Reducing image sticking in AMOLED displays with time-ratio gray scale by analog calibration

Dong-Yong Shin (SID Student Member) Jong-Kwan Woo Yongtaek Hong (SID Member) Keum-Nam Kim Do-Ik Kim Myoung-Hwan Yoo Hye-Dong Kim Suhwan Kim **Abstract** — Early loss of image uniformity has been a critical drawback of active-matrix organic lightemitting-diode (AMOLED) displays operated in time-ratio gray-scale mode. This problem is addressed with an analog calibration technique which measures the voltage across each OLED for a given current and subsequently controls the supply voltage of pixels and the voltage drop across the driving thin-film transistor (TFT) of each OLED. The uniformity of test cells, which were aged to produce image sticking in a chessboard pattern, were improved. A measure of image sticking, called the extracted imagesticking value (EISV), was formulated, which is developed and used for the quantitative evaluation of the calibration method. OLED voltages over a range of about 0.35 V were compensated to produce more uniform OLED currents than those before aging. The variation of luminance associated with image sticking was reduced by about 40% for a full-white image after between 2 and 10 hours of accelerated aging with a constant voltage of 8 V across an OLED.

Keywords — *OLED*, image sticking, time-ratio gray scale, digital driving, calibration. DOI # 10.1889/JSID17.9.705

1 Introduction

Active-matrix organic light-emitting-diode (AMOLED) displays have several advantages over the more commonly used thin-film-transistor liquid-crystal displays (TFT-LCDs) for mobile applications. These advantages include a wider viewing angle, a thinner panel, and lower power consumption. However, it is difficult to obtain a uniform image on an AMOLED display because the OLED current, to which the amount of light emission in a pixel is proportional, is sensitive to the variation in the current-voltage (I-V) characteristic of a driving TFT. Moreover, an OLED tends to degrade earlier than is appropriate for commercial requirements. The result is so-called image sticking, producing variations in brightness across the image, which reduces the lifetime of a display.¹ Image uniformity and display lifetime are therefore critical to the development of AMOLED display technology.

Various driving methods and pixel circuits have been developed to overcome the sensitivity of the OLED current to the I-V characteristic of the driving TFT.^{2–13} Among them, a time-ratio gray-scale method with a simple pixel circuit comprised of two transistors and a storage capacitor, is known to give excellent image uniformity.^{14,15} In this method, a gray level is produced by turning the OLED in each pixel on or off during each of multiple subframe periods.^{6–9,12} This approach can achieve a very high-resolution AMOLED display with more than 300 ppi because it requires a small number of TFT devices in each pixel and few global signal or power lines across a pixel.¹⁶ The power consump-

tion of each pixel is also less than that with analog gray-scale methods,¹⁷ because the voltage drop across a driving TFT is much smaller. However, the excellent image uniformity of the time-ratio gray-scale display declines quickly as its OLEDs age and vary in their I-V characteristics, and image sticking appears earlier than it does with other gray-scale methods in which the OLED current is less sensitive to the I-V characteristic of the OLED. This problem with the time-ratio gray-scale method occurs because the driving TFT connected to each OLED serves as a switch to deliver the supply voltage and cannot keep the OLED current constant as the OLED I-V characteristic varies.

It is possible to compensate for image sticking by continuous digital calibration. This involves estimation of OLED degradation by repeated monitoring of the video data, bit-depth expansion of the time-ratio gray scale, and reassignment of gray levels to each pixel. However, this form of monitoring requires additional memory. Even if the degradation of each red, green, and blue subpixel were to be estimated simply by counting the number of frame periods during which light is emitted all the time, a memory space of 16 bits per subpixel would not be sufficient to monitor just for 20 minutes. Moreover, expansion of the bit-depth implies expansion of the frame memory and requires a faster and more complicated driving method. These factors undermine the effectiveness of the digital-calibration approach.

We have previously proposed an analog method of calibrating the supply and data voltages, which can keep the OLED current uniform across a display panel. This method

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D-Y. Shin is with Seoul National University and Samsung Mobile Display, Korea.

J-K. Woo, Y. Hong, and S. Kim are with Seoul National University, Department of Electrical Engineering, Kwanak P.O. Box 34, Seoul, 151-600, Korea; telephone +82-2-880-9571, fax +82-2-871-3284, e-mail: suhwan@snu.ac.kr.

