DIGITAL COLOR PRINTING 1995: A RETROSPECTIVE FROM THE TRENCHES

Giordano B. Beretta, Hewlett-Packard Laboratories, Palo Alto, California

ABSTRACT

This session in the middle of the decade seems to me a good time for reflection. We have here an excellent selection of papers that will outline what the remainder of the decade might have in store for us. It is time to look back and assess first of all how we got here, and then what were our goals for the future when we started. I will keep my presentation at a fairly abstract level, without mention of specific non-impact printing technologies, and the daily struggles thereof.

For the first task—how we got here—it is useful to review the problems we were trying to resolve ten years ago, and what became of them. For the second task—what our goals were for this decade—I will recall some of the strategic plans devised five years ago.

I trust this overview, from the personal perspective of an observer in the trenches, will put this session's papers in perspective and underline their importance for the remainder of this decade.

1985: TEN YEARS AGO

The Typical Computer Platform

Ten years ago a typical workstation deployed in a research laboratory had a microcoded architecture delivering about 1 MIPS "horsepower." At 530M bits/sec the bus was barely fast enough to display a full color 24 bit color image at a low resolution of only 640×480 pixels.[10] That workstation had a primary black and white display with the full 1024×808 resolution for all tasks other than displaying color images.

The main memory was typically 16M bytes and the local disk 315M bytes, while the servers on the network typically had 1260M bytes of storage. The imaging software supported device-dependent RGB and CMYK color model operators.[19] Mapping between these spaces was by simple arithmetic inversion. When "perceptually friendlier" color model operators were provided, they were transformations of RGB, requiring the smallest possible number of computer instructions.[16]

Main Applications

In computer science, the main applications of those workstations were electronic design for VLSI chips, and research in computer graphics, most notably rendering algorithms. Early in the Eighties researchers had begun to use workstations for promoting desktop publishing, or document preparation systems, as they were then called.[9] Each of these efforts had an impact on the future of color printing and color standards.

Design Automation, Avionics, and Color Selection. The VLSI design applications needed fast large-format color printers for check plots. Pen plotters were too slow, and liquid toner electrostatic plotters became the preferred printer solution. Because these printers allowed a much larger freedom of choice than pen plotters for the color selection, the obvious question was to apply color science to come up with color palettes that maximized the readability of check plots.[1] Readability was very important because check plots—as the name implies—were used to check VLSI layouts for design rule violations.

VLSI layout readability is related to visual search, a problem that had been extensively researched for avionics applications and for similar applications in submarine sonar shacks. Some of the most influential work in this field had been carried out by Louis Silverstein[15] and David Post,[11] who established the vision and color science foundation critical for further work. However, their methods are for maximal color discriminability, which does not result in good VLSI layout readability. Eduard Imhof's principles for map design—still taught to pupils in Swiss schools—proved to be a valuable guide when combined with the basic theory developed for the avionics applications.

As already Imhof noted, the systematic use of color leads to esthetically pleasing artwork, so the tools created to select colors for VLSI layout design could be generalized. This work naturally led to more general color selection tools that helped the early users of desktop publishing systems to make more effective, accurate, and esthetically pleasing use of color.[2]

Printing Illustrations of Rendering Algorithms. The power of those workstations, coupled with the advantage of bitmapped architecture, led to big strides in image rendering research. Algorithms were designed to simulate natural phenomena such as fog, mist, haze, etc. As researchers published their work, they wanted to illustrate the results in printed conference proceeding.

When skilled graphic arts specialists in the print shops mistakenly cleared up the fog and haze from the images, this became evident: if computer graphics researchers wanted to preserve in print the effects they meticulously designed on their CRT display monitors, they had to learn about color printing and take the separation process in their own hands.[17] This involved direct output to a scanner using the DDES standard, in creating which Patrice Dunn and the late Dr. Thomas Dunn had played a major role. The researchers themselves had to solve the color and the gamut mapping problems across devices.[18, 7]

Electronic Imaging. Finally, it became clear that just scanning an image, placing it in a document, and printing the document was a simplistic use of digital technology. The slogan "scan—think—print" was coined. Fast workstations allowed two classes of operations on digital images: enhancement and creative manipulation.

The enhancement referred to operations that could be applied—in the main, automatically—to images for improving their appearance. Examples of such operations were tone reproduction curve correction and histogram equalization, color balance correction, and sharpening.

Creative manipulation included such operations as cutting out objects from images scanned at various resolutions and combining them to create new original images. The objects could be of arbitrary shape and transparency; they could be transformed geometrically by resampling the bitmap representation to create new perspectives or views.

