CGR2025 — Lecture 2:
Radiometry, Photometry, and Colorimetry

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Abstract

These lecture notes introduce radiometric, photometric, and colorimetric foundations required in computer graphics, imaging, and vision. The presentation emphasizes the physical definitions, the relationships among quantities, and the mathematical transforms used to convert spectra into device color representations.

1 Motivation and overview

Light is the fundamental medium in imaging and rendering: all visual appearance arises from light interacting with surfaces and sensors (or eyes). To reason quantitatively about appearance we must distinguish three related but distinct disciplines:

- **Radiometry:** measures electromagnetic energy physically (power, energy, flux), independent of perception.
- **Photometry:** measures light as perceived by the human visual system; it weights radiometric quantities by the eye's sensitivity.
- **Colorimetry:** formalizes how spectral distributions map to perceived color using standard observer functions (CIE), and how to convert those perceptual descriptions into device color spaces.

In computer graphics, radiometry, photometry, and colorimetry interact as three essential layers that bridge the physical behavior of light, human perception, and digital representation. Radiometry provides the physical foundation: it describes light strictly as electromagnetic energy, quantified in watts per unit area, per unit solid angle, and per wavelength. Rendering systems rely on radiometric concepts such as radiance because they capture the physically correct transport of energy through a scene. By tracing radiance along rays and surfaces, a renderer ensures that global illumination, shading, and light transport are modeled in a way that conserves energy and produces physically plausible results.

Photometry comes into play when the physically correct radiometric outputs need to be related to what a human observer would perceive as brightness. Humans are far more sensitive to some wavelengths (especially around 555 nm) than others, so a purely radiometric rendering might allocate equal energy to blue and green light, but the observer would perceive the green as brighter. By weighting radiometric spectra with the luminous efficiency function $V(\lambda)$, graphics systems can generate images that match expected brightness levels under human vision. This is particularly important for tone mapping, display calibration, and realistic lighting simulation, where subjective brightness matters as much as objective physics.

Colorimetry ties these two domains together by providing a standard way of mapping physical spectra into perceptual tristimulus values. It defines how to transform a full spectral distribution into the three-dimensional CIE XYZ space and then into device-dependent RGB values. In practice, this allows rendering systems to collapse high-dimensional spectral data into the three channels that displays can reproduce, while still aligning with how humans perceive color differences and similarities. Colorimetry also introduces concepts like chromatic adaptation and gamut mapping, which are necessary when moving from one illumination or device to another.

Taken together, radiometry ensures that graphics simulations are physically correct, photometry ensures that the simulated brightness corresponds to human visual sensitivity, and colorimetry ensures that the colors produced are both perceptually meaningful and reproducible on digital devices. The interaction among these domains underpins every step of modern rendering pipelines, from physically based shading models to display-ready RGB pixel values. Without this triad, computer graphics would lack both physical accuracy and perceptual realism.

2 Radiometry

Radiometry provides the language and units for describing the physical flow of electromagnetic energy. Radiometry is indispensable in computer graphics whenever physically accurate light transport is needed. For example, simulating the way sunlight diffuses through atmospheric haze requires measuring energy flow per wavelength to capture color shifts at sunrise and sunset. In architectural visualization, computing irradiance on building surfaces determines whether daylighting designs meet energy efficiency standards. Rendering materials such as glass or polished metals depends on radiance and solid angle relationships to reproduce specular highlights and reflections faithfully. Even in visual effects, accurate radiometric modeling ensures that virtual lights blend seamlessly with live-action footage, since the brightness and contrast of rendered elements must match those of real-world cameras. These scenarios highlight why radiometry, with its physically grounded units and conservation principles, forms the foundation for realistic and reliable image synthesis.

2.1 Basic radiometric quantities

We summarize the primary radiometric quantities and their units.

Radiant energy. Denote radiant energy by Q. It is the total electromagnetic energy measured in joules (J).

Radiant flux (power). Radiant flux, often written Φ_e (or simply Φ), is energy per unit time:

$$\Phi_e = \frac{dQ}{dt},$$

with SI unit watts (W). It measures how much radiant energy is emitted, transmitted, or received per second.

Radiant intensity. For a point-like emitter the radiant intensity I_e is the radiant flux per unit solid angle:

$$I_e = \frac{d\Phi_e}{d\omega},$$

units W/sr.

