

Abstract

Georges Seurat first used his divisionist painting technique on *A Sunday on La Grande Jatte – 1884* beginning in October 1885. Painting with pigments representing colours seen in the visible spectrum that were minimally mixed on the palette and using divided brushstrokes, he aimed to impart luminosity to the surface and to explore 19th century ideas of colour theory, such as simultaneous contrast. Pigment analysis has disclosed that the brushwork containing zinc yellow has darkened significantly: Yellow, green-yellow, and orange brushstrokes have become brown, olive-green, and reddish brown, respectively. Additionally, the painting has further darkened due to the natural ageing of the oil medium. By performing spectral reflectance measurements in situ on darkened areas of the painting and on paint-outs of comparable unaltered colours, using Kubelka–Munk turbid media theory, imaging the painting with colour-managed digital photography, and image editing with Adobe® Photoshop®, a digital version of the original, more luminous appearance of *La Grande Jatte* was simulated.

Keywords

digital rejuvenation, divisionism, Kubelka–Munk, digital imaging, zinc yellow

Rejuvenating the appearance of Seurat's *A Sunday on La Grande Jatte – 1884* using colour and imaging science techniques: a simulation

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Introduction

During the summer of 2004, the Art Institute of Chicago organized the exhibition, *Seurat and the Making of La Grande Jatte*, providing an opportunity to re-evaluate this Neo-Impressionist masterpiece, both from art historical and scientific perspectives (Herbert 2004).

Georges Seurat painted *A Sunday on La Grande Jatte – 1884* in three distinct campaigns. He began working on the painting in May 1884 in preparation for the Société des Artistes Indépendants exhibition, scheduled for March 1885. For the first campaign, Seurat used a palette that included high chroma pigments as well as earth colours and a minimum of black. His palette consisted of vermilion, red lake, burnt sienna, iron oxide yellow, chrome yellow, cadmium yellow, viridian, emerald green, ultramarine blue, cobalt blue, lead white and black (Fiedler 1984, 2004). Seurat's technique at this time was similar to the Impressionists, although his subject matter was rendered more exacting. The Indépendants exhibition was postponed and Seurat suspended work on the large canvas until the fall. When Seurat resumed work on *La Grande Jatte* in October 1885, he incorporated his new divisionist technique and colour theories that he began formulating during the summer while painting in Grandcamp. For his second campaign, Seurat revised both palette and technique to conform to his new ideas. His palette consisted solely of prismatic colours that were minimally mixed together. He abandoned the use of iron oxide yellow, burnt sienna and black while adding zinc yellow and additional hues of chrome yellow, vermilion and red lake. He modified his painting technique employing brushwork in the form of small dots, dabs and dashes (for simplicity referred to as 'dots') that were applied next to one another without blending or mixing on the canvas. Seurat also altered the figures and animals by enlarging or adding contours to their forms. The painting was exhibited in its revised form in May 1886 at the eighth and last Impressionist exhibition.

The third campaign consists of a border added sometime in 1888–1889. Seurat used a limited palette for the border; the pigments consisted of vermilion, red lake, cadmium yellow, chrome yellow, cobalt blue and lead white. Of the painting's many colourants, red lake, cadmium yellow, chrome yellow, zinc yellow, emerald green and ultramarine blue (mixed with white) are all capable of achieving colours that are simultaneously light and high in chroma, owing to their sharp absorption spectra. These perceptions lead to 'luminosity,' stimuli that have the property of light sources. Of the three yellows, only zinc yellow appeared without any red or green tint and, thus, best represented yellow seen in the spectrum. His second and third campaign palette included all dominant hues seen in the visible spectrum.

