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Printing with light: daylight–fluorescent inks for large-gamut multi-color printing

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Abstract

With printing technologies continuously reaching ever higher degrees of performance and quality, the need for novelty and impact and also keeps increasing. Specialty inks have always played an important role here, albeit not without challenges. Often the use of such materials involved dedicated solutions that deal with these inks outside of the constraints of normal pipelines and workflows, which constrains their application and results in limited use. This is so since specialty inks, such as fluorescents, behave differently to traditional dye or pigment-based ones. So much so that most applications use specialty inks as spot colors, explicitly determining (by means of a separate layer in the input) where they are to be used for given content. For example, for materials such as fluorescents or quantum dots, the possibility of presenting more light at a given wavelength than is incident at that wavelength, breaks some of the basic assumptions of current processes, from how they are measured to how they can be used in building color separations all the way to how color management deals with them. In this paper we describe first experiments of using fluorescent inks that are activated by visible – instead of the more customary UV – radiation, showing performance of spectrophotometer measurement with a dedicated model to handle the specific properties of these inks, as well as results of the impact such inks can have on extending color gamuts that go significantly beyond current printing gamuts and therefore also pose new challenges.

Introduction

Which colors can be reproduced or produced in print depends on a printing system's color gamut, which in turn is the result of the material properties of the inks and media it uses, the writing system it employs and the printing pipeline that makes choices about what ink (and ink overprint) combinations to use in response to a given color input. The larger a printing system's gamut the greater a variety of colors it can potentially match, the more impactful its prints' appearance can be and the more effective it can be in conveying creativity or the more powerfully it can transmit a message. While many of the components of a printing system that contribute to its color gamut have seen significant advances, the colors of inks used in printing have reached a limit, which is also apparent from the largest color gamuts having remained essentially unchanged over the last 10 years.

An underlying cause of such a plateauing is that the basic principle of color formation in print is approaching its limits. Being constrained by exercising control only over how much incident radiation to reflect versus absorb at each wavelength in the visible range of electromagnetic radiation means that the brightest printable color is the unprinted, blank substrate and that secondaries are necessarily darker than primaries (since they combine the absorptions of constituent primaries).

Photoluminescent materials, such as quantum dots, laser dyes or fluorescents, can absorb electromagnetic radiation from one wavelength range and emit it in another. Effectively, energy can be translated: one range of wavelengths absorbs energy and a different range emits it, with the effect that an inked surface is perceived as emitting light, since it has a brightness that exceeds that of the blank, uninked substrate (Figure 1a). Photoluminescent materials have been employed in printing in the past in the form of additives to existing, conventional inks, e.g., by taking a magenta ink and adding fluorescing agents to it, to boost its brightness and colorfulness. Such approaches, however, have a serious limitation, in that the illumination that the photoluminescent material is able to effectively modulate, is also modulated (and absorbed from) by the conventional ink colorants. The end effect is only a moderate improvement to the preexisting ink's color, which can lead to a visual impact that may be only just perceptible in complex, photographic images.

Another example are systems like the Seiko IIT ColorPainter W series printers [7], where flurorescent pink and yellow are used as process colors, but which has not seen broad adoption. In the same category is the study by Rossier and Hersch [1], where fluorescent magenta and yellow inks are added to an existing CMYK ink set, but where only limited benefits are reported, with the resulting gamut not exceeding the lightness of the unprinted media.

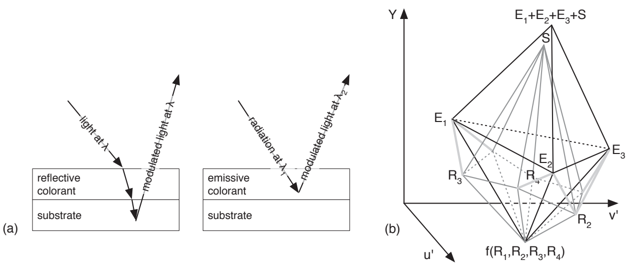

Figure 1: (a) Reflective versus emissive color formation, (b) a hybrid emissive-reflective gamut.

Using photoluminescent materials as the sole colorants of new inks, and adding them to existing, reflective, ink sets, instead yields a hybrid system (from the perspective of color formation), where the reflective inks provide a broad set of dark colors, while the emissive inks give access to a wide, light color gamut (Figure 1b). However, such a system poses a serious challenge to the imaging pipeline and faces obstacles in terms of how to make the two types of inks co-exist – an obstacle side-stepped by Rossier and Hersch [1], where a priori pairings of inks were pre-defined, but where access to all possible combinations of the ink set was sacrificed. As part of our solution, the question of how to handle such fundamentally different inks so that the union of their gamuts could be accessed, has led to the use of the Halftone Area Neugebauer Separation (HANS) pipeline [2].

