Appearance Degradation and Chromatic Shift in Energy-Efficient Lighting Devices

Charles E. Hunt**, Jesús Quintero, Josep Carreras

IREC, Catalonia Institute for Energy Research, Jardí de les Dones de Negre 1, PL2, 08930, Barcelona, SPAIN

California Lighting Technology Center, University of California 633 Peña Ave, Davis California, 95618, USA

Abstract

All artificial lighting devices undergo some color shift over the course of their useful lifetime. Unlike incandescent and halogen lamps, which display a gradual shift along the Plankian locus, energy-efficient lamps degrade Color-Correlated Temperature (CCT), in a non-blackbody manner. This exacerbates a generally poor appearance, and can impede public acceptance, especially among residential users. We show the trend of degradation and chromatic shift of the two available incandescent replacements for residential general lighting, Light-Emitting Diode (LED) Compact Fluorescent (CFL). It is found that over the useful lifetime, not only does the efficiency of the lamp decrease, but the CCT and Color Rendering Index (CRI) of these lamps shifts continuously in an unfavorable manner. The majority of the shift is due to differential phosphor aging. In several cases, the shift is alarming in that the lamps start in a part of color space which is tenuous in its color acceptability, and shift into substantially inferior color space, with poor CRI and undesirable CCT. Possible solutions, using current LED and CFL technology, can only be implemented by paying a price in energy efficiency. Some solutions for the future which retain reasonable color and efficiency over lamp lifetime are discussed.

Introduction

The mandate for change to energy-efficient lighting devices for illumination implies important changes in the appearance of general lighting. Right now, approximately 22% of all electrical usage in the USA is for lighting, and roughly half of this is for residential lighting. The remaining half (commercial, industrial, and institutional lighting) has already overwhelmingly made the transition to energy-efficient lighting (predominantly using linear fluorescent lamps), in large measure due to regulatory codes. New US regulations, commencing in 2012, will change much of residential general lighting as well, both in the US and abroad. To date, acceptance of alternative, energy-efficient lamps, primarily of the Compact-Fluorescent Lamp (CFL) variety, and more-recently, Light Emitting Diode lamp (LED) types, has not been enthusiastic by consumers, primarily due to appearance issues. (Note: there are also other serious impediments to public acceptance, such as high cost, environmental unfriendliness, heat, inapplicability to in-place lighting fixtures, etc.; but these issues will not be addressed here.) As of this writing, there are other energy-efficient general lighting technologies, such as Organic LED (OLED) and Electron-Stimulated Luminescence (ESL), which are not yet broadly available to consumers, and these are not analyzed here.

The ubiquitous incandescent lamp, being a blackbody radiator, appears “natural” to consumers. One reason is its near-perfect color rendering; but another is the fact that even over the lifetime of the lamp, the radiated output remains on the Plankian locus, albeit shifting progressively in color temperature.

By contrast, both LED and CFL lamps, when new, start with a Color-Correlated Temperature (CCT) which emulates the incandescent lamp; but have compromised color rendering, typically with general Color Rendering Index (CRI) values of R_a = 78-85. These lower values are primarily due to the use of PhotoLuminescent (PL) phosphors in both the CFL and LED lamps, and their inherent limitations. All phosphors degrade (“age”) with usage, predominantly due to the loss of radiative activity of the dopants (“activators”) within the host matrix of the phosphor. This loss is primarily due to issues pertaining to energy dissipation (mostly, heat) in the phosphors. The activator materials are absolutely necessary in the phosphors in order to obtain radiative output in the visible spectrum, so the loss of this activity has consequences in the device’s performance as a lamp. The result, in the context of CFL and LED lamps, is a continuous degradation of the lamp appearance over its useful lifetime, due primarily to a chromatic shift of the lamp’s radiative output.

The following sections explain the necessary compromise conditions in CFL and LED lamps separately, given that the operational mechanisms of these lamp types are significantly different. The expected evolution of these lamp types’ appearance are also presented. It is highly unlikely, barring major technological breakthroughs, that the issues discussed here can be satisfactorily mitigated in a manner which will make these lamp types illuminate with superior appearance, using the current device operational architectures. Finally, some suggestions for solutions in future lamps are offered.

