MCSL

Munsell Color Science Laboratory

1999

Annual Report

Munsell Color Science Laboratory
Overview & History

The Munsell Color Science Laboratory (MCSL) was established in 1983 after the dissolution of the Munsell Color Foundation, Inc. The aims and purposes of the Munsell Foundation as stated in its bylaws were "... to further the scientific and practical advancement of color knowledge and, in particular, knowledge relating to standardization, nomenclature and specification of color, and to promote the practical application of these results to color problems arising in science, art, and industry."

The following four basic objectives guide the activities of the Munsell Color Science Laboratory:

1) To provide undergraduate and graduate education in color science,
2) To carry on applied and fundamental research,
3) To facilitate spectral, colorimetric, photometric, spatial, and geometric measurements at the state of the art, and
4) To sustain an essential ingredient for the success of the first three — namely, liaison with industry, academia, and government.

Mark D. Fairchild has been Director of the Munsell Color Science Laboratory since 1996.

Richard S. Hunter Professorship

The Richard S. Hunter Professorship in Color Science, Appearance, and Technology was established in 1983 by a gift from Richard and Elizabeth Hunter. They recognized a need for perpetual education and research in this critical area.

Franc Grum was the first Hunter Professor and Director of MCSL from 1983 until his untimely death in 1985. He was a leader in the color science community and well-known for his work in colorimetric standardization and colorimetry of fluorescent materials. Roy S. Berns has been the R.S. Hunter Professor since 1987 and served as Director of MCSL from 1986 until 1996.

Who We Are

The Munsell Color Science Laboratory is made up of five faculty, five staff, and approximately 30 graduate students and visiting scientists. Research in the laboratory falls into the general areas of appearance modeling and psychophysics, fundamental color science, color measurement, and image reproduction. MCSLis made up of seven main laboratories devoted to research and education in these areas and housed in R.I.T.'s Chester F. Carlson Center for Imaging Science. Further information can be found throughout this report and by visiting our website at *www.cis.rit.edu/mcsl.*

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Director's Report

Mark D. Fairchild, Director, MCSL (716)457-2784, mdf@cis.rit.edu
Ph.D., Vision Science, University of Rochester, 1990.
M.S., Imaging Science, Rochester Institute of Technology, 1986.
B.S., Imaging Science, Rochester Institute of Technology, 1986.

With 1999 ending, we are not only wrapping up another very busy and successful year within MCSL, but we are completing our first full decade of existence. While MCSL was born and nurtured in the 80's, we have clearly matured in the 90's. This is not to say that the lab will become static in any way. I fully expect it to remain a dynamic and evolving place far beyond the duration of my career. Now that MCSL is mature, our task becomes assuring that the metaphor of a life becomes inappropriate as we strive to create an immortal entity as envisioned by the Munsell Foundation in 1983.

Last year, one of our major goals was to expand and stabilize our research funding. I'm happy to report that, while this is never-ending task, we have made great strides through the efforts of all our faculty and staff. We now have significant research funding from a number of sources including Canon Information Systems, Dupont, Eastman Kodak, Fuji Photo-Film, Hewlett Packard, IBM, NSF, NYSTAR, Pixel Physics, and Sony with several other proposals pending. We have also received various types of support from a number of other sources including consortia membership, visiting scientists, and gifts in kind. These are all listed on page 23 of this report.

As a challenge for the coming year, we are hoping to reach a wider audience of students through both our degree programs and short courses. With that in mind, we are implementing a major revision of our industrial short courses this coming June with the first offering of our *MCSL Summer School*. The summer school will consist of six days of industrial short courses. Participants will be able to choose to attend as many as three out of six offered courses. Additionally, we will include more "hands-on" activities with morning lectures followed by afternoon laboratory experiences. We hope this will attract a larger, more diverse, set of participants. For our degree programs, we are instituting a variety of activities to spread the word in order to attract greater numbers of applicants and better match the ever-increasing numbers of opportunities for graduates. A related activity is our efforts in the growing domain of distance learning. MCSL faculty and staff will have a significant role in the development and delivery of internet-based graduate courses that will allow students to complete an M.S. degree in Imaging Science with a color imaging concentration (or just take a few color science courses) without ever setting foot on the RIT campus. We expect to have this program started during the latter part of 2000.

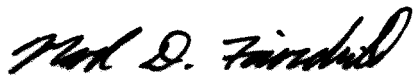
There have been no changes in the MCSL faculty during 1999. However, we are again working without our full compliment as Roy Berns is enjoying his sabbatical leave at the National Gallery of Art. We're happy to hear that Roy is having a productive time and we all look forward to his return later in 2000. On the staff side, Lisa Reniff decided to take an early retirement to spend more time with our daughter, Acadia. While she has given up her office and regular hours, she is still associated with the lab helping us out a few hours a week on special projects. Lisa's office wasn't empty for long as we hired Pano Spiliotis, a recent graduate of the Imaging Science B.S. program, to help maintain the lab's instruments and computer systems. We are all happy to welcome Pano to the MCSLfamily. In one other staff change, Mitch Rosen has transitioned from half-time to full-time as of January 1, 2000.

As usual, the constant flow of students and visitors through the lab gives us the energy to complete our mission. During 1999, Gus Braun, Kathrine Loj, Jonathan Phillips, Mark Reiman, Mark Shaw, Di-Yuan Tzeng, and Barbara Grady completed their degrees and moved on to new careers or returned to their full-time jobs. At the same time we are happy to welcome Scot Fernandez, Sun Ju Park, Lawrence Taplin, and Deniz Schildkraut as new graduate students in the lab. Visiting industrial scientists continue to be a significant part of MCSL. Hideto Motomura of Matsushita Research Institute (Panasonic), Akihiro Ito of Fuji Xerox Company, Masayoshi Shimizu of Fujitsu Laboratories Ltd., and Takaomi Sekiya of Asahi Optical Co., Ltd. (Pentax) completed their stays in the lab during 1999 and returned to their companies. We truly enjoyed having each of them with the lab during their stay and we look forward to continuing our relationships with them. Hirokazu Kasahara of Epson Research and Development and Nobuhito Matsushiro of Oki Data Corporation are currently visiting scientists with the lab. We wish everyone who left the lab in the past year all the best for a successful future and we extend a warm welcome to all our newcomers with all our hopes for a productive stay.

This annual report provides a glimpse of the essence of life within MCSL. As with any such report it cannot be complete. However, I do invite you to read through the report to learn more about the people that make up the lab, our research and teaching activities, and some of the history of the lab. We hope this report will pique your interest in the lab and the field of color science and inspire you to look for more. One place to learn more about MCSL and other aspects of color science is our website at *www.cis.rit.edu/mcsl*, which I encourage you to explore as well.

I'd now like to turn to some of my personal activities. You can read more about my research on page 15, so I'll focus on other aspects here. During 1999, I managed to somewhat curtail my travels to spend some much-needed time at home after my sabbatical year. With my trip to the ISCC annual meeting unexpectedly cancelled, the only conference I personally attended was the Color Imaging Conference in Scottsdale this past November. As usual, it was a most enjoyable and enlightening meeting. (This relaxed pace will change quickly as I already have 6 trips planned for 2000!) My teaching activities in the past year have focused on updating several courses. These included my *Color Appearance* and *Color Measurement Laboratory* courses that were revised substantially in the past year and my *Image Rendering* course that was offered for the first time in 1999. I look forward to continuing to teach these courses in the coming years and to the challenge of developing distance-learning courses for our new offerings. Many of us around Rochester (and the whole country) have begun working hard on plans for the AIC'01 meeting to be held in Rochester. We're busy around MCSL making plans for many aspects of the meeting, not the least of which is an exciting welcoming party to be hosted at RIT. Lastly, I have been busy coordinating our new *MCSL Summer School* offerings for the coming year.

In closing, I thank everyone who has supported MCSLin any way during 1999. Our success would not be possible without the generous support we receive from industry, government, and academia and the amazing hard work of our students and staff. Thank you all for making possible the unique experience that is the essence of MCSL.



Mark D. Fairchild, Ph.D.
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Richard S. Hunter Professor's Report

Roy S. Berns, Richard S. Hunter Professor, (716)475-2230, berns@cis.rit.edu
Ph.D., Color Science, Rensselaer Polytechnic Institute, 1983.
M.S., Textile Science, University of California at Davis, 1978.
B.S., Textile Science, University of California at Davis, 1976.

For the first time in my professional career as an academic, I'm writing my annual report contribution from a new location, the conservation science department of the National Gallery of Art. Beginning September, I've been in residence as an Andrew W. Mellon Senior Fellow at the Gallery. My goal while here is to look for new research directions merging color science and conservation science.

Perhaps my most memorable highlight of this year occurred quite recently. Francisco Imai, my postdoctoral fellow, and Mitch Rosen, senior scientist, came to Washington to help in measuring the spectral properties of one of the Gallery's van Gogh paintings, a self portrait. We used conventional small-aperture spectrophotometry, multi-spectral photography, and multi-filter digital capture. My goal is to produce a spectral image that can be used in our ongoing spectral color reproduction research and for preliminary research in art conservation science. I'm sure I will have lots more to report next year. It is remarkable to have access to such interesting "scenes;" paintings are certainly more interesting than ColorCheckers!

