SIGGRAPH2010

The People Behind the Pixels

SIGGRAPH 2010

Color Enhancement and Rendering in Film and Game Production

- Film Simulation for Video Games

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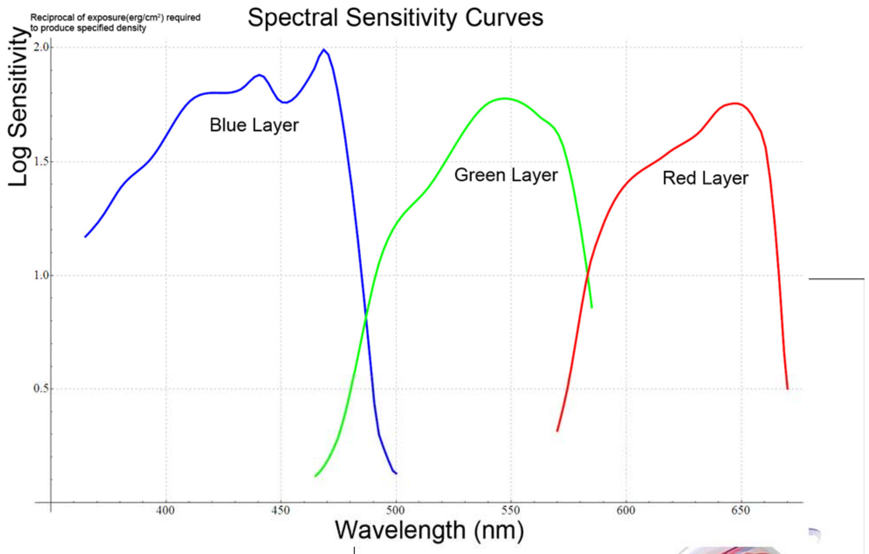
Motivation

- Use film characteristics as a standard for tone-mapping
  - Tried several tone-mapping algorithms
    - Artistically not satisfying
  - Companies have designed many types of film
    - Engineers have been trying to improve quality to reproduce
      - High fidelity colors
      - Memory colors

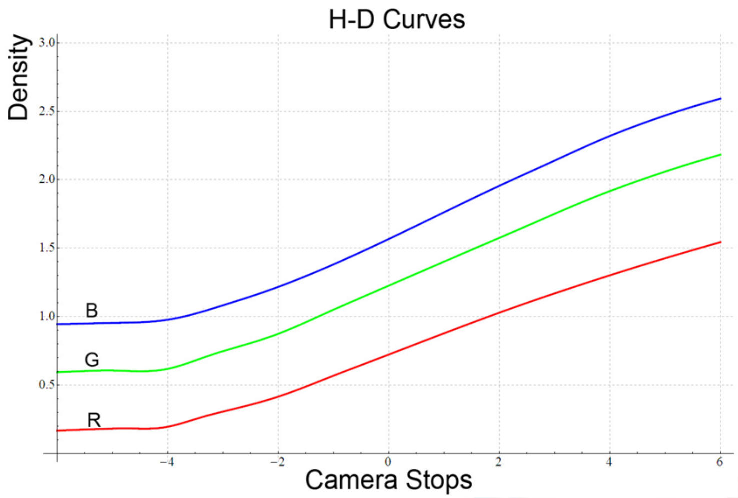
Film specification

- Spectral Sensitivity Curves (SSC)
  - The relative sensitivity of a particular emulsion to specific bands of the spectrum within the films sensitivity range



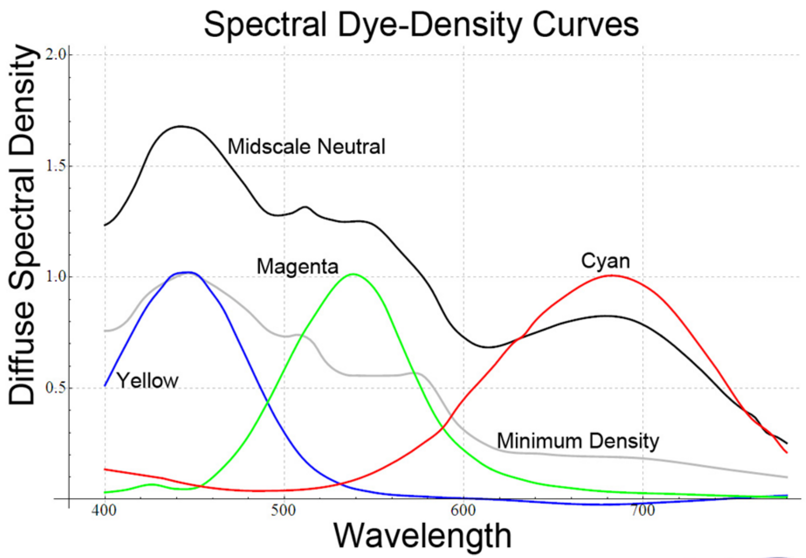
Film specification

- H-D curves
  - The graph made by plotting the density of a film sample against the log of the exposure that made that density
  - Also called
    - Hurter-Driffield curves
    - Characteristic curves
    - D-logE curves
    - D-logH curves



Film specification

- Spectral Dye-density Curves (SDC)
  - A graph
    - Of the total density of the three dye layers measured as a function of wavelengths
    - Of the visual neutral densities of the combined layers similarly measured



