Artist material BRDF database for computer graphics rendering

Justin Ashbaugh

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Artist Material BRDF Database for Computer Graphics Rendering

by

Justin C. Ashbaugh

B.A. University of Colorado, Boulder, Colorado, 2003

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science in Color Science

College of Science
Rochester Institute of Technology
Rochester, New York
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The M.S. Degree Thesis of Justin C. Ashbaugh has been examined and approved by two members of the Color Science faculty as satisfactory for the thesis requirement for the Master of Science degree.

Dr. Roy S. Berns, Thesis Advisor  Date

Dr. James A. Ferwerda  Date
Artist Material BRDF Database for Computer Graphics Rendering

by

Justin C. Ashbaugh

Abstract
The primary goal of this thesis was to create a physical library of artist material samples. This collection provides necessary data for the development of a gonio-imaging system for use in museums to more accurately document their collections. A sample set was produced consisting of 25 panels and containing nearly 600 unique samples. Selected materials are representative of those commonly used by artists both past and present. These take into account the variability in visual appearance resulting from the materials and application techniques used. Five attributes of variability were identified including medium, color, substrate, application technique and overcoat. Combinations of these attributes were selected based on those commonly observed in museum collections and suggested by surveying experts in the field.

For each sample material, image data is collected and used to measure an average bi-directional reflectance distribution function (BRDF). The results are available as a public-domain image and optical database of artist materials at art-si.org. Additionally, the database includes specifications for each sample along with other information useful for computer graphics rendering such as the rectified sample images and normal maps.
i. ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

The primary goal of this thesis was to create a physical library of artist material samples. The objective in creating these samples ties into a larger research effort to develop a practical imaging goniospectrometer, capable of capturing bi-directional reflectance distribution function (BRDF) data, for use in a museum setting. For each artist material sample, the set of images obtained using the MCSL Imaging Goniospectrometer are used to estimate BRDF data for each of the various materials. This BRDF data provides a basis for model development that can be used to simplify the gonio-imaging workflow and make it feasible for use in a museum setting. The collection of samples aims to be representative of materials and techniques seen in museum collections. That is, these samples are not a comprehensive collection of all artist materials, but rather a representative set of the most common materials used by artists both past and present.

The second goal of this research project was to use the BRDF measurements obtained using the Imaging Goniospectrometer in the development of a public-domain image and optical database of artist materials. BRDF databases such as MERL\textsuperscript{1,2} and CUReT\textsuperscript{3,4} contain BRDF data for many common materials, but there is a lack of BRDF data available for artist materials. The BRDF data for artist material samples may prove useful in computer graphics applications when creating virtual environments that include artwork. The database includes BRDF data for artist materials along with the raw images captured with the Imaging Goniospectrometer. Additionally, descriptions and images of how the samples were made are included as a reference for others attempting to recreate the samples for use in their research. The database is available at art-si.org.
CHAPTER 2: BACKGROUND

2.1. Limitations of Traditional Museum Imaging Techniques

Digital images are used by many museums to document their collections for archival purposes. This digital record is typically limited to a handful of images captured from a single straight-ahead viewpoint under diffuse illumination. This method results in a static representation, limited in its ability to convey visual qualities that become apparent when viewing the artwork in a museum setting. Features that require examination from multiple angles to comprehend, such as gloss and three-dimensional surface structure, are reduced to two dimensions, thereby producing a specific viewing experience constrained by aesthetic choices made by the photographer.

Figure 2.1 illustrates this point with images of the same painting captured using two different lighting conditions. The image on the left was taken under diffuse lighting conditions while the one on the right was captured using directional lighting.

Figure 2.1. Two images of the same painting each captured under a different lighting configuration. The image on the left was captured using diffuse lighting, where the image on the right was captured with a directional light source placed at an oblique angle.
It is apparent from the two images in Figure 2.1 that when the direction of the lighting is changed the painting takes on a very different appearance. Areas of gloss become visible using directional lighting, which are not apparent under diffuse illumination; additionally, the surface texture of the painting is much more pronounced under the directional lighting. It is evident that when a museum limits their digital record to a single image, attributes such as gloss and surface texture are not always accurately represented.

The MCSL Imaging Goniospectrometer aims to overcome these limitations by separating the image capture and rendering into two distinct elements. First, image data are collected and used to define the physical qualities of the artwork that includes spectral reflectance factor, BRDF, and surface normal information. This information can then be used to render the artwork for various viewing angles and lighting directions. In utilizing this system, museums would have the ability to archive their collection as dynamic three-dimensional depictions of the original.

2.2. Artist Material Samples vs. Imaging Actual Artwork

As seen in the previous section, traditional imaging techniques used in museums to document artwork have their shortcomings, which the MCSL Imaging Goniospectrometer aims to overcome. To develop a practical imaging system capable of measuring BRDF, it is first necessary to reduce the number of images needed to measure BRDF. In its current state, the goniospectrometer system captures something on the order of 100 or more images to measure BRDF. This quantity of images is not practical
for a museum photographer, so it is essential to reduce this number to a manageable quantity.

The means to reduce the number of images is accomplished by identifying the important measurement geometries necessary to measure BRDF. In order to determine these geometries, a set of targets representative of artwork found in museums needs to be imaged using the system, but using actual artwork has various limitations. An example of these limitations is illustrated in Figure 2.2. When using a painting as an image target, such as the one shown in this example, there is a large degree of spatial non-uniformity and variations in color from pixel to pixel. This variability makes it difficult to achieve measurement repeatability.

![Figure 2.2. A target area indicated by the red circle on a painting imaged at 0° (left) and at an angle (middle). When image captured at an angle is then rectified to 0° (right) the effective target becomes an ellipse.](image)

Furthermore, the fact that the Imaging Goniospectrometer images artwork at various angles presents a problem. In Figure 2.2, the image of the painting on the left was captured at a normal to the surface viewpoint while the image in the middle was
captured at an angle. If the area of interest is represented by the red circle, we see that when the angled image is rectified back to 0°, as shown on the right, the circle becomes an ellipse thus changing the effective target area. This makes it difficult to maintain an accurate target area when using actual artwork because of the varying color and texture information.

Given the constraints presented above, it was impractical to use artwork as image targets with this system. With this in mind, it was required to create a set of targets that overcame these limitations and encompassed the scope of artist materials. The solution was to create a library of artist material samples. Each of these samples would consist of a single medium presented as a uniform square that could be used for development of the MCSL Imaging Goniospectrometer. Three representative samples from the artist material library are shown in Figure 2.3. As shown in these examples, the samples are of a uniform size and as spatially uniform as possible, thereby making measurement repeatability straightforward. Also, the small size of each patch makes it possible to arrange several of them on a target panel, allowing multiply samples to be imaged simultaneously. This reduces the time required for image capture significantly.

Figure 2.3. Samples from the artist material database, from left to right: acrylic on canvas, watercolor wash on paper and colored pencil on smooth paper.
2.3. Bidirectional Reflectance Distribution Function (BRDF)

BRDF is a four-dimensional function that defines the interaction of light with an opaque surface. It is based on the relationship between light incident on a surface and light reflected off of that surface into the hemisphere above with respect to the surface normal. The surface normal is the vector perpendicular to the surface and can be used to describe the large-scale three-dimensional surface structure of an object.

Figure 2.4, drawn by Lawrence Taplin, demonstrates this relationship between the incident and reflected light used to define BRDF. Both the incident light, $L_i$, and reflected light arriving at the observer, $L_r$, are defined by two dimensions, the azimuth angle, $\phi$, and the polar angle, $\theta$, giving us the four dimensions that describe BRDF.

![Figure 2.4. The four dimensions used to define BRDF. $\theta_i$ and $\phi_i$ are used to describe the light incident on the surface and $\theta_r$ and $\phi_r$ are used to describe the light reflected back to the observer.](image-url)
In terms of the light reflected off the surface, there are two extreme cases. On one end of the continuum we have diffuse reflection, where the light is reflected back equally in all directions. On the other end, specular reflection, where all the light is reflected back in a single direction. In reality most real materials possess a combination of diffuse and specular reflective properties.

2.4. BRDF Models

BRDF data obtained with a gonio-based measurement system can be fit using analytical models. Using optimization techniques, the measured data is fit to model parameters to obtain BRDF. These models can be empirically or physically based, although both types are only approximations of the reflective properties of the actual material. Physically based models are grounded in optics and physics with each parameter having a physical correlate relating to the actual properties of the object. Empirical models, on the other hand, are based on fitting the measured data well and are not particularly concerned with the physical meaning of the parameters.

There are many models that can be used to define a material's BRDF. Two popular models are the Ward and Cook-Torrance models, useful because of their simplicity, small number of model parameters, and optimization efficacy. Within the greater context of defining the appearance of artist materials, these models have already been selected for computer graphics rendering by the advisor of this thesis. Therefore, these two models are described below.
2.4.1. Ward Model

The Ward BRDF model is a relatively simple but physically plausible empirical model that uses three parameters to describe BRDF. These parameters include the diffuse reflectance, specular reflectance and a term describing the width of the specular lobe, which varies as a function of surface roughness. Equation 2.1 depicts the relationship of these model parameters.

\[
\rho(\theta_i, \phi_i, \theta_o, \phi_o) = \rho_d + \rho_s \times \frac{\exp[-\tan^2 \delta / \alpha^2]}{4\pi \alpha^2 \sqrt{\cos \theta_i \cos \theta_o}}
\]  

(2.1)

The \(\rho_d\) term describes the size of the diffuse lobe and is the portion of the model that accounts for color information. The specular portion of the equation, which describes the glossy appearance of the material, is defined by two parameters in the Ward model. The \(\rho_s\) term describes how much specular reflection there is, and the \(\alpha\) term describes the spread of the specular reflection. A small \(\alpha\) term indicates that the surface acts more like a mirror and a larger \(\alpha\) term indicates a greater spread and produces a semi-gloss appearance.

2.4.2. Cook-Torrance Model

The Cook-Torrance BRDF model is physically-based and assumes the reflective surface is made of small planar facets, each with its own angle and size. The light reflected off each surface point is described by Equations 2.2-2.5 in which \(i\) describes the light incident on a point, and \(o\) describes the light reflected off that point based on the distribution \(f_r\).

