyond "business as usual" methods of projecting photographs onto a classroom wall, I will rehearse two techniques in Chapter 1 that form the backbone of my reconstructions: *modeling* and *rendering*. Modeling is the construction of the surface of an object in three-dimensional coordinate space, displayed in two dimensions by the GUI. Rendering is the process by which a picture of the model is generated by algorithms that code transformations in the brightness of the object, calibrated within the color space permitted by the digital display. These algorithms allow the user to control and manipulate a vast range of optical variables.

⁶ For a first-hand account, see Greenhalgh, "Art History," 222-238.

⁷ Greenhalgh, "Art History," 242-244.

Chapter 1. The Digital Foundations of Virtual Worlds

This dissertation uses virtual reconstructions of historical sites to explore the relationship between pictures and light. Since my analysis relies heavily on these reconstructions, I first provide an overview of my methods for creating these models.

The revolution in desktop rendering technology that has reorganized spatial visualization and analysis in architecture and archaeology has largely gone unnoticed in art history. For this reason, it is necessary briefly to review the technologies that make possible the virtualization advocated in this thesis. Taken together, the digital transcription of images and the computational manipulation of parameters of visibility provide a new medium for art historical research. After translating pictures into computational components—digital bitmaps—or utilizing digital photographs that are now widely available, we can reconfigure the digital data as a model that replicates the conditions of viewing the object, such as a picture or building.

Modeling

Digital reconstructions of objects in visual space are composed of a “wireframe,” an closed set of intersecting planes described by “wires” that delimit them, processed by algorithms specific to the rendering program being used.

Wireframes (or “meshes”) are the fundamental building blocks of any virtual model. Planes located in coordinate space are conjoined at one or more of the same points, such that the model remains “sealed” without visible gaps even when it is translated or rescaled. This makes wireframes much more versatile than analog representations of three-dimensional objects, such as blueprints. Blueprints cannot be rescaled without producing distortions. The lines in blueprints (which have no area) seem to have area after the blueprints have been scanned—in the process of magnification, crispy edges become fuzzy, and the area of the lines which demarcate areas becomes problematic. Wireframes can be moved or rescaled without distorting the model, because these operations merely entail a numerical transformation of the coordinates linked by wires.

Early wireframe projects were severely limited by the computational power of available commercial processors. Therefore experimentation was restricted to primitive geometric objects—industrial models that were composites of cubes, spheres, and pyramids. Two parallel innovations in the past twenty years have greatly improved our ability to model complex surfaces: the development of specialized graphical-user interface processors (and drivers) specifically designed to handle the computations run by rendering programs, and the industry-wide adoption of a three-point (triangular) “face” as the foundational unit for all wireframe construction of all surfaces, regardless of shape. Figure 1.1 shows a complex model of a car that is composed of wires, shown in white. The curved surfaces of the wireframe model have been broken down into rectangular units (indicated in thin grey lines), each composed of two faces.

Triangulated surfaces in wireframes allow for the fabrication of complex objects in less processing time than would be required if faces were constructed in four or more points. Additionally, in the initial stages of processing, the rendering engine can often simplify the model by clustering several wireframe triangles into a single triangle.⁸

In architectural visualization, a simple wireframe can be built from computerized architectural drawings (CAD) or adapted from traditional blueprints. In the past five years, a cottage industry of simplified wireframe editing has sprung up to provide beleaguered students and nonprofessionals with quick, user-friendly interfaces that lend themselves to intuitive independent learning that requires no programming background.⁹

When more complex surfaces must be modeled --irregular surfaces that cannot be conveniently constructed by extruding or rescaling elements of primitive geometric shapes-- the wireframe can be composited using photogrammetric software. Photogrammetric technology automates the trigonometry initially used in aerial surveys in the middle of the twentieth century. When digital photographs are input as prototypes, the photogrammetric program uses edge-detection algorithms (leveraged against the known resolution of the photograph) to determine what the focal length of the lens had been in making the photograph, therefore specifying its three-dimensional parameters. (Most analog photographs are too grainy to be used in photogrammetric reconstructions, but satisfactory results can still be obtained with large, high-quality prints, though in this case the focal length of the lens needs to be known). Once the full set of digital photographs has been entered, the user must identify and cross-reference recognizable points that recur throughout the set--typically edges and surfaces of the object that are easily identified. As the number of points that are cross-referenced increases, so too does the accuracy of the wireframe relative to the original object.

Digital photogrammetry has advanced substantially since its inception at the US Defense Mapping Agency in the mid-1980s (we are currently seeing the third generation of commercial programs), and it represents the most cost-effective means of modeling complex surfaces. (The most advanced program, Photomodeler Scanner, prices out at 1/10th the cost of a comparable laser scanner). Nonetheless, digital photogrammetry has several serious drawbacks. In order for the location of points in

⁸ The relationship between wireframe technology and computer hardware is described in detail in Kristine Fallon, "Early Computer Graphics Developments in the Architecture, Engineering, and Construction Industry," *Annals of the History of Computing*, IEEE 20 (1998): 20-29.

⁹ For a summary of these programs see Yehuda Kalay, "The Impact of Information Technology on Design Methods, Products and Practices," *Design Studies* 27 (2006): 357-380.

coordinate space to be registered, all relevant surfaces must be accessible to the camera—the user must be able to navigate a space to record all of its surfaces (in some cases, like caves, this is simply not possible). Since the focal length of the lens cannot be changed from photograph to photograph in the set, accuracy is dramatically reduced in most cases if objects are more than fifty meters away, since most cameras cannot reproduce an object with sufficient resolution at this distance. All this means that a good data set requires hundreds of photographs (or thousands, depending on the complexity of the project) taken with a powerful camera stabilized on a tripod.

In preparing the analysis presented in this thesis, I photographed objects with a high-resolution digital camera and used photogrammetric software to construct a wireframe of the photographed object. The photogrammetric program that I used, 123D Catch, uploads the photographs (with their marked points) into a supercomputer for processing, greatly reducing the time required for a model to be generated. 123D Catch allows the user to measure distances within the model, and these were cross-referenced with available plans and elevations.¹⁰

Rendering

Rendering is the computational manipulation of bitmaps. Bitmaps, the basic building blocks of new media, are a form of raster graphics—a structure of isometric (evenly spaced”) data points displayed as pixels in an external device. Every reconstruction that accompanies this dissertation is a bitmap or sequence of bitmaps. Strictly speaking, we never see a bitmap, only a virtual object constructed from one. Early bitmap images were crisp, rectilinear configurations in a limited range of colors that were used to create logos on electronic marquees or avatars in primitive arcade games. Experiments in digital data storage at Bell Labs in the 1970s and subsequent research by scientists at Fuji in the 1980s resulted in a portable digital data storage mechanism, now known as a charge-coupled device (CCD), in which images refracted through a photographic lens and projected onto a light sensor were recorded as bitmaps. Digital photography was born.¹¹

Computational breakthroughs in raster graphics in the 1970s and early 1980s allowed researchers to construct a bitmap of the surfaces of the prototype objects (initially they did not represent illumination of the object—see Figure 1.2a).¹² Subsequent research resulted in algorithms that were able to represent the full range of illumination of lit

¹⁰ For the history of photogrammetry, see Sanjib Ghosh, "History of Photogrammetry," *ISPRS Journal of Photogrammetry and Remote Sensing* 29 (1992): 311-327.

¹¹ For a history of the CCD, see James Janesick, *Scientific Charge-coupled Devices* (Bellingham, WA: SPIE Press, 2001), 1-21.

¹² See Lev Manovich, *The Language of New Media*, (Cambridge, MA: MIT Press, 2001), 178-180.

surfaces in the real, visual world (Figures 1.2b and 1.2c) The set of algorithms that rendered Figure 1.2b and 1.2c are typically streamlined in desktop software packages as *local illumination models*; they are a set of equations, or “shaders,” designed to model light that falls on an object directly from a nearby source. Henri Gouraud published a method for virtualizing continuous diffuse light across the faces of a wireframe model in 1971 (Figure 1.2b).¹³ Photometric values are mapped onto the wireframe as a continuous gradient, “smoothing out” the object in the process. In 1975, Bui Phong updated Gouraud’s shading algorithm to render highlights—areas of an object where reflectance appears disjunct as a result of light falling on a glossy surface (Figure 1.2c).¹⁴

Phong’s algorithm (and those derived from it) plausibly models the effect of a single illuminant—such as the light of a candle or incandescent bulb—on a single glossy object. But local illumination models often have no means of computing more complex phenomena of illumination that occur in the real world. In particular, the interreflection of light between objects (that is, indirect lighting) could not be rendered, even though it is ubiquitous. The first *global illumination* algorithm capable of rendering ambient light and indirect illumination was the ray tracing technique written by Turner Whitted in 1979.¹⁵ Whitted adapted machine-vision algorithms that traced the visual rays from the virtual viewpoint in the rendering through each pixel (a computational construction of the classical perspectival ‘window’ that converts the linear visual rays into light vectors). Each target pixel in the bitmap is an intersection of the visual rays and light rays emanating from light sources in the visual space. This allows the rendering of reflection, refraction, and attenuation (for example, Figure 1.3). In Figure 1.3, colored light reflects onto nearby surfaces, and the glass sphere plausibly refracts the light passing through it (it also reflects the light mounted in the ceiling). Global illumination could be photometrically calibrated after James Kajiya introduced an equation that calculated luminance gradients across each surface of the objects being represented in the model. In this way, the full behavior of light in the virtual space as it affects the surfaces of the objects can be rendered quite realistically.¹⁶

There are different computational methods for accurately solving this equation (known simply as “the rendering equation”). As a result, a number of algorithms that vary in accuracy and computational demand have sprung up. The most common rendering

¹³ Henri Gouraud, “Continuous Shading of Curved Surfaces,” *IEEE Transactions on Computers* 100 (1971), 623–629.

¹⁴ Bui Phong, “Illumination for Computer Generated Pictures,” *Communications of the ACM* 18 (1975): 311–317.

¹⁵ T. Whitted, “An Improved Illumination Model for Shaded Display,” in *ACM SIGGRAPH Computer Graphics* 14 (1979): 343–349.

¹⁶ J. T. Kajiya, “The Rendering Equation,” *ACM SIGGRAPH Computer Graphics* 20 (1986): 143–150.

engine currently used, Mental Ray, enables users photometrically to manipulate optical parameters in order to specify a light source (or sources).

When a three-dimensional object is displayed in a rendering program, the material of the surfaces is given a default representation. The default setting usually represents the object as perfectly diffuse and gray surfaces that reflect light equally in all directions. But this is of course quite unrealistic. Additional transformations are required if the wireframe is supposed to mimic the appearances of real-world surfaces more closely.

