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Program Objectives

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. The Munsell Color Science Laboratory 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."

Both endowed programs operate hand in hand on a daily basis. The following four basic objectives help guide their activities: 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.
1992 was a year of self-evaluation. This was somewhat predicated by knowledge I gained through attending a quality seminar presented by W. E. Deming. Along with 999 other students, I learned about quality circles, continuous improvement, and management philosophy and responsibility. It was very exciting to experience Dr. Deming firsthand. I soon had several opportunities to apply my new knowledge. The first occurred while grading laboratories. A new student turned in his first write up and I found that the style and content were not what was required. In the past, I would give a low grade with a written explanation. Deming would argue that this would be demoralizing to the student, squelch his motivation, and subvert his productivity. Instead, I wrote "redo" on his work and spent time with him to explain what I wanted. To my great surprise, the redone write up was excellent as were all of the other required write ups. More importantly, he became very enthusiastic about the subject and a part of our research program. I'm sure this wouldn't have occurred if I had taken my past approach to grading. I also learned to appreciate how each member of the Laboratory contributes to our total environment of education and research. The success of an individual should be based, in large part, on the success of the team. Thus although I have the honor of "directing" the Laboratory, our successes come from all of us learning to interact effectively.

Another issue during the seminar was the importance of communication that is exemplified by the quality circle. Accordingly we began a newsletter, The Chroma Zone, so that we could have more frequent contact with our supporters. In it are contained recent research results, editorials, and related activities.

During the year, we evaluated our M.S. program in Color Science to determine whether we were meeting the needs of our constituency and to improve our teaching efficiency. After polling the Munsell Color Science Laboratory Advisory Board, our students and staff, Mark and I made several changes to the curriculum. The first was to introduce a non-thesis option. For some students (especially part time), they already have extensive research experience. For these students, the thesis can be replaced with additional elective coursework and an independent study. We have also dropped the Theory of Color Measurement course and added a course on Color Appearance to reflect the emergence of color appearance models as an important area of knowledge. The details of all the changes can be found within the report.

Another internal event was the formation of the RIT Color Consortium. Its scope is to increase interaction among faculty and staff engaged in color activities on campus. Participants have come from the School of Photography, the School of Printing Management and Science, the National Technical Institute for the Deaf, the School for American Crafts, and the School of Fine and Applied Arts. We
are trying to identify ways to share resources and learn about each others’ definition of color. In a sense, the Color Consortium is a micro-ISCC.

The third Franc Grum Memorial Scholarship was presented to Ms. Audrey Lester. Audrey has a background in chemistry and quite a bit of industrial experience. She has returned to academia after putting her career on hold to start a family. Since joining the Laboratory, she has shown tremendous leadership and research potential, two traits synonymous with Franc Grum. A second endowed scholarship was established toward the end of the year. The Kollmorgen Foundation divested its assets to RIT to establish the Macbeth-Engel Fellowship in Color Science. This will be a competitive scholarship to support graduate research in color. We are very thankful to Kollmorgen and hope to continue the tradition of supporting high-quality scholarship begun by Kollmorgen several decades ago.

Our research in colorimetric-based color reproduction and color-appearance psychophysics continues to generate support and interest. Mark has established a research program to evaluate appearance matching between soft copy and hard copy supported by Eastman Kodak, and between soft copy and projected slides supported by the National Science Foundation, New York State, and Industry. In order to support his efforts we have been active in device characterization. This year we purchased, via these research projects or received as gifts, a Kodak dye-diffusion thermal-transfer printer, MGI Solitaire film recorder, and Howtek desktop drum scanner. All require colorimetric characterization and I am finding that models successful for describing the coloration of materials also apply to imaging devices. We also received a two year grant from Dupont Imaging to evaluate the tradeoffs between densitometric, colorimetric, and multispectral scanners for high-quality color reproduction. An area I am interested in applying our knowledge of colorimetric color reproduction towards is the problem of reproducing paintings accurately in posters, textbooks, and catalogs. I have visited with the Getty Conservation Institute and the Art Institute of Chicago and, hopefully, 1993 will find the Laboratory engaged in this area of research and development.

As always, the scope and quality of our activities would not be possible without the financial and intellectual help from all our friends and supporters. Within the Annual Report is a listing of our supporters during 1992. In particular, I would like to thank Mrs. Elizabeth Hunter, Kollmorgen, Dupont, and Kodak for their significant support of color science research and education. I also would like to thank our students and staff for their dedication and hard work. Without them, most of our achievements would not have been possible.

Roy S. Berns, Ph.D.
Richard S. Hunter Professor
Director, Munsell Color Science Laboratory

January 1993
Faculty and Staff Activities

The following reports summarize the activities during 1992 of faculty, staff, and visiting scholars.

Mark D. Fairchild, Assistant Professor, (716) 475-2784

Another year, another annual report. Time seems to be moving faster than it used to. I think that has something to do with Weber’s Law, but I’ll leave that for another paper. Last year, I was foolish enough to suggest that perhaps my life was settling down. There are many aspects to a university … none of which have anything to do with settling down. Life at a university means getting used to changes and controversy.

Changes at a university are many fold. One of the best, and at the same time worst, is the constant change in researchers in our laboratory. Students, visiting scholars, staff, and administrators are constantly coming and going as time and circumstance bring them to MCSL and take them away again. More than anything else in the past year, I have learned how to keep a coherent research program flowing through these constant changes. Believe me, that is no small feat.

Controversies are also not sparse in a university setting. There are the never ending internal battles over topics such as curriculum, the definition of imaging science, the fundamental nature of color science, and square footage. I won’t bore you with the details of such pedantic controversies. I have also been involved in my share (or perhaps more than my share) of controversies involving the color science community as a whole. The first of these was an exchange of letters to the editor of Color Research and Application with Professor Nayatani. It seems that he has some disagreements with some of the statistical analyses that Elizabeth Pirrotta and I included in our paper on the lightness of chromatic object colors. While it appears the exchange of letters did little to change either of or minds on the topic, I am sure that both of us have now seen things from another point of view and perhaps the readers of CR&A will gain some insight into how statistics can be used to achieve differing objectives. William Thornton published a three-part article in CR&A and made several presentations at the 1992 ISCC annual meeting on his work on color matching functions. While he presented some useful data, many of his conclusions exceeded the bounds of his experiments. This has led to much confusion in the color community regarding the applicability of basic colorimetry. Since I have collected and published some relevant data, I was encouraged to write a Color Forum for CR&A attempting to clarify some of these issues. Of course, being a glutton for punishment, I jumped right into the fray. I prepared a Color Forum on the topic which has been accepted for publication and will appear in 1993. Although the
Color Forum was not a letter to the editor on Thornton’s papers, the editor has seen fit to let him respond in writing in the same issue. I am anxious to see that response and to see how this particular controversy unfolds in the color science community. Lastly a small controversy came up with the ISCC. Several participants noted the paucity of brewed alcoholic beverages at the 1992 Princeton meeting and I was forced to write a column in our newsletter, The Chroma Zone, suggesting that perhaps we have an ISCC wine, beer, and cheese reception at future meetings in honor of Lovibond (who was a brewer and invented a colorimeter). I am happy to report that we will have the option of consuming “Lovibond Golden Amber” at the 1993 ISCC meeting. These important scientific issues must be addressed properly.