In a review written for the 1887 *Les XX* exhibition held in Brussels, the poet

Emile Verhaeren (1887) especially noted *La Grande Jatte's* luminosity. (Seurat initially referred to this new painting style as 'chromo-luminarisme'.) By 1892, however, severe colour changes had occurred, turning many of the second campaign luminous brushwork to darkened 'holes.' These changes were observed by Félix Fénéon, who noted that the painting had lost its luminous quality and although certain colours were preserved, such as the reds and blues, 'the Veronese greens had turned olive-greenish and the orange tones which represented light now represent nothing but holes' (Fénéon 1892). Fiedler (1984) was the first to identify that the darkening was due to an unstable zinc yellow pigment. Chemically, the zinc yellow used by Seurat is a zinc potassium chromate, whose spectral properties changed in a way equivalent perceptually from yellow to brown. The specific causes for this colour change are presently under investigation. In the sunlit grass, the yellows containing zinc yellow became brownish, similar to an ochre, and greenish yellow containing mixtures of zinc yellow and emerald green became a drab olive. In the juncture between the shadowed and sunlit grass as well as along the edges of many of the figures, the orange turned reddish brown. Because the sunlit grass dominates the background, these colour changes have dramatically influenced the painting's luminosity. With the passage of time, the overall painting has also darkened and yellowed due in part to the ageing of the drying oil medium.

Because the unstable zinc yellow was used only in the second campaign, the affected areas are readily discernible and fairly easily isolated. It seemed feasible that an image of *La Grande Jatte* could be created in which the zinc-yellow-containing dots could be re-coloured appropriately.

Sample preparation

To obtain reference spectra for the unaltered painting materials, dispersions of dry pigments and linseed oil were prepared and applied onto a wooden panel prepared with several coats of a gesso and glue ground. Zinc yellow was used singly and in mixtures with lead white, emerald green, and vermilion; a paintout of lead white in linseed oil was also made.

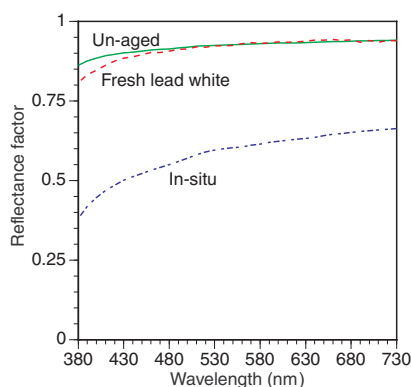


Figure 1. Spectral reflectance factor of fresh lead white oil paint, an in situ measurement of pure lead white, and the un-aged measurement using Equation (1). (Measured reflectance for the entire painting ranged between 0.041 and 0.664 where 1.0 defines the perfect reflecting diffuser.)

In situ spectral and paint analyses

The painting was removed from exhibition, taken out of its frame and glazing, and studied on two occasions. Spectral reflectance measurements of over 50 locations across the paintings were taken. Two reflection spectrophotometers were used: a GretagMacbeth EyeOne and GretagMacbeth SpectroEye, both with 4.5 mm circular measurement apertures. In addition, paint samples were taken at selected locations to determine pigment composition. Of particular interest was the pure lead white measurement, corresponding to the sailboat in the upper left-hand portion of the painting. In Figure 1, there is a comparison of this in situ measurement with the fresh lead white. It is clear that the painting has darkened considerably.

Colorimetric imaging

To obtain CIELAB coordinates for the painting in its entirety we had to image *La Grande Jatte* with a colour-managed digital camera. A Jenoptik Laser, Optik, Systeme GmbH eyelike precision M11 digital camera was used. Four Hensel Xenon strobes were bounced off foam-core to provide uniform illumination across the painting.

Two test targets were also imaged, the GretagMacbeth ColorChecker DC (CCDC) consisting of 240 colour patches, and a 60-colour-patch custom target, made using 30 pigments of the Gamblin Conservation Colors applied in mixtures with titanium white at two different ratios. The samples of each target were measured using the SpectroEye and CIELAB coordinates calculated for the 1931 CIE observer and illuminant D50. The colorimetric and camera data of the CCDC were used to create an ICC (International Color Consortium) colour profile. The mathematical transforms consisted of three non-linear functions

accounting for the Tiff file encoding and a linear matrix. (See Berns (2000, 2001) for a numerical example.) Comparisons are listed in Table 1. The performance was reasonable and typical of this type of camera and method of profile generation.