Modeling and Rendering as Research in Art History

In this dissertation, I use renderings of digital models to investigate the ways in which depictions mobilize light pictorially, using examples carefully selected from different traditions of artmaking at different times and places. My text—short compared to the dissertations produced in some subfields of art history—is supplemented by daylight simulations rendered by a supercomputer (the GarageFarm computing network). Each of these models took months to build—on average, a single model took between four hundred and five hundred hours to construct. For each model, photographs of the object (when it still exists) taken with a Canon EOS Rebel T1i digital camera were uploaded into photogrammetric software and cross-referenced with any existing plans and elevations. On average, six hundred photographs were taken of each object. Archival records and archaeological reports were used to whether significant architectural features that existed at the time the object was used should be rendered.

Photographing sites (when they still exist) for photogrammetric purposes required extensive travel. Two trips to Rome (June 2008 and July 2010) were required to photograph Santa Maria in Vallicella (the subject of Chapter 5). A trip to Teotihuacan (December 2010) allowed me to photograph the Palace of the Jaguars and observe alignments during the winter solstice (see Chapter 3). Two trips to Antwerp (July 2010 and December 2010) were required to photograph Onze-Lieve-Vrouwekathedraal (see Chapter 5).

In most of the renderings, I adopt a point of view 1.828 meters (six feet) above the level of the floor at that location. Occasionally—as in my renderings of the Palace of the Jaguars and Onze-Lieve-Vrouwekathedraal—I have adopted a higher viewpoint to afford a more expansive view light passing through the picture's environment, even though this could be described as less realistic in terms of visual experience. Figure 1.4 suggests that effects of pictorial luminance that I am most interested in would be visible within a range of viewpoints, though some of them could not be occupied. In Figure 1.4, I have rendered Rubens's *Descent from the Cross* on 25 July 1612 at 2:45 PM from a height of 2 meters, 5.5 meters, and 20 meters above the ground (the pictures are displayed in this order).

Chapter 2: Pictorialized Illumination in the History of Art

Pictures and Images, Looking and Watching

We see by virtue of signals: radiation in our local environment is transduced from the retina as electric signals in the optic nerve, and processed in the visual cortex. Visual culture is the preservation and redistribution of these signals in so-called optical media. Art historians are quick to point out the constitutive (and often overlooked) role that the viewer plays in visual culture—a kind of interpretive competence that Ernst Gombrich termed “the beholder’s share.”¹⁷ The beholder’s share is comprised of the associational skills and interpretive posture necessary for the receiver of a given signal to process and respond to it in accordance with conditions of satisfaction designated at the outset. When a viewer understands a Renaissance *poesia*, or a driver stops at an imaginary line that parallels a red hexagon with “STOP” written on one side, she is fulfilling these conditions of satisfaction.

Art historians often assume that one looks at a picture in order to “get a grip” on the figurative and rhetorical aspects of a depiction. However, looking may be more complex than has hitherto been assumed. For example, it may be necessary to watch a picture in order to grasp its significance because multiple *images may* become apparent in it. Sequences of images can assemble as virtual pictorial worlds in the nexus of optical processing and pictorial interpretation.

Although art history recognizes that aspects of a picture can vary, it often proceeds as if this variance was irrelevant to understanding. Pictures, like all other objects, vary optically depending on their conditions of visibility. The art historian often trains herself to “look through” some of these variations (the play of light across the surface of the picture, for example) in order to observe the picture supposed as such. Variant images of the picture are bracketed off. Contemporary museums often reify this one-to-one correlation between the picture and a privileged visual image of it by hanging paintings at typical eye level under electric spotlights.¹⁸ While viewers often assume that this architectural configuration grants maximal access to “visual details” that are

¹⁷ Ernst Gombrich, *Art and Illusion; a Study in the Psychology of Pictorial Representation* (New York: Pantheon Books, 1960), 154-204.

¹⁸ For a general introduction to museum lighting, see Garry Thomson, *The Museum Environment* (London: Butterworths, 1986), 2-58, 158-197. For a summary of the latest developments in museum lighting, see James Druzik and Bent Eshøj, “Museum Lighting: Its Past and Future Development,” in *Museum Microclimates* ed. Tim Padfield and Kim Borchersen (Copenhagen: National Museum of Denmark, 2007), 51-56.

attributed to the historical producer of the picture, these particular conditions often minimize what I will *pictorialized illumination*.¹⁹

However, it would be erroneous to assume that a picture requires only one image. We watch certain pictures when they give us multiple images, constituted by changes in standpoint or light levels, for example. In turn, these variations can often be used in order to construct the picture itself. Although the picture will always *appear* different as conditions of observation change, it sometimes *depicts* differently (as I will argue). This is because the same pattern of marks can be replicated in perception in different visual events—that is, as distinct possibilities of what is sometimes called *seeing-as*. Any array of marks insofar as it sustains seeing-as has *pictoriality*. When a pattern of marks is recruited to a specific event of seeing-as, it has been successfully *pictorialized*.²⁰

Sometimes, we watch pictures in order to stabilize a particular pictorialization. In these cases, variant aspects of the picture—changing patterns of light and shadow, for example—are perceptually distinguished from the depiction. The *reflectance* of the picture—the light reflected from its surface—has pictoriality that is independent of its *illuminance*, the light arriving at the surface of the picture.

In other cases, however, when the light *in* the picture is patterned by the light *of* the picture (that is, by the real light falling on its surface), the picture incorporates what I will call *pictorialized illumination*. In these special but important cases, the *luminance* of the depiction—its brightness—is pictorialized as a function of illuminance. (The crucial distinction between luminance and illuminance will be fully explicated later in this chapter.) When a viewer watches a picture *depict* a light source that is located in real space (as distinct from being merely illuminated by it), they are pictorializing illumination.

In order to recognize pictorialized illumination and outline its typology (as I will do in Chapter 3), we must proceed forensically. The full range of parameters of illumination in which a viewer encountered the picture must be reconstructed, enabling us to determine the optical thresholds at which the different images of it may have been constituted. The sequence of images in the picture can thus be revirtualized—watched again, on a different display. When controlled by this theoretical framework, reconstruction (though technically complex) can be used rigorously for art historical purposes.

These reconstructions can be performed by a variety of rendering programs, high-end software used by architects and computer graphics professionals to model the

¹⁹ For a summary of the various lighting configurations documented for pictures prior to modern electric spotlighting, see Andrea Kirsh, *Seeing Through Paintings: Physical Examination in Art Historical Studies* (New Haven: Yale University Press, 2000), 254-259.

²⁰ As defined in Whitney Davis, *A General Theory of Visual Culture* (Princeton: Princeton University Press, 2011), 150-151.

behavior of light realistically. They register changes in the apparent brightness of an object by correlating its reflectance (the amount of light an object reflects) with its illumination (the amount of light that falls upon the surface of the object). As art-historical descriptions of virtual worlds, what matters is not the “realism” of the reconstruction in its pictorially irrelevant details—although these can certainly help us orient ourselves within a virtual world—but rather the computational determination of luminance thresholds that actually constitute the pictorial space.²¹

Luminance and Illumination in Constructing Virtual Pictorial Space

For the first time, art history has computational resources to model the optical variance of its objects. Unfortunately, many subfields of art history subscribe to the belief that some objects—stained glass windows or icons decorated with gold leaf—are more configured by illumination than others.²² Indeed, many of the objects in which light is widely understood to be constitutive are more luminous compared to others: given constant illumination, many Byzantine icons reflect more light than most oil paintings. But we would be jumping the gun if we were to assume that as crude a metric as reflectance accurately describes the role of light (depicted and real) in disclosing virtual worlds in their original optical ecologies, often painstakingly engineered.

Although the perception of lightness and brightness constancy has long been studied by perceptual psychologists and vision scientists, pictorialized illumination was not recognized as a distinct phenomenon until the early twentieth century in the groundbreaking theoretical work on lightness constancy and illumination by David Katz. Katz was primarily responsible for clarifying most of the philosophical and terminological confusion that had plagued debates in experimental psychology on brightness. Katz formulated the terminology that perceptual psychologists and vision scientists continue to use in describing the appearance of illuminated surfaces.

²¹ The accuracy of the rendering software used in this thesis has been experimentally validated. See Christoph Reinhard and Pierre-Felix Breton, “Experimental Validation of 3ds Max® Design 2009 and Daysim 3.0,” *Building Simulation* 11 (2009): 1514-1521.

²² Special attention is often given to visual artifacts that are more reflect or refract more light than pictorial works on canvas or paper. For excellent introductions to these objects and their relationship to light, see Otto Demus, *Byzantine Mosaic Decoration* (Routledge/Kegan Paul: New York, 1953) and Meredith Lillich, *The Armor of Light: Stained Glass in western France, 1250-1325* (Berkeley: University of California Press, 1994). Since many early modern and modern works of art are mobile (that is, not produced *in situ*) our knowledge of their original lighting conditions is limited by the archival record; for a useful overview, see Andrea Kirsch and Rustin Levenson, *Seeing Through Paintings* (New Haven: Yale University Press, 2000), 254-259.

Illuminance is the quantity of light that a surface receives. We perceive it as the intensity of illumination given off by a light source. *Reflectance* is the amount of light reflected by an object as a ratio of the total amount received from illuminants. Together, illuminance and reflectance determine *luminance* – the pattern of light that reaches the eye from the object as a range of light and dark.²³

Katz devised a phenomenology that allowed him to quantify apparent brightness (luminance) as a function of reflectance and illumination levels. Katz restricted his experiments to “surface color,” the luminance of which provides information about the intensity and location of the illuminant. In his most famous experiment, Katz proved that brightness constancy (our ability to perceive uniform reflectance across one or more surfaces that are unequally illuminated) and lightness contrast (real variations in reflectance across or between surfaces) are inversely correlated: Two monochromatic arrays observed simultaneously under different illumination levels could appear equiluminant if the white on their surface areas was adjusted. Katz’s experimental setup is shown in Figure 2.1. One monochromatic disc is in ambient light, the other in shadow. Observers were instructed mechanically to adjust the level of contrast on the directly-illuminated array until the brightness of each disc appeared equal to them. In this way, transformations in lightness contrast presented virtual configurations of illumination: when the discs appear equiluminant, perception of shadow on the surface of left disc has been suppressed.²⁴

After the arrays had been matched by the observer, Katz took the proportion between the luminance values of each disc (i.e., the ratio of their brightness) as a measure of constancy, which he called the “brightness quotient”. The higher the constancy, the greater the contrast. Because he supposed that we tend to constitute greater brightness constancy in larger objects, Katz concluded that visual perception tends towards brightness constancy by transforming an “abnormal” luminance gradient (such as a high-contrast illuminated field) relative to a gradient perceived nearby that can more readily be seen as equiluminant throughout, i.e. a more “normal” luminance gradient. Katz called this the “Law of Field Size”. He believed that the law identifies a normal perception of the relation between reflection and luminance.