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\[ f_r(i,o) = \rho_d + \rho_s \frac{DFG}{\pi (i \cdot n)(o \cdot n)}, \quad (2.2) \]

\[ G = \min(1, \frac{2(h \cdot n)(o \cdot n)}{o \cdot h}, \frac{2(h \cdot n)(i \cdot n)}{o \cdot h}) \quad (2.3) \]

\[ F = R + (1 - R)(1 - i \cdot n)^5 \quad (2.4) \]

\[ D = \frac{e^{-\tan^2 \alpha/m^2}}{4m^2 \cos^4 \alpha} \quad (2.5) \]

The \( \rho_d \) term describes the diffuse lobe, \( \rho_s \) the specular lobe, \( n \) the surface normal, and \( h \) the halfway vector of \( i \) and \( o \). The \( \alpha \) term describes the angle between \( h \) and \( n \). The \( m \) represents the specular roughness, which alters the glossiness of the surface. The smaller the \( m \) value the glossier the surface appears.\(^{11}\)

The geometrical attenuation factor, \( G \), is shown in Equation 2.3 and accounts for the shadowing and masking of one facet by another. The Fresnel term, \( F \), shown in Equation 2.4, describes how light is reflected from each smooth facet. The facet slope distribution, \( D \), is shown in Equation 2.5 and describes the fraction of facets that are oriented towards \( h \), the halfway vector.\(^{10}\)

### 2.5. BRDF Databases

BRDF databases exist that provide reflectance measurements for real-world materials. The data provided in these databases are useful for various applications including computer graphics applications such as rendering real-world environments. Two of the more notable of these databases are briefly described below.
2.5.1. CUReT

The CUReT BRDF database\textsuperscript{3,4} of real world materials was the first of its kind. The 61 materials included were chosen to include a wide range of geometric and photometric qualities and include materials such as salt crystals, moss, crumpled paper and tree bark. The common theme of the materials selected for this particular database is that each possesses a rough texture of varying scale.

In addition to the BRDF data, the CUReT database also includes a bidirectional texture function (BTF), which describes the dependency of texture on viewing and illumination directions. Both the BRDF and BTF databases were derived from 12,000 images, captured with over 200 combinations of viewing and illumination directions for each of the selected materials.

2.5.2. MERL

The MERL BRDF database\textsuperscript{1,2} includes reflectance functions for a large representative set of common materials including metals, paints, fabrics, minerals and organic materials. The database is derived from a sampling based approach for modeling surface reflectance that interpolates/extrapolates new BRDFs from the representative data and has parameters that allow users to change the characteristics of the output BRDF. The reflectance functions for the 100 different materials included in the MERL database are derived from image-based BRDF measurements, which are sampled densely, on the order of 20-80 million BRDF samples per material.
CHAPTER 3: MATERIALS AND TECHNIQUES

3.1. Overview

This chapter provides an overview of the various materials and techniques represented in the artist material database. A primary goal when considering the materials and techniques to be included was to achieve a range of visual appearances by altering various characteristics of the samples. Five attributes were identified that could be independently altered to vary the appearance of the samples. Each of the five attributes, that is medium, substrate, color, technique and overcoat, are highlighted in this section. Each selected material and technique is considered in detail to emphasize its significance in the sample set. In some cases, the historical relevance of the material is considered to provide further context.

3.2. Material Selection

The groundwork for this research was laid by first sorting out the seemingly endless variety of materials artists utilize. It was important to understand the range of possible artist materials and gain a sense of which comprised the bulk of what museums have in their collections. Aside from selecting individual materials, it was also essential to understand the possible combinations of materials, such as potential medium and substrate groupings. For instance, it was apparent that a material such as oil paint was to be included, but understanding the choices of substrate that oil paint is typically executed on was also of great importance.

First, an online investigation was performed utilizing the public domain databases of several prominent museums. The online inquiry was followed by a survey distributed
to several experts in the artist material world. The survey provided the basis for the final selections to be included. Finally, Mark Gottsegen, former Materials Research Director for the Intermuseum Conservation Association, reviewed the final selections and offered his expert opinion in finalizing the materials to be included in the sample set.

3.2.1. Online Investigation

To gain a sense of what materials are common in museum collections, the online databases of two large museums provided a viable means to accomplish this task. The descriptions contained in the searchable databases of The Museum of Modern Art, New York and The National Gallery of Art, Washington, D.C. provided a window into what medium and substrate combinations are most common. The range of artwork represented in these two museum collections spanned a timeframe of several hundred years and included not only centuries old paintings done with oils or egg tempera, but also modern works created using contemporary materials such as acrylic paints.

The process of reviewing these databases began by spending several days looking at as much art as possible and creating a list of mediums from the descriptions of each piece. After reviewing several hundred paintings and drawings, a list began to take shape with the most used mediums totaling twelve or so. After compiling this list, each medium was examined and the typical substrates used in conjunction with each medium was determined. This was carried out by again using the detailed descriptions accompanying each piece of artwork on the museum websites.
3.2.2. Artist Material Survey

A survey was compiled using the results from the online search outlined in the previous section. Shown in Figure 3.1, the survey was distributed to various experts in the field of art materials to help determine the final sample set.

![Artist's Material Survey](image)

**Figure 3.1.** Art material survey used to determine the final sample set. Participants were asked to check either “common” or “uncommon” for a list of medium/substrate combinations.
The survey lists numerous medium/substrate groupings and allows contributors to choose either “common” or “uncommon” for each combination. The choices also include whether specific combinations typically have a varnish layer applied to them. It was extremely valuable to have input from a variety of individuals whose professions are tied to artist materials in various ways. Respondents to the survey included museum conservators and paint makers.

The survey also had space for comments, to which some respondents contributed additional information not specified in the list. The comments provided insights such as additional medium/substrate combinations not listed in the survey that may have otherwise been missed in the final sample set.

After the results from the survey were analyzed, the final list of materials took shape. With input from artist material professionals, combined with the extensive examination of museum collections, the selections were determined to be the best fit for the sample set. To complete the list of samples to be included, Mark Gottsegen provided expert guidance along with instruction of application techniques through demonstrations that will be considered in detail in the Sample Creation section.

3.3. Mediums

A total of twelve mediums were selected for inclusion in the sample set. These mediums represent a range of history, from egg tempera, which has been used for hundreds of years as a painting medium, to materials such as marker that are more recent additions to the artist’s cache. The selected mediums, shown in Figure 3.2, can be divided in two subsets: mediums that are used to paint with and those that are used to draw with. The
twelve selected mediums are comprised of six drawing mediums and six painting mediums.

3.3.1. Oils

Oil paint, consisting of particles of pigment suspended in a drying oil, first came into prominence for use in easel painting during the fifteenth century; by the seventeenth century, it was in universal use. Since being embraced in the seventeenth century, oil paint remains to this day the standard technique for easel painting. Oil paint has remained the principal painting technique for so long due to several advantages when
compared to other painting mediums. One of the greatest advantages of oil paint is its adaptability, making it simple to manipulate and achieve a wide range of effects. Furthermore, the colors of oil paint do not change a significant amount after drying, so the artist gets the tonal effect desired even after the paint has cured.

Oil paint is characterized by its slow drying time and is comprised mostly of binder and pigment, but also usually includes drying agents and stabilizers. The most common binder in commercial brands is linseed oil, which is extracted from the pressed seeds of the flax plant. Drying agents are often added to produce paints that have similar drying rates, while stabilizers help provide a buttery texture across a range of colors. Gamblin Artist’s Oil Colors were used for the oil paint samples and are summarized in Table 3.1.

Table 3.1. Summary of oil paints used for the samples.

<table>
<thead>
<tr>
<th>Oil Paint Name</th>
<th>Pigment(s)</th>
<th>Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamblin Venetian Red</td>
<td>Synthetic Red Iron Oxide (PR 101)</td>
<td>Alkali Refined Linseed Oil</td>
</tr>
<tr>
<td>Gamblin Chromium Oxide Green</td>
<td>Anhydrous Chromium Sesquioxide (PG 17)</td>
<td>Alkali Refined Linseed Oil</td>
</tr>
<tr>
<td>Gamblin Portland Grey Medium</td>
<td>Titanium Dioxide, Zinc Oxide, Bone Black (PW 6, PW 4, PBk 9)</td>
<td>Alkali Refined Linseed Oil</td>
</tr>
<tr>
<td>Gamblin Ivory Black</td>
<td>Bone Black (PBk 9)</td>
<td>Alkali Refined Linseed Oil</td>
</tr>
<tr>
<td>Gamblin Titanium-Zinc White</td>
<td>Titanium Dioxide, Zinc Oxide (PW 6, PW 4)</td>
<td>Alkali Refined Linseed Oil</td>
</tr>
</tbody>
</table>
3.3.2. Acrylic

Acrylic paint, or more specifically acrylic dispersion paint, is a twentieth-century innovation making it a relatively new addition to the collection of artist materials. By the 1950s many abstract and Pop artists had embraced this new medium because of its durability and flexibility. Consisting of an acrylic resin dispersed in water, the synthetic binder for acrylic dispersion paints is complex and often contains a mixture of other synthetic dispersions in addition to the acrylic dispersion.

Acrylic paints are quite versatile and can be thinned with water, yet form a tough film when dried. They behave very much like oil paint and can be used in a similar manner to attain comparable effects. Furthermore, acrylics utilize the same tools, brushes and substrates as oil paints, yet have some notable differences. Compared to oil paints, which take weeks to fully dry, acrylic paints dry rapidly due to the high water content of the paint, although thick impasto can often take days to fully dry. Oil paints also have some unique manipulative qualities, such as smooth blended tones and greater control of opacity, not offered by acrylic paint. Golden Acrylics were used for all acrylic paint samples and are summarized in Table 3.2.
<table>
<thead>
<tr>
<th>Acrylic Paint Name</th>
<th>Pigment(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Golden Acrylics Red Oxide (Golden #1360-2)</td>
<td>Synthetic Red Iron Oxide (PR 101)</td>
</tr>
<tr>
<td>Golden Acrylics Chromium Oxide Green (Golden #1060-2)</td>
<td>Anhydrous Chromium Sesquioxide (PG 17)</td>
</tr>
<tr>
<td>Golden Acrylics N5 Neutral Gray (Golden #1445-2)</td>
<td>Titanium Dioxide Rutile, Ivory Black, Burnt Sienna (PW6, PBk9, PBr7)</td>
</tr>
<tr>
<td>Golden Acrylics Bone Black (Golden #1010-2)</td>
<td>Bone Black (PBk 9)</td>
</tr>
<tr>
<td>Golden Acrylics Titanium White (Golden #1380-2)</td>
<td>Titanium Dioxide Rutile (PW6)</td>
</tr>
</tbody>
</table>

3.3.3. **Watercolor**

Watercolor as a medium has been in use for centuries in various forms, dating as far back as ancient Egypt in which pigment dispersed in water was used to paint the plaster walls of tombs.\(^\text{15}\) Although versions of watercolor painting had been used for hundreds of years, watercolor as a school of painting originated with the landscape painters of eighteenth-century England. The techniques developed by these artists utilized the brilliant white of the paper to give glowing, luminous quality to their work. The luminous characteristic of watercolor painting is achieved by the application of thin washes that allow light to penetrate the surface and reflect from the paper though the paint layer.\(^\text{16}\) Artists of today use watercolors in a range of ways including opaque techniques. The practice in which the paint is thinned with water is called *aquarelle* by the French to separate it from opaque techniques, although most do not make this distinction, simply referring to the translucent technique as watercolor.\(^\text{13}\)

Watercolor paints dry very quickly and are most commonly painted on a heavier weight paper. Painting in watercolor relies on the paper’s capacity to hold pigment
particles. It is dissimilar to oil and acrylic painting methods in that the watercolor paint layer is more of a stain on paper rather than a continuous film.\textsuperscript{12} The paint is composed of transparent pigments ground to an extremely fine texture, and suspended in an aqueous solution comprised most commonly of gum arabic.

