Unit 3

Viewing in 3D
&
Light
&
Colour

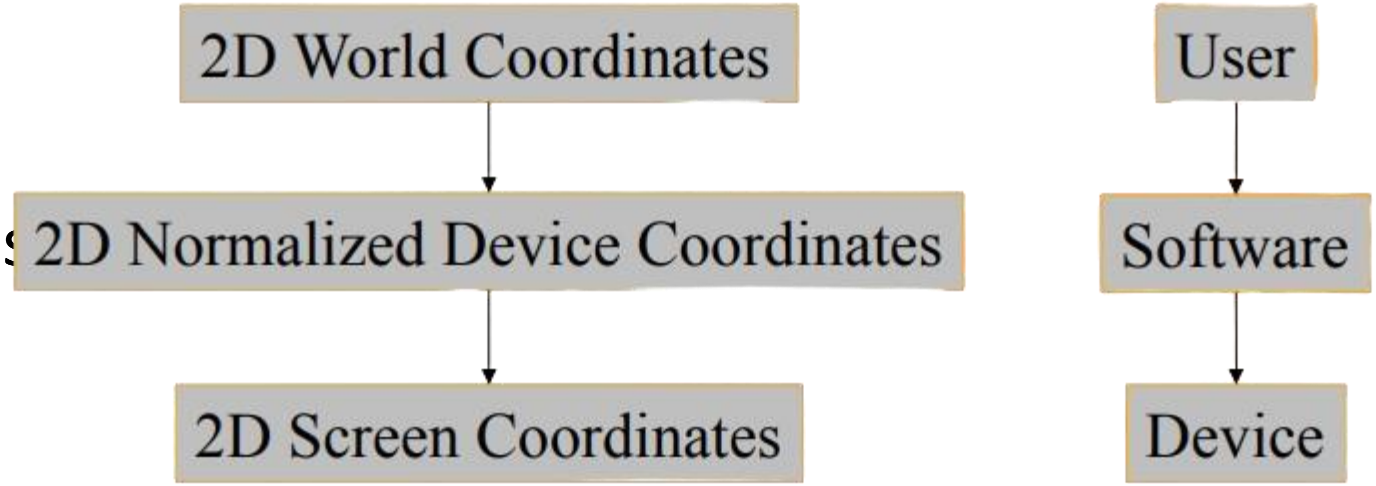
2D Viewing Transformation

• Converting 2D model coordinates to a physical display device

– 2D coordinate world

– 2D screen space

– Allow for different device res



3D viewing

- 3D viewing in computer graphics refers to the process of creating a 2D representation of a three-dimensional scene.
- This is an essential aspect of computer graphics, as it involves transforming the 3D coordinates of objects into 2D coordinates that can be displayed on a 2D screen.
- **The primary goal is to simulate the perspective and depth perception that humans experience in the real world.**

- Here are some key concepts and techniques involved in 3D viewing:
- Projection: The process of projecting 3D points onto a 2D plane is fundamental to 3D viewing. There are two main types of projections:
  - Orthographic Projection: This type of projection preserves parallel lines, making it suitable for architectural and engineering drawings. However, it doesn't provide a realistic sense of depth.
  - Perspective Projection: This type of projection mimics the way humans perceive depth in the real world. Objects that are farther away appear smaller, and converging lines meet at a vanishing point.

- Viewing Transformation: The transformation involves positioning and orienting the camera (or the eye) in the 3D scene. This includes setting the camera's position, specifying the direction it is facing, and defining an "up" vector to determine the orientation.

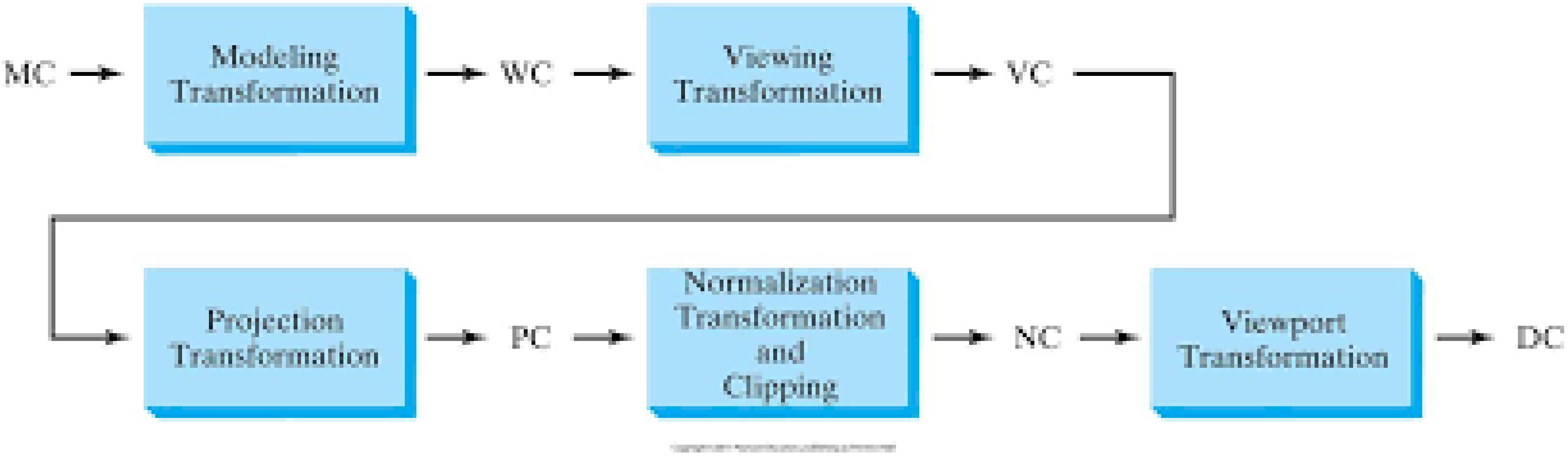
- Clipping: Clipping involves removing any parts of objects that fall outside the view frustum (the portion of space that is visible in the camera's view). This helps optimize rendering and improves performance.

- Viewport Transformation: This step maps the normalized device coordinates resulting from the viewing transformation to the actual screen or window coordinates. It involves scaling, translating, and possibly flipping the coordinates to fit the screen.

- Depth Cueing: To enhance the perception of depth, depth cueing can be applied. This involves adjusting the intensity or color of objects based on their distance from the camera, simulating atmospheric effects.

- Hidden Surface Removal: To determine which surfaces are visible and which ones are hidden by others, algorithms like the Z-buffer or depth-buffering are used. These techniques prevent rendering hidden surfaces, improving the overall realism of the scene.

3D Viewing Stages



- Viewing in 3D is divided mainly into following stages:
- Modelling transformation
- Viewing transformation
- Projection transformation
- Normalization transformation and Clipping
- View Port transformation

1. Modelling Transformation:

- Modelling Transformation can be obtained with the help of 3D transformations.
- It transforms the object (Modelling) coordinates (MC) into 3D world coordinate system, will generate output as 3D world coordinates (WC). (3D to 3D).

2. Viewing Transformation:

- The viewing-coordinate system is used in graphics packages as a reference for specifying the observer viewing position and the position of the projection plane.
- It transforms the world coordinate into viewing coordinates (VC) by performing clipping against canonical view volume.

3. Projection Transformation:

- Projection operation converts the viewing-coordinate description (3D) to coordinate positions on the projection plane (2D).
- It projects the coordinates onto projection plane as Projection Coordinates (PC). (3D to 2D)

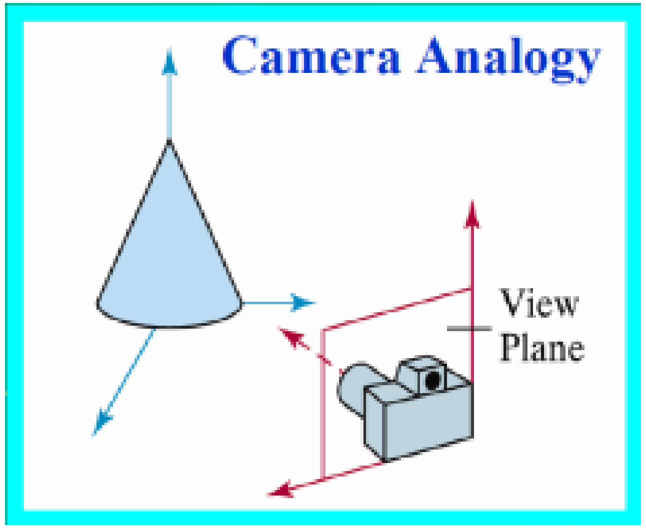
4. Normalization Transformation and Clipping:

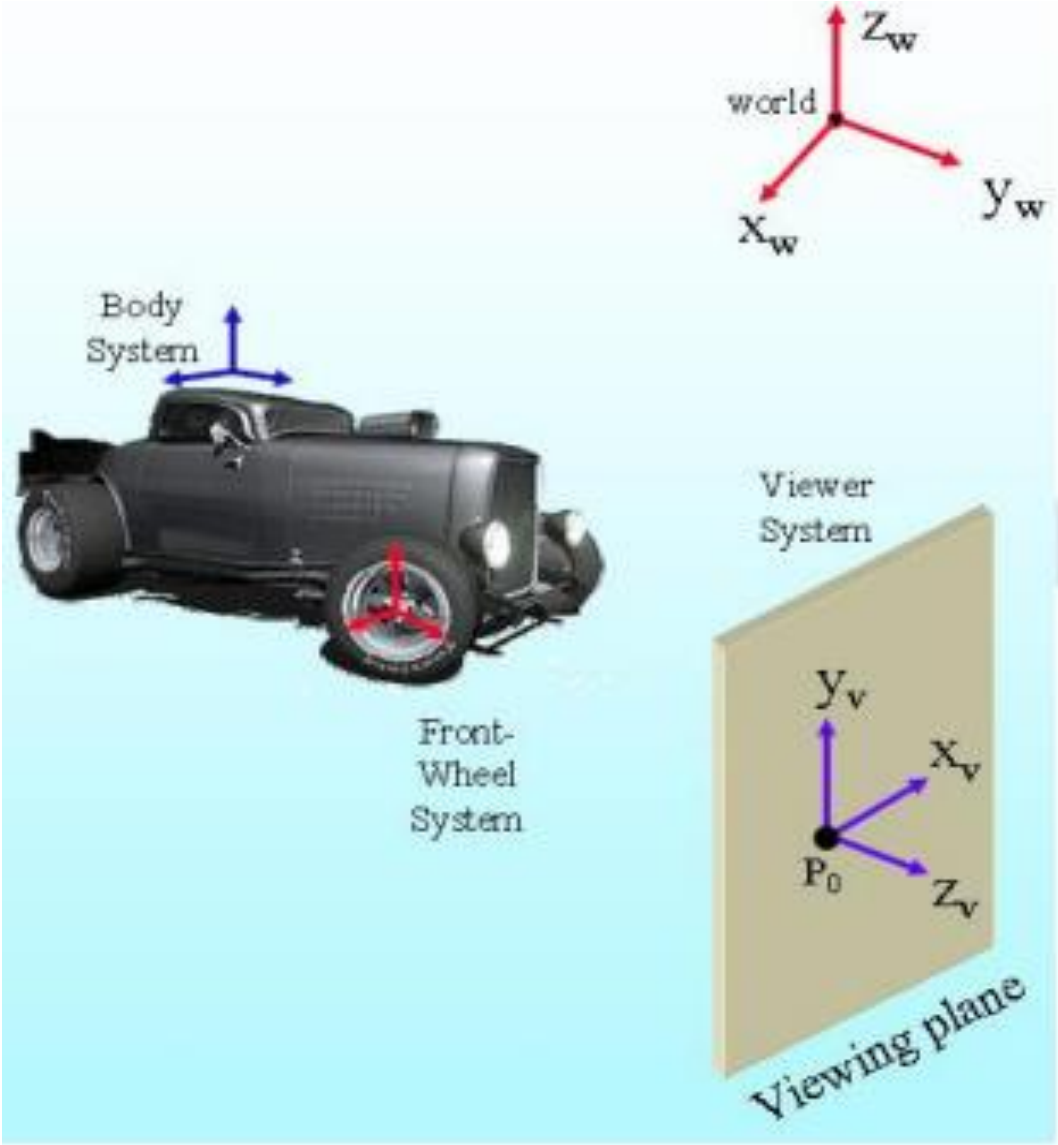
- The coordinates outside the view volume will get clipped and the transformation will get normalized and the Normalized Coordinates (NC) will be generated.
- This normalization is often done to simplify calculations and ensure consistency across different applications and rendering pipelines.

5. Viewport Transformation:

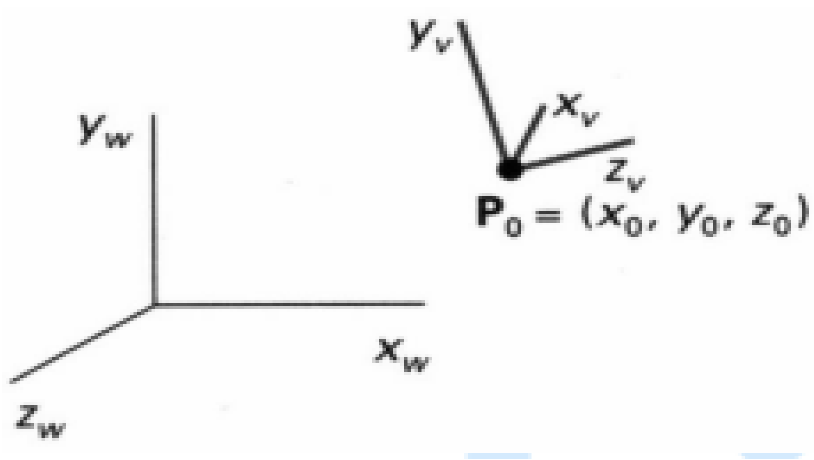
- It maps the coordinate positions on the projection plane of the output device.
- It transforms Normalized Coordinates into viewport is 2D Device coordinates (DC) or display.

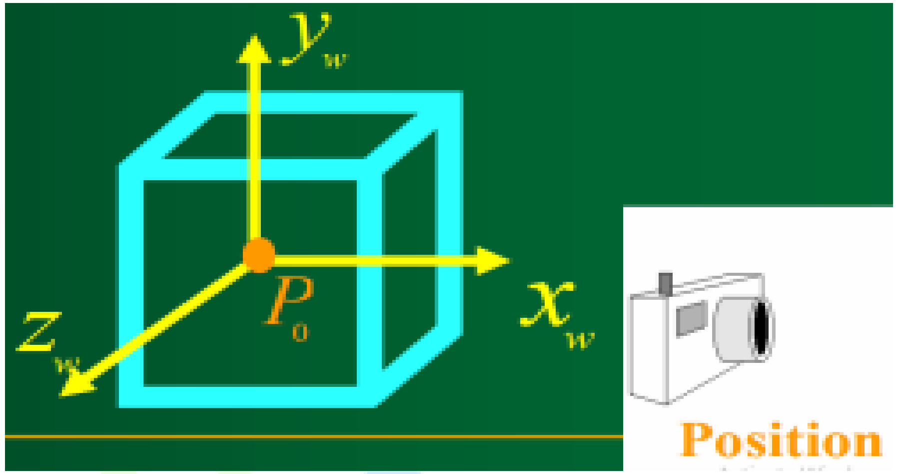
- Viewing Coordinates
    - Viewing coordinates system described 3D objects with respect to a viewer.
    - A Viewing (Projector) plane is set up perpendicular to zv and aligned with (xv,yv).


Camera Analogy
View
Plane

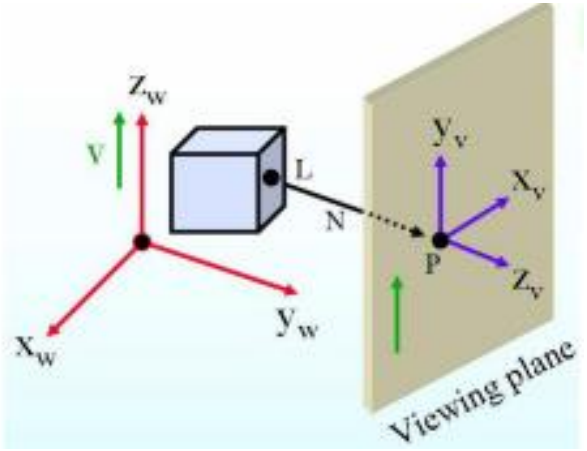

z_w
world
y_w
x_w
Body
System
Viewer
System
Front-
Wheel
System
y_v
x_v
P_0
z_v
Viewing plane

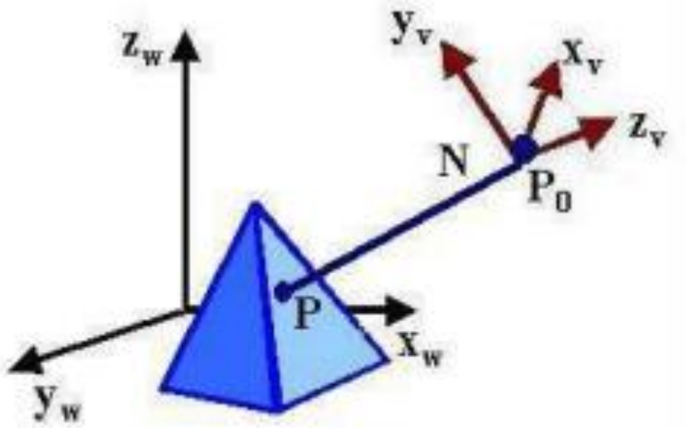
- Specifying the Viewing Coordinate System (View Reference Point)
  - We first pick a world coordinate position called view reference point (origin of our viewing coordinate system).
  - P0 is a point where a camera is located.
  - The view reference point is often chosen to be close to or on the surface of some object, or at the center of a group of objects.