Table 1. Colorimetric accuracy of the camera colorimetric characterization

Target	Mean ΔE_{00}	Maximum ΔE_{00}	Standard deviation ΔE_{00}
ColorChecker DC	1.9	13.7	1.8
Gamblin	2.4	7.1	1.6

'Un-ageing' *La Grande Jatte*

The optical behaviour of *La Grande Jatte* was modeled using Kubelka–Munk turbid-media (KM) theory (Nobbs 1985, Berns 2000). The yellowing and darkening (that is, ageing) due to the variation of the absorption and scattering properties of the paint surface causes a reduction of the maximum reflectance factor across the entire painting. From the perspective of using KM theory, this optical effect can be related to an 'ageing spectrum' so that the overall painting can be un-aged by removing this factor, in the same way as one could remove a specific material from a mixture to achieve a specific colour:

$$\left(\frac{K}{S}\right)_{\lambda, \text{un-aged}} = \left(\frac{K}{S}\right)_{\lambda, \text{in-situ measurement}} - \left(\frac{K}{S}\right)_{\lambda, \text{ageing spectrum}} \quad (1)$$

where $(K/S)_{\lambda}$ is the KM absorption (K) and scattering (S) ratio and $(K/S)_{\lambda} = (1-R_{\lambda})^2/2R_{\lambda}$ where R is the decimal fractional reflectance at wavelength, λ .

The measurements shown in Figure 1 were used to calculate the ageing spectrum. It was assumed that the ageing spectrum was equivalent to the $(K/S)_{\lambda}$ of the in situ pure lead white scaled by a factor such that when subtracted from the in situ measurement, it resulted in the identical lightness to the fresh lead white paint out. This ageing spectrum could be added to the spectra of fresh pigments to 'age' them in a similar fashion to how Seurat's palette has aged and more importantly, could be subtracted from in situ measurements to un-age the overall appearance of the painting. The CIELAB coordinates for the fresh, in situ and mathematically un-aged lead white are listed in Table 2. Un-ageing the in situ lead white has made it lighter and less yellow, the expected colour change.

Table 2. CIELAB coordinates of lead white.

	Fresh lead white	In situ lead white	Un-aged in situ lead white
L^*	97.13	82.12	97.13
a^*	0.14	0.52	0.06
b^*	2.12	7.44	1.35

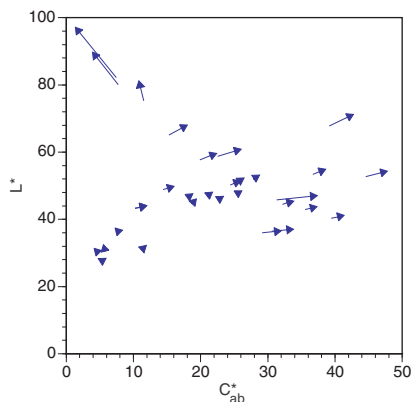


Figure 2. CIELAB difference vectors comparing in situ measurements before (located by the end of the arrow) and after (located by the arrowhead) un-ageing (Equation (1))

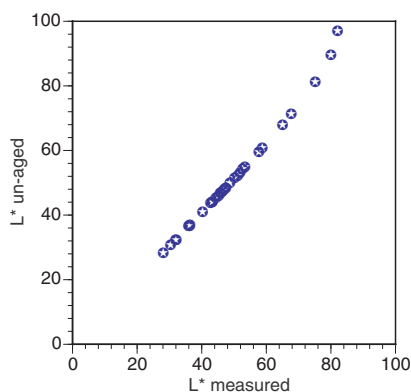


Figure 3. Scatter plot of lightness comparing in situ and un-aged in situ measurements

The in situ spectral measurements were un-aged and CIELAB L^* and C^*_{ab} coordinates calculated, plotted in Figure 2. For pale colours, there was a significant colour change: colours became much lighter and less yellow. For medium-chroma colours, there was an increase in chroma and a slight increase in lightness. For dark colours, there was minimal change.

Scatter plots of the CIELAB coordinates before and after un-ageing revealed clear systematic effects for the range of colours contained in *La Grande Jatte* (see, for example, Figure 3). These relationships were modeled empirically, and used to create one-dimensional look-up tables that could be accessed by Adobe Photoshop as custom curves.

'Un-darkening' the spectra of dots containing zinc yellow

In concept, dots containing the darkened zinc yellow could be 'un-darkened' by replacing the unstable yellow with a yellow that only underwent expected ageing, such as the other paints on Seurat's palette. Several complications immediately arose. First, what were the spectral properties of Seurat's zinc

yellow? Second, what was the colour strength of Seurat's yellow and when it was used in mixtures with either emerald green or vermilion, what were the various concentrations? Finally, how does the colour of underlying layers affect our perception of the uppermost brushstrokes? One might imagine that these questions could be answered by taking samples and analysing them. Although useful for providing compositional information, it is extremely difficult to relate microscopic analyses to macroscopic reflection properties; moreover, it is unfeasible to take a sample of every darkened dot. The approach taken was to use KM theory as an analytical tool to determine the amount of darkened zinc yellow and the proper amount of fresh zinc yellow as the replacement.

