# Reflectance Analysis

## Based on the Dichromatic Reflection Model

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# Outline

1. Reflectance
2. DRM
   - Chromaticity
3. Illumination Chromaticity
   - Dichromatic-based color constancy using dichromatic slope and dichromatic line space
   - Color constancy thought Inverse-Intensity chromaticity space
   - On determining the color Illuminant using the dichromatic reflection model
4. Components Separation
   - Robby-Ikeuchi Method
   - Kuk-jin Method

# Reflectance

Figure: Specular and diffuse reflection in natural scene

- The dichromatic reflection model proposed by Safer [4], describes the surface reflection for dielectric materials as the sum of two components, the **diffuse** and **specular** terms.
- The **diffuse reflection** component exhibits the color by material as different wavelenght are more or less absorbed within the material as light is scattered.
- The **specular reflection** component is essentially determined by the color of incident light.

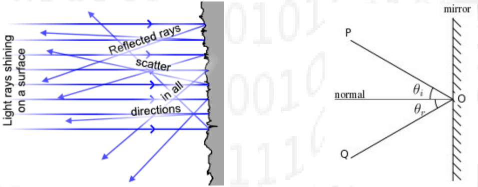

Figure: Diffuse and Specular reflections

# Dichromatic Reflection Model

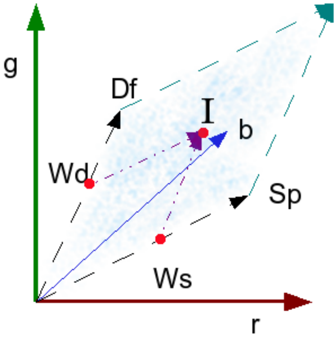

Figure: Dichromatic Reflection Model Scheme

$$I = w_d Df + w_s Sp$$

- The color of a uniform color surface is represented by the blue region, where *Df* is the body color (depending of diffuse albedo), *Sp* is the light color.
- Because the geometry is different at each point, the scale factors $w_d$ and $w_s$ vary from point to point.

## Model of a image taken with a CCD digital camera

$$I(x) = w_d(x) \int_\Omega S(\lambda,x)E(\lambda)q(\lambda)d\lambda + w_s(x) \int_\Omega E(\lambda)q(\lambda)d\lambda \qquad (1)$$

- $I = \{I_r, I_g, I_b\}$ is the color of image intensity or camera sensor.
- $x = \{x, y\}$ are the two dimensional space coordinates.
- $q = \{q_r, q_g, q_b\}$ is the three-element-vector of sensor sensitivity.
- $w_d(x)$ and $w_s(x)$ are the weighting factors for diffuse and specular components, they depend of the geometric structure at location $x$.
- $S(\lambda,x)$ is the diffuse spectral reflectance.
- $E(\lambda)$ is the spectral power distribution function of illumination source, it is independent of the spatial location $x$ because we assume a uniform illuminant light color.
- The integration is done over the visible spectrum $\Omega$.

# Model of a image taken with a CCD digital camera

**Model of a image taken with a CCD digital camera**

$$I(x) = w_d B(x) + w_s G \tag{2}$$

- $B(x) = \int_\Omega S(\lambda, x) E(\lambda) q(\lambda) d\lambda$
- $G = \int_\Omega E(\lambda) q(\lambda) d\lambda$

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# Chromaticity

## Normalized RGB

$$\sigma(x) = \frac{I(x)}{I_r + I_g + I_b} \tag{3}$$

## Diffuse Chromaticity

$$\Lambda(x) = \frac{B(x)}{B_r + B_g + B_b} \tag{4}$$

## Specular or Illumination Chromaticity

$$\Gamma = \frac{G}{G_r + G_g + G_b} \tag{5}$$

# Image expressed in terms of chromaticity

**Image model expressed in terms of chromaticity**

$$I(x) = m_d(x)\Lambda(x) + m_s(x)\Gamma \tag{6}$$

where

- $m_d(x) = w_d(x)\left[B_r(x) + B_g(x) + B_b(x)\right]$
- $m(x) = w_s(x)\left(G_r + G_g + G_b\right)$