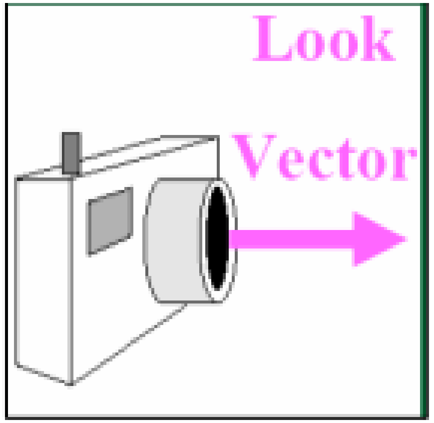




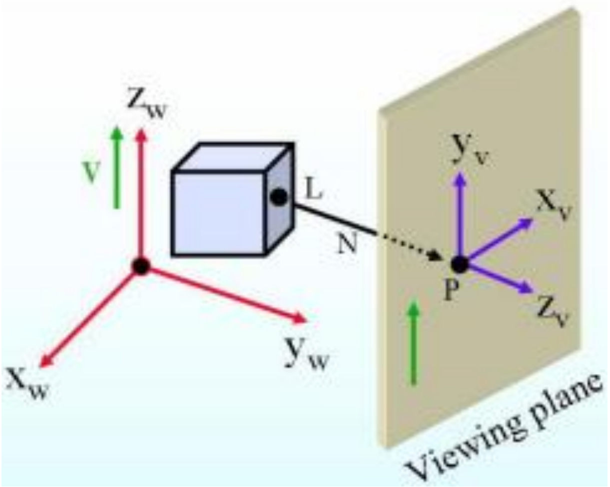
- Specifying the Viewing Coordinate System (Zv Axis)
  - Next, we select the positive direction for the viewing zv axis, by specifying the **view plane normal vector**, N.
  - The direction of N, is from the look at point (L) to the view reference point.

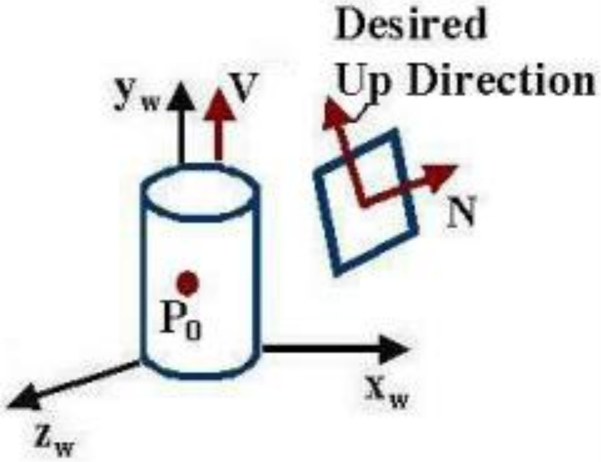


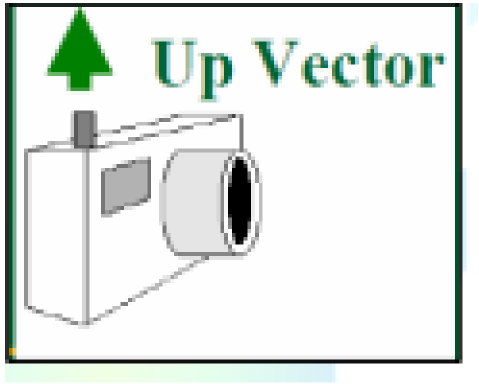




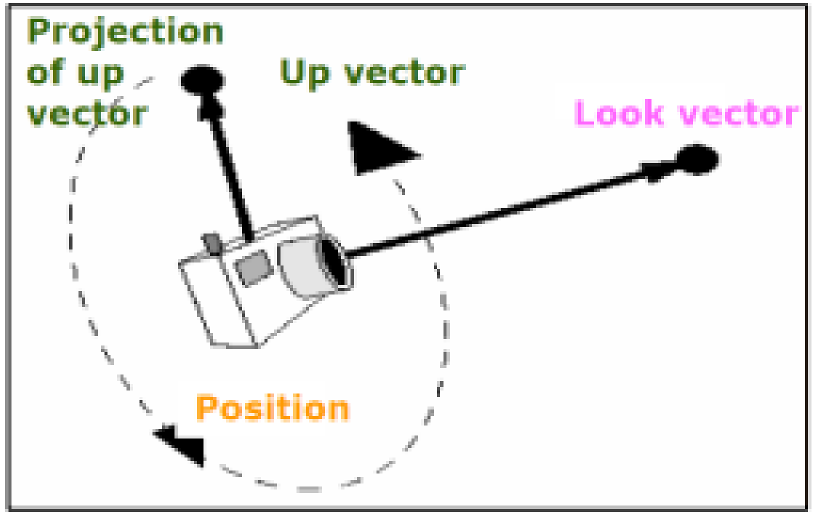
- Specifying the Viewing Coordinate System (yv Axis)
  - Finally, we choose the up direction for the view by specifying a vector V, called the **view up vector**.
  - This vector is used to establish the positive direction for the yv axis.
  - V is projected into a plane that is **perpendicular to the normal vector**.



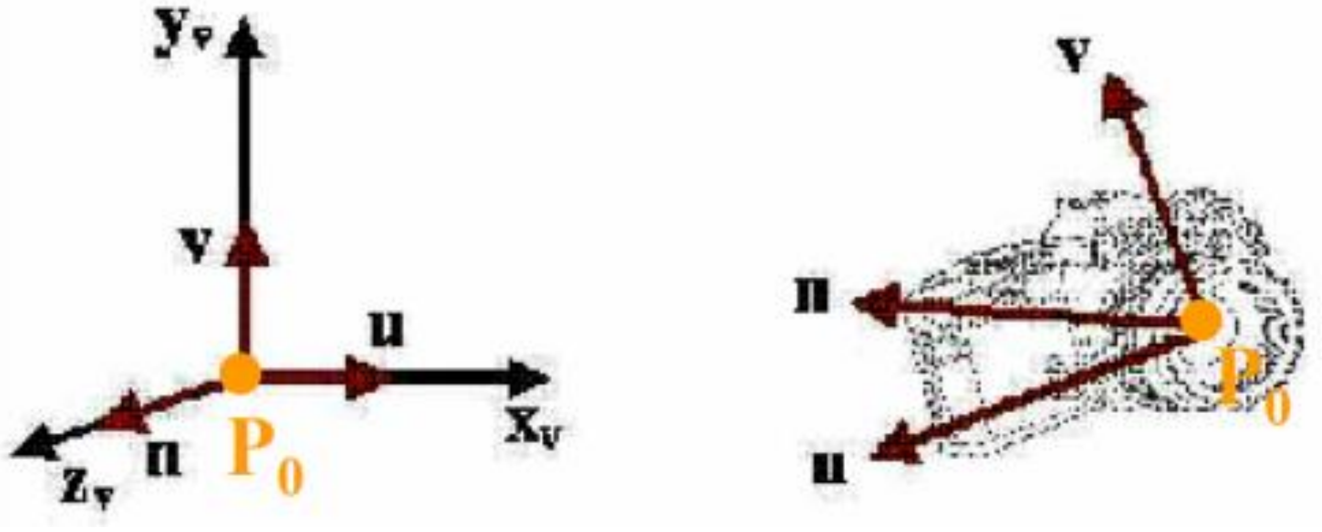




- **Look and Up Vectors**
  - the direction the camera is pointing
  - three degrees of freedom; can be any vector in 3-space
  - determines how the camera is rotated around the Look vector
  - for example, whether you’re holding the camera horizontally or vertically (or in between)
  - projection of Up vector must be in the plane perpendicular to the look vector
  - an "up vector" is a term used to describe a vector that specifies the orientation of an object or a camera relative to the world or another coordinate system. This vector defines the direction that is considered "up" from the object's perspective.

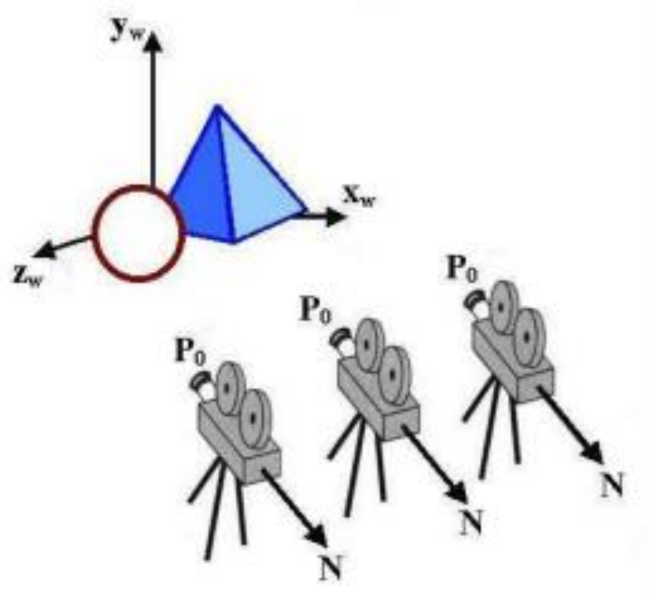


- Specifying the Viewing Coordinate System (xv Axis)
  - Using vectors N and V, the graphics package computer can compute a third vector U, perpendicular to both N and V, to define the direction for the xv axis.



- Graphics package allow users to choose the position of the view plane along the zv axis by specifying the view plane distance from the viewing origin.
- The view plane is always parallel to the xvyv plane.
- To obtain a series of view of a scene, we can keep the view reference point fixed and change the direction of N.

- Simulate Camera Motion
  - To simulate camera motion through a scene, we can keep N fixed and move the view reference point around.



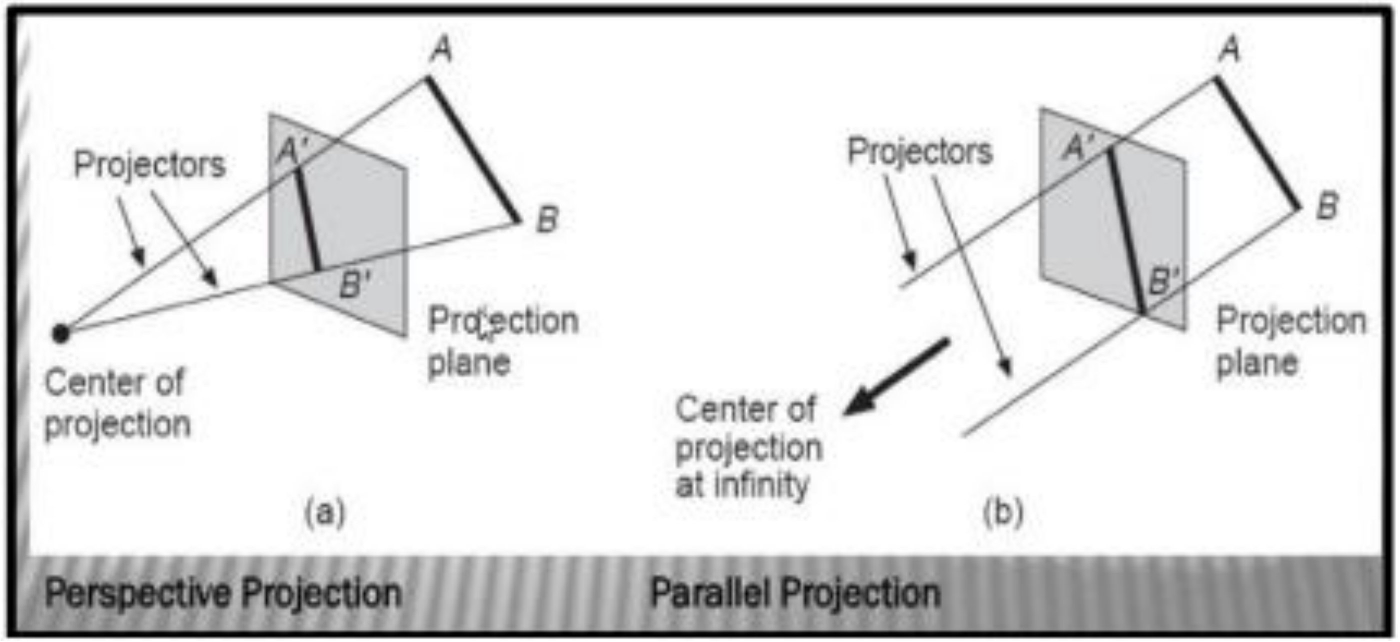
Canonical View Volume

- In computer graphics, the canonical view volume (CVV) refers to a standardized, normalized viewing region or volume within which a scene or objects are defined and rendered.
- It's a **conceptual space** that simplifies the process of rendering objects within a scene.
- The concept of the canonical view volume is often used in **3D graphics rendering** pipelines for various purposes, including clipping, culling, and perspective transformations.
- The canonical view volume typically represents **a unit cube** or box in 3D space, **centered at the origin (0, 0, 0) and with sides of length 2 units(-1 to 1)**.
- The purpose of the CVV is to provide a **standardized reference frame** for transforming and projecting 3D scenes onto a 2D display, such as a computer screen.
- It simplifies the process of applying perspective transformations and clipping operations, as all objects within the CVV are mapped to the same normalized space before being projected onto the screen.

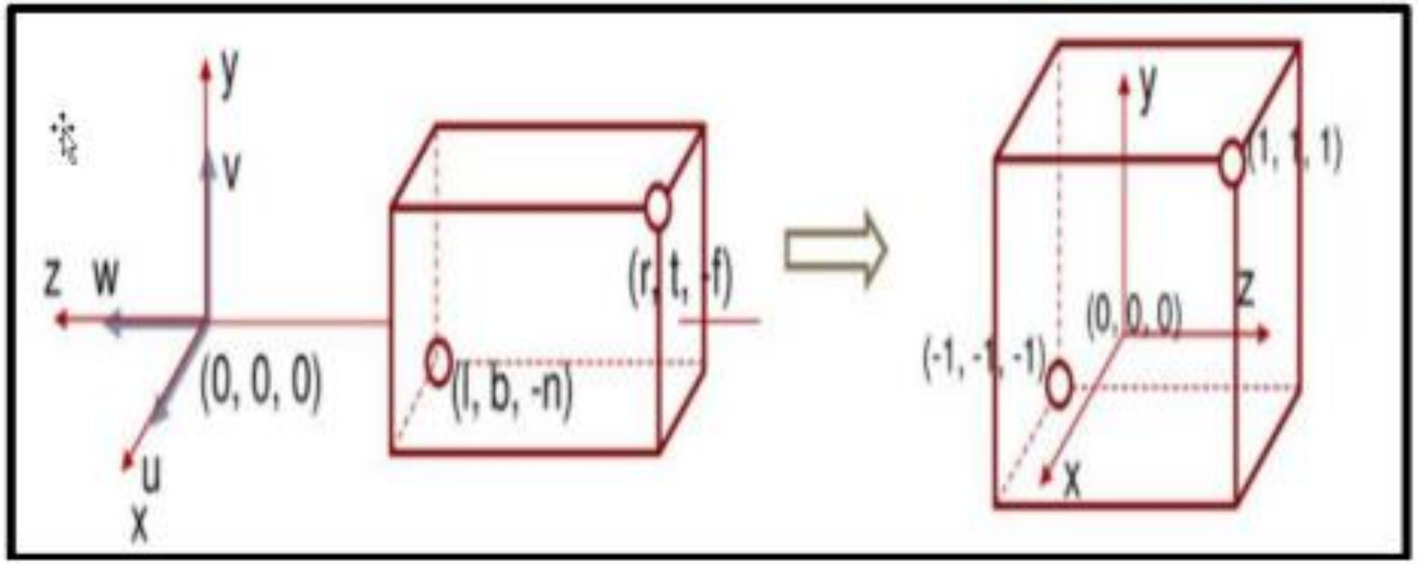
- During the rendering process, objects and vertices outside the canonical view volume are typically **clipped** or discarded, as they are not visible within the final rendered image.
- This clipping helps improve rendering performance and efficiency by focusing computation only on the visible portions of the scene.
- The canonical view volume is often transformed into the **view frustum**, which represents the visible portion of the scene from the viewer's perspective. The view frustum is defined by six planes (near, far, left, right, top, and bottom) that bound the visible region of the scene and determine which objects are visible to the viewer.
- Overall, the canonical view volume serves as a standardized reference frame that simplifies the rendering process and helps ensure consistency in rendering across different scenes and applications.

