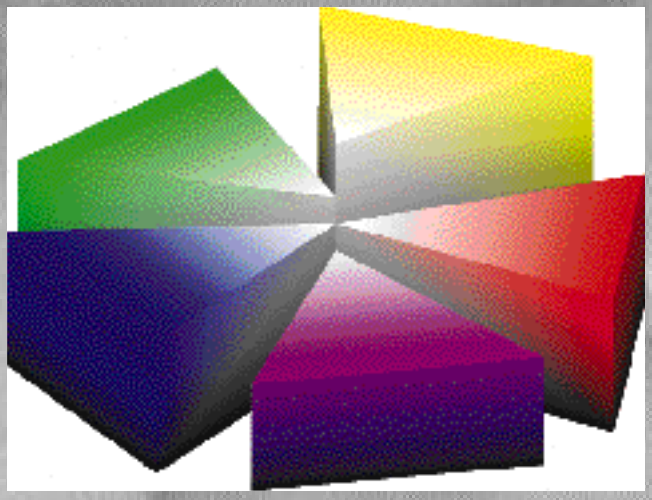
MCSL

Munsell Color Science Laboratory

1998
Annual Report



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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 research and development in color and appearance,
3) To maintain the facility to perform spectrophotometric, colorimetric, and geometric measurements at the state of the art, and
4) To provide an essential ingredient for the success of the first three — namely, liaison with industry.

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, four 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. MCSL is 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 web site < http://www.cis.rit.edu/mcsl>.

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Director's Report

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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.

Time has a way of passing by unnoticed; perhaps because it never takes a break while the rest of us must. This annual report serves many purposes for MCSL, not least of which might be to remind all of us that another year has quickly passed us by. It also gives us a formal opportunity to catch our breath and examine what we've done in the past year as we prepare for the next. This is my third annual report as MCSLDirector, a position I assumed in 1996 after Roy Berns and I decided to make some strategic changes in the lab. At that time, we outlined a 3-5 year plan to grow the lab in order to better serve the increasing numbers of students and industrial partners interested in color science. This past August, we had a day-long MCSL retreat to make plans for the immediate future. As part of that retreat, we re-examined our strategic plan of 1996 and were pleasantly surprised to find that we have achieved all of the goals that we laid out. Of course, we didn't do everything exactly as planned, but we have successfully moved the lab to the level we envisioned. It is now time for us to take a breather and focus on maintaining the quality of our lab given its new, larger size. That is where our attention will be in the coming 2-3 years. In particular, we will be focussing on expanding and stabilizing our funding base.

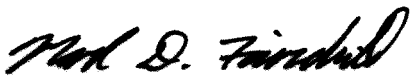
We are very happy to announce that the lab has grown with the addition of one faculty member and one staff scientist in the past year. Dr. Noboru Ohta has joined the Center for Imaging Science faculty as the Xerox Professor of Color Imaging Systems. Professor Ohta is well known to the constituents of MCSL as a former member of our advisory board and through his many years of outstanding research at Fuji Photo Film. Noboru plans to become an integral part of the MCSL program and we are all very excited to have him with us at RIT. At the same time, Mitch Rosen joined us a Senior Color Scientist. Mitch comes to us from Polaroid and will be working with Noboru to set up a new Color Engineering Laboratory. We know Mitch well as he is an MCSLalumnus and we are very happy to have him back in the lab. I am also happy to report that nobody has left the MCSL faculty or staff in the past year meaning we have reached the full compliment of 5 faculty and 5 staff that we envisioned 3 years ago.

Students continue to be our lifeblood at MCSLand our supply continues to be renewed and refreshed. In the past year, Garrett Johnson, Dave Wyble, Fritz Ebner, and Scott Bennett all completed their degrees at MCSL and moved on to the next phases of their careers. We are also happy to welcome Arturo Aguirre, Mihai Cuciurean-Zapan, Sharron Henley, Jason Gibson, and Sergio Gonzalez who joined us as new graduate students in the past year. Visiting industrial scientists continue to be a significant component of our lab. Hideto Motomura of Matsushita Research Institute (Panasonic), Akihiro Ito of Fuji Xerox, Masayoshi Shimuzu of Fujitsu and Takaomi Sekiya of Asahi Optical/Pantax all spent some time during 1998 as visiting scientists while Akio Tsujita of Hitachi-koki, Katsuya Itoh of Toyobo, and Shinya Yamaguchi of Nippon Paper Industries completed their stays at MCSL and returned to their companies. We wish everyone who left the lab in the past year all of the best for a bright future and we welcome all of the newcomers with our best wishes for a productive and enlightening stay.

As you can see through the remainder of the report, all of our students, visitors, staff, and faculty have been very busy and productive in the past year. I encourage you to read through the personal statements and research summaries on the following pages. I hope this report will provide a good sense of what the MCSL family is all about. I think it is clear that we can be quite happy with the accomplishments of 1998 as we look forward to the challenges of 1999.

At this point, I'd like to highlight some of my personal activities of the past year. I returned to RIT on September 1 after 15 months on sabbatical leave as a Visiting Associate Professor in Cornell University's Program of Computer Graphics. My time at Cornell was very productive and a wonderful experience that I will cherish for the rest of my career. My research activities at Cornell focussed on two areas. The first was the development of a multi-scale model of vision and adaptation with applications in image tone mapping, color appearance, and image quality and the second was work on spectroradiometric rendering of images for systems simulations. Further details of these projects are given in the research section. As the culmination of my work in computer graphics, I traveled to SIGGRAPH'98 in Orlando this past July where I shared in the presentation of our research results to an audience of several thousand! It was certainly the largest audience I have ever had and the largest (*i.e.,* overwhelming) conference I have ever attended. Earlier in the year (February), I traveled to the ISCC Williamsburg conference on design in the 21st century where I very much enjoyed the rare opportunity to simply be a member of the audience and take in the presentations. As autumn came and I returned to RIT, I was responsible for organizing the ISCC annual meeting in Baltimore along with a joint ISCC/OSA symposium on color differences. The meetings went quite well and were marked by an unforgettable crab feast at the Baltimore waterfront and the completion of my 3-year term on the ISCC Board of Directors. A few weeks later I traveled to the University of Derby to serve as the external examiner on a Ph.D. dissertation. It was a wonderful experience and a great chance to visit the new Color and Imaging Institute at Derby. (It also allowed me a very special opportunity to make a side trip to the Old Course at St. Andrews.) Finally, as the year came to an end we made our annual pilgrimage to the Color Imaging Conference in Scottsdale. It was a very big event for us with MCSLstudents, faculty, staff, and visitors involved in 10 different presentations. The conference also gave us an opportunity to visit with alumni, renew many contacts, and make plans for future collaborative research with both potential industrial supporters and university colleagues. On returning to RIT I also began teaching again. In the fall, I taught the *Color Measurement Laboratory I* course which I plan to be re-designing with more modern instrumentation in the coming year. As I write this report, I am teaching a refurbished version of my *Color Appearance* course since this is the first time it has been taught with my book available. Finally, I am developing a new course on *Image Rendering* that I will offer in spring of 1999 based on some of the work I did at Cornell. Of course, I continue to be busy supervising graduate student research, which is summarized in the research section of this report.

In closing, I wish to thank everyone who has supported the activities of the Munsell Color Science Laboratory in any way during 1998. Our success would not be possible without the generous support we receive from industry and government and the amazing hard work of our staff and students. Thank you all. You've allowed us to create and experience a very special place. For more information on our activities please visit the lab's web site at <www.cis.rit.edu/research/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.

This past year has been filled by several major activities. The first was completing the Center's search to fill the newly established Xerox Professorship in Digital Color Imaging Systems. The Center established a set of demanding criteria including fame and the potential for fortune through new avenues of research. Dr. Noboru Ohta, formally of Fuji Photo Film Ltd., has come to the Center and Munsell as our first Xerox Professor. Dr. Ohta began his duties during the Fall and he is quickly making an impact on our research and educational programs. This is personally very gratifying; I've known Dr. Ohta since my days as a graduate student. His research in spectral analyses was an enabling technology to my own dissertation. He has been a member of the MCSL advisory board since its inception. His industrial experience and expertise in color reproduction and color science will be a great benefit to MCSL

My second major activity is writing the third edition of Principles of Color Technology. This book was key to my current position. When deciding on a graduate school, one of my professors at UC Davis pulled out a copy to point out that Fred Billmeyer had a graduate program at Rensselaer Polytechnic Institute. Working with Fred and Max Saltzman has been very interesting and I'm looking forward to finishing the manuscript during the next three to four months. The book will also give me some practical experience in color management; I hope to use device profiles for a digital camera and four-color printing.