Katz believed that artists organized compositions to have high levels of brightness contrast in order to create virtual illuminated worlds. The light depicted in the picture was perceived to be distinct from lighting in the environment in which it was displayed. When discussing the extensive modeling of depicted volume that was typical of European painters during and after the Renaissance, Katz suggested that their pictures

²³ David Katz, *The World of Colour* (London: Kegan Paul, Trench, Trübner & Co., 1935), 75-141. For a summary of Katz's contribution to modern perceptual psychology, see Alan Gilchrist, *Seeing Black and White* (Oxford: Oxford University Press, 2006), 26-47.

²⁴ Katz, *World of Colour*, 82-95.

produced an articulated virtual field that was perceptually distinct from the architectural space in which the painting was illuminated. If the beholder of the painting limits her view of it so as to see only a small portion, such as a single shape with uniform color, this portion (Katz believed) would seem much brighter than the painting viewed as a whole. For Katz, this proved that light depicted in the painting must have organized the beholder's perception of the whole, suppressing or superseding her awareness of the real illumination of individual areas.²⁵

Katz's investigations laid the groundwork for the first truly systematic art historical inquiry into the relationship between pictoriality and lighting in situ, Wolfgang Schöne's *Über das Licht in der Malerei*.²⁶ Schöne described the seemingly non-naturalistic lighting constructed in Byzantine depictions made of highly reflective glass tesserae and gold leaf, in which the objects depicted were modeled in ways that do not seem to virtualize a consistent light source.²⁷ Schöne argued that this was a means of capturing the light reaching their surfaces from nearby light sources such as windows. Only fragments of Schöne's study have been translated into English, and it has been largely forgotten by English-speaking historians despite the widespread interest it generated when it was published.²⁸ Nevertheless, the book remains influential in German-speaking art historical communities, where it has shaped investigations into the interaction between depicted light (*Bildlicht*) and light sources illuminating the object (*Sendelicht*) for over fifty years.²⁹

²⁵ Katz, *World of Colour*, 224-229.

²⁶ Wolfgang Schöne, *Über das Licht in der Malerei* (Berlin: Gebr. Mann, 1954).

²⁷ Schöne directly acknowledged Katz's contribution to his own project in the introduction to the book. See Wolfgang Schöne, *Über das Licht*, 6.

²⁸ The book was positively reviewed in Alfred Neumeyer, "Review of *Über das Licht in der Malerei*, by Wolfgang Schöne," *The Art Bulletin* 37.4 (1955): 301-304.

²⁹ Indeed, art historians continue to try to reconcile Schöne's taxonomy of *Bildlicht* with more recent art historical and psychological research. See Brigitte Borchhardt-Birbaumer, *Imago noctis: die Nacht in der Kunst des Abendlandes vom Alten Orient bis ins Zeitalter des Barock* (Wien: Böhlau, 2003); Andreas Prater, *Licht und Farbe Bei Caravaggio: Studien zur Ästhetik und Ikonologie des Helldunkels* (Stuttgart: Franz Steiner Verlag, 1992); Kaspar Spinner, "Helldunkel und Zeitlichkeit," *Zeitschrift für Kunstgeschichte* 34 (1971): 169-183. Schöne's work continues to be useful in modern studies of light and color. See, for example, John Gage, *Color and Meaning: Art, Science, and Symbolism* (Berkeley: University of California Press, 1999), 37-38; Wolfgang Schivelbusch, *Disenchanted Night: The Industrialization of Light in the Nineteenth Century* (Berkeley: University of California Press, 1998), 172.

Since such real light is always changing, many different external light sources interact with the reflectance of the object. In his research on mosaics and icons, Schöne determined the original illumination conditions for these objects to show how their pictoriality would vary under changing illumination. A simulation by Eva Zanyi of the icon of Christ Arakiotis (Figure 2.2), originally from the Church of Panagiatou Araka in Lagoudera (twelfth century; Archbishop Makarios III Cultural Center, Nicosia) illuminated by beeswax candles held under different angles clearly illustrates the complex relationship between the depiction and the illuminant (Figure 2.3).³⁰ Looking directly at the icon, the observer sees rays from local illuminants placed to the side of the icon (*Sendelicht* from oil lamps or candles that are part of a procession or being lit to be presented to the picture) falling on the surface of the picture at oblique angles, seemingly inconsistent with the strong overall lighting that falls virtually (as *Bildlicht*) over Christ's body, as if from a light source placed directly in front of the icon. The small portion of gold leaf that fills the negative space of the picture reflects much more light than the painted figure of Christ (Figure 2.3a and 2.3c). However, when the candle is placed directly in front of the icon, the illusion of the body of Christ as self-refulgent pops into focus. The luster of the gold leaf gives the impression that the figure of Christ is nested within a cube of ambient light (Figure 2.3b).³¹

Observers who maneuver the candle in their space use the icon's gold leaf to activate a photometric threshold at which they stop perceiving an object as being illuminated, and begin seeing it as a source of illumination. Although Schöne did metrically describe *Eigenlicht*, recent research by Frederick Bonato and Alan Gilchrist has identified a proportional relationship between reflectance and luminosity. When about 1.8 times more light from an illuminant is reflected by the gold leaf in the picture than from the lightest tone in its luminance gradient, the icon appears self-luminous, perceived as a source of light in its own right.³²

Schöne realized that the putatively primitive modeling of pictures in icons and similar objects was part of a complex circuitry: depicted light (*Bildlicht*) had to be seen as a function of light reflected from the most reflective surface of the depiction

³⁰ For forensic experiments with the illumination of icons and mosaics (including the icon illustrated here) see Eva Zanyi et al., "High dynamic range display of authentically illuminated byzantine art from Cyprus," in *VAST '07: Proceedings of the Symposium on Virtual Reality, Archaeology and Cultural Heritage* ed. Bill Ribarsky and John Dill (Hampshire: Palgrave Macmillan, 2007), 40-52.

³¹ Schöne, *Über das Licht*, 20-36.

³² For more on this ratio (the "luminosity threshold,"), see Frederick Bonato and Alan Gilchrist, "Perceived Area and the Luminosity Threshold," *Attention, Perception, & Psychophysics* 61 (1999): 786-797.

(*Sendelicht*), such that the viewer might seem to take up a 'god's eye view' of the icon or mosaic, bathed in heavenly light from within. He termed the phenomenon—the canonical means of virtualizing light until Giotto's putative reformulation of the problem in the fourteenth century—*Eigenlicht*, "self-light." Schöne's insights were based primarily on research conducted at the recently restored murals of San Vitale and Sant' Apollinare in Classe in Ravenna, where archaeological excavations in the 1930s had unearthed evidence of the original windows of each structure. Schöne hypothesized that the original window grills, whose latticework was thicker than the modern fenestration and inset with colored glass roundels, would have resulted in substantially lower levels of ambient lighting in the churches (see Figure 2.4). For participants concluding the mass at San Vitale (held right before dawn in the Byzantine liturgy), the mosaics of Justinian and Theodora (ca. 547 CE; *in situ*) would have been flooded with the light filtered through the red, blue, and green glass roundels, giving the impression that the imperial couple, now illuminated, watch Christ (depicted in the apsidal dome above) resurrected with the rising sun (Figure 2.5 features a digital photograph, above, and my simulation of this phenomenon, below). The imperial family, awash with illumination reminiscent of a sunrise, observes the self-lighted Christ hovering above them in the apsidal dome.³³

For Schöne, the self-light coordinated by the Byzantine icons and the apsidal mosaics at Ravenna was displaced when artists began to systematize pictorial lighting such that depicted illumination could be perceived as independent of illuminants located in real space. In Giotto's *Last Judgment* at the Arena Chapel in Padua (Figure 2.6), cast shadows radiate outward from the body of Christ to indicate that he is the source of light in the virtual space of the picture, rather than the windows above him. In brief, a unified *Bildlicht* replaces recursions of pictoriality in *Sendelicht*. Transmitted light from real space is no longer necessary for pictorializing light in the virtual world.

At the level of depiction, then, Schöne identified two methods for handling pictorial information (Figure 2.7). In the first, objects modeled as inflections of self-light were composed of discrete fields of reflectance virtually equivalent to the surface reflectance of a real object. In this case, viewers watch contrast increase across surfaces with low initial contrast until constancy is suppressed. Byzantine mosaicists had secured this effect by carefully arranging highly reflective colored tesserae to be illuminated by light streaming through stained glass windows in such a way as to synthesize the light source and the illuminated depiction. In Schöne's account, we understand that

³³ Schöne, *Über das Licht*, 43-55. For restorations of the mosaics and related excavations, see Deborah Deliyannis, *Ravenna in Late Antiquity* (New York: Cambridge University Press, 2010), 10-15. For the original glass at San Vitale, see Carlo Cecchelli, "Vetri da finestra del S. Vitale di Ravenna," *Felix Ravenna* 2 (1930): 1-20.

Eigenlicht is historical enactment of the constancy experiments that Katz had used to develop the Law of Field Size.

In the second, the continuous luminance gradient of the entire depiction had to be compressed into a gradient constructed by the virtual illuminant. So long as the virtual illuminant is taken as the brightest area in this compressed luminance scale, we perceive the object to be illuminated by a light source internal to the pictorial world. However, there is an analytic error in Schöne's account, though it has never been noticed. There is no reason that depictions whose luminance has been compressed to virtualize an illuminant, such as Giotto's, cannot virtualize pictorially in relation to illuminants in real space. Furthermore, the luminance profile of *any* depiction is dramatically compressed relative to its real-world prototype, whether a virtual illuminant is present or not.³⁴ Margaret Livingstone has provided an insightful comparison between the luminance profile of a particular environment and the luminance profile of a photograph of it. Figure 2.8 shows an array of colored blocks whose luminance has been sampled (along the horizontal black line). Luminance ranges from five to 240 foot-candles. When Livingstone sampled the luminance values of a photograph of the same setting (along the same points indicated by the black line), she found that the photograph greatly compressed the luminance range of the blocks. While the luminance of the real environment varied by a factor of 48, the photograph only registered a fifteen-fold difference.³⁵

We might better understand the interplay of internal and external light sources as a case of the logical conjunction of two variables, luminance of the picture and illumination (Figure 2.9). The intensity of each of these variables varies in accordance with light levels; luminance of the picture ranges from "dark" to "light," and illumination ranges from "dim" to "bright". When the picture is visible, luminance of the picture and illumination are continuous; the apparent brightness of the picture follows from the distribution of light in the environment. For illumination to be pictorialized, environmental illumination must be integrated the luminance distribution of the picture. As we shall see in Chapter 3, several types of integration are possible.