Using HANS, color formation is managed as an area-coverage weighted average of Neugebaur Primaries, which are combinations of the system's colorants specified at a single halftone pixel. E.g., the overall color, or spectrum, of an area of a halftone, where half is covered with one NP and half with another, is the linear, area-coverage-weighted average of the two NPs' colors. Thus, a system with emissive and reflective primaries can be controlled analogously and regardless of the constituent inks' color formation principles. Furthermore, since fluorescent inks interact strongly with others, the ability to control whether they combine (overprint) or not (remain side by side) is critical and a lack of such control means that the effect of quenching, whereby the fluorescent effect is impacted or eliminated due to interactions with other materials, impedes the pipeline benefitting from the full effect. The HANS print-control paradigm has this ability natively at its disposal. NPs that would result in quenched fluorescent effects can be avoided altogether while those that have the desired effect can be given prominence [3].

Finally, an important consequence of using HANS here is the convexity of the total volume of available colors or spectra, which delivers a union of what each of the reflective and emissive inks could address separately. By adding the ability to accurately predict the color of a stack of ink drops, where some are emissive while others are reflective, existing HANS solutions for building color separations and applying them can be used, once checks for reflectances not exceeding 100% (which are good sanity checks in the reflective case) are removed. Such an extension of the color model can be obtained by complementing the subtractive color formation modeled using the Kubelka-Munk, Yule-Nielsen, Neugebauer and T-matrix models [4] by a simple, spectrally-additive mechanism.

In this paper we describe results of characterizing the available color gamut of a printing system that combines both traditional, reflective primaries as well as fluorescent ones. Since the measurement of these samples requires particular attention, we also describe a method to use standard spectrophotometers, not designed to measure fluorescent materials, to do so via a predictive spectral model. We conclude by highlighting challenges in color management that follow from a pipeline that natively uses fluorescents as process colors and therefore results in unusual color gamuts that can exceed (in certain parts) the object color solid.

Hybrid Color Gamut

The photoluminescent material we focus on for the sake of determining our solution's feasibility is the Rhodamine B organic dye at 0.25% concentration. An important feature of Rhodamine B is that it's fluorescence is activated by visible radiation (i.e., light) instead of using the more typical UV activation mechanism, meaning that the excitation wavelengths as well as emission wavelengths both lie within the visible range of the electromagnetic spectrum and therefore the effect of fluorescence can and does occur under daylight illumination (e.g. CIE D50) (Figure 2). As a consequence, the fluorescent effect – and the results reported in this paper – comes about even when prints are viewed under light sources that emit no UV radiation.

Note that this dye is already in common use at higher concentrations, where its fluorescence is quenched by itself and the effect on color gamut highly dampened. Figure 3a shows a comparison of this Rhodamine agent in a clear carrier fluid, compared against a 12-ink photo printer's gamut (the HP DesignJet Z3200) inkjet printer. The spectral reflectances of both a standard magenta ink as well as that of Rhodamine B (spectral power distributions measured with a PR650 telespectroradiometer, normalized by a white-tile measurement) are also shown in Figure 3(b). The reflectances of both the traditional magenta ink and the Rhodamine are well behaved under illuminant CIE D50 in Figure 3(c) and the effect is preserved and visible. Using the HANS paradigm, it is then the union, the convex hull, of the Z3200 gamut and the Rhodamine samples that a pipeline will give access to, which is shown in Figure 3(d). In terms of gamut volume, in cubic LAB units that relate to the number of only-just distinguishable colors, the addition of a Rhodamine ink alone – not including interactions with other inks – would expand the Z3200's gamut of 764K cubic LABs to 842K, a 10.3% increase from a single ink used in isolation.

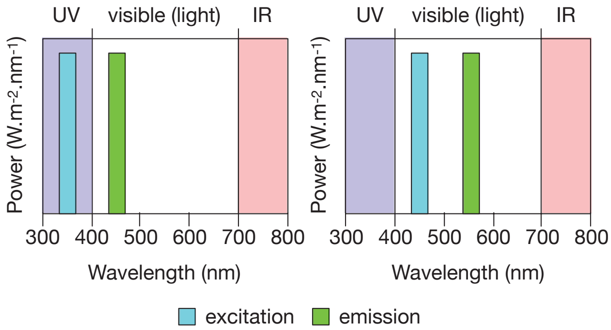

Figure 2: Schematic illustration of fluorescent activation by (left) UV versus (right) visible radiation.