In summary, in 1992 I taught some courses, did some research, served on lots of committees, wrote some papers, gave some talks, and tried to keep things interesting in the color science world. I’ve really enjoyed almost all of it (I could do without most of the committees). Welcome to all of the new faces around MCSL and I wish all of those that have left or are leaving us the best of luck in their future endeavors. I hope everyone’s experiences in our laboratory are positive ones. Lastly, thank you to all who have supported me and MCSL over the past year.

Lisa Reniff, Associate Scientist, (716) 475-7188


As the snow continues to fall in upstate New York, it is a good time to reflect on the past year. However, my memories of this year start to intertwine and blur with the past years. Buying equipment, helping students, answering phone calls, installing software, and keeping track of events, people and things are all common denominators and important in their own right. One of the events that stands out significantly is the continuing work performed in the area of accurate measurement of materials. This past year I have been training Colleen to perform the many routine measurements. She has become very good at making repeatable measurements. Although this is not terribly exciting work, I have managed to fool Colleen into believing that it is.

I have been excited over the investigation into the temporal response of chromatic adaptation that Mark and I have performed this year. Our first attempt was a flop due to large observer uncertainty. The experiment was redesigned so the observer’s responses were constrained to movement with one degree of freedom (as was determined allowable in the previous experiment) instead of two. We anticipate presenting the results of this work at OSA next fall.

I was fortunate enough to attend the Williamsburg conference last spring (it was still winter up here) and delve into the midriff of problems involved in the pursuit of reproducing color images. I found the format of the conference very conducive to good discussions, including an interesting by-product on the effect (negative and positive) of proprietary research.
This coming year will bring new dimension to my responsibilities. I will be teaching a course on optical radiation measurements. This was due to a rearrangement of the masters curriculum in order to make a more logical study plan for the students. I am looking forward to this new teaching challenge; as the adage goes ‘you don’t know the material until you can teach it’. I continue to enjoy my job, and that is due in part to having Roy as my “boss”.

...time for another year!

Mike Stokes, Associate Scientist, (716) 475-7186
B.S., Mathematics, University of Texas at Austin, 1989.

The last year has gone by quickly for me with my time at the Munsell Lab split between providing students with both color and computer support, writing software utilities, installing new equipment and software, and performing basic color research. In addition to these tasks, I squeezed in time to design and create a new color display outside of Roy’s office demonstrating various areas of our current research including color appearance modeling, compression, color spaces, and color manipulations in CIELAB.

Providing student support included both the daily run-of-the-mill problems and questions and some basic software coding to help implement their thesis research. The software support included comparing color appearance models using UNIX shell scripts, integrating JPEG compression algorithms into our existing color reproduction software base, and coding a multi-ink spectral neugebauer model. I’ve found all of this work fascinating in both variety and difficulty.

On a more general level, a significant portion of my time was spent creating a number of software utilities for both the Macintosh and UNIX environments. The Macintosh utilities include helping Mark code a set of basic Photoshop® plug-in filters for color space transformations and an interface to Gretag SPM model spectrophotometers. The UNIX utilities were extensions of the color reproduction software that I had written previously. These extensions include the ability to manipulate spectral images, user definable storage and computational precision for color space transformations and manipulations, and input/output utilities for Pixar, ppm, and plain text files.

Much of my research this last year has been on the Solitaire film recorder. This includes studying a method to set up the internal controls for intensity and tone control and deriving an analytical model to convert colorimetric values to digital counts. Finally I published an industrial note in Color Research and Application on an efficient method for computing ΔH^*_{ab}.
Toru Hoshino, Visiting Scholar
B.S., Imaging Science and Engineering, Chiba University, 1986.
Working for Konica Corporation from 1986 to present

Spending the last twenty three months, I characterized a dye diffusion thermal transfer printer, calibrated a scanner, and finished one color gamut mapping experiment. I spent most of the time writing software and debugging, I think. For people who are going to do this kind of research, I’d like to express how painful it was. After finishing all processes of measurements, computations, and other things very carefully, reproduced images didn’t sometimes look OK. Why? I don’t know. Let’s start debugging again. Do I want to get rid of doing these things, escape to Aruba, and live there enjoying windsurfing every day? Definitely. But, I have to go back to Japan and work for Konica with my new career of color science.

With good facilities and people, I learned not only fundamental color science but also application techniques for color reproduction and image processing. I could apply most of the things I learned here to my color reproduction software.

I’d like to keep expanding my knowledge of color science, and try to contribute to Konica which gave me this opportunity of being here.

Taek Gyu Kim, Visiting Scholar, (215) 388-5334
M.S. Candidate, Imaging Science, Rochester Institute of Technology.
Working for DuPont from 1989 to present.

It was a great experience for me being a visiting scholar at MCSL. I think I absorbed an enormous amount of knowledge in the color area for one year. Meaningful discussions with colleagues also helped to expand my knowledge in the field.

Studying and performing experiments on color appearance models was an adventure. Without so many agonizing nights and weekends to understand models, code them, debug and run, I could not have done the experiment. I had to watch out for so many things to execute the experiment correctly. When the first images came out with alot of out-of-gamut colors, when the diffuser arm was broken in the middle of the experiment, and when solenoids burned out, it was really embarrassing.

After all, I really appreciate the help that I got from MCSL people. I am planning to publish the work that I have done at MCSL. I hope to meet all DuPont’s needs with the knowledge that I got from MCSL, meanwhile continuing such a relationship with Roy and Mark, et al.
Hiroshi Uno, Visiting Scholar

B.S. Electrical Engineering, Science University of Tokyo
M.S. Electrical Engineering, Science University of Tokyo
Working for NEC Corporation from 1984 to present.

