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CIC@20: The continuing "Tale of Two Paradigms"

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Abstract

This talk is about the state of color over the two decades of our Color Imaging Conference (CIC). It describes what led to the first meeting. It has a general discussion of two of the important paradigms in thinking about color over these 20 years; the expansion of colorimetry to device profiles; and the expansion of color constancy to spatial image processing. It also describes the critical role of measuring human color image vision to understand how to design systems that reproduce appearances found in art, photography and image processing.

Introduction

It is an honor to be asked to give a review of the 20 years of our IS&T and SID Color Imaging Conference. These meetings have presented so many diverse and fascinating aspects of color that any attempt to recapitulate the entire program would be futile. Other talks by Shoji Tominaga, Jan Morovic, Ronnie Luo and Joyce Farrell will follow. Here, I hope to simply describe some of the ideas and important trends in color before and during the meeting's history.

COLOR : Theory and Imaging Program (1973)

In November 1973 Ray Eynard organized a meeting on Color. It was sponsored by the Rocky Mountain Chapter of the Society of Photographic Scientists and Engineers (now IS&T) as a two and one-half day tutorial in Denver.[1] The tutorial was repeated in Washington DC the following year. In the preface to the proceedings book, Eynard wrote: "Electronic imaging in color may shortly begin to replace the use of film for color cinematography. Compactness, ease of operation, and the capability of instant review should lead to acceptance of this innovation." This was nearly a decade before Sony's Chairman Morita first demonstrated digital photography.

The tutorial and book *COLOR: Theory and Imaging Systems* (Figure 1) reviewed the history of color perception, colorimetry, measurement, of silver halide and electronic color imaging systems. Table 1 lists Eynard's topics and authors. It is a valuable time capsule on color before CIC.

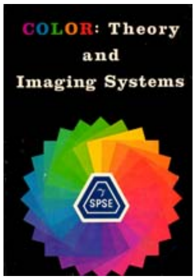
COLOR: Theory and Imaging Systems

***Figure 1.** Ray Eynard's 1973 tutorial on color.*

Contents

COLOR PLATES

1 HUMAN COLOR PERCEPTION
Mr. John J. McCann
Polaroid Corporation
Vision Research Laboratory
Cambridge, Massachusetts

2 COLORIMETRY
Dr. Gunter Wyszecki
National Research Council of Canada
Ottawa, Ontario

3 COLOR DENSITOMETRY
Mr. C. S. McCamy
Macbeth Research Laboratories
Macbeth Color & Photometry Division
Kollmorgen Corporation
Newburgh, New York

4 COLOR SENSITOMETRY
Mr. William F. Voglesong
Eastman Kodak Company
Photographic Technology Division
Rochester, New York

5 A REVIEW OF THE OLD AND NEW METHODS OF EVALUATING THE IMAGE STRUCTURE OF COLOR FILMS
Dr. Michael A. Kriss
Eastman Kodak Company
Research Laboratories
Rochester, New York

6 MASKING AND COLOR REPRODUCTION
Mr. Milton Pearson
Graphic Arts Research Center

7 COLOR REPRODUCTION IN COLOR TELEVISION
Mr. L. E. DeMarsh
Eastman Kodak Company
Research Laboratories
Rochester, New York

8 THE CHEMISTRY OF COLOR DEVELOPMENT
Dr. Emil B. Rauch
GAF Corporation
Binghamton, New York

9 COLOR REVERSAL SILVER HALIDE SYSTEMS
Dr. Raymond A.J. Roosen
Dr. Karel G.M. Staes
Mr. Roland G.L. Verbrugghe
Agfa-Gevaert N.V.
Research Laboratories
Mortsel, Belgium

10 COLOR NEGATIVE AND POSITIVE SILVER HALIDE SYSTEMS
Mr. Hobson J. Bello
Eastman Kodak Company
Research Laboratories
Rochester, New York

11 HISTORICAL AND RECENT APPLICATIONS OF SILVER DYE BLEACH COLOR COPY MATERIALS
Dr. Dietrich F. Schultze
Agfa-Gevaert, Inc.
Teterboro, New Jersey

12 COLOR PROCESS QUALITY CONTROL
Mr. Gil Stark
GAF Corporation
La Habra, California

13 COLOR FILMS FOR AERIAL PHOTOGRAPHY
Mr. Norman L. Fritz
Eastman Kodak Company
Research Laboratories
Rochester, New York

14 GENERATION OF COLOR IMAGERY FROM EARTH RESOURCES TECHNOLOG SATELLITE (ERTS) DATA RETURN
Mr. John E. Polger
General Electric Company
Beltsville, Maryland