The Incandescent Standard

The incandescent lamp, including halogen variants, is a blackbody radiator. The color temperature of the lamp is determined by the resistance of the filament. Over time, the resistance, and correspondingly, the color temperature, of the filament changes. However, the lamp remains a Plankian radiator, with highest color rendering. Although appearance issues, especially glare, can be a problem, lamp and fixture manufacturers have presented solutions for all of these for some time. Therefore, consumer satisfaction over appearance is generally high, and the incandescent lamp is justifiably held as the standard to which residential general-lighting devices are compared. Figure 1 shows the spectrum associated with an ordinary 3,000K "white light" incandescent lamp.

Compact Fluorescent Lamps (CFL)

The CFL lamp is a scaled-down version of the ubiquitous linear-fluorescent tube, provided with an integral power supply ("ballast") in the base of each lamp. Each CFL lamp has a tiny amount of elemental mercury sustained in vapor phase due to the sub-atmospheric pressure within the tube. Therefore, the CFL is operated as a mercury-vapor lamp with the invisible ultraviolet spectral lines of the mercury use to excite the PL phosphor on the inside of the glass envelope. Note that, because of the slight vacuum within the tube, the visible-spectrum output of this mercury-vapor lamp is negligible. Therefore, emitting at 404.7nm (slight), 365.4nm, and 253.7nm, the tube is essentially used as a UV pump to excite the PL phosphors which emit in the visible range. The most-common phosphor coating is a mixture of $LaPO_4:Tb^{3+},Ce^{3+}$ (the Tb and Ce being the dopants for green and blue) and $Y_2O_3:Eu^{3+}$ (the rare-earth dopant providing the red output of the lamp.) The spectral output of this lamp, as new, is also depicted in Figure 1. Compared to the incandescent-lamp spectrum, it is clear that the CFL lamp is missing key content in the visible range. This is not only the reason that CFL lamps do not render certain colors well (notably, in the red-orange), but also why the general population has a natural reaction to CFL light ("It doesn't look 'natural' to me.")

The PL phosphors for CFL need to have strong excitation spectra at the available UV lines from the mercury plasma, in order to be energy efficient. This constraint severely limits the number of PL phosphors which can be used to create an energy-efficient lamp, and even more so if good color rendering is desired. Even the Y_2O_3:Eu red phosphor, which must be included in the mix if red is to be rendered at all, is a serious compromise in that it degrades the overall lamp efficiency. It is generally considered, at this time, that a satisfactory PL phosphor (or mix of phosphors) does not exist which can fill in the missing colors in CFL, without a significant compromise with energy efficiency. There are, in fact, "Natural daylight" fluorescent lamps available, with R_a values exceeding 85; but all of them have energy efficiency significantly inferior to what can be achieved using the standard mix, because the extra phosphors they contain are not efficiently excited by the specific lines from mercury vapor. Consequently, CFL lamps, if they are to be energy-efficient, will always have an inherently sub-optimal color-rendering capability and R_a value. The search for a broadband UV plasma source for pumping fluorescent lights without mercury has been on for over 50 years, without any success.

Light-Emitting Diode Lamps (LED)

There are essentially two types of "LED lamp" for general-lighting. The first uses multiple semiconductor diodes, having 2, 3, or even 4 colors emitting in parallel. These are, most commonly, Red, Green, Blue (or "RGB primary colors") diodes used together to obtain white light. It has been shown that among solid-state lighting (SSL) energy-efficiency options, this method has the best potential for efficiency, albeit with significant compromises in color rendering [1]. This technique has a host of technical problems, although it is postulated that eventually solutions will be found which will improve the technique sufficient to allow for both efficiency and good color rendering, as well as solving other problems (heat generation, cost, glare, etc.) [1]. Because this method does not use phosphors, it also represents, potentially, the longest lifetime solution, given that diodes can potentially operate in excess of 100,000 hours. However, there are not products readily-available to consumers which use this method, and have appearance which is deemed satisfactory for residential general lighting, and therefore this SSL method is not considered further here.