In addition, from their definitions we can obtain:

$$(\sigma_r + \sigma_g + \sigma_b) = (\Lambda_r + \Lambda_g + \Lambda_b) = (\Gamma_r + \Gamma_g + \Gamma_b) = 1$$

# Methods

In this section, we will to describe some methods for the Illumination chromaticity estimation:

1. Dichromatic-based color constancy using dichromatic slope and dichromatic line space[8]
2. Color constancy thought Inverse-Intensity chromaticity space[5]
3. On determining the color illuminant using the dichromatic reflection model[2]
4. Color line search for illuminant estimation in real-world scenes [1]

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# Image chromaticity and dichromaticity line space

This method is based on the specularity invariant dichromatic slope and the three-dimensional dichromatic line space.
From equations (3) and (6) we can derive the following equation:

$$I_c(x) = \Lambda_c(x) + \frac{m_s(x)}{m_d(x) + m_s(x)} (\Gamma_c - \Lambda_c(x)) \quad (7)$$

Defining *s(x)* as

$$s(x) = \frac{m_s(x)}{m_d(x) + m_s(x)} \quad (8)$$

and $0 < s(x) \leq 1$.

# Dichromatic slope

Image chromaticity can be expressed as:

$$I(x) = \Lambda(x) + s(x)\left(\Gamma - \Lambda(x)\right) \tag{9}$$

We can derive the following equation from (9) by differentiating image chromaticity $i_r(x)$ w.r.t $x$.

$$\frac{\partial i_r(x)}{\partial x} = \frac{\partial \Lambda_r(x)}{\partial x} + \frac{\partial}{\partial x}\left[s(x)\left(\Gamma_r - \Lambda_r(x)\right)\right] \tag{10}$$

# Dichromatic slope

$\frac{\partial \Gamma_r(x)}{\partial x}$ is assumed to be zero under a single uniform illumination. In addition $\frac{\partial i_g(x)}{\partial x}$ is close enough to zero to be neglected. Then equation (10) can be simplified to:

$$\frac{\partial i_r(x)}{\partial x} = \frac{\partial s(x)}{\partial x} \left(\Gamma_r - \Lambda_r(x)\right) \tag{11}$$

We can derive respect $i_g(x)$:

$$\frac{\partial i_g(x)}{\partial x} = \frac{\partial s(x)}{\partial x} \left(\Gamma_g - \Lambda_g(x)\right) \tag{12}$$

# Dichromatic slope

Finally, using (11) and (12)

**Dichromatic slope $\alpha(x)$**

$$\frac{\frac{\partial i_r(x)}{\partial x}}{\frac{\partial i_g(x)}{\partial x}} = \frac{\Gamma_r - \Lambda_r(x)}{\Gamma_g - \Lambda_g(x)} \triangleq \alpha(x) \tag{13}$$

# Dichromatic Line Space

In the two dimensional space, a line can be described by identifying one point on it and its slope.

**Dichromatic line**

$$g(r) = \alpha(x)(r - i_r(x)) + i_g(x) \tag{14}$$

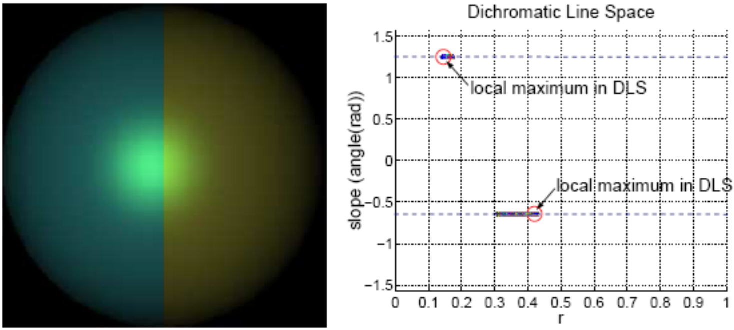
- $(i_r(x), i_g(x))$ and $\alpha(x)$are the image chromaticity and the chromaticity slope at *x*.
- In a three-dimensional space $(i_r, i_g, \alpha)$ represents a line that passes$(i_r, i_g)$ with slope $\alpha$.

# Illuminant Chromaticity Estimation

- Illuminant chromaticity can be estimated by finding the intersections of dichromatic lines when are two or more colors.