15 EARTH RESOURCES MULTISPECTRAL PHOTOGRAPHY
Mr. James H. Sasser
National Aeronautics and Space Admin
Manned Space Center
Houston, Texas

16 MICROFILMING IN COLOR – REVIEW OF TECHNIQUES AND MATERIALS
Mr. W. W. Rickman
Eastman Kodak Company
Business Systems Markets Division
Rochester, New York

17 "RAPID ACCESS" COLOR HARDCOPY – AN OVERVIEW
Mr. Harold Bogdonoff
Xerox Corporation
Rochester, New York

18 COLOR XEROGRAPHY
Mr. W. L. Rhodes
Xerox Corporation
Rochester, New York

19 COLOR-IN-COLOR
Dr. Douglas H. Dybvig
Dr. Thomas J. Evensen
Mr. John W. Ulseth
Mr. Joseph A. Wiese
3M Company
St. Paul, Minnesota

INDEX

***Table 1.** Speakers at SPSE 1972 Tutorial.*

Annette Jaffe's Proposal

United Airlines introduced Mary and me to Annette Jaffe by seating us in the same row on a flight to Tokyo. About half-way across the Pacific Ocean, Annette asked us why we were traveling to Japan. It turned out that Shin Ohno from Sony had invited both of us to speak at *Japan Hardcopy '88*.

In 1992 I joined Annette on the Board of SPSE. She was the Science VP, and I the Engineering VP. Under the leadership of President Fred Guevara and Director Calva Lotridge Leonard the Board was challenged to organize new meetings to serve the Members. Annette proposed that the management for color printers and displays was a topic of growing interest. We worked together to make a plan for the IS&T Board for an organizing meeting on Color. IS&T had a very successful annual meeting on Non-Impact Printing (NIP). SID had a very successful conference on Displays that rotated around the world. Managing color images was a problem for both technologies. Each had different characteristics, but they shared many of the same problems in interfacing with cameras and computers. Rather than organizing a color meeting for printing we felt that it would be better to organize a meeting for color imaging. We approached SID and met with Andy Lakatos and Larry Tannas to organize a joint IS&T/SID program. Annette suggested Scottsdale in the fall after NIP as a good place and time for the meeting. Calva found a resort for a single-track meeting between 100 and 200 participants. Both Boards approved the plans. Andy supplied our distinctive CIC logo.

The first meeting had a number of invited talks. As program chair, I began by inviting Bob Hunt to participate. When he agreed that made my job a lot easier. Mark Fairchild and Roy Berns joined from Rochester and Brian Funt from Vancouver. Andy recruited Rob Buckley and Lou Silverstein. John Meyers recruited papers from HP by Joyce Farrell and Ricardo Motta and Jim King from Adobe. Shin Ohno invited Miyake, Marcu, and Kotera from Japan; and Kim and Ha from Korea. We looked for papers in many aspects of color theory, computer image processing, printing and displays. The call for papers augmented the invited talks. The list of speakers is shown in Table 2. The program ended with Glen Reitmier's panel discussion on HDTV, and a summary by Dusty Rhodes.

The first CIC successfully stimulated the interest in a stand-alone meeting for color. The emphasis shifted from recruited papers to submitted abstracts. The CIC community included industrial engineers designing imaging devices, academic researchers studying color and color standards. The meeting served as a co-location venue for many International Color Consortium [2] meetings. The Inter-Society Color Council has cosponsored two co-located meetings. In 2002 the European Conference on Colour in Graphics, Imaging, and Vision (ECVP) spun off CIC in even years in Europe. The International Symposium on Multispectral Colour Science (MCS) has been collocated with CGIV. The CIC meeting has become a focal point of color research and engineering.

The entire proceedings of the 20 CIC and 6 CGIV conferences are available at IS&T website.[3]

