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From color to appearance in the real world

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Abstract

X-Rite's declared ambition is to create a digital ecosystem for appearance; a daunting challenge that has many dimensions and has not been accomplished so far. In this short paper we sketch a path from color to full appearance which aims at solving this challenge.

1. Introduction

Advances in material models, acquisition techniques and technology and rendering technology have all contributed to an increasing demand for realistic materials. These methods must consider light interaction, environment influence, and observer perception. This shift toward full appearance models represents the next frontier in virtual material acquisition, representation, and rendering.

1.1. Beyond color: understanding appearance

Rendering systems (including both ray-tracing and rasterization based ones) focus on color. Color is the main attribute passed along the ray or processed in the pixel. Objects, however, are more than just color. They have shape, size, weight, construction, surface texture, gloss, translucency and transparency, sparkle, coarseness, temporal variation, and angular dependence (and more) attributes. Some of these physical attributes are geometric in nature. These geometric attributes, such as shape, size, weight, and construction are generally treated separately from the other attributes. These other attributes, of which color is one, are generally associated with the material. As clear as this designation may seem, some geometric attributes are integral to the material definition. In fact, this differentiation ultimately depends on the scale at which the object is observed. Furthermore, the individual observer and viewing conditions also play a significant role. These aspects factor into the perceptual appearance of an object and should not be ignored. All of these characteristics make up what we call the Foundations of Appearance (see Figure 1.) This foundation of appearance has been adapted from the appearance framework proposed by the CIE Technical Committee 1-65 of Division 1, "Vision and Colour."

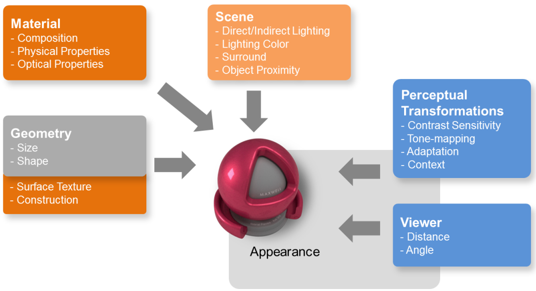

Figure 1: *Foundations of appearance*

1.2. Material Models

The collection of characteristics and mathematical methods which represent these aspects of appearance are what is known as a material model. Material models vary widely both in the kinds of materials that can be represented and their accuracy. Some models are computationally more expensive and only suitable for off-line rendering, while others are cheaper and appropriate for real-time rendering, usually with a speed vs. accuracy trade-off. In order to accurately convey each material, it is conceivable that a material might be communicated via multiple models, each producing the desired results for a given situation. In any case, it may not be necessary to represent the material with full accuracy in all circumstances; rather the material's model may be context dependent.

2. Towards Capturing Appearance

The rendering capabilities of todays' systems are astounding, particularly considering the state of the art just 10 years

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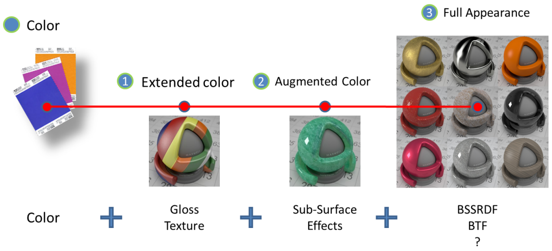


Figure 2: *The journey from color to appearance.*

ago. Nevertheless, in the last several years, content creators have become discontented with standard operating procedures where materials are painstakingly crafted by hand. But the bridge between physical reality and virtual reality is still under construction. To complete the transition, we suggest a series of steps designed to bring full appearance into virtual reality (see Figure 2).

2.1. Color integration

As already mentioned, material models typically have colors as attributes. Instead of guessing at colors using color wheels, designers are picking from established well-defined color sets from companies such as Pantone LLC, or using devices to measure and match colors, such as the X-Rite CAPSURE$^{\text{TM}}$.The output of such devices can be integrated directly into the existing workflow. The difficulty with such an approach is that the color being measured or selected may not correspond to the color as the model uses it. Designers must use the input as a starting point rather than end, often taking into account the material model and interpreting the way that the color will be used.

2.2. Extended Color

Obviously, most materials are not fully defined by a single color attribute. They have additional attributes that define their appearance, some of which have nothing to do with color. We believe that two main categories stand out as the first frontier in measured color integration. These are color spatial variation (commonly referred to as texture) and gloss. For instance, plastics, architectural paints, and laminates are a few materials whose appearance is significantly affected by these categories. Standard models for the Bidirectional Reflectance Distribution Function (BRDF) such as suggested by Ashikmin-Shirley [AS00] (among others), provide single color gloss highlights and are combined with a simple texture map to provide albedo variation in most rendering systems. In addition, simplified models of more complex materials also use these categories for approximation. Advances in measurement to obtain such parameters require multi-angle instruments such as the X-Rite MA98 spectrophotometer or calibrated digital cameras. The Bidirectional Texture Function (BTF) and the surface-varying BRDF (SVBRDF) combine these two types of material characteristics into one mathematical representation that can be used as a material model. Several devices capable of producing BTF or SVBRDF data exist but are large and difficult to use.

