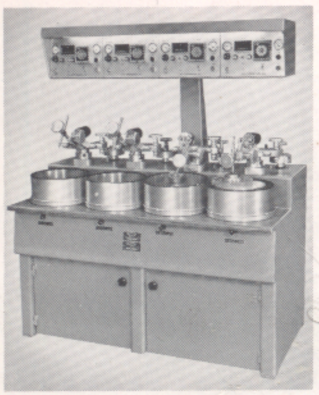
LENSES

Lenses are shaped and polished pieces of glass, plastic, silica, Zinc Selenide, Sodium Chloride, Sapphire, etc., and their main goal in life is to redirect wavefronts. They

PRECISION POLISHMASTERS



MODEL 6DE (*) (**) 1, 2, 4, or 6 Spindles – Pan Size: 14″
SUPER SMOOTH

Ideal – High Speed – Reliable – Small to Medium Size.
CONTROLS – for highest output, designed so operator can make all adjustments momentarily by handwheel.
SPEED CONTROL – a separate Variable Speed Transmission provided for each "spindle" and each "overarm", infinitely variable without stopping the machine.
DIGITAL TACHOMETERS – show speed on each spindle and eccentric.
CONNECTING ROD ENDS – Precision ground self-aligning.
INDICATOR DIALS – for precision rapid adjustments.
BEARINGS – permanently lubricated sealed ball bearings.
FRAME – extra heavy all steel.

MODEL 6 "O" (*) – 1 Spindle – Pan Size: 48″

IT'S LARGE! IT'S HEAVY! IT'S SOLID! IT'S NIMBLE!

This machine can handle very large as well as very close tolerance work. Yet it is easy and fast to set up, and also handles smaller work efficiently. The speeds are momentarily and infinitely variable both on the oscillating and spindle by handwheel control. The gears and bearings are well sealed and permanently lubricated. The construction is heavy, rigid, neat, simple, and compact. Stainless steel and other non-corrosive metals are used wherever practical to make a clean, long lifed machine. The pan is moulded fiberglass with smooth round corners for easy cleaning.

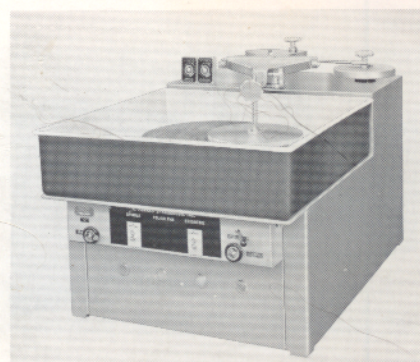


Figure 1: Lens grinding machines, courtesy R. Howard Strasbaugh, Inc., Huntington Beach, CA.

are usually ground on machines like those in Figure 1. Two blanks are placed in contact, one is held rigidly and the other is spun against it. An abrasive is applied to their interface and glass is removed by the grinding action. One piece is ground concave, the other convex. The resulting shape is usually spherical. There are six combinations of one or both sides of a lens having such shapes. Figure 2 shows the possibilities.

