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The Perceptual Color Space of Digital Image Display Terminals

The geometric properties of the set of colors that can be displayed on the TV monitor of a digital image processing terminal are discussed in the framework of the Commission Internationale de l'Eclairage (CIE) 1976 (L^* u^* v^*) color space. Quantitative results are presented for the HACIENDA image processing system. The use of lightness, chroma, and hue angle for the representation of multi-band images is briefly discussed.

Introduction

Most digital image processing applications do not require an accurate characterization of the colors being displayed on the TV monitors commonly used; three bands that very often do not correspond to the red, green, and blue regions of the electromagnetic spectrum are usually displayed by applying some kind of pseudo-coloring. However, references to concepts related to color perception are frequently found in the literature, although in general the structure of the perceptual color space is not properly taken into account. For instance, the so-called "intensity-hue-saturation" representation (supposedly applied to optimize subjective color discrimination) is in most cases defined paying no attention to the perceptual characteristics of the standard observer.

A correct understanding of the colors that can actually be displayed on a given digital image processing terminal is always helpful in obtaining high-quality displays and is obviously essential for those applications requiring real colors. The objective of this paper is to emphasize the necessity of such understanding, proposing at the same time a way to describe the discrete set of colors that can be handled in a common TV-monitor-based digital image display terminal, with particular reference to the HACIENDA image processing system [1, 2].

Our approach is based on the use of the Commission Internationale de l'Eclairage (CIE) 1976 (L^* u^* v^*) or CIELUV color space [3], which allows the definition of a representation of the intensity-hue-saturation type based on perceptual color considerations. As a matter of fact, this perceptual color space has been recommended for measuring small color differences, in contradistinction to the Uniform Color Scale (UCS) of the Optical Society of America [4], which has been designed for large color differences. However, the errors introduced by the limited quality of TV monitor displays may in general be larger than those due to the use of the CIELUV coordinate system to measure large color differences. On the other hand, the CIELUV coordinates are given by much simpler formulas and allow the existence of a chromaticity diagram independent of lightness.

Interest in the study of the perceptual color space of computer-driven display monitors is already evident in the work of Meyer and Greenberg [5], who refer mainly to the Munsell color book [6] and the Optical Society of America UCS, although a thorough study, equivalent to those of Wallis [7] and of Juday [8] for film recorders, is still lacking for digital TV displays. Actually, each primary color in a digital image display system can take on only a limited number of values (usually a 3- to 8-bit number), often much smaller than the set of possible values of the data to be displayed (a 6- to 10-bit number). The video look-up table (VLT) cannot therefore be naively used to compensate the nonlinear relationship between the digital counts applied to the monitor and the coordinates of the perceived color without dramatically reducing the gamut of available colors.

Color display features of digital image processing systems

The display part of an image processing system consists essentially of a refresh buffer and a video look-up table. Certain systems also contain additional band buffers, look-up tables, arithmetic and logic units, and microprocessors to perform certain image processing functions locally (see, for instance, [2]). However, none of these components plays any role in connection with the display characteristics with which we are involved in this paper.

The information contained in the refresh buffer is sent at video rate through the video look-up table (VLT) to the TV monitor in order to continuously refresh the image displayed on the screen. For our purposes, a refresh buffer can be thought of as a two-dimensional array of q-bit words. Of the q bits of these words, k bits are used to store what we call image data, and the remaining bits are used to contain other kinds of data as overlays to be displayed on the image monitor and, sometimes, on another monitor intended mainly for alphanumeric information. The video look-up table consists of 2^k p-bit words, where, in general, $p = 3n$ or $p = 3n + 1$, with n being an integer number.

The image data stored in the refersh buffer are used to index the video look-up table, and the contents of the selected location (p bits) are sent to the homologous location on the monitor screen. The lowest n bits are used to control the signal acting on the blue phosphor, the next n bits are used to control the green signal, and the highest n bits are used to control the red signal. When there is an additional bit ($p = 3n + 1$), it is used to determine whether the screen location is set to blink.

The colors that can be used in an image display system are therefore determined by the two numbers k and n. Only 2^k colors can be simultaneously displayed on the monitor provided that the image data part of the refresh buffer can store numbers from 0 to $2^k - 1$. These colors can indeed be chosen from among the 2^{3n} possible colors which correspond to the 2^{3n} different values that can be stored in a VLT location.

