Optics for Machine Vision Practitioners

BY PERRY WEST
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This material provides an overview of basic optical phenomena, components, and measurements encountered in machine vision practice. It is intended to provide machine vision practitioners with an understanding of basic optical principals that affect their work. This material does not cover the steps and considerations in applying optical principles to the design of a machine vision system; that coverage is left to other papers.

This whitepaper is not theoretically rigorous; you can find such a treatment in most college textbooks on optical physics or other advanced references on optics. Use this material only as a supplement to such books; this is not a reference work.

A rigorous optical development includes careful sign convention. For example, magnification is negative because the image is inverted. In this work, such sign conventions are ignored for convenience.

I relied heavily on several sources for the preparation of this material. One of the most valuable resources is the material developed by Dr. Kenneth Womack. He presented talks on optical physics at the first two Lighting and Optics for Machine Vision clinics I chaired, and many illustrations used in this write-up are derived from his. Another person who has significantly influenced this work is Kevin Harding now working from his own consulting company, Optical Metrology Solutions LLC. Keven was also a presenter at several clinics I chaired. However, these individuals did not design or review this write-up, and are not responsible for its contents. A resource which I consult regularly is the book "Optics and Lasers", by Dr. Matthew Young formerly with the National Institute of Technology and Standards in Boulder, Colorado and now retired. Other valuable references include “The Photonics Handbook” and “The Photonics Dictionary” from the Laurin Publishing Company. Although no longer available in print, they are available at www.photonics.com/EDU/.

A whitepaper that deals with a technical subject, such as this one on optics, greatly benefits the reader if it includes a glossary defining the technical terms. You will find the glossary at the end of this document.
A – Absorbed energy
B – The magnitude of the blue light signal in a tristimulus signal
D – Diameter of a lens or pupil
D_i – Image distance
D_o – Object distance
D_p – Increased distance of the optical path
E – Energy, usually in joules
E – Irradiance
E – Étendue or optical throughput
F – Focal length
f – f-number
G – The magnitude of the green light signal in a tristimulus signal
H_i – Image height
H_o – Object height
I – Optical intensity
Inv – Optical invariant or Lagrange invariant
L – Luminance
M – Radiance
M_i – Image (or lateral) magnification
M_L – Longitudinal magnification
M_o – Object magnification
N – Number of absorbers per unit length
NA – Numerical aperture
Q – Optical energy
R – Reflected energy
R – The magnitude of the red light signal in a tristimulus signal
R – Airy disk radius or diffraction limit of resolution
R – Limit of resolution on the image plane
T – Thickness (e.g., of a window)
T – Transmitted energy
c – The speed of light
c_0 – The speed of light in a vacuum (299,792,458 meters/sec. or 3x10^8 meters/sec.)
d – Dispersion
d – Depth-of-field
dN – Depth-of-focus
f_w – Working f-number
f# – f-number
h – Planck’s constant (6.624 x 10^{-34} Joule second or 4.136 x 10^{-15} eV second)
i – Angle of incidence
iN – Angle of reflection
i_c – Critical angle (of incidence)
i_B – Brewster’s Angle
l – Thickness
m – Mass; usually in kilograms
n – Index of refraction
r – Fraction of light reflected
t – Fraction of light transmitted
u – Ratio of indices of refraction
u – The ordinate of the 1960 CIE chromaticity diagram
uN – The ordinate of the 1976 CIE chromaticity diagram
v – Abbe v-value
v – The abscissa of the 1960 CIE chromaticity diagram
vN – The abscissa of the 1976 CIE chromaticity diagram
x – The ordinate of the 1931 CIE chromaticity diagram
y – The abscissa of the 1931 CIE chromaticity diagram
Φ – Light flux (power)
θ – The half-angle of the acceptance cone
Ω – The solid angle of the cone with a base equal to the lens aperture and a height equal to the object distance
λ – The wavelength of light in meters
σ – The effective cross section of an absorber
ν – The frequency of light in Hz
THE NATURE OF LIGHT

This section deals with four concepts of light: as an electromagnetic field, as an electromagnetic wave, as a ray, and as a particle. These concepts provide the foundation from which to understand how light behaves and how it can be managed. Since the machine vision practitioner must provide light energy, direct it onto the scene, and then focus it into an optical image on a sensor, it is incumbent upon them to begin with a clear concept of what light is in order to be prepared to understand optical components and effects and to use this knowledge in their work.

A classic or strict definition of light is the portion of the electromagnetic spectrum that is visible, having wavelengths from 700 nm to 380 nm. Commonly, an informal and more flexible definition is accepted: light is energy with physical phenomena explained by the duality of electromagnetic waves and particles\(^1\) where the particles have the properties of photons. This extends light from far infrared, 25\(\mu\)m wavelength, to far ultraviolet, 100\(\text{nm}\) wavelength, and even to x-ray radiation.

ELECTROMAGNETIC FIELD

Early 19\(^{\text{th}}\) century physicists considered light a form of energy, likely corpuscular, that propagated in an unknown substance or frame of reference called the luminiferous aether. They knew light was energy and that it had a characteristic velocity – the speed of light. They reasoned it traveled along some straight line, called a ray, until some object affected its path. As the understanding of physics progressed, the notion of a light ray did not explain many observed phenomena such as how an incandescent lamp produces light or the spreading of a spectrum by a prism.

In 1873 James Maxwell combined mathematical equations from Gauss, Faraday, and Ampere that each described a property of electricity or magnetism and extended Ampere’s equation. This collection of equations, known as Maxwell’s equations, became a cornerstone of modern physics and led to discoveries about light, quantum physics, and relativity.\(^2\)

\[^1\] Later we will discuss that light particles, photons, are not actually physical particles. For now, though, the concept of a light particle is sufficient.

\[^2\] Fortunately for those of us in machine vision, we do not have to work with Maxwell’s equations. It is enough to appreciate their contribution and significance.
A pair of Maxwell’s equations is of particular interest in optics. One, Faraday’s law, observed that a changing magnetic field produces a changing electrical field. The other, Ampere’s law, originally stated that an electrical current produces a magnetic field. To complete his equations, Maxwell needed to extend Ampere’s law to account for the observed effect that a changing electric field produces a changing magnetic field even in the absence of current flow. Thus, a changing electric field is always accompanied by a changing magnetic field, and a changing magnetic field is always accompanied by a changing electric field.

Maxwell’s equations opened the concept of electromagnetic fields and waves. These waves only exist when both the electric and the magnetic components are varying. The two components are in phase but rotated 90 degrees with respect to each other.

Maxwell made a startling discovery from his equations. The velocity of an electromagnetic wave was equal to that for light within experimental precision. This observation led Maxwell to propose, correctly, that light was electromagnetic radiation.

A field has certain properties that can be important to understanding the behavior of light. One of these properties is that a field cannot be stopped abruptly.
Consider the consequences if energy is stopped instantaneously at a point or surface. Deceleration would be infinite; and the resulting force would be infinite. Therefore, when we consider light to stop at a surface or to reflect from a surface, it actually penetrates a short distance beyond the surface. The penetration distance is on the order of microns, and the field decays rapidly within this distance. The field that penetrates beyond the surface is called an evanescent field.

Another property is that a field is a vector sum of component fields. That is, if there are two fields each having its own orientation, the resultant field is the vector sum of these two fields. Conversely, any existing field can be decomposed into vector components that will sum to the observed field.

**ELECTROMAGNETIC WAVE**

The working model of light that emerged from Maxwell’s work is that of an electromagnetic wave. The wave represents the propagation of changes in the field. As discussed above, waves have time-varying electric and magnetic components that propagate in the same direction and are at right angles to one another. The usual convention in optical discussions and formulations is to consider only the electric wave unless the magnetic wave has some unique properties that contribute to a concept.

As an electromagnetic wave, light is part of the electromagnetic spectrum. It has a frequency and wavelength related by:

$$\lambda = \frac{c_0}{n \gamma}$$  \hspace{1cm} (1)
Where:

- \( \lambda \) is the wavelength in meters
- \( c_0 \) is the speed of light in a vacuum in meters/sec.
- \( n \) is the index of refraction (1.0 in a vacuum)
- \( \nu \) is the frequency of light in Hz

In optics used for visible light, the wavelength of light is usually expressed in nanometers \( (10^{-9} \) meter). In optics for infrared, the wavelength is usually expressed in micrometers \( (10^{-6} \) meter).

Optics is the discipline where devices and systems are engineered by modeling light as a wave. Its domain includes lenses, mirrors, and other common optical components.

**RAYS OF LIGHT**

The earliest physical concept of light as a ray is still very useful even if not theoretically correct. The use of geometrical models and ray tracing is still the most practical tool available for optical design. The ray represents the normal to the wavefront pointing in the direction of propagation.
PHOTON

The concept that light was a propagating electromagnetic field or wave explained many physical phenomena such as how a lens focuses light. However, it did not explain certain phenomena such as observations of extremely faint light showed it pulsed rather than existed in a steady state. It also did not explain the “ultraviolet catastrophe” where the light energy radiating from a heated body declined below some peak wavelength rather than continuing to increase as predicted by classical physics.
With the discovery of quantum physics – that energy exists in only discrete quanta – the notion of a photon was realized. The photon is often called a particle, but it has no mass. It is more accurate to think of a photon as a small packet of light energy.

Photons have energy as given by the formula:

\[ E = h \gamma \]  \hspace{1cm} (2)

Where:

- \( E \) is the photon energy
- \( h \) is Planck’s constant (6.624 x 10^{-34} \text{ Joule second})
- \( \gamma \) is frequency

Because wavelength is more common in optical design, the corresponding equation is:

\[ E = \frac{hc}{\lambda} \]  \hspace{1cm} (3)

Where:

- \( E \) is the photon energy
- \( h \) is Planck’s constant
- \( c \) is the speed of light
- \( \lambda \) is the wavelength of light associated with the photon
The discovery of energy quanta led to two competing schools of thought: one holding light energy is corpuscular – that is photons, and the other holding light energy is a wave phenomenon. Each side could back up their assertion. The conversion of energy to light, such as in a glowing filament, is best explained by energetic particles of light. The refraction of light, as in a lens forming an image, is best explained when light is considered a wave. Einstein settled the disagreement between wave and particle proponents by pointing out that waves and particles are different ways of representing the same phenomena – the flow of energy. Therefore, light can be a continuous wave and it can be discrete quanta, and the model that best fits the application is the one to use.

Energy conversion, whether from heat to light, electricity to light, or light to electricity, is best explained by the absorption or emission of a photon. A model based on the random emission of photons best explains most light sources. For example, an incandescent lamp filament converts its thermal energy into light energy by expelling photons. The probability of emission of a photon of some energy is dependent on the filament’s temperature and, to a lesser degree, on the filament’s physical properties.

When light, as a photon, strikes a crystalline semiconductor material and is absorbed, an electron is raised in energy and freed from its lattice bond leaving a hole. Without any other force present, the electron rejoins the hole, and the energy is released as heat. If an electric field is present, the electron and hole are pulled apart resulting in charge flow.

Photonics is that discipline where devices are designed using light modeled as a photon. Most light emitters, such as the LED, and all light detectors are part of photonics. Usually, photonics involves the conversion between light and electrical energy, and the term is a concatenation of photon and electronics. A synonymous term for photonics is optoelectronics.

**SUMMARY**

Light may be viewed strictly as visible radiation. However, a more liberal view is that light is all electromagnetic energy that can be modeled as both a wave and a particle.

Early scientists considered light as a ray of energy that traveled through the aether. Although it is now known that light is not a ray and that there is no aether, light is still commonly modeled as a ray for the design of optical components and systems.
From Maxwell’s equations, we know light is an electromagnetic field that has the properties of a propagating wave. The frequency and the wavelength of the light are inversely related by the speed of light. A field does not end abruptly; the field that exists beyond a surface is the evanescent field. Using vector addition, two fields can combine their effects, or one field can be decomposed into two fields with different directions. Optics is scientific discipline where devices and systems are engineered by considering light a wave.

Some effects of light, such as black body radiation and the conversion of light energy to electrical charge, cannot be adequately modeled by a wave. A particle theory, where light is a photon, can be used to explain these effects. The model of light as a wave and as a photon can be mathematically equated. A significant result of this relationship is that photons can only have a specific energy related to wavelength or frequency. Therefore, light energy exists only in discrete quanta. Photonics is the scientific discipline where devices and systems are engineered by considering light as a photon; especially when performing the conversion between light and electrical energy.
QUIZ

1) The most technically correct description of light is a/an:
   a) Ray
   b) Electromagnetic field
   c) Physical particle
   d) Electric wave

2) Early scientists considered light to be:
   a) Rays of energy propagating through the aether
   b) Energetic particles propagating through the aether
   c) Waves of energy propagating through the aether
   d) None of the above

3) Light being focused by a lens is best explained by considering light a/an:
   a) Ray
   b) Particle
   c) Electromagnetic wave
   d) Electromagnetic field

4) Design of an optical system is best performed by modeling light as a/an:
   a) Ray
   b) Particle
   c) Electromagnetic wave
   d) Electromagnetic field

5) The detection of light by an image sensor is best explained by considering light a/an:
   a) Ray
   b) Particle
   c) Electromagnetic wave
   d) Electromagnetic field

6) For a constant level of light energy, if the wavelength becomes shorter, the number of photons will:
   a) Increase
   b) Decrease
   c) Stay the same
   d) Depend on external forces
7) You are laying out an optical system including lighting, lenses, camera, filters, mirrors, etc. What model of light would you use?
   a) Field
   b) Wave
   c) Ray
   d) Particle

8) You are investigating the efficiency of photocells for your home. What model of light would you use?
   a) Field
   b) Wave
   c) Ray
   d) Particle

9) You are investigating the effect when two beams of light intersect. What model of light would you use?
   a) Field
   b) Wave
   c) Ray
   d) Particle
PROPERTIES OF LIGHT

At a macro level, light has many interesting characteristics. Principal among them are color or wavelength, coherence, and polarization. This section examines each of these properties and their significance to machine vision. While it might be intuitively obvious that a machine vision practitioner will need to deal with color, if the practitioner’s work goes beyond the very mundane, at some point they will also need to deal with polarization and coherence. This may come about either from the need to exploit these properties or to mitigate the effects of these properties.

COLOR

The wavelength of light, and therefore the energy of a photon, corresponds to the property of light known, at least in the visible portion of the spectrum, as color. Because the optical behavior of all materials, their reflectivity, index of refraction, opacity, as well as other properties, varies with different wavelengths of light, the wavelength becomes a key attribute of light.

When relating wavelength to color, it is important to remember color is synonymous with an attribute of visual appearance. There are colors such as brown, for which no wavelength exists: brown is a mixture of many wavelengths. In addition, in optical physics, the term light includes wavelengths encompassing infrared and ultraviolet which are not visible. For these reasons, in optical physics the term wavelength is more proper than color unless the visual appearance of something is being discussed. However, in casual discussions the term color is still commonly used as a synonym for wavelength or limited range of wavelengths.
In practice, certain portions of the electromagnetic spectrum relating to light and its "color" are given labels. The visible spectrum has wavelengths from about 380 to 700nm. Below the visible spectrum (longer wavelengths) is the near infrared (NIR) spectrum with wavelengths from 0.7 to 1,100μm. The short-wave IR (SWIR) spectrum covers from 1.1 to 3μm; the mid-IR spectrum covers from 3 to 8μm; the long-wave IR covers from 8 to 15μm; and the far IR covers from 15μm to 1,000μm.

Above the visible spectrum is the ultraviolet (UV) spectrum spanning from about 100 to 380nm. Wavelengths in the range of 300 to 380nm are sometimes called near-UV, and wavelengths between 100 and 300nm are called far-UV.

- 100 – 380 nm: Ultraviolet (UV)
  - 122 – 200nm: far UV
  - 200 – 300nm: middle UV
  - 300 – 400nm: near UV
- 390 – 720 nm: visible
- 0.7 – 1,000 μm: infrared (IR)
  - 0.7 – 1.1μm: near IR
  - 1.1 – 3 μm: short-wave IR
  - 3 – 8μm: mid IR
  - 8 – 30μm: long-wave IR
  - 30 – 1,000μm: far IR

In theory, light energy can exist at a single wavelength. In practice, perfection in this regard is very difficult to achieve. Lasers and some scientific light sources that rely on excitation of certain molecules come close. Light sources for machine vision are typically a narrow to broad range of wavelengths.

**COHERENCE**

Coherence in light is the degree to which all the light energy behaves similarly in time, in space, or both. Coherence can provide an engineer with the ability to approach the theoretical performance of optics. For example, the most valuable feature of the laser is its ability to provide light that is both temporally and spatially coherent. Coherence can also lead to unwanted effects such as interference.
**Temporal Coherence**

When all light energy is at the same wavelength, the light is temporally coherent – that is, coherent in time. Such light is also called *monochromatic*. However, the relative spatial positions of the wavefronts constituting the light energy can be unoriented with respect to each other. Temporally coherent light is composed of waves of the same frequency but with no phase relationships with respect to each other and propagating in random directions.

**Spatial Coherence**

Light is spatially coherent when the wavefront of the propagating light maintains a spatial relationship. Light from a point source is spatially coherent; the light propagates outward with wavefronts in concentric spheres.

**Incoherence**

The concept of coherent light suggests the existence of incoherent light. In fact, most light sources, lasers being an exception, produce incoherent light. The light energy is comprised of a continuous unrelated stream of photons or wave packets. Each photon has an individual energy level (wavelength) and an individual direction of travel.
POLARIZATION

Since light is a propagating wave, there are two directions associated with it. One is its direction of travel. The other is its direction of oscillation that is in a plane perpendicular to the direction of propagation. The light’s polarization is the pattern it makes when passing through the plane of polarization.

For easy reference, visualize an X-Y-Z frame of reference. By usual optical convention, the Z axis is in the direction that light is propagating. The X axis will be in the plane polarization in the direction of preferred polarization, and the Y axis will be in the plane of polarization perpendicular to the direction of preferred polarization.

Unpolarized light consists of a collection of waves each of which has an independent orientation in the plane of polarization.

Most light is unpolarized. That is, it consists of a very large number of independent wave packets, each having an independent frequency and an independent orientation in X and Y. Such light is **unpolarized** because there is no preferred direction of polarization. Unpolarized light can be transformed into polarized light by means of a polarizer (see page 100).
**Linear Polarization**

When the pattern of the light waves on the plane of polarization is a group of straight, parallel lines, the light is linearly polarized. This is independent of the angular orientation of the group of lines. If an observer could see a linearly polarized light wave coming toward them, it would appear as a line. If there were a group of waves, all oscillating in the same direction, the observer would see a field of parallel lines. Light with all component waves oscillating in the same direction is *linearly polarized*.

Consider this question. Let a perfect polarizer be one that transmits light of one and only one linear polarization. If such a polarizer is placed in the path of unpolarized light, does the light transmitted through the polarizer consist of only those waves that were incident in the direction of preferred polarization? If so, only a negligible fraction of the light would be transmitted because only a negligible fraction of the waves has the correct orientation out of the possible range of orientations. Such a polarizer would be useless.

An actual polarizer transmits closer to 50% of the unpolarized light energy because it transmits the light as a function of the wave orientation. For example, the polarizer transmits 100% of the light in the preferred polarization, 0% of the light with an orientation at 90 degrees to the preferred polarization, and 70.7% of the light with an orientation 45 degrees to the preferred polarization.
Some arbitrarily chosen wave will not likely oscillate exactly parallel to either the X or Y axes. However, the direction of oscillation can be decomposed into vector components one of which is parallel to the X axis and the other is parallel to the Y axis. That component of the wave in the X direction, the preferred polarization direction, will be transmitted by the polarizer while the component of the wave parallel to the Y axis will be blocked.

So, light oriented at 45 degrees to the direction of polarization has two components; one parallel to the X axis with an amplitude of 70.7% and the other component parallel to the Y axis also with an amplitude of 70.7%. The component parallel to the X axis is transmitted, but the component parallel to the Y axis is blocked.

**Circular and Elliptical Polarization**

We have considered that any periodic wave can be expressed as the sum of other waves with the same frequency. That is, we have considered that a light wave can be represented as the sum of two other light waves of the same frequency and phase but differing in amplitude and orientation around the Z axis. To be truly general, it is necessary to consider the case where the two component waves also differ in phase along the Z axis.

To illustrate, consider a light wave decomposed into equal magnitude components parallel to the X & Y axes. For linearly polarized light, say at 45 degrees, the two components are in phase along the Z axis. However, there is no reason why the two components necessarily must be in phase. Consider adding two waves of equal magnitude. One is parallel to the X axis and the other parallel to the Y axis, but the two waves differ in phase by 90 degrees. The result is a wave when viewed in the direction of propagation that describes a circle. In three dimensions, it has the shape of a helix. Such a light wave is *circularly polarized light*.