First approach

- Used a simple tone mapping pipeline

$$v'_{hdr} = \underbrace{M_{pre}}_{\text{Pre-color matrix}} \cdot \underbrace{v_{hdr}}_{\text{Input Color}}$$

For each component (r,g,b) :

$$v_{ldr(r,g,b)} = \underbrace{f(v'_{hdr(r,g,b)})}_{\text{Non-linear conversion}}$$

(with texture fetch)

$$\underbrace{v_{out}}_{\text{Output Color}} = \underbrace{M_{post}}_{\text{Post-color matrix}} \cdot v_{ldr}$$

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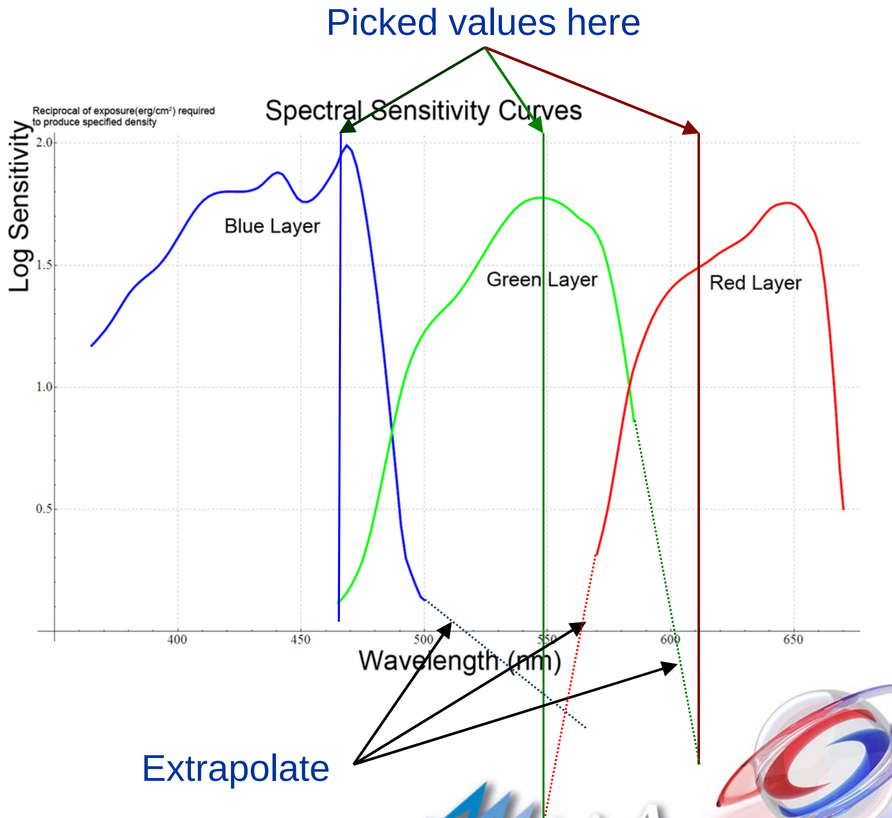
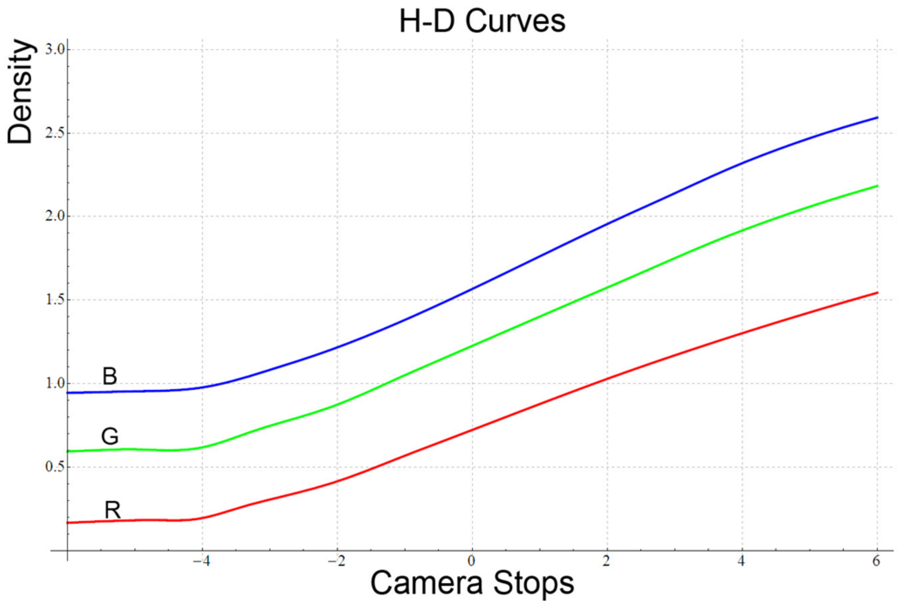
Pre-color matrix

- Use Spectral Sensitivity Curves
  - No integrals
  - Just pick values at 464, 549, 612nm for the matrix
  - Extrapolate the graph if no values at the wavelengths needed