In the IBM Madrid Scientific Center, three different image display systems which are representative of the devices now existing on the market are or have been used:

- Ramtek GX100B, with 510 × 640 8-bit refresh buffer locations to store image data and 12-bit VLT locations. Therefore, 256 colors out of 4096 can be simultaneously displayed.
- Ramtek 9351, with 512 × 512 words in the refresh buffer with 11 bits to hold image data and a 12-bit VLT. Thus, 2048 colors out of 4096 can be simultaneously used.
- HACIENDA, with 1024 × 1024 locations in the refresh buffer with 12 bits to hold image data and a 15-bit VLT. Consequently, 4096 colors selected from among 32 768 possible colors can be simultaneously displayed [2].

In a digital display system with n bits allotted to drive each electron gun, the digital counts R_c, G_c, and B_c applied to control the red, green, and blue signals can take the values 0, $1, 2, \cdots, 2^n - 1$.

The relationship between the digital counts applied and the values of the red, green, and blue tristimulus R_d, G_d, and B_d of the color displayed strongly depends on the particular CRT used. First of all, the directions in color space of the $\boldsymbol{R}_d$, $\boldsymbol{G}_d$, and $\boldsymbol{B}_d$ tristimulus are given by the chromaticities of the screen phosphors, and their relative lightnesses depend on the neutral color to which the tube is set. But furthermore, that relationship also varies over the screen surface as a consequence of the nonuniform phosphor distribution and efficiency and the defects in electron beam convergence. These relationships can be approximated by power laws [5, 8] of the form

$$\begin{aligned} R_d &= (R_c/2^n - 1)^{\gamma_r}, \\ G_d &= (G_c/2^n - 1)^{\gamma_g}, \\ B_d &= (B_c/2^n - 1)^{\gamma_b}. \end{aligned} \qquad (1)$$

The three exponents are approximately equal to one another and lie in the range 2.5 to 3.0. These formulas constitute a good appproximation for mid-range values of the digital counts. For highly accurate work, however, each monitor should be calibrated after every adjustment of the tube, and formulas more sophisticated than Eq. (1) should be used.

The approximate perceptually uniform color space

One of the approximately uniform color spaces recently recommended by the CIE [3] is CIELUV. It is produced by plotting in rectangular coordinates the quantities L^* (CIE 1976 psychometric lightness), u^*, and v^* defined by

$$\begin{aligned} L^* &= 903.3(Y/Y_n), \qquad Y/Y_n \leqq 0.008856, \\ L^* &= 116(Y/Y_n)^{1/3} - 16, \qquad Y/Y_n \geqq 0.008856, \\ u^* &= 13\, L^*(u' - u'_n), \\ v^* &= 13\, L^*(v' - v'_n), \end{aligned} \qquad (2)$$

where

$$u' = \frac{4X}{(X + 15Y + 3Z)},$$

$$v' = \frac{9Y}{(X + 15Y + 3Z)}, \qquad (3)$$

and u'_n and v'_n are the values of u' and v' for the neutral color. In terms of these quantities, the CIE 1976 chroma (C^*_{uv}), CIE 1976 hue angle (h_{uv}), and saturation (s_{uv}) are defined as

$$C^*_{uv} = \sqrt{u^{*2} + v^{*2}}\,,$$

$$h_{uv} = \arctan \frac{v^*}{u^*}\,,$$

$$s_{uv} = 13 \sqrt{(u' - u'_n)^2 + (v' - v'_n)^2} = \frac{C^*_{uv}}{L^*}. \qquad (4)$$

This color space, as well as the other recommended by the CIE [CIE 1976 ($L^*\,a^*\,b^*$) or CIELAB] is really intended to approximate the difference between colors (defined by means of the Euclidean distance) when it is not larger than 10 just-noticeable difference (*JND*) units. For large color differences it is in principle more appropriate to use the Uniform Color Scale (UCS) of the Optical Society of America (OSA). Despite this fact, we prefer to use the CIELUV space for the following reasons:

First of all, the uncertainties in the coordinates of colors displayed on a TV monitor are rather large, as a consequence of the inhomogeneous distribution and efficiency of the phosphors over the screen, the defects in electron beam convergence, and the departures of the relations between the tristimulus values (R_d, G_d, B_d) and the digital counts (R_c, G_c, B_c) from the power laws given by Eq. (1).