These gains in gamut are of a magnitude that is inconceivable using traditional ink chemistry and are the result of emissions peaking at around 1.6x the reflectance of the white tile, or in other words, 1.6x more light being emitted at some of the wavelengths than the most light that can be reflected from a perfect white diffuser (Figure 3(b)). The above test was used to formulate the hypothesis of potential gamut gains and relied on assumptions.

Next, in order to test the behavior of the Rhodamine dye with a standard set of CMYK inks and to validate the claim of convexity afforded by the HANS paradigm, a printing system was set-up that used CMYK+Rhodamine inks and a chart that included combinations of Neugebauer Primaries that involved combinations of all available inks was explored. An important question here is whether both a magenta and a fluorescent (a bright pink) are needed or whether any one of them would suffice. The theory outlined earlier already indicates that both should be required in order to represent lighter colors (using Rhodamine) as well as keep the darker colors (using magenta combined with black). In order to identify the quantitative contributions, the experiments involved building three subsets of the ink-set: the baseline here is the CMYK, with alternatives being CRYK (Rhodamine replacing magenta), or CMRYK (Rhodamine complementing magenta). Figure 4 shows a CIE a*b* for the three configurations as well as L*a* and L*b* views of the CMRYK case and Table 1 quantifies the impact on overall gamut volume and Figure 5 shows the visual impact for some ink combinations. As can be seen from the data, the addition of Rhodamine affects all areas of color gamut that it interacts with in a convex fashion, going significantly beyond the earlier example where Rhodamine was considered in isolation with respect to all other inks.