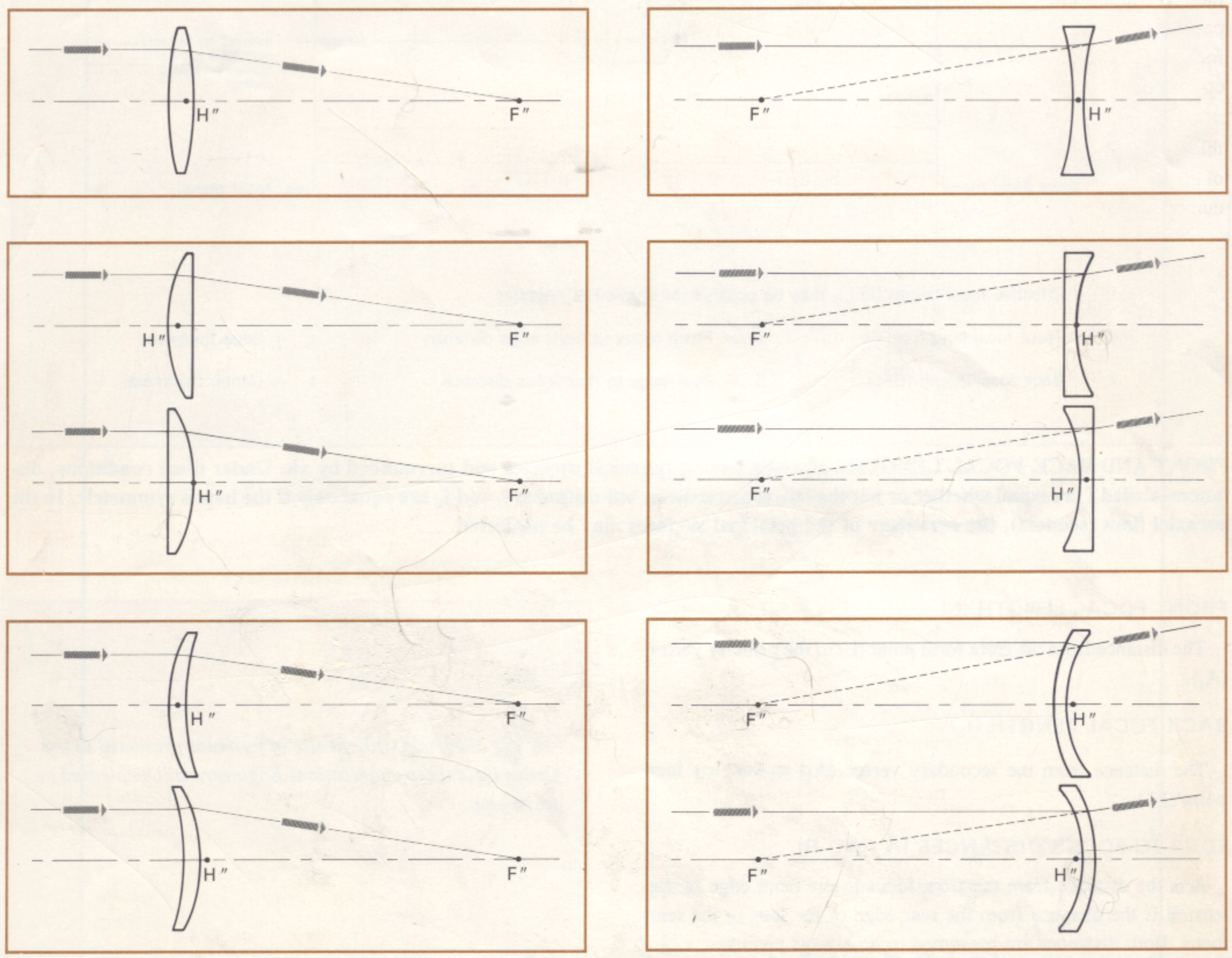


Figure 2: Lens shapes and their principal point locations, courtesy Melles Griot, Irvine, CA.

Lenses thicker in the middle than at the edges have converging power, focussing a parallel wavefront to a spot one focal length away from the principal plane of the lens, whereas those thinner in the middle than at the edges have diverging power, and their virtual focal lengths are assigned negative numbers. H" in each of the boxes in Figure Two refers to the actual physical location of the starting point of the measurement of the focal length for each of the lenses' shapes for the possible orientations, the nodal point, and gives the centerpoint of the Principal Plane.

FOCUSSING CHARACTERISTICS COMMON TO ALL POSITIVE FOCAL LENGTH LENSES

The geometry of being thicker in the middle than in the edges leads to image-forming; rays diverging from a certain point source sized spot on an object can encounter the lens and be redirected so that they will all be reunited at a certain location, the image point for that object spot. There is a corresponding image spot for each and every object spot. The whole surface of the lens contributes to imaging each and every object spot, and although it looks like a piece of glass just sitting there, it is really quite busy, acting like a traffic cop redirecting light rays from their original direction to a new one, following Snell's law.

The image of each object point will be formed at a given locale by the rules of ray-tracing, or more accurately by computation, starting with the simple lens formula. The crux of the positioning rules is that the farther an object is away from the lens, its image spot will be formed closer to the lens.

Explication of Figure Three: At the farthest extreme, an object at optical infinity, like the sun or the moon, the image will be formed in plane that is the closest that is allowed for a real image for that lens, which is one focal length from the principal plane of the lens. As the object moves closer in, the image moves further from the lens, until at an object position two focal lengths from a lens the image plane the image plane is that same distance away on the other side of the lens. The image is the same size as the object. Inbetween one and two f, the object is imaged even further away from the lens, and the image is larger than the object. No image is formed by an object point placed one f away, since the rays will emerge from the lens parallel, thanks to the law of Optical Reversibility. (If parallel rays converge thanks to a lens one f away from it, rays diverging from one f away will emerge parallel.) Another lens could capture those parallel rays and convert them to an image. All the above images mentioned so far have been real, focussable on a screen, but when the object is less than one f away from the lens, a virtual image of it is formed, and it is magnified.

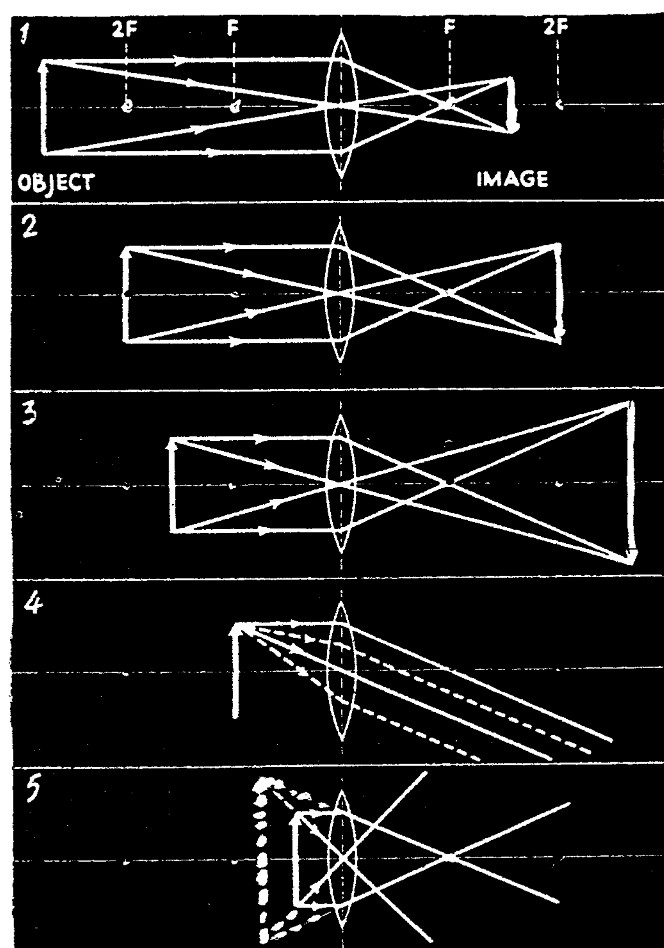


Figure 3: Object-Image relationships for a + lens. From Vitalized Physics, Robert H. Carleton, College Entrance Book Company, 1960.