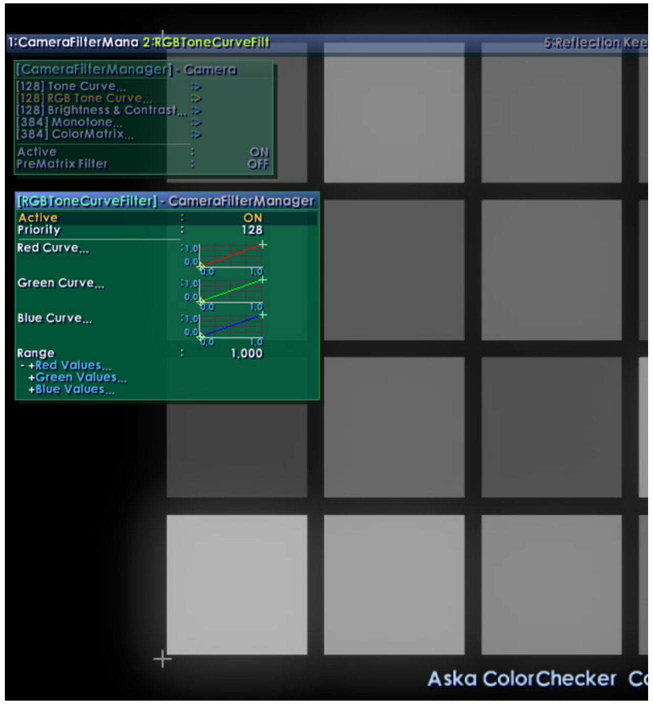
Tone curve texture

- Use H-D Curves
  - Just apply the curves as tone curve
  - Apply gamma correction
  - Edit tone curve manually



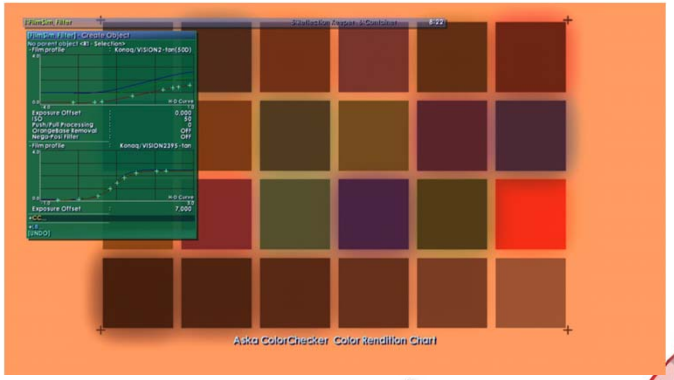
Post-color matrix

- No film data used
  - SDC is not used
  - Manual color filters
    - Contrast / Brightness
    - Color temperature
    - Etc…



Duplication process

- Is applied when a negative film is chosen
  - Orange removal
  - Print film spec is also multiplied
    - Only tone curve texture
    - No SSC is used



