DEFINING THE APPLICATION

The first step to solving any optical problem is to assess the application. What am I trying to accomplish? For an optical system it is important to first determine whether you need an *imaging system* or *non-imaging system* because the performance requirements are different for each type.

Imaging System
Imaging systems transfer a representation of the object to a detector, such as a CCD or your eye. Some examples of imaging systems are: electronic imaging for inspection, image projection systems and relay systems. The goal of an imaging system is to provide sufficient image quality to enable extraction of desired information about the object from the image. Note that what may be adequate image quality for one application may prove inadequate in another. Some of the components of imaging quality are resolution, image contrast, perspective errors, geometric errors (such as distortion) and depth of field.

Non-Imaging System
Non-imaging systems collect, disperse, resize, focus, or collimate light. Some examples of non-imaging systems are: illumination projection, fiber coupling and laser projection. The performance of a non-imaging system can be quantified by its throughput, field efficiency, spot size (focusing systems) and angular resolution. Throughput is a measure of the energy transmitted through the lens system. Field efficiency is the system's ability to accommodate a large detector area or source size. Angular resolution is generally used to specify the minimum angular separation needed between two objects in order for the lens system to resolve them. Spot size is used to evaluate a focusing lens's performance.

The next step is to determine the primary parameters of your system. Then, you can begin a design form for your application. Below are the primary parameters defined.

Conjugate Distances
The distance from the lens to the object/source (object distance) and the distance from the lens to the detector/image (image distance). For example, in an infinite conjugate design one of these distances approaches infinity.

Conjugate Sizes
The size of the object/source (object size) and the size of the detector/image plane (image size). For example, in systems with an infinite conjugate, the conjugate "size" can be expressed as an angle.

Numerical Aperture (NA) and F-Number (F/#)
A measure of the cone of light accepted or emitted by the lens system.

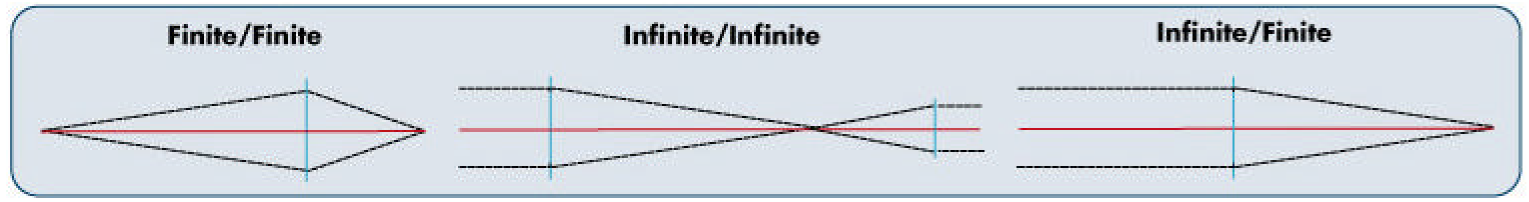
Resolution and Spot Size
In imaging system terms, this refers to the smallest feature of an object distinguishable by the system. (This value may be magnification limited or diffraction limited). In non-imaging systems, spot size is a way to characterize the performance needed. Infinite conjugate systems are often defined in terms of angular resolution.

SOLUTION FORMS

Most application solutions can be divided into three types of designs: Finite/Finite Conjugate, Infinite/Infinite Conjugate, or Infinite/Finite Conjugate. A finite/finite conjugate design is one in which light from a source (not at infinity) is focused down to a spot. Most video lenses, which take the image of an object at a finite distance away and focus it onto a CCD array, are designed for this scenario. An infinite/infinite conjugate application takes incoming collimated (parallel) light, changes the beam diameter according to the magnification, and emits the collimated light. An infinite/finite conjugate design combines these two concepts by focusing a source placed at infinity down to a small spot.

In order to choose the appropriate design it is best to begin with the "paraxial solution." A paraxial solution allows a designer to approximate first order properties such as conjugate distances, image and object heights, magnification, etc. Paraxial calculations utilize paraxial elements - theoretically perfect lenses that do not introduce system aberrations associated with lens thickness, radius of curvature, glass type and dispersion effects. Note: the only specifications for a paraxial lens are its position relative to the image and object plane, lens diameter, and focal length. After finding the paraxial solution you can begin to select the best real lens solution for your application, making allowances for lens thickness, dispersion effects, etc. in your calculations. Because the calculations for real lens solutions can be long and tedious, we've helped to create a new optical design software, OLIVE - Optical Layout Including Video Elements, which is intended to help the novice and non-optical engineer integrate real lenses into their applications (software can be found here).

Each design form below illustrates different lens combinations and the performance associated with them. Please note that you are not limited to just these lens combinations.