Color Theory & Spaces	Color at the Desktop	Applications of Color Systems (cont)
Bob Hunt	Rob Buckley	Mehmet Celenk
Joanne Taylor	Paul Roetling	Y. Shimizu, H. Haneishi* & Y. Miyake
Steve Shevell	Gerald Murch	Yoichi Miyake & Hideaki Haneishi
John McCann	Jim King	Robert Amantea, et al.
Jan Walraven & Marcel Lucassen	Gary Starkweather	Anthony Maeder & Binh Pham
Joyce Farrell & B Wandell	Gaurav Sharma & H. J. Trussell	Glen Pringle & Binh Pham
Brian Funt	Ian Bell & William Cowan	Shin Ohno
Taek Gyu Kim, Roy Berns, & Mark Fairchild	Henry Chen & King Lung Huang	Yoichi Miyake & Teiichi Nishioka
Henry Kang	Richard Brown	Nathan Moroney & Mark Fairchild
Ricardo Motta & Joyce Farrell	C.B. Chittineni	Raymondo Schettini
Robert Meyer	Ed Kelley, Bruce Field, & Charles Fenimore	Joanne Taylor
Dave Spooner	Jim Quarato, Bayles Holt, & Jerry Harris	A Jaramillo & K Yamaba
Jeog-Yeop Kim &Yeong-Ho Ha	Gao-Wei Chang & Shyang Chang	Shoji Tominaga
Gabriel Marcu & Kansei Iwata		Michael E. Trenchard, et al.
Robert Rolleston & Raja Balasubramanian	Applications of Color Systems	Sarah A. Rajala & Atish P. Kakodkar
E Fedorovskaya, FJJ. Blommaert & H de Ridder	H Kotera, et al.	R Donofrio, D Hess & W Sember
Y Arai, Y Nakano, T Iga, & S Usui	Maureen Stone	Dmitry A. Novik
D. Adkins, V. Cherkassy & E. Olson	Bernice Rogowitz & David Rabenhorst	R E Burger
K Muray, I Reti, I Giczi, & Janos Schandra	Jan Allebach, James Chang, & Charles Bouman	S Xu & PB Crilly
N Hashimoto, T Maegawa, M Okumura, & K Sato	Louis Silverstein & Thomas Fiske	R Cook
Harry Shamir	Lindsay W. MacDonald	R G Guay & M Hernandez
S Derbal	Gary Meyer, Linda Peting & Ferenc Rakoczi	
V Petrov	D.P. Huijsmans & A. Son	

Table 2. *Speakers at CIC1.*

Two Paradigms: Pixel vs. Spatial

In such a diverse and inclusive range of topics it is difficult to summarize the trends in thinking about color over the two decades of CIC. In some ways the fundamentals of color have not changed. In others ways, the use of technology of color imaging has shown unprecedented change. In 1992, digital color printers were rare and CRT's were the standard color display technology. Color management was controlled internally within companies for their line of products. WYSIWYG was a promise, but results were limited. Today, color printers, LCD displays, and color images transformed by profiles are ubiquitous. LEDs are changing the illumination world and OLED displays have reached the market.

The fundamental scientific understanding of color has not changed radically, just expanded. The following discussion attempts to outline these expansions. This task is too big to properly incorporate all the thinking of the past 20 years, so I am sure I owe apologies to many.

"Color Perception" 1972

In 1972 Ray Enyard and Al Shepp invited me to give the first paper on "Color Perception"[4] in the **COLOR** *Theory and Imaging Systems* tutorial. The assignment was to review the history of approaches to understanding color.

From Newton to Young to Maxwell to Helmholtz

Understandably, the first part of the talk reviewed the ideas of Newton, Young, Maxwell, and Helmholtz, using a series of quotes that recount the essence of their contributions.

Wyszecki's Colorimetry

Gunter Wyszecki gave the second tutorial talk "Colorimetry".[5] He explained the 1931 CIE standard that converts radiance to tristimulus values XYZ and chromaticities x,y. He also explained the importance of the Munsell Book of uniformly space color samples and color difference evaluations. He used MacAdams 1960 CIE provisional Uniform Color Space Diagram (UCS) to calculate $\triangle$E using the current formulation or u,v. He wrote[5]: "The CIE colorimetry committee is actively engaged in trying to improve the method of color-difference evaluation. However, despite continuous efforts made by many different investigators the problem will most likely not be resolved in the near future[.6]" Color difference formulas remain an active topic for research today.

He also warned us, "The tristimulus values and thus the chromaticity of a color stimulus do not offer any direct clues as to what color perception will be perceived".[5] Additional variables, such as the other colors in the field of view, the state of adaptation of the receptors, and spatial relationships in each scene determine the color appearance. In order to measure appearance one needs to match a test color to a sample in a library of standard colors in a constant complex scene.[7] In the proceedings Wyszecki wrote: "Sometimes we encounter beautifully colored chromaticity diagrams intended to display the color world in a way we are considered to perceive it. The whites in the center, the reds in the right corner, the blues in the left corner, the greens at the top, and so on. Although these are often masterpieces of painting, they can be quite misleading as to the real purpose of the chromaticity diagram".[5] What he said in is talk was more direct. He said: "Whenever you find a colored chromaticity diagram, burn it!"