By changes in the relative phase angles or magnitudes of the two components, a wave can be constructed which appears as an ellipse in the direction of propagation. This wave is *elliptically polarized*.
SUMMARY

Three properties of light are its color or wavelength, its degree of coherence, and its degree of polarization.

Color, as a property of light, relates to wavelength. The principal spectral regions for machine vision application are long-wave IR (8 to 30μm), mid IR (3 to 8μm), short-wave IR (1.1 to 3μm), near IR (0.7 to 1.1μm), visible (380 to 700nm), near UV (300 to 380nm), mid UV (200 to 300nm), and far UV (100 to 200nm).

Optical properties of materials are a function of the wavelength of light.

The degree of temporal coherence is the how closely all light energy has the same wavelength or frequency. The degree of spatial coherence is how well a wavefront is preserved as the light energy propagates. Incoherent light is light that has very little or no temporal or spatial coherence.

Linearly polarized light is light in which the electric (or magnetic) component of the field of all the waves is oscillating in one direction perpendicular to the direction of light propagation. As a wave of linearly polarized light passes normal through a plane, its electric field vector will trace a straight line on the plane.

Circularly polarized light is light in which the electric (or magnetic) component of the field is oscillating in a circle. Such light can be decomposed into two linearly polarized components of equal amplitude that differ in phase by 90 degrees. Elliptically polarized light is similar to circularly polarized light except if it is decomposed into two equal amplitude linearly polarized components, the phase difference will not be 90 degrees or if the light is decomposed into two linearly polarized components that are 90 degrees out of phase, their amplitudes will not be equal.
QUIZ

1) Which of the following is NOT a property of light?
   a) Color
   b) Coherence
   c) Polarization
   d) Direction

2) Temporal coherence is the degree to which light waves:
   a) Are in temporary agreement
   b) Propagate in the same direction
   c) Have the same frequency
   d) Have the same polarization

3) Spatial coherence is the degree to which light waves:
   a) Are evenly spaced
   b) Fill all space
   c) Maintain wavefronts as they propagate
   d) Have the same polarization

4) Linear polarization is:
   a) When all photons are traveling in a straight line
   b) When all wave vibrations are in the direction of wave propagation
   c) When all wave vibrations are in the same direction normal to the direction of propagation
   d) None of the above

5) Circular polarization requires:
   a) A light wave with equal components vibrating orthogonal to each other
   b) A light wave with equal components 90 degrees out of phase
   c) Both a and b
   d) Neither a or b

6) How would you describe the color of light coming from an incandescent lamp?
   a) Monochromatic (principally one wavelength)
   b) Narrow band of wavelengths
   c) A series of wavelengths (multiple wavelength peaks)
   d) A continuum of wavelengths over most of the visible spectrum
7) How would you describe the coherence of light coming from an incandescent lamp?
   a) Incoherent
   b) Spatially but not temporally coherent
   c) Temporally but not spatially coherent
   d) Both temporally and spatially coherent
8) How would you describe the polarization of light coming from an incandescent lamp?
   a) Linearly polarized
   b) Circularly polarized
   c) Unpolarized
   d) None of the above

9) How would you describe the color of light coming from a laser?
   a) Monochromatic (principally one wavelength)
   b) Narrow band of wavelengths
   c) A series of wavelengths (multiple wavelength peaks)
   d) A continuum of wavelengths over most of the visible spectrum

10) How would you describe the coherence of light coming from a laser?
    a) Incoherent
    b) Spatially but not temporally coherent
    c) Temporally but not spatially coherent
    d) Both temporally and spatially coherent

11) How would you describe the polarization of light coming from a laser?
    a) Linearly polarized
    b) Circularly polarized
    c) Unpolarized
    d) None of the above
OPTICAL EFFECTS

Conservation of energy requires accounting for all light energy incident on some point in space, say the surface of an object. There are three fundamental effects light can undergo when it strikes a surface: reflection, absorption, and transmission. This section explores each of these affects and the different ways they can occur.

A machine vision practitioner needs careful understanding of each of these affects. They are the primary determinant of objects' appearance in the image.

The three effects are often summarized in what is called the “RAT” formula:

\[ E = R + A + T \]  

(4)

Where:

- \( E \) is the total incident light energy
- \( R \) is the total reflected energy
- \( A \) is the total absorbed energy
- \( T \) is the total transmitted energy

Each of these processes of transmission, reflection, and absorption is complex. They depend on the wavelength of light, angle of incidence, polarization, as well as the properties of the material(s) involved.

Two other effects of light are diffraction and interference. These affects also impact machine vision systems.

Ultimately, in their system design, the machine vision practitioner must manage the effects of light.

REFLECTION

Any time light energy is incident at the interface of two materials and is deviated, but continues to propagate in the original material, the light has been reflected. For example, say light energy is travelling in air and comes to an interface between air and some other surface such as metal or plastic. If the light is deviated so that it continues to travel in air, then it has been reflected.
Specular Reflection

Light energy that reflects from the interface of two materials such that the continuity of the wavefront is preserved (i.e. there is a one-to-one correspondence between an incident and reflected ray) is said to be **specular**. For a ray, the angle of reflection equals the angle of incidence where the angles are measured from the surface normal. Reflection off a mirror is the most widely known example of specular reflection.

The plane formed by the incident and reflected ray is the **plane of reflection**.

Diffuse Reflection

Many objects do not reflect all or even some light specularly, but rather scatter some or most of the light over a range of directions. Such surfaces are **diffuse reflectors**. Diffuse reflection is often characterized by its spread angle: the angle between where the light energy is 50% of the peak diffusely reflected light energy. The spread angle will change for different angles of incidence. Normally the spread angle is the same regardless of the rotation of the surface. Such a surface is isotropic. Some materials such as rolled metal that has a very fine grain structure will have a reflectance characteristic that is dependent on the rotation of the material. Such materials are anisotropic. The presence of anisotropy is usually due to some form of surface texture. However, it can be caused by the structure of the material such with fabrics or composite materials (e.g., fiberglass).

The most effective model for this reflection is to consider the surface made up of a sheet of broken mirror shards each of which is microscopically small. Such a model is called the facet model.
Because of the effects of Fresnel reflection (covered later starting at page 30) on polarization and because diffusely reflected light may be reflected many times off the surface, when polarized light is diffusely reflected it becomes either partially or wholly unpolarized.

**ABSORPTION**

Conservation of energy requires light energy absorbed by a material to be converted to some other form or forms of energy: heat, mechanical, electrical, chemical, or other wavelengths of light.

The most common conversion of absorbed light is to heat energy. Usually the energy of the light absorbed is so small we cannot sense the increase of temperature of the material absorbing the energy. However, in the presence of a very intense light source, an object can absorb sufficient energy to become very hot.

Light can be used to generate mechanical energy. An example of this is photo-induced acoustic waves. Engineers use a pulse of energy from a laser to induce acoustic waves (mechanical vibrations) in materials.

The detectors used in image sensors depend on the conversion of light to electrical charge.

Photography depends on the conversion of light energy to chemical energy. When light strikes the silver-halide grains in the emulsion of a film, it causes a chemical change making the grains remain on the film after development. This chemical change is what makes photography possible.

Absorption is commonly a function of the light wavelength. For example, a black surface appears to absorb most light energy. However, some black materials reflect substantial energy in the infrared region. Metals appear to reflect most light, but they tend to absorb much of the ultraviolet light. We consider air a transmissive media for light, yet it has significant absorption bands in the infrared.
Lambert expressed absorption in the equation:

\[ T = E e^{-N\sigma l} \]  

(5)

Where:

- \( E \) is the initial incident light energy
- \( N \) is the total number of absorbers per unit length
- \( \sigma \) is the effective cross section of an absorber
- \( l \) is the thickness of the material
- \( T \) is the transmitted light energy

Surface texture effects the amount of light absorbed as a percentage of the incident light, mainly because it affects the percentages reflected and transmitted. Generally, a rough surface absorbs more light than a smooth polished surface. This is because a portion of the light energy is absorbed each time light strikes the surface. For a rough surface, the light often reflects off several facets before leaving the surface. At each reflection, the surface absorbs another fraction of the light that strikes it.

**Fluorescence**

When a photon of light is absorbed, it increases an electron’s energy state from a nominally stable condition to a higher energy level that is less stable. The electrons seek to return to a stable position in the atomic structure. As the electron falls back into the stable state, it releases the excess energy.

For some materials, the energy released by the electron is itself a photon. The energy of the photon, and therefore its wavelength, is dependent on the change of energy of the electron. Because this energy change is a predictable property of the material, the emitted light wavelength is nearly monochromatic. Materials that reemit absorbed light energy as light energy as said to fluoresce.
TRANSMISSION

Whenever light energy enters a material and emerges from that material, the light is transmitted. A material may transmit the light either directly or diffusely.

Transmittance of light through a vacuum is independent of the frequency of the light. In all materials, transmittance, if any, is a function of the wavelength of the light being transmitted. Common glass, for example, transmits visible light with little attenuation, yet it is nearly opaque to ultraviolet light. Germanium, which is a gray crystalline material, is opaque to visible light, yet it is a popular material for making lenses in the mid-IR and far-IR ranges.

Direct Transmission

When a ray of light passes into or through a material and is preserved as a single ray, it is direct transmission. The ray thus transmitted may or may not be traveling along the original path. Since the ray is a normal to the light wavefront, direct transmission preserves the wavefront integrity; although, the direction and shape of the wavefront may be altered. Light passing through a window or a lens is an example of direct transmission.
**Refraction**

If the path of light was unaffected when it was directly transmitted from one material to another, the optical effects of the materials, except transmittance, could be ignored. However, this is not the case. The velocity of light differs from material to material. The quantity that characterizes this change is the *index of refraction*. The velocity of light is given by:

\[
c = \frac{c_0}{n}
\]

Where:
- \( c \) is the velocity of light in the material
- \( c_0 \) is the velocity of light in a vacuum
- \( n \) is the index of refraction in the material

The speed of light is a maximum in vacuum; the index of refraction of vacuum is 1. In all other materials, the speed of light is lower than in a vacuum, and the index of refraction is greater than 1.

It follows, if the speed of light changes in a medium, either the frequency or wavelength must change. Conservation of energy requires the energy of a photon remain constant when entering or leaving a material. Therefore, the frequency of the light wave stays constant, and the wavelength changes. The wavelength is given by:

\[
\lambda = \frac{c_0}{n \gamma}
\]
Where:

\( \lambda \) is the wavelength
\( c_0 \) is the speed of light in a vacuum
\( n \) is the index of refraction of the material
\( \nu \) is the frequency of light

The effect of this change in velocity when a light ray enters a material is the change in direction of the ray. Snell’s law gives the amount of change:

\[
n \sin(\phi) = n' \sin(\phi') \tag{8}
\]

Where:

\( n \) is the index of refraction of the first material
\( \phi \) is the angle of incidence measured from the normal to the surface
\( n' \) is the index of refraction of the second material
\( \phi' \) is the angle of propagation measured from the surface normal

This change in direction is **refraction**. Refraction is the principle that makes lenses work.

**Total Internal Reflection**

Consider a light ray passing from a medium with a high index of refraction to a medium with a lower index of refraction. In this case \( n > n' \); and then:

\[
\sin(\phi) = \frac{n'}{n} \sin(\phi') \tag{9}
\]

In this case, \( \phi < \phi' \). Therefore, \( \phi < 90^\circ \) when \( \phi' = 90^\circ \). This is the critical angle given by:

\[
\sin(\phi_c) = \frac{n'}{n} \tag{10}
\]
When $\phi > \phi_c$, then there is no refraction, the light is reflected off the surface back into the material – total internal reflection. Total internal reflection is a useful optical tool. It is the basis for using prisms to reflect light.

Prisms are often used as reflectors in optical systems. They have the advantage of being rugged and relatively easy to manufacturer. A minor disadvantage to prisms as reflectors is the small amount of light reflected from the entrance and exit surfaces.

**Dispersion**

The index of refraction in a material is not constant and varies as a function of the frequency of light. Although the variation is nonlinear, one common measure of dispersion of optical glass is the Abbe $v$-value:

$$v = \frac{n_D - 1}{n_F - n_C}$$

Where:

- $v$ is the Abbe $v$-value
- $n_D$ is the index of refraction at 587.56 nm
- $n_F$ is the index of refraction at 486.1 nm
- $n_C$ is the index of refraction at 656.3 nm

The dispersion ($d$) of optical glass is often reported as:
Dispersion is the reason a prism spreads an incident beam of white light into a fan of colored light. It is also the reason that a simple lens cannot focus all wavelengths of light to the same point.

**Diffuse Transmission**

When a ray of light is scattered upon entering into or passing through a material, the wavefront is broken up and is no longer continuous; many different wavefronts emerge. Such transmission is **diffuse transmission**.

Diffuse transmission is caused by random refraction and/or reflections of light off scattering centers in the material and on the surface of the material. Light entering the diffusely transmitting material has individual small sections of its wavefront repeatedly refracted and reflected so its energy is dispersed over a range of directions.

A perfect diffuser is considered one that scatters the light energy proportional to the cosine of the angle of exit. This pattern is called **Lambertian**, and the diffuser with this pattern is called a Lambertian diffuser. Any view of the uniformly illuminated surface subtending a constant solid angle receives the same amount of light energy regardless of its relative angle.
REFLECTION FROM TRANSPARENT SURFACES

When light strikes a surface of a transparent material, not all the light is transmitted; a portion is reflected. The portion reflected is given by:

\[ R = \left( \frac{u - 1}{u + 1} \right)^2 \]  

(13)

Where:

- \( R \) is the fraction of light reflected when the light strikes the surface at the normal.
- \( n \) is the index of refraction of the original material.
- \( n' \) is the index of refraction of the new material.
- \( u \) is the ratio of the indices of refraction: \( u = n'/n \)

For optical glass, with an index of refraction of around 1.5, the energy reflected off the surface is around .04 (4%). A lens has two surfaces that interface with air; the total reflected energy from a simple glass lens is around 8%.

If the interface between the materials is not clean and smooth, the reflectance can be higher. There is a way to reduce reflectance at the surface (see page 88).

**Fresnel Reflection**

When light reflects off a transparent material there is a polarization effect.

Augustin-Jean Fresnel, a French physicist, provided the generalized equations of reflection from a dielectric (transparent) surface for both directions of polarizations. If we consider the plane of incidence defined by the incident, reflected, and refracted rays, we can define wave components with polarization parallel and transverse to the plane. This is **Fresnel reflection**. These equations are known as Fresnel’s laws:

\[ r|| = \frac{\tan(\varphi - \varphi')}{\tan(\varphi + \varphi')} \]  

(14)
\[ t\parallel = \frac{2 \sin(\varphi') \cos(\varphi)}{\sin(\varphi + \varphi') \cos(\varphi - \varphi')} \quad (15) \]

\[ r\perp = \frac{-\sin(\varphi - \varphi')}{\sin(\varphi + \varphi')} \quad (16) \]

\[ t\perp = \frac{2 \sin(\varphi) \cos(\varphi')}{\sin(\varphi + \varphi')} \quad (17) \]

Where:

- \( r\parallel \) is the fraction of light reflected having its polarization parallel to the plane of incidence
- \( t\parallel \) is the fraction of light transmitted having its polarization parallel to the plane of incidence
- \( r\perp \) is the fraction of light reflected having its polarization perpendicular to the plane of incidence
- \( t\perp \) is the fraction of light transmitted having its polarization perpendicular to the plane of incidence

In Figure 35 notice several things. The reflection for the two different orientations of polarization behaves differently. Therefore, reflectance is a function of the direction of polarization. That is, a mirror is more reflective when polarization is perpendicular to the plane of reflection. Further, if the polarization of light is not either parallel or perpendicular to the plane of reflection, the two polarization components will be reflected differently, and there will be a change in the direction of polarization.

Also illustrated in Figure 35 is that while Fresnel reflection applies to dielectrics such as glass, metals exhibit a somewhat analogous behavior; except that reflection from metals does not exhibit the complete extinction of one polarization as does reflection from dielectrics.
**Brewster’s Angle**

The incident angle for the condition where the reflected and refracted rays are separated by 90 degrees is Brewster’s angle, and is given by:

\[
\phi_B = \tan^{-1}\left(\frac{n'}{n}\right)
\]  

(18)

Where:

- \(\phi_B\) is Brewster’s angle
- \(n\) is the index of refraction of the material of the incident light
- \(n'\) is the index of refraction for the material of the transmitted light

At Brewster’s angle, light polarized transverse to the plane is partially reflected, but light polarized parallel to the plane is not reflected at all. The reflected ray is completely polarized. Because, at Brewster’s angle, not all the transversely polarized light is reflected, the refracted ray is only partially polarized.

**DIFFRACTION**

When light passes by an edge, the wave fronts passing by the edge tend to spread their energy. Each point on the wavefront can be considered an independent radiator of energy. By blocking the energy at an edge, the points near the edge radiate some of their energy into the area left vacant by the blocked light. The result is light emerging near a corner tends to spread out in a circle around the corner.

If the light is passing through a small slit, the wavefronts are modified by diffraction until at some distance the wavefront is circular and diverging.
INTERFERENCE

Interference occurs when light waves from two paths intersect. The net intensity at some point is controlled by the instantaneous vector sum of the two wave components at that point. If both waves are at a peak, say positive peak, their magnitudes add, and it is constructive interference. If the vector magnitudes have different signs, the wavefronts subtract, and it is destructive interference.

If the light from the two sources is coherent or nearly so, the points of constructive and destructive interference are stable. This gives stationary light and dark bands. While incoherent light also interferes, the superposition of the interference of all pairs of wavefronts yields just a constant intensity. Light from coherent sources, such as lasers, has interference effects that result in localized maxima and minima. This is why a laser beam has speckle -- it appears grainy.

The usual method of generating an interference pattern is to combine the diffracted components of two or more small apertures illuminated by a common light source. Another method of generating an interference pattern is to split the light from a source into two paths using a beamsplitter. When the paths are recombined coming from different directions, an interference pattern results.

An interferometer normally uses temporally coherent light (i.e. monochromatic or very narrow band). Two different path lengths are created. The first path is the light reflected from or transmitted through the subject. The second path is a reference path with the light reflected off a stable mirror.
The interference pattern at the image indicates changes in relative path distance. The distance (in Z) between maxima and minima is equal to one-half the wavelength of light used.

In machine vision, usually interference is considered a problem unless the application is specifically designed to utilize interference.

**SUMMARY**

There are five principal optical effects: reflection, absorption, transmission, diffraction, and interference.

Incident light energy will be reflected, absorbed, and/or transmitted. Most of the time two or three of the effects are significant.

Transmission may be either direct or diffuse. Light that is directly transmitted is refracted when the speed of light changes between the two materials. The ratio of the speed of light in a vacuum to that in a material is the material’s index of refraction. Diffusely transmitted light is scattered by reflections and refractions at the surface and inside the material.

Reflection may be specular or diffuse. Specular reflection preserves the continuity of the wavefront, although it may distort it. Diffuse reflection scatters light and may act to randomize the polarization. Light partially reflects off the surface of transparent materials depending on the indices of refraction of the two materials and on the angle of incidence. When light is incident on a surface moving from a higher to a lower index of refraction with an angle of incidence is greater than a critical angle, it will be totally reflected internally.

Fresnel reflection identifies that unpolarized light reflected from a transparent material will become partially polarized. At Brewster’s angle, the reflected light will be completely polarized. Metals exhibit a similar, but not as pronounced effect when reflecting light.

When light energy is absorbed, it is transformed into another form of energy including heat, electrical, chemical, mechanical, and light (fluorescence).
Diffraction is an effect that causes the ends of wavefronts to distort. It is caused by every point along the wavefront being a radiator of energy. Where the wavefront is continuous, the superposition of the individual radiating elements recreates the wavefront. Where the wavefront ends, the radiated energy spreads out.