Example of CVV:

- CVV is related to Projection transformation i.e. Orthographic (parallel) projection and Perspective projection as shown in the below figure:



- Both types of projections, transform a given viewing volume to the canonical viewing volume (CVV):



- Note that n and f are typically given as distance which is always positive and because we are looking towards the –z direction, the actual coordinates become –n and –f.
- Also note the changes in the z-direction. This **makes objects further away from the camera to have larger z values**. In other words, CVV is a left - handed coordinate system.
- We need to map the box with corners at (l, b, -n) and (r, t, -f) to the (-1, -1, -1) and (1, 1, 1) of CVV.

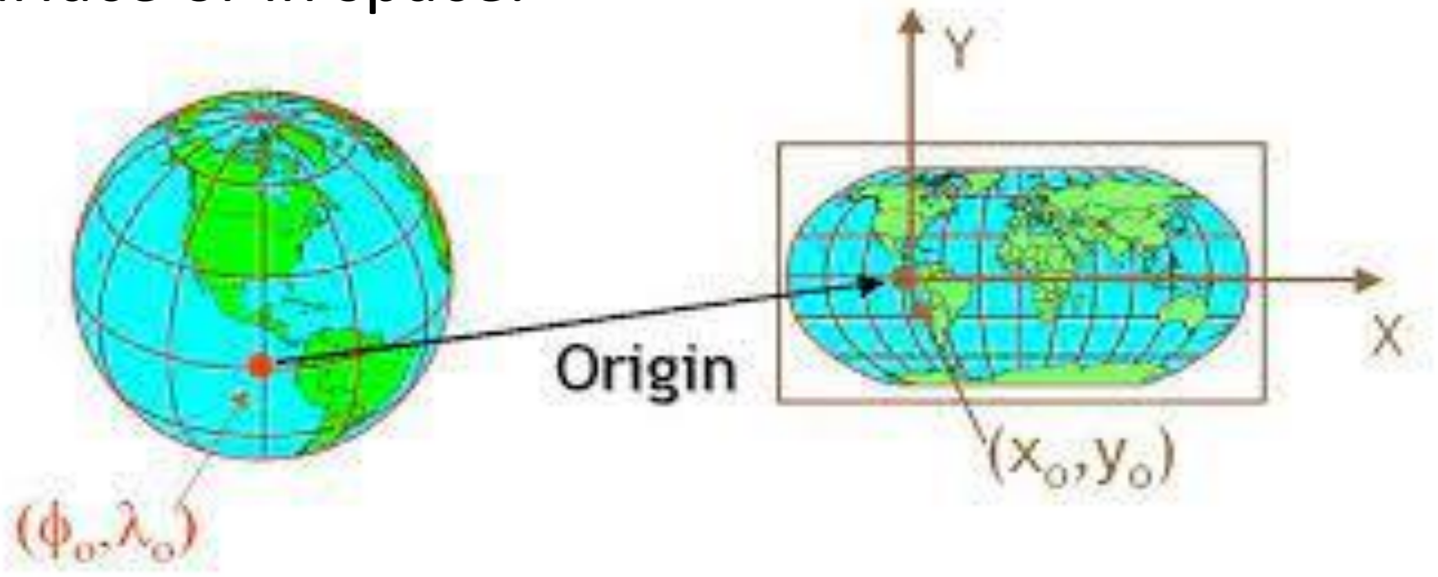
- This is accomplished by the following matrix,

$$M_{orth} = \begin{bmatrix} \frac{2}{r-l} & 0 & 0 & -\frac{r+l}{r-l} \\ 0 & \frac{2}{t-b} & 0 & -\frac{t+b}{t-b} \\ 0 & 0 & -\frac{2}{f-n} & -\frac{f+n}{f-n} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

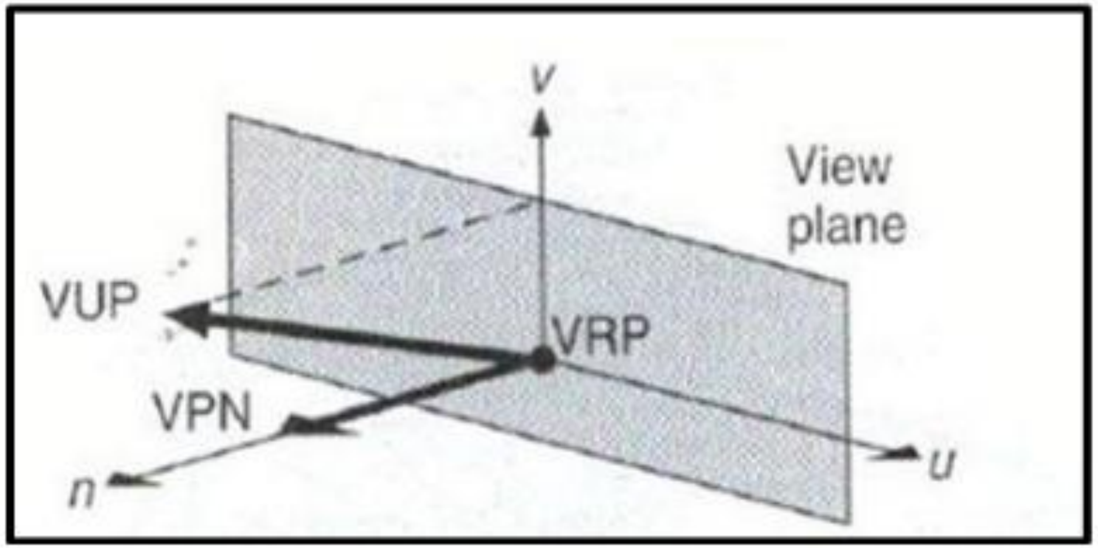
SPECIFYING AN ARBITRARY 3D VIEW

- We can view the object from the side, or the top, or even from behind.
- Therefore, it is necessary to choose a particular view for a picture by first defining a view plane.
- A view plane is nothing but the film plane in a camera which is positioned and oriented for a particular shot of the scene.
- World coordinate positions in the scene are transformed to viewing coordinates, and then viewing coordinates are projected onto the view plane.
- The procedure to project from 3D to 2D given a finite view volume, will be as follows:
    - Apply a normalizing transform to get to the canonical view volume.
    - Clip against the canonical view volume
    - Project onto the view plane
    - Transform into viewport

- To specify an arbitrary view, we should be able to place the view plane anywhere in 3D. Specify the direction of the plane and its position in the world reference coordinate system (WRC).
- WRC refer to different coordinate systems depending on the context. In general, it's a standardized method for defining locations on the Earth's surface or in space.



- A common way to specify an arbitrary view is to specify the following:
  - A View Reference Point (VRP) which is to point on the plane.
  - A View Plane Normal (VPN) which is the normal vector to the plane.
  - A View Up Vector (VUP) which is a vector from which we determine which way is up.
- Coordinate Systems:
  - WC: World Coordinates - normal, 3-space (x, y, z)
  - VRC: Viewing Reference Coordinates - defined by VRP, VPN and VUP



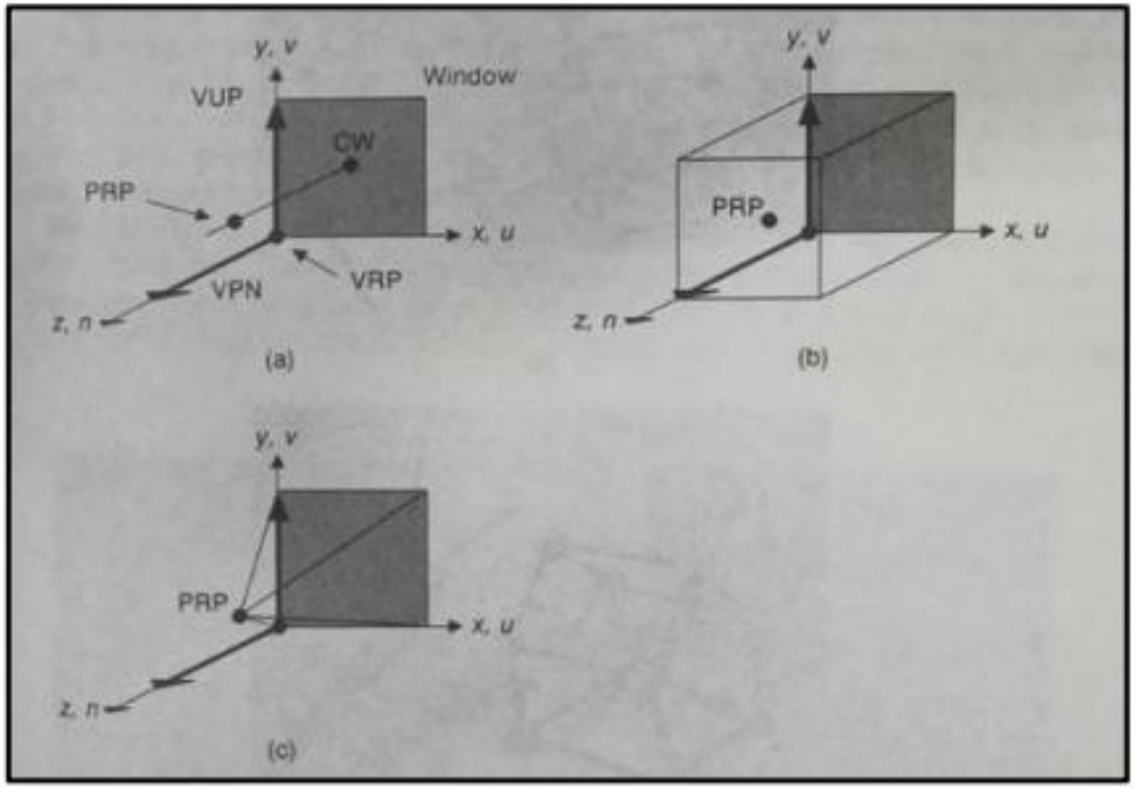
- Figure: The view plane is defined by VPN and VRP, the v axis is defined by the projection of VUP along VPN onto the view plane. The u axis forms the right-handed VRC system with VPN and v.

- Window on View plane:
  - PRP: Projection Reference Point
  - CW: Centre of Window
  - COP: Centre of Projection (Perspective Projection)
  - DOP: Direction of Projection (Parallel Projection)
  - PRP and CW are used to determine COP and DOP
  - Perspective: COP = PRP
  - Parallel: DOP = PRP – CW

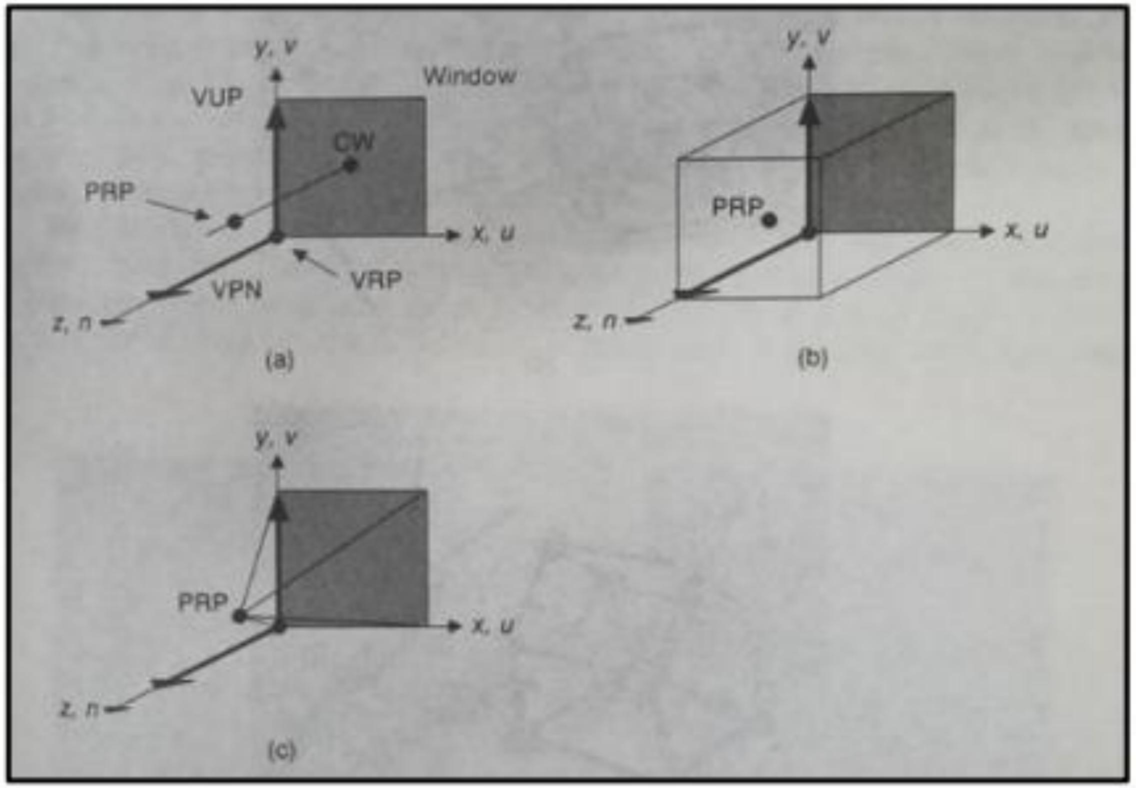
EXAMPLES OF 3D VIEWING

- In 3D viewing examples, we are going to set value for VRP, VPN, VUP, PRP, VRC and F and B of VRC based on the type of projection along with x, y and z principal axes.
- Where,
- VRP View reference point
- VPN View plane normal
- VUP View up vector
- PRP Projection Reference point
- VRC Viewing reference co-ordinate
- F and B of VRC front and back of VRC

- The notation (WC) or (VRC) is added to the table as a prompt of the coordinate system in which the viewing parameters is given. The form of the table is demonstrated for the default viewing specification used by PHIGS.
- The defaults are shown in below figure (a). The view volume corresponding to these defaults is shown in figure (b). If the type of projection is perspective rather than parallel, then the view volume is the pyramid as shown in (c).



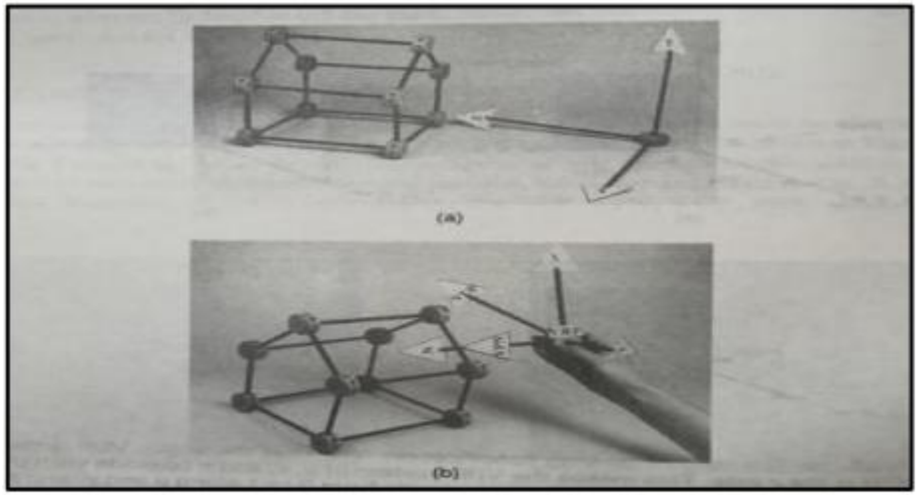
- Fig: (a) The default viewing specification: VRP is at the origin, VUP is the y axis, and VPN is the z-axis. This makes the VRC system of u, v and n coincide with x, y, z world-coordinate system. The window extends from 0 to 1 along u and v, and PRP is at (0.5, 0.5, and 1.0). (b) Default parallel projection view volume. (c) View volume if default projection were perspective.