Similarly in 1987, W. D. Wright wrote in Color Research and Engineering: "Where does colorimetry end and appearance science begin? An interesting question. My short answer would be that colorimetry ends once the light has been absorbed by the colour receptors in the retina and that appearance science begins as the signals from the receptors start their journey to the visual cortex. To elaborate a little, tristimulus colour matching is governed solely by the spectral sensitivity curves of the red-, green-, and blue-cone receptors (if we may be allowed to call them that), whereas the appearance of colours is influenced by all the coding of the signals that takes place along the visual pathway, not to mention the interpretation of the signals once they arrive in the visual cortex".[8]

As compelling as the science of colorimetry is at predicting accurate color matches, it cannot predict the color appearance of a particular XYZ triplet. This is hardly news to people who study color, in that the discussion of the influence of scene content goes back more than a century before Newton's prisms. The history of the spatial color was also reviewed in "Color Perception".[4]

From daVinci to Hering to Land

An alternative paradigm to pixel-based colorimetry builds images out of spatial comparisons. Around 1500, Leonardo da Vinci wrote: "Of colours of equal whiteness that will seem most dazzling which is on the darkest background, and black will seem most intense when it is against a background of greater whiteness. Red also will seem most vivid when against a yellow background, and so in like manner with all the colours when set against those which present the sharpest contrasts." [CA, 184 V.C]. [9]

Leonardo da Vinci started the study of how appearance is influenced by the content of the image. Experiments by physicists, Otto von Guericke(~1670) and Count Rumford, (1875); writers, Goethe (1810); chemists, Chevreul (1837); psychologists, Hering (1872); and designers, Albers(1963) amassed a great variety of evidence that appearance was not pixel-based.[4] The rest of the image affected appearance.

Edwin Land's experiments, first with Red and White photography, and later with Mondrians, present many clear examples of how spatial image processing generated color sensations from scene content. His 1963 *Retinex Theory* explained color constancy as three independent spatial processes.[10] Experiments measuring the appearances in color constancy and their departures from perfect constancy supported this theory. [7] Experiments with rod images when combined with long-wave cone images generated color images showing the color as the comparison of independent spatial processes.[11,12]

This was the state of color in 1972. The field supported two distinctly different paradigms of how human vision worked: pixel based colorimetry, and spatial processing of scene content.

Pixel theories and algorithms

Both of these approaches, pixel and spacial comparison imaging have expanded considerably since then. Both have played a central role in CIC. Each has improved as the result of scientific study. The following gives a brief summary of these advances.

Colorimetry

Color matching functions, based on psychophysical measurements have solidified over the years.[13] Mike Brill, Claudio Oleari and others have kept us up to date on new colorimetric topics, such as the evaluation of Thornton's *Prime wavelengths*.

Following the pioneering work by Paul Brown and George Wald[14]; Marks, Dobelle and MacNichols[15], and subsequent work by Dartnall, Bowmaker and Mollon[16], we know the absorption spectra of cone visual pigments.[13] We know the psychophysical and physical response functions of the cones.

Herman von Helmholtz coined the phrase "discount the illuminant"[17] as a suggestion for explaining color constancy. If we can somehow get the spectra of the illumination, we can correct the cone responses so that the output LMS cone information is proportional to the reflectances of the objects in the scene. Three different versions of "discounting the illumination" are actively pursued today: Two are theoretical and the third is practical. The first (bottom up) adapts the cone response at the start of the visual pathway, the second (top-down) recognizes the illuminant and transforms the cone responses; the third practical solution is to measure the XYZ of illumination and the XYZ of the object in the scene.

CIELAB & CIELUV

In 1978, six years after the SPSE color meeting, CIE published the L*a*b* and L*u*v* standards for uniform color spaces.[18] Both standards measured the XYZ of the stimulus and divided it by the XYZ of a white in that illumination; both normalized XYZ to get reflectance. Next, they both scale Y with a cube-root function measured from the Munsell lightness function. Stiehl et al. in 1983 showed that the cube root of scene radiance resulted in log luminance on the retina.[19] In other words, the color matching XYZ responses were corrected for intraocular scatter in order to fit Munsell UCS data. The a* formula:

$$a^* = 500 * \left[\left(\frac{X}{X_n} \right)^{1/3} - \left(\frac{Y}{Y} \right)^{1/3} \right] \tag{1}$$

$$a^* \sim 500 * \left[log\left(X\right) reflectance_{retinal} - log\left(Y\right) reflectance_{retinal} \right] \tag{2}$$

$$a^* \sim 500 * \left[X \,/\, Y \right] reflectance_{retinal} \tag{3}$$

or, 5 times stretch of the ratio of (X/Y) retinal reflectances. The b* formula is 2*(Y/Z) retinal reflectances.

