TONE REPRODUCTION FOR COMPUTER GRAPHICS
USING PHOTOGRAPHIC PRINCIPLES

by

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ABSTRACT

Tone Reproduction for Computer Graphics Using Photographic Principles

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Directed by Professor John Sibert and F. Kenton Musgrave

Since its inception, one of the major goals of computer graphics has been the quest for photorealism in the synthesis of computer generated imagery. In pursuit of this goal, the field has relied on a photographic metaphor whereby the transport of light is traced from a scene, through a camera and onto an image plane. In the final stage of the synthesis process, the tone reproduction stage, simulated illuminance values are converted to appropriate pixel values for eventual display.

Most work in tone reproduction for computer graphics has focused on modeling of the human visual system. In this work, an alternate means of tone reproduction based on photography is described. The dissertation specifies a system that models individual components of a photographic system (including the camera, enlarger and photographic materials) and simulates the mechanisms by which photographic prints are created.

The proposed system is validated through a suite of informal tests and formal experiments whereby simulation results are compared with actual photographic negatives and prints. Visual inspection of validation test results illustrates that the simulation can satisfactorily produce renderings that match closely with actual negatives and prints. Numerically, error differences in tone between simulation results and actual processed images range from 0 - 10%.

The system enables tone reproduction to be applied to computer generated imagery using the same parameter space available to photographers. As such, the system can be used to experiment with different photographic parameters, immediately illustrating the results of a set of photographic choices. Application of the system in photographic education, rendering system validation, and digital cinema is also discussed.
DEDICATION

To my parents, Alfred and Grace Geigel and to my wife Marie.
ACKNOWLEDGMENTS

This dissertation has taken me on an academic journey lasting 10 years and through four separate cities. I’ve had the pleasure of interacting with a number of great people along the way who helped guide my direction, and provide me with the inspiration required to complete this task. I would like to make special note of some of them here.

The journey began in New York City, where I had the pleasure of working under the guidance of Ken Perlin at New York University. It was during this time that, thanks to Ken, I first became interested in Computer Graphics, interested enough to spend the next ten years studying it.

Next stop, Washington D.C., where I enrolled in the doctorate program at the George Washington University. I am grateful to John Sibert, who originally took me on as a student and introduced me to the world of academic research. After several changes in direction, it would be John who would also guide me through to the completion of this work. I would like to thank James Hahn for laying the foundations of my studies in Computer Graphics and Ken Musgrave, whose unique perspectives on art, graphics, and life provided me with new ways of perceiving my own personal tasks. It was Ken who took enough of an interest in this topic to encourage me to see it through as a dissertation.

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The next destination on the journey is Pittsburgh, PA, where I took a research programming position with the Biomedical Group at the Pittsburgh Supercomputing Center. At this point, I thought that my journey was complete. I was ready to simply take what I had learned and move on to a new path not involving the completion of the doctorate. I’d like to thank Mr. James Rowan who had enough foresight to convince me otherwise and had me apply for a Leave of Absence rather than leaving the CS program at GWU. Many thanks go out to Dr. David Deerfield, manager of the Biomedical
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**photography**, n., the process or art of producing images of objects by the action of light on a sensitized surface, esp., a film in a camera.

1.1 **Computer Graphics as Virtual Photography**

Since its inception, one of the major goals of computer graphics has been the quest for photorealism in the synthesis of computer generated imagery. Simply stated, given a description of a virtual scene, can a computer generate a rendering of this scene that is indistinguishable from a photograph? In pursuit of this goal, the field has mimicked the process by which photographic images are created. The primary component of this process can be summarized in one word: Light.

As specified in the dictionary definition of photography given above, photographic images are the result of light interacting with a sensitized surface. In fact, in considering the derivation of the word photography (photo-+graphy), photography literally means “writing with light.” This paradigm is no different from the means by which our own visual system operates. Our eyes are nothing more than light sensitive receptors. Our ability to see is enabled by the perceptual response to light in the world. Since both vision and photography are grounded in the same paradigm, it is not surprising that the field of computer graphics has also chosen the same approach to the image synthesis process. This process primarily involves the simulation of the interactions, distributions, and responses to light.

For computer generated imagery, the processes of a typical image synthesis system for are illustrated in Figure 1-1. First, modeling is performed. During modeling, a description of the scene to be rendered is supplied to the system. Modeling not only involves the specification of the shape and position of objects in the scene, but just as importantly, includes object appearance (i.e., color, texture, shading), definition and placement of light sources, and definitions of atmospheric properties.

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1 This pipeline is generalized from the framework presented in [GREE97]
In viewing or photographing a scene, light comes to the eye or camera through the processes of reflection, refraction, scattering, in addition to directly from a light source. During the illumination process, this transport of light within the scene is simulated. A large segment of the research in Computer Graphics in the last 15 years has focussed on this area. The outcome of this research has resulted in a variety of techniques and algorithms ranging from efficient and simple heuristics to complex simulations based on electromagnetic physics.

Images are 2D representations of a 3D world viewed from a given perspective. In creating an image, light in the 3D environment is projected or focussed onto a 2D plane. This projection is performed during the capture process. In some cases, capture is combined with the illumination step. Whether considered as part of illumination or as a separate process, the capture phase will rely on the use of a camera model that defines the means by which this projection is performed.

The image synthesis process is not complete until tone/ color reproduction is achieved. It is during this process that the response to light is defined and utilized. Using a response function, simulated light energy incident on the 2D plane (as captured and focused by the camera model) is converted to appropriate pixel values for inevitable display or output.
As illustrated in Figure 1-2, this pipeline presented above is quite analogous to the process of capturing photographic images. In photography, all of the processes are physical processes occurring in the real world, whereas in computer graphics, all of these physical processes are simulated.

### Figure 1-2 Similarity between image pipelines for photography and computer graphics

#### Photography:
- real scene
- camera (captures light)
- photo processing
- photographic print

#### Computer Graphics:
- 3D models
- camera model (focuses simulated lighting)
- tone reproduction
- synthetic image

### 1.2 Tone Reproduction

This thesis will address the problem of tone reproduction. The fundamental problem of tone reproduction has to do with the disparity between the light levels in the real world versus light levels that can be displayed by a given output device. The human visual system responds to light in the range of $10^6$ cd/m$^2$ to $10^{+8}$ cd/m$^2$, a distance of 14 log units [HOOD86]. A typical CRT displays intensities of near 50 cd/m$^2$ with a range of only 100:1. Even photographic systems, which are considered superior in capturing scenes with high dynamic range, have an average sensitivity range of, at most, four log units.

During physically accurate rendering simulations, lighting quantities are calculated. However, due to the limitations of output technologies, there is no possible way in which any output device can accurately reproduce these simulated quantities of light. Instead, tone reproduction operators are constructed to preserve the perceptual sensation of a rendering within the limitations of any output technology. This distinction between the physical and the perceptual is a very important concept and is at the very crux of tone reproduction. Up until the tone reproduction phase, all of the processes...
presented in Figure 1-1 could be performed in the realm of physics. The physics of light and light transport involves energy, not brightness. It is during the tone reproduction phase that the jump from the physical to the perceptual is made. It is during this phase, and possibly, this phase alone, that response to light energy is considered.

The ultimate goal of tone reproduction is to produce an image, based on the light emitted from a virtual scene, such that the image will invoke the same visual sensations as if one was looking at the scene directly. This is not only true in Computer Graphics, but also as noted in [NELS77], true in photography as well. This is most significant, as the need for this perceptual accuracy has driven the photographic industry to optimize the materials and processes of photography precisely toward this primary goal.

The importance of appropriate tone reproduction cannot be underestimated. Consider the following example, first presented in the seminal paper on tone reproduction by Tumblin and Rushmeier [TUMB93]. In Figure 1-3, the results of two lighting simulations are presented. In the image on the right, the strength of the emitted light is equal to that of a firefly, whereas in the figure on the left, the light source has the power of an aircraft searchlight. In both cases, an ad-hoc method of tone reproduction that scales the simulated values based on the minimum and maximum values from the simulation is used. The similarity of the two renderings is absurd and most misleading; far from what would be expected if the scene were viewed or photographed.

![Figure 1-3 - Tone reproduction using ad-hoc scaling (from [TUMB93])](image)

2 Even color, which is discussed in more detail in Chapter 2, is perceptual and not physical.

3 Although this tone reproduction method may seem simple, or even absurd, it is the tone reproduction method traditionally used by many renderers.
This example may be a bit contrived, however, the point that it makes is clear. Tone reproduction, which has been until recently, generally ignored in Computer Graphics, must be considered as an integral part of the image synthesis pipeline. Furthermore, care must be taken in the approach to tone reproduction, otherwise, inaccurate and misleading renderings can result from otherwise accurate and rigorous lighting simulations.

1.3 Goals of this Work

In this thesis, we approach tone reproduction by simulating the response of photographic materials and systems. The goal of this work is to define a tone reproduction system based on the principles and parameters of photography.

Creation of such a system has a number of advantages:

- **Use of existing photographic research.** – Over the past century, photography has become the primary means of capturing and producing images of the real world. One might argue, as famed essayist, Susan Sontag does, that as photography becomes more a part of popular culture, the line between photography and reality becomes increasingly blurred. In [SONT77] Sontag writes:

  “Instead of just recording reality, photographs have become the norm for the way things appear to us, thereby changing the very idea of reality and of realism.”

The truth is that most people today rely heavily on photography to capture the reality of their lives. In short, photography has proven itself more than an adequate means of image production; a process backed up by years of perceptual satisfaction. Photographic scientists and engineers have spent the last century optimizing and updating the materials and processes of photography with the goal of creating the most visually pleasing images possible. Creation of a tone reproduction system based on photography would allow for application of this large body of photographic knowledge to computer generated imagery.

- **Artistic expression** – It was mentioned previously that the ultimate tone reproduction operator would be one that produces an image of a scene that most closely reproduces the human visual sensation of viewing the actual scene. Although this may be the ideal tone reproduction operator,
it may not be the most desired. Consider artistic photography where faithful depiction of reality may not be the ultimate goal. The famed photographer Ansel Adams described photography as a visualization process whereby the photographer first visualizes the final rendering of a scene and then uses the controls of photography to realize this vision [ADAM82a]. During his lifetime, Adams has written a large collection of books on photography (e.g. [ADAM82a, ADAM82b, ADAM82c]) that teach, not how to capture reality with a camera, but rather, how to achieve one's artistic vision of a scene captured on film. A tone reproduction operator based on photography will allow these artistic techniques to be applied during the creation of computer generated imagery.

• Simulation of “film look” – On a more practical note, there are cases where simulation of the look of images captured on film (i.e. the “film look”) is not only desirable, but also necessary. Take for example, the case of motion picture special effects where computer graphics elements are combined with scenes captured on film. In order for this composition to be seamless, the elements created on computer must take on the same image characteristics as the film-based images. A tone reproduction operator that produces this “film look”, defined using the parameter space of a photographer or cinematographer, would be an invaluable tool for performing these kinds of compositions.

The simulation of the “film look” will also prove to be essential in the emerging field of digital cinema. In May of 1999, George Lucas, creator of the Star Wars films, shocked the film industry by declaring that his next Star Wars film will be filmed and delivered entirely using digital technologies [LARI99]. Removing motion picture film from the movie making process presents quite an artistic challenge to filmmakers and cinematographers, especially since most have refined and mastered their art under the assumption that film will be used as the recording medium. An operator that recreates the film look, while, once again, working in the parameter space of photography, would be taking the first step towards a bridge between the artistic craft of the cinematographer and new emerging digital technologies. Such a system would allow the filmmaker to continue to work within the parameter space in which he/ she is familiar, though this parameter space may be inappropriate using new digital devices. At the same time, the expected
result from a set of photographic choices will be preserved when displayed using the new technologies.

Working under the assumption that a tone reproduction system based on the principles of photography is indeed beneficial, the requirements necessary to make such a system effective are considered. The proposed tone reproduction system is designed with the following goals in mind:

1. **Accuracy** - The operator should be able to accurately model the responses of existing photographic materials and systems. Towards this goal, we strive for physical accuracy. The mechanisms of photography are comprised, measured, and defined purely by physical processes, values, and responses. The measured responses of photographic materials must be maintained between simulation and photographic reality. In order to measure the success towards this goal, not only is a tone reproduction system proposed, but this system is also validated by comparing the results of using the operator with actual photographs.

2. **Utility** - In order to simulate the response of existing materials and systems, the system should only make use of data about these materials and systems that are commonly available.

3. **Generality** - In addition to being able to model existing photographic materials, the system should be general enough to allow for experimentation with all types of photographic parameter settings, even those beyond which are attainable using actual photographic means.

4. **Consistency** - The system should use a parameter set consistent with that utilized in actual photography. This will assure that techniques defined within this space can easily be applied to computer generated imagery.

### 1.4 Outline of Dissertation

In this work, a system for tone reproduction based on photography is developed, described, and tested. Focusing on both the capture and processing areas of the pipeline presented in Figure 1-2, the system will be comprised of a camera model and a model for simulating the photographic development process. These two models are assembled into a complete system that, given a rendered scene, will perform tone production based on parameters familiar in the world of photography, and produce an image suitable for display on a given output device.
The remainder of the thesis is organized as follows. In Chapter 2, we begin by introducing definitions of photographic terms, measurements, and physical units. This is followed by an overview of photographic image formation in Chapter 3. This chapter will address both the details of the photographic development process, as well as introduction to photographic optics.

In Chapter 4, the model for simulating the photographic development is given, followed by a discussion on camera modeling in Chapter 5. The complete tone reproduction system is described in detail in the following chapter, Chapter 6. In Chapter 7, some visual examples of using the system are presented. This is followed, in Chapter 8, by a presentation of the methods used to formally validate the proposed system along with a discussion of the validation results. Finally, future work is discussed and conclusions are presented in Chapter 9.
As with any intellectual discipline, in discussing tone reproduction, it is best to do so using a common vocabulary. The work described in this dissertation is based on the physics of light as they relate to the mechanisms of photography. In this chapter, the basics of light and photography are outlined in terms of the measures and units used in each of these disciplines.

2.1 Light

In this section, units and measurements concerning light are discussed.\(^4\)

2.1.1 Nature of Light

The Random House Concise English dictionary defines light as “electromagnetic radiation to which the organs of vision respond.” Two important distinctions can be derived from this definition. First, light is electromagnetic radiation. Electromagnetic waves carry energy through a continuum of frequencies and wavelengths. The complete electromagnetic spectrum contains waves with wavelengths ranging from \(10^{16}\) nm to \(10^9\) nm.\(^5\) (Figure 2-1)

\(^4\) For a straight-forward and quite readable description of lighting units, see the first chapter of [ASHD94].

\(^5\) A nanometer (nm) is equivalent to \(10^{-9}\) meters.
The second distinction states that light energy is the subset of the electromagnetic spectrum to which the human visual system is sensitive. This range is only a small subset of the entire electromagnetic spectrum ranging from 350nm to 750nm. Humans perceive light at different wavelengths as a continuum of colors in this visual spectrum, ranging from violet (400nm) to blue (450nm) to green (550nm) to yellow (600nm) to red (700 nm).

### 2.1.2 Radiometric Units

**Radiometry** is the science of measuring light in any portion of the electromagnetic spectrum. In this section, the major radiometric units are discussed.

**Radiant energy**, $Q$, is the energy traveling in the electromagnetic light waves. Like all energy, light is measured by its capability to perform work. When light strikes a light meter, the light energy is converted to an electric current that is measured by the meter. Radiant energy is measured in Joules.

**Radiant Flux (Radiant Power)**, $\Phi$, is the time rate of flow of light energy, or energy per unit time. It is defined as $\Phi = \frac{dQ}{dt}$ and expressed in Joules / second or Watts (W).

In discussing radiometric units, it is convenient to think of light traveling in geometric rays. These rays can be thought of as infinitesimal lines through space, which indicate the direction of light energy. When factored into radiometric measurement, these infinitesimal rays are represented as elemental
cones defined by a differential solid angle, \(d\omega\). A solid angle (\(\omega\)) can be measured in terms of the surface area (A) of a sphere that it intersects as \(\omega = A / r^2\) where \(r\) is the radius of the sphere. The units for solid angles are steradians (sr).

Getting back to the discussion of units, **Radiant Intensity**, \(I\), is the radiant flux from a point source of light travelling in a given direction. It is given by \(I = d\Phi / d\omega\) and is expressed in Watts/steradian (W/sr).

**Radiance**, \(L\), is defined as the power per unit area perpendicular to a ray travelling in a given direction. Intuitively, radiance can be thought of as the amount of light arriving at (or leaving) a point from (in) a given direction. A point is defined as a surface with differential area of \(dA\). Radiance is defined as \(L = d^2\Phi / dA \ d\omega \cos \theta\) where \(\theta\) is the angle between the ray direction and the normal vector at the point.\(^6\) It is expressed in W / (m\(^2\) sr).

Finally, **Radiance Flux Density**, is the flux per unit area at a given point. Flux leaving the point is called **Radiant Exitance**, \(M\). Flux arriving at a point is called **Irradiance**, \(E\). Both radiant exitance and irradiance are given by \(d\Phi / dA\) (where \(dA\) is the differential area surrounding the point) and are expressed in W / m\(^2\). Radiance flux density can be calculated by integration of the radiance at a point over all ray directions.\(^7\) Irradiance is particularly relevant in the definition of our tone reproduction system as it represents, at each point, the amount of light energy present on the surface of a piece of photographic film.

It should be noted that each of the quantities mentioned above is generally spectrally dependent; i.e. the quantities may vary as a function of wavelength. In cases where this dependency is to be emphasized, the prefix “spectral” is used before each particular measure (e.g. spectral radiant energy, spectral radiant flux, etc.). In general, the non-spectral units are defined to be the values of the spectral units integrated over all wavelengths in the visible spectrum.

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\(^6\) The cosine term in the definition of radiance is due to the fact that the cross-sectional area of ray onto the differential surface \(dA\) is considered when calculating radiance. This cross-sectional area is given by \(dA \cos \theta\).

\(^7\) In fact, all of the radiometric units can be derived from the radiance. (See [ZIMM98] for details).
2.1.3 Photometric Units

Photometry is the science of measuring visible light in units that consider the sensitivity of the human visual system. Unlike radiometric units, photometric units are intended to reflect the perceived brightness of light rather than just the power distribution of the light energy.

In 1924, the Commission Internationale d’Eclairage (International Commission on Illumination or CIE) performed a series of perceptual experiments with the goal of determining the visual response of a “standard observer” to light under normal viewing conditions. The result of this work was the Photopic Luminous Efficiency Function, $V(\lambda)$, which gives the relative “perceived brightness” of light as a function of wavelength. A graphical representation of this function is given in Figure 2-2.

![Figure 2-2 - Photopic Luminous Efficiency Function (after [WYSZ82]).](image)

The theory behind photometric measurements is no different from that of radiometric theory. The only difference is in their respective units of measurement. The CIE luminous efficiency provides a standard scaling function that can be used to convert radiometric units to photometric units and visa versa. The set of photometric units and these conversions are now discussed below.
Luminous Flux (Luminous Power) is photometrically-weighted spectral radiant flux (power). Its unit of measurement is the lumen (lm) which is defined as 1/683 watts of radiant power at 555 nm.\(^8\) Formally, luminous flux, \(\Phi_v\), is defined as:

\[
\Phi_v = K \int \Phi_{\epsilon, \lambda} V(\lambda) d\lambda
\]

where \(\Phi_{\epsilon, \lambda}\) is the spectral radiant flux at wavelength \(\lambda\) and \(K\) has the value of 683 lm/W.\(^9\)

Luminous intensity is photometrically weighted radiant intensity and gives the amount of luminous flux from a point source traveling in a given direction. Luminous intensity is given in lumens/steradians (lm/sr) which is equivalent to the candella (cd).

Luminance is photometrically weighted spectral radiance. Intuitively, luminance is an approximate measure of the brightness on a surface viewed from a given direction.\(^10\) Its unit of measurement is candella/m\(^2\) (cd/m\(^2\)) which is defined as a nit.

Finally, Luminous Flux Density is photometrically weighted spectral radiant flux density and gives the total amount of luminous flux arriving at or leaving a point from all directions. Illuminance is the photometric equivalent of irradiance and luminous exitance is the photometric equivalent to radiant existence. Luminous flux density is measured in lumens/m\(^2\) (lm/m\(^2\)) which is equivalent to the lux.

2.1.4 Light and Color

Color is the perceptual response of the human visual system to light at various wavelengths. It is important to note that color is a perceptual quality and not a physical one. In the physical world, light is described as having components corresponding to a spectrum of power frequencies. The power spectrum for light is very often given using a Spectral Density Function (SDF), a function that

---

\(^8\) 555nm is the wavelength at which the CIE luminance efficiency is equal to 1. Note that this definition was developed to maintain the values and relationships of existing photometric measurements and theory, which predates the 1924 CIE experiments.

\(^9\) All photometric weightings are assumed to account for this constant \(K\) as well as the values of \(V(\lambda)\).

\(^10\) Luminance used to be termed photometric brightness, however, this term is no longer used since perceived brightness depends on many other variables besides luminance.
relates relative power of energy with wavelengths within the visible spectrum. Figure 2-3 below gives the SDF for a Tungsten Halogen light source.