Following the photographic tradition, terms like *Digital Darkroom* were used for workstation-based image manipulation systems.[6] For the monitor-to-print research there were two schools, which used different terms for their technologies. One school believed that the correct approach was to match by colorimetry the colors on the print with those on the monitor, with an affine mapping to allow for the different gamuts; they called their method *calibrated color reproduction*.[18] The other school advocated the use of a more empirical cross-media mapping called *WYSIWYG color* that would optimize the visual color quality in each medium.[7]

Impact on Future Work

None of these applications had a direct commercial impact. The importance of this work did not lie in the applications themselves but in the research that was the necessary condition for realizing them.

The investigators had to learn the color science developed for offset printing in the Fifties[21] by people like J.A.C. Yule, Hans Neugebauer, Dusty Rhodes, William Schreiber, and translate it into the digital domain. Because the new environment of networked workstations was an open system, as opposed to the closed digital pre-press systems developed earlier,[14] device-independent color representations and standards became an important issue.

In retrospect, the important achievements of those early researchers included the definition of standards, developing device characterization and calibration procedures, inventing gamut mapping algorithms and other algorithms to transform color descriptions from device coordinates to device-independent coordinates and *vice versa*. All this included considerable work to enhance the imaging modules in operating systems. Such enhancements included standardized color model operators and efficient implementations of the related mapping operations.

The various instruments used to characterize the devices were not easy to use. CRT colorimeters were very crude and spectroradiometers required exact control of the measurement geometry as well as controlled ambient temperature and humidity.

The original applications developed during the Eighties disappeared into oblivion. Again, they were not important by themselves but for the research they required for their realization.

1990: FIVE YEARS AGO

From Research to Products…

By the end of the Eighties, the issues were well understood and a viable technology was in place. This meant that the torch could be passed from the research lab to the engineering business units.

Reliable CRT colorimeters became available, as well as hand-held spectrophotometers that could be operated by technicians. The colorimetric characterization of color printers had become completely automatic. The processes used in color printers had become more stable and a printer's characterization could be applied to a whole model series instead of a single unit.

The system issues, however, were ignored in the commercialization process. While during the previous decade in the laboratory the imaging modules in operating systems were revised and upgraded with new capabilities, commercial providers of operating systems did not recognize the value of color imaging. As one influential business person stated, to sell a system it was important to have some colors, say 8 or 16, but it did not matter what these colors were and it was not worth spending the extra dollar for the additional floppy disk required if the operating system included color management.

This created an opportunity for companies like Adobe, which added device-independent color representation to the PostScript page description language. Third party vendors like Electronics for Imaging, Kodak, Light Source, Radius, Savitar, SuperMac, Tektronix, and others introduced utilities for the precise control of color. Printer companies like Hewlett-Packard, Apple and Canon shipped color matching drivers with their color thermal ink jet printers.

This infrastructure allowed the successful commercial development of new applications, like Photoshop, Illustrator, Freehand, Cachet, etc. These applications evolved independently of the work done a decade earlier, as was the case also for the color selection utilities, which were reborn as much more powerful and useful tools.[12, 13, 8] For example, the new contemporary color selection tools take into account spatial and semantic information, thus considerably empowering users.

This empowerment has been quite dramatic in terms of required skill levels and time to perform a task. Take for instance the design of a pleasing desktop, *i.e.*, the selection of a color scheme for icons, fonts, backgrounds, etc. When done with traditional tools like Munsell chips and Pantone airbrushes, this task required months of hard work by an industrial designer. The digital tools of the mid-Eighties reduced this time to a couple of weeks, but still required the skills of an industrial designer. The reason was that these tools were not able to obey a basic tenet of esthetics, namely that shape has to be defined before color (*Form + Farbe*), because colors interact.

The early color selection tools were loosely inspired by the color sequencing work undertaken by the Belgian sculptor Georges Vantongerloo and the Swiss painter Max Bill. They only dealt with relations among concrete colors. With the new color selection tools of the Nineties—like those invented by Bernice Rogowitz and her co-workers—untrained computer users can design a pleasing personalized color scheme for their computer desktops in a matter of hours, because these new tools take spatial vision into account for the selection of colors.

…and Strategies

Companies like to draft long term plans and set goal or *hoshins*, as the Japanese say, at the beginning of decades. 1990 had been an important year for strategic thinking in the business of color non-impact printing.

In the Eighties this business was mainly technology driven. Companies examined the fruits they could harvest in their technology portfolios and combined them into cocktails that would give them a competitive advantage. Even among companies driven more by market share goals than by the desire to make technical contributions, shelf space in retail stores was conquered by highlighting technical features.