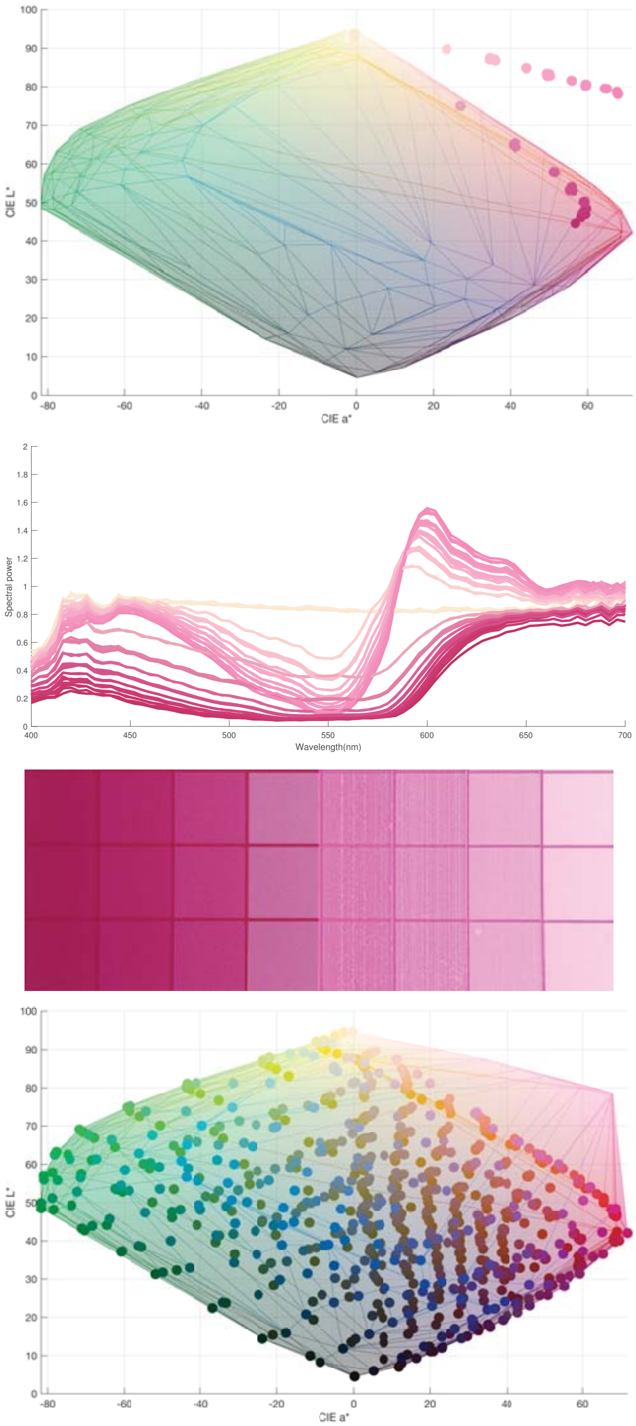

*Figure 3: Z3200 gamut (solid), magenta ink (in-gamut) and Rhodamine B at 0.25% concentration in CIE L*a* view (top). Media-normalized reflectances of magenta and Rhodamine as well as media white – clearly distinguishable between each other, photo of Rhodamine (right-most 4 columns) versus magenta (left-most 4 columns) ink ramps, the union of the Z3200 gamut and the Rhodamine samples (hull) with the Z3200 samples shown as points.*

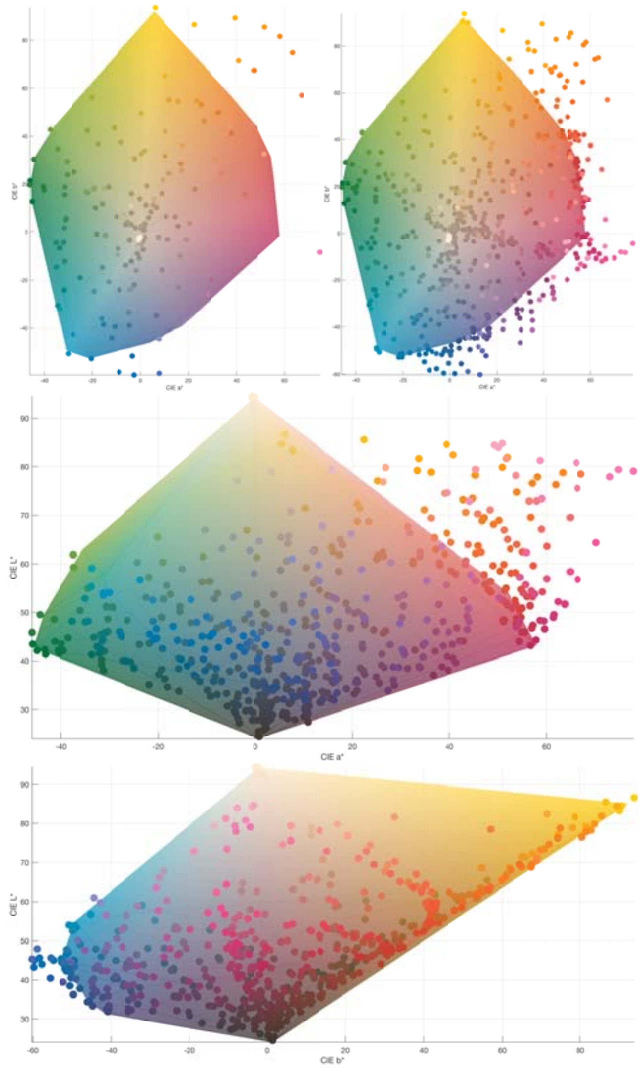

*Figure 4: Top left - CIE a*b* view of CMYK gamut (convex hull) vs CRYK gamut (points); top right- CMYK gamut (hull) vs CMRYK gamut (points). Middle and bottom: CMYK gamut (convex hull) vs CMRYK gamut (points) L*a* (middle) and L*b* (bottom) views.*

Table 1: Gamut volumes for various ink-set measurements.

CMYK	255,233	
CRYK	340,607	+34% vs CMYK
CMYK+CRYK	403,181	+58% vs CMYK
CMRYK	418,388	+64% vs CMYK

A comparison was also made vs the Object Color Solid – the theoretical body of physically realizable reflective objects in nature (including narrow band reflectances, but not including self-luminous objects or fluorescents). As can be seen in Figure 6 in spite of the effects of accuracy and error in the pipeline and printing, samples using the fluorescent Rhodamine still fall outside of the theoretical OCS, showing how color gamuts accessible by adding these fluorescent inks are substantially out of reach for standard ink formulations.