Irradiance. Irradiance E_e measures how much radiant flux strikes a surface per unit area:

$$E_e = \frac{d\Phi_e}{dA},$$

units W/m^2. If the surface is oriented, the projected area must be considered (cosine factor).

Radiant exitance (emittance). Radiant exitance M_e is the radiant flux leaving a surface per unit area (also $\mathrm{W/m^2}$).

Radiance. Radiance $L_e(\mathbf{x}, \omega)$ is the fundamental quantity most used in computer graphics. It measures radiant flux per unit projected area per unit solid angle along direction ω:

$$L_e(\mathbf{x}, \omega) = \frac{d^2\Phi_e}{dA_\perp \, d\omega},$$

where $dA_\perp$ is the area projected perpendicular to ω. Radiance units are $\mathrm{W{\cdot}m^{-2}{\cdot}sr^{-1}}$. Radiance is conserved along lossless geometric rays (in absence of scattering/absorption), which makes it especially useful in rendering and transport equations.

2.2 Spectral quantities

All radiometric quantities can be defined per wavelength (or per unit frequency). For example, spectral radiant flux $\Phi_{e,\lambda}(\lambda)$ is the radiant flux per unit wavelength (commonly W/nm). The total (broadband) quantity is obtained by integrating over wavelength:

$$\Phi_e = \int_{\lambda_{\min}}^{\lambda_{\max}} \Phi_{e,\lambda}(\lambda) \, d\lambda.$$

Typical integration limits for visible light are 380–780 nm, though conventions vary.

2.3 Why radiance matters for rendering

Radiance directly relates to what a camera or eye perceives from a small patch of scene: the power per unit area per solid angle that reaches the sensor. Rendering equations are usually written in terms of radiance and spectral radiance (radiance as a function of wavelength), which then links naturally to BRDFs, scattering, and emission models.

3 Photometry

Photometry uses radiometric quantities but remaps them to human perception of brightness. The remapping is accomplished through the *luminous efficiency function* (also called the luminosity function), usually denoted $V(\lambda)$ for the photopic (daylight, cone-mediated) observer. Photometry becomes crucial whenever graphics systems must account for how bright a scene will appear to a human observer, rather than how much energy is physically present. For instance, a streetlight and a neon sign might emit very different spectra, but by converting their radiant output into lumens, a renderer can determine which will dominate human attention in a nighttime city scene. In tone mapping high dynamic range (HDR) images, photometric quantities guide how to compress large ranges of physical luminance into a displayable range while preserving perceptual brightness relationships. Similarly, in realistic lighting design for games or VR, photometric units such as lux and candela are used so that virtual light sources mimic the brightness of their real-world counterparts, ensuring that a digital lamp set to "60 W equivalent" looks correct to the player.

3.1 Luminous efficiency and the 683 lm/W constant

The photopic luminous efficiency function $V(\lambda)$ expresses the average sensitivity of the human eye to monochromatic light at wavelength λ. By definition, at the peak sensitivity (nominally

555 nm), 1 watt of monochromatic radiant power corresponds to 683 lumens of luminous flux. Thus, a standard conversion from spectral radiant flux $\Phi_{e,\lambda}(\lambda)$ to luminous flux Φ_v is:

$$\Phi_v \;=\; 683\ \mathrm{lm/W} \int_0^{\infty} V(\lambda)\, \Phi_{e,\lambda}(\lambda)\, d\lambda. \tag{1}$$

In practice the integral is taken over the visible range (380–780 nm). The constant 683 lm/W is a convention chosen to make the physical and photometric units align with historic definitions.

3.2 Photometric quantities

The photometric counterparts to the radiometric quantities have the same names but different units:

- **Luminous flux** Φ_v (lumens, lm) — photometric analogue of radiant flux.
- **Luminous intensity** (cd = lm/sr) — luminous flux per unit solid angle.
- **Illuminance** E_v (lux = lm/m^2) — luminous flux incident per unit area.
- **Luminance** L_v (cd/m^2) — luminous analogue of radiance: luminous flux per unit projected area per unit solid angle.