SHAPES OF POSITIVE LENSES

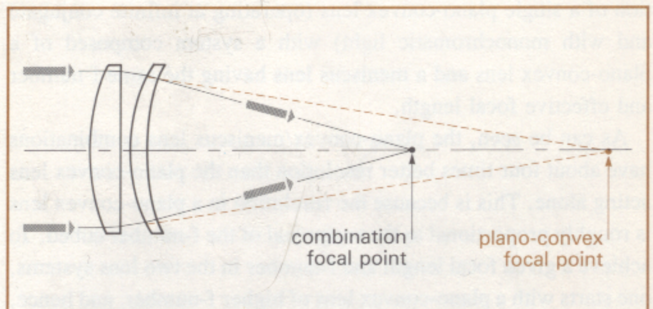
Double Convex Lenses: Both sides are shaped, and contribute to the converging power, making the focal length quite short for the diameter and radius of curvature, which is useful for compact designs. But this can influence the aberrations severely, especially for far away objects. But for a symmetrically-shaped double convex lens used in the symmetric

object distance = 2f = object distance

configuration, (See Figure Three, Cell Three) or unit magnification, coma, distortion, and lateral chromatic aberration almost exactly cancel, and spherical aberration is at the minimum possible for a single element, making them the ideal choice for simple copy cameras or projectors, relay systems, etc. For magnified virtual images as in magnifying glasses they are the primary recommendation. They are used in combination with other lenses, either in contact like in achromatic doublets, or separated, like in a Cooke Triplet or other photographic lens.

Plano-Convex Lenses: One side is ground convex, the other polished flat. Because of this shape, they are best used for imaging objects very far away, at optical infinity, with the flat side toward the focal plane. This make them ideal for refracting telescopes, laser beam collimators, and focussing light onto detectors.

Positive Meniscus Lenses: Both surfaces have their curved surfaces facing the same way; but the inside curve has a larger radius of curvature then the outside one. This makes the lens thicker in the middle than at its edges, so it has converging power. They are best used in conjunction with other lenses to shorten their focal length and then lower their f/number. See Figure Four. They were used as single element photographic objectives from the time of Daguerre, and even through to the sixties for the bargain basement brands.



A MENISCUS LENS BEING USED TO SHORTEN THE FOCAL LENGTH OF A PLANO-CONVEX LENS. The focal length of the plano-convex lens alone is indicated, as is the combination focal length of the system including the meniscus lens. The meniscus lens should always be oriented with the concave surface towards the focal point, a shown above.

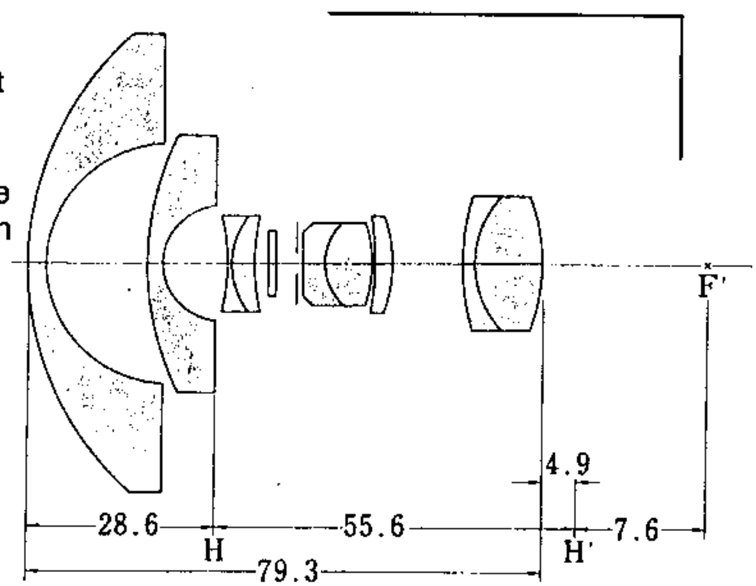
Figure 4: Courtesy Melles Griot.

SHAPES OF NEGATIVE LENSES

Double Concave Lenses: Just like double convex lenses, both sides contribute refraction, but this time in the divergent sense, so their negative focal lengths are quite short. They are useful for spreading low power laser beams quickly. There is a problem with doing the same for higher-powered lasers as even the weak Fresnel reflection from the concave surface could be strong enough that when it is focussed in air it could cause a flash or spark from breakdown of the air. Anti-reflection coatings would help. Double Concave Lenses can be used in conjunction with other lenses to modify their focal lengths or minimize their aberrations, like in an achromatic doublet or Cooke Triplet.

Plano-Concave Lenses: The aberrations for this lens are at a minimum when it is used to diverge collimated beams or collimate convergent beams with the curved side toward the parallel rays side. As an example, when it is used as an eyepiece in a Gallilean telescope, the flat side is toward the exit side of the objective. Like the above, they can be used as laser beamspreaders, even for higher powered lasers if the plano side is towards the incoming beam, so there are no focussing reflections from the concave side. The specular reflection from the flat side should not be allowed to travel back into the laser tube or especially amplifiers rods, as this backward wave may get amplified enough by the last amplifier to cause serious damage to rods further down the system. AR coatings again would be helpful. Unfortunately this orientation is the reverse of the minimal aberration best-form condition. These lenses are used in conjunction with positive lenses to lengthen their focal lengths, as in the telephoto photographic lens design. Coating the concave side makes an excellent imaging mirror.