![Figure 2-3 - Spectral Density Function for Tungsten Halogen Lamp](image)

The human visual system perceives light with a given spectral density function as exhibiting a given color. Our vision system is inherently trichromatic. Our eyes contain receptors that are sensitive to light perceived as red, blue, and green. All other color sensations are achieved by an additive mixture of these three particular sensitivities. Since color sensation is a perceptual matter, it will vary from person to person. This being said, it is often convenient, especially in performing physically based lighting simulations, to specify physical values using a “standard” color definition. In 1931, the CIE went about to create this standard. Similar to the method used in determining the luminous efficiency function, perceptual experiments were performed with the goal of defining a “standard” definition for color. In these color-matching experiments, subjects were shown a monochromatic test light and were asked to mix red, green, and blue light\(^\text{11}\) such that the mixture appeared the same as the light from the monochromatic source. This methodology is illustrated in Figure 2-4.

\(^{11}\) The red, green, and blue lights were monochromatic light sources at 700, 546.1, and 435.8 nm respectively.
The result of these experiments is a set of **RGB color matching functions** (Figure 2-5). These functions provides, for each wavelength in the visible spectrum, the mixing ratios of red, green, and blue light required to produce light that perceptually matched the color of light at that wavelength.\(^\text{12}\)

Using these color matching functions, a spectral density function \(P(\lambda)\), can be converted to a “color” (represented as a triplet of values (R, G, B), one for red, one for blue, and one for green) using the equations:

\(^{12}\) The negative values in the color matching function represents cases where either red, green or blue light had to be added to the monochromatic source being matched.
\[ R = \int_{\lambda=350}^{700} P(\lambda)\bar{r}(\lambda) d\lambda \quad G = \int_{\lambda=350}^{700} P(\lambda)\bar{g}(\lambda) d\lambda \quad B = \int_{\lambda=350}^{700} P(\lambda)\bar{b}(\lambda) d\lambda \] (2-2)

One failing with the RGB color matching functions lies in the fact, for some wavelengths, the matching functions are negative. This can possibly result in negative R, G, and B values for some SDFs, which is undesirable. To remedy this situation, the CIE defined a set of imaginary primaries such that the values of the color matching functions for these primaries were positive for all wavelengths. These color-matching functions, shown in Figure 2-6, create the basis for the CIE XYZ Color Space.

Like with RGB triplets, the XYZ color matching functions provide, on a wavelength-by-wavelength basis, mixing ratios of the X, Y, and Z primaries required to match the sensation of a monochromatic light at a given wavelength. These X, Y, and Z primaries do not exist in the real world, however, they provide a convenient mathematical framework for converting to and from different color spaces. The XYZ color space was designed such that the intensity or brightness response of the human visual system is solely a function of the Y primary. For this reason, the y color matching curve and the Photopic Luminous Efficiency Function, \( V(\lambda) \), are identical.

Given the SDFs of a light source \( P \), it can be converted to a color expressed by an XYZ triplet in a manner similar to converting to RGB triplets. The only difference is the set of color matching functions used. The equations for this conversion are given below:
One of the fundamental concepts in color science is that the color matching functions for all sets of color primaries are simple linear combinations of each other [GIOR98]. Thus, a matrix operation can be used to perform conversions from the color matching functions of one set of primaries to another. More specifically, given an image with pixel values expressed in some RGB color space, these pixel values can be converted to the XYZ color space by a matrix operation. It can be shown that if the RGB primaries of the input color space are expressed in terms of XYZ, then the conversion can be expressed as:

\[
\begin{bmatrix}
    X \\
    Y \\
    Z
\end{bmatrix}
= \begin{bmatrix}
    r_x & g_x & b_x \\
    r_y & g_y & b_y \\
    r_z & g_z & b_z
\end{bmatrix}
\begin{bmatrix}
    R \\
    G \\
    B
\end{bmatrix}
\]

(2-4)

where the RBG primaries are expressed as \((r_x, r_y, r_z)\), \((g_x, g_y, g_z)\), and \((b_x, b_y, b_z)\), respectively [GART90].

The X, Y, and Z primaries are used in the calculation of tri-stimulus ratios called chromaticity coordinates. The chromaticity coordinates, x, y, and z, are used to define color quality separate from its luminance. They are defined as follows:

\[
x = \frac{X}{X + Y + Z} \quad y = \frac{Y}{X + Y + Z} \quad z = \frac{Z}{X + Y + Z}
\]

(2-5)

From this definition, it can be seen that \(x + y + z = 1\). Thus, the chromaticity can be uniquely defined by two of the three coordinates. Traditionally, x and y are chosen for this purpose. A plot of y vs. x is called a chromaticity diagram (Figure 2-7).

13 The inverse conversion from XYZ to RGB can also determined, albeit, in not as straight forward a manner. For a good derivation of this inverse transform, see the Appendix of [GART90].
Points representing the chromaticities of monochromatic light at given wavelengths are found on the horseshoe shaped outline, called the **spectrum locus**. The line connecting the endpoints of the spectrum locus is called the **purple boundary**. The chromaticity coordinates of all physically realizable colors lie in the area bounded by the spectrum locus and the purple boundary.

The gamut of realizable colors using a particular color space with given primaries can be ascertained by plotting the chromaticity coordinates of each of the primaries on the chromaticity diagram, and connecting the endpoints to form a triangle. In Figure 2-8 below, the range for the primaries used in the CIE color-matching experiments is shown. Note that the range of the XYZ color space using the imaginary X, Y, and Z primaries totally encompasses the range of physically realizable colors.
The chromaticity coordinates are defined to convey color information independent of luminance or brightness (which is defined by Y in the XYZ color space). A complete specification of color stimulus is very often given in xyY coordinates, whereby both the chromaticity coordinates and the luminous strength are provided.

### 2.2 Photographic Units

We now turn to the definition of photographic units. In photographic systems, the basic units of measurement are exposure and density.

#### 2.2.1 Exposure

**Exposure** is a measure of the quantity of light striking the surface of a photographic material. Exposure not only considers incoming flux but also considers the amount of time that the flux is incident on the material. Historically, photographic science has used photometric units when describing quantities of light. Formally, exposure is given as the product of the illuminance incident up the surface of the material and the time during which the material is exposed to the light. It is given by the expression:

\[
E = It
\]  

\[(2-6)\]
where \( I \) is the illuminance (expressed in lux) incident of the surface and \( t \) is the amount of time exposed (expressed in seconds). Exposure is expressed in lux-seconds. One can speak of spectral exposure which is the exposure resulting from light energy of a given wavelength:

\[
E_\lambda = I_\lambda t
\]  

(2-7)

Total exposure is the integral of spectral exposure over all wavelengths:

\[
E = \int E_\lambda d\lambda = \int I_\lambda t d\lambda
\]  

(2-8)

2.2.2 Density

Density is a logarithmic measure that describes the opacity of an exposed and developed photographic material. Density comes in two flavors: For transparent materials such as photographic film, slides, and motion picture prints, opacity is measured by transmission density: Transmission density is given by:

\[
D_T = \log_{10} \frac{1}{T} = \log_{10} \frac{1}{(I_t / I_i)}
\]  

(2-9)

where \( T \) is a transmission factor that gives the fraction of light that can pass through the material. This transmission factor is the ratio of the light transmitted by the material \( (I_t) \) to the light incident upon it \( (I_i) \). The higher the density, the more opaque the material and the less light that can pass through it.

For reflective materials such as photographic paper, opacity is described using reflective density. Reflective density is defined similarly to transmission density, except that it is based on the fraction of light that reflects off of the base of the material instead of the fraction of light that goes through the material. Reflective density is given by:

\[
D_R = \log_{10} \frac{1}{R} = \log_{10} \frac{1}{(I_r / I_i)}
\]  

(2-10)
where $R$ is a reflection factor that is defined as the ratio of the light reflected by the material ($I_r$) to the light incident upon it ($I_i$).
3 PHOTOGRAPHIC IMAGE FORMATION

Our system will mimic the process by which photographic prints are created. In this chapter, a brief introduction of this process is given. The chapter will give an overview of the process and discuss the details of photographic materials and processes, including the science of lens optics. The chapter will also serve as an introduction to the vocabulary of photographic science and optic with new terms given in **bold italics**. In order to illustrate the basics of the photographic process, the discussion will focus on black and white print photography.\(^\text{14}\) This discussion follows the lead of photographic science and describes lighting quantities using photometric units.

### 3.1 Photographic Print Formation

Photographic images are produced as the result of light energy striking the surface of light sensitive photographic materials. Print photography (Figure 3-1), is a two-stage process whereby the radiance from a scene is initially captured by a camera and focused onto the plane of photographic film. Once processed, this film produces a negative image where dark areas represent regions of high illuminance on the surface of the film. This negative is then placed into a printer/enlarger, where light is shown through it onto photographic paper. Since more light will be transmitted through the less dense area of the negative (and visa-versa) the printing process acts as a second reversal procedure and re-establishes the relationship of light and dark that exists in the original scene. Once developed, the processed paper results in the final print.

\(^{14}\) Color photography is based upon the same fundamental principles of black and white photography. The difference is in the number of color channels captured by a material. Black and white materials consist of a single layer which records the brightness of a scene. Color materials contain 3 layers, one for capturing the red, green, and blue components of a scene.
The mechanisms of photographic image creation thus depends upon two sets of components: optical systems (camera and enlarger) and photographic materials (film and paper). Below, each of these components is discussed in turn, starting with photographic materials.

### 3.2 Photographic Materials

Photographic materials are light sensitive materials that produce images as a response to the light energy incident upon it. Both film and paper are examples of photographic materials. This sensitivity is based on the chemical interaction of silver halide with light energy to produce metallic silver [JAME77]. Photographic materials consist of microscopic silver halide grains embedded in a gelatin (photographic emulsion). When exposed to light, these grains undergo a chemical change to form an invisible latent image. This latent image is an invisible precursor to the image that will appear upon photographic processing. It is during the development process, that this latent image becomes realized. During this process, the material is placed in a chemical developer which forces the transformation of a fraction of grains adequately exposed to light from silver halide to metallic silver. The set of converted metallic silver grains gives the photographic material its visible density. This conversion from silver halide to metallic silver is binary (i.e. a grain is either silver halide or metallic silver), with the threshold for the change being dependent upon the amount of light received by the grain, the chemical developer used, and the time of processing.
The quality of an image is directly related to the characteristics of the emulsions that make up the material used in creating the image. For over a century, photographic scientists have been concerned with the measurement and study of the response of photographic emulsions to radiant energy. This science, called **sensitometry**, provides empirical measures that can be used to quantify the characteristics of an emulsion [TODD74].

Emulsions are classically characterized in four categories: density response, spectral sensitivity, resolution and graininess [CARR80]. For each category, a well-defined sensitometric measure is used to describe the quality of an emulsion. These measures are described in the sections below.

### 3.2.1 Density Response and the Characteristic Curve

On a macroscopic level, emulsions have a non-linear response to radiant energy. This relationship is customarily illustrated by an emulsion’s **characteristic curve**, a plot that relates input exposure (on a logarithmic scale) to output density. The characteristic curve for a typical emulsion is given in Figure 3-2 below.

![Figure 3-2 - Characteristic curve for a typical emulsion](image)

In determining density response from the characteristic curve, exposure is considered as an absolute and atomic unit. The use of exposure in this manner is sometimes described as the

---

15 The characteristic curve is also known as the D-Log E curve or the H & D Curve (after Hurter and Driffield who introduced its use in 1890).
**reciprocity law.** As defined by Todd [TODD74]: “The image formed by a radiation sensitive process is dependent only on \( E \) [exposure], not on the \( I \) [illuminance] and \( t \) [time] components of the exposure”. This law holds true for most photographic situations. However, being a chemical process, the response of photographic materials does have its practical limits. There is a minimum amount of light required to be incident on the surface before any chemical reaction can occur. These limits may cause inaccuracies in the characteristic curve, especially for very low values of illuminance or time. This breakdown is known as the **reciprocity law failure** and must be considered when trying to capture low luminance scenes (as in the case of astronomical photography).\(^{16}\)

An emulsion has a finite density scale, which is the difference between the maximum and minimum density response (also known as **fog**).

A characteristic curve can be divided into four sections. In the **toe**, the curve begins at the fog density and indicates the first significant response to exposure. As we move along the exposure scale, we reach the **straight-line portion** where the logarithmic response to exposure becomes linear. This response starts to level off toward \( D_{\text{max}} \) in the **shoulder** region. In some emulsions, there is a **region of solarization** where an increase of exposure will actually result in a decrease of measured density.

The gradient of the characteristic curve in its straight-line section is an important indication of the contrast of an emulsion as it defines the change in density due to a given change in log exposure. This measure, termed **gamma**, is analogous to gain measures in other display systems and acts as a gauge for the contrast range of an emulsion. It is important to note that although gamma measures the slope of the curve in its linear portion, it really describes the non-linearity of an emulsion’s response as the characteristic curve is plotted on a log-log scale [POYN96]. Recall that density is already a logarithmic measure.

The sensitivity of an emulsion is indicated by its speed. A higher speed emulsion is more sensitive to low levels of light than a lower speed emulsion. Speed is defined as

\[
SP = \frac{K}{E_m}
\]

\(^{16}\) Thankfully, for most computer generated scenes, reciprocity law failure is not an issue.
where $K$ is a constant and $E_m$ represents the exposure necessary to produce a density of $m$ units above the fog density. Current standards for the speed of photographic materials define $K = 0.8$ and $m = 0.1$ for photographic films [ANSI79], and $K = 1000$ and $m = 0.6$ and for photographic papers [ANSI93a].

The density response of a processed emulsion depends not only on the nature of the emulsion, but also on development conditions (i.e. developer solution, temperature, time of development). Consequently, the shape and positioning of a characteristic curve, and thus its gamma, speed, density scale, and fog, will vary based on these conditions. Generally, a family of characteristic curves, as shown in Figure 3-3, is specified for a given film/developer combination. Each curve in the collection indicates the response of the emulsion when processed for a given amount of time.

![Figure 3-3 - Family of characteristic curves (after [NELS77])](image)

### 3.2.2 Spectral Sensitivity

Untreated, silver halide grains are only sensitive to the blue and ultraviolet wavelengths of the spectrum. Specially formulated dyes that extend the responses of the grains to longer wavelengths are introduced into emulsions in order to increase the spectral sensitivity to include the rest of the visible spectrum.

Spectral sensitivity, being a measure of sensitivity, is formally defined in the same manner as the speed of an emulsion. This sensitivity, however, is expressed as a function of wavelength, which indicates an emulsion's sensitivity to different portions of the visible spectrum:
\[ S_D(\lambda) = 1 / E_D(\lambda) \]  \hspace{1cm} (3-2)

\( E_D \) is the exposure (in radiometric units) necessary to produce a pre-selected reference density \( D \) at each wavelength \( \lambda \). The plot of this function for a given reference density is known as the \textbf{spectral sensitivity curve}. Figure 3-4 shows a series of spectral sensitivity curves for a variety of reference densities.

By definition, the spectral sensitivity of an emulsion can be measured by generating a family of characteristic curves, one curve for each wavelength of interest, and calculating the speed point directly from these curves.\(^{17}\) The fact that an emulsion has different characteristic curves for different wavelength is particularly significant when dealing with photographic papers. The level of contrast in these characteristic curves can change significantly with spectral distribution of the light source used during printing. Standard filters are often used in the darkroom to raise or lower the contrast of a print [VEST84]. In many cases, paper manufacturers will provide a family of characteristic curves

\[^{17}\text{To cover the entire visible spectrum in 10 nm increments, a total of 31 separate characteristic curves would need to be generated. In practice, the determination of spectral sensitivity is made by generating this large number of characteristic curves. [ATLM77]}\]
based on these standard filters. An example of such a family of curves is illustrated in Figure 3-5. The label on each curve indicates the standard filter that should be used during printing to obtain a particular response.

![Figure 3-5 - Family of characteristic curves for paper considering spectral filters](image)

An alternative and more useful method of specifying spectral sensitivity is by a spectral response curve (or wedge spectrograph). These curves provide a measure of relative sensitivity to light based on wavelength. Figure 3-6 shows the spectral response curves for three film types with different spectral sensitivities: panchromatic (sensitive to entire visible spectrum), orthochromatic (sensitive to green and blue light), and blue-sensitive (untreated).
3.2.3 Resolution and the Modulation Transfer Function

3.2.3.1 Modulation Transfer Function

The resolution of an emulsion defines its ability to clearly reproduce the spatial detail of an image. Internal scattering of light between the grains within an emulsion causes a degradation of the recorded image. As illustrated in figure 3-7, a point source ray of light incident to a film’s surface, rather than producing a single transmitted ray, will instead produce a distribution of light. This distribution, termed the point spread function (PSF), is instrumental in determining the resolution of an emulsion. Assuming the film to be isotropic, the point spread function is rotationally invariant.

Figure 3-6 - Spectral Response Curves for three types of films (after [NELS77])

Figure 3-7 - Point Spread Function
The line spread function, $A(x)$, which is defined by:

$$A(x) = \int_{-\infty}^{\infty} PSF(x, y)dy$$

(3-3)

gives the scattering response to an infinitesimal line of light. This function can be determined by measuring the response to a knife-edge exposure. Since most films can be considered isotropic, this function serves as a primary means for obtaining the PSF of an emulsion.

Although the macroscopic response of an emulsion is non-linear (as is evident by the characteristic curve), the internal scattering of light due to the microscopic grains can be modeled as a linear system. This response can be simulated by performing a convolution of the input image with the point spread function [DAIN74]. In the frequency domain, the effect of the scattering is given by the modulation transfer function (MTF ($\omega$)) which is the Fourier transform of the line spread function (Figure 3-8). The MTF can be determined directly from the line spread function, measured using the response of a sinusoidal exposure input, or calculated mathematically using Monte Carlo methods. [DEPA72].

The structure of a photographic emulsion can be greatly affected by the chemical interactions that occur during development. These interactions usually occur near image edges as the result of development chemicals being able to escape from an area where a great deal of development is taking place to an area where no development is taking place. These effects, called adjacency effects or edge effects, influence the spatial acuity of an emulsion and as such, its MTF.
The discussion on MTFs is applicable not only to photographic emulsions, but generally to any optical system. One advantage of using MTFs is that the spatial response of a system consisting of several components can be described by a single MTF, which is simply the product of the MTFs for individual components. This process, known as cascading, is particularly useful when discussing photographic systems. A final photographic image will be affected by the responses of a number of optical materials, including the film and paper emulsions, as well as the lens of the camera and printing systems.\(^\text{18}\)

### 3.2.3.2 Resolving Power

A numerical measure for an emulsion's resolution is its **resolving power**. This measure, expressed in cycles/mm, is an estimate of the finest detail that can visibly be observed on the photographic material. By definition [ANSI93b], resolving power is determined by visual inspection. Thus, it is a measure of not only the frequency response of a material, but rather of the entire photographic system used in formulating an image on a material. (This system will include other optical components such as the camera and the enlarger).

\(^\text{18}\) In theory, cascading can only be applied when the systems being combined are linear systems. Fortunately, it has been shown, theoretically and experimentally, that cascading can be utilized in photographic analysis without introducing much error, despite the non-linearities of the photographic process [LAMB61].
3.2.4 Graininess

3.2.4.1 Selwyn Granularity

Graininess is the visual perception of the non-uniformity of a processed emulsion due to the random placements of the grains within it. Since grains in an emulsion are microscopic in nature, graininess for most emulsions is observable only upon magnification. The graininess becomes more apparent as the magnification of an exposed emulsion is increased.

The objective measure of graininess is called granularity and can be determined by examining the microstructure of an emulsion. Using the traces obtained by a microdensitometer, fluctuations in density of a uniformly exposed emulsion can be measured and recorded. These measurements can be used to statistically model the grains within an emulsion and provide a measure for the granularity.

The root mean square (rms) deviation provides an indication of the uniformity of a sample. It is obtained by computing the differences in density from a mean over an entire photographic sample. Assuming N independent sample points in a trace, the rms is calculated as:

$$\sigma^2 = \frac{1}{N} \sum_{i=1}^{N} (\Delta D_i)^2$$  \hspace{1cm} (3-4)

where $\Delta D_i$ is the deviation from the density mean of the ith sample point.

Analysis of microdensitometer traces of many films has indicated that the density fluctuations of processed emulsions tend to follow a Gaussian distribution [ALTM77], although the above definitions hold for any probability distribution assumed.

Although the rms is a natural choice for a measure of granularity, it is ineffective as an absolute measure as its value depends upon the area of the aperture used in making the measurement. The relationship between granularity and scanning area has been investigated using empirical models where developed grains are represented using circular disks [DAIN74]. This simple model leads to the Siedentopf formula:

$$\sigma^2 = 0.434D \cdot \frac{\alpha}{f}$$  \hspace{1cm} (3-5)
In this expression, $D$ represents the density of the sample, $f$ is the area of the measuring aperture and $a$ is the cross sectional area of the developed grains that contribute to the sample density. This expression holds only if the area of the measuring aperture is much greater than the mean grain area and if individual grains are considered statistically independent. These conditions are met for black and white films, and apertures greater than $10\mu m$ in diameter [KELL93].

From equation 3-5, it can be shown that for a given density, the product of the scanning aperture and the rms is a constant. This was first observed by Selwyn[SELW35] who developed a measure for granularity, based on this observation. This measure, known as the Selwyn granularity, is given by:

$$G = \sqrt{2A}\sigma$$

(3-6)

where $A$ is the area of the scanning aperture and $\sigma$ the square root of the rms density fluctuation.