2.3. Augmented Color

While extended color primarily deals with the color at the surface of the material, augmented color goes below the surface. Materials which require sub-surface scattering (such as semi-opaque or translucent plastics or glass) and sparkle or other metallic effects (such as automotive paint) would fall into this category. The material models are typically layered or volumetric. These are generally more computationally expensive and more difficult to represent. For distant illumination these effects can be captured by a BTF but not a SVBRDF. Laser systems, structured lighting and spectral imaging systems are some of the tools required to characterize the internal light transport characteristics of these types of material.

2.4. Full Appearance

Full appearance models aim to capture all input and output light transport, which is a daunting challenge given the extremely large amounts of data that need to be measured when done in a naive way. Ultimately we believe solutions in this area will be a result of decomposition. The goal will be to separate the various types of light transport into manageable pieces with reasonably well-known accuracy. By selecting the best of all worlds, the representation will be as small and efficient as possible.

3. Towards Communicating Appearance

When considering colors as RGB triplets, it would appear as though communicating color would be a simple thing. However, all RGB triplets belong to a particular color space. In order to correctly understand the color, it is necessary to identify the color space (from among known color spaces, such as sRGB or Rec. 709) or characterize the color space using a profile, white point and/or gamma curves. In addition, depending on the type of data, the color space may be bounded (low dynamic range with a gamut), or unbounded (high dynamic range). While characterizing the color space allows the color to be communicated and displayed correctly under many illumination conditions, typically this is not enough to capture true light-material interaction. A solution is obtained by using a spectral color representation for both lighting and materials, using typically between six and 31 color channels per color. Recently there has been a push to incorporate such spectral rendering capabilities into existing systems.

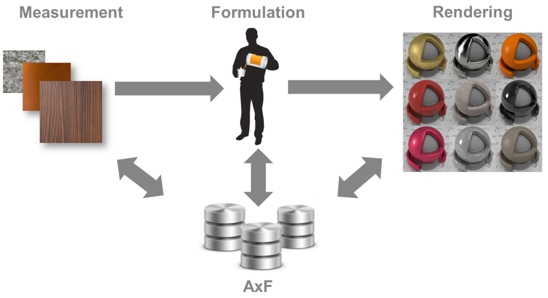
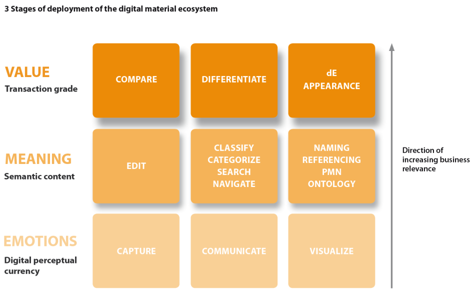


Figure 3: *The Appearance chain using AxF.*


3 Stages of deployment of the digital material ecosystem

VALUE Transaction grade	COMPARE	DIFFERENTIATE	dE APPEARANCE
MEANING Semantic content	EDIT	CLASSIFY CATEGORIZE SEARCH NAVIGATE	NAMING REFERENCING PMN ONTOLOGY
EMOTIONS Digital perceptual currency	CAPTURE	COMMUNICATE	VISUALIZE

Direction of increasing business relevance

Figure 4: *The business of appearance.*

3.1. AxF

As we develop additional appearance characteristics, the need for standardization is apparent. Despite the fact that these standards have yet to be determined, the existing Color Exchange Format (CxF) [CxF] framework provides a pattern we can use for moving forward (Figure 3). We will propose a new standard container, the Appearance Exchange Format (AxF), which will be derived from the current standardized CxF format.

3.2. Ontology

To use such a format efficiently, it will become necessary to separate characteristics into a smaller set of well-known and commonly accepted representations. These smaller separable parts become features in a "tensor-product" type of material composition. Each of these components represents a particular physical or optical characteristic of the material. Consider for example the hybrid carpaint model from Rump et al. [RMS*08] which factors the paint into a combined pigment component, a flake component and the clearcoat all represented using quite different models. If materials are categorized according to the types of components that they present as part of their representation, this directs us toward an ontology, or characteristic-based categorization, of materials. As Mendeleev's Periodic Table of elements is grouped by a combination of chemical and physical properties, so this ontology groups materials according to their representative composition.