Illumination can be integrated into luminance whether or not a light is depicted in the picture. Following Schöne, we can concede that a painting such as Caravaggio's *Calling of St. Matthew* can indeed configure a depicted light (Figure 2.10). In the preparatory stages of painting, Caravaggio illuminated the real models with lanterns, and painted them individually as so illuminated. Then he stitched these separate

³⁵ Margaret Livingstone, *Vision and Art: The Biology of Seeing* (New York: Abrams, 2002), 110-111.

pictures together in a spatial configuration that suggests that the entire virtual space is illuminated by sunlight streaming through an open window (Figure 2.11).³⁶

However, this depicted light also serves to pictorialize illumination. When Caravaggio's altarpiece was displayed in the Contarelli Chapel in San Luigi dei Francesi in Rome (Figure 2.12), the dimness of the small chapel was such that the figures could only be visible at select times, when real light streaming across the surface of the painting from a western window activated the virtual relations that Caravaggio had mapped out: the figures are illuminated both by the illuminant of the window, now pictorialized, and the depicted illuminant, the figure of Christ. In this case, there is a complex overlap of luminance and real illumination in pictoriality. The virtual figures are illuminated not only by sunlight streaming through the window, but also by the figure of Christ, whose refulgence is responsible for the additional light that sculpts the figures.

A Note on Cognitive Aspects of Brightness Perception

When we look at any object, algorithms process luminance transitions as edges, using additional cues to orient the surfaces relative to the observer. The relative brightness of the surfaces defined by the edges determines the position and intensity of their illuminants. This processing in human vision was discovered by the psychologist David Marr, a pioneer in computational neuroscience. In his experiments with brightness filters (originally designed to refine object recognition in machine vision) Marr discovered that human vision is basically a processing of ranges of luminance (i.e., "intensity gradients"), some of which are finely resolved and some of which are coarse. Vision proceeds from coarse resolution to fine; as it constructs "brightness disjunctions" in "intensity gradients," it "computes" the object.³⁷

However, more than one configuration can be constituted from the same affordance as we process luminance transitions. Sometimes, as in the famous "duck-rabbit" sketch (Figure 2.13), multiple images are embedded within a single picture; depending on how we see the finer resolutions of luminance as attributes of animal physiognomy, we may alternately visualize a duck or a rabbit. Although this phenomenon is commonly encountered in some types of pictorial illusion (so-called bistable images), there is no reason that real configurations of objects could not also relay multiple images in luminance (Figure 2.14).

³⁶ David Stork and Gregory Nagy, "Inferring Caravaggio's studio lighting and praxis in *The Calling of St. Matthew*," *SPIE* 22 (2010): 753-762.

³⁷ David Marr and Ellen Hildreth, "Theory of Edge Detection," *Proceedings of the Royal Society of London. Series B, Biological Sciences* 207 (1980): 187-217; David Marr, *Vision: a Computational Investigation into the Human Representation and Processing of Visual Information* (San Francisco: W.H. Freeman, 1982).

These “bivirtual” configurations are the building blocks of digital media, whether archaic or new. In visual processing, they can be resolved to one of two discrete states relative to others that would be equally satisfactory. We can repicture a simple bivirtual picture with a luminance component. In Figure 2.15, I have successively brightened one of the fields of the Necker cube such that the viewer is much more likely to perceive it to be pointing up than down. The unstable configuration has been rendered quasi-stable.

Chapter 3. A Typology of Pictorialized Illumination

When changing illumination in an environment interacts with transformations of the spatial configuration of depiction (registered in luminance), reflectance values of the material format as illuminated have been recruited to pictoriality. That is, a picture works *as a picture* partly by way of its illumination. I have been referring to the interplay between depicted luminance and real illumination as *pictorialized illumination*. Throughout world art history, pictorialized illumination has been constructed by imagemakers in many visual cultures. When the pictoriality is continuously correlated with a local illuminant, figure-ground relations are analogical functions of luminous flux. I will call this type of pictorialized illumination *identity* (Figure 3.1A). When continuous correlation changes, the gradients of luminance are reconfigured, and the picture seems to be transformed. I will refer to this method of pictorializing illumination as *overlap* (Figure 3.1B). When the picture constructs more than one pictorialized illuminant, luminance gradients must be partitioned internally. This type of pictorialized illumination is *nesting* (Figure 3.1C).

1. Identity

In cases of identity in pictorialized illumination, real illumination of the object and the luminance of the depiction cannot be differentiated. Picturemakers may have exploited this possibility of identity between luminance and illumination for as long as they have been making depictions. Digital simulations of Paleolithic reliefs illuminated by torchlight by Alan Chalmers have dramatized our awareness that some reliefs were highly responsive to the movement of lamps (Video A).³⁸ When a viewer held a lighted lamp in front of a relief of a bison at Cap Blanc cave complex in southern France, for example, the animal appears to flex as the clay arms and legs cast long shadows. Chalmers's work corroborates a longstanding hypothesis about "cinematic" effects in Paleolithic parietal art, noted by modern observers as they navigated the pictures with modern portable lamps.³⁹

The Paleolithic examples are highly speculative; our knowledge of the role of pictorialized illumination in early human history is severely constrained by what little

³⁸ For a description of the scanning technology and illumination see Alan Chalmers et al., "Illuminating the past: state of the art," *Virtual Reality* 14.3 (2010): 155-182.

³⁹ Two independent observations of this effect can be found in Gerold Noxon, "Pictorial Origins of Cinema Narrative: The Illusion of Movement and the Birth of the Scene in the Paleolithic Wall Paintings of Lascaux," *The Journal of the Society of Cinematologists* 4 (1964): 20-26, and Edward Wachtel, "The First Picture Show: Cinematic Aspects of Cave Art," *Leonardo* 26.2 (1993): 135-140.

evidence we have of early picture making. However, we can clearly see the role of identity in pictorialized illumination in well-documented anthropological cases. A spirit board (*Titi Ebihai*) from Goaribari Island in the Gulf of Papua, now at the M.H. de Young Memorial Museum in San Francisco, has been tentatively dated to the eighteenth or nineteenth century by radiocarbon dating (Figure 3.2). For several generations, it was kept in the ceremonial men's house at Ebihai village. Dances held at night in the men's house were intended to secure success in warfare, and the heads of conquered warriors were displayed near the spirit board. At night, a bundle of reeds was stuck into the hole drilled at the top of the board, and it was removed from the Bihure section of the house (a dark area to which access was restricted) to the open area where ceremonial dances were held.⁴⁰

During the dance, the board was held by a dancer so that onlookers—other members of the men's house—could see the flickering being that emerged, a face given the personal name Mobei to distinguish it from other spirit boards. Mobei's face and the concentric circles that frame it have been painted in a deep red. The background of the board is composed of a dramatic luminance gradient, which transitions from white (at the bottom of the board) to black (at the top). As the dancer moved the board through space, changing the angle between the surface of the face and the observers (and jostling the reed bundle), the quantity and direction of light falling on the board would have varied. Under torchlight, the striking contrast between the deeply saturated red that defines Mobei's face and the luminance gradient that bedecks the background of the spirit board would have been reduced as a function of both the decreased levels of ambient illumination, and the correlated color temperature of the burning reeds (Video B) (Local illuminants whose visual energy is produced by combustible organic material, like candles or oil lamps, emit wavelengths of light that shift the apparent surface color of nearby objects in the orange-red part of the spectrum). The concentric circles framing Mobei's face would have enhanced this effect, producing an illusion of movement even when the board was still. As a result, it would have been difficult to tell where the board began and the face ended; Mobei was animated by the light projected onto him.

So far we have been dealing with luminance, but it is important to realize that luminance most often has a chromatic component. It is now known that color and luminance are processed independently, even though they are unified in the appearance of the object. Indeed, a pictorial array of white, red, and black (as seen in the Goaribari spirit board and in many pictographic traditions) usually constitutes the basic building block of any virtual structure activated by illumination. The phenomenological

⁴⁰ The spirit board is catalogued in M.H. De Young Memorial Museum, *New Guinea Art: Masterpieces from the Jolika Collection of Marcia and John Friede* (San Francisco: Fine Arts Museums of San Francisco, 2005), 165.

unity of the illuminated picture belies the fact that two gradients are processed independently and simultaneously: a chromatic ramp and a luminance ramp.

Why black, white, and red? Retinal anatomy contributes significantly to this bias. 560nm cones, capable of detecting spectra above 650 nm (so-called warm colors), are prevalent throughout the entire retina. By contrast, the cones responsible for detecting so-called cool colors are not uniformly distributed. The central fovea—upon which we depend for sharp, crisp detail in the visual field that we use to read—is “blue-blind”, equipped only with cones that detect longer wavelengths. It lacks 430 nm. cones, the short-wavelength pigment primarily responsible for our detection of cool colors. Our optical sensitivity to red may predispose picturemakers to use red hues in pictures intended to be viewed in low light. Mobei’s red face would be much more difficult for observers to track during the dance if it were painted in a cooler hue, like green or blue.⁴¹

We are also predisposed to coping with red cognitively. In their classic study of color terminology, Berlin and Kay found that all natural languages develop two classificatory terms, one focalized on the dark, cool vector of color space and the other focalized on the warm, bright one. Because we are relatively more sensitive to the warm/bright category than its cool/dark counterpart, we discriminate among these hues first, generalizing a third category corresponding to the English “red.” Further parsing in this area continues as languages develop, resulting in a disproportionate number of red-tinged color terms relative to other hues. We develop a color semantics that is red-heavy.⁴²

2. Overlap

Analytically, in *overlap*, transformations in the luminance of the picture—in changing illumination of its material substructure—become transformations of light in the depicted world.

A simple example will suffice. At portico 10 of the Palace of the Jaguars at Teotihuacan (c. 450 CE), the western wall has been aligned with the azimuth of the setting sun on the summer solstice—the day that marks the highest azimuth of the sun and its longest sweep north-south. A *talud*—a sloped panel at the base of the wall—is angled 19° from the floor of the portico, and decorated with jaguar figures (Figure 3.3).

⁴¹ For a detailed discussion of the relationship between ocular anatomy and color terminology see Floyd Ratliff, “On the Psychophysiological Bases of Universal Color Terms,” *Proceedings of the American Philosophical Society*, 120 (1976), 311–330.

⁴² Originally reported in B. Berlin and P. Kay, *Basic Color Terms: Their Universality and Growth* (Berkeley: University of California Press, 1969); for a revised account (developed from a much larger linguistic sample), see Brent Berlin, *Basic Color Terms: Their Universality and Evolution* (Berkeley: University of California Press, 1991).