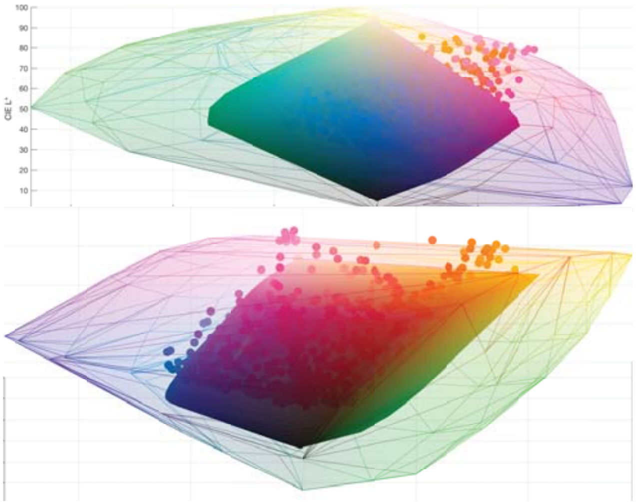

*Figure 5: Object Color Solid (pastel hull) vs the a typical printer gamut (dark hull) vs CMRYK measurements (points) shown in CIE L*a* view (top) and L*a*b* view from the dark side (bottom). Both views show how some of the points (especially pink and orange) fall just outside of the theoretical Object Color Solid.*

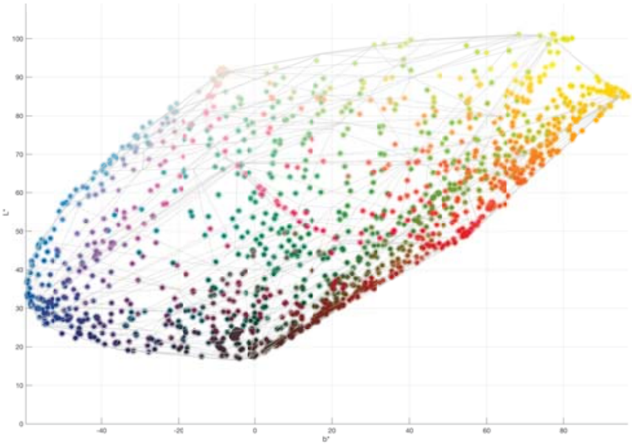

Figure 6: A comparison of two prints and measurements with CMYK + Fluorescent pink and yellow inks. The second data set (shown in color) is a re-interpolation and re-tesselation of the first (shown as a grey mesh hull) and shows good correspondence between the two.

Finally, Figure 6 shows results using a different, dye-sublimation textile printing prototype system with both fluorescent pink and yellow inks along with CMYK, used to both compare the effect of the added fluorescent inks as well as the assumption of convexity that HANS affords. Figure 6 shows the results in terms of gamut shape and volume. Note that two data sets are plotted, the first data-set is an irregular characterization chart, while the second data set is a re-interpolation of the first one's convex surface. Since there are no regions in the first convex hull that exceed the results from the second chart, the assumption of convexity is confirmed with the second re-tesselated, printed and measured data.

Color measurement of fluorescing materials

To quantify the color gamut benefits of photoluminiscent materials, these were printed on standard satin inkjet media (HP Photo Satin) and measured using a PhotoResearch PR650 telespectroradiometer (TSR) under controlled lighting conditions in a viewing booth (including CIE D50, the printing standard). Both a white calibration tile and standard ink samples were measured under the same conditions, for direct illuminant and reference comparison. The result were spectral power distributions (SPDs) of samples that can be evaluated spectrally and colorimetrically, and from which reflectances can also be computed. The reason for using TSR instead of spectrophotometer measurements is that it allows for measurements to be taken under a variety of conditions that stress the robustness of the emissive properties and also since spectrophotometers are built to deliver reliable measurements of reflectances of up to approximately 100% and not much above. As a result, spectrophotometers used in the Graphic Arts tend to significantly underreport the effect of fluorescence. A drawback of this device and set-up is that measurements are done of one patch at a time and manual intervention is required – keeping the measurement/illumination geometry constant while moving the samples in the viewing booth. Figure 7 shows a diagram of the measurement set-up.

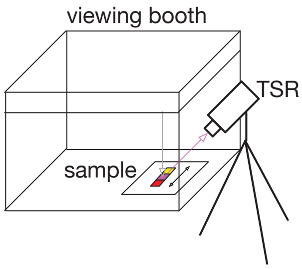

Figure 7: Measurement set-up geometry.