Result

Reinhard

K-reversal

Result

F-reversal

K-reversal

Result

F-reversal 2

K-negative

Comparisons

Reinhard

K-reversal

F-reversal

K-negative

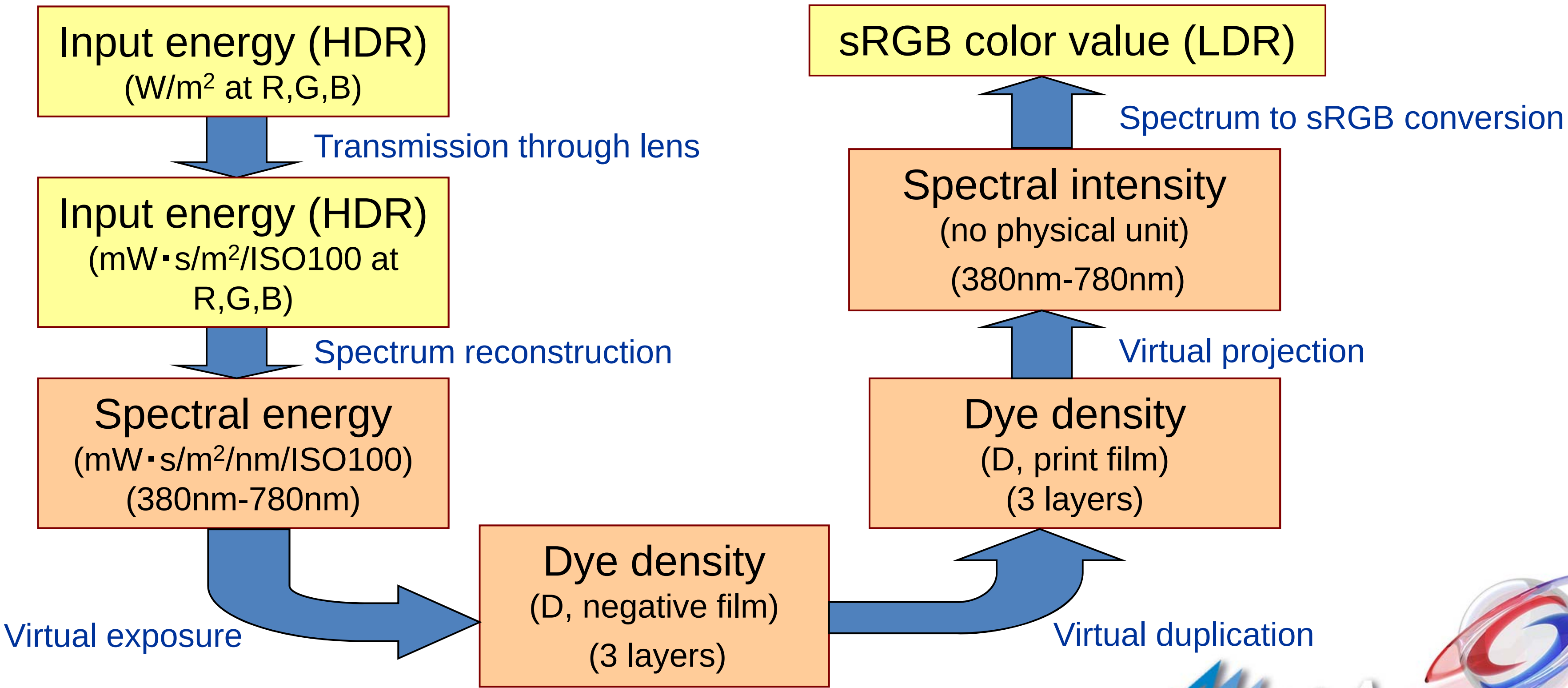
No film simulation

- First approach was NOT a simulation
  - Used film data for the existing tone mapping pipeline
  - No film specific characteristics at all
    - Only color matrix and tone curve were used

Second approach

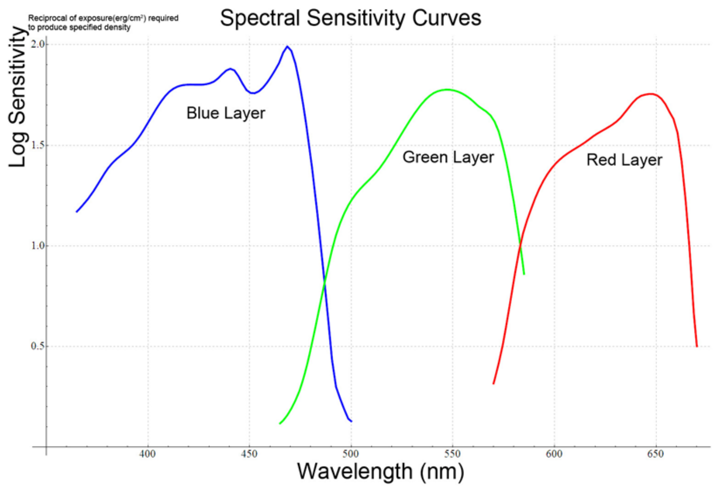
- Try to reproduce film specific characteristics
  - Simulate each color process as best as possible from the spec sheets
    - Spec sheet missing information
    - Interpolate or complement missing information

Simulation overview



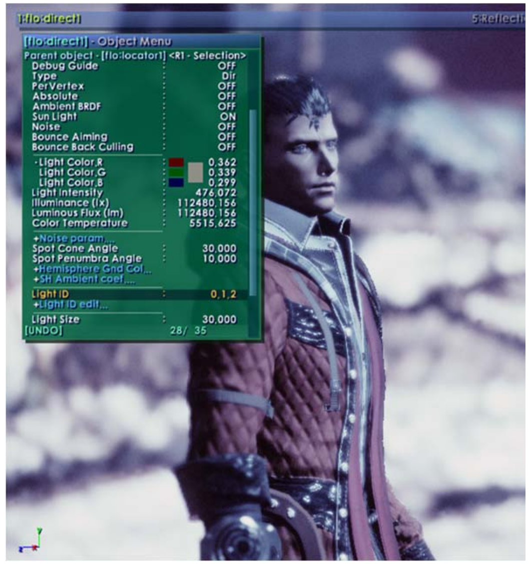
Step 1.0 - Input Energy

- Stored in the frame buffer
  - We store energy (mW/m^2) in the frame buffer
  - Need the physical unit due to Spectral Sensitivity Curves
    - e.g. erg/cm^2



Step 1.1 - Physical units for lights

- Physical units are used for intensity of lights
  - Basically, W/m^2 in R,G,B
  - Conversion
    - Lux to W/m^2
    - Lumen to W/m^2
    - Color temperature to R,G,B
      - 6,500K is white (sRGB)



Step 2 – Precision problem & Conversion

- For low precision frame buffers
  - e.g. 8bit, 7e-3 (10bit)
  - Real dynamic range is too wide
    - Banding
  - Unit is converted for utilizing dynamic range efficiently and SSC requirement
    - mJ / m^2 / F / ISO100

$$\overbrace{c}^{\text{Scale factor for conversion}} = \frac{1000\overbrace{t}^{\text{Shutter speed}}}{\underbrace{F}_{\text{F-stop}} \cdot \left.\frac{ISO}{100}\right\}\text{ISO sensitivity}}$$

Image with banding

Step 3 - Spectrum reconstruction

- Spec sheets require spectral information
  - RGB should be converted to a spectrum
  - Create discrete spectral data from R,G,B using a conversion matrix

Frame Buffer

$$\underbrace{I_\lambda}_{\text{Discrete Spectral Data (Vector)}} = \underbrace{M}_{\text{Reconstruction Matrix}} \cdot \underbrace{v_{r,g,b}}_{\text{Input Color}}$$