The second, and the only widely-available LED white-light method, uses a blue (460nm) III-nitride semiconductor diode which acts both as a source of the blue primary color and also as a pump for PL phosphor which supplies the remaining portion(s) of the visible spectrum for obtaining "white" light. This method cannot, inherently, be ultimately as efficient as the all-semiconductor method, given that it requires two energy-conversion processes (and one, in series), namely the electroluminescent process in the semiconductor for the blue, and the PL process in the phosphor pumped by some of that blue output. Even so, Nakamura et al. devised a reasonable technique at Nichia, described in numerous publications and a summary book [2], which combines the blue semiconductor output with emission from a YAG:Ce broad-band yellow phosphor (peaking in intensity near 560nm), resulting in a bright white light with reasonable efficiency (40+ lm/W, in a lamp) and borderline CRI ($R_a = 80$). This fundamental approach to high-power SSL is the foundation of virtually all commercial products described as "LED lamps", although it is evident that the LED (a semiconductor) is only part of the structure. Hundreds of incremental improvements have been made, some of which are also detailed by Tsao, et al. [1]. An example of the combined blue+yellow output spectrum is also shown in Figure 1. Varying the ratio between blue and yellow output results in variations in the efficiency vs. CRI tradeoff [2].

The key to performance in this method is the combination of a reasonably-efficient semiconductor, in conjunction with an efficient, thermally-stable yellow phosphor which uniquely excites in the visible at 460nm. However, a limitation of this method is that there are no other PL phosphors, besides the YAG:Ce, which excite, efficiently, at 460nm. Conversely, although there are numerous PL phosphors which can be excited by broad-band UV radiation (especially peaking at approximately 345nm), but there are no efficient semiconductor diodes found (yet) which emit optimally in the UV. Vigorous research is underway for a compromise, using PL phosphors excited by a Near UltraViolet (NUV) semiconductor [3]; but commercial products, acceptable for residential general lighting, remain unavailable.

As with fluorescent lighting, an attempt to improve CRI by supplying PL phosphors which fill in the "missing" colors has been demonstrated. The CRI does, indeed, improve; but always at the expense of energy efficiency. This is predominantly due to the fact that (other than YAG), all of the PL phosphors have very inefficient excitation spectra at 460nm.

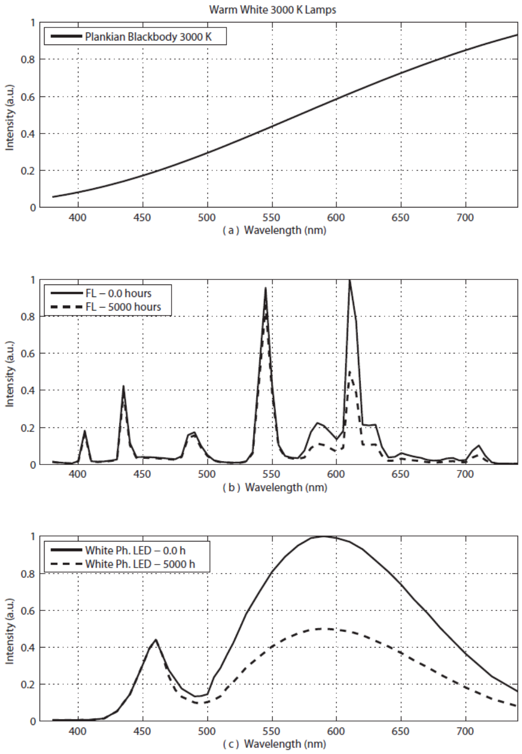

Figure 1. Visible spectra of 3000K incandescent (top), fluorescent (middle) and LED (bottom) lamps. The solid lines represent 0 hours of operation and the dashed lines represent 5,000 hours of operation.

Degradation of Lamps over Lifetime

There are multiple degradation mechanisms in both commercial CFL and LED lamps. Here we consider the most significant one with ramifications to color and appearance, namely degradation of the phosphors. PL phosphors diminish in luminosity primarily through deactivation of the dopants, or damage to the crystal structure of the host matrix. In the case of the activators, this typically through diffusion, agglomeration, oxidation or chemical contamination. As for the host material, the most common is oxidation or generation of surface defects which result in non-luminescent recombination processes. In fluorescent lamps, there is also chemical contamination from diffused mercury.

Whether the activator or the host crystal, these degradation mechanisms are strongly sensitive to temperature and environment (moisture and oxygen, especially), as well as the power-density of the excitation source. Since, for general lighting, a high luminance is desired, this assures that all lighting devices are operated under high power densities. For example, the standard "high-power" nitride semiconductor diode used for LED lamps operates in the range of 1.0-1.2W for each junction. This typically results (depending on the heat-sinking technology employed) in junction temperatures during operation in the range of 80-120°C.

