

Causes of Color: Especially Interference Color

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Abstract

Webster's asserts that color is "a phenomenon of light or visual perception that enables one to differentiate otherwise identical objects," and then goes on to say that the Latin root is *celare*, "to conceal." It's a fine definition, because human perception of color is seamless to the extent that it conceals from us almost every causal detail. This talk will discuss common sources of light, the interaction of resultant source spectra with objects of interest, and aspects of how the resultant light is perceived as color. Particular emphasis will be placed on light modulated through interference and displays based on interferometric principles.

Introduction

Since light (electromagnetic radiation) contains no inherent color information, the first step to understanding the causation of color might well be dispensing with the notion that making the link from light to color is the critical step toward understanding. Light is best characterized by associating a particular wavelength to a particular energy and to a particular color, while keeping in mind that a particular color should not be associated with a particular wavelength. Color is best linked to the animals that perceive it rather than to the physics of light, and human animals have evolved to perceive a version of color supported by a narrow band of wavelengths comprising less than 2% of the electromagnetic spectrum. It's reasonable to assume that evolution selected for that narrow range because it spans the energies at which most of the worthwhile interactions between electromagnetic radiation and bound electrons occur. At longer (lower energy) wavelengths the interaction of radiation with physical objects creates atomic vibrations, principally generating heat, and there's little worthwhile differentiation (other than shape) between hot cars and hot cows. At shorter wavelengths, sufficient energy is available for radiation incident on surfaces to cause ionization, permanently changing the chemical make-up of the surfaces, and leaving little information about the original surfaces for humans to perceive. We're much more effective when we view someone's shoulders in the red and determine that sunburn has occurred in the recent past than we would be viewing those same shoulders in the infrared, where we would see only that they're hot, or viewing them in the ultraviolet where we would see almost nothing.

Human vision picked the "visible" wavelengths because those wavelengths of radiation interact strongly and non-destructively with energy transitions in the objects around us and through absorption, transmission, and reflection encode the light reaching our eyes with the greatest wealth of information regarding the objects.

Centered within this chosen band of "visible" wavelengths there is a specific wavelength that is more chosen than others. The human vision system is most sensitive to light around 550

nanometers in wavelength, which corresponds closely to the most prevalent wavelength emitted by our sun. It might seem that a carefully engineered system would be more sensitive to the less abundant wavelengths (in order to extract the widest range of information), but the architecture of the vision system currently in use by humans seems to have been more opportunistic than that.

The following sections of this paper will discuss in turn the way in which humans utilize the limited visible spectrum to create the perception of color, some selected characteristics of the color vision system, the ways in which those characteristics can be exploited to facilitate the display of electronic images for human viewing, and an in-depth consideration of one particular example of such a display.

Light and the Perception of Color

Light entering the human visual system (wherein the light will be perceived as color) can be characterized as being contained within a spectral envelope. In the light we perceive, for every wavelength between the long wavelength limit of our perception (around 700 nanometers) and the short wavelength limit (around 400 nanometers), there is a corresponding value for the intensity of light at that wavelength. The variety of spectra confronting the vision system is dramatic.

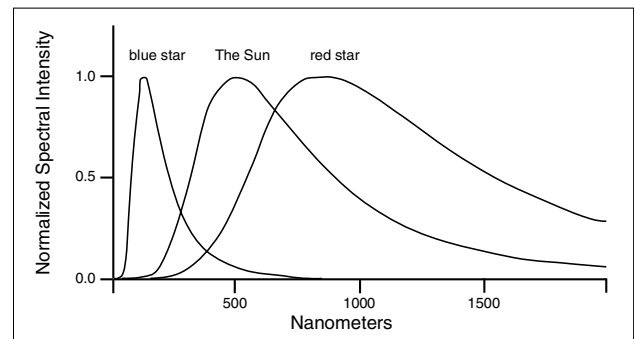


Figure 1: The solar spectrum and spectra from a hotter and a colder star

The spectrum of light from our Sun can be represented by the smoothed spectral envelope shown in Figure 1. The actual spectral envelope is significantly more complex, with many specific wavelengths absorbed by gases near the sun's surface. However, the smoothed envelope of Figure 1 is adequate for a general discussion. Along with the spectral envelope of the Sun (a 'yellow' star) the spectral envelopes of a 'red' star and a 'blue' star are shown, normalized to a peak intensity of unity. The shapes of these spectra are essentially black body radiation curves of the type shown in Figure 2, where each curve is characteristic of an otherwise non-emissive object at a particular

temperature. The peak of a ‘white’ star spectrum would fit in between the ‘yellow’ and ‘blue’ peaks of Figure 1.