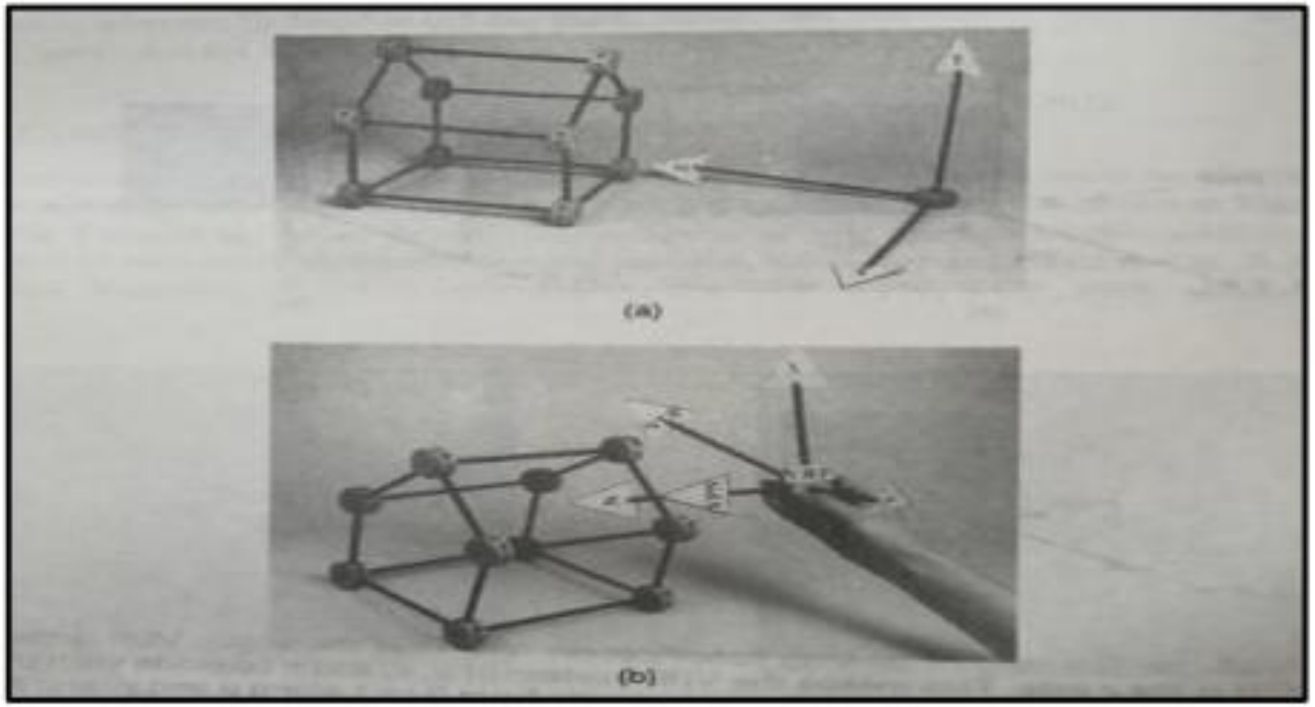
- The corresponding values for default view volume is given by,
- Viewing parameter Value Comments

VRP(WC)	(0,0,0)	Origin
VPN(WC)	(0,0,1)	Z axis
VUP(WC)	(0,1,0)	Y axis
PRP(VRC)	(0.5,0.5,1.0)	
Window(VRC)	(0,1,0,1)	
Projection type	parallel	

- Readers wanting to review how all these parameters interconnect are encouraged to construct a house, the world coordinate system, and the VRC system with Tinker Toys, as pictured in Fig.
- The idea is to position the VRC system in world coordinates as in the viewing example and to imagine projectors from points on the house intersecting the view plane. In our experience, this is a valuable way to know 3D viewing concepts.



- Fig: Stick models useful for understanding 3D Viewing. (a) House and World-coordinate system. (b) House and VRC system



(a)

(b)

- Multi-view 3D Model of Chair
  - 3D model is represented by a set of rendered views an object chair. The visual similarity between the views of two models is regarded as the model difference.
- Architect Floor Plan
- 3D view of Car

THE MATHEMATICS OF PLANAR GEOMETRIC PROJECTIONS

- The mathematics of planar geometric projections is a fundamental concept in geometry and computer graphics. It involves the transformation of 3D objects or scenes into a 2D representation on a plane, such as a computer screen or a piece of paper.
- This process is essential for creating realistic images and graphics in fields like computer-aided design (CAD), architecture and more.

There are various types of planar geometric projections, each with its own mathematical principle.

1. Orthographic Projection

- In orthographic projection, objects are projected onto a plane from a direction perpendicular to the plane. This type of projection **preserves relative sizes and angles of objects**.
- The mathematical transformation involves dropping the z-coordinate, resulting in 2D representation. The equations for orthographic projection are straightforward and involve simple multiplication.

2. Perspective Projection

- Perspective projection simulates how objects appear in a 2D image when viewed from a specific point (the viewer's eye) in 3D space. It accounts for **foreshortening**, which means objects farther from the viewer appear smaller.
- The mathematics of perspective projection is more complex and involves dividing by the z-coordinate in addition to other transformations.

3. Vanishing Points

- In perspective projection, vanishing points play a crucial role. These are points at which parallel lines in 3D space converge in the 2D projection.
- The mathematical determination of vanishing points depends on the **viewing angle and the positions of objects** in 3D space.

4. Camera and Projection Matrix

- In computer graphics, a camera model is often used to represent the viewer's perspective. A camera matrix or projection matrix is used to describe the transformation from 3D coordinates to 2D screen coordinates.
- This matrix includes parameters for the camera's position, orientation, and field of view.

5. Homogeneous Coordinates

- Homogeneous coordinates are frequently used in geometric projections to simplify the mathematics of transformations.
- These coordinates allow for translation and perspective projection to be expressed as matrix multiplication, making the process more efficient and versatile.

6. Clipping

- Clipping is the process of discarding or adjusting portions of the 3D scene that are outside the view frustum (the 3D space that the camera can see).
- This is important for optimizing rendering and preventing objects from being rendered outside the camera's view.

7. Rasterization

- After the projection, the resulting 2D image is typically divided into pixels on the Screen.
- Rasterization involves determining which pixels are covered by the projected 3D objects and determining the color or texture for each pixel.
- This is a fundamental step in computer graphics rendering.

8. Rendering Pipeline

- Modern graphics hardware and software follow a rendering pipeline that includes various stages, such as vertex transformation, projection, shading, and texture mapping.
- Each stage involves its own mathematical operations to produce the final 2D image.

9. Shader Programs

- Shader programs, such as vertex and fragment shaders in OpenGL or DirectX, allow developers to write custom code to perform transformations, lighting calculations, and other operations in the rendering pipeline.
- The mathematics of planar geometric projections is at the core of computer graphics and 3D modeling, allowing us to create realistic and visually appealing representations of 3D worlds on 2D screens.
- These concepts are fundamental for anyone working in fields that involve computer-generated imagery which considers the projection plane, center of projection, view point, distance etc.

COMBINED TRANSFORMATION MATRICES FOR PROJECTIONS AND VIEWING

- In computer graphics and 3D rendering, combined transformation matrices are often used to efficiently apply both projection and viewing transformations to 3D objects or scenes.
- These matrices allow you to convert 3D world coordinates into 2D screen coordinates while taking into account perspective projection and the position and orientation of the virtual camera (viewer).

- Here's how these matrices work and how they are constructed:

1. Model-View Matrix (M)

- The model-view matrix represents the combined transformation that includes both the model's local transformation (e.g., translation, rotation, scaling) and the viewer's transformation (camera position and orientation).
- This matrix moves 3D object coordinates from their local space to the viewer's world space. It is often expressed as M = V*M, where V is the viewer's transformation matrix, and M is the local model transformation matrix.

2. Projection Matrix (P)

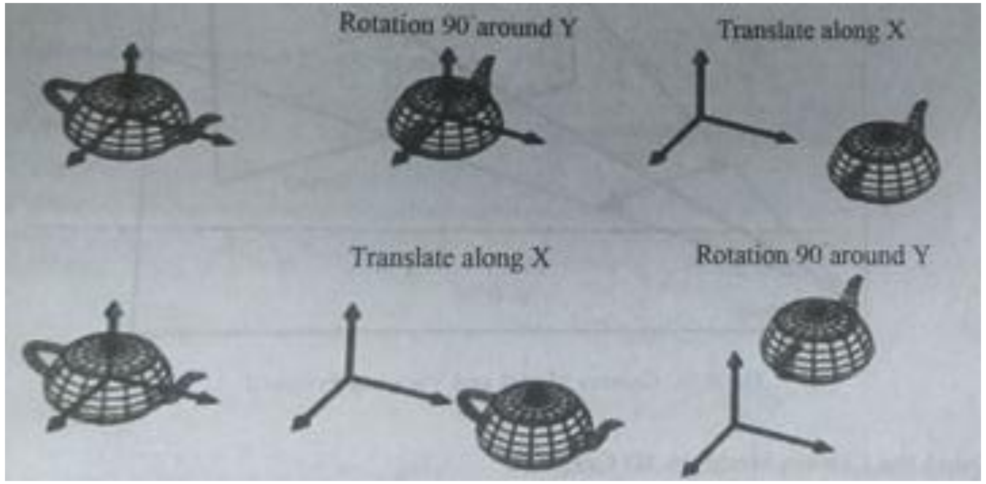
- The projection matrix is responsible for applying perspective projection, which simulates how objects appear smaller as they move farther from the viewer. It typically involves dividing by the z-coordinate to achieve this effect. The specific form of the projection matrix can vary (e.g., orthographic, perspective), but it's often denoted as P.

3. Combined Transformation Matrix (MVP)

- To apply both the model-view transformation and the projection in a single step, you can create a combined transformation matrix, often referred to as the MVP matrix. This matrix is computed by multiplying the projection matrix (P) by the model-view matrix (M): MVP = P* M.
- The MVP matrix allows you to transform 3D object coordinates into homogeneous clip coordinates, which are then divided by the w-coordinate to produce normalized device coordinates (NDC) that fall within the range [-1, 1] in all dimensions. These NDC coordinates can be further transformed into screen coordinates using the viewport transformation. The viewport transformation maps NDC coordinates to the pixel coordinates on the screen.

- Here's the order of transformations
- 3D object coordinates (in local space) -> Model-View Matrix (M) -> Viewer's World Space.
- Viewer's World Space -> Projection Matrix (P)-> Homogeneous Clip Coordinates.
- Homogeneous Clip Coordinates -> Divide by w-coordinate -> Normalized Device Coordinates (NDC).
- Normalized Device Coordinates (NDC) -> Viewport Transformation -> 2D Screen Coordinates.

- Example
- The transformations that we can use in vector spaces are scale, translation and rotation. It's important to notice that every transformation is always relative to the origin, which makes the order we use to apply the transformations themselves very important. If we rotate 90° left and then translate we obtain something very different to what we get if we first translate and then rotate 90°.



COORDINATE SYSTEMS

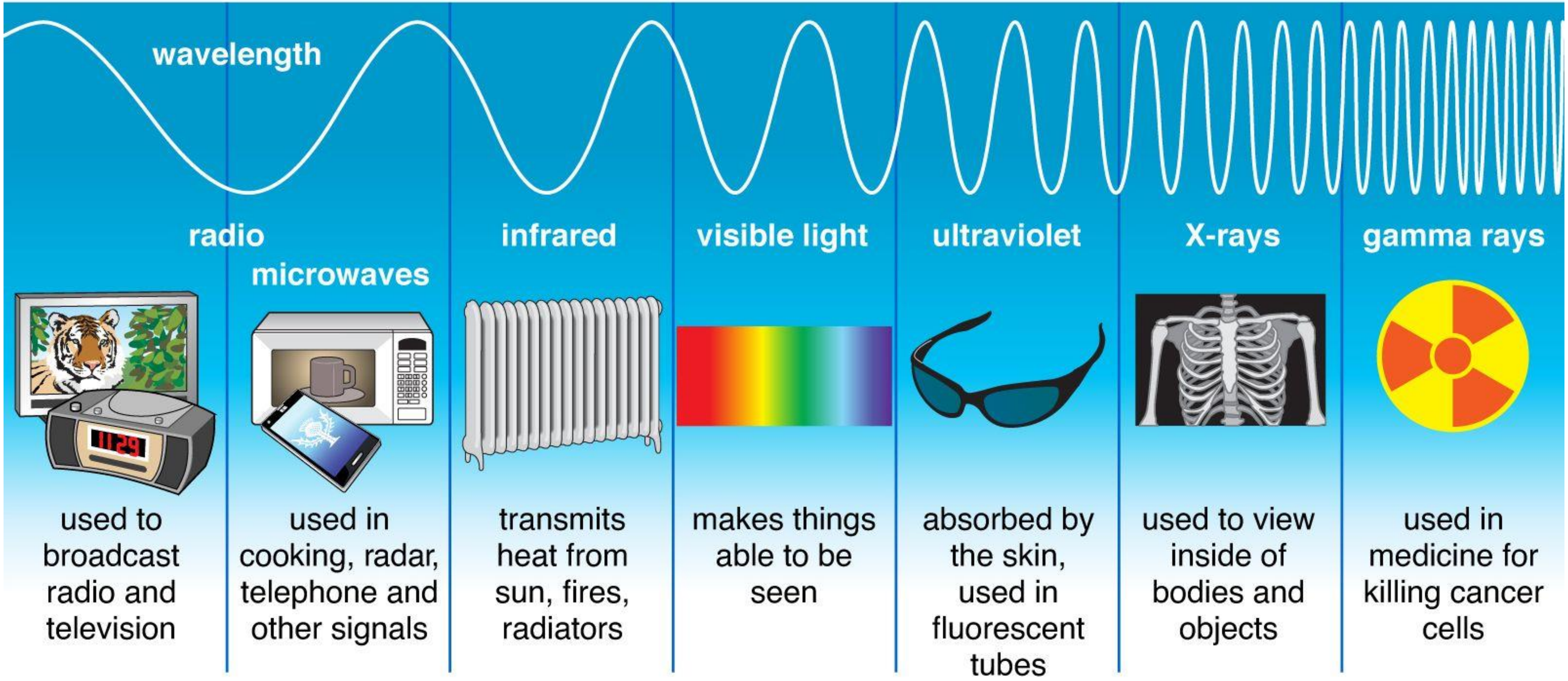
- Coordinate systems play a fundamental role in computer graphics, providing the **mathematical framework** to represent and manipulate objects and scenes in both 2D and 3D space. Understanding these concepts is crucial for tasks such as transformations, rendering, and modeling.
- **2D Cartesian coordinate system:** In 2D graphics, the Cartesian coordinate system is commonly used. It consists of two axes (X and Y) that intersect at the origin (0, 0). The X-axis typically extends to the right, and the Y-axis extends upward.
- **3D Cartesian coordinate system:** In 3D graphics, an extension of the 2D Cartesian system is used, introducing a third axis (Z). The X, Y, and Z axes are usually orthogonal to each other, forming a right-handed or left-handed coordinate system depending on the convention.
- **Homogeneous Coordinates :** Homogeneous coordinates are often employed in computer graphics to represent both 2D and 3D points. These coordinates use a four-dimensional vector (X, Y, Z, W) to simplify transformations. By dividing all box components by W, you can obtain the standard 2D or 3D coordinates.
- **Screen/Viewport Coordinates:** In 2D graphics, screen or viewport coordinates represent the final pixel positions on the display. The origin (0, 0) is often placed in the upper-left corner of the screen, with positive X extending to the right and positive Y extending downward.

LIGHT

- Light is defined as an **electromagnetic radiation**.
- The visible light that we see is only a tiny fraction of the electromagnetic spectrum, extending from very low frequency radio waves through microwaves, infrared, visible and ultraviolet light to x-rays and ultra-energetic gamma rays.
- Our eyes respond to visible light, identifying rest of the spectrum needs an arsenal of technical tools ranging from radio receivers to impressive counters.
- **Light is radiant energy**. When light is absorbed by a physical object, its energy is converted into some other form.

- For example: -
- In microwave oven, when we heats a glass of water then its microwave radiation is absorbed by the water molecules. The radiant energy of the microwaves is converted into thermal energy (heat).
- Similarly, visible light causes an electric current to flow in a photographic light meter then its radiant energy is transferred to the electrons as kinetic energy. Radiant energy (denoted as Q) is measured in **joules**.

Types of Electromagnetic Radiation



RADIOMETRY

- Radiometry is the **science of measuring radiant energy transfers**.
- Radiometric quantities have physical meaning and can be directly **measured** using proper equipment such as spectral photometers.
- Radiometry is the science of measuring light in any portion of the electromagnetic spectrum. In practice, the term is typically limited to the measurement of infrared, visible and ultraviolet light using optical instruments.
- The practice includes the scientific instruments and materials used in measuring light, including radiation thermocouples, bolometers, photodiodes, photosensitive dyes and emulsions, vacuum phototubes, charged-coupled devices and a plethora of others.

Units of radiometry

- Radiometric quantities are expressed in **radiant units** (such as watt) in general case or in **visual units** when we are only interested in the fraction of light in the visible part of the spectrum.
- Visual units are useful in many applications such as multimedia, lightning system etc.
- Table below shows radiometric quantities in Radiant and Visual units.