Being with energetic, competent, and kind people here at the Center for Imaging Science, I have spent the last five months rather meaningfully since I came from Tokyo. Living and studying in this beautiful country, I have learned a lot and enjoyed much culture shock(!?). However, I am gradually growing accustomed to American culture and "Winter of Rochester," I might add. Recently, my English seems to change from mumbling to kinds of speaking. However, I still feel awkward to call people by their first name, because Japanese don't call each other by their first names socially. Imagine, if I would call my boss by his first name, I could not be in my office, forever.

My resolution of this year is to become a Man of Color Science. I have been dealing with monochrome technology in NEC, so I will master color science here and develop easier color matching design method for O.A. equipment. In addition, I am interested in color halftone technology, I will develop a new one that expresses color images more beautifully and can be compressed effectively.

Through these activities, I do hope I can contribute to RIT academic activities and enjoy the remainder of my seven months here.
Students

The following are students studying color science.

**FULL TIME GRADUATE**

**Timothy Kohler, M.S. Candidate, Color Science**  

**Audrey Lester, M.S. Candidate, Color Science**  

**Nathan Moroney, M.S. Candidate, Color Science**  

**Elizabeth Pirrotta, M.S. Candidate, Color Science**  

**Karen Rybarczyk, Ph.D. Candidate, Imaging Science**  
B.S., Physics, Canisius College, 1991.

**James Shyu, M.S. Candidate, Color Science**  

**PART-TIME GRADUATE**

**Jim Adams, Ph.D. Candidate, Imaging Science**  
B.S., Physics, Monmouth College, 1979.  
B.S., Electronic Device Physics, Monmouth College, 1979.  
M.S., Optics, University of Rochester, 1984.

**Seth Ansell, M.S. Candidate, Color Science**  

**Peter Burns, M.S. Candidate, Imaging Science**  

**Cathy Daniels, M.S. Candidate, Color Science**  

**Jack Rayhill, M.S. Candidate, Imaging Science**  

**Debbie Vent, M.S. Candidate, Imaging Science**  
B.S., Optics, University of Rochester, 1988.

**FULL-TIME UNDERGRADUATE**

**Chris Hauf, B.S. Candidate, Imaging Science**

**Barb Grady, B.S. Candidate, Imaging Science**

**Daniel Smith, B.S. Candidate, Imaging Science**
Funding

The Richard S. Hunter Professorship and Munsell Color Science Laboratory have been generously supported by industrial and individual donors. Many of our research efforts, the maintenance of our facilities, and the support of students would not be possible without this support. The support from instrument manufacturers continues to flourish. Having state-of-the-art instrumentation makes our industrial seminars and our academic coursework much more relevant.

The following lists our non-contract supporters during the time period of this annual report. Specific projects and sources of funding are described in the next section.

ENDOWED SCHOLARSHIPS
Two endowed scholarships have been established to support graduate education in color science.

Franc Grum Memorial Scholarship
Macbeth-Engel Fellowship in Color Science

SCHOLARSHIPS
Scholarship support is difficult to quantify. Corporations may contribute direct and future funding, technical support, hardware, and Summer intern positions. The total costs for a full-time student including course work, 12 month stipend, and laboratory support are approximately $40,000 per calendar year. The following scholarships were established or continued during 1992:

Eastman Kodak Company
R.R. Donnelley & Sons, Incorporated
BASF Corporation
DuPont Imaging Systems

UNRESTRICTED RESEARCH GRANTS AND GIFTS
Elizabeth Hunter.................................................................$10,000
3M..................................................................................$5,000
Miles Inc., Organic Products Division..............................$2,500
Miles Inc., Industrial Chemicals Division......................$2,000
Welch Allyn.................................................................$5,000
DEVICES

<table>
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<tr>
<th>Donor</th>
<th>Device</th>
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<tr>
<td>BYK Gardner, Incorporated</td>
<td>Color View Spectrophotometer</td>
<td>$13,000</td>
</tr>
<tr>
<td>Graseby Optronics</td>
<td>Autoranging Optometer</td>
<td>$1,400</td>
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<tr>
<td></td>
<td>IEE-488 Optometer</td>
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<tr>
<td></td>
<td>Illuminance Sensor</td>
<td>$395</td>
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<td></td>
<td>CRT Brightness Sensor</td>
<td>$365</td>
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<tr>
<td>Gretag Data &amp; Image Systems</td>
<td>Spectrophotometer</td>
<td>$12,000</td>
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<tr>
<td>Howtek, Incorporated</td>
<td>Scanmaster D4000</td>
<td>$40,000*</td>
</tr>
<tr>
<td>Huntsman Film Products</td>
<td>Diagonistic Materials</td>
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<td>LMT</td>
<td>The Photonics Directory</td>
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<td>Management Graphics</td>
<td>Image Recorder</td>
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<td>Macbeth</td>
<td>Spectralight II-D75 Booth</td>
<td>$3,900</td>
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<td>Milton Roy Company</td>
<td>Colorscans (4)</td>
<td>$60,000</td>
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<tr>
<td>Rolf G. Kuehni, Miles Inc.</td>
<td>Color: Essence &amp; Logic Textbooks</td>
<td>$500</td>
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<tr>
<td>UMAX Technologies, Inc.</td>
<td>Color Scanner</td>
<td>$5,495</td>
</tr>
<tr>
<td></td>
<td>Transparency Adaptor</td>
<td>$895</td>
</tr>
</tbody>
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* Partial Donation
Research

Research topics that were investigated in the past year are listed below in no particular order. The sources of funding are listed in brackets. The acronym MCSSL indicates that the research was supported with the general research funds of the Munsell Color Science Laboratory. The acronym RSHP indicates that the research was supported through the Richard S. Hunter Professorship. We have provided a brief description on what each topic is about and this year’s progress. Please refer to the publications list on pages 20-21 and 30-33 for references to more information on this research and feel free to contact any of us at the laboratory.

Color Appearance Modeling: RLAB
[MCSSL]
Mark Fairchild, Roy Berns

A color appearance space, based on CIELAB, has been developed for applications in color reproduction. This space includes features to account for chromatic adaptation, cognitive effects, luminance level and surround. An article on this work will appear in CR&A in 1993 and it is being presented at the 1993 SPIE/IS&T Electronic Imaging meeting.