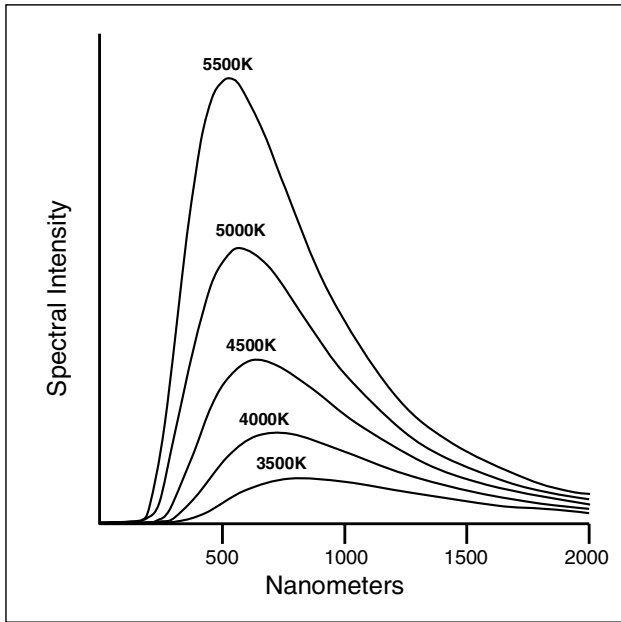


Figure 2: Spectral intensity plotted against wavelength for black bodies at various temperatures

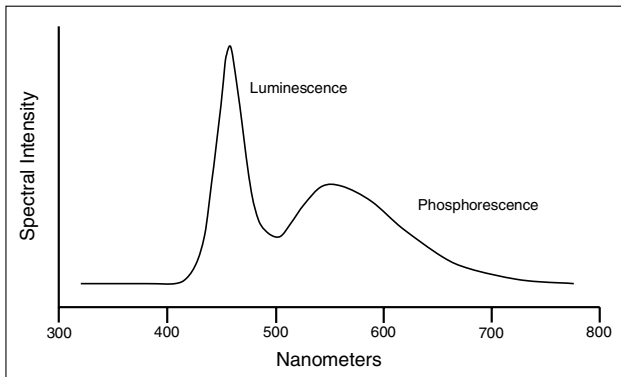


Figure 3: Spectral Intensity vs. wavelength for a ‘white’ LED source

The emission of a ‘white’ light emitting diode source is shown in Figure 3. The inherent LED emission constitutes the ‘blue’ peak near 460 nanometers, and phosphorescent dye coated onto the source provides the ‘yellow’ peak near 560 nanometers. The human vision system perceives that color-wise a broad continuous spectrum such as that emitted by the Sun is essentially equivalent to the spectrum dominated by two separate peaks depicted in Figure 3. This aspect of our color perception, and similar perceptual limitations, facilitate mere humans in the conception and creation of electronic displays that come close to representing real scenes. Figure 4 shows an example of a skeletal spectrum that also provides the perception of white light. Three narrow band laser sources are combined to create an intense ‘white-light’ source that can be used in projection display systems.

Given that these widely variant stimuli are perceived as ‘white’ light, the question turns to how the color vision system responds to these stimuli to yield the same result. Part of the answer is shown in the familiar graph of Figure 5, where the wavelength dependent responses of the tri-stimulus cone structures within the human eye are shown. The color vision system has separate channels responsive to short, medium, and long wavelength regimes (normalized here to unity response), but the broad and overlapping sensitivity regimes of the cone receptors are far divergent from the narrow and discrete inputs of the laser-based system of Figure 4. Yet at the simplest level, stimuli that deliver energies ES, EM, and EL to the short, medium, and long wavelength receptors respectively will be perceived as having the same color.