During twilight, as our eyes cope with decreasing levels of light, our ability to detect strong red hues falls off, even while our eyes remain sensitive to equally saturated greens and (to a lesser extent) blues—a phenomenon known as the Purkinje effect (Figure 3.4).⁴³

As the sun began to set, a shadow cast eastward by the edifice opposite the wall would begin to creep up the surface of the picture (Video C). About a half hour before sunset, the Purkinje effect would begin to alter the viewer's perception of the colors of the mural. The blue and green hues that define the mass of the jaguar's body (as well as the ground line and upper register framing the *talud*), reflected by azurite and malachite respectively, would seem to "jump off" the beige surface of the wall and the red hand glyph upon which the jaguar sits (Figures 3.5 and 3.6).⁴⁴

If Teotihuacanos associated the jaguar with nocturnally-apparent astronomical phenomena (or perhaps, a nocturnal sun) along the same lines as subsequent Mesoamerican cultures, the creatures depicted in the murals could be understood to transform from flat pictures with low tonal contrasts into virtualized beings emerging from the surface of the wall. Viewers congregated in the courtyard and portico during

⁴³ For an ophthalmological explanation of the Purkinje effect, see Robert Boynton, *Human Color Vision* (New York: Optical Society of America, 1979), 114. Discovery of the phenomenon has traditionally been attributed to Jan Evangelista Purkinje. For his original description see Jan Evangelista Purkinje, *Neue Beiträge zur Kenntniss des Sehens in subjectiver Hinsicht* (Berlin: Reimer, 1825), 109-110. However, the first modern description of the effect (by a painter, nonetheless) is Matthias Klotz, *Gründliche Farbenlehre* (München: Lindauer, 1816); see also Josef Brozek, Vilem Kuthan, and Katherine Arens, "J.E. Purkinje and Mathias Klotz: who first described 'the phenomenon'?", *Perceptual and Motor Skills* 73.4 (1991): 511-514.

⁴⁴ Solstitial alignments at Teotihuacan are described in detail in Ivan Šprajc, "Astronomical Alignments at Teotihuacan, Mexico," *Latin American Antiquity* 11, no. 4 (2000): 403-415. For archaeoastronomic reconstructions of the Palace of the Jaguars see María Elena Ruiz Gallut, Jesús Galindo Trejo, and Daniel Flores Gutiérrez, "Implicaciones Arqueoastronómicas de Pórticos con Felinos en Teotihuacan," in *La Pintura Mural Prehispánica en México*, ed. Beatriz de la Fuente (México, D.F.: UNAH Press, 1995) 1.2:343-360. The murals are discussed in Beatriz de la Fuente, "Zona 2: Conjunto de los Jaguares," in *La Pintura Mural Prehispánica en México*, ed. Beatriz de la Fuente (México, D.F.: UNAH Press 1995-2008) 1.1:115-121. Reconstructions of the now-faded feline murals of portico 10 appear in Arthur G. Miller, *The Mural Painting of Teotihuacan* (Washington, D.C.: Dumbarton Oaks, 1973), 54-55 (figs. 39-43).

the winter solstice would watch the jaguars hover in space above them, as if drawn towards the setting sun.⁴⁵

Evidence indicates that pictorialized illumination has been an established device utilized by image-makers to shore pictoriality up against the low light levels that were characteristic of preindustrial visual worlds, and even to take advantage of them for purposes of pictorialization. For example, the blue background commonly found in late archaic and early Classical Greek polychrome architectural relief created virtual depth in its contrast with the sculpted figures in front of it, which were gilded and painted with warmer hues of reds, oranges, and yellows.

Recent reconstructions of the western pediment of the Temple of Aphaia at Aegina (c. 500 BCE; Glyptothek, Munich; see Figure 3.7) allow us to appreciate the role of the Purkinje effect in pictorializing the illumination of the pediment sculptures. In the Western pediment group, Athena watches over the second Trojan War, flanked by Ajax and Hector. For most of the day, when the sun was more or less overhead, interreflected ambient light emphasized the elaborate coloring of the figures of Athena and the surrounding warriors. The blue background would have played a more significant role in the late afternoon, when it was directly illuminated.

At twilight, when the Purkinje effect plays an appreciable role, one would notice transformations in pictorial depth similar to those seen at Teotihuacan.⁴⁶ The brightness of the red band (upon which all of the sculptures were placed) would attenuate faster than that of the blue background, such that the figures seem to emerge from the pediment toward the viewers down below. Relative to the blue background, the figures and the red ground of the pediment would seem to recede into space, dramatizing the

⁴⁵ For a general discussion of jaguar iconography, see Mary Miller and Karl Taube, *An Illustrated Dictionary of Ancient Mexico and the Maya* (New York: Thames and Hudson, 1997), 102-104. The relationship between jaguar imagery and Mayan calendrics is discussed in Susan Milbrath, *Star Gods of the Maya: Astronomy in Art, Folklore, and Calendars* (Austin: University of Texas Press, 1999), 95, 120-126. Regarding the Aztec deity Tezcatlipoca's association with the jaguar, see Alfonso Caso, *The Aztecs: People of the Sun* (Norman: University of Oklahoma Press, 1958), 14-15.

⁴⁶ Given the site's azimuth and latitude, we can be certain that the west pediment was continuously illuminated at sunset throughout the year; for measurements of azimuth and declination of the celestial sphere directly above the temple, see Efrosyni Boutsikas, "Placing Greek Temples: An Archaeoastronomical Study of the Orientation of Ancient Greek Religious Structures," *Archaeoastronomy: The Journal of Astronomy in Culture* 21 (2009): 4-16. For chromatic reconstructions based on trace pigment analysis, see Vinzenz Brinkmann, "The Prince and the Goddess: The Rediscovered Color on the Pediment Statues of the Aphaia Temple," in *Gods in Color: Painted Sculpture of Classical Antiquity*, ed. Vinzenz Brinkmann (Munich: Stiftung Archäologie, 2007), 70-97.

ferocity of the battle described in the *Iliad*, which came to a halt when a ceasefire was called at sunset.⁴⁷ The battle would resume as the sun rose the following morning and the viewer once again experienced the Purkinje effect, (re)dramatizing the spatial presence of the interdependent figures. At the Temple of Aphaia at Aegina, the Purkinje effect creates an overlap in pictorialized illumination whereby viewers watched the sun set over one of the great battles of the Trojan war in conjunction with their own real sunset.

3. Nesting

In the Jaguar mural from Teotihuacan, we saw how colors shifted to pictorialize illumination. Artists utilize a third method to pictorialize illumination: they nest one or more luminance gradients within one produced by an illuminant in real space.

When only one luminance gradient is present in the picture, continuous correlation with its illuminant results in a steady virtual state that I have called identity, such as the chromatically-determined one in the Goaribari spirit board. The icon of Christ Arakiotis discussed in Chapter 1 is a clear example in Western art. The highly reflective gold surface that frames the body of Christ folds the light cast by the local illuminant—here, a beeswax candle—into Christ’s face and hand as seemingly self-refulgent.

Pictorialized illumination can be constructed in the relation between two gradients—what I will call nesting. An example of this phenomenon can be found in Rembrandt’s *Philosopher in Meditation* (1632; Musée du Louvre, Paris; see Figure 3.8). The solemn mood of the oil painting is evoked by the dark tones that dominate its surface; save the alcove beneath the stairwell, the entire scene is registered in black and dark brown pigments. The philosopher sits lost in thought, his eyes downcast. In the real spatial configuration of the scene of this study, the brightness of the window would have approached the limit of the range that an observer is capable of comfortably seeing, and in a room that dark, the figure would have been partially washed out in glare. The reflectance of Rembrandt’s pigments offered a much narrower range of luminance. The light yellow pigment that comprises the window only reflects fifteen times more light than the black brushwork that defines the leftmost quarter of the painting, though the real luminance of the environment could easily have a hundred-fold variations between these spaces.⁴⁸

Yet, Rembrandt has managed to register lightness significantly brighter than the pigment scumbled as the light-flooded window. This fact becomes apparent if we

⁴⁷ Identifications of the figures can be found in Raimund Wünsche, *Glyptothek München : Meisterwerke griechischer und römischer Skulptur* (München: C.H. Beck, 2005), 34. The first skirmish between Hector and Ajax concludes after Idaios notes that night has fallen; see Homer, *Iliad* 7.329-343.

⁴⁸ The luminance of the painting is discussed in Margaret Livingstone, *Vision and Art: The Biology of Seeing* (New York: Abrams, 2002), 125.

digitally edit the picture so that the hazy penumbra that frames the scene matches the luminance levels of the alcove and stairs (which comprise the tonal midrange in the original painting) (Figure 3.9). Although the lightness of the window has not been adjusted whatsoever, it appears much dimmer.

The window dazzles us in spite of the constraints on Rembrandt's palette because the painter has arranged two contrasting luminance scales so that the smaller gradient—the window—appears much lighter than it actually is. Since we are more sensitive to local luminance disjunctions than gradual shifts over a greater area, we overestimate contrast between the two gradients as we stitch their signals together in the visual cortex.⁴⁹

In *Philosopher in Meditation*, we see how illumination can be pictorialized in steady, ambient light by nesting luminance gradients. In virtue of nesting, the intersection between real illumination and the depicted luminance of the bright window seems scaled to the luminance of the entire depiction (Figure 3.10). However, nested luminance gradients can also pictorialize changes in illumination. When one luminance gradient in the picture changes relative to the background gradient, real illumination of a portion of the picture will cause the luminance gradients of that portion of the picture to change (i.e., to become brighter). This new luminance gradient is now differently nested in relation to all other luminance gradients. In turn this can be used to pictorialize illumination.

Giotto's *Last Judgment* on the western wall of the Arena Chapel is generally lit in ambient light (Figure 3.11). However, the composition of the lower half of the fresco was configured such that it would be specially illuminated during morning Mass on the feast day of the Annunciation, the day on which the chapel was dedicated (Figure 3.12). The dedication of the chapel is depicted at the bottom of the painting, where the patron, Enrico Scrovegni, presents a model of the building to the Virgin and her attendants. As Giuliano Romano and Hans Michael Thomas have shown, in early morning on March 25, a beam of light projected through a window on the south wall passes through the space between Scrovegni and the outstretched hands of the Virgin as if to enter the chapel. While no directional light source is implied when we view the depiction of the chapel in ambient illumination, the directly illuminated model of the chapel clearly implies a light source placed above and to the viewer's left—that is, from a window in the south wall. In this way, the dedication scene is bracketed off from the lighting dominant in the rest of the *Last Judgment*: Christ and the window directly above him. Giotto's arrangement of the figures that accompany the model anticipates this configuration; within the scene, a church father seen in profile holding the model

⁴⁹ Livinstone, *Vision and Art*, 125.

watches the drama of illumination unfold through the same window that the light enters.⁵⁰

⁵⁰ The illumination of the fresco on the feast day of the Annunciation was first discussed in Giuliano Romano and Hans Michael Thomas, "Sul significato di alcuni fenomeni solari che si manifestano nella cappella di Giotto a Padova," *Ateneo Veneto* 178 (1991): 213-56. The relationship between late medieval Annunciation imagery and the staging of the Arena chapel is discussed in Laura Jacobus, "Giotto's Annunciation in the Arena Chapel, Padua," *The Art Bulletin* 81.1 (1999): 93-107.