Interference occurs when two intersecting wavefronts of light of the same frequency either add, constructive interference, or subtract, destructive interference. The result is a pattern of light and dark bands created by the phase difference of the two wavefronts.
QUIZ

1) The three optical affects do not include which of the following:
   a) Reflection
   b) Absorption
   c) Transmission
   d) Filtering

2) Ways in which a material can transmit light include:
   a) Direct
   b) Diffuse
   c) Both a and b
   d) Neither a or b

3) Refraction is caused by
   a) A change in the velocity of light
   b) Light seeking the path of least resistance
   c) The effects of surface roughness
   d) Light is absorbed and reemitted

4) A ray of light traveling in air \((n = 1.0)\) is incident on the surface of glass \((n = 1.5)\) at an angle of 20 degrees to the normal. The ray of light will continue in the glass at the following angle to the normal:
   a) 0 degrees
   b) 13.2 degrees
   c) 20 degrees
   d) 30.8 degrees

5) Dispersion is a measure of:
   a) The change in index of refraction as a function of wavelength
   b) The amount of light scattered when it is incident on a surface
   c) The angle at which light is bent when it enters or leaves a material
   d) None of the above
6) A Lambertian diffuser is one which:
   a) Diffuses normally incident light energy so the reflected light energy density is equal in all directions
   b) Only partially diffuses the light
   c) Diffuses the light into a circle or other designed pattern
   d) None of the above
7) Specular reflection:
   a) Maintains the integrity of the wavefront
   b) Is characterized by the angle of reflection equaling the angle of incidence
   c) Happens with a mirror
   d) All of the above

8) Which of the following is true about incident light reflecting from a transparent surface?
   a) No light reflects off the surface
   b) All light reflects off the surface
   c) A portion of the light reflects off the surface
   d) Reflection only happens when light is moving into a material with a higher index of refraction

9) Total internal reflection occurs when:
   a) Light is incident on a material with a lower index of refraction
   b) Light is incident on a material with a higher index of refraction
   c) The angle of incidence must be greater than the critical angle
   d) Both a and c

10) The reflectance of a surface:
    a) Depends on the polarization of the light
    b) Is independent of the polarization of the light
    c) Varies with the angle of incidence
    d) Both a and c

11) Light incident on glass at Brewster’s angle:
    a) Is not reflected
    b) Has its reflected component completely polarized
    c) Has a 90 degree angle between the reflected and transmitted light
    d) Both b and c

12) Diffuse reflection:
    a) Scatters the reflected light over a range of angles
    b) Tends to depolarize the light
    c) Can be modeled as a mirror broken into tiny pieces
    d) All of the above

13) The energy of absorbed light may be:
    a) Converted to heat
    b) Converted to electrical energy
    c) Converted to light of a longer wavelength
    d) All of the above
14) Diffraction is caused by:
   a) Darkness attracting some light energy away from the beam
   b) Radiation of light energy at the ends of wavefronts
   c) The tendency of photons to repel each other
   d) None of the above

15) Interference is caused when:
   a) Wavefronts add or subtract
   b) Photons collide with each other
   c) Light energy is blocked
   d) None of the above
COLOR PERCEPTION

There are two views of color, that of spectroscopy and that of appearance. Spectroscopy considers the wavelengths of light and is not necessarily limited to wavelengths to which the human eye is sensitive. Appearance considers a perceived property and is a function of the responsivity of the human eye.

Color is important to the machine vision practitioner in several ways. It can be used to identify different objects such as fuses of different ratings in an automotive fuse block. It can be used to determine quality level as when inspecting agricultural produce for ripeness and blemishes. It can be managed with filters to help optimize the quality of an image.

This section explores color mainly as perception. That is, it does not consider wavelengths that are not visible to humans. It covers the principle of mixing colors, the sensitivity of the human eye to color, primary color systems, and different systems for representing color.

Simple experiments verify people perceive certain wavelengths as specific colors. In fact, certain emission wavelengths of gases are used as both wavelength and color standards.

If all light energy has the same wavelength, the light is **monochromatic**. In visual perception, monochromatic light is a **pure** or **totally saturated** color. In visual perception, when light consists of a range of wavelengths with some dominant wavelength, the color is **partially saturated**. The degree of saturation depends on the degree of predominance of the major color. When the light energy is rather evenly dispersed over a broad range of wavelengths, the light is **achromatic**. In visual perception, achromatic light is white or totally unsaturated.
MONOMERS & METAMERS

Perceived color is complex. For example, light with a wavelength of 525 nm is perceived as green. However, a mixture of blue light, with a wavelength of about 480 nm, and yellow light, with a wavelength of about 575 nm, can produce a similar perceived green color as the 525 nm light, and yet there is no light present with a wavelength corresponding to green.

Light that has a spectral distribution with a single mode at the wavelength corresponding to the perceived color is a monomer. Light that has a spectral distribution with two or more modes, none of which is necessarily near the wavelength corresponding to the perceived color is a metamer.

PHOTOPIC AND SCOTOTOPIC RESPONSE

The human eye has two different sets of commingled sensors, rods and cones. The cones sense color and work well in moderate to high illumination levels. The cones have a photopic spectral response to light that has peak sensitivity in the green.

The rods do not sense color, but work in much lower light levels. Rods have a different spectral response than the cones; their peak sensitivity is shifted toward the shorter, blue, wavelengths. This spectral responsivity of the rods is scotopic. Vision at intermediate light levels is a mixture of photopic and scotopic.

For most technical purposes, unless the situation clearly dictates use of the scotopic response, human vision is considered to have the photopic response.
CIE CHROMATICITY DIAGRAM

For appearance purposes, color is often evaluated in coordinates displayed on the CIE chromaticity diagram. The various possible hues are arranged circumferentially. Where wavelengths of light correspond to perceived colors, the wavelengths are displayed along the edges. The purity, or saturation, of the color is displayed radially, increasing toward the outside. At the edges, the colors are pure, completely saturated, and monochromatic. The CIE chromaticity diagram does not represent the intensity of the light.

The diagram has the approximate shape of a truncated ellipse (it has been called a horseshoe shape). In the 1976 version of the curve, regions of constant color appear as constant size ellipses on the chart; however, the orientation of the ellipses varies as a function of color.

The original 1931 CIE diagram had axes labeled x (horizontal) and y (vertical). In 1960, the shape of the diagram was revised to have the area of indiscernible color change a constant size. The axes were labeled u and v respectively. In 1976, the shape was again modified and the axes were labeled u’ and v’.

PRIMARY COLOR SYSTEM

A primary color system is any set of colors in which the specified colors can be mixed in proportions to obtain a range of colors. However, no primary color (in the specified set) can be formed by any combination of the other primary colors.

Common primary color systems use three colors. The most common are red, green, and blue (RGB); and cyan, yellow, and magenta (CYM).

The coordinates of the CIE curves can be calculated from the standard CIE tristimulus values of red, green, and blue as:

\[ x = \frac{R}{R + G + B} \]  

(19)
\[ y = \frac{G}{R + G + B} \]  

(20)

Where:

- \( x \) is the horizontal axis of the 1931 CIE chromaticity diagram
- \( y \) is the vertical axis of the 1931 CIE chromaticity diagram
- \( R \) is the red signal from a calibrated tristimulus detector
- \( G \) is the green signal from a calibrated tristimulus detector
- \( B \) is the blue signal from a calibrated tristimulus detector

There is a \( z \) value calculated as:

\[ z = \frac{B}{R + G + B} = 1 - (x + y) \]  

(21)

Since the \( z \) value is a linear combination of \( x \) and \( y \), it adds no information to the CIE curve.

For the 1960 CIE curve the axes values can be calculated from:

\[ u = \frac{4R}{R + 15G + 3B} \]  

(22)

\[ v = \frac{6G}{R + 15G + 3B} \]  

(23)

The 1976 CIE coordinates are given by:

\[ u' = \frac{4R}{R + 15G + 3B} \]  

(24)

\[ v' = \frac{9G}{R + 15G + 3B} \]  

(25)
RGB AND CYM

The red, green, and blue (RGB) color space commonly used in imaging and image display and the cyan, yellow, and magenta (CYM) color space commonly used in printing are actually the same color spaces when diagrammed as a color cube.

Cyan is actually white minus red, yellow is actually white minus blue, and magenta is actually red minus green. Where RGB is an additive color space, color is added to black, the CYM color space is subtractive, color is subtracted from white. When blue is added to black, the effect is increasing blue. When yellow is added over white, it reduces, or subtracts, the blue from the white.

In actual practice in the printing industry, the CYM color space is augmented with black because the three ink colors together do not produce a good black even though they should subtract all color from the white. The color system becomes CYMK where K is black.

L* A* B*

The L*a*b* system is a Cartesian system providing the ability to display hue, saturation, and intensity. The L* axis represents intensity. The a* and b* axes allow representation of color, both hue and saturation. The coordinate 0, 0 for a*, b* represents white (or gray); other coordinates represent varying levels of hue and saturation.
IHS

The IHS system can be thought of as the L*a*b* system, except in cylindrical coordinates. The I axis represents intensity and is the same as L*. The hue (H) and saturation (S) axes represent the color information in polar coordinates. Hue is the angular displacement, and saturation is the radial displacement. This color system is known by other designations such as HSI and HSB where B stands for brightness.

SUMMARY

Color can be used in machine vision to identify objects, inspect for product quality, and improve image quality.

Monochromatic light, where light energy has just one wavelength, is a pure or totally saturated color. When light energy consists of a limited range of wavelengths around a dominant or peak wavelength, the light is partially saturated. When the light consists of roughly equal parts of all wavelengths, the light is achromatic or unsaturated.

A monomer is a color with a single modal wavelength. A metamer is a color with two or more modal wavelengths (i.e., mixed colors).

The retina of the human eye has both rods and cones as light sensors. Cones sense color; they need an adequate light level to work; they are principally responsible for the eye’s photopic response that peaks in the green wavelengths. Rods do not sense color; they are used for vision in low light conditions; they have a scotopic response that peaks in the blue wavelengths. Most optical work related to the human eye uses the photopic response.

The CIE chromaticity diagram represents colors perceived by the human eye; it does not represent intensity. The original 1931 version used x and y values as coordinates of a color. The latest version, in 1976, uses u’ and v’ as color coordinates.
A primary color system is any three or more colors that can be mixed to produce a range of colors, but no one of the primary colors can be produced by any mixture of the other colors. Common primary color systems are red, green, and blue (RGB), an additive color system, and cyan, yellow, and magenta (CYM), a subtractive color system.

A primary color system is not convenient to analyze, the data can be translated into other color systems for easier analysis. Common color systems are intensity, hue, and saturation (IHS) and L*a*b*.
QUIZ

1) Which of the following is/are uses for color in machine vision?
   a) Object identification
   b) Inspection for product quality
   c) Improvement of image quality
   d) All of the above

2) Light that consists of a range of wavelengths around a dominant wavelength is:
   a) Saturated
   b) Partially saturated
   c) Unsaturated
   d) Achromatic

3) Which of the following is a metamer?
   a) Green light
   b) A mixture of blue and red light
   c) A mixture of white and yellow light
   d) None of the above

4) Which of the following is/are true about photopic vision?
   a) It uses the rods on the retina
   b) It senses color
   c) Its sensitivity is maximum at green wavelengths
   d) All of the above

5) The CIE chromaticity diagram represents:
   a) Perceived colors
   b) Wavelengths of light
   c) Intensity of light
   d) Tristimulus values
6) Which of the following is a set of primary colors?
   a) Red, green, and blue
   b) White, black, violet, and yellow
   c) Red, yellow, and green
   d) Blue, cyan, and magenta

7) Which of the following is not a set of primary colors but a color system useful for analysis?
   a) HIS
   b) RGB
   c) CYM
   d) CYMK
THE MEASUREMENT OF LIGHT

Although the machine vision practitioner may often be able to develop systems without becoming involved in complex light measurement, an understanding of the terminology and basic measurement principles will help them select optical components such as lamps and cameras. Should the need arise when light measurement is needed, the basics that follow will be indispensable.

This section covers the difference between radiometry and photometry and why neither of these measurement domains is ideal for machine vision as well as the basic terminology and methods for measuring the quantity of light which covers power, intensity, illuminance or irradiance, and brightness.

There are two basic systems in use for measuring the quantity of light: radiometric and photometric. The two differ in how they treat the spectrum. Radiometry treats all wavelengths equally. That is, there is no spectral weighting. Photometry weights light based on its wavelength according to the photometric response of the human eye. That is, if light at a wavelength of 555nm (green, the peak photometric response of the human eye) has a radiometric energy of 1 joule, it will have a photometric luminous energy of 1 Talbot. However, light at a wavelength of 510nm (blue-green color) that has a radiometric energy of 1 joule will have a photometric energy of 0.503 Talbot because the sensitivity of the eye at this wavelength is only 50.3% of its sensitivity at 555nm.

Two observations are worthwhile here. First, because the energy of a photon is given by hv as stated at the beginning of this paper, the number of photons for a given energy is dependent on frequency or wavelength. The energy of a photon is proportional to frequency or, more practically stated, inversely proportional to the wavelength. For example, light energy of 1 joule at 400nm will have half the number of photons as light energy of 1 joule at 800nm because a photon at 400nm is twice as energetic as a photon at 800nm.
The second observation is that neither radiometric nor photometric measurements are ideally suited to machine vision. What would be desirable would be a measurement that related to the imaging systems’ response as affected by lighting, the camera’s spectral sensitivity, and the transmissive effects of filters, lenses, etc. Unfortunately, this encompasses an enormous degree of variability, and thus no standardized units are possible. For example, the camera’s spectral sensitivity varies depending on the technology used to produce the image sensor, on the cover glass over the sensor and the lens, and whether or not the camera incorporates an infrared cutoff filter.

Glass normally used in the window over the image sensor and in the lens is opaque to ultraviolet. Therefore, the sensitivity of most cameras will fall to zero around 300nm even though the sensor has the potential to sense shorter wavelengths. It is common, but not universal, for cameras to incorporate an infrared cutoff filter. This is because common lenses do not work well in both the visible and infrared, and therefore degrade image quality unless the infrared is eliminated. Also, cameras that are sensitive to the infrared can have images that do not match what the human observer sees. While in some applications this is desirable, in many it is undesirable.

Because the spectral responsivity of cameras resembles the human eye more closely than they resemble a true radiometric sensor, most optical measurements for silicon cameras and systems that use them utilize the photometric measurement of light.

To make matters a bit more confusing, while radiometric measurements are now always specified in the SI metric system, photometric measurements may be specified in the SI metric system or the imperial (English) measurement system. Fortunately, SI units are becoming more preferred for photometric measurements.
<table>
<thead>
<tr>
<th>Radiometric Units</th>
<th>Photometric Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Quantity</strong></td>
<td><strong>SI</strong></td>
</tr>
<tr>
<td>Energy (Q)</td>
<td>Joules (J)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Radiant Power</td>
<td>Watt (W)</td>
</tr>
<tr>
<td>Radiant Flux (Φ)</td>
<td>Joules/second (J/s)</td>
</tr>
<tr>
<td>Radiant Intensity (I)</td>
<td>Watts/steradian (W/sr)</td>
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<tr>
<td>Irradiance (E)</td>
<td>Watts/meter(^2)</td>
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<tr>
<td></td>
<td>(W/m(^2))</td>
</tr>
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</tr>
<tr>
<td>Radiance (M)</td>
<td>Watts/steradian-meter(^2) (W/sr-m(^2))</td>
</tr>
<tr>
<td>Exitance</td>
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</tbody>
</table>

Table 1 – Units of Light Measurement

From an examination of Table 1 it is evident that the basic unit for light measurement is the Watt for radiometric measurement and its parallel, the lumen, for photometric measurement. All other measurement units are derived from these. For practical purposes, this is true. As a side note, though, the international standards setting body adopted the candela as the base unit for the SI system with all other light measurement units derived from it.

There are several quantities of interest to the machine vision practitioner:

- Total power of a light source
- Intensity of a light source
- Power of the light that is incident on a scene
- Brightness of an illuminated scene
- Light energy captured by a lens and delivered to an image sensor
POWER

Light energy is important to machine vision practitioners when considering exposure of a solid-state image sensor\(^3\) or when considering the temperature rise that will be caused by an illumination source. However, energy is difficult to measure directly. Power, or flux, is more practical to measure, and since energy is just the product of power and time, calculating energy from power (flux) is straightforward.

The measurement of light power is usually performed with an integrating sphere. An integrating sphere is a hollow sphere that is coated internally with a diffuse reflective material with very high reflectance so that all light incident on any spot is scattered in all directions. A detector is mounted in a small opening that is protected by a baffle so no light reaches the detector without first being diffusely reflected (integrated).

INTENSITY

Intensity is a measure of the amount of light radiated in a given direction defined by the solid angle and is expressed in Watts/steradian or candelas (lumens/steradian). By using the solid angle rather than onto an area, the measurement is independent of distance. It is a good measure of the output of a light source. Intensity is measured by a radiometer or photometer.

---

\(^3\) While camera exposure is commonly specified in Lux, the sensitivity of the image sensor itself is usually specified in the energy, in microjoules, required to achieve maximum signal from an individual sensing element.
For a directional light source such as a projector bulb with a built-in reflector or an LED, intensity is usually the measurement of choice. The photometer or radiometer normally subtends a very small solid angle and uses a lens to focus on a “point” on the source. Because the photometer/radiometer’s geometry is known, the result can be scaled to physical units.

**ILLUMINANCE OR IRRADIANCE**

When measuring the level of illumination reaching a surface without regard for the direction or source, irradiance or illuminance is the appropriate measurement. Illuminance is measured with a light meter. The light meter gathers in all incident light energy regardless of its direction. Therefore, if direction is important to the measurement, either the source must be limited with baffles for the measurement or some other measure taken to make sure only light from the proper direction is included in the measurement.

Illuminance is also the standard method by which the sensitivity of cameras is specified. That is, the surface of the image sensor is uniformly illuminated to produce the desired output, and then the illumination level (illuminance) is measured in lux.

**BRIGHTNESS**

When measuring light coming from a surface or scene, the correct measurement is radiance or luminance. In colloquial terminology, this is often called brightness. Radiance or luminance is measured with a radiometer or photometer. Note that since the measurement of radiance or luminance subtends a solid angle that for a uniformly emitting surface, the measurement is independent of the distance.
Measuring the light from a scene might sound like a very desirable measurement. If the scene averages 50% reflectance or transmittance, the measurement might be reasonable. It is more common for the majority of the scene to be light or dark, and a measurement of the average light coming from the scene can therefore be misleading.

**SPECTRUM**

In addition to the measurement of the quantity of light, it is sometimes necessary to measure the spectrum of light – the relative power as a function of wavelength. This may be necessary to determine the correct wavelength, or wavelengths, that will good contrast in the image. It might be necessary to determine what type of imager will work satisfactorily.

The measurement instrument for determining the spectrum is called a spectrometer, spectrophotometer, or spectroradiometer. A spectrometer is a general term for a measurement device designed to measure the quantity of light as a function of wavelength over a portion of the electromagnetic spectrum. A spectrophotometer is an instrument designed to measure the spectrum of light reflected or transmitted by a sample. A spectroradiometer is an instrument designed to measure the radiated light as a function of wavelength.

In principle, all of these devices are very similar. Light enters through a slit and is collimated by a lens. A prism or a grating refracts or diffracts the light energy through a range of angles where the angle depends on the wavelength. A second lens images the separated light energy onto a detector. Often the detector is a line-scan imaging array or a linear array of photo detectors.

The ability of the spectrometer to separate wavelengths depends on both the resolution of the detector and the width of the slit. As the detector becomes higher in resolution, the photodetectors on it become smaller and less sensitive. As the slit is narrowed, the separation of wavelengths increases but there is less light energy. Selection of the spectrometer and its setup is very dependent on the application requirements.
SUMMARY

Light measurement may be made by radiometry where all wavelengths are equally weighted, or it may be made by photometry where wavelengths are weighted according the photometric response of the eye. Because image sensors do not typically match the response of the human eye, neither radiometric nor photometric measurements are ideal.

The sensitivity of cameras is normally specified in lux, a photometric measurement.

Radiometric measurements are now preferably made in the SI system of units. Photometric measurements may be made in the SI or in the Imperial system of units.

Power is the measurement of total light flux in all directions. It is usually measured with an integrating sphere and expressed in either Watts (radiometric) or Lumens (photometric).

Intensity is the measurement of light radiated in a certain direction or range of directions. It is measured with a photometer or radiometer and expressed in either Watts/steradian (radiometric) or candelas (photometric).

Illuminance or irradiance is the measurement of energy density onto a surface from all directions. It is measured with a light meter and expressed in either Watts/meter$^2$ (radiometric) or lux or footcandles (photometric).

Brightness or radiance or luminance is the measurement of the light energy emitted by a surface of given area in a given direction or range of directions. It is measured with a photometer or radiometer and expressed in either Watts/steradian-meter$^2$ (radiometric), or apostilbs, or footlamberts (photometric).

The spectrum of light energy is measured with a spectrometer. A spectrophotometer measures the spectrum of transmitted or reflected light energy. A spectroradiometer measures the spectrum of emitted light energy.
QUIZ

1) Radiometry and photometry differ principally in:
   a) The system of measurement units
   b) The weighting of the optical spectra
   c) The equipment used to make measurements
   d) There is no fundamental difference

2) Camera sensitivity is normally specified in:
   a) Lux
   b) Candela
   c) Watts
   d) Joules

3) The most appropriate measurement for the output of a household incandescent light bulb is:
   a) Power in Watts
   b) Power in luminos
   c) Intensity in Watts/steradian
   d) Intensity in Candela

4) The most appropriate measurement for the amount of light incident on a scene when the image sensor has a sensitivity approximating that of the human eye is:
   a) Watts/meter²
   b) Lux
   c) Watts/steradian-meter²
   d) Footlamberts

5) The most appropriate measurement for an LED indicator with a focused beam is:
   a) Watts
   b) Candela
   c) Footcandle
   d) Joule

6) The most appropriate measurement for the output of a CRT display is:
   a) Lux
   b) Footcandle
   c) Watts/steradian
   d) Candela
7) To measure the spectrum of transmitted light energy, you would use a:
   a) Spectrometer
   b) Spectrophotometer
   c) Spectroradiometer
   d) Laser
A principal goal of the machine vision practitioner is to create an optical image. It is therefore essential that they understand the principles behind image formation.