My third major activity is formalizing my interest in art archiving and reproduction. Much of spring was spent writing a multi-million dollar proposal to the National Science Foundation titled, "Preserving and accessing national treasures via a multi-modal image archive." My goal was to combine color, imaging, library, and conservation sciences. The proposal joined RIT with the National Gallery of Art. The research included imaging paintings to record their spectral, colorimetric, goniophotometric, and topographic properties, developing efficient data archives, using the archive for accurate internet images, and producing printed catalogs and posters that are close spectral matches to the original objects. Unfortunately, the proposal was not considered for funding. However, the process of writing down my ideas has been invaluable. I am having discussions with other funding agencies as well as companies. There seems to be considerable interest in this research. In fact, I plan to learn much more about the needs of the art community during the end of 1999 and most of 2000; I have applied for a sabattical for the 1999/2000 academic year to reside in a major museum.

During 1998, I was busy advising our many color and imaging science students and visiting scientists. It has been very rewarding working with Scott Bennett (gamut surface generation given a set of colorants), Greg Howell (predicting colorant concentration using a digital camera), Mark Reiman (color management of a colorimetry textbook), Deepthi Sidavanahalli (parametric effects on lightness perception), Dave Wyble (critical review of color modeling of halftone printing), Di-Yuan Tzeng (multi-color printing algorithms), Pat Igoe (color discrimination model based on cone fundamentals), Hideto Motomura (categorical gamut mapping), Akihiro Ito (color management of a electrophotographic printer), and Francisco Imai (multi-spectral image acquisition).

As always, I am very lucky to be associated with the Munsell Color Science Laboratory. 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.

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.

In the fall of 1998, I was appointed to the first Xerox Professor. It is indeed a great honor to me and I will put forth every effort to enhance and to expand the color imaging activities of MCSL.

Since 1968 and until my resignation this fall, I held the position of research scientist at Fuji Photo. Between 1973 and 1976, I was a research associate of the National Research Council of Canada. At Fuji Photo, I studied theoretical analysis and numerical optimization of color reproduction in color photography. I also developed relevant techniques for measuring color reproduction quality. My research results have been partially published in more than 80 papers and have also been summarized in two textbooks.

At RIT, I will pursue three major objectives. They are firstly to teach students, secondly to conduct research with graduate students and visiting scientists, and thirdly to strengthen relationships between the MCSL and industries particularly focusing on Japanese industries. More specifically for the first objective, I will create graduate laboratory courses for basic color science and for color optimization. As for the second objective, through developing a Color Engineering Laboratory (CEL) for various researches, I will initiate a series of research programs in digital color imaging systems. For the third objective, in an attempt to strengthen relationships with Japan, I will teach both undergraduate and graduate courses at Chiba University in winter term. At the same time, I will visit a variety of Japanese industries and will lecture for researchers in industries and also for Japanese academic societies.

More substantially, after my appointment, I have promptly launched the above-mentioned three activities. As an initial step, I have outlined the activities of CEL and built up a rough sketch of necessary facilities including input, display, and output devices. The CEL computing facilities will include a powerful host machine and a number of small-sized flexible machines, and software such as IDL, Matlab, or Mathematica. I have also started the preparation for a course to be held next spring. The course will deal with the optimization of color reproduction in color imaging systems. There I will introduce graduate students to a variety of optimization techniques primarily focusing on spectral characteristics of image forming dyes. As academic and technical conferences are very important to my major objectives, I have attended the 6th Color Imaging Conference at Scottsdale, AZ, during 17-20 November. This has enriched my knowledge and interests for my future works. In support of industrial relationships, I have initiated with Professor Roy Berns a joint project with a leading Japanese imaging company. My PhD student Quan Shuxue will be fully involved in this project with close cooperation from our Senior Color Scientist, Mitchell Rosen. I have also initiated preliminary discussions for our future joint projects with two additional Japanese companies. Along this line, I hope to widen the horizon of industrial relationships with world-wide industries particularly focusing on those from Japan.

Finally, although I am as the Xerox Professor somewhat free to choose the degree to which I would like to associate with the MCSL, my activities are definitely not possible without variety supports from the MCSL. My activities would also not be possible without the financial support through the Xerox Professorship and a number of industries, and intellectual support from my colleagues and staff. 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.

The past year has been very fruitful, both personally and professionally. I was invited to serve on a faculty search committee at Linkoping University in Sweden. The new faculty position is a Chaired Position in Digital and Hard Copy Imaging and represents a new program initiative at Linkoping. The committee interviewed several candidates and elected Professor Bjorn Kruse for this position. Closer to home, I invited professor Jan Allebach of Purdue to consult with us on a joint project with Hewlett Packard. The interaction lead to a funded project with HP and is currently supporting a graduate student to develop new experimental techniques for microdensitometry. Also, professor Geoffrey Rogers was invited to consult with us for a day. This lead to a collaboration in the field of substrate optics and some papers which significantly enhance our understanding of halftone image reproduction.

On the teaching front, I am still very much involved as the CIS Undergraduate Program Coordinator, and a major effort over the past year has gone into the development and implementation of a new undergraduate curriculum. Also a major effort has gone into developing a more proactive and holistic advising program for undergraduates. As part of the new undergraduate curriculum, a course in colorimetry has now been added to the required sequence of courses for undergraduates in Imaging Science. In all likelihood, I will be asked to teach that course next fall, and I look forward to the opportunity. A new course in the undergraduate Imaging Science curriculum is *Imaging Systems Lab*, which involves experimental analysis of imaging systems and images. The lab involves a variety of experiments in imaging and color reproduction. I also enjoy teaching a course called *Color Reproduction*. This course has been developing over the past two years as a part of a new format for the MS in Imaging Science. The course has evolved with an emphasis on the physical mechanisms of color imaging and is expected to run this year with most of the typical start-up bugs ironed out.

Research this year has gone very well thanks to a couple of motivated students and three visiting scholars from industry. Shinya Yamaguchi, Katsuya Ito, and Akio Tsujita worked with undergraduate students Chris Blehm and Yat-Ming Wang, and the team together produced some very exciting results which significantly expand our understanding of the interactions between light, inks, and substrates in color reproduction. All of these people produced work which lead to journal publications. More is on the way!

On the fun side, I am still advising the amateur radio club on campus. I arranged a meeting between the club and Campus Safety, and this has lead to a volunteer program of well trained, student radio operators helping Campus Safety in monitoring campus parking lots for potential crimes. The students are working hard to be a service to the community!

I am still active in the Society for Imaging Science & technology in several ways. I serve as a counselor for the Rochester Chapter, an advisor for the Student Chapter, and as a reviewer for the journal of IS&T. In addition, I helped develop a new program for IS&T called the "Conference Docent" program to promote student involvement in the society. Student "Docents" were invited to participate in the recent NIP-14 Conference in exchange for helping with audio-visuals at the conference. The conference and the Docent program were quite successful.

Recently, I got involved in a program to offer a science workshop for grade school science teachers this summer of '99. The idea is to promote Imaging and Color science in the grade school science curriculum as well as to provide an educational opportunity for teachers. So, if successful, high school kids will go off to college thinking of their favorite color in terms of xy coordinates! I had promised myself to drop a few projects, but it seems I've added as many this year as I dropped. But RIT, CIS, and MCSL are just too much fun to say no! Busy is fun when you have such great colleagues to work with.

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

At the beginning of this year I was fortunate enough to attend my first ISCC Conference on *Color and Design: 21st Technology and Creativity*. Since I am currently working towards my bachelor's degree in Business and Graphic Design, this conference was a great opportunity for me to enhance my education and I was able to personally meet the many people I have talked with over the years. In addition to the courses for my degree, I attended an *Adobe Photoshop* workshop this summer to learn photo improvement techniques which I hope to incorporate into future projects. I ended this year's supplementary trainings by attending a seminar on *Managing Multiple Projects, Objectives, and Deadlines*. I learned that the majority of what I already do is good practice–and that was encouraging! I also got some tips on how to manage procrastination, plan efficiently and prepare for upcoming deadlines. I hope these procedures will help me assist my bosses with their projects and enable me to monitor my various projects.