When companies forged their strategic plans for the Nineties, they realized that office automation products had failed to improve productivity. From technology driven, the industry was required to move to be human factors or relevance driven. A product would sell if it was relevant to users and improved their productivity; a cost had to be justifiable on the basis of business returns.

This had several repercussions. One was printer pricing. At the end of the Eighties it was believed that non-impact color printers would be priced at approximately $10,000 because of the emphasis on technical features. It was believed that market share could be expanded significantly by trimming down prices to, say, $7,500 per unit, using clever manufacturing technology and shifting the profit source from printers to supplies. As the cocktail became richer, prices could be gradually increased for larger profits.

The new thinking led to the realization that customers spent for each peripheral device about a third of the amount they spent on the processing unit itself.[4] Combined with ferocious competition, this led to the dramatic price reductions we have witnessed: a good color printer costs under $500 and prices are falling while quality improves.

Moreover, companies realized that, to bring about a paradigm shift in desktop publishing, they had to strive for high quality, strictly adhere to industry standards, and build open systems.[3] In their quest to avoid stagnation of intellectual investigations, and looking for the non-obvious to enhance user relevance, companies came up with novel technologies like ColorSmart, presented at last year's Congress,[20] and the ColorAdvisor presented at this Congress.

1995: STATUS AND OUTLOOK

If we extrapolate from the progress in the first half of this decade, the second half looks very promising. With ColorSync 2 and Windows 95, commercial operating systems are finally providing adequate support for color; ColorSmart has shown the way for ease of use.

One common problem I still encounter day to day is that when people ask me why they do not get satisfactory color output, I find that they often have a number of color managements system extensions in their operating systems, all conflicting with one another. The work of the International Color Committee (ICC) presented in Dr. Has's focal paper will solve this problem and is very important for the widespread acceptance of electronic color imaging and non-impact color printers.

Even if the printer hardware can produce perfect hard dots without feathering or bleeding, and the driver software can achieve perfect color matches, this does not yet guarantee pleasing color images. Categorization is a cognitive skill that is hard to acquire; reasoning and discoursing about color is an art that takes a long time to learn. For color applications to succeed, users need guidance in their use of color as this is shown in Mr. Larry Lavendel's paper.

For the same reason, the research performed at the Helsinki University of Technology is very important because it allows non-skilled persons to improve the visual quality of poor images. Their automatic color correction method operates globally by adjusting the gray balance and tone reproduction curve, as well as locally by adjusting important reference colors.

Ms. Patrice Dunn will take us step by step through the digital color process and show how international standards have enabled the creation of tools for open digital color process control. Color quality requires meticulous work, which is manageable only when good standards are in place. Her presentation covers the issues of developing consistent characterizations and profiles for the various color devices that might participate in the work-flow steps preceding color hardcopy devices.

Traditional page description languages like Postscript were designed with applications such as typography and graphics in mind. They lack important features for electronic imaging, such as transparency and efficient support for devices with relatively small frame buffers. Canon Information Systems Research Australia proposes a new page description language that is tailored for electronic imaging applications.

Each device has a different color gamut, so colors that can be printed on one printer may not be reproducible on a different printer, requiring mapping a gamut into another. The gamut mapping problem is still more an art than a science. Therefore, gamut visualization is an important tool for the design of color rendering algorithms. Dr. Gabriel Marcu will present the work in progress at Array Corporation and the University of Tokyo.

To achieve fast printing times with economical processors, color mapping is performed by table lookup and interpolation. Memory is expensive; to keep the system price low, the lookup tables must be as compact as possible. This requires a careful design of the interpolator. ITRI has developed in Taiwan a new powerful interpolation architecture. ITRI's paper concludes the Color Session.

Last but not least, Hewlett-Packard has been one of the companies that has put considerable effort in the development of the color facsimile standard. Almost a year after the standard has been approved, HP researchers are reporting some of their implementation experience in the Poster Session immediately following this Session.

ADDENDUM

The new *CIE 1994 (ΔL^* ΔC^*_{ab} ΔH^*_{ab}) colour-difference model* for industrial color-difference evaluation, with abbreviation CIE94, has been published[5] and should be used instead of the old CIE 1976 $L^*a^*b^*$ color-difference recommendation. The new formula has added corrections for variations in perceived color-difference resulting from chroma level of the color standard:

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2} \quad (1)$$

The weighting functions S_i correct for global non-uniformity and have the values

$$S_L = 1$$
$$S_C = 1 + 0.045 \quad C^*_{ab} \quad (2)$$
$$S_H = 1 + 0.015 \quad C^*_{ab}$$

The parametric factors k_i correct for conditional effects. Under the reference conditions their values are

$$k_L = k_C = k_H = 1 \quad (3)$$

The reference visual conditions are: D_{65}, 1000 lx, color normal observer, neutral gray background field with L^* = 50, object viewing mode, sample field greater than 4˚, sample pairs in direct edge contact, sample color difference magnitude 0–5 CIELAB units, and homogenous color samples. Currently the only different parametric correction used in practice is $k_L = 2$, common in the textile industry.