This measure was historically preferred, as it did not vary with scanning aperture. 19

Indicative from equation 3-5, granularity, and therefore graininess, is also dependent on the density level of a sample. Experiments have shown granularity, for black and white materials, to be approximately proportional to the cube root of the density [HAUG63].

3.2.4.2 Print Through Granularity

For photographic prints, the contribution of paper grain to print granularity is very small relative to the contribution of the negative grain. Because of this, granularity values are very rarely reported for photographic papers. Print graininess does vary, however, based on parameters of the printing system and the paper used. This relationship between print granularity, negative granularity and printing parameters was originally explored by Doerner[DOER62] and later simplified by Einhaus[EINH90], and can be expressed by:

$$\sigma_{PT} = \sigma_N \cdot \frac{A_N}{A_p} \cdot M \cdot MTF_p (1) \cdot MTF_{PR} (1) \cdot \gamma_p$$

(3-7)

Modern color materials do not satisfy the assumptions leading to the Selwyn Granularity definition. Thus, currently, the Selwyn Granularity is very rarely reported on data sheets. Instead, rms values are given in conjunction with the scanning aperture used. The scanning aperture has been standardized at a diameter of $48 \mu m$ with a 12x enlargement, based on the optical properties of the human visual system. The Selwyn Granularity measure, however, still remains a useful measure for our simulations.
Here, $\sigma_{pt}$ is the print-through rms granularity, $\sigma_N$ is the rms granularity of the negative, $A_N$ and $A_P$ are the diameters of the scanning aperture used to measure the rms values for the negative and the print respectively, $M$ is the magnification factor, $\text{MTF}_P(1)$ and $\text{MTF}_{Pr}(1)$ are the values of the modulation transfer function of the paper and the enlarger at 1 cycle/mm and $\gamma_p$ is the gamma of the paper characteristic curve.

3.3 Optical Systems
The purpose of optical systems in the photographic chain is to focus light onto the surface of the photographic material. Photography makes use of a point perspective projection to project light from a 3D scene onto a 2D surface. The center of projection, as shown in Figure 3-9 is at the opening where light from the scene is allowed to enter.

![Figure 3-9 - Pinhole camera](image)

Figure 3-9 illustrates a classic pinhole camera, where the size of the lens opening is infinitely small. In reality, optical systems like cameras and enlargers make use of a lens, or a system of lenses to focus light energy. Lenses operate by the principles of geometrical optics and focus light on the basis of the geometrical relations between the paths of light rays entering and leaving the lens. The effect of lenses can be divided into two areas: geometric effects, which address the modification of the direction of a light ray due to the optical characteristics of a lens, and radiometric effects, which describe how a lens affects the measured quantity of the light passing through it.
3.3.1 Geometric Effects

3.3.1.1 Refraction

Lenses bend light based on the principle of refraction. When a light ray strikes the boundary between two transparent media (like air and glass), the direction of the ray is abruptly changed. The amount of bending is given by Snell's Law:

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]  

(3-8)

Where \( n_1 \) and \( n_2 \) are indices of refraction of the two media and \( \theta_1 \) and \( \theta_2 \) are the angles of incidence between the light ray and the normal to a surface at the point of the bending (Figure 3-10).

The bending capabilities of a lens can thus be controlled by modifying the amount of refraction performed on light by the lens. Considering Snell's Law, this can be achieved by either: (a) modifying the material from which the lens is made (and as such, changing the index of refraction), or (b) changing the shape of the lens (thus changing the surface normal at which the refraction occurs).

3.3.1.2 The lens equation

The fundamental properties of lens optics are based on the refractive properties of lenses. The simplest of these properties can be illustrated by use of the thin lens approximation which assumes a lens with circular symmetry, a finite opening (or aperture) and negligible thickness. Since thickness is considered negligible, light passing through the lens is refracted only in a single plane, the principle
plane. As illustrated in Figure 3-11 below, light coming from an object $O$ in front of a lens is focused in a single point $O'$ behind the lens.

![Figure 3-11 - Light passing through a simple lens](image)

When an object is at a far distance, the rays emitted from the object are essentially parallel to the optical axis (figure 3-12).

![Figure 3-12 - Image formation by a simple lens. (a) lens focused at infinity; (b) object at a finite distance from lens (from [JACO88])](image)
In this situation (also known as focussing at infinity), the plane behind the lens at which these rays are focused is known as the principle focal plane $F'$. For a flat distant object and an “ideal” lens, every point in the image will be focussed on to this plane. The distance on the optical axis between this plane point and the principle plane is known as the focal length ($F$) of the lens. Only for objects at infinity, will the image distance $v$ from the lens to the focal plane be equal to the focal length. For objects closer than infinity, the relationship between the distance of the object from the principle plane ($u$), and the distance from the principle plane to the plane at which the object will be in perfect focus ($v$), is given by the lens conjugate equation (or simply lens equation):

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{F}$$  \hspace{1cm} (3-9)

Note, true to the definition of focal length, that $v$ goes to infinity, the $\frac{1}{v}$ term will tend towards zero, and the distance $u$ from the principle plane to the focus plane is simply the focal length.

3.3.1.3 Focus and Depth of Field

Cameras and enlargers allow one to focus on a particular object by providing variable control of the positioning of the principle plane of the lens. This allows for modification of the length ($v$) between the principle plane and the surface of the photographic material. When this distance coincides with the corresponding distance ($u$) from the lens to the object (as defined by the lens equation), the object will appear in focus on the film plane. When the distance between the film plane and the lens is not equal to the value of $v$, as calculated by the lens equation, light from points on the object will, instead, result in a circle of light on the film surface (Figure 3-13).
This circle, termed the **circle of confusion**, will result in the object seeming out of focus. The larger the circle of confusion, the more out of focus an object will appear. Theoretically, an object is in focus only when the circle of confusion converges to a point. The human visual system is more forgiving and will perceive an object to be in perfect focus when radius of the circle of confusion is within a given range.\(^{20}\) For a given image distance, \(v\), the range of distances, \(u\), at which objects will be focussed with adequate sharpness is called the **depth of field**.\(^{21}\) Control of the depth of field is used extensively in photography, especially in creatively distinguishing foreground objects from background object in photographed scenes.

### 3.3.2 Radiometric Effects

The radiometry of a lens system describes the relationship between luminance emitted from a scene and image forming illuminance that is focused by the lens upon the surface of a photographic material. This relationship was initially investigated by Jones and Conduit in 1941[JONE41]. In this work, a mathematical expression for describing this relationship is derived. Despite being published over 50 years ago, the equation published in this paper is still the primary means for calculating exposure from scene luminance. In this section, the various factors contributing to the final calculation are discussed individually. The complete equation is given at the end of the section.

\(^{20}\) In [POTS81], it is suggested that this range is \(U/1000\) where \(U\) is the viewing distance of the final image.

\(^{21}\) It is important to note that depth of field is defined as a perceptual measure rather than a physical one.
3.3.2.1 Aperture

The amount of light passing through a lens obviously depends greatly upon the size of its opening, or the aperture. The level of illuminance, however, will also depend upon the focal length of a lens, since more illuminance will be detected when the film plane is closer to the principle axis of the lens. Accounting for this fact, a lens aperture is usually specified by the ratio of its focal length to its diameter. This measurement, termed the F-number (or f-stop), describes the light collecting power of a lens. F-numbers are usually denoted in the form f/F. For example, a lens with a focal length of 50mm and an opening with a diameter of 25mm would be marked as f/2, indicating that the focal length is twice as large as the opening. The ratio of the focal length to the F-number is known as the relative aperture, and is simply the reciprocal of the F-number.

Lenses on most professional cameras and enlargers provide for a variable aperture, allowing the photographer to set the F-number of the lens system. Generally, the aperture control on such lenses is maintained using a discrete scale, where a single increase on the scale (also known as a stop) corresponds to a doubling of the amount of light transmitted through the lens. As will be illustrated in the following section, the illuminance at a point on the film surface is inversely proportional to the square of the F-number of the aperture through which the light travels. Thus, an aperture increase of one stop (resulting in a doubling of the illuminance) is equivalent to an increase of $\sqrt{2}$ in the F-number. A list of standard F-numbers with relative diameters and opening areas is given in Table 3-1.

---

22 This kind of scaling makes control of exposure convenient as it makes both the doubling the exposure time or opening the aperture 1 stop equivalent, in theory, to doubling the exposure.

23 Note that most lenses will not allow settings for the full range of F-stops in this table. In addition, many lenses provide even finer control, usually subdividing the scale into 1/3 stops.
### Table 3-1 - F-Numbers with relative diameters and areas

<table>
<thead>
<tr>
<th>F-Number</th>
<th>Relative Diameter</th>
<th>Relative area</th>
</tr>
</thead>
<tbody>
<tr>
<td>f/45</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>f/32</td>
<td>1.4</td>
<td>2</td>
</tr>
<tr>
<td>f/22</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>f/16</td>
<td>2.8</td>
<td>8</td>
</tr>
<tr>
<td>f/11</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>f/8</td>
<td>5.6</td>
<td>32</td>
</tr>
<tr>
<td>f/5.6</td>
<td>8</td>
<td>64</td>
</tr>
<tr>
<td>f/4</td>
<td>11.3</td>
<td>128</td>
</tr>
<tr>
<td>f/2.8</td>
<td>16</td>
<td>256</td>
</tr>
<tr>
<td>f/2</td>
<td>22.6</td>
<td>512</td>
</tr>
<tr>
<td>f/1.4</td>
<td>32</td>
<td>1024</td>
</tr>
<tr>
<td>f/1</td>
<td>45.3</td>
<td>2048</td>
</tr>
</tbody>
</table>

#### 3.3.2.2 Basic radiometry

Given the focal length and size of the aperture opening, we can now derive a basic expression for the light energy going through the lens and onto a photographic surface.\(^{24}\) In order to compute the illuminance \(E\) at a given point \(x\) on the surface of a photographic material, we need to integrate the radian at \(x\) over a solid angle subtended by the lens area (Figure 3-14).

![Figure 3-14 - Calculation of irradiance from lens geometry (from [KOLB95])](image)

Recalling the definition of radian and solid angle, and letting \(L(x, x')\) be the radian present at \(x'\) towards \(x\), this can be expressed as:

\(^{24}\) There are several different derivations for this expression. In this discussion, we follow the derivation presented in [KOLB95]. Another good derivation that only considers simple geometry is presented in Chapter 5 of [JACO90].
\[ E(x) = \int_{x \in D} L(x', x) \frac{\cos \theta \cos \theta'}{\|x' - x\|^2} dA' \]  

(3-10)

If the photo material is parallel to the lens opening, then by similar triangles, \( \theta \) will be equal to \( \theta' \) and the distance from \( x \) to \( x' \) will be constant for all \( x' \) (equal to \( Z \cos \theta \) where \( Z \) is the axial distance from \( x \) to \( x' \)). The expression can then be simplified as:

\[ E(x) = \frac{1}{Z^2} \int_{x \in D} L(x, x') \cos^4 \theta dA' \]  

(3-11)

Assuming the exit pupil subtends a small solid angle from \( x \), \( \theta \) can be considered constant and set equal to the angle between \( x \) and the center of the lens area. The expression now further simplifies to:

\[ E(x) = L \frac{A}{Z^2} \cos^4 \theta \]  

(3-12)

If the lens is focused upon an object at distance \( u \) from the lens, we must replace \( Z \) with the distance from the lens \( v \), at which the object is in greatest focus. Recalling that the F-number of the lens (\( f \)) is the ratio of the focal length (\( F \)) to the lens diameter (\( D \)), we arrive at the final expression:

\[ E(x) = L \frac{\pi \left( \frac{D}{2} \right)^2}{v^2} \cos^4 \theta = L \frac{\pi}{4} \frac{F^2}{v^2 f^2} \cos^4 \theta \]  

(3-13)

Note that when the lens is focused on an object at infinity, \( v = F \) and the expression becomes:

\[ E(x) = L \frac{\pi}{4} \frac{\cos^4 \theta}{f^2} \]  

(3-14)
3.3.2.3 Correction for objects at finite distance.

In the final expression above, we assumed that the camera in question is focussed on an object at infinity. Objects, on the average, are not at infinity; thus, a correction is necessary to account for finite object distances. From the lens equation (Equation 3-7) it can be shown that for an object at a finite distance \( u \),

\[
\frac{F}{v} = \left( \frac{u - F}{u} \right) \tag{3-15}
\]

and,

\[
E(x) = L \frac{\pi}{4} \frac{F^2}{v^2 f^2} \cos^4 \theta = L \frac{\pi}{4} \left( \frac{u - F}{u} \right)^2 \frac{\cos^4 \theta}{f^2} \tag{3-16}
\]

Thus, the expression \( \left( \frac{u - F}{u} \right)^2 \) can be seen as a correction factor in the case where a lens is focussed at a finite distance. Note that as \( u \) goes to infinity, this expression will converge to 1.25

3.3.2.4 Vignetting

In most photographic lens systems, the design of the lens barrel and the lens mount may be such that some oblique rays are cut off (Figure 3-15). Consequently, the image plane will receive progressively less light as the angle from the primary lens axis increases. This effect, which is known as vignetting (or mechanical vignetting) can be significant in wide-angle lenses or when using a lens at full aperture.

---

25 This correction factor is very often given in the mathematically equivalent form of \( 1 / (M + 1)^2 \) where \( M \) is a magnification factor. The use of this form is more convenient when calculating the effect of lenses in the printing process.
Mechanical vignetting effects should not be confused with the natural falloff of light due to the geometry of image formation (which is sometime known as natural vignetting). This falloff, expressed by what is known as the Cos$^4$ Law, states that, irrespective of any vignetting, the illuminance on the surface of a film will diminish by a factor of $\cos^4 \theta$, where $\theta$ is the angle between a ray at the center of the lens perpendicular to the primary plane, and a ray from the center of the lens to a given point on the surface.

This natural falloff is accounted for in the exposure equation, as shown in the derivation presented in Section 3.3.2.2.

3.3.2.5 Lens Transmittance
Most optical systems in photography, rather than using a single lens, make use of a system of lenses with several individual lens elements. At each air glass boundary, light is lost due to the reflection of light at the surface as well as absorption of light by an individual element. The transmittance of a lens system is the fraction of incident light that is transmitted through the receiving end of the system. Based on classical optical physics originally derived by Fresnel, the transmittance can be expressed as:

$$
\tau = \left[ 1 - \frac{(n-1)^2}{(n+1)^2} \right]^k (1-a)^l
$$

(3-17)
where $n$ is the index of refraction of the lens material, $k$ is the number of air/glass boundaries in the lens system, $a$ is the absorptance per unit thickness and $t$ is the thickness of a given element in the lens system. Because the absorption of optical glass used in the manufacture of photographic lenses is on the order of 1% per centimeter, light lost due to absorption can be considered negligible [GREE50] simplifying the expression for transmittance to:

$$\tau = \left[1 - \frac{(n-1)^2}{(n+1)^2}\right]^k$$

(3-18)

Because of the transmittance factor, lenses with identical F-numbers will have significantly different light passing abilities. For example, when comparing a four-element f/2.8 lens with 14-element f/2.8 zoom lens, it is not uncommon for the zoom lens to allow a third of a stop less light than the simpler lens. [GOLD92]. Because of this, a photometrically determined value called the T-stop or T-number was introduced.\(^{26}\) This new measure is defined as:

$$T\text{-}Number = \frac{F\text{-}Number}{\sqrt{\tau}}$$

(3-19)

Thus, an f/2.8 lens with a transmittance of 0.85 would have a T-number of T/3.0. For the ideal lens system (with transmittance of 1.0), the T-number and F-Number are identical.

3.3.2.6 Flare

In addition to the light entering a lens from a scene or given source, extra non-image forming light originating from the lens system may contribute to the total illuminance that falls on the photographic material. This additional light, known as flare, is primarily due to inter-reflections of light as it travels between individual lens elements. Additional flare can result from flaws in the glass, scratches, dirt, fingerprints or reflections off the lens mount and shutter blades.

Since flare has a greater effect on the shadow tones than on highlights, its introduction results in a reduction of the contrast of an image. This is evident in the curve shown in Figure 3-16. This is an

\(^{26}\) This new metric was introduced by the motion picture industry to allow for consistency amongst film clips shot from different cameras.
example of a **flare curve**, where the luminance in front of a lens system is plotted against the luminance detected behind it on a log-log scale.

For a flare free lens system, the data in this graph would form a straight line with a slope of 1. Instead, as the curve shows, the flare greatly affects areas of low luminance in the scene, but has little contribution to areas of high luminance.

Flare is a difficult factor to model as it not only depends upon the camera and lens system used, but also on the type of scene being captured. In their classic study of scene brightness and photographic exposure [JONE41], Jones and Conduit photographed several outdoor scenes to experimentally determine the effect of flare on photographic images. In this study, they found that the ratio of the luminance scale of the scene and the luminance scale of the images varies between 1.15 and 9.50 depending on the individual scene. The average value for this ratio (known as the **flare factor**) was determined to be 4.0.\(^{27}\)

---

\(^{27}\) At the time of the study, the average value of the flare factor as 4.0 was standardized by both the British and American standards bodies. Since then, thanks to improved camera and lens designs, an average flare factor of 2.5 has been adopted. [DUNN74].
3.3.2.7 Shutter Efficiency

Exposure is defined as the product of the illuminance and the time of exposure. In the case of a camera, the time of exposure is controlled by use of a shutter that opens and closes thus allowing or disallowing light to enter through the aperture. Ideally, the opening and closing of a camera shutter would be instantaneous. In practice, since a shutter is a mechanical device, the movement of the shutter does take a finite amount of time. Measuring the amount of light transmitted through a lens during the operation of the shutter, the measured light will increase gradually as the shutter opens, remain constant during the time in which the shutter is fully opened, then decrease gradually as the shutter is closed. A graphical representation of this situation is given in Figure 3-17 below.

![Figure 3-17 - Shutter efficiency for fully opened shutter](image)

Shutter efficiency ($\eta$) is defined as the ratio of a shutter’s actual performance with the performance of an ideal shutter that opens and closes instantaneously. This measure represents the fraction of light that is transmitted by the actual shutter when compared to the light that would be transmitted by a perfect shutter. Approximating the shutter operation by a trapezoid (as in Figure 3-17), the shutter efficiency can be computed by considering the areas under the curves representing exposure through the shutter. This can be mathematically expressed as:

$$\eta = \frac{h \cdot (0.5t_1 + t_2 + 0.5t_3)}{ht} = \frac{0.5t_1 + t_2 + 0.5t_3}{t}$$

(3-20)

where $t_1$ is the time that the shutter takes to open, $t_2$ is the time during which the shutter is fully opened, $t_3$ is the time that the shutter is closing, and $t = t_1 + t_2 + t_3$ is the total exposure time.
For longer exposure times, the time that a shutter is in motion becomes negligible with respect to the total exposure time. For shorter exposure times, however, the time a shutter takes to open and close can be a significant fraction of the marked exposure time. Note also, as illustrated in Figure 3-18, that as the size of the aperture decreases, the amount of time the shutter is in motion also decreases. As a result, $t_1$ and $t_3$ will be shorter with respect to $t_2$ and the efficiency will increase.

![Figure 3-18 - Shutter efficiency for half opened shutter](image)

3.3.2.8 Mathematical Expression

Finally, accounting for all of the factors listed above, the relationship between scene luminance and film or paper illuminance can be mathematically expressed as:

$$I = \frac{L \cdot \pi \cdot \left(\frac{u - F}{u}\right)^2 \cdot \cos^4 \theta \cdot V(\theta) \cdot \tau}{4f^2} + I_{flare}$$

(3-21)

where:

$I = \text{illuminance incident on the surface of the photographic material (in lux)}$

$L = \text{scene luminance as measured at the principle plane of the lens system (in cd/m}^2\text{)}$

$\theta = \text{angle from a point on the surface of photographic material to the center point of the lens}$

$V = \text{lens barrel vignetting factor}$

$\tau = \text{lens transmittance factor}$
\[ I_{\text{flare}} = \text{Illuminance resultant from flare} \]

\[ f = \text{lens aperture (f-number)} \]

\[ u = \text{subject to lens distance (in mm).} \]

\[ F = \text{focal length (in mm)} \]

If the \( T \)-number (\( T \)) of the lens is known, the transmittance is accounted for, and the expression becomes:

\[
I = \frac{L \cdot \pi \cdot \left( \frac{u - F}{u} \right)^2 \cdot \cos^4 \theta \cdot V(\theta)}{4T^2} + I_{\text{flare}} \quad (3-22)
\]

Exposure (\( E \)) is calculated by multiplying the illuminance (\( I \)) by the time (\( t \)) of exposure. In the case of a camera, shutter efficiency (\( \eta \)) must be accounted for. Thus, our final expression for exposure is:

\[
E = I\eta t \quad (3-23)
\]

For printing systems that do not utilize shutters, we can assume \( \eta \) to be equal to 1.0.