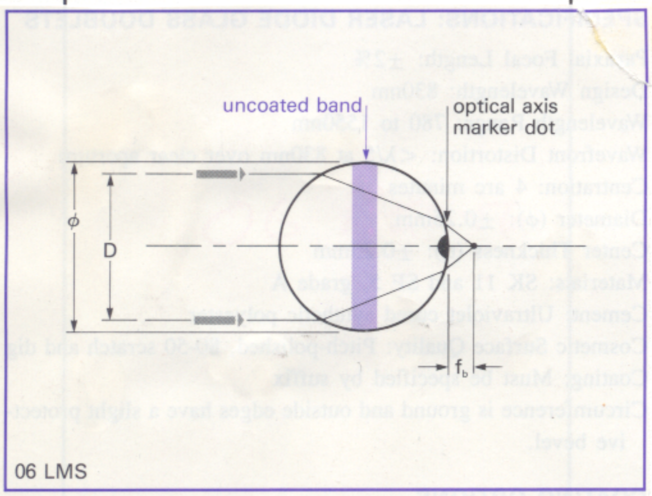
Negative Meniscus Lenses: Like their positive counterparts, they have one side concave, the other convex. However the smaller radius is the concave, while the flatter or longer side is the convex, making the center thinner than the edges, a trait shared by the last two types mentioned above. They are most commonly used to correct myopia in eyeglass or contact lens prescriptions. Extreme cases of this type of design are the first elements of fisheye lenses, as in Figure 5.

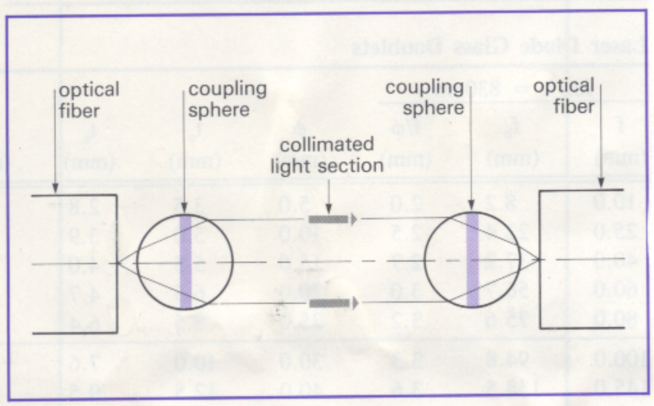


Optical formula of Fish-eye Nikkor 1:5.6 f=7.5mm.

Figure 5: Fisheye-Nikkor, f=7.5 mm, 1:5.6. From Nikon F Nikkormat Handbook of Photography, Cooper and Abbott, Amphoto, 1968.

THE ULTIMATE SPHERICAL LENS is simply a sphere of transparent material. Such elements are manufactured in small sizes, <5 millimeters, to couple laser light into optical fibers. Spheres are much easier to fabricate than any other shape at this scale. Figure 6.





FIBER COUPLING USING SPHERES. Lateral positioning sensitivity is greatly reduced by this method.

Figure 6: Uses of Micro-Spheres. Courtesy of Melles Griot.

Achromatic Doublets: These are formed by cementing two spherical lenses, of different refractive indices, together, although there are air-spaced versions for some applications, such as the long-focal lengths necessary for telescopes or for use with high power lasers which could damage the glue. This type of combination corrects chromatic aberration, as shown in Figure 7, and provides a much sharper image than any other single element lens mentioned above. Figure 8 shows the supeiority of this lens compared to a single element of the same focal length and f/# by the lack of spherical aberration. They are of course much more costly. They can be identified by looking for the line along the circumference showing that they were built up of two lenses. The preferred orientation is for the more steeply curved side to face the far-away focus and the lesser curved side the near focus.

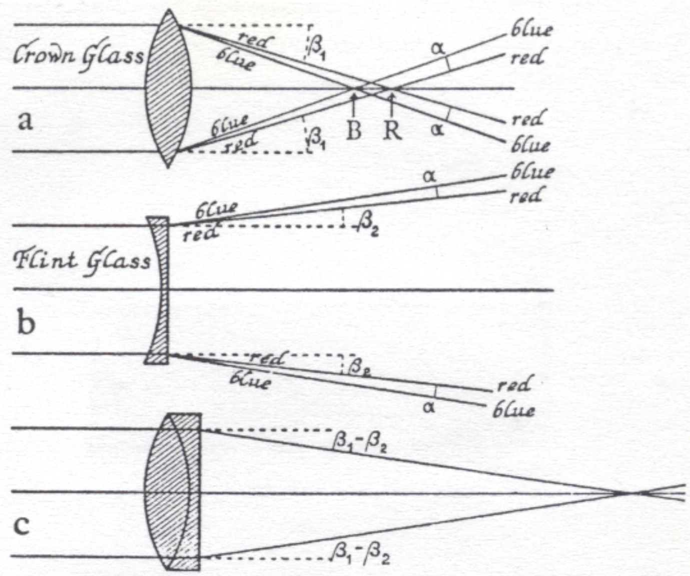


Fig. 56. The top figure shows a lens of crown glass. Its converging power is indicated by the magnitude of the angle β_1. The amount by which it separates blue from red is indicated by the angle α. The middle figure shows a flint glass lens, with a diverging power indicated by β_2, less than β_1: but it produces the same separation of red from blue as the other lens. The two together, in the third figure, do not separate blue from red, but possess a converging power $\beta_1 - \beta_2$.

Figure 7: Principle of the Achromatic Doublet. From <u>The Universe of Light</u>, by Sir William Bragg, Dover Publications, 1960.