K-N. Kim, D-I. Kim, M-H. Yoo, and H-D. Kim are with Samsung Mobile Display, Korea.

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involves measurement of the OLED voltage for a given OLED current (I_{ON}) , adjustment of the negative supply voltage of the pixels (V_{cathode}), and individual control of the voltage drop across a driving TFT when an OLED is on. It also includes a reverse bias operation which restores the I-V characteristics of the OLEDs.¹⁸ Simulation results suggested that a longer time to image sticking may be attainable with this analog calibration method. In this paper, we present an improvement on this earlier method, a performance measure to evaluate image sticking, and experimental results obtained from test cells with real devices. In this improved method, the positive supply voltage of a pixel (V_{DD}) is kept constant, rather than being switched, which reduces the complexity of the control logic and eliminates the extra time and energy previously required to charge a bypass capacitance.

2 Modified analog calibration method

select

A conventional OLED pixel circuit for the time-ratio grayscale method comprises two TFTs, a storage capacitor, and an OLED. To support calibration, a switching TFT (M3) is

bration. In Fig. 1(b), the measured OLED voltage corresponds to a point where the load line of that OLED crosses a horizontal line of I_{ON} . The OLED load line also determines the OLED current where it crosses the load line of the driving TFT. Decreased OLED current of the most degraded OLED is restored by adjusting $V_{cathode}$, and on-currents of the less-degraded OLEDs are adjusted by individually controlling the voltage drop across a driving TFT, as shown in Figs. 1(b) and 1(c).

Our new analog calibration method implements the above-mentioned technique and comprises three operations, which are shown in Fig. 2 and described below.

added to the conventional circuit, as shown in Fig. 1(a). The OLED voltage is measured through M3 and used for cali-

(1) Measurement of an OLED voltage for a given I_{ON} : When a display device is powered on, $V_{cathode}$ is set to V_{SS} . All the rows of pixels are then scanned with "select" signals for M2 and OLEDs are turned off by a data voltage of V_{DD} . As a result, each data line is precharged to V_{DD} .



FIGURE 2 — Pixel-circuit operations for the proposed calibration method: (a) measurement of the OLED voltage for a given $I_{ON'}$ (b) calibrated image display, and (c) reverse bias of the OLEDs.



This reduces the time to charge parasitic capacitance of the data line during measurement on the first pixel row. With a current of I_{ON} supplied to each data line, all the rows of pixels are scanned with "measure" signals for M3, as shown in Fig. 2(a). At the same time, the OLED voltages, measured as anode voltages, are sequentially digitized by an analog-to-digital converter (ADC) and stored in an age memory. The relative freshness of each OLED, defined as the difference between its anode voltage and the maximum anode voltage among all the measured anode voltages, is then calculated and the age memory is updated.

Relative freshness
$$= V_{anode, \max} - V_{anode}$$
, (1)

The maximum anode voltage, $V_{anode, \max}$, is also stored in a register.

(2) Calibrated image display: before the image is displayed, $V_{cathode}$ is adjusted to $V_{SS} - \Delta V$, where

$$\Delta V = V_{anode,\max} - V_{DD}, \qquad (2)$$

to compensate for the maximum increase in anode voltage, as shown in Fig. 1(b). During image display, the voltage drop across the driving TFT (M1) that turns on each OLED is individually controlled by reducing the source-gate voltage of M1 (V_{SG}) in accordance with the calibrated data voltage from a digital-to-analog converter (DAC), as shown in Fig. 1(c). The relationship between the relative freshness and the calibrated data voltage is incorporated in a DAC with a non-linear transfer characteristic, which can be implemented by means of a resistor string with several reference voltages. This relationship only depends on the characteristic of the driving TFT and can be measured by sweeping the reference voltages for a constant input to the DAC. With all the M3 TFTs turned off, the image is displayed in the same way as it is in the conventional time-ratio gray-scale method.^{6,8,9} During each subframe period, one bit of the video data is provided for each pixel. If that bit is zero, each bit of the input code to the DAC is one. Otherwise, the relative freshness code (RF code) is the input to the DAC. The DAC output for an input value of 0 turns off the OLED and needs no calibration.

