

# HANS – A New Color Separation and Halftoning Paradigm

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## Abstract

Traditionally the choices made by color separation are expressed as amounts of each of the available colorants to use for each of the reproducible colors. Halftoning then deals with the spatial distribution of colorants, which also results in the nature of their overprinting. However, having a colorant space as the way for color separation to communicate with halftoning gives access only to some of the possible printed patterns that a given printing system is capable of and therefore only to a reduced range of print attributes. In the present paper a method – HANS – is proposed to gain access to all possible, printable patterns by specifying relative area coverages of a printing system’s Neugebauer primaries instead of only colorant amounts. This results in delivering prints with more optimal print attributes than were possible using existing methods, allowing for up to 34% less ink use while delivering a 10% greater color gamut on a test printing system using CMYKcm inks.

## Introduction

Print is the result of a number of colorants of different colors being superimposed on top of a substrate. Since the majority of printing technologies only allow for a very small number of levels of ink to be deposited at a given location on a substrate, halftoning is used to obtain ink patterns that result in a given color when seen from an appropriate viewing distance. These halftone patterns also result in inks being deposited on top of or next to one another in a specific way, giving a color that relates non-linearly to the amounts of the inks used.

How much of an ink to use is the result of color separation, where ink amounts are chosen for each printable color. This is preceded by color management, where a choice of color reproduction objective (e.g., accuracy or pleasingness) can be made, where differences between the color gamuts of source content and the destination printing system are dealt with and where a color characterization of a printing system is employed with the aim of accurately rendering the chosen color reproduction objective

Early color separation methods for three-ink printing systems, used since the late 19th century,<sup>1</sup> involved the photomechanical construction of halftone patterns by filtering a projection of an original image through a set of color filters, each determining how much of a cyan, a magenta and a yellow ink to use, and then through a halftone screen, which resulted in the formation of dots of proportional sizes on the three printing plates. Here color separation filters determined ink amounts while halftone screens resulted in corresponding per-ink patterns, which were finally superimposed. The effectiveness of such methods was relatively limited given their very indirect control over the resulting printed patterns and therefore colors.

Such control was significantly increased when computational color reproduction was pioneered during the first half of the 20th century. Here Neugebauer’s model of halftone color reproduction<sup>2</sup> was key, which in its simplest form states that the color of a halftone pattern is the convex combination of the colors (i.e., CIE XYZs<sup>3</sup>) of the Neugebauer Primaries (NPs) used in it. Here an NP is one of the possible ink overprints, with its convex weight being the relative area covered by it (Fig. 1).

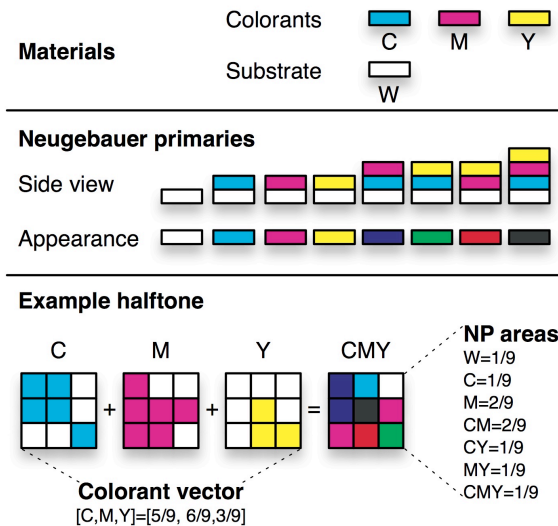


Figure 1. Relationship between print materials (top), resulting Neugebauer Primaries (center) for a three-colorant, bi-level printing system and an example of how colorant amounts and Neugebauer Primary area coverages relate in a halftone (bottom).