By the way, this year marks my tenth year at MCSLof which I have enjoyed every day. I am proud to have been a part of MCSL's development and I look forward to another ten years of growth and opportunities.

Francisco Imai, MCSL Post Doctoral Fellow, (716)475-7842, fhipci@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.

When Colleen asked me for this report, I realized that more than one year has passed since I started working here at the Munsell Color Science Laboratory. During the past year I was active in research involving camera characterization as part of the multi-spectral high-resolution acquisition system. These efforts have led to some presentations in conferences. The approach I've been working in provides spectral image archives with sufficient spatial resolution and colorimetric accuracy for artwork imaging. In this system, a multi-band, low-spatial resolution multi-spectral image is combined with a high-spatial resolution lightness image (from either a monochrome digital or digitized photograph) to generate a high-spatial resolution spectral image.

During spring I had the opportunity to travel two weeks in Europe to attend the Europto/SPIE International Symposium on Electronic Imaging Capture and Publishing hold in Zürich, Switzerland to present a paper and during this conference it was possible to visit GRETAG IMAGING Company as well as the Electronics Laboratory of the Swiss Federal Institute of Technology. Just before the conference I visited the Technical Electronics Department at the Technical University of Aachen in Germany. The department is directed by Prof. Bernhard Hill who was very kind to introduce his laboratory and their research on theoretical and practical aspects of multi-spectral image acquisition besides many other interesting works done by their scientists and students. Before returning to Rochester, I visited Dr. Udo Lenz and Dr. Reimar Lenz at the Technical Electronics Institute of München University of Technology and they were also very kind to show me the imaging system of the Fine Arts Museum (Pinakothek München) that uses a high-resolution camera they developed. This travel was really worthwhile because I met many scientists whose researches are related to my current project at Munsell Color Science Laboratory. As a consequence of this trip to Europe I have begun to design an alternative way to capture multi-spectral images by combining a trichromatic camera and a set of absorption filters to overcome technical problems inherent to the use of interference filters.

In summer I traveled to South America to present a paper at ARGENCOLOR 98 conference in Oberá, Argentina hold by the Argentinean Color Group. I also went to Brazil in order to help Brazilian scientists to found the Brazilian Color Study Association (abec), whose foundation act was signed on August 4. And in the fall I presented a paper in Scottsdale, Arizona during the Sixth Color Imaging Conference.

I would like to thank Roy for the discussions and guidance. I cannot forget to acknowledge Dave, Lisa and Colleen, people who always helped me during the last year. Finally, I look forward to increase involvement and enthusiasm in my research learning more and more from the lab's old members as well as the new members Dr. Noboru Ohta and Mitch Rosen.

Ethan D. Montag, Research Assistant Professor, (716) 475-5096, montag@cis.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.

This year my teaching responsibilities included *Vision and Psychophysics*, *Color Science Seminar*, and *Color Measurement Laboratory II*. I also participated in team teaching an undergraduate psychology, class on *Motion and Depth Perception* with Eriko Miyahara as part of the Psychology Departments new Visual Perception Track. I very much enjoy the collaborative nature of my teaching activities. The contribution of the faculty, visiting scientists and postdoc, to *Color Science Seminar* has made this class very enjoyable and educational. Roy's creative input and experience has been invaluable in my efforts for the lab course. As always, teaching these classes has been challenging yet rewarding. In addition to teaching students, I have increased my involvement in the research of graduate students including advising and supervising students' research activities. It is very rewarding to be part of the students' experience from teaching their first graduate class, *Vision and Psychophysics*, to serving on their thesis committees.

I have increased my participation in the research activities of the MCSL Industrial Color Difference Consortium as well as continued work on color gamut mapping. I have also begun a new research initiative on the use of color in multidimensional graphical information display. The goal of this research is to optimize the display of graphical information based on the characteristics of the human visual system so that the user can easily and accurately interpret an image. By using color it may be possible to display multiple dimensions of information simultaneously. If an image is to be assessed by a human observer, the final link in the image processing chain, as much care should be used in displaying the image properly as is used in obtaining the image.

I'm sure the rest of the staff and faculty share my relief that Mark's sabbatical is over. It was hard to imagine what the year would be like without our Director, but we rose to the challenge and survived. I am pleased that I can now, once again, walk over to his office to get answers to questions and advice on my research. I would also like to welcome Dr. Ohta as the Xerox Chair. Already his presence has increased the lab's enthusiasm and I anticipate that I will learn a lot from his participation.

I look forward to increased involvement with student in the coming year as well as continued research. I also can't forget to mention how much Colleen, Lisa, and Dave have helped me during the year (Thanks!) and I anticipate that next year will be no different.

Lisa A. Reniff, Color Scientist, (716) 475-7188, larpci@rit.edu
M.S., Color Science, Rochester Institute of Technology, 1989.
B.S., Chemistry, Rochester Institute of Technology, 1986.

This year has seen a continued increase in the size of the Munsell Color Science Laboratory, with the addition of Dr. Ohta and Mitch Rosen bringing the number to five faculty and four staff. This is a long way from the days of Roy, Mark, Colleen and myself packing our own boxes and running our own cables. With this addition is an increase in the breadth of knowledge that will surely lead to greater prominence of the laboratory.

This year I have been sorting through our current color measurement instrumentation and defining our needs for the future. This involves the not so exciting work of checking out the equipment we own and either finding the best location and computer host in the lab or handing it down to a more needy laboratory. Of course, I am always on call to help anyone who asks in the use of the equipment or any other topic of concern. This year I was also able to attend the ISCC meeting in Baltimore. I enjoyed listening to many of the talks and renewing conversations with colleagues. I was happy to see that so many people remembered me after my absence from ISCC for a few years since I continue to work in the laboratory on a part-time basis.

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.

This past September marks my return to the RIT campus after nearly a decade in industry. In September of 1998 I was granted leave from Polaroid and am now participating in the Center for Imaging Science's Ph.D. program. I have been honored to have been asked to be the part-time assistant to the Xerox Chair, newly occupied by Dr. Noboru Ohta. It is a great privilege to work with Dr. Ohta. I hope to use my experience in imaging systems quality evaluation, specification and simulation as well as my algorithm development background to help build the recently dedicated Color Engineering Laboratory under Dr. Ohta's direction and also to assist him in preparing for his upcoming course on color reproduction.

For my family and me, moving to Rochester has been quite an adventure. While we miss Cambridge and Boston, we have been enjoying our time here. In 1989 I last lived in Rochester, moving that summer to the Boston area after completing course work for my Imaging Science Master's degree, and there joining Polaroid's Image Science Laboratory. [Two children and four years later I completed writing my thesis.] Working closely, once again, with the Munsell Color Science group has been a nice homecoming. Although having grown in numbers considerably since the late 80's, the Munsell Color Science Lab remains a friendly environment filled with interesting and accomplished individuals.

Dave Wyble, Color Scientist, (716) 475-7189, wyble@cis.rit.edu
M.S., Color Science, Rochester Institute of Technology, 1998.
B.S., Computer Science, SUNY Brockport, 1992.

My second year in the Lab is drawing to a close and I can say that I am very happy with the with the niche I have found. I enjoy the daily interaction I have with everyone involved with the Lab. It is often surprising to look back at a busy week and see the great things that were accomplished, some of which were not even on the drawing board when that week began! Lisa and I (and now Mitch) spent a lot of time improving the facilities of all the laboratories, and I am pleased with the direction we are heading. I hope everyone agrees that we are in a much better situation than we were even a year ago. Of course, there are still many more things to do!

As I write this I am planning the coursework for my first teaching opportunity, the undergraduate *Introduction to IDL Programming*. I am looking forward to this interesting challenge. There are many advantages to be gained by this interaction with undergraduates. I hope the Lab can benefit as much as I will from this teaching experience.