During the fall, Di-Yuan Tzeng completed his doctoral degree in imaging science. We've been working closely for many years and I am both proud of his success and sad that we won't be working together on a daily basis. His research culminated with multi-ink prints closely matching the spectral and colorimetric properties of original test targets and paintings. It was quite a sight to see images matching while toggling the illumination. During the summer, three of our visiting scientists working with me, Hideto Motomura, Akihiro Ito, and Masayoshi Shimizu departed. All were successful in completing interesting research. While in Japan for a conference on multi-spectral imaging, Hideto, Akihiro, Masayoshi, and many of our past visiting scientists met in the Izu peninsula for a MCSL reunion. It's always great to reconnect with our many alumni. Koichi Iino of Toppan, who worked with me for nearly three years, received his doctorate from Chiba University based on research performed while at MCSL. In addition, his two-part article Color Management of Printers detailing his research with us was awarded the best scientific paper to appear in the Journal of Imaging Science and Technology during 1998.

Spectral-based color reproduction was my major research activity during 1999. This included both image acquisition and image reproduction. Francisco Imai has been leading our research efforts in developing practical methods of spectral estimation. More details are described in the research section. We applied for a patent along with the usual conference presentations and journal articles. The image-reproduction research, performed by Di-Yuan Tzeng, was generously supported by DuPont Photopolymers & Electronic Materials. For the 1999 academic year, our goal is to merge these two pieces of research by making a multi-ink reproduction of the van Gogh self portrait.

Last year, as this year, I've spent every free moment writing the third edition of *Billmeyer and Saltzman's Principles of Color Technology*. It is nearly complete; the goal is to have the book available March, 2000. It has been a very instructive process in desktop publishing: I have a much better appreciation for the difficulties in implementing color management within the graphic arts industry.

As always, I'm very lucky to be associated with MCSL. My activities would not be possible without the financial support through the Hunter Professorship, industry, and personal contributions from Mrs. Elizabeth Hunter, and intellectual support from my students, colleagues, and staff. Thank you all very much. I would also like to acknowledge my new colleagues from the National Gallery of Art who have been very kind and welcoming.

Xerox Professor's Report

Noboru Ohta, Xerox Professor, (716)475-7061, noboru.ohta@cis.rit.edu
Ph.D., Applied Physics, Tokyo University, 1973.
M.S., Physical Chemistry, Tokyo University, 1968.
B.S., Chemistry, Tokyo University, 1966.

Through close cooperation with our staff, I have made healthy progress toward my objectives. At the Industrial Associates Meeting held on November 18, 1999, I reviewed the present status briefly.

With respect to teaching, I opened a new Spring Course on *Color Reproduction Optimization Methods* for graduate students. Here, students are taught means for the optimization of spectral absorption bands for three subtractive color dyes by using various criteria such as the area of obtainable color gamut or the stability of selective grays. The optimizations are implemented by the students through extensive programming in IDL or MATLAB. Last year, they all enjoyed their tasks. Eventually the students discovered that the three dyes in current use, selected through the benefit of many years' experience, happen to be very close to the optimum. As a fall course, I presented *Applied Colorimetry* using a textbook entitled *Color Engineering.* This book is an English translation of my first book which has been published in Japanese by Tokyo Denki University Press, Tokyo, 1993. In this course the basis and application of colorimetry is described. The students also enjoyed a variety of homework where they implemented relevant computer programs.

My research progress for this year is described in detail in the research section on page 19 of this report. Research activities have picked up at a very fast pace owing to close and enthusiastic cooperation of my three Ph.D. students. The participation of new visiting scientists and the initiation of new joint projects have also provided fuel to our research activity.

To strengthen relationships with partners outside of RIT, I have initiated a number of cooperative activities with universities and industry. Among them, a faculty exchange program with Chiba University is worth noting. We plan to exchange the faculty between RIT and Chiba University once a year. On that occasion, we will hold a symposium on imaging science. Our hope is to expand this liaison in such a way that our Japanese and, eventually, European partner universities come together with RIT to form a strong and active *imaging science triangle*. As a first step, a group of Professors from Chiba University visited RIT in September, 1999 and delivered a series of valuable and interesting lectures. They are Professors Yoichi Miyake, Takashi Kitamura, Hirohisa Yaguchi, and Hideaki Haneishi. This symposium was held at CIS with participation of the four Chiba Professors. Professor Miyake described *Education of imaging science in Chiba University* and *Multi-spectral imaging and its application*. Professor Kitamura introduced *A high definition color hard copy and rewritable marking.* Professor Yaguchi reviewed his recent work *Categorical colors in a color appearance space.* And Professor Haneishi lectured on *Color image processing, image reconstruction, and image processing.* All lectures were stimulating and deeply impressed the audience. During their stay at CIS an official contract on the faculty exchange program was signed. We introduced our activities in imaging science at CIS, and on return, our faculty will visit Chiba University sometime during 2000.

Finally, it goes without saying that many of these activities are only possible owing to a variety of supports from the MCSL and CIS staff, the financial support from the Xerox Professorship, and a number of corporate sponsors. Taking this opportunity, I would like to heartily thank you all.

Faculty & Staff Activities

Jonathan S. Arney, Associate Professor, (716) 475-7322, jsapci@rit.edu
Ph.D., Chemistry, University of N.C., Chapel Hill, 1975.
B.S., Chemistry, Wake Forest University, 1968.

Most of the year was focused on new educational programs in the Center for Imaging Science, with a central theme of increasing enrollment in the undergraduate program and providing professional work experiences for undergraduates in the program. The mechanism for both was a workshop for high school teachers on the use of imaging technology for teaching science, math, and technology in high schools. The idea is to place the term "imaging science" in the high school environment and to associate the term with RIT. Several undergraduate students in the Center were hired to work as paid assistants to develop and present the workshop. Results thus far have been very satisfying. Teachers who have been through the first workshops have been very positive in their feedback, and students who have worked with the project have earned the admiration of the faculty and staff for their hard work and creativity. The project will continue as a permanent part of the Center in partnership with an Arizona based organization called Center for Image Processing inEducation (CIPE). Thus, the *National Imaging Technology in Education Conference* will be held this summer on RIT campus.

Two new courses for the undergraduate curriculum were implemented for the first time this year. The courses are *Colorimetry* and *Color and Tone Reproduction.* Our undergraduates will now graduate with a considerably better understanding of these topics.

A lot of other things have been going on this year. I was asked to serve as “Opponent” for Mr. Per-Ake Johansson's Ph.D. defense at the Swedish Royal Institute of Technology in Sweden. Also, four publications from my lab were included in a monograph called *Recent Progress in Digital Halftoning,* published by IS&T. Three other papers on halftone systems made it in print in Journal of Imaging Science and Technology, and a new project has been started in partnership with Dr. Peter Anderson (Computer Science at RIT) to develop and characterize new ideas in digital halftoning. Very good work was done during the Summer by one of my undergraduates to calibrate a 3-chip color camera for color microdensitoemtry. Work with this instrument is focused on understanding micro-color distributions in halftones. Preliminary results clearly show the Neugebauer model is exactly the way color is NOT distributed in halftone images. The work is expected to lead to much better alternatives for color calibration of color halftone processes. One ambitious goal of the current work is to be able to calibrate a color printer so it remains in calibration even with a change in halftone process (65 LPI to 200 LPI, or clustered dot to error diffusion, etc.) It's a long way from the usual “n” factor!

Publications:
J.S. Arney, E. Pray, and K. Ito, “Kubelka-Munk Theory and the Yule-Nielsen effect on Halftones,” *J. Imag. Sci. and Technol,* 43(4), 353 (1999).

J.S. Arney, and S. Yamaguchi, “Symmetry Properties of Halftone Images I: Scattering Symmetry and Pattern Symmetry,” *J. Imag. Sci. and Technol,* 43(4), 359 (1999).

J.S. Arney and A. Tsujita, “Symmetry of Halftone Images II: Accounting for Ink Opacity and Dot Sharpness,” *J. Imag. Sci. and Technol,* 43(4),359 (1999).

Colleen M. Desimone, Secretary, (716) 475-7189, cmd9553@rit.edu
A.A.S., Business, Rochester Institute of Technology, 1995.

Every year I look for new challanges and opportunites of growth but this year they found me–this year sure has proven one of growth and change for me as well as MCSLand CIS. I was out on maternity leave the early part of 1999 for my second child. I now have the so-called “perfect family”, a boy, Michael (four-years-old) and a girl, Nicole (1-year old), but no dog. Soon after returning to work, Ian Gatley (CIS Director) offered me the opportunity to put some of my graphic design education to work and design a CIS newsletter and continue as managing editor with design and layout my primary focus. With my boss’s permission, I took on the challange. For the first time in my

eleven years with MCSL I am an employee of CIS! I successfully completed the first issue of the *Imaging Connection* this past fall and am currently planning the next issue. It is published semi-annually at the time of the Industrial Associates Meeting. I'm proud to say I've been with the lab since close to it's inception, with Roy, Mark, Lisa and myself as the nucleus but it is exciting to see how we've grown and what we've accomplished. Many times expansion can occur too quickly but MCSL has always made specific efforts to take small, managable steps. Currently we have five faculty, five staff, one post-doctoral fellow, three visiting scientists, ten full-time and six part-time students; our numbers are comfortable for faculty, staff and visiting scientists but we are actively seeking to expand our full-time graduate enrollment. Extra efforts will be taken in the recruiting area within MCSL as well as the CIS.

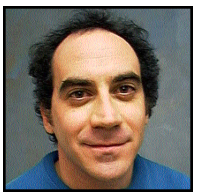
Francisco Imai, MCSL Post Doctoral Fellow, (716)475-7842, imai@rit.edu
Ph.D., Imaging Science, Chiba University, 1997.
M.S., Electronics & Computer Eng., Technological Institute of Aeronautics, Brazil, 1993.
B.E., Electronical Engineering, Technological Institute of Aeronautics, Brazil, 1990.

