Chrominance Subsampling in Digital Images

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ABSTRACT

The JPEG and TIFF digital still image formats, along with various digital video formats, have provision for recording the chrominance information (which conveys in a special way what the lay person would describe as the "color" of the pixels) in a resolution lower than that of the image being encoded. This concept, followed for over half a century in television broadcasting, takes advantage of the properties of the human perceptual system to reduce the amount of data required to convey an acceptable full-color image of certain pixel dimensions. There are various standard "patterns" for performing this "chrominance subsampling", and several curious and confusing systems of notation for indicating them. In this article we discuss the concept of chrominance subsampling and describe various systems of notation used in this area.

BACKGROUND

The color space

A digital image that is to be encoded using the JPEG image data coding and compression system, one form of the TIFF image coding system, and various digital video formats is first put into what is called a luma-chrominance color space. In this form, the color of a pixel is described by two values, one (*luma*) essentially (but not exactly) describing its *luminance* (brightness), and one (*chrominance*) describing what a lay person would think of as its "color". The latter is a slightly different concept from the basic color science concept of *chromaticity*, but we need not concern ourselves here with the distinction. The metric for chrominance is, as we might expect, two-dimensional in the mathematical sense: two numerical values are actually required to express it (a total of three values for the color).

As hinted at just above, the first value in this scheme does not actually describe the luminance of the pixel's color. As a result, it is often called "luma", a term borrowed from the analog system used for television signals. This term is a tip that the value does not quite describe luminance, because of its nonlinear form. And in fact, paralleling this, the value pair giving the chrominance is also sometimes called "chroma", again primarily to tip us off to its nonlinear form. But here we will use the term *chrominance*, as it best matches normal editorial practice for the topic area we are considering.

Thus, for each pixel, there are three numerical values that collectively describe its color. They are identified as Y, Cb, and Cr. Y is the *luma* value, and Cb and Cr collectively form the *chrominance* value. These are derived from an RGB color space, where R, G, and B are nonlinear representations of the relative contributions of three primary chromaticities (also called R, G, and B.

Chrominance subsampling

During the early work on color television systems (analog, of course), note was taken of the fact that the human eye is able to discern finer detail conveyed by differences in luminance than for detail conveyed by differences in chromaticity. The encoding scheme adopted there separately conveys the luminance-related value *luma* and the chromaticity-related value *chroma* (chrominance) over "subchannels" having different bandwidth (and thus supporting different levels of resolution)—the chrominance subchannel having reduced resolution capabilities. The result was a system that well matched human perceptual response, allowing the conveyance of quality images with less overall bandwidth requirement than if equal bandwidth were allocated to luma and chrominance information.

Not surprisingly, the developers of systems for the encoding of digital still images decided to exploit this same consideration to get the "biggest bang for the bit" in digital images being prepared for transmission or storage. There, the process is called *chrominance subsampling*.

Simply stated, here is the principle. We include in the digital data stream to be encoded by the JPEG system the luma value (Y) for each pixel in the image. But we only include a single Cb + Cr pair (a "chrominance value", often described as a *chrominance sample*) for a group of pixels—which in the schemes generally recognized can comprise 2, 4, or even 8 image pixels. Thus the data load for the chrominance information—which otherwise would be twice that for the luma information (Y, Cb, and Cr are all recorded in the same number of bits, usually 8)—is now reduced by a factor of 2, 4, or even 8.