This characteristic allows human perception of the broad-spectrum ‘white’ star and the narrow bimodal spectrum of the ‘white’ LED to be quite similar. We experience many such ‘shorthand’ perceptions every day without giving them a second thought. We accept ‘red’ stars and ‘blue’ stars but are seldom troubled by the lack of the ‘green’ stars that energetically must lie between them. In point of fact, the ‘red’ stars are not red, and the ‘blue’ stars are not blue. Overlapping the spectra of Figure 1 onto the sensitivities of Figure 5 shows that we will perceive relatively cold stars as red and slightly hotter stars as yellow as they stimulate the cone sensitivities on the long wavelength side of the visible spectrum. As temperature increases beyond yellow stars, the spectra of more energetic stars will stimulate all three receptors and appear white. Even hotter stars will provide decreased stimulation of the mid and long wavelength receptors, and will appear blue. The star spectra walk across the visible spectrum but are too broad to stimulate perception of individual colors in the mid-wavelengths. There are indeed billions of ‘green’ stars, but humans will never see them as green.

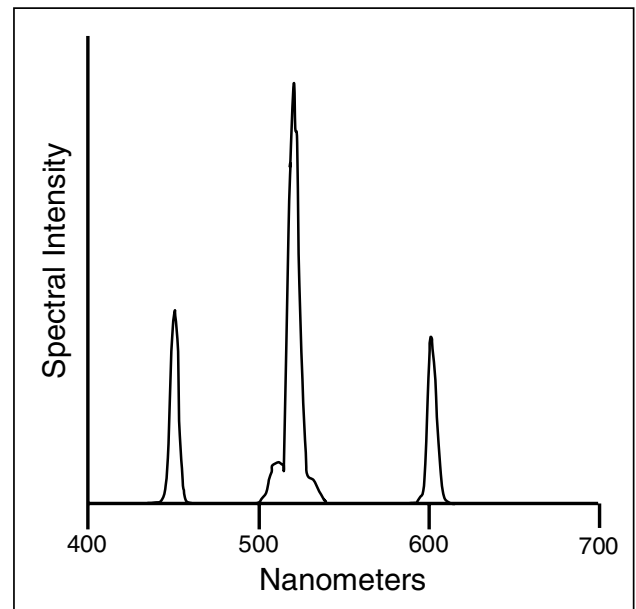


Figure 4: Spectral intensity vs. wavelength for a tri-stimulus laser diode source

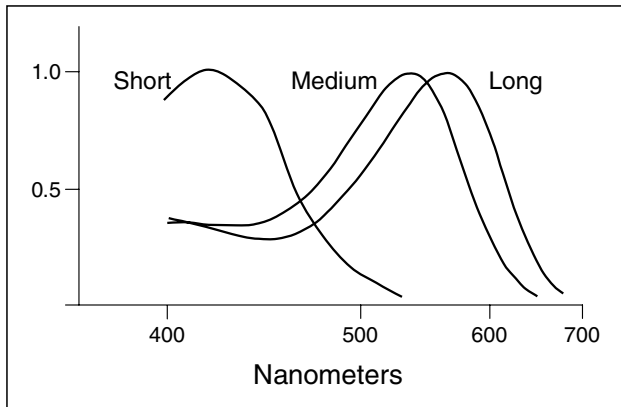


Figure 5: Normalized sensitivity of the short, medium, and long wavelength receptors

Modulated Light – The Sources of Color

Having talked about light predominantly in the context of white light (and the almost-white-light of our slightly yellow Sun) one might begin to wonder why our world does not appear much whiter than it does. Especially considering that our indoor light, which hasn't come from the sun, is emitted by man-made sources that are advertised to be equivalent to daylight except for being a bit 'warmer,' meaning enriched at the long wavelengths, or being a bit 'cooler,' meaning enriched at the short wavelengths.

The answer of course is that most of the light we perceive has bounced off grass or trees or buildings or people or dogs or furniture or a myriad of other things before reaching our eyes. The interaction of the fundamentally white light with the electrons, vibrational modes, surface structure, and other properties of our surroundings modulates the spectral envelope of the source light to provide the limitless variety of spectra that stimulate the gigantic range of perceptions which to a large extent define the world for the sighted populace.

The light that leads to the colors we perceive can be conveniently (although somewhat arbitrarily) divided into three classes, although for the purposes of this particular paper we shall allow a fourth class of particular interest to the author.