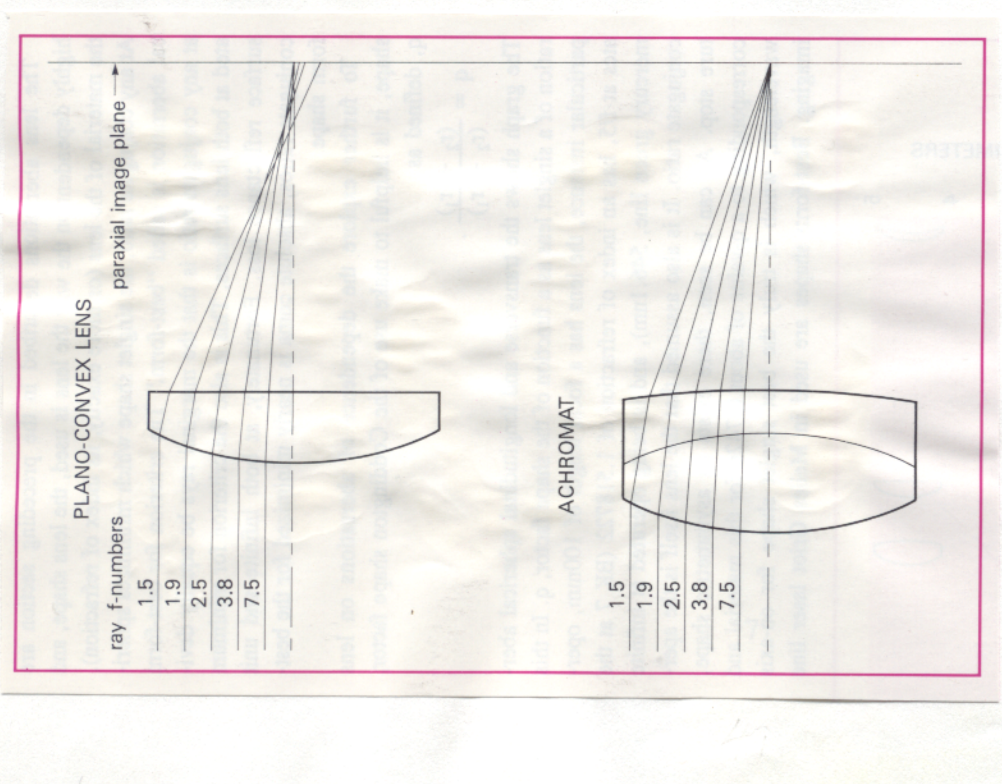


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Figure 8: Improvement in image quality, achromat versus singlet. Courtesy Melles Griot.

NON-SPHERICAL LENS SHAPES

Cylindrical Lenses: A sphere can be considered as having the same radii of curvature in two orthogonal planes to give it a round shape. But what if there were only a radius of curvature in one plane, like the lens were sliced from a can instead of a ball? Such a cylindrical lens could have either positive or negative focal lengths in one plane only, depending if the curved surface were concave or convex, as in Figures 9 and 10. Their most common usage is to correct for astigmatism of the eye, by adding or subtracting focussing power in only one direction. When a laser beam passes through it, the divergence is in one plane only, so the laser beam is transformed from a spot to a line, and if there is enough scattering sites in the air a triangular shaped plane of light is observed. A pair of cylindrical lenses can create anamorphic images, where the magnification is different for the vertical and horizontal aspects of the object, as shown in figure 11.

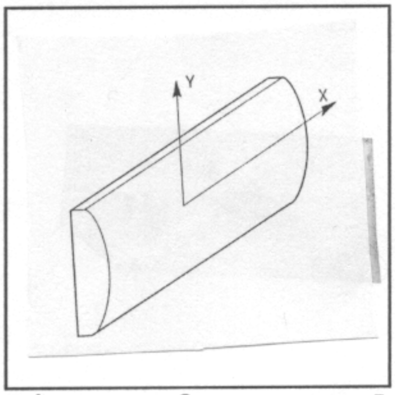


Figure 9: A Positive Cylindrical Lens. Courtesy Newport Corporation.

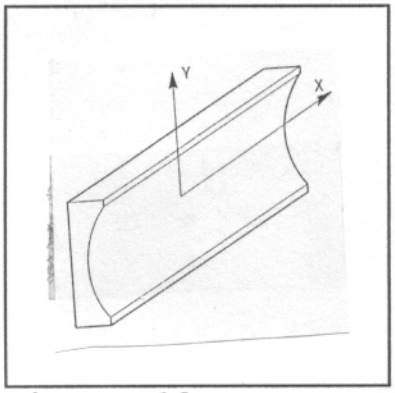


Figure 10: A Negative Cylindrical Lens. Courtesy Newport Corporation.

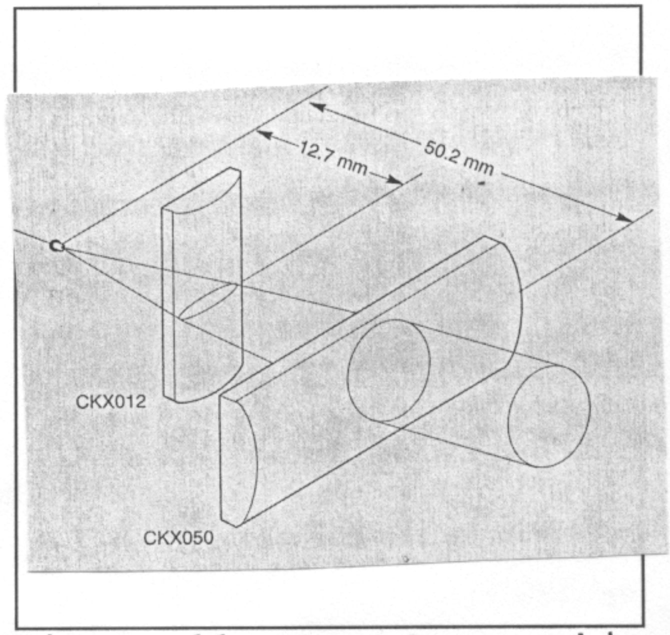


Figure 11: Anamorphic Cylindrical Lens Pair. Courtesy Newport Corporation.

Aspheric Lenses: Their name implies that the curved surfaces are not the simple circle in cross-section, but other geometric shapes, typically parabolic. The advantage is that ipso facto the spherical aberration is eliminated; but other off-axis aberrations like coma, astigmatism etc., may still exist. The major disadvantage is that they are hard to form. The Eastman Kodak Company considers their performance so advantageous that they equip their Disc Cameras (with a 13 by 17 mm film format) with this type of objective. Figure 12 shows an aspheric condenser lens that has an f/number less than 1!.