In fact, it is often useful to think of this in terms of the chrominance being given for "chrominance pixels" which are 2, 4, or even 8 times the size of the image pixels.
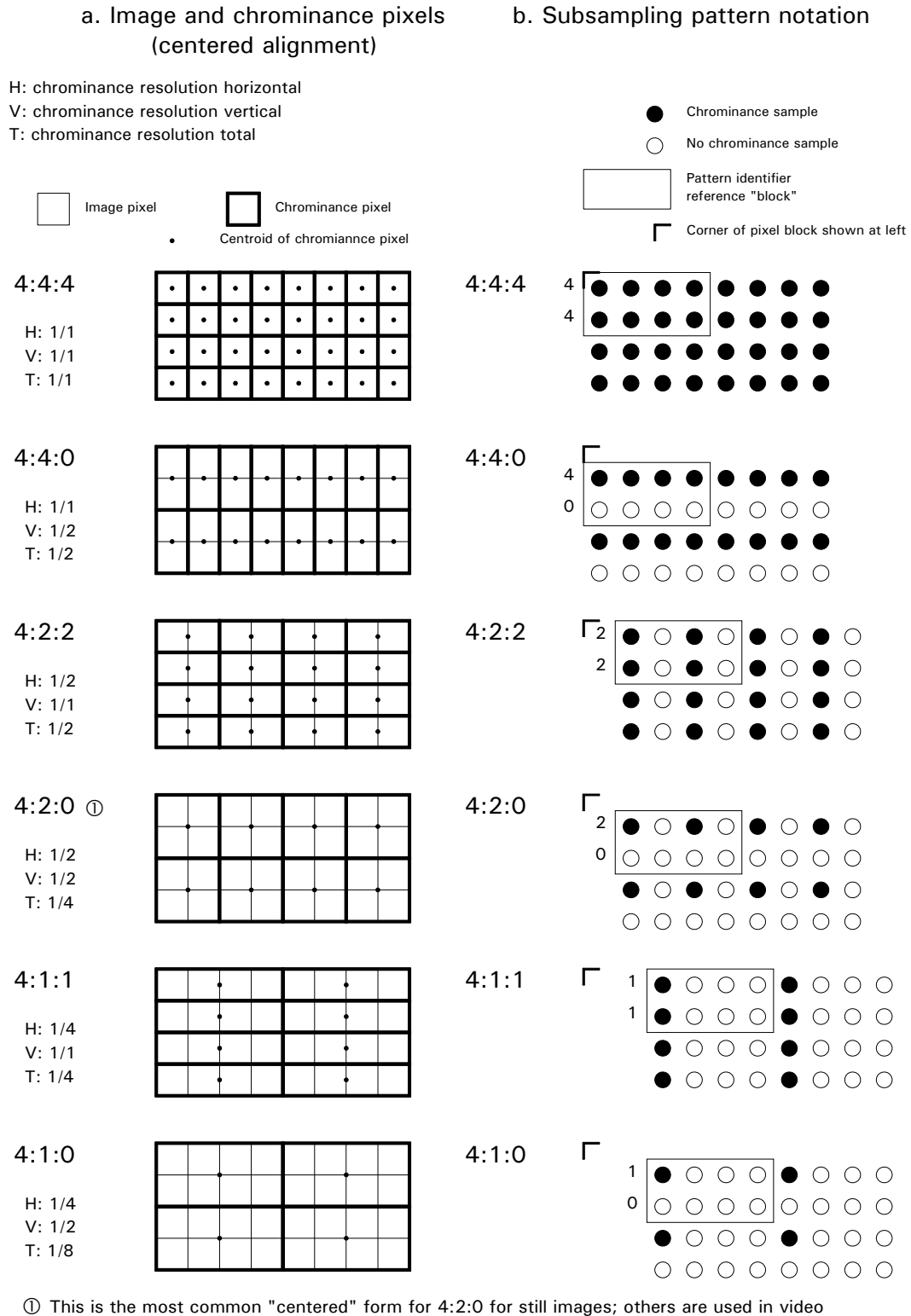
This process is sometimes spoken of as "chrominance decimation", where *decimation* (in this context) essentially "means thinning out a data set by discarding all but a certain fraction of the values" [1]. However, the way chrominance subsampling is usually done does not exactly fit that definition.

"Siting" of the chrominance samples

This now leads to another issue. Suppose we are using a pattern in which the "chrominance pixel" is twice as wide and twice as high as an image pixel. Should its "centroid" be at the center of an image pixel, or should it be at the center of the group of four image pixels? In fact, there can be advantages to each, and both possibilities are potentially available for each subsampling pattern. We'll hear more about that later.

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[1] *Decimation* originally referred to the practice in Roman times of killing one-tenth of the citizens of a rebellious town. It later came to be misunderstood to mean **keeping** only one-tenth of a population of items (perhaps data points), and was then broadened to the more general meaning used today.

a. Image and chrominance pixels (centered alignment)

b. Subsampling pattern notation

H: chrominance resolution horizontal
V: chrominance resolution vertical
T: chrominance resolution total

Figure 1. Chrominance subsampling patterns (centered alignment)

SUBSAMPLING PATTERNS

Figure 1 shows, in part **a**, six chrominance subsampling patterns (actually, the first one is no subsampling at all), including all the ones widely used in common image

encoding schemes. These patterns are identified by a notation system we will describe shortly.