Chapter 4. One Picture and Multiple Illuminants: A Case Study of Pictorialized Illumination in Leonardo's *Last Supper*

In the preceding chapters, I outlined the three types of pictorialized illumination: identity, overlap, and nesting. Although we examined two paintings (Caravaggio's *Calling of St. Matthew* and Giotto's *Last Judgment*) that pictorialize illumination in conjunction with depicted light, we have not in detail considered any pictures that oscillate *between* these types of pictorialized illumination. I will now consider a picture whose perspectival construction allowed it to oscillate between two modalities of pictorialized illumination, namely, overlap and identity: Leonardo da Vinci's *Last Supper* mural at the refectory of Santa Maria delle Grazie in Milan (Figure 4.1).

The refectory that houses the mural today has been substantially altered since Leonardo painted the mural. As is well known, the building was heavily damaged by bombing in the Second World War; in rebuilding, architects thickened the walls to add additional structural support. The fenestration has also changed; in the early seventeenth century, the original windows were filled in and new ones were installed around them. However, portions of the original window sills have been discovered in subsequent restorations, and I have used their measurements to place the windows of my reconstruction of the refectory as it stood in 1498, when the *Last Supper* was completed.⁵¹

Leonardo worked on the mural continuously for three years (from 1495 to 1498), and we are told by Matteo Bandello, a writer who visited the refectory while Leonardo was working on the mural, that he would visit the mural at different times of day, making adjustments to the picture as he saw fit.⁵² He likely played a role in deciding where windows would be installed in the building; a record of payment from 1497 to a stonemason indicates that adjustments were made to the windows while the mural was being painted.⁵³ Leonardo was specially interested in lighting effects particular to late afternoon, when he believed that the angle and quality of sunlight falling on the surface of an object create the distribution of shadow that is the most replete.⁵⁴

⁵¹ For details on the original fenestration, see Gisberto Martelli, "Il Refettorio di Santa Maria delle Grazie in Milano e il Restauro di Luca Beltrami nell'ultimo Decennio dell'Ottocento," *Bolletino d'arte* 6 (1980): 55-72; Antonio Migliacci, "Il Refettorio Di S. Maria delle Grazie. Opere di Consolidamento Statico," *Arte Lombarda* 62 (1982): 23-30.

⁵² Matteo Bandello, *Novelle* (Milano: Formiggini, 1927), 57.

⁵³ Michael Ladwein, *Leonardo: Das Abendmahl: Weltendrama und Erlösungstat* (Dornach: Pforte, 2004), 93.

⁵⁴ Leonardo's writings on the subject have been collated in Martin Kemp and Margaret Walker, *Leonardo on Painting* (New Haven: Yale University Press, 1989), 161-165; for a detailed explanation of how Leonardo was concerned with handling light in his

In the *Last Supper*, there are five sources of depicted light. Three windows in the back of the *coenaculum* (a dining room in a Roman house, in which Christ and the apostles sit) illuminate the side of the ceiling beams that face the viewer. The light from these windows has attenuated by the time it reaches the table –there is no backlighting to obscure the strong modeling of Christ and the apostles. These figures are partially illuminated by the fourth source of depicted light, located directly in front of the picture plane. It causes the shadows back cast by the tablecloth (onto the legs of the seated figures), Bartholomew's chair, and the two legs of the table visible on the left side of the mural.

The fifth depicted light illuminates the table laterally from above and to the left of the viewer. The shadows cast onto the table as a result of the lateral light source are well preserved –the pewter plates, loaves of bread, and the hands of the figures leaning over the table all cast shadows to the beholder's right. The lateral light also produces some of the shadows cast in the foreground of the painting. Although the ground depicted below the table is heavily abraded (most of the details have been lost), some trace of the shadows that Leonardo painted remains there. For example, the two rightmost legs of the table and Simon's stool cast shadow, and a shadow attached to the right foot of St. Bartholomew also remains visible.

This fifth light source is unpictured, and the angle at which cast shadows caused by it might suggest that it originates from a window high in the wall. The depicted light might correspond to the real window that is nearest to the mural in the western wall. However, as I shall show, Leonardo has configured the depicted space such that this virtual window may or may not be located in real space, depending on how illumination was pictorialized.

The organization of perspective in the *Last Supper* is ambiguous. This has been noted by many viewers, who have often noticed pictorial idiosyncrasies while viewing the work in situ that tend to be downplayed or occluded entirely in printed or photographic reproductions.⁵⁵ Most of the confusion stems from the fact that the orthogonals of the floor of the *coenaculum* indicate that it is wider than the view of it framed by the picture plane, while the orthogonals of the tapestries and ceiling seem to indicate that these surfaces are fully enclosed by the view that is framed by the picture plane: the architrave and tapestries seem to meet at right angles (Figure 4.2), and the ceiling (a grid six modules wide and six deep, like the tiled floor) seems to be shown in its entirety.

paintings, see John Shearman, "Leonardo's Colour and Chiaroscuro," *Zeitschrift für Kunstgeschichte* 25 (1962): 13-47.

⁵⁵ For a catalogue (with commentary) of these copies, see Leo Steinberg, *Leonardo's Incessant Last Supper* (New York: Zone Books, 2001), 226-271.

Only two possible solutions would allow us to construe the perspective of *The Last Supper* as a representation of a physically possible space.⁵⁶ One solution requires that only part of the ceiling is pictured –that the architrave of the refectory functions to block out portions of both the ceiling *and* the walls. As reconstructed by Francis Naumann, the space of *The Last Supper* can only be considered perspectively sound if we imagine that the architrave of the refectory is identical to an unpictured corner pier that abuts the two corners of the depicted room closest to the viewer (Figure 4.3). Although this solution is the one most commonly accepted by scholars, it problematizes other aspects of the perspectival construction. If the orthogonals of the architecture of the coenaculum describe a room with parallel sides, we must accept that the tapestries on each wall are different sizes; the further they are from the viewer, the greater their real size (Figure 4.4).⁵⁷

If we understand the ceiling to terminate where its orthogonals intersect the picture plane, we pictorialize a trapezoidal floor plan (Figure 4.5). Since the orthogonals that describe the architecture of the *coenaculum* in this view do not describe walls that are parallel to one another, this solution allows us to picture the tapestries to be uniform in size.

Leonardo seems to have configured each of these perspectival possibilities as functions of pictorialized illumination. That is, depending on illumination, either one of these possibilities could be pictorialized at different times. Leonardo carefully observed the behavior of sunlight in the refectory as he laid out the composition of the mural in red chalk (*terra rosa*) on the wall.⁵⁸ For any one of the many configurations of real light that are possible within the refectory, one of two permutations of pictorialized illumination would be visible: The lateral light source could appear to behind the corner piers (as an unpictured window), or in front of the painting (pictorialized as a function of the real window nearest the painting on the west wall of the refectory). When the painting is directly illuminated, we see the room in its trapezoidal configuration; the light depicted in the mural is not possible if we virtualize the corner piers, since they would partially obstruct the light streaming into the *coenaculum* from

⁵⁶ See, for example, Martin Kemp, *Leonardo da Vinci: the marvellous works of man and nature*, 1981 (Oxford: Oxford University Press, 2006), 196.

⁵⁷ Francis Naumann, 'The 'Costruzione Legittima' in the Reconstruction of Leonardo Da Vinci's 'Last Supper,'' *Arte Lombarda* 52 (1979): 63-89.

⁵⁸ Although the condition of the mural does not allow for the complete underdrawing to be visualized by infrared imaging, traces of the underdrawing were observed during the mural's most recent restoration. Although the traces of the underdrawing are fragmentary, we can be certain that (at the very least) Leonardo laid out reference points (from a cartoon) on the wall. See Pinin Brambilla Barcilon and Pietro Marani, *Leonardo: The Last Supper* (Chicago: University of Chicago Press, 2001), 425-426.

the window such that the shadows cast on the table would not be possible and it would be necessary to have a shadow cast by the pier (see Figure 4.6). In this trapezoidal *coenaculum*, light streams directly from the refectory into the unobstructed table space of Christ and the apostles. This is a case of overlap; a real light source in the room (the western window closest to the northern wall) pictorializes some of the light depicted in the mural.

When the painting is not directly illuminated, we can virtualize the corner piers to obstruct a portion of the left wall that contains a hidden window (Figure 4.7). As is evident in a comparison of Figure 4.3 and 4.4, the unpictured portion of the walls is much greater in the cuboid pictorialization of the *Last Supper* than the trapezoidal one. In the trapezoidal configuration, this unpictured space is minimal, approximately .6 meters deep. Indeed, it is minimal enough that no pictorial consideration need be given to it for the purpose of interpretation. However, in the cuboid configuration, a considerable section of the wall is obscured—1.6 meters, enough for a small window. (The actual refectory windows are 1.2 meters wide.)

When the painting is not directly illuminated (i.e., its virtual space is cuboid), the illumination pictorialized is a case of identity: the lightness or dimness of the *Last Supper* seen in ambient lighting is continuously correlated with levels of real light in the room.⁵⁹

The two versions of virtual space that the *Last Supper* permits (and perhaps oscillates between), I now turn to the actual play of light within the refectory throughout the year, enabling an iconographic explanation of each version of virtual space in terms of pictorialized illumination.

Reconstruction of Lighting in the original Refectory of Santa Maria delle Grazie

I will begin with the appearance of the *Last Supper* at the winter solstice, vernal and autumnal equinoxes, and the summer solstice (in that order). Throughout much of the year the mural is indirectly illuminated (0:08-0:25 in the simulation of winter solstice of 1498 [Video D]; 0:00-0:06, 0:20-0:27 in the equinox simulation [Video E], and all of the summer solstice simulation [Video F]). However, as I shall describe in detail, “spotlight” effects are pictorialized in the morning and late afternoon, when sunlight passes through windows in the eastern and western walls of the refectory.

⁵⁹ In the cuboid configuration, the lighting of the room seen through the aperture is structured by a photometric gradient that Leonardo had observed in architectural settings: when two spaces are equally illuminated by ambient light, an observer situated in one luminance array can easily observe details in the other through an aperture (such as a doorway or window). See Kemp and Walker, *Leonardo on Painting*, 69.