I am presently in my third year here at the Munsell Color Science Laboratory. During the past year I was active in research involving multi-spectral image capture and reproduction. Based on the alternative way to capture multispectral images by combining a trichromatic camera and either a set of absorption filters or multi-illumination that was developed during last year, I worked in the evaluation and comparison of the spectral reconstruction performance in different spaces, such as reflectance, and Kubelka-Munk. These efforts have led to some presentations in conferences, an application for a patent, and a journal manuscript.

In October, I had a great opportunity to travel to Japan with Prof. Roy Berns and Mitch Rosen to attend the *International Symposium on Multispectral Imaging and Color Reproduction for Digital Archives*, organized by Prof. Yoichi Miyake, my Ph.D. degree adviser. It was exciting to be there at the conference considering that it is the first conference exclusively on multi-spectral imaging and color reproduction, sponsored by the Society of Multispectral Imaging of Japan. After the symposium, I, Mitch, and Roy had a marvelous time at Toi hot springs in West Izu Peninsula with many of the alumni visiting scientists of MCSL thanks to Hideto Motomura's kind arrangements. After the retreat I spent two weeks in Japan visiting research centers, universities related to my field of research: Akasaka Natural Vision Research Center in Tokyo which conducts a project to realize a system that reproduce the accurate color of objects based on multispectral imaging and multiprimary color display, Optics Laboratory of Prof. Kazue Ishikawa at Sophia University, the Advanced Technology Development Center at Fuji Xerox arranged by Akihiro Ito, the Color Imaging Group at Sony arranged by Naoya Katoh, the Image Processing Laboratory at Epson in Nagano arranged by Hirokazu Kasahara, the Display Group at Mitsubishi Electric in Kyoto arranged by Tetsuya Kuno, the laboratory of Prof. Shoji Tominaga at the Osaka Electro-Communication University, and the Information and Network Research Laboratory at Matsushita Research Institute Tokyo arranged by Hideto Motomura. Besides visiting the laboratories I gave presentations on the MCSL multispectral reproduction system.

Following this travel to Japan, I went to Scottsdale, Arizona to present a paper at the Seventh Color Imaging Conference. After the Color Imaging Conference I visited Prof. Brian Wandell's Laboratory in Stanford, California. These travels were really worthwhile because I met many scientists whose researches are related to my current project. I also realize that there are a lot of groups working with multispectral imaging capture but few groups working with end-to-end spectral reproduction from scene to hardcopy that gives us a position of front runner in this kind of research. We are very fortunate to have Dr. Di-Yuan Tzeng's (who graduated last year) spectral printing process and I've been working closely to Mitch Rosen, Xiao-Yun Jiang and Dave Wyble in our end-to-end spectral reproduction project. It is particularly exciting to have Prof. Roy Berns on sabbatical at the National Gallery of Art in Washington, D.C. because it created us a great opportunity to implement the multispectral project applied for artwork reproduction. In this initiative, I and Mitch Rosen went to Washington, D.C. in December to perform preliminary image acquisition and spectral measurement of a self-portrait painting by Vincent van Gogh.

Finally, I would like to use this opportunity to thank all the faculty, staff and students who have helped and supported my activities in the MCSL.



Ethan D. Montag, Research Assistant Professor, (716) 475-5096, edmpci@rit.edu
Ph.D., Experimental Psychology, University of California at San Diego, 1991.
M.S., Experimental Psychology, Universify of California, at San Diego, 1986.
B.S., Psychology, University of Pennsylvania, 1985.

Looking back over the past year I am not so much reminded of what I have accomplished but what I have started. The past year was filled with new activities and initiatives that will keep me busy in the year 2000 and beyond. Last year, during our MCSL faculty and staff retreat, we pondered the question of the existence of the lab, its roles and functions, and its future. As I think about the past year it reminds me that the Munsell Lab is still very much a vital and evolving institution.

During the past year my teaching responsibilities included *Vision and Psychophysics*, *Color Science Seminar*, and *Color Measurement Laboratory II.* Each year I am surprised at how much I learn from the students while teaching each class. *Color Science Seminar* is especially interesting as students prepare presentations relating to their upcoming thesis work and other diverse areas of Color Science. The participation of visiting scientists, staff, postdoc, and other faculty always makes this class lively and surprising. Currently I am also co-teaching *Color Perception*, an undergraduate psychology class, with Eriko Miyahara.

This year I began an initiative as part of RIT's First-in-Class initiative to implement the Masters in Imaging Science with the color imaging concentration as a distance learning program. Together with other faculty from the Center, we have met numerous times with the staff at Distance Learning to learn about this process. *Vision and Psychophysics* will be offered in the fall 2000 as a distance class so I will be very busy getting this on line.

With Roy on sabbatical I assumed some of his duties as coordinator of the color science program. I would like to thank Colleen for her patience and help in this endeavor.

It hasn't been all teaching and administration. Although the MCSLIndustrial Color Difference Consortium has been dissolved I have continued research on color tolerances. I have also been involved in advising Alexei Krasnoselsky who is completing his masters thesis involving texture and color differences. Support from the Dean's Program Initiative Grant program allowed me to complete an initial research project on the use of pseudocolor in image display. I have also been busy with setting up grants and contracts for new research involving image quality and spectral rendering. I look forward to continued activity in all these areas of research.

Lisa A. Reniff, Color Specialist, larpci@rit.edu
M.S., Color Science, Rochester Institute of Technology, 1989.
B.S., Chemistry, Rochester Institute of Technology, 1986.

This past year has been one of great change for me. At the end of the academic year I stepped down as a part-time employee of MCSL for personal reasons. However, I am continuing to work for the lab on an as needed basis, based at home. This past summer and fall I have been creating some presentations for the *Color Measurement Lab I* and summer short courses. Although I am based at home (*i.e.* no office), I try to come into the lab on a regular basis and am always available via email.

Mitchell Rosen, Sr. Color Scientist, (716)475-7691, rosen@cis.rit.edu
M.S., Imaging Science, Rochester Institute of Technology, 1994.
B.S., Computer Science, Tufts, 1984.

The Color Engineering Laboratory has taken form this year. As a facility for imaging research, it has acquired a critical amount of computational and imaging resources. As a collection of students and researchers, it now reflects a high level of cohesiveness. I have enjoyed participating and helping Dr. Noboru Ohta in the management of Color Engineering's early growth. CEL is sure to continue maturing and reshaping itself in the years to come. It is comforting to know that we have laid a strong foundation.

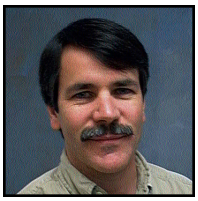
My own research has seen progress this year. I have been concentrating on building infrastructure for my *Spectral Color Management* and *Data-Efficient Imaging Spectrometry* project. This summer, with the assistance of Willie Jiang, a spectral portrait of Roy Berns was captured. As a spectral image, we were able to derive an estimate of the complete spectral reflectance at every pixel of the scene. We also developed novel approaches to image processing spectral images which, in this case, allows us to prepare them for printing on a 6-color printer. These approaches were built upon the recently completed Ph.D. work of Di-Yuan Tzeng. To our knowledge, we produced the first end-to-end spectral reproduction of a complex scene since the photographic work of Gabriel Lippmann at the end of the 19th Century. The results of our spectral portraiture were presented in Chiba, Japan at the *First International Symposium on Multispectral Imaging and Color Reproduction*.

A very rewarding aspect to my work has been the growing interactions between my projects and those of others here in the Munsell Laboratory. With a number of us spending increasing time looking into various aspects of spectral imaging, I expect these interactions to continue. As we each bring our own strengths to bear on these problems, we are finding that the whole is often far more than the sum of the parts.

Pano Spiliotis, Assistant Color Scientist, (716)475-7188, pano@cis.rit.edu
B.S., Imaging Science, Rochester Institute of Technology, 1999.

My first year here at MCSL has been one of transition. It has been pretty painless going from a student to an employee of RIT. I thank the Lab and the Center for Imaging Science for all their help with this transition.

This past year has been one of upgrading. We have upgraded the majority of our computer facilities and ensured that the instrumentations are compatible with the upgraded computers. In the upcoming year we will be completing the upgrade to the rest of the facilities. In the past year, I had the opportunity to help with the marketing of the Color Science Program. I am pleased that I can bring my marketing knowledge and experience to the Lab. This past year has been enjoyable and I'm pleased to be working with a great group.



Dave Wyble, Color Scientist, (716) 475-7310, wyble@cis.rit.edu
M.S., Color Science, Rochester Institute of Technology, 1998.
B.S., Computer Science, SUNY Brockport, 1992.

It seems like every time I turn around, Colleen is asking for annual report input again. Another year has flown by, and I am really excited about where the lab is going as we enter the colloquial -"new millennium." As the saying goes, the only thing constant this year has been the change. Not all of these changes were positive. In particular, I do miss the expertise Lisa lent when she was here half-time. Although we still see her around some, I respect this difficult personal decision and I wish her the best in her new life. I am enjoying the interaction with our new staff scientist Pano. Bringing in some youth can never hurt an organization. Perhaps I am simply relishing the idea that I am no longer the new kid on the block!

I am getting more comfortable with the organization of the Lab. Everyone appears to be settling into the cycles of Dr. Ohta's presence. (Although I will be glad when this cycle of faculty sabbaticals ends!) I find myself increasingly relying on the help of Mitch and the others involved in the Color Engineering Lab. We have shown that when we pull together great things can be accomplished. I expect this interaction to continue strengthening to everyone's advantage. As this happens, it is impressive to see the grand picture of the whole Lab grow all around us.