Each example shows a portion of the original image 8 pixels wide and 4 pixels high, and indicates (with heavy lines) the boundaries of the "chrominance pixels". The chrominance of all the image pixels covered by each chrominance pixel is averaged and included (as a pair of Cb and Cr values) in the image data for the chrominance pixel. The dots show the centroids of these chrominance pixels, and also help us do a visual "head count" of the chrominance values. Note that all these examples show the "centered" alignment: the centroids of the chrominance pixels are located in the center of the set of the centroids of the associated luminance pixels. The chrominance pixels each embrace a set of integral image pixels.

Just below indicator for the pattern (*e.g.*, 4:4:4—don't worry for the moment about what that means or why) we show how the resolution of the chrominance pixels compares to the resolution of the image itself. The H value is the relative resolution in the horizontal direction, the V value is the relative resolution in the vertical direction, and the T ("total") value is the relative resolution in terms of pixel count (sometimes called the "areal" resolution), all as fractions.

Note that each image pixel gets a luma value (luma sample). In most writings about this matter, resolution comparisons are made between the "chrominance samples" and "luma samples", rather than between the "chrominance pixels" and "image pixels", as we do here. And often the "ratio" is described other-side up as a sampling factor—a sampling factor of "4" in the horizontal or vertical direction means a resolution of 1/4 the image (or luma) resolution.

The first pattern shown (4:4:4) is in fact the case where there is really no chrominance subsampling at all—every image pixel has its chrominance value included.

There are two patterns (4:4:0 and 4:2:2) which have chrominance pixels twice the size of image pixels (T:1/2). In the first of these the (rectangular) chrominance pixels are vertically-oriented, and in the other, horizontally-oriented. There are two patterns (4:2:0 and 4:1:1) which have chrominance pixels four times the size of image pixels (T:1/4). In the first of these the chrominance pixels are square, and in the other, rectangular and horizontally-oriented.

In the last pattern (4:1:0), the chrominance pixels are eight times the size of the image pixels (T:1/8), and are rectangular and horizontally-oriented.

Note that the specification for the kind of JPEG image file used today by most digital still cameras (the JPEG Exif file), only two of these patterns are allowed: 4:2:2 and 4:2:0.[2]

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[2] The 4:2:0 scheme is often incorrectly identified as "4:1:1". The origin of this widespread error is not known to me.

Image and chrominance pixels
(co-sited alignment)
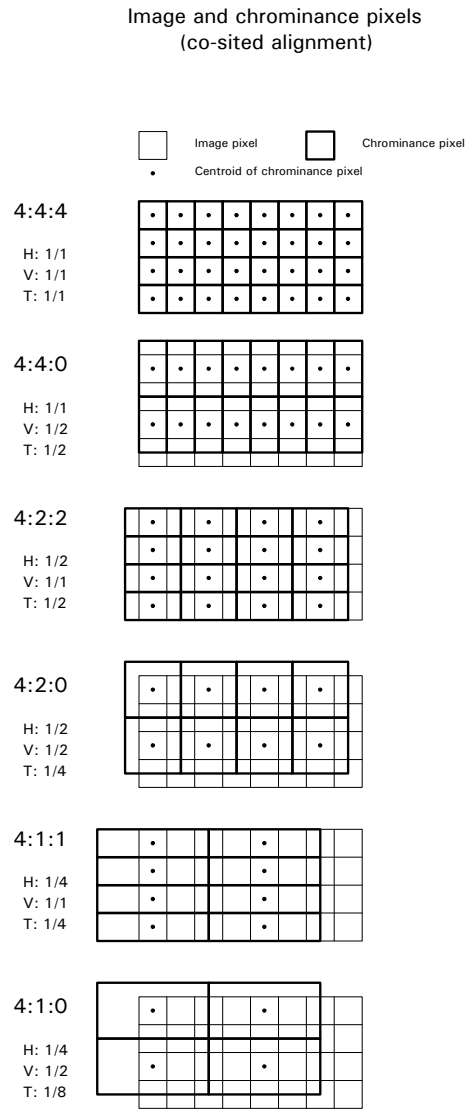
Figure 2. Image and chrominance pixels (co-sited alignment)

Chrominance pixel alignment

The examples in Figure 1 all show the arrangement when the implied chrominance pixel actually embraces a number of full image pixels (known as the "centered" alignment). There, each implied chrominance pixel is centered on the center of the related pixel block.

