Bit stealing: How to get 1786 or more gray levels from an 8-bit color monitor

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BIT-STEALING:
HOW TO GET 1786 OR MORE GREY LEVELS FROM AN 8-BIT COLOR MONITOR

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ABSTRACT

The precision of human vision requires displays to be accurate to about 0.2% of the luminance range. We present a technique by which this grey-level precision can be achieved with the use of an 8-bit color monitor. The basic idea is to "steal" adjacent bits from the color variation for use in increasing the precision of the luminance variation. On a monitor with 8 bits per color gun, the technique can provide 1786 or more grey levels at a cost of one bit of color jitter, with standard D/A hardware. The color variations are invisible under almost all conditions.

THE BIT-STEALING CONCEPT

A typical color display has three color guns, each with 8 bits of luminance variation on the digital/analog converter (D/A) driving it, which provides 256 luminance levels for each color. Normally, luminance and color are specified independently in the three-dimensional vector controlling the D/A. The color is specified by two ratios between the three guns, while the luminance is set by the sum of the three, which is a third parameter independent of the two color ratios. The bit-stealing technique provides a way to readjust the magnitudes of these vectors to match the requirements of human vision.

For equal values in the R, G and B registers for the D/A inputs, the monitor output will typically be close to a neutral grey. If these RGB values are held at the same ratio there will be 256 available luminance levels corresponding to the 256 levels on each color register. (It will be assumed for the purpose of this presentation that the luminance outputs of the three color guns have the same transform nonlinearity, although they have different absolute levels of luminance on each of the three guns.) Thus, a 24 bit color display with 8 bits per gun still has only 256 possible levels of luminance at a constant color ratio, even though it may be able to present 256^3 = 16,777,216 different color/luminance combinations. This luminance restriction is present regardless whether the color palette is limited to 256 values, or can present a larger number up to a different value for each screen pixel.

We have developed a practical technique to "steal" some of the least-significant color information to allow considerably finer variations luminance than are normally available. Consider first the case where luminance variation alone is desired in the display, i.e. the color ratio should be maintained at unity. One level of color variation can be "stolen" for refining the luminance setting to provide three independent values to use between each pair of the 256 luminance levels. The jitter of the color to this extent is well below psychophysical detection threshold for most of the luminance range, and is undetectable in many applications. Conversely, under optimal conditions the method can provide a greatly enhanced control of fine luminance variations, which are often readily detectable and even intrusive on a standard 8-bit display. This idea is similar to the spatial dither techniques in common use to enhance gray scale, except that bit-stealing operates within a single pixel.

CONSTRUCTION OF THE LOOK-UP TABLE

Optimal use of one bit of color variation is obtained if the luminances of the three guns cane be set in the ratio of 1:2:4. In this case, a binary sequence of steps on the three D/A registers provides 7 steps of luminance information for every step in a fixed color-ratio scheme. This approach therefore provides a D/A output table with 7 x 255 + 1 = 1786 levels (10.8 bits), or almost 7 times the normal luminance resolution. (Note

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that the level formula includes only one level at the highest base value, since the increments are available only between each base value and the next one.)

TABLE I
LUMINANCE SPECIFICATION

BLUE STEPS (x1)	RED STEPS (x2)	GREEN STEPS (x4)	LUMINANCE STEPS (SUM)
0	**0**	**0**	**0**
1	0	0	1
0	1	0	2
1	1	0	3
0	0	1	4
1	0	1	5
0	1	1	6
1	**1**	**1**	**7**
			. . .
14	**14**	**14**	**98**
15	14	14	99
14	15	14	100
15	15	14	101
14	14	15	102
15	14	15	103
14	15	15	104
15	**15**	**15**	**105**
			. . .
254	**254**	**254**	**1778**
255	254	254	1779
254	255	254	1780
255	255	254	1781
254	254	255	1782
255	254	255	1783
254	255	255	1784
255	**255**	**255**	**1785**

To obtain this kind of luminance control, the binary bit-stealing scheme is conceptualized in Table I, in which it is assumed that the luminances are linearly related to the D/A step values. Departures from this assumption will be considered below. The full steps where all three guns have the same step value are shown in bold in Table I.

As is evident, none of the color values in this scheme stray by more than one level from those of its companions, while the summed value representing the net luminance output increases steadily in steps of 1/7th of the increment required to advance all three RGB values by one step. To implement a bit-stealing system, all that is required is to construct a D/A output table of the 1786 luminance entries from calibration of the individual color gun outputs. The table is then used in reverse to determine the three RGB values required for each D/A input corresponding to the desired luminance level for a given pixel.

A sample of the luminance output for such a table is provided in Fig. 1. The left panel shows the steps obtained when a system with fixed color ratios attempts to depict a luminance ramp defined by the oblique line. In the right panel, each RGB value is allowed to jitter by one level from those of its companions; the summed value representing the net luminance output increases steadily in steps of 1/7th of the fixed-color increments.

The arguments here and for the bulk of this article are developed assuming the standard 8-bit luminance resolution. It should be noted that the bit-stealing approach is equally applicable to color displays of other bit resolution. For example, another common display specification is four bits per color gun. The same scheme as shown in Table I can, in principle, be applied to such a 4-bit display to increase its luminance resolution from 16 levels to 106 levels. The top set of these output levels are given as the center group of rows in Table I. (Similarly, a display with six bits per color gun could be enhanced from 64 to 442 luminance levels.) The color ratios required to achieve bit-stealing will be proportionately larger in these lower resolution displays, but may be acceptable under some conditions (such as lower-contrast LCD displays in lap-top computers, for example).