The Neugebauer model enabled much tighter control over a printing system and was used as follows: For each color to be reproduced, find the amounts of inks, which, when halftoned using a given halftoning method, match that color. This involves having a model of the halftoning method, which for given ink amounts predicts corresponding NP area coverages. Having measured the NPs and using the Neugebauer model, a prediction can then be made of the resulting color from the NPs’ colors and their area coverages. Using these two models in reverse, appropriate ink amounts can be obtained for in-gamut colors. Broadly the same principle is employed even in the most recent color separation approaches<sup>5-9</sup> and halftoning techniques.<sup>4, 10-15</sup> A key to the success of such color separation is the accuracy of the model used and there have been numerous improvements here since the Neugebauer model’s introduction in 1937.<sup>2,16-21</sup>

In the above approaches, color separation and halftoning communicate via an ink space where color separation determines amounts of inks to use for a given color and halftoning then constructs patterns that deliver them. However, only certain

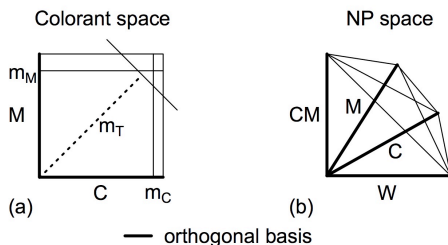
combinations of Neugebauer Primaries are accessible in this way, namely exactly one per ink amount combination. For three inks, the choices are therefore limited to choices in that 3D space, while the full range of NP combinations occupies a  $2^3=8D$  space for a bi-level printing system.

There are examples though in the literature of methods that make color separation choices in the NP domain. Ostromoukhov and Hersch<sup>22</sup> established an analytical tetrahedralization of NP colorimetries while Chosson and Hersch<sup>23</sup> evaluate all possible such NP colorimetry tetrahedralizations and select from among them the one that minimized artifacts for their chosen halftoning technique. These approaches are an important departure from an ink space based color separation and give access to patterns that are otherwise not accessible. Both of them are constrained to using at most four NPs at a time though and are tied to halftoning schemes also having such constraints.

The present paper introduces a new approach to print control where color separation has access to all printable patterns that span the Neugebauer Primary area coverage (NPac) space and where this NPac space connects it to halftoning.

## HANS – Halftone Area Neugebauer Separation

For a two-ink printing system, e.g., using a C and an M ink, a ink vector approach results in some part of the two-dimensional CM ink space being accessible. This is delimited by the maximum total ink amount ( $m_T$ ) that does not result in ink-substrate interaction artifacts (e.g., bleeding, coalescence,<sup>24</sup> etc. for ink; peeling, etc. for toner) and the maximum amounts ( $m_C$  and  $m_M$ ) of the two inks by themselves that result in a ink amount – color relationship that is usable (e.g., monotonic) when forming ink vectors (Fig. 2a).



**Figure 2:** Print control spaces for a two-ink (C and M), bi-level printing system: (a) the colorant space and (b) the Neugebauer Primary space.

Each of the ink vectors from the accessible polygon can be specified at a pixel that is an input to the subsequent halftoning. The combined result of the available ink space, the halftoning, the two inks and the substrate is a curved surface in a color space (e.g., CIE XYZ, CIE LAB, etc.), to which input colors need to be gamut mapped.<sup>25</sup>

However, these two inks result in four NPs: W (the blank substrate), C, M and the CM overprint. If more than two levels of ink can be specified at each halftone pixel, then the space is of higher dimensionality still.

Without constraints from ink-media interaction, the accessible part of the NP space is a  $k^D$ -dimensional simplex – i.e., in the bi-level, CM case it has the 100% area coverages of the W, C, M and CM NPs as its vertices (Fig. 2b). The effect of ink-

substrate imposed constraints is the intersection of this simplex with half-planes defined by  $m_C$ ,  $m_M$  and  $m_T$ .

The use of the NP space gives access to any pattern made up of a system's NPs and printed output becomes analogous to mosaics assembled from individual NP tiles. This way of working directly with NP area coverages is akin to the type of control Maxwell exercised by adjusting the angular subtenses (and therefore areas) of differently colored paper sectors on a spinning top<sup>26</sup> to achieve a color, which is the components' convex, area-weighted combination. The same principle underlies halftoning itself<sup>12</sup> and the novelty of the present approach is simply to exercise direct control over the basic building blocks of color halftones – the Neugebauer Primaries.