Description of Variables

H_i , H_o Image and object height, respectively. This represents HALF of the actual full image and object size. In afocal systems, this represents half of the full beam waist.

I , O Image and object distance measured from the lens closest to the image and object respectively.

F_i , F_o Focal length of the lens closest to the image and object, respectively.

F Effective focal length of the entire lens system.

M Magnification is the system's ability to produce an enlarged/reduced image or projection of an object.

D Distance between two elements.

q FULL angle of the cone of light accepted or emitted by a lens system (closely linked to numerical aperture).

a_i , a_o Angular HALF field of view in infinite conjugate systems.

TP Throughput is the system's ability to transfer light.

F/# F/# is the lens' ability to focus light.

Sign Convention

Positive Values: The following quantities are expressed as positive values: heights above the optical axis, distances measured to the right of a reference point, focal length of focusing lenses, and angles that are measured counter clockwise from the optical axis.

Negative Value: The opposites of the above quantities are expressed as negative values. (i.e. - While height measured above the optical axis is expressed as a positive quantity, height measured below the optical axis is expressed as a negative quantity).

Reference Point for Equations Given: Lens Position.

Chart Legend

The criteria used to evaluate each type of lens under different configurations is as follows:
• = poor to •••• = excellent

Low F/#: Lens' ability to work at low f/# (i.e., large incoming light diameter or high NA). Low f/# applications should use lenses with (•••••) rating.

Polychromatic: Lens' ability to hold performance with white light illumination (as opposed to monochromatic sources such as lasers or some LEDs). Applications with broadband illumination and no filtering should use lenses with (•••••) rating.

Field Efficiency: Lens' ability to accommodate a large sensor (image), source (object), or angular field of view (in afocal systems). Applications with large image/objects should use lenses with (•••••) rating.

Cost: This is a comparison of the cost of each type of configuration (i.e takes into consideration the number of elements in that configuration). Low cost - $, High cost - $$$$$

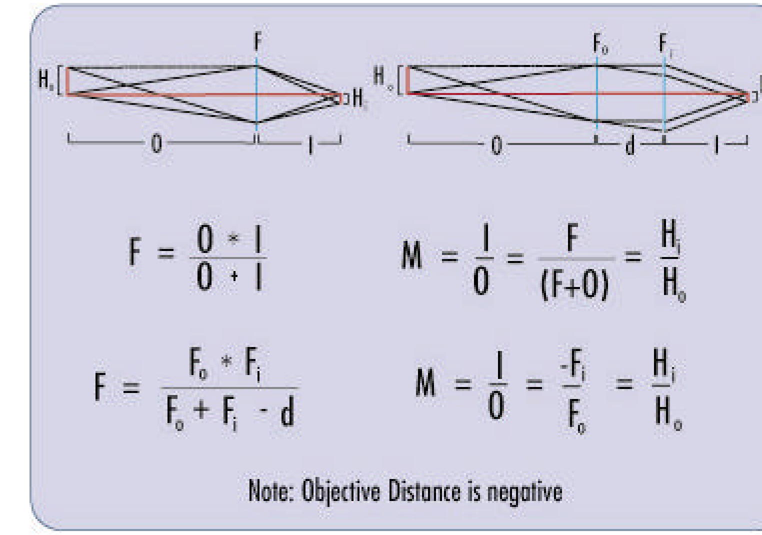
Case 1: Finite/Finite Conjugates

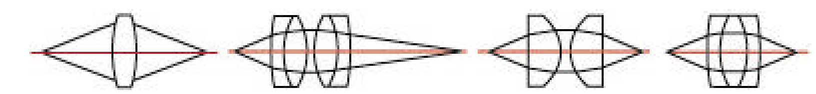
Common Applications: Electronic Imaging, Relay Systems and Image Projection

Single Element: The simplest form of a finite/finite conjugate system is one with a single element in which the effective focal length is equal to the focal length of the single lens in the system. Some advantages of this design are its cost effectiveness and its simplicity of design. The following equations determine the first order optical properties of a single lens.

Two Element: You can combine elements to achieve different effective focal lengths while increasing the image performance of the system drastically. The design becomes a bit more complex, though one method of simplifying it is to place the object at the focal point of the object lens and the image at the focal point of the image lens.

Real Lens Solutions: For imaging applications, achromats are typically used in order to yield better image quality with a single element. Singlets (PCX or DCX) are typically used in illumination based relays which do not require high resolution.