Quantities	Symbol	Radiant units	Visual Units
Energy	Q	Joule (J)	Joule(J)
Flux	F,P(ϕ)	Watt (W)	Lumen (lm)
Irradiance/Illuminance	E	$W.m^{-2}$	Lux
Intensity	I	$W.sr^{-1}$	Candela (cd)
Radiance/Luminance	L	$W.m^{-2}.sr^{-1}$	$Cd.m^{-2}$

Uses of Radiometry

- Following are the application areas based on Radiometry:
  - Public: Camera, Photography, TV.
  - Biomedical: Optical instrumentation, Medical imaginary.
  - Industry: Photovoltaic, Lightning, Security, Non-destructive testing.
  - Spatial: Planetary or deep space observation, Satellite design.
  - Defence: Identification, Navigation.

Radiant Energy:

- Light is **radiant energy**.
- Electromagnetic radiation (wave and particle, depends on the measurement) transport energy through space.
- When light is absorbed by physical objects, its energy is converted into some other form.
- For example, Microwave oven heats a glass of water then its microwave radiation is absorbed by the water molecules. The radiant energy of the microwaves is converted into thermal energy (heat).
- Similarly, visible light causes an electric current to flow in a photographic light meter when its radiant energy is transferred to the electrons as kinetic energy.
- Radiant energy is denoted as **Q and is measured in joules**.

Spectral Radiant Energy :

- A broadband source such as the sun emits electromagnetic radiation throughout most of the electromagnetic spectrum, from radio waves to gamma rays.
- Though, most of its radiant energy is connected within the visible portion of the spectrum.
- On the other hand, a single wavelength laser is a monochromatic source; all of its radiant energy is emitted at one specific wavelength.
- Spectral radiant energy is the amount of **radiant energy per unit wavelength interval** at wavelength λ. It is given by,
- **Spectral Radiant energy = Radiant energy/ wavelength**
- Defined as, $\mathbf{Q_\lambda = dQ/d\lambda}$
- Spectral radiant energy is measured in **joules per nanometer**.

Radiant Flux (Radiant Power):

- **Energy per unit time is power**, which we measure in joules per seconds or watts.
- Light flows through space, and so radiant power is more commonly referred to as the time rate of flow of radiant energy, or radiant flux which is denoted by ϕ.
- It is given by, **Radiant flux (power) = Radiant energy/time**
- Defined as, $\boldsymbol{\phi = dQ/ dt}$, Where, Q is radiant energy and t is time.

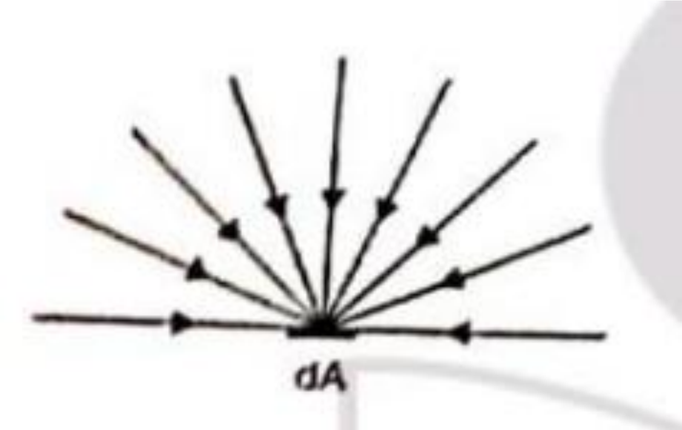
Spectral Radiant Flux

- Spectral radiant flux is **radiant flux per unit wavelength interval** at wavelength λ.
- Spectral radiant flux is denoted by ϕ_λ , it is given by,
- **Spectral Radiant flux = radiant flux/ wavelength**
- **It is measured in watts per nanometre**.

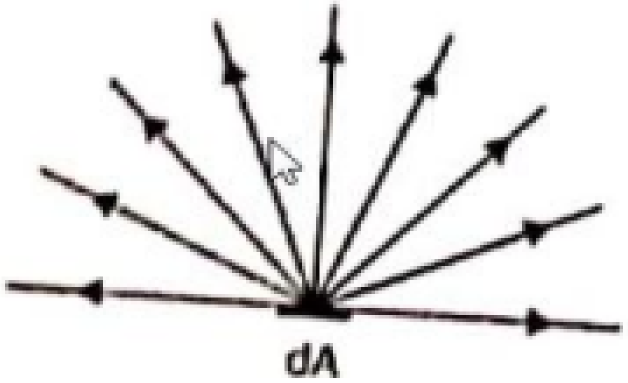
Radiant Flux Density (Irradiance And Radiant Exitance)

- Radiant flux density is **the radiant flux per unit area at a point on a surface**, where the surface can be real or imaginary (i.e. an exact plane).
- There are two possible conditions:
- **Irradiance**
- **Radiant exitance**

- **Irradiance**: The **flux can be arriving at the surface,** in which case the radiant flux density is referred to as irradiance. The flux can arrive from any direction above the surface, as indicated by the rays.
- Irradiance is defined as: **E= dϕ / dA**
- Where,
- ϕ is the radiant flux arriving at the point.
- dA is differential area surrounding the point.



- **Radiant exitance**: The flux can be **leaving the surface** due to emission and/or reflection. The radiant flux density is then referred to as radiant exitance.
- As with irradiance, the flux can leave in any direction above the surface.
- The definition of radiant exitance is: **M = dϕ/dA**
- Where,
- ϕ Is the radiant flux leaving the point.
- dA is the differential area surrounding the point



- Radiant flux density can be measured anywhere in three dimensional is the space between them (e.g. in air or a vacuum), and inside transparent media such as water and glass.
- Radiant flux density is measured in **watts per square meter**.

Spectral Radiant Flux Density

- Spectral radiant flux density is **radiant flux per unit wavelength interval** at wavelength λ.
- When the radiant flux is arriving at the surface, it is called spectral irradiance denoted by E_λ , and is defined as: $\mathbf{E_\lambda = dE/ d\,\lambda}$
- When the radiant flux is leaving the surface, it is called spectral radiant exitance denoted by M_λ , and is defined as: $\mathbf{M_\lambda = dM/d\,\lambda}$
- Spectral radiant flux density is measured in **watts per square meter per nanometer**

Radiance

- **Radiance is the radiant flux emitted, reflected, transmitted or received by a given surface, per unit solid angle per unit projected area.**
- In geometry, a solid angle is a measure of the amount of the field of view from some particular point that a given object covers.
- Where, a solid angle is the 2D angle in 3D space that an object subtends at a point.
- It is a measure of how large the object appears to an observer looking from that point. In the international system of units (SI), **a solid angle is expressed in a dimensionless unit called a steradian.**

- The radiance at that point for the same angle is represented as **$d^2 \phi /[dA(d\omega \cos \theta)]$**, or radiant flux density per unit solid angle.
- Where,
- ϕ is the radiant flux,
- dA is the differential area surrounding the point,
- $d\omega$ is the differential solid angle of the elemental cone,
- θ is the angle between the ray and the surface normal n at the point.
- Unlike radiant flux density, the definition of radiance does not distinguish between flux arriving at or leaving a surface.
- Radiance is measured inn watts per square meter per steradian.

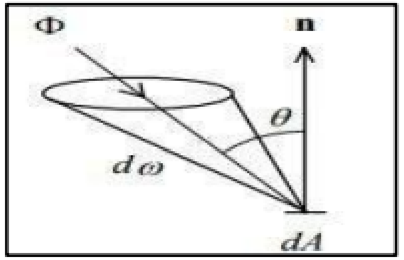


Fig. 8.4 Radiance (arriving)

Spectral Radiance

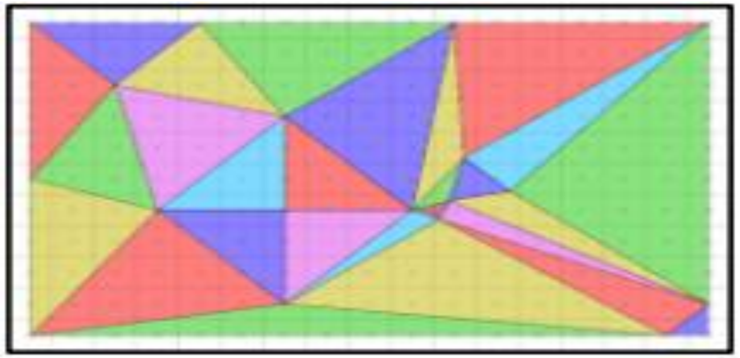
- Spectral radiance is radiance per unit wavelength interval at wavelength λ denoted by L_λ .
- It is defined as: $\mathbf{L_\lambda = d^3\phi / [dA(d\omega\cos\theta)d\lambda]}$
- And is measured in watts per square meter per steradian per nanometer.

TRANSPORT

- The **amount of light transported is measured by flux density, or luminous flux per unit area** on the point of the surface at which it is measured.
- Light transport theory deals with **the mathematics behind calculating the energy transfers between media that affect visibility.**
- Rendering converts a model into an image either by simulating a method such as light transport to get physically based photorealistic images, or by applying some kind of style as non-photorealistic rendering.
- The two basic operations in light transport are **transport** (how much light gets from one place to another) and **scattering** (how surfaces interact with light).
- Many rendering algorithms have been researched and software used for rendering are employed by using a number of different techniques to obtain a final image.
- Tracing every particle of light in a scene is nearly always completely impractical and takes more amount of time.
- Even tracing a large enough portion produce an image that takes an excessive amount of time if the sampling is not intelligently limited.

- Therefore a few families of more-efficient light transport modeling techniques have emerged and they are as follows:
  - Rasterization
  - Ray Casting
  - Ray tracing
  - Radiosity

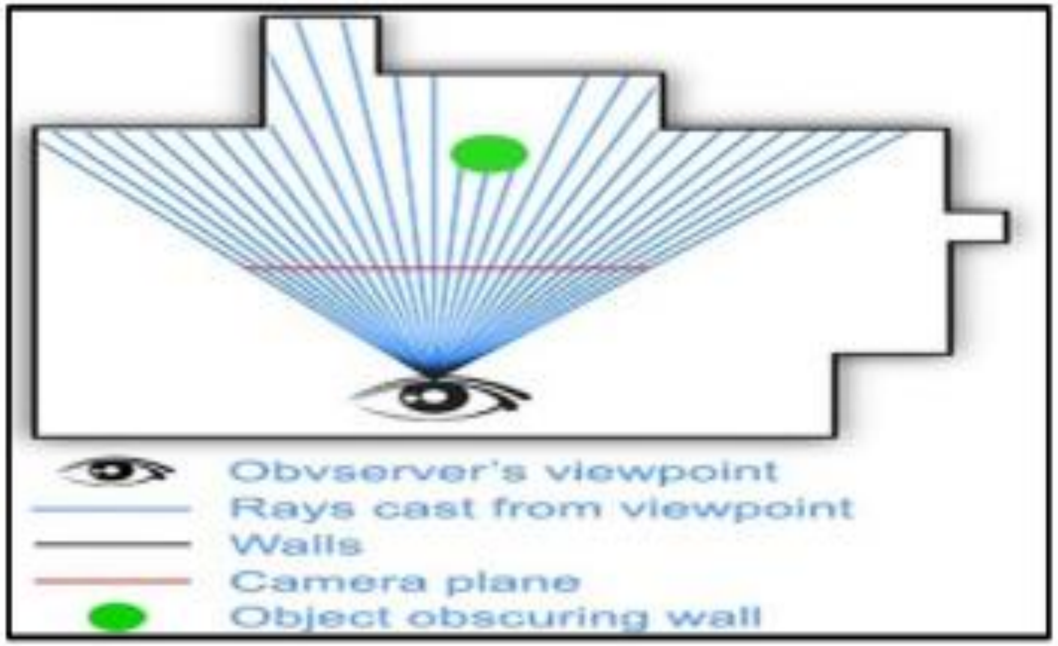
Rasterization



- It assumes an image defined in a vector graphics format (shapes) and **converting it into a raster image** (a series of pixels, dots or lines, which, when displayed together, creates image which was represented via shapes).
- The rasterized image may then be displayed on a computer display, video display or printer, or stored in a bitmap file format.
- Rasterization may refer to either the conversion of models into raster files, or the conversion of 2D rendering primitives such as polygons or line segments into a rasterized format.

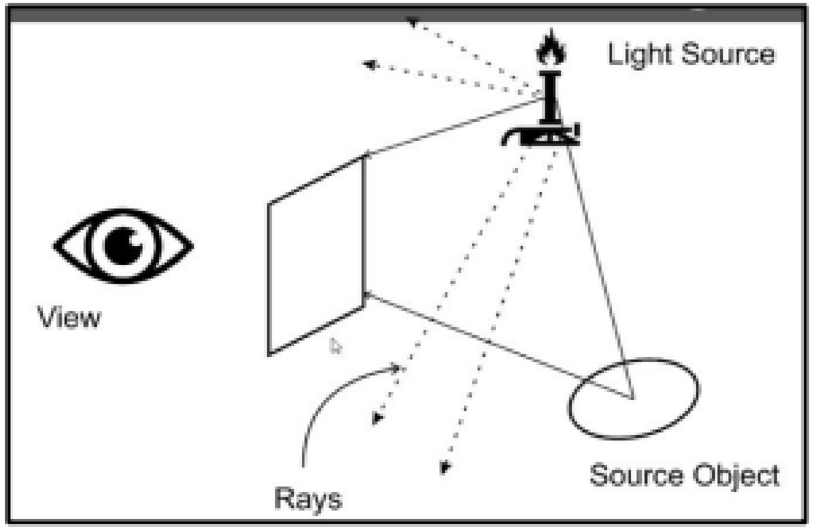
Ray Casting

- In 1982 this term was first stated in computer graphics by Scott Roth to define a technique for rendering constructive solid geometry models.
- It is a technique that alters a limited form of data into a 3Dprojection by **tracing the ray from view-point into the viewing volume**.
- Ray casting is much more simplified way than ray tracing and it can be done in real time applications.
- **Ray casting calculates a color for each pixel in the image plane by firing a ray through the view volume.**
- It considers the scene as observed from a specific point of view, calculating the observed image based only on geometry and very basic optical laws of reflection intensity.



Ray tracing

- This is similar to ray casting, but employs more progressive optical simulation, and uses Monte Carlo techniques to obtain more realistic results.
- It is a technique for generating an image by tracing the path of light through pixels in an image plane.
- They apply scan-line rendering method. But there is greater computational cost involved.
- Ray tracing is mostly used for application where image can be rendered slowly ahead of time such as in still image, film, T.V and poorly used for application like computer games where speed is critical.



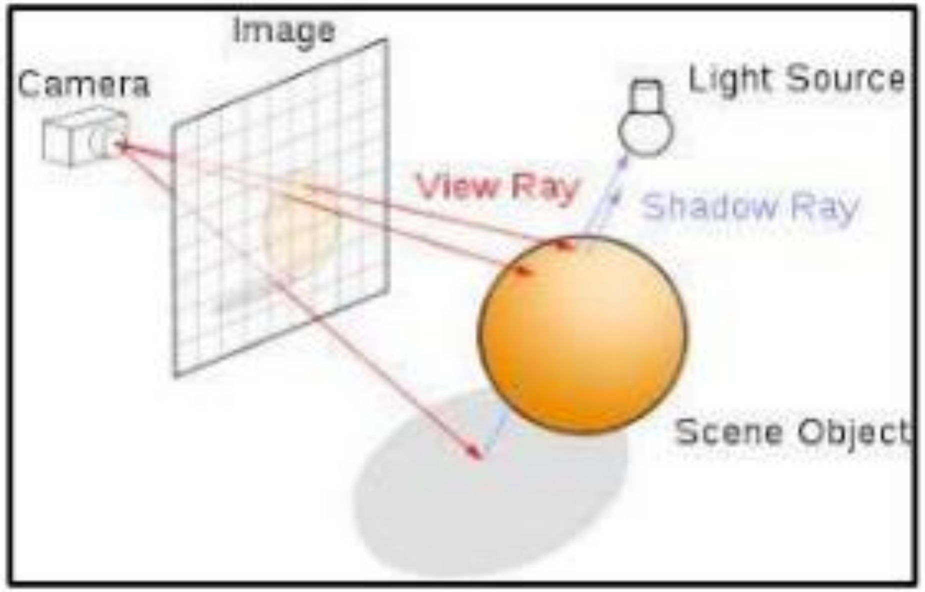
a) A ray tracing is so named because it tries to stimulate the path that light rays take as they bounce around within the world.

b) They are outlined through the scene.

c) The objective is to determine the color of each light ray that strikes the view window before reaching the eye.

d) In this method consider tracing one ray through a scene with one object as mention.

e) We start from light bulb source then we need to decide, how many rays to shoot out from the bulb, then for each ray we have to decide in what direction it is going.



f) There is infinity of directions in which it can travel, to choose one direction we are tracing a number of photons, some will reach the eye directly, other will bounce around, some and other will reach the eye and many more will never hit the eye at all.

g) For all the rays that will never reach the eye, effort for producing tracing will be of no use.

h) In order to save our wasted effort, we need to trace only those rays that are guaranteed to hit the view window and reach the eye.

i) Instead of tracing rays starting at light source we trace them backward starting at the eye.

j) Consider any point on view window whose color we are trying to determine. Its color depends on the color of light rays that pass through that point in view window and reach the eye.

k) For solving this problem we develop two rays: Original ray and backward ray.

  i) If Original ray come directly from light source, then backward ray will go directly to light source.