In the final steps the two standards differed. It turns out that L*a*b* has been used in most work evaluating prints, while L*u*v* has been used in most work evaluating displays.

CIECAM

Bob Hunt's first paper at CIC described the 22 calculation steps he the used to model color vision.[20] Over the course of CIC meetings we have seen the refinement and standardization of this model in the CIE Color Appearance Model. [21-23] The development of this model has been a central theme of CIC with many contributions from Bob Hunt, Mark Fairchild, Ronnie Luo, Nathan Moroney and many others. This topic will be described by Ronnie in a talk later in the program.

As in CIELAB the illumination is a given input value. The equations transform the sample, adapting field, background, illuminant and reference white. The response to scene content is controlled by a list of specific values of variables: c, N_c, F, for modeling the effect of the rest of the field of view. These factors are applied uniformly to the entire image.

sRGB and Gamma

Another essential theme in CIC has been the calibration of cameras, printers, and displays. Early work by Bill Cowan [24], Roy Berns and Riccardo Motta, and M.S. Gorzynski [25,26] expanded to meet a major industrial requirement.[27] Color devices had to talk the same language to each other. Gerry Murch, Bill Cowan and Riccardo Motta spoke in the first CIC meeting.

ICC Profiles

In 1993 the International Color Consortium (ICC) was set up by eight industry vendors to create, promote and encourage the standardization and evolution of an open, vendor-neutral, cross-platform color management system architecture and components. The outcome of this co-operation was the development of the ICC profile specification.[2]

The ICC specification is now widely used and has been specified in many international standards. It has itself recently been published as an International Standard, ISO 15076-1:2005. Tom Lianza is the current ICC Chairman and Phil Green is the Technical Secretary.[28] Over years many of the CIC most active contributors also played a important role in ICC Profile standards. They include Phil Green, Tom Lianza, Dave McDowell, Jack Holm, Sabine Susstrunk, Ingeborg Tastl, Ann McCarthy, Harold Boll, Michael Bourgoin, Francisco Imai, Rob Buckley, Mitch Rosen, Eric Walowit, Nicolas Bonnier, Michael Vrhel and many others.

The ICC profile format is a platform that allows complex color transformations to be applied using pixel-based color corrections.

Spatial theory and algorithms

The other paradigm for color uses all pixels in the entire image to influence the output of each pixel's color appearance. Human vision is an example of such a system. Experiments that measure color appearances show that both gray and color appearance depend on the specific image content. [29, Sect D,E] Models of human vision need to use the entire field of view if they want to explain color constancy, contrast and assimilation. Experiments with complex scenes, such as 3-D Mondrians,[30] show that edges in illumination are as good as edges in reflectance in generating large changes in appearance. The eye does not discount the illuminant, rather builds sensation from edges and gradients whether they are associated with reflectances or illumination. Ratios of reflectances can predict appearances in flat test targets with uniform illumination, but cannot predict appearances in real life scenes. The unifying principle of most natural images is that the illumination is nonuniform, both spatially and in spectral content. Most of us do not live outside in a desert. Most of us live a world of complex variation in illumination.

Models of Color Constancy

Computational models of color constancy have successfully predicted observer matches in Color Mondrian using algorithms that built their output values from edges in the input image.[7] Further, these algorithms are insensitive to global and local adaptation.[29 Chapt. 27] They predict the departures from perfect constancy observed by human matches in variable illumination.[31,32] These spatial models are consistent with observer data from 3-D Mondrians in which edges are formed by both objects' reflectance and illumination.[30]