To virtual exposure

See the course notes for details

Difference from the matrices

Standard reconstruction matrix

Another reconstruction matrix

Color balance of this matrix is
not adjusted properly

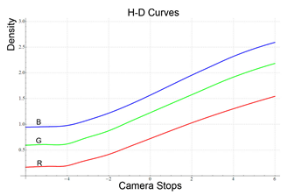
Step 4 - Virtual exposure

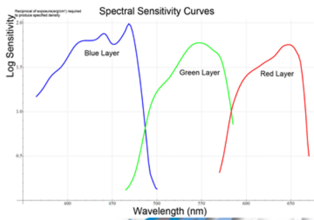
From spectrum reconstruction
or virtual projection
(explained later)

- Get densities of 3 dyes

For each R,G,B dye :

$$\underbrace{D_{r,g,b}}_{\text{Dye densities}} = \underbrace{f_{r,g,b}}_{\text{H-D curves}}\left(\log_{10}\left(\left(diag\left(\underbrace{c_{r,g,b}}_{\text{Matching Vector}}\right)\cdot \underbrace{w_{r,g,b}}_{\text{Spectral Sensitivity Curves in linear space}}\right)\cdot \underbrace{I_{\lambda}}_{\text{Discrete Spectral Energy}}\right)\right)$$





To duplication or projection

Density

- Definition of density
  - How much light gets through (transmission) and how much light doesn't (opacity, the reciprocal of transmittance).

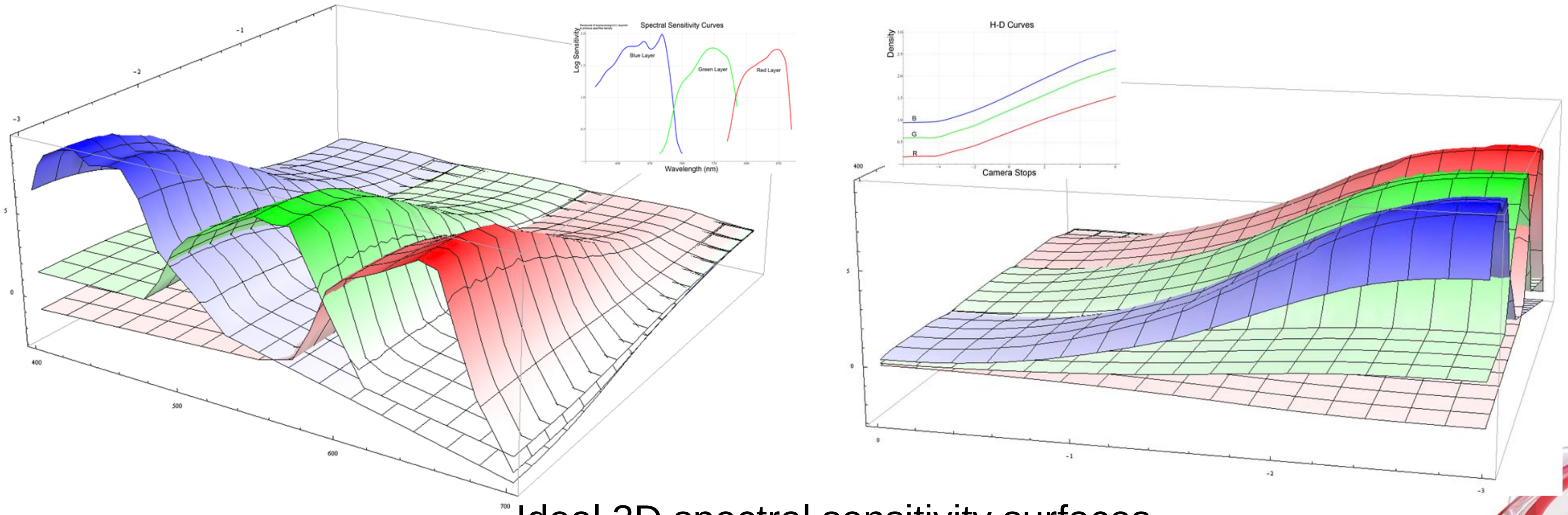
$$D = \log_{10} \frac{P_o}{P_t}$$

P_o: Light incident on processed film

P_t: Light transmitted by the film

Matching Vectors

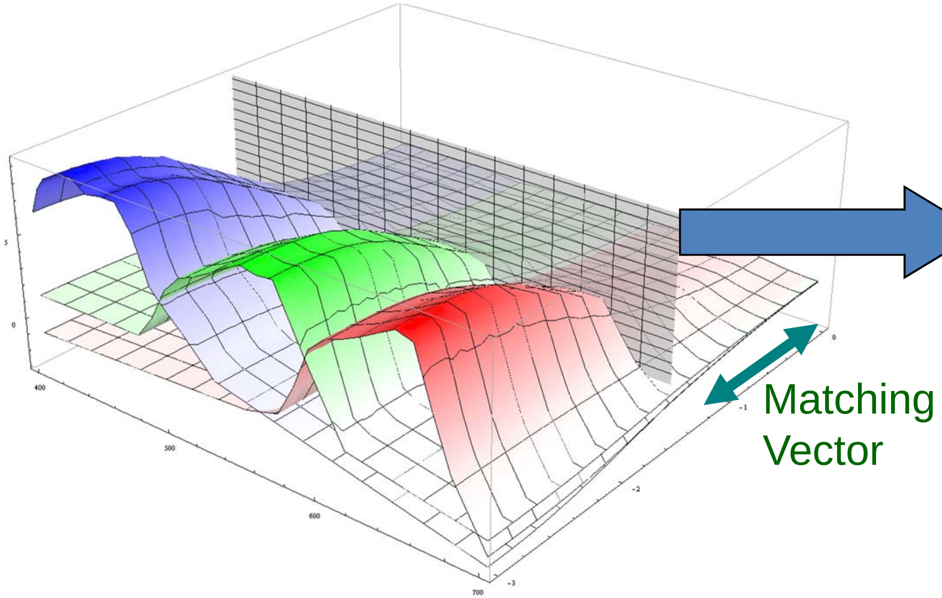
- Vector to connect Spectral Sensitivity Curves and H-D Curves
  - Ideally 3D spectral sensitivity surfaces are required