During winter (and throughout the year at midday), the refectory is rather dark, and artificial light was likely used at these times. However, since no evidence for the placement of original light fixtures survives, I have omitted these from my reconstruction. Although these artificial lights would have partially offset the dramatic “spotlight” effect of light projected through the refectory windows, rays of sunlight in a dark room would have been nonetheless substantially brighter than the light produced by candles or oil lamps (and thus just as noticeable, if not more so).

When the diurnal path of the sun is lowest in the sky, at the winter solstice, rays of sunlight streaming onto the painting through three eastern windows passes over the painting early in the morning (0:00-0:09 in Video D). The first ray of light that appears passes over the depicted ceiling of the *coenaculum*, and disappears when its edge vertically aligns with the rightmost edge of the tapestry furthest from the viewer on the eastern wall. The second ray of light that appears passes over the back wall of the *coenaculum* until it reaches the window directly behind Christ, and disappears (seemingly exiting through the window). In the late afternoon, sunlight projected through a window in the western wall seems to emerge from a central window in the back wall of the *coenaculum*, and then seems to move into our space as the light moves across the eastern wall of the refectory before disappearing (0:25-0:29).

At the vernal and autumnal equinoxes (when the ecliptic intersects the celestial equator and the sun’s apparent altitude is midway between those of the solstices) sunlight projecting through the eastern window in the morning passes over the apostles on the left side of the table and disappears out the door depicted in the middle of the eastern wall of the *coenaculum* (0:06-0:11 in Video E). The other patches of sunlight projected through the eastern windows pass over the north wall (below the mural) and the floor of the refectory, and disappear directly below Christ’s outstretched right hand. In the afternoon, a patch of sunlight emerges through the rear depicted window of the western wall of the *coenaculum*; the other patches of projected sunlight appear directly below Christ’s outstretched left hand (0:19-0:29). In late afternoon on the equinox, these lights project onto the eastern wall to align with the orthogonals of the tapestries depicted on the eastern wall of the *coenaculum*.

On the summer solstice, when the sun is highest in its diurnal motion, the mural is never directly illuminated, but the outstretched hands of Christ still pace the appearance and disappearance of sunlight projected through the windows (Video F). In the morning, swathes of sunlight pass down the western wall and disappear underneath the left hand of Christ (0:01-0:12); in the afternoon, light emerges beneath his right hand to climb the eastern wall (0:17-0:30).

Leonardo likely planned the “spotlighting” that configures the *coenaculum* as a trapezoid as an effect to be observed by monks eating in the refectory during winter and spring –the *Last Supper* would serve as a virtual backdrop to the dining hall during the portion of the year in which Christ was born and died. As such, the real light that

seems to pass through the *coenaculum* before exiting through a depicted window could be understood as an allegory of transubstantiation; the Holy Spirit passes over the group as Christ reaches for the bread and wine. This effect would have been particularly poignant in the spring, the time during which the Last Supper actually occurred; light passes over the table directly in front of Christ before disappearing.

The trapezoidal floor plan of the directly-illuminated configuration echoes that of the main chapel of Santa Maria delle Grazie, which Leonardo would have observed being built while he was at work on the *Last Supper*. The polygonal apse of the chapel was finished the same year as the *Last Supper*, and Leonardo might have had it in mind as a model for the trapezoidal *coenaculum*. In this sense, Leonard could have been pictorializing the *coenaculum* as the first chapel; as the Holy Spirit figuratively passed through the room (as overlap in pictorialized illumination), the space is that of a polygonal apse.

In summer, when identity in pictorialized illumination virtualizes a cuboid space, these “spotlighting” effects can also be understood iconographically. Light disappears (and reappears) beneath the outstretched hands of Christ. The places on the wall at which these rays of light appear and disappear implies the base of a triangle, with Christ at its apex (as many scholars have noted, the figure of Christ himself seems to have been fitted into a triangle, presumably reference to the trinity). These light effects extend that triangle—perfectly aligned with the orthogonals of the picture—into real space. Leonardo could have imagined these patches of light would frame figures seated directly below the mural.

When we pictorialize illumination of the mural as a case of identity, the room is cuboid, and we observe Christ reaching for the bread and wine to conduct the first Communion. When we pictorialize illumination of the room as overlap, a different temporality is at work; viewers would see Christ standing before a polygonal apse, presenting the sacrament *to them*. Overlap and identity in pictorialized illumination partition virtual space as separate moments, restaged over and over again as the *Last Supper* painted in the refectory perpetuated the historical Last Supper.

Chapter 5. One Illuminant and Multiple Pictures: A Case Study of Pictorialized Illumination in Peter Paul Rubens's *Descent from the Cross*

So far, my discussion has been limited to multiple illuminants of a single picture. I will now consider how a single illuminant can be used to pictorialize illumination in more than one picture. I will focus on the work of Peter Paul Rubens, who pictorialized illumination within pictures displayed in the same location, and viewed sequentially. In his altarpiece for the Guild of the Arquebusiers at Onze-Lieve-Vrouwekathedraal in Antwerp, Rubens used a set of pictures to stage a narrative in pictorialized illumination.

In my reconstruction of Leonardo's *Last Supper*, I presented an example of pictorialized illumination that was fastidiously tailored to the architecture that houses it (This observation is by no means limited to the refectory of Santa Maria delle Grazie -- we may also note this at the Arena Chapel in Padua and the Palace of the Jaguars at Teotihuacan.) When a picturemaker is able to anticipate variable illumination patterns, she can construct a picture that is "flexible" enough to accommodate it. However, unforeseen conditions of illumination can easily derail the visual machinery of a picture. Like many painters, Rubens learned this lesson the hard way: he designed a painting that did not properly anticipate the impact of certain real illuminants.

Rubens realized that all illuminants must be accounted for in staging pictorialized illumination as a result of his struggles with his most important Roman commission, *Saint Gregory with Saints Domitilla, Maurus, and Papianus*, originally intended to serve as the High Altar for the Oratorian congregation at Santa Maria in Vallicella (Figure 5.1). Rubens received the commission on 25 September 1606 and finished by 25 May 1607, the feast day of St. Philip of Neri, the founder of the Oratorian order. The Oratorian Fathers were dissatisfied with the appearance of the altarpiece when it was illuminated in winter, and demanded a replacement in January 1608. The new altarpiece, a slate triptych, was completed between July and October 1608.⁶⁰

Video G reconstructs the conditions of light in the choir of the Chiesa Nuova that Rubens could have observed when he secured the commission. The ample fenestration and whitewashed stucco walls in the nave of the Chiesa Nuova presented Rubens with a novel configuration of illumination—light entering through windows was reflected by the diffuse surface of the walls, resulting in a space much brighter than any Rubens had ever worked in. (In the video, the first altarpiece has been added for reference; although it was not installed until summer 1607, its inclusion helps us to appreciate some of the light effects Rubens anticipate as he worked on the painting.) In early morning in September, real light flooded the choir from the lateral eastern window, illuminating

⁶⁰ Michael Jaffe, "Peter Paul Rubens and the Oratorian Fathers," *Proporzioni* 4 (1963): 209-241.

the lower right-hand corner of the altar. The entire altarpiece was directly illuminated in late afternoon by light from the western choir window.

Rubens integrated these parameters of real illumination (so far as sunlight in the choir was concerned) into the composition of the altarpiece. In *Saint Gregory with Saints Domitilla, Maurus, and Papianus*, Rubens attempted to pictorialize illumination to make the figures in the depicted icon materialize in real space.

In the painting, there are two sources of depicted light (Figure 5.2). Depicted rays of divine light originate above left, fall on the central icon, and create cast shadow beneath the foliage that wraps around the putto. The second light source is directly in front of the picture, and highlights the figures that flank St. Gregory. St. Achilles seemingly faces into the beam arriving from above left, although he is also illuminated by the frontal light.

When the painting was partially illuminated in the morning (0:09-0:13), the depicted illuminant directly in front of the altarpiece is pictorialized; light appears stream through his outstretched hand onto his robes, as well as those of St. Domitilla. The perspective of the painting dramatizes this pictorialization –the figures are situated above the viewer. By placing St. Gregory’s hand at the same level as the lower extremity of the eastern window, Rubens was able to fold the raking light produced by the real illuminant into deep modeling of the robes of the saint.

When real light floods the choir in the late afternoon (0:34-0:38), it brightens the painting, and as Rubens scholar Francis Huemer has said, lights it up “like a jewel.”⁶¹ Real light falls across the surface of the painting at the same angle as the first depicted light that illuminates the depiction of the icon. This depicted illuminant accommodates real illumination from above left; heavy scumbles of pigment show divine light saturating the icon above the archway. To the amazement of the putti circling it, the icon comes to life as rays of light brighten it; Rubens has replicated the composition of the original Vallicella icon, though exaggerating the modeling of Christ’s right arm, and adding a cast shadow in Mary’s lap such that the baby seems to learn forward out of the picture plane. In addition, the purple drapery and light blue bodice of St. Domitilla, the gold luster implied by the yellow-white pigments of the armor of St. Maurus, and the ornate detail of the ecclesiastic robes of St. Gregory are dramatically magnified, seemingly as a function of the depicted illuminant located in front of them in virtual space. In this instance, *both* depicted light sources are functions of pictorialized illumination.

The effects I have described were prominent when Rubens began the altarpiece, and likewise were pronounced by the date of completion specified by the contract (see Video 12). On that day, May 25, light passing through the lateral choir windows in late morning perfectly fills the area of floor before the altar (0:06-0:12), probably meaning

⁶¹ Francis Huemer, *Rubens and the Roman Circle* (New York: Garland, 1996), 182.

that it flooded the altar itself. In late afternoon beams of light illuminate the altar frame, but not the painting itself (0:26-0:40).