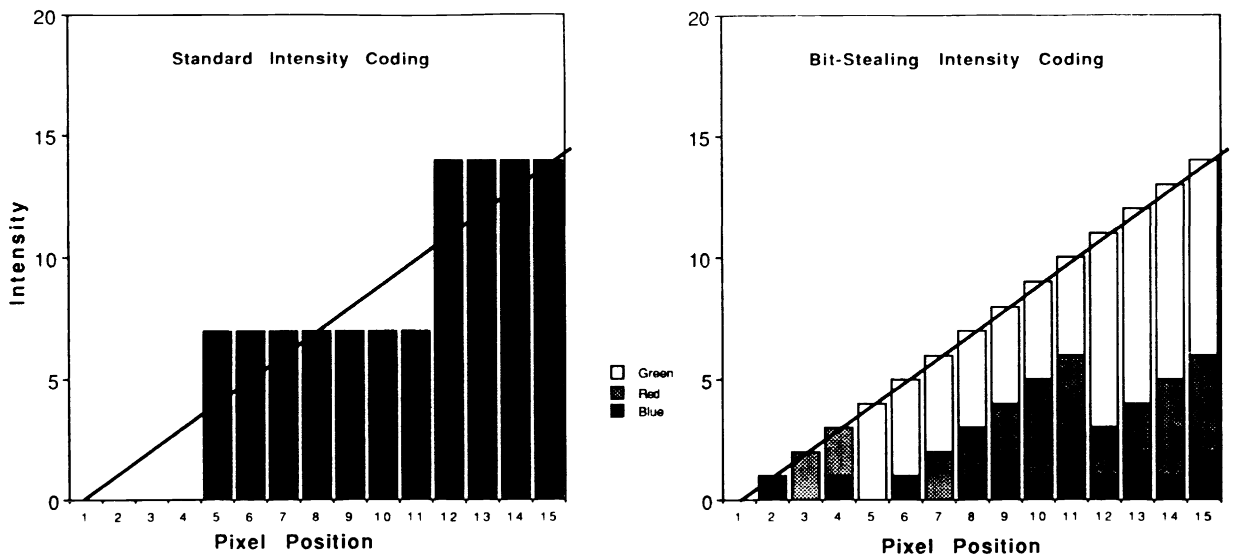

Figure 1. Standard and schematized 1-step bit-stealing representations of a luminance ramp. Left panel:- steps obtained when a system with fixed color ratios attempts to depict a luminance ramp. Right panel:- each RGB value is allowed to jitter by one level from those of its companions; the summed value representing the net luminance output increases steadily in steps of 1/7th of the fixed-color increments. For simplicity the luminances are assumed to be linearly related to the step values.

PRACTICAL CONSIDERATIONS OF THE PHOSPHOR LUMINANCES

In practice, color monitors rarely have a luminance ratio of 1:2:4, but they may be relatively close, or have some other relationship that can be utlized effectively. Our Macintosh monitor has a mean luminance ratio of B : R : G at 1.0 : 2.0 : 6.5 (as measured on the Minolta Chromameter Model CS-100), with variations due to the small differences in the luminance nonlinearities of the three phosphors. Three approaches may be adopted to jittering the ratio for optimal bit-stealing performance.

1. Adjusted Bit-stealing. If the monitor has independent luminance adjustments for each color gun, they may physically be adjusted to match the bit-stealing requirements of a 1:2:4 ratio. The bit-stealing technique then follows the simple scheme outlined for Table 1.

2. Filtered Bit-stealing. If the monitor luminances are not adjustable, one can use color filters designed to produce the required adjustments after convolution with the phosphor transmittance spectra and human spectral sensitivity. We have surveyed over 1000 combinations of up to three gelatin filters (Phoebus Lighting Co.) to find a pair that produces the required luminances ratios with the minimum loss of luminance. The best combination turned out to be a pair of filter specified as Roscoe Cinegel Color Correction Filter #3308 and Gamcolor Deep-Dyed Polyester Color Filter #980. The XY chromaticity coordinates (measured by the transmission of the Apple white of .273, .292 as defined by the Minolta Chromameter Model CS-100) were .283, .240 and .254, .241 for the two filters, respectively, providing a combined chromaticity of .262, .198. The net result was a luminance ratio of B : R : G at 1.0 : 2.18 : 4.13, with an overall transmittance of 0.30. This scheme is then designed to use the outputs of Table I. An example of the improvement in luminance profile obtained is given in Fig. 2

In schemes 1 and 2, the color of the monitor at equal relative positions on the three guns moves down from the standard white point and becomes a pastel shade of fuchsia, as shown on the CIE diagram in Fig. 3. The original monitor coordinates are given by the filled triangle, the effect of the filter pair by the open square, and the direct reduction of scheme 1 by the filled square. The specified and measured color gamuts of the phosphor are given by the dashed and full-line triangles, respectively. The color shift of those bit-stealing schemes that require it does not seem to be objectionable for work with luminance information (after all, many video displays have inherent colors such as green or orange). It is an inherent consequence of the spectral properties of the three phosphors. However, the color shift can be corrected by the use of the direct compensation bit-stealing technique (scheme 3). It is also not an issue in the "color bit-stealing" technique discussed below.