3.3.3 Optical Transfer Function

Similar to photographic emulsions, light transmitted through a lens system will be spatially degraded because of the light’s interaction with the lens. Thus, a point source ray of light, incident to a lens, will produce a distribution of light as opposed to a single transmitted ray. For lenses, this distribution is a result of the diffraction of light and can be determined mathematically based on optical physics. Since diffraction is dependent upon the wavelength of light, so too, is the point spread function of a lens. This point spread function takes the form of a series of concentric rings of increasing radii and decreasing brightness. (Figure 3-19).
This pattern, known as the **Airy disk** [PROU97], is a function of the wavelength of light and the size of the aperture opening. For an ideal, aberration free lens, the radii of each of the rings in the pattern are given by the expression:

\[ R = K\lambda f \]  

Where \( \lambda \) is the wavelength of light, \( f \) is the F-number of the lens and values of \( K \) are given in Table 3-2 below.

<table>
<thead>
<tr>
<th>Ring</th>
<th>K</th>
<th>Relative Peak Illumination</th>
<th>Amount of Light in Ring (%)</th>
<th>Light remaining Outside of Ring (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center</td>
<td>0</td>
<td>1.00000</td>
<td>83.9</td>
<td></td>
</tr>
<tr>
<td>First Dark</td>
<td>1.22</td>
<td>16.1</td>
<td>7.1</td>
<td>9.0</td>
</tr>
<tr>
<td>First Bright</td>
<td>1.64</td>
<td>0.01745</td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>Second dark</td>
<td>2.23</td>
<td>0.00415</td>
<td>5.7</td>
<td>9.0</td>
</tr>
<tr>
<td>Second bright</td>
<td>2.68</td>
<td>0.00165</td>
<td>5.2</td>
<td></td>
</tr>
<tr>
<td>Third Dark</td>
<td>3.24</td>
<td>0.00078</td>
<td>4.7</td>
<td></td>
</tr>
<tr>
<td>Third Bright</td>
<td>3.69</td>
<td>0.00016</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>Fourth Dark</td>
<td>4.24</td>
<td>0.00007</td>
<td>3.7</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-2 - Radii and illumination of rings of Airy Disk (from [PROU97])
The spatial response of lenses can also be expressed using a modulation transfer function. For lenses, the MTF is often referred to as the **Optical Transfer Function (OTF)**. Based on the point spread function defined by the Airy disk, the OTF for a lens can be expressed by the equation\(^{28}\):

\[
OTF(\omega) = \frac{1}{\pi} \left[ \cos^{-1} \left( \frac{\omega}{\omega_0} \right) - \left( \frac{\omega}{\omega_0} \right) \sqrt{1 - \left( \frac{\omega}{\omega_0} \right)^2} \right]
\]  

(3-25)

where \(\omega_0 = 1/\lambda f\).

A family of OTFs for lenses with varying aperture openings is illustrated in Figure 3-20 below. In these graphs, the wavelength is held constant at 550nm.

Since the Airy disk varies with wavelength, as evident in equation 3-22 above, so too does the MTF. In Figure 3-21 below, the OTFs for a lens with constant aperture are given for red, green, and blue light.

\(^{28}\) This result is presented in Chapter 17 of [PROU97]. A complex and complete derivation can be found in [BORN65].
3.4 Photographic Choices in Print Photography

Working within the photographic process, a photographer has a number of choices that need to be made. Note that the amount of control employed by a particular individual in making these choices can vary widely depending on the intention and expertise of the photographer. For example, on one end of the spectrum is a photographic artist (like Ansel Adams) who requires complete control of the entire process from capture to processing to printing. The photographic artist generally utilizes a variety of cameras and lenses, experiments with different films and papers, and uses his or her own darkroom to process and print the final image. At the other end is the casual picture taker who may capture a scene using a single use, point and shoot camera and has their processing done by their local photofinisher.

Whether choices are made by the photographer or automatically determined by a well defined process, there are a number of photographic parameters that will need to be determined before a print can be realized. The parameters can be separated into two categories based on two processes illustrated in Figure 3-1, namely capture and printing. Within each of these processes, choices can be categorized into the following classes:
1. Characteristics of the optical system – These include the choice of camera or enlarger and the characteristics of the lens system employed by the chosen optical device.

2. Choice of Photographic Material – Simply put, what film or paper is to be used.

3. Exposure parameters – Including aperture setting and specification of exposure time.

4. Development parameters – Including choices made during processing, such as choice of chemicals, temperature, and processing time.
At the heart of our tone reproduction system is the accurate simulation of the response of photographic materials. In this chapter, a model for performing this simulation is presented\textsuperscript{29}.

### 4.1 Photographic Modeling

At the lowest and most abstract level, the recording of any spatial image can be modeled simply by the response of a collection of photon receptors to packets of light energy. Using this approach, imaging can be described without regard to the underlying technology, electronics, or chemistry of the actual recording receptors. This approach to image modeling, known as the study of Detective Quantum Efficiency (DQE), is the basis of the model described by Dainty and Shaw in their 1974 text [DAIN74]. Photographic image formation is described as a specialization of this general model whereby the recording receptors are silver halide grains and the receptor responses are based in the underlying chemistry of photographic processing. At this low level, photographic image formation can be modeled by considering the size and distribution of grains within the emulsion. From an academic standpoint, the DQE approach is attractive as it derives the basics characteristics of photographic materials, presented separately in Chapter 3, from a single underlying model.

Despite the completeness of the DQE approach, it is inappropriate for our purposes since the low-level data upon which this model is based is rarely made available by the manufacturer of photographic materials. Instead, a model defined at a more macroscopic level is required.

The ideal photographic system would model the process by a single linear filter relating input exposure to output density. This way, the photographic process could be considered as just another linear system that can be analyzed and modeled by means similar to electronic systems using Fourier Theory [POUL91]. However, as evident by the characteristic curve, general photographic responses are highly non-linear. Despite this non-linearity, Kelly, in 1960, introduced a means of applying Fourier techniques and linear systems analysis to the photographic process [KELL60]. The basis of

\textsuperscript{29} This model was first presented in [GEIG97].
his model was the separation of the linear and non-linear processes into separate stages. His complete model consisted of 3 separate stages and is illustrated in Figure 4-1:

![Figure 4-1 - Three stage model proposed by Kelly.](image)

The first stage represents the scattering of light due to the grain distribution within an emulsion. This stage is modeled as a linear system and defined by an emulsion’s modulation transfer function. The result of this stage, termed “effective exposure,” is passed into the next module which represents the macroscopic, non-linear response of the emulsion as defined by the characteristic curve. The final stage models the effects of chemical processing (e.g. adjacency effects). This stage is also modeled by a linear filter and defined by a chemical spread function (the chemical equivalent to the MTF).

4.2 Overview of Our Model

Our model is inspired by Kelly’s work described above. Although we don’t attempt to model the photographic process completely by linear filters, we do build on the basic structure of his model and present our model as a pipeline of image processing modules. Each module will perform an image processing operation on its input, passing the result to the next module in the chain. The modules are controlled through parameters based on the sensiotomic metrics discussed in Section 3.2.

The model is physically based, i.e., the pixel values of images passed through the pipeline modules are floating point values and represent physical or photographic quantities corresponding to the image at each pixel sample. Note that the interpretation of pixel values may change as an image passes through a given module. For example, the characteristic curve relates input exposure to output density.
module that uses the characteristic curve will expect the pixels of its input to represent exposure values but will produce an image with pixel values representing density. The situation is similar when viewing the pipeline as a whole. Like actual photographic situations, the input to the pipeline will be an image whose values represent spectral exposure. The output will be an image whose pixel values represent transmission ratios (when simulating the development of a negative) or reflection ratios (when simulating the development of a print).

The operation performed by each module will be described in mathematical terms. A glossary of terminology to be used for physical quantities corresponding to pixel values and sensiotomic functions and parameters used by the modules is given in Tables 4-1 and 4-2.

<table>
<thead>
<tr>
<th>D (x,y)</th>
<th>Density value of the image at pixel position x, y</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD(x,y)</td>
<td>Randomly deviated density value of image at pixel position x,y</td>
</tr>
<tr>
<td>E (x, y)</td>
<td>Integrated exposure on the surface of the material at pixel position x, y (expressed in lux-sec)</td>
</tr>
<tr>
<td>E_λ(x, y)</td>
<td>Exposure on the surface due to light of wavelength λ on the material at pixel position x, y (expressed in lux-sec)</td>
</tr>
<tr>
<td>EE (x, y)</td>
<td>Effective exposure of the image at pixel position x, y (expressed in lux-sec)</td>
</tr>
<tr>
<td>GNoise_σ (x,y)</td>
<td>Image of random values from -1 - 1 determined using a Gaussian Distribution with mean 0 and standard deviation of σ.</td>
</tr>
<tr>
<td>R (x, y)</td>
<td>Reflection ratio of the image at pixel position x, y</td>
</tr>
<tr>
<td>T (x, y)</td>
<td>Transmission ratio of the image at pixel position x, y</td>
</tr>
</tbody>
</table>

Table 4-1 - Interpretation of pixel values input to pipeline modules
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>Selwyn Granularity</td>
</tr>
<tr>
<td>γₚ</td>
<td>Gamma of paper characteristic curve</td>
</tr>
<tr>
<td>h</td>
<td>Assumed height of photographic material (in mm)</td>
</tr>
<tr>
<td>hₚ</td>
<td>Assumed height of paper (in mm)</td>
</tr>
<tr>
<td>hₙ</td>
<td>Assumed height of negative (in mm)</td>
</tr>
<tr>
<td>H</td>
<td>Height of image in pixels.</td>
</tr>
<tr>
<td>HD(log e)</td>
<td>Characteristic Curve (e corresponds to exposure)</td>
</tr>
<tr>
<td>M</td>
<td>Magnification factor between negative and print</td>
</tr>
<tr>
<td>MTF (ω)</td>
<td>Modulation Transfer Function (ω corresponds to spatial frequency)</td>
</tr>
<tr>
<td>Spec (λ)</td>
<td>Spectral Response Curve</td>
</tr>
<tr>
<td>σₙ</td>
<td>Rms granularity of negative</td>
</tr>
<tr>
<td>σₚₜ</td>
<td>Print thru rms granularity</td>
</tr>
<tr>
<td>T</td>
<td>Exposure time (in seconds)</td>
</tr>
<tr>
<td>w</td>
<td>Assumed width of photographic material (in mm)</td>
</tr>
<tr>
<td>wₚ</td>
<td>Assumed width of paper (in mm)</td>
</tr>
<tr>
<td>wₙ</td>
<td>Assumed width of negative (in mm)</td>
</tr>
<tr>
<td>W</td>
<td>Width of image in pixels.</td>
</tr>
</tbody>
</table>

Table 4-2 - Sensitometric measures used in simulation pipeline

### 4.3 Simulation Pipeline

An overview of the model pipeline is illustrated in Figure 4-2. The pipeline begins with an image of spectral exposure values and produces an image of transmission or reflection ratios. For the sake of discussion, we will assume the input to consist of full spectral exposure (i.e. Eₗ is defined for all wavelengths λ in the visible spectrum).  

---

30 In reality, most renderers will not provide full spectral irradiances. In fact, most do not even consider physically based units when performing their simulations. These issues will be addressed when discussing the full tone reproduction system in Chapter 6.
Note that the pipeline represents the processing of a single photographic material. In order to produce a simulated print, the model would have to be utilized twice, once for the processing of the film into a negative and again when processing photographic paper in producing a print. We now consider each module individually.

### 4.3.1 Spectral Sensitivity

In this module, spectral responses to light at given wavelengths, given by the spectral response curve, are used to scale the spectral exposure values. These exposure values are then integrated with respect to wavelength to produce a single exposure value per pixel. The result of this module can be stated as follows:

\[
E(x, y) = \int_{\lambda} E_{\lambda}(x, y) \cdot Spec(\lambda) d\lambda
\]  

(4-1)

### 4.3.2 Resolution

The resolution module models the image blurring that occurs as a result of the scattering of light by grains within an emulsion. As suggested by Kelly’s model [KELL60], this blurring can be performed in the frequency domain using the modulation transfer function as a filter. Since most manufactures will factor adjacency effects into the MTF reported on data sheets [HIGG71], the chemical spread...
function of Kelly’s model is not explicitly considered by our model. Instead, it is assumed that the MTF used by our model represents the cascading of MTFs due to both light scattering and chemical processing. We borrow the term of effective exposure to describe the result of this blurring which can be mathematically expressed as:

\[ EE(x, y) = \mathcal{F}^{-1}\left(\mathcal{F}(E(x, y)) \cdot MTF(f)\right) \]  

(4-2)

Computationally, this operation can be performed using a 2D DFT. However, since the MTF is expressed in physical units (cycles/mm), special attention must be taken with respect to the assumed size of the photographic material as well as the pixel resolution of the image. When performing a DFT on a set of samples with sampling rate of \( r \), the greatest frequency for which data will be calculated is \( \frac{1}{2r} \). Accounting for the assumed width and height of our image, the sampling rates in the x and y direction respectively will be \( \frac{w}{W} \) and \( \frac{h}{H} \). Given the high resolution of most photographic films, and the relatively low resolution of computer rendered images, the effects of this module may be negligible. For example, assume that we have an image rendered at 640 by 480 pixels, which is to be used to represent a 35mm negative (which has dimensions of 35mm by 24 mm). For purposes of the simulation, the sampling rates in the x and y directions are calculated to be approximately 0.05 mm/pixel. The DFT will provide us with data for frequencies in the range of 0 – 9 cycles / mm. If the film being simulated has a typical MTF (for example, the MTF shown in figure 3-8 and figure 4-3 below), the responses for all available frequencies will be close to 100%. Thus, doing spatial filtering in this case would be wasted effort.

\[ \text{In this expression we use the symbol } \mathcal{F} \text{ to indicate the 2D Fourier Transform operation.} \]
The resolution of the final output should also be considered during this step. Even if, given the resolution of the image and assumed size, the blurring performed by this module is non-trivial, the resolution of the output device must be fine enough to display the blurring effects. Consideration of the output device can provide an upper limit on the frequencies to be modulated at this step. This is of particular importance as this module is the most computationally intensive step of the entire pipeline.

### 4.3.3 Density Response

In the density response module, exposure values are converted to density values using a characteristic curve. The characteristic curve used by this module should not only reflect the attributes of the material being simulated, but also the choice of processing conditions (e.g. time of processing, temperature, processing chemicals). Recall that the characteristic curve relates the logarithm of exposure to density, thus making the result of this module:

\[
D(x, y) = HD(\log_{10}(EE(x, y)))
\]  

(4-3)

### 4.3.4 Grain

Grain effects are achieved by stochastic deviation of density values. Since graininess in actual photography tends to follow a Gaussian distribution, we use Gaussian noise in this module. The standard deviation for the distribution used can be calculated from the Selwyn Granularity value.
Using the assumed area of a pixel in the image as the target area in the definition of Selwyn Granularity (equation 3-5), the standard deviation for the distribution can be expressed as:

$$\sigma = \sigma_N = G \cdot (2 \cdot (h/H) \cdot (w/W))^{1/2}$$

(4-4)

When simulating the printing process, the print through granularity, as defined in Section 3.2.4.2 is used\(^2\) I.e:

$$\sigma = \sigma_{PT} = \sigma_N \cdot \frac{(h_N / H) \cdot (w_N / W)}{(h_p / H) \cdot (w_p / W)} \cdot M \cdot \gamma_p$$

(4-5)

The operation of the grain module can then be expressed as

$$DD(x, y) = D(x, y) + G\text{Noise}_g (x, y)$$

(4-6)

4.3.5 Conversion

In the final module, density values are converted to either transmission ratios (for negatives) or reflective ratios (for prints) using the definition of density as presented in Equations 2-9 and 2-10. The mathematical result for this module can be expressed as:

$$T(x, y) = 10^{-DD(x,y)}$$

(4-7)

for negatives, or for prints:

$$R(x, y) = 10^{-DD(x,y)}$$

(4-8)

Note that since density is always non-negative, the result of this module, as well as the result of the entire pipeline, will always be in the range (0, 1].

\(^2\) Here we assume that the MTF of the paper and the MTF of the enlarger are both equal to 1 at 1mm/cycle.
5 Camera Modeling

5.1 Camera Models in Computer Graphics

Since the early days of computer graphics, the camera model has been the primary means for specifying view parameters in rendering systems. This is not surprising, given that the basic pipeline of image synthesis in computer graphics so closely follows the paradigm of photography. Most renderers employ some variant of the basic pinhole camera in order to achieve a perspective projection when viewing a scene.

The first realistic camera effect to be introduced into the rendering pipeline was depth of field. In 1981, Potmesil and Chakravarty introduced an algorithm for simulating the effects of lens and focus on an already rendered image [POTM81]. In this algorithm, which is employed as a post-processing step, the rendered image is blurred via convolution using a kernel based on the Airy Pattern and a calculated circle of confusion. Since the processing on the image is done post-rendering, the accuracy of the algorithm is limited because visibility is only considered from a single point, namely the center of the lens.

Cook, et al, addressed this shortcoming by incorporating similar effects directly into a ray tracing system [COOK84]. Cook’s method achieves these effects by stochastically spawning rays based on the size of the lens and the light seen at the film surface as derived by the lens equations. This algorithm also allows for the simulation of motion blur, an effect that occurs when objects move while the lens aperture is opened.

In both of the works above, the algorithms are derived using the simple lens approximation, making it difficult to model the effects of actual, more complex lens systems. In 1995, Kolb, et al, published a complete, physically-based camera model [KOLB95] that uses basic ray tracing to trace light through individual lens elements of a complete lens system. Because the model is defined using detailed
physically based data, not only are the geometric effects of the lens system calculated correctly, but the model also effectively accounts for radiometric effects such as vignetting.

Another complete camera model, designed for interactive applications, was introduced by Heidrick, et al [HEID97]. This model is based on the observation that a lens separates 3D space into two light fields\(^{33}\), one in front of the lens representing the scene, and the other behind the lens toward the film plane. The geometrical effects of a lens then can be defined by a mapping between these two light fields. Their algorithm also uses ray tracing through lens elements to determine this mapping. Although the ray tracing step is computationally expensive, it need be done only once per lens system. Once this mapping is acquired, it can be used to approximate geometrical lens effects in close to real time with the assistance of graphics hardware.

Both [KOLB95] and [HEID97] consider radiometry in the synthesis of their final renderings. Using a simplified version of Equation 3-19\(^{34}\), irradiance on the surface of the film is calculated and used as a basis in the calculation of the final rendered image. Neither, however, takes the simulation to the next step by employing photographic responses in this mapping.

5.2 A Complete Radiometric Optical Model

In this section, a model for simulating the effects of optical systems in photography (i.e. cameras and enlargers) is defined.

As pointed out in [COOK84], the geometrical effects of a lens are best simulated when incorporated directly into the rendering process. For the purposes of tone reproduction, we are primarily concerned with the quantity of light that strikes a photographic material, and not necessarily the object from which the light originated. Thus, in building a camera model, we consider only the radiometric effects of a lens and assume that all geometric effects have been considered during rendering.

\(^{33}\) By light field we mean the 4D plenoptic function which describes the flow of light in all directions (as defined in [GORT96] and [LEVO96])

\(^{34}\) These models ignore the effects of flare and shutter efficiency and assume a lens transmittance of 1.
As in the photographic simulation model presented in Chapter 4, our optical model is presented as a physically based dataflow pipeline with variable interpretation of image pixel data. This pipeline is presented below in Figure 5-1.

The input to the model is assumed to be an image whose pixel values represent full spectral radiance emitted from a scene. The model produces an image of full spectral exposure values, representing the light incident on the surface of a photographic material. In the sections below, each module of the pipeline is mathematically described. Table 5-1 gives the nomenclature used for interpreting pixel values, and Table 5-2 gives nomenclature for the various parameters of the model.