Since there is no single operational standard for either CFL or LED systems, we consider here some average conditions of operation, but note that the general trend, for either technology, remains the same.

CFL Degradation

Although new lamps have a phosphor blend which is selected to balance the best tradeoff between efficiency and color space, this changes immediately upon use. The aging rate of the two primary phosphors, $LaPO_4:Tb^{3+},Ce^{3+}$, and $Y_2O_3:Eu^{3+}$ differ. The characteristics of aging in Lanthanum phosphates has been studied for years. Consequently, the maturity of the technology is high, and the production of commercial materials takes into account all of the anticipated degradation mechanisms within the fluorescent lamp system. These materials are uniformly accepted as linearly degrading to 90% of initial luminance at 5,000 hours of operation, under normal conditions associated with residential lighting, and having no more than 25,000 total hours of serviceable lifetime [4]. The less-efficient red, $Y_2O_3:Eu^{3+}$, however, is continuing as an active subject of development (and the target of elimination, if at all possible, due to limited rare-earth supplies.) In a recent study [5], even with Li doping enhancements, it is found that under high-power densities (such as in the CFL) the luminosity has dropped by 45% at 3,000 hours. Therefore, it is clear that the phosphors are degrading at substantially differing rates. Not only is the luminance dropping, but also the luminous efficacy of radiation is changing, with a corresponding overall drop in lamp efficiency, as well as CCT and CRI. By every metric, the lamp is degrading in efficiency and appearance immediately upon use.

LED Degradation

The use of "white-light" LEDs is potentially a more serious situation than the CFL. This is made worse by ubiquitous marketing hyperbole touting, "Lamps which last over 50,000 hours …", which is only a reasonable statement if only the blue semiconductor is considered. The original Nakamura concept placed the YAG:Ce phosphor in a reflective cup in intimate proximity of the semiconductor. Because of the high-power operation of the diode itself, this caused the phosphor to be operated at extreme temperatures, with correspondingly fast degradation. As a result, a great deal of product development has focused on the design of phosphor substrates and reflectors with optics, which helps significantly reduce the phosphor temperature, in comparison with the junction temperature. The reported results, however, all show the same trend. One (better-case) study [6] showed a drop to 40% of initial luminance (in the YAG:Ce phosphor) after 5,000 hours of pumping from a semiconductor operating at the (relatively-typical) junction temperature of 107°C.

More recent technology has switched to the more-complicated, but slower-degrading use of "remote phosphor" LEDs, where there is little or no chance of thermal conduction between the semiconductor and the phosphor. Although this technique has other degradation issues which affect the phosphor, the loss of luminance is slowed. There are many variants of this technique, but a typical example [7] shows that the use of a remote YAG:Ce phosphor would likely be at 88% of initial luminance at 5,000 hours. Although this is a significant improvement, the trend of degradation is identical to the more-common, intimate-phosphor case.

Regardless of intimate or remote placement of the phosphors, and even regardless of if only YAG:Ce, or a mixture of phosphors is used, the same situation exists with LED White Lights as with CFL: The initial CCT, efficiency, and CRI are degrading immediately with operation. In the LED case, this is especially significant because of the high cost, and because the degradation continuously drifts towards the color space of the unappealing blue semiconductor.

Comparative Chromatic Shift

The change in chromaticity for CFL and LED lamps, although the result of the same basic mechanisms, is not similar in appearance. This is due to the substantially-differing phosphor mixtures used in these two lamp types and also, in LED lamps, the inclusion of the primary blue from the semiconductor itself. To demonstrate the trend of chromatic shift which is observed in CFL and LED lamps, we have calculated the relevant photometric values for operational times t = 0 and t = 5,000 hours by following the procedure of CIE13.3 1995 ("*Method of measuring and specifying colour rendering properties of light sources*"). The values of consideration due to the phosphor degradation are Luminous Efficacy of Radiation (LER), Color-Coordinated Temperature (CCT) and Δuv (the deviation from Plankian locus in color space), and CRI (general Color Rendering Index, or R_a). The results are shown in Figure 2. As a point of reference, the incandescent lamp is also included, although the photometric shift is considered negligible over lifetime with these.