To illustrate the increased range of patterns accessible to HANS, let us take a particular ink vector:  $[c_C, c_M]=[0.5, 0.5]$  in a space where vector members express ink amounts (and therefore also ink area coverages). From the point of view of the NP space, each, single ink vector corresponds to a continuum of NP area coverage vectors, which satisfy the following constraints:

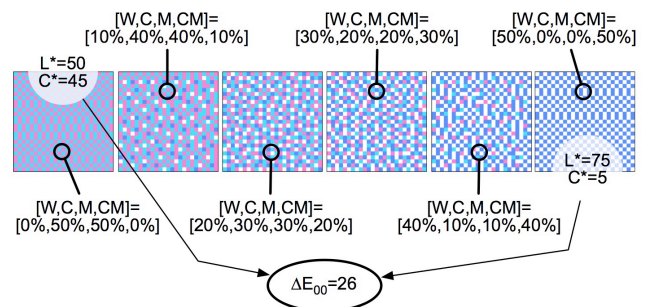
$$a_C + a_{CM} = c_C \quad (2)$$

$$a_M + a_{CM} = c_M \quad (3)$$

where  $a_X$  represents the area coverage of NP X and  $c_Y$  represents the area coverage of ink Y.

Figure 4 shows halftone patterns that match the example ink vector but differ in their NPac vectors and colors when printed on a HP Designjet Z3100 printer on Hahnemühle Smooth Fine Art paper. The extremes of the NPac range differ by 26  $\Delta E_{2000}$  color difference units.<sup>27</sup>

For an ink space approach the halftoning results in one of the patterns shown in Fig. 3, while HANS can access the entire continuum. Direct NP control gives access to metamers (i.e., halftone patterns that differ from one another but result in the same color under given viewing conditions) even when only two inks are used, while ink-based color separation only attains this possibility with four or more inks.

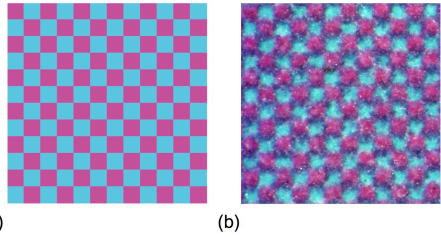


**Figure 3:** Continuum of halftone patterns corresponding to a single colorant vector:  $[c_C, c_M]=[50\%, 50\%]$ .

## NPac – colorimetry model errors

It is important to note that the linearity and convexity referred to above only hold in the NPac space (and do so by definition). Such convexity would only hold in colorimetric space too if digital halftone patterns were exactly matched in a physical print – i.e., ink drops resulted in tessellating squares of uniform thickness and there was no optical or physical dot gain. In all printing systems

there are notable departures from such an idealized state though, as a result of factors like the following (Fig. 4):



**Figure 4:** Differences between a digital halftone pattern (a) and the resulting printed pattern (b) on a HP Designjet Z3100 printer using Hahnemühle Smooth Fine Art paper.

1. Square digital ‘halftone pixels’ result in ink drops making irregular, ellipsoidal shapes on paper, accompanied by satellites (smaller drops that land some way away from the main drop).<sup>28</sup>
2. Ink drops do not tessellate, but instead overlap and result in unwanted NPs.
3. Ink drops do not land where they are meant to and, instead of even a uniform, overlapping structure of ellipsoids, in practice there is error added to the placement of drops.<sup>29</sup>
4. Ink drops are neither of uniform thickness nor of uniform colorimetry.<sup>30</sup>
5. Light filtered by ink drops scatters into the substrate, leading to optical dot gain, whose modeling too may involve errors.<sup>31</sup>

Here the first three types of error may result in color gamut concavity, since printed patterns will have more overlap among inks than is specified, leading to NPs with higher numbers of inks and a less colorful result. Model errors also impact optimizations computed in the NPac space, since they can either lead to some metamers not being considered, potentially limiting the range of output properties, or NPacs being considered as metamers that are not and therefore introduce a color error. Numerous enhancements to the Neugebauer model have been proposed.<sup>23, 32, 33</sup> How they benefit HANS over the Yule–Nielsen modified Neugebauer model used here, will be explored in future work.

The caveats described here clearly have the potential to limit the benefits obtained from HANS. These caveats though are like noise and the difference between ink space approaches and HANS is that while in the former such noise is added to a single pattern per ink vector, with HANS the same noise is added to a vastly greater space of printable patterns. Adding noise can make distinct patterns the same, but it is likely that some of the theoretical benefits will survive it. How much that is the case for a chosen printing system will be shown in the Results section.