Three colors of watercolor: red, green and black, were used for the artist material samples. The black watercolor paint took on a grayish appearance when applied as wash, making the creation of gray samples (using gray watercolor) redundant and unnecessary. White was not needed either because a watercolor wash relies on the paper for white tones. M. Graham Watercolor’s Terra Rosa (PR 101) and Ivory Black (PBk 9) were used along with Da Vinci Watercolor’s Chromium Oxide Green (PG 17).

\textbf{3.3.4. Gouache}

Gouache is an opaque type of watercolor paint made by mixing pure pigments with gum arabic and precipitated chalk. The addition of the white chalk gives gouache its opaque appearance, although some high quality brands use little or no chalk, just pure pigment.\textsuperscript{13} When applied undiluted, gouache paint dries to a matte finish that looks very different from the more translucent appearance of watercolor. Although gouache paints can produce works with an appreciable paint layer with noticeable film thickness, they still cannot be used to create heavily painted passages or impasto, as these tend to crack when dry.\textsuperscript{12} Rather, gouache is best utilized in a way that retains the appearance of delicate brushstrokes and makes use of areas of very slight impasto.\textsuperscript{13} Gouache can also be diluted with water and applied as a wash similar to watercolor.
Heavy paper is the substrate of choice for gouache, as a thinner paper is not rigid enough to keep the gouache painting from bending and cracking when handled. In the case of the artist material samples, gouache was painted on a heavy weight paper as a wash and also undiluted in a more opaque style. Schmincke-Horadam Gouache English Red (No. 646) and Chromium Oxide Green Brilliant (No. 522) were used for the red and green samples. For the white and black gouache samples, M. Graham Gouache was used in Ivory Black and Titanium White.

3.3.5. Ink

Ink is often thought of as strictly a drawing medium, however it can also be used as a paint to create colored washes similar to watercolor. Inks maintain many of the qualities of watercolor, namely the transparency and luminosity, but ink washes dry much faster. Also, unlike watercolor, the diluted consistency of inks make it possible to apply as a wash straight out of the bottle so that intense tones can be produced.\(^1\) Inks come in two varieties, water-soluble and waterproof. Water-soluble inks can be dissolved with water and the colors blended after they are applied. Waterproof inks, on the other hand, have added shellac so the ink will not dissolve when dry. This allows additional paint layers to be added without ruining the underlying ink layer.\(^2\)

Inks also come in both dye and pigment based formulas. Pigment based inks are generally preferred by artists as they are more lightfast than dye-based inks and resist fading. The pigment-based version consists of very finely ground pigment dispersed in a water-based binder.\(^3\) Higgins pigment-based permanent drawing inks were used as washes in green, red and black.
3.3.6. Egg Tempera

The earliest evidence of egg tempera painting is found in Egypt where tombs dating to the first century AD were decorated with paint made by mixing pigments with egg yolk and water. In the ensuing centuries, egg tempera became the dominant easel painting technique and although tempera paint can be mixed using other binders, egg yolk became the foremost choice due to its availability and ease of use. Much of the religious panel painting done between the twelfth and fifteenth centuries was created using this medium, until ultimately being replaced by oil paint in the seventeenth century.

The term “tempera” is derived from the Medieval Latin temperare, which means to mix or blend. Specifically, egg tempera contains an emulsion which is a stable mixture of a fatty substance and a watery substance. The egg yolk, containing egg oil (the fatty substance) and albumen (the watery substance), provides a natural emulsion. As the water in egg tempera evaporates and the paint dries, it becomes very inflexible; therefore, egg tempera paintings are best executed on rigid panels that have been primed with an absorbent ground. Usually left unvarnished by artists both past and present, egg tempera paintings have a natural faint gloss finish. This natural luminous quality is a hallmark of the medium and makes egg tempera easy to identify compared to paintings done in oils or acrylic.

Egg tempera is made by today’s artists using the same basic materials and procedures employed in the past. This process, in which finely ground pigment is mixed with egg yolk and water, was used to make the egg tempera samples contained in the artist material library. The pigments that were used include Venetian red (PR 101), chromium oxide green (PG 17), bone black (PBk 9), and titanium white (PW 6). The
details of making egg tempera are found in the next chapter, in the *Sample Creation* section (Section 4.2).

### 3.3.7. Colored Pencil

Colored pencils consist of pigments mixed with clay and a small amount of wax, wrapped in a wooden case. They come in a variety of textures ranging from soft to hard, with a higher wax content producing a harder pencil.\(^{17}\) The harder varieties tend to produce light, translucent colors and work best for delicate lines and precise drawing. The softer types are more chalky and opaque; because the color comes off quite smoothly, these are generally used for covering large areas with color.\(^{18}\)

Generally speaking, it is difficult to achieve intense tones with colored pencil, therefore they work best for small-scale drawing. Also, they cannot be blended like paints so they are produced in many different colors, shades and tints and are often applied in layers to create a visual blending of colors. The semi-transparent nature of colored pencil is such that light reflects off the white paper, giving them a luminous quality not unlike watercolor.\(^{18}\) Paper with slight texture is the preferred substrate for colored pencil so that the pigment has some texture to adhere to. The appearance of the artwork can vary, depending on how the colored pencil is applied to paper. When put down using light pressure, the color only adheres to the raised part of the paper, thereby producing a light grainy appearance. When heavier pressure is used, the pigment is deposited in the depressions of the paper, resulting in a more smooth opaque appearance. Caran d'Ache Pablo Colored Pencils were used for the artist material samples. These pencils have a soft texture and produced fairly smooth, even coverage. The selected
colors include: Burnt Sienna (#069), Moss Green (#225), Slate Grey (#495), Black (#009) and White (#001).

3.3.8. Marker

Markers, or felt-tip pens as they are also known, were introduced to the artist’s cache in the mid-twentieth century. The original markers consisted of a glass tube of ink with a felt wick to apply the medium; although markers of today are made of different materials, they still employ this same basic design. Markers can be water or alcohol-based. Both varieties, but particularly the alcohol-based type, dry very quickly by evaporation of the solvent that carries the colorant.¹³

Markers are often used in mixed media applications. The saturated color of the medium lends itself to bold line work that complements more subtle techniques such as watercolor washes. Marker is typically used on paper of varying textures, and even on a more coarsely textured paper it produces very smooth even color. For the artist material samples, Prismacolor Premier Double-Ended Markers were used. These markers have both a fine point for detailed line work and a broader tip for laying down large areas of color. Only the broad end was used, as the aim of the samples was to produce a large uniform area of the medium. The following colors were used: Crimson Red (PM 4), Mahogany Red (PM 150), Dark Olive Green (PM 28), Dark Green (PM 31), Cool Grey 80% (PM 115), Warm Grey 90% (PM 107), and Black (PM 98).

3.3.9. Pastel

The use of colored chalks as a means to create artwork dates to prehistoric times, however pastel as a distinct medium has its origins early in the early eighteenth century
when it began to be used to create full color portraits. In the years preceding the emergence of pastel as a fully realized medium, colored chalks were used as accents in drawings and to sketch the beginnings of a painting, but as time went on pastel was used to fully model pictures and create entire works by itself.

Pastel consists of pure pigment mixed with a small amount of gum binder. The virtually pure pigment composition of pastel provides its characteristic luminous and brilliance of color. Lighter tints of pastel also contain added white chalk or pigment. Since pastels cannot be mixed like paints, they are available in a large variety of colors and typically come in one of three grades: soft, medium and hard. Soft pastels are the most popular choice with artists as the texture produces the characteristic velvety appearance associated with the medium. Blending with a finger or a small piece of tissue paper is particularly easy with soft pastels and is a common technique used to combine colors and tones. Paper with slight texture is the preferred support and frequently colored paper is used with the medium. For protection, finished pastel drawings are often framed behind glass or treated with a fixative spray to bind the pigment particles, which helps keep the colors from dusting off.

Ready-made soft pastel was used for the artist material library samples. Unison Colour Soft Pastel sticks were used for the Red (RE 6), Green (YGE 6) and Gray (GREY 15) pigments. Schmincke “Serious Black” and Art Spectrum brand “White” completed the set of five pigments.
3.3.10. Charcoal

The use of charcoal dates to prehistoric times when ancient man used sticks of charred wood to draw on cave walls. Today, charcoal is regarded as the most universal drawing medium and is used for both simple sketches and complete works of art. It is very versatile in terms of the array of effects that can be produced. Expressive and sweeping line work is a common characteristic of charcoal drawings, making it ideal for large-scale works. Finished charcoal drawings are quite fragile and susceptible to smudging, therefore it is necessary to treat finished works with a fixative.

Charcoal comes in several forms including vine and compressed. Vine charcoal, made by baking willow dowels until they are reduced to pure carbon, comes in sticks that are usually 5-6 inches long and are available in ranges of thicknesses. Compressed charcoal is vine charcoal that has been compressed into hard sticks. Compressed charcoal can be sharpened to a very fine point so it is well suited for applications where precise details are desired. Coates Willow Vine Charcoal, of a medium thickness, was used for all charcoal samples.

3.3.11. Graphite

Graphite, a crystallized form of carbon, had been used as a drawing medium for millennia, however it was in sixteenth century England that the first wood encased graphite pencil was introduced. These first pencils used pure sticks of graphite, until further refinement in the eighteenth century when the graphite was mixed with clay to form a dough and then baked into hard sticks. This process, with minor modifications, is still used today to make graphite pencils.
Graphite pencils are graded by the H and B system, which indicates the hardness of the graphite core. The scale ranges from approximately 9H (the hardest) to 8B (the softest). The degree of hardness is determined by the amount of clay in the mixture, with a higher proportion of clay producing a harder pencil. The hardness of the graphite also determines the range of appearances that the pencil can produce. Harder pencils leave a light mark and are well matched for precision drawing, while the softer variety generally have a darker tone and can be used to create soft lines and shade large areas. The most common choices for drawing are usually in the 2B-5B range; in our case, a Pentalic 4B graphite pencil was used for all graphite samples.

3.3.12. Conté Crayon

Conté crayon consists of high-grade compressed chalk and graphite blended with gum and a small amount of grease, and formed into small square sticks. French in origin, Conté crayons are named after their inventor, Nicolas-Jacques Conté and are slightly harder and oilier than pastels. This slightly hard, waxy texture can be used to produce marks of varying delicacy. Broad sweeping strokes create a soft muted appearance while more precise details can be achieved with hard linear marks. Traditionally Conté crayons were used for tonal drawings and came in limited colors: black, white and muted red tones. Nowadays they are available in a range of color choices, although artists often still prefer the traditional colors as they impart a ‘classical’ look to the work.