ACKNOWLEDGEMENTS

This introduction was suggested to the Program Committee by Xerox PARC's Maureen Stone, who also provided many of the audiovisuals used in the presentation. Giuliana Lavendel, also from Xerox PARC, graciously helped to express these thoughts with clarity.

REFERENCES

1. Giordano B. Beretta, "Selecting Colors for Representing VLSI Layout," *Xerox PARC Technical Report* EDL–88–7, 1988.
2. Giordano B. Beretta, "Color Palette Selection Tools," in *Conference Summaries of SPSE's* [now IS&T] *43rd Annual Conference*, 94–96, 1990.
3. Giordano B. Beretta, "Color Strategy," *Canon Developers Conference Proceedings*, 1991.
4. Giordano B. Beretta, "Color Appearance in Computer Applications," *Canon Information Systems Technical Report CIS–N–743*, also available from the National Technical Information Service (NTIS), PB94–102167, 1993.
5. CIE, "Industrial Colour-Difference Evaluation," *Technical Report 116–1995*, 1995.
6. Michael G. Lamming, "Digital Darkroom," *ACM Siggraph Video Review CHI '89*, **48**, 4, 1989.
7. Michael G. Lamming and Warren L. Rhodes, "A Simple Method for Improved Color Printing of Monitor Images," *ACM Transactions on Graphics*, **9**, 4, 345–375, 1990.
8. Larry A. Lavendel, "Color: Use and Abuse," in *Proc. IS&T's Eleventh International Congress on Advances in Non-Impact Printing Technologies*, 1995.
9. Jürg Nievergelt, Giovanni Coray, Jean-Daniel Nicoud, and Alan C. Shaw, Editors, *Document Preparation Systems*, North-Holland, 1982.
10. Kenneth A. Pier, "A Retrospective on the Dorado, A High-Performance Personal Computer," in *Proceedings of the 10th Symposium on Computer Architecture*, SigArch/IEEE. Stockholm, 252–269, 1983.

11. David L. Post, “Applied-Color Vision Research,” in *Color in Electronic Display*, Heino Widdel and David L. Post, Editors, Defense Research Series, **3**, Plenum Press, 137–173, 1992.

12. Bernice E. Rogowitz, John A. Gerth, and David A. Rabenhorst, “An Intelligent Tool for Selecting Colors and Fonts for Graphical User Interfaces,” in *SPIE Proceedings*, **2411**, 35–43, 1995.

13. Youichi Sato and Johji Tajima, “A Color Scheme Supporting Method in a Color Design System,” in *SPIE Proceedings*, **2411**, 25–34, 1995.

14. William F. Schreiber, *Fundamentals of Electronic Imaging Systems*, Springer-Verlag, 1986.

15. Louis D. Silverstein, “Human Factors for Color Display Systems: Concepts, Methods, and Research,” in *Color and the Computer*, H. John Durrett, Editor, Academic Press, 27–61, 1987.

16. Alvy Ray Smith, “Color Gamut Transform Pairs,” *Computer Graphics*, **12**, 3, 12–19, 1978.

17. Maureen C. Stone, William B. Cowann, and John C. Beatty, “A Description of the Reproduction Methods Used for the Color Pictures in this Issue of Color Research and Application,” in *Color Research and Application*, **11**, Supplement 1986, S75–S83, 1986.

18. Maureen C. Stone, William B. Cowann, and John C. Beatty, “Color Gamut Mapping and the Printing of Digital Color Images,” *ACM Transactions on Graphics*, **7**, 4, 249–292, 1988.

19. Daniel C. Swinehart, Polle T. Zellweger, Richard J. Beach, and Robert Hagmann, “A Structural View of the Cedar Programming Environment,” *ACM Transactions on Programming Languages and Systems*, 1986.

20. David Wetchler and Will Allen, “Automatic Print Quality Adjustment with HP’s ColorSmart,” in *Proc. IS&T's Tenth International Congress on Advances in Non-Impact Printing Technologies*, 581–583, 1994.

21. J.A.C. Yule, *Principles of Color Reproduction*, Wiley, 1967.