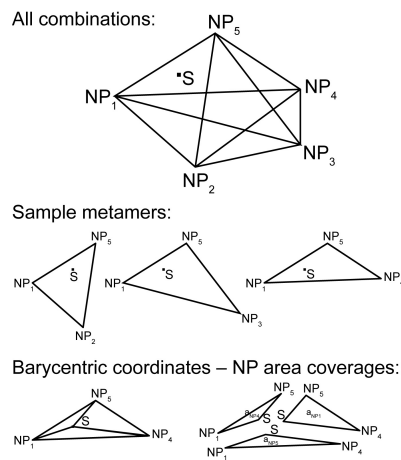
### Outline of HANS color separation

Based on the above NPac paradigm, the following method of computing a color separation to NPac space can be used, assuming no constraints from the colorant–substrate interaction and using the original Neugebauer model:

1. Print and measure all NPs.
2. Compute NP convex hull in CIE XYZ and sample it.

3. For each sample from step 2 compute the corresponding metamer set (Fig. 5).
4. From each metamer set select the NPac that is optimal in terms of the chosen (combination of) print attributes.

The end result is a set of CIE XYZ coordinates that span the full color gamut and where each has an NPac assigned to it. To compute the NPac color separation for an arbitrary, in-gamut CIE XYZ input, the CIE XYZs from step 2 need to be tessellated (e.g., using Delaunay tessellation<sup>36, 37</sup>), the tessellating tetrahedron enclosing the input color needs to be found and barycentric coordinates for the vertex NPacs can be computed. These barycentric coordinates then form an NPac<sub>2</sub> (i.e., a vector whose members specify area coverages for NPac<sub>1</sub>s) with the vertex NPacs, which can finally be re-expressed as an NPac<sub>1</sub> (i.e., a vector whose members specify area coverages for NPs) before proceeding to halftoning.



**Figure 5:** Illustration of metamer sets using 5 NPs in a 2D color space. Top: all triangles formed by NP set; middle: triangles enclosing sample S; bottom: barycentric coordinates and NPac relative area coverages of S in one of the enclosing triangles.

Applying this algorithm to an entire, in-gamut CIE XYZ image will result in a corresponding NPac<sub>1</sub> image, which is then the input to the next, halftoning stage.

### From NPac to Halftone

The HANS halftoning stage maps NPac<sub>1</sub>s to drops per ink (or NPs) per pixel and the halftoning technique that applies most directly is error diffusion.<sup>4, 11, 12</sup>

Here, from each input pixel’s NPac, select a single NP that satisfies a given criterion and distribute the difference between the selected NP and the original NPac<sub>1</sub> among neighboring pixels (Fig. 6). The final result is an image in which each pixel contains a single NP, but, on average, its neighborhood approximates the original NPac<sub>1</sub>.

Changing what region to diffuse the error in, how to diffuse it and what the criterion is for selecting the NP at a given pixel, allows for a range of spatially differing outputs from the same NPac input. E.g., the whole image can be processed sequentially, row by row, in serpentine order, propagating the error with directional weights similar to Floyd–Steinberg and to pick the NP with maximum area coverage specified in the NPac<sub>1</sub>. Alternatively,

make a random choice that follows the area coverage distribution of NPs. This method is slower but better approximates the original NPac<sub>S</sub> for small regions.

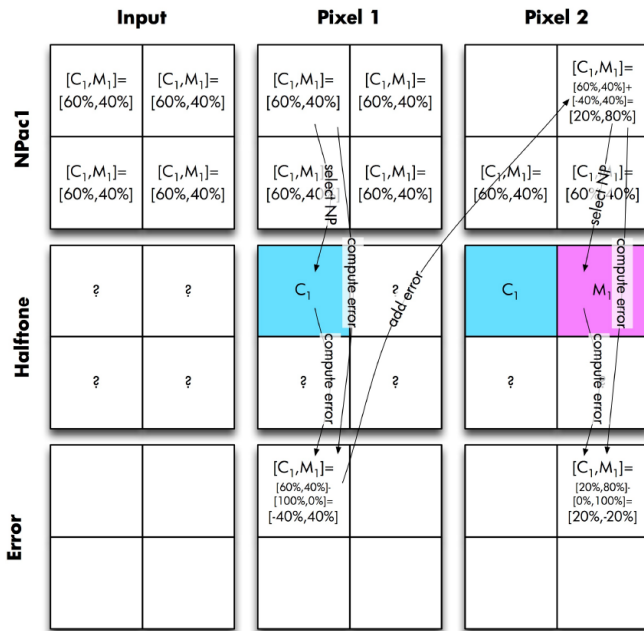


Figure 6: Step-by-step NPED halftoning process that uses maximum area coverage criterion to select the NP to be placed. For the sake of clarity, error is simply added to the next pixel in row instead of using Floyd-Steinberg dithering.