3. Direct Compensation. Alternatively, the monitor may be viewed in its original state, if the use of a filter or its consequent color change is undesirable, or if a greater luminance is required. The bit-stealing scheme of Table I would then provide a set of 1786 luminance levels, but the step size would vary through the table. However, for use in generating smooth luminance gradients this simple scheme would provide less advantage, because the limiting feature for gradient perception is a value of one step. For general application, this is the largest value of any step, when the steps are of different sizes. For the Apple RGB Monitor, the B : R : G ratio of 1 : 2 : 6.5 means that the largest luminance step under bit-stealing would be 3.5 times the smallest, and 3.5/9.5 = 0.37 of the standard steps. This approach would provide a worst-case grey level resolution equivalent to 255 / 0.37 + 1 = 693 levels without a screen filter, which is still an improvement of almost three times the 8-bit level, or 9.4 effective bits.

A depiction of the display output under the 1-step bit-stealing scheme 2 is provided in Fig. 2, which compares the lowest 1/16th of the D/A range with and without bitstealing. In standard mode, this range produces 16 steps of equal width around the circle (upper). The luminance steps are readily discriminable, especially at thelower end of the range. In the bit-stealing implementation of the same luminance range (lower), each step is broken down into seven levels which are virtually undetectable in this configuration. The entire span of 112 levels now looks like a continuous ramp. Again, no colors were noticeable in the original display when viewed with the requisite filter.

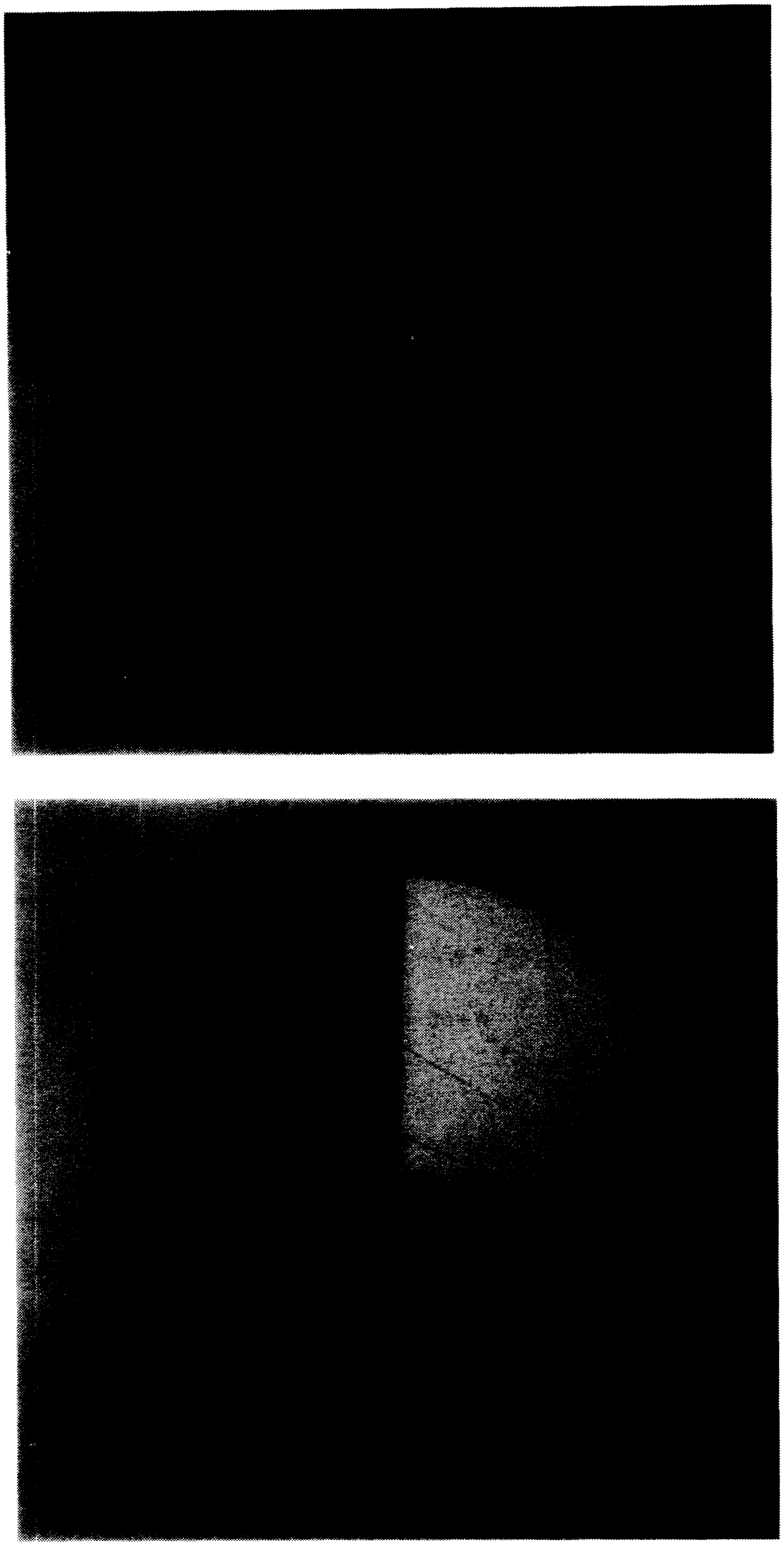

Fig. 2. Photographs of radial display of a radial luminance ramp depicted by the lowest 1/16th of the D/A register. Upper panel - standard 8-bit output format. Lower panel - the same register output range restructured through the 1-step bit-stealing scheme. The sharp discontinuities of the standard output are rendered virtually invisible by the bit-stealing arrangement.