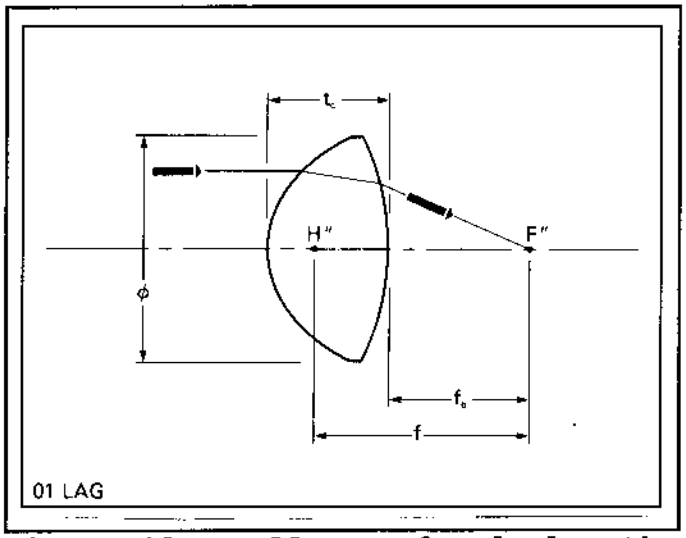


Figure 12: 33 mm focal length, f/.63 Condensing Lens. Courtesy Melles Griot.

Conical Lenses: The cone has a large tip angle, and the Lens in cross-section looks like a pair of prisms laid edge to edge. They can be positive or negative in focal

TYPICAL APPLICATIONS OF AXICONS

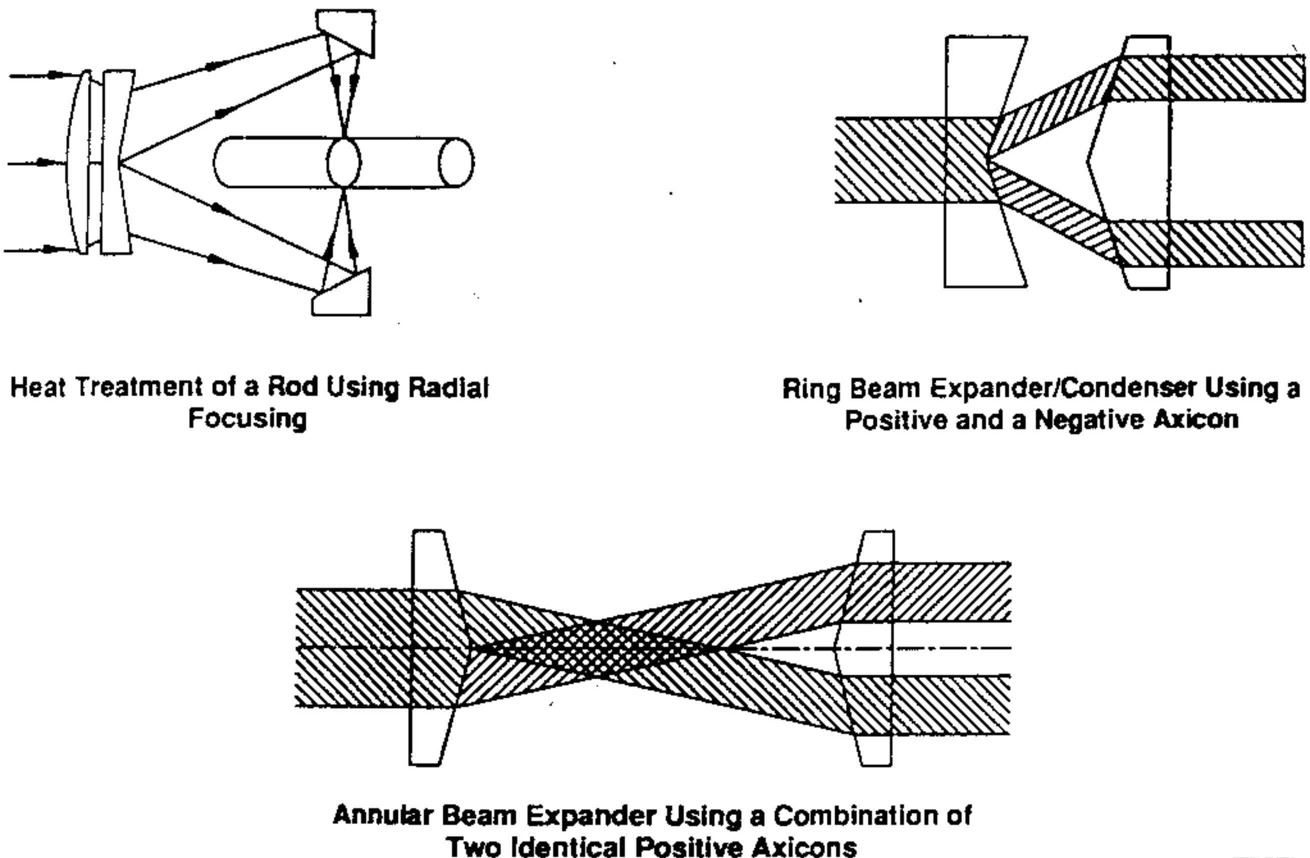


Figure 13: Applications of Diamond-turned Zinc Selenide Axicon for High-power CO_2 Lasers. Courtesy Laser Power Optics.

length, depending on the thickness of the center, and don't focus the light to a spot but to a line, and after that the light expands into a ring. Figure 13 shows some applications for these elements.