This section covers ray tracing, the most common design methodology for imaging components and systems, simple equations used by machine vision practitioners when working with lenses, the f-number of a lens, diffraction effect of a lens and how it fundamentally limits achievable resolution, aberrations caused by lenses, and a lens’ depth-of-field.

**RAY TRACING**

Consider what happens to a bundle of parallel light rays that strike a spherical glass surface. If the surface is convex, refraction bends all rays so they converge to a point. This point is the *focal point*. The rays are said to be in focus at this point.

Now, consider a lens that consists of two glass surfaces with at least one of them curved. Again, the parallel rays refract to come together at a focal point. As a simplification, if the lens is very thin, all rays can be considered to bend once about a plane passing through the lens rather than twice, once at each surface. This is the thin lens model, and the imaginary plane is the *principal plane*. The distance from the principal plane to the focal point is the *focal length*. There exists a focal point on both sides of the lens, and, for the thin lens assumptions, the focal lengths on both sides of the lens are equal.

As a practical matter, a lens’ focal length is determined by the curvature of its surfaces and the index of refraction of the material from which it is made.
BASIC IMAGING

A lens is designed so that a bundle of parallel light rays incident upon the lens is refracted so that all the rays converge to a focal point.

It is also true that if light rays are emanating from a point source at the focus of a lens, the lens will refract the bundle into parallel rays; a collimated bundle.

External to the lens, the rays appear to bend at specific planes called the principal planes. The location of these planes depends on the thickness, index of refraction, and radius of curvature of the lens. We will develop the imaging equations assuming a thin lens model. In the thin lens model, the lens is so thin that the two principal planes are in the same location, and, for conceptual purposes, the lens can be replaced with a single plane.

The focal distance or focal length of the lens is the distance between the focal point and its corresponding principal plane. A lens has the same focal length regardless of which way it is oriented; however, the distance between the focal point and the surface of the lens may well be different for the two sides of the lens.

Figure 60 below shows a lens imaging an object. It also annotates the important dimensions.
We can define image magnification as:

\[ M_I = \frac{H_I}{H_o} \]  

(26)

Where:

- \( M_I \) is image magnification
- \( H_o \) is the height of the object or the whole field-of-view
- \( H_I \) is the height of the image of the object or the image height itself

It should be evident that magnification can also be calculated from widths as well as heights.

Sometimes lens designers use object magnification for the image projected onto the field-of-view (\( M_o \)), but this is unusual in machine vision work. For most of our work we can just refer to magnification (\( M \)) when we mean the magnification of the image.

It has become popular to refer to \( M_I \) as primary magnification, or PMAG. This resulted from microscopy displayed on a monitor where system magnification was the ratio of the size of the image on the monitor to the size of the field-of-view imaged. The system magnification consisted of the magnification of the field-of-view onto the camera’s image sensor, primary magnification or PMAG, times the magnification of the image sensor onto the monitor’s screen, secondary magnification or SMAG.
In Figure 61, the triangles for object height with object distance and image height with image distance are similar. This gives:

\[
\frac{H_o}{D_o} = \frac{H_i}{D_i}
\]  \hspace{1cm} (27)

Where:

- \(D_o\) is the object distance
- \(D_i\) is the image distance

This gives:

\[
\frac{D_i}{D_o} = \frac{H_i}{H_o} = M_i
\]  \hspace{1cm} (28)

So, image magnification is also the ratio of image and object distances.
Notice in Figure 62 the triangles formed by the object height with the object distance less the focal length is similar to the one formed by the image height with the focal distance. This gives the relationship:

\[
\frac{H_o}{D_o - F} = \frac{H_i}{F}
\]  (29)

Rearranging gives:

\[
\frac{H_i}{H_o} = \frac{F}{D_o - F} = \frac{D_i}{D_o}
\]  (30)

Which can be further rearranged to give the Gaussian form of the lens equation:

\[
\frac{1}{F} = \frac{1}{D_i} + \frac{1}{D_o}
\]  (31)

While the Gaussian form of the equation is a little awkward for most practical needs, it can be recombined with the expression for magnification to give the following more useful equations:

\[
F = \frac{D_o M_i}{1 + M_i}
\]  (32)

\[
F = \frac{D_i}{1 + M_i}
\]  (33)

\[
D_o = \frac{F (1 + M_i)}{M_i}
\]  (34)

\[
D_i = \frac{F}{1 + M_i}
\]  (35)

\[
F = \frac{D_o + D_i}{2 + M_i + 1/M_i}
\]  (36)

\[
D_o + D_i = F (2 + M_i + 1/M_i)
\]  (37)

\[
AOV = 2 \tan^{-1}\left(\frac{H_i}{2F}\right)
\]  (38)

\[
H_o = H_i \left(\frac{D_i}{F} - 1\right)
\]  (39)
THE F-NUMBER

It should be obvious for a lens of fixed focal length, the bigger its diameter, the more light energy it will gather. The common relationship for the light gathering power of a lens is the f-number, given by:

\[
f = \frac{F}{D}
\]

(40)

Where:

- \(f\) is the f-number of the lens
- \(F\) is the lens’ focal distance
- \(D\) is the diameter (effective) of the lens

In later sections, it will become apparent that in addition to controlling the amount of light collected by the lens, the f-number is also significant in determining the resolving power and depth-of-field of a lens.

An examination of the equation for the f-number makes it evident that as the lens becomes smaller, and its light gathering ability is reduced, the f-number becomes larger. Therefore, there is an inverse relationship between the f-number and the light gathering ability (or speed) of the lens.

Further examination should also make evident that while the f-number is a function of a lens’ diameter, light energy admitted by the lens is a function of its area. Since area is related to the square of diameter, a change in the f-number by some ratio will change the light gathered by the lens by the square of that ratio. For example, if the aperture of a lens is changed from f4 to f8, the working diameter has decreased by a factor of two, and the light gathering ability has decreased by a factor of four.

When a lens is focused at infinity, its image distance is equal to its focal length. As the lens focuses closer than infinity, the image distance becomes larger. When this happens, the cone formed by the lens diameter and the image distance subtends a smaller angle at its vertex. This reduces the light energy focused on each area of the image plane. For calculating exposure, the effective or working f-number is given by:
\[ f_{\text{eff}} = f \left( 1 + M_I \right) \] (41)

Where:

- \( f_{\text{eff}} \) is the effective f-number
- \( f \) is the calculated f-number
- \( M_I \) is the image magnification

The f-number as derived, is for paraxial rays, those rays close to and parallel to the lens’ optical axis. When the light source moves away from the optical axis, then the size of the cone of focused light becomes smaller; the lens admits less light. For a source located an angle \( \varphi \) off the optical axis, the reduction in light admitted by the lens is proportional to \( \cos^4(\varphi) \).

For lenses that work very close, such as microscope objectives, a different, but related, term is preferred: numerical aperture (NA). The numerical aperture is the sine of the half-angle of the cone of acceptance on the object side of the lens times the index of refraction. The index of refraction is present in the equation to facilitate oil immersion microscope objectives. For air, \( n \) is so close to 1 that it is ignored.

\[ NA = n \sin(\theta) \] (42)

Where:

- \( NA \) is the numerical aperture
- \( \theta \) is the half-angle of the acceptance cone
- \( n \) is the index of refraction of the media on the object side of the lens

The f-number and numerical aperture can be expressed for either the image or the object side of a lens. For small angles, they are related by:

\[ f = \frac{1}{2 NA} \] (43)
THE OPTICAL INVARIANT

Looking again at the thin lens model, we examine the marginal ray shown in Figure 66. The ray is called the marginal ray because it passes through the edge or margin of the lens.

Notice that the following relationships hold:

\[ \tan(\varphi) = \frac{x}{D_o} \]  
(44)

\[ \tan(\varphi') = \frac{x}{D_i} \]  
(45)

Then:

\[ x = D_o \tan(\varphi) = D_i \tan(\varphi') \]  
(46)

\[ \frac{D_i}{D_o} = \frac{\tan(\varphi)}{\tan(\varphi')} = M_i = \frac{H_i}{H_o} \]  
(47)

\[ H_o \tan(\varphi) = H_i \tan(\varphi') = \text{Inv} \]  
(48)

\[ M_i \tan(\varphi') = \tan(\varphi) \]  
(49)

Where: Inv is the optical invariant for the specific system.

This shows that for an optical system without loss, the value of \( H_o \tan(\varphi) \) is a constant or invariant for that particular system. That is, as an image is formed and relayed in the optical system, the product of the image height and the tangent of the angle formed by the bundle of rays creating the image will equal this constant\(^4\). The constant is called the optical invariant, the Lagrange invariant, the Helmholtz invariant, and the Helmholtz-Smith invariant. Of course, if the

\(^4\) Most books on optics develop the expression for the optical invariant assuming the paraxial condition where angles are small and the angle is a very close approximation to the sine or tangent. Also, in the derivation above, the index of refraction is not included. When the index of refraction is included and the angle is used for its tangent, the expression for the optical invariant becomes \( H_o n \tan(\varphi) \).
optical system has loss (e.g., a stop in the optical path), then the optical invariant is changed. Effectively, this reduces the diameter of the lens admitting light into the system.

**ÉTENDUE**

Of significant interest to machine vision engineers, is the light energy gathered by an optical system if it is an imaging system or the light effectively directed if it is an illumination system. Looking at an imaging arrangement, it becomes apparent that the light flux gathered by the arrangement is the product of the luminance or radiance of the scene, the area of the scene, and the light capturing ability of the lens as a function of the subtended solid angle.

Mathematically, the light gathered by the lens can be expressed as:

\[
\Phi = \int \int \Omega \ dL \ dA
\]  

(50)

Where:

- \(\Phi\) is the total light flux collected by the optical system
- \(\Omega\) is the solid angle subtended by the lens
- \(dL\) is the increment of luminance (or radiance)
- \(dA\) is the increment of area

For simplification, if we assume an average luminance (L) over the area (A), then the equation becomes:

\[
\Phi = L \Omega \ A
\]  

(51)

Where:

- \(L\) is the average luminance of the area \(A\)
- \(A\) is the area imaged by the lens

---

5 See the earlier section that covers light measurement for a discussion of luminance and radiance.
Once the total admitted flux is known, the illuminance or irradiance of any image formed in the system, assuming no losses, can be determined by dividing the flux by the area of the image.

It is evident that once a certain amount of light flux (power) has been admitted into the system, it cannot be increased except by some form of amplification. It can be reduced by attenuation or by obstruction. Inexperienced designers have been known to work diligently trying to increase the light power by changing the optics internally to the system when the limitation was simply the amount of flux admitted by the system.

The product $\Omega A$ is called the étendue ($E$) or throughput of the system. It is directly related to the square of the optical invariant. Since the optical invariant is a constant and the square of a constant is a constant, the étendue of a system is also a constant.

$$E \alpha Inv^2$$  \hspace{1cm} (52)

What this also reinforces is that once light is admitted into an optical system, the size of an image and its corresponding angle are inexorably related unless light is obscured. This explains why it is not possible to collimate the light bundle in an imaging system. Once an area is imaged with a lens, the relationship between the area and angle are established. The angle can be reduced optically only by either increasing the area or by blocking some of the light. Blocking the light is equivalent to reducing the area imaged with a corresponding reduction in the solid angle subtended.

While the discussion of étendue has focused on imaging systems, it is also equally relevant to the design of illumination systems.

**DIFFRACTION AND INTERFERENCE OF A PLANE WAVEFRONT BY A LENS**

For clarity, rays are used to describe how lenses work, and almost all lens design, even quite sophisticated design, is performed by ray tracing. However, light is not a ray. It is necessary to examine how wavefronts behave when they encounter a lens to really understand the lens and its limitations.

To provide a conceptual framework, consider plane waves incident on an ideal lens (i.e., the source is located at infinity). This lens has been designed so that the incident rays (indicating the direction of propagation of the wavefront) are refracted to exactly converge at the focal point of the lens.
In an imaging system, the physical image forming element (e.g. a lens) is finite in size. Therefore, light at the edge of the aperture diffracts. This diffraction distorts the edges of the wavefronts and prevents the imaging system from producing an infinitely small image of an infinitely small object. The larger the lens, the less pronounced is the diffraction effect as a proportion of the total wavefront.

In addition to refraction and diffraction, the principle of equal path length is important. Light wavefronts must interfere constructively at the point of focus to form an image. We expect the optical path length to be equal for every ray. The optical path length is the physical length multiplied by the index of refraction. Imaging with a lens is actually development of an interference pattern. For wavefronts to be circular, each point on the wavefront must be delayed a precise amount by its passage through the lens. Practical lenses do not achieve this with precision; the focused wavefront, although converging to a focus, is distorted.

The image of a point is actually a small bright disk surrounded by concentric rings of decreasing intensity. This pattern is the point spread function of the lens. Over eighty percent of the light energy is in the bright disk, the first ring has five percent of the energy, and successive rings are significantly dimmer. The central disk is Airy disk.

**LIMIT OF RESOLUTION**

The resolving power or limit of resolution of an image formed by a lens in the absence of other aberrations is taken to be the minimum separation of airy disks that can be distinguished. Assume a lens images two closely spaced points. Each point creates an airy disk on the image plane. As the points move closer, the airy disks begin to overlap. When the overlap is such that it is impossible to distinguish whether the feature in the image was created by two points or some other individual artifact in the scene, the lens has exceeded it resolving power.
The limit of resolution of an imaging system is taken to be the radius of the Airy disk as limited by diffraction. The disk has a radius of:

\[ R = 1.22 \lambda \frac{D_i}{D} \]  \hspace{1cm} (53)

Where:

- \( R \) is the Airy disk radius or diffraction limit of resolution
- \( \lambda \) is the wavelength of light (in air or vacuum)
- \( D_i \) is the image distance
- \( D \) is the diameter of the lens

The resolving power is a function of the wavelength and the diameter of the lens. The resolution capability of a lens is limited by the longest wavelength used and by its diameter. Using shorter wavelength light or a larger lens aperture improves potential (theoretical) resolution.

Since \( D_i \) is usually close to \( F \), and \( F / D \) is the f-number, often the equation for the resolution limit is written:

\[ R = 1.22 \lambda f \]  \hspace{1cm} (54)

There is not general agreement on the factor of 1.22. Sometimes the equation is written using a more conservative factor of 2.44:

\[ R = 2.44 \lambda f \]  \hspace{1cm} (55)

That is, the resolving power of an ideal lens degrades for higher f-numbers. The material that follows will show there are considerations in addition to diffraction that can limit the performance of a lens.

All real lenses have some aberrations. However, when the aberrations do not exceed the diameter of the Airy disk, the lens is considered **diffraction limited**.

The resolution limit can be reversed to reflect objects on the object plane by using the equation:

\[ R = 1.22 \lambda \frac{D_o}{D} \]  \hspace{1cm} (56)
Where:

\[ D_0 \] is the object distance

**ABERRATIONS**

Lenses are not perfect imaging devices. In addition to diffraction, which is caused by the lens being a finite diameter, lenses are subject to a range of imperfections called aberrations. Principal among these are:

- Field curvature
- Spherical aberration and coma
- Chromatic aberration
- Distortion
- Astigmatism

Aberrations are caused by practical compromises in design and by manufacturing tolerances. The first compromise is that most practical lens elements are made with spherical surfaces for ease of manufacturing. The ideal shape for a lens is aspherical (not a sphere); a spherical surface is a close, but imperfect compromise. The second compromise is while the lens designer has a range of materials (glasses and plastics) from which to fabricate lenses, these materials are all imperfect in that they have dispersion and do not refract all wavelengths the same. The lens designer uses a series of lens elements to compensate for the compromises, and achieves a high degree of performance, but not perfection, so the lens gives adequate performance over a range of wavelengths and magnifications.

A lens where the principal limitation on performance is diffraction is a diffraction limited lens. While other aberrations are still present in such a lens, diffraction dominates. Even if the lens designer worked to further reduce aberrations, any improvement in lens performance would not be noticeable. These lenses are considered the best possible lens designs and are usually quite expensive. To achieve this performance, these lenses must be used under strict design restrictions on wavelength and working distance. High quality microscope objectives are examples of commonly available diffraction limited lenses.

Although most of the common CCTV and 35mm camera lenses do not approach diffraction limited performance, better quality lenses have very low aberrations, and their performance can be more than adequate for all but the most exotic machine vision applications.
**Field Curvature**

A lens exhibits field curvature when for a plane surface in object space the surface of best focus is not a plane but a curved surface. Alternatively, for a flat image plane, the plane of best focus in object space is curved. For many lenses designed to image distant scenes, such as almost all CCTV lenses and almost all 35mm camera lenses, this is not a problem, and the lens designer makes little effort to correct for it.

For most macro lenses, enlarger lenses, and metallurgical microscope objectives, the lens design eliminates, or at least substantially minimizes, field curvature. Such lenses are called flat-field lenses.

Field curvature is proportional to the size of the aperture and to the square of the field angle. Therefore, to minimize field curvature, use a smaller aperture (larger f-number), and increase the focal length of the lens (smaller field angle).

**Spherical Aberration and Coma**

Spherical aberration and coma are very similar. The cause of each is that rays from the object do not converge to a point but to an area. For spherical aberration, this is evident as a larger blur circle than would be predicted by the diffraction limit. For coma, this is evident as a blur circle with a tail similar to that of a comet. This aberration is caused by design

---

6 The term flat-field lens should not be confused with the term flat-field correction which was coined later (presumably in ignorance of the prior use of flat-field in optics). Flat-field lenses minimize field curvature, an optical phenomena, while flat-field correction is an image processing technique that corrects for the variation in gain, and sometimes offset, for individual pixels in an image.
compromises; the principal one being the use of spherical surfaces rather than more idealized aspherical surfaces.

Both spherical aberration and coma are proportional to the square of the aperture diameter. Coma is also proportional to the field angle. Therefore, using a smaller aperture (larger f-number) greatly reduces both spherical aberration and coma.

**Chromatic Aberration**

If the index of refraction of glass did not change with wavelength, then all wavelengths of light would focus to the same point. However, because of dispersion, this is not the case. In designing a lens, lens designers use lens elements made from different glasses with different dispersions to help minimize the resulting chromatic aberration.

Chromatic aberration may exhibit as lateral chromatic aberration where the different wavelengths focus to different places on the image. Chromatic aberration may also exhibit as longitudinal aberration where colors focus at different distances from the lens. The lens can focus one color on the image with other colors out of focus. Changing focus brings another color into focus while taking the first color out of focus.

An achromatic lens is designed so that two wavelengths in the visible spectrum have exactly the same focal distance. Other visible wavelengths focus close to this distance. An apochromat lens is designed so that three wavelengths in the visible spectrum focus at the same distance; they produce negligible chromatic aberration in the visible region.

Generally, unless a lens is specifically designed for use outside the visible spectrum, there is no correction of chromatic aberration except in the visible region.

Chromatic aberration is affected by both the lens aperture and the field angle. Using a smaller aperture and increasing the focal length of the lens tend to reduce chromatic aberration.
**Distortion**

Depending on its design, the magnification of a lens can change across the image plane. When the magnification increases outward from the center, the corners of an imaged square appear to poke outward like the corners of a pincushion. This is pincushion distortion. When the magnification decreases outward from the center, the sides of an imaged square appear to bulge outward like the sides of a barrel. This is barrel distortion.

Distortion is proportional to the square of the field angle with respect to the optical axis. Therefore, increasing the focal length of a lens, which reduces the field angle, significantly reduces distortion.

Lenses design to minimize distortion incorporate lens elements to compensate for distortion. This may result in pincushion distortion in part of the image and barrel distortion in other parts of the image. This distortion is sometimes called moustache distortion.

**Astigmatism**

Optical engineers describe lines that are aligned radially with the optical axis as sagittal. Lines that are aligned to be tangent to a circle centered about the optical axis are called tangential.

Astigmatism is present in a lens when the orientation of features, whether they are sagittal or tangential, causes them to focus at different distances.
Astigmatism is proportional to the lens diameter and to the square of the field angle. To reduce astigmatism, increase the f-number and increase the focal length of the lens.