In figure 2, we see the other alternative (the "co-sited" alignment) in one form. There, each implied "chrominance pixel" is centered on the upper-left image pixel of the related pixel block.

Some implications of this will be discussed in a later section.

THE BOTTOM LINE

The intricacies of the charts above (and of the common notation system for subsampling patterns, already glimpsed above, and to be explained shortly) hide the fact that, for the cases of common interest to us, the subsampling pattern can really be described by two numbers of simple meaning: the horizontal and vertical subsampling factors:

- The *horizontal subsampling factor* tells us for how many image pixels, in the horizontal direction, is there a chrominance "sample" ($Cb + Cr$). If that factor is 4, then there is one chrominance sample for every 4 image pixels in the horizontal direction.

- The *vertical subsampling factor* tells us for how many image pixels, in the horizontal direction, is there a chrominance "sample" ($Cb + Cr$). If that factor is 1, then there is one chrominance sample for every image pixel (that is, for every row of image pixels) in the vertical direction.

Often, these two defining factors are called "h" and "v", respectively, and are often written in the form (for the examples above): "4x1" or "4/1". Note that the latter does not in any way have the significance of a fraction.

SUBSAMPLING PATTERN NOTATION

Unfortunately, the subsampling patterns we encounter are not ordinarily described by the straightforward "h/v" notation, but rather by something far more arcane. We saw it in the figures above, and now we are ready to tackle it. We can follow the action on part b of figure 1.

The scheme indicator is of the form J:a:b. The notation revolves around the concept of a "reference block"—a conceptual region J image pixel spacings wide and 2 image pixel spacings high. (For all schemes we encounter, J, by convention, is 4.) This block is not necessarily exactly aligned with the grid of image pixels (and luminance values). The small chevron at the upper left of each reference block shows the relative location of the upper left corner of the block of image pixels as shown to the left.

The dots in the figure (white and black) represent the chrominance samples (each recorded as a Cb value plus a Cr value) **that would exist if there were no subsampling**. The black dots show the chrominance values that actually exist for this scheme.

Note that, if we consider our reference block, the indicator value **a** shows the number of chrominance samples actually present in the top row of the block; the indicator value **b** shows the number of chrominance subsamples actually present in the bottom row of the block. We see that emphasized by the little figures to the left of the reference block in the figure.

Note that there is a one-to-one correspondence between the black dots in part b of the figure and the little black dots indicating the centroids of the chrominance pixels in part a of the figure.

Note that the 4:2:2 pattern could as well have been designated "2:1:1", as the purpose of the notation is to convey relative sampling "frequencies". However, for patterns where the ratios involve only the numbers 1, 2, and/or 4, it is customary to always make $J = 4$. There are patterns, used in some specialized video systems, in which J is 3, thus accommodating these patterns' chrominance subsampling factor of 3 in the horizontal direction.

Relationship with "h/v" notation

The correspondence between the J:a:b notation and the "h/v" notation is shown here all the possible variations (including some rarely-encountered ones):

J:a:b	h/v
4:4:4	1/1
4:4:0	1/2
4:2:2	2/1
4:2:0	2/2
4:1:1	4/1
4:1:0	4/2

Irregular notation

Recall that the vertical subsampling factor is expressed in the J:a:b notation in terms of a pattern of two consecutive rows of pixels. The scheme only allows for value of "v" of 1 and 2, as follows:

$v = 2$: $b = 0$

$v = 1$: $b = a$

In some situations, we encounter a pattern in which both v and h are 4. This cannot be represented by the J:a:b notation as defined above.

A special convention has apparently been adopted to cater to this. It works like this:

J:a:b	h/v
4:4:1	1/4
4:2:1	2/4

Basically, if J is 4, and b 1, but a is not 1, then the vertical sampling factor is 4. (One can construct all sorts of clever rationalizations for this; I leave that exercise to the reader.)

Misunderstandings

Not surprisingly, this peculiar system of notation has been subject to some misunderstandings, unfortunately widespread. We will mention three of them here.

The meaning of **a** and **b** in the "J:a:b" notation

Often, especially in the area of digital video work, we hear the subsampling pattern notation system described this way:

> "The first number gives the number of luma samples that we consider. The second number gives the number of Cb values over that span, and the third number gives the number of Cr values over that span."