- **Light from Emissive Devices:** including incandescent sources such as black bodies like stars (see above) and tungsten filament lamps. Non-black-body lamps are included, most notably vapor lamps such as the sodium lights that, because of their specific atomic transitions, make large parts of Chicago appear yellow when viewed from the air. These lamps cause the disorienting parking lot effect in which the color of one's car will seem either dramatically altered or essentially black. The spectrum of the lamp is so narrow, and the absorption of the dyes in the auto's paint so effective that little light is left to stimulate the eye.
- **Light Reflected from Absorbers:** such as fabric dyes, gem stones, minerals, photochromic materials (such as light activated sunglasses), and semiconductors – materials whose detailed band, orbital, and lattice structure determines which

wavelengths they will absorb and which wavelengths will be reflected. A rare but beautiful example (caused by vibrational coupling) is the "ice blue" color of frozen water that can occasionally be seen in pristine environments.

- **Light Modified by Physical Optics Mechanisms:** such as the *dispersion* that gives us rainbows when sunlight reverses direction inside raindrops (providing a primary rainbow when a single intra-drop reflection is involved and a secondary rainbow when a double intra-drop reflection is involved) and the highly elusive green flash at sunset. *Scattering* gives us red sunsets as blue light is scattered away from us, blue sky as the blue light is scattered back to us, and the amazingly intense (but temporary) eye color of some babies. *Diffraction* is a third physical optics effect that 'bends rays' but which we tend to experience in day-to-day life only when it combines with *interference*.

- **Light Modified by the Particular Physical Optics Mechanism of Interference:** This is the property of the wave nature of light in which light interferes with itself to intensify some wavelengths and damp out others. *Interference* is often the partner of *diffraction* in the sense that diffraction steers light in various directions, and the results are only visible after the light has interfered with itself. From interference we get anti-reflection coatings, blazing cats' eyes, and the iridescence of peacock feathers, mother of pearl, and the iMod™ reflective display.

The Brain and the Perception of Color

We have seen above that a wide variety of dissimilar but energetically equivalent scenes can lead to equivalent color perception, and we have also seen that a wide range of mechanisms in the physical objects around us can receive incoming light and modify its spectral content before passing the light on to the viewer. We can identify numerous cases where the color vision system is slightly confused, and we can use our knowledge of the system to create highly unlikely scenes that confound the system. However, these are isolated cases, and the brain is too clever to be deceived in any broad sense.

Experimentation has demonstrated that identical scenes that are not energetically equivalent, and hence might be presumed to be capable of fooling the color receptors in the eye, are in the vast majority of cases perceived as being color equivalent. This happens because the human color vision system is not just a detector system – it implements extensive post-processing.

Firmware near the center of our brains and algorithms executing in the occipital lobes disambiguate the signals received from the retina. The algorithms evaluate the general quality of a viewed scene and its illumination and constantly color-correct, so that we aren't startled by walls, furniture, and pets changing color every time we open or close the drapes. They compensate for dynamic range changes, and accomplish myriad other tasks that enable us to understand the scenes we view. The work done within the brain has greater impact upon our perception of color than does the precise nature of the light

that illuminates our world or the manner in which the objects in our world modulate that light.

In spite of its prodigious capabilities, the human visual system has limitations. If this were not the case, it would be very difficult to make useful electronic displays for the presentation of images. If human vision had unlimited spatial resolution, pixel sizes would need to be impossibly small. If human vision had infinitesimal response times, frame refresh rates would need to be impossibly fast and field sequential displays, such as Texas Instruments' DLP™, would never have left the drawing board. If human vision had decades and decades of dynamic range, displays would face unconquerable brightness and contrast ratio challenges. Luckily for display manufacturers, human vision is limited in all of these areas, and a wide range of useful displays has been created. All successful display types, and the image capture, storage, and transmission systems behind them, have paid close attention to the limits of human vision.

The iMod™ - An Interferometric Display

The straightforward introduction to interference phenomena considers wave behavior in the case where multiple waves of precisely matched wavelength interact. An example is shown in Figure 6 where two waves such as "A" and "B" propagating in the same direction are superposed, enforcing each other constructively, and resulting in the increased amplitude of wave "C." A second case is shown where the waves "D" and "E" are exactly 180 degrees out of phase and result in the non-wave "F." Such perfectly matched waves are seldom found in nature.