**RECONCILING DIFFRACTION AND ABERRATIONS**

From the material covered above on diffraction and aberrations in lenses, it is evident that both are affected by the f-number of the lens. Smaller f-numbers reduce aberrations but increase the effects of diffraction. At some f-number, the lens gives its best performance in terms of minimum size blur circle. This point is different for different lens designs and may even vary from lens to lens of the same design. What can be stated at a general rule of thumb for ordinary lenses (e.g., excluding designs such as zoom lenses) is that the more elements that make up the lens assembly the more the designer has corrected for aberrations, and the better performance will be obtained at lower f-numbers.

It is well to remember that the working f-number affects exposure and depth-of-field as well as diffraction and aberrations. Therefore, it may not always be practical to use the f-number that gives the best resolution.

**MODULATION TRANSFER FUNCTION**

As features in the image become smaller, the lens’ ability to resolve the features decreases. This is evident by a decrease in contrast as shown in Figure 79. As the features get smaller, there comes a point where the lens does not produce any contrast at all.
Typically, the resolving capability of a lens is given by the modulation transfer function, or MTF. This gives the contrast (contrast modulation) as a function of the spatial frequency on the image. You will notice in Figure 80 that there is a diffraction limit which is the resolution of an ideal lens limited only by diffraction due to the lens’ aperture and with no aberrations. When aberrations are factored in, the lens performance is always less than the diffraction limited performance.

The resolution performance of a lens is affected by its aperture, the working distance, and the wavelength of light. The aperture changes both the diffraction limit and the magnitude of aberrations as discussed above.

The working distance will also change aberrations. The lens is designed to be optimal at some working distance. Most general purpose lenses are infinite conjugate lenses, which means their design is optimized for focus at infinity. As the working distance decreases, aberrations increase – usually very slowly for modest decreases, but increasingly greater as the working distance becomes very short.

From Equation 54, the wavelength of light also affects the resolving power of a lens. Shorter wavelengths tend to give higher resolution. However, a lens design is optimized for a certain range of wavelengths. Wavelengths outside of the design range will give poor performance.

The MTF uses spatial frequency given in cycles per millimeter (cycles/mm). Although test targets are available where the reflectance or transmittance is a sine wave, it is much easier to make a target that consists of just light and dark bars. When such a set of bars is used rather than a sine pattern, the resulting chart is the contrast transfer function, or CTF. Since the MTF and CTF curves are roughly similar, most testing takes place with dark and light bars.
DEPTH-OF-FIELD

Depth-of-field is defined as the change in object distance over which the image appears to be in focus. A very similar, and related, property is depth-of-focus which is the amount the image distance can vary and still have the image appear in sharp focus.

Suppose a point is sharply focused on an image plane. As discussed previously, a lens does not produce an infinitely sharp image, but a very small blurred spot due to the effects of diffraction and lens aberrations. This small spot is called the blur circle or the circle of confusion. If the image plane is then moved slightly nearer or further from the lens, the blur circle will increase in size due to defocusing. As long as the blur is not greater than the resolution limit of the image sensor, the image appears to be sharp.

When estimating depth-of-field or depth-of-focus, it is common to consider only geometrical optics, and ignore diffraction and aberration effects. In other words, the assumption is that the only contribution to the blur circle is defocusing. This is a matter of practical convenience because the magnitudes of the aberrations are usually not known. It also implies that the actual depth-of-field will be greater than the calculated geometric depth-of-field.

Looking at Figure 82, it is apparent the triangle formed by the lens diameter (D) and the marginal rays focused to a point is similar to the triangle formed by the marginal rays and the minimum resolution size (R). The amount the image distance can vary and still have the image appear in focus is the depth-of-focus. This can be calculated as:

\[
d' = \pm R \frac{D_l}{D}
\]  

(54)
Where:

- $d'$ is the depth-of-focus
- $R$ is the resolution limit on the image plane
- $D_i$ is the image distance
- $D$ is the diameter of the lens aperture

For most practical imaging applications, $D_i \approx F$, the lens' focal length. The formula for approximating the depth-of-focus becomes:

$$d' = \pm R f$$  \hspace{1cm} (55)$$

Where:

- $f$ is the f-number

Using the imaging equations provided earlier, it is possible to develop equations for the limits of depth-of-field:

$$D_{ON} = D_o \left[ 1 - \frac{R f (D_o - F)}{F^2 + R f (D_o - F)} \right]$$  \hspace{1cm} (56)$$

$$D_{OF} = D_o \left[ 1 + \frac{R f (D_o - F)}{F^2 - R f (D_o - F)} \right]$$  \hspace{1cm} (57)$$

Or alternatively and equivalently:

$$D_{ON} = \frac{F^2 D_o}{F^2 + f R (D_o - F)}$$  \hspace{1cm} (58)$$

$$D_{OF} = \frac{F^2 D_o}{F^2 - f R (D_o - F)}$$  \hspace{1cm} (59)$$

Where:
Another approach to calculating depth-of-field can be approached by considering the smallest acceptable imaging angle as defined by the resolution limit. This approach allows the use of a small angle approximation where the sine or tangent of an angle can be replaced by the angle itself. Since the imaging angle subtended by the circle of confusion in any practical imaging system is so small, this approximation has negligible error.

Notice that:

\[ \omega = \frac{R}{D_I} \]  \hspace{1cm} (60)

Where:

\[ \omega \] is the imaging angle subtended by the resolution limit or circle of confusion
\[ D_I \] is the image distance

From similar triangles:

\[ \omega = \frac{R_O}{D_O} = \frac{R_F}{D_O - \Delta_F} = \frac{R_N}{D_O - \Delta_N} \]  \hspace{1cm} (61)

And:

\[ \frac{D}{D_O} = \frac{R_N}{\Delta_N} = \frac{R_F}{\Delta_F} \]  \hspace{1cm} (62)

Where:

\[ D \] is the aperture diameter \((= F / f)\)
Combining the equations and substituting $M_i D_O$ for $D_i$ gives:

\[
D_{ON} = D_O \left( 1 - \frac{R}{D M_i + R} \right) \tag{63}
\]

\[
D_{OF} = D_O \left( 1 + \frac{R}{D M_i - R} \right) \tag{64}
\]

These equations express the depth-of-field in terms of object distance ($D_O$), resolution ($R$), magnification ($M_i$), and aperture ($D$).

Further examination of the depth-of-field shows that it is primarily dependent on the magnification, f-number, and acceptable blur circle. The focal length of the lens has very little effect. Therefore, changing the lens’ focal length while maintaining the same magnification does not appreciably affect the depth-of-field.

**SCHEIMPFLUG CONDITION**

In developing the imaging concepts to this point, the object and image planes have been parallel. However, there are situations where this is not the case. A classic example is the tourist’s picture of a skyscraper that shows perspective distortion. The photo has two problems. One is the perspective distortion that makes the nearer features at the bottom of the building larger in the image than features further away at the top of the building. Another problem is that depth-of-field limitations may prevent the entire building from being in focus; the middle of the building may be in focus while the top and bottom are out of focus.

The Scheimpflug condition addresses the depth-of-field problem. This principle states that for optimum focus the object plane, the principal plane of the lens, and the image plane must all intersect along a common line. Normally, all three of these planes are parallel; they intersect at infinity. In the case of the photo of the skyscraper, the object plane (the front of the building) is no longer parallel to the image plane nor the principal plane of the lens. Hence, the camera has focusing problems. View cameras are made with provision to tilt the lens to satisfy the Scheimpflug condition.
It should be noted that while tilting the lens gives good focus, it exacerbates the perspective distortion.

Any time the object and image planes are not parallel, the image will have perspective distortion. To eliminate the perspective distortion in the picture of the skyscraper, the film plane (image plane) needs to be parallel to the front of the building. Of course, it is no longer practical to image the entire front of the building – unless the lens is moved upward while leaving the film plane stationary. Again, view cameras are made to allow the lens to “swing” (be offset) to handle this situation without perspective distortion. Again, all three planes (object, principal, and image) are parallel satisfying the Scheimpflug condition. However, the centerlines of the planes are offset.

In theory, the lens forms an image plane that extends to infinity in all directions. Of course, in practice, this is far from true. Each lens design has an image size that it is designed to cover called an image circle or illumination circle or circle of good definition. When the lens is offset and the image plane translated, the required image size is larger. Therefore, if the image is offset by very much, a lens designed to cover a much larger image size must be selected.

Also, aberrations generally increase with the image angle. Using an offset lens increases the image angle and may well increase aberrations in the image.
A lens refracts light rays emanating from a point to converge to a point called the focus. Characteristics of a simple thin lens are its focal length \( F \) and its diameter \( D \). From these characteristics, it is possible to determine, for a specific imaging situation, the object height \( H_O \), the image height \( H_I \), the object distance \( D_O \), the image distance \( D_I \), the lateral or image magnification \( M_I \), and the f-number \( f \).

Useful equations:

\[
M_I = \frac{H_I}{H_O} = \frac{D_I}{D_O}
\]  

\[
F = \frac{D_O M_I}{1 + M_I}
\]  

\[
D_O = F \frac{1 + M_I}{M_I}
\]  

\[
F = \frac{D_I}{1 + M_I}
\]  

\[
f = \frac{F}{D}
\]  

\[
R = 1.22 \lambda f
\]  

\[
d = \pm \frac{R f}{M_I^2}
\]

A lens’ f-number determines its light gathering ability, the amount of diffraction affecting the image, and the depth-of-field. It also strongly influences aberrations. The light gathering ability of a lens is inversely proportional to the square of the f-number. Another expression for a lens’ light gathering ability is the numerical aperture (NA).

The light gathering ability of a lens decreases as the object or rays move away from the optical axis by the cosine of the angle to the fourth power.
For a given imaging setup, there is an invariant, called the optical invariant or the Lagrange invariant, that is the product of the distance from the lens of the object or image with the tangent of the imaging angle. This means that it is not possible to vary the distance without also varying the of the cone of light brought to a focus.

Another constant, étendue or throughput, is related to the optical invariant. Étendue is the solid angle subtended by the lens with the area imaged. It says that it is not possible to create a perfectly collimated light beam from a light source of finite size.

Because a lens is finite in size, there is diffraction at the edges. This diffraction causes a point in object space to be imaged as a diffraction pattern called the Airy disk. The diameter of the Airy disk limits the image’s sharpness. The size of the Airy disk depends on the wavelength of light and the lens’ f-number. The resolution limit of a lens due to diffraction is given by:

\[ R = 1.22 \lambda f \]  

A lens produces aberrations – errors that degrade the quality of the image. Principal aberrations are field curvature, spherical aberration and coma, chromatic aberration, distortion, and astigmatism. For a specific lens, most aberrations can be reduced by using a higher f-number. When the effects of aberration are less than the effect of diffraction, the lens is said to be diffraction limited.

Field curvature is not considered a problem for lenses designed to image very distant scenes. Lenses that are designed to work at closer distances have an extra lens element included to flatten the field and are called flat field lenses.

Spherical aberration and coma result from the lens’ surface shapes approximating the ideal shape. Lenses with specially shaped surfaces, called aspheric, can reduce spherical aberration. Also, by combining lens elements together, spherical aberration and coma can be reduced.

Dispersion causes chromatic aberration. Lens designs incorporate multiple lens elements, each fabricated with a material with different dispersion, to mitigate chromatic aberration.

Distortion is a change in effective magnification as a function of the field angle from the center of the image.

Astigmatism is an effect where the best focus of a line by a lens depends on the direction of the line.
The resolving ability of a lens is a function of both diffraction and aberrations, and both diffraction and aberrations are affected by the f-number. For any lens, there will be some f-number that produces the best compromise between diffraction and aberrations and gives the best resolution.

Depth-of-field is the range of object distances over which a scene will appear to be in sharp focus. It is dependent on the blur circle, or circle of confusion, as compared to the resolving capability of the image sensor. The blur circle is affected by diffraction, aberrations, and defocus. One expression for depth of field considering only geometric optics (and ignoring diffraction and aberration) is:

\[
D_{ON} = D_0 \left[1 - \frac{R_f (D_0 - F)}{F^2 + R_f (D_0 - F)}\right] \tag{73}
\]

\[
D_{OF} = D_0 \left[1 + \frac{R_f (D_0 - F)}{F^2 - R_f (D_0 - F)}\right] \tag{74}
\]

The Scheimpflug condition states that the object plane, the principal plane of a lens, and the image plane must all intersect along a common line for correct focus. An offset lens may be used to image an offset object without causing perspective distortion.
QUIZ

1) Which are characteristics of a lens:
   a) Focal length
   b) Diameter
   c) Object distance
   d) Both a and b

2) For simple ray tracing of a lens, light rays appear to bend at:
   a) The principal plane(s)
   b) The focal points
   c) The image plane
   d) A plane at the surface of the lens

3) Image magnification is:
   a) The ratio of image height to object height
   b) The ratio of object height to image height
   c) The ratio of image height to object distance
   d) The distance from the lens to the object

4) A lens’ f-number determines or significantly influences:
   a) Light gathering ability
   b) Aberrations
   c) Depth-of-field
   d) All of the above

5) If an f-number doubles, the light gathered by the lens will:
   a) Not change
   b) Double
   c) Decrease by a factor of 2
   d) Decrease by a factor of 4

6) The criteria that explains why it is not possible to achieve perfect collimation is:
   a) Étendue
   b) Magnification
   c) Aberrations
   d) The Scheimpflug condition
7) Because of diffraction at the edges of a lens, a point in object space appears as a diffraction pattern in the image called the:
   a) Airy disk
   b) Blur circle
   c) Circle of confusion
   d) f-number

8) Among aberrations affecting lenses are:
   a) Spherical aberration
   b) Chromatic aberration
   c) Distortion
   d) All of the above

9) A flat field lens:
   a) Eliminates field curvature
   b) Has flat surfaces
   c) Eliminates the cosine to the fourth effect
   d) Can only image flat scenes

10) Chromatic aberration is caused principally by:
    a) Dispersion
    b) The natural tendency for light of different wavelengths to separate
    c) Mistakes in manufacturing a lens
    d) No one really knows

11) Depth-of-field is affected by:
    a) The f-number
    b) Magnification
    c) The resolving capability of the image
    d) All of the above

12) The Scheimpflug condition states:
    a) The object plane, lens’ principal plane, and image plane must intersect to achieve focus
    b) The object and image planes must always be parallel
    c) Resolution decreases away from the center of the lens
    d) Perspective distortion can be corrected with good focus
When a machine vision practitioner successfully employs optical components, they must apply their understanding of the principles of optics. This section covers optical components commonly used in machine vision, and the optical considerations that go with their selection. One exception is lenses that are covered in the previous section on imaging.

The coverage of components starts with coatings. While one might remark that a coating is not a component of and by itself, coatings are integral to almost all optical components. Coatings enhance reflection where it is desired, diminish reflection where it is disadvantageous, create filters for spectral selectivity, and on occasions provide protection for otherwise delicate surfaces.

Other components covered are windows, mirrors, prisms, beamsplitters, filters, and polarizers.

**COATINGS**

Coatings are used on optical materials to:

- Reflect light
- Reduce reflections (anti-reflection)
- Selectively transmit or reflect wavelengths (filter)
- Protect delicate surfaces

Materials used in coatings include metals and dielectrics. Dielectrics are electrical insulators, and, like glass, they are often transparent. Metals in the very thin layers used in optical coatings may be opaque or partially transparent.

Many of the optical components purchased by machine vision practitioners will be coated. In specifying custom optics, the practitioner needs to consider the need for coating to achieve satisfactory system performance. Finally, depending on the materials involved, coated optics may be more durable than uncoated optics or they may need special handling and cleaning techniques.

![Figure 88 – Reflectance of Silver](image)
**Reflective Coatings**

Most common reflective coatings are metallic. Metallic coatings have the advantage of being spectrally broadband. Typical coatings are aluminum, gold, and silver. It is common to overcoat the metals with a dielectric to prevent corrosion, provide mechanical protection against damage, and to enhance the reflectance.

Silver is more reflective than aluminum in the visible and near-infrared regions. However, silver oxidizes very quickly. Silver is used only on second surface mirrors and on prisms. With second surface mirrors, the reflection is off the metal in contact with the substrate where it does not corrode. Where silver is chosen for use on a first surface reflector, it is protected from corrosion and damage with a dielectric overcoat.

Aluminum is highly reflective; reflecting between 85% to more than 95% of the incident light. It is efficient in the visible, near-infrared, and near-ultraviolet range. However, aluminum oxidizes, and the oxide reduces the aluminum’s reflectance significantly in the ultraviolet and causes scattering throughout the spectrum.
Protected aluminum is a coating of aluminum that in turn is coated with a protective film such as silicon monoxide. The coating protects the aluminum from oxidation and prolongs the high reflectance.

Enhanced aluminum is a coating of aluminum overcoated with multiple layers of dielectrics. This coating not only protects the aluminum but also enhances its reflectance in the visible regions. The enhanced visible reflectance is gained at the expense of reduced reflectance in the near-infrared and near-ultraviolet regions.

Gold is widely used as a reflector in the infrared region. In the mid-to far-infrared spectrums, its reflectance is better than 99%
**Anti-Reflection Coatings**

Many optical systems have numerous surfaces. A modern lens can consist of five or more elements, many of the element surfaces have air to glass interfaces. With 4% of the light lost to reflection off an uncoated element surface, light loss could easily exceed 30 percent in one lens assembly if the individual elements were not anti-reflection coated.

Coating the lens with a thin film, usually a quarter wavelength, of a dielectric with an index of refraction between the air and glass, reduces total reflection. Not only does the lower index of refraction cause less light to be reflected, but also the quarter wave thickness causes the light reflected off the second interface with the coating to be 180 degrees out of phase with the reflected light from the first surface. These two reflections tend to cancel, further reducing the total reflected light.

A coating of magnesium fluoride can reduce surface reflectance to less than 1.5% over the visible spectrum. Multilayer coatings can reduce reflectance to less than 0.1% at selected wavelengths.

**WINDOWS**

Windows are plates of transparent material, usually glass, but other materials, such as quarts and sapphire, are used outside of the visible spectrum. Normally a window is used to protect an optical system from the external environment. Windows seal optics from dust, dirt, moisture, and heat or cold.
When a window is placed in the optical path, it becomes an element of the optics and affects optical performance. There are two effects a window has on the optical path that should be appreciated. One is the window lengthens the optical path and the other is the window adds spherical aberration.

**Lengthening the Optical Path**

Because of refraction, the optical path will be longer when light passes through a window. The increased length depends on the index of refraction of the window and the angular range of the light rays.

It is possible to work from the known angles of incidence, the indices of refraction, and the thickness of the window to calculate an exact distance the presence of the window will add to the optical path. Most optical engineers, though, use a simple approximation. The window has its index of refraction, air is assumed to have an index of refraction of 1 (actual value is around 1.003, but varies with humidity and ambient pressure), and the angle of incidence is assumed small so the sine of the angle is just the angle itself. Then the distance added to the optical path length is:

\[
D_p = T \left(1 - \frac{1}{n'}\right)
\]  

(75)

Where:

- \(D_p\) is the added distance to the optical path length
- \(T\) is the thickness of the window
- \(n'\) is the index of refraction of the window

**Spherical Aberration**

If the expression for the increase in optical path length is fully developed, it will show that the increase is a function of the angle of incidence. Therefore, rays converging to a focus will be refracted so that they will no longer converge to a focus. Thus, if a window is placed in an imaging path, as is common, it will contribute some degree of spherical aberration.
One solution to this problem that is common in sophisticated optical systems is to design the lens and window together. By that means, the lens corrects for the spherical aberration introduced by the window. Biological microscope objectives use this approach. They are designed to work with a specific thickness cover glass over the specimen. If the cover glass is not used, the microscope objective will not deliver optimum performance.

Generally, the closer the window is to the lens, and the thicker the window, and the greater the working f-number, the greater is the contributed spherical aberration by the window. The means of coping would be to keep as much distance between the lens and the window as possible. However, this usually requires a larger window that, for mechanical reasons, must be thicker. As long as the angle-of-view is reasonable (e.g., no wide-angle lenses), the spherical aberration introduced by a window is much less of a problem for the imaging than would exist without the window’s protection.

It should also be noted that because of dispersion, the window also adds some chromatic aberration in an imaging path.

**MIRRORS**

Everyone is familiar with household mirrors that have the reflective coating on the back of the mirror. These are rear surface or second surface mirrors. High quality imaging systems use front surface mirrors also called first surface mirrors where the reflective coating is on the front of the mirror.

Mirrors are used in optical systems mainly to aid in achieving packaging density by folding the optical path. Thus, a long optical path can be folded with mirrors to fit into a more compact space. The machine vision practitioner may fold the path of the illumination or the imaging or both.