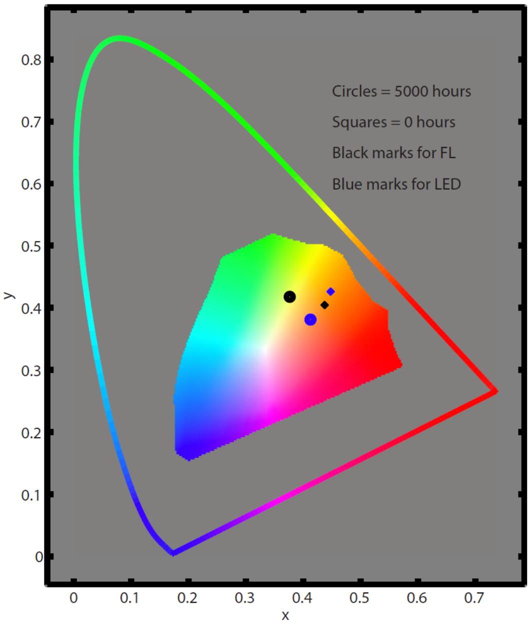

Figure 2: Color space of CFL and LED lamps on initial use (diamonds) and after 5,000 hours. The CFL drifts distinctly towards green, whereas the LED drifts directly towards blue

The numerical values of the results are given in Table 1. The value of 5,000 hours is chosen for these data with consideration that a typical CFL product available to consumers warrantees this lifetime. Average LED products typically claim longer lifetime, and average incandescent lamps demonstrate shorter lifetimes.

Table 1: Photometric parameters for CFL and LED white lights unused, and after 5,000 hours of operation

	Fluorescent		White LED	
	0.0 h	5000 h	0.0 h	5000 h
LER [lm / W]	353.1	367.4	311.5	292
CCT [K]	3001	4357	3000	3268
Δuv	0.000	0.019	0.007	-0.006
CRI	83.1	71.5	75.4	79.8

Discussion

Observation of the initial spectra associated with energy-efficient residential general-lighting devices, in comparison with the incandescent standard which they are meant to replace, as depicted in Figure 1, makes it clear why consumers immediately perceive the difference, despite the fact that the CCT is similar, and the CRI of all three are, at least, reasonable. The shift in appearance over lifetime, which is clearly seen in Figure 2, however, is evident as a major, if not THE major, factor in consumer aversion to both CFL and LED lamps. CFL lamps drift towards green and LED lamps drift towards blue. The CRI values also change. Interstingly, although the LED steadily loses efficacy over its lifetime, it is seen that there is a slight rise in CRI from the initial value, due to a balance between the semiconductor blue and the phosphor yellow (as seen in figure 1). However, with further use, the yellow continues to drop, and the blue shift causes the CRI to drop as well as the efficiency. Both of these trends do not enhance typical environmental illumination scenarios in residential usage, such as interacting with people and observing such things as skin tones, food, clothing and colors of printed or decorative materials. Given the current CFL and LED products available to consumers, and the technology upon which these are designed, there are no known practical solutions which mitigate these trends.

Summary and Recommendations

The transition to energy-efficient general-lighting devices for residential consumers necessitates a tradeoff between efficiency and color quality. Although a typical 4x, or greater, improvement in energy efficiency can be expected from CFL or LED products, there is also an expected reduction of CRI to a minimally-acceptable value from these products, as new. Over a 5,000-hour period of usage, it can be expected that efficiency will drop somewhat; but also that color quality will degrade. This degradation proceeds towards green or blue regions, respectively, in color space, with consequential diminishing color quality and CRI.

In the case of the CFL lamp, because there are no known replacement plasma excitation sources, and because the selection of efficient PL phosphors which are viable for use with the 253.7nm major UV line of the Hg now used, it is unlikely there is anything more than incremental solutions which are available to lamp manufacturers, and therefore consumers cannot expect significant improvements in the present available products. It is considered that environmental concerns over mercury usage will eventually bar these products from the marketplace, which renders the desire for appearance improvement moot.

For the case of LED lamps, there remains a similar situation as with CFL, in that significant improvements are unlikely with current product technology. However, there is substantial room for improvement, both through the use of NUV or UV semiconductors as phosphor pumps, as well as through encouraging improvements in PL phosphors which have significant excitation spectra either at the NUV or UV range. In the former case, encouraging work is underway to improve semiconductor materials and device technologies such that diode radiometric efficiencies in the NUV or 345nm range increase. This work, at present, focuses on both semiconductor epitaxy technologies, as well as diode design [8].