Black and white Conté crayons typically come in three grades: HB (medium), B and 2B (the softest). The softer the crayon, the more intense the mark it makes and the easier it is to blend. Textured paper is well matched for Conté crayon as it grabs hold of
the medium, but smoother paper is also a suitable choice. Black, medium hardness (HB) Conté a Paris brand crayons were used in the creation of samples.

3.4. Substrates

3.4.1. Canvas and Masonite

The substrate, also called the support, is the most important structural element in a painting. Artists throughout the centuries have utilized nearly every manner of flat surface to paint on including walls, metal and glass. Although the choices of painting supports were numerous, just two of the more common paint substrates, canvas and hardboard, were selected for the artist material samples. Two varieties of canvas were used: a coarsely woven linen canvas and cotton canvas with a finer texture.

The surface texture of the substrate had a pronounced visual effect on the finished samples, even after the supports were primed and painted on. Figure 3.3, in which acrylic paint is shown brushed onto Masonite, fine canvas, and coarse canvas, illustrates the range of appearances achieved by altering the support.

Figure 3.3. Chromium oxide green acrylic paint brushed onto three different supports. The brushstrokes are the most visible on the Masonite sample (left). On the fine canvas (middle), the texture of the substrate is visible along with brushstrokes. Finally, on the coarse canvas (right), the texture of the canvas dominates the appearance.
As the texture of the substrate becomes rougher and more pronounced, the brushstrokes are masked and begin to disappear. Shown on the left in Figure 3.3, the smooth appearance of the Masonite makes the brushstrokes very distinct. In the case of linen canvas (shown on the far right), the texture of the canvas persists through the gesso and paint layers, masking the brushstrokes. In the middle sample, the finer textured cotton canvas produces a visual effect that incorporates both the texture of the brushstrokes and the canvas. From this example it is evident that the texture of the substrate selected by the artist has a considerable visual impact on the finished work.

*Linen Canvas*

Linen canvas, which is naturally brown in color, is made from the woven fibers of the flax plant. Compared to cotton canvas, canvas made from linen is stronger and more durable, owing to the length of the individual flax fibers. It comes in various textures ranging from coarse to fine. Typically, heavier grades of linen canvas are selected for large-scale works while finer textured canvas is used for smaller paintings. Traditionally, painters took great care in ensuring that none of the texture of the canvas showed through in the final painting; this was achieved by applying several layers of gesso and smoothing the final surface with fine sand paper. Modern techniques of painting take advantage of the texture of the canvas and incorporate it into the look of the final painting. The canvas selected for use with artist material samples was a coarsely woven linen canvas. Purchased in one bulk piece, the untreated linen canvas was sealed and primed prior to use, which is discussed in detail in the next chapter.
Cotton Canvas

Cotton duck canvas came into wide use for painting in the early twentieth century as an alternative to linen canvas. Cotton canvas is generally thought of as a less desirable alternative to linen canvas. The shorter fibers of cotton produce a canvas that is more difficult to stretch compared to linen canvas. Moreover, cotton canvas generally has a more mechanical weave, which many artists dislike for aesthetic reasons.\textsuperscript{13}

The cotton canvas selected had a very tight weave and was finely textured. The fine texture of the cotton canvas would be most suitable for applications such as portrait painting where refined details are important. Two types of cotton duck canvas were used. The first was stretched over a cardboard backing to provide support, while the other was stretched over a wooden frame. Made by Art Alternatives, both came triple primed with acrylic gesso.

Masonite

Masonite is a type of hardboard made by blasting wooden chips into long fibers with steam and then forming the pulp into boards. No glue, binder or other material is needed as the wood fibers are held together by lignin, a natural element in the wood.\textsuperscript{13} Finished Masonite, which has a very smooth uniform texture, is moisture resistant and does not warp easily, making it an excellent support for painting.

3.4.2. Paper

Watercolor Paper

Arches Aquarelle cold-pressed 140lb. watercolor paper was used for several sample types including both painting and drawing mediums. The heavier 140lb. weight paper was
chosen because lighter weight watercolor paper tends to warp and buckle when excessive water is applied to it. The heavier weight watercolor papers tend to soak up more paint then lighter weight papers, so that richer colors are necessary to compensate for the loss in color. Watercolor paper comes in a variety of textures ranging from smooth to more coarsely textured. Cold-pressed watercolor paper represents the more coarsely textured variety. The cold-pressed watercolor paper is made by pressing the paper pulp through a press to create a uniform flat sheet. Sizing is added during the pulp stage of manufacture to prevent bleeding and spreading of the paint on the finished paper.

Cold-pressed paper is ideal for watercolor paint, although the texture of the paper does not directly contribute to the adhesion of the paint particles, as all uncoated paper types will take hold of paint particles. Rather, the grain and texture of a more coarsely textured paper contributes sparkle and brilliance to the visual appearance of the work. The texture of this rougher textured paper is also suitable for use with drawing mediums, particularly powdery media. Mediums such as charcoal and pastel need a substrate with enough texture or “tooth” to hold on to pigment particles; charcoal and pastel sticks tend to slide around on smooth paper and the mediums smudge easily after being applied.

*Sketch Paper*

Pentalic “Nature Sketch” paper was used for several mediums and has a slightly rough texture, though not as much tooth as cold-pressed watercolor paper. The smooth texture is suitable for use with a variety of painting and drawing mediums, including graphite, pastel, and charcoal among others. The Pentalic sketch paper, used for the samples, is 25% cotton, 130lb. weight, and a natural white color.
3.5. Color

The goal in selecting the colors to be represented in the artist material library was to include a range of opaque pigments while at the same time limiting the quantity to a manageable number. The five colors chosen for inclusion are shown in Figure 3.4.

![Paint pigments](image)

*Figure 3.4. Paint pigments, from left to right: red oxide, chromium oxide green, neutral gray, bone black and titanium white.*

The selection of colors was chosen from oil and acrylic pigments and includes: red oxide, chromium green oxide, neutral gray, bone black and titanium white. The choice of pigments was based on their dominant scattering ability so they would appear opaque when applied to a substrate.

For the remaining color mediums, the colors were generally not specified by the same pigment name provided for the oils and acrylics. In this case, the closest visual match to the oil and acrylic paint colors were selected.

3.5.1. Pigments

*Green*

Chromium oxide green (PG 17), a low-chroma pigment whose muted and earthy tones are well suited for natural scenes such as landscapes, was selected for the green colorant. This synthetic inorganic pigment was known since 1809 and introduced commercially as
an artist pigment in 1862.\textsuperscript{12} Chromium oxide green is known for its excellent permanence and has been frequently used in many industrial applications, such as tinting plastics.\textsuperscript{13}

\textit{Red}

Introduced as an artist’s pigment in 1862, Venetian red (PR 101), or red iron oxide, is a synthesized inorganic pigment derived from manufactured iron (ferric) oxide (Fe\textsubscript{2}O\textsubscript{3}).\textsuperscript{12} Described as a dense brick red, Venetian red is very opaque and possesses excellent permanency.

\textit{Gray}

Two different grays were used in the sample creation, one each for the acrylic and oil paints. Both were very neutral in appearance and contained an ivory black (PBk 9) and titanium white (PW 6) pigment blend. Additionally, the Golden Acrylic’s Neutral Gray N5 had added a minute amount of burnt umber (PBr 7) in this particular gray. The Gamblin Portland Grey Medium also contained zinc oxide (PW 4).

\textit{Black}

Used as a colorant since prehistoric times, ivory black (PBk 9) is made from the amorphous carbon produced by charring animal bones, hence its other common name, bone black. Extremely opaque, ivory black is a good all-purpose black that’s excellent for mixing grays, tinting, and mixing with other colors.\textsuperscript{12}

\textit{White}

The pigment blend of Gamblin Titanium Zinc White differed slightly from that of Golden Acrylic Titanium White. Both contain titanium white (PW 6), an inorganic pigment that first came into prominence as a painter’s colorant in the early twentieth century.\textsuperscript{13} Titanium white is the most opaque of all the whites and has a soft velvety appearance, but
when dry it often becomes soft and chalky. For this reason, titanium white is often blended with zinc white (PW 4) in oil paint, as is the case with the selected Gamblin white. Not only does zinc white produce a harder paint film in oil paint, it also helps produce an excellent mixing white because it takes a considerable amount of color to tint pure titanium white.

3.6. Technique

The array of possible application techniques was seemingly endless considering the variety of mediums and choice of application tools, combined with the expressive choices made by each artist. To narrow the field, it was advantageous to focus on the appearance resulting from a particular technique rather than the techniques themselves. In order to have the finished samples functional as image targets it was essential to have each one as uniform as possible. With this in mind, many possible techniques could be eliminated, given that it would be difficult to produce a consistent appearance across the entire sample area. The techniques that were chosen were done so with the intent of varying the appearance by using assorted tools and also altering the way the tools were used to apply the medium.

3.6.1. Painting Techniques

*Brush Application*

Brushstrokes and particular painting techniques are often associated with specific artists and give that painter’s work a distinct appearance. Varying the look of a medium can be
accomplished by utilizing different brushes or varying the direction of application to produce unique visual elements such as ridges and swirls of paint.

In terms of different brush types, the choices are abundant. Natural bristle brushes, usually made from hog hair, are prized by artists while synthetic materials such as polyester and nylon are used to make lower quality brushes. Different brush types also leave different marks. Rounds have a pointed tip with long bristles that are well suited for detail work. Flats are used for applying paint over a large area, while brights are the same shape as flats but with short stiff bristles used for strongly textured strokes. A Princeton 1/2” angular shader brush was used for the oil, acrylic and egg tempera samples. This type of small angled brush is quite versatile and can be used for both general paint application and for more detailed work. In terms of application, the paint was applied with vertical strokes in a single coat.

*Palette Knife Application*

Palette knives come in numerous shapes and sizes. A palette knife consists of a tempered steel blade that is attached to a raised handle, designed to keep the painter’s knuckles out of the painting. The flat part of the flexible blade can be used to apply large smooth areas of paint in an even sweeping motion. The palette knife can also be used to directly apply thick areas of paint. These thick, highly textured passages are referred to as “impasto,” an Italian word that means “dough” or “mixture.” Impasto techniques are best used in moderation throughout a painting, combined with thinner passages, as large thick layers tend to crack and separate from the support.

The palette knife was used to produce the samples shown in Figure 3.5. In the first example (shown on the left), acrylic paint was smoothed on to the canvas with the
palette knife, producing a relatively level paint layer yet still possessing some slight three-dimensional ridges of paint. The palette knife was also used to “pull-up” on the paint once it was applied to the support to achieve a spiky appearance, shown in the example on the right of Figure 3.5.