GRIN Rods: Although they may look on the outside like a simple glass stirring rod, they are quite complex on the inside. The material they are made from (SELFOC, registered trademark of the Nippon Sheet Glass Company) is not dielectrically homogenous, but has a refractive index that varies smoothly from large in the middle to lower toward the edges. This **G**radient **R**efractive **IN**dex change bends light inside the glass rod in such a way to provide a real focus. They can be distinguished from a simple rod because an image is seen when looking through the circular cross-section. They are used most often for coupling laser light into fiber optics. Figure 14 shows that the image plane is a function of the length of the rod as opposed to its shape.

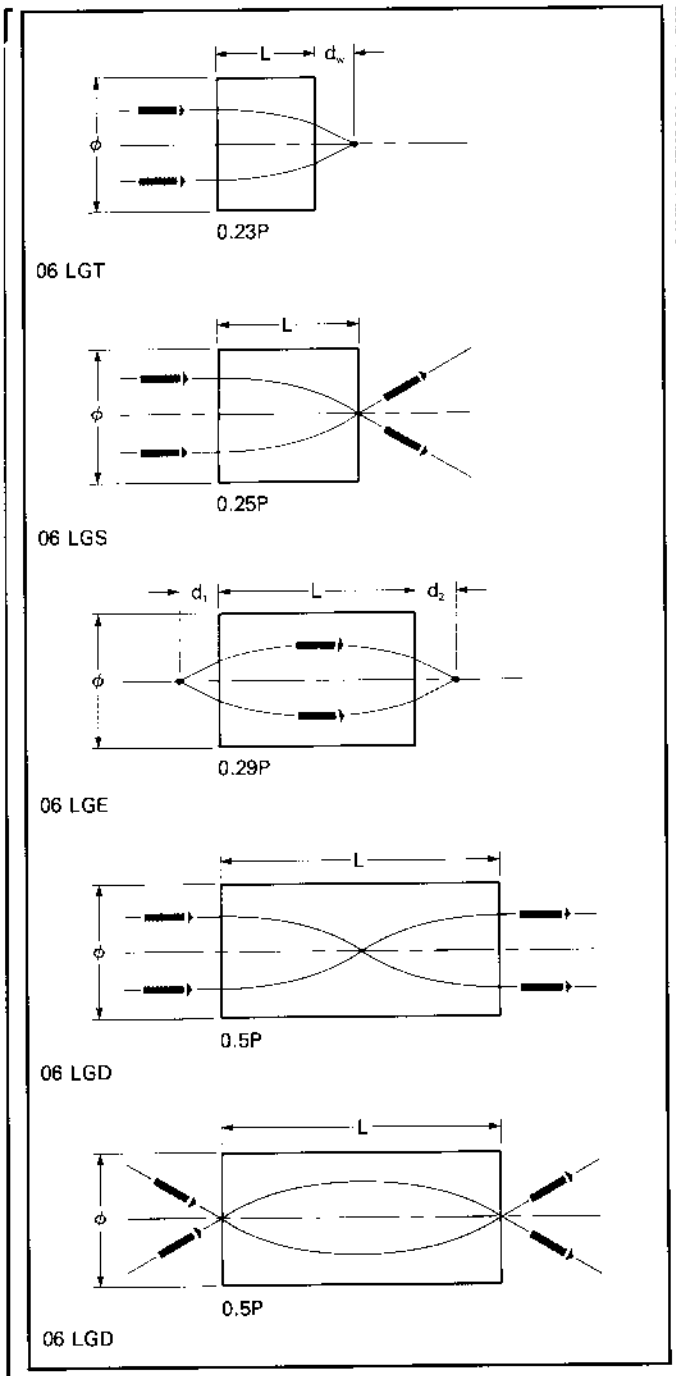


Figure 14: Focal point locations of different lengths of GRIN rods. Courtesy Melles Griot.

Fresnel Lenses provide positive or negative focussing power by having an array of rings prismatic in cross-section provide the bending power instead of the smoothly curved shape, like in Figure 15. They are lighter and cheaper to make, usualy of injection molded plastic, and are mainly used in non-imaging

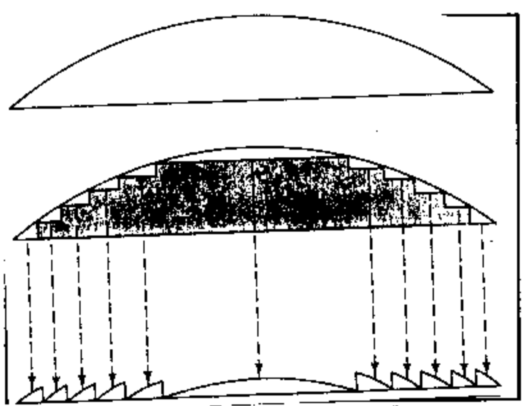


Figure 15: Fresnel Lens Profile, from Seeing the Light, David Falk et al., John Wiley and Sons, 1986.

applications, such as lighthouse beacons or traffic lights, with the most familiar use as field lenses in overhead projectors.

LENS COMBINATIONS

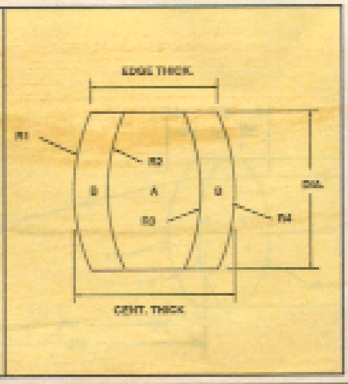
There are several common lens designs that are composed of combinations of positive and negative elements that are the workhorses of optics. The aberrations of one of the elements of the design is cancelled out by another, but which may introduce a different aberration, which may have to be corrected by yet a third lens. Contemporary computer-aided designs can juggle all these variables for an optimal solution, but in the history of optics before digital design there have been several noteworthy prescriptions which have immortalized the inventor's name.