(3) Reverse bias of the OLEDs: After the display period and just before power-off, all the M1 and M2 TFTs are turned off and all the M3 TFTs are turned on. All the OLEDs are then reverse-biased by a data voltage of V_R to restore their *I*–*V* characteristics. A value of V_R which is more negative than $V_{cathode}$ is preferred.^{19,20}

3 Test cell and driver board

3.1 Test-cell design

The proposed analog calibration method was assessed with real devices on a test cell. The test cell was designed to have large pixels so that the current and the area of each pixel may be sufficiently large for accurate current and luminance measurements. A large pixel consists of 1200 subpixels in parallel, each of which has the same size and pitch as those in a 3-in. WVGA (480RGB $\times 800$) panel. Therefore, a largepixel current as 1200 times large as a subpixel current in a real display device is obtained without changing the current density through an OLED for the same voltage levels of signals and supplies.

A merged OLED device is simply obtained by merging the anode electrodes of the individual OLEDs because a single sheet of cathode metal layer is shared by the cathode electrodes of all the OLEDs. A large-area metal of indium tin oxide (ITO) anode layer was designed to have an area of $1643 \times 1646 \ \mu\text{m}^2$ and arranged with narrow spaces of 4 and 7 μ m between each other. The ITO layer was then patterned with a process not verified for such a large area and a small space, and a distribution of shrunken rectangles of OLED area was obtained. This distribution is desirable for the experiment on the distributed *I*–*V* characteristics of OLEDs. As the area of the shrunken rectangle varies, the number of individual OLED devices in parallel varies and so does the *I*–*V* characteristic of the merged OLED device.

The test cell is composed of the large pixels in an 8×8 array, as shown in Fig. 3. For the simplicity of experiments, all the test cells were fabricated as a monochrome display only with green subpixels. A pixel current, *i.e.*, a current through a merged OLED in the pixel is measured while only the single pixel under measurement is turned on. Therefore, there may be a discrepancy between the distribution of measured pixel currents and the distribution of pixel currents of a full-white image. This discrepancy originates from the different supply-voltage (IR) drop for a different image and can be minimized by choosing green subpixels which require less current than red or blue ones. This advantage of the green test cell remains in the measurement of pixel



FIGURE 3 — Test cell in the chessboard pattern for aging experiments. Each square represents a large pixel composed of 1200 subpixels in parallel.

luminance. I_{ON} for a green subpixel was about 200 nA for a V_{DD} of 5 V and a $V_{cathode}$ of 0 V.

3.2 Driver board design

A block diagram of the driver board is shown in Fig. 4. All the signals are controlled by a central processing unit (CPU) in a microcontroller. The select [7:0] and measure [7:0] signals are provided through two 8-bit ports of the microcontroller, and their voltages are shifted by level shifters with adjustable output voltages. $V_{cathode}$ is set by the microcontroller through a 12-bit DAC and an inverting amplifier. The output current of the inverting amplifier is enhanced by a p-n-p bipolar-junction transistor.

During the measurement of an OLED voltage for a given I_{ON} , current sources of I_{ON} are connected to data [7:0] through eight 2:1 multiplexers (MUXes). The anode voltages available at data [7:0] are scaled down by a factor of 1/4 by voltage dividers and transferred to a 12-bit successive-approximation (SAR) ADC via an 8:1 MUX. The input range of the ADC is from 0 to 2.5 V. The whole bits of the 12-bit ADC are utilized to keep the measurable range of V_{anode} wide, even though a fine resolution is required, and it leaves the experiment flexible. However, the bit resolution of the ADC can be reduced if the input range is adjusted to around the V_{DD} and the voltage dividers for scale-down are not used.

During the calibrated image display, non-inverting amplifiers with a gain of 4 and an offset of $-3 V_{os}$ are connected to data [7:0] through the eight 2:1 MUXes. The calibrated input code that is obtained from a look-up table (LUT) is transferred from the microcontroller to the 12-bit

Microcontroller

Memory

resistor-string DACs with a common single reference voltage, via an inter-integrated circuit (I^2C) bus. The output range of the DACs is from 0 to about 2.5 V. Because the 12-bit DACs have a linear transfer characteristic, an LUT is required to achieve a non-linear transfer characteristic. In addition, the whole bits are also utilized to achieve a fine resolution within the range of the calibrated data voltage, while a wide voltage swing of data [0:7] is obtained. If the DACs have a non-linear transfer characteristic and a wider output range, the bit number of the DACs can be reduced, and neither the LUT nor the non-inverting amplifiers are required. For the conventional image display, only two values of the input code are used.