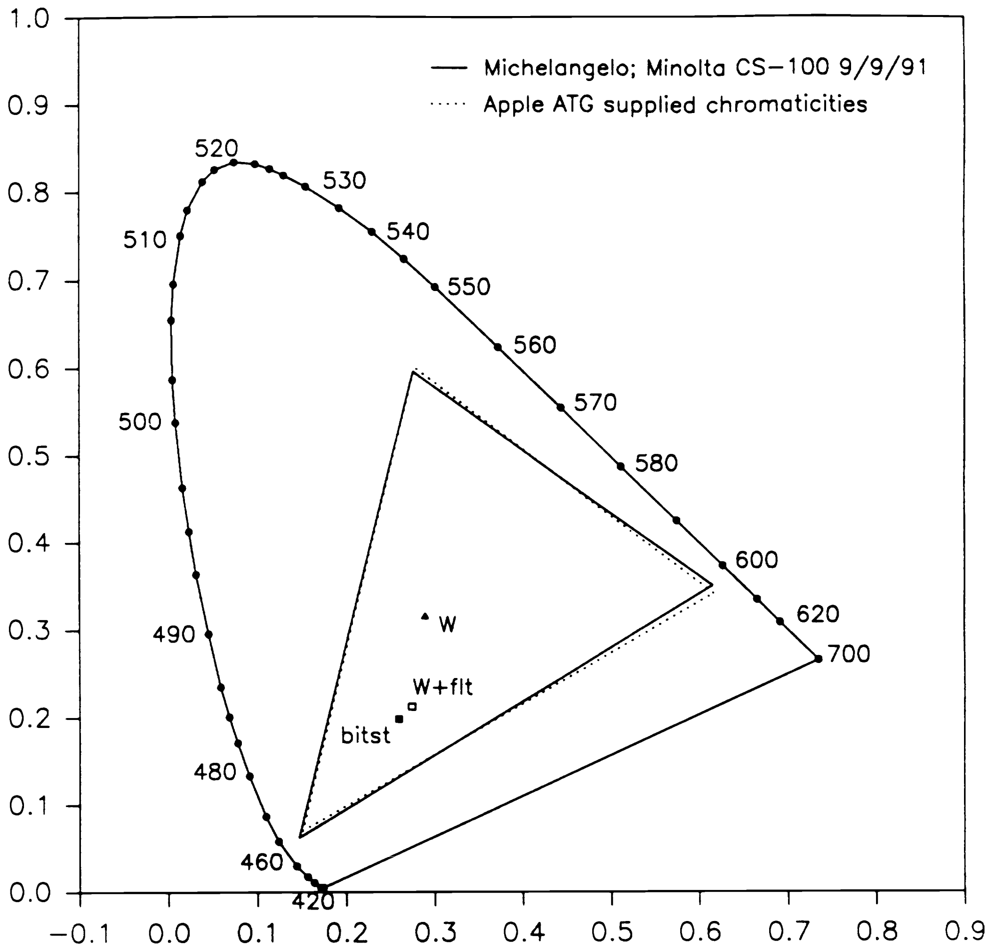

Fig. 3. CIE color diagram showing the XY coordinates of the color monitor. Dashed triangle shows range of color gamut specified by Apple Computer. Outline triangle shows coordinates of color gamut obtained by calibration of our computer ("Michelangelo") with a Minolta Chromameter. The filled triangle (W) shows the XY coordinates of the neutral grey on the monitor. The open square (W + flt) shows the XY coordinates after passing through the filter required for the filtered bit-stealing scheme. The filled square (bitst) shows the XY coordinates for the direct compensation version of the bit-stealing scheme without a filter. See text for details.

However, a much better solution is available without either adjusting or filtering the monitor. This direct compensation method is particularly applicable to contrast detection experiments or other display applications where it is important to obtained the highest grey-level resolution only in limited regions of the D/A input registers. The direct compensation variant can actually provide even better resolution than the filtered case, by generating a table without the 1 step restriction on color jitter.

As an example of the direct compensation method, the luminance relations for our Apple RGB monitor were employed to construct a D/A output table in which the color jitter is relaxed to allow $\pm$ 2 levels on each gun. For this scheme, the desired color ratio for a given pixel on the screen is converted into target RGB levels of high-precision by conversion through the calibrated luminances for each step in the D/A input registers. A local table is then constructed of all possible combinations of the three guns within the range defined by $\pm$ 1 step on the gun with the largest step size. For example, if the G step size is 6.5 luminance units, and the desired output is 100 luminance units (from a total of (1 + 2 + 6.5) x 255 = 2422.5 luminance units), all the combinations of steps between 93 and 107 would be computed, as depicted in Table II.

TABLE II
DIRECT COMPENSATION RESOLUTION

BLUE STEPS (x1)	RED STEPS (x2)	GREEN STEPS (x6.5)	LUMINANCE STEPS (SUM)	
10	9	10	93	
9	10	10	94	
10	**10**	**10**	**95**	
11	10	10	96	
10	11	10	97	
11	11	10	98	
9	*9*	*11*	*98.5*	
12	*11*	*10*	*99*	
10	*9*	*11*	*99.5*	≤
11	*12*	*10*	*100*	
9	*10*	*11*	*100.5*	
12	*12*	*10*	*101*	
10	10	11	101.5	
11	10	11	102.5	
10	11	11	103.5	
11	**11**	**11**	**104.5**	
12	11	11	105.5	
11	12	11	106.5	
12	12	11	107.5	

Table II shows somewhat more than one iteration of the binary sequence for the direct compensation scheme. (The steps available without bit-stealing, shown in bold, are 10 10 10 and 11 11 11; a total of 13 steps are inserted between them for one cycle of the bit-stealing procedure). The rows in which the RGB values are separated by more than one step are shown in italics. These may be considered to be the combinations that are inserted beyond those available from the 1-step procedure in Table I. Although these represent larger color fluctuations than occur in the adjusted and filtered bit-stealing schemes, we have seen no visible color variations in high or low contrast images with this scheme.