On the other hand, it is also a noisier measurement procedure since ultimately reflectance is required and the process of normalizing spectral power distributions with that of a white tile has its perils. Figure 8 shows a plot of measuring the white tile repeatedly in the viewing booth (same geometry, same location, same white calibration tile):

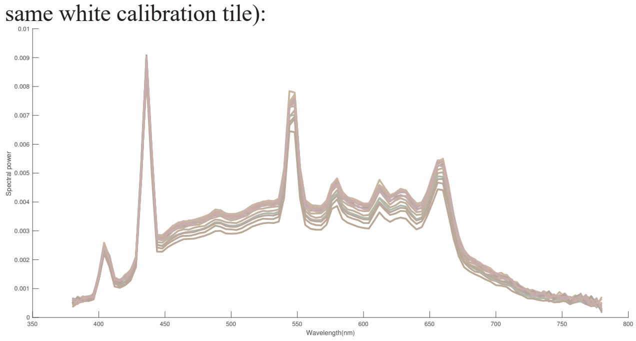

Figure 8: White calibration tile telespectroradiometer spectral measurement variability across multiple measurements. Above plot uses 380nm to 780nm at 4nm steps resolution, native to PR650 capture.

The impact of the combination of the variability of the white tile measurement (that can be mitigated by means of averaging), as well as the same variability of print and measurement for the remaining samples results in a repeatability that is worse than typical controlled conditions in printing and measurement processes.

To evaluate the repeatability of this process, the same CMYK and CRYK charts have been printed repeatedly and measured repeatedly, with the results shown in Table 2 in terms of the impact on gamut volumes.

Table 2: Gamut volumes for repeated measurements.

CMYK	255,233	265,820	4% difference
CRYK	340,607	318,580	7% difference
CRYK		316,432	(re-measured)

Overall the differences are 4% - 7% in gamut volume terms with larger differences seen in the Rhodamine B plots compared to the CMYK ones. Figure 9 also shows a gamut plot comparing the two sets of new measurements for a CRYK chart printed and measured twice.

The above results also indicate a negligible (and invisible) effect of fading due to light-fastness. Both the numerical results above (318K vs 316K LAB units) measured about 2 months apart, and looking at the prints, no appreciable difference can be seen. While the measurements correspond well, in one case they are consistently more colorful - this can be due to the normalization by different white references (as shown earlier).

In the above data (CRYK) we can also look at point-by-point print & measure repeatability, which is reported and plotted in terms of CIE ΔE 2000 color difference statistics between two sets of CRYK prints & measurements (Table 3, Figure 10).

All the above data was measured in the way outlined earlier, using a telespectroradiometer, one patch at a time, applying a white-tile normalization in order to obtain reflectances. This is a labor-intensive and fragile process (as the repeatability results also show). While there are also devices that are capable of measuring reflectance of fluorescent materials directly (such as the Barbieri Spectro LFP qb), most don't and typically significantly under-estimate the effect of fluorescence since they tend to expect, at most, the effect of optical brighteners in the substrates. In order to mitigate this as well, as to be able to use existing devices – whether benchtop (e.g. devices like the i1O, or Minolta FD family) or embedded in printers – it is worth exploring whether existing devices can still be used. To obtain data that is not native to these devices, such as the measurements of fluorescing materials, we approach the problem using the tools of supervised learning and furthermore make assumptions about the conditions under which such model would be used. The model derived from this process does not need to be able to measure arbitrary surfaces with arbitrary levels of fluorescence, but very specific ones – printed using the available inks of a device on valid substrates of the device using a limited set of fluorescent agents. Given this, more limited, domain, high degrees of accuracy can be achieved.

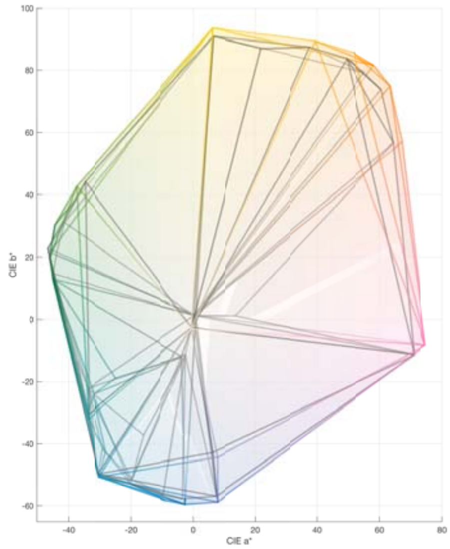

Figure 9: CRYK (first set of measurements, wireframe gray lines) vs CRYK (second set of measurements, solid color hull) print and measure repeatability.