Despite the planning of the pictorialized illumination in the choir, Rubens's orchestrations were frustrated. We know from surviving correspondence between Rubens and church officials (unearthed by Michael Jaffé) that Rubens did not correctly anticipate that light falling directly on the painting would interfere with its visibility.⁶² Because he did not paint the altarpiece *in situ*, he probably did not realize that light from windows in the nave would illuminate the altar, not only the light he pictorialized entering through fenestration in the choir. In winter, when the sun is closest to the horizon, sunlight streaming in from windows in the nave disrupted the carefully plotted depicted lighting in relation to the real illumination Rubens had planned for — namely, light from the chapel windows only. These effects are clearly visible in a lighting simulation of 1 January 1608 (Video 13). In late afternoon, two rays of light projected through windows in the nave pass over the altarpiece (0:26-0:29). Since the distribution of both is not reconcilable with the depicted lighting of the altarpiece (and the correlated modeling of the figures), the pictorialized illumination that Rubens mapped out as a function of real illumination by the choir windows falls flat. Seen from the nave, this lighting could have also resulted in glare on the surface of the painting that obscured the depicted lighting effects on the drapery and faces of the figures. Indeed, we know from a letter Rubens wrote to Chieppio in February 1608 that the members of the Congregation of the Roman Oratory had rejected his altarpiece based on dissatisfaction with the glare on its surface, and that Rubens's payment for the work would be contingent upon producing a new version "painted on stone or a material that absorbs the colors so that they do not receive glare from this perverse lighting" ("dipingendola in pietra o materia che sorba li colori a fine che non ricevono lustro da quei perversi lumi"). As a result, Rubens replaced *Saint Gregory with Saints Domitilla, Maurus, and Pappianus* with three paintings on slate, two to be placed below the choir windows (and to cover them slightly) and one to replace the High Altar.⁶³

To produce the slate replacements, likely Rubens (then in Antwerp) was provided with first-hand accounts of the problematic illumination (possibly including measurements) from his numerous contacts who remained in Rome. In the slate configuration, he relegated the *sacra conversazione* to the panels flanking the central panel; the central panel, *Virgin and Child adored by Angels*, shows the Vallicella icon held

⁶² Jaffé, "Peter Paul Rubens and the Oratorian Fathers," 221. Although Rubens surely visited Santa Maria in Vallicella before he began painting the altarpiece, he likely disregarded the possibility that light projected through the nave windows would significantly impact the appearance of the altarpiece.

⁶³ For the correspondence between Rubens and Oratorian officials, see Jaffé, "Peter Paul Rubens and the Oratorian Fathers," 220-221.

above an audience of angels by a group of putti (Figure 5.3). Rubens did away with the frontal light source in *Saint Gregory with Saints Domitilla, Maurus, and Papianus* that was disrupted by the distribution of the winter sun shining into the choir from the nave. All of the depicted light transmitted into the slate panel placed to the right of the altar (*Sts. Nereus, Domitilla, and Achilleus*) originates in the central panel slate panel from a light source located directly above the icon of the Madonna (Figure 5.4). The figures in the panel that was installed to the left of the altarpiece (*Sts. Gregory, Maurus and Papianus*) are illuminated by a second depicted light source located in front of the picture in the nave (Figure 5.).

The configuration of the slates effectively resolved the problematic illumination evident in the first Chiesa Nuova altarpiece during winter months (Video J). The lower reflectance of the slate support mitigated the glare. The configuration of depicted light in all three panels results in pictorialized illuminations that accommodate the full range of illumination from light in the choir *and* the nave. Early in the morning, real light streaming in from the eastern window spotlights the icon of the Madonna; this real light is framed by the clouds that surround the putti holding the icon (0:00-0:04). At midday, light from the windows in the nave passes through the choir, falling first on the leftmost slate panel to configure the pictorialized illumination that produces the shadows cast by the figures (0:17-0:18). Then, the uppermost swathe of light passes over the audience of angels who behold the icon; one by one, they are illuminated by a patch of light that also falls on the lowest portion of the icon (0:19-0:21). They are individually bathed in the pictorialized illumination of the depicted light source located directly above the Madonna. In the evening, two patches of light (which also stream into the choir from windows in the nave) pass over the altarpiece, but not the leftmost panel (0:26-0:30). One of these patches of lights spotlights the individual angels, as we saw at midday; the second spotlights the Madonna. The icon of the Madonna is now configured as the source of light; it appears that the depicted light reflects off of the depicted painting onto the angels below.

In the slate configuration, Rubens did away with shadow cast by the hand of Christ to accommodate the double spotlighting effect pictorialized in January. The actual icon of the Madonna della Vallicella, which features the same patterns of cast shadow as the depicted icon in Rubens's original altarpiece, was only displayed on significant feast days (most notably, May 25, Philip of Neri's feast day) when Ruben's version of the icon was removed to reveal the real icon, mounted behind the altarpiece on the apsidal wall.⁶⁴ When sunlight streaming through the choir windows passed directly in front of the altar frame (as on May 25, Video H), these shadows would appear as functions of the depicted lighting above the Madonna. The actual icon of the Madonna of the

⁶⁴ Hans Belting, *Likeness and Presence: A History of the Image before the Era of Art*, trans. Edmund Jephcott (Chicago: University of Chicago Press, 1994), 488.

Vallicella would seem to “come to life” as a function of pictorialized illumination configured by the slate panel that houses it.

Rubens would utilize this spotlighting effect to stage the *Descent from the Cross*, the central panel of a large altarpiece commissioned by the guild of Arquebusiers for their altar to St. Christopher in the southern transept of the Church of our Lady in Antwerp (Figure 5.6). Although the central panel was installed in September 1612, the wings of the triptych were not delivered until much later –March 1614.⁶⁵ In the central panel of the *Descent from the Cross*, heavy modeling of the figures emphasized their strained musculature as they bear the weight of Christ’s body. Their struggle indicates the unifying theme of the altarpiece (“Christ-topfen” or Christ-bearing, a play on the name of the patron saint of the Arquebusiers’ guild).⁶⁶

Unlike Santa Maria in Vallicella, the Church of our Lady has no lateral windows to provide side-lighting to the altarpiece when the sun approaches the horizon. The only windows are located high above the altarpiece (16 meters above the ground). As a result, the *Descent from the Cross* was subject to even more dramatic fluctuations in illumination than the Chiesa Nuova altarpieces. Although the service of the Arquebusiers (as professional soldiers) warranted frequent travel, they did hold mass at the altarpiece on the feast day of St. Christopher, July 25. For those watching the altarpiece at midday on that day, high ambient lighting would disappear over the course of half an hour, such that many of the painting’s details were nearly invisible (0:18-0:21) in Video K). This decrease in ambient lighting dramatically recalls the eclipse that occurred around noon (“the sixth hour,” as the Synoptic gospels say) at the moment of Christ’s death. Then, as the sun aligned with fenestration in the western wall of the southern transept, the altarpiece would be brightly illuminated at an angle that matches the tilt of Christ’s body (0:22-27). The cast shadows in the painting are pictorialized as functions of real illumination streaming onto the painting from across the transept (behind the viewer, on her right side); this is most evident in the heavy shadow cast onto the ground by the ladder and St. John. A second patch of light passes over the upper left portion of the painting before it disappears in the darkness of

⁶⁵ For details on the commission, see John Martin, *Rubens: The Antwerp Altarpieces* (New York: Norton and Co., 1969), 43-52.

⁶⁶ Seeking to serve Christ through good works, a man named Offero approached a hermit, who directed him to sit by a bridgeless river and help travelers cross it. The hermit left, and Offero lived by the river for some time, assisting passers-by in crossing. Eventually, a young child came to Offero, who bore him across the river on his shoulders. Upon crossing the river, Offero remarked on that the child was unexpectedly heavy. To this the child remarked that he bore the weight of the world upon his shoulders, and revealed himself as Christ. Subsequently the man was called Christ-Topfer, “Bearer of Christ.”

evening; it illuminates the dark patches of clouds and passes over the strained back of the figure who leans over the left arm of the cross, dramatizing his motion as he reaches towards corpse of Christ (0:27-0:29). Rubens has taken care to highlight the dark, billowing drapery of the figure with the same pigment that defines the clouds behind him in such a way that that he seems briefly to hover in the air in the final moments of pictorialized illumination in the altar.

In designing the wings of the altarpiece, Rubens chose to accommodate the same lighting effects. In *St. Christopher and the Hermit*, the composition painted across the back panels of the altarpiece's wings (Figure 5.7), one first source of light depicted in the painting is held by the hermit, whose lantern swings open along the same axis that divides the diptych. The lantern illuminates Christ, who turns to face it. The inclusion of a waning crescent moon makes a symbolic connection between the sunlight reflected by the satellite and Christ's ability to reflect the "Light of Truth" (commonly associated with the hermit's lantern). The other source of light depicted in the painting spotlights the figure of St. Christopher from above right, strongly defining his torso and resulting in shadows cast by his staff and right leg onto the ground behind him.

In the weeks leading up to July 25, then the altarpiece was closed, *St. Christopher and the Hermit* dramatized the diurnal play of light in the transept (Videos L and M). When light levels drop at midday, the figures of Christ and St. Christopher are hard to distinguish in the dim light; except for his lantern, the hermit completely disappears (0:21-0:25). All of the figures reappear dramatically as the first swathe of light passes over the entire painting at an angle echoed by the rocky outcropping in the lower right-hand corner (0:26-0:29). When directly illuminated in this way, both depicted illuminants are pictorialized --the light of the hermit's lantern and the spotlight (now pictorialized as the light streaming through a window in the southern wall of the transept). When the second swathe of light passes over the painting in the late afternoon, only the spotlight is pictorialized; it seems to be the real light streaming into the church that guides Christ across the river (0:30-0:31).

When the altarpiece was opened, the wings (*The Visitation*, on the left, and *The Presentation in the Temple*, on the right; Figure 5.8) also pictorialize the spotlight depicted in *The Descent from the Cross* (Videos N and O). When the first swathe of light passes over the altarpiece, it fully illuminates *The Visitation* and falls across *The Presentation in the Temple* at such an angle that it appears to pass through the temple archway to illuminate the face of the priest holding Christ, who looks upwards (seemingly anticipating this effect) (0:22-0:25). When the second swathe of light passes over the altarpiece, the figures standing atop the bridge in *The Visitation* are illuminated (0:27-0:29). The dramatic shadows cast by the architecture in *The Visitation* pictorialize this spotlighting effect, and a shadow cast by the wall opposite Mary perfectly bisects her belly (foreshadowing Christ's death).

Towards a Vocabulary of Baroque Pictorialized Illumination

Scholars have long disputed the motivations behind the rejection of Rubens's first altarpiece for the Oratorians. Some, like Frances Huemer and Hans Belting, interpret the iconographic differences between the Chiesa Nuova altarpieces as a function of the death of Cardinal Caesar Baronius, who had overseen the early stages of the commission.⁶⁷ My reconstruction indicates that the "perversi lumi" described by the Oratorians was not simply a metaphor for their dissatisfaction. Research by Ilse von zur Mühlen has suggests that Rubens began developing a complex pictorial vocabulary for describing visionary experience while he worked in Rome, and my research suggests that von zur Mühlen's analysis could be extended to the viewer's phenomenological experience of viewing *The Descent from the Cross* (and, likely, other works).⁶⁸

⁶⁷ Huemer, *Rubens and the Roman Circle*, 91-94; Belting, *Likeness and Presence*, 488.

⁶⁸ Ilse von zur Mühlen, *Bild und Vision: Peter Paul Rubens und der "Pinzel Gottes"* (Berlin: Peter Lang, 1993).

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