1. The first step is to detect specular pixels and project them in to the dichromatic line space according to their chromaticities and dichromatic slopes.
2. Local maxima in the dichromatic line space are detected. A maximun in the dichromatic line space represents a line in the dichromatic space.

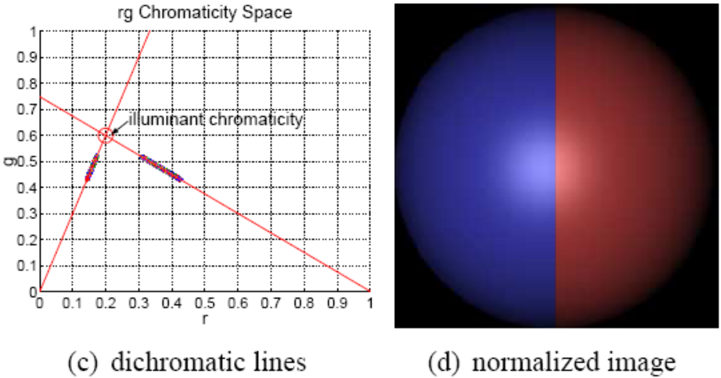
# Illuminant Chromaticity Estimation



(a) input image (b) $r$-$\alpha$ view

Figure: Dichromatic Line Space for a synthetic surface

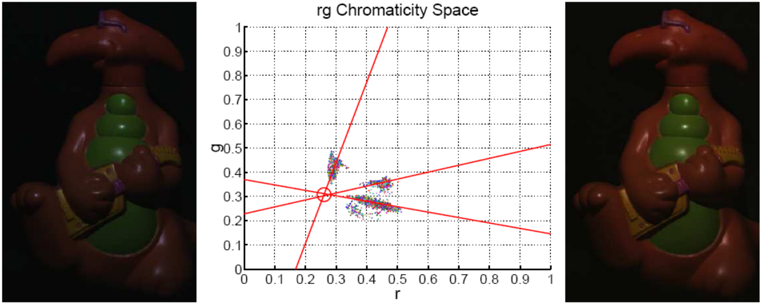
# Illuminant Chromaticity Estimation



(c) dichromatic lines (d) normalized image

Figure: Dichromatic Line Space for a synthetic surface

# Illuminant Chromaticity Estimation



(a) input image (b) dichromatic lines (c) normalized

Figure: Dichromatic Line Space for a natural surface

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# Image Chromaticity and Intensity

By substituting each color channel's intensity in equation (3) with its definition (6) the chromaticity can written in terms of dichromatic reflection model:

**Chromaticity expressed in DRM**

$$\sigma(x) = \frac{m_d(x)\Lambda_c(x) + m_s(x)\Gamma_c}{m_d(x)\Sigma\Lambda_i(x) + m_s(x)\Gamma_i} \tag{15}$$

By deriving the last equation, we can obtain the relation between specular and diffuse coefficients

$$m_s = \frac{m_d(\Lambda_c - \sigma)}{\sigma - \Gamma_c} \tag{16}$$

# Image Chromaticity and Intensity

Then substituting (16) in (6) we can obtain:

**Illumination expressed in DRM**

$$I_c = m_d\left(\Lambda_c - \Gamma_c\right)\left(\frac{\sigma}{\sigma - \Gamma_c}\right) \qquad (17)$$

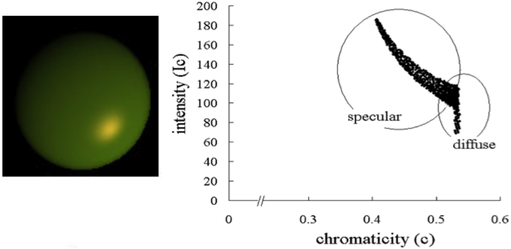


Figure: Chromaticity-Intensity Space

# Image Chromaticity and Illumination Chromaticity

By introducing $p = m_d(\Lambda_c - \Gamma_c)$ we can derive the next equation:

**The core of method**

$$\sigma = p\frac{1}{\Sigma I_i} + \Gamma_c \tag{18}$$

The specular pixels can be grouped in into a number of clusters with the same value $m_d$. In this group, we can consider *p* as a constant. Equation (18) become a linear function, with *p* as a its constant gradient.