While most mirrors are flat, curved mirrors are used. One common use of a curved mirror is in concentrating illumination. Many projector lamps come with integrated prefocused mirrors that concentrate the light from the filament onto a region of specified size at a specified distance from the lamp. Another use for curved mirrors is in imaging. Many telescope and long focal length lens designs use spherical or parabolic mirrors as optical elements. When used for imaging, mirrors are free from chromatic aberration, but still contribute to other aberrations such as spherical aberration.
When a flat mirror is used in the imaging path, surface flatness is very important. Any deviation from flatness will distort the reflected wavefront and contribute to aberrations in the image. Mirror surface flatness is usually specified in fractions of a wavelength. The wavelength is the test wavelength. For example, a mirror with a flatness of $\frac{1}{4} \lambda$ when tested at a wavelength of 632.8 nm will have a surface deviation from flat that is no more than $632.8 / 4 = 158.2$ nm. To understand the degree of flatness required to avoid significant aberration takes careful optical system design.

**Second Surface Mirrors**

A second surface mirror has the reflective coating on the back surface. The reflective coating is overcoated with a protective material to minimize oxidation and handling damage.

Second surface mirrors are very durable. Because their reflective surface is well protected, they can be cleaned without undue care. However, they suffer from ghost reflection from the front surface. While the ghost reflection can be reduced with an anti-reflection coating, this makes the mirror more expensive.

Second surface mirrors are very satisfactory for folding the illumination path where a ghost reflection is not an issue.

**First Surface Mirrors**

First surface, or front surface, mirrors have the reflective coating applied to the first surface of the mirror. Therefore, there is no ghost reflection, and image quality is much improved over second surface mirrors. The compromise is that the reflective coating is now exposed to damage by the environment, handling, or cleaning.
PRISMS

A prism is any transparent optical object that has flat non-parallel sides. There are many different shapes of prisms. While the most well-known use of a prism is to break a beam of white light into its component colors, in machine vision, the common important characteristic is total internal reflection.

When used as a reflector in an optical path, the optical thickness of the prism, the distance the light travels through the glass or other material, is relatively long. This causes the same effects as discussed for windows above: the optical path length increases, and the prism can introduce spherical and chromatic aberration.

Prisms most commonly used in machine vision are: right-angle, roof, penta, and dove.

Right-Angle and Roof Prisms

The right-angle prism is a simple structure consisting of two plane surfaces at right-angles to each other with a third plane surface as the hypotenuse of a triangle at 45 degrees to the other two surfaces. A roof prism is just a right-angle prism with the edges ground off. Both prisms mirror the image top to bottom when it is reflected. The roof prism also flips the image side-to-side so that the resulting image still reads correctly.

The most common use of this prism is as a reflector. Light that enters one face of the prism reflects off the long surface and exits the other face. The right-angle and the roof prisms have the advantages of a second surface mirror, but without the drawback of ghost reflection. Like an image reflected off a mirror, the image is reversed when reflected off a right-angle prism.

When used in an application where the incident light has a large angle of included rays, some of the rays may not cause total internal reflection. Also, any damage to or dirt on the hypotenuse face where reflection takes place will degrade the performance of the prism. For this reason, many right angle and roof prisms have their hypotenuse faces coated with a reflective coating similar to a second surface mirror.
**Penta Prism**

The penta prism is used as a reflector similar to the right-angle prism except that since there are two internal reflections, the image is not reversed upon reflection. Also, where the alignment of the prism is critical, the penta prism always reflects light at right angles regardless of small errors in rotation.

**Dove Prism**

The dove prism is used for rotating an image. As the prism is rotated, the image transmitted through the prism rotates with twice the angle. The restriction on the dove prism is that the light bundle must be nearly collimated. This requires a high working f-number and may not be suitable for a system where light sensitivity is an issue. Having a substantial additional amount of glass, the dove prism has the potential to introduce significant spherical aberration. However, a nearly collimated light bundle reduces this effect, and with a well-designed system, spherical aberration is not a problem.
**BEAMsplitters**

The purpose of a beamsplitter is to reflect some light and transmit some light. Beamsplitters are designed for specific applications.

A common beamsplitter is a two-way mirror. The mirror is partially reflective. A portion of the incident light is transmitted and a portion reflected. In machine vision, the most common use is in directing illumination coaxially with the imaging path.

Beamsplitters are designed with specific ratios of reflectance and transmission. The 50:50 beamsplitter, where 50% of the light is reflected and 50% transmitted, is the most common, but other ratios are available. Changing the angle at which the beamsplitter is used will change its ratio of transmitted to reflected light.

The most common beamsplitters are plate, pellicle, cube, and polka-dot.

**Plate Beamsplitter**

Plate beamsplitters are made by depositing a semitransparent coating on one side of a glass plate. These beamsplitters suffer from ghost reflections off the uncoated side, but those ghost reflections can be reduced substantially with an anti-reflection coating. Due to Fresnel reflection, the plate beamsplitter has a preferred direction of polarization. If the incident light is unpolarized, the reflected and transmitted light will be partially polarized. If the incident light is polarized, the ratio of reflected and transmitted light will be affected by the direction of the polarization.

Care must be taken when handling the plate beamsplitter to not damage the reflective coating. It must be protected from external hazards when installed in the optical system.
**Pellicle Beamsplitter**

The pellicle beamsplitter overcomes the problem of ghost reflections by using a tightly stretched plastic film, usually nitrocellulose, with a thickness of only about 5μm. This is so thin that the ghost reflection is only displaced 7μm from the principal reflection. The plastic film is usually coated to control the ratio of reflection and transmission.

The pellicle beamsplitter is very delicate. The pellicle must not be touched; it can be deformed or damaged with even the slightest touch. Cleaning a pellicle beamsplitter is limited to the use of a very gentle flow of clean, dry air.

Pellicles can vibrate when subject to transmitted mechanical shock or vibration. This vibration will substantially degrade the performance of any optical system in which they are installed. Usually, pellicle beamsplitters are used only in specialized instruments where their environment can be closely controlled.

**Cube Beamsplitter**

A cube beamsplitter consists of two prisms cemented together to form a cube. One of the contacting surface of one of the two prisms is coated with a partially reflecting coating. This beamsplitter has the advantages of being very rugged; mechanically, it can withstand rough handling, and the reflective surface is protected from damage.

Cube beamsplitters can contribute significantly to spherical aberration. They are best used in optical systems that include them in the design of the lenses or in optical systems where the light is very nearly collimated.
Polka-Dot Beamsplitter

A polka-dot beamsplitter is a glass plate with an array of very small reflective dots with each dot surrounded by clear (transmissive) glass. It has the advantage of being very spectrally broad, and its reflection to transmission ratio is almost independent of the orientation angle of the beamsplitter. However, the dot pattern creates an array of apertures, each contributing to diffraction. Such a beamsplitter might compromise a system’s resolution based on increased diffraction.

FILTERS

Filters reduce the light’s temporal (wavelength), or intensity properties. The machine vision practitioner will certainly need to use filters to improve contrast and to optimize the optical performance of the systems they design.

This section covers absorptive filters, interference filters, and neutral density filters.

Absorptive Filter

Absorptive filters are made from glass doped with metallic salts or from dyed gelatin. Their transmittance is a property of the material and its thickness and is a function of wavelength. With absorptive filters, the transition between wavelengths that are transmitted and those that are absorbed is not sharp.

Glass filters have reasonably stable properties; gelatin filters tend to change when exposed to light for a long time especially ultraviolet light.

Glass and gelatin filters are ordered from a catalog. The only practical customization is specifying the shape, and, for glass filters, the thickness which affects its transmissivity across the spectrum.

For the most part, these filters absorb light and convert it to heat. In the imaging path, the incident light energy is usually so low, that heating of the filter is not discernable. When filters are used in a light source, the light energy can be significant, and heating of the filter can become a concern. Some absorptive filters fluoresce when exposed to ultraviolet.
Transmittance of absorptive filters is specified for rays normal to the filter. Light rays passing through the filter at an angle will pass through an increased thickness determined by the angle of incidence and the index of refraction of the filter material. Attenuation of the light energy increases as the thickness of the optical path increases. While there will be no wavelength shift, the attenuation will increase, both in-band, and out-of-band, for light rays incident at an angle. In most optical systems, the bundle of light rays is either converging or diverging. So, most of the light energy will be incident on a filter at some angle. An absorptive filter will generally have somewhat greater attenuation in an optical system than predicted from the filter’s specification.

**Interference Filter**

A Fabry-Perot resonator can be constructed from two metal plates separated by a known distance. Consider the metal plates to be thin semi-transparent metal coatings, and the space a layer of dielectric with an optical distance \( n D \); the index of refraction times the physical distance) equal to 1/2 of a specific desired wavelength. This structure is sometimes called *metal-dielectric-metal* (MDM) structure.

Light of the desired wavelength is incident on the resonator; some enters and some is reflected. For the light that enters the resonator and reaches the other metal layer, again, some is transmitted and some is reflected. The light reflected off the second layer arrives back at the first layer where some is reflected and some transmitted; and so forth.

![Figure 109 – Fabry-Perot Resonator](image)
Because the reflected light travels a round trip of one wavelength, but undergoes a phase inversion upon reflection, the portion that is again transmitted out of the first layer is out of phase with the light reflected off the first layer. Continuing the analysis, the incident light reflected off the first layer undergoes destructive interference, and the light that is transmitted through the second layer undergoes constructive interference. The result is the resonator reflects nearly none of the light energy at the desired wavelength but transmits nearly all of that light energy.

Other wavelengths are not in or out of phase after reflection or transmission. The result is much of the energy at other wavelengths is reflected, and little transmitted. The Fabry-Perot resonator produces transmission peaks at the design frequency and each integral multiple of the frequency.

Interference filters are constructed of a stack of thin dielectric and metal layers on a substrate. The indices of refraction and thickness of the layers are chosen to tune the filter. Unlike absorptive filters, the interference filter transmits selected wavelengths, and reflects all other light. Very sharp and very narrow passbands are possible with interference filters. Quite a number of companies specialize in producing custom interference filters to specific customer requirements.

Because the frequency response of the filter is dependent on the thickness of the layers, the responsivity must be specified for a particular angle of incidence, usually normal to the surface. At other angles of incidence, the effective path length through the layers increases and the relative phase of the light also changes. The result is a shift in the filter's frequency response toward shorter wavelengths. The exact amount of wavelength shift depends on the materials from which the filter is made. This phenomenon is sometimes used to “tune” a filter by tilting or rotating it. As noted above, most optical systems have bundles of light in which the rays are converging or diverging. Therefore, most light does not pass through the filter normal to the surface. For this reason, interference filters in an optical system will normally exhibit a response very slightly higher in frequency than that specified for the filter.

![Figure 110 – Interference Filter](image-url)
Neutral Density

There are neutral-density filters that are designed to attenuate the transmitted light by some specific amount and be relatively independent of wavelength. Usually, the filters are made of semi-transparent metal evaporated onto a glass substrate.

The neutral-density filters are often supplied with calibration charts and are used in laboratory setups to provide controlled attenuation of light. One use of this is to carefully measure the dynamic operating range of an optical system without changing any parameter other than light intensity. Another example is the adjustment of intensity without changing a lens’ f-number, and thereby maintaining constant resolving power.

POLARIZERS

One of the properties of light discussed earlier was polarization. In discussing reflection, it was shown that reflection has the potential to alter polarization of light, either for the better or the worse. Because the machine vision practitioner has to deal with polarization, either by default or by design, to enhance some characteristic of the scene, it is useful to understand a bit more about how polarization can be created and controlled. This section briefly covers polarizers, their properties, and birefringent materials that affect polarization.

Polarizers have the effect of transmitting light of one polarization (or the component having the preferred polarization) and either reflecting or absorbing light of the opposite polarization.

Wire Grid Polarizer

Perhaps the least complex polarizer to understand is the wire grid polarizer. If a grid of wires is constructed where the spacing of the wires is less than the wavelength of light, only light with the electrical field polarization perpendicular to the wires passes. This construction is common for polarizers for longer wavelength light in the mid- to far-infrared.
For shorter wavelength light, a polarizer is often made of a stretched plastic that is then dyed. The strain from stretching causes the plastic's molecules to align along the lines of strain. The dye attaches itself to the aligned molecules and creates a structure which is optically similar to the wire grid, but with spacing on the molecular level. Light with electric field polarization parallel to the direction of strain is absorbed by the dye; light with perpendicular electric field polarization is transmitted.

Components constructed to take advantage of Brewster’s angle are also used as polarizers.

Common measurements of the effectiveness of polarizers include the transmittance and extinction ratio. The transmittance for unpolarized light is expected to be no greater than 50% for a good polarizer. However, for linearly polarized light correctly aligned with the polarizer, the transmittance can be much higher. As with all optical components, the transmittance is a function of wavelength and the specific materials used.

The extinction ratio is a measurement of the quality of polarization. It is the ratio of the transmitted light energy of opposite polarizations. For a perfect polarizer, the extinction ratio is zero. The extinction ratio varies with wavelength; practical polarizers are optimized for certain spectral wavelengths.

**Birefringence**

The physical properties of certain materials vary with direction. For example, in calcite, quartz, and mica the index of refraction is different for different orientations in the material. An optic axis in these materials is defined as the axis of symmetry -- parallel to the plane in which the index of refraction varies. Thus, light traveling along the optic axis is not influenced by different indices of refraction.
If an unpolarized beam of light is normal to the surface of a cube of one of these materials, and not parallel to the optic axis, some components of the light propagate faster than other components. Two beams emerge from the material. One beam, the ordinary ray, passes straight through and has one direction of polarization. The other beam is displaced laterally and has the other direction of polarization. It is the extraordinary ray because it appears to violate Snell's law.

Birefringent materials can be used to construct polarizers. They can also be used to construct other useful optical components.

**SUMMARY**

Coatings are used to reflect light, reduce light reflection, and filter light. Coatings are thin layers of metals and dielectrics (transparent insulators). A great percentage of optical components are coated.

Reflective coatings include silver, which tarnishes; protected silver, which has a protective coating to prevent tarnishing; aluminum, which can oxidize; protected aluminum, which has a protective coating to prevent oxidation; enhanced aluminum, which has coatings that boost its reflectivity in the UV; and gold, which is very reflective in the IR.

Anti-reflective coatings consist of one or more thin layer of dielectrics that have an index of refraction mid-way between the two materials. The lower change in index of refraction reduces the reflected light. The thickness is also controlled to be about one-quarter of the wavelength of light. This causes the reflected light to destructively interfere with the incident light and cancels out some of the reflected energy. Magnesium fluoride is a common anti-reflection coating material.

Windows are used to protect optical systems from the environment. A window is an optical element; it affects the optical performance of the system. Windows lengthen the optical path and can add spherical aberration.
Mirrors are used to fold optical paths. Back surface mirrors are durable and suitable for folding the illumination path, but not usually suitable for folding the imaging path because of ghost reflections. First surface mirrors are preferred for folding the imaging path because they don’t have ghost reflections; however, and they are more delicate.

Prisms are transparent optical components with flat parallel sides. They are most often used as reflectors in imaging systems. Prisms are rugged, but because of the thickness of the glass, they lengthen the optical path and can contribute to increased spherical and chromatic aberration.

Right-angle and roof prisms have two surfaces at right angles to each other and a hypotenuse surface at 45 degrees to the other two surfaces. Light enters one of the surfaces, reflects off the hypotenuse, and exits the other surface. These prisms reverse the image, top-to-bottom, on reflection; the roof prism also flips the image right-to-left.

Penta prisms also reflect light at right angles. Because there are two reflections, penta prisms do not reverse the image. Penta prisms are also less sensitive than right-angle prisms to their angular orientation to achieve right angle reflection.

Dove prisms are used to rotate an image. However, the light bundle must be nearly collimated for a dove prism to work without corrupting the image.

Beamsplitters are designed to reflect some light and transmit the rest of the light. Typically, beamsplitters reflect 50% of the light and reflect 50% of the light, but other ratios are possible. They are typically positioned at 45 degrees to the optical path. The most common use in machine vision is to create coaxial illumination.

Plate beamsplitters are a plate of glass with a semitransparent coating on one surface. They can create ghost reflections.

Pellicle beamsplitters are extremely thin sheets of coated plastic. They are very delicate and are subject to mechanical vibration.

Cube beamsplitters are a pair of cemented right-angle prisms with a semitransparent coating at the joined surface. They are very rugged, but can contribute spherical and chromatic aberration.

Polka-dot beamsplitters are glass plates with an array of closely spaced very small reflective dots. Their ratio of reflectance to transmission is largely unchanged by the angle of the incident light. They can contribute diffraction errors to an image.
Common filters used in machine vision include absorptive filters, interference filters, spatial filters, and neutral density filters.

Absorptive filters may be glass or gelatin. They are constructed to absorb certain wavelengths of light, converting the energy to heat, and transmit other wavelengths. Absorptive filters are used for limiting the wavelengths that are used by a vision system. Glass filters have good long term stability; gelatin filters do not.

Interference filters are built from successive thin films of metals and dielectrics. They transmit certain wavelengths and reflect others; in principle, no energy is absorbed.

Neutral density filters attenuate the light uniformly across the specified spectrum. They can be used for experimentation and testing optical setups.

Polarizers transmit light energy having the desired polarization direction. Common polarizers are made as a grid of absorbers or reflectors. The grid may be either fine closely spaced wires for long wavelength light or dyed molecules for light nearer the visible spectrum.

A transparent material may be used as a polarizer for light reflected at Brewster’s angle. Polarizers can also be made from birefringent materials.

Two important characteristics of a polarizer is its transmittance, the percentage of unpolarized light it transmits, and its extinction ratio, the amount of cross polarized light it blocks.

A birefringent material is one in which the index of refraction differs for different directions of polarization.
QUIZ

1) Which of the following metals is/are used for reflective coatings:
   a) Silver
   b) Aluminum
   c) Gold
   d) All of the above

2) Anti-reflection coatings work by:
   a) Reducing the index of refraction mismatch
   b) Causing destructive interference of the reflected energy
   c) Creating a barrier so reflected light cannot escape
   d) Both a and b

3) A window is most likely used to:
   a) Protect optics from the environment
   b) Make an optical system look better
   c) Improve the performance of an optical system
   d) All of the above

4) A window can contribute to:
   a) Spherical aberration
   b) Chromatic aberration
   c) Distortion
   d) All of the above

5) Which of the following is NOT a disadvantage of a second surface mirror:
   a) Causes spherical aberration
   b) Creates ghost reflections
   c) Creates distortion
   d) Affect light polarization

6) Which of the following is an advantage of a first surface mirror?
   a) No ghost image
   b) Eliminates chromatic aberration
   c) Easy to keep clean
   d) Higher reflectivity
7) Which type of prism is NOT used to reflect light at right angles:
   a) Right-angle
   b) Roof
   c) Penta
   d) Dove

8) Prisms contribute to what kind(s) of optical effects:
   a) Path lengthening
   b) Spherical aberration
   c) Chromatic aberration
   d) All of the above

9) Which of the following beamsplitters is the most rugged?
   a) Plate
   b) Pellicle
   c) Cube
   d) Polka-dot

10) Which of the following beamsplitters would least affect the optical path:
    a) Plate
    b) Pellicle
    c) Cube
    d) Polka-dot

11) Which of the following is NOT a filter commonly used in machine vision:
    a) Spectral, absorptive
    b) Spectral, interference
    c) Neutral density
    d) HEPA

12) Absorptive filters may be made from:
    a) Glass
    b) Gelatin
    c) Both a and b
    d) Neither a nor b
13) Light not transmitted by spectral filter is:
   a) Absorbed
   b) Reflected
   c) Either a or b
   d) Neither a nor b

14) Which type of filter is made from alternating layers of metals and dielectrics:
   a) Absorptive
   b) Interference
   c) Spatial
   d) Neutral density

15) What filter is used to reduce light intensity without altering the spectrum:
   a) Absorptive
   b) Interference
   c) Spatial
   d) Neutral density

16) Which is NOT a way to make a polarizer:
   a) Wire grid
   b) Stretched and dyed plastics
   c) Light reflected at Brewster’s angle
   d) A sandblasted surface

17) When using a polarizer to block polarized light, which of the following characteristics is the most important:
   e) Transmittance
   f) Extinction ratio
   g) Thickness
   h) Color

18) A birefringent material has:
   a) Two outputs
   b) Polarization dependent index of refraction
   c) Scattering sites aligned with the optic axis
   d) Internal strain that polarizes light
SENSING LIGHT

After the machine vision practitioner has created an optical image, that image must be sensed before it can be digitally processed. While there are techniques for processing images in the optical domain, such techniques have not been able to be migrated into practical vision systems. The image sensor, therefore, becomes the final optical element in the vision system. It is necessary for the machine vision practitioner to understand how light interacts with the image sensor to be converted into an electrical signal.

SEMICONDUCTOR BASICS

A semiconductor is a material that is neither a good conductor nor a good insulator. Silicon, germanium, and even carbon in its diamond form are elemental semiconductors. All of these elements are in group four of the periodic table of elements. This means they have four electrons in their valance band.