To minimize any detectable color fringes, the application of bit-stealing should be limited to luminance ranges where changes in color ratios are small relative to the human detection threshold, which ranges from about 3% of the opponent luminance modulations at the maximum display luminances to more than 20% at the lowest display luminances[1]. The RGB register values shown in Table II around level 100 should therefore be close to threshold, and should remain so as the table is taken through the luminance range. Note that the mean color (and mean luminance) of the display remain unaffected in this direct compensation scheme.

To achieve this resolution, the grey-scale stimulus should be arranged so that it is presented around a mean value corresponding to the center of this high resolution range (as indicated by the horizontal line in Table II, for example). This approach is particularly applicable to detection experiments, where the resolution is needed most as the stimulus is reduced toward zero contrast. It would be possible to generate outputs with a minimum display step down to values of 0.04% of the full range, if the phosphors had linear light outputs. Such fine resolution, together with the 3 times increase in luminance compared with the filtered approach, makes the direct compensation bit-stealing approach a valuable option in designing high-resolution displays.

COMPENSATION FOR PHOSPHOR NONLINEARITIES

Most video monitors have a nonlinear relation between the luminance output of the phosphors and the voltage into them from the D/A converters. The luminance is often roughly proportional to the voltage to a power of about 2. The calibrated luminance values relative to the D/A values ($V_{D/A}$) for our Apple proprietary monitors are shown in double-logarithmic coordinates in Fig. 4. They were obtained for a square patch of 5 cms on a side and variable color palette with a mid-grey surround over the rest of the screen, which corresponds to the conditions to be used in our experiments. The monitor "brightness" control was set to maximum and the "contrast" control to the preset position. Note that the three luminance calibration curves are asymptotic to straight lines with double logarithmic slopes of 1.57, 1.65 and 1.85 for the blue, red and green phosphors at higher luminances, respectively, but level off at an approximately constant value at low luminances. The net slope, P, of the luminance function under each bit-stealing scheme is therefore derived according to the equation

$$\log L = V_{D/A} \,.\, \log (B^{1.57} + R^{1.65} + G^{1.85})$$

$$\sim V_{D/A} \,.\, \log (w^{P})$$

where B, R and G are the luminance values applicable under each scheme, and w is the resulting luminance of the combined "white". For example, under full bit-stealing, B, R and G are in the ratio of 1 : 2 : 4, for which the combined slope (P) would be 1.72 for the white resultant at its mid point of 166.

We made the assumption that the low luminance asymptote in Fig. 4 corresponds to scattered light from the surround, and should therefore not be summed in triplicate with the addition of the three individual phosphor luminances. The luminance of the zero D/A output of the guns was therefore first subtracted from each of the phosphor luminance values before the three were added together, then added in again to the total to provide the most accurate estimate of the final output luminance.

For complete accuracy, the particular luminance output relationship must be determined empirically for each monitor, and will vary significantly between the three phosphor colors as exemplified by Fig. 4. The implication of these nonlinearities is that the bit-stealing procedure cannot operate with full accuracy from an analytic matrix such as that in Table I, but requires a more empirical scheme. The basic idea (for an image with constant chromaticity) is to generate the complete table of calibrated luminances available with the desired color jitter, as in Table I or II. The D/A output table is then generated by searching through the luminance column to find the one closest to the target luminance.