Luminance is especially important because it describes perceived surface brightness and is what displays and cameras ultimately try to match (after device-specific transforms). For an emissive or reflective patch whose spectral radiance is $L_{e,\lambda}(\lambda)$, the photopic luminance L_v is:

$$L_v \;=\; 683 \int_{\lambda} V(\lambda)\, L_{e,\lambda}(\lambda)\, d\lambda.$$

3.3 Trichromatic Theory of Light

The **trichromatic theory of light**, also known as the **Young–Helmholtz theory of color vision**, is a foundational model of human color perception. It states that the sensation of color arises from the activity of three distinct types of cone photoreceptors in the retina, each sensitive to a different range of wavelengths:

- **S-cones (short-wavelength):** peak sensitivity in the blue region, around 420 nm.
- **M-cones (medium-wavelength):** peak sensitivity in the green region, around 530 nm.
- **L-cones (long-wavelength):** peak sensitivity in the red region, around 560 nm.

According to the theory, any perceived color is determined by the relative stimulation of these three cone types. For instance, yellow light (at ~580 nm) does not activate a dedicated "yellow receptor." Instead, it is perceived because it produces a particular ratio of responses between L- and M-cones, with minimal stimulation of S-cones.

This theory provides the perceptual foundation for *tristimulus color models* such as CIE XYZ or device RGB systems. Since the human eye reduces the continuous spectrum of light into three response channels, it is possible to reproduce any visible color by mixing appropriate amounts of three primary lights. An important implication of this is the phenomenon of *metamerism*: two physically different spectral distributions can appear identical if they yield the same relative cone responses.

4 Colorimetry

Colorimetry formalizes how spectral power distributions (SPDs) map to perceived color. Because human color vision is trichromatic (three cone classes), any SPD visible to a human can be reduced to three numbers (tristimulus values) under a chosen standard observer, plus an overall intensity. Colorimetry is essential whenever accurate reproduction of perceived colors is required in computer graphics. For example, a physically correct spectrum of a surface under daylight may contain hundreds of wavelength samples, but by converting it into CIE XYZ tristimulus values, the renderer can faithfully display the same color on an RGB monitor. In film production, colorimetry underpins the workflow of matching on-set footage with computer-generated imagery, since both must be represented in a common color space such as ACES or sRGB. In product visualization, manufacturers rely on colorimetry to ensure that the digital render of a textile, paint, or plastic swatch matches the way the item will appear under standard illuminants in real life. Without colorimetric transforms, such comparisons would be impossible, because two spectra that appear identical to the eye might otherwise be treated as different by the rendering system.

4.1 The Color Matching Experiment

The **color matching experiment** is a classic psychophysical procedure that provided the basis for modern colorimetry and the development of the CIE color spaces. It was first systematically conducted by James Clerk Maxwell in the mid-19th century and later refined in the 20th century by the Commission Internationale de l'Éclairage (CIE).

In the experiment, an observer is presented with a split visual field. One half shows a *test light* of a specific wavelength, while the other half shows a *mixture field* composed of adjustable amounts of three fixed *primary lights*. The observer's task is to adjust the intensities of the primaries until the mixture field appears perceptually identical to the test light.

Key observations from the experiment include:

- Three primaries are sufficient to match *any* test color, provided they are suitably chosen and not themselves metamers.
- For some test wavelengths, a match cannot be achieved using only additive combinations of the primaries; instead, one primary must be added to the test side. This effectively corresponds to assigning a *negative* weight to that primary in the mixture.
- The set of matching coefficients obtained across the visible spectrum defines the **color matching functions** for the given observer and choice of primaries.

The CIE standardized this procedure in 1931, adopting a set of primaries and observer data to define the **CIE 1931 2° Standard Observer**.

4.2 From Experimental RGB to CIE XYZ

The color matching experiments of the early 20th century produced a set of *color matching functions* based on three chosen primaries, typically denoted $R(\lambda)$, $G(\lambda)$, and $B(\lambda)$. These functions describe how much of each primary is required to match a monochromatic test light of wavelength λ. The resulting *RGB color space* is entirely dependent on the specific primaries chosen for the experiment.

Although useful, the original RGB system has two major drawbacks:

- Some wavelengths required *negative* amounts of one primary, meaning the primary had to be added to the test field rather than the mixture field. This is mathematically valid but awkward for practical use.

- The RGB system is not standardized, since different choices of primaries yield different matching functions.