This year brought many interesting challenges and some tough personal choices on my part. With Mark's help, I am feeling very good about the direction the Lab is heading, and the role I will have in fulfilling Lab goals. I look forward to continued and new work with all of the students, staff, and faculty in and around the Munsell Lab.

Publications

D.R. Wyble and R.S. Berns, "ACritical Review of Spectral Models Applied to Binary Color Printing," *Color Res. Appl*., **25**, 4-19 (2000).

D.R. Wyble and M.D. Fairchild, "Prediction of Munsell Appearance Scales Using Various Color Appearance Models," *Color Res. Appl.,* in press (2000).

Visiting Scientists

Hirokazu Kasahara, Visiting Scientist, Epson Research & Development, Japan
Researching with Dr. Noboru Ohta

My first five months at MCSL as a visiting scientist have past. During this time, I have received a lot of useful information regarding basic and applied color science from valuable courses like, *Applied Colorimetry*, *Vision and Psychophysics*, *etc.* Discussions with MCSL faculty, staff and students have been helpful too. I want to thank everyone who has supported my research so far.

I have two themes to research while at MCSL. The first work involves the analysis of image quality with Dr. Ohta and Dr. Montag. In recent years, it has been shown in various researches that image quality is affected by sharpness, graininess and color gamut of image, but it is not clear which parameter is the most effective. In order to increase the image quality of printing, I will construct image quality scales by using psychophisical techniques and measure physical values of image, *e.g.* sharpness and graininess, and make clear the relation between psychophisical scales and each physical value.

The second work involves the characterization of an inkjet printer. Although we can make the model which has practically enough accuracy by empirical approach, I will use the physical model because it needs less number of measurements for optimization. The aim of this work is to establish the model which is as accurate as empirical approach and can be optimized easier.

Nobuhito Matsushiro, Visiting Scientist, Oki Data, Japan
Researching with Dr. Noboru Ohta

My research theme is “Mathematical Optimization Based on Information Theory About Color Science.” My basic specialty is information theory and now I have a great interest in its application to color science. A portion of my achievement was presented by Dr. Ohta at CIC98 entitled “Inverse of Designing Illuminants Based on Information Theory.” A paper coauthored with Dr. Ohta will be presented in a Japanese academic society, entitled “Orthogonal Lighting Model and Its Applications.” We expect to submit an extended version to several journals this year. These research findings will be applied to color engineering in my company. The education and information I learn while at the Munsell Color Science Lab and the Color Engineering Lab will bring a great benefit to my company.

It's my great pleasure to do my research at the best place for color science in the world.

Graduate Students

Arturo Aguirre, Full-Time, M.S. Candidate, Color Science
B.S., Chemical Engineering, ITESM Mexico, 1997.
Thesis Topic: Color Printing Modeling

Gus Braun, Full-Time, Ph.D. GRADUATE, Imaging Science, 1999.
M.S., Imaging Science, Rochester Institute of Technology, 1991.
B.S., Imaging Science, Rochester Institute of Technology, 1989.
Thesis Topic: Color Gamut Mapping

Doug Corbin, Part-Time, M.S. Candidate, Color Science
M.S., Photographic and Imaging Science, Rochester Institute of Technology, 1982.
B.S., Chemistry, University of California at Santa Barbara, 1974.
Thesis Topic: Colorimetric Modeling of a CRT-Based Digital Film Recorder

Mihai Cuciurean-Zapan, Full-Time, Ph.D. Candidate, Imaging Science
M.S., Imaging Science, Rochester Institute of Technology, 1997.
B.S. & M.S., Mathematics, Al.I.Cuza University, Romania, 1982.
Thesis Topic: TBD

Clara Cuciurean-Zapan, Part-Time, Ph.D. GRADUATE, Imaging Science
B.S. & M.S., Mathematics, Al.I.Cuza University, Romania, 1982.
Project Topic: Colorimetric and Spectral Modeling of Texture

Scot Fernandez, Full-Time, M.S. Candidate, Color Science
B.S., Imaging & Photographic Technology, Rochester Institute of Technology, 1999.
Thesis Topic: TBD

Jason Gibson, Full-Time, M.S. Candidate, Color Science
B.S., Imaging Science, Rochester Institute of Technology, 1994.
Thesis Topic: Color Tolerances on Various Image Displays

Sergio Gonzalez, Full-Time, M.S. Candidate, Color Science
B.S., Chemical Engineering, ITESM Mexico, 1997.
Thesis Topic: Fluorescence Colorimetry of Printing Materials

Barbara Grady, M.S. GRADUATE, Color Science, 1999.
B.S., Imaging Science, Rochester Institute of Technology, 1993.
A.A.S., Optical Engineering Technology, Monroe Community College, 1990.
Project Topic: Illuminant Sensitivity of Printing Materials

Sharron Henley, Full-Time, M.S. Candidate, Color Science
B.S., Printing & Packaging Technology, West Herts College, England, 1997.
Thesis Topic: Color Appearance in Mixed Adaptation

Pat Igoe, Part-Time, M.S. Candidate, Color Science and Imaging Science
M.S., Software Development & Management, Rochester Institute of Technology, 1996.
B.S., Computer Science, Rochester Institute of Technology, 1992.
Project Topics: Development of a New Cone-Fundamental Based Color Space with Uniform Small Color Differences, Models of Mixed Adaptation

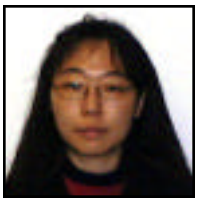
Xiao-Yun (Willie) Jiang, Full-Time, Ph.D. Candidate, Imaging Science
M.S., Optical Engineering, Beijing Institute of Technology, 1996.
B.S., Optical Engineering, Beijing Institute of Technology, 1993.
Thesis Topic: Computational Approaches to Color Vision

Garrett Johnson, Full-Time, Ph.D. Candidate, Imaging Science
M.S., Color Science, Rochester Institute of Technology, 1998.
B.S., Imaging Science, Rochester Institute of Technology, 1996.
Thesis Topic: Measuring and Modeling Image Quality, Spectral Rendering

Alexei Krasnoselsky, Full-Time, M.S. Candidate, Color Science
Ph.D., Chemistry, Institute for Bioorganic Chem., Moscow, Russia, 1990.
Thesis Topic: Effects of Illumination Geometry on the Color Difference Judgements of Textured Color Samples

Katherine Loj, Part-Time, M.S. GRADUATE, Color Science, 1999.
B.S., Optics, University of Rochester, 1987.
Project Topic: Color Management in Printing Systems

Susan Lubecki, M.S. Candidate, Color Science
B.S., Mathematics and Computer Science, University of Notre Dame, 1984.
Project Topic: Verification of ICC Profiles



Sun Ju Park, Full-TIme, M.S. Candidate, Color Science
M.S., Software Development & Management, Rochester Institute of Technology, 1997.
Thesis Topic: TBA

Mark Reiman, Part-time, M.S. GRADUATE, Color Science, 1999.
B.S., Chemistry, Rochester Institute of Technology, 1987.
Project Topic: Testing and Optimizing Color Management Software for Digital Photography and Color Printing

Mitchell Rosen, Full-Time, Ph.D. Candidate, Imaging Science
M.S., Imaging Science, Rochester Institute of Technology, 1994.
B.S., Computer Science, Tufts, 1984.
Thesis Topic: Spectral Color Management

Deniz Schildraut, Part-Time, M.S. Candidate, Color Science
Ph.D., Analytical Chemistry, University of Oklahoma, Norman 1982.
Thesis Topic: TBD

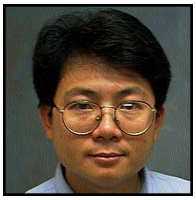
Mark Shaw, Full-Time, M.S. GRADUATE, Color Science, 1999.
B.Sc., Graphic Media Studies, Print. & Pub. Tech., West Herts College, England, 1997.
Thesis Topic: Evaluation of the Accuracy of Various Sets of Color Matching Functions and Cone Responsivities

Quan Shuxue, Full-Time, Ph.D. Candidate, Imaging Science
M.S., Optical Insturment, Beijing Institute of Technology, 1997.
B.S., Opto-Electronic Technology, Beijing Institute of Technology, 1994.
Thesis Topic: Spectral Sensitivity Optimization for Digital Color Imaging

Qun (Sam) Sun, Full-Time, Ph.D. Candidate, Imaging Science
M.S., Physics, Flordia International University, 1997.
B.S., Electronic & Science Technology, East China Normal University, 1985.
Thesis Topic: Image-Based Spectral Rendering and Spectral Image Quality

Richard Soursa, Part-Time, M.S. Candidate, Color Science
B.S., Imaging Science, Rochester Institute of Technology, 1987.
Project Topic: Evaluation of Retinex Algorithms

Lawrence Taplin Full-Time, M.S. Candidate, Color Science
B.S., Computer Science, University of Delaware, 1996.
Thesis Topic: TBD



Di-Yuan Tzeng, Full-Time, Ph.D. GRADUATE, Imaging Science, 1999.
M.A., Mathematics, Central Connecticut University, 1994.
B.S., Printing Technology, Chinese Culture University, 1988.
Thesis Topic: Spectral-Based Color Separation Algorithm Development for Multiple-Ink Color Reproduction