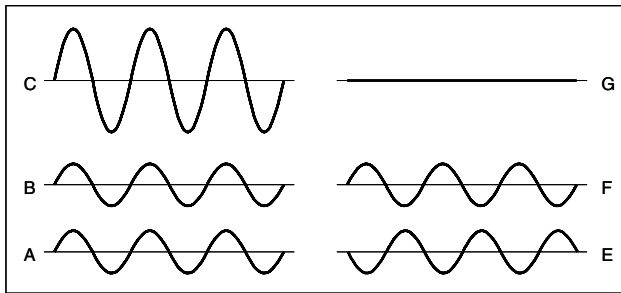


Figure 6: Constructive and destructive interference

A common natural phenomenon which generates interference color is created by thin oil films on top of puddles. This situation is shown in Figure 7. A wavefront of incident light "A" falls on the oil surface. A ray of one particular wavelength is traced through the oil, down to the water. Some of that light will continue through the water, but for this example we've assumed it is absorbed in the soil below. The remaining light reflects back through the oil to the air. The oil thickness was selected to be near three wavelengths for this particular angle of incidence. The reflected light emerges into the air just where a second ray from wavefront "A" impinges and partially reflects. This ray has traveled one wavelength longer in air than did the initial ray, so the two rays tracing path "B" would be nearly in phase were it

not for the fact that the ray reflected from the high index oil surface undergoes a phase change amounting to one-half wavelength. The two rays are hence nearly out of phase, and cancel each other.

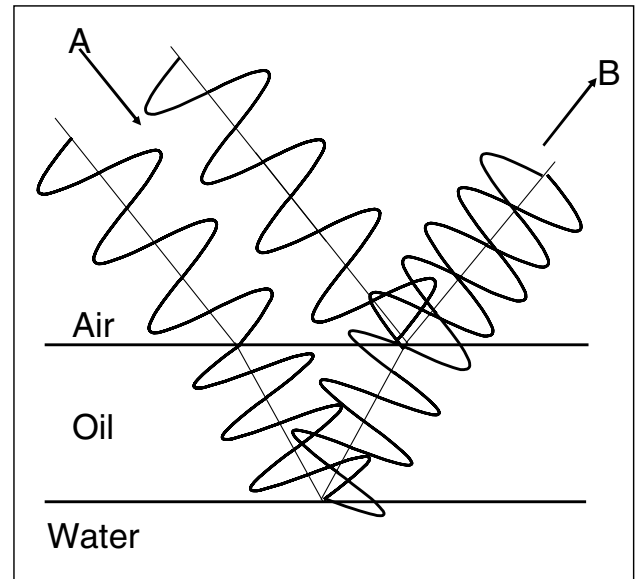


Figure 7: Interference caused by an oil film

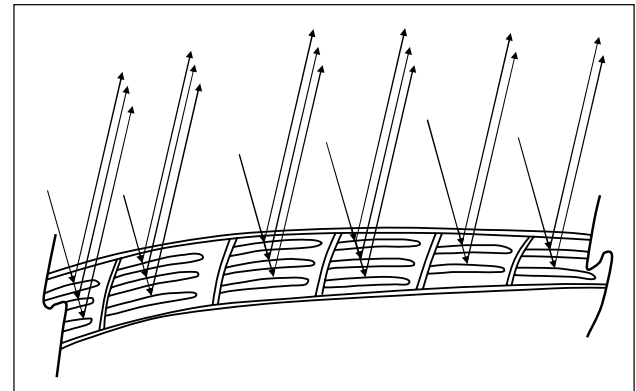


Figure 8: Interference caused by multi-level structures in a butterfly wing

Observed at any given angle, one wavelength will be in phase after traversing the oil and the rest will be out of phase to a greater or lesser degree. The result will be a rainbow of colors visible across a range of viewing angles or a rainbow of colors as the oil film thickness changes across the puddle.