![Figure 3.5. Venetian red acrylic applied to canvas using two different impasto techniques. A palette was used to smooth the paint onto the canvas producing a smooth appearance with slight ridges of paint (left). It was also used to pull-up on the paint creating a spiky appearance (right).](image)

3.6.2. Drawing Techniques

Each drawing medium has its own unique physical characteristics that can be exploited to produce effects ranging from smooth blended tones to expressive line work. Softer, more powdery mediums such as pastel and charcoal lend themselves to techniques that utilize blending to merge tones and colors. Pencils, both graphite and colored, are very versatile mediums that can be manipulated in a variety of ways. The sharpened pointed part of a pencil can make crisp lines, while shaded areas can be produced by angling the pencil. The texture of the paper also has a prominent effect on the appearance of the drawing
medium. Line work has a tendency to emphasize the texture of the paper while blending can often mask the substrate.

The direction that the drawing mediums were applied had a noticeable impact on the appearance of samples as well. For the artist material samples, the direction of application was varied to achieve different levels of paper coverage, thereby changing the appearance. When applied in multiple directions, the medium covered both the “peaks” and “troughs” of the textured paper surface so that very little of the paper white was visible. Alternatively, application in only one direction left more of the paper showing resulting in a mottled appearance that combined the medium and paper white. The visual effect resulting from the direction of application is demonstrated in Figure 3.6. Both drawn with red colored pencil, the sample on the left has the medium applied in one direction while the one on the right was applied in multiple directions. The visual difference between the two samples is apparent with the sample on the left (medium applied in one direction) producing an appearance that distinctly combines the colored pencil and the white of the paper, while the multidirectional application of pencil covers the paper more completely.
Even when applied in multiple directions, as shown on the right of Figure 3.6, it is difficult to achieve a completely opaque appearance with some mediums that have a hard, waxy composition. Pastels and charcoal, on the other hand, quite efficiently cover the paper and additional blending with a small piece of paper ensures a uniform opaque appearance. Line drawing techniques commonly used with pencils, such as crosshatching, were not used to create samples for the artist material library. It is difficult to produce large uniform areas using these techniques, therefore they were omitted.

3.6.3. Washes

The term “wash” used in reference to watercolor, gouache and ink techniques has various connotations. Many think of a wash simply as a broad area of thinned paint applied in a flat manner, however painters often use the term to describe a single brushstroke of fluid paint. In our case, “wash” refers to the technique of laying thin paint over a large region
to produce a uniform area of color. The technique of overlaying thin areas of paint originated with the watercolor painters of eighteenth century England, in which they carefully built up subtle layers until a sense of depth was achieved in the painting.\textsuperscript{12} Applying washes in this manner produces layers of paint that are fairly transparent and requires a paint blend with a very high proportion of water. It is important when applying a wash not to overwork the paint, but rather apply it in a few smooth strokes. Often, the paint looks uneven when wet, but appears flat and even after drying. Also, since painting with only washes is such a subdued technique, a paper with pronounced texture is critical for adding visual interest to the piece.\textsuperscript{18}

For the artist material samples, different ratios of water to paint were mixed to produce washes of varying appearance. In Figure 3.7 a watercolor wash containing a relatively high concentration of paint is shown after applied to paper. This type of dense wash might be applied as a final layer in a painting due to its opaque appearance. A wide bristled brush with soft texture is ideal for applying a wash. A Princeton Art and Brush Company 3/4" synthetic sable flat wash brush was used for the all samples where a wash was applied.
3.7. Overcoat

3.7.1. Varnishes

Artists frequently choose to apply a final surface coating to their paintings and drawings, both for aesthetic reasons and to protect the artwork from harmful environmental factors such as UV radiation, atmospheric pollutants, and dirt. For paintings, particularly oil and acrylic, a varnish is often brushed on as a final coat that dries as a transparent film. Varnishes range in composition and can be made from either natural compounds, such as damar which is derived from tree sap, or synthetic materials such as acrylic resins. Often the varnish layer yellows and accumulates dirt over time. For this reason, it is important that the overcoat is easily removed with mild solvents that won’t harm the paint layer beneath.\textsuperscript{13}
The level of gloss exhibited by the varnish layer can have a profound effect on the appearance of the finished work. For oil and acrylic paintings, glossier finishes are common, although artists sometimes choose a matte or semi-gloss finish. Shown in Figure 3.8 are two samples that were prepared identically, except that one was left unvarnished and the other was varnished with a glossy overcoat. The visual difference produced by the varnish layer is striking. The reflective quality of the gloss varnish not only creates clear specular highlights, it also helps emphasize the three-dimensional characteristics of the surface. For the artist material samples, a few varieties of varnish were used in both gloss and matte finishes, the details of which are outlined below.

Figure 3.8. Two Venetian red acrylic samples both applied with a palette knife to linen canvas. The sample on the left is unvarnished, while the one on the right was finished with a gloss Golden MSA Varnish.
Golden MSA Varnish with UVLS (Matte and Gloss)

Golden Mineral Spirit Acrylic (MSA) Varnish is a mineral spirits-based acrylic resin varnish. Acrylic resin varnishes have a high molecular weight and are notable for the clear coat they produce which has been found to be very resistant to yellowing over time. Both a matte and gloss version of this varnish were used for the sample set.

Gamblin Gamvar

Gamvar, made by Gamblin, is a low molecular weight synthetic resin varnish. The Gamvar kit comes in two parts, a jar containing Regalrez resin granules, developed by René de la Rie at the National Gallery, and a solvent, which are mixed together to prepare the varnish.\textsuperscript{21}

The low molecular weight of Gamvar allows it to conform to the contours of the painting, which is especially advantageous when the painting has significant three-dimensional texture. Gamvar is quite glossy and similar in appearance to more traditional varnishes that are made from natural resins such as damar and mastic. Although visually similar to traditional natural resin varnishes, Gamvar offers some distinctive advantages. Unlike damar and mastic, Gamvar does not yellow over time. Furthermore, it does not cross-link with the paint layer, making it easy remove.

3.7.2. Fixatives

Fixatives are applied as a final coating to pastel and charcoal drawings to bond the pigment particles together and also adhere the medium to the support.\textsuperscript{13} This overcoat is applied as a fine dilute mist dispensed from an aerosol can or spray gun. Fixative should be used lightly to reduce the fragility of the finished work, but not overly affect the
appearance of the artwork. Golden Archival Spray Varnish was used, in both a matte and
gloss finish, resulting in a set of pastel and charcoal samples for each fixative.
CHAPTER 4: SAMPLE PREPARATION

After considering each material and technique, as detailed in the previous chapter, the specific methods used to build the artist material library are outlined in this chapter. Each of the 574 samples comprising the artist material library was made by hand under the direction of art materials expert Mark Gottsegen. Mr. Gottsegen spent the bulk of two days at the Munsell Laboratory imparting his extensive knowledge of art materials by means of hands-on demonstrations. The demonstrations were videotaped and were an indispensable reference when executing the final sample set. Each material was experimented with extensively, producing numerous test samples to ensure the final samples were the highest quality possible. Of equal importance, Mr. Gottsegen explained and demonstrated procedures to help protect the environment and the artist when handling these often hazardous materials.

4.1. Panel Layout and Construction

Each of the 574 samples comprising the artist material library measures approximately 38mm square and is arranged in a five-by-five pattern on a 25cm square panel. Aside from the similarity in physical layout, panels were constructed in a variety of ways depending on the medium/substrate combination. In addition to the samples executed on Masonite and canvas stretched on a wooden frame, the remaining samples were affixed to a DiBond panel. DiBond is a thin but rigid board with a thermoplastic core sandwiched between two very thin aluminum sheets. The backing panels provided the support needed to keep substrates, such as canvas, inflexible while remaining lightweight. Samples were either painted directly onto prepared panels, as was the case with oil,
acrylic and egg tempera paint, or done on paper that was then cut and adhered to the DiBond panel.

4.1.1. Oil, Acrylic, and Egg Tempera Samples

Two types of canvas were used in combination with oil and acrylic paint: coarse linen and fine cotton. In addition to canvas, Masonite was used for the oil, acrylic and egg tempera paints. Coarse linen canvas was obtained in raw form, un-stretched and unprimed. The raw canvas was handled in two different ways. A panel of oil samples was painted on canvas prepared in the traditional method that requires stretching it over a wooden frame; alternatively, the raw canvas was directly adhered to a DiBond panel using 3M Super 77 multipurpose adhesive, an aerosol based bonding agent.

To prepare the raw canvas and Masonite for paint, both substrates were first sized with Golden GAC 700 Clear Sealing Polymer. The polymer was used to seal the substrate to inhibit Support Induced Discoloration (SID) in which water-extractable materials in the substrate produce a yellow or brown discoloration. The polymer coat also helps prevent the linseed oil in the oil paint from penetrating into canvas, which would cause deterioration of the canvas fibers. The polymer was applied in a single layer with a 1 ½” brush dampened with water.

After being treated with a single application of sealant, the linen canvas was primed with four coats of Golden Gesso, an all-acrylic liquid ground, to ensure an even and uniform coat. Gesso, Italian for chalk, was traditionally powdered calcium carbonate mixed with animal glue that was applied as a primer coat to the substrate to provide a uniform white surface for painting. Gesso provides texture, or “tooth,” to the substrate
and promotes the adhesion of the paint. A dampened 1 ½” brush was used to apply the
gesso with adequate drying time allowed between each application. Each coat was
applied at 90° to the previous layer to ensure even coverage.

To prepare the Masonite hardboard for egg tempera paint, Golden Absorbent
Ground was used. An absorbent ground allows the egg tempera paint to permeate the
surface and form a bond with the substrate. The Golden acrylic gesso, used with oil and
acrylic paint samples, is neither chemically compatible nor absorbent enough for use with
egg tempera. Three coats of absorbent ground were applied to the panel, which was
finished with a light sanding using 220 grit sandpaper to smooth out imperfections.

The sealing polymer, combined with the gesso, noticeably decreased the amount
of texture exhibited by the linen canvas although a fair amount remained after the canvas
was primed. Additionally, a single panel of raw linen canvas, unsealed and unprimed,
was used as a support for acrylic paint. Although it is uncommon for paintings to be
done on raw canvas, it is a choice sometimes made by the artist. It was also useful to
have samples on raw canvas for comparison with the identical samples painted on primed
canvas.

The fine cotton canvas used was of two varieties. The first came stretched over a
cardboard panel and the other stretched on a wooden frame. Both versions came triple
primed with acrylic gesso. Two additional coats of gesso were applied to ensure surface
consistency with the other panels. Additionally, the cotton canvas stretched on cardboard
was adhered to a DiBond panel with spray adhesive for added support.
Once the canvas and Masonite panels were gessoed they were sectioned into 38mm squares using vinyl tape. A prepared Masonite panel ready for paint is shown in Figure 4.1.