As the research proceeded, we recognized that, ideally, the paint outs of fresh chromatic pigments should have been made on a substrate with the same colour as the first campaign grass, instead of a white support. To account for this, KM theory and nonlinear optimization was used to synthesize a spectrum with the same CIELAB coordinates as the average colour of the sunlit grass, where pigment analysis revealed that Seurat used chrome yellow, emerald green, and lead white. Changes in opacity were modeled by using a blending function:

$$\begin{aligned} \left(\frac{K}{S}\right)_{\lambda, \text{translucent}} &= \beta \left(\frac{K}{S}\right)_{\lambda, \text{fresh}} + (1 - \beta) \left(\frac{K}{S}\right)_{\lambda, \text{background}} \\ 0 \leq \beta \leq 1. \end{aligned} \quad (2)$$

A $\beta = 1$ corresponded to opacity. Changes in this constant result in various amounts of show-through. The optimal constant would depend on how thickly paint was applied by Seurat as well as the inherent opacity of his paints. 'New' paint outs were simulated at two opacities, β of 0.75 and 0.5.

As seen in Figure 4, the fresh and darkened zinc yellows absorb light strongly below 470 nm, resulting in low reflectance. Changes in concentration or tinting strength change the amount of light absorption, by definition, predominantly in this wavelength region. This principle enabled the estimation of the strength of Seurat's zinc yellow. The fresh zinc yellow was scaled so that its spectrum when added to the aging spectrum most closely matched the average in situ yellow spectrum between 380 and 470 nm. That is, we determined the concentration of fresh yellow that minimized the sum-of-square spectral difference to the average in situ darkened yellow, as shown in Equation (3) for $\beta = 0.75$:

$$\begin{aligned} \left(\frac{K}{S}\right)_{\lambda, \text{un-darkened}} &= c_{\text{yellow}} \left(\frac{K}{S}\right)_{\lambda, \text{fresh}} + \left(\frac{K}{S}\right)_{\lambda, \text{ageing}} \\ & \quad \beta=0.75 \quad \text{spectrum} \\ \text{Minimize} \left[\sum_{\lambda=380-470} \left\{ \left(\frac{K}{S}\right)_{\lambda, \text{average}} - \left(\frac{K}{S}\right)_{\lambda, \text{undarkened}} \right\}^2 \right]. \end{aligned} \quad (3)$$

The result is shown in Figure 4. This curve simulates an in situ measurement if Seurat's zinc yellow had not deteriorated.

Six dark-green dots were measured spectrophotometrically and the spectra were averaged. Microscopic analyses of samples from these dots revealed that they contained various proportions of zinc yellow and emerald green and, in some cases, small amounts of lead white. Previous analyses indicated that emerald green had not darkened significantly, although it has been reported that emerald green can also darken over time (Fiedler 1984, Fiedler and Bayard 1997). If only zinc yellow darkened, then it should be possible to match this spectrum by a combination of darkened zinc yellow (obtained by the average in situ measurement of yellow dots), fresh emerald green, fresh lead white, and the aging spectrum:

$$\begin{aligned} \left(\frac{K}{S}\right)_{\lambda, \text{mix}} &= c_g \left(\frac{K}{S}\right)_{\lambda, \text{fresh}} + c_y \left(\left(\frac{K}{S}\right)_{\lambda, \text{average}} - \left(\frac{K}{S}\right)_{\lambda, \text{ageing}} \right) \\ & \quad \beta=0.75 \quad \text{green} \quad \text{in-situ} \quad \text{yellow} \\ & \quad + c_w \left(\frac{K}{S}\right)_{\lambda, \text{fresh}} + \left(\frac{K}{S}\right)_{\lambda, \text{ageing}} \\ & \quad \text{white} \quad \text{spectrum} \end{aligned}$$