Time-Course of Chromatic Adaptation
[MCSSL]
Mark Fairchild, Lisa Reniff

Previous work on this topic is being extended to provide more accurate and precise data on the time-course of chromatic adaptation to different chromaticities. This work has an impact on cross-media color reproduction studies in that it helps to define the viewing requirements for comparison of images with differing white points. Results of this study should be presented at the 1993 OSA annual meeting in Toronto.

Helmholtz-Kohlrausch Effect Modeling
[MCSSL]
Mark Fairchild, Elizabeth Pirrotta, Nathan Moroney

Given high and low chroma object colors of equal luminance factor, the high chroma color will appear lighter. This phenomenon is sometimes referred to as the Helmholtz-Kohlrausch effect. Previous work on this topic was extended at the request of ISCC project committee #44. More data were collected over the past year. These data will be used by the ISCC committee and tend to verify the previous results.
Evaluation of Object Texture Using Colorimetry-Based Image Processing
[BASF, MCSL]
Seth Ansell, Roy Berns

The aim of this project is to find a color space that can be used for representing images in which it is possible to separate the visual aspects of color and texture. These analyses will aid in the formulation of textured materials and the simulation of images of these materials. During 1992, video cameras and flat-bed scanners were evaluated for colorimetric precision and accuracy. We decided on using a U-Max scanner as the input device. The remainder of the year was spent in software development and in evaluating a wedge-ring detector to reduce the amount of stored spatial information. This project is Seth’s Color Science M.S. thesis.

Development of Colorimetric Plug-In Filter Modules for Adobe Photoshop®
[BASF, MCSL]
Mark Fairchild

Colorimetric image processing routines were developed for use on Apple Macintosh® computers with Adobe Photoshop®. These “plug-in filter modules” allow users to perform colorimetric conversions and manipulations on images in a very user-friendly and accurate way. This work was performed in conjunction with BASF to investigate the colorimetric image analysis of carpet fibers. An MCSL technical report that describes the use of these filters (along with the modules themselves on disk) is available.

Testing Chromatic Adaptation Transforms for Single Stimuli
[R.R. Donnelley & Sons Company, MCSL]
Elizabeth Pirrotta, Mark Fairchild, Roy Berns

Prediction of the effects of chromatic adaptation is critical in many areas of color science. This project, Elizabeth’s Color Science M.S. thesis, will mathematically compare the predictions of various chromatic adaptation models for a limited set of object colors and a range of viewing conditions. Then a pair of viewing conditions will be chosen for which the models make the most different predictions. A paired-comparison visual experiment will be carried out under these conditions to derive an interval scale that quantifies the quality of the models. Elizabeth has been on leave much of 1992, but should return in 1993 to complete this work.
Testing Chromatic Adaptation Transforms for Pictorial Stimuli
[Dupont Imaging, MCSL]
Taek Kim, Roy Berns, Mark Fairchild

Taek Kim, as a Visiting Scholar from Dupont, just completed a visual experiment to test a number of chromatic adaptation models for pictorial images viewed under fluorescent daylight and incandescent illuminations at three illuminance levels. The experimental design is identical to Elizabeth Pirrotta’s. Preliminary analyses indicate that von Kries based models with the exception of Nayantani’s model have the best performance. Judd-type models (e.g. CIELUV) performed the poorest. An article describing the experiment in detail is in preparation.

Colorimetric Calibration of a Digital Film Recorder
[MGI, MCSL]
Roy Berns, Mike Stokes

This year we updated our film recorder to an MGI Solitaire. We have been developing software and metrology to optimize its tone reproduction characteristics and neutral tracking with a minimum of iterations and measurements. We have also begun to develop a spectral model to predict spectral transmittance from digital data based on Beer’s law. Eigenvector analyses are used to define the film’s spectral sensitivities and determine the amount of dye exposure. A statistical model will be optimized to relate the digital data to the amount of dye. We are hoping to write several articles on this project.

Testing Color Appearance Models for CRT-to-Print Comparisons
[Eastman Kodak Company, MCSL]
Mark Fairchild, Karen Rybarczyk

Karen Rybarczyk is in the Imaging Science Ph.D. program and is investigating the appearance of color images in different media and viewing conditions. This research will be directly applicable to the work of CIE TC 1-27. The objectives are to test various color appearance models for predicting matches between various imaging modalities. The first phase of this research, currently underway, will examine the effects of various viewing setups for the psychophysical comparison of CRT displays and prints.

Testing Color Appearance Models for CRT-to-Projected Slide Comparisons
[NSF/NYS IUCRC, MCSL]
Mark Fairchild, Audrey Lester

This project extends the work testing color appearance models to comparisons between CRT displays and projected 35mm slides. Audrey Lester will be working on this project as her Color Science M.S. thesis. Currently a special facility for the high-quality (calibrated) projection and viewing of 35
mm slides is being constructed and calibrated. In addition, direct comparisons between the projected image and a CRT display will be possible. The facilities will be completed and calibrated during 1993 and psychophysical testing should begin by the end of the year.

**Color Science Education through Interactive Computer Graphics**

[MCIS]

Brian Rose, Mark Fairchild

Graphics-based computer systems have provided new tools for scientists and designers that allow the manipulation of color in ways that are unfamiliar to many. Education in the fundamentals of color science, perception, and design would be very beneficial to these users. Brian Rose, for his Color Science M.S. thesis, has created an interactive computer graphics program for the Macintosh that can be used by anyone with access to a color Macintosh and an interest in color to explore fundamental concepts of color science. Brian has completed his degree and is currently employed with Apple Computer.

**Sensitivity Analysis of the Hunt Color Appearance Model**

[MCIS]

Chris Hauf, Mark Fairchild

This is a senior research project in Imaging Science designed to investigate the effect of variation in the various input parameters of the Hunt model on the predicted appearance correlates. This is a numerical analysis that should lead to a better understanding of the Hunt model and, perhaps, future psychophysical experiments on the importance of viewing condition parameters.

**Comparison of Color Reproduction of Various Color Print Films**

[MCIS]

Barbara Grady, Mark Fairchild

This is a senior project in Imaging Science to evaluate the quality of color reproduction for three color print films: Kodak Ektar 100, Kodak Gold Plus 100, and Fujicolor Reala. The objective is to determine both overall color reproduction accuracy and to evaluate the reproduction of metameric samples. The "fourth-layer" in Reala should result in reproduction of metameric samples that correlates more closely with visual perception.
Color Difference Modeling
[RSHP]
Roy Berns

Three data bases were compiled by CIE TC 1-29: those of Luo and Rigg, Witt, and our RIT-Dupont data base. An analysis was performed to evaluate systematic and random differences between these data bases. It was found that lightness differences were dependent on viewing conditions and that the CMC lightness weighting was inconsistent with independent experiments. All three data bases showed consistent trends in chroma and hue differences that depend on the chroma location of the difference pair. A hue angle dependency that was statistically significant could not be derived. A composite color difference equation that is likely to be recommended by TC 1-29 was developed based on the three data bases.