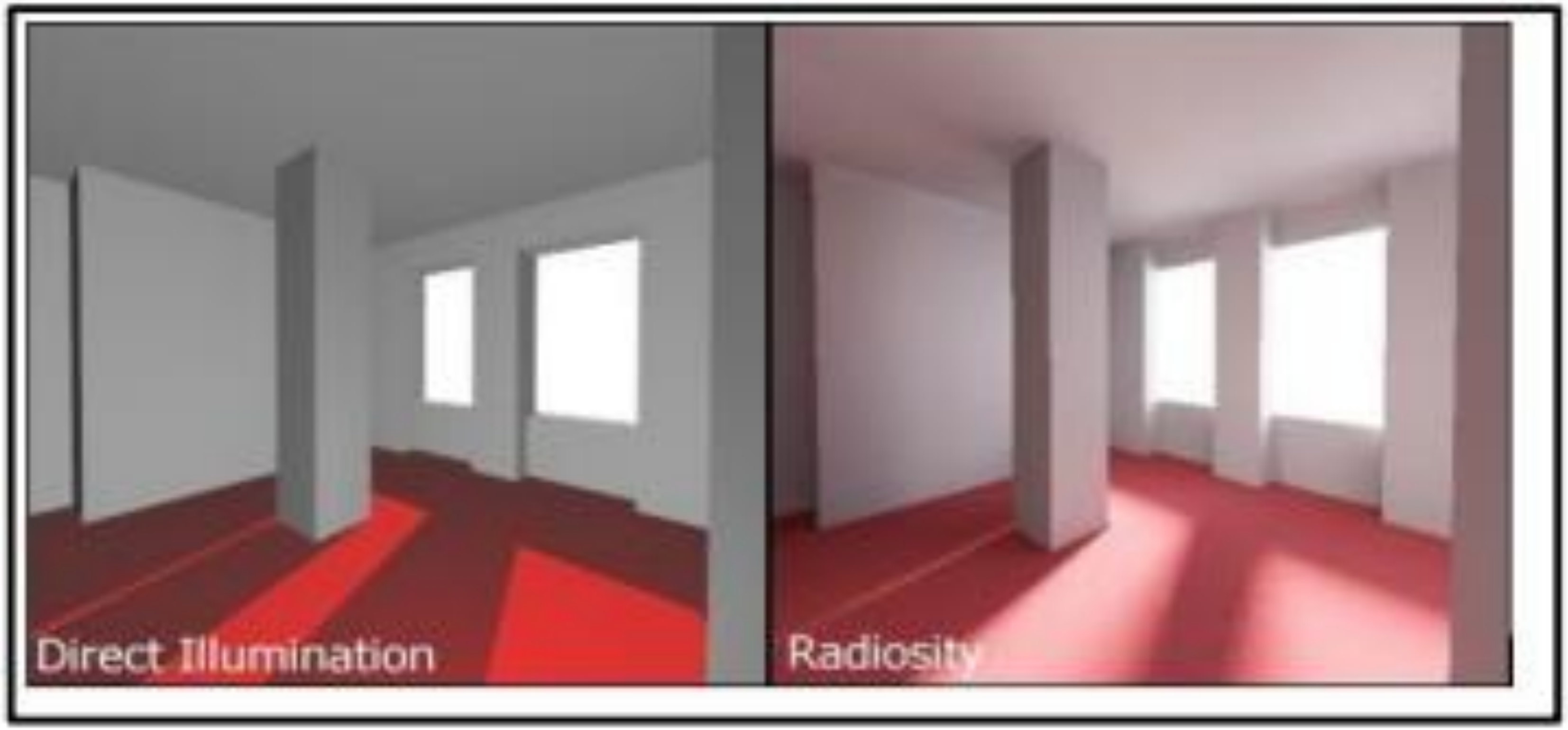
  ii) If Original ray bounce off the table first, then the backward ray will also bounce off the table.

  iii) We can clearly see this looking at the above figure again by reversing the directions of the arrow.

  iv) So backward method does same thing as the original method but it will not waste any kind of efforts for the rays that will never reach the eye

Radiosity

- The radiosity method of light interaction was developed by researchers at Cornell University and Hiroshima University, as a method for computing **radiant heat exchange between surfaces**.
- This is a method which attempts to pretend the way in which **directly illuminated surfaces act as indirect light sources** that illuminate other surfaces. This produces more realistic shading and seems to better capture the „ambience‟ of an indoor scene.
- It is a global illumination algorithm used in 3D computer graphics rendering.
- It is an application of the finite element method to solve the rendering equation for scenes with diffused surface.


Direct Illumination
Radiosity

- The image on the left was rendered with a typical direct illumination renderer.
- There are three types of lighting in this scene which have been exactly chosen and placed by the artist in an attempt to create realistic lighting:
  - Spot lighting with shadows (placed outside the window to create the light shining on the floor)
  - Ambient lighting (without which any part of the room not struck directly by a light source would be totally dark)
  - Omnidirectional lighting without shadows (to reduce the flatness of the ambient lighting).
- The image on the right was reduced using a radiosity algorithm.
- There is only one source of light: an image of the sky placed outside the window. The difference is marked. The room glows with light. Soft shadows are visible on the floor, and indirect lighting effects are visible around the room.
- Besides, the red color from the carpet has drained onto the grey walls, giving them a somewhat warm advent. None of these effects were exactly chosen or planned by the artist.

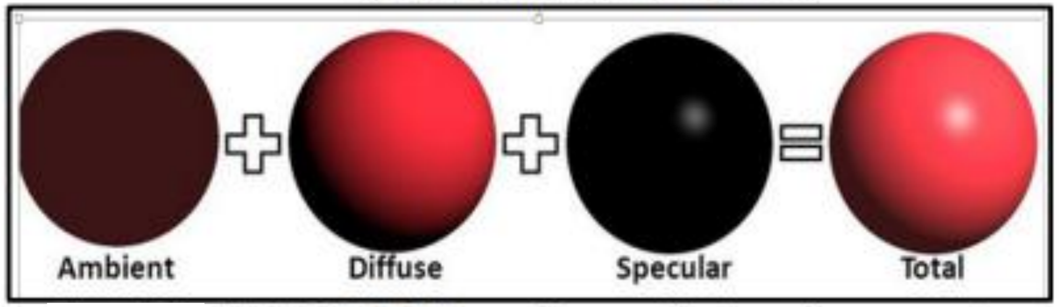
- Because of this, radiosity is a prime component of leading real-time rendering methods, and has been used from beginning-to-end to create a large number of well-known recent feature-length animated 3D-cartoon films.
- There are two types of radiosity:
  - Progressive radiosity: - It solves the system iteratively in such a way that each iteration, we can get an intermediate radiosity value for the patch.
  - Shooting radiosity: - It iteratively solves the radiosity equation by shooting the light from the patch with most error at each step.

TRANSPORT: EQUATION

- The light performance onto an object is analyzed and divided into three unique components. To actually compute the rays is too expensive to do in real-time.
- **Light at a pixel from a light = Ambient + Diffuse + Specular contributor**

$$I_{light} = I_{ambient} + I_{diffuse} + I_{specular}$$

(As given in below diagram)

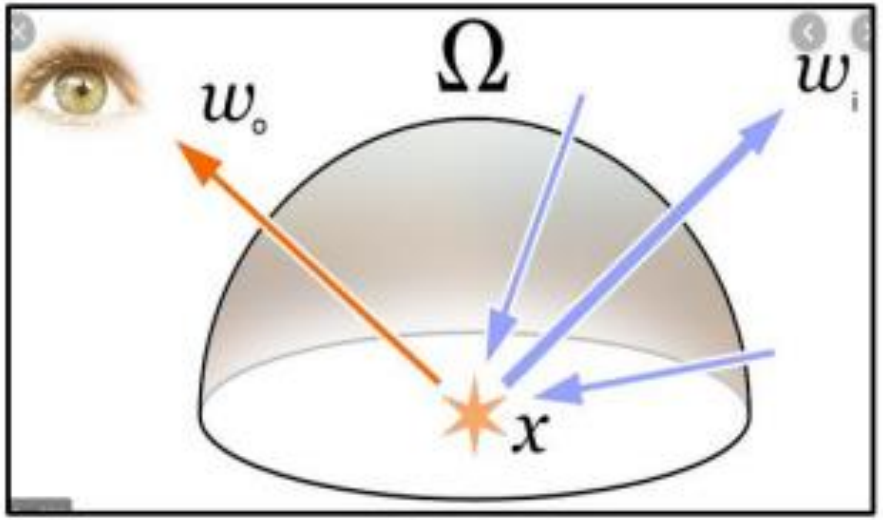


Light Model Depending on Various Components

- Most important equation for radiance can be obtained as follows:
- **Total radiance= emitted + reflected radiance**

$$L(x,\omega_0) = L_e(x,\omega_0) + \int_{\Omega+} fr(\omega_i, x, \omega_0) L_i(x,\omega_i) cos\theta_i d\omega_i$$

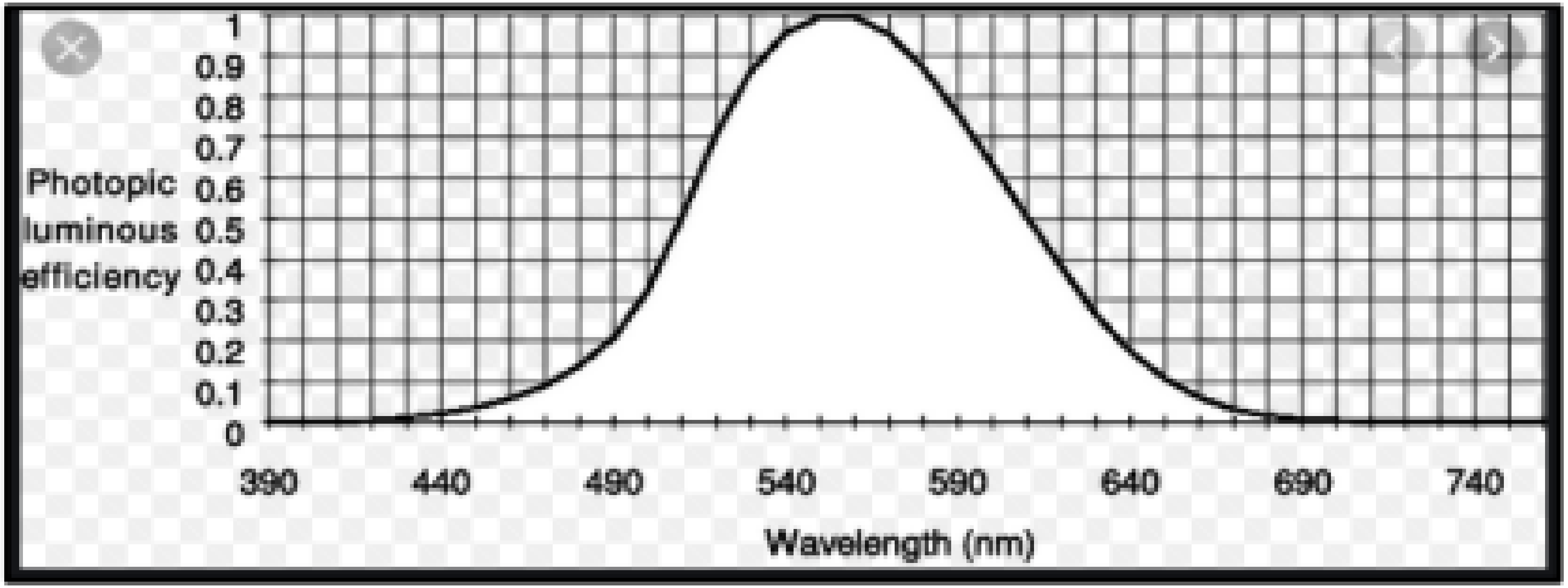
x	**Surface position**
ω_0	Outgoing direction
ω_i	Incoming illumination direction
$fr(\omega_i x, \omega_o)$	BRDF: bidirectional reflectance distribution function
$L(x,\omega_0)$	Represent total visible surface radiance



PHOTOMETRY

- Photometry is the science of **measuring visible light** in units that are biased according to the **sensitivity of the human eye**.
- It is different from radiometry, which is the **science of measurement of radiant energy** (including light) in terms of absolute power.
- **Photometry is a branch of science concerning light in terms of color apparent by the viewer from the physical inspiration of imposing photons into the eye and the combined response with the brain.**
- The purpose of photometry is to measure light in a way that takes the sensitivity of human visual system into account.
- Photometry is essential for evaluation of light sources and objects used for lighting, signaling, displays, and other applications where light is envisioned to be seen by humans.

- It is a **quantitative science based on a statistical model** of the human visual responses to light that is, our perception of light under wisely precise conditions.
- The human visual system is an amazingly **complex and highly nonlinear sensor of electromagnetic radiation** with wavelength ranging from **380 to 770 nanometers** (nm).
- Light of different wavelengths is perceived as a range of colors ranging through the visible spectrum **650 nm is red, 540 nm is green, and 450 nm is blue**, and so on.
- This task is complicated immensely by the eyes nonlinear response to light.
- It varies not only with wavelength but also with the amount of radiant flux, whether the light is constant or flickering, the spatial complexity of the scene being perceived, the alteration of the iris and retina, the psychological and physiological state of the observer, and a host of other variables.



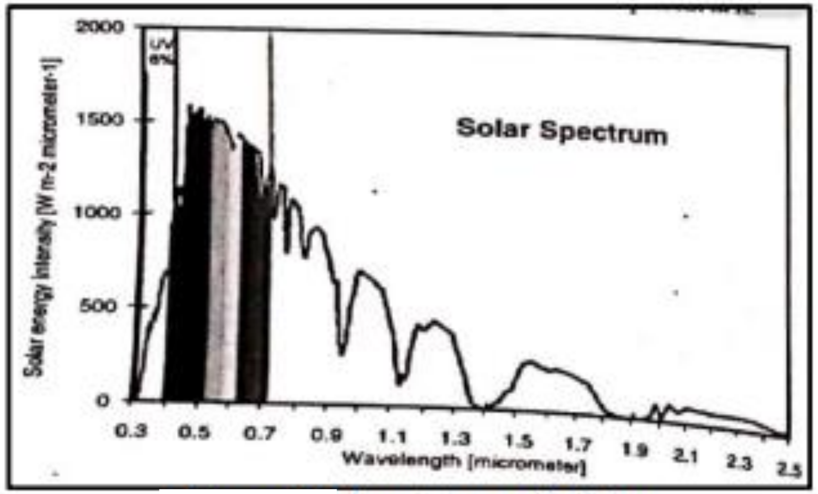
CIE photometric Curve

- In 1924, the commission Internationale d‟Eclairage (International Commission on Illumination, or CIE) enquired over one hundred observers to visually match the “brightness” of monochromatic light sources with different wavelengths under controlled conditions.
- The statistical result so called CIE photometric curve in above figure shows the photonic luminous effectiveness of the human visual system as a function of wavelength.
- It provides a **weighting function** that can be used to convert **radiometric into photometric measurements.**
- Photometric theory **does not** address how we notice colors.
- The light being measured can be monochromatic or a combination or continuum of wavelengths; the eye‟s response is determined by the CIE weighting function.
- This emphasizes a vital point: The only difference between radiometric and photometric theory is in their units of measurement.

COLOR

- It is defined as an **quality of an object or substance with respects to light reflected by an object**, usually determined visually by measurement of hue, saturation and brightness of the reflected of light.
- It is also defined as an **quality of visual insight** consisting of any arrangement of **chromatic** and **achromatic** content this attribute can be described by chromatic color names such as yellow, orange, brown, red, pink, green, blue, purple, etc., or by achromatic color names such as white, gray, black, etc., and qualified by bright dim, light, dark, etc., or by combination of such names.

- Light is a mixture of radiations having different wavelength where different wavelength implies different colors.
- Light maybe decomposed into a spectrum that is the separation of photos (light quanta) with respects to the different wavelength i.e. different colors.
- Spectrum is measured as **Watt per square meter per nanometer.**
- The spectrum is condition that has infinite numbers of independent elementary colors present in it.



Spectrum of Light

COLOR: COLORIMETRY

- Science related to the **perception of colors** is known as **Colorimetry**.
- The Science of Colorimetry is used to quantify the response of the human visual system and match human color perception for applications in a variety of industries.
  - Display Manufacturing: - Quality control for industrial production lines and incoming inspection of display glass. Display calibration for LED, LCD, Plasma, projection, CRT displays.
  - Broadcasting: - Measuring and standardizing video walls for color accuracy, uniformity of brightness and white balance.
  - Graphic Design and Computer Animation: - Professionals who rely on color accuracy and precision color measurement benefit from understanding Colorimetry.