In the phosphor case, there are significant improvements in PL phosphors, predominantly nitrides and oxides, with superior color space (for better gamut in making white lights), and correspondingly greater thermal stability and lifetime. At this writing, these materials are expensive due to complicated synthesis techniques; but it is reasonable to expect an eventual decrease of these costs [9]. The development of new phosphors, especially using novel techniques such as combustion synthesis or non-equilibrium processing, is a vigorous area of research.

Finally, there are other lamp types, such as ESL, OLED, field-emission lamps and quantum-dot or nano-crystal lamps, which are on a trajectory to become available to consumers. Each of these has potentially superior color quality, and has differing degradation mechanisms than CFL or LED lamps. It is expected that, eventually, there will be energy-efficient replacements for incandescent lighting which conform to the residential consumers' expectations concerning color quality over the lamp's useful lifetime.

References

[1] J. Y. Tsao, M. E. Coltrin, M. H. Crawford and J. A. Simmons, "Solid-State Lighting: An Integrated Human Factors, Technology, and Economic Perspective," Proc. of the IEEE, 98, 1162-1179 (2010)

[2] S. Nakamura,S. J. Pearton and G. Fasol, "The Blue Laser Diode: the Complete Story," (Springer, New York, NY, 2000)

[3] K. Kobashi and T. Taguchi, "Warm white LEDs lighting over Ra=95 and its applications", Proc. of SPIE Vol. 6486, 648610, (2007)

[4] N. Narita, "Phosphors for Lamps", Phosphor Handbook, W. M. Yen, S. Shionoya and H. Yamamoto, Ed.s, (CRC Press, Boca Raton, FL, 2007) p. 449

[5] A. Nayak, et al., "Luminescence Efficiency of Eu^{3+} in Y_2O_3", Ind. J. Pure and Appl. Phys, 47, 775 (2009)

[6] N. Narendran, Y. Gu, J.P. Freyssinier, H. Yu and L. Deng, "Solid-State Lighting: Failure Analysis of White LEDs", J. Cryst. Gro, 268, 449 (2004)

[7] C.C. Tsai, J. Wang, M.-H. Chen, Y.-C. Hsu, Y.-J. Lin, C.-W. Lee, S.-B. Huang, H.-L. Hu and W.-H. Cheng, "Investigation of Ce:YAG Doping Effect on Thermal Aging for High-Power Phosphor-Converted White-Light-Emitting Diodes", IEEE Trans. Dev. And Mat. Reliabil., 9, 367 (367)

[8] M. S. Shur and R. Gaska, "Deep-Ultraviolet Light-Emitting Diodes", IEEE Trans, Elect. Dev., 57, 12 (2010)

[9] R.-J. Xie and N. Hirosaki, "Silicon-Based Oxynitride and Nitride Phosphors for White LEDs", Sci. Tech. Adv. Matl. 8, 588 (2007)

Author Biography

Charles E. Hunt *received his Ph.D. in EE, with emphasis on Electronic Materials Science, from Cornell University (1986). He now is Professor of ECE and Design at UC Davis, and a PI at the California Lighting Technology Center (CLTC.) He is on assignment in the Lighting Group of the Catalonia Institute for Energy Research (IREC). He is an Executive Committee Member of the Luminescent Materials Division of the Electrochemical Society.*

Jesús Quintero *received in 2007 the degree of specialist on Industrial Automation and Control from the National University of Colombia. Presently he is lecturer at the Electrical and Electronic department at the same university, with appointments in the Light and Lighting program. He is in his third year as Ph.D. fellowship at the Institute for Energy Research of Catalonia (IREC), his research centers on high-power light-emitting diodes, luminescent materials and color technology.*

Josep Carreras *received his B.S., M.S. and PhD. (Cum Laude, with Honors) in Physics from the University of Barcelona. Over his career, he has conducted research on Silicon Photonics and LEDs from practical and theoretical standpoints. He is the Leader of the Lighting Group at the Catalonia Institute for Energy Research (IREC). His main research areas involve, among others, Energy Efficient Lighting, Color Science and Technology, Simulations, Photometry, and Intelligent Lighting.*