Table 3: Measurement repeatability of CRYK chart.

Median:	1.6
95th %tile:	2.7
Max:	5.9

To train the model, a set of patches for a given printing system needs to be designed, with the objective of covering the type of content that will be measured both in color terms and in spectral terms. A HANS NPac chart can be designed such that it includes patches that build ramps of increasing area coverage for all possible NPs of a printing system. The result is both color gamut spanning and will also contain the full spectral variety possible on a given system.

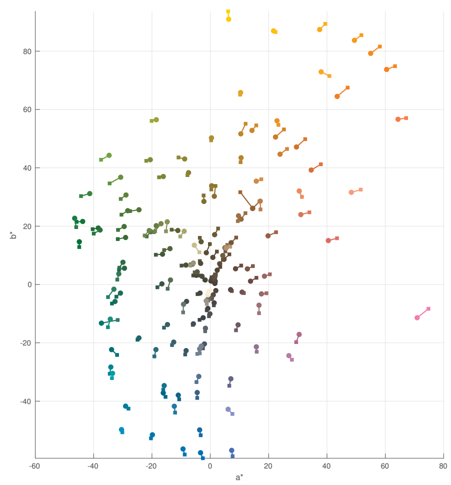

Figure 10: CRYK (first set of measurements, denoted by a circle) vs CRYK (second set of measurements, denoted by a square) print and measure repeatability. Corresponding samples are connected by a line.

This chart is then printed on the substrates for which the prediction model is to be applied and subsequently measured with a standard spectrophotometer to obtain the raw measured data. The same chart is also measured with a telespectroradiometer in a viewing booth under one or more target illuminants (as described earlier).

From these two corresponding data sets – one measured using a standard device and one measured using a specialized device – a regression model can be built that maps the spectrophotometer data (that can be measured on-line or using off the shelf devices) to the desired data from a telespectroradiometer.

Figure 11 shows the data of a chart printed with a an ink-set that includes a fluorescent along with traditional CMYK inks, from a spectrophotometer (top, note how the peak is around 1.2), a telespectroradiometer under D50 (middle, note the peak reaching 1.8 reflectance - about 2x that of yellow around 600nm) and finally the result of using a spectral model applied to the spectrophotometer data (bottom, note the similarity of shapes to the middle plot).

The data furthermore shows the color accuracy of this process, whereby the errors correspond to: the color difference between the top plot (spectrophotometer data) and the middle plot (telespectroradiometer data) performing no compensation and the difference between the middle plot (telespectroradiometer data) and the bottom plot in Figure 12 (compensated spectrophotometer data) based on performing the proposed compensation – confirms the accuracy of this process, resulting in errors of DE2000, as shown in Table 4 below and plotted in Figure 12.

To put this in perspective, two measurements with two telespectroradiometers will differ between each other only slightly less than the accuracy of this model (see Figure 10 and results).

An important insight here is the use of cross-terms – interactions between neighboring wavelengths [5, 6]. This is inherent to the effect of fluorescence, where it is precisely the interactions between wavelengths that are important information-bearing elements, since fluorescence specifically is the effect of absorbing energy at one wavelength and down-converting it in frequency terms, hence emitting it at higher wavelengths. Finally, due to the supervised learning nature of this approach, any additional data that becomes available (e.g. if the measurement of more samples offline with a telespectroradiometer and the on-line measurements are also available for the same data) can be used to continuously improve the model. Likewise, if the model is only applied to a sub-set of the data that a printing (imaging) device is capable of then the model can be tuned to perform particularly well on that domain.

Conclusions

The first results of adding a purely photoluminescent ink – a fluorescent pink – to a traditional, reflective ink set, printing and measuring it, and seeing a dramatic visual effect, are extremely promising. Next steps will involve testing of conventional ink properties where light fastness and color constancy will need to be stressed in particular, due to the nature of emissive color formation, as well as exposing the newly available color gamut upstream to color management where challenges such as gamut expansion, memory colors will be particularly relevant.