<table>
<thead>
<tr>
<th><strong>Symbol</strong></th>
<th><strong>Description</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_{\lambda}(x, y)$</td>
<td>Exposure on the surface due to light of wavelength $\lambda$ on the material at pixel position x, y (expressed in lux-sec)</td>
</tr>
<tr>
<td>$EI_{\lambda}(x, y)$</td>
<td>Effective illuminance on surface due to light of wavelength $\lambda$ on the material at pixel x, y (expressed in lux)</td>
</tr>
<tr>
<td>$I_{\lambda}(x, y)$</td>
<td>Illuminance at wavelength $\lambda$ on the material at pixel position x, y (expressed in lux)</td>
</tr>
<tr>
<td>$L_{\lambda}(x, y)$</td>
<td>Luminance at wavelength focused on the material at pixel position x,y (expressed in nits)</td>
</tr>
<tr>
<td>$\text{Neg}(x, y)$</td>
<td>Transmission of negative at pixel position x,y.</td>
</tr>
<tr>
<td>$R_{\lambda}(x, y)$</td>
<td>Radiance at wavelength $\lambda$ focused on the material at pixel position x,y (expressed in W/m²sr)</td>
</tr>
</tbody>
</table>

Table 5-1 - Interpretation of pixel values input to camera model modules
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>lens aperture (f-number)</td>
</tr>
<tr>
<td>F</td>
<td>focal length (in mm)</td>
</tr>
<tr>
<td>(I_\text{flare})</td>
<td>Illumination introduced by camera lens flare</td>
</tr>
<tr>
<td>m</td>
<td>Magnification factor</td>
</tr>
<tr>
<td>(\eta)</td>
<td>shutter efficiency</td>
</tr>
<tr>
<td>(\text{OTF}) ((\omega))</td>
<td>Optical Transfer Function ((\omega) corresponds to spatial frequency)</td>
</tr>
<tr>
<td>(\tau)</td>
<td>lens transmittance factor</td>
</tr>
<tr>
<td>t</td>
<td>Exposure time (in sec.)</td>
</tr>
<tr>
<td>(\theta)</td>
<td>angle from a point on the surface of photographic material to the center point of the lens</td>
</tr>
<tr>
<td>u</td>
<td>subject to lens distance (in mm)</td>
</tr>
<tr>
<td>(V(\lambda))</td>
<td>CIE Photopic Luminous Efficiency Function</td>
</tr>
<tr>
<td>(V_g(\theta))</td>
<td>lens barrel vignetting factor</td>
</tr>
</tbody>
</table>

Table 5-2 -- Optical parameters used by camera model

5.2.1 Illumination

In this module, the illuminance incident on the surface of a photographic material resulting from the radiance passed in as input is calculated. This calculation is a direct application of Equation 3-19. Since illuminance is photometric rather than radiometric, scaling by the CIE Photopic Luminous Efficiency Function is also performed by this module. The mathematical results of this module can be expressed as:

\[
L_\lambda (x, y) = V(\lambda) \cdot \frac{1}{683} \cdot R_\lambda (x, y) \tag{5-1}
\]

\[
I_\lambda (x, y) = \frac{L_\lambda (x, y) \cdot \pi \cdot \left(\frac{u - F}{u}\right)^2 \cdot \cos^4 \theta \cdot V_g(\theta) \cdot \tau}{4f^2} + I_\text{flare} \tag{5-2}
\]

When modeling an enlarger, this module will represent the light that is shone through a processed negative onto photographic paper during the enlargement process. Thus, the transmission properties of the negative, as well as the characteristics of the light source used by the enlarger must be considered. In this case, we consider \(L_\lambda (x,y)\) to represent the spectral luminance emitted by the light source of the enlargement system, and \(\text{Neg} (x,y)\) to represent the transmission of the negative. For
convenience, we also use the alternate correction factor for finite distances expressed in terms of magnification, making the illuminance expression for enlargers:

\[
I_\lambda (x, y) = \frac{L_\lambda (x, y) \cdot \pi \cdot \cos^4 \theta \cdot V_g(\theta) \cdot \tau}{4 f^2 \cdot (M + 1)^2} \cdot \text{Neg}(x, y) + I_{\text{flare}}
\]  

(5-3)

5.2.2 Resolution

In this module, spatial blurring due to diffraction is added to the image. Similar to the spatial filtering performed during the photographic simulation, we use the optical transfer function as a filter in the frequency domain. We refer the result of the blurring as effective illuminance, which can be expressed as:

\[
EI_\lambda (x, y) = \mathcal{F}^{-1}(\mathcal{F}(I_\lambda (x, y)) \cdot \text{OTF}(\omega))
\]  

(5-4)

5.2.3 Exposure

Finally, exposure is calculated by multiplying the illuminance by the exposure time. For optical components with shutters (e.g. cameras), shutter efficiency must also be considered.\(^{35}\):

\[
E_\lambda (x, y) = I_\lambda (x, y) \cdot \eta \cdot t
\]  

(5-5)

\(^{35}\) The optical efficiency for an enlarger is assumed to be 1.0.
In chapters 4 and 5, the models for individual components of a photographic chain were described. In this chapter, we combine these models, defining a full tone reproduction system based on the photographic process. Before describing the details of our system, a review of Tone Reproduction from both a Computer Graphics and photographic perspective are given.

6.1 Tone Reproduction - A Computer Graphics Perspective

As mentioned in the introduction, the problem of tone reproduction was introduced to the Computer Graphics community by Tumblin and Rushmeir in their seminal 1993 paper [TUMB93]. In addition to providing a mathematical solution to the tone reproduction problem by means of an operator, the work, more importantly describes a framework that clearly illustrates the role of tone reproduction in the rendering pipeline. This framework, illustrated in Figure 6-1, also defines the major distinct components required by a tone reproduction system. These required models include: a device model that is used to account for the response of an output device, and an observer model that is used to simulate the response of a human viewer. The observer model is applied twice, once to the actual scene, and once to the representation of the scene displayed on the device once the tone reproduction operator has been applied. If the tone reproduction operator works correctly, the output of both of these models should match.
Development of a device model is a straightforward task since the output response of a device for a given set of inputs should be well defined by the specification of the device. Even if the specification of a device is lacking in details, at the very least, this response, given the right tools, can be easily measured.

The challenge in the creation of a tone reproduction operator is in the definition of the observer model. Despite years of research, the eye’s response to light is still not fully understood. In Tumblin and Rushmeier’s work, the observer model is designed to preserve psychophysical brightness relationships and is based upon brightness perceptual studies done by Stevens and Stevens in 1963 [STEV63]. The validity of basing the operator on this particular study is suspect, however, the point is clear that the observer model should have some perceptual basis in order for it to be effective.

In 1994, Ward introduced a tone reproduction operator that was designed to preserve perceived contrast as opposed to brightness response [WARD94]. In his operator, just noticeable contrast differences (JND) in the scene are mapped to just noticeable differences in an image. The determination of the JNDS is based on threshold contrast sensitivity data reported by Blackwell in 1981 [CIE81].

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36 Even Tumblin and Rushmeier admit that they chose the Stevens model for mathematical convenience rather than perceptual accuracy.
Ferwerda, et al [FERW96] introduced an extended appearance model for visual adaptation that takes a similar, JND approach. Their model is based on threshold responses of the photoreceptors (rods and cones) in our eyes, and also models the effects of adaptation on color appearance, visual acuity, and changes in visual sensitivity over time. This model was later extended by Ward-Larson, et al for use on high dynamic range imagery using a histogram adjustment technique [WARD97].

In addition to [FERW96], other tone reproduction techniques have been developed that consider the spatial aspects of vision. Nakamae, et al [NAKA90] and Spencer [SPEN95] have developed algorithms for adding glare effects to areas of high luminance in a scene. Visual Masking, which explains how different spatial frequencies affect the visual recognition of objects in an image, is addressed by Ferwuka, et al [FERW97] and Bolin and Meyer [BOLI95]. This later work is the first attempt of incorporating a perceptual vision model (developed in the computer vision community) with a ray tracing system. The algorithms presented in both [FERW97] and [BOLI95] have been incorporated into larger and more complete systems ([PATT98] and [BOLI98], respectively) that employ full multi-layered vision models based on their respective research.

Finally, based on research that suggests that sensitivity is greater in the direction of viewing, Tumblin, et al. introduced a method of tone reproduction that adjusts the displayed image to preserve local contrast in a small neighborhood centered on the area of viewing focus [TUMB99].

### 6.2 Tone Reproduction - A Photographic Perspective

The one commonality of the approaches to tone reproduction mentioned above is that they all attempt to directly model the response of the human visual system. The general idea behind these operators is clear. By modeling human visual response directly, an effective operator will result in a match of the response between the real and the simulated. Photographic systems set out to do the same thing. However, photographic systems introduce an intermediate representation of the scene, namely the print. An observer will not respond perceptually to this print until it, itself, is illuminated (Figure 6-2).\(^{37}\)

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\(^{37}\) In the case of slide or motion picture photography, the recorded scene is perceived during projection.
Based on the success of the photographic industry over the past century, we can assume that photographic systems perform with admirable success as tone reproduction systems. Since photographic systems can produce images that adequately match the perceptual response of a captured scene, they can, in essence, replace the real world observer in the traditional tone reproduction pipeline presented in Figure 6-1. From a simulation point of view, this is a real advantage since photographic systems, unlike the human visual system, can be simulated using only physical models that are far more understood than their perceptual counterparts. Consideration of human perception is accounted for in the design of photographic materials and in the proper setting of photographic parameters, issues that photographic scientists have been studying for over a century.

With photographic tone reproduction, one still needs to consider the second observer in the pipeline, which represents the actual viewing of a photograph. The response of this observer depends not only on the reflective nature of the print, but also on the illumination and lighting conditions present when viewing the print. When designing a tone reproduction system that mimics photography, the goal is to

---

38 This is not to say that photographic tone reproduction is without its flaws. Photography still has a problem with reproducing high dynamic range scenes, thus forcing the need for dodging and burning while in the darkroom. Tone reproduction operators in Computer Graphics (e.g. [WARD97]) can produce an adequate reproduction of scenes with high dynamic range, however, given the limitations of the physical processes behind photography, it is unlikely that traditional silver halide photography ever will.
have the perceptual response of an display match the perceptual response of an observer viewing a photographic print under a given set of viewing conditions (Figure 6-3).

The requirements on our tone reproduction system can be simplified if the range of the viewing illumination is limited to match that of the display device. In this case, the device observer can be removed, and it will be sufficient if the illumination of the output device matches that of the illumination reflected off the print (Figure 6-4). This is not an unreasonable limitation, since, if we consider our output device to be a CRT, this would limit the viewing illumination to be within the output range of a CRT, which is equivalent to typical indoor viewing conditions.

The requirements are further simplified if our output is produced by a hardcopy device such as a printer. In this case, reflectance values of the print and reflectance values of the printed output can be compared directly (Figure 6-4).

These simplifying assumptions are extremely significant as they eliminate the need for an observer model and thus allow modeling to take place purely in physical domain. This is not to say that the perceptual aspects of tone reproduction are unimportant or to be ignored. Instead, human perception is indirectly accounted for by the appropriate modeling of photographic materials and processes. As

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30 Note that this is the approach recommended by the CIE in performing hardcopy/softcopy comparisons (see [ALES94])
mentioned previously, these materials and processes have be optimized based on human visual perception.

![Figure 6-4 - Simplified tone reproduction goals for mimicking photography](image_url)

### 6.3 A Tone Reproduction System based on Photography

With the goals of the pipeline illustrated in Figure 6-4 in mind, we now present our full tone reproduction system. We assume that the input to the system is an image with pixel values representing radiance values emitted from a scene projected through a camera model. The system is intended to be applied post-rendering, thus all geometric effects of the camera model used are assumed to be simulated during the rendering process. The output of the system will be a one channel grayscale image rendered specifically to be displayed using a particular output device.

#### 6.3.1 Parameters

The primary components of the system are based on the simulation and camera models described in Chapters 4 and 5 respectively. Thus, the parameters that control the system are the same parameters that control these simulation models. These parameters are summarized in Table 6-1.
One of the stated goals of our system is that the set of parameters that control the system should be consistent with those used in actual photography. Although the size of the parameter list presented in Table 6-1 may seem daunting, the values of many of these parameters can be derived from the photographic choices described in Section 3.4. For example, the choice of film combined with choice of processing chemicals, temperature, and time of development will uniquely determine the characteristic curve to be used for film simulation. Lens characteristics are derived directly by the choice of camera, enlarger, and lens used. These characteristics can be obtained from the lens specs provided by a manufacturer, or, assuming the correct set of tools, measured directly. Lacking such data, standard defaults that represent “typical” lens systems can be employed. Table 6-2 illustrates the relationship between system parameters and photographic choices, and gives appropriate default values for these parameters.

---

40 [GOLD92], Chapter 7 provides an excellent discussion on lens testing and measurement.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Determination</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>Explicitly set by user</td>
<td>none</td>
</tr>
<tr>
<td>Exposure Time</td>
<td>Characteristic of camera or enlarger and lens system.</td>
<td>2.5</td>
</tr>
<tr>
<td>Flare</td>
<td>Characteristic of camera or enlarger and lens system.</td>
<td>1 ms</td>
</tr>
<tr>
<td>Focal length</td>
<td>Characteristic of camera or enlarger and lens system.</td>
<td>none</td>
</tr>
<tr>
<td>Shutter opening time (cameras only)</td>
<td>Characteristic of camera or enlarger and lens system.</td>
<td>See Eqn 3-23</td>
</tr>
<tr>
<td>OTF</td>
<td>Characteristic of camera or enlarger and lens system.</td>
<td>0.90</td>
</tr>
<tr>
<td>Transmittance</td>
<td>Characteristic of camera or enlarger and lens system.</td>
<td>1.0</td>
</tr>
<tr>
<td>Vignetting factor</td>
<td>Characteristic of camera or enlarger and lens system.</td>
<td>none</td>
</tr>
</tbody>
</table>

Film / Paper

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Determination</th>
<th>Default value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic Curve(^{41})</td>
<td>Determined by choice of material, processing chemicals and processing conditions</td>
<td>none</td>
</tr>
<tr>
<td>Granularity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MTF</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral Response Curve</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-2: Relationship between Tone Reproduction System parameters and photographic choices (defaults obtained from [DUNN74] and [GOLD92]).

6.3.2 System Pipeline

Like the descriptions of the other simulation models presented in previous sections, our full system is presented as a dataflow pipeline. The complete system pipeline is presented in Figure 6-5.

\(^{41}\) Note that for papers, as mentioned in Section 3.2.2, the characteristic curve used may also account for the spectral qualities of the light/filter combination used during printing. In this case, paper spectral sensitivity data would not be explicitly required.
As illustrated above, the system is comprised of three major modules. At the heart of our system is a **simulation module** that combines the camera model described in Chapter 5 with the Photographic Simulation model presented in Chapter 4. Since both of these models are physically based (i.e. they perform computation on images with floating point pixel values representing physical quantities), so too is this central module. Images input to the system, however, will depend upon the nature of the rendered image source, and may or may not contain physically based pixel values. Similarly, the devices used to display the output of the system will expect images with 24 bit integer pixel values, as opposed to images with physically based floating point pixel values. The pre-processing and post-processing modules are introduced to accommodate for this difference in image pixel representations. The **pre-processing module** will convert the pixels of an input image to physically based quantities suitable for input to the simulation module. Similarly, the **post-processing module** will take the physically based results of the simulation module and convert the pixel values to a form appropriate for a given display device. The three system modules are discussed individually in more detail below.
6.3.2.1 Preprocessing Module

The pre-processing module is responsible for converting the pixel values of the input image into a representation suitable for input to the simulation module. There are two issues that the pre-processing module needs to address. The first issue involves the interpretation of the pixel values of the input image. Depending upon the level of physical accuracy of the renderer that produced the image, the input pixels can be interpreted in different ways. The pre-processing module is designed to be general enough to handle output from a variety of different renderers, yet robust enough to accommodate the output of more physically accurate rendering systems. Three types of input images are allowed for, indicated by input image paths 1, 2, and 3 in Figure 6-5. These input types are summarized in Table 6-3.

<table>
<thead>
<tr>
<th>Renderer Type</th>
<th>Example Implementation</th>
<th>Pixel values</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Traditional</td>
<td>Most commercial and academic rendering systems.</td>
<td>24 bit integer. Each channel quantized to integer value between 0 – 255.</td>
</tr>
<tr>
<td>(2) Physically Based</td>
<td>RADIANCE [WARD 98]</td>
<td>Floating point representing scene radiance</td>
</tr>
<tr>
<td>(3) Physically Based with Physically Based Camera Model</td>
<td>[KOLB95] [HEID 97]</td>
<td>Floating point representing exposure.</td>
</tr>
</tbody>
</table>

Table 6-3 - Images produced by different types of rendering systems

Only input images of Type 1 (24 bit integer RGB pixel values) require attention with regards to level of physical accuracy of pixel values. For these types of images, it is assumed that the pixel values represent radiance emitted from objects in the scene that have been quantized to integers between 0 - 255. An additional system parameter, maximum scene brightness, is used to determine the scaling between integer values and their floating-point radiance equivalents.

The second issue that needs to be dealt with by the pre-processing module is that involving color. Our simulation module is designed to work best when provided with full spectral radiance data (with one color channel per wavelength, sampling the full visible spectrum at 5-10 nm interval between samples). Although renderers that produce this kind of output are under development (e.g. [JOHN99]), at the time of this writing, they are still quite uncommon. Most renderers, even physically based renderers, still provide only three channels of output, one channel each for the red, green, and blue areas of the visible spectrum. Converting from spectra to RGB triplets is a straightforward transformation
(Equation 2-2). However, because many spectra can correspond to a single RGB color combination, calculation of the inverse transformation has proven to be a formidable task. Several researchers have developed techniques for performing this inverse transformation (e.g. [SUN99, GLAS89, MEYE88]). However, as pointed out by Johnson and Fairchild [JOHN99], any attempt to convert from RGB to full spectral distributions will fall short since much of the data contained in spectral curves is already lost when sampled down to 3 representative wavelengths.

In order to keep our system practical, it must accept input images with three channels, RGB color data. Since the system must operate within a trichromatic spectral system, we chose to perform all internal color calculations in CIE XYZ color space since it provides the broadest range of trichromatic color values. The responsibility of the pre-processing module with respect to color then becomes conversion of the input values from RGB to XYZ. As mentioned in Section 2.1.4, this conversion is possible, as long as the values of the red, green, and blue primaries, expressed in terms of X,Y, and Z, are known. Lacking this knowledge, the system assumes the RGB color space to follow the specification of the ITU Standard Rec 709[ITU90], which is indicative of many CRT devices.

6.3.2.2 Simulation Module

The simulation module is the heart of our tone reproduction system. It is the responsibility of this module to convert spectral scene radiances to print reflectance values. The major components of this module are the physically based photographic simulation and camera models discussed in Chapters 4 and 5. Images input to this module will have already been converted to spectral, physically based values by the preprocessing module. There are two entry points into the module. If the image data passed from the preprocessing module represent spectral scene radiances, the image is passed through the camera model, whereby the radiances are converted to exposure incident on the surface of the film. For images on Input Data Path 3 in Figure 6-5, this step can be skipped, as the conversion from radiance to exposure would have already been considered during the rendering process.

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42 If full spectral, physically based pixel values are available, the pre-processing module could be superseded and the simulation module would make use of the full spectral curves provided as parameters to the simulation module.

43 sRGB [STOK96], a color space defined by Microsoft and Hewlett-Packard, is another good candidate for the assumed color space as it has become a de facto standard for general purpose digital imagery. The correct color space to be assumed, of course, would depend upon the RGB color space assumed during rendering.
The image, whose pixel values now represent exposure, will go through the film processing model where the response of the film is simulated. The resultant image, after passing through this model, will become the virtual negative with pixel values representing transmission ratios. This negative is then passed on to the enlarger model.

The enlarger model will simulate the shining of light through the negative and onto the surface of photographic paper. In using this model, it is assumed that the effects of spectral sensitivity are reflected in the characteristic curve chosen for the given photographic paper. As such, spectral sensitivity of photographic papers need not be explicitly considered. The pixel values of the resultant image will represent exposure incident upon the surface of the paper.

Finally, these exposure values are passed through the print processing module, which will convert this exposure data to values representing print reflection ratios.

6.3.2.3 Post-processing

The simulation module produces an image of reflection values, ranging from 0 to 1, on a linear scale. It is the responsibility of the post-processing module to convert these reflectance values to values suitable for output by a given device. In the discussion below, we focus on CRT output. However, printers have a transfer function similar to that of CRTs[POYN96], so the discussion below is applicable to hard copy output as well.

CRTs are additive color devices that produce various intensities of lights from red, green, and blue phosphors. The light emitted by the phosphors is controlled by control voltages specified digitally via 24 bit control codes (8-bits for each of the phosphors). A “well-calibrated” CRT has a well-defined and consistent white point (the chromaticity coordinates of the light produced when R = G = B = 255) that remains constant for any set of equal RGB codes. In this case, the complete grayscale range producible by the monitor can be specified by a single control code, which is used to specify each of the red, green, and blue control voltages. The grayscale luminance emitted by a monitor can be

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44 Note that spectral data, at this point, should be interpreted as 3 channel spectral data in XYZ space. All spectral curves used by the simulation module should also be converted to XYZ coordinates.

45 Data sheets for photographic papers very often consider spectral characteristics when reporting characteristic curves (See Figure 3-5).

46 A typical CRT has a standard white point, D65 with chromaticity equal to (x=0.3127, y = 0.3290).
described by a luminous factor \(y\) defined as the relative luminance emitted by the CRT with respect to the maximum luminance that can be emitted by the monitor.

The luminance factor for a CRT has a non-linear relationship with the RGB control codes that control it. For conventional CRTs, this relationship can be described by the following equation [GIOG98]:

\[
y = k \left( \frac{C_{RGB}}{255} \right)^\gamma + Y_0
\]

where

\(C_{RGB}\) is the control code \(R = G = B\)
\(Y_0\) is a black-offset constant that indicates the level of luminance present when \(R = G = B = 0\) (controllable via a monitor's brightness control)
\(k\) is a normalizing factor determined such that \(Y = 1.0\) when \(C_{RGB} = 255\).
\(\gamma\) - exponent of the power relationship. Gamma for most typical monitors is 2.5.

In the discussion on tone reproduction presented in Section 6.2, the observation is made that with print photography, the image is not perceived until it, itself, is illuminated. It is also stated, that when displaying the results of the tone reproduction system on a CRT, it can be assumed that the view lighting conditions match that of the luminous output of the monitor. In this case, the luminance reflected off our simulated print should be equal to the grayscale luminous output of the display. Since the reflectance values \(R\) of the simulated print and the luminance factor of the CRT both act as a scale factor of the maximum display luminance, these two values should also be equal.\(^{47}\) The control codes that are produced by the post-processing module can thus, be ascertained by solving Equation 6-1 for \(C_{RGB}\):

\(^{47}\) Here, we assume that during viewing, the monitor is the sole source of luminance in the room (i.e. the CRT is being viewed in dark surround).
This process, known as **gamma correction**, is occasionally performed as a matter of course by high end imaging applications (e.g. Adobe Photoshop).