Visual Determination of Constant Hue Loci
[Konica Corp., MCSL]
Po-Chieh Hung, Roy Berns

A visual experiment was performed using a CRT graphics display to determine loci of constant perceived hue for a wide variety of colors. The data have been analyzed in CIELAB, CIELUV, Hunt 1991, and Nayatani appearance spaces. Preliminary evaluations indicate that Hunt's space may have the best hue linearity for stimuli within CRT color gamuts. An article is in preparation for submission to Color Research and Application.

Investigation of Observer Metamerism
[Kollmorgen Foundation, New York State Center for Advanced Technology in Optics, MCSL]
Amy North, Mark Fairchild

This work involved the measurement of color matching functions for the determination of inter- and intra-observer variation. An article on the techniques and a second that evaluates the CIE method for predicting observer metamerism have been accepted for publication in Color Research and Application.

Modeling the Spectral Reflectance of a Dye-Diffusion Thermal-Transfer Printer
[RSHP]
Roy Berns

This year we finally moved beyond CRT displays as stimulus generators in our research. We have started using continuous-tone dye-diffusion thermal-transfer printers, in particular the JVC SP5501 (Dupont 4Cast) and Kodak XLT7720. We found that tristimulus empirical models based on multiple-linear regression were inadequate; as a consequence, the use of Kubelka Munk (KM) was
evaluated to develop a spectral model. The model is based on the transparent form of KM and includes terms for diffusion back onto the donor supply and dye transfer inhibition. The results are equal to tetrahedral interpolation techniques. This research was presented at the AIC conference on colorant formulation and the Center for Imaging Science Industrial Associates fall meeting. An article for submission to the Journal of Electronic Imaging is nearing completion.

Generic Approach to Color Modeling

[RSHP]
Roy Berns

After teaching the coloration of textiles, polymers, and paints, and the color formation of imaging devices including photography, CRT displays, and continuous-tone printers, I found there are many commonalties. I presented the "generic" approach to color modeling at the AIC conference on colorant formulation using the JVC printer as an example. I hope to write the approach in a form suitable for publication in Color Research and Application.

Optimization of a Drum Scanner for Colorimetric Performance

[Dupont Imaging, Howtek, Inc.]
Roy Berns, James Schyu

For color WYSIWYG, it is necessary to colorimetrically characterize scanners for a variety of CIE illuminants. There are three approaches that can be used to accomplish this. The first is to empirically convert from scanner RGB to XYZ using multi-dimensional interpolation or multiple-linear regression. The second method is to design the scanner to have responsivities that are linear transformations of illuminant-observer color matching functions. The third method is to transform the three-channel scanner to a spectral scanner. All three methods will be compared. James Schyu will be aiding in this research and it will serve as his M.S. thesis in Color Science.

Multi-Channel Analysis of Object-Color Spectra

[Xerox, RSHP]
Debra Vent, Roy Berns

An optimization will be carried out to determine a set of channel responses for measuring object-color spectra. The optimization set will consist of the minimum number of channels, their wavelength locations, and bandwidths necessary to obtain accurate colorimetric results for illuminants D65, F2, and A when the estimated object spectra are converted to tristimulus values. This project is Debra’s M.S. thesis in Imaging Science.
Spectral Matching Using Multiple Ink Sets to Minimize Metamerism

Roy Berns, Timothy Kohler

Traditional four-color printing is colorimetrically inaccurate and by definition metameric to original scenes and objects. This is an acute problem when reproducing artwork for use in high-quality texts and catalogs, as one example. This problem can be avoided if a spectral match can occur between the original artwork and its reproduction. A theoretical analysis and limited pilot experiment will be performed to evaluate the feasibility of using greater than four inks to generate spectral matches rather than colorimetric matches. To predict the spectral reflectance factor of multi-ink printing from dot areas, Neugebauer, Demichel, and Kubelka-Munk models will be employed. This project will serve as Tim’s M.S. thesis in Color Science.

Gamut Mapping Psychophysics

Toru Hoshino, Roy Berns

A visual experiment is underway to evaluate a number of gamut mapping techniques between rear-illuminated photographic transparencies and dye-diffusion thermal transfer reflection prints. The first set of experiments will address lightness mapping where clipping, nonlinear mapping, and linear mapping techniques will be compared for two different ranges of lightness reproduction. The second experiments will explore chroma mapping techniques. The Hunt 1991 color appearance space will be used to define each medium’s color gamut. A presentation was given at the SPIE Meeting, January 1993, in San Jose, CA.

Gamut Mapping Algorithms

Rab Govil, Roy Berns, Mark Fairchild

Software is under development to efficiently gamut map images within a uniform color space that will expand and compress images as needed to fully exploit a device’s color gamut. Based on a set of a priori rules such as clipping or compression with constant hue or minimum color difference, images will be remapped to fill the destination gamut. The rules will be determined independently based on psychophysical experiments.
1992 Publications

The following is a list of reviewed articles and papers or abstract proceedings published or accepted for publication by faculty, staff, visiting scholars, and students of the Munsell Color Science Laboratory (listed in bold) during 1992. Past publications are listed beginning on page 26.


1992 Presentations


R.S. Berns, "Color Science: Fundamentals and Advances," Imaging Colloquia, Polytechnic University, Brooklyn, April.

M.D. Fairchild, "Chromatic Adaptation to Image Displays," Eastman Kodak, Rochester, April.


M. Stokes, "Colorimetrically Quantified Tolerances for Pictorial Images, ISCC/TAGA Williamsburg Conference, February."
Munsell Color Science Advisory Board

The Munsell Color Science Laboratory Advisory Board is an advisory group composed of industrial and academic experts in color science and color aesthetics. Their role is to insure that the activities of the Munsell Color Science Laboratory are in concert with industrial needs, to evaluate the degree program in color science, to promote funding opportunities, and to provide employment opportunities to Color Science and Imaging Science graduates focused on color-related problems.