# Image Chromaticity and Illumination Chromaticity

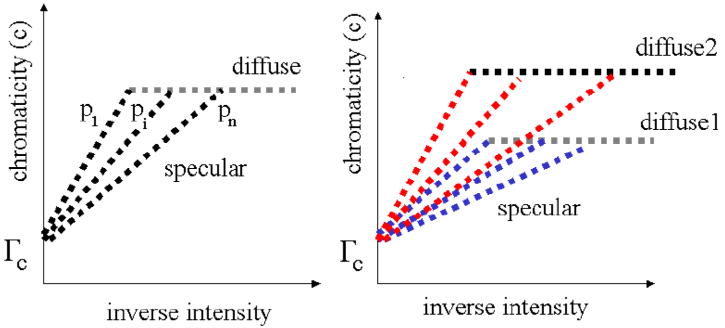


Figure: Sketch of specular points of a single surface in inverse-intensity chromaticity space

# Image Chromaticity and Illumination Chromaticity

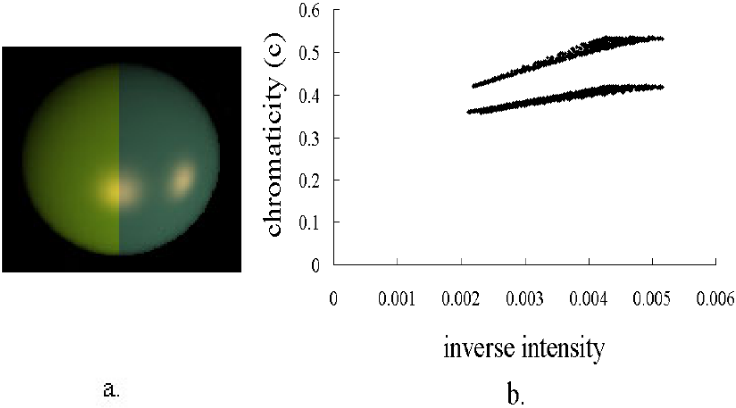
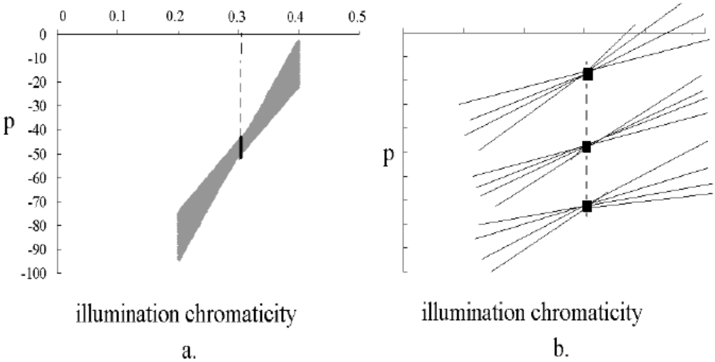


Figure: Synthetic image with multiple surface colors

# Estimating Illumination Chromaticity

- Hough transform.
- *x*-axis represent $\Gamma_c$ and *y*-axis represent $p$
- All intersections will be concentrated in in a single value $\Gamma_c$, with a small range of *p*'s values.



# Estimating Illumination Chromaticity

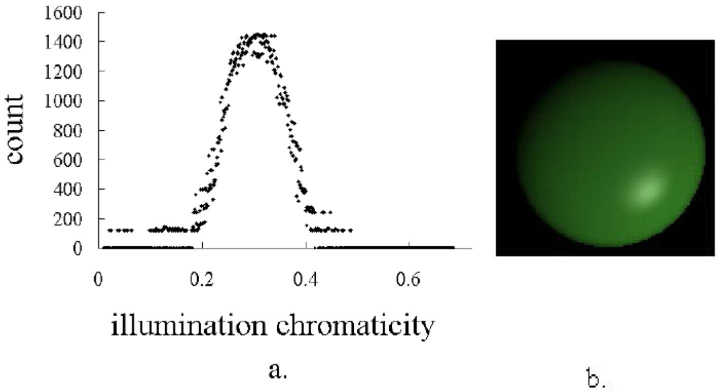


Figure: Intersection counting distribution in the green chromaticity channel of chromaticity