Neurophysiology

Over the past century physiological experiments have provided overwhelming evidence that vision is a result of spatial processing of receptor information. Hecht and others showed that the threshold detection mechanism uses pools of retinal receptors. Rod and cone receptors respond to light over a dynamic range of over 10 billion : 1. That is the range of radiances from snow on a mountaintop to the half-dozen photons needed for a dark-adapted observer to say he saw the light. In 1953 both Kuffler and Barlow independently showed that the signal traveling down the optic nerve has spatial-opponent signal processing. In one example, the center of the cell’s field of view is excited by light (more spikes per second). The receptors in the surround of the cell’s field of view are inhibited by light (fewer spikes per second). The net result is the cell does not respond to uniform light across its field of view and is highly stimulated by edges. It has the greatest response to a white spot in a black surround. It is important to note that the firing rate of ganglion cells is slightly greater than 100:1. The dynamic range of rod and cone sensors is 10^8 times greater than the dynamic range of the ganglion cells. Dowling showed pre- and post-synaptic behavior of the retina establishing post receptor spatial interactions.[33] Hubel and Wiesel studied the organization of the primary visual cortex’s response to stimuli projected on a screen in front of the animal. In each small volume of the cortex they found a three-dimensional array of different representations of the visual field. Each segment of the visual field has columns of cortical cells that report on the left-eye image next to a column for the right-eye image. The cells perpendicular to the left/right eye columns respond to bars of different orientations. The third dimension has cells with different retinal size segments of the field of view. David Hubel described the role of *blobs* in color at CIC 6.[34]

In 1963 Land proposed his Retinex theory[10], asserting that these cone types act as sets, where the response was determined by their spatial interactions. The phenomenon of color constancy is best explained by independent long-, middle-, and short-wave spatial interactions. Zeki found color-constant cells in V4 with predicted spatial properties.[35]

Opponent color

Opponent color processing was suggested by Hering (1872). Ladd Franklin and Konig suggested Helmholtz trichromacy was followed by Hering opponency in the neural pathway. Dorothea Jameson and Leo Hurvich added quantitative modeling of opponent processes. Rus DeValois's (1986) neurophysiology experiments brought opponent processing into the spotlight of a field dominated by trichromatic theory at the time. Color opponent processes are found in the optic nerve. Color opponent processes amplify color differences.[7] Nigel Daw and Bevil Conway[37] have studied spatial double opponency.

Color opponent processes are also spatial. Leo Hurvich points out that Hering never suggested that opponency was spatial, as described by Rus DeValois.[36]

D'Andrade's Transform: Cones to Munsell Space

Indow and Romney have studied the properties of the transformation of cone responses to Munsell Space location. The idea is simple. Take the Munsell Book in daylight and calculate the L,M,S cone responses for all the chips. We know that the Munsell Book has equally spaced color samples, so we can calculate the transform from cone response to UCS response.

D'Andrade and Romney[38] fit the Munsell book using the cube root of integrated cone response and opponent color processing that mimic the cells in the lateral geniculate.

The cube root played an essential role, in that it modified all the colors with a single, simple transform corresponding to the correction of scatter. The color-opponent process counteracts crosstalk [31,32] (or sharpen the spectral response - another CIC favorite topic). Although the cones have very little difference in their spectral responses, humans' color vision stretches those small differences to enhance differences in chroma.

Spatial models

Spatial image processing plays a role in digital imaging at all scales. Edge enhancement uses spatial comparisons at the smallest scale. Older silver halide processes also used chemical edge enhancement because the distances were so small. The advent of digital imaging made spatial processing practical.

Jpeg compression is spatial, but over larger segments of the image. Using the eye's fall-off in sensitivity with increasing spatial frequency, we can remove large amounts of redundant information.

Spatial filtering of the entire image has been used extensively since the 1960s, assisted greatly by Coole & Tukey's the 1965 *Fast Fourier Transform (FFT)*[39]. Without it, today's millions-of-pixels images would make these techniques extremely slow. They are in wide use today with standard computer processing power.

Retinex, Horn, Stockham, NASA, Kotera

Retinex image processing uses physiological background for making algorithms that mimic human vision. The idea is not to model the actual behavior of visual cells, but to abstract its underlying mechanisms. The mechanisms can then be applied to image processing problems.

The pair of documents, Land and McCann [41] and Land et al. patent [42], described analog embodiments of calculating matches from arrays of luminances. The paper and patent introduced the idea of non-linear reset to the maxima that is critical in distinguishing Retinex processing from spatial-frequency filtering. Human vision normalizes to local maxima, rendering them as white or near white.[29, Sect. D] This property of vision is modeled by the reset to maximum in Retinex algorithms (29, Chapt. 32]

Tom Stockham saw one of Land’s frequent lectures demonstrating the Black and White Mondrian experiment at MIT. Stockham (1972) wrote a paper on rendering high-dynamic-range scenes using a low-spatial frequency filter to compress the image. Human vision has different properties. Human vision uses the equivalent of scene-dependent spatial-frequency filtering. The reset in Retinex introduces this special kind of spatial response to the scene. Human vision and the reset-Retinex algorithm with fixed model parameters generates scene-dependent rendering [29, Chapt. 32]