For hard copy output, a similar relationship exists between control codes and reflectance values. Thus, gamma correction is also important when using a printer as the output device. Since photographic prints and hard copy images are both reflection media, no additional consideration regarding viewing illumination is required. The only necessary condition is to assure that the illumination used in viewing a print and the output of a printer is identical when making visual comparisons.

### 6.4 Implementation

The system presented in Figure 6-5 is implemented in software as a Java 2 [HORS98] application. The application, called the **Virtual Darkroom (VDR)**, is designed as a virtual equivalent to the photographic tool set available to photographers in the real world. In this section, an overview of this application is given. Additional implementation details, as well as screen shots for the system GUIs, are provided in Appendix A.

VDR is designed using a “user as photographer” metaphor. Using this metaphor, the image input to the system represents the scene to be captured and processed into a print. The system provides simple controls for the basic photographic parameters representing the photographic choices discussed in Section 3.4. Using an intuitive GUI, a user may choose a film and paper, and provide the settings for aperture and exposure time for both the camera and the enlarger. The data from a variety of actual films and papers are available for use by the system. The click of a single button will run the simulation, after which the user can immediately view the results of his/her photographic choices.

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48 V1.2.1 of the Java2 SDK was used in the implementation.

49 This data is derived from datasheets provided by the manufacturer.

50 Using a Pentium II based, 200 MHz laptop computer running Windows 98, a 640 by 480 pixel image, with MTF processing turned off, can be processed in a matter of seconds. With MTF filtering, the processing may take up to a minute.
The swift response of the system allows for quick experimentation with a variety of photographic settings.

For the more advanced user, the system also allows for specification of most of the system parameters listed in Table 6-2. The system includes a film and paper editor that can be used to manipulate the various sensiotomic curves associated with a photographic material. Film and paper data can be saved to, and retrieved from files using a VDR defined file format. This provides the user with the ability to design and use new types of photographic materials that may not even exist in the real world.

The application is designed to work in two modes: an interactive mode, whereby the results of a simulation is displayed visually, or a batch mode where simulation results are immediately stored as an image file.

Table 6-4 provides a summary of the various controls provided by VDR. The controls are logically grouped by photographic component, and include most of the parameters required by the system. When using the system in interactive mode, controls for these parameters are specified via a GUI (see Appendix A). When running the system in batch mode, the values for these parameters are supplied on the command line.

Additional controls are provided to instruct the system to produce either a virtual negative or a virtual print. In addition, the user can specify that the input image be interpreted as a negative from which a virtual print can be created. This option was especially useful during the validation process (Chapter 8) where a scanned negative was used as a transparency map when creating the image that is eventually compared to an actual print. Other system parameters include assumed resolution of the final output, and the assumed processing time for simulating the development of the negative.

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51 Certain parameters like lens transmittance, mechanical vignetting, flare, and other lens properties are currently, hard coded into the system. Including controls for these parameters would be a straightforward enhancement to the existing system.
### Table 6-4 – Virtual Darkroom controls

<table>
<thead>
<tr>
<th>Photographic Component</th>
<th>Control</th>
<th>Means of specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>Scene Brightness (for radiance estimation)</td>
<td>Direct user input</td>
</tr>
<tr>
<td></td>
<td>Exposure Time</td>
<td>Selection from a set of standard camera shutter times</td>
</tr>
<tr>
<td></td>
<td>Aperture Setting</td>
<td>Selection from a set of standard aperture settings (F-stops)</td>
</tr>
<tr>
<td>Film / Paper</td>
<td>Characteristic Curves</td>
<td>Interactive curve editor</td>
</tr>
<tr>
<td></td>
<td>Spectral Response Function</td>
<td>Interactive curve editor</td>
</tr>
<tr>
<td></td>
<td>MTF</td>
<td>Interactive curve editor</td>
</tr>
<tr>
<td></td>
<td>Granularity</td>
<td>Direct User Input</td>
</tr>
<tr>
<td>Enlarger</td>
<td>Brightness of light source</td>
<td>Direct User input</td>
</tr>
<tr>
<td></td>
<td>Exposure Time</td>
<td>Direct User Input</td>
</tr>
<tr>
<td></td>
<td>Aperture Setting</td>
<td>Selection from a set of standard aperture settings (F-stops)</td>
</tr>
<tr>
<td></td>
<td>Magnification</td>
<td>Selection from a set of standard magnifications.</td>
</tr>
</tbody>
</table>

The Virtual Darkroom application is used for generation of the examples presented in Chapter 7 as well as for producing the images used in the validation experiments described in Chapter 8.
In this chapter, examples from initial testing of the tone reproduction system are presented. These tests are intended as an informal guide to assure that the model produces images as expected given a set of parameters. A more formal and precise validation process is described in Chapter 8.

The test images used were created by a traditional rendering package, and were comprised of 24 bit, integer, RGB pixel values. A maximum brightness of 300 cd/m$^2$ is assumed for all images. All of the sensiotomic data used by the tone reproduction system was obtained directly from data sheets from actual photographic materials manufactured by the Eastman Kodak Company. For print simulation, all examples make use of data corresponding to Kodak POLYMAX II RC photographic paper, a medium grade paper with gamma of 1.67 and speed of 250.

7.1 Film Parameters

In this first suite of tests, the effects of varying film sensitometry are shown. In each test, the measures corresponding to one of the basic film characteristics (speed, gamma, grain, spectral sensitivity, and resolution) are modified in order to illustrate the effect of the characteristic on the final rendering.

7.1.1 Film Speed

Figure 7-1 illustrates the effect of film speed on the final image. The original color image is simulated using characteristic curve data from Kodak films TMAX 100 (speed 100), TMAX 400 (speed 400) and TMAX 3200 (speed 1000) with the exposure time, aperture setting, and film gamma remaining constant. As expected, the higher speed films, being more sensitive to low levels of light, produce images that appear much brighter than those processed with the lower speed films.

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52 Special thanks go out to the creators of these images, Dave Florek and Ken Musgrave, who graciously allowed them to be used in this initial testing.

53 For some tests, this data is exaggerated to showcase a given effect. In these cases, the exaggeration will be explicitly mentioned.
7.1.2 **Film Gamma**  
Figure 7-2 illustrates the effect of gamma on film curves. For each of the examples, the color image is processed using data from TMAX 400 film. The curves chosen from the data sheet reflect film development times of 6 minutes, 8 minutes, and 10 minutes. Note that as the processing time increases, so too does the gamma of the characteristic curve. As a result, a noticeable increase in contrast is evident.

7.1.3 **Grain**  
The effects of granularity are illustrated in Figure 7-3. The figure shows three magnifications of an image, all processed using the same granularity value. Since most films are designed to minimize the amount of grain, the granularity values used in the simulation have been exaggerated to emphasize the grain effect. As expected, the graininess in the image becomes more apparent as the magnification of the image increases.

7.1.4 **Spectral Sensitivity**  
Figure 7-4 illustrates the effects of a film’s spectral sensitivity on the final image. In this example, an artistic challenge is to properly expose the image as to maintain the brightness of the scene yet at the same time, emphasize the detail in the rocks. Attempts using a panchromatic, orthochromatic and untreated film are shown, with exposure time chosen so that the mountain is properly exposed. Because of the extended spectral sensitivity in the panchromatic and orthochromatic films, it is difficult to capture the bright blue sky in its full brilliance without running the risk of overexposure of the mountain area. With the untreated, blue-sensitive film, this is not a problem since the majority of the film’s sensitivity lies in the blue range of the spectrum. Increasing the exposure as to capture the detail in the rocks, an area to which the film is not very sensitive, will only result in the overexposure of the sky. When processed, the sky appears white in the final print, thus giving a feeling of brilliance. This kind of image is indicative of many old time landscape photographs taken before the introduction of sensitizing dyes that extend the spectral sensitivity of an emulsion.
Figure 7-1 - Effects of film speed

Figure 7-2 -- Effects of film gamma
Figure 7-3 - Grain effects
Figure 7-4 - Effects of spectral sensitivity

(a) original image
(b) panchromatic film
(c) orthochromatic film
(d) blue sensitive film
7.1.5 Modulation Transfer Function
Using the MTF to model the resolution can be useful when degradation of an image is required (e.g. when combining computer generated elements with existing photographic images.). Figure 7-5 shows a magnified portion of the image presented in Figure 7-3 processed with and without MTF filtering. The MTF used is exaggerated to illustrate the effect. As evident by the example, the effects of MTF filtering on printed output, even when exaggerated, are quite subtle. The combination of MTF filtering and the addition of grain produces a more striking degradation which results in a more photographic look to computer generated imagery (Figure 7-5c). Considering the large difference between the resolution of film and the resolutions of CRTs and printers, the benefits of MTF modeling for general purpose use becomes questionable. However, as display device technology approaches High Definition Television (HDTV) (which is designed to have resolution that equals that of photography[BE91]), the use of MTF filtering may become more appropriate.

7.2 Camera Parameters
The next suite of tests illustrates the effects of camera parameters on the final image. In all the examples in this suite, the data for TMAX 400 film processed at 8 minutes is used in the simulation.

7.2.1 Aperture Change
Figure 7-6 illustrates the effects of camera aperture. In this test, the results of simulation using apertures of f/4, f/5.6, f/8 are presented. Exposure time is kept constant at 1/30 sec. for all three images.

7.2.2 Exposure Time
The effects of exposure time are illustrated in Figure 7-7. In this test, the aperture setting is kept constant at f/5.6 and exposure time is varied. Exposure times of 1/15 sec, 1/30 sec, and 1/60 sec are used in the simulation. Comparing these results to the images in Figure 7-6, it is evident that, from a photographer’s perspective, the results of reducing the aperture one stop is equivalent to the results obtain by reducing the exposure time by one half.
(a) original unfiltered image

(b) processed using MTF filtering
(c) processed using MTF filtering and grain

Figure 7.5 - Effects of MTF filtering
Figure 7-6 - Effects of aperture

(a) original image                            (b) aperture setting f/ 4
(c) aperture setting f/ 5.6                   (d) aperture setting f/ 8

Figure 7-7 - Effects of exposure time

(a) original image                           (b) exposure time of 1/ 15 sec
(c) exposure time of 1/ 30 sec           (d) exposure time of 1/ 60 sec.

Figure 7-7 - Effects of exposure time
In Chapter 7 results of informal testing of the tone reproduction system were presented. In these informal tests, the system yielded predictable results where the relationship between the photographic parameters modified and the final simulated prints was maintained as expected.

In this chapter, a more formalized approach to validating the system is described, where simulation results are compared with negatives and prints produced using the actual photographic process.

8.1 Experimental Setup
During this validation, a comparison between the actual response of photographic materials to a given scene and the simulated response to a virtual representation of the same scene will be made. Figures 8-1 and 8-2 illustrate this process for comparison of transmission values (negative validation tests) and comparison of reflection values (print validation tests). In both cases, two parallel paths are presented: one for the recording of the scene by real materials (real path) and the other for simulating this process by the model (virtual path).

Figure 8-1 – Pipeline for Negative Validation Tests
On the real path, a scene is captured on photographic material. This material is then developed and processed, producing a negative or a black and white print. On the virtual path, a virtual representation of the scene is run through the tone reproduction system using parameter values which represent the conditions of capture used in the real path. Transmission values are determined from negatives using a film scanner whereas reflection values are determined from prints using a photograph or flatbed scanner. The resultant digital images are then compared to their simulated counterpart.

### 8.2 Physical Setup

In performing the validation experiments, a physical realization of the general paths presented in Figures 8-1 and 8-2 above is created. In this section, the specifics about the components of this physical setup are discussed.

#### 8.2.1 Test Scene

The Macbeth Color Checker Chart [MCCA76] is used as the test scene. This chart consists of a 4 x 6 array of color patches which include a range of neutral gray values, additive and subtractive color primaries, and a variety of colors useful in evaluation of photographic and television systems (Figure 8-3).
Each patch is 50 mm square and is characterized by full spectral reflectance factors, an assigned name, and CIE \( xy \bar{Y} \) values. The patches are designed to provide perfectly diffuse reflections. A list of color patch names is given in Figure 8-4 below. CIE \( xy \bar{Y} \) triplets and full spectral reflectance for each patch are provided in Appendix B.
The chart is illuminated by a Broncolor Hazylight Soft\textsuperscript{54} photographic lighting system. The system is designed to provide diffuse illumination using a pair of Tungsten-Halogen lamp heads with a color temperature of 3000K.\textsuperscript{55} A constant light setting is used for all of the tests performed. The radiance provided by the lighting system at this setting was measured using a radiometer and determined to be 8.66\(\mu\)W/sr-cm\(^2\).

The chart is positioned at a distance of 1.5 m from the camera and is aligned so that the center of the chart coincides with the center axis of the camera lens.

### 8.2.2 Camera/Enlarger

A Minolta 35mm X-370 camera is used for scene capture. This camera is a standard, 35mm SLR camera with manual exposure settings ranging from 0.001 sec to 1 sec. The camera is equipped with a standard Minolta MD-50 1:1.7 lens. This lens has six air/glass boundaries, a focal length of 50mm and variable aperture setting ranging from f/1.7 to f/22.

For enlarging, an Omega ProLab 4x5 Condenser Enlarger with a 75 W Tungsten light source is used. This enlarger is equipped with a variable aperture lens with focal length of 50mm and f-stop settings ranging from f/1.7 to f/11. The exposure for the enlarger is electronically controlled by a GraLab 450 controller, allowing for exposure times ranging from 0.1 – 99 seconds.

### 8.2.3 Photographic Materials and Processing

In order to minimize the effects of manufacturing variability among film vendors, all photographic materials tested were made by the same manufacturer. Kodak products were chosen since they provided the largest variety of black and white materials of all the major film manufacturers.\textsuperscript{56} Sensiotomic data used as input to the tone reproduction system is derived directly from data sheets.

\begin{footnotes}
\item The Broncolor Hazylight 2 is manufactured by SnarBron Imaging.
\item The spectral density function of this lighting source is the example SDF given in Figure 2-3.
\item Unfortunately, black and white photography isn't as popular as it once was. As a result, our choice of available materials was quite limited, which, in turn, limited the number of tests that could be run.
\end{footnotes}
published by Kodak. When processing the photographic materials, care was taken to use the same processing conditions (chemicals used, processing temperature) as specified on these data sheets.

### 8.2.4 Scanners

A Kodak Professional RFS2035 Film Scanner is used for scanning negatives. Negatives are scanned at 1000dpi, producing images with resolution of 1536 by 1024 pixels.

For scanning prints, a Plustek Optic Pro 4831P Flatbed Scanner is used. 8" x 10" prints are scanned at 150dpi (producing images with resolution of 1440 x 1138 pixels) whereas 3" x 5" and 5" x 7" prints are scanned at 300dpi, producing images with resolution of 1351 x 1118 pixels and 2018 x 1405 pixels respectively.

In both validation paths, since the scanners are performing the function of a densitometer, the responses of each scanner to linear transmission or reflection scales need to be considered during the validation. Response measurements were performed by scanning and recording the response to well calibrated test targets. These responses are reported in Appendix D.

### 8.3 Experimental Design

#### 8.3.1 Tests performed

The tests performed during the validation focus on the effects of common photographic controls used by photographers. Experiment sets, each consisting of a number of individual tests, are used to monitor the accuracy of the system with respect to individual factors. Within a given experiment set, a single factor is varied while the values for all other factors remain constant.

A total of nine experiment sets were run. The sets can be categorized by the photographic component whose control is varied (e.g. camera, film, enlarger, paper). The means by which the factor is varied depends upon the nature of each individual control, and can be direct or indirect. For example, camera aperture can be varied directly, simply by changing the aperture setting on the camera lens. Varying the gamma of a film, on the other hand, can be achieved indirectly by varying the processing

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57 This data is listed in Appendix C.

58 For the film scanner, a Kodak Q60 Transmission Test target is used. For the flatbed scanner, a Kodak Q13 Reflection Target is used.
time when developing the negative. A categorized list of experiment sets, with corresponding variable controls, is summarized in Table 8-1 below. Details on each of the experiment sets are given in subsequent sections.

<table>
<thead>
<tr>
<th>Component Tested</th>
<th>Factor tested</th>
<th>Method of variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera</td>
<td>Aperture</td>
<td>Aperture setting</td>
</tr>
<tr>
<td></td>
<td>Exposure time</td>
<td>Exposure setting</td>
</tr>
<tr>
<td>Film</td>
<td>Gamma</td>
<td>Variation of processing time</td>
</tr>
<tr>
<td></td>
<td>Speed</td>
<td>Use of different films</td>
</tr>
<tr>
<td></td>
<td>Grain</td>
<td>Use of different films</td>
</tr>
<tr>
<td>Enlarger</td>
<td>Exposure Time</td>
<td>Exposure setting</td>
</tr>
<tr>
<td></td>
<td>Magnification</td>
<td>Variation of print size</td>
</tr>
<tr>
<td>Paper</td>
<td>Gamma / Speed</td>
<td>Use of different filters during printing</td>
</tr>
<tr>
<td></td>
<td>Grain</td>
<td>Variation of print size</td>
</tr>
</tbody>
</table>

Table 8-1 - List of experiment sets performed

Because most available black and white films are panchromatic, the effect of spectral sensitivity was not considered. In addition, the experiment is designed to focus on the tone of the images produced by the system, rather than the spatial resolution. Thus, the effect of variable MTFs was also not considered in the validation tests.

8.3.2 Image comparisons

When comparing the results of the simulation with actual scanned negatives and prints, comparisons are made on a patch-by-patch basis. Individual patches of the Macbeth Color Checker chart are carefully calibrated as to produce the reported spectral reflectances. The background on which the patches are affixed, however, is not. Thus, accurate spectral reflectance data is only provided for the patch areas.

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59 Although Kodak does make a 35mm infrared film, this film was not included in the experiment set as the spectral reflectances of the test scene in the infrared portion of the spectrum were not available.

60 Since the resolution of most photographic materials far exceeds the resolution of moth display systems, for many applications, spatial resolution is not an issue.
Dealing with photographic images, noisy images are expected. Because of this, a statistical comparison is made, rather than a comparing the images pixel by pixel. For each patch of a scanned negative, scanned print, or simulation result, a 100 x 100 pixel sample is taken. The mean tone and the rms deviation of the grayscale pixel values for each patch sample are computed, and these values are used as the basis for comparison between corresponding patches.

In order to achieve a fair comparison, the images produced by the simulation are modified appropriately to account for the response of the film or print scanner. The measured responses of the scanners are given in Appendix D.

### 8.4 Negative Validation Tests

This section discusses the experiment sets corresponding to the Negative Validation test whose pipeline is illustrated in Figure 8-1. The Negative Validation Tests involves simulation of the first stage of the photographic print process; namely, generation of a negative based on light emitted from the test scene. The photographic components tested in this path are the camera and the film.

#### 8.4.1 Input Scene

A digital version of the Macbeth Color Checker was created and used as the input to the tone reproduction system, with resolution matching that of the scanned negatives. XYZ color values for each patch are obtained from the documentation provided by Gretag-Macbeth and are listed in Appendix B. Spectral reflectance data for each patch, also listed in Appendix B, were obtained from [GLAS95].

In addition to the spectral reflectance data of the test patches, the spectral distribution of the light source also needs to be considered. For this purpose, the spectral density function of a Tungsten-Halogen lamp at 3100° K, illustrated in Figure 2.3, is used to scale the spectral data of each of the patches.

The availability of full spectral reflectance data for the test scene provides a unique opportunity for testing the effectiveness of using trichromatic color values in relation to our photographic simulation. All tests in the negative validation path are run twice, once using the reported XYZ values, and again using the full spectral reflectance data.
8.4.2 Camera Parameters

For experiments in the negative validation path, the settings in Table 8-2 for the camera parameters listed in Table 6-1 are used.

<table>
<thead>
<tr>
<th>Camera Parameter</th>
<th>Parameter setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>Variable, depends on experiment set</td>
</tr>
<tr>
<td>Exposure Time</td>
<td>Variable, depends on experiment set</td>
</tr>
<tr>
<td>Flare</td>
<td>0.0025lux(^{61})</td>
</tr>
<tr>
<td>Focal length</td>
<td>50mm</td>
</tr>
<tr>
<td>OTF</td>
<td>Not considered</td>
</tr>
<tr>
<td>Shutter efficiency</td>
<td>A shutter opening and closing time at full aperture of 1 ms. was used</td>
</tr>
<tr>
<td>Transmittance</td>
<td>0.75, derived from equation 3-17</td>
</tr>
<tr>
<td>Vignetting factor</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 8-2 - Settings for camera parameters required by the simulation

In addition to these camera parameters, the distance from the camera to the test chart (1.5m) and the measured scene radiance of the light source at the camera position (8.66µW/sr-cm\(^2\)) are supplied as input to the simulation.

8.4.3 Film Parameters

Film parameters supplied to the simulation system are all derived from the choice of film used and the processing conditions assumed. For the negative validation path, the Kodak TMAX family of Professional black and white films is used. This family consists of three types of film: TMAX100 (a 100 speed film), TMAX400 (a 400 speed film), and TMAX3200 (a 1000 Speed film\(^{62}\)). All sensitotomic data required by the simulation is obtained from the data sheets published by Kodak. This data is given in Appendix C. Film development is performed manually using a small tank with processing conditions matching those specified on these data sheets. Processing time, which determines the gamma of the film characteristic curve, varies with each individual experiment set, as does the choice of film type.