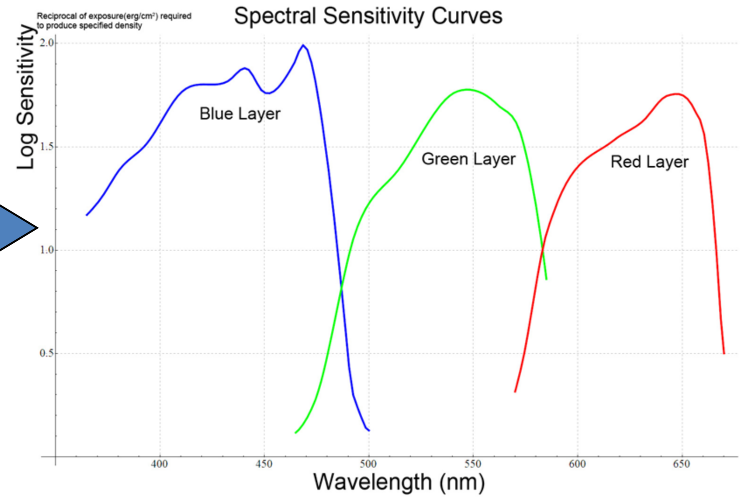


Ideal 3D spectral sensitivity surfaces

Matching Vectors

- Assume that SSC is scaled by the factor from H-D curve



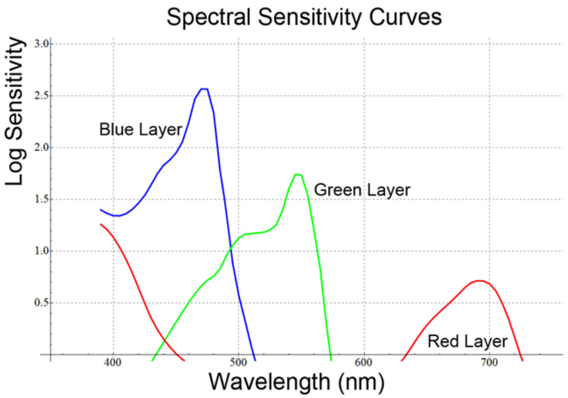


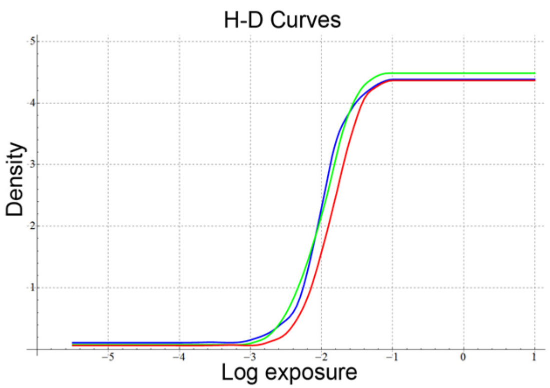
Step 5 – Virtual duplication

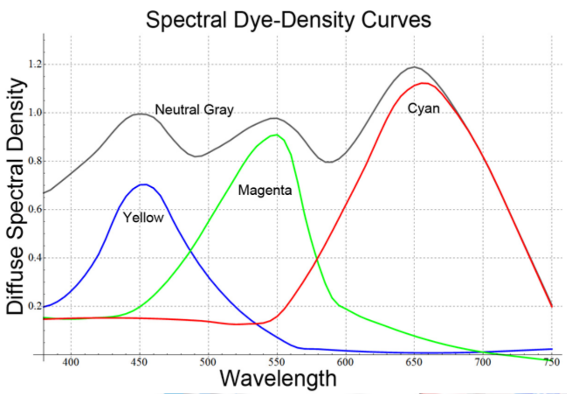
- For negative films
  - Color is reversed
  - Duplication process is required to see the film with proper colors

Step 5 – Virtual duplication

- Shoot a negative film with print (or intermediate) film
  - Need a light source for duplication process
  - Assumed use of color filters and lamp specified by spec sheets
    - 400nm – 1,000nm