To accommodate a characteristic variation of the test cells, the magnitudes of I_{ON} and V_{os} are controlled by variable resistors in the reference generator and in the offset generator. All the current sources were matched by placing resistors of the same resistance after resistance measurement, to make the uniformity of the current sources comparable to that of a monolithic integrated circuit (IC).^{21,22} For the same purpose, all the resistors of the voltage dividers and those of the non-inverting amplifiers with an offset were also matched to one another, and the input code of each DAC was summed with an offset code for that DAC. When I_{ON} was adjusted to 250 μ A, the maximum current difference between two current sources was less than 0.3% of the average current. Figure 5 shows the differences between the data voltages for the same input code, which were measured after the offset adjustment. The maximum difference for an average data voltage ranges from 2 to 16 mV. This is comparable to the results from monolithic ICs, which are less than 8 mV. 23,24

Two types of LUT were prepared, according to the procedure illustrated in Fig. 6(a), and their contents are plotted in Fig. 6(b). One is based on the current measure-



FIGURE 5 — Differences between data voltages for the same input code. The data voltages from the driver board were adjusted to be uniform across all the channels, to obtain a degree of uniformity comparable to that of a monolithic integrated circuit.

6



Level



FIGURE 6 — (a) Construction procedure of a look-up table (LUT) in three steps and (b) look-up tables obtained by measurement of a single pixel (SP-LUT) and of a full-white image (FW-LUT).

ment of a single pixel (SP-LUT). The other was obtained with a full-white image (FW-LUT). The single pixel was chosen to be at the 4th column in the 5th row, *i.e.*, near the center of the pixel array. The construction procedure of an LUT consists of three steps. First, a current through a set of reference pixels is measured with an RF code of zero, and defined as I_{ON}. Next, V_{cathode} is lowered by increasing its control code. Finally, the DAC input code to turn on the reference pixels is increased until the measured current through them becomes I_{ON} . As a result, V_{SC} is reduced and a calibrated input code is obtained for the relative freshness of the same value as the Vcathode shift. In this way, calibrated data voltages for a display panel can reflect the I-V characteristics of the driving TFTs in that panel. Each of SP-LUT and FW-LUT contains 624 items and has a size as small as 160 bytes. Figure 7 shows a fabricated test cell and its driver board.

4 Experiment on image sticking

An experiment on the capability to compensate for the distributed OLED voltages and relieve image sticking was performed. The test cell was aged with an 8×8 chessboard pattern in acceleration, and the pixel current and luminance of each large pixel were measured after every 2 hours of the accelerated aging. Each OLED was aged under a constant



FIGURE 7 — Test cell driven by the driver board of Fig. 4. Beneath the vacuum-fluorescent display (VFD) is a microcontroller. The test cell is under accelerated aging.

voltage of 8 V and turned on with a 5-V supply voltage during measurements. Even though a luminance difference as small as 2–3% is noticeable,^{25–27} the experiment was performed until the non-uniformity of image after compensation reached a value larger than 10%. The release time between the accelerated aging operations was not controlled, and the restoration operation was not performed.

4.1 Measured anode voltage, pixel current, and pixel luminance

Pixel currents of the conventional method and those of the proposed method with the SP-LUT are shown in Figs. 8(a) and 8(b), respectively. These currents correspond to the measured OLED anode voltages shown in Fig. 8(c). Such a wide distribution of the anode voltages was obtained by using narrowly spaced large-area ITO rectangles for the anode electrodes of merged OLED devices, as described before. Uniformity improvement by the proposed method is apparent. The proposed method with the FW-LUT produced very similar results to those in Fig. 8(b). This suggests that current measurement on more than a single pixel (SP-LUT) is not required for constructing an LUT. In other words, the *I–V* characteristic of the driving TFT in a real display panel may be represented by a measured characteristic of a small group of subpixels such as a single large pixel. The proposed method has been tested for the anode voltages distributed over a range of about 0.35 V, although the variation in the



FIGURE 8 — (a) Pixel currents obtained from the conventional method, (b) pixel currents from the proposed method with the SP-LUT, and (c) anode voltages for an OLED current of I_{ON} with reference to the anode voltage of pixel number 0. These quantities were repeatedly measured after every 2 hours of accelerated aging. The pixel number is 8× (row number) + (column number).