Furthermore, the ambient conditions of a digital image processing laboratory do not conform in nature, luminance, and chromaticity to those of color difference experiences, and the sizes of the color fields displayed on the screen are not similar to those of the tiles used for color difference measurements.

Therefore, the effect that the colors displayed on the screen produce on the observer (even assuming that he is the CIE standard observer to avoid personal differences) may differ from the predictions of any color coordinate system more than these predictions differ from each other. The simplicity of the formulas in the CIELUV system thus clearly favor the use of this space to approximate the observer's response to displayed colors. In particular, the existence of a chromaticity diagram (u', v') and the consequent definition of color saturation with independence of lightness and hue (which cannot be defined either in the CIELAB or in the OSA UCS) constitute major advantages for the CIELUV space.

The linear transformation that relates the two sets of tristimulus values (X, Y, Z) and (R_d, G_d, B_d) can be straightforwardly obtained from the chromaticity coordinates of the three primaries and the neutral color to which the monitor is set. These coordinates are usually given in the CIE 1931 (x, y) chromaticity diagram. For further details, as well as for a thorough discussion of the Riemannian nature of the real perceptual color space (to which the CIELUV and the other spaces here mentioned are Euclidean approximations), the interested reader is referred to the books of Wyszecki and Stiles [9] and of Judd and Wyszecki [10].

Table 1 Chromaticity coordinates of the HACIENDA primaries and neutral color.

	x	y	u'	v'
Red	0.62	0.33	0.43	0.52
Green	0.29	0.60	0.12	0.56
Blue	0.14	0.09	0.15	0.22
White	0.31	0.32	0.20	0.46

Table 2 CIELUV coordinates of the primary and complementary colors in the HACIENDA image processing system.

	L^*	u^*	v^*	C^*_{uv}	$h_{uv}/2\pi$	s_{uv}
Blue	41.8	−28	−133	136	0.717	3.25
Red	58.6	176	46	182	0.041	3.11
Magenta	68.7	73	−90	116	0.859	1.69
Green	82.4	−87	107	138	0.359	1.67
Cyan	88.7	−82	−21	85	0.541	0.96
Yellow	95.0	23	108	110	0.217	1.16

The perceptual color space of the HACIENDA image processing system

We now describe the perceptual color space of the HACIENDA image processing system. The color space of any other TV-monitor-based digital image display device can straight-forwardly be studied in the same way.

Table 1 contains the chromaticity coordinates of the screen phosphors in the CIE 1931 (x, y) chromaticity diagram and the (u', v') chromaticity diagram associated with the CIELUV space. They have been obtained by measuring with a digital photometer the light emitted by each phosphor in three different spectral windows. Table 2 lists the CIELUV coordinates of the primary colors and their complementaries that are obtained when the monitor is adjusted to have the standard illuminant C as neutral color.

Figure 1 shows the gamut of chromaticities available with the actual phosphors of this screen represented in the usual CIE 1931 (x, y) diagram. Lines of constant CIELUV hue ($h_{uv} = 0, \pi/12, 2\pi/12, \cdots, 23\pi/12$) and saturation ($s_{uv} = 0.25, 0.50, \cdots, 3.00$) have been drawn with the standard illuminant C as neutral color. This gamut is only available at low values of the psychometric lightness. Above $L^* = 41.8$ this gamut begins to shrink as certain regions of it become