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# DRM

## Image in DRM

$$I = \int_{-\infty}^{+\infty} [s_M R_M(\lambda)E(\lambda) + s_S R_S(\lambda)E(\lambda)]\, S(\lambda) d\lambda \tag{19}$$

- $R_M(\lambda)$ is the object reflectance with regard to the matte reflection
- $R_S(\lambda)$ is the object reflectance with regard to the specular reflection
- $s_M$ and $s_s$ are scaling factors depending of the geometry
- $E_i(\lambda)$ is the irradiance falling onto the object
- $S(\lambda)$ is the vector with the response functions of the sensor

# DRM

## Image in DRM

$$I_i = s_M R_{M,i} E_i + s_S R_{S,i} E_i \tag{20}$$

Assuming that the specular reflection behaves like a perfect mirror $R_{S,i} = 1$

$$I_i = s_M R_{M,i} E_i + s_S E_i \tag{21}$$

- $C_M = [R_{M,r}E_r, R_{M,g}E_g, R_{M,b}E_b]$ be set the measured matte color and
- $C_s = [E_r, E_g, E_b]$ be the color of illuminant
- The two vector, $C_M$ and $C_s$ , define a plane inside RGB space

# DRM

- The points are projected in the *r+g+b=1* plane
- The two points which define the line are the chromaticities of the measured object color $[r_O, g_O]^T$ and the chromaticities of the color illuminant $[r_E, g_E]^T$ .

**Dichromatic line**

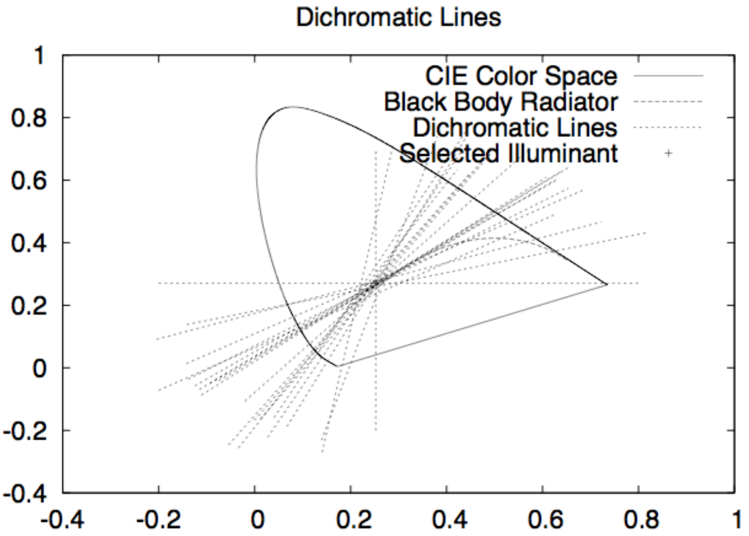
$$\begin{pmatrix} r \\ g \end{pmatrix} = s \begin{pmatrix} r_O \\ g_O \end{pmatrix} + (1-s) \begin{pmatrix} r_E \\ g_E \end{pmatrix} \tag{22}$$

For some scaling factor *s*. The data points which belong to a uniformly colored surface will all be distributed along this line.

# Estimating the Illuminant's color

- The noise is removed by pre-filtering the image using a Gaussian or median filter.
- Achromatic regions are removed.
- The dichromatic line $\mathscr{L}_j$ of region $j$ is given by $\mathscr{L}_j = \{a_j + se_j | with s \in \mathbb{R}\}$
    - $a_j$ is the average chromaticity
    - $e_i$ is the normalized eigenvector which corresponds to the largest eigenvalue for the region $j$.

# Estimating color in the CIELab Space



There are a number of methods for separate specular and diffuse components

1. Separating reflection components of textured surfaces using a single image [7, 6]
2. Fast separation of reflection components using a specularity-invariant image representation [9]
3. Dichromatic Reflection separation from a single image [10]
4. Separation of Highlight Reflections on textured surfaces [3]

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# Normalization

- The specular component must be pure white ($\Gamma_r = \Gamma_g = \Gamma_b$)
- This process requires the value of $\Gamma^{est}$, which can be obtained by some previously shown methods