I-V characteristic of the driving TFT was restricted by the parallel combination of 1200 subpixels. For a pristine test cell, compensation for the distributed OLED voltages is not required since there is no image sticking. The pixel currents of a pristine test cell are included in Fig. 8(a) and designated by 0 hours. Each pixel current was measured via a V_{DD} line while only the pixel under measurement was turned on by a data voltage of interest.





FIGURE 9 — (a) Full-white image obtained with the conventional method, (b) a full-white image obtained with the proposed method using the SP-LUT, and (c) a full-white image obtained by manual compensation. As a reference to assess image sticking, an image with hardly noticeable image sticking was prepared after each aging period by setting the input codes manually.

(c)

On the other hand, the image sticking in a display panel driven by the conventional method was also apparently reduced by the proposed analog calibration method, as



FIGURE 10 — (a) Measured luminance values after 4 hours of accelerated aging (*ML*), (b) normalized luminance values estimated with respect to the extracted reference luminance values (*NL_E*), and (c) comparison of performance measures for image sticking. The *NL_I* represents the normalized luminance based on initial luminance. The extracted image-sticking value (EISV) of this work is more consistent with the images in Fig. 9 than the image-sticking value (ISV) of the prior publications. The pixel number is 8× (row number) + (column number).

shown in Figs. 9(a) and 9(b). The measured luminance values after 4 hours of accelerated aging are presented in Fig. 10(a). The luminance of each pixel was measured with a spectroradiometer while that pixel alone was turned on. Within the allowable luminance levels that avoid a zeropoint shift in the spectroradiometer, the light-emitting area of a large pixel was smaller than the area required to obtain

an absolute value. Therefore, the measured luminance values are described in arbitrary unit (a.u.) even though they were read in cd/m^2 . To quantitatively compare the results from the conventional method and those from the proposed method, a method of estimating the extent of image sticking was developed, as explained in the next subsection.

4.2 Measure of image sticking

Several methods have been published for the quantitative evaluation of image sticking. Some of them take the longrange non-uniformity (LRNU) of a displayed image into account and utilize a chessboard pattern to assess the image sticking.²⁷⁻²⁹ In those methods, the initial luminance of each pixel is measured before aging and used as a reference for normalizing subsequent luminance measurements. The LRNU pattern is removed by normalization. Each measured luminance is normalized by dividing it by the reference,^{27,28} or by subtracting the reference from it.²⁹ An image-sticking value (ISV), which is larger for severer image sticking, is then estimated with the normalized luminance measurements. In our experiment, however, the LRNU pattern was changed by the proposed calibration method, and therefore the initial luminance was not appropriate for the reference. When estimated with the initial luminance, the ISV of unrelieved image sticking [Fig. 9(a)] was smaller than that of compensated one [Fig. 9(b)], as shown in Fig. 10(c).

To evaluate image sticking consistently, without regard to the change in LRNU pattern, we developed a new method to extract a set of references from the measured luminance values. During aging with a chessboard pattern, the OLEDs in white pixels are stressed to degrade while those in black pixels are released. As a result, the luminance distribution of the black pixels may not be affected by aging process. In our extraction method, each black pixel is defined as a reference pixel and the luminance when it is turned on becomes its reference luminance. By a simple interpolation, the reference luminance for a white pixel is calculated as the average of reference luminance values of the four adjacent black pixels. Naturally, the number of the adjacent black pixels must be reduced to three at the edge of the pixel array and to two at the corners. All the reference luminance values are scaled after extraction so that the average of them equals the average of the measured luminance values. The reference luminance values obtained in this way were used for the normalization. In our experiment, normalization by division or that by subtraction made no significant difference when the LRNU pattern was removed with the extracted references. Figure 10(b) shows the normalized luminance values obtained by dividing the luminance values in Fig. 10(a) by the extracted reference luminance values.