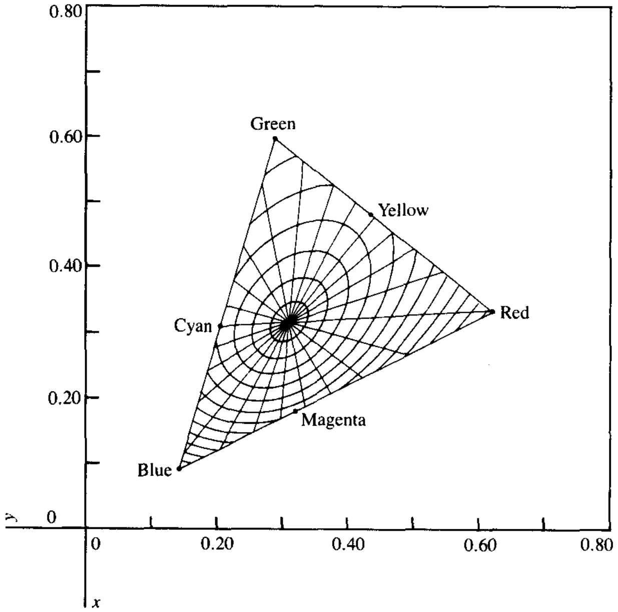

Figure 1 CIE 1931 (x, y) chromaticity diagram showing the gamut of chromaticities available to the HACIENDA monitor at low lightness values. The radial lines represent loci of constant CIE 1976 (L^* u^* v^*) hue angle ($h_{uv} = 0, \pi/12, 2\pi/12, \cdots, 23\pi/12$) and the curves represent loci of constant CIE 1976 (L^* u^* v^*) saturation ($s_{uv} = 0.25, 0.50, \cdots, 3.00$). Standard illuminant C is taken as neutral color.

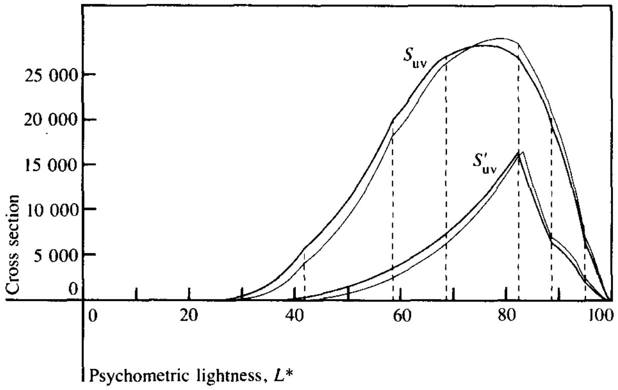

Figure 2 Cross sections S_{uv} and S'_{uv} of the color solid in the CIE 1976 (L^* u^* v^*) space as functions of the CIE 1976 psychometric lightness. Data correspond to the HACIENDA monitor adjusted to the standard illuminant C as neutral color. The dashed lines indicate the lightnesses of the primaries and their complementary colors.

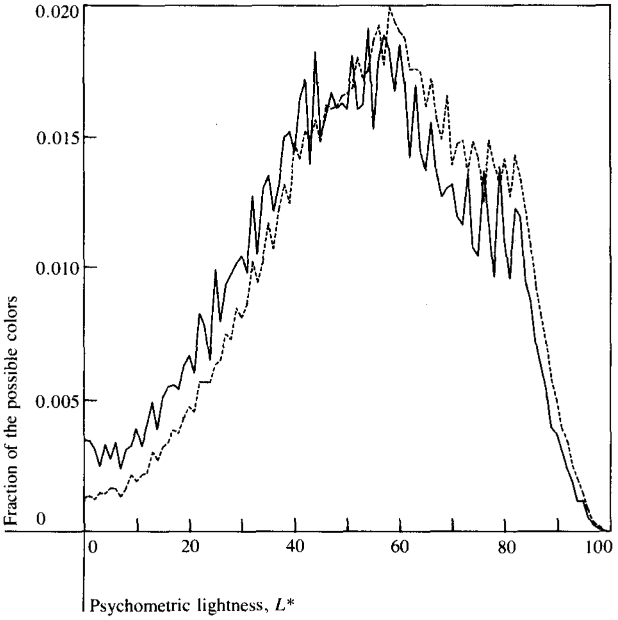

Figure 3 Fraction of the total number of colors that can be generated on the HACIENDA per unit of psychometric lightness. (This is equivalent to the density with which the three-dimensional color grid maps onto the L^* axis.) The solid line corresponds to $\gamma_r = \gamma_g = \gamma_b = 2.5$ and the dashed line to $\gamma_r = \gamma_g = \gamma_b = 3.0$.

unattainable: The saturated blue disappears first, then the red, magenta, green, cyan, and finally the yellow. The cross sections S_{uv} of the color solid (*i.e.*, the domain defined by $0 \leqq R_d \leqq 1, 0 \leqq G_d \leqq 1, 0 \leqq B_d \leqq 1$) by planes orthogonal to the L^* axis in the CIELUV space is plotted in Fig. 2 as a function of L^*. The shape of this curve is the result of the opposite effects of increasing the area of the u^* v^* plane with L^{*2} and the shrinkage of the chromaticity gamut.