LENS TYPE	LOW f/#	POLYCHROMATIC	FIELD EFFICIENCY	COST	SUGGESTED APPLICATION
Plano-Convex (PCX)	•	•	••	$$	use in pairs
Double-Convex (DCX)	••	•	•••	$	single element
Achromat	••••	••••	••••	$$$$	use in pairs
Hastings	••••	•••••	••••	$$$$$	use in pairs
Steinheil	•••••	•••••	•••••	$$$	single element

Case 2: Infinite / Infinite Conjugates

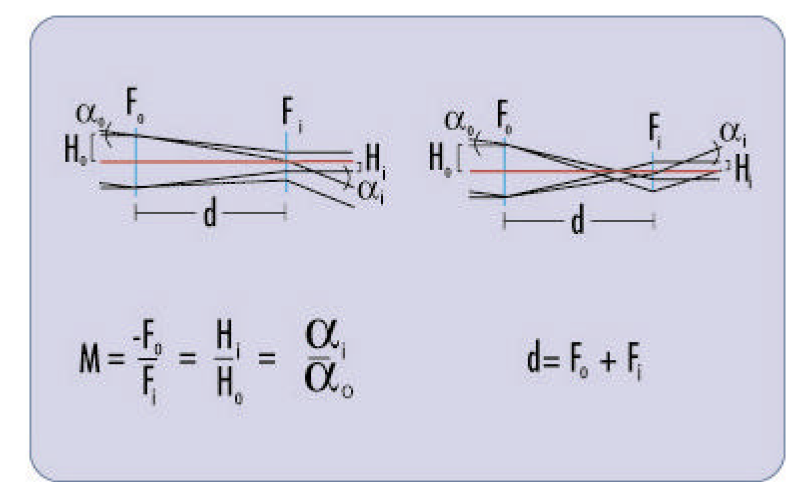
Common Applications: Telescopes and Beam Expanders

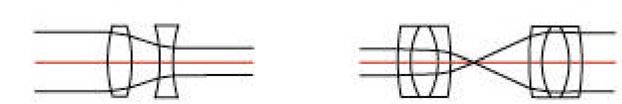
Two Positive Elements: Using two positive elements yields an intermediate image which is useful for applications requiring use of a crosshair or other type of reticle. Using two positive elements will result in a negative magnification such that a prism erector or intermediate relay lens would be needed for erect image viewing.

One Positive Element and One Negative Element: Most high power laser applications utilize this form for beam expansion. One advantage of this form is that system length is greatly reduced while an erect image is maintained.

Real Lens Solutions: Achromatic lenses are typically used for improving field efficiency.

Note: Eyepiece designs can be used as the imaging lens to improve performance.



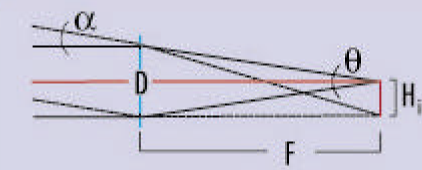


LENS TYPE	LOW F/#	POLYCHROMATIC	FIELD EFFICIENCY	COST	SUGGESTED APPLICATION
Plano-Convex (PCX)	••	•	••	$$	imaging, illumination
Double-Convex (DCX)	•	•	••	$$	—
Achromat	••••	••••	••••	$$$$	imaging, illumination
Hastings	••••	•••••	•••••	$$$$$	imaging, illumination
Steinheil	•••	•••••	••	$$$$$	—

Case 3: Infinite / Finite Conjugates

Common Applications: Autocollimators, Light Detection and Infinity-Corrected Objectives

Single Element: Except in the case of infinity-corrected objectives, this solution generally does not require use of more than one element and the image can be found at the focal point of the lens. An important function of an infinite/finite conjugate system is the throughput (flux per unit radiance or luminance) seen by the detector. The following paraxial equations can be used to estimate the amount of throughput generated by the lens system.



$$\theta = 2*\sin^{-1}(NA)$$

$$F/\# = \left(\frac{1}{2*NA}\right) = \left(\frac{F}{Dia}\right)$$

$$\alpha = \tan^{-1}\left(\frac{H_i}{F}\right)$$

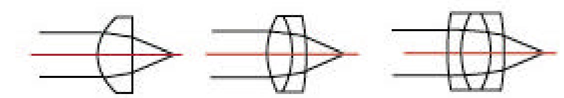
$$Z = 1+\left(1+X^2\right)*Y^2$$

$$TP = G*\pi^2*\left(\frac{D^2}{2}\right)$$

$$X = \frac{H_i}{D*F/\#} \quad Y = 2*F/\#$$

$$G = \frac{Z-\sqrt{Z^2-4*X^2*Y^2}}{2}$$

Real Lens Solutions: A singlet will provide sufficient results for most applications that focus an extended light source upon a detector.



LENS TYPE	LOW F/#	POLYCHROMATIC	FIELD EFFICIENCY	COST	SUGGESTED APPLICATION
Plano-Convex (PCX)	••	•	••	$	detector, illumination
Double-Convex (DCX)	•	•	••	$	—
Achromat	••••	••••	••••	$$	imaging
Hastings	•••••	•••••	•••••	$$$	imaging
Steinheil	•••	•••••	•••	$$$	—