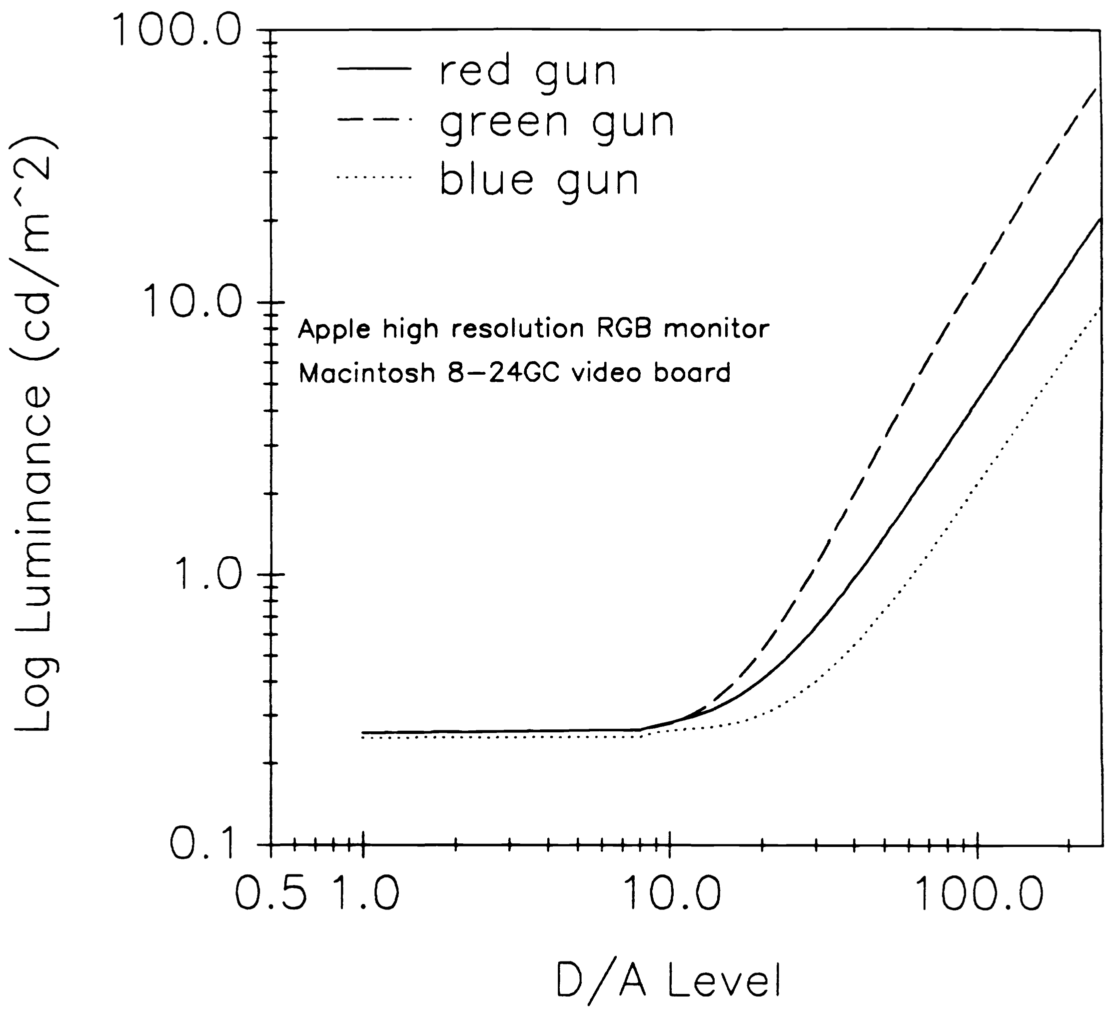

Fig. 4. Calibrated luminance output for each of the phosphors on the Apple RGB Monitor as a function of D/A input level from 1-255, on double logarithmic coordinates. Note the nonlinearity of the functions, in that they deviate from straight lines with slopes of 1 in both their slopes and intercepts.

It is important to note that the luminance output functions are essentially flat for about the first 10 D/A steps. This means that any bit-stealing jitter in the color values is not applicable until this level on the D/A, limiting the range of color ratios which are presented by the display. The shallow slope of the function as it emerges from this point further limits the color ratios. At a D/A step of 10, for example, the slope is about 0.5. Thus the range of color ratios from 12/10 to 10/12 (to take the lowest useful values in the 2-step bit-stealing table) gives a maximal effective color ratio of

$$((12 / 10) / (10 / 12))^{0.5} = 1.2$$

This ratio happens to be right at the low luminance detection threshold for color ratios, implying that the color differences should be undetectable at the bottom of the display luminance range. The color differences are proportionately reduced as luminance is increased, because the step jitter is always limited to 2, while the base number of steps progressively increases. However, both the luminance nonlinearity and the human chromatic sensitivity increase with luminance, tending to counteract the D/A ratio reduction.

It is therefore an empirical question whether the color ratios ever reach the level of detectability under this scheme, and whether such detectability is relevant to a particular display application. Here, we simply make the caveat that, if the color ratios are likely to present a problem in a particular application, the detectability should be modeled appropriately and the bit-stealing implementation limited to those ratios which fall below the detectability criterion. This can be implemented interactively with the assignment of the luminances from the bit-stealing table. Where the desired value exceeds the limiting color ratio, the table can be searched for the closest luminance value that does not exceed that ratio.

Specification of the RGB values corresponding to each luminance level is required for each of the 256 entries in the color palette (which assigns the specified RGB values to all image pixels that have been associated with each color palette entry). For our experimental paradigms, we present a stimulus image in gradations of contrast over time, for which 20 separate RGB tables of 256 entries are prespecified and cycled through the D/A registers in one second. A search process therefore has to be used 20 x 256 = 5,120 times to set up the output tables each time a new stimulus contrast is specified, which may happen every experimental trial. It is important to optimize the search procedure for each individual palette entry to take as little time as possible.

The search procedure we have implemented optimizes the search by starting (or seeding) each search at the value of the previous palette entry, which is likely to be close to the current value as long as the luminance changes gradually with progression through the color palette. The search proceeds linearly through the conversion table in the direction which reduces the difference between the start value and the target value. We tried the alternative procedure of a binary bisection procedure for each luminance, but this proved to be slower than the seeded linear search. On a Mac IIfx, a bit-stealing color palette is computed and loaded in an average of 19 msec, compared with 12 msec for a standard palettes. The times for the Mac IIsi are longer by a factor of 2.3. For our application of animating a dynamic pattern through a range of 20 color palettes, the total set-up time is thus 380 msec for the IIfx and 920 msec for the IIsi, allowing each animation sequence to be changed in less than a second.

PRACTICAL LUMINANCE RESOLUTION WITH BIT-STEALING

The phosphor nonlinearities also limit the luminance resolution that can be achieved in practice. The D/A position required to achieve a mid-range luminance, for example, is 166 out of 256 (from the data of Fig. 4). At this luminance, the function is substantially steeper than would be obtained from a strictly linear relation. The increase in the step size is a factor of 1.72 for the combined output of the three color guns. The implication of this increase is to reduce the effective luminance resolution for any of the methods by the same factor. The final values of luminance resolution and other data for the various methods are given in Table III.