## Normalized Image

$$I'(x) = m'_d(x)\Lambda'(x) + \frac{m'_s(x)}{3} \tag{23}$$

## Renormalization

$$m_d(x)\Lambda(x) = [m'_d(x)\Lambda'(x)]\Gamma^{est} \tag{24}$$

$$m_s(x)\Gamma = \left[\frac{m'_s(x)}{3}\right]\Gamma^{est} \tag{25}$$

# Specular-to-diffuse Mechanism

## Maximum chromaticity

$$\tilde{\sigma}' = \frac{max\left(I'_r(x), I'_g(x), I'_b(x)\right)}{I'_r(x) + I'_g(x) + I'_b(x)} \tag{26}$$

$$\tilde{\sigma}'_{diff} > \tilde{\sigma}'_{spec} \tag{27}$$

$$\tilde{\Lambda}' > \frac{1}{3} \tag{28}$$

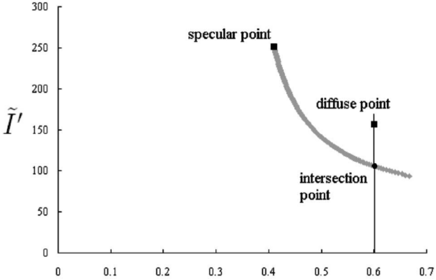
# Specular-to-diffuse Mechanism

## Curved line

$$\tilde{I}'(x) = m_d'(x)\frac{\left(\tilde{\Lambda}'(x) - \frac{1}{3}\right)\tilde{\sigma}'(x)}{\tilde{\sigma}'(x) - \frac{1}{3}} \tag{29}$$

## Diffuse weighting factor

$$m_d'(x_1) = \frac{\tilde{I}'(x_1)\left[3\tilde{\sigma}'(x_1) - 1\right]}{\tilde{\sigma}'(x_1)\left[3\tilde{\Lambda}'(x_1) - 1\right]} \tag{30}$$



# Specular Free Image

- We need a geometrically identical image without specular component.
- To generate a Specular Free Image, we simply set the diffuse maximum chromaticity equal to an arbitrary scalar value $\frac{1}{3} < \tilde{\Lambda}' \leq 1$ .

**We formally describe a Specular Free Image as:**

$$\mathring{I}(x) = \mathring{m}_d(x)\mathring{\Lambda}(x) \tag{31}$$

# Specular Free Image

$$\overset{\circ}{m}_d(x) = m_d^{'}(x)\frac{3\tilde{\Lambda}'(x) - 1}{3\tilde{\Lambda}^{new}(x) - 1} \tag{32}$$

$$\overset{\circ}{I}(x) = m_d^{'}(x)k(x)\overset{\circ}{\Lambda}(x) \tag{33}$$

where $k(x) = \frac{3\tilde{\Lambda}'(x)-1}{3\tilde{\Lambda}^{new}(x)-1}$

# Separation Method

$$log(I'(x)) = log(m'_d(x_1) + log(\Lambda')$$

$$log(\overset{\circ}{I}(x_1)) = log(m'_d(x_1) + \ldots$$
$$\ldots + log(k) + log(\overset{\circ}{\Lambda})$$

$$\frac{\partial}{\partial x} log(I'(x)) = \frac{\partial}{\partial x} log(m'_d(x_1))$$

$$\frac{\partial}{\partial x} log(\overset{\circ}{I}(x)) = \frac{\partial}{\partial x} log(m'_d(x_1))$$

# Separation Method

**The method is based in the difference of the differential logarithmic**

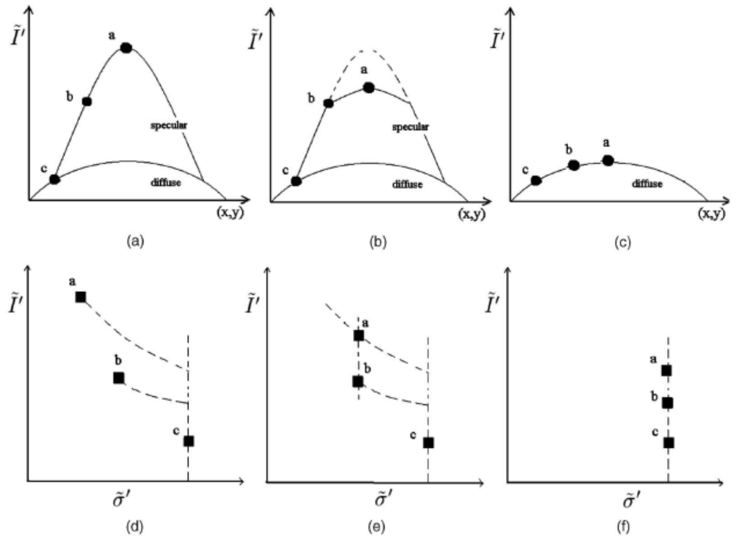
$$\triangle(x) = dlog(I'(x)) - dlog(\overset{\circ}{I}(x)) \tag{34}$$