This is generally followed by something like this:

> "Notations such as 4:2:0 do not follow the rule." (No kidding!)

Note that the erroneous definition does in fact appear to be true when $a = b$.

We will see later that this in fact describes a different notation system that has been used in the past; it does not apply to the system mostly encountered today (which is why it seems anomalous).

4:2:0 vs. 4:1:1

Very commonly, the 4:2:0 pattern is erroneously described as "4:1:1". The author has not been able to track down the origin of this error.

This error is found in many image editing packages offering the opportunity to select different subsampling patterns when an image is saved in JPEG form.

U and V vs. Cb and Cr

This is not really an error, but a matter of editorial practice. It can however be confusing in following the literature.

Often we will hear the Cb and Cr values described as **U** and **V**.

U and V are the coordinates of the color space YUV color space which underlies the YCbCr color space. Cb and Cr are the quantized digital representations of the U and V values of a color in the YUV color space. Thus it may be reasonable to speak, conceptually, of the chrominance of a pixel itself in terms of U and V, or of a chrominance **sample** as comprising U and V values. However, in a digital image context, it is more useful to make reference to Cb and Cr (which is how the values are designated in the actual digital image data).

REPRESENTATION IN Exif FILES

Two different ways of representing the chrominance subsampling are used in Exif files. We would not ordinarily be interested here in such "internal "representations, but in fact two systems used to present a subsampling pattern, or even to set it in

an image-generating program, flow directly from these. Those "human" notation schemes are best understood by first looking at the "file" context.

Uncompressed JPEG Exif files

In an uncompressed JPEG Exif file (rarely encountered), the subsampling pattern is represented in the most straightforward way we will encounter.

The metadata tag *YCbCrSubSampling* comprises two eight-bit numbers, the horizontal and vertical "subsampling factors". These are just the horizontal and vertical subsampling factors, h and v, discussed above.

In compressed JPEG Exif files

In a compressed JPEG Exif file (the type we almost always encounter in digital photography), a different scheme of representing the subsampling pattern is used.

Here, in marker *SOF0*, there are four 8-bit values, designated H1, V1, H2, V2, H3, and V2. Each pair (e.g., H1 and V1) is listed in the portion of the marker pertaining to one of the three "components" of the image, Y, C_b, and C_r. They are said to be the *chrominance subsampling factors*, in the horizontal and vertical directions, of those three components.

But that is misleading as to H1 and V1, since there is no subsampling of the Y (luma) component. Actually, those two values are reference values. They can be thought of as describing the horizontal and vertical dimensions (in pixels) of a block of pixels defined only for purposes of stating the subsampling arrangement. (They are rather like the value "J" in the J:a:b: scheme of notation.)

The subsampling factors (in the same sense as mentioned earlier) for C_b and C_r are these:

$$\text{For } C_b\text{—horizontal (h): } \frac{H1}{H2}; \text{ vertical (v): } \frac{V1}{V2}$$

$$\text{For } C_r\text{—horizontal (h): } \frac{H1}{H3}; \text{ vertical (v): } \frac{V1}{V3}$$

Of course, in most cases of interest, the subsampling factors are the same for C_b and C_r, and among other things, this means that H3 = H2 and V3 = V2.

In table 3 we show the implications of 12 patterns of the H- and V- values both in J:a:b notation and h/v notation. The reason for the choice of this particular repertoire will be seen shortly.

Compressed JPEG Exif file							
H1	V1	H2	V2	H3	V3	J:a:b	h/v
1	1	1	1	1	1	4:4:4	1/1
1	2	1	1	1	1	4:4:0	1/2
1	4	1	1	1	1	4:4:1*	1/4
1	4	1	2	1	2	4:4:0	1/2
2	1	1	1	1	1	4:2:2	2/1
2	2	1	1	1	1	4:2:0	2/2
2	2	2	1	2	1	4:4:0	1/2
2	4	1	1	1	1	4:2:1*	2/4
4	1	1	1	1	1	4:1:1	4/1
4	1	2	1	2	1	4:2:2	2/1
4	2	1	1	1	1	4:1:0	4/2
4	4	2	2	2	2	4:2:0	2/2

* Irregular notation

Figure 3. Compressed JPEG Exif file subsampling encoding

It would seem that these three H/V combinations would produce the same subsampling pattern (shown in J:a:b and h/v notation):

   1,2,1,1,1,1   4:4:0   1/2

   1,4,1,2,1,2   4:4:0   1/2

   2,2,2,1,2,1   4:4:0   1/2

As you can see from the table, there are other seemingly-redundant sets of values. This may just be an artifact of this peculiar notation, although there may in fact be some subtlety of the notation unknown to me that would give these combinations different implications.