Since colors are often referred to by their lightness, chroma, and hue, it is also useful to know the maximum chroma that can be achieved for all hues at a given psychometric lightness. The area S'_{uv} of the circle on the u^*v^* plane with center at the origin and radius equal to that value of the chroma is also plotted in Fig. 2 as a function of L^*. S'_{uv} increases steadily with L^{*2} until the shrinking border of the chromaticity gamut intercepts the outer closed line of constant saturation. Above that value of L^*, S'_{uv} decreases quite rapidly. S_{uv} and S'_{uv} are, therefore, equal respectively to L^{*2} times the area of the color gamut in the (u', v') chromaticity diagram, and L^{*2} times the area of the greatest circle with center at (u'_n, v'_n) that can be drawn inside that gamut.

The colors that can be displayed on an image processing monitor are a discrete set of points in the color space that in the (R_c, G_c, B_c) coordinate system form a regular cubic lattice. Their coordinates in the CIELUV spaces are obtained by means of Eqs. (1) and (2).

Figure 3 shows the number of possible colors as a function of lightness L^*. This corresponds to the density with which

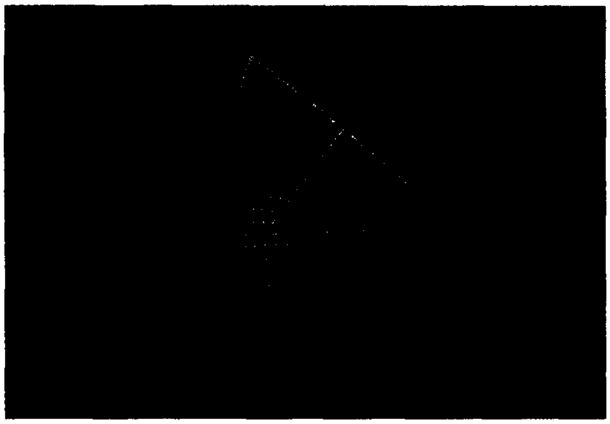

Figure 4 Colors that can be generated on a digital image display terminal with 4 bits per primary represented according to their CIE 1931 x, y coordinates.

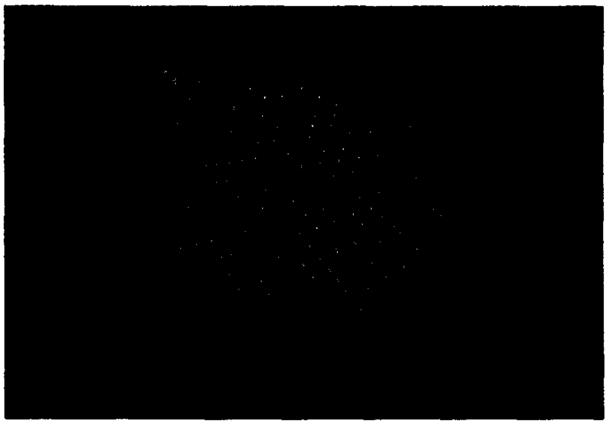

Figure 5 Colors that can be generated on a digital image display terminal with 4 bits per primary represented according to their CIE 1976 u^*, v^* coordinates.

the set of points (R_c, G_c, B_c) maps onto the CIELUV space. For the integer values of L^*, the number of colors with lightness in the interval $[L^* - 0.5, L^* + 0.5]$ is plotted normalized to the total number of possible colors. The color distribution is very irregular because the color space is rather "empty" in certain regions. The two curves correspond to the extreme values of the exponents in Eq. (1): $\gamma_r = \gamma_g = \gamma_b = 2.5$ and $\gamma_r = \gamma_g = \gamma_b = 3.0$.

That the distribution of possible colors is far from being homogeneous appears evident from the comparison of Figs. 2 and 3: The cross section of the continuous color solid and the number of possible colors per unit of psychometric lightness are very dissimilar. In particular, too many dark colors can be generated. It must indeed be emphasized that two points of the (R_c, G_c, B_c) lattice do not represent different colors if their CIELUV distance is smaller than one JND unit.