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\(^{61}\) Flare was estimated from examination of the scanned negative

\(^{62}\) TMAX3200 is actually a variable speed film with speed dependent upon the chemicals used during processing and processing conditions. In our experiments, the film was developed as to maintain a film speed of 1000.
8.4.4 Variable Parameters for Negative Validation Tests

In Table 8-3, the settings of variable parameters for each individual experiment set involving the camera or film are given. These parameters represent common photographic controls, which include camera aperture, camera exposure time, choice of film, and processing time (which, in turn, determines the gamma of the characteristic curve).

<table>
<thead>
<tr>
<th>Test Set/variable factor</th>
<th>Aperture</th>
<th>Exp Time</th>
<th>Film</th>
<th>Process Time</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera Aperture</td>
<td>Varying</td>
<td>1/ 30 sec</td>
<td>TMAX3200</td>
<td>10 min</td>
<td>0.8</td>
</tr>
<tr>
<td>Camera Exposure Time</td>
<td>f5.6</td>
<td>Varying (1/250 - 1/8 sec)</td>
<td>TMAX3200</td>
<td>10 min</td>
<td>0.8</td>
</tr>
<tr>
<td>Film Gamma</td>
<td>f5.6</td>
<td>1/ 15 sec</td>
<td>TMAX400</td>
<td>Varying (5-11min)</td>
<td>Varying (0.5 - 1.0)</td>
</tr>
<tr>
<td>Film Speed</td>
<td>f5.6</td>
<td>1/ 15 sec</td>
<td>Varying (TMAX100/ 400 / 3200)</td>
<td>7min/ 10min&lt;sup&gt;13&lt;/sup&gt;</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 8-3 - Variable parameters settings for camera/film test sets

Since granularity is dependent upon density, settings for the film grain test were chosen such that the average density of the images compared remained constant as the granularity value varied. All of the TMAX films have different granularities; thus, variability in granularity is achieved by the use of different film types. The parameter settings for the individual tests of the Film grain experiment set are given in Table 8-4. Granularity is reported on data sheets as rms granularity using a standard scanning aperture with a diameter of 48µm.

<sup>13</sup> Processing time set as to obtain a constant gamma for all 3 types of films.
8.4.5 Results of Negative Validation Tests

In this section, the results of the experiment sets for the negative validation tests are presented. For tests involving tone (i.e. all tests except for the film grain test set), graphs are presented that display the mean percent differences, amongst all the test patches, between the actual negative tones and tones generated by the simulation. Results of tests performed using XYZ values and full spectral values are shown side by side for each experiment set. 95% confidence intervals of the means are indicated by error bars.

In addition to the graphs, visual results of the simulation, compared side by side with the scanned negatives, are given for each of the test sets. The simulation results shown in these figures are computed using the full spectral reflectance data. In addition, to allow for a fair comparison, the simulated tones have been modified to account for the response of the film scanner. All patches, for both the simulation results and the scanned negatives, have been placed on a uniform background, thus eliminating the effects of surround when making visual comparisons.

For the film grain test, the measured rms of the patch samples of the scanned negative and the measured rms of the samples produced by the simulation are compared. Mean differences amongst all of the test patches are provided in the graph. Rms values on the x-axis represent the rated rms granularity as reported on the data sheets (measured using a scanning aperture with a diameter of 48µm). The values on the y-axis represent rms values of the scanned samples of individual patches (scanned at 1000 dpi). Since granularity is dependent on density, the average tone differences for each of the tests are indicated on the graph as well. Again, error bars are used to indicate 95% confidence intervals of the individual means.
8.4.5.1 Camera Aperture Experiment Set

The results of the camera aperture experiment set, where the opening of the camera aperture is the variable factor, are shown in Figure 8-5. Visual results are shown in Figure 8-6.

![Camera Aperture Experiment Set](image)

As indicated in the graph, differences in this experiment set ranged from 0 - 10% with greater differences evident at larger aperture openings.\(^{64}\) This increase in error is likely due to vignetting effects, not considered in the test runs, which are more likely at larger aperture settings.

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\(^{64}\) Recall that the F-number and the aperture opening are inversely proportional.
Figure 8-6 - Visual results of Camera Aperture Test Set
8.4.5.2 Exposure Time Experiment Set

Results of the Exposure Time Experiment Set are shown in Figure 8-7. In this set, the camera exposure time setting is varied. Visual results of this set are shown in Figure 8-8.

![Camera Exposure Time Experiment Set](image.png)

In this experiment set, the error ranges from –2 to 10%. As with the camera aperture tests, the error is more evident in areas of lower exposure, most likely due to the significant underexposure of images produced using smaller exposure times.
Figure 8-8 - Visual Results of Camera Exposure Test Set
8.4.5.3 Film Gamma Tests

Results for the Film Gamma Experiment set are presented in Figure 8-9. In this experiment set, the gamma of the characteristic curve is varied by varying the processing time of the negative. Gamma values are given on the x-axis of the graph. Visual results for this experiment set are shown in Figure 8-10.

![Graphical results of the film gamma experiment set](image)

Figure 8-9 - Graphical results of the film gamma experiment set

Tone differences for the test runs of this set all lie below 5%, with no significant difference between the error values between individual test runs.
Figure 8-10 - Visual results of film gamma test set
8.4.5.4 Film Speed Tests

Graphical results from the Film Speed experiment set are given in Figure 8-11. In this experiment set, film speed is the variable factor. Variability is obtained by running each individual test using a different film from the TMAX family. Processing times for the films were chosen to maintain a constant gamma of 1.7 amongst the individual test runs. Visual results for this experiment set are presented in Figure 8-12.

The error in the tests from this experiment set ranges from 0 - 10%. The nontrivial variability in error amongst the film speed is not surprising, as each test used a different type of film. Although the three films used in the experiment set are from the same family, each has minor differences in spectral sensitivity and granularity as well as the obvious difference in characteristic curves. A certain amount of variability between the three films is therefore expected.
Figure 8-12 - Visual results of film speed test set
8.4.5.5 Observations about Color

Two interesting observations about color can be made in analyzing the data from the experiment sets above. The first concerns the representation used in describing color in the test scene. In each of the experiment sets above, no significant difference was found between the mean error of individual tests run using XYZ triplets and the mean error of corresponding tests run using full spectral reflectance data.\[^{65}\] This observation indicates that, with regards to our simulation, there is no significant loss of accuracy introduced by approximating color using trichromatic values.

Further analysis on the experiment set data above was performed to discover if there is a relationship between scene color and calculated tone differences. In short, we wished to determine if the simulation works equally well, independent of the colors from the test scene. Mean differences of the tone differences at each color patch of the test scene were calculated from the tests of all of the experiment sets described above. The results are presented in Figures 8-13 and 8-14.

---

\[^{65}\] Mean differences may seem to be a bit greater for tests using XYZ triplets. This trend, however, can be shown to be statistically insignificant using a z-test on the means with a 95% confidence level. (See [FREU80], pg 393.)
In general, the mean error due to each patch ranges from 0 - 10%. The variability of error between patches, however, cannot be considered insignificant. Next, a correlation analysis was performed on the data. In this test, the visible spectrum was divided into 10 regions of 40nm each. The amount of energy present in each region was determined from the spectral reflectance function for each patch. The correlation between each wavelength region and tone difference was then calculated. These results are presented in Figure 8-15.
As the graph indicates, greater error is evident in the middle portion of the visible spectrum. In fact, the shape of the correlation curve is similar to the Photopic Luminous Efficiency Function shown in figure 2-2. Since photography is defined using photometric units, and all light quantities used by the simulation are scaled by the luminous efficiency function, this similarity is not surprising. Since light with high luminous efficiency contributes more to the results of the simulation, it is expected that light at these highly efficient wavelengths will also contribute more to tone differences.

Another interesting observation from Figure 8-15 is the negative correlation between color at the higher wavelengths and error for tests run using XYZ data, as opposed to full spectral data. Although these negative correlations are not statistically significant, the correlation difference between corresponding values for tests run using full spectral data is worth noting. Considering the XYZ color matching curves (Figure 2-6), data in this high wavelength area is not well represented by XYZ color triplets. Also, considering the fact that there is no significant difference between the error from simulations using XYZ data vs. full spectral reflectance data, we can conclude that the energy in this area of the spectrum is also not very significant and does not contribute much to the accuracy of our simulation.
8.4.5.6 Film Grain Experiment Test

In Figure 8-16 below, graphical results of the Film Grain Experiment Set are given. In this experiment set, film granularity is the variable factor. Variability is achieved by the use of different films, each with a different rated granularity value. Since granularity is dependent on density, exposure, aperture settings, and processing times were chosen as to maintain a constant average density among the compared images from individual tests. (See Table 8-4).

Visual results for this experiment set are presented in Figure 8-17. Unlike the visual results of the previous tests, for the film grain tests, only the patches on the bottom row of the test chart are presented. These patches are enlarged in order to provide easier comparison of the grain effects.

![Film Grain Experiment Set](image)

Figure 8-16 - Graphical results from the film grain experiment set

At first glance, the results presented in Figure 8-16 seem not as promising as the results from the other experiment sets. For example, consider the data for the low grain film (rms granularity of 8) where the rms difference is almost 50% of the actual rms of the scanned negative. However, accounting for the difference in tone between the simulation result and the actual negative, this difference is not surprising. As the graph clearly indicates, the difference in measured sample granularity is proportional

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66 These patches represent neutral grays in the test scene ranging from black to white.
to this mean tone difference. This is predictable, given the relationship between granularity and density.

Examination of the visual results presented in Figure 8-17 shows that despite the large percentage of error, even with the low grain film test, the difference in graininess of the samples is not very noticeable. This is to be expected, as the real effect of grain is far more visually evident in the print rather than the negative.

8.5 Print Validation Tests
The Print Validation Tests involve simulation of the second stage of the photographic print process, namely generation of a print given a negative. In these tests, the photographic components tested are the enlarger and the paper.

8.5.1 Input Image
In order to localize tone differences as resulting from the printing portion of the pipeline, for tests involving tone comparisons, a scanned negative is specified as input and used as a transparency mask for the test in these experiment sets. The image is transformed by the inverse of the film scanner response curve assuring that the effects of the scanning process are not propagated into the simulation.

Using a scanned negative as input to the simulation will result in grainier images produced as output since the grain is already inherent within the negative. In addition, the effects of magnification and print through granularity cannot be easily considered. Because of this, for the print grain test set, both stages of the simulation (negative processing and print processing) are run using the full spectral scene data as input.

In order to correctly model the process using a scanned negative as input, either the size of the resultant image would have to be increased to account for the simulated magnification, or the grain would have to be removed from the negative prior to running the simulation.
Figure 8.17 - Visual results of Film Grain Experiment Set
8.5.2 Enlarger Parameters

Settings used for the enlarger parameters required by the simulation (see Table 6-1) are given in Table 8-5.

<table>
<thead>
<tr>
<th>Camera Parameter</th>
<th>Parameter setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture</td>
<td>Depends on experiment set</td>
</tr>
<tr>
<td>Exposure Time</td>
<td>Variable, depends on experiment set</td>
</tr>
<tr>
<td>Flare</td>
<td>0.0</td>
</tr>
<tr>
<td>Focal length</td>
<td>50mm</td>
</tr>
<tr>
<td>OTF</td>
<td>Not considered</td>
</tr>
<tr>
<td>Magnification</td>
<td>Variable, depends on experiment set and determined by print size.</td>
</tr>
<tr>
<td>Transmittance</td>
<td>1.0</td>
</tr>
<tr>
<td>Vignetting factor</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 8-5 - Settings for camera parameters required by the simulation

Enlarger parameters varied in the experiment sets include exposure time and magnification. The magnification factor is determined by the print size. When varying the magnification, prints were created that approximate the standard print sizes of 8” x 10”, 5” x 7”, and 3” x 5”.

There is great disparity in illumination between different types and brands of enlargers. Print enlarging is more of an art than an exact science. Usually, the photographer determines the proper exposure setting for a particular enlarger and for a particular print by trial and error rather than by making radiometric measurements [VEST84]. For the purposes of our validation, however, radiometric quantities are required. For our particular enlarger, direct measurement of radiance behind the lens was difficult. Instead, a measurement of the irradiance in front of the lens for an 8x10 enlargement with an aperture setting of 5.6 was made. The radiance emitted by the enlarger’s light source was then estimated by application of Eqn. 3-21. The radiance value used for the enlarger experiment sets was estimated as $307 \mu W/cm^2\cdot sr$.

During the enlargement process, especially for large magnifications, the effects of natural vignetting ($\cos^4$ falloff) become quite evident. These vignetting effects become more problematic in practice as the center of the print is not always aligned with the center axis of the lens from which the $\cos^4$ falloff is calculated. For purposes of the validation, the offset from the center of the print area and the
center lens axis is measured and supplied to the system as a simulation parameter. Falloff values for each test run were confirmed via radiometric measurements.

8.5.3 Paper Parameters
Kodak PolymaxII RC Professional Black and White paper is used as the paper in this suite of experiment sets. Polymax II is multicontrast, multispeed paper, with variable characteristic curves dependent upon the spectral properties of the light source. A variety of gamma and speeds can be obtained by using this paper in conjunction with a standard set of Kodak Polymax filters similar to those described in Section 3.2.2. In the experiment set for paper speed and gamma, three combinations of speed and gamma are simulated, each corresponding to the characteristic curve resulting from the use of a given Polymax filter during printing. These characteristic curves are provided in Appendix C and the speed and gamma values are summarized in Table 8-6.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Gamma</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (white light)</td>
<td>1.7</td>
<td>400</td>
</tr>
<tr>
<td>#2</td>
<td>1.4</td>
<td>200</td>
</tr>
<tr>
<td>#4</td>
<td>2.8</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 8-6 - Effects of Polymax filters on paper speed and gamma

Being a resin coated paper, Polymax II RC paper is appropriate for automatic development using an activation development machine. Such a processor, the Kodak RoyalPrint Processor (Model 417), is used to develop the prints for this suite of experiment sets.

8.5.4 Variable Parameters for Print Validation Tests
In Table 8-7, the settings of the variable parameters for each individual experiment set involving the enlarger and paper are given. Variable controls include enlarger exposure time settings and magnification (which is determined by the print size), and paper speed/gamma (which are controlled by the filter used during printing).

The effects of print grain are most evident when comparing prints made from negatives with different levels of graininess. Print grain validation is performed by simulating the printing process using negatives with different granularity values. Again, for the print grain experiment set, both the negative
and print creation processes are simulated. The films and film processing conditions for the Film Grain experiment set are used as film related input to the simulation for this experiment set.

<table>
<thead>
<tr>
<th>Test Set/Variable factor</th>
<th>Aperture</th>
<th>Exposure Time</th>
<th>Magnification</th>
<th>Filter</th>
<th>Gamma</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enlarger Exposure Time</td>
<td>f5.6</td>
<td>Varying 10-25 sec</td>
<td>13.25 (8x10)</td>
<td>None</td>
<td>1.7</td>
<td>400</td>
</tr>
<tr>
<td>Enlarger Magnification</td>
<td>f5.6</td>
<td>15 sec</td>
<td>Varying 13.25-7.0 (8x10, 5x7, 3x5)</td>
<td>None</td>
<td>1.7</td>
<td>400</td>
</tr>
<tr>
<td>Paper Speed/ Gamma</td>
<td>F5.6</td>
<td>15 sec</td>
<td>13.25 (8x10)</td>
<td>Varying None, #2, #4</td>
<td>Varying 1.7 - 2.8</td>
<td>Varying 100-400</td>
</tr>
<tr>
<td>Paper Grain</td>
<td>F11</td>
<td>15 sec</td>
<td>8.0 (5x7)</td>
<td>None</td>
<td>1.7</td>
<td>400</td>
</tr>
</tbody>
</table>

Table 8-7 - Variable parameters for test in Print Validation Path

8.5.5 Results of Print Validation Tests

The numerical results of the experiment sets for enlarger and paper controls are presented in this section. Like with the graphs in Section 8.4.5, except for the paper grain test results, the graphs display the mean percent differences between the actual print tones and tones generated by the simulation amongst all the test patches. 95% confidence intervals are indicated by the error bars.

Graphical results for the paper grain set show the mean differences of the measured rms between the print and simulation results over all of the color patches. The mean rms values amongst the patches of the actual scanned print are also provided on the graph.

Visual results of the simulation, compared side by side with the scanned prints are also provided. The images presented in these visual results have been modified in a manner similar to the visual results presented in Section 8.4.5, accounting for the response of the flatbed scanner.

8.5.5.1 Enlarger Exposure Time Experiment Set

Figure 8-18 shows the results from the Enlarger Exposure Time Experiment Set, where the print exposure time is varied. Visual results are presented in Figure 8-20.
8.5.5.2 Enlarger Magnification Experiment Set

Graphical results from Enlarger Magnification Experiment Set are given in Figure 8-19. In this experiment set, the magnification factor is varied by changing the size of the resultant print. Both the magnification factor and the approximate print size are listed on the x-axis of the graph. Visual results for this experiment set are presented in Figure 8-21.
Figure 8-20 - Visual results for enlarger exposure experiment set
Figure 8-21 - Visual results from enlarger magnification experiment set
8.5.5.3 **Paper Speed/ Gamma Experiment Set**

In Figure 8-22, graphical results for the Paper Speed/Gamma Experiment Set are presented. Variability in the paper characteristic curve is achieved by use of specially defined filters during printing. On the graph, the filter used, and the speed and gamma of the resultant curve, are listed. Note that in this experiment set, an additional transparency factor is used to scale the enlarger source radiance, thus accounting for the loss of light due to the absorption of the filter.

Visual results for this experiment set are given in Figure 8-23.
Figure 8-23 - Visual results for paper speed/gamma experiment set
8.5.5.4 Paper Grain Experiment Set

Graphical results for the Paper Grain Experiment Set are provided in Figure 8-24. In this experiment set, final print grain is varied by varying the granularity of the negative used in producing the print. For tests in this experiment set, both the negative and print creation processes are simulated by the system. Film parameter values are identical to those used in the Film Grain Experiment Set (Section 8.4.5.6).

Visual results for this experiment set are presented in Figure 8-25. Similar to the visual results of the film grain experiment set, the bottom row of the test chart is enlarged in order to aid in making the visual comparison.

The results from the print grain experiment set are a bit more promising than that of the film grain experiment set with rms differences ranging from 7 - 20% of the measured rms values for the scanned prints. Considering the values in the confidence intervals, this difference can be as high as 50% for any given patch. Despite the high difference values, as observable from the visual results, the structure and quantity of the grain in the simulated prints closely match that of their actual print counterpart. A noticeable blurring of the grain, however, is evident in the scanned print but not in the simulation. As a result, the simulation results take on more of a synthetic quality compared to actual prints. This
blurring is a result of the OTF of the enlarger lens, which was not considered during the simulation. These results serve to illustrate the importance of proper spatial filtering when simulating magnification from a photographic negative or slide.

### 8.6 Discussion

Overall, the validation tests illustrate that the simulation can produce visually satisfying results that match closely with actual negatives and prints. Considering merely the numerical results, however, the results of the validation may not seem to be as positive. These numerical results, for tests run with full spectral input, are summarized in Table 8-8. For each experiment set, the range of mean error percentages between the real and synthetic images is given. For tests involving grain, the range of rms differences is listed. Noted observations about individual test sets are provided in the notes column.

<table>
<thead>
<tr>
<th>Experiment Set</th>
<th>Mean Error Range</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Camera/ Aperture</td>
<td>1.1% - 7.8%</td>
<td>Variation among individual tests due to lens vignetting.</td>
</tr>
<tr>
<td>Camera/ Exposure Time</td>
<td>0.7% - 8.2%</td>
<td>Variation among individual tests due to underexposure of images with low light levels</td>
</tr>
<tr>
<td>Film / Gamma</td>
<td>0.5% - 2.3%</td>
<td>Consistently good results amongst all tests.</td>
</tr>
<tr>
<td>Film / Speed</td>
<td>2.2% - 8.2%</td>
<td>Variation among individual tests due to variable film types</td>
</tr>
<tr>
<td>Film / Grain</td>
<td>0.05 – 0.6</td>
<td>Rms error proportional to tone differences.</td>
</tr>
<tr>
<td>Enlarger/ Exposure Time</td>
<td>1.3% - 5.6%</td>
<td>Consistently good results amongst all tests.</td>
</tr>
<tr>
<td>Enlarger / Magnification</td>
<td>1.3% - 4.6%</td>
<td>Consistently good results amongst all tests.</td>
</tr>
<tr>
<td>Paper/ Speed-Gamma</td>
<td>2.3% - 6.5%</td>
<td>Consistently good results amongst all tests.</td>
</tr>
<tr>
<td>Paper/ Grain</td>
<td>0.04 – 0.6</td>
<td>Rms error proportional to tone differences. Blurring due to OTF is noticeably lacking in simulation results.</td>
</tr>
</tbody>
</table>

Table 8-8: Summary of validation results
Figure 8-25 - Visual results of Paper Grain Experiment Set

Using TMAX100 Film (rms 0.008)

simulated

actual

Using TMAX400 Film (rms 0.010)

simulated

actual

Using TMAX3200 Film (rms 0.018)

simulated

actual
Analysis of the data in Table 8-8 raises the question of the proper threshold for error differences to be used in such a study. Due to the variable nature of the photographic development process, some degree of error is expected. However, how good is good enough? Is a 10% difference in tone values or a 50% difference in grain rms perceptually significant? The answer to this question, of course, will depend upon the nature of the application to which the validation results are applied, and factors such as viewing distance, magnification, viewing conditions, etc. A logical next step for analysis of the data from these experiments, or others like it, might be the development of perceptual guidelines that can be used to gauge the effectiveness of the simulation system for given applications.