4. The Business of Appearance

We separate our business interest in appearance into three categories of increasing business value. The bottom level is the emotional consumer level. The middle tier is the semantic level, addressing the needs of solution providers. The top level is the transaction level where the greatest value is achieved (Figure 4).

4.1. Digital perceptual currency

At the basic consumer level, we separate the business of appearance into three different categories: capture, communicate and visualize. At this level, the consumer's emotions trigger buying decisions according to what looks nice and makes them feel good. Producers are interested in making sure that the product's appearance is correctly communicated up and down the supply chain. Products must be clearly advertised and virtually represented in order to maintain good relations with the consumer. This is the fundamental exchange of perceptual information in the digital world, or digital perceptual currency.

Until now the variation in presentation quality (from print to television) has enabled companies to present products whose virtual appearance is far from the actual product's appearance. But the move to shopping by internet (removing the controlled time frame and the controlled presentation style) and display improvements (i.e. high definition displays and wide gamut displays) have offered the consumer a much higher fidelity viewing experience - both of which drive the need for more accurate appearance.

4.2. Semantic content

In order to offer the ability to edit, search, categorize and classify appearance, the definition of a material needs to contain semantic content. The appearance of a material is described with words which have some semantic content. Here classifying a material by name, material characteristics and/or appearance into a recognizable system becomes valuable. We suggest the Pantone Material Nomenclature (PMN) as one possible method. In this nomenclature, which would relate to the current Pantone Color System, materials would have a unique ID that is indicative of its classification. Solution providers (Pantone LLC, PLM vendors, search engines, design software etc.) would be involved in creating and managing this content. However, standardization of the semantics of a material is a very difficult task. Usually the semantics are culturally dependent, and additionally dependent on the industry. For example, it may be clear in the printing industry how to make a particular color be "ruddy" but in the plastics industry, this phrase may not be clear.

4.3. Transactional Appearance

At the tip of the appearance pyramid lays the industrial definitions of appearance. These representations provide real-world costing input, they establish approval criteria, they are the foundation of material specifications and they can be rigorously measured and tracked. The market for such material specification is smaller, but for this group, the representation is extremely critical. At this level lives the perceptual difference metric: the "dE for appearance". Up to this point, establishing dE criteria for colors has been the standard methodology for color. Additional standards for other material characteristics (such as gloss or orange peel) have been developed and standardized by the ASTM and are available for use. But each of these characteristics is used independently. It may difficult to understand what a single number means for an appearance difference, but at some point, within industry quality control, it will be necessary to provide some global difference measure.

5. Challenges

Although consumer and industry demand will accelerate the drive toward full appearance, there are some key issues that need to be resolved or managed. Fortunately, the current pace and direction of technology advancement will assist this cause, but is unlikely to overcome all the challenges.

5.1. Measurement to model decomposition

The key to providing measured materials lies in the ability to decompose what is measured into components of a digital model. Most often, model parameters are not directly measureable. Optimization is frequently used to determine the best parameters for a given model, but when multiple models are used, the problem becomes extremely difficult.

5.2. Appearance Displays

The quality of a display determines the maximum fidelity of the appearance of an object. Displays with higher resolution, higher dynamic range, and no visible glare will be sought after for the next generation of appearance rendering. Currently, many of the issues with current displays are controlled by managing the environment in which they are viewed. But increasingly, mobile devices are the display platform regardless of the provider's intent.

5.3. Mobile acquisition

Just as mobile devices are becoming the display platform of choice, there will be a dramatic shift toward more portable acquisition. For some materials, acquisition can be made with instruments which are currently considered to be part of the mobile device category, using primarily camera sensors which are nearly ubiquitous in this market. For other materials, specialized portable devices will likely be more appropriate, but the requirement for portability will stand. In addition to considering form factor, processing power and functionality will also be a factor. Most methods of acquiring data require significant processing time to make the data usable in an appearance type of display. In addition, most mobile graphics APIs do not yet support the complicated processing that is currently necessary.

5.4. Appearance standardization

Although a format such as AxF as suggested above may provide a reasonable container for standardized appearance models, the process of standardization of appearance will likely be a difficult task. Each material may have several models designed for different purposes (for example, real-time vs. off-line virtualization) and agreement must be reached on each one. Current material standards (such as the Pantone Textile Color System®) provide an example of the variety of materials that need to be virtualized.

6. Conclusions

The trend toward full appearance among both industry and consumer will continue to put positive pressure on efforts to enhance acquisition, communication, and rendering. As we develop better models, the ability to edit or otherwise modify the materials to suit our needs will increase providing more business value in the appearance framework. This will in turn foster consumer demand for products that are made to specification in a much broader range of appearance characteristics. The advancement of technology on its current course will provide much of the horsepower and raw materials for accomplishing this task; however a lot of research still lies ahead.

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