Dr. Dave Alman
DuPont
P.O. Box 2802
Troy, MI 48007-2802

Mrs. Joy Turner Luke
Box 18 Route 1
Sperryville, VA 22740

Dr. Fred W. Billmeyer, Jr.
1294 Garner Avenue
Schenectady, NY 12309-5746

Mr. Calvin S. McCamy
54 All Angels Hill Road
Wappingers Falls, NY 12590

Mr. Leroy DeMarsh
Eastman Kodak Company
Rochester, NY 14650

Mr. Cornelius J. McCarthy
35 Stonington Drive
Pittsford, NY 14534

Mr. Peter Engeldrum
Imcotek, Inc.
P.O. Box 17
Winchester, MA 01890

Dr. Yoshinobu Nayatani
Osaka Electro-Communication University
18-8 Hatsu-uh
Neyagawa, Osaka 572
Japan

Dr. Henry Hemmendinger
438 Wendover Drive
Princeton, NJ 08540

Dr. Noboru Ohta
Fuji Photo Film Company, Ltd.
210 Kakanuma, Miniami-asigara
Nagawa-ken 250-01
Japan

Dr. Jack Hsia
National Institute of Standards and Technology
Bldg. 220 B-306 / Div. 534
Gaithersburg, MD 20899

Mr. Milton Pearson
RIT Research Corporation
75 Highpower Road
Rochester, NY 14623

Mr. Norbert Johnson
3M
3M Center 582-1-15
St. Paul, MN 08540

Dr. Danny C. Rich
Datacolor International
P.O. Box 5800
Princeton, NJ 08540

Mr. Rolf G. Kuehni
Miles Inc.
Mobay Road
Building 14, 1st Floor
Pittsburgh, PA 15205-9741

Dr. Alan R. Robertson
National Research Council
Division of Physics
Ottawa, Ontario K1A OR6
Canada

Dr. Joann Taylor
17890 NW Deer creek Court
Portland, OR 97208
Color Science Courses

Some minor revisions have been made in the Color Science M.S. curriculum. The order of presentation of the courses has been revised such that students can complete their course work by the end of Fall quarter of their second year and thereby begin thesis work earlier. This was accomplished by changing the Optical Radiation Measurements course from a 4 credit hour lecture and laboratory to a 2 credit hour laboratory-only course and moving it from Spring of the second year to Fall of the first year. In addition, the Theory of Color Measurement course was replaced with a new course entitled Color Appearance. The new course will include much of the same material and will appear in Spring of the first year rather than Fall of the second year. Finally, Color Science Seminar has been moved from Winter to Fall of the second year.

A proposal was also prepared for a non-thesis option in the Color Science M.S. program. It is expected that this option will attract more part-time students from local industry. This should have a positive impact on enrollment without putting undue demands on limited faculty and laboratory resources for theses. This proposal is still under review. Students enrolled in the non-thesis option will be required to complete a 1-quarter, 4-credit-hour, Color Science M.S. Project in lieu of a thesis. This project will be required to be of the same intellectual level as an M.S. thesis although less extensive. The student will then be required to fulfill the remaining credit hour requirements with professional electives. A list of the current catalog descriptions of the required courses for the M.S. in Color Science follows. The instructor's name follows the course description in parentheses.

<table>
<thead>
<tr>
<th>Course</th>
<th>Credit Hours</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIMC-700</td>
<td>4</td>
<td>VISION AND PSYCHOPHYSICS</td>
</tr>
<tr>
<td>Registration#0926-700</td>
<td></td>
<td>This course provides an overview of the human visual system and psychophysical techniques used to investigate it. Topics include: the optical design of the eye; mechanisms of photoreception; neural coding; processing of visual information; and experimental techniques. Emphasis is placed on the mechanisms of color vision. (Fairchild)</td>
</tr>
<tr>
<td>PIMC-701</td>
<td>3</td>
<td>APPLIED COLORIMETRY</td>
</tr>
<tr>
<td>Registration#0926-701</td>
<td></td>
<td>An introduction to the measurement and specification of color. The CIE system of colorimetry is presented with an emphasis on its practical application to common problems in quality control, reproduction, imaging, and formulation. The laboratory stresses the instrumental measurement of color and appearance. (Berns)</td>
</tr>
<tr>
<td>PIMC-706</td>
<td>2</td>
<td>APPLIED COLORIMETRY LABORATORY</td>
</tr>
<tr>
<td>Registration#0926-706</td>
<td></td>
<td>Accompanying laboratory to Applied Colorimetry. Course stresses technical writing and scientific reasoning applied in a laboratory environment. Laboratories include: spectroradiometry of natural daylight, glossimetry, visual colorimetry, color tolerance determination, and colorimetric precision and accuracy analysis of color measuring instrumentation. (Berns)</td>
</tr>
</tbody>
</table>
This course is designed for students with an understanding of the applications of colorimetry and presents the transition from the measurement of color matches and differences to the description and measurement of color appearance. This seminar course is based mainly on review and discussion of primary references. Topics include; appearance terminology, appearance phenomena, viewing conditions, chromatic adaptation, and color appearance modeling. (Fairchild)

A seminar course in which the students will study the literature in particular areas of color science and present that material to the class. Topics will be chosen based on student interest and current issues in the field. (Berns and Fairchild)

An in-depth treatment of the instrumentation and standardization required for accurate and precise measurements of optical radiation. The optical properties of objects and radiation sources will be covered. The optical and electronic design of spectroradiometric and spectrophotometric instrumentation is discussed in detail. The use of standard reference materials for the calibration and evaluation of instrumentation is explored. The laboratory is heavily stressed with students fully analyzing the design and performance of various instruments. (Reniff)

This course explores mathematical techniques for predicting the coloring of various imaging systems including self-luminous displays, reversal color films, thermal dye transfer printers, and color scanners. Emphasis is placed on both analytical-physical and empirical-phenomenological approaches. Models include Kubelka-Munk turbid media theory for opaque, transparent, and translucent systems; Grassmann's laws for additive systems; and linear and higher order masking equations. Statistical techniques include multiple-linear regression and non-linear optimization via the simplex method. Accompanying laboratory stresses the characterization, calibration, and prediction of various imaging devices in a systems approach. (Berns)

An independent project in an area of color science that serves as the major culminating experience for students in the non-thesis option of the Color Science M.S. program. This project can be an experiment, critical literature review, demonstration, or other appropriate work. This course requires a formal proposal and a faculty sponsor. A written technical report and oral presentation of the results are required.