TABLE III

EFFECTIVENESS OF DIFFERENT IMPLEMENTATIONS

METHOD	Standard 8-bit	Standard 10-bit	Adjusted Bit-stealing	Filtered Bit-stealing	Compensated Bit-stealing
LUM. LEVELS	256	1024	1786	1786	3316
D/A BITS	8	10	10.8	10.8	11.7
D/A RESOL'N	$^1/_{256}$	$^1/_{1024}$	$^1/_{1786}$	$^1/_{1786}$	$^1/_{4846}$
ACTUAL RESOL'N	1.34%	0.34%	0.19%	0.19%	0.07%
EFFECTIVE BITS	7.2	9.2	10.0	10.0	11.5
RELATIVE LUM.	1.0	1.0	0.74	0.3	1.0

The first row (METHOD) gives the luminance compensation method to be considered, beginning with two standard display configurations (8- and 10-bit D/As). Note that the fourth, fifth and sixth columns corresponds to methods 1 (Monitor-adjusted bit-stealing), 2 (Filtered bit-stealing), and 3 (Direct compensation without filter). The row values each give a different specification of the luminance resolution that, in many cases, cannot be derived directly from the other rows.

The second row (LUMINANCE LEVELS) show the number of different luminance levels available under each method. Note that, if the color palette is limited to 256 entries, for example, then only 256 of these levels could be displayed on the screen at any time, but the row shows the number of luminance levels from which the color palette may select for display.

The third row (D/A BITS) shows the number of levels in the previous row specified in terms of the number of bits of information inherent in that number of levels.

The fourth row (D/A RESOLUTION), shows the full scale resolution of the D/A output implied under each scheme, assuming linearity but with the register outputs scaled in proportion to the relative luminances on the three color guns.

The fifth row (ACTUAL RESOLUTION) shows the percent resolution of the display output taking into account the luminance nonlinearity of the phosphors. The phosphor nonlinearity means that the resolution varies with position on the D/A output. The resolution must therefore specified with respect to a particular position, which is chosen as the level which gives 50% of the maximum luminance of the display under each output scheme. At this position, the resolution is given as a percentage of this chosen level, which is lower by a factor of two than the resolution specified in terms of full range. The luminance nonlinearity, as described above, reduces the resolution at the mid-luminance by a further factor of 1.72. The actual percent resolution (R_A) is therefore derived from the D/A resolution ($R_{D/A}$) by the formula:

$$R_A = R_{D/A} \times 100 \times 2 \times 1.72$$

The sixth row (EFFECTIVE BITS) gives the effective number of bits implied by the actual resolution of the output image at the mid-luminance position. These values correspond to the number of bits that would be required by a D/A converter with linear luminance output to achieve the same resolution as the methods described, combined with the nonlinear luminance outputs shown in Fig. 4. Note that these values do not correspond to the actual number of levels available under any of the schemes, both because the luminance nonlinearity decreases the number of levels available around the midpoint, and also because the unfiltered bit-stealing scheme increases the number of levels around that point.

The seventh row (RELATIVE LUMINANCE) simply tabulates the luminance reduction required to implement each method, relative to the Standard 8-bit output.

Table III shows that the phosphor nonlinearity reduces the effective bits of an 8-bit display to 7.2 bits, giving an actual resolution of 1.34% at mid-range. The 1-step bit-stealing schemes (columns 2 and 3), which provide 1786 steps of luminance, increase the effective bits to 10, for an actual resolution of 0.19%. Both schemes, however, reduce the display luminance. The final bit-stealing scheme, direct compensation with a 2-bit range (Table II), increases the available luminance levels substantially, providing an actual resolution of up to 0.07% in the optimal luminance ranges. It should also be recognized that the minimum resolution of this scheme is 1/9.5 of the standard steps (see Table II). At mid-range luminance , this translates into an actual resolution of 0.14% (10.5 effective bits). The maximum resolution is obtained only in the ranges where the table increments in steps of 0.5, represented by the bold numbers.

It is interesting to compare the luminance resolution of the bit-stealing technique with sophisticated commercial hardware, which has 10-bit D/A outputs. As shown in Table III, the effective resolution of a 10-bit D/A is about 9.2 bits (0.34%) at mid-range, which is not quite sufficient for the most demanding visual display applications. The direct bit-stealing scheme for an 8-bit D/A , on the other hand, provides a minimum resolution better than twice this value (0.14%), with twice again available (0.07%) for applications where the whole image is at low contrast. If bit-stealing were applied to a 10-bit color D/A, of course it could quadruple the resolution in any of the specified 8-bit conditions. It is not clear where such resolution would be needed, however.

GENERAL DERIVATION OF BIT-STEALING IMPROVEMENT

The analysis thus far has focussed on the development of specific cases. A more general specification of the improvement under bit-stealing is in order. We focus on the question of the optimum improvement in resolution obtained as a function of the number of bits stolen, and what particular luminance ratios are required for the output of the bit-stealing table to have uniform increments. For the case of Table I, 7 equal steps were obtained by using all possible combinations of a 1-step jitter (1-bit). Table II uses two steps of jitter, but it does not use all possible combinations. For a given G level, there are all permutations of two steps of the other two guns available, but they are available both above and below their designated levels. In fact, the combinatoric formula for the number of permutations, P, of n levels taken 3 at a time is given by:

$$P = 2.(n + 1)^2 - 1.$$

This gives values of 17 levels for the case of 2-step jitter, 31 levels for 3-step jitter, and so on. The luminance resolution under each of these schemes is finer than that of a standard scheme by an amount which is almost proportional to P (after missing negative values in the initial cycles are taken into account).

