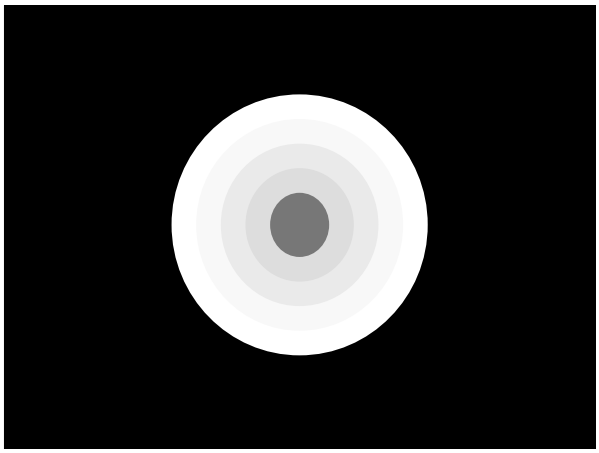


Color
in Informatics and Media Technology
A snapshot of the field

Prof. Jon Y. Hardeberg
NTNU, Gjøvik, Norway
jon.hardeberg@ntnu.no, http://www.colourlab.no

Guest Lecture, NTNU, Gløshaugen, April 11, 2016

Introduction

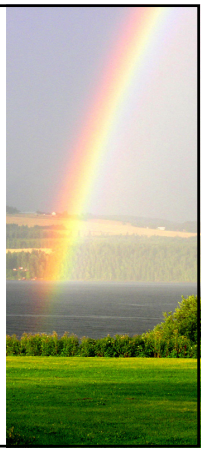
- You handle color images and video
  - Capturing with a webcam
  - Processing to improve quality
  - Analyzing to track people
  - Visualizing on a display
  - Printing
  - Programming and system integration

Introduction

- You need to
  - Understand color perception
  - Make sure What You See Is What Others See
  - Be able to judge image quality

Outline

- Introduction
- Color Science
- Color Management
- Color Image Quality



What *is* Color?

7

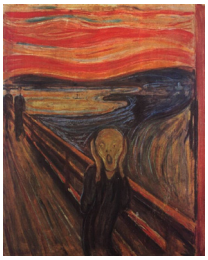
What *is* Color?

"Color consists of the characteristics of light other than spatial and temporal inhomogeneities; light being that aspect of radiant energy of which a human observer is aware through the visual sensations which arise from the stimulation of the retina of the eye." [OSA 1940]

8

What is Color?

"Color consists of the characteristics of light other than spatial and temporal inhomogeneities; light being that aspect of radiant energy of which a human observer is aware through the visual sensations which arise from the stimulation of the retina of the eye." [OSA 1940]



- Color is a sensation
  - Interaction between the physical world and our senses
  - Psychophysics

- When a tree falls in the forest, and no one is around to hear it, is there a sound?
  - Is the tree green if no one's there?
- "I want you to realize that there exists no color in the natural world, and no sound - nothing of this kind; no textures, no patterns, no beauty, no scent." (Sir John Eccles)

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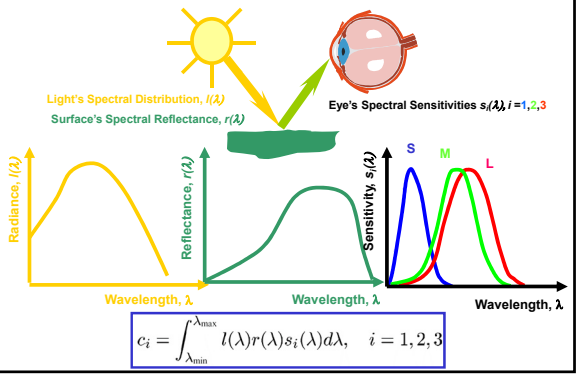
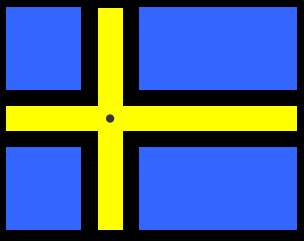
Color: Light, surface, eye



$$c_i = \int_{\lambda_{min}}^{\lambda_{max}} l(\lambda) r(\lambda) s_i(\lambda) d\lambda, \quad i = 1, 2, 3$$

Stare at this flag for 30 seconds...



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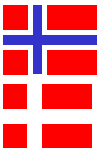
Complementary after-images

- What did you see?
  - #1: A white screen only
  - #2: The Norwegian flag
  - #3: The Danish flag
  - #4: First #3 then #2



- Conclusions
  - The eye is quite different from a CCD sensor
  - Our linear model is limited (but very useful)

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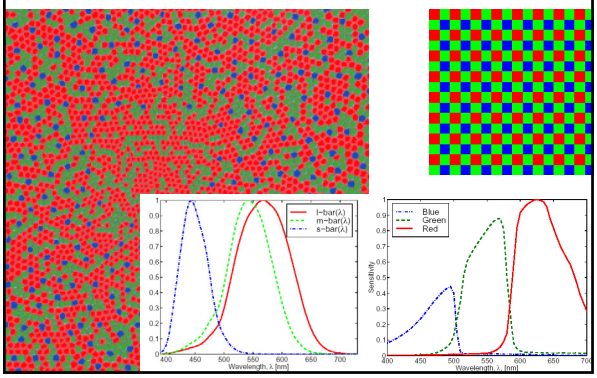
Retinal cone distribution vs. CCD sensor



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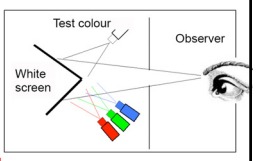
Colorimetry

- International Lighting Commission – CIE
  - 1931 Standard Colorimetric Observer
  - Determined based on color matching experiments



- Provides a standardized way of quantifying color
  - CIEXYZ
  - Foundation for consistent communication of color

$$X = k\sum \bar{x}(\lambda)R(\lambda)S(\lambda)\Delta\lambda$$
$$Y = k\sum \bar{y}(\lambda)R(\lambda)S(\lambda)\Delta\lambda$$
$$Z = k\sum \bar{z}(\lambda)R(\lambda)S(\lambda)\Delta\lambda$$
$$k = \frac{100}{\sum \bar{y}(\lambda)S(\lambda)\Delta\lambda}$$

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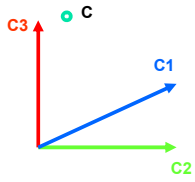
Color Spaces

- 3 different photoreceptors, L, M, S
  - 3-output linear model
  - Color can be specified by three numbers
  - Color space - analogy to geometrical 3D space



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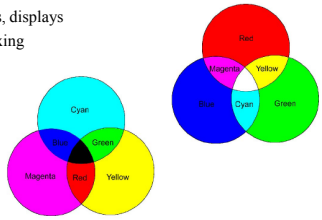
Color spaces for images and video

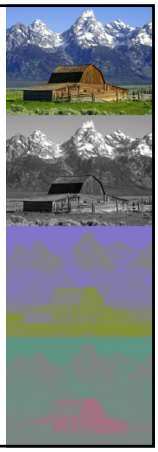
- RGB space is most common
  - Native to cameras, scanners, displays
  - Based on additive color mixing
- CMY(K) for printing
  - Subtractive color mixing



- Luminance-chrominance spaces
  - Important to separate, for instance for "Chroma Subsampling"
  - HSV, HSL, YIQ, YUV, YCbCR, Lab, Luv, …

YC_bC_r Color Space

- A luminance-chrominance color space: YC_bC_r
  - Standardized for digital video by Recommendation ITU-R BT.601.4
  - Used in JPEG image compression and MPEG video compression.
  - Closely related to the YUV transform.
- Luminance Y' (a.k.a. "Luma")
  - $Y' = 0.299R' + 0.587G' + 0.114B'$
  - Calculated from gamma-corrected signals R', G', B'
  - Note difference from colorimetric luminance Y
- Chrominance C_b and C_r
  - $Cb = ((B' - Y') / 1.772) + 0.5$
    $Cr = ((R' - Y') / 1,402) + 0.5$



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Device independence

- Device-independent color spaces
  - Defined according to colorimetry
  - LMS, CIEXYZ, CIELUV, *CIELAB*, *sRGB* …
- Device-dependent color spaces
  - Monitor RGB, Printer CMYK, Scanner RGB ...

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sRGB Color Space

- Standardized RGB
  - 1996
  - Device independent
  - Definition based on a typical PC monitor
- Advantages:
  - Ease of use
  - International Standard (IEC/ISO)
  - Endorsed by major business players (HP, Microsoft)
  - A common color language - Scan to sRGB - Print from sRGB - - -
  - More and more consumer imaging devices "speak" sRGB
- Disadvantages:
  - Yes…
  - 20 years since 1996

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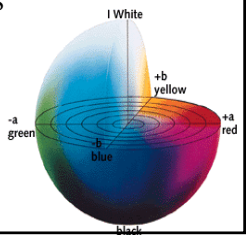
CIELAB color space (a.k.a. L*a*b*)

- Device independent
- Pseudo-uniformly related to human perception:
  - Defined according to a standard observer
- International Standard (CIE)
- Used in Color Fax and CMS
- Lightness *L**
  - L* = 100 = white
  - L* = 0 = black
- Chromaticity *a** and *b**
  - a* = green (-) to red (+)
  - b* = blue (-) to yellow (+)



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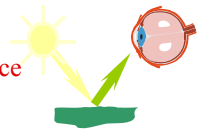
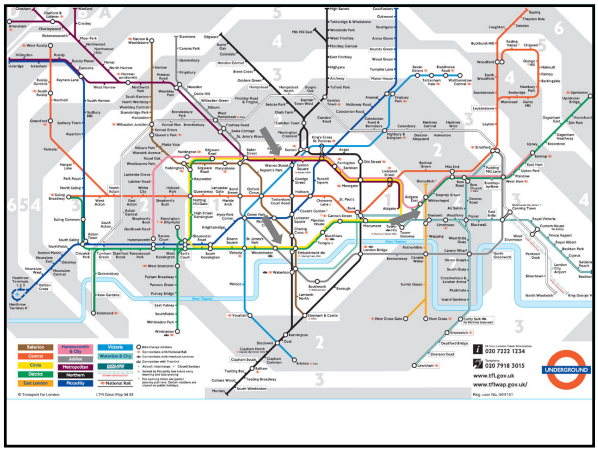
Perceived color depends on...



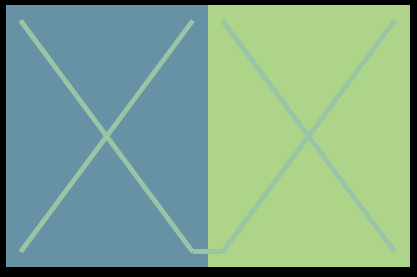
- Spectral distribution of light
- Spectral reflectance of surface
- Spectral sensitivity of eye

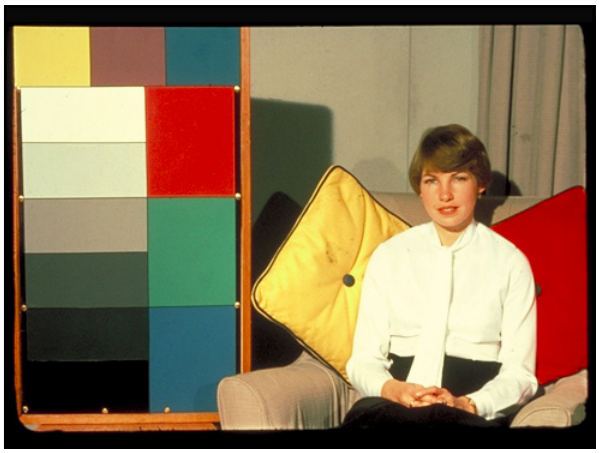
… but also on …

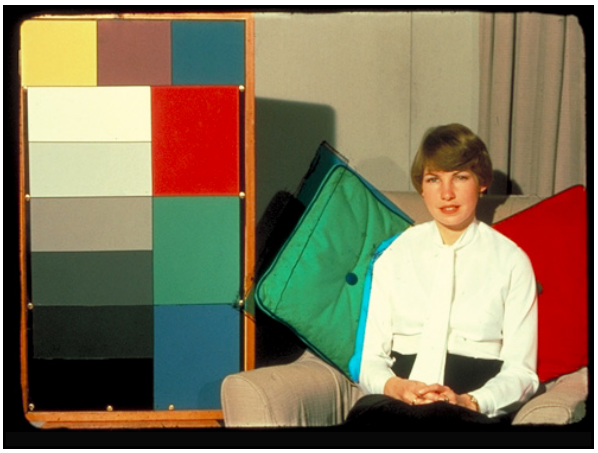
- Size of area
- Viewing direction
- Viewer adaptation
- Surrounding color
- Local contrast …



Simultaneous contrast







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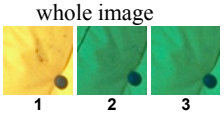
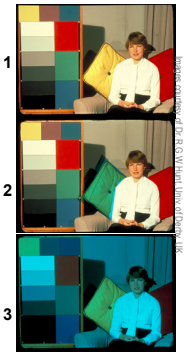
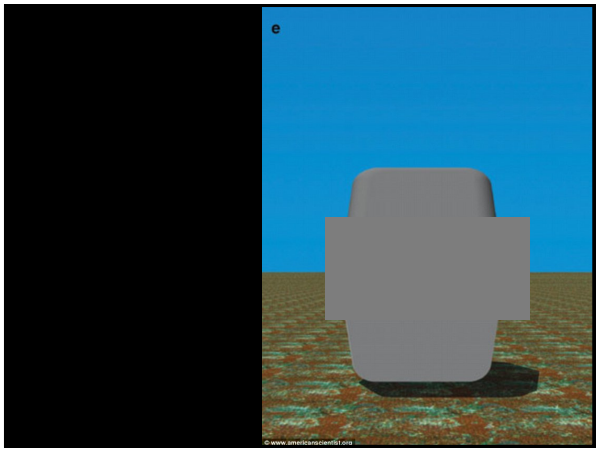
Local vs. global color changes

1. Original image
2. Adding a cyan filter over the cushion
3. Adding a cyan filter over the whole image





- Illustrates adaptation to white point - color constancy
- White balance for cameras
- Color appearance modeling – CAM
- Locality vs globality



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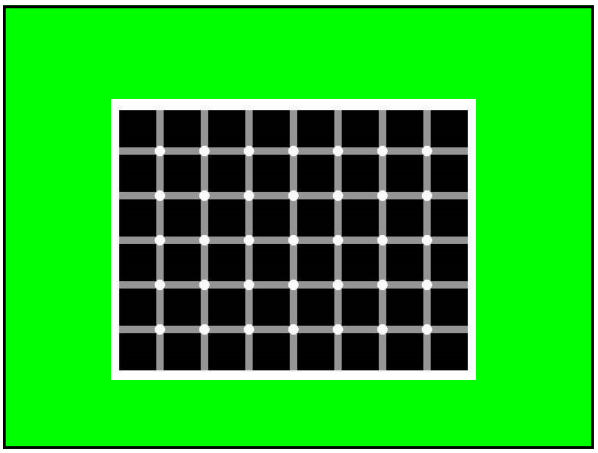
#THE DRESS

NOW BACK IN STOCK

DEBATE NOW



Outline

- Introduction
- Color Science
- Color Management
- Color Image Quality

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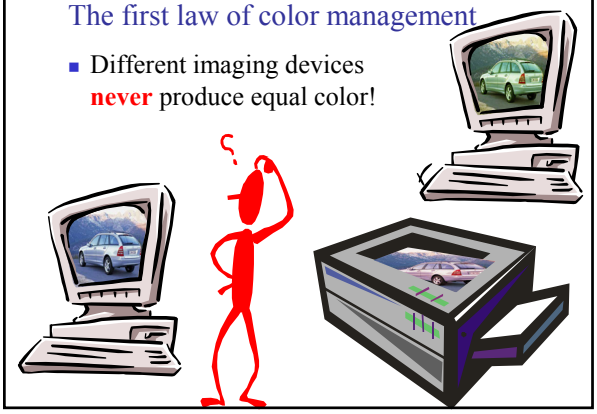
The first law of color management

- Different imaging devices **never** produce equal color!



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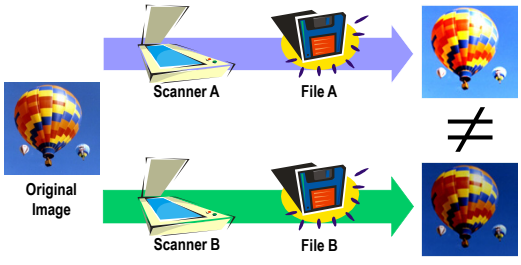
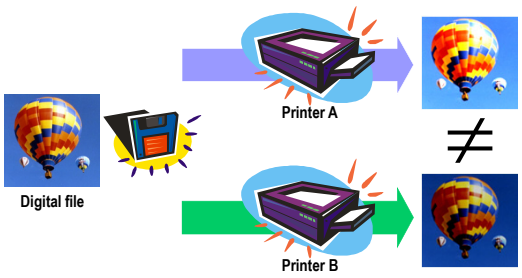
Scanners 'speak' color differently



36

Printers 'speak' color differently



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We speak color differently

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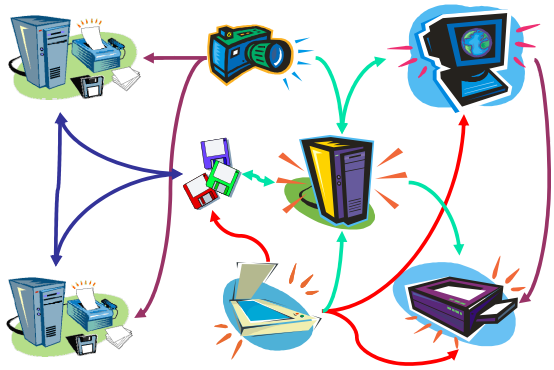
Complex imaging systems



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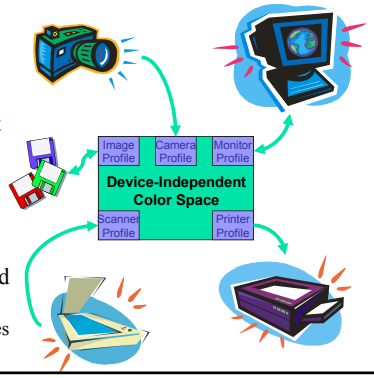
Principle of Color Management

- Image interchange through Device-Independent Color Space
  - Esperanto of colors
- Imaging devices characterized by Profiles
  - Dictionaries



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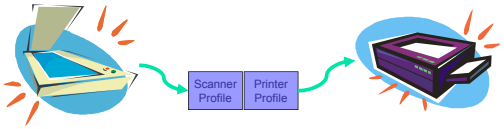
Principle of Color Management

- Color conversion between devices by "coupling" two profiles - source and destination



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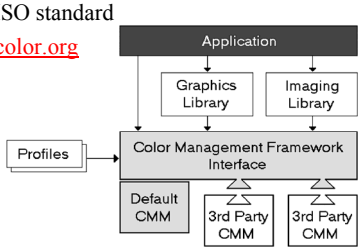
International Color Consortium - ICC

- International standard for Color Management
  - Architecture of Color Management Systems
  - ICC Profile file format
  - Now also ISO standard
  - See www.color.org



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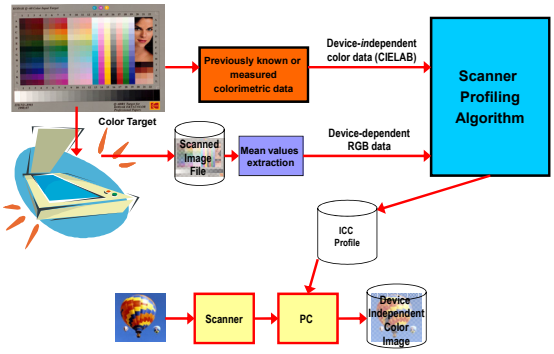
Input Device Profiling (scanner)



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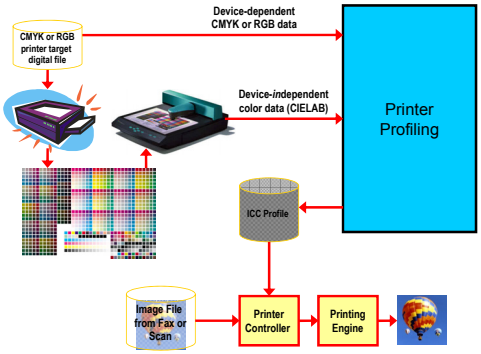
Output Device Profiling (printer)



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Approaches to device profiling

- A.k.a colorimetric device characterization
- Typical algorithms based on
  - Physical models
    - GOG model for CRT displays
      - "Gamma"-correction
    - Neugebauer model for halftone print
    - ++
  - Data-driven models
    - 3DLUT Interpolation
    - Polynomial regression
    - Neural networks
    - Thin-plate splines
    - ++

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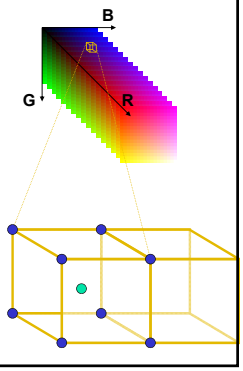
LUT-based colorspace conversion

- One look-up table (3DLUT) per conversion
  - Pre-calculated conversion for a subset of all possible input colors
- Interpolation for in-between values
- Content of LUTs depends on the actual devices, and is determined by device profiling
  - A.k.a colorimetric characterization



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Some active research areas

- Improved algorithms for device profiling / colorimetric characterization
  - LCD and DLP projection displays
  - Hue-preserving camera characterization model
- Compensation for varying viewing conditions
  - Color appearance modeling
- Color gamut mapping
- Spectral reproduction
- Workflow issues
  - Ease of use
  - Get people to do the right things
  - New areas such as digital film production

L. Seime and J.Y. Hardeberg, **Colorimetric Characterisation of LCD and DLP Projection Displays,** *Journal of the Society of Information Display*, 11(2): 349-358, 2003

C.F. Andersen and J.Y. Hardeberg, **Colorimetric characterization of digital cameras preserving hue planes**, Proceedings of the 13th Color Imaging Conference, pp. 141-146, Scottsdale, Arizona, November 2005

J.Y. Hardeberg, **Colorimetric Scanner Characterization**, *Acta Graphica*, 155, 2005

J.Y. Hardeberg, I. Farup, Ø. Kolås, and G. Stjernvang, **Color management in digital video: Color Correction in the Editing Phase**, In Proc. IARIGAI Conference, pp. 166-179, Lucerne, Switzerland, September 2002

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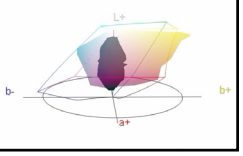
Color Gamut Mapping

- Imaging devices have only a limited number of reproducible colors: Color Gamut
- What to do if your image contains "out-of-gamut" colors?
  - Can't print anything "more yellow" than the yellow ink!
- Need for Gamut Mapping
  - "Do the best you can with the colors you have"
  - Huge unsolved problem in color imaging R&D
  - Clipping out of gamut colors is not good enough



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Gamut Mapping and Visualization

- Current research topics
  - Image-dependent and/or interactive new gamut mapping algorithms
  - Importance of gamut boundary descriptors:
    - Segment-maxima, convex hull, alpha-shapes, regular structure, …
  - Spatial gamut mapping
    - With University of Milano
- Popular freeware tool developed by us
  - ICC3D
  - http://www.colorlab.no/icc3d/

Ivar Farup and Jon Y. Hardeberg, **Interactive Color Gamut Mapping**, Proceedings of the 11th International Printing and Graphic Arts Conference, Bordeaux, France, October 2002

Ivar Farup, Jon Y. Hardeberg, and Morten Amsrud, **Enhancing the SGCK Colour Gamut Mapping Algorithm**, Proc. CGIV 2004, pp. 520-524, Aachen, Germany, April 2004

I. Farup, J. Y. Hardeberg, A. M. Bakke, S. Kopperud, and A.Rindal, **Visualization and Interactive Manipulation of Color Gamuts,** Proc. 10th Color Imaging Conference, pages 250-255, Scottsdale, Arizona, November 2002

Outline

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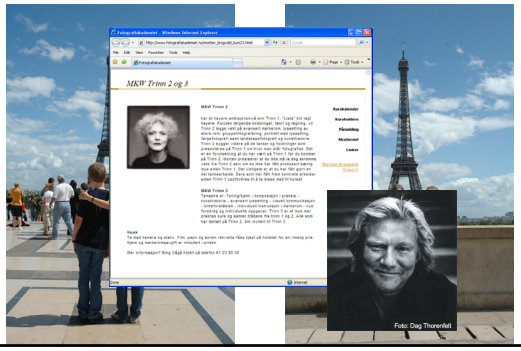
What is color image quality?



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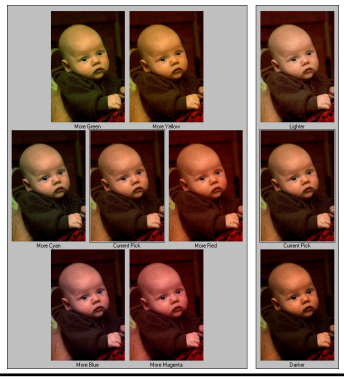
What is color image quality?



What is color image quality?

What is color image quality?

- What is color?
- What is an image?
- What is quality?
  - Dictionary: “Degree of excellence”
  - ISO9000: “The features of a product (or service) which are required by a customer”

Quality is what the customer wants!
Quality is what the customer wants!
Quality is what the customer wants!
Quality is what the customer wants!
Quality is what the customer wants!
Quality is what the customer wants!
Quality is what the customer wants!
Quality is what the customer wants!

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Customer-driven quality definition

- Norwegian governmental purchase of digital print equipment
- E.g. letterhead quality of primordial importance

DET KONGELIGE
SAMFERDSELSDEPARTEMENT

P. Nussbaum and J.Y. Hardeberg, **Print Quality Evaluation for Governmental Purchase Decisions**, Proc. IARIGAI Conference, Copenhagen, September 2004

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How to evaluate color image quality?

ØNSKER EGEN MINISTER: *Rune Indrøy, informasjonsdirektør i TV 2 og Espen Trygve Hansen, generalsekretær i Fagpressen.*

FORNØYD MED DAGENS SITUASJON: *Jan Erik Knarbakk, konserndirektør i Schibsted og Se og Hørs sjefredaktør Knut Haanæs.*

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NOT How to evaluate color image quality?

- From the web site of a major French consumer electronics retailer:
  - Qualité [illegible] dpi point x
  - Image quality – [illegible] x color depth

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NOT How to evaluate color image quality?

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NOT How to evaluate color image quality?

Samsung Offers 10 MP Camera Phone With 3x Zoom, MP3 Storage, Bluetooth

March 15, 2006 – Samsung introduced the 10 megapixel SCH-B600 camera phone at CeBIT last week. The phone comes equipped with a 3x zoom lens and a 2.2-inch LCD screen with 160,000 pixels. When users aren't talking on it or snapping photographs, they can listen to MP3 files from the SCH-B600. In need of a scanner? No problem; the Samsung B600 camera phone also has a business card reading function. The Samsung SCH-B600 will be available in Europe and Korea within a few months.

The Samsung SCH-B600 is the first camera phone to include 10 megapixels. Cramming out camera phones with high resolution seems to be an area of strength for Samsung. It released the first 5 megapixel camera phone in October 2004, then upped the ante to release the first 7 megapixel model in July 2006. The world's first 8 megapixel camera phone was announced in November 2006 and now Samsung tops it off with the 10 megapixel SCH-B600.

"As consumers' needs of mobile entertainment are growing rapidly, we are continuously introducing breakthroughs in mobile phones," said Kitae Lee, president of Samsung's telecommunication network business, in a March 9 press release. "The SCH-B600... will satisfy mobile users who are seeking higher quality photography in his or her mobile. I would like to see our technological advances contribute to the future of this industry and improve the way of our future life style."

The B600 shows its dual functions in its design. The front looks like a cell phone and the back looks like a digital camera. The camera phone's thickness is more reminiscent of a digital camera as many cell phones are shrinking thinner and thinner. The stout Samsung SCH-B600 has an auto focus assist lamp and a flash, and can record video clips with 320 x 240 pixels at 30 or 15 frames per second.

Videos can then be watched on the LCD, which supports satellite digital multimedia broadcasting. There are dual speakers to listen to the 128 polyphonic sounds in stereo and an AV-out jack too. The Samsung SCH-B600 is Bluetooth enabled and also uses the MMCmicro memory card.

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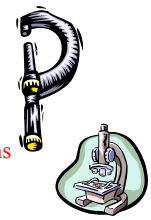
How to evaluate color image quality?

- Measurements
  - Colorimetric and planimetric
  - Pixel-by pixel comparisons
  - Perceptual models etc.
- Subjective evaluations
  - "Expert opinions"
  - Customer's choices
- Psychophysical experiments
  - "Panel tests"
  - Statistical analyses



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Psychophysical experiments

- Different protocols
  - Category judgment
  - Rank order
  - Pair comparison
- Time consuming
- Thorough statistical analysis
  - But some questionable assumptions?

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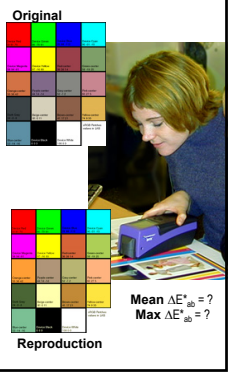
Measuring color image quality

- By color measurements
  - Match of specific colors
    - E.g. Company logo
  - Match monitor/print
    - Typical consumer user scenario
  - Match original-reproduction
    - Color copy, fax
  - Match to a reference print
- Do not use numbers blindly!



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Preferred color reproduction

- Generally it is not desired to reproduce the colorimetry of the original scene

(Giorgianni&Madden, 1997)

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Colorimetric match ≠ visual match

- Basic colorimetry is inadequate for cross-media color reproduction

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Perceptual image difference metrics

- Exactly how big is the difference between these two images?

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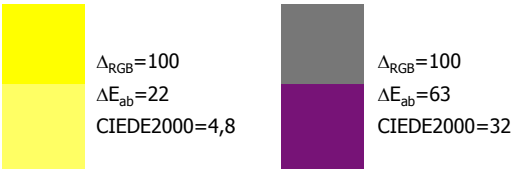
Inadequacy of RGB color difference



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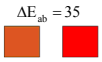
Inadequacy of pixel-by-pixel difference

- Reproduction 1 and 2 have the same average ΔE_{ab} of 0.6
- CIE ΔE_{ab} colour difference equation is designed to quantify the colour difference for single pair of colour patches
- Don't ever use RMS or PSNR to evaluate your image compression algorithm again!

$\Delta E_{ab} = 35$



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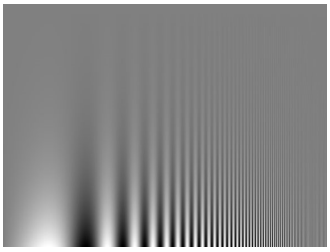
Perceptual image difference metrics

- Metrics taking into account visual CSFs have been proposed
  - s-CIELAB
  - iCAM
- Many other metrics
  - SSIM



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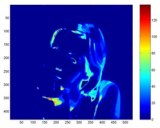
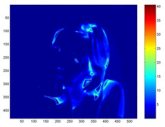
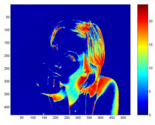
Perceptual image difference metrics

Original

Reproduction







S-CIELAB iCAM CIELAB

Image difference maps

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Perceptual image difference metrics

- We found no correlation between current image difference metrics and perceptually evaluated image differences
- Higher-level cognitive processes come into play
- Current active research area

E. Bando, J.Y. Hardeberg, D. Connah, **Can Gamut Mapping Quality be predicted using Colour Image Difference Formulae?,** SPIE Proc. 5666, 2005

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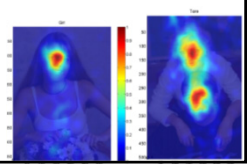
Perceptual image difference metrics

- Research project funded by the Research Council of Norway
  - Ca 5.4 MNOK over 4 years 2007-2011
- Related project funded by Océ Print Logic Technologies (Paris, France)
  - Ca 1.4 MNOK over 4 years 2007-2011
- New metrics development/evaluation
  - Implement and evaluate existing methods
  - New metrics based on improved colour difference metrics
  - New metrics based on perceptual predictors
    - Such as Retinex
  - New metrics based on saliency maps
    - Eye tracking experiments
  - New metrics based on multilevel methods
- Using metrics to improve reproduction&representation
  - Standard optimization methods
  - Heuristic methods
  - Variational methods
- Applications
  - Image compression
  - High dynamic range tone mapping
  - Colour gamut mapping
  - Halftoning



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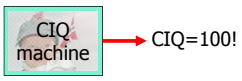
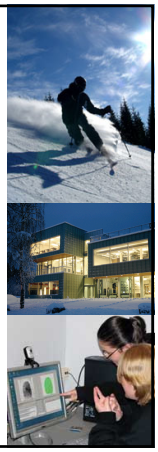
Perspectives on image quality research

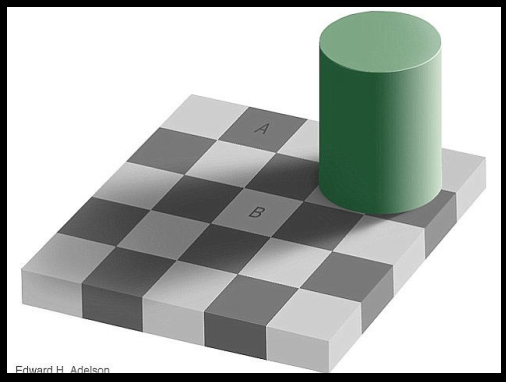
- "Most studies on image quality employ subjective assessment with only one goal – to avoid it in the future"
  - Yendrikhovskij



Outline

- Introduction
- Color Science
- Color Management
- Color Image Quality
- Questions?
  - jon.hardeberg@ntnu.no
  - www.colourlab.no





Research exercise

- Groups of three
- One research paper per group
- Study paper for 30 minutes
- Present
  - Main idea and overview of paper (5 min)
  - Scientific critisism (2 min)
  - Ideas for related research (3 min)
- Discussion

Research exercise

1. C F Andersen & J Y Hardeberg. Colorimetric Characterization of Digital Cameras Preserving Hue Planes. IS&T/SID Color Imaging Conference, Pages 141-146, 2005
2. M. R. Rosen and N. Ohta, Spectral Color Processing using an Interim Connection Space, IS&T/SID Color Imaging Conference, 2003
3. Ali Alsam, Ivar Farup, Spatial Colour Gamut Mapping by Orthogonal Projection of Gradients onto Constant Hue Lines, Advances in Visual Computing, Lecture Notes in Computer Science, Volume 7431, 2012, pp 556-565
4. M.D. Fairchild and G.M. Johnson, Meet iCAM: An Image Color Appearance Model, IS&T/SID Color Imaging Conference, 2002