IN IMAGE EDITING PROGRAMS

Image editing programs generally allow the user to choose which subsampling pattern will be used when writing JPEG files, generally one factor in establishing a "degree of compression" or, conversely, an "image quality". Rarely is the degree of compression expressed in a way that is easily grasped by the user (such as the "h/v" notation).

Further, in the three programs described here, only one offers the widely-accepted (if still confusing) J:a:b notation, and it gets it wrong in one choice out of three.

In Photoshop

In Photoshop CS2 (the latest version I have!) one can change the compression settings for saved JPEG files, but there is no explicit setting for the chrominance subsampling aspect. Rather, one of two patterns is preordained for any given numerical "quality" level.

In the regular Save As operation, where the "quality" can be set over the range 0 through 10, for all values up through 6 the chrominance subsampling is "2x2" (4:2:0); for 7 and above it is "1x1" (4:2:2).

In the Save for Web operation, where the quality can be set from 0-100 (go figure!), for all values up through 50 the chrominance subsampling is "2x2" (4:2:0); for 51 and above it is "1x1" (4:2:2).

In Paint Shop Pro

The popular image editing program Paint Shop Pro 9 allows the user to set one of 12 different subsampling patterns to be used for the writing of JPEF Exif files. There are described in the H1,V1,H2,V2,H3,V2 notation actually used inside the file (completely incomprehensible to the user), which was described above.

The presentation in the Save Options dialog, Chroma Subsampling dropdown box, looks like this:

    YCbCr 2x1 1x1 1x1

where the six numerical values are H1, V1; H2, V2; and H3, V3.

The repertoire of combinations is in fact that seen in the table of Figure 1 (that's why it was chosen there: to get ready for this section).

In fact, although we might expect the 1x2, 1x1, 1x1 and 2x2, 2x1, 2x1 choices to produce the same subsampling pattern, the resulting file sizes are slightly different, so there is certainly some subtlety there I do not pretend to understand.

In Picture Publisher

In Picture Publisher 10, when you invoke File>Save As, if you select the JPEG file type, the Save As dialog includes an Options button, which brings up the JPEG Options dialog. It includes a dropdown selector for Subsampling, which offers these choices:

    YUV 4:4:4 (High Resolution)   That produces 4:4:4, or 1x1.

   YUV 4:2:2 (Medium Resolution)   That produces 4:2:2, or 2x1.

    YUV 4:1:1 (Low Resolution)   That produces 4:2:0, or 2x2.

The misidentification of the 4:2:0 pattern as "4:1:1" is widespread. The misidentification of the encoding system as YUV (rather than YC_bC_r) has been earlier discussed.

DATA PACKING

Although it is not part of the real topic of this article, an interesting related matter is the way in which the Y, Cb, and Cr values for an image are arranged as a data stream, perhaps for presentation to the software routines that encode the ensemble of data into JPEG or TIFF form (a matter often called *data packing*). For each

subsampling pattern, there may be several standardized data packing arrangements. Just to give some insight into this, we show on figure 4 a common data packing arrangement for the 4:2:0 subsampling pattern (centered alignment).
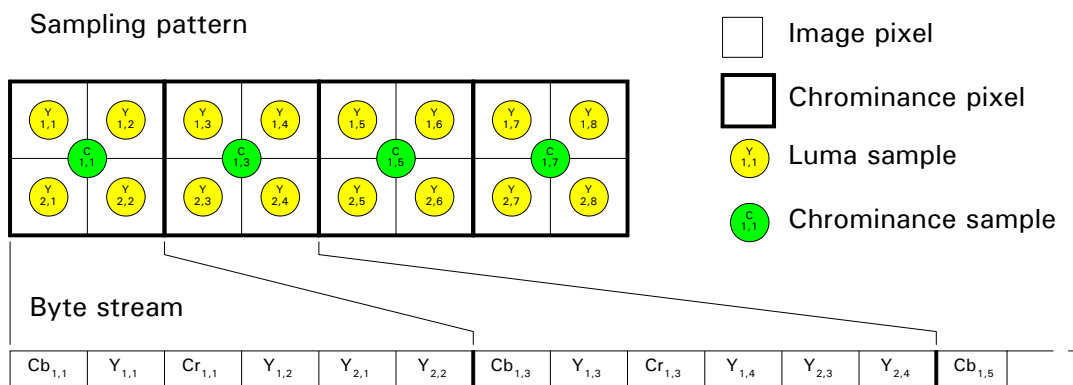
Figure 4. Data packing for 4:2:0 subsampling