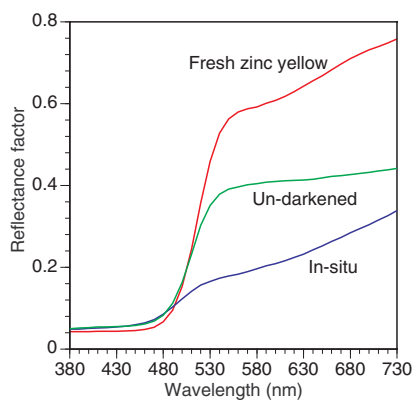


Figure 4. Spectral reflectance factor of fresh zinc yellow oil paint, the average in situ measurement of pure zinc yellow, and the un-darkened zinc yellow at $\beta = 0.75$

$$\text{Minimize } \left[\sum_{\lambda} \{R_{\lambda, \text{average}} - R_{\lambda, \text{mix}}\}^2 \right]$$

in-situ
green

where

$$R_{\lambda} = 1 + \left(\frac{K}{S} \right)_{\lambda} - \left[\left(\frac{K}{S} \right)_{\lambda}^2 + 2 \left(\frac{K}{S} \right)_{\lambda} \right]^{1/2} \quad (4)$$

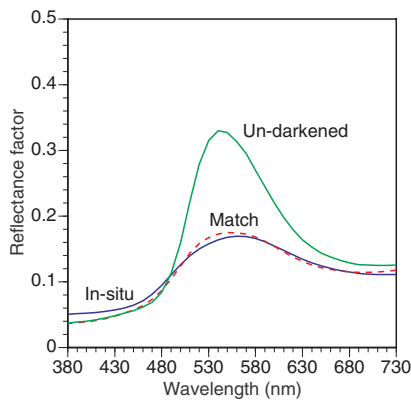


Figure 5. Spectral reflectance factor of the average in situ measurement of green-yellow, its spectral match (Equation (6)) (dashed line), and after un-darkening at $\beta = 0.75$

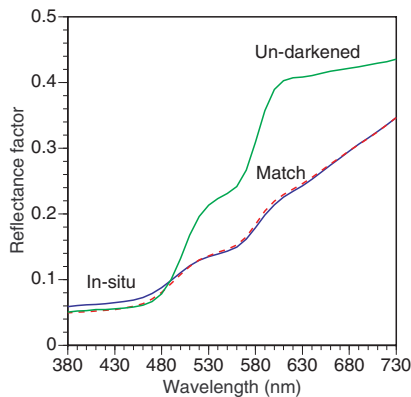


Figure 6. Spectral reflectance factor of the average in situ measurement of orange, its spectral match (dashed line), and after un-darkening at $\beta = 0.75$

Concentrations were determined that minimized sum-of-squared spectral reflectance error. The concentrations were constrained for non-negativity. The result is plotted in Figure 5. The close similarity between the two curves confirmed Fiedler's analyses. The optimization determines concentrations of each constituent. Using the same approach used to un-darkening zinc yellow, an appropriate concentration of fresh zinc yellow with $\beta = 0.75$ was determined. The final spectrum was calculated by adding the appropriate amounts of each constituent, also shown in Figure 5.

The same procedure used to un-darken emerald green and zinc yellow dots was performed on dots containing vermilion, zinc yellow, and lead white, shown in Figure 6. All three optimizations were repeated at an opacity of $\beta = 0.5$. (The purpose for the two opacities is described below.)

Rejuvenating dots containing zinc yellow on images

The CIELAB coordinates of the average dots both before and after un-darkening at each opacity were calculated from spectra listed in Table 3. For each average colour, this shift in colour was described mathematically as a translation. By applying the appropriate translation to each dot containing zinc yellow, the colours could be un-darkened.