Thesis based on experimental evidence obtained by the candidate in an appropriate topic as arranged between the candidate and the coordinator of the program.
Industrial Courses

Short Courses
"Colorimetry: An Intensive Short Course for Scientists and Engineers" has been long running and has been well received filling its enrollment every year since its inception. Colorimetry will be offered May 11-13, 1993. The three-day course is designed to teach the effective applications of colorimetry to persons involved in coatings, textiles, polymers, reprographics, and electronic imaging. The course stressed instrumental measurements particularly useful for instrumental quality control.

As you may recall, we offered new advanced industrial courses this past summer. Unfortunately, we did not receive the anticipated number of participants. So each course objectives were reviewed and changes made accordingly. Additionally, the advertising method was adjusted to distribute two separate brochures instead of a combined brochure. The advanced courses consist of "Device-Independent Color Imaging," to be held on July 20-21, 1993; it is an in-depth short course designed to teach the theory and practice of colorimetry as applied to imaging, so called device-independent color. The other is "Quantitative Visual Evaluation of Color and Images," to be held July 22-23, 1992. This two-day course covers the quantitative evaluation of visual stimuli, known as psychophysics. Special emphasis is given to the application of psychophysical techniques to the analysis of color and images. We hope to attract more individuals interested in advanced colorimetry and psychophysics via these changes.

The Principles of Color Reproduction: An Intensive Short Course taught by Dr. R.W.G. Hunt nicely complements our Colorimetry course. We recently held this course in October of 1992. Dr. Hunt spends half of the course teaching about how color is formed using photographic, television, and reprographic imaging modalities. We have not determined the dates for 1993 although it will most likely be offered in the Fall.

The Munsell Laboratory's short courses for industry have and will continue to be a major part of the laboratories dedication to a useful interaction with industry and this past years are listed below.

Berns: "Colorimetry" section (8 hours instruction) of Imaging Science and Technology Training Program, Eastman Kodak Company, Rochester, January and February.

Berns: "Colorimetry for Electronic Imaging" (24 hours instruction): Xerox Corporation, El Segundo, California, January; Lexmark Corporation, Lexington, Kentucky, January; Xerox Corporation, East Rochester, June

Berns: "Colorimetry" section (8 hours instruction) of Color Principles for Graphics Systems offered through IMCOTEK: Lexmark Corporation, Lexington, Kentucky, May and September; Hewlett Packard Corporation, San Diego, California; Bedford Stauffer, Bedford, Massachusetts.

Fairchild: "Vision and Color" sections (16 hours instruction) of Hybrid Imaging Technology Systems, Eastman Kodak Company, Rochester, February through March.
Technical Reports

The following list Munsell Color Science Laboratory Technical Reports published to date. These reports contain various types of information and are written by faculty, staff, and students studying color science. 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.


Long-Term Calibration of a Diode-Array Radiometer, Fairchild and Berns, May, 1986.
Past Publications

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

1991


1990


1989


1988


1987


1986

1985


Facilities

The Munsell Color Science Laboratory is housed on the third floor of the Chester F. Carlson Center for Imaging Science, at the Rochester Institute of Technology. This a facility dedicated in October of 1989 in the memory of Chester Carlson, inventor of Xerography, and that serves as a comprehensive center for education and research in imaging science. Color science is one of several major research themes of The Center for Imaging Science. The main laboratory contains many color measuring instruments and instruction area, while small rooms off the main area are dedicated to specific tasks. These areas contain low and high resolution image processing and display systems with input and output devices, spectroradiometric and photometric measurement equipment and visual apparatus. One room was specially designed for high accuracy optical radiation measurements and houses several spectrophotometers used for research and calibration services, and goniospectrophotometric research. Research on color vision and image perception is performed in another laboratory located on the same floor. This laboratory contains computer systems optimized for visual display and psychophysical experimentation, and other apparatus for the study of vision. Color Science research and education through the color science master’s degree program and industrial seminars is conducted in the Munsell Color Science Laboratory and associated laboratories. The current list of equipment is given below.

Optical Properties of Materials

BYK-Gardner Colorgard System 1000 Colorimeter
- 0/45
- Donation by BYK-Gardner

BYK-Gardner Glossgard II
- 20, 60 and 85 degree
- Donation by BYK-Gardner

BYK-Gardner Color-view Spectrophotometer
- 380-720nm, 45/0, 32 diode array detector, color matching software
- Donation by BYK-Gardner

BYK-Gardner The Color Sphere Spectrophotometer
- 380-720nm, 4d/0, 32 diode array detector,
- Donation by BYK-Gardner

Cary 17D Spectrophotometer
- 186-2650 nm range, digital and analog
- Donation by Eastman Kodak Co.

Cosar Pressmate I Densitometer
- Hand held, Status T, reflection
- Donation by Cosar Corp.

Cosar 75 CompuPlus Densitometer
- Status A and M, transmission/reflection
- Donation by Cosar Corp.

Datacolor Intl. Chroma-Sensor CS-5 Spectrophotometer
- 400-700 nm, d/0, interference wedge mono
- Chroma-Calc color matching software for paints, textiles, and inks
- Decorator 300 software
- VCS-11 software
- Donation by Datacolor Intl.

Diano Match Scan II Spectrophotometer
- 380-1000nm, d/0, reversible optics, grating monochromator
- Donation by MiltonRay APD

General Electric Recording Spectrophotometer
- 380-700nm, 0/d, analog, D & H tristimulus integrater

Gretag SPM 60 Spectrophotometer
- 380-700nm, 45/0, portable
- Donation by Gretag
HunterLab D25A-9 Tristimulus Colorimeter
45/0, 4 filtered detectors, Ill. C
Donation by Hunter Associates Laboratory

HunterLab D25D-2 Tristimulus Colorimeter
45/0, 4 filtered detectors, Ill. C
Donation by Hunter Associates Laboratory

HunterLab Dori-gon Meter D47-6
Abridged Goniophotometer
Donation by Hunter Associates Laboratory

HunterLab Labscan Spectrophotometer
400-700nm, 0/45, interference-wedge mono
Donation by Hunter Associates Laboratory

HunterLab MiniScan Spectrophotometer
Portable, 400-700nm, 45/0
Donation by Hunter Associates Laboratory

HunterLab Modular Model D48-7 Gloss Meter
20 and 60 degree heads
Donation by Hunter Associates Laboratory

HunterLab UltraScan SpectroColorimeter
375-750nm, d/0, 76 diode-array detector
Donation by Hunter Associates Laboratory

IBM Model 9420 Spectrophotometer
190-900nm, transmission/reflection
Donation by IBM

Macbeth 1500/Plus Spectrophotometer
400-700nm, d/0, 16 diode-array detector,
Optiview, Optimatch, CIE-to-Munsell
Donation by Macbeth

MCSL Goniospectrophotometer

Variable illumination and viewing angles
Partially donated by Eastman Kodak Co.