COLORIMETRY CONCEPTS IN DISPLAY TEST AND MEASUREMENT

- Color: Color perception is naturally independent. The objective capacities of the color of a source object is alleged by a standard human observer that also can be measured.
- Various standard human observers are defined in the disciple of Colorimetry.
- According to standard model, the perceived color of a given spot can be reduced to **a three-dimensional value**. The three dimensions of color can be described as color of **brightness, hue and purity or saturation**.

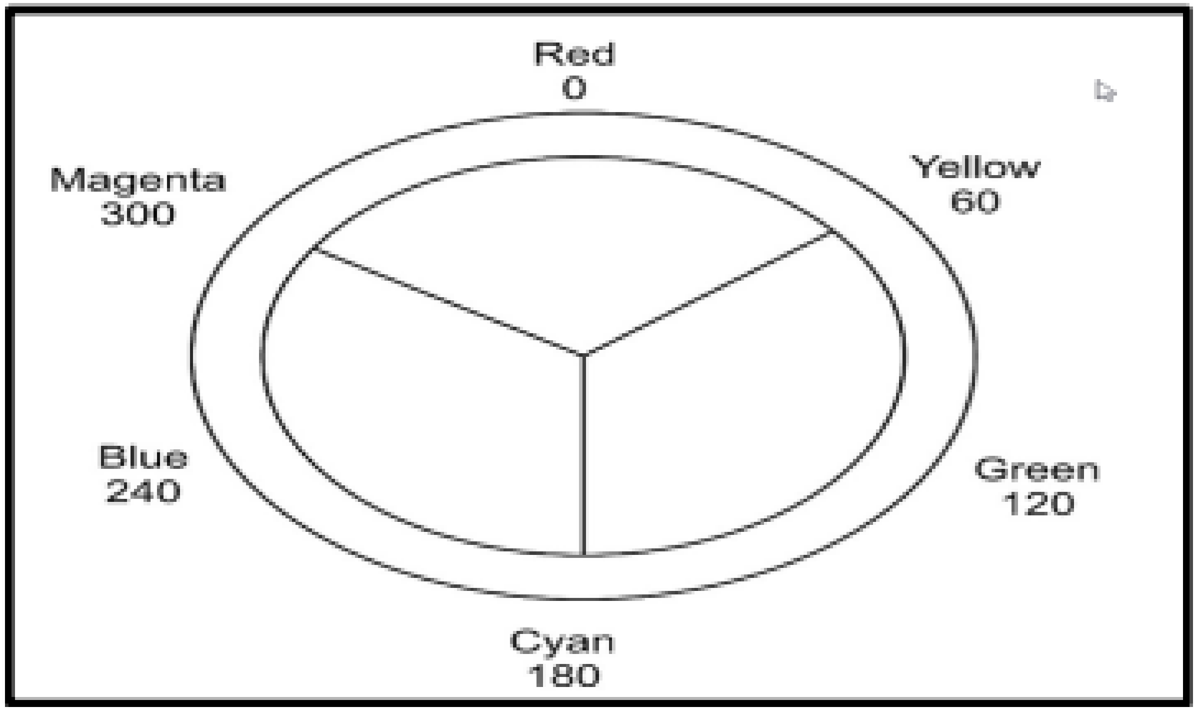
- Chromaticity: A two-dimensional explanation of color has the mixture of hue and purity, neglecting the third dimension of brightness. The luminance (brightness) and chromaticity of a spot on a display, taken together, provide a complete depiction of its color.
- Gamut mapping (RGB plotting): All colors that are produced by a display device are created by combination of Red, Green and Blue colors.
- Each display color can be described in terms of the amount of R, G and B primaries present.
- If the chromaticity directs the three primaries are plotted in a chromaticity diagram, the triangle enclosed by these points represents the full range of colors reproducible by the display. This range is the displays of **color gamut**.

- Correlated Color Temperature (CCT): This is a metric used to define the color of a white light by comparing its chromaticity to that of an idealized radiant source, known as a **black body**.
- The color of a bright source (which glows due to heat) depends upon its temperature; lower temperature sources are bluer.
- The CCT of a white light is the high temperature of the black body which almost closely matches its chromaticity.

- Dominant Wavelength and Purity: These values taken together to represent a substitute description of chromaticity.
- Dominant wavelength corresponds to hue, while purity corresponds to saturation.
- The relationship between wavelength and hue can be tacit in terms of the colors of the visible spectrum, as perceived in the rainbow: Shorter wavelengths resemble to violet and blue hues; medium wavelengths to greens and yellow; longer wavelengths to orange and red hues.

COLOR SPACES

- A range of colors that can be created by the primary colors of pigment and these colors then define a specific color space.
- It is a way to represent colors, usually used in relation to computers or graphics boards.
- Color includes levels of grey. Number of bits specifies color space. **1 bit** color is black and white combination. Grey scale pattern refers **2 bits** to generate black, dark grey, light grey, white colors.
- Color space, also known as the **color model** (or color system), is an abstract mathematical model which simply describes the range of colors as tuples of numbers, typically as 3 or 4 values or color components (e.g. RGB). It is an elaboration of the co-ordinate system and sub-space.
- Each color in the system is represented by a single dot.
- A **Color wheel** is a tool that offers a visual representation and relationships between all possible hues.
- The primary colors are arranged around a circle at equal (120 degree) intervals. Color Wheels often depict “Painter’s Colors” primary colors, which leads to a different set of hues.

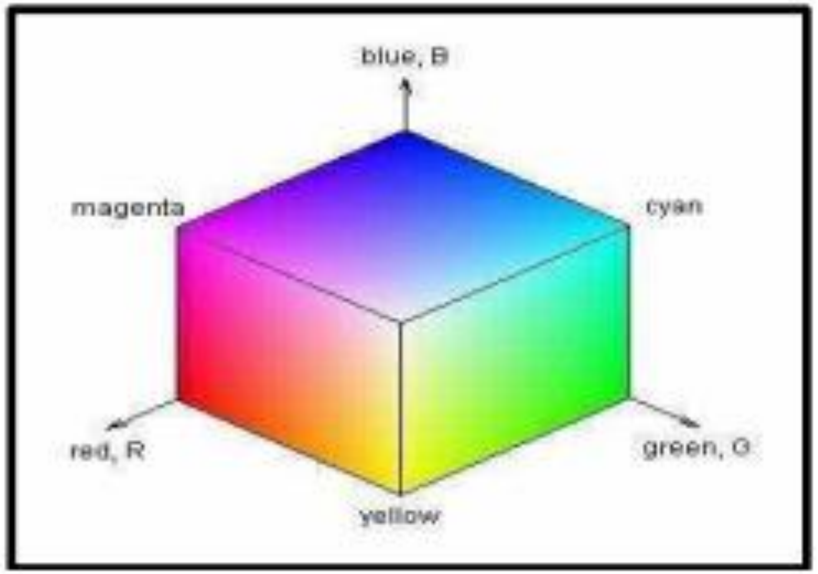


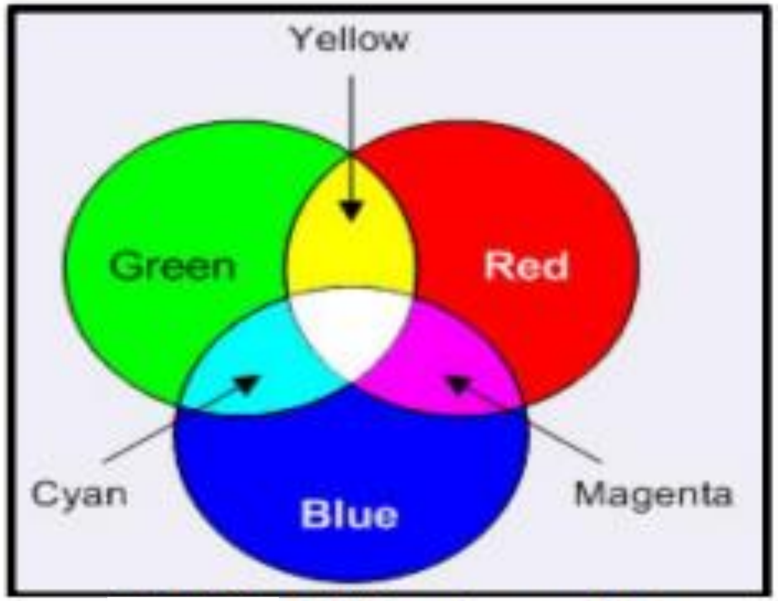
Color Wheel

- A **Color model** is an abstract mathematical model describing the way **colors can be represented as tuples of numbers**, typically as three or four values or color components.
- When this model is associated with a precise description of how the components are to be interpreted (viewing conditions, etc.), the resulting set of colors is called **color space**. This section describes ways in which human color vision can be modeled.
- There are three different color models that describes the different perceived characteristics of color are RGB model, CMY model, HSV or HLS Model.

RGB Color model:

- The RGB color model is an **additive color model** in which red, green, and blue light are added together in various ways to reproduce a broad array of colors.
- The name of the model comes from the initials of the three additive primary colors, red, green, and blue.
- The main purpose of the RGB color model is for the sensing, representation, and display of images in electronic systems, such as televisions and computers, though it has also been used in a conventional photography.
- Before the electronic age, the RGB color model already had a solid theory behind it, based on the human perception of colors.



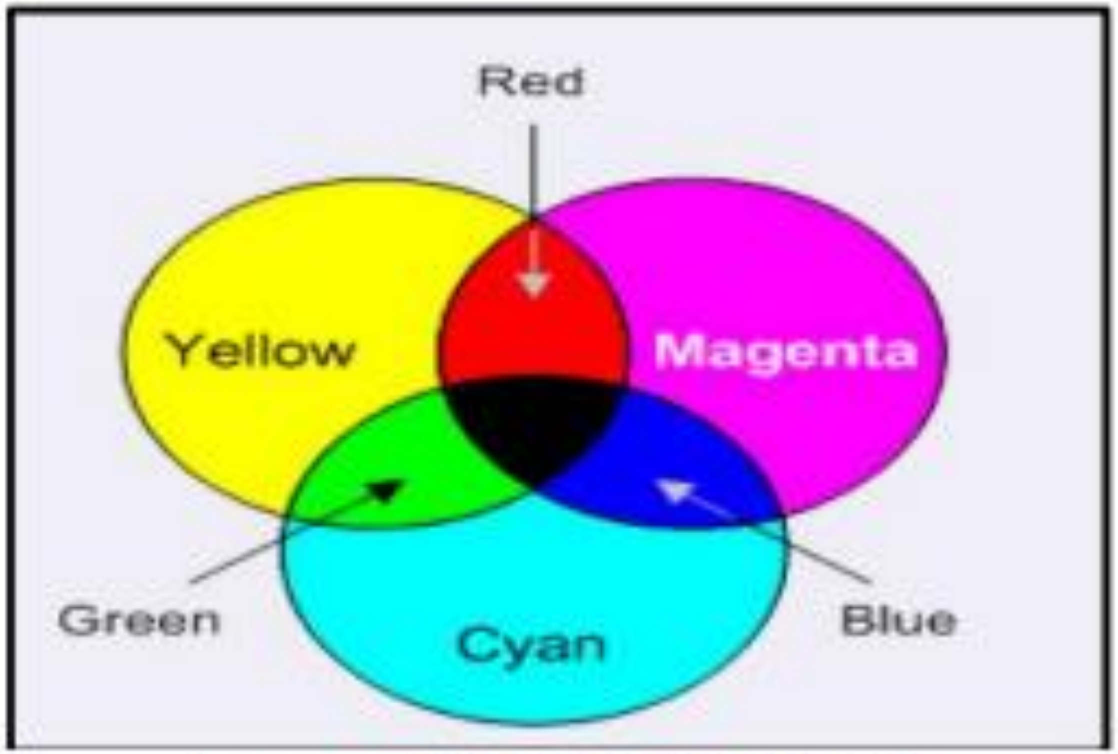


RGB color model

- In the RGB color model, we use red, green, and blue as the three primary colors.
- Black is [0,0,0], and White is [255, 255, 255].
- We **do not actually specify what wavelengths these primary colors correspond to**, so this will be different for the different types of output media, for example, different monitors, films, videotapes, and slides.
- This is an **additive model since the phosphors are emitting light**.
- A **subtractive model** would be the one in which the color is the **reflected light**.
- We can represent the RGB model by using a unit cube. Each point in the cube (or the vector where the other point is the origin) represents a specific color. This model is the best for setting the electron guns for a CRT.

CMY Color model

- CRTs produce color by the emission and use of the RGB model.
- Printers produce color by the **reflective light**, so it is a **subtractive process** and uses a model based on the colors i.e. **cyan, magenta, and yellow (CMY).**
- CMYK (short for cyan, magenta, yellow and key or black), or the process color (the four-color model) is a subtractive color model used in the color printing, also used to describe the printing process itself.
- The CMYK model works by partially or entirely masking, certain colors on the typically white background (that is absorbing particular wavelengths of light). Such a model is called subtractive because the inks subtract the brightness from white .

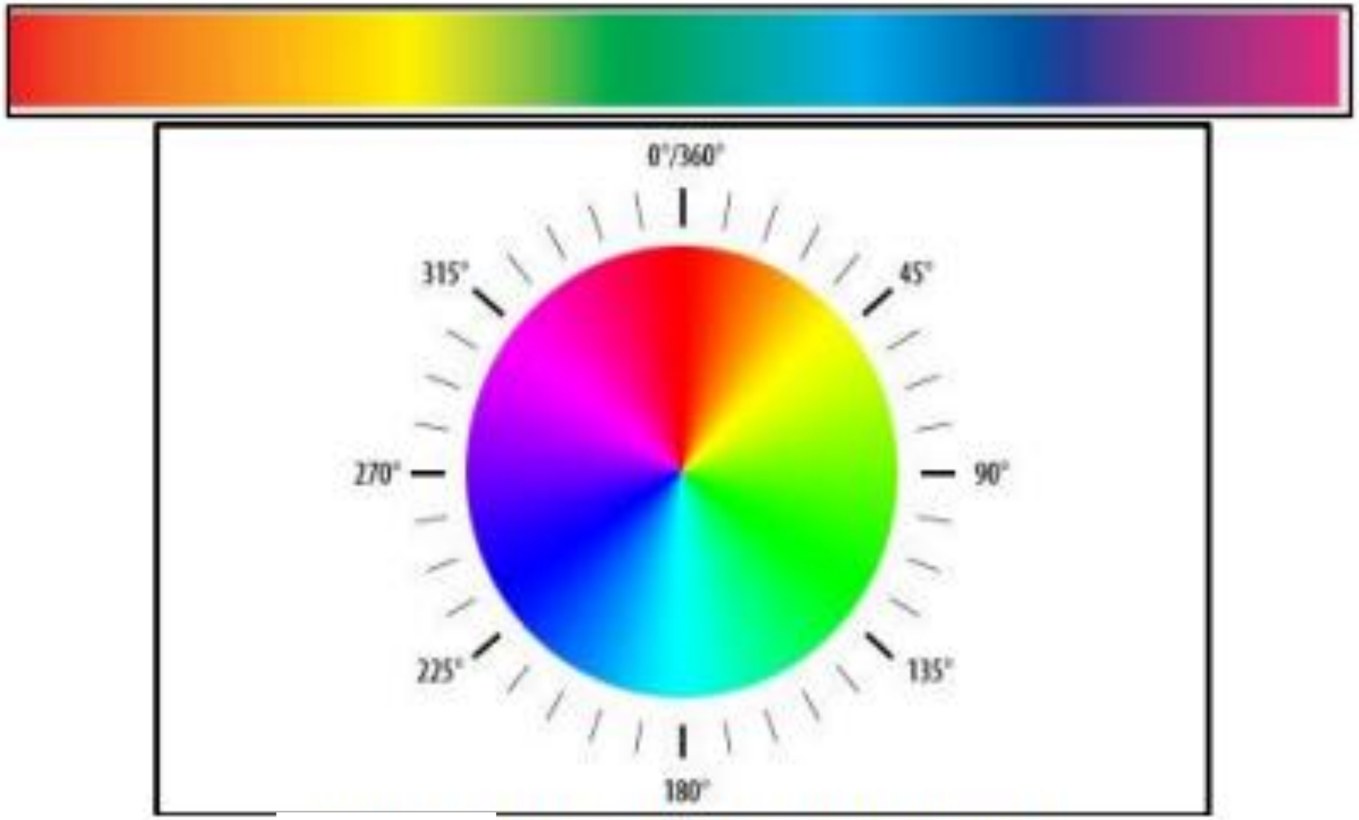


CMY color model

- Remember that cyan - green+ blue, go the light reflected from a cyan pigment has no red component, that is, red is absorbed by cyan. Similarly, magenta subtracts green, and yellow subtracts blue.
- Printers usually use four colors: cyan, yellow, magenta, and black. This is because cyan, yellow, and magenta together produce a dark grey rather than a true black.
- White is [0,0,0].
- The conversion between the RGB and CMY is easily computed as
    - Cyan-1-Red
    - Magenta-1-Green
    - Yellow 1-Blue
- The reverse mapping is similarly, obvious.
    - Red-1-Cyan
    - Green-1-Magenta
    - Blue-1-Yellow

HSL Color model

- An HSL model is based on the parameters **hue, saturation, and lightness.**
- The HSL is another way to describe a color with the three parameters. The RGB model is the way computer screens a work, but not very intuitive.
- The nicest application of this color model is that you can easily create the rainbow gradients or change the color, lightness or saturation of an image with this color model.