if $\triangle(x)$= 0, then is a diffuse pixel, otherwise is a specular or discontinuity pixel .

**Color discontinuity**

$$(\triangle r > thR \ and \ \triangle g > thG) \begin{cases} true : & Color\, discontinuity \\ false : & Otherwise \end{cases} \tag{35}$$

# Specularity reduction



(a) (b) (c)

(d) (e) (f)

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# Specularity-Invariant color image representation

When $I_g(x_1) \geq I_r(x_1)$ and $I_g(x_2) \geq I_r(x_2)$

- $\hat{I}(x_1) = I_g(x_1) - I_r(x_1)$
- $\hat{I}(x_2) = I_g(x_2) - I_r(x_2)$

$\hat{I}$ *is independent* of the specular reflection component and depends only of the diffuse reflection component.

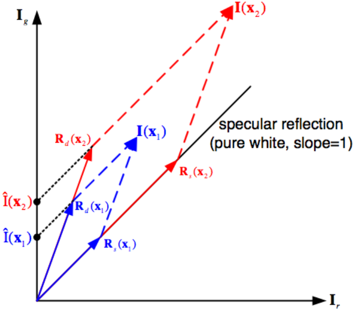

Figure: Specularity-invariant value and radio

# Specular-Free Two-Band Image Generation

$$\tilde{I}(x) = min\{I_r(x), I_g(x), I_b(x)\}$$

$$\tilde{\Lambda}(x) = min\{\Lambda_r(x), \Lambda_g(x), \Lambda_b(x)\}$$

$$\tilde{I}(x) = m_d(x)\tilde{\Lambda}(x) + \frac{m_s}{3} \qquad (36)$$

## Specular-free two-band

$$\hat{I}(x) = I(x) - \tilde{I}(x) = m_d(x)\left[\Lambda(x) - \tilde{\Lambda}(x)\right] \qquad (37)$$

# Local Ratios

**Diffuse Ratio**

$$r_d = \frac{\sum_{c \in \{r,g,b\}} \hat{I}_c(x_1)}{\sum_{c \in \{r,g,b\}} \hat{I}_c(x_2)} = \frac{m_d(x_1)}{m_d(x_2)} \tag{38}$$

**Diffuse and Specular Ratio**

$$r_{d+s} = \frac{\sum_{c \in \{r,g,b\}} I_c(x_1)}{\sum_{c \in \{r,g,b\}} I_c(x_2)} = \frac{m_d(x_1) + m_s(x_1)}{m_d(x_2) + m_s(x_1)} \tag{39}$$

- If $x_1$ and $x_2$ are specular pixels, then $r_d$ and $r_{d+s}$ are the same because $m_s(x_1)$ and $m_s(x_2)$ are equal to zero.
- We can generate a diffuse image making $r_{d+s} = r_d$.

# Iterative Framework

**Iteration when $r_{d+s} > r_d$**

$$I^{t+1}(x_1) = I^{t}(x_1) - \frac{m}{3} \tag{40}$$

$$m = \sum_{c\in\{r,g,b\}} I_c^t(x_1) - r_d \sum_{c\in\{r,g,b\}} I_c^t(x_2)$$

**Iteration when $r_{d+s} < r_d$**

$$I^{t+1}(x_2) = I^{t}(x_2) - \frac{m}{3} \tag{41}$$

$$m = \sum_{c\in\{r,g,b\}} I_c^t(x_2) - \frac{\sum_{c\in\{r,g,b\}} I_c^t(x_1)}{r_d}$$

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