Joan Zanghi, Part-Time, M.S. GRADUATE, Color Science, 1999.
B.S., Computer Science, SUNY Brockport, 1988.
Project Topic: Flesh Color Tolerance Comparison Using Patch and Image Stimuli

MCSL Alumni

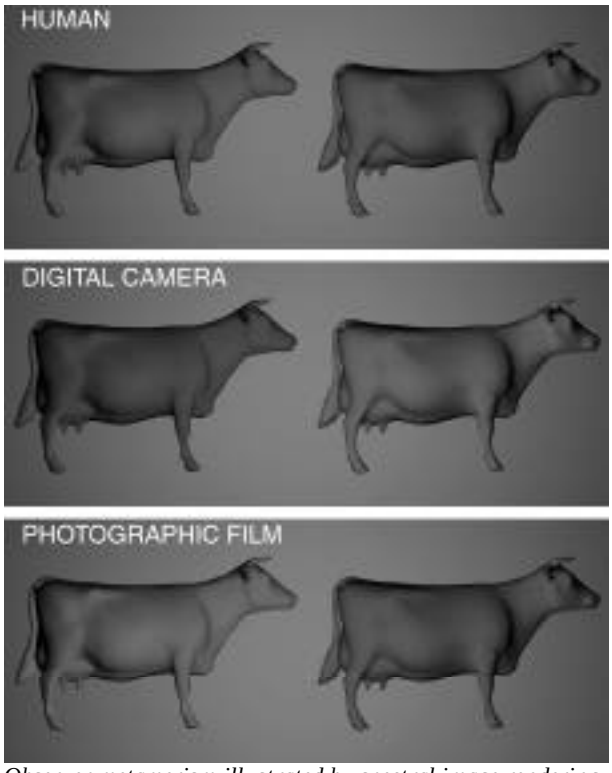
Seth Ansell, M.S., Color Science, 1995.
Richard Alfvin, M.S., Color Science, 1995.
Scott Bennett, M.S., Color Science, 1998.
Gus Braun, Ph.D., Imaging Science, 1999.
Karen Braun, Ph.D., Imaging Science, 1996.
Peter Burns, Ph.D., Imaging Science, 1997.
Cathy Daniels, M.S., Color Science, 1996.
Denis Daoust, M.S., Imaging Science, 1987.
Fritz Ebner, Ph.D., Imaging Science, 1998.
Mark Fairchild, M.S., Imaging Science, 1986.
Sue Farnand, M.S., Imaging Science, 1995.
Wayne Farrell, M.S., Imaging Science, 1987.
Mark Gorzynski, M.S., Imaging & Color Science, 1992.
Barbara Grady, M.S., Color Science, 1999.
Brian Hawkins, M.S., Color Science, 1997.
Christopher Hauf, M.S., Color Science, 1997.
Garrett Johnson, M.S., Color Science, 1998.
Naoya Katoh, M.S., Color Science, 1998.
Taek Kim, M.S., Imaging & Color Science, 1992.
Audrey Lester, M.S., Color Science, 1994.
Yan Liu, M.S., Color Science, 1991.
Katherine Loj, M.S., Color Science, 1999.
Mitch Miller, M.S., Imaging Science, 1989.
Nathan Moroney, M.S., Color Science, 1993.
Ricardo Motta, M.S., Color Science, 1991.
Amy North, M.S., Imaging Science, 1991.
Jonathan Phillips, M.S., Imaging Science, 1999.
Kelvin Peterson, M.S., Imaging Science, 1989.
Jason Peterson, M.S., Imaging Science, 1994.
Elizabeth Pirrotta, M.S., Color Science, 1993.
Yue Qiao, M.S., Imaging Science, 1996.
Jack Rahill, M.S., Imaging Science, 1996.
Mark Reiman, M.S., Color Science, 1999.
Lisa Reniff, M.S., Color Science, 1989.
Rich Riffel, M.S., Imaging Science, 1992.
Brian Rose, M.S., Color Science, 1992.
Mitch Rosen, M.S., Imaging Science, 1993.
Mark Shaw, M.S., Color Science, 1999.
Hae Kyung Shin, M.S., Imaging Science, 1996.
James Shyu, M.S., Color Science, 1994.
Greg Snyder, M.S., Imaging Science, 1991.
Michael Stokes, M.S., Color Science, 1992.
Debra Seitz Vent, M.S., Imaging Science, 1994.
Di-Yuan Tzeng, Ph.D., Imaging Science, 1999.
Alex Vaysman, M.S., Imaging Science, 1997.
Dave Wyble, M.S., Color Science, 1998.
Joan Zanghi, M.S., Color Science, 1999.

Research - Mark D. Fairchild

Better Color Images Everywhere

My research has continued to touch on a variety of interesting topics in color science. The freedom to pursue whatever seems interesting at the time is one of the great benefits of an academic research environment. As difficult as it is to place a single descriptor on my research interests, it is clear that my focus has usually been on making color images in every domain better for those experiencing them. As with the lab as a whole, my research is energized by the students working with me. I have been fortunate to have a large number of excellent students working with me over the past year. For each student, the main research sponsor is listed in parentheses.

Gus Braun (Xerox, NSF, NYS) completed his Ph.D. on the development and testing of general-purpose gamut-mapping algorithms and moved on to a full-time job with Eastman Kodak in Rochester. Gus prepared a number of presentations and papers on his work during 1999 and you will continue to see the results of this research well into 2000. Mihai Cuciurean-Zapan (Fuji) began work with me on the extension of a multiscale model of spatial and color vision to be used as the basis for an image quality metric. In the coming year he will be testing the model and comparing it with other models for the measurement of image differences. Jason Gibson (IBM) is working on the psychophysical measurement of color tolerances in pictorial images on a variety of displays ranging from a typical CRT, to prints, to a prototype high-resolution LCD display. Sergio Gonzalez (Labsphere) is examining the use of bispectral measurements of fluorescent printing materials and the errors introduced by neglecting fluorescence in typical colorimetric measurements. Sharron Henley (Canon) is investigating color appearance in cross-media color reproduction (CRT to print comparisons) under typical viewing situations with mixed adaptation and the application of CIECAM97s to these situations. Garrett Johnson (Kodak, Fuji) has been using his spectral image rendering software to create very-high-resolution, noise-free, spectral images for use as test targets in image-systems simulation. He will also be using these and other test images in an extensive psychophysical examination of the perception of image sharpness as a function of several physical image parameters. Matt Ochs is working with me on his undergraduate senior project trying to derive a linear equivalent of the chromatic adaptation transform in CIECAM97s that could greatly simplify its robust use and practical application. Mark Shaw completed his M.S. thesis on observer metamerism and the accuracy of color matching functions (once again illustrating the quality of the CIE functions) and moved on to a new job with Applied Science Fiction in Austin, Texas. Sam Sun (Kodak) began research with me on image-based spectral rendering of human portraiture and is currently focusing on the spectral capture of a pleasant, high-quality, human portrait. I also had a number of part-time graduate students who worked on M.S. projects with me. These included Clara Cuciurean-Zapan, Barb Grady, Kathy Loj, Susan Lubecki, Jonathan Phillips, and Richard Suorsa who worked on a variety of topics in image and color reproduction.



Observer metamerism illustrated by spectral image rendering. The two cows match for human observers, but do not match for a digital camera or photographic film. This result cannot be obtained with traditional RGB computer graphics.

Lastly, I managed to spend some time in the past year on some personal research on the relationship between image contrast and perceived brightness and on various techniques of image rendering. I have

truly enjoyed taking the opportunity to write my own computer programs, run my own visual experiments, and analyze my own data. It definitely helps me keep a good perspective on what I am asking my graduate students to do in their projects.

For more information on these and other research projects, please refer to my web page at *www.cis.rit.edu/fairchild* or the MCSL page at *www.cis.rit.edu/mcsl.*

Publications

D.R. Wyble and M.D. Fairchild, "Prediction of Munsell Appearance Scales Using Various Color Appearance Models," *Color Res. Appl.,* in press (2000).

K.M. Braun and M.D. Fairchild, "Psychophysical Generation of Matching Images for Cross-media Color Reproduction," *J. of the Society of Information Display,* in press (2000).

G.J. Braun and M.D. Fairchild, "Image Lightness Rescaling Using Sigmoidal Contrast Enhancement Functions," *Journal of Electronic Imaging,* **8**, 380-393 (1999).

G.M. Johnson and M.D. Fairchild, "Full-spectral Color Calculations in Realistic Image Synthesis," *IEEE Computer Graphics & Applications,* **19:**4, 47-53 (1999).

M.D. Fairchild, and G.M. Johnson, "Color Appearance Reproduction: Visual Data and Predictive Modeling," *Color Res. Appl.,* **24**, 121-131 (1999).

Presentations

S. Gonzalez and M.D. Fairchild, Evaluation of bispectral spectrophotometry for accurate colorimetry of printing materials, CORM Annual Meeting, Rochester, in press (2000).

M.D. Fairchild, Modeling color appearance, spatial vision, and image quality, Color Image Science 2000, Derby, in press (2000).

M.D. Fairchild, On the perception of brightness and contrast of variegated backgrounds, ISCC 2nd Panchromatic Conference, Savannah, in press (2000).

G.J. Braun and M.D. Fairchild, General-purpose gamut-mapping algorithms: Evaluation of contrast-preserving rescaling functions for color gamut mapping, IS&T/SID 7th Color Imaging Conference, Scottsdale, 167-192 (1999).

M.D. Fairchild, A victory for equivalent background — On average, IS&T/SID 7th Color Imaging Conference, Scottsdale, 87-92 (1999).