The figure shows a block of image pixels 8 pixels wide and two pixels high, divided into chrominance pixels 2 x 2 image pixels in size, in the way intimated by the "centered" form of the 4:2:0 subsampling pattern. The yellow dots show the centroids for the luma samples, the green dots the centroids for the chrominance samples. The indexes for the chrominance samples (and their Cb and Cr values) are those of the nearest luminance sample above and to the left.

The data packing arrangement operates on an entire chrominance pixel at a time and then moves to the next chrominance pixel; it does not operate the basis on image pixels. The four Y values (one for each image pixel) and the Cb and Cr values (for the chrominance pixel) are placed in the byte stream as shown.

The calculation of the analog quantities U and V underlying Cb and Cr involve B and R, respectively, thus the notation Cb and Cr. The reason the color space is called YCbCr (rather than YCrCb) is because of the natural order of U and V.

A word of caution: especially for other subsampling patterns, there are data packing arrangements which seem to follow a similar principle regarding the placement of Cb and Cr but in which their order is opposite that shown here, the idea being to more closely match the familiar sequence R, (G), B.

A UNIQUE VARIANT

The "DV" digital video standard, in its "European" (PAL-compatible) version, uses a unique form of the 4:2:0 subsampling pattern. It is shown in figure 5.
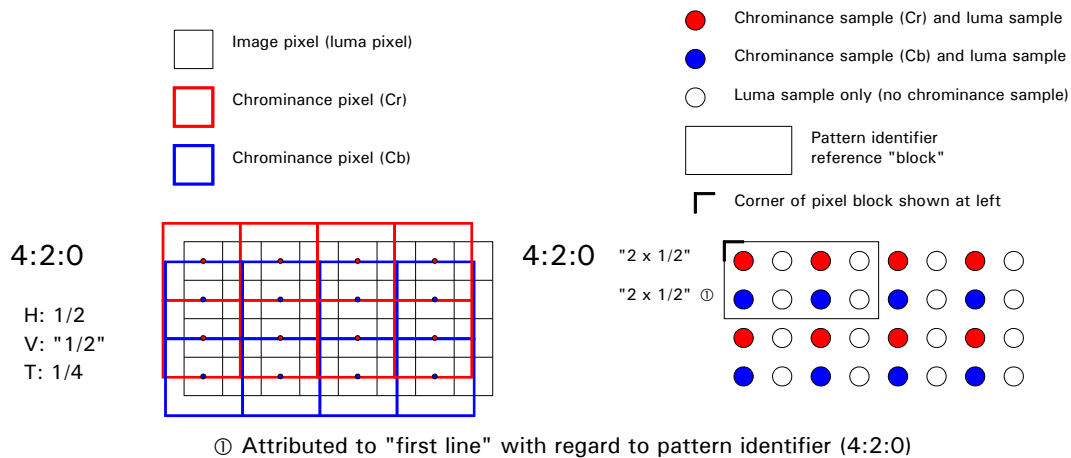
Figure 5. DV-PAL subsampling pattern

The unique feature of this pattern is that the Cb and Cr values are not associated with the same location on the image; that is, to use our notation, with the same chrominance pixel.

If in fact the chrominance values are derived from true chrominance pixels (that is, as an average of the chrominance over several image pixels), it probably has to be done as a weighted average over nine image pixels (all of which fall, at least in part, within the chrominance pixel). The figure shows the chrominance pixels based on that concept.

However, evidently the standard for this subsampling pattern does not prescribe just how that is to be done.

Of course, associating a J:a:b identifier with this subsampling pattern requires a little creativity; the notation system doesn't really apply cleanly there. Officially, it is given the identifier 4:2:0. The right hand part of the figure offers a fanciful rationale for that.

AN EARLIER FORM

Early in the development of digital imaging, another form of subsampling notation was used, one that unfortunately was presented in just the same form as the J:a:b notation used today. We still find it used today in articles about subsampling, often mixed with J:a:b notation without the difference being mentioned.