Figures 4 and 5 display the set of colors that can be generated in a display system with four bits per primary. Every color appears in a location given by its (x, y) coordinates in Fig. 4 and its (u^*, v^*) coordinates in Fig. 5. When more than one color has the same coordinates, only the brightest one appears. These colors, therefore, represent the 4096 colors available, for instance, with the Ramtek 9351 terminal. Indeed, the pictures have been taken from the HACIENDA unit, which can generate eight times more colors, although only 4096 can be simultaneously displayed.

To obtain the (u^*, v^*) coordinates used in Fig. 5, it has been assumed that $\gamma_r = \gamma_g = \gamma_b = 2.7$, which gives a good approximation of the actual calibration of the HACIENDA monitor at the IBM Madrid Scientific Center when the photographs were taken. However, these pictures should be considered merely as illustrative of the color coordinates, provided that no care has been taken to preserve color fidelity through the photographic and printing processes. (For a discussion of the difficulties inherent in obtaining such fidelity, see, for instance, [11]).

The lightness-chroma-hue image display

The two usual forms of displaying multi-band images are

1. Assign three bands to the red, green, and blue primaries.
2. Assign three bands to the intensity, the hue, and the saturation of color defined in some way.

The former representation simply consists of assigning values proportional to the amplitudes of the three bands that will be displayed to the digital counts R_c, G_c, and B_c (or better to the tristimulus values R_d, G_d, and B_d).

The latter, usually called *intensity-hue-saturation* representation, is normally used to display uncorrelated bands, the so-called principal components (see, for instance, [12]). The tristimulus value Y and the hue and saturation defined on the CIE 1931 chromaticity diagram are commonly used. Such a representation is indeed not really suited to the color discrimination characteristics of the standard observer and should be replaced by its CIELUV counterpart.

What is intended in a representation of this kind is to transmit a maximum of information to the observer. As is well known from the theory of coding [13], this is achieved when each "symbol" represents the same number of picture elements. For a visual observer, the "symbols" are domains of the uniform color space with equal volume and homogeneously distributed over this space. Lightness, chroma, and hue angle (L^*, C^*_{uv}, h_{uv}) are therefore the most suitable variables to be assigned the amplitudes of the three image bands.

An optimum color assignment is extremely difficult due to the complex shape of the color solid in a perceptual space. The band assigned to the lightness can easily be equalized to have a histogram proportional to the color solid cross section, either S_{uv} or S'_{uv}. If S'_{uv} is used, the set of possible chroma values is a function of L^*, but if S_{uv} is used, the set of chroma values also depends on the hue angle. Finally, although the hue always takes values in the interval $[0, 2\pi]$, the color difference between two given hues increases linearly with the chroma. In consequence, the rigorous use of this representation always requires the equalization of the three-dimensional histogram of the three image bands.

It should be noted that the saturation s_{uv} is not an appropriate variable to be used in this representation since the color difference between two given saturations of the same hue increases linearly with L^*.

On the other hand, a good choice for the representation of two uncorrelated bands is the plane u^*v^*. The lightness can be fixed at the value for which S'_{uv} is maximal, and the two bands can then be assigned to u^* and v^*. From the coding point of view this representation is not optimal because band histograms are not equalized, but the colors directly obtained in this way are actually homogeneously distributed for the standard observer.

Summary

We have discussed in this paper the geometric properties of the set of colors that can be generated on the TV monitor of a digital image processing terminal in the framework of the CIELUV approximately uniform color space recommended by the CIE, making special reference to the HACIENDA system. We have assumed that the tristimulus values of the three screen phosphors are related to the digital counts applied to the electron guns by the power laws given in Eq. (1). In consequence, our results constitute a first approximation that can be applied in general to any similar display monitor. For more accurate and quantitative work, a more careful fit of those relationships is required. The functions obtained are in general different from one CRT to another, and even for the same tube they vary for each setting of the monitor controls. Obviously, it has also been assumed that the convergence of the three electron beams is correct all over the screen.

Good color rendering is obtained with a subset of the set of possible colors whose points are homogeneously distributed in a uniform color space. Since the distribution of possible colors in any approximately uniform color space is highly inhomogeneous, the number of elements of this subset will be a small fraction of the number of possible colors. Therefore, it is advisable for the design of digital image display units that the number of output bits from the video look-up table be as high as possible, while the number of image data bits in the refresh buffer does not need to be so high.

Acknowledgments

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