It is also possible to specify the relative luminance required to achieve equal increments throughout the bit-stealing table. Again, for the 1-step table they were 1:2:4. For a full 2-step table (unlike Table II), the availability of two steps means that the second gun does not need to be incremented until a level of 3, and the third until a level of 13. The optimum luminance ratios are therefore 1:3:13. The combinatoric formulas for the optimum second and third levels, given minumum step of 1, are:

$$2nd = n+1$$

$$3rd = 2(n + 1)^2 - n - 3.$$

Under this optimized bitstealing schemes, a full 2-step table can produce an output of 4332 luminance levels (more than 12 bits of D/A output). To achieve this, the typical ratio of 6.5:2 for G:R is already close. One would need to reduce the R by the equivalent of 0.5 of its 2 units, and the blue from 1 to 0.5. Such values easily can be obtained with filter of a light green hue, but we have not yet implemented such a scheme. Note that the actual output resolution by this 2-step method, at 11.3 bits, would be slightly less than the regions of maximum resolution obtained by the direct compensation 2-step bit-stealing (Method 3).

The formulas provided are predicated on the assumption of uniform increments. It appears that this assumption excludes the use of a smaller set of combinations including both positive and negative steps from the gun with the highest level. It is certainly possible to obtain even greater resolution by including these steps (as shown by our Method 3, for example), but the result necessarily will be a table with uneven increments, we believe. We have not subjected this possibility to scrutiny, however, so there may be some combination of levels that produces a table arrangement of higher resolution that is acceptable for some particular application.

COLOR BIT-STEALING

Bit-stealing may also be implemented for images that are not limited to a uniform color ratio. In fact, application of bit-stealing to images of arbitrary chromatic content may be achieved at a cost of reducing the available color gamut by, for example, up to one bit for each gun ($127^3 + 1 = 2,048,384$ values). Given that this reduction is limited to the least significant bits in color space, it is a small price to pay for the tremendous increases in the luminance resolution specified in Table III.

In the most general application of color bit-stealing, every RGB value can be considered a vector in the luminance/color threespace. The array of vectors consist of all possible positions in the threespace that are accessible given the hardware of the D/A converter and the monitor, with its phosphor nonlinearities. For a typical color display application, the output vector for a particular value in the color palette is chosen as the set of RGB values closest in this threespace to the desired vector. In the bit-stealing approach, the desired vector is segregated into its univariate luminance component and its bivariate chromaticity component. Vectors of equal luminance to the desired luminance vector form a plane in the threespace normal to the luminance axis. Bit-stealing is then implemented for minimizing the distance in threespace for selection of the output vector by biasing the vectors with a greater weight for distances normal to the equiluminance surface, and a lower weight for distances parallel to the surface. In this way, the vector minimization procedure achieves greater precision for the luminance component by allowing more freedom in the chromaticity component.

For optimal application, the search region for the chromaticity component can be adapted to the threshold of human discrimination of color differences at each specific chromatic locus throughout the color space by transforming to a coordinate system of approximately equal discriminability on both the luminance and chromaticity axes[2]. The bit-stealing would then consist of selecting the RGB values closest to the desired vector in this equal discriminability coordinate system, and always would remain below the threshold for detection of both luminance and color differences.

Although we have not yet fully developed the benchmarks for this method, we have implemented color bit-stealing by the following scheme. Starting with the desired tristimulus color values and the desired luminance level to high precision, we transform these to the required R,G and B luminances for the three phosphors. The RGB values for the D/A input are then derived to 8-bit resolution through the calibration curves, such as illustrated in Fig. 4. To improve the resolution of the luminance specification beyond the 8-bit level, a 2-step bit-stealing table is generated of all combinations of RGB values within $\pm$ 1 level on each gun (a total of 27 combinations). The high-precision luminance values for each combination are summed to provide the set of levels generated with the direct-compensation bit-stealing display. This combination is the one used for the color palette entry, allowing the color ratios to vary by $\pm$ 2 levels as required to provide finer specification of the luminance level. Individual steps are no longer visible.

Color bit-stealing may be applied independently to each of the entries in the color palette, allowing complete freedom in selecting the color palette except for the loss of the least significant bit. The same is true in systems that allow an indefinite number of colors (as opposed to those whose color palette is limited to 256 entries, for example). Thus color bit-stealing provides a flexible method of controlling the luminance precision with a wide variety of applications. One application to the examples discussed would be to set the color to compensate for the gelatin filters required under Method 2 to optimize the step sizes of the three phosphors. In this way, the color could be adjusted to a neutral grey, while still retaining the advantage of the finest possible luminance resolution within a 1-step variation in color ratios.

One caution in the application of bit-stealing in general is that it cannot provide a greater number of grey levels than are available from the color palette of the display output. Many displays are limited to a palette of 256 different entries (each keyed to an arbitrary number of screen pixels). Thus any image can only be portrayed to a total resolution of 8 bits, regardless of the bit-stealing scheme employed. Bit-stealing is thus useful under any of the following conditions;

1. The color palette available is larger than the basic grey-scale range (for full-scale images)

2. The image displayed is limited to a grey-scale range less than that of the color palette (as for psychophysical detection targets)

3. The desired grey-scale function is different from that generated by the phosphor nonlinearity. The new levels required for modified grey-scale may be positioned accurately by means of bit-stealing, avoiding the constraints of the levels inherent in the standard output.

REFERENCES

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