As we mentioned at the outset, in the NTSC television signal format (the standard for North American analog television broadcast, among other things), a luma-chrominance scheme is used (called YIQ). The two axes of the chrominance plane were designated I and Q—a back-formation from the way they are conveyed, by quadrature amplitude modulation of a subcarrier (**I** relates to the **i**n-phase component, while **Q** relates to the **q**uadrature component).

As we mentioned before, the resolution of the chrominance component is lower than that of the luma component (exploiting the greater acuity of the human eye for luminance changes than for chromaticity changes). But beyond that (not mentioned earlier), the resolution of the Q coordinate of chrominance is less than that for the I coordinate. This is to exploit the fact that the acuity of the human visual system to chromaticity difference was less along the Q axis than along the I axis. The benefit is that even less total bandwidth is thus required to transport the entire signal. The way this is done is very clever and a bit tricky, but we need not go into it for our purposes here.

When digital representation of images was coming into play, some workers wanted to follow the YIQ concept, including using a lower "resolution" for the Q chroma axis. To express this, a forerunner of the J:a:b notation system was used, which I will call "K:c:d". Here, as in the modern scheme, K represented (arbitrarily) the resolution of the luma (Y) coordinate; c represented the horizontal resolution of the i coordinate (the digital equivalent of I), and d the horizontal resolution of the q coordinate (the digital equivalent of Q). There was no concept of vertical subsampling: each row had the same pattern of Y and $i+q$ values.

A common format, expressed in K:c:d: form, was "4:2:1". This meant that for every four pixels (and thus every four luma values), there were two i values but only 1 q value.

When the YCbCr coordinate system came into play, there was an early attempt to follow the same concepts of asymmetrical resolution in the chrominance plane: different subsampling for Cb and Cr. Again, the hope was to reduce the overall required "bandwidth" (of course, we were now actually speaking of *bit rate*, but by parallel to the analog situation, this was often called "bandwidth", as unfortunately it is today) without degradation of perceptual quality.

This never really caught on, for a couple of reasons, one of which was that the C_b and C_r axes did not correspond to the highest- and lowest-chromatic acuity axes of the human eye—they were not chosen for that (as were the I and Q axes), but just flowed from the R and B coordinates of the RGB color space, which were dictated by the R and B primaries.

Unfortunately, when the J:a:b notation for (symmetrical) subsampling came into play, the presentation looked just like K:c:d.

Interestingly enough, the arrangement we today call "4:2:2" would also be called, in "K:c:d" notation, "4:2:2" (even though the meaning of the third number differs between the two conventions). The arrangement we call today (in J:a:b form) "4:2:0" cannot be represented in K:c:d form (since that does not accommodate any vertical subsampling: different subsampling on even and odd rows).

Similarly, the arrangement called, in K:c:d form, "4:2:1" (not often encountered today) cannot be represented in J:a:b form (since that does not accommodate different subsampling for Cb and Cr values).

There is some possibility that the confusion between K:c:d notation and J:a:b notation is responsible for some of the errors we find in this area, although I cannot construct a scenario for that.

A DOSE OF REALITY

In order to most clearly illustrate the concepts and principles involved, I have spoken in terms of "chrominance pixels" and have intimated that the chrominance values are in fact determined over these (by some appropriate type of averaging of the their chrominance values.

But that is not always done. In some cases, a more primitive means of determining what chrominance to "send" is used. In the worst case, the chrominance of one image pixel is snagged and transmitted on behalf of the chrominance pixel.

In any event, what happens at the "receiving" end? There, decoding the YCbCr data stream (which does not contain Cb and Cr values for every pixel) is expected to produce a Y, Cb, and Cr value for **every** image pixel. From those values, we derive an RGB representation of every pixel for further handling.

Ideally, this would be done by interpolation between the transmitted chrominance samples. But that's not always done. For example, in many video systems (especially those using a co-sited arrangement of chrominance pixel centroids), the value of a received chrominance sample (one Cb,Cr pair) is used for the reconstruction of several image pixels (four pixels if we imagine a 4:1:1 subsampling pattern).

This typically results in the following:

• The chromaticity of the resulting image will seem to be applied in "blobs", rather than changing smoothly as we move across an object.

• The chromaticity will seem to be shifted to pixels to the right compared to the luminance (by two image pixels in the example of 4:1:1).

#