and evaluated in terms of its impact on ink use, which in commercial and industrial printing is a key attribute. The evaluation was performed on a HP Designjet L65500 latex large format signage printer using CMYKcm inks on Avery Glossy Self-Adhesive Vinyl media and comparisons were made between various pipeline configurations possible using current means and an ink use minimizing HANS pipeline. The results of such evaluation are reported in terms of how much ink is used to print a unit area and are shown in Fig. 7.

The results show a 34% saving in ink use versus the current default color separation and profiling settings. Setting the current pipeline's GCR to maximum (i.e., the ICC profiling option leading to least ink use) still results in the HANS pipeline using 20% less ink, which is the level of ink use reduction HANS delivers over and above what commercially available ink-reduction solutions that are constrained to operating in colorant space provide. Note that the HANS pipeline also delivers a gamut increase of around 10% for this system, due to having access to the full NP convex hull (Fig. 8).

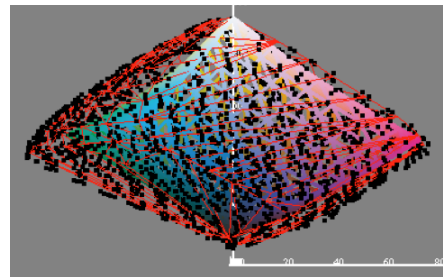


Figure 8: Projection of ISO coated v. 2 (thick, colored wireframe), current (thin, red wireframe) and HANS (black squares) color gamut samples onto CIE LAB a\*L\* plane.

## Results

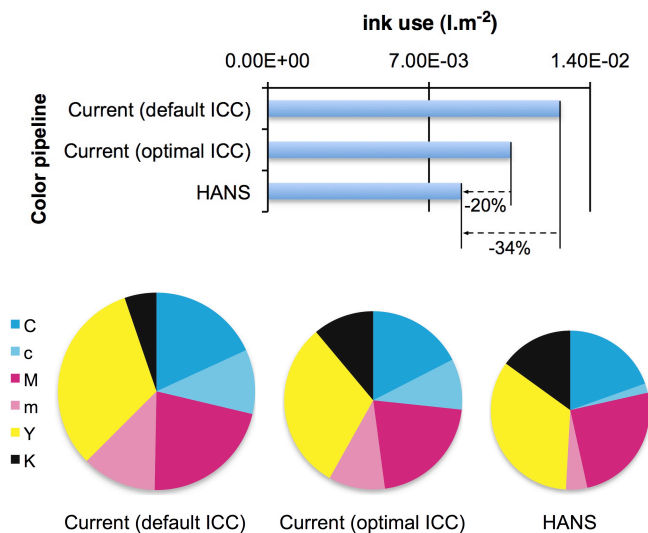


Figure 7: Ink use results of current and HANS pipelines: (top) in l.m<sup>-2</sup> and (bottom) as proportions of the six inks (chart areas correspond to ink use).

A complete color and halftoning pipeline has been implemented on the basis of the HANS principle described above

While the greater degree of K ink use in HANS (Figure 7) is likely to be a result of it having access to a wider variety of halftone patterns, HANS also derives greater benefit from the light inks as a result of obtaining a color separation from explicit optimization instead of only being able to adjust parameters in a fixed algorithm of the current pipeline. Fig. 9 shows how much light ink is used to reproduce each of 748 samples spanning the ISO coated v. 2 gamut and reveals that HANS uses light inks in a very localized way where there are colors for which these light inks are a significant component. This is the case predominantly in those parts of color space where the c and m inks add to the CMYK gamut. The current pipeline, on the other hand, uses light inks for all colors and to a similar extent.