While I continue to learn the ropes around the Lab, I am increasingly involved with interactions within and outside RIT. I enjoy the frequent associations with corporate people and researchers from other academic institutions. These interactions have helped me move my own research ideas forward as well as bringing me further into the research of students and faculty here in the Munsell Lab. This has been an important year in terms of my professional growth, and I would like to thank everyone for helping me out in this respect.

Visiting Scientists

Hideto Motomura, Visiting Scientist, Matsushita Research Institute Tokyo, Inc. (Panasonic)Japan
Researching with Dr. Roy Berns

I have spent one year in MCSLas visiting scientist. During this time, I have received a lot of useful information regarding basic and applied color science by participating classes, having discussion with MCSLfaculty, staff and students. I want to thank everyone who has supported my research. My original experiments started this June to develop universal gamut mapping strategy. Based on my idea, gamut mapping techniques need many kinds of technologies among several scientific and engineering fields (e.g. device characterization, color appearance model, psychophysical technique to evaluate image quality, geometric transformation, etc.). Therefore, classes coordinated and instructed by MCSL were very useful to design and carry on my research.

Using the GOG model and Prism interpolation, CRT is controlled accurately in a darkened room (*e.g.* color difference in ΔE^*_{ab} is about 1.0 on average and about 2.5 at maximum). I am trying color mapping between 9300K -whitepoint-CRT and 5000K-whitepoint-CRT so as to minimize color appearance difference by my original idea, which is called "Categorical Color Mapping." The basic idea has been presented at the 5th IS&T and SID Color Imaging Conference in Scottsdale, Arizona in November, 1997. Improvements on this idea have been achieved from the viewpoint of evaluation function and simplification in order to search for the best mapping point in destination color space. "Categorical Color Mapping" can be also applied to gamut mapping. Therefore, my idea will be compared with conventional techniques for gamut mapping regarding reproducibility, universality, processing-speed and ease of implementation.

I hope that our efforts will enable us to establish a useful and faithful cross-media color communication system. Once again, I want to thank everyone who has supported my research.

Akihiro Ito, Visiting Scientist, Fuji Xerox Co., Ltd., Japan
Researching with Dr. Roy Berns

I have two themes to research in this year. The first work involves the characterization of an electrophotographic printer. Although we can make the model which has practically enough accuracy by empirical approach, I will use the model based on 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. The Yule-Neilsen effect complicates the model; in order to improve the Yule-Nielsen effect, I will use the model based on the probability function. However, there is the difficulty of taking colorimetric measurements of image microstructure when the model is used for color halftone, and it goes against the aim. I will attempt to optimize the parameters for the model from macroscopic spectral reflectance measurements instead of using a microdensitometer. I will finish the first work by the end of 1998, and I will begin the second part of my research in the new year.

The second part of my research will involve the application of a color appearance model. In order to develop a color management system for cross-media system, I will need to use a color appearance model. At first I will probably try to use color appearance model on actual CRT and printer system. However, I have not decided the details of the plan for this work yet. I will decide the detail after taking Mark's *Color Appearance* class this coming winter.

Masayoshi Shimizu, Visiting Scientist, Fujitsu Laboratories LTD., Japan
Researching with Dr. Roy Berns

I have spent three months as a visiting scientist here at MCSL since I came from Japan in the end of August. While I was in Japan, I was working on color management techniques for several kinds of imaging devices, especially for printers. I am interested in how to reduce difficulties in utilizing color management systems for unskilled PC users, such a technology as a simple and easy method for them to characterize imaging devices. During the past three months, I attended Roy's class, *Applied Colorimetry* and Ethan's class, *Color Science Seminar* which provided me with a lot of aspects of color science. Now, I am looking forward to attending classes in the field of color science held in the following quarter. I also attended 6th Color Imaging Conference held in Scottsdale, Arizona, and made a presentation about a study on a gamut mapping algorithm which I researched while I was in Japan with my colleagues there. The title is "Gamut Mapping Algorithm Suitable for Implementation to Device Profiles". During the preparation of my presentation here at MCSL, I received a lot of advice from members of MCSL and I would like to take this opportunity to thank them. At the conference, I enjoyed talking with a lot of alumni of MCSLand felt glad to be a member of MCSL. Now, I have started building my research program concerning my interests described above. I hope to start my research project soon and get fruitful results during my one year stay.

Takaomi Sekiya, Visiting Scientist, Asahi Optical Co., Ltd.(PENTAX), Japan
Researching with Dr. Jonathan Arney

I am working with Dr. Arney to assemble a device called an Optical Coherent Tomographic (OCT) instrument. This instrument uses the optical properties of a Super Luminescent Diode (SLD) to probe the three dimensional microstructure of scattering materials up to a depth from microns to several millimeters. Based on a principles called "heterodyne detection", this technique has been reported in the literature as a useful tool for 3D medical imaging of soft tissue. Our plan is to develop the technique as a means of probing the 3D microstructure of printing substrates such as coated papers and synthetic substrates in order to understand better the optical properties of complex substrates and the optical mechanisms involved in color reproduction on these substrates.

Graduate Students

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

Scott Bennett, Part-Time, M.S. GRADUATE, Color Science, 1998.
B.S., Computational Mathematics, Rochester Institute of Technology, 1995.
Thesis Topic: Gamut Surface Generation given a Set of Colorants

Gus Braun, Full-Time, Ph.D. Candidate, Imaging Science
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, Full-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. Candidate, Imaging Science
B.S. & M.S., Mathematics, Al.I.Cuza University, Romania, 1982.
Thesis Topic: Colorimetric and Spectral Modeling of Texture

Fritz Ebner, Part-Time, Ph.D. GRADUATE, Imaging Science, 1998.
M.S., Electrical Engineering, University of Rochester, 1990.
B.S., Electrical Engineering, Carnegie Mellon, 1986.
Thesis Topic: Gamut Mapping Derived from Observer Matches in Simple Graphics and the Influence of Context on Gamut Mappings

Jason Gibson, Full-Time, M.S. Candidate, Color Science
B.S., Imaging Science, Rochester Institute of Technology, 1994.
Thesis Topic: TBD

Sergio Gonzalez, Full-Time, M.S. Candidate, Color Science
B.S., Chemical Engineering, ITESM Mexico, 1997.
Thesis Topic: TBD

Barbara Grady, Part-Time, M.S. Candidate, Color Science
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: TBD

Greg Howell, Part-Time, M.S. Candidate, Color Science
B.S., Electrical Engineering, Ohio University, 1985.
Project Topic: Predicting Colorant Concentrations Using a Digital Camera

Pat Igoe, Part-Time, Ph.D. Candidate, Imaging Science
M.S., Software Development & Management, Rochester Institute of Technology, 1996.
B.S., Computer Science, Rochester Institute of Technology, 1992.
Thesis Topic: Development of a New Cone-Fundamental Based Color Space with Uniform Small Color Differences

Garrett Johnson, Full-Time, Ph.D. Candidate, Imaging Science
M.S. GRADUATE, Color Science, 1998.
B.S., Imaging Science, Rochester Institute of Technology, 1996.
Thesis Topic: TBD

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

Kathy Loj, Part-Time, M.S. Candidate, Color Science
B.S., Optics, University of Rochester, 1987.
Project Topic: TBD

Susan Lubecki, Part-Time, M.S. Candidate, Color Science
B.S., Mathematics and Computer Science, University of Notre Dame, 1984.
Project Topic: TBD

Mark Reiman, Part-Time, M.S. Candidate, Color Science
B.S., Chemistry, RIT, 1987.
Project Topic: Testing and Optimizing Color Management Software for Digital Photography and Color Printing

Mitchell Rosen, Ph.D. Candidate, Imaging Science
M.S., Imaging Science, Rochester Institute of Technology, 1994.
B.S., Computer Science, Tufts, 1984.
Thesis Topic: TBD

Mark Shaw, Full-Time, M.S. Candidate, Color Science
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

Deepthi Sidavanahalli, Full-Time, M.S. Candidate, Color Science
M.S., Graphic Arts System, Rochester Institute of Technology, 1996.
B.S., Photography & Photo Journalism, University of Mysose, India 1990.
Thesis Topic: Parametric Effects on Lightness Perception in Color-Difference Evaluation

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: Optimization of Micro-Colorimeter

Richard Soursa, Part-Time, M.S. Candidate, Color Science
B.S., Imaging Science, Rochester Institute of Technology, 1987.