Semiconductors can be made by combining equal parts of materials in group three and group five together. Gallium arsenide is a common III-V semiconductor. The same works for combining materials from groups two and six. The discussion in this section will concentrate on silicon because it is the easiest to understand and the dominant material for solid-state image sensors.

The characteristic that makes semiconductor materials work is that in their crystalline form all the valence electrons are bound in the crystal lattice, and not available to contribute to conduction. However, a modest amount of energy (e.g., incident photons) can elevate these electrons out of the valence band and into the conduction band.

To aid conductivity and to give the semiconductors special useful properties similar to a built-in electric field, the materials are selectively “doped” with “impurities” (also called dopants) from either group three or group five of the periodic table. This doping is at very small levels, on the order of parts per million. Where a group five atom, having five electrons in its valence band, displaces a silicon atom, four of its electrons are bound up in the crystal lattice, but the fifth is unattached and relatively mobile. This fifth electron can move and contribute to conductivity.
Likewise, when an atom from group three replaces a silicon atom, its three electrons in the valence band are tied up in the crystal lattice, leaving the lattice short one electron. This space in the lattice missing an electron is known as a hole. A wandering electron finds it very easy to fill the space in the hole but leaves a hole where it was previously located. In effect, the hole appears to move around in the material.

**LIGHT AND QUANTUM EFFECTS**

Modern image sensors are based on the effect light (photon) produces in a semiconductor. When a photon is absorbed by a material such as a semiconductor, the energy of that photon is transferred to the material. This transfer may create heat energy, or, as in the case of semiconductors such as silicon, the photon’s energy may transfer to an electron elevating it from the stable valence band to the mobile conduction band.

In any material, electrons can only have discrete energy levels. For an electron to move from one energy level, the valence band, to another level, the conduction band, requires that it either gain or lose a specific amount of energy. The difference between the energy levels is the band gap. Electrons are “forbidden” to have energy in this range. The band gap is a characteristic of the materials.

The band gap for silicon between an electron in the valence band and one in the conduction band is 1.14eV. Recall that the energy of a photon is given by $hc/\lambda$, and that shorter wavelength photons have higher energy. This tells us there is some wavelength below which photons have too little energy to excite electrons into the conduction band. For silicon, this wavelength is 1100nm. Therefore, silicon can have no measurable response to light with wavelengths longer than 1100nm. Light with wavelengths longer than 1100nm is either absorbed in the silicon generating heat or it is transmitted through the silicon (silicon is used to make lenses in the far IR). For wavelengths shorter than 1100nm, each absorbed photon raises one electron from the valence to the conduction band.
The energy of a photon is inversely proportional to its wavelength. So, for constant level of light energy, the number of photons is also inversely proportional to the wavelength, and the number of electrons elevated into the conduction band is also inversely proportional to the wavelength of the incident light.

Figure 115 shows the relative number of potential electrons that would be freed for constant incident light energy at the indicated wavelengths. Designers of image sensors specify the quality of their designs by the quantum efficiency where quantum efficiency is the fraction of the actual number of photo-generated electrons to the total possible number of electrons. Figure 115 represents 100% quantum efficiency. Any real photosensor will have a lower response than what is indicated in the graph for any number of reasons.

OTHER FACTORS AFFECTING PERFORMANCE

Some of the fundamental effects that reduce quantum efficiency are:

- Reflection off the sensor’s surface
- The photon’s penetration depth
- The ability of the sensor to capture the photo-generated electron

Surface Effects

If it were practical to have light incident on an uncoated silicon surface, with an index of refraction around 4, silicon would reflect about 36% of the incident light. However, it is not practical to have a bare silicon surface. The surface is covered with thin layers of material. Typical materials are silicon dioxide, silicon nitride, and polycrystalline silicon (polysilicon). These layers are necessary for fabricating and/or protecting the sensor. Because some of these layers have indices of refraction between air and silicon, they do work somewhat as anti-reflection coatings, albeit inefficient ones. The layers may also create interference filters that can reflect even more light energy at specific wavelengths. Then too, some materials like polysilicon will absorb some light energy. Image sensor designers use these layers and their thicknesses to help shape the sensor’s responsivity to different wavelengths of light. While every image sensor design differs in its surface construction, all sensors reflect or absorb a significant amount of the light energy at their surface, and that the light loss is a function of wavelength.
Penetration Depth

The depth to which a photon penetrates is based on the likelihood of absorption. That is, a photon may have a 50% probability of being absorbed in the first micron of penetration. If it succeeds in penetrating the first micron, it has a 50% chance of being absorbed in the second micron, and so forth. Thus, the probability of absorption is an exponential function of depth of penetration.

Photons that do penetrate into the silicon are absorbed at different depths depending on their wavelengths. The electrons absorbed by longer wave photons are more difficult to capture because the absorption takes place deeper into the silicon. Figure 117 shows the depth into silicon by which a photon has a 50% chance of being absorbed.

Capture of Photo-Generated Electron

When an electron is raised into the conduction band, it leaves a “hole” in the valence band. Left unaffected, the freed electron wanders around and eventually falls back into its own or another “hole” releasing its excess energy as heat. The distance over which the electron wanders is called the diffusion distance, and for an individual electron, is a statistical phenomenon. The diffusion distance is that distance at which the electron has a 50% chance of returning to the valence band. For lightly doped silicon, the diffusion distance is on the order of 30μm; for heavily doped silicon, the diffusion distance is much shorter.
If the electron freed by light is affected by an electric field, it will be propelled toward the positive side of the field and not recombine. The movement of the electron creates a photo-generated charge or current. A critical element of a semiconductor image sensor design is creating the field that will capture the photo-generated electrons. One major difference in image sensors is in how the depletion region is created.

The common characteristic of the sensing elements in silicon is that the electric field that captures the photo-generated electrons is associated with a depletion region. A depletion region is caused when a region of the semiconductor material is depleted of carriers (holes or electrons). To accomplish this, requires an electric field across the depletion region.

When a photo-generated is generated in the depletion region or when it reaches the depletion region in its travels, it will be captured as part of the charge or current. Generally, most electrons generated by short wavelength light are close to the surface of the photosensor and are captured. Photons in the near infrared can penetrate quite far into the silicon before being absorbed. The resulting photo-generated electrons are able to migrate into other photosensor sites and cause a degradation of the image. Highly doped regions are used to prevent this from happening.

**SUMMARY**

Almost all image sensors used in machine vision are made from silicon, a semiconducting material. Semiconductors are characterized by having four valence electrons or by a combination of elements where the average number of valence electrons is four.

The band gap in a semiconductor is the energy between the valence and the conduction bands. Every photon with an energy greater than the band gap has the ability to be raise an electron from the valence to the conduction band when it is absorbed. For silicon, photons with wavelengths 1100 nm and shorter have sufficient energy to photo-generate electrons.

For photons with sufficient energy, there is at best a one-to-one correspondence between incident photons and photo-generated electrons. For shorter wavelengths, photons are more energetic, and it takes fewer photons to achieve a given energy level. Therefore, shorter wavelength light potentially yields fewer photo-generated electrons.

When every incident photon generates a captured electron, the light sensor is said to have 100% quantum efficiency.

Factors that reduce quantum efficiency are surface reflections, the photon’s penetration depth, and the ability of the sensor to capture photo-generated electrons.
A photon’s penetration depth is a function of its wavelength. Shorter wavelength photons are absorbed at shallower depths. Longer wave photons may penetrate too deeply to contribute to captured photo-generated electrons.

A photo-generated electron must be captured with an electric field. The electric field is associated with a depletion region. A photo that frees an electron in a depletion region will be captured. An electron freed by a photon outside of a depletion region will travel some distance, statistically, the diffusion length, before being reabsorbed. If, in its travels, the photo-generated electron reaches the depletion region, it will be captured; otherwise, it will not contribute toward the sensed light.
QUIZ

1) Which of the following is not a semiconductor?
   a) Silicon
   b) Germanium
   c) Gallium arsenide
   d) Iridium

2) Semiconductors have how many electrons in their valence band:
   a) 2
   b) 3
   c) 4
   d) 5

3) The longest photon wavelength that can be sensed by silicon is:
   a) 1100 nm
   b) 1100μm
   c) 400nm
   d) 800μm

4) For equal light energy on an ideal silicon light sensor, light with 400 nm wavelength will have how much response compared to light with 800 nm wavelength?
   a) 200%
   b) 100%
   c) 50%
   d) 33%

5) Which of the following affects a light sensor’s spectral response?
   a) Films on top of the semiconductor
   b) The wavelength of the light
   c) The ability of the sensor to capture photo-generated electrons
   d) All of the above
6) For some wavelength, if 50% of the incident photons are absorbed when they reach a depth of 5μm in silicon, what percentage of the incident photons will be absorbed when they reach a depth of 10μm?
   a) 100%
   b) 75%
   c) 50%
   d) 33%

7) At which of the following wavelengths is a photon likely to penetrate the deepest into silicon?
   a) 250nm
   b) 500nm
   c) 800nm
   d) 1100nm

8) The diffusion distance is:
   a) The depth that impurities diffuse into silicon
   b) The distance of travel for a photo-generated electron where it has a 50% chance of being reabsorbed
   c) The depth to which light penetrates into a semiconductor
   d) The distance a photon travels before being reflected or refracted

9) Which of the following is needed for a photo-generated electron to be captured?
   a) An electric field
   b) A dielectric (insulator) over the surface of the silicon to prevent the electron’s escape
   c) A heavily doped region of semiconductor
   d) Nothing, all photo-generated electrons will be captured
Abbe v-value – A measurement of dispersion in optical glass or other medium. Specifically, it is \((n_d - 1)/(n_F - n_C)\); where \(n_d\) is the index of refraction at 587.6nm (the Fraunhofer d yellow helium line), \(n_F\) is the index of refraction at 486.1nm (the Fraunhofer F blue hydrogen line), and \(n_C\) is the index or refraction at 656.3 (The Fraunhofer C red hydrogen line).

aberration – Any error in an imaging device that prevents it from producing the theoretically best image whether through design limitations or fabrication errors. (See also astigmatism, chromatic aberration, coma, field curvature, distortion, and spherical aberration.)

absorption – Process by which light or other electromagnetic radiation is converted into heat or other radiation when incident on or passing through a material.

absorptive filter – An optical filter which transmits some light wavelengths and absorbs other wavelengths. The absorbed light energy is usually converted to thermal energy. When used over a lens, the thermally generated energy is usually negligible. When used over a light source, the thermally generated energy may be significant. Common absorption filters are made from dyed glass or from gelatin (plastic film). Liquids are also used as absorption filters in high energy situations.

achromatic – A neutral color that has no hue such as white, gray, or black.

achromatic lens – A lens consisting of two or more elements that has been corrected for chromatic aberration at two selected wavelengths.

aether – In medieval times a material believed to fill the region not occupied by solid material and conducted light and gravity. Also spelled ether.

airy disk – The image of a point source formed by diffraction-limited optics. The Airy disk appears as a bright central disk surrounded by alternately bright and dark rings. The size of the Airy disk is the diameter of the first dark ring. See also circle of confusion and point spread function.

angle of incidence – The angle between the axis of an light beam incident on a surface and the perpendicular to the surface at the point where the light beam strikes.
angle of reflection – The angle between the axis of a light beam reflected from a surface and the normal to the surface at the point of reflection.

anisotropic – A material or a surface that has different properties when light propagates along different axes (transmission) or when light is incident from different directions (reflection).

anti-reflection – Any treatment to reduce reflections from a surface. Typically, a thin coating applied to an optical surface to reduce reflectance and thereby increase transmittance. The coating may consist of one or more thin layers of different transparent materials.

aperture – 1) An opening that passes light, electrons, or other forms of radiation. 2) The effective diameter of a lens that controls the amount of light reaching the image plane. The aperture is usually specified by a f-number.

apochromat – A lens or optical system that has been corrected for chromatic aberration at three wavelengths.

apostlib – A photometric unit of illuminance which uses lumens instead of candelas to measure the luminous flux of a source.

appearance – The visual properties of a material or object; especially when relating to color matching.

aspheric – A surface which is not spherical. By inference, it is not flat (a sphere of infinite radius) or some other easily definable shape; it is usually shaped somewhat like a spherical surface. In optics, aspheric surfaces are used to correct for spherical aberration.

astigmatism – A lens aberration in which the best focus of an off-axis feature depends on the feature's orientation with respect to the optical axis. The effect is that the lens may not be able to focus both arms of a cross simultaneously.

barrel distortion – An effect that makes an image appear to bulge outward on all sides like a barrel. Caused by a decrease in effective magnification as points in the image move away from the image center.

beamsplitter – A device for dividing one light beam into two or more separate beams traveling in different paths.
birefringent – A material with the property where the velocity of light is different in different directions through the material. A significant effect is, for certain axis of the materials, light will be retarded differently depending on its polarization.

blur circle – The image of a point source formed by an optical system at the image plane. The size of the blur circle is affected by the quality of the optical system and its degree of focus. Defocussing a lens increases the blur circle. (See also Airy disk and circle of confusion.)

Brewster’s angle – For a transparent medium (dielectric), the angle of incidence for which the reflected and refracted rays are at right angles. The reflected light is polarized perpendicular to the plane of incidence.

brightness – 1) The total amount of visible light per unit area of an emitting surface. The same as luminance. The unit of measurement is the lambert. 2) Brightness is commonly used loosely and interchangeably with intensity to refer to the relative amount of light either emitted or incident.

candela – The unit of luminous intensity equal to one sixtieth (1/60) the luminous flux of a one square centimeter blackbody at the solidification temperature of platinum. Very roughly equal to the amount of light generated by one candle. Abbreviated cd.

CCTV – Acronym for Closed-Circuit Television.

chief ray – An oblique light ray that passes through the center of an aperture. Sometimes called principal ray.

chromatic aberration – An optical effect in an imaging device such as a lens which causes different colors (different wavelengths of light) to be focused at different distances from the lens. This also changes the lens’ magnification. The effect is due to dispersion in the lens material; the variation of index of refraction with wavelength. In some cases, it may be observed in the image as color fringes or halos near bright areas.

CIE – Acronym for Commission Internationale de l’Eclairage; the International Commission on Illumination. It is the standard setting body on matters such as the eye responsivity of a standard observer as well as color perception.

circle of confusion – In an image, the circle of image data produced from the image of a point due to diffraction limitations and aberrations when it is at its best focus. See also airy disk, blur circle, and point spread function.
**circular polarization** – The condition where light can be decomposed into two orthogonal linearly polarized beams of light of equal magnitude and differing in phase by $1/4$ wavelength.

**coaxial illumination** – Illumination which reaches the scene along the direction of the viewing axis.

**coherence** – Light in which the difference in phase between any two points in the field is constant while the light lasts. See also spatial coherence and temporal coherence.

**collimated light** – A light bundle in which the rays are parallel or so nearly parallel that the result is the same as if the rays were precisely parallel.

**color** – 1) A hue caused by a predominance of certain wavelengths of light over other wavelengths (a monomer) or by two or more dominant wavelengths (a metamer) that cause the perception of a single dominant wavelength (e.g., mixing yellow and blue to make green). 2) A perceptive phenomena characterized by hue, equivalent to the perceived predominant wavelength, and saturation, the perceived purity of the color. Usually characterized by a coordinate system such as the $x,y$ coordinates of the CIE color space. 3) Colloquially when referring to light, a synonym for wavelength which may include wavelengths outside the visible region of the spectrum.

**coma** – An aberration in imaging systems which makes a very small circle appear comet-shaped at the edges of the image with its tail pointing toward the center of the image. It is related to spherical aberration and can be decreased by using a smaller aperture.

**conduction band** – In a material, the energy level of an electron which is sufficient to allow the electron to become mobile and contribute to the conduction of electric current.

**constructive interference** – That portion of an interference pattern where the waves combine so as to add having a net resulting amplitude that is greater than any one of the waves.

**contrast transfer function** – A measure of the resolving capability of an imaging system. Shows the square-wave spatial frequency amplitude response of a system. See also modulation transfer function. The abbreviation for contrast transfer function is CTF.

**critical angle** – In optics, the angle with respect to the surface normal at which the refracted ray is parallel with the surface; the angle at which total internal reflection commences.

**CTF** – Abbreviation for contrast transfer function.
cube beamsplitter – A beamsplitter made from two right-angle prisms where the long sides are mated together such that a cube is formed. The mated long sides have a partially reflective coating so that some of the light is transmitted through and some is reflected at 90 degrees.

depth-of-field – The in-focus range (for objects) of an imaging system. With the image distance fixed, depth-of-field is the range of object distance variation through which a surface appears to be in sharp focus. For a given magnification, the depth-of-field depends only on the f-number of the lens, and not on the lens’ focal length.

depth-of-focus – The range of lens to image plane distance over which the image formed by the lens appears to be in focus with object distance held constant.

destructive interference – That portion of an interference pattern where the waves combine so as to cancel or have a net resulting amplitude that is less than any one of the waves.

dielectric – An electrically insulating material which transmits an electric field but not electric charge. Because light is electromagnetic, it is affected by a dielectric.

diffraction – The property of light where each point along a wavefront radiates a spherical wavelet. The superposition of all the wavelets from all points along the wavefront determines the shape of the propagating wave. The effect is the bending of light around a corner.

diffraction limited – An optical system of such quality that its performance is limited primarily by the effects of diffraction rather than aberrations.

diffuse – In optics, light in which wavefronts are not preserved. The opposite of spatial coherence.

diffuse reflection – A process where incident light is redirected over a relatively wide range of angles (scattered) while being reflected from a material. The integrity of the incident wavefront is lost.

diffuse transmission – The processes where an incident light ray is transmitted by scattering or redirection so that the light passes through the material and emerges in a large range of angles. The integrity of the incident wavefront is lost.

direct transmission – Light transmission without scattering; the integrity, but not necessarily the shape, of the wavefront is preserved.
dispersion – 1) The degree to which a material's index-of-refraction changes as a function of the wavelength of light. For example, when a ray of white light is incident on a prism, the spectrum of colors exits the prism; the larger the dispersion of the prism material, the larger the angle over which the colors are dispersed 2) The act of separating light into its component wavelengths through a dispersive element like a prism.

distortion – 1) Non-proportional representation of an original. 2) An undesired change in the shape of an object's image from the object's actual shape.

dopant – An impurity added in minute quantities to a material to affect the material's properties.

dove prism – A special prism which rotates an image projected through it at two times the rate at which it is mechanically rotated.

electromagnetic spectrum – The range of detectable frequencies of electromagnetic radiation.

elliptical polarization – A light beam whose electric or magnetic vectors can be decomposed into two perpendicular components differing in amplitude or phase.

energy – The capability of an object or field to do work on another object. It can be force times distance or power times time.

étendue – The product of the cross-sectional area of a light beam and its subtended solid angle.

evanescent field – An oscillating electromagnetic field that does not propagate but stays in the vicinity of the source.

extinction ratio – The ratio of the transmitted energy for a polarizer when parallel to the plane of polarized light to the transmitted energy when the polarizer is perpendicular to the same plane polarized light.

extraordinary ray – The component of a light ray which is parallel to the optic axis. The extraordinary ray is bent by refraction even if it is normal to the surface.

f-number – The ratio of the focal length of a system to the diameter of the entrance pupil. A measure of an imaging device's ability to gather light. See also numerical aperture and working f-number.
Fabry-Perot resonator – An optical resonator consisting of two parallel surfaces where light reflects alternately off one and then the other. See metal-dielectric-metal (MDM) structure.

far infrared – Radiation with a wavelength between 30 and 1000 microns.

far ultraviolet – Radiation with a wavelength between 100 and 300 nanometers.

field – In physics, a region, bounded or unbounded, that has a property distributed and measurable throughout it. The property could be a static force (e.g. magnetic field) or radiation (e.g., electromagnetic energy).

field angle – In imaging, the angle formed by to lines from the principal point to the extreme of the image or object plane.

field curvature – The amount by which the off-axis image (best focus) departs from the ideal flat image plane when referenced to the on-axis image. In most imaging systems, if field curvature is present, the center of the image will be in focus while the edges of the image will be out of focus.

first surface mirror – A mirror where the reflecting surface is the surface of the substrate (e.g. glass) on which the light is first incident. The light does not have to travel through the substrate to be reflected, and there is no ghost image created.

flat field lens – A lens designed and constructed so as to eliminate field curvature.

flatness – (See surface flatness.)

fluoresce – The action of producing light by fluorescence.

fluorescence – An optical effect where a material absorbs and reradiates energy, with the reradiated energy typically in the visible spectrum and at a longer wavelength than the incident energy. The radiation lasts only as long as the incident energy is present.

flux – The amount of energy per unit time (power) falling on a surface (incident flux) or emitted by a surface (radiant flux).

focal distance – (See focal length.)
focal length – The distance from a lens’ principal point to the corresponding focal point. The distance between a lens’ principal point and the plane of best focus when the lens is focused at infinity. Also referred to as the equivalent focal length and the effective focal length.

focal point – The point at which a lens will focus incident light which is parallel with its optical axis.

focus – 1) In imaging, the point at which light (or other radiation) from a point forms the minimum size spot. The plane of the most distinct image; the image plane. 2) The degree to which an image is distinct or clearly viewable.

folded optical path – An optical path which uses reflections off mirrors or prisms to direct the light for the convenience of packaging the optics.

footcandle – A measurement of incident light (illuminance) equal to one lumen/ft². One footcandle is equal to 10.76 lux.

footlambert – A unit of emitted or reflected light (luminance) equal to one candela per square foot. The uniform luminance of a perfectly diffusing surface emitting or reflecting light at the rate of one lumen per square foot. A lumen per square foot is a unit of incident light and a footlambert is a unit of emitted or reflected light. For a perfectly reflecting or perfectly diffusing surface (no absorption of light), the number of lumens per square foot is equal to the number of footlamberts.

forbidden band – In quantum physics, a range of energy levels which an electron is not able to attain. The electron is allowed to attain higher or lower energy. An electron with energy in the forbidden band, will transition to a lower allowed energy level and release the excess energy.

frequency – Temporal frequency: the number of times an event occurs per unit of time measured in cycles per second or Hertz (Hz).