Acknowledgements

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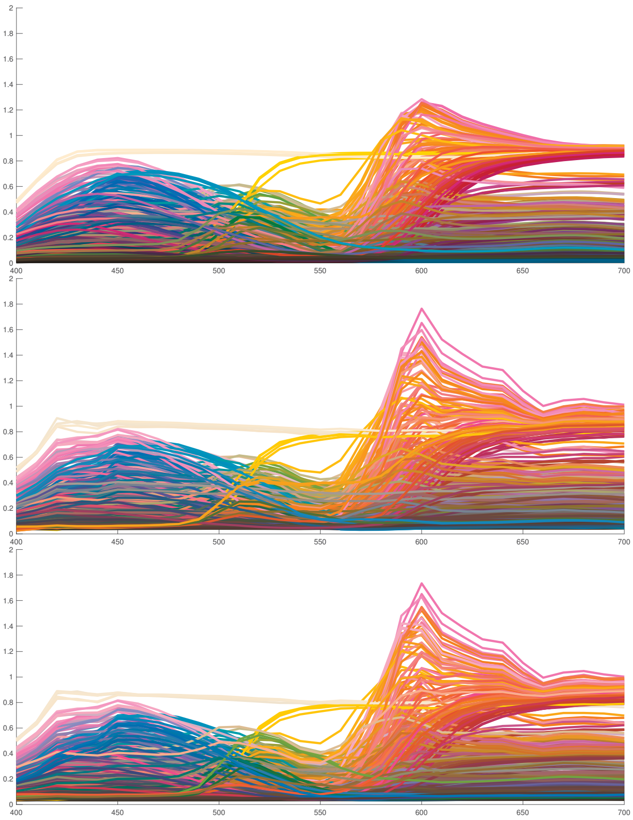

Figure 11: Measurements with a standard spectrophotometer (top), with the PR650 telespectroradiometer (middle) and predictions using our model (bottom). The plots use a spectral sampling of 400nm to 700nm at 10nm steps, native to the spectrophotometer measurement device used.

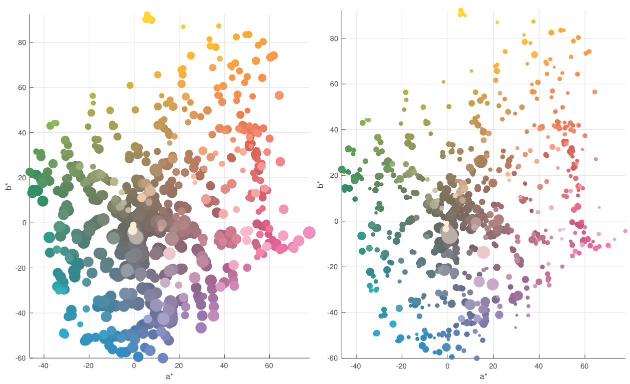

Figure 12: CIE DE 2000 color difference under CIE D50 of spectrophotometer measurements without correction (left) and after correction (right). Size of markers indicates relative magnitude (same in both figures) of DE 2000 error.

Table 4: Measurement and prediction accuracy.

	Direct	Predicted
Median	4.14	0.843
95th %tile	8.62	2.617
Max	12.20	8.622

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Peter Morovič received his Ph.D. in computer science from the University of East Anglia (UK) in 2002 and holds a B.Sc. in theoretical computer science from Comenius University (Slovakia). He has been a senior color and imaging scientist at HP Inc. since 2007, has published 50+ scientific articles and has 150+ US patents filed (54 granted) to date. His interests include 2D/3D image processing, color vision, computational photography, computational geometry and his Erdős number is 4.

Ján Morovič received his Ph.D. in color science from the University of Derby (UK) in 1998, where he then worked as a lecturer. Since 2003 he has been at Hewlett-Packard in Barcelona as a senior color scientist and later master technologist. He has also served as the director of CIE Division 8 on Image Technology and Wiley and Sons have published his 'Color Gamut Mapping' book. He is the author of over 100 papers and has filed 150+ US patents (57 granted).

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Garry Hinch has been a chemist at HP for 12 years after working for Sharp Labs of America, Lexmark, and Ricoh over a 25+ year career. He has worked in both electrophotographic and inkjet technology and is currently doing materials development for 3D printing. Prior to his industry career Garry received a B.S. degree in chemistry from the University of Missouri - Columbia and a Ph.D. degree in inorganic chemistry from the University of Arizona.

Jim Stasiak is an HP Labs Distinguished Technologist. He currently leads the HP Labs' Voxel Physics Research Group in Corvallis, Oregon. He is recognized as a pioneer in the transformation of digital inkjet technology into a new platform for fabricating and manufacturing using additive methods and functional materials. Currently, he is applying HP's Multi Jet Fusion 3D printing technology to develop and tailor the physical properties of new materials - digitally and at voxel-scales.