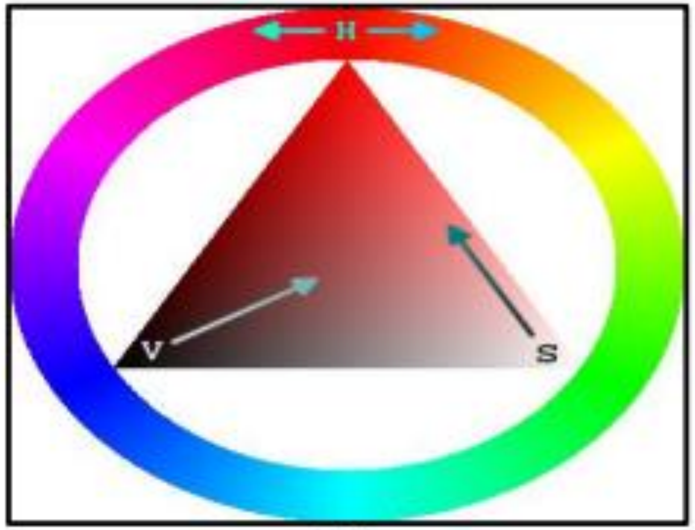


Hue in HSL Color model

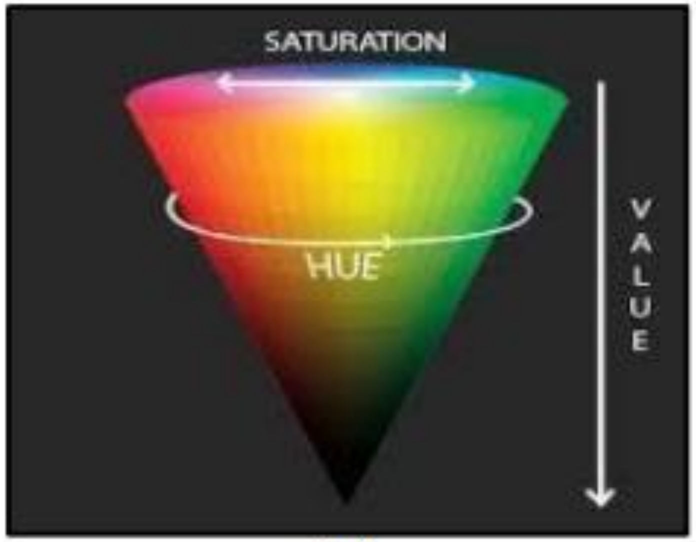
- The hue indicates the color sensation of light. In other words, if the color is red, yellow, green, cyan, blue, and magenta, this representation looks almost the same as the visible spectrum of light, except on the right is now the color magenta (the combination of red and blue), instead of violet (light with a frequency higher than blue).
- The hue works **circular**, so it can be represented on a circle instead.
- **A hue of 360° looks the same again as a hue of 0** .
- The saturation indicates the degree to which the hue differs from a neutral gray. The values run from 0 percent (which is no color) to 100 percent (which is the fullest saturation) of a given hue at a given percentage of the illumination. The more the spectrum of the light is concentrated around one wavelength, the more saturated the color will be.
- The lightness indicates the illumination of the color. At 0 percent, the color is completely black, at 50 percent, the color is pure, and at 100 percent, it becomes white.
- The HSL, color model is, for example, used in Corel Paint Shop Pro* Photo X2 color picker and other color-processing software packages.

HSV Color model

- The HSV (hue, saturation, value), also called the HSB (hue, saturation, brightness) model, defines a color space in terms of three constituent components: **hue, saturation, and value.**
- The HSV color model is more intuitive than the RGB color model.
- The user specifies a color (hue) and then adds white or black.
- Changing the **saturation** parameter corresponds to **adding or subtracting white** and changing the **value** parameter corresponds to **adding or subtracting black**.
- A 3D representation of the HSV model is derived from the RGB mode cube.
- If we look at the RGB, the cube along the gray diagonal, we can see a hexagon that is the HSV hex-cone. The hue is given by an angle about the vertical axis with red at 0°, yellow at 60°, green at 120°, cyan at 180°, blue at 240°, and magenta at 300°. Note that the complementary colors are 180° apart.



(a)



(b)

3D presentation of an HSV model
(a) Color model (b) Color cone

- Saturation S, varies between 0 and 1, is the ratio of purity of a related hue to its maximum purity at saturation equal to 1.
- Also S=0 yields the grayscale corresponding to value V of HSV that is the diagonal of the RGB cube with V=0 being black and V=1 corresponding to white.
- The HSV color wheel is used to pick the desired color. The hue is represented by a circle in the wheel.
- A separate triangle is used to represent the saturation and the value.
- The horizontal axis of the triangle indicates the value, and the vertical axis represents the saturation. When you need a particular color for your picture, first you need to pick a color from the hue (the circular region), and then from the vertical angle of the triangle, you can select the desired saturation. For brightness, you can select the desired value from the horizontal angle of the triangle.

- Sometimes, the HSV model is illustrated as a **cylindrical or conical object**.
- When it is represented as a conical object, a hue is represented by a circular part of a cone. The cone is usually represented in a 3D form. A **saturation** is calculated using the **radius of the cone**, and the **value** is the **height of the cone**. A hexagonal cone can also be used to represent an HSV model.
- The advantage of the conical model is that it is able to represent the HSV color space in a single object. Due to the 2D nature of computer interfaces, the conical model of HSV is best suited for selecting colors for computer graphics.
- The colors used in HSV can be clearly defined by the human perception that is not always the case with RGB or CMYK.
- The HSV color space is widely used to generate high-quality computer graphics. In simple terms, it is used to select different colors needed for a particular picture. An HSV color wheel is used to select the desired color.
- A user can select a particular color needed for a picture from the color wheel. It gives the color according to the human perception.

CHROMATIC ADAPTATION

- The surroundings in which viewer objects and images has a larger effect on how we perceive those objects/ the range of viewing environment (i.e., by mean of light) is very large, from sunlight to moonlight or from candle light to luminous light.
- The lightning condition is not only involving a very high range of light but also varies greatly in the range of color which emits light.
- A human visual system accommodates these change in the environment through a process called as **adaptation**.
- There are three types of adaptation:
  - Light adaptation
  - Dark adaptation
  - Chromatic adaptation

- Light Adaptation:

  1) It refers to the change occurs when we move from very dark to very light environment i.e., dark -> light

  2) When this happens we are dazzled at first by the light but soon we adapt to the new situation and then we begin to distinguish objects in our environment.

- Dark Adaptation:

  1) It refers to the change occurs when we move from very light to very dark environment i.e., light -> dark

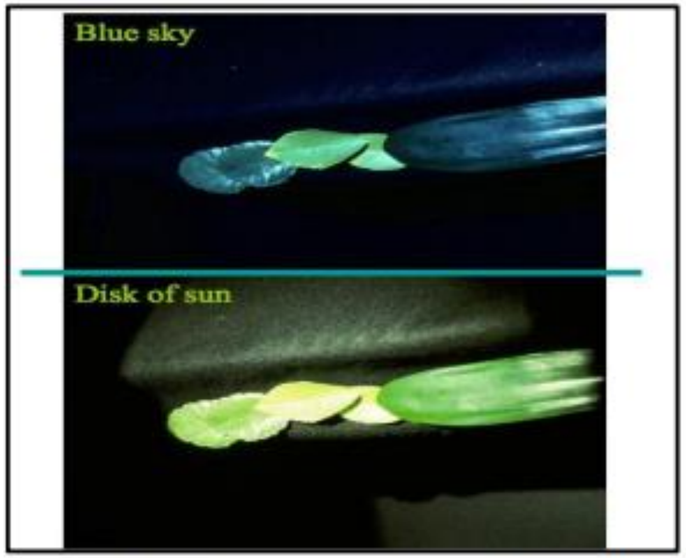
  2) When this happens we see very little at first but after some time the details of an objects starts appearing in front of us.

  3) Time needed to adapt objects in dark adaptation is much longer than that of light adaptation.

- Chromatic Adaptation:

  1) It refers to the human's ability to adjust and largely ignore differences in the color of the illumination. Although, we are able to largely ignore the changes in the viewing environment but we are unable to do it completely. For example, color appears much more colorful in a sunny day as compare to a cloudy day.

  2) **Chromatic adaptation is the ability of the human visual system to discount the color of a light source and to approximately preserve the appearance of an object.** For example, a white piece of paper appears to be white when viewed under sky light and tungsten light (light under a light bulb). However, the measured tri-stimulus values are quite different for the two viewing conditions for e.g., sky light is bluer and contains shorter wavelength energy than tungsten light which is illustrated in fig.



Chromatic adaptation under daylight and blue sky light

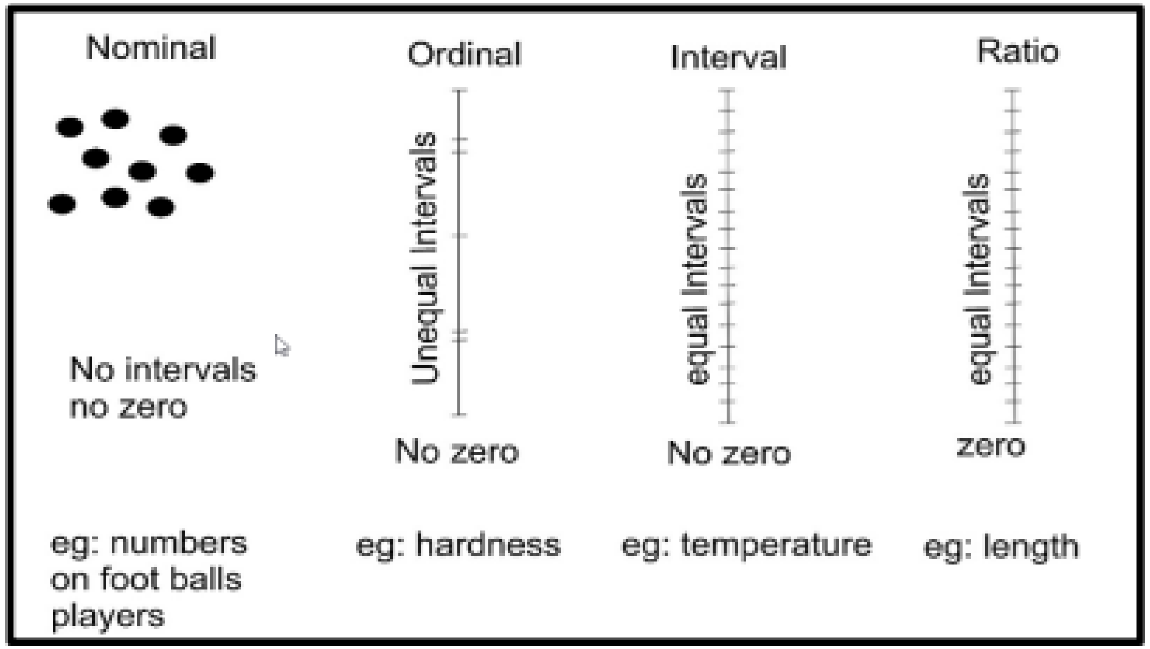
3) **Chromatic adaptation is the biological equivalent of a white balancing operation that is available on most of the modern cameras. It allows white objects to appear white for a large number of lightning conditions.**

4) Digital imaging systems, such as digital cameras and scanners, do not have the ability to adapt to the light source. Scanner usually use fluorescent light sources. For digital cameras the light source varies with the scene, and sometimes within a scene. Therefore, to achieve the same appearance of the original or original scene under different display conditions (such as a computer monitor or a light booth), the captured image **tri-stimulus values** have to be transformed to take into account the light source of the display viewing conditions such transformation are called chromatic adaptation transforms (CATs)

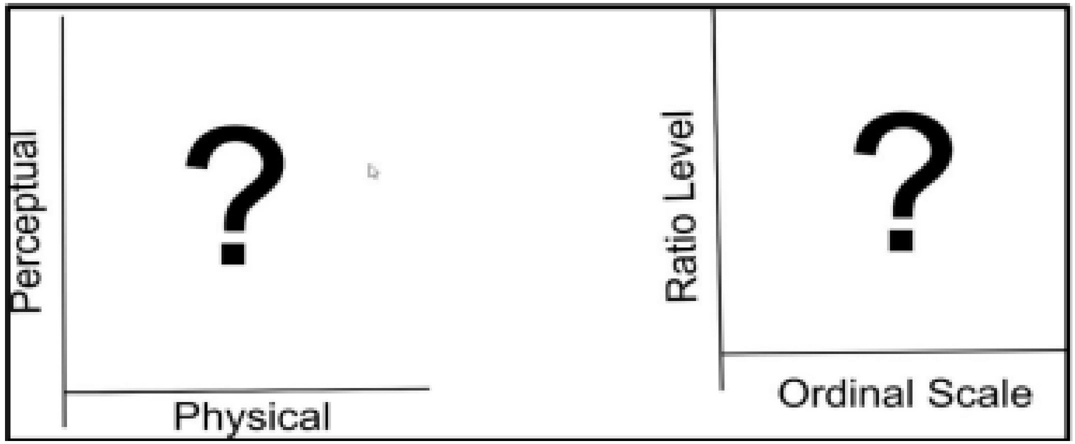
5) The adapting illumination can be measured off a white surface of a scene. In a digital image, the adapting illumination came be approximated as the maximum tri-stimulus values of the scene.

COLOR APPEARANCE

- Colorimetry allows us to precisely require and communicate color in device independent manner and chromatic adaptation allows us to predict color matches across changes in illumination but these tools are still inadequate to define how color actually look like.
- A Color appearance Model provides mathematical formulae to transform Physical measurements of the stimulus and viewing environment into Correlates of perceptual attributes of color (eg. lightness, Chroma, hue, etc.).
- Based on this colors are divide in four types, viz. Nominal, Ordinal, Interval and Ratio. Below Fig Shows this four types along with examples. This types are based on the values found after plotting as shown in the next figure below.



Stimulus Perceptual Attributes of Color



Plotting used for stimulus perceptual attributes of color

- To predict the actual perception of an object, we required to know more information about an environment. The human visual system is constantly adapting to this changing environment thus the perception of color is highly affected by such changes.
- There are different parameters used for color appearance which are given as follows:
  - HUE
  - Brightness
  - Lightness
  - Colorfulness
  - Chroma
  - Saturation

- HUE: It is an **Attribute of a visual sensation** according to which an area appears to be similar to one of the perceived colors i.e. pure color: red, yellow, green, and blue, or to a combination of two of them. Hue is a more technical definition of our **color perception** which can be used to communicate color ideas.
- Brightness: It is an **Attribute of a visual sensation** according to which an area appears to emit more or less light. It is referred to as the absolute level of the perception.
- Lightness: It is a representation of **variation in the perception of a color or color space's brightness**. It is referred to as relative brightness normalized for changes in the illumination and viewing conditions. Lightness defines a range from dark (0%) to fully illuminate (100%). Any original hue has the **average lightness level of 50%.** Lightness is the range from fully shaded to fully tinted. We can lighten or darken a color by changing its lightness value
- Colorfulness: It is an **attribute of a visual sensation** according to which the perceived color of an area seems to be more or less chromatic (e. multiple color variations).

- Chroma: Chroma is a component of a color model. There's a blue yellow and a red-green chroma component.
- Saturation: Saturation is used to determine certain color and measured as percentage value. Saturation defines a range from pure color (100%) to gray (%) at a constant lightness level.
- A pure color is fully saturated.
- A de-saturated image is said to be dull, less colorful or washed out but can also make these attributes are also unable to predict the changes in impression of being softer.
- A color appearance model (abbreviated CAM) is a mathematical model that seeks to describe the **perceptual aspects of human color vision**, i.e., viewing conditions under which the appearance of a color does not tally with the corresponding physical measurement of the stimulus source.
- In contrast, a color model defines a coordinate space to describe colors, such as the RGB and CMYK color models.
- Thus there are several mathematical models are used to improve the color appearance.