G.J. Braun and M.D. Fairchild, Gamut mapping for pictorial images, TAGA Proceedings, 645-660 (1999).

G.J. Braun and M.D. Fairchild, Image lightness rescaling using sigmoidal contrast enhancement functions, Color Imaging: Device Independent Color, Color Hardcopy, and Graphic Arts IV, Proc. SPIE 3648, 96-107 (1999).

Research - Roy S. Berns

Multi-Spectral Image Acquisition

This year's research has concentrated on spectral estimation from multi-illuminant or multi-filter trichromatic image capture. Essentially, color images are collected for multiple illuminations, yielding multi-band information in sets of three. Using six or nine eigenvectors from *a priori* spectral analyses, spectral images are estimated. This research has been carried out by Francisco Imai. We have presented our results at the Color Imaging Conference in Scottsdale and the first Multispectral Imaging Conference at Chiba University. We have also applied for a patent.

Spectral Printing Models

Research supported by DuPont Photopolymers & Electronic Materials has been aimed at spectral-based color printing. Specifically, our interests include the multi-variate analysis of objects requiring printed reproductions, the multi-variate analysis of ink sets, and the selection of an ink set that leads to minimal metamerism between an original and its printed reproduction. Di-Yuan Tzeng has been carring out this research. This year, he has focused on building a multi-ink spectral printing model based on the research of Iino, and adding this to the previous years' research. This project was completed during the fall in which DuPont Waterproof images were made of a ColorChecker and several paintings. The results were very encouraging and suggest that multi-ink printing in which the separation algorithm is optimized for minimal metamerism can be a viable approach to color printing. Di-Yuan presented his research results at the CIC conference in Scottsdale and the joint ISCC / TAGA conference in Vancouver.

Self portrait of van Gogh which is the subject of MCSL spectral imaging research.

Art Conservation Science

This is a new research section. My first project at the National Gallery of Art has been in colorant selection for inpainting minimizing metamerism. "Inpainting" is a restorative technique for paintings that have undergone degradation resulting in losses. Missing areas are filled and painted such that the conserved area is indistinguishable from its surround under typical museum illumination. Ideally, the selected colorants should result in minimal metamerism. Using single-constant Kubelka-Munk theory, forward-selection stepwise multiple-linear regression, small-aperture reflectance spectrophotometry, and a customized colorant database, colorants can be selected that result in minimal metamerism. This is being tested on two paintings: one by Barnett Newman and the other by Sanford Gifford. An article is in preparation for Studies in Conservation.

Publications

R. S. Berns, “Challenges for Colour Science in Multimedia Imaging Systems,” in L. MacDonald and R. Luo, eds., *Colour Imaging: Vision and Technology*, John Wiley & Sons, England, 99-127, 1999.

E.D. Montag and R.S. Berns, “Visual Determination of Hue Suprathreshold Color-Difference Tolerances using CRT-generated stimuli,” *Color Res. Appl,.* **24**, 164-176 (1999).

F.H. Imai, R. S. Berns,and D.Y. Tzeng ,”A Comparative Analysis of Spectral Reflectance Estimated in Various Spaces Using a Trichromatic Camera System," *Imag. Sci. Tech.*, in press, 2000.

T. Deguchi, N. Katoh, and R.S. Berns, “Clarification of 'Gamma' and the Accurate Characterization of CRT Monitors,” *Proceedings SID International Symposium*, (1999).

Invited Presentations

R. S. Berns, “Munsell Color Science Laboratory industrial color difference consortium – current initiative and future directions,” Proceedings ANTEC 99, Plastics bridging the Millenium, Society of Plastics Engineers, 2873-2877, 1999.

F. H. Imai and R. S. Berns, “Spectral estimation using trichromatic digital cameras,” Proc. Intl. Sym. Multispectral Imaging and Color Reproduction for Digital Archives, Chiba University, in press.

Presentations

D. Y. Tzeng and R. S. Berns, “Spectral reflectance prediction of ink overprints by Kubelka-Munk turbid media theory,” Proc. TAGA, in press.

D. Y. Tzeng and R. S. Berns, “Spectral-based ink selection for multiple-ink printing II. Optimal ink selection,” Proceedings IS&T / SID Seventh Color Imaging Conference, in press (1999).

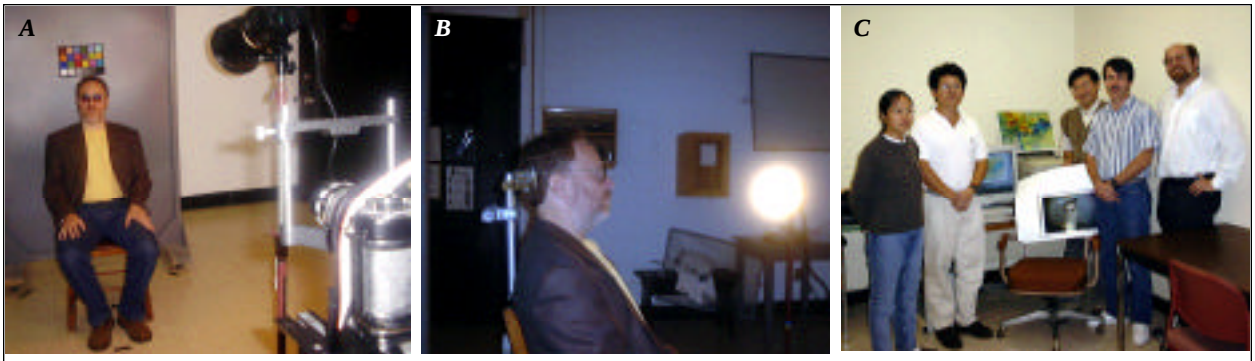
F. H. Imai and R. S. Berns, “Acomparative analysis of spectral reflectance reconstruction in various spaces using a trichromatic camera system,” Proceedings IS&T / SID Seventh Color Imaging Conference, in press (1999).

P.D. Burns and R. S. Berns, “Quantization in multispectral color image acquisition,” Proceedings IS&T / SID Seventh Color Imaging Conference, in press (1999).

Research - Noboru Ohta

Spectral Color Management and Data-Efficient Imaging Spectrometry

Color reproduction today is based on the trichromatic principle. This is true for color photography, printing, television, and hard copying. However trichromatic color reproduction relies on the principle of metamerism. Metamerism is a cumbersome problem in the world of color management where color is manipulated under different illumination conditions and among different color media. In order to alleviate this difficulty, color management extended beyond trichromaticity is now begining to be explored. Mitchell Rosen has been working toward the development of this spectral color management as his Ph.D. dissertation. He has already made a noteworthy progress for the image-input part and has presented the result at the international symposium held at Chiba University in Japan.



(A) *An effort capture a full-spectral image of a face culminated with Roy Berns sitting as model in front of a spectral image capture system.* ***(B)*** *Roy had to sit perfectly still through 16 exposures (410nm to 710nm by 20nm increments). Lights were powered so high for several exposures that Roy ended up with a slight sunburn.* ***(C)*** *Spectral imaging group with 6-color MatchPrint spectral reproduction of Roy's face combining work of Noboru Ohta and Roy Berns to realize end-to-end spectral imaging systems.*

Optimization of Spectral Sensitivities of Color Imaging Devices

Spectral sensitivities are one of the most important factors to control color reproduction quality in color imaging devices. From the theoretical viewpoint, optimal spectral sensitivities are defined simply as linear combinations of the CIE color matching functions. However from the practical viewpoint, this definition is quite useless since the spectral sensitivities corresponding to actual color primaries have negative portions that are physically infeasible. Therefore actual spectral sensitivities of color imaging devices such as color photography have been designed not theoretically but based on long year's experience. Quan Shuxue has been carrying out the optimization of spectral sensitivities by using a variety of evaluation criteria. As a first step, he has evaluated a series of hypothetical spectral sensitivities by using a q-factor and a mu-factor. He will present the results in part at the forthcoming PICS meeting next year.

Estimation of Illuminants Irradiating Object Colors from Their Colorimetric Values

When object colors are photographed with conventional or digital cameras, they are reproduced either on a CRT screen or on a color print. When reproducing color images properly, the information about the taking illuminant is necessarily required. However the information is generally not recorded in the camera. As such, the estimation of the taking illuminant is very important in order to reproduce high-quality color images. A number of methods such as an integrating-to-gray hypothesis, have been proposed to estimate the taking illuminant. However none of them has been fully successful. Jiang Xiaoyun (Willie) has just started a challenging project to establish a reasonable and robust algorithm for estimating the taking illuminant. As a first step, she will evaluate and intercompare existing algorithms so far proposed.

Physical and Psychological Evaluation of Ink-jet Color Images

Recently photographed images are not only printed on conventional photographic color prints but also on color hard copies using an ink-jet process, dye sublimation process, and xerographic process. Each new process is always aiming a target of "photographic quality". However it is not easy to correctly define features of the photographic quality. Hirokazu Kasahara has been carrying out a project, with a close cooperation with Ethan Montag, to elucidate physical factors controlling the photographic quality in color

hard copies. Then he will optimize these physical factors in an attempt to exceed the present photographic color prints with a particular application to an ink-jet process in mind.

Mathematical Analysis of Colorimetric Problems Using Information Theory

There are a number of problems in color science waiting for a sophisticated mathematical analysis. They are, for example, metamerism, color vision model, or line elements. After joining us this fall, Dr. Nobihito Matsushiro, a talented mathematician with specialty in information theory, has been quickly making a noteworthy progress. First he elegantly applied a variation method for optimizing color matching functions experimentally obtained by Mark Shaw and figured out very smooth and plausible color matching functions. Next he has started a theoretical analysis of counting metamers and color constancy. He will present the results at forthcoming conferences next year.