Di-Yuan Tzeng, Full-Time, Ph.D. Candidate, Imaging Science
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

Dave Wyble, Part-Time, M.S. GRADUATE, Color Science, 1998.
B.S., Computer Science, SUNY Brockport, 1992.
Project Topic: A Critical Review of Spectral Models Applied to Binary Color Printing

Joan Zanghi, Part-Time, M.S. Candidate, Color Science
B.S., Computer Science, SUNY Brockport, 1988.
Project Topic: TBD

MCSL Alumni

Seth Ansell, M.S., Color Science, 1995.
Richard Alfvin, M.S., Color Science, 1995.
Scott Bennett, M.S., Color Science, 1998.
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.
Brian Hawkins, M.S., Color Science, 1997.
Garrett Johnson, 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.
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.
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.
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.
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.
Alex Vaysman, M.S., Imaging Science, 1997.
Debra Seitz Vent, M.S., Imaging Science, 1994.
Dave Wyble, M.S., Color Science, 1998.

Research - Mark D. Fairchild

Improving Color Image Experiences

Color images and imaging systems are now literally everywhere. However, the quality of these ubiquitous color images has not improved and perhaps it could even be argued that quality has declined substantially. The overriding theme of my research is to make the experience of viewing and using color images better for everyone involved. Specific activities in this domain range from mathematical simulation of fundamental aspects of image formation and processing to the ultimate perceptual experience of image observers.

While I try to have at least one research project that I am undertaking completely on my own, the vast majority of my research activity involves working closely with my graduate students and it is best summarized by reviewing their projects. Gus Braun has continued work on the development of a general-purpose gamut-mapping algorithm that serves as his Ph.D. dissertation. He presented a paper on the hue-linearization of CIELAB space and had another on a generalized technique for lightness mapping accepted for an upcoming presentation. Mihai Cuciurean-Zapan returned to RIT to pursue a Ph.D. and is currently working on a project with me to extend the work performed at Cornell toward the development of an image quality metric. Clara Cuciurean-Zapan is a part-time Ph.D. student who is developing a research project on the colorimetric and spectral modeling and synthesis of texture. Fritz Ebner was another part-time Ph.D. student who completed his degree in 1998. His work ultimately focussed on the perception of hue and the development of a new color space that, while being a very simple formulation, resulted in hue descriptors superior to those in CIELAB and CIECAM97s. Garrett Johnson accompanied me on my sabbatical at Cornell. There we completed an image-color appearance matching study that will appear in *Color Research and Application*. Garrett also completed his M.S. thesis on the computer synthesis of full spectroradiometric images that can be used for imaging-systems simulation, psychophysical experimentation, and educational purposes. He has now enrolled in the Ph.D. program where he will continue this, and other, research. Finally, Mark Shaw has begun working with me on his M.S. thesis examining the accuracy of various proposed color matching functions in order to check, once again, to see if significant improvement can be made to the CIE 1931 Standard Colorimetric Observer.

On the personal side, I am currently planning a series of visual experiments to examine the relationship between perceived brightness and contrast with the hope that they might shed some light on just what in the visual world sets an observer's state of adaptation. I have been working on two collaborations with Dave Wyble. One to examine the spacing of Munsell colors in various color appearance spaces and a second project that evaluated the potential for colorimetric characterization of a new desktop LCD computer display. I also spent a lot of time working with James Ferwerda, Sumanta Pattanaik, and Donald Greenberg of Cornell on a multi-scale model of vision. We hope to continue working on this project and other collaborations with Cornell in the future.

Lastly, some past work made it into print during 1998. This includes projects that were completed with Karen Braun, Ethan Montag, Alex Vaysman, and Kazu Takemura. Further information on this research, publications, and other interesting tidbits can be found on my personal web page at <www.cis.rit.edu/people/faculty/fairchild> or on the MCSL main page at <www.cis.rit.edu/mcsl>.

Book

M.D. Fairchild, "Color Appearance Models," *Addison-Wesley*, Reading, Mass.(1998).

Publications

M.D. Fairchild, and G.M. Johnson, "Color Appearance Reproduction: Visual Data and Predictive Modeling," *Color Res. Appl.,* **23**, in press (1999).

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 (1998).

M.D. Fairchild and D.R. Wyble, "Colorimetric characterization of the Apple Studio Display (Flat panel LCD)," *MCSL Technical Report* (1998).

Presentations

G.J. Braun and M.D. Fairchild, "Image Lightness Rescaling using Sigmoidal Contrast Enhancement Functions, SPIE / IS&T Electronic Imaging '99," San Jose, in press (1999).

S.N. Pattanaik, M.D. Fairchild, J.A. Ferwerda, and D.P. Greenberg, "Multiscale model of adaptation, Spatial Vision, and Color Appearance," *IS&T/SID 6th Color Imaging Conference,* Scottsdale, 2-7 (1998).

E.D. Montag and M.D. Fairchild, "Color Gamut Mapping: Evaluation of Chroma Clipping Techniques for Three Destination Gamuts," *IS&T/SID 6th Color Imaging Conference*, Scottsdale, 57-61 (1998).

G.M. Johnson and M.D. Fairchild, "Computer Synthesis of Spectroradiometric Images for Color Imaging Systems Analysis," *IS&T/SID 6th Color Imaging Conference*, Scottsdale, 150-153 (1998).

F. Ebner, and M.D. Fairchild, "Development and Testing of a Color Space (IPT) with Improved Hue Uniformity," *IS&T/SID 6th Color Imaging Conference*, Scottsdale, 8-13 (1998).

G.J. Braun, F. Ebner, and M.D. Fairchild, "Color Gamut Mapping in a Hue-Linearized CIELAB Color Space," *IS&T/SID 6th Color Imaging Conference*, Scottsdale, 163-168 (1998).

D.R. Wyble and M.D. Fairchild, "Quantitative Testing of Color Appearance Models Unit the Munsell Renotation Data," *ISCC Annual Meeting,* Interest Group I, Baltimore (1998).

G.M. Johnson and M.D. Fairchild, "Computer Synthesis of Spectroradiometric Images for Color Imaging Systems Analysis," *ISCC Annual Meeting,* Contributed Posters, Baltimore (1998).

S.N. Pattanaik, J.A. Ferwerda, M.D. Fairchild, and D.P. Greenberg, "AMultiscale Model of Adaptation and Spatial Vision for Image Display, *Proceedings of SIGGRAPH 98*, 287-298 (1998).

F. Ebner and M.D. Fairchild, "Finding Constant Hue Surfaces in Color Space," *Color Imaging: Device Independent Color, Color Hardcopy, and Graphic Arts III, Proc. SPIE 3300*, 107-117 (1998).

A. Vaysman and M.D. Fairchild, "Degree of Quantization and Spatial Addressability Trade-Offs in Perceived Quality of Color Images," *Color Imaging: Device Independent Color, Color Hardcopy, and Graphic Arts III, Proc. SPIE 3300,* 250-261 (1998).

M.D. Fairchild, "The ZLAB Color Appearance Model for Practical Image Reproduction Applications," *Proceedings of the CIE Expert Symposium '97 on Colour Standards for Image Technology, CIE Pub. x014*, 89-94 (1998).

M.D. Fairchild, "Progress Report of CIE TC1-34 with an Introduction of the CIECAM97s Colour Appearance Model," *Proceedings of the CIE Expert Symposium '97 on Colour Standards for Image Technology, CIE Pub. x014,* 77-80 (1998).

K. Takemura and M.D. Fairchild, "Some Considerations About Corresponding Hues Across Cross-Media Color Reproductions," *Proceedings of the CIE Expert Symposium '97 on Colour Standards for Image Technology, CIE Pub. x014,* 104-115 (1998).

Research - Roy S. Berns

Color Tolerances

Color tolerance research is supported through the MCSL Industrial Color Tolerance Consortium. We currently have nine members. This last year, our research on hue tolerances was published in *Color, Research, and Application*. These results will be used by the new CIE technical committee charged with developing an improved color difference equation based on CIE94. Ethan Montag and I had an article accepted in CR&A describing the use of a computer-controlled CRT display for measuring color tolerances. We are using this system to study factors affecting lightness tolerances such as background lightness, sample separation, and texture. This work is being performed by Ethan and two graduate students, Deepthi Sidavanahalli and Alexei Krasnoselsky.