![Figure 4.1. A Masonite panel ready for paint, sealed and primed with gesso. The tape, which is removed when the paint has dried, provides a way to create square uniform samples.](image)

### 4.1.2. The Remaining Mediums

The other nine mediums, all used in combination with paper, were attached to the panels using a different method than oil, acrylic and egg tempera paint. The paper samples were adhered to the panels using a double-sided adhesive film, which was first applied to full sheets of paper. After applying medium to the paper, the sample was cut to size using a 38mm punch. Using this process, samples turned out very uniform with consistent medium coverage since there was a large area of medium from which to punch the
sample. The samples were then fixed to the panel using a template to ensure even spacing.

4.2. Sample Creation

4.2.1. Oil and Acrylic

The process used to create oil and acrylic paint samples were very similar aside from differences in preparing the medium prior to use. Galkyd, made by Gamblin, is an alkyd resin blended with Gamsol and was used to decrease drying time for the oil paint. Several proportions of Galkyd mixed with paint were tested to determine the optimal mixture that would decrease the drying time, while not thinning the oils so much that an impasto could not be built up. A mixture of ten parts oil paint to one part Galkyd, by weight, was found to sufficiently decrease drying time while at the same time leaving the paint thick enough to achieve texture. Acrylic paint was ready to use out of the tube and required no additional preparation.

Using panels prepared following the procedures described in Section 4.1, paint was applied utilizing a single technique per panel. The various techniques of brush and palette knife application were carried out as described in Section 3.6.1 with successful results in nearly all cases. One exception was the palette knife application of ivory black oil paint. In this case the surface impasto did not retain its crisp peaks, but rather took on a bumpy appearance when dry. This could have been a result of too high of a concentration of Galkyd added to the paint mixture.

Once paint was applied and allowed to dry, the tape sectioning off each sample was removed, leaving clean lines between individual samples. Oil paint, even with the
addition of Galkyd, was allowed to dry for upwards of several weeks to make certain that the paint was completely set.

The final step in preparing the oil and acrylic samples was to apply a varnish layer. To ensure that the varnishing was carried out in the most precise means possible, Mark Gottsegen again lent his help. Mr. Gottsegen performed the overcoat application for all samples requiring varnish to ensure it was done properly. In terms of organization, each row of the oil and acrylic samples were varnished using a different product or application technique as shown in Figure 4.2.

![Figure 4.2. Acrylic on canvas with a different type of varnish applied for each row.](image)

The first row of each oil and acrylic panel was left unvarnished as a reference for comparison with the varnished samples, and also to represent an aesthetic choice occasionally made by artists.
In the second and third rows, the matte and gloss version of Golden MSA varnish were used. Three parts varnish was mixed with one part Crown brand mineral spirits. The varnish was applied in two coats with drying time allowed between applications. Each coat consisted of two passes of a 1 ½” varnish brush across the painted surface.

The fourth and fifth rows were varnished with Gamvar using two different techniques. Gamsol was used to thin the Gamvar and was mixed 3:1, Gamvar to Gamsol. Again, the varnish was applied in two coats, each consisting of two passes of a 1 ½” varnish brush.

The application technique of the Gamvar was varied in the fifth row to attempt a more matte appearance. To do this, the varnish was brushed in the exact same way as the other varnished samples, but then blotted with a rag to coarsen the surface. This technique did not produce the expected results of a more matte appearance, but rather produced a more mottled appearance in which some areas appear glossy and other areas do not.

4.2.2. Watercolor, Gouache and Ink

Watercolor paper, both cold and hot-pressed, was prepared by first adhering double-sided adhesive film to each sheet so that the samples could be adhered to the panels after being cut using a 38mm punch. No additional preparation of the watercolor paper was performed, yet it should be noted that artists typically take preliminary steps in preparing watercolor paper for use. Watercolor paintings in particular can buckle while drying, owing to the large amount of water used while painting. This can be minimized by stretching the paper by soaking the paper in water, taping it to a stiff backing, and
allowing it to dry. Since in our case a small section was cut for the actual sample, this was not a critical issue and therefore the additional stretching step was not performed.

Watercolors, gouache and ink were all used as washes using a Princeton Art and Brush Company 3/4" synthetic sable flat wash brush. Watercolor and gouache were diluted to different concentrations to achieve washes of varying opacity. As more water is added, the wash becomes more transparent and the color more muted. Through experimentation with paint and water proportions, washes of approximately equal opacity were achieved for each paint pigment. Ink was used undiluted as its consistency is very thin and can be applied without adding extra water.

Watercolors were diluted to two different proportions for each color, depending on the strength of the pigment. The watercolors used were very concentrated so a high proportion of water was added to each mixture. Measured by weight, the water to paint ratios ranged from 15:1 to 60:1. A mix with a high proportion of water was produced for each pigment, which would be used as a nearly transparent layer when starting a watercolor painting. The second mixture, containing less water, produced a more vibrant wash typically used as a secondary layer in a watercolor painting.

Gouache, like watercolor, was diluted in two different proportions to produce washes of varying coverage. Unlike watercolor, gouache, which is typically used as a more opaque paint, was used at 100% strength. The washes included 50:50 paint to water mix which is nearly opaque, along with a more diluted and semi-transparent 10:1 mix. The washes, along with the full strength gouache, were applied in two ways: the first method employed horizontal brushstrokes only and the second technique consisted of applying these in all directions.
Ink was applied as a wash without the addition of any extra water. While ink is often thought of as a drawing medium, it can also be applied with a brush and is sometimes used in combination with other paint mediums. The resulting samples of ink washes were semi-opaque with the paper white contributing to the overall appearance.

4.2.3. Egg Tempera

Masonite panel, primed with an absorbent ground, was the substrate of choice for egg tempera paint samples. Egg tempera paint was prepared using egg yolk, artist-grade dried pigment and water. First, the dried pigment was thoroughly mulled using the flat portion of the palette knife to make certain that the pigment was a consistent particle size. Next, a small amount of water was added to the dried pigment to wet each of the particles and create a thick paste. Following the preparation of the pigment, an egg yolk was carefully separated from the egg white, ensuring that the yolk sack remained intact. After drying the yolk by rolling it in paper towel to prevent rupturing, it was pierced to drain the yolk while holding between the thumb and forefinger. It is important to be cautious with this step to prevent any of the sac membrane from getting in the mixture. The yolk was next mixed with a small amount of water to produce a less viscous consistency. Lastly, approximately equal parts of pigment paste and yolk were mixed on a large glass palette at which point the egg tempera paint was ready for use.

Before using the egg tempera paint to create samples, the paint mixing procedure was tested to ensure proper mixing so that the paint would dry correctly. A large stripe was painted onto a glass palette and allowed to dry for several hours, after which it was
removed with a razor blade. When the paint peeled off in one piece, this indicated that
the mixing procedure was correct.

Generally speaking, when applying egg tempera, plenty of water should be used
to guarantee that the paint will not dry too quickly and become difficult to brush. In our
case, the samples were all created within a few minutes of mixing the paint so the rapid
drying time was not a concern and the excess water was not needed. Furthermore,
eliminating the excess water during paint application allowed for greater control in
creating uniform samples. The egg tempera paint was applied using single brushstrokes
applied in one direction. Applying the paint in this manner prevented overworking the
medium, which can cause it to become gummy and difficult to brush. After the paint had
dried the panel was complete, as egg tempera is typically not varnished.

4.2.4. Drawing Mediums

Colored pencil, marker, pastel, charcoal, graphite and Conté crayon (the so-called
drawing mediums) were all used in a similar manner for sample creation. Concerning the
preparation of these mediums, all six came ready for use and did not require additional
steps to prepare. All of the drawing mediums, aside from pastel, were applied to both
smooth textured Pentalic sketch paper and coarsely textured cold-pressed watercolor
paper.

To further contrast the appearance of the drawing medium samples, the
application technique was varied. All of the drawing mediums, with the exception of
pastel, were applied in either multiple directions or a single horizontal direction. In both
cases full sheets of paper were secured to a hard surface using tape so that they would not
move when the medium was applied. For both application techniques the resulting appearance varied depending on the medium used. Soft mediums, like marker, provided excellent paper coverage, while harder mediums, like colored pencil, did not coat the paper as well.

Application in multiple directions consisted of a sweeping hand motion with layers put down 45° relative to the previous direction. The multiple direction application technique produced samples that had good medium coverage with a minor amount of paper white still visible. When applied in a single direction, a side-to-side hand motion was repeated, making certain the medium was applied as uniformly as possible. In most cases this technique, depending on the medium, produced samples that had a sparse medium coverage and had a fair amount of paper white still visible.

The application of pastel was carried out by applying the medium in multiple directions and then lightly blending with a small piece of tissue paper. Blending the pastel gave the sample a smooth and uniform appearance. Furthermore, the blending helped adhere the pastel to the paper and allowed excess pigment to be eliminated from the sample. Sketch paper was the only substrate used in conjunction with pastel. Artists prefer relatively smooth textured paper, as more coarsely textured paper tends to be too abrasive for the powdery character of pastel.

Pastel and charcoal, which are powdery and susceptible to smudging, were treated with a fixative as a layer of protection. Golden spray varnish, in both a matte and gloss finish, was used to fix the charcoal and pastel samples. The spray varnish was applied as per the manufacturer’s directions in four light coats with drying time allowed between
each application. Furthermore, each application was sprayed perpendicular in relation to the previous one to ensure even coverage.

It should be pointed out that artists often leave pastel and charcoal works unvarnished, as these are often protected with a glass casing in museums. With this in mind, it would have been ideal to retain a set of unvarnished pastel and charcoal samples, but protecting the samples with glass was not practical. Furthermore, if left unvarnished and unprotected the samples would quickly degrade from handling and also potentially contaminate other samples and equipment. The fixative layer quite noticeably altered the appearance of both the pastel and charcoal samples. The pastel in particular, which has a light, airy appearance when left unvarnished, looked quite different after fixative was applied. Although the fixative did alter the appearance of these mediums, the samples were still considered representative, considering artists often times do use fixative with these mediums.