Alessandro Rizzi introduced the term *locality* influence to describe properties of the visual system's spatial processing. Vision is neither a global process, nor a local one. Whenever you measure the influence of scene content you find a complex result that is between local and global. Rizzi, Marini, Provenzi, Bertalmio, and Cowan have all modeled locality influence using the Milan reset mechanism.[29, Chapt 33,34]

Efficient spatial processing is critical for applications of spatial algorithms. The early path algorithms were replaced by multi-resolution processes in 1980.[29, Chapt. 32] With a linear increase in computations the process compared an exponential number of pixels. It has O(N) computation efficiency. It is an extremely fast computational model, and is even more efficient when combined with both special purpose hardware, and Sobol's modifications.[43,44] The HP 945 digital camera, and others in that camera line used Retinex image processing in their firmware.

Spatial image processing has played an important role in CIC meetings with the work of Jobson, Rahman, Funt, Rizzi, Marini, Kotera, Finlayson, Fairchild, Johnson and Kuang and many more.

HDR Imaging

At Siggraph the problem of High Dynamic Range (HDR scene capture goes back to 1984 & 85 tutorials. Techniques using low-slope slide duplication film, a graphic-arts scanner and Retinex digital image processing.[45].

Although these conferences were early in the Siggraph series, they were very well attended by enthusiastic computer scientists eager to develop Computer Graphics for real scenes. The HDR breakthrough happened 13 years later when advances in the technology of digital imaging made it much easier. Following the lead of 19th century photographers [29, Chapt. 5] electronic camera applications by Ochi & Yamanka, (1985), Alston et al. (1987), Mann (1993), Mann & Picar, (1995) used multiple exposures to extend range. Debevec & Malik (1997) claimed that multiple-exposure data measured scene luminance.[29, Chapt. 9] The Debevec & Malik paper stimulate a large number of papers on HDR imaging including the work of Greg Ward, Eric Reinhard, Jack Tumblin, Mark Fairchild and many others.

Physical limits

The claims that multiple-exposure HDR algorithms capture wider scene luminances, or colors than previously possible are severely limited by scene and camera veiling glare.

Veiling glare limits HDR imaging because camera glare limits the luminance range that can be accurately measured. Multiple exposures improve the spatial details, but fail to accurately record scene luminance. [29, Chapt. 11]

Cannot omit hybrids: Computer vision

Obviously the segmentation of all of color into two paradigms is a major oversimplification. The scientific process always generates hybrids that combine features of different concepts. We have seen that at CIC as well.

Mark Fairchild and Garret Johnson's iCam model is a good example. It uses CIECAM as the front end ands ads spatial-frequency filtering models[46], or bilateral filters.[47]

The search for intrinsic properties in Computer Vision is another hybrid example. Here algorithms using grayworld, White reference, Max RGB have seen considerable interest. These algorithms use the information of the entire scene to derive average illumination characteristics, such as chromaticities. Usually that means that the image statistics, such as histograms, are analyzed to generate a global correction factor. If this global factor is an accurate assessment of the illumination the algorithm can predict the objects reflectance.

We have seen this hybrid Computer Vision approach used by Berthold Horn, Tom Stockham, Brian Funt, Mark Drew, Kobus Barnard, Grayham Finlayson, Paul Hubel, Steve Hordley, Florian Ciurea, Mark Ebner, Irwin Sobel, Ron Kimmel, Fredo Durrand and many others.

The one important idea the distinguishes computer vision algorithms from human vision models is the different definitions of reflectance. *Physical reflectance* is the measured surface property of the object of interest. In vision the *psychophysical integrated reflectance* [7] is the spatial comparison of the object to a white surround using the cones' spectral sensitivities. The object of interest's surface is unchanged with changes in illumination, so *physical reflectance* is constant. However, *integrated reflectance* values change with changes in illumination. The large overlap in spectral sensitivity of the cones causes crosstalk that makes *integrate reflectance* respond to illumination. Measurements of the departures from perfect constancy in humans show that appearance correlates with *integrated reflectanc*e not *physical reflectance*. These observations are central to models of human color constancy. This subtle difference between *physical reflectance* and *integrated reflectance* defines a watershed that distinguishes different types of models. The differences between *vision* and *computer vision* model is even more apparent in studies of 3-D Mondrians. Observers report appearance consistent with edges not physical reflectances.[30]

Computer vision models have to predict accurate *physical reflectance* values. That calculation from camera images are hampered by the limitations in accurate scene capture. Veiling glare limits the range of correlation with camera digit and scene radiance. All normal camera firmware has to be removed that affect tone scale and color masking found in Jpeg and ordinary RAW images. Even with RAW unprocessed files the range of linear response is limited by glare and anti-blooming signal processing. Although the camera sensors are linear over their entire range, camera responses are not. [50]

Selecting the best model?