Presentations

N. Ohta, "Color Engineering," Dept of Eng, Chiba Univ, Chiba, Winter Quarter, 1999.

N. Ohta, "Color Reproduction," Dept of Eng, Chiba Univ, Chiba, Winter Quarter, 1999.

N. Ohta, "Introduction to Color Engineering," Japan Technology Center, Tokyo, Jan. 1999.

N. Ohta, "Color Engineering and Its Application," Japan Industrial Technology Center, Tokyo, Jan. 1999.

A. Ito and N. Ohta, "Optimization of Probability Model for Color Halftone by Macroscopic Spectral Reflectance," PICS meeting, Savanna, November 1999.

Invited Presentations

N. Ohta, "Introduction to Color Reproduction," Sony Corporation, Tokyo, February 1999.

N. Ohta, "Teaching and Learning at RIT," Osaki High School, Tokyo, June 1999.

N. Ohta, "Designing a Color Reproduction System: A Perspective View," 7th Color Imaging Conference, Scottsdale, November 1999.

N. Ohta, "Optimization of Color Reproduction: Past Results and Future Prospects," Xerox Corporation, Webster, November 1999.

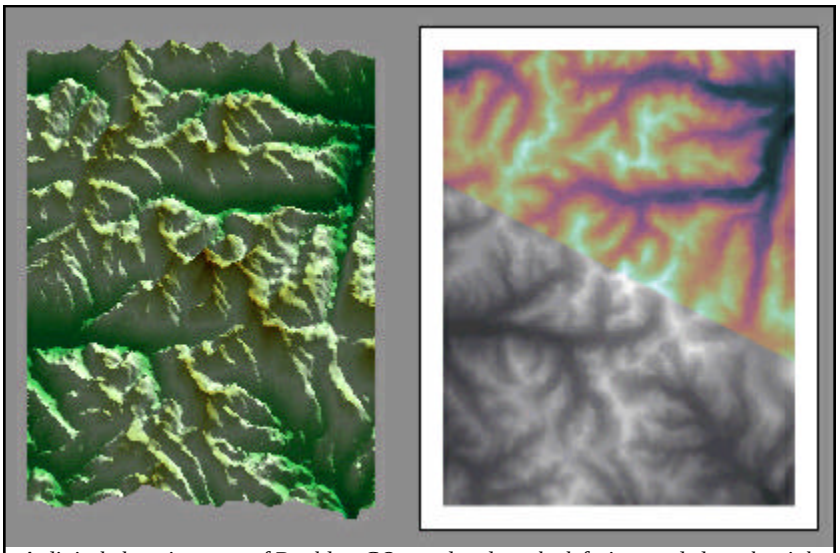
N. Ohta, "My Work on Color Reproduction," Fuji Photo Film Company, Minami-Ashigara, December 1999.

Research - Ethan D. Montag

Industrial Color Tolerance

Our article on the feasibility of measuring color tolerance using CRT-generated stimuli was published in *Color Research and Application* this year. In this article we stated that the use of the CRT can aid in the efficient and economical determination of color tolerance and the examination of parametric effects on color tolerance. This year we have followed up on this by conducting experiments examining the influence of texture on color tolerance.

We conducted a study to determine whether there is tolerance for lightness is dependent on the lightness level. This dependency is part of the CMC color difference formula but there was not enough evidence for it in the development of the CIE94 color difference equation. One (of many) differences between the data sets used to determine these equations is that the CMC data was derived on judgments using samples of sewing thread wound onto cards while uniform, glossy panels were used to collect the data modeled by the CIE94 equation. Perhaps the hue dependency is an effect of the texture.



A digital elevation map of Boulder, CO, rendered on the left, is encoded on the right using two different color scales. An experiment was performed to psychophysically evaluate subjects' performance in interpreting the image using five different encoding schemes.

In order to test this we simulated the texture of the wound thread samples on stimuli presented on a CRT. Lightness tolerances were determined for uniform samples and the simulated texture plus a texture that was intermediate between the two. The results indicated that there is a lightness dependency but that for uniform samples, this dependency is noticeable only at high lightness levels. The form of the lightness dependency for all three stimulus sets was characterized well by a straight line if the data was replotted as traditional TVI curves on log axes.

Work on the effect of texture on color tolerances is being continued by Alexei Krasnoselsky as part of his masters thesis. He is also using a CRT to measure color tolerances for simulated textures for a variety of color centers and directions in color space. His stimuli look quite convincingly like textured object colors.

Pseudocolor

I completed a first study examining the use of color in the display of multidimensional information. In particular I examined how well subject performed at judging values in a data display that was encoded by a variety of different gray scales. This work was sponsored by the Dean's Project Initiation Grant Program.

The gray scales used in the experiment differed in their gamma and in their chromatic content. The results indicated that lightness scaling had a significant effect on performance and that color aided the subjects' performance especially in conditions in which a legend was provided. These results were presented at the Color Imaging Conference in Scottsdale.

I am very much interested in continuing research on using color in visualization. In particular I am planning to look at combining color scales in bivariate data maps in order to develop perceptually salient color schemes for revealing interactions and correlations between variables.

Bits and Pieces

A couple of other projects were initiated last year involving image quality and spectral imaging. I have been working on the implementation of a statistical method known as *Dual Scaling* for use in analysis of psychophysical judgments of image quality. I am also working with Francisco Imai on a project involving spectral imaging to collect data which will be used in the rendering of biomedical simulations.

Publications

E.D. Montag and R.S. Berns, "Visual Determination of Hue Suprathreshold Color-Difference Tolerances Using CRT-Generated Stimuli," *Color Res. Appl*., **24**, 164-176 (1999).

E.D. Montag and R.S. Berns, "Lightness Dependencies and the Effect of Texture on Suprathreshold Lightness Tolerance," *Color Res. Appl*., (in press).

Presentations

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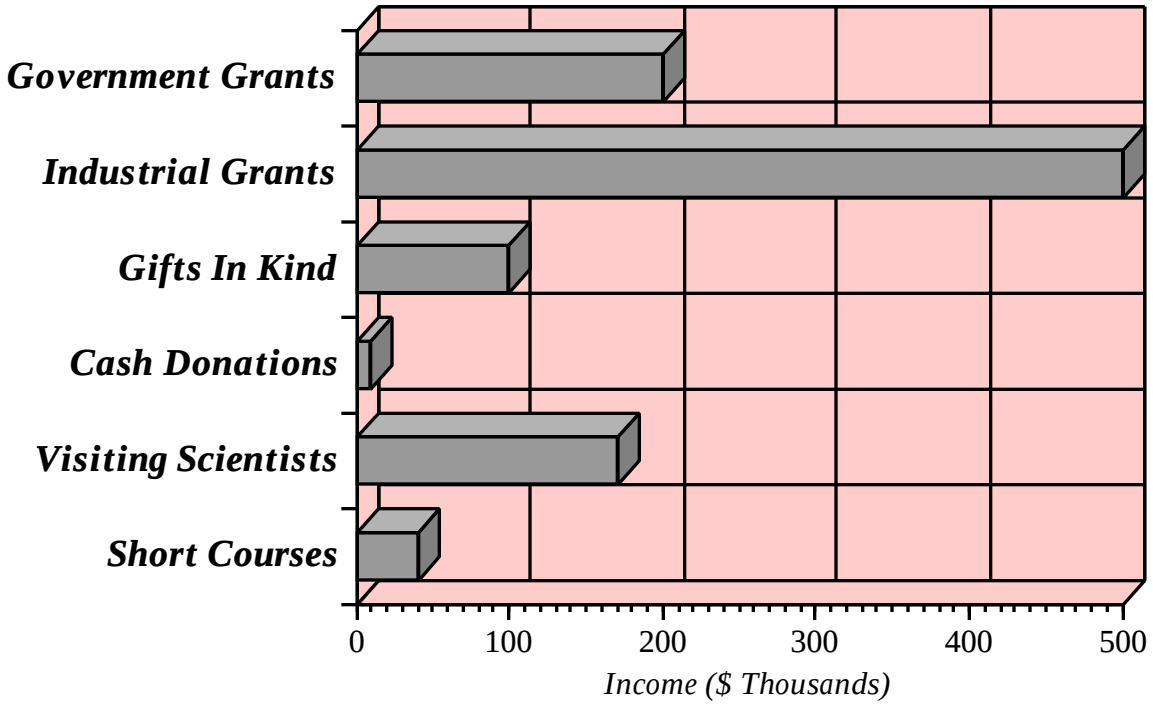
Funding

The total MCSL budget for 1999 was approximately $1.02 million (excluding the Hunter Chair, Xerox Chair, and Munsell Lab endowment income and faculty base salaries provided by RIT). As illustrated in the chart below, 50% of MCSL funding is from industrial grants, 20% from government grants, and about 15% from visiting scientists support. The largest expenditures are for student, staff, and faculty salaries and benefits. Sources of grants, gifts, and equipment donations are acknowledged below.



Sources of Support

Gifts, Grants, and Other Donations

Canon Information Systems, Color Curve Systems, Cyberchrome, Datacolor International, DuPont, Eastman Kodak, Epson, Fuji Photo Film, Fuji Xerox, Fujitsu Laboratories, Gretag-Macbeth, Hewlett-Packard, Mrs. Elizabeth Hunter, IBM Watson, Inter-Society Color Council, Labsphere, Matsushita Research Institute (Panasonic), NYSSTF-CAT, NSF-NYS IUCRC, Oki Data, Pixel Physics, PPG, Sony, Xerox.