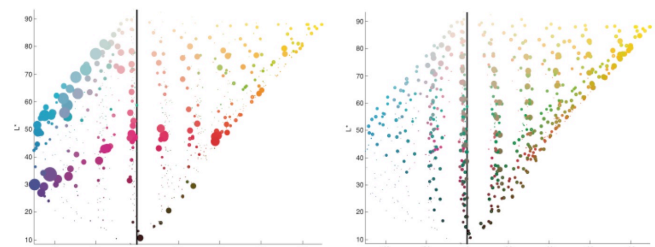
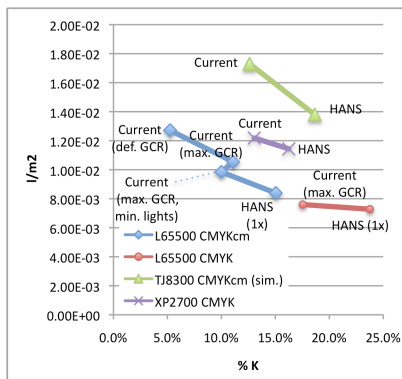


Figure 9: Magnitude of light ink use in HANS (left) and current pipeline with new separation (right) as a function of color space location in projections onto b\*L\* plane in CIE LAB.



**Figure 10:** Image quality comparison between current pipeline at maximum GCR (left) and HANS (right).

A key question raised by the results seen in terms of ink use reduction (and in particular K ink use increase) is whether this comes at an image quality price. To this end the *Altona Visual Test* image was printed on the L65500 using the current pipeline with maximum GCR and using the HANS pipeline and a scan of the result for one of the component images is shown in Figure 10. As can be seen there, and as is confirmed when interviewing observers viewing the original prints, the level of grain exhibited by the HANS print is in most cases lower and at worst the same as the current pipeline's output – however, the HANS print uses 20% less ink. Furthermore the HANS print is more colorful (having a greater color gamut) and sharper.



**Figure 11:** Ink use changes between various current and HANS pipelines on four printing systems.

Since HANS has access to changing what is controlled both by ICC profiles and color separation (i.e., light ink splits in the case of this ink set) in the current separation, a comparison was also made between HANS and a current pipeline that approximates the HANS pipeline's light ink use (Fig. 11). Under these conditions HANS resulted in a 15% saving and a 10% saving was achieved even when the current pipeline was made to use no light inks at all (and resulted in a smaller gamut than that delivered by HANS). Even in the case of a CMYK ink set on the L65500 and using the least amount of ink possible in the current pipeline, HANS can deliver an additional saving of 4.2%. Note also that comparable results were also obtained on other printing systems – the HP Scitex XP2700 and HP Scitex TJ8300 large format printers

– using simulation, which consisted of using the Neugebauer model to predict colorimetry for the result of using a simulation instead of printing and measuring the results as was the case for the HP Designjet L65500. To evaluate the reliability of the simulation approach, it was also applied to the L65500 setup, where it yielded ink use predictions that deviated from measured ones by between -1.3% and +2.4% depending on the specific printing system configuration.

## Conclusions

Halftone Area Neugebauer Separation (HANS) provides full access to the Neugebauer Primary (NP) space, which is vastly greater than the ink spaces used traditionally. This results in benefits like those measured in the experiment reported here, where HANS provided 34% less ink use and 10% more color gamut than an ink space based approach. In addition to greater ranges of print attributes being accessible and directly optimizable, HANS is also fundamentally ink set agnostic, where the same process can be followed to control a duotone or a CMYKRG B printing system.

The focus of future work will be the continued exploration of the benefits of HANS, the use of more accurate printer models and its application to the optimization of new print attributes. Note, that an extended version of the present paper has been submitted for journal publication.<sup>39</sup>

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## Author Biographies

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*Peter Morovič received his Ph.D. in computing sciences from University of East Anglia, UK in 2002 and holds a B.Sc. degree in theoretical computer science from Comenius University, Slovakia. He has been working as Color Imaging Scientist at Hewlett Packard since 2007. He has published 40+ journal and conference articles and his research interests include computer vision, color reproduction, image processing and computational geometry. Dr Morovič received the IS&T’s Raymond Davis Scholarship (2001) as well as a JSPS Post-doctoral Fellowship (2005).*

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