Unfortunately, the easiest way to evaluate our favorite algorithm is to make two versions *experiment* and *control*, and ask ourselves and others to pick the winner. Just like the "Miss America" contest observers are able to make selections of preferences. In vision research that creates a serious problem. Let us say that our algorithm has performed a spatial transformation of the image. When we look at that print or display of our processed digits we are using our human spatial image process to see those calculated digits. How do we separate the spatial algorithm in the computer from our vision's spatial processing. If the algorithm models vision, the algorithm must model measurements of vision. The array of measured scene radiances need to be converted by models of veiling glare to scene radiances on the retina. The algorithm then generates an array of digital values that must be compared with the array of measurements of scene appearances. Although difficult, such experiments can accurately evaluate vision.

There are many situations when working on a commercial imaging product that modeling vision is not desirable. The only product that has a slope 1.0 response function is slide duplication film. It accurately records luminance.[29, Chapt. 5] Slope 1.0 reproductions do not make the most desirable pictures because those reproductions are not preferred by observers.[48]

Models that mimic vision

Our scientific goal is to do something that mimics vision rather that replicates it. We all have seen the benefits of device calibration using ColorChecker and other test targets. As well we have seen remarkable progress in the past 20 years in color instrumentation. There are many successes based on our ability to measure and model the physical properties of samples and their appearance using CIECAM. There are also limitations when we go from the flat test targets in uniform illumination to real scenes.

The almost universal characteristic of natural images is that the illumination is nonuniform, both spatially and in spectral content. Shadows and reflections modulate the light from real objects, dramatically increasing the dynamic range of scene radiances. Nonuniform illumination increases the range of light on the camera sensors. By limiting measurements to test targets in uniform illumination, we get an incomplete calibration of camera response. Accurate calibration requires an understanding of the effects of the scene content on a camera's optical and digital responses. Glare, and departures from linear response to light, limit the accuracy of image and camera calibrations.

Accurate capture and reproduction of scene information is not possible, and is not necessary. By capturing and rendering the spatial content of scenes one can reproduce the appearance of high-dynamic-range scenes using low-dynamic-range media. Spatial algorithms that mimic human neural contrast make it possible for computers to do what painters and photographers have done for centuries.

Our biggest problem is that almost all spatial processing that accentuates edges and minimizes gradients works quite well. We have an extremely hard time evaluating all the different flavors of models because they all work to some extent. The challenge is to design the evaluation protocol that can differentiate the more successful candidates from the hundreds of others. Forty years of beauty contests have not provided clear discrimination among algorithms.

General solution requires a scientific metric

If one accepts the premise that HDR image processing should mimic vision, then one can improve the evaluation process by evaluating all types of images. Apply an algorithm with constant parameters to low-, normal-, and high-contrast scenes. Apply it to scenes in uniform and highly nonuniform illumination. Apply it to scenes with more than one spectral illuminant. Finally apply it to well-known visual illusions, such as simultaneous contrast, assimilation, and Sinha's double gradients.

Hopefully, in the future we will replace the beauty contest with numbers calculated from images, not different observers. Hopefully, algorithms will be evaluated across many, very different real-life scenes.[49]

Vision has some fascinating properties, in that it does not have a single response function to light. When we compare the change in luminance from white to black we get different answers with different scene contents. In high-glare, low-retinal-contrast scenes, the range requires 1.5 log units of retinal luminance. In low-glare, high-retinal-contrast scenes the range requires 4 log units of retinal luminance.[51] We need to mimic this property to reproduce all scenes well.

If we evaluate our algorithms using all these test targets we can get a sense of how good they are as the general solution for mimicking vision.

Future as an extension of the past

As in every science, successful techniques migrate across disciplines. During CIC color naming has been transformed from the duty of the National Bureau of Standards to crowd sourcing. Thanks to the work of Berlin & Kay, Nathan Moroney, Giordano Beretta and Steve Palmer, color naming has grown to be a valuable tool. We will see it used in studying other problems.

The increase in efficiency of LEDs and OLEDs assures their future growth. The issues they present in color rendering are also of considerable interest.

The solutions to new problems and the application of tools will continue to be scrambled along with the familiar pixel and spatial color paradigms for the forseeable future.

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