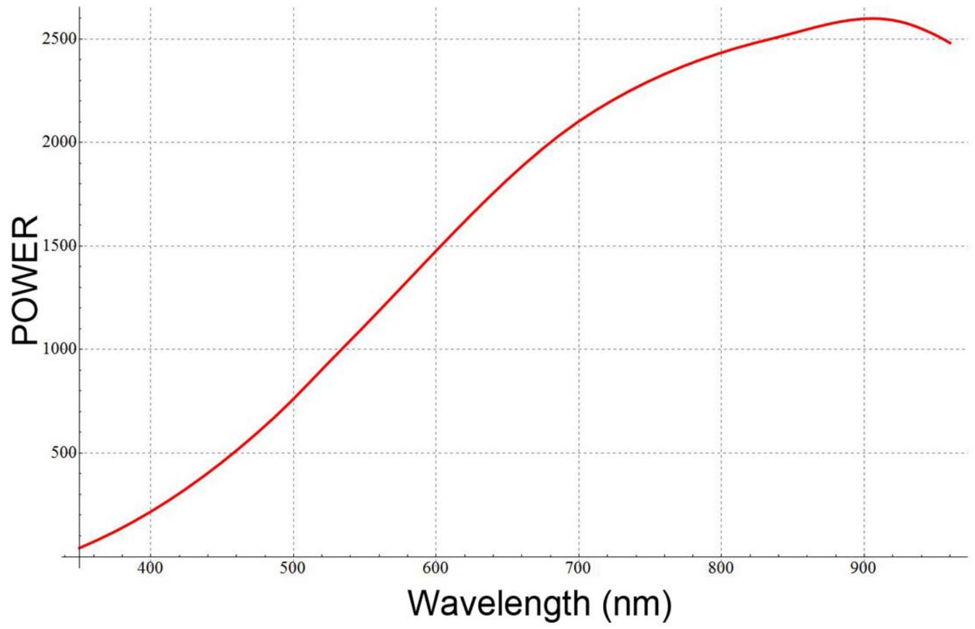






Virtual light source

- Spectrum pattern of tungsten light

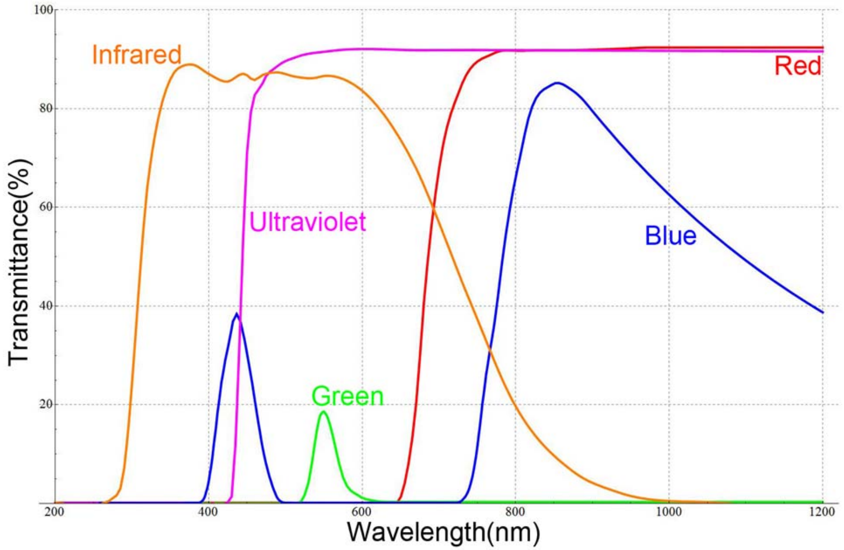


Color filters for the light source

- Documentation recommends these color filters
  - KODAK WRATTEN Gelatin Filters
    - Red No. 70 for red separation
    - Green No. 99 for green separation
    - Blue No. 98 for blue separation
    - 2B filter for UV filter
    - No. 2043 for Infrared filter (not WRATTEN filter)
    - ND filters

Color filters and ND filters

- Filters that we used
  - Appropriately designed based on recommended filters



Color Filter	ND Filter Magnitude
Red	0.5
Green	0.55
Blue	0.9

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Calibration

- Printing calibration
  - Acquire the correct white balance and brightness of the print film
    - Using negative film, shoot an 18% gray card with proper exposure and develop it
    - Adjust spectrum of the virtual light to get the specified densities according to the spec sheet
  - Iteratively computed in our implementation
    - Practically one iteration is enough, because color separation is good

Approximation of SDC

From exposure of negative film

- SDC of negative film for duplication is approximated

$$\underbrace{\sigma(\lambda)}_{\text{Output spectrum}} = \underbrace{l(\lambda)}_{\text{Spectrum of projection light}} \cdot 10^{-\left(\underbrace{S_{\min}(\lambda)}_{\text{Spectrum of D-min in SDC}} + \underbrace{c}_{\text{Matching constant}} \cdot \sum_{r,g,b} \left(\underbrace{S_{r,g,b}(\lambda)}_{\text{SDC}} \frac{\overbrace{D_{r,g,b}}^{\text{Densities from virtual exposure}} - \overbrace{D^{\min}_{r,g,b}}^{\text{D-min in H-D Curves}}}{\underbrace{D^{mid}_{r,g,b}}_{\text{Midscale density from H-D Curves}} - \underbrace{D^{\min}_{r,g,b}}_{\text{D-min in H-D Curves}}} \right) \right)}$$

To virtual exposure of print film

Two calibration modes

- Calibrate the spectrum to get the densities specified by the print films’ spec sheet
  - Follow the printing method
    - 18% gray doesn’t become perfect gray due to the balance of Spectral Dye-density Curves
- Calibrate the spectrum to get densities for Equivalent Neutral Density 0.7 (E.N.D. 0.7)
  - To get neutral gray

Comparison of two calibration modes

Based on spec sheet

Based on neutral gray

Same negative and print film

Infrared

- The red dye peak sensitivity in the print film is closer to the infrared domain than camera film
  - Why? Maybe for color separation
  - The red dye tends to be influenced from infrared
    - Over 800nm spectrum affects our result