Multi-Spectral Image Acquisition

This research area has been ongoing for the last few years. Our first area was noise analysis techniques where Peter Burns performed an experiment to evaluate whether his noise models predicted actual digital camera measurements. The predictions were very good and this was presented at the Color Imaging Conference (CIC) in Scottsdale. Francisco Imai has been working with an IBM digital camera and evaluating various methods of image capture and spectral estimation of paintings. Our goal is to develop practical methods applicable to museum environments. Francisco presented his results at both CIC and Europto 98 in Zurich.

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 carrying out this research. This year, he has focused on analyzing objects and deriving a set of reasonable statistical colorants that, hopefully, are very similar to the actual colorants used by the artist. He has also been evaluating the use of Kubelka-Munk theory to predict color-printing overprints. Di-Yuan presented his research results at the CIC conference in Scottsdale. A tutorial article on the use of principal component analysis for spectral estimation is nearly completed for submission to *Color, Research, and Application.*

Artwork Image Archiving and Reproduction

During this last year, I formalized my research plans to develop practical methods of archiving the spectral properties of paintings, and using the data for accurate image display and printed reproductions that are minimally metameric. The general research scheme was presented at the ISCC Williamsburg Conference, the University of Derby, and Europto 98. I also submitted proposals to the National Science Foundation and the National Gallery of Art.

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, in press.

Y. Qiao, R.S. Berns, L. Reniff, E. Montag, "Visual Determination of Hue Suprathreshold Color-Difference Tolerances," *Color Res. Appl.*, **23,** 302-313 (1998).

K. Iino and R.S. Berns, "Building Color Management Modules Using Linear Optimization I. Desktop Color System," *J. Imag. Sci. Tech.*, **42**, 79-94 (1998).

K. Iino and R.S. Berns, "Building Color Management Modules using Linear Optimization II. Prepress System for Offset Printing," *J. Imag. Sci. Tech.*, **42**, 99-114 (1998).

E.D. Montag and R.S. Berns, "Visual Determination of Hue Suprathreshold Color-Difference Tolerances using CRT-Generated Stimuli," *Color Res. Appl.,* in press.

Invited Presentations

R.S. Berns, "Spectral Based Color Reproduction - Possibilities," *ISCC Williamsburg Conference*, February, 1998.

R.S. Berns, "The Importance of Colour Imaging Education," *Inauguration of Colour and Imaging Institute at the University of Derby*, March, 1998.

R.S. Berns, "Challenges for Color Science in Multimedia Imaging," *Proceedings Colour Imaging in Multimedia*, Derby University, in press (1998).

R.S. Berns, "Industrial Color Difference Equations - Current Initiatives and Future Directions," *Joint symposium of ISCC/OSA*, October, 1998.

Presentations

D.Y. Tzeng and R.S. Berns, "Spectral-Based Ink Selection for Multiple-Ink Printing I. Colorant Estimation of Original Objects," *Proceedings IS&T/SID Sixth Color Imaging Conference*, 106-111(1998).

F.H. Imai and R.S. Berns, "High-Resolution Multi-Spectral Image Archives - A Hybrid Approach," *Proceedings IS&T/SID Sixth Color Imaging Conference*, 224-227 (1998).

P. Burns and R.S. Berns, "Image Noise and Colorimetric Precision in Multispectral Image Capture," *Proceedings IS&T/SID Sixth Color Imaging Conference*, 83-85 (1998).

K. Iino and R.S. Berns, "Perceived Spatial Image Quality Evaluation for Black Printer Algortihms Employing a Colorimetric Paradigm," (Japanese) *Proceedings 100th Spring Conference of the Japanese Society of Printing Science and Technology,* 73-76 (1998).

T. Kusunoki and R.S. Berns, "Visual Scaling of Image Quality for CRT Displays," *Proceedings SID annual meeting*, in press (1998).

R.S. Berns, F.H. Imai, P. D. Burns, and D.Y. Tzeng, "Multi-Spectral-Based Color Reproduction Research at the Munsell Color Science Laboratory," *Proceedings Europto 98, SPIE,* in press (1998).

Research - Jonathan S. Arney

Ink Spread and Penetration with Thermal Ink Jet

A probability based model of halftone imaging, which was developed in previous work to describe the Yule-Nielsen effect, is shown in the current work to be easily modified to account for additional physical and optical effects in halftone imaging. In particular, the effects of ink spread and of ink penetration on the optics of halftone imaging with an ink jet printer is modeled. The modified probability model was found to fit the experimental data quite well. However, the model appears to overcompensate for the scattering associated with ink penetration into paper.

Modeling the Yule-Nielsen Effect on Color Halftones

The Neugebauer approach to modeling color cmy halftones generally has to be modified in order to correct for the Yule-Nielsen light scattering effect. The most common modification involves the Yule-Nielsen "n" factor. A less common, but more fundamentally correct modification of the Neugebauer model involves a convolution of the halftone geometry with the point spread function, PSF, of the paper. The probability model described in the current report is less complex than the PSF convolution approach but is still much less empirical than the Yule-Nielsen "n" model. The probability model assumes the Neugebauer equations are correct and that the Yule-Nielsen effect manifests itself in a variation in the XYZ tristimulus values of the eight Neugebauer primary colors as a function of the amounts of c, m, and y printed. The model describes these color shifts as a function of physical parameters of the ink and paper which can be measured independently. The model is based on the assumption that scattering and absorption probabilities are independent, that the inks obey Beer-Lambert optics, and that ink dots are printed randomly with perfect hold-out. Experimentally the model is most easily tested my measuring the shift in the color of the paper between the halftone dots, and experimental microcolorimetry is presented to verify the model.

Scattering Symmetry and Pattern Symmetry of Halftone Imaging

Previous work has shown that the mechanism of color and tone reproduction in halftone imaging systems can be described quantitatively by modeling functions for mean level probability, P_{ij}, for light scattering from region i to region j, where regions i and j may be, for example, regions of the printed paper covered by different inks in the halftone process. The value of P_{ij} has been shown to be a function of the area fractions of the regions, fi and fj. In the past, the P_{ij} functions were written empirically to fit observed data or determined by convolution calculations involving the paper point spread function, PSF, and the transmittance geometry of the halftone pattern, T(x,y). In the current work it is shown that characteristics of the P_{ij} functions can be deduced from symmetry properties of light scattering in paper and symmetry properties of the halftone pattern. This allows some P_{ij} functions to be derived directly without the need to carry out a convolution with the point spread function of the paper. Models of these symmetry properties and methods for experimental analysis are presented.

Accounting for Ink Opacity and Dot Sharpness in a Halftone Model

Previous work has shown that tone reproduction characteristics of halftone images can be modeled with knowledge of the probability function P_{00}, for light to reflect from the paper between the halftone dots after having entered the paper between the halftone dots. In the current report, experimental measurements of the micro-reflectance, R_p, of the paper between the dots is measured as a function of dot area fraction, F, and used with the model to calculate experimental values for P_{00} versus F. It is then shown that the model can be modified to account for inks that have significant scattering. The model is shown to fit data on halftones printed with electrophotography toner which is highly opaque. In addition, the model is further modified to account for the effects of the non-sharpness of the edges of halftone dots. Using both of these effects, the model is shown to fit well with measured data from a variety of AM and FM halftones printed at different resolutions with different colorants. In addition, the model is shown to fit experimental data on the tone reproduction characteristics of a continuous tone, electrophotographic, office copy machine.

Kubelka-Munk Theory and the Yule-Nielsen Effect

This report experimentally relates the Yule-Nielsen n parameter for optical dot gain to the scattering and absorption parameters, S and K, of Kubelka-Munk theory. The relationship between the parameters is made through another metric of light scatter, k_p, defined as the inverse of the frequency, w in cy/mm, at which the MTF of the paper equals 1/2. The value of n is related exponentially to k_p, as shown in earlier work, and the current work indicates that $k_p = c/S$, where c is a constant equal approximately to 10. However, contrary to some intuition and to previous theoretical projections, the absorption coefficient of the paper, K, has no significant influence on k_p or the MTF of paper.