To address these issues, the CIE (Commission Internationale de l'Éclairage) defined in 1931 a new set of basis functions, $\overline{x}(\lambda)$, $\overline{y}(\lambda)$, and $\overline{z}(\lambda)$, chosen as linear combinations of the experimental RGB functions:

$$\begin{bmatrix} \overline{x}(\lambda) \\ \overline{y}(\lambda) \\ \overline{z}(\lambda) \end{bmatrix} = M \begin{bmatrix} \overline{r}(\lambda) \\ \overline{g}(\lambda) \\ \overline{b}(\lambda) \end{bmatrix},$$

where M is a fixed 3×3 transformation matrix. The transformation was designed to satisfy two properties:

1. All three CIE color matching functions are non-negative over the visible spectrum.
2. The $\overline{y}(\lambda)$ function is identical to the photopic luminous efficiency function $V(\lambda)$, so that the Y tristimulus value corresponds directly to perceived luminance.

Given a spectral power distribution $P(\lambda)$, the tristimulus values in the XYZ system are obtained as:

$$X = \int P(\lambda)\,\overline{x}(\lambda)\,d\lambda, \quad Y = \int P(\lambda)\,\overline{y}(\lambda)\,d\lambda, \quad Z = \int P(\lambda)\,\overline{z}(\lambda)\,d\lambda.$$

Thus, the XYZ color space can be seen as a standardized, device-independent reformulation of the original experimental RGB space. From XYZ, other device-dependent spaces (such as sRGB) can be derived by applying an additional linear transformation defined by the primaries and white point of the display system.

4.3 Chromaticity and the xyY representation

Tristimulus values (X, Y, Z) can be decomposed into a chromaticity pair and a luminance: the (x, y) chromaticity coordinates are

$$x = \frac{X}{X+Y+Z}, \qquad y = \frac{Y}{X+Y+Z},$$

and Y carries the luminance (or relative brightness). The CIE chromaticity diagram (the so-called horseshoe) depicts the gamut of human-visible chromaticities; spectral colors lie on the outer boundary.

4.4 Metamerism and limitations

Because the mapping from infinite-dimensional spectra (functions of λ) to 3 tristimulus numbers is many-to-one, different spectra can produce identical tristimulus values — this is metamerism. Two metamers are spectrally different but perceptually identical under a given observer and illuminant. Metamerism is a central concept in color reproduction: devices reproduce tristimulus values, not arbitrary spectra, which leads to gamut and metameric mismatches especially under different illuminants or for observers with different spectral sensitivities.

5 Practical considerations for graphics and imaging

5.1 Spectral rendering vs. RGB rendering

- **Spectral rendering** treats light as functions over wavelength and integrates with spectral BRDFs and color matching functions. It correctly models metamerism, wavelength-dependent phenomena (dispersion, fluorescence), and interactions with narrowband light sources. It is more computationally expensive and requires spectral data for illuminants, materials, sensors, and displays. - **RGB or tristimulus rendering** operates on three color channels. It is efficient and sufficient for many applications where spectral effects are negligible, but can produce errors with narrowband lighting, interference effects, or when accurate color reproduction under varied illuminants is required.

5.2 Device gamuts and limitations

Real devices have finite gamuts; many real-world colors (as given by spectral reflectances) simply cannot be reproduced by a specific set of primaries. When mapping, common strategies are gamut clipping, gamut mapping, or remapping colors to perceptually uniform spaces with appropriate constraints.

5.3 White balancing and chromatic adaptation

Perceived colors depend strongly on the illuminant. Chromatic adaptation transforms attempt to account for different scene illuminants so that colors appear consistent. Transformations like Bradford or von Kries operate in a cone-referenced color space and are widely used in imaging pipelines.

6 Summary table

Radiometric quantity	**Photometric quantity**	**Colorimetric quantity**
Radiant energy Q (J)	—	—
Radiant flux Φ_e (W)	Luminous flux Φ_v (lm)	Tristim. values (X, Y, Z)
Radiant intensity I_e (W/sr)	Luminous intensity I_v (lm/sr)	Chromaticity (x, y)
Irradiance E_e (W/m^2)	Illuminance E_v (lux = lm/m^2)	—
Radiant exitance M_e (W/m^2)	Luminous exitance M_v (lm/m^2)	—
Radiance L_e (W·m^{-2}·sr^{-1})	Luminance L_v (cd/m^2)	lightness, hue, chroma
Spectral quantities per λ	Spectral luminous efficiency $V(\lambda)$	Color matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$

Table 1: Correspondence between radiometric, photometric, and colorimetric quantities.