A more complex example is generated by the structure of some butterfly wings. The classic example is the Blue Morpho. Within the wing, a vertical structure between the top and bottom wing surfaces supports a series of features at regular intervals. As shown in Figure 8 the repetitive structure creates multiple reflected rays leading to multiple instances of constructive interference and a dramatic iridescent coloration.

Such structural color was the inspiration of the interferometric modulator (iMod™) being produced by

QUALCOMM MEMS Technologies. The structure of the device is shown schematically in Figure 9. Following current flat panel display fabrication practice, and to ensure low manufacturing costs, multiple displays are fabricated simultaneously on a large sheet of glass. Fabrication begins by depositing a thin film optical stack directly on the surface of the glass plate. The stack comprises a transparent conducting layer, a partially reflecting layer, and a transparent insulating layer. These layers are patterned into stripes that will define the horizontal rows of pixels in the display. A sacrificial layer is deposited on top of this optical stack. The term “sacrificial” reflects the fact that before the display is completed this layer will be completely removed from the display structure.

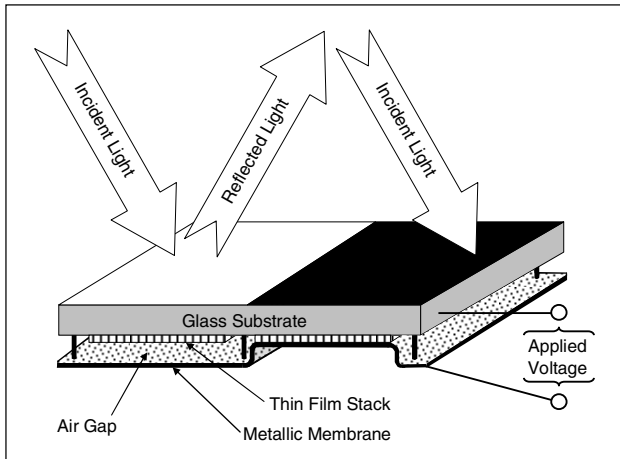


Figure 9: Interferometric ‘on’ and ‘off’ pixels

Vias are created through the sacrificial layer, and post structures are created within the vias. A highly reflective and mechanically flexible membrane is deposited on top of the wide expanse of sacrificial material generally and on top of the posts specifically where they reach through the sacrificial layer. The membrane is patterned into stripes that will define the vertical columns of pixels in the display. After the membrane is patterned, a gas-phase etchant removes the sacrificial layer, and each pixel that remains is an individual interferometric cavity similar to but much more precise than the oil layer described above.

Ambient light enters the interferometric cavity through the glass plate and the transparent conductor. The partial reflector constitutes one wall of the resonant cavity. The insulating layer, together with the air gap (which occupies the space previously taken up by the sacrificial layer), constitute the cavity itself. The reflective membrane constitutes the second wall of the interferometric cavity. The display of Figure 9 is monochromatic with all cavities tuned to resonate a particular wavelength at normal incidence of light.

To create images it is necessary for each pixel to have a non-reflecting state in addition to the reflective resonant state. This is achieved by applying voltage between the transparent conductive layer and the reflective metallic membrane. At a sufficient voltage, electrostatic attraction between these two

layers causes the flexible membrane to collapse against the insulating layer. The thickness of the resonant cavity, which is the thickness of the insulating layer when the membrane is in the collapsed state, is dramatically reduced. The thin cavity resonates in the ultraviolet portion of the spectrum at a much shorter wavelength. Humans can’t see the resultant reflected light and determine that the pixel has gone into a black state.

Color displays are created by composing pixels using three different thicknesses of sacrificial layer. Thick layers create thick resonant cavities and hence pixels that resonate at red wavelengths, thinner cavity pixels resonate in green, and the thinnest layers of sacrificial material yield blue sub-pixels. Such a display is shown schematically in Figure 10, and Figure 11 shows the spectral output of the three colored states as well as the common ‘black’ state that occurs when the membranes are pulled down against the thin film optical stack.

As mentioned above in the discussion of interference colors in oil films, resonant wavelength will change with viewing angle. Consequently, a diffusive film covers the front surface of iMoD displays. This film mixes incoming and outgoing rays across angles so that a range of colors is seen at each viewing angle. This mixing impacts the widths of the spectrum bands seen in Figure 11 and allows the display to be customized for color bandwidth over viewing angle.