Table 3. CIELAB coordinates of the average spectra before and after rejuvenation for $\beta = 0.75$

Colour category	CIELAB coordinates	In situ measurement	Un-darkened	Un-darkened and un-aged
Yellow	L^*	49.63	66.48	69.78
	a^*	3.87	-0.62	-0.72
	b^*	30.71	57.74	62.31
Green	L^*	46.12	57.88	59.89
	a^*	-7.61	-21.92	-24.14
	b^*	22.56	43.99	46.44
Orange	L^*	47.48	58.75	60.85
	a^*	11.27	15.05	17.06
	b^*	24.51	46.36	49.12

For each colour category, there is a range of colours, particularly the green-yellow and orange dots. As mixtures, the proportions varied quite a bit, confirmed by microscopic analysis. Depending on the thickness and opacity of a dot, the colour varied. Compositionally, a range of colour was expected. The translation operation maintained the colour range. The limitation to this approach was the assumption that the range of colours was independent of the average colour. That is, as colours were un-darkened, they would have the same colour variability. Theoretically, this assumption is false because the range of colours that can be made from pigments have fixed endpoints of black and white. As colours get very dark or light, their range, by definition is reduced. Fortunately, for these three colours, they were neither very dark nor light before and after un-darkening; thus, this assumption was a reasonable one. Furthermore, performing the translation on the CIELAB coordinates rather than the camera signals also improved the rendering since CIELAB has a perceptual basis as well as better linearity than the camera with respect to K/S.

The data in Table 3 were used to create six one-dimensional look-up tables that could be accessed by Adobe Photoshop as custom curves. Each un-darkened set of dots as well as the un-ageing curves was a separate adjustment layer.

Adobe Photoshop's magic wand image-selection tool provided the needed precision and accuracy to select each dot, one by one, on the digitized image of

the painting and assign it to one of the six adjustment layers forming image masks. This process took several months and required repeated viewing of the actual painting. The vast majority of darkened dots were categorized at $\beta = 0.75$ opacity although, to some extent, the opacity level was subjective.

Side-by-side comparisons of *La Grande Jatte* before and after digital rejuvenation are shown in Figures 7 and 8. The brushstrokes that Fénéon described as ‘holes’ in the sunlit grass, appearing as a strong speckled pattern, have now blended together with the background colours. The lightness contrast is now a colour contrast where these dots are points of coloured light. The grass has less image texture and is less prominent compared with the figures. Our visual system is much more sensitive to lightness contrast than colour contrast causing the speckled grass to draw our gaze as noted by Fénéon. The overall luminosity of the painting has increased, there is a greater sense of depth because figures are more easily discerned from their backgrounds, and the complementary haloes Seurat painted are more visible.



Figure 7. *A Sunday on La Grande Jatte* – 1884 before (left) and after (right) digital rejuvenation

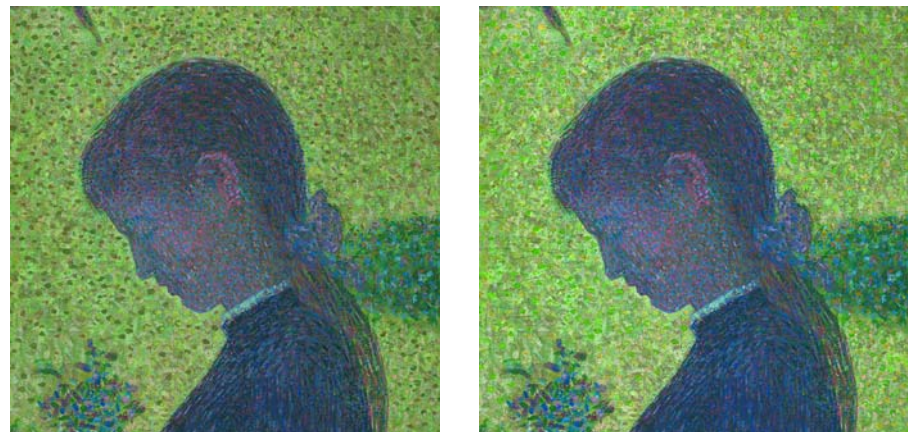


Figure 8. Detail of *A Sunday on La Grande Jatte* – 1884 before (left) and after (right) digital rejuvenation

Conclusions

Colour and imaging science have been used to simulate the appearance of what *La Grande Jatte* looked like during the late 1880s. Although a scientific approach was taken, the results are still speculative. It is clearly evident that the zinc yellow darkened the second campaign divisionist brushstrokes, and that the painting has generally darkened over time. However, it is unclear how closely the un-darkening and un-ageing simulations predicted the actual appearance of the painting. It does seem that the simulations are reasonable and consistent, based on contemporary written accounts of the painting. Despite the unfortunate darkening of zinc yellow, *La Grande Jatte*'s iconic significance is well deserved.

Acknowledgements

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