4.3. Final Sample Set

The final collection making up the artist material library consists of 574 unique samples, which are summarized in Table 4.1. After the final sample set was created, the finished panels were now ready for use with the Imaging Goniospectrometer. A wooden cabinet was constructed to house these 25 panels and is shown in Figure 4.3.
Table 4.1. Summary of the 574 samples comprising the artist material library.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Substrate</th>
<th>Color</th>
<th>Technique</th>
<th>Overcoat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Acrylic</td>
<td>Coarse Linen Canvas</td>
<td>Venetian Red, Chromium Green Oxide, Neutral Grey, Bone Black, Titanium White</td>
<td>Brushed, Palette Knife (Smooth), Palette Knife (Impasto)</td>
<td>Unvarnished, Gamvar, Golden MSA Matte, Golden MSA Gloss</td>
</tr>
<tr>
<td></td>
<td>Fine Cotton Canvas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Masonite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Masonite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Masonite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cold-Pressed Watercolor Paper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cold-Pressed Watercolor Paper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ink</td>
<td>Hot-Pressed Watercolor Paper</td>
<td>Red, Green, Black</td>
<td>Brushed</td>
<td>Unvarnished</td>
</tr>
<tr>
<td></td>
<td>Cold-Pressed Watercolor Paper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Egg Tempera</td>
<td>Masonite</td>
<td>Venetian Red, Chromium Green Oxide, Bone Black, Titanium White</td>
<td>Brushed</td>
<td>Unvarnished</td>
</tr>
<tr>
<td>Colored Pencil</td>
<td>Sketch Paper</td>
<td>Burnt Sienna, Moss Green, Black, Slate Grey, White</td>
<td>Applied in one direction, Applied in all directions</td>
<td>Unvarnished</td>
</tr>
<tr>
<td></td>
<td>Cold-Pressed Watercolor Paper</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marker</td>
<td>Sketch Paper</td>
<td>Crimson Red, Dark Green, Black, Neutral Grey</td>
<td>Applied in one direction, Applied in all directions</td>
<td>Unvarnished</td>
</tr>
<tr>
<td>Pastel</td>
<td>Sketch Paper</td>
<td>Red, Green, Black, White</td>
<td>Applied in all directions and blended with tissue paper</td>
<td>Matte Fixative, Gloss Fixative</td>
</tr>
<tr>
<td>Charcoal</td>
<td>Sketch Paper</td>
<td>None</td>
<td>Applied in one direction, Applied in all directions</td>
<td>Matte Fixative, Gloss Fixative</td>
</tr>
<tr>
<td>Graphite</td>
<td>Sketch Paper</td>
<td>None</td>
<td>Applied in one direction, Applied in all directions</td>
<td>Unvarnished</td>
</tr>
<tr>
<td>Conte Crayon</td>
<td>Sketch Paper</td>
<td>None</td>
<td>Applied in one direction, Applied in all directions</td>
<td>Unvarnished</td>
</tr>
</tbody>
</table>
Two finished panels are shown in Figure 4.4. On the left is Panel 2, oil paint applied with a palette knife on linen canvas. The palette knife was used to achieve a spiky appearance by pulling up on the paint with the flat surface of the tool. Different varnishes were applied to each row. Panel 21 is shown on the right, consisting of the marker and charcoal samples.
Figure 4.4. Two finished sample panels. Oil paint on linen canvas (left) and marker and charcoal on various papers (right).
CHAPTER 5: NON-IMAGING OPTICAL MEASUREMENTS

5.1. BYK-mac Measurements

The BYK-mac, a multi-angle spectrophotometer made by BYK-Gardner, was used to obtain spectral and colorimetric measurements for each sample. Shown in Figure 5.1 measuring a panel, the BYK-mac uses 45° illumination and is able to capture measurements from six in-plane aspecular angles: -15°, 15°, 25°, 45°, 75°, and 110°.

![Figure 5.1. Measurements being made with the BYK-mac on an acrylic sample panel.](image)

The measurements obtained using the BYK-mac made it possible to quantify changes in color and spectral reflectance as a function of viewing angle. Given that the Imaging Goniospectrometer captures images from multiple angles, it was valuable to...
have a corresponding dataset that substantiates the visual changes seen in samples as they are rotated. The data obtained from the BYK-mac measurements showed significant changes in spectral reflectance as the viewing angle was varied. There were also substantial changes in spectral reflectance between samples that were identical other than different varnish layers. The plot in Figure 5.2 illustrates this point in which spectral data obtained at various viewing angles from two acrylic paint samples was plotted. One sample was finished with a glossy varnish and the other a matte varnish.

![Figure 5.2](image.png)

*Figure 5.2. Reflectance measurements obtained for multiple viewing angles for both a glossy and matte acrylic sample using the BYK-mac.*

There are large variations in spectral reflectance that occur when the viewing angle is changed for both the glossy and matte acrylic sample. There was also a significant difference when comparing the spectral reflectances between the glossy and
matte samples. At the -15° and 15° detector angles, the glossy sample had a significantly higher spectral reflectance when compared to the matte sample. At the remaining four detector angles, the reflectances were more similar although the glossy samples were still slightly higher.

The changes in color as a function of viewing angle are also quite significant. When viewing images captured with the Imaging Goniospectrometer from various angles, the color noticeably changes as the panel is rotated. The colorimetric data obtained with the BYK-mac, calculated using the 2-degree observer and D65 illumination, confirms the visual observation. This is evidenced by the a*b* plot in Figure 5.3, showing the data obtained from two different oil paint samples, one Venetian red and the other chromium oxide green. Both samples in this plot were unvarnished and painted on cotton canvas with a relatively smooth appearance. The a*b* coordinates of the two samples, plotted at -15°, 15°, 25°, 45°, 75°, and 110° reveal drastic changes in color. The red oil paint sample shows an increase of both the a* and b* values as the viewing angle increases. The green oil paint sample shows a decreasing a* and increasing b* as the viewing angle increases. The majority of samples in the artist materials library exhibited similar color changes as the viewing angle was shifted, although some were more dramatic than others, depending on the physical characteristics of the sample.
Figure 5.3. $a^*b^*$ plot of two different oil paint samples measured from various angles. As the measurement angle changes, the color differences are quite severe - both visually and colorimetrically.
CHAPTER 6: ARTIST MATERIAL DATABASE

The artist material library is a valuable resource that can be used in computer graphics applications when creating virtual scenes that include artwork. With this in mind, the BRDF data obtained from the artist material samples was made accessible in the form of a public domain image database that is available online at art-si.org. The artist material database is the first of its kind in that it focuses exclusively on artist materials. The database is divided into three major sections, each highlighted below.

6.1. The Table of Included Materials

The first section is designated the Table of Included Materials. This portion of the database focuses on details relating to the materials and techniques used to create the samples. A portion of the table is shown in Figure 6.1. The Table of Included Materials provides a comprehensive listing of all materials and techniques organized by the five attributes of variability, medium, substrate, color, technique and overcoat, each in its own column. Each item on the table is linked to its own page that provides extensive written details along with images of the materials and video clips of the techniques used.
Figure 6.1 shows an example of how one of the pages, in this case the page for oil paint, is laid out. Each dimension, as it relates to oil paint, is outlined and also linked to its own page describing that particular material or technique. This includes details for each substrate and how it was prepared, colorant and overcoat descriptions, and also the techniques utilized. For example, if a user clicked on the *Masonite* link under *Substrates* as seen in Figure 6.2, they would be brought to the page shown in Figure 6.3.

<table>
<thead>
<tr>
<th>Medium</th>
<th>Substrate</th>
<th>Color</th>
<th>Application Technique</th>
<th>Overcoat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil</td>
<td>Canvas</td>
<td>Venetian Red, Chromium Oxide Green</td>
<td>Brush</td>
<td>Unfinished, Canvar, Gold MSA Matte, Gold MSA Gloss</td>
</tr>
<tr>
<td></td>
<td>Linen</td>
<td>Red Oxide, Chromium Oxide Green</td>
<td>Brush</td>
<td>Unfinished, Canvar, Gold MSA Matte, Gold MSA Gloss</td>
</tr>
<tr>
<td></td>
<td>Masonite</td>
<td>Terra Ross, Chromium Oxide Green</td>
<td>Wash: mixed 15:1 water to paint, Wash: mixed 30:1 water to paint</td>
<td>None</td>
</tr>
</tbody>
</table>

Table of included materials:

- **Medium**
- **Substrate**
- **Color**
- **Application Technique**
- **Overcoat**

Figure 6.1. Screen shot of the Table of Included Materials. Organized by the five attributes of variability, each item in the table is linked to its own page that details that particular material or technique.
Figure 6.2. A screen shot of the Oils page from the artist material database. Each dimension of variability, as it relates to oil paint, is detailed with links provided to obtain additional information about the listed items.
Figure 6.3 illustrates how the detail pages describe the material and also provides additional links to other materials and techniques relating to that item. In the case of application techniques, the detail pages also provide short video demonstrations to show how the materials were used. The hope in providing this level of detail is that it will aid others in recreating the samples if necessary when utilizing the database in their research efforts.

6.2. The Aggregated Datasets

The next section of the artist material database, The Aggregated Datasets, makes available two large datasets, both downloadable as single files. Shown in Figure 6.4, both the measurement data obtained with The BYK-mac multi-angle spectrophotometer and the surface normal maps of all 574 samples are provided in this section.
The BYK-mac measurement data are provided in a single Excel workbook and includes spectral reflectance factor and colorimetric data from six measurement angles for each sample. All of the surface normal maps for the samples can be downloaded in this section as a single Zip file.

### 6.3. Sample Panel Summary

Shown in Figure 6.5 is a portion of the final section, the *Sample Panel Summary*. Organized by panel, datasets for both the rectified sample images and normal maps are included in this section for each of the samples.
As seen in Figure 6.5, specifics about the substrate and application techniques are provided to assist locating specific panels easily. To further enhance the search capabilities, users can drag the mouse over a panel thumbnail image to enlarge the selected panel and allow the visual details to be seen more clearly. Clicking on a panel number links the user to another page, where each sample on the panel is identified and described. Shown in Figure 6.6 is the detail page for Panel 1, which is oil paint on canvas.

<table>
<thead>
<tr>
<th>PanelNum</th>
<th>Medium</th>
<th>Substrate</th>
<th>Technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Oil</td>
<td>Canvas - Gessoed (x4) Coarse Linen</td>
<td>Applied Side-to-Side with palette knife - very slight impasto</td>
</tr>
<tr>
<td>2</td>
<td>Oil</td>
<td>Canvas - Gessoed Fine Cotton</td>
<td>Applied with palette knife - &quot;bumpy&quot;/impasto</td>
</tr>
<tr>
<td>3</td>
<td>Oil</td>
<td>Mascotite - Gessoed (x4)</td>
<td>Applied with palette knife - very slight impasto</td>
</tr>
<tr>
<td>4</td>
<td>Oil</td>
<td>Canvas - Gessoed Fine Cotton</td>
<td>Applied with palette knife - &quot;bumpy&quot;/impasto</td>
</tr>
<tr>
<td>5</td>
<td>Oil</td>
<td>Canvas - Gessoed Fine Cotton</td>
<td>Brushed - one direction (vertically)</td>
</tr>
<tr>
<td>6</td>
<td>Oil</td>
<td>Canvas - Gessoed Fine Cotton</td>
<td>Applied Side-to-Side with palette knife - very slight impasto</td>
</tr>
<tr>
<td>7</td>
<td>Oil</td>
<td>Canvas - Gessoed Fine Cotton</td>
<td>Applied with palette knife - &quot;bumpy&quot;/impasto</td>
</tr>
<tr>
<td>8</td>
<td>Oil</td>
<td>Canvas - Gessoed Fine Cotton</td>
<td>Brushed - one direction (vertically)</td>
</tr>
</tbody>
</table>

Figure 6.5. The Sample Panel Summary section of the database. Extensive details about each panel are provided to make locating specific samples straightforward. Clicking on the corresponding panel number brings users to another page that describes each sample on that particular panel.
On each panel detail page, the position of the individual samples on that panel is expressed in terms of row and column. Additionally, the five dimensions of variability are highlighted for each sample, making it easy to identify the exact visual qualities for a particular sample. The 94 rectified images can be downloaded as a single Zip file. Also, the normal map for each sample can be downloaded as an EXR image file.