Color Science M.S. Curriculum

Enrollment in the Color Science M.S. program during 1999 there was 9 full-time and 7 part-time students.

Required Courses

Fall (Yr. 1)

1050-701 Vision and Psychophysics	4 Credit Hours
1050-702 Applied Colorimetry	4 Credit Hours
1050-721 Color Measurement Laboratory I	2 Credit Hours

Winter

1050-703 Color Appearance	3 Credit Hours
1050-722 Color Measurement Laboratory II	2 Credit Hours

Spring

1050-813 Color Modeling	4 Credit Hours

Fall (Yr. 2)

1050-801 Color Science Seminar	3 Credit Hours

Many of our students have interests in color imaging. The following is a typical schedule of available courses for full-time students. Other imaging courses are available as electives.

Color Imaging Course Track*

Fall (Yr. 1)

1050-701 Vision and Psychophysics	4 Credit Hours
1050-702 Applied Colorimetry	4 Credit Hours
1050-721 Color Measurement Laboratory I	2 Credit Hours
0307-801 Design of Experiments I	3 Credit Hours

Winter

1050-703 Color Appearance	3 Credit Hours
1050-722 Color Measurement Laboratory II	2 Credit Hours
1051-726 Computing for Imaging Science	4 Credit Hours

Spring

1050-813 Color Modeling	4 Credit Hours
1051-753-01 Color Reproduction: Optimization Methods (Systems)	4 Credit Hours
1051-753-02 Digital Color Encoding	4 Credit Hours
0307-802 Design of Experiments II	3 Credit Hours

Fall (Yr. 2)

1050-801 Color Science Seminar	3 Credit Hours

* If a student does not want the M.S. degree to concentrate in the color imaging area, other course options are available under advisement.

MCSL Summer School of Industrial Short Courses
June 12-17, 2000

For 2000 the MCSL will be offering a week-long summer school of industrial short courses. Participants will be able to choose from one or more (up to three) of the following two-day intensive courses.

June 12-13

Principles of Color Technology, Roy Berns and Mark Fairchild

This course introduces basic colorimetry through derivation of the CIE system of tristimulus values, color spaces such as CIELAB, and color difference equations such as CIE94 and CMC. It also describes instrumentation for colorimetry and the evaluation of measurement accuracy and precision. Colorimetry is used in a variety of industries including coatings, textiles, automobiles, plastics, and image reproduction. It is safe to assume that any colored product has undergone some form of colorimetric evaluation during its manufacture or use.

June 14-15

Color Reproduction, Jonathan Arney

The basic principles behind the detection and reproduction of color will be modeled in terms of five generic functions in an idealized "Maxwell Color Copy System". Several color reproduction systems, including TV, color film, electrophotographic copy machines, and various hybrid systems will be examined in terms of the five generic functions (capture, processing, transmission, processing, output). The chemical and/or physical mechanisms of the components will be examined in terms of their impact on the quality of color reproduction. Specific attention will be given to different mechanisms of output, including CRT, continuous tone film, and halftone printing.

Vision and Psychophysics, Ethan Montag and Mark Fairchild

This course provides an overview of the structure, function, and performance of the human visual system as well as providing a detailed introduction to visual psychophysics. Virtually every application of color or imaging produces an object to be viewed and evaluated by human observers. Understanding of human vision and the psychophysical techniques used to measure human visual performance provides significant insight into a variety of problems. Psychophysical experiments allow quantitative measurement of visual perceptions and have applications in areas such as color tolerances, image quality, algorithm evaluation, etc.

Instrumental-Based Color Matching, Roy Berns

Instrumental-based color matching exploits colorimetry, color physics, and computer science, resulting in systems that aid colorists in matching existing and new colors. Color mixing "laws", such as Kubelka-Munk theory for complex subtractive mixing, are used to determine colorants and their amounts in order to match a standard. This course will cover the basic concepts of color mixing for transparent and opaque materials, colorant identification, spectral matching, and colorimetric matching. Through hands-on laboratories, participants will learn the importance of the colorant database and attaining the least metameric match.

June 16-17

Color Appearance Models, Mark Fairchild

This course provides a detailed review of the CIECAM97s color appearance model as well as covering the fundamental phenomena and techniques of color appearance modeling. Color-appearance models extend basic colorimetry, as typified by CIE tristimulus values, to the prediction of color matches and color appearance across widely varying viewing conditions. Advances in open systems for electronic image reproduction have accented the need for accurate and efficient color appearance models to allow transformation of image data across media and viewing conditions.

June 16-17

Device Profiles for Color Management, Roy S. Berns and Mitch Rosen

Device profiles incorporate device characterization, color gamut mapping, and color appearance models. This course will focus on device characterization techniques and their implementation into an ICC-compatible device profile. Device characterization describes the relationship between a device's user controls, such as digital counts, and its spectral and colorimetric output, that is, its color. Three techniques can be used to characterize a device: direct measurement and multi-dimensional interpolation, multiple-linear regression, and analytical modeling. The last two techniques will be used to characterize desktop scanners, digital cameras, computer-controlled CRT displays, and desktop printers (inkjet and electrophotographic).

Registration Fees:

Any combination of courses for the full week (6 days or 3 courses) costs $2000. Individual 2-day courses cost $850 each. This fee includes educational materials, textbook stated per course, lunches. Not included travel, hotel, and dinners.

For More Information:
www/cis.rit.edu/mcsl

1999 Industrial Short Course Report

"Principles of Color Technology for Materials Systems"

Some participating companies included: Bayer Corporation, Eastman Chemical, Datacolor International, IIMAK, DuPont, Loreal and Sherwin Williams.

Principles of Industrial Color Measurement

- *Instructors:* Drs. Roy S. Berns and Mark D. Fairchild
- 21 participants

Industrial Instrumental Color Matching

- *Instructor:* Mr. Ralph Stanziola
- 18 participants

"Foundations of Color Management for Imaging Systems"

Some participating companies included: Lexmark International, Hewlett Packard, Estee Lauder, Sun Chemical and Xerox Corporation.

Colorimetry for Imaging and Colorimetric Device Characterization

- *Instructors:* Dr. Roy S. Berns
- 9 participants

Color Appearance Models

- *Instructor:* Dr. Mark D. Fairchild
- 10 participants

Facilities

The Munsell Color Science Laboratory is very fortunate to be one of the world's most well-equipped laboratories for color science research and education. The estimated value of the instrumentation, computers, materials, and literature in the laboratory is in excess of two-million dollars. Much of the equipment has been donated or loaned by our many industrial sponsors over the laboratory's history. The equipment is housed in seven large (and several smaller) laboratories within R.I.T.'s Chester F. Carlson Center for Imaging Science. A complete list of MCSL facilities is available upon request. A brief explanation of the function of the seven large laboratories is given below.

76-3215 MCSL Main Laboratory
This laboratory houses the main meeting facilities for classes and general-purpose spectrophotometers, color order systems, materials, light booths and the MCSLlibrary. Adjacent rooms are dedicated to cross-media image reproduction research, image I/O, spectroradiometry, and color modeling research and education.

76-3111 Optical Radiation Measurement Standardization
This laboratory includes high accuracy spectrophotometers, material standards, a spectroradiometer, and a research goniospectrophotometer.

76-3105 Color Image Perception
The color image perception laboratory is dedicated to psychophysics research and houses SGI workstations for interactive image display, an image projection area, and a custom-built room for critical viewing of prints and comparison with other displays.

76-3234 Color Media Systems
Research in this laboratory is aimed at colorimetric and multispectral digital image capture and output. It also includes a flexible optical table setup that can be used in various experiments.

76-3150 Color Engineering Lab (CEL)
This facility houses a variety of state-of-the-art color imaging devices and high-end computational platforms used to support research in imaging systems simulation and other related work.

76-A110 Imaging Materials
The imaging materials laboratory provides areas for chemical analysis of various colored materials, inks, dyes, substrates, *etc.*

76-A120 Image Microstructure
This laboratory houses a microdensitometer, microscopes, black and white and color microscopic analysis cameras and various output devices for the study and measurement of the microstructural properties of hard-copy imaging media.

Publications

The following is a list of previous articles published by faculty, staff, and students of the Munsell Color Science Laboratory.

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Technical Reports

The following is a list of MCSL Technical Reports written by faculty, staff, and students studying color science over the last five years. The purpose of these reports is to provide additional information on subjects that are not appropriate for journal publications, either due to their information content or their length.

- **Colorimetric Characterization of Three Computer Displays (LCD and CRT)**, J. Gibson and M. Fairchild, January 2000.
- **Multi-spectral Image Acquisition and Spectral Reconstruction using a Trichromatic Digital Camera System Associated with Absorption Filters, Part II Iterative Non-Linear Spectral Reconstruction**, F. Imai, September 1998.
- **Multi-Spectral Image Acquisition and Spectral Reconstruction using a Trichromatic Digital Camera System Associated with Absorption Filters**, F. Imai, August 1998.
- **A Critical Review of Spectral Models Applied to Binary Color Printing**, D. Wyble and R. Berns, May, 1998.
- **Colorimetric Characterization of the Apple Studio Display (Flat Panel LCD)**, M. Fairchild and D. Wyble, July 1998.
- **The Spectral Modeling of Large-Format Ink-jet Printers**, R. Berns, A. Bose, and D. Tzeng, 1996.
- **A Simple Printer Calibration Technique for "Good Enough" Color Reproduction of CRT Images**, M. Fairchild, January 1994.

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