Milton Roy Color Mate HDS Spectrophotometer
400-700nm, 45/0, 16 diode array detector
Donation by Milton Roy APD

Milton Roy ColorScan Spectrophotometer
350-780nm, d/0, grating monochromator
Donation by Milton Roy APD

Milton Roy ColorScan / 45 Spectrophotometer (4)
350-780nm, 45/0, grating monochromator
Donation by Milton Roy APD

Minolta Chroma Meter CR-221 Colorimeter
compact, 45/0, D65, C
Donation by Minolta Corp.

Minolta CM-1000 Spectrophotometer
Portable, 400-700nm, d/0, diode array detector
Donation by Minolta Corp.

Minolta CM-2002 Spectrophotometer
Portable, 400-700nm, d/0, diode array detector
Donation by Minolta Corp.

Optronic 746-D Spectrophotometer
280-2500nm, 0/d, grating monochromator

Photodyne 99XL Densitometer
Portable, transmission/reflection
Donation by Photodyne

X-Rite 968 Spectrophotometer
400-700nm, 0/45, portable
Donation by X-Rite

Radiometry

Graseby Optronics UDT Photometer (2)
Autoranging, Digital, CRT sensor head
Donation by Graseby Optronics

LMT C1200 Colorimeter
17 filtered detectors, 2° obs.
Donation by LMT

Minolta Chroma Meter II Incident Colorimeter
Hand held, 2° obs.
Donation by Minolta Corp.

Minolta Chroma Meter CS-100 Colorimeter
Hand held, spot reflex viewing
Donation by Minolta Corp.

Minolta Color Analyzer CA-100Colorimeter
4 filter, designed to measure CRT, 2° obs.
Donation by Minolta Corp.

Optronic Model 740 Spectroradiometer
280-1100 nm range, double monochromator,
calibrated detector
Donation by Optronic Laboratories Inc.
Photo Research PR-703A Spot SpectraScan Spectroradiometer (2)
   256 diode-array, Pritchard optical system
   Donation by Photo Research

Photo Research PR-1500 SpotMeter Radiometer/Photometer
   PMT, Pritchard optical system

Partial List of Visual Apparatus

Breneman Visual Colorimeter
   Donation by Eastman Kodak Co.

Color Curve Color Communication System
   Master and gray & pastel atlases
   Donation by Color Curve

Dianolite Viewing Booth (3)
   D65, A, and UV
   Donation by Milton Roy APD

D & H Color Rule (3)
   Metameric slide rule

Datacolor International VCS-10
   Maxwell disk colorimeter
   Donation by Datacolor Intl.

Datacolor International Tru-Vue Viewing Booth
   D65, A, CWF, and UV
   Donation by Datacolor Intl.

Farnsworth-Munsell 100 Hue Test (2)
   Color discrimination test

Graphiclite Show-Off Portable Viewing Booth
   D50, reflection and transparency viewing

ICI Color Atlas

ISCC Color Aptitude Test
   Color discrimination and aptitude test

Isochromatic Plate Color Blindness Charts
   Ishihara, Dvorine, and American Optical Co.

Color Display and Reproduction

Barco "Calibrator" Color Video Monitor
   19V, black dot mask,
   Donation by Barco Industries

Donation by Photo Research

Schoeffel Monochromator (2)
   blazed at 500nm and 300nm

Tracor Northern DARSS Spectroradiometer
   240-870 nm range, 512 diode-array

HP 9000/375TSRX Computer System
   HP 9000/375 host computer
   graphics accelerator & processor, 1280x1024x8
   Donation by Hewlett-Packard
HP 98745A Color Video Monitor
Sony Trinitron, 19V
*Donation by Hewlett-Packard*

HP 98789 Color Video Monitor
Sony Trinitron, 16V
*Donation by Hewlett-Packard*

HP Paintjet Color Printer
*Donation by Hewlett-Packard*

Howtek 4000D Scanner
4000 dpi, drum scanner, refl. or trans.
*Partial Donation by Howtek*

Howtek Scanmaster Color Scanner (Sharp JX450)
300dpi, flat bed, color

Javelin JE2362 CCD Camera.
RS-170 sync, 576x485

Kodak XLT 7720 Printer
203 dpi, continuous tone, D2T2

Kodak SV-6510 Still Video Printer
Color dye-diffusion printer

Macintosh Quadra 900
Sony 16V, 24bit, 52MB RAM

Macintosh II Computer System
Sony 13V, 24 bit, 8MB RAM

Management Graphics Solitaire16 Image Recorder
35mm, 4x5, 16K lines
*Partial Donation by Management Graphics*

Pixar II Computer System
Sun Microsystems 3/160HM, host computer,
2M Pixels x 48, 60MB RAM

Pixar II Computer System
Sun Microsystems 3/260HM, host computer,
10M Pixels x 48, 60MB RAM
*Donation by R. R. Donnelley*

Sharp JX-610 Scanner
600 dpi, flat bed
*Donation by Sharp Corp.*

Sony GDM-1950 Color Video Monitor (2)
19V, Trinitron CRT

Sony PVM-1942Q Digital Color Video Monitor
19V, Trinitron, RS-170, RGB, NTSC, PAL, SECAM

Tektronix 650HR-C Color Video Monitor
13V, Trinitron
*Donation by Tektronix*

Tektronix 690SR Color Video Monitor
19V, dot mask
*Donation by Eastman Kodak Co.*

Tektronix Color Quick Ink-jet Printer
216 DPI, CMYK ink system
*Donation by Tektronix*

NEXTdimension Computer System
4m pixels x 32
Phillips color 17V, 1120x832x32 monitor
For More Information

For more information concerning the activities of the Richard S. Hunter Professor or the Munsell Color Science Laboratory, please contact:

Dr. Roy S. Berns
Richard S. Hunter Professor
Director, Munsell Color Science Laboratory

Rochester Institute of Technology
Munsell Color Science Laboratory
Chester F. Carlson Building
P.O. Box 9887
Rochester, New York 14623-0887
Telephone: 716-475-2230
FAX: 716-475-5988

Colleen M. Desimone
Secretary, Munsell Color Science Laboratory

Rochester Institute of Technology
Munsell Color Science Laboratory
Chester F. Carlson Building
P.O. Box 9887
Rochester, New York 14623-0887
Telephone: 716-475-7189
FAX: 716-475-5988