Figure 6.6. Clicking on a panel number in the Sample Panel Summary section brings users to a detail page for that panel. For each Panel Summary (shown here is Panel 1) a full description of each sample is provided along with links to download normal map and image data information.
CHAPTER 7: CONCLUSIONS AND FUTURE RESEARCH

A library of artist materials was created containing 574 unique samples that represent the common materials and application techniques used by artists, both past and present. The BRDF measurements obtained from this collection of samples are used to develop models that, when incorporated into the imaging workflow, make possible an imaging goniospectrometer system that can be implemented in a museum setting. This type of system provides a means to more accurately document artwork by capturing images from multiple angles that can be used to simulate different lighting and viewing environments.

The artist material BRDF data are also available online as a searchable database for use in computer graphics applications such as the rendering of real world surfaces. The database, available at art-si.org, has numerous features. Descriptions of the materials and application techniques used to make the samples are provided to aid others in recreating the samples. Furthermore, image data and normal maps are provided so that other researchers can fit new BRDF models if desired.

In the future, as imaging techniques improve, the samples comprising the artist material database will continue to prove valuable. The unique qualities of the samples make them a powerful resource in the characterization of gonio-imaging systems. Specifically, the uniform composition of each sample makes them ideal for use as gonio-imaging targets and eliminates the majority of shortcomings associated with using actual artwork. Furthermore, the individual attributes of the samples are organized in a manner that allows users to easily compare single variations between two otherwise identical samples. For instance, a Venetian red acrylic paint sample with impasto can be easily located in the database, both unvarnished and varnished, for use in comparative analysis.
of gloss properties. An example highlighting how the sample set can be utilized is presented in Appendix Section 9.1; it should be emphasized that this illustrates a single example of how the artist material samples can be used. The samples are currently, and will in the future, be utilized in applications to improve the gonio-imaging process.
CHAPTER 8: REFERENCES


CHAPTER 9: APPENDICES

9.1. Appendix One: Example Usage of Artist Material Database

9.1.1. MCSL Imaging Goniospectrometer

The MCSL Imaging Goniospectrometer (shown in Figure 9.1), is a single imaging system capable of measuring spectral reflectance factor, BRDF, and surface normal.\textsuperscript{22,23} In developing this system, it was important to keep the equipment for image capture, along with the software needed for post-processing of the images, practical enough for use in a museum setting. To accomplish this, the camera, lighting, and object positioning are separated into three distinct components rather than integrating these elements into a single instrument.\textsuperscript{24} An Apple iMac computer, seen in the foreground of Figure 9.1, is

\textit{Figure 9.1. The MCSL Imaging Goniospectrometer room. The computer in the foreground is used to control the imaging process. The three-axis sample positioner is visible in the center of the room.}
used to control the entire imaging process. The computer, utilizing class-based libraries written within MATLAB, automates the positioning of the sample panels and the sequencing of the detector measurements. Only the changing of the sample panels and repositioning of the light source requires manual intervention\textsuperscript{24} The Imaging Goniospectrometer set-up is enclosed in a light-tight space by means of a heavy black curtain; this arrangement ensures that when the imaging process is in progress, no stray light illuminates the samples.

![Image of Imaging Goniospectrometer](image)

*Figure 9.2. The various detectors used in the MCSL Imaging Goniospectrometer which are mounted on a motorized translation axis, allowing them to be repositioned to collect data from the same vantage point.*

Three detectors, shown in Figure 9.2, make up the Imaging Goniospectrometer and include a Canon 5D camera, the MCSL-Sinar Multispectral Camera\textsuperscript{25} and a Konica Minolta CS-2000 Spectroradiometer. In the Imaging Goniospectrometer configuration,
the detectors are positioned approximately 8 feet from the target. The Canon 5D is an RGB camera and is fitted with a 135mm lens. The spectroradiometer is coupled with a pan-tilt mirror so that measurements can be made at various locations on the target without having to move the detector. The multiple detectors sit on a motorized translation axis, as seen in Figure 9.2. The translation axis is controlled via computer and allows each detector to be consecutively placed at the same viewpoint.

An Oriel tungsten source (shown in Figure 9.3) with a constant current power supply, was used to illuminate the sample panels during image capture. The lamp had an aperture size of 10mm x 7mm and was positioned 6 feet from the target. The small aperture size approximates a point source, which helps simplify the BRDF model fitting procedure.
Lastly, the sample positioner, shown in Figure 9.4, allows any flat target (up to 10 pounds) to be positioned at multiple angles through rotation about three axes relative to the center of the target. As the sample positioner moves the target through various angles with respect to the light and camera, images are captured at each orientation. The light source and camera remain stationary at a fixed angle relative to one another throughout the image capture process.

![Image of the sample positioner](image)

*Figure 9.4. The positioning system used in the MCSL Imaging Goniospectrometer. This sample positioner has three degrees of freedom, allowing any flat target to be oriented at various angles relative to the camera and light source.*

### 9.1.2. Image Capture

Each of the 25 panels of artist material samples was imaged using the Imaging Goniospectrometer. In the current arrangement of the system, the Oriel point source is
repositioned manually at various angles relative to the detector bank. These various orientations between light source and detector are necessary to measure BRDF for each sample. The various angles are also used to estimate the Fresnel coefficients, which require near specular measurements at multiple angles. Since the light source has to be moved by hand, only three illumination angles were used. The Oriel light source was placed at 13.4°, 45° and 90° relative to the camera, resulting in a total of 94 measurement angles for each sample panel.

The Canon 5D was used to obtain image data for each of the measurement angles. Canon Raw image files (CR2) were captured using three exposure times, 1/15, 1 and 8 seconds. The multiple exposures were taken so that HDR images could be generated in the post-processing stage. The camera was set to an ISO setting of 200 and an aperture of f22. The small aperture size allows for the entire sample to remain in focus when the panel was tilted at steep angles relative to the camera.

9.1.3. Image Processing

Figure 9.5 shows an example of three raw images that were captured using the multiple exposure times from a sample panel consisting of acrylic paint on canvas with various types of varnish applied to each row. The first step in processing the raw images was to combine the three exposures into a single OpenEXR format floating point HDR image.
The HDR images were then divided by the diffuse reference white to obtain data scaled to reflectance factor. A square PTFE standard tile was used as the reference white, which was imaged at each of the 94 measurement angles. This procedure was used to correct for non-uniformities in the lightfield, lens falloff and per-pixel non-uniformities in the camera sensor. The resulting images were saved as OpenEXR files.

The next step in processing the images was to rectify and align all images to 0°. The Imaging Goniospectrometer captures images with the sample panels at various angles relative to the camera. The images captured at these angles need to be corrected, or rectified, so that each appears as though it was taken from the same straight-ahead viewpoint. The rectification and registration of the images is an automated process that relies on fiducial markers placed around the sample panel clamping system used in combination with the known system geometry. First, a nominal rotation is calculated based on the geometry of the sample holder. Next, using the registration tools in the MATLAB image processing toolbox, a 4x4 transform is estimated based on the autocorrelation of the fiducial markers. This calculation is performed at a sub-pixel level. Each sample measures 38mm square, with each pixel measuring approximately 0.17mm. The final rectification is based on combining these two transforms and applying it to the

Figure 9.5. Three exposure times were combined to create an HDR image. The exposure times were 1/15 second (left), 1 second (middle), and 8 seconds (right).
original image. This process results in a collection of 94 images of the same panel shot at different angles with corresponding pixels placed at the same spatial locations in each image. This process is illustrated in Figure 9.6 in which the image on the left was captured at a sharp angle. The angled image was then rectified and registered, resulting in the straight-on image shown on the right of Figure 9.6.

![Figure 9.6](image)

*Figure 9.6. Each image captured at an angle needs to be corrected so that it appears to have been shot from a straight-ahead point of view. The original image captured at an angle (left) is rectified and registered to the 0° viewpoint resulting in the straight-on view (right).*

Lastly, for each panel, the set of images for each material sample was extracted to create an image stack of 94 measurement-angle images for each. Each image set is comprised of 230x230 pixels for each of the RGB channels and is bundled with descriptive metadata about that sample.

### 9.1.4. BRDF Fitting

The image data captured with the Imaging Goniospectrometer was used to perform BRDF model fitting for each of the artist material samples. The resulting model parameters and surface normals were then used to render images for various lighting directions. The key steps of this procedure are outlined in the following sections, which
are derived from the work of Chen, et al. who carried out the BRDF model fitting procedure. For further detail please refer to this document.

The first step in the BRDF fitting process was to parameterize each of the 94 measurements obtained with the Imaging Goniospectrometer using a spherical coordinate system. Cartesian coordinates \((x, y, z)\) are used to describe the three degrees of freedom afforded by the sample positioning system that is used to orient the panels at various viewing angles. The Cartesian coordinates are converted into spherical coordinates using the following relationship:

\[
\begin{align*}
    r &= \sqrt{x^2 + y^2 + z^2} \quad (9.1) \\
    \theta &= \tan^{-1}(y/x) \quad (9.2) \\
    \phi &= \cos^{-1}(z/r) \quad (9.3)
\end{align*}
\]

Next, both the diffuse and specular surface normals are computed. The success of the BRDF model fitting relies on accurately determining surface normal, which is used to describe the three-dimensional geometry of the surface. These variations in texture are most notable for oil and acrylic paint samples with impasto; the majority of samples only have small changes in surface normal.

The photometric stereo method was used to calculate the diffuse surface normals. This method relies on observing an object under diffuse lighting conditions and is based on two assumptions: that the object has Lambertian reflectance and that the lights used are point sources. Specular normals, used to describe bright highlights on each sample due to its gloss level, were also calculated. The specular normals are
calculated presuming that the specular lobe of the BRDF has its peak at the specular reflection direction. The measurements were fit using two different models, the Ward and Cook-Torrance BRDF models.

9.1.5. Rendering

The recovered BRDF and diffuse surface normals were used to render images of the artist material samples under an interactively controlled distant point light source. Two of the panel renderings are shown in Figure 9.7. In this example, the panels in the top row are images captured with the Imaging Goniospectrometer, while the bottom two panels are the corresponding renderings. The panels in this example are acrylic paint on coarse linen canvas with different varnishes applied to each row.
Figure 9.7. The recovered BRDF along with the diffuse surface normal was used to render images under a point light source. The two panels in the top row are images captured with the Imaging Goniospectrometer, while the images in the bottom row are rendered images of the corresponding panels.