Fresnel reflection – Reflection off an interface with a dielectric surface. The magnitude of the reflection and transmission for polarization both parallel and perpendicular to the plane of reflection is given by Fresnel’s equations.

front surface mirror – (See first surface mirror.)

ghost reflection – A secondary reflection off an optical surface that is intended not to contribute a reflection. For example, a second surface mirror has its principal reflection off the rear side that is coated to reflect light. The front side of the mirror will also reflect a small amount of light.
**hole** – In solid-state physics, a virtual or real positive charge created in the material when an electron is missing or removed from the crystal lattice.

**IHS** – Acronym for intensity, hue, and saturation; a form of representing a color image. Also called luminance, hue, and saturation.

**illuminance** – Luminous flux incident per unit area on a surface; luminous incidence.

**image distance** – The distance between the principal plane, or the rear principal plane if there is more than one, and the image plane.

**image height** – 1) The height (or width) of an image or an image plane; especially as compared to the height (or width) of the imaged scene or object plane. 2) The height in an image of an object in the scene.

**image magnification** – The ratio of a length in an image to the corresponding length in the object plane. It is the reciprocal of object magnification.

**image plane** – 1) The imaginary plane where the desired scene is imaged. 2) The surface on which the optical image should be focused (e.g. the target of the image sensor). 3) The plane perpendicular to the optical axis where the image is formed.

**impurity** – In a semiconductor, the non-semiconductor element introduced in small quantities to give the semiconductor the desired electrical properties.

**incoherence** – Light comprised of a continuous flow of energy bursts none being necessarily in-phase or of the same frequency or propagating in the same direction as the others. Standard light sources (e.g. the sun, incandescent lamps, and fluorescent lamps) produce incoherent light.

**index of refraction** – For a material, the ratio of the speed of light in vacuum to the speed of light in the material. One effect of the index of refraction is that light refracts: changes direction when entering the material from any direction other than normal to the material’s surface.

**infrared** – The region of the electromagnetic spectrum adjacent to the visible portion of the spectrum but having longer wavelengths from 0.700 to 1000 microns.
**intensity** – 1) The radiated light power per steradian. For radiometric measurements, it is watts/steradian. For photometric measurements, it is candelas (lumens/steradian). 2) Commonly, the term intensity is used loosely and interchangeably with brightness to refer to the relative magnitude of either radiated or incident light (exitance or irradiance).

**interference** – The effect when two or more light wavefronts intersect. If the light is coherent, it will produce an interference pattern.

**interference filter** – An optical filter which is formed by a series of thin layers of transparent materials. The interference filter transmits some light wavelengths and reflects others.

**IR** – Abbreviation for infrared.

**irradiance** – The radiant flux incident per unit area of a surface.

**isotropic** – 1) Rotationally invariant. 2) The velocity of light is the same in all directions through the object (i.e., not birefringent). 3) Having optical properties of transmission or reflection that are consistent for a given angle of incidence regardless of the azimuth of the incident light.

**joule** – The unit of energy in the metric MKS system; $10^7$ ergs. Abbreviated J.

**L*a*b*** – A representation scheme for color image information in spherical coordinates. $L^*$ represents the intensity, and $a^*$ and $b^*$ are orthogonal axis which represent the color, both hue and saturation.

**Lagrange invariant** – (See optical invariant.)

**Lambertian** – A diffusing surface having the property that for normally incident light the intensity of light reflected or transmitted in a given direction from any small surface component is proportional to the cosine of the angle (Lambert’s cosine law for a perfect diffuse reflector). Therefore, the light flux into a constant cylinder is invariant to the angle of incidence of the cylinder with the surface. The apparent brightness of a Lambertian surface is constant regardless of the viewing angle.

**lateral magnification** – The ratio of the size of an object in an image to the actual size of the object; both measured perpendicular to the optical axis. Also known as image magnification and linear magnification.
lens – 1) A transparent, refractive optical component consisting of a piece of optical glass or plastic with one or more curved surfaces (usually spherical) that cause incident light rays to converge or diverge when transmitted. Most commonly, but not always, used for creating an optical image of a scene. 2) An assembly of two or more lens (elements) working in series in the optical path to perform an imaging function.

light – 1) Electromagnetic radiation detectable by the human eye, with wavelengths in the range of 380 to 700 nanometers. Also called visible light. 2) Less rigorously but more generally, it is electromagnetic radiation in the infrared, visible, and ultraviolet regions.

linear polarization – The polarization of light in which the electric field vector is constant in one plane.

longitudinal magnification – The ratio of the change in image distance to the corresponding change in object distance. It is the square of the lateral magnification.

lumen – The unit of luminous flux. It is equal to the flux of one candela from a point source through a unit solid angle (steradian) or to the flux on a curved unit surface of which all points are at a unit distance from a point source of one candela. Abbreviated lm.

luminance – Luminous intensity (formerly known as photometric brightness) of any surface in a given direction per unit of projected area of the surface as viewed from that direction, measured in nits, apostils, or footlamberts.

luminous – Having or pertaining to electromagnetic energy (light) where the energy is weighted by the responsivity of the standard observer.

lux – International System (SI in which the meter is the unit of length) unit of the density of incident illumination. One lux equals one lumen per square meter. One lux equals .0929 footcandles. Abbreviated lx.

machine vision – 1) A branch of computer vision involving the use of computer vision in industrial applications; 2) The automatic acquisition and analysis of images by non-contact means to obtain desired data for controlling an activity or process.

marginal ray – A light ray that passes through an optical system near the edge of the limiting aperture.
MDM – Abbreviation for metal-dielectric-metal structure.

metal-dielectric-metal structure – A Fabry-Perot resonator comprised of two thin layers of metal separated by a thin layer of dielectric material. Such a structure will resonate at a wavelength that is twice the wavelength of light through the dielectric as well as all higher harmonics of this wavelength.

metamer – A color in which the dominant hue is created by the combination of other hues. Green, when made by mixing yellow and blue light, is a metamer.

mid infrared – The portion of infrared spectrum between 3 and 30 microns.

mirror – An optical device designed to reflect light without diffusion. Most mirrors are flat; however, they can be curved to perform some optical function such as imaging. See also first surface mirror and second surface mirror.

modulation transfer function – A measure of the resolving capability of an imaging system. Shows the sine-wave spatial frequency amplitude response, or contrast, of a system or lens. The acronym for modulation transfer function is MTF.

monochromatic – Light which is composed of only one wavelength.

monomer – A color with a hue which is the result of a colorant having the corresponding spectral wavelength rather than being a hue created by a mixture of other hues. See also metamer.

MTF – abbreviation for modulation transfer function.

near infrared – The shortest wavelength radiation in the infrared region. Usually considered as wavelengths in the range from .700 to 3 microns adjacent to the visible spectrum.

near ultraviolet – The longest wavelength radiation in the ultraviolet region. Usually considered the wavelengths in the range from 300 to 400nm adjacent to the visible spectrum.

neutral density filter – A passive optical device that reduces the intensity of light without changing the spectral distribution of light energy.

nit – A unit of measurement of luminance equal to one candela per square meter. From the Latin word nitere that means to shine.
**numerical aperture** – A measurement of the light gathering power of a lens or optical fiber, the sine of the half-angle of the accepted cone of light times the index of refraction of the medium (usually air with an assumed index of refraction of one). Used commonly in microscopy and fiber optics. The larger the numerical aperture, the greater the light gathering power.

**object distance** – 1) The distance between the object (plane) and the first optical surface of an imaging lens. 2) The distance, parallel to the optical axis, from an object to the first principal plane of an imaging system.

**object height** – 1) The height (or width) of the scene or object plane. 2) The height (or width) of an object in the scene, usually when related to its height in the image.

**object magnification** – The ratio of a length in the object plane to the corresponding length in the image. It is the reciprocal of the image magnification.

**object plane** – An imaginary plane containing the scene and objects therein that is focused onto a lens' specified image plane. That plane which is focused on the image sensor.

**opacity** – 1) The reciprocal of transmittance. 2) The degree to which a material obscures a transmitted pattern.

**optic axis** – In a doubly refracting material (birefringent), the direction along which double refraction does not take place (i.e. the direction along which the index of refraction is constant without regard to the direction of polarization of the light).

**optical invariant** – An optical principle which gives the rule that the apparent luminance of a point viewed through an optical system (neglecting insertion losses) depends only on the solid angle imaged from that point and not the focal length or aperture of the imaging system.

**optics** – That branch of the physical sciences concerned with the phenomena of energy in the optical spectrum. Now often replaced by the term photonics when light is modeled as a photon. Optics can be restricted to the discipline where light is modeled as a wave.

**optoelectronics** – Devices for converting light energy to electrical energy or electrical energy to light energy. Also, the discipline for designing and using these devices.
ordinary ray – The component of a light ray that is perpendicular to the optic axis of a birefringent material. If the ordinary ray is normal to the surface, it is not bent by refraction. See also extraordinary ray.

particle – In quantum physics, an elemental increment of energy having corpuscular properties including mass as well as energy. A photon is an example of such a particle.

passband – The range of frequencies or wavelengths that are transmitted through a filter.

pellicle beamsplitter – A beamsplitter made from a very thin partially transparent film. The thickness of the film is so small that there is effectively no ghost reflection.

penta prism – A five-sided prism that has the property that light is redirected (through internal reflections) by exactly 90 degrees throughout range of incident angles.

photometer – 1) Any instrument for measuring light energy weighted for the visible response. 2) An instrument that compares the luminous intensities of two sources by comparing the illuminance they produce.

photometric – Light measurements which are spectrally weighted to correspond to the photopic responsivity of a standard human observer.

photon – The smallest quantum of electromagnetic energy. It has a single wavelength (energy level), direction of travel, and angle of polarization. It is sometimes considered as if it were a particle.

photonics – The discipline where devices are engineered by considering light modeled as a photon. Often, but not exclusively, this involves the conversion between light and electrical energy. Photonics is a concatenation of photon and electronics.

photopic – Human vision at moderate and high levels of luminance (.01 lux to around 100 lux) permitting distinction of colors. This is light adapted vision. It is attributed to the retinal cones in the eye. The contrasting capability is twilight or scotopic vision.

photosensor – Any device for detecting light. Such a device might be a discrete item, or it might be one element among many as with the individual sensing elements on a solid-state image sensor.
**pincushion distortion** – An effect that makes the sides of an image appear to bulge inward on all sides like a pin-cushion. Caused by an increase in effective magnification as points in the image move away from the image center.

**plane of reflection** – The plane containing the incident light ray, the reflected light ray, and the normal to the surface at the point of incidence.

**plate beamsplitter** – A beamsplitter made from a plate of transparent optical material with one side coated to be partially reflecting. The uncoated surface is usually anti-reflection coated to prevent ghost reflection.

**point spread function** – The expression of how an imaged point is represented on the image plane. An imaged point is represented by a region with peak intensity at the center of the region with the intensity falling off as the distance from the image of the point increases. See also circle of confusion and airy disk.

**polarization** – Restricting the vibrations of an electric or magnetic field vector to a specific orientation.

**polarizer** – Any one of a number of devices or materials which filter light based on its polarization. Only that component of light which is polarized in the accepted direction is transmitted; other polarizations are reflected, absorbed, or refracted.

**polka-dot beamsplitter** – A beamsplitter made from a transparent substrate with one side patterned with highly reflective dots such that a portion of the incident light energy is reflected off the dots and a portion is transmitted through the space between dots.

**polysilicon** – Polycrystalline silicon used in the fabrication of semiconductor devices as contrasted with crystalline silicon. It is used in MOS and CMOS devices as well as one element of an MIS capacitor used as a photosensor.

**power** – 1) The rate of energy; energy per unit time. 2) Shortened form for magnifying power or magnification.

**primary colors** – Three or more colors wherein no mixture of any two colors can produce the third. The most common groups of primary colors are RGB (red, green, and blue) and CMY (cyan, magenta, and yellow).
**principal plane** – An imaginary plane in or near a lens where the light rays appear to bend. A lens assembly can have many principal planes; the most significant are the front principal plane and the rear principal plane.

**principal ray** – (See chief ray.)

**prism** – A transparent optical device with flat non-parallel sides. It is used to change the direction of light by refraction or internal reflection. There are many different types of prisms, each with different applications.

**purity** – In color, the degree of saturation of a color. A heavily saturated color is said to have high purity or to be “pure”.

**quantum efficiency** – For detectors, the ratio of the number of electron/hole pairs generated to the number of incident photons.

**quantum physics** – That branch of physics which deals with energy that can exist only at discrete levels or quanta.

**radiance** – The power radiated into a unit solid angle by a unit projected area.

**radiant** – 1) Having the property of emitting energy. 2) Having to do with the electromagnetic energy where all wavelengths are weighted equally.

**radiometer** – Any instrument for measuring light energy where all wavelengths are weighted equally.

**radiometric** – The science of measuring electromagnetic radiation, especially power, where all wavelengths of energy are weighted equally. Most often used with relation to energy in the infrared through ultraviolet range.

**ray** – A representation of the direction of light travel. A light ray is the normal to a light wavefront as it propagates.

**ray tracing** – An optical design technique which calculates the path of a light ray as it travels through an optical system.

**rear surface mirror** – (See second surface mirror.)
**reflection** – 1) The process by which incident light leaves a surface or medium from the side on which it is incident without a change in wavelength and effectively without entering the reflecting medium. 2) Light, especially light that is imaged, that has been reflected as off a mirror.

**reflectivity** – The ratio of the intensity of the total reflected radiation to the intensity of the total incident radiation.

**refraction** – The bending of a light ray as it passes from one media into another due to the difference in velocity of the light wave in the two media.

**resolving power** – The smallest separation between two points for the two points to be distinguishable in the image.

**right-angle prism** – A prism having one 90 degree and two 45 degree vertices. Its usual use is to deflect light by 90 degrees by internal reflection from the two sides that are 90 degrees to each other.

**roof prism** – A prism in which one of the surfaces for internal reflection is beveled from side to side at 90 degrees to resemble the roof of a house. The roof prism flips a reflected image by 90 degrees.

**saturation** – The degree to which a color is monochromatic; the color’s purity. The departure of a color from a shade of gray of the same lightness.

**scene** – The 3-dimensional environment from which the image is generated. Often used interchangeably with object plane and field-of-view.

**Scheimpflug condition** – A geometric rule that states for an image to be in focus, the image plane, the principal plane of a lens, and the object plane must all intersect along a common line. For most optical systems, all three planes are parallel and, in concept, meet at infinity.

**scotopic** – Vision which occurs in faint light (typically below .01 lux) or in dark adaptation. It is attributed to the retinal rods in the eye and is characterized by no color perception. Its peak responsivity is in the blue light region. (See also photopic vision.)

**second surface mirror** – A mirror in which the reflective coating is placed on the second surface, or back, of the glass. In addition to the primary reflection off the coating there is a secondary or ghost reflection off the front of the glass which may be reduced an with anti-reflection coating.
**semiconductor** – A material which is neither a good electrical conductor nor a good electrical insulator. Its conductivity can be changed by the introduction of small amounts of other materials called impurities or dopants. These impurities create electrons or holes that are more mobile and can more easily contribute to the conduction of electrical current.

**Snell’s law** – The relationship that defines the refraction of light based on the velocity of light or index of refraction. Mathematically it is:

\[ n \sin(i) = n' \sin(i') \]

Where:

- \( n \) is the index of refraction in the initial media
- \( n' \) is the index of refraction in the final media
- \( i \) is the angle of incidence measured from the surface normal
- \( i' \) is the angle of refraction measured from the surface normal

**spatial coherence** – Light in which the phase difference between any two points perpendicular to the direction of travel is constant. Light in which the rays appear to emanate from or converge to a single point.

**spatial filter** – A mask placed in an optical path to block unwanted light components (e.g. the pinhole placed at the focus of a laser beam condenser lens to remove unwanted, non-collimated, light).

**spatial frequency** – for imaging, the number of light and dark cycles per millimeter in a given field, usually the image or the field-of-view.

**spectroscopy** – The science of measuring and understanding the spectrum of light produced by or reflected by or transmitted by an object or substance.

**specular** – Reflection of light from a smooth surface (e.g., a mirror) where the light is not scattered when reflected. The angle of reflection equals the angle of incidence. The integrity of the incident wavefront is preserved after reflection.

**spectrometer** – An instrument for measuring the spectrum of light energy. See also spectrophotometer and spectroradiometer.
**spectrophotometer** – An instrument to measure the spectrum of transmitted or reflected light energy.

**spectroradiometer** – An instrument to measure the spectrum of emitted light energy.

**spherical aberration** – A degradation of an image due to the shape of lens elements. Rays from the point in where the optical axis intersects the object plane are focused at different distances depending on the location the ray enters the lens measured radially from the center of the lens. Rays from the point that enter at the edge of the lens will be focused at a different distance than rays that pass near the center of the lens.

**stop** – Any physical barrier placed in the optical path to restrict the bundle of light rays transmitted by the system. See also aperture.

**surface flatness** – The degree to which a surface is perfectly flat. Usually measured in fractions of a wave of light having a wavelength of 555nm.

**Talbot** – The SI unit for quantity of light; expressed as lumen-second.

**temporal coherence** – Light in which the phase difference between any two points in the direction of propagation is constant. See also monochromatic.

**thin lens** – A lens, usually single element, which can be modeled as having only one principal plane as if its thickness was zero.

**throughput** – (See étendue.)

**transmission** – The conduction of a signal or energy such as light through a medium.

**transmissive** – Having the property of allowing electromagnetic radiation to pass through.

**transmissivity** – The percent of the energy a material will transmit per unit thickness. It does not include potential losses in coupling the energy into and out of the material.

**transmittance** – The percentage of incident light transmitted. It is a function of a material's transmissivity and the efficiency of coupling the energy into and out of the material.

**ultraviolet** – The region of the electromagnetic spectrum immediately above the visible portion of the spectrum; generally having wavelengths between 100 and 400 nm.
**unpolarized** – Light which is characterized by waves having all possible electric field orientation.

**UV** – Abbreviation for ultraviolet.

**valence band** – In an atom, the outer most or most energetic orbit of electrons when the atom is not externally excited. Chemical bonds are formed by electrons in the valence band.

**Watt** – The unit of power, equal to one joule of energy expended in one second.

**wave** – An undulation or vibration. Usually considered sinusoidal unless otherwise stated.

**wavefront** – The surface connecting all points in a field that are equidistant from the source and traveling with the same velocity as the field.

**wavelength** – Reciprocal of frequency. The distance covered by one cycle or event; the distance a wave travels in the time it takes for it to complete one cycle.

**window** – A sheet of glass with plane parallel surfaces used as a cover for an optical assembly to exclude contaminants such as dirt and moisture.

**working f-number** – The primary f-number times the quantity one plus the image magnification. It scales the light gathering capability of the lens as magnification is increased. Only at high magnifications, typically greater than 0.2, does the working f-number differ significantly from the primary f-number.
In addition to the references below, the machine vision practitioner will find a basic college physics text book covering optics a valuable reference work.


A handbook rather than a text book. Very thorough on infrared, but also a lot of good general optics information. This set of books is probably too comprehensive to be of use to most machine vision practitioners.


This is the classical text on optics; a “must have” for the library of the serious optics professional. However, the book is very technical, detailed, and mathematical, and may be too advanced and complex for the typical machine vision practitioner.


A text book on basic optics.


Walker, Bruce; "Optical Engineering Fundamentals"; SPIE Press, 1997


This catalog is no longer published. In its day, it was filled with helpful tutorial articles about optical components. Now, the Edmund Optics catalog has similar tutorials that may be of value.