Implementation comparison

With infrared domain

Without infrared domain

Same negative and print film

Step 6 – Virtual projection

- Projection to see the developed film
  - Spectral Dye-density Curves show how much light passes through from the light source in spectral domain when projected
    - Ideally these curves should be provided as 3D graph
    - Assume that real curves are proportionally scaled by density
  - Light source is assumed to be 6,500K ideal black-body light
    - For sRGB
    - For theaters, should be about 5,500K

Step 6 - Virtual Projection

From exposure of positive or print film

- Print and positive film don't have D-min
  - Simpler expression

$$\underbrace{\sigma(\lambda)}_{\text{Output spectrum}} = \underbrace{l_p(\lambda)}_{\text{Spectrum of projection light}} \cdot 10^{-\left(\sum_{r,g,b} \underbrace{S_{r,g,b}(\lambda)}_{\text{SDC}} \cdot \underbrace{D_{r,g,b}}_{\text{Densities from virtual exposure}}\right)}$$

To RGB conversion

Step 7 - Final conversion

- Final spectral data is converted to sRGB
  - The discrete spectral vector is converted to an sRGB vector using the matrix
    - The matrix is designed using Color Matching Function Table in the white paper of XYZ color space
    - RGB primaries are based on sRGB color space
  - Gamma correction is applied also

Computation

- These computations in steps 1 - 7 are too expensive to do in real-time
  - Pre-computed and stored in a volume texture
    - 3D LUT
  - 32x32x32 is ideal resolution for performance
    - However, it has insufficient precision

Compression

- Compressed in log-space
  - ISO sensitivity is a scalar value multiplied to the input color
  - U,V,W coordinates for texture fetch are converted to log-space

$$U = 0.534577 + 0.217563 \cdot \log_2(u + 0.191406)$$

Result

Reinhard

F-Reversal

Result

K-Reversal

F-Reversal

Result

K-Negative

F-Reversal 2

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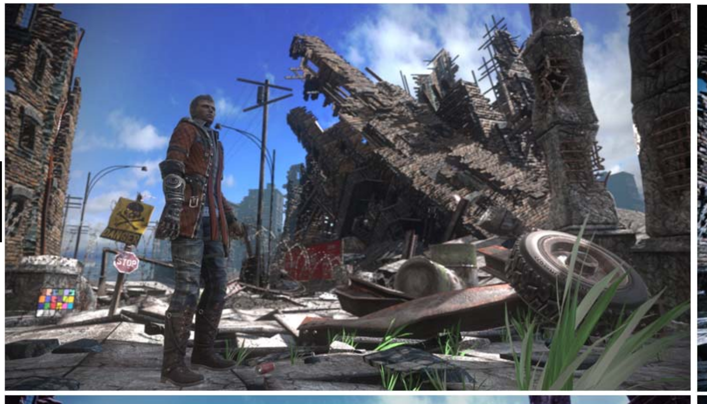
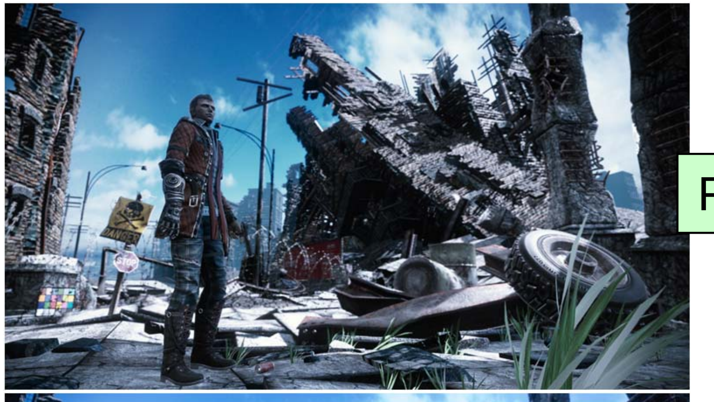
Comparison

Reinhard

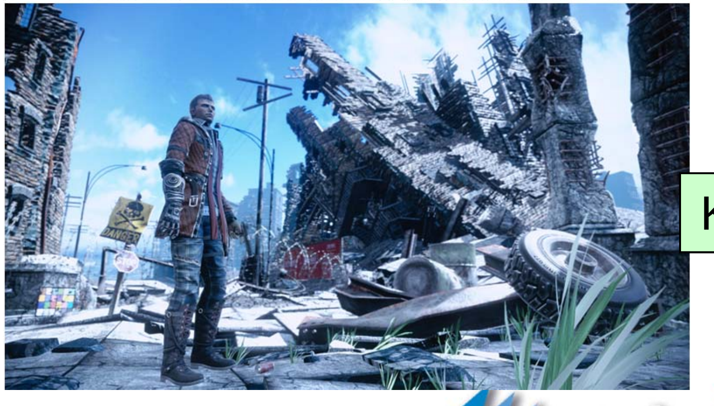


F-Reversal



K-Negative

K-Reversal



Comparison

New K-Reversal

Old K-reversal

Comparison

New F-Reversal

Old F-reversal

Comparison

New K-Negative

Old K-negative

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Conclusion

- Our simulation seems to successfully reproduce film characteristics
- Using spec sheets as parameters is not enough
- Film simulation can be an attractive tone-mapping representation

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- R&D programmers:
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Thanks

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