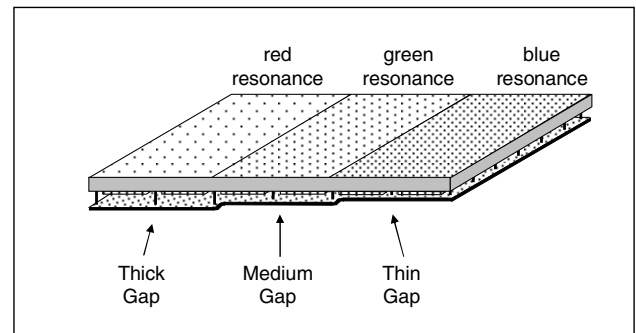


Figure 10: Gap size determines bright-state wavelength

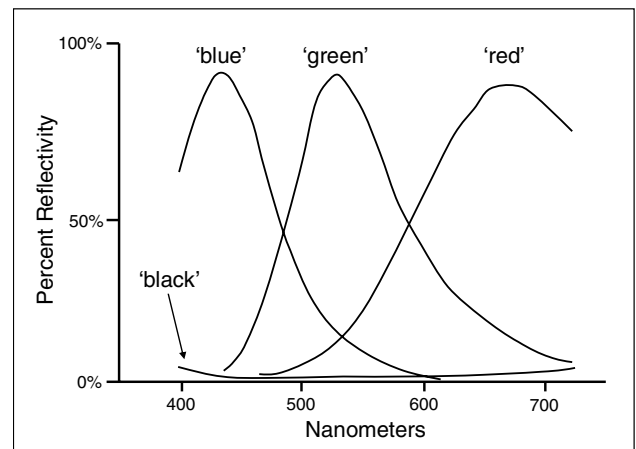


Figure 11: Optical spectrum of the iMoD color display

A key operating principle of the iMoD™ is common to almost all electrostatically-driven micro-electro-mechanical systems (MEMS). As voltage is applied to the flexible membrane it deflects gradually until it has moved approximately one-third of the way through the cavity. At this point an over-center phenomenon causes the mirror to collapse against the optical stack. The mirror springs back up when the applied voltage is reduced well below the voltage required to cause the collapse. This leads to the mechanical hysteresis loop shown in Figure 12. At the “Hold Voltage” shown in the figure, both collapsed and non-collapsed states are stable and allowed. This enables images to be held indefinitely with zero power consumption, since the resonant cavity is a capacitor, and although voltage is applied no current is flowing across the capacitive cavity.

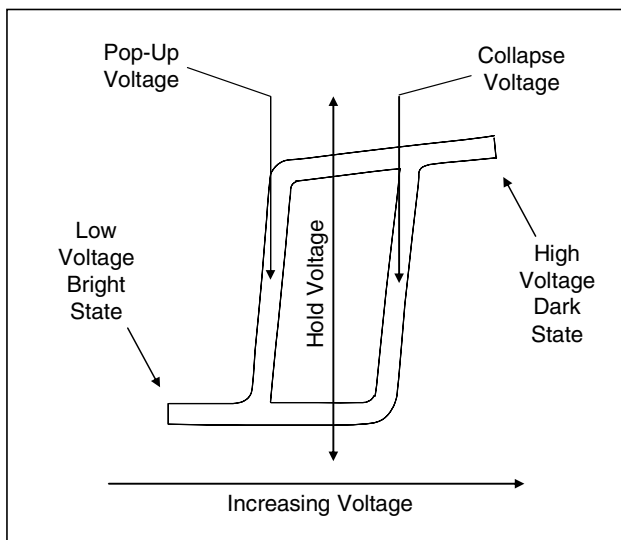


Figure 12: iMoD mechanical hysteresis

Summary

Color exists only in the brain of the beholder. Light that illuminates the environment plays an important role, but the brain can disambiguate large variations in illumination condition to extract a robust constancy in the perception of color. The objects that make up our environment determine which portion of the illumination reaches the viewer, and understanding the variety and complexity of schemes that modulate incident light could be a life's work. A few physical optics effects elegantly color our world, and if they are not simple to comprehend, then at least they are straightforward. One such effect is interference, and the promise exists that in the near future we will be using colorful low-power displays based on this most elegant of effects.