Publications

J.S. Arney and M.L Alber, "Optical Effects of Ink Spread and Penetration on Halftones Printed by Thermal Ink Jet," *J. Imag. Sci. & Tech.*, **42**(4), 331(1998).

J.S. Arney, T. Wu, and C. Blehm, "Modeling the Yule-Nielsen Effect on Color Halftones," *J. Imag. Sci. & Tech.*, **42**(4), 335(1998).

J.S. Arney, E. Pray, and K. Ito, "Kubelka-Munk Theory and the Yule-Nielsen effect on Halftones," *J. Imag. Sci. & Tech.*, in press (1998).

J.S. Arney, and S. Yamaguchi, "Symmetry Properties of Halftone Images I: Scattering Symmetry and Pattern Symmetry," *J. Imag. Sci. & Tech.*, in press (1998).

J.S. Arney, Akio Tsujita, "Symmetry of Halftone Images II: Accounting for Ink Opacity and Dot Sharpness," *J. Imag. Sci. & Tech.*, in press (1998).

Presentations

J.S. Arney and Hung, "A Microgoniophotometer You Can Build," *IS&T PICS Meeting*, Portland, OR, May 1998.

J.S. Arney and Y. Wong, "Modeling the Reflection Histogram of Halftones," *IS&T PICS Meeting*, Portland, OR, May 1998.

Research - Ethan D. Montag

Industrial Color Tolerance

During the past year I have become more active in research involving measuring color tolerance as part of the MCSLIndustrial Color Difference Consortium. These efforts have led to the publication of two articles in *Color Research and Application*. In addition, we have begun a number of new project initiatives related to color tolerance:

Hue dependency: As a follow-up to Yue Qiao's masters thesis which measured the hue dependency of hue suprathreshold color-differences, we performed experiments to replicated a portion of her experiments in order to try to reduce the uncertainty in her data. Hue tolerance was remeasured in four of the color centers using samples provided by Dupont as well as using the original samples. We found that this uncertainty was inherent in the methods used to determine hue-tolerance thresholds and was not caused by unwanted lightness and chroma shifts in the samples which required different statistical analysis. These data were incorporated into Yue's results in the publication that came out this October.

CRT-feasibility: As part of the previous experiments, hue-tolerance thresholds were measured using CRT-generated stimuli. Our results, which are in press, showed that we can efficiently measure color-differences on using a CRT. This method of sample presentation not only reduces the labor and time needed to perform these experiments but also reduces within- and between- subject variability.

Texture: Using a CRT, we have begun examining the effect of texture on color-tolerance. We have simulated textures based on digital images of wound thread typical of those used in the experiments leading to the CMC equation. We have measured lightness-tolerance thresholds as a function of mean lightness using textured and uniform patches. Our first set of experiments show that texture not only changes the perceptibility of the lightness differences but also the function relating the tolerance threshold to the mean sample lightness. The experiment will also be useful in determining what type of lightness-dependency may be needed in an industrial color-difference equation and how it might be implemented for different types of surfaces. I plan on continuing this research by measuring how texture may effect hue, lightness and chroma judgments in different regions of color space.

I am also involved in the research projects of two graduate students working in the area of industrial color tolerance. One project involves determining the effects of parametric change such as background intensity and sample separation, on color-tolerance. The second project is examining methods for accurately simulating and measuring textured sample on a CRT.

Gamut Mapping

Following up on previous research on color gamut mapping, I performed an experiment to test various methods for mapping out of gamut image colors into a smaller destination gamut. Based on the previous research I tested a number of algorithms that clip chroma values in various ways using simple images of single colored objects. In addition, the mapping was performed using three destination gamuts of different shape in order to see whether any particular method would universally be more effective than the others.

The results indicate that although straight clipping, keeping lightness constant, is predominantly the most preferred algorithm, it is not always the best algorithm. The best algorithm is dependent upon the image content (color of the object) and the size and shapes of the original and destination gamuts. These results have implications for the development of a "universal" gamut mapping strategy because they indicate that gamut mapping may need to be tailored to fit the particular pairs of gamuts in question, and the content and color of the image to be mapped.

Pseudocolor

Pseudocolor is the buzz word used to describe a new area of research I am beginning to explore. In many areas of imaging an image is constructed that encodes three or more dimensions of information. An example of this is a map of ground elevation of an area where the first two dimensions are the spatial coordinates (x,y) and a third dimension, elevation above sea level, is displayed on the map. In this case, the third dimension might be displayed using a gray scale. However, how this gray scale should be constructed is not well known. Typically, digital RGB values may be used, however when displayed on a CRT, this gray scale is not perceptually linear. When a fourth dimension is added, color must be added to convey the additional data.

I am beginning research to explore how best to use color to display multiple dimensions. There are a number of issues involved in this research. One issue is the dimensionality of the appearance of color and whether observers can abstract separate dimensions. Another issue is the intrinsic sensitivity of the visual system to changes in both color and spatial variation. A third issue is the ability to use color to increase the amount of information presented in a map, for example, can 10-bits of variation be displayed on a monitor with 8-bits of variation per channel.This research has implications for a wide variety of imaging applications including remote sensing, medical imaging, meteorological imaging, and astronomical imaging. Possible applications also include heads-up displays and the presentation of multivariate data in, for example, economics. I received the College of Science Dean's Project Initiation Grant to begin this research and have assembled a work station and software dedicated to this research. I have begun working on the design and implementation of experiments aimed at addressing these issues.

Publications

Y. Qiao, R.S. Berns, L. Reniff, and E.D. Montag, "Visual Determination of Hue Suprathreshold Color-Difference Tolerances," *Color Res. Appl.,* **23**, 302-313 (1998).

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Presentations

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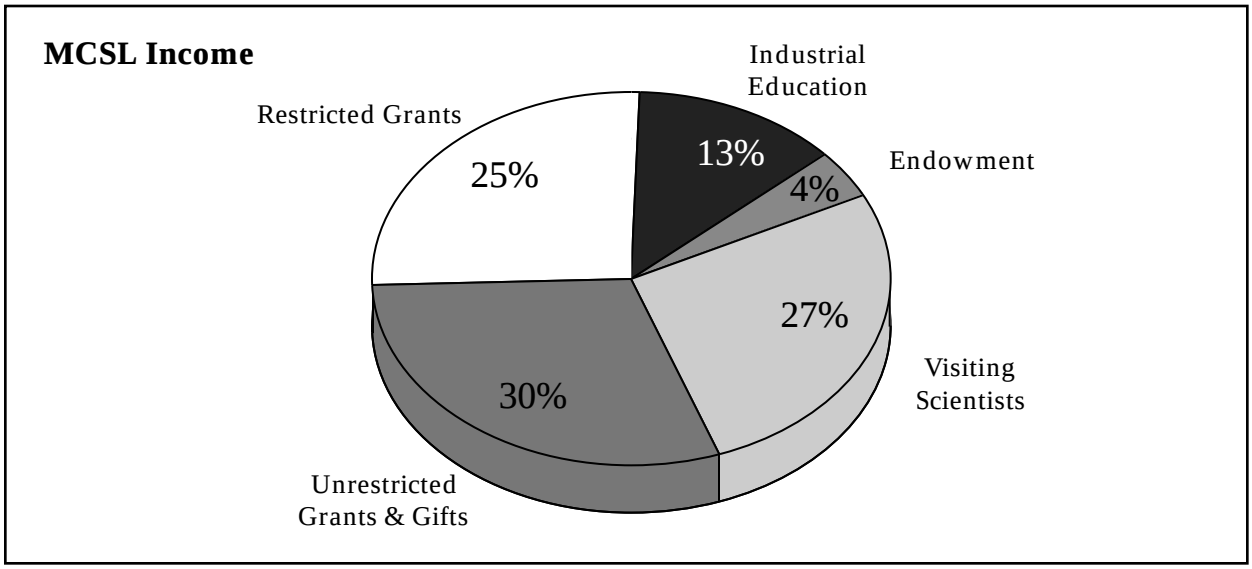
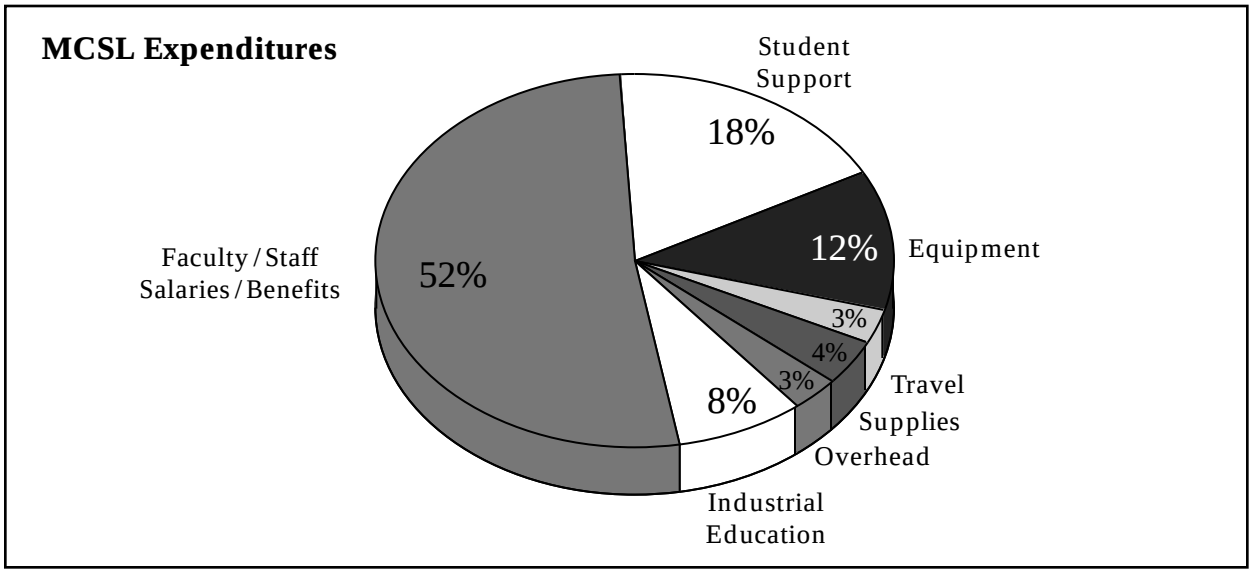
Funding