Hastings Achromatic Triplets: A pair of concave meniscus elements cemented to a

Technical Spec Achromatic Lenses

TECHNICAL SPEC HASTINGS TRIPLET ACHROMATS
Hastings Triplets are the most popular high-power magnifiers available today, because their unique three-element design provides the ultimate in distortion-free, color-correct viewing. The lenses in the series are computer-designed to interact with each other, contributing to the reduction or elimination of "pin-cushion" distortion and chromatic and spherical aberrations. The triple lens system is made up of two concave meniscus elements cemented to a double convex lens. **All dimensions in mm.**

SPECIFICATIONS:
Material: F2/BK7/F2
Diameter: ±0.05 mm
Focal Length: ±2%
Center & Edge Thickness: ±0.45 mm
Surface Quality: 80/50

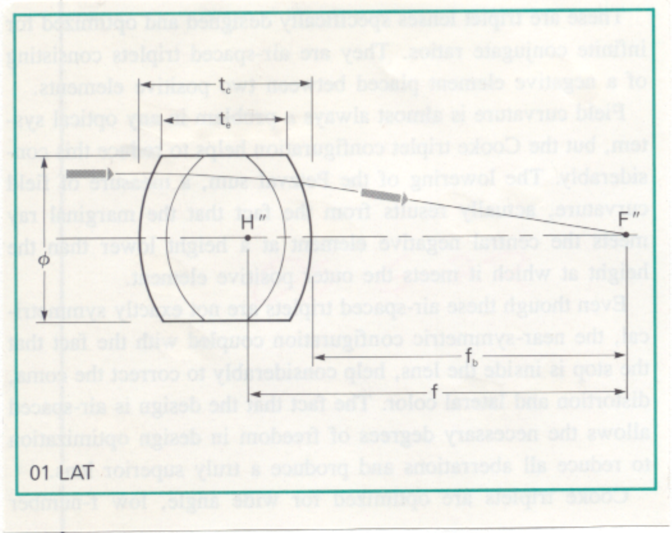


Stock #	Price	Diameter (mm)	Effective F. L. (mm)	Back F. L. (mm)	Center Thick (mm)	Edge Thick (mm)	Radius (mm)				Glass Type		Center Thickness (mm)	
							R1	R2	R3	R4	A	B	A	B
N36,187	$35.28	8.00	12.50	9.9	7.18	5.41	9.48	4.66	-4.66	-9.48	K5	F2	5.40	0.89
N30,120	$31.40	15.01	25.40	20.0	12.77	9.41	19.00	9.30	-9.30	-19.00	BK7	F2	10.21	1.14
N30,229	$31.40	23.00	40.30	33.9	18.00	13.79	32.48	18.15	-18.15	32.48	BK7	F2	11.00	3.50

Figure 16: Courtesy Edmund Scientific Company, Barrington, NJ

positive convex lens provides color-corrected high-power magnification. Pin-cushion distortion is reduced or eliminated, and because it is an achromat chromatic and spherical aberrations are low. Figure 16 shows a typical advertisement for them.

Steinheil Achromatic Triplets: Figure 17, next page. A combination of elements similar to the above, with the outside ones high refractive index flint glass and the central one lower index crown glass. This variation is designed to work best at unit magnification, as it is symmetric, and is still useful at conjugate ratios up to five, (1/5X



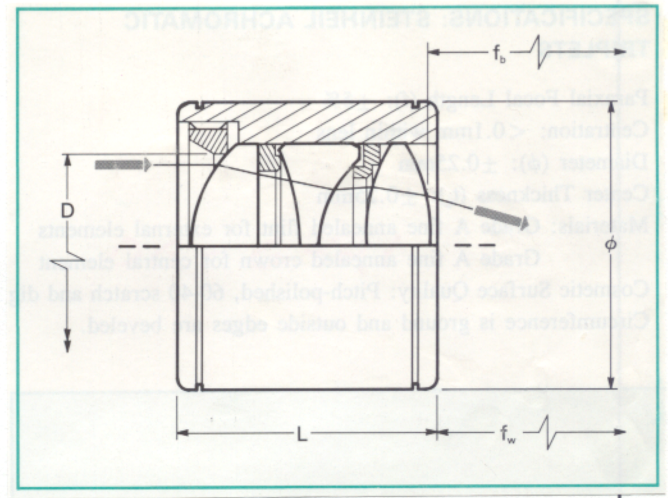


Figure 17: Courtesy Melles Griot.

Figure 18: Courtesy Melles Griot.

minification up to 5X magnification), where performance is surpassed by the less expensive achromatic doublets.

Cooke Triplets: Figure 18. These are the grandaddies of normal photographic objectives. (See section below.) A negative element is positioned between a pair of positive ones. There is no symmetry to the formula, as it is designed for imaging far away objects with great off-axis performance. The design is achromatized, and curvature of field is kept to a minimum.

Condensing Pairs: The plano-convex shape is utilized in less expensive condensing pairs, Figure 19, with the light source at the focal point of the collecting lens, and the light emerges more or less parallel from here and enters the second lens of the pair, which concentrates the light onto the item to be illuminated. The two lenses may or may not be the same focal lengths, which is helpful in designing systems to meet space requirements. This tricky configuration can be used improve the imaging properties of this type of lens at nearer than infinity positions. Figure 20 shows a full-blown projection system using higher performance and cost aspheric optics.

Microscope Objectives: These multi-element packages are designed to provide a specific magnification at a specific working distance. Objectives team up with eyepieces in mechanically standardized units, and the overall magnification is simply the product of the marked magnifications of the components.

In addition to the magnifying power marked on the objective, there is another number engraved on the barrel, the **Numerical Aperture**. It is a measure of the light gathering power of the objective