Tests from the Print Validation path gave exceptionally good results. This is to be expected, given the careful measurement of the irradiance emitted by the light source on the surface of the paper. In general, enlargers are somewhat difficult to model and this type of radiometric information will not always be available. This need for careful measurement of the enlarger illumination is only one example of the importance of data accuracy in performing this type of validation. The characteristics of an enlarger can vary greatly, not only between manufacturers and models, but also between individual units of the same model. This is also true with photographic materials. Although manufacturers do provide sensitometric data for photographic products, these curves are meant merely as guidelines. Results may vary between materials manufactured at different times or even among materials from the same manufacturing lot.

These validation experiments bestow a deep appreciation for the extreme variability of photographic image formation. Because of this variability, extreme care must be taken for applications that require precise comparisons between simulation and reality (e.g. the use of photographic simulation for benchmarking the effectiveness of rendering algorithms). For such applications, a more controlled development and printing method should be employed that makes use of well-defined photographic processes and photofinishing machinery. Many of the photographic controls are lost taking this alternate approach, however, applications that require a high level of numerical accuracy, most likely are not concerned with creative control that can be applied in the darkroom. In addition, more careful sensitometric measurements of the actual materials used in the experiments should be performed (as opposed to obtaining general measurements from manufacturer's data sheets). Finally, rather than using film and flatbed scanners, which do not have a perfectly linear response, densitometers, which
accurately measure reflective and transmission density, should be used in generating a digital version of a physical negative or print.
9 SUMMARY AND CONCLUSIONS

In this dissertation, a system for tone reproduction, based on the principles of photography, was presented. This work presents an alternate approach to the tone reproduction problem in Computer Graphics. Whereas most work in this area focuses on simulating the response of the human visual system, our system, based on the success of photography over the past century, uses photography as the basis for converting scene illuminances to image tones. Using this approach, models of human vision, necessary in traditional tone reproduction pipelines, can be replaced by a model that simulates the photographic processing. Being a physical rather than perceptual process, the mechanisms of photography can be modeled more easily than the human visual system. At the same time, human perception is not ignored, as the mechanisms of photography have been fine-tuned to produce images for optimal viewing pleasure and accuracy.

The system is based on a simulation of photographic processes, whereby each component of a photographic system (e.g. camera, enlarger, film, and photographic paper) is individually modeled. System parameters are chosen to match closely with the choices available to photographers in actual photographic situations, thus enabling the effects of these choices to be applied to computer generated images.

Informal tests using the system yielded predictable results, where the relationship between the photographic parameters modified and the final simulated prints was maintained as expected.

These relationships are further confirmed through formal validation experiments, whereby results of the simulation are compared with actual negatives and photographic prints. Overall, visual inspection of the validation results illustrates that the simulation can produce satisfying results that match closely with actual negatives and prints.
In consideration of the numerical validation results, however, the importance of the subtleties of the photographic process as well as the use of the full set of model parameters must be emphasized. Subtleties such as lens vignetting and optical blurring, although not directly controlled by the photographer, can play an important part in the accuracy of a simulation. A full characterization of the printing and enlarging system to be simulated is also required to insure simulation precision.

The positive visual results seem to indicate that the structure and architecture of the proposed model is sound. The use of accurate data during the simulation, however, is essential for obtaining favorable validation results. Because of the great variability in the photographic development process, a great deal of great care is required when choosing the sensiotomic data to be supplied as input to the simulation system. Sensiotomic data published in manufacturer’s data sheets may not be precise enough for certain applications. Instead, individual measurements of the particular materials used in a validation test may be necessary. Additional care must also be taken during photographic processing to assure that the data used in the simulation reflect the processing conditions used when collecting the data.

Even with the discrepancies discussed above, the system adequately simulates photographic responses, thus allowing the controls of photography to be applied to computer generated imagery and, as a result, provides a convenient means for experimenting with different photographic parameter settings. The system can be used to instantly explore the result of a particular set of photographic choices, thus eliminating the need to spend countless hours experimenting in a physical darkroom. The system also saves on the cost of photographic materials that would be used during such experimentation.

9.1 Potential Applications

The proposed photographic simulation system may be useful in a variety of different applications. Several of these applications are discussed below.

9.1.1 Photographic Education and Experimentation

Although there are volumes of how-to books published on photography, the most effective means of learning photography is by doing. In the introduction of his series on photography, a series that is considered as one of the most comprehensive, Ansel Adams writes:
"The reader must bear in mind that what these books are intended to accomplish is to present a concept (visualization) and a modus operandi (craft) to achieve desired results. This is obviously directed to serious participants in photography, but it should not be interpreted as dogma; each artist must follow his own beacons and chart his own journey over the medium's seas and deserts” [ADAM81b]

One inherent problem with this “learning by doing” approach is the investment in time, money, and materials required to perform all of these trial and error discoveries. The initial motivation behind the development of this model, and the creation of the Virtual Darkroom application, was to allow for photographic experimentation using a computer. This would allow one to learn the principles of photography, while at the same time eliminating the need to purchase loads of photographic materials and spend hours in the darkroom.

VDR was originally developed with the novice photographer in mind. However, the system could be just as useful for professionals who are experimenting with new techniques, materials, or processes. It remains to be seen if “digitally processed” images produced by a system like the one described in this dissertation could match the quality requirements of a seasoned professional. However, a system like VDR can most certainly be useful as a guide for narrowing down the range of possible photographic choices.

9.1.2 Validation of Rendering Algorithms

For over 25 years, one of the goals of the Computer Graphics community has been the accurate simulation of the transport of light in a virtual scene. Validation of rendering algorithms developed for this purpose has proven to be a challenging task as the light emitted from an actual scene must be carefully measured and compared with its virtual counterpart. Approaches taken for this type of validation includes comparison by visual inspection [MEYE86] and direct illumination measurement of the test space [RUSH95, BOUG91, BELL93]. Both of these methods require a great deal of overhead: the first method requiring a set of volunteer observers, and the later requiring careful placement of light measuring devices within the test scene. Under the assumption that a
photographic simulation model can perform within an acceptable degree of accuracy\textsuperscript{68}, a simpler methodology for performing validation of rendering algorithms can be developed whereby a photograph of the test space is used to gauge the light levels in the real scene. The photographic simulation can be applied to the synthetically rendered image using the same photographic parameters used when capturing the real scene on film. The resultant image can then be directly compared with the real photo thus providing a metric for comparison between the lighting in the real and virtual spaces.

\textbf{9.1.3 Digital Cinema}

With advances in digital technology, it has now become feasible for motion pictures to be filmed, edited, processed and projected without the use of photographic film. Photography as a means for scene capture, although effective, is far from perfect. The graininess and blurring inherent with photographic capture and display gives photos, and more importantly, motion pictures a characteristic look. Digital technologies can eliminate these artifacts and produce a clearer, crisper, and more realistic depiction of a scene. This can be considered both an advantage and a shortcoming. Although photography produces these artifacts, they are artifacts that a movie-goer expects to see. Furthermore, filmmakers, many times, can exploit these artifacts to achieve a particular artistic effect (e.g. as described in [FIEL85] or [CLAR64]). A system, as that described in this work, can be used a part of a digital cinema pipeline to essentially replace the artifacts removed by moving the motion picture process into the digital domain. This way, a filmmaker can work using a digital medium, yet still work within the parameter space of photography, a space to which he/she might be more accustomed.

\textsuperscript{68} System accuracy is discussed further in Section 9.2.5.
\section*{9.2 Future Work}

The system presented in this dissertation serves merely as an introduction to the ways photographic knowledge can be applied to the image synthesis process. Having shown the advantage of this approach in the limited scope of this thesis, there are many future directions that this work can follow. Several of these future directions are discussed below.

\subsection*{9.2.1 Extension to Color}

The most obvious enhancement to this work would be the extension of the model to simulate color as well as black and white photography. Color photography is an extension of black and white photography, where the materials consist of three separate layers of emulsion, each sensitive to light from different regions of the visible spectrum. The system could, in a very straightforward manner, be modified to simulate the processing on three separate image planes, each with its own set of sensiotomic curves, representing each emulsion layer of the color material.\footnote{This approach is taken by Rob Gougher in his Masters Thesis\cite{Goug99}.}

There are several challenges that must be overcome to assure accuracy of such an extension. For example, interactions between the emulsion layers will have to be correctly modeled. In addition, several of the assumptions made for black and white photography break down when considering color materials. Most notably, the Selwyn Granularity measure is inappropriate for use with color films due to the nature of color emulsion. Color materials have their own separate measure, the print grain index, for describing granularity that would have to be incorporated into the extended system. Finally, issues in color management whereby computed color values may lie outside the gamut of a given output device, will have to be addressed.

\subsection*{9.2.2 In-depth MTF Analysis}

Although MTFs and spatial resolution are considered by the model, a great deal of emphasis was not placed on the effects of the MTF since, for many applications, these effects would be negligible.

During the print validation process, however, the importance of considering the effects of the MTF in cases where enlargement is performed, became evident. This problem will only multiply when considering simulation of projection systems whereby the magnification factor is far greater than that.
of printing systems (e.g., consider simulating the projection of motion picture film for display on a
digital cinema system).

For these applications, inclusion of MTF effects is not only beneficial, but absolutely essential. Future
work on modeling the effects of the MTFs with respect to particular applications should be
undertaken to determine the relationship between a particular output device and the correct level of
MTF modeling required.

9.2.3 Visual Thresholds for Error
As mentioned in the validation section, analysis of the numerical results of the validation is somewhat
subjective, as the perceptual thresholds for error in tone and grain are not clearly specified. A useful
enhancement to this work would be the development of guidelines, based on perceptual studies, which
could be used to gauge the effectiveness of the simulation system for a given application.

9.2.4 Modeling of Creative Photographic Techniques
The main premise of this work is that the computer graphics community should be able to take
advantage of the wealth of knowledge in the photographic arena and apply it to the tone reproduction
problem. Our system successfully addresses the use of scientific photographic knowledge by defining
a model based on a set of photographic parameters.

The next step would be to model some of the more creative controls developed by photographers.
Incorporation of advanced photographic techniques (e.g. the use of the Zone System [ADAM82b] or
the effective use of photographic filters) would not only provide heuristics for determining effective
values for system parameters, but would also allow the creative methods of the photographic world to
be more easily applied to computer generated imagery.

9.2.5 More Rigorous Validation Methods
Although the results of the validation presented in Chapter 8 are promising, a number of shortcomings
of the validation method were identified. These shortcomings make the procedure somewhat
inappropriate for use in applications where a high degree of accuracy is required (e.g. the validation of
rendering algorithms discussed in Section 9.1.2). For such applications, it would be useful to redefine
the validation methodology using more rigorous procedures and running the simulation using more accurate sensiotomic measurements.

As previously discussed, the validation method described in Chapter 8 can be improved in a number of ways. First, a more automated means of photographic processing of the test material should be employed. The use of automated photofinishing machinery could reduce the error introduced by manual processing as the processing temperature, time, and chemical mixes would be mechanically and electronically controlled. Secondly, direct measurements of the materials to be simulated should be taken rather than relying on curves published in manufacturer’s data sheet. This could reduce the error due to variability of materials manufactured at different times. Finally, the use of macro and micro-densitometers should be used in creating the digital images to which the simulation results are compared. This will correct the non-linearity introduced into the process by the use of scanners for this purpose.
BIBLIOGRAPHY


APPENDIX A – THE VIRTUAL DARKROOM (VDR)

A.1 Code Organization

The Virtual Darkroom is an application, written in Java2, that implements the simulation system presented in this dissertation. The implementation consists of 100 separate classes organized into a number of Java packages as listed below. Note that VDR was implemented before the introduction of the Java Advanced Imaging (JAI) libraries[SUNM99]. The JAI package supports an image pipeline architecture and provides functionality that had to be independently developed for VDR. Now that the JAI libraries are being freely distributed by Sun, it would be beneficial to base any future versions of VDR on this package.

- vdr.awt - Contains classes defining all GUI widgets used by the application. This package includes vdrApp, the main class for the application.
- vdr.awt.igraph - General classes that are used in defining the behavior of editable graphs (e.g. characteristic curves, MTF, spectral response curves). See Section A.3 for examples of such graphs.
- vdr.fft - Classes that perform FFT and inverse FFT operations. The functionality of classes in this package are now available with JAI libraries.
- vdr.io - Classes that deal with the reading and saving of files used by VDR. This includes classes that read PPM image files as well as parse film and paper files stored on disk.
- vdr.model - Classes representing the various photographic components that are modeled by the system.
- vdr.model.film - Classes representing standard films types.
- vdr.model.paper - Classes representing standard paper types.
• vdr.pipeline - Classes implementing an image processing pipeline architecture. Classes providing this kind of functionality are now available in the JAI library.

• vdr.util - General utility classes.

A.2 Command Line Options

VDR is invoked by issuing the following command:

```
java vdrApp [options] infile outfile
```

where infile is the name of the file to be processed and outfile indicates the name of an image file where the simulation results will be stored. For sake of convenience, VDR only supports PPM (portable pixmap) as an image file format.\(^7\)

Options are supplied as flag / value pairs. The values associated with an option can either be a floating point number, a string, or a boolean value, depending upon the nature of the option. Boolean values are specified by the strings “true” and “false”.

- `-a <f-stop>` sets the camera aperture to the option argument (default: 5.6)
- `-b <brightness>` sets the scene brightness to the option argument. Expressed in cd/m\(^2\). (default: 300.0)
- `-B <true/false>` indicates whether the application should be run in batch mode. If the value of this option is true, no GUI will be displayed and the simulation results will be immediately written to the specified output file. (default: false)
- `-e <exposure time>` sets the camera exposure time setting to the option argument (default: 0.0333)
- `-Ea <f-stop>` sets the enlarger aperture to the option argument (default: 11.0)

\(^7\) PPM was chosen for its simplicity. In addition, many imaging applications such as Photoshop or Paint Shop Pro support conversion of files to PPM format.
-Eb <brightness> sets the brightness of the enlarger light source to the option argument. Expressed in cd/m² (default: 300.0)

-EE <exposure time> sets the enlarger exposure time setting to the option argument. (default: 15.5)

-f <filmfile> specifies the name of a file containing data about the film to be used during the simulation. (default: Default VDR film, based on data from Kodak TMAX 3200 film)

-M <magn factor> sets the magnification factor used in simulated printing to the option argument. (default: 1)

-N <true/false> indicates whether the input file should be interpreted as a negative. By default, the input image is assumed to represent the scene being captured.

-p <paperfile> specifies the name of a file containing data about the paper to be used during the simulation. (default: Default VDR paper, based on data from Kodak Polymax II RC Paper)

-Pr <true/false> indicates whether full print processing should be performed. If the option value is false, the system will produce a virtual negative rather than a virtual print. (default: true)

-pT <proctime> sets the film processing time to the option argument. (default: default processing time as defined in film file)

-r <dpi> sets the assumed output resolution (in dots per inch) to the option argument (default: screen resolution)

A.3 GUI Components

When invoked in interactive mode, system and simulation parameters can be specified via the use of GUI widgets. In this section, screen captures of the various VDR interface windows are illustrated.

Figure A-1 shows the main VDR window. The main window displays the current values of the main simulation parameters.
When running VDR in interactive mode, both the original image and the results of the simulation are displayed in separate windows. This is also illustrated in Figure A-1.

Parameters for individual photographic components are modified via component editors. Each editor is contained within its own Frame and consists of a number of tabbed panes, one pane for each editable parameter.

Figure A-2 through A-4 show the panes for the Camera Editor. This editor allows for the specification of scene brightness, camera aperture, and camera exposure time.
Figure A-2 Control pane for scene brightness

Figure A-3 Control pane for Camera Exposure Time
Figures A-5 through A-7 show the control panes for editing of Enlarger parameters. The Enlarger Editor allows for the specification of exposure time, aperture, and magnification.
Figures A-8 through A-11 illustrate the control panes provided by the Film and Paper Editors. These editors allow for interactive specification of the sensitometry data used by the simulation. Note that in panes displaying a curve, points surrounded by the squares can be adjusted by clicking on the point and dragging it up and down in the y direction. The distance between sample points for characteristic
curves and spectral response curves can be specified by the user. In addition, spectral response curves and MTF curves can be displayed on either a linear or log-log scale.

Figure A-8 Characteristic Curve Editor

Figure A-9 - Spectral Response Curve Editor
Figure A-10 – Modulation Transfer Function Editor.

Figure A-11 – Granularity Editor
Curve editors also allow for direct input for values at sample points. The numeric input mode of the characteristic curve editor is shown in Figure A-12.

![Characteristic Curve Editor in Numeric Mode](image)

Other system parameters can be specified through the System Options Editor. The editing panes for this editor are shown in Figures A-13 through A-15.
Figure A-13 Input Specification Pane of System Option Editor

Figure A-14 – Output resolution pane of System Options Editor
Figure A-15 - Processing pane from System Options Editor.
In the Table below, the xyY values for the patches of the Macbeth Color Checker Chart are given. These values are obtained directly from Gretag-Macbeth who manufactures the test chart.

Full spectral reflectances are graphed in Figures B-1 thru B-4. These values are obtained from the Appendix of [GLAS95].

<table>
<thead>
<tr>
<th>Patch color</th>
<th>x</th>
<th>y</th>
<th>Y</th>
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<td>.350</td>
<td>10.1</td>
</tr>
<tr>
<td>Light skin</td>
<td>.377</td>
<td>.345</td>
<td>35.8</td>
</tr>
<tr>
<td>Blue sky</td>
<td>.247</td>
<td>.251</td>
<td>19.3</td>
</tr>
<tr>
<td>Foliage</td>
<td>.337</td>
<td>.422</td>
<td>13.3</td>
</tr>
<tr>
<td>Blue Flower</td>
<td>.265</td>
<td>.240</td>
<td>24.3</td>
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<tr>
<td>Blueish Green</td>
<td>.261</td>
<td>.343</td>
<td>43.1</td>
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<tr>
<td>Orange</td>
<td>.506</td>
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<td>Purplish Blue</td>
<td>.211</td>
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<td>Moderate red</td>
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<td>.306</td>
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<td>.285</td>
<td>.202</td>
<td>6.6</td>
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<tr>
<td>Yellow Green</td>
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<td>.489</td>
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<tr>
<td>Orange yellow</td>
<td>.473</td>
<td>.438</td>
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<tr>
<td>Blue</td>
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<td>Green</td>
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<td>Red</td>
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</table>

Table B-1 - xyY color values for Macbeth Color Checker patches
Figure B-1 – Full spectral reflectance for Macbeth Color Checker - Tones

Figure B-2 – Full spectral reflectance for Macbeth Color Checker - Primaries
Figure B-3 – Full spectral reflectance for Macbeth Color Checker – Row 1

Figure B-4 – Full spectral reflectance for Macbeth Color Checker – Row 2
APPENDIX C - FILM AND PAPER DATA

This Appendix contains the sensiometric data for the films and paper used in the validations described in Chapter 8.

All spectral response curves have been scaled such that the response at 560nm equals 1.0. RMS granularity values measured with a 48µm aperture.

C.1 TMAX 100 Film

Data obtained from Kodak Publication F-32, July 1999.

**Figure C-1 Characteristic Curve for TMAX100 film**

**Figure C-2 Spectral Response Curve for TMAX100 film**

**Rms Granularity : 8 (x 1000)**
C.2 TMAX 400 Film

Data obtained from Kodak Publication F-32, July 1999.

![Characteristic Curve](image)

Figure C-3 Characteristic Curves for TMAX400 film

![Spectral Response](image)

Figure C-4 Spectral Response Curve for TMAX400 film

**Rms Granularity**: 10 (x 1000)
C.3 TMAX 3200 Film

Data obtained from Kodak Publication F-32, July 1999.

**Figure C-5** Characteristic curve for TMAX3200 film

**Figure C-6** Spectral Response Curve for TMAX3200 film

**Rms Granularity**: 18 (x 1000)
C.4 PolymaxII RC paper

Data obtained from Kodak Publication G-26, June 1996.

Figure C-7 – Characteristic curves for Polymax II RC Paper
APPENDIX D - SCANNER RESPONSES

In this Appendix, the measured responses of the film and flatbed scanners used in the validation experiments are given.

D.1 - Kodak RFS 2035 Film Scanner

The Kodak Q60 Transmission target was used to measure the following response.

![Film Scanner Response](image)

Figure D-1 – Measured response of RFS2035 Film Scanner
D.2 - PlusTek Optic Pro 4831P Flatbed Scanner

The Kodak Q13 reflection target was used to measure the following response.

![Flatbed Scanner Response](image)

Figure D-2 Measured response of Plustec Optic Pro 4831P Flatbed Scanner