The total MCSLbudget for 1998 was approximately $600,000 (excluding the Hunter and Xerox Chairs and their related accounts). The charts below illustrate the distribution of MCSL income and expenditures. The majority of our income (82%) is cash generated by research projects through grants, gifts, and visiting scientist research. The largest expenditures (70%) are for student, staff, and faculty salary and benefits. Sources of grants, gifts, and equipment donations are acknowledged below. All financial calculations are based on the fiscal year from 7/1/97 to 6/30/98.





Sources of Support

Gifts & Grants

3M, Asahi Optical(Pentax), Bayer, Datacolor International, Detroit Colour Council, DuPont, DyStar, Eastman Kodak, Fuji Xerox, Fujitsu Laboratories, Gretag-Macbeth, Hitachi, Hewlett-Packard, Inter-Society Color Council, Matsushita Research Institute(Panasonic), Nippon Paper, NYSSTF-CAT, NSF-NYS IUCRC, PPG, Society of Plastics Engineers, Toyobo, and Xerox.

Other Donations

BYK-Gardner USA, Color Curve Systems, Cyberchrome Inc., Hewlett-Packard, IBM T.J. Watson Research Ctr., Sherwin-Williams Company, and Yale University Press.

Color Science M.S. Curriculum

Enrollment in the Color Science M.S. program during 1998 was 9 full-time and 10 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
1050-801 Color Science Seminar	3 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 courses for full-time students. Two color imaging courses are included in this schedule, *Color Reproduction* and *Color Systems.*

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
1051-749 Color Reproduction	4 Credit Hours
1051-726 Computing for Imaging Science	4 Credit Hours

Spring

1050-813 Color Modeling	4 Credit Hours
1051-816 Color Systems	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.

1998 Industrial Short Course Report

"Principles of Color Technology for Materials Systems"

Some participating companies included: Adobe Systems, BYK-Gardner, Cedar Graphics, Spectronic Instruments, Lord Corporation, Hach Company, BASF, Sherwin Williams, Veka Inc., PPG, and Bayer.

Principles of Industrial Color Measurement

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

Industrial Instrumental Color Matching

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

"Foundations of Color Management for Imaging Systems"

Some participating companies included: Adobe Systems, Welch Allyn, Xerox, Lexmark International, Hewlett-Packard, Tally Printer Corp., IBM Watson Research Center, Dulux (Australia), Polaroid, Eastman Kodak, and Intel.

Colorimetry for Imaging and Colorimetric Device Characterization

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

Color Appearance Models

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

1999 Scheduled Short Courses

"Principles of Color Technology for Materials Systems"

June 7-9, 1999 Principles of Industrial Color Measurement

This three-day intensive short course designed to teach the color science principles necessary to make effective use of color measurement instrumentation. Key topics include: spectrophotometry, derivation of colorimetry through CIELAB, and CIE94 and CMC color tolerance equations. The course consists of lectures, instrument demonstrations, visual experiments, and an open laboratory session. Instructed by Dr. Roy S. Berns and Dr. Mark D. Fairchild.

June 10, 1999 Industrial Instrumental Color Matching

This one-day intensive short course designed to help participants make more effective use of computer colorant formulation systems. Key topics include: spectral analyses of colorants, color matching theory, batch correction, and getting the most out of a system. The course consists of lectures, in-class formulation hand calculations, current software demonstrations, and a problem-solving session. Instructed by Mr. Ralph A. Stanziola of Industrial Color Technology.

"Foundations of Color Management for Imaging Systems"

This is a five-day, intensive short course designed to teach the underlying principles for implementing color management. The course is divided into three sections: colorimetry, modeling imaging peripherals for device profiles, and color appearance models. Participants *can participate in any or all of the sections.* These foundations are incorporated into color management systems such as Postcript Level II, ICC, and KPCMS providing "plug and play" capabilities.

Section one, Colorimetry for Imaging, offered on June 14, 1999 will be taught by Dr. Roy S. Berns, the R. S. Hunter Professor in Color Science, Appearance, and Technology. Topics include an overview of color vision and appearance, photometry, colorimetry mathematics, color measurement instrumentation, color space transformations, and color quality metrics.

Section two, Colorimetric Device Characterization, offered on June 15-16, 1999 will be taught by Dr. Roy S. Berns. Topics include scanner colorimetry using multiple-linear regression and spectral estimation techniques; CRT colorimetry using the CIE technique; binary printer colorimetry for cluster dot, FM screening, and conventional rotated screen halftoning devices; continuous tone printer colorimetry using Kubelka-Munk theory; and the basics of building device profiles.

Section three, Color Appearance Models, offered on June 17-18, 1999 will be taught by Dr. Mark D. Fairchild, Director of the Munsell Color Science Laboratory. 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. Topics include: important aspects of human vision, color appearance terminology, color-appearance phenomena, derivation of color appearance models (including, Nayatani, Hunt, RLAB, LLAB, CIELAB, ATD, and CIECAM97s), testing of color-appearance models, applications, and implementation.

The courses will consist of classroom lectures, demonstrations, laboratory sessions, and social times for informal interaction with other students and staff. Early registration is recommended.

For more information or to pre-register see our WebSite at:

www.cis.rit.edu/mcsl/courses.html

or contact:
Colleen M. Desimone
Telephone: (716)475-7189 FAX: (716)475-5988
E-mail: CMD9553@rit.edu

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 MCSL library. 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 new facility will house a variety of state-of-the-art color imaging devices and high-end computational platforms which will be 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.

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.

- **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.
- **Colorimetric Characterization of the Solitaire 16 Film Recorder for Kodak Ektachrome Plus Professional 100: A Pilot Study**, R. Berns, May 1993.
- **Spectral Modeling of a Dye Diffusion Thermal Transfer Printer**, R. Berns, May 1993.
- **Colorimetric Characterization of Sharp JX610 Desktop Scanner**, R. Berns, April 1993.
- **MCSL Apple Macintosh-Gretag Spectrophotometer Software Interface**, M. Stokes, January 1993.

Publications

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

1997

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K.M. Braun and M.D. Fairchild, "Testing Five Color Appearance Models for Changes in Viewing Conditions," *Color Res. Appl.,* **22**, 165-174 (1997).

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