In prior publications, an ISV for quantitative evaluation of image sticking has been defined as

$$ISV = 1 - NL_{\min}/NL_{\max},$$
(3)

in terms of the maximum $(NL_{\rm max})$ and minimum $(NL_{\rm min})$ values of the normalized luminance.^{26,27,29} To provide a reference to assess image sticking, an image with hardly noticeable image sticking, such as that shown in Fig. 9(c), was prepared after each aging period. This was achieved by a manual calibration, in which the image uniformity was monitored by human eyes. Estimation with Eq. (3) did not effectively discriminate these images from the images compensated with the SP-LUT or FW-LUT. In Fig. 10(c), the "1-min/max" value of the normalized luminance based on extracted reference (NL_E) for the manually compensated image [Fig. 9(c)] is larger than that value for the image compensated with SP-LUT [Fig. 9(b)].

By using the coefficient of variation, which is commonly used in dispersion comparison,³⁰ instead of Eq. (3), and combining it with the reference extraction method, we have derived a new measure for image sticking, refered to as the extracted image-sticking value (EISV). The EISV is expressed in terms of the standard deviation (σ_{NL}) and average (μ_{NL}) of the normalized luminance:

$$EISV = \sigma_{NL} / \mu_{NL} \,. \tag{4}$$

As shown in Fig. 10(c), normalization with respect to the extracted reference values correctly represents the reduction in image sticking achieved by the proposed calibration method, and application of Eq. (4) presents a quantity consistent with a further reduction in image sticking achieved by manual calibration. The EISV can also be applied to current measurements as well.

4.3 Quantitative evaluation of image sticking

Estimated EISVs are shown in Fig. 11(a) for current and in Fig. 11(b) for luminance. Before aging, no calibration was applied since there was no image sticking. Therefore, initially, the proposed method produces the same EISV as the conventional method. Subsequent EISVs for current show that the proposed method effectively compensates for the non-uniform currents caused by the distribution of OLED voltages up to about 0.35 V. The EISV of the proposed method with either the SP-LUT or the FW-LUT remained below 1.1% for 10 hours of accelerated aging, whereas the EISV of the conventional method reached 6.18%. With the SP-LUT, the EISV after 10 hours is 0.65%, even less than 0.86% of the conventional method before aging.

In terms of luminance, the reduction in image sticking was less effective because of the degraded luminous efficiency of the aged OLEDs. The EISV of the proposed method with the SP-LUT reached 9.7% after 10 hours, while the figure for the conventional method was 16.4%. The EISV of the proposed method with the FW-LUT reached 9.23%. The proposed method with the SP-LUT and that with the FW-LUT have similar EISVs for current and luminance at all time steps. This implies that basing an LUT on current measurements of a single pixel (SP-LUT) is sufficient for the compensation. To overcome the degradation



FIGURE 11 — Quantitative evaluation of image sticking using extracted image-sticking value (EISV) (a) for current and (b) for luminance. The EISV was subsequently estimated after every 2 hours of accelerated aging.

of luminous efficiency, the currents of the OLEDs with large OLED voltages can be enhanced by increasing the relative freshness (RF) in Eq. (1) and ΔV in Eq. (2) by a certain factor for each, as follows.

$$(\Delta V)_{\text{modified}} = (\Delta V)_{\text{measured}} \times (1 + \alpha/100),$$
 (5)

$$RF_{\text{modified}} = RF_{\text{measured}} \times (1 + \beta/100).$$
 (6)

When α and β were set to 40 and 100, respectively, the EISV for luminance of an aged test cell was reduced from 10.2 to 8.0%.

5 Conclusions

We have presented an analog calibration method to reduce image sticking in AMOLED displays with time-ratio gray scale. A new estimate of image sticking, refered to as the extracted image-sticking value (EISV), has also been provided for quantitative evaluation. With the EISV, we could evaluate image sticking without regard to the change of long-range non-uniformity pattern. Experiments with test cells demonstrated a significant improvement in the uniformity of the pixel current by the proposed analog calibration method. Various OLED voltages over a range of about 0.35 V were compensated to produce uniform OLED currents with an EISV less than 1.1%. Consequent improvement in the uniformity of pixel luminance and reduction in image sticking were also observed. Image sticking was reduced by about 40% for a full-white image, when estimated as an EISV for luminance, after between 2 and 10 hours of accelerated aging with a constant voltage of 8 V across an OLED.

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