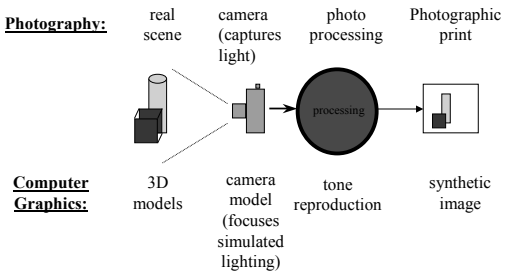
Tone Reproduction

Logistics

- Paper summaries on Tone Reproduction
  - Any takers?

Computer Graphics as Virtual Photography



Tone/Color Reproduction (On the home stretch)

- Where are we?
  - Described our scene during modeling
  - Simulated light transport during rendering
  - Captured and projected light from the scene onto a 2D plane during capture
  - Now we must convert this simulated light capture into an image for display

Tone Reproduction

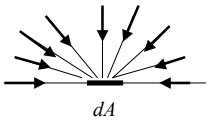
- Definition
  - Compressing the dynamic range of a scene's luminances/radiances so that it can be displayed on a given device in such a way that minimizes the perceptual difference between viewing the scene and viewing the rendering of the scene.

Tone Reproduction

- Definition
  - Dealing with Luminances / radiances
  - Rendering will be displayed on a given device
  - Minimize perceptual difference between real and created.

Tone Reproduction

- Radiance / Luminance
  - Flux arriving at or leaving from a given point or surface *in a given direction*.
  - Radiance measured in W / m^2 /sr
  - Luminance measured in cd/m^2 (nit)

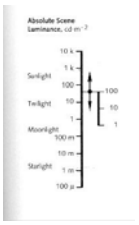


Tone Reproduction

- Luminance levels

Sky = 12400 nits

Trees = 64 nits

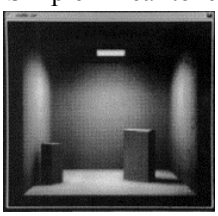


Tone Reproduction

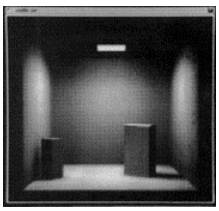
- Using 0 – 1 to indicate light intensity
  - What does 1 mean?
- CG tends to use intensity space of output device
- Images optimized for a given output device.
- In typical CG apps, tone reproduction is simply linear scaling.

Tone Reproduction

- Simple Linear tone reproduction



Light source = firefly



Light source = Searchlight

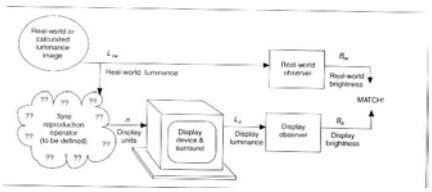
Tublin-Rushmeier (1993)

Tone Reproduction

- Why bother
  - Human response to light is neither simple nor linear.
  - Most display devices are not linear
  - Incorrect response modeling results in incorrect perception of results.

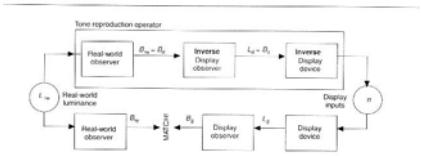
Tone Reproduction

- Basic pipeline [Tumblin93]



Tone Reproduction

- Basic solution



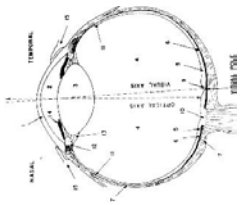
Tone / Color Reproduction

- Response / Observer
  - How does a system (like the human visual system or photography) respond to the collected light
- Display
  - How do we translate that response using a particular output device (like a CRT or printer)

Response Models

- Applying response/observe model will result in the luminances as seen by your display observer.
  - I.e. Will be in luminance range of your output device.
- Observer/Response Models
  - Human Visual System
  - Photographic Systems

Human Visual Response



Human Visual Response

- Pupil
  - Regulates the amount of light that gets to the retina
- Photoreceptors
  - Rods
    - 75 - 150 million
    - sensitive to 10^{-6} to 10^{2} cd/m^2 (low light levels)
    - Achromatic (detects "brightness")
  - Cones
    - 6 - 7 million
    - sensitive to 0.01 to 10^{8} cd/m^2 (high light levels)
    - Responsible for color vision

Human Visual Response

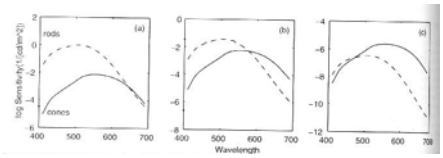
- Levels of Brightness Response
  - Scotopic
    - 10^{-6} to 10^{2} cd/m^2 /primarily rods
  - Photopic
    - 0.01 to 10^{8} cd/m^2 / Primarily Cones
  - Mesopic
    - 0.01 to 10^{2} cd/m^2
    - Both rods and cones
    - Little known -- active area of research

Human Visual Response

- Spectral response
  - Human Visual System is sensitive to light in the wavelength range of approx. 350 - 700 nm.
  - Sensitivity changes dependent on illumination level

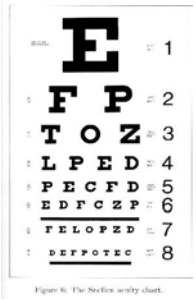
Human Visual Response

- Spectral Sensitivity



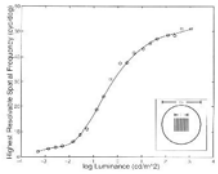
Human Visual System

- Acuity
  - Ability to resolve spatial detail
- Snellen Chart
  - View from 20 ft away
  - Line 8 subtends 1 min of visual angle
  - People who can read this is said to have 20/20 vision



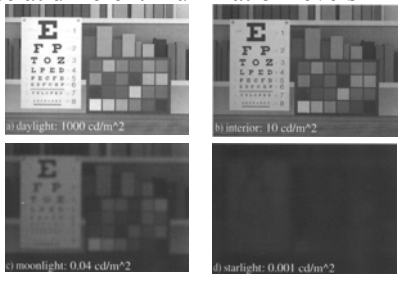
Human Visual System

- Acuity also changes dependent on luminance level



Human Visual System

- Response at different illumination levels



Human Visual System

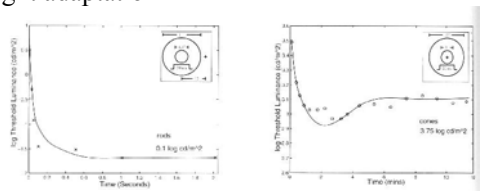
- Adaptation
  - Our vision system has the ability to adapt to a given luminance level
  - Light Adaptation - from darkness to light
  - Dark Adaptation - from brightness to dark
  - Adaptation is gradual, not immediate

Human Visual System

- Threshold Studies
  - determines the threshold at which a person can notice the change between a light sample given a certain background luminance.

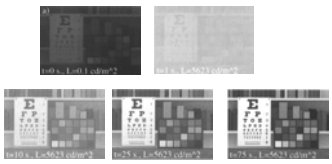
Human Visual System

- Light adaptation



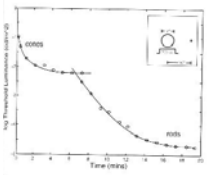
Human Visual System

- Light adaptation



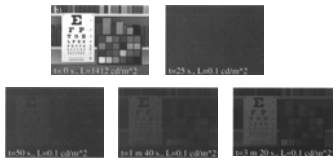
Human Visual System

- Dark adaptation



Human Visual System

- Dark Adaptation



Human Visual System

- Ferwerda's model
  - Scales luminances as to preserve perceived contrast using psychophysical data as a guide.
    - $L_w = mL_d$
  - Different models for scotopic and photopic vision with slider to blend the two to simulate mesopic vision.
    - m will vary dependent upon whether scene is in scotopic, photopic, or mesopic range.

Human Visual System

- CG Tone Reproduction Operators
  - "Tone Reproduction and Physically Based Spectral Rendering" by Devlin, et al. EUROGRAPHICS 2002.
  - Questions?

Photographic Response

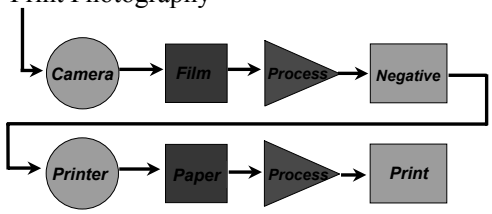
- An alternative to modeling visual response directly.
- Models response to photographic materials.

Photographic Response

- Why bother with photographic model?
  - Far better understood than human visual system.
  - Optimized for human viewing
  - Artistic photography
  - Composition of CG elements with scenes captured on film.

Photographic Response

- Print Photography



Photographic Response

- Photographic Materials
  - Comprised of microscopic grains of silver halide in a gelatin (emulsion)
  - Latent image formed when exposed to light
  - Silver halide converted to metallic silver during processing.
  - Converted silver results in opacity

Photographic Response

- Brightness Response - high level response of an emulsion to light
- Spectral Sensitivity - Response of a material to different wavelengths of light
- Acuity - Level at which material can reproduce spatial details
- Graininess - Observed variation due to grain distribution

Photographic Response

- Sensitometry
  - The science of measuring the sensitivity of photographic materials
  - Each characteristic has its own unique sensitometric measure.

Photographic Response

exposure

$$E = It$$

I = Illuminance (lux)
t = time (sec)
E = exposure (lux-sec)

density

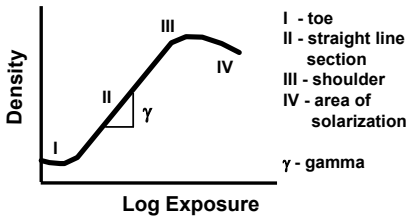
$$D = \log (O)$$

O = opacity = 1 / T
T = transmission
$= I_t / I_o$

I_t = transmitted light
I_o = incident light

Photographic Response

- Brightness Response / Characteristic Curve

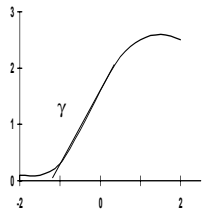


I - toe
II - straight line section
III - shoulder
IV - area of solarization

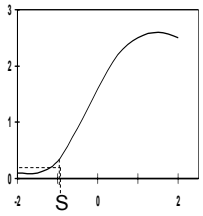
γ - gamma

Photographic Response

gamma - slope of region II gives contrast range



speed - indicates sensitivity to light



Photographic Response - Speed


Original


100 Speed Film


400 Speed Film


800 Speed Film

Photographic Response - Gamma

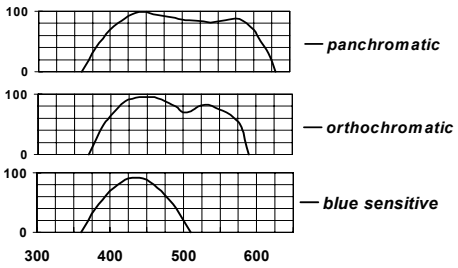

Original


Low Contrast


Medium Contrast


High Contrast

Photographic Response
Spectral Response

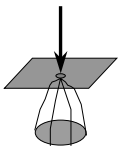


Photographic Response
Spectral Response

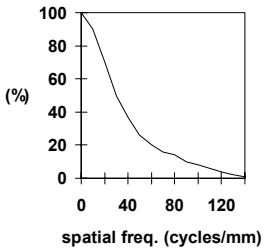
Original Panchromatic Blue Sensitive

Photographic Response - Acuity

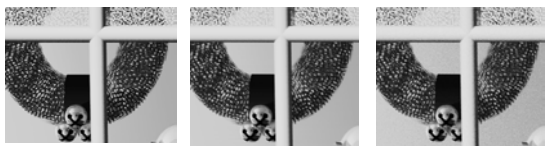
point spread function



modulation transfer function



Photographic Response - Acuity



Without MTF With MTF With MTF & Grain

Photographic Response - Grain

rms deviation:

$$\sigma^2 = \frac{1}{N}\sum(\Delta D_i)^2$$

ΔD_i = *deviation of sample i from the mean*

Selwyn Granularity:

$$G = \sqrt{(2A)}\,\sigma$$

***A** = area of scanning aperture*

Photographic Response - Grain

Original w/grain Magnified 2x Magnified 4x

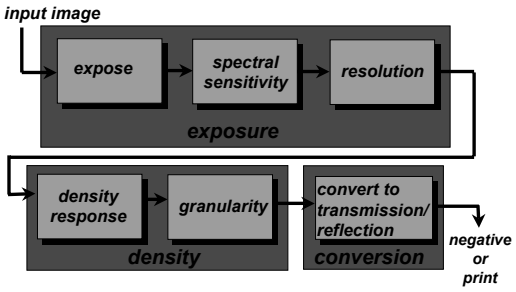
Photographic Response

- High level description of photographic response
  - Can model process at grain level but impractical to do so for our purposes.
  - Thankfully, all of these sensiometic measurements are available for photo materials from the manufacturer.

Modeling Photographic Response

- Uses sensitometric measures to model characteristics of photo materials
- Physically based
- Built using an imaging pipeline where each module in the pipe represents an image processing operation.

Modeling Photographic Response



Modeling Photographic Response

- Must run thru pipeline twice, once for capture on film and once for printing
- Result of model
  - Image of floats [0, 1]
  - Represents transmission or reflection values

Modeling Photographic Response

- Recall
  - Prints are reflective media
  - Are not visible unless illuminated
  - values from model must be modified to account for the luminance / color characteristic of the assumed print illumination
  - Thankfully, luminance / color of CRTs approximates normal interior viewing conditions fairly well.

Modeling Photographic Response

- Virtual Darkroom Applet

Tone Reproduction

- Summary
  - Means of compressing dynamic range of scene to fit that of display
  - Observer / Response Model
    - Human Visual System
    - Photographic Systems
  - Device Model

Tone Reproduction

- An almost final word on Tone Reproduction
  - Things we did not discuss today:
    - Display model
    - Color
    - Viewing conditions also affect perception
      - TR Operator should also make modifications if viewing conditions of world observer does not match that of display observer
  - These issues + a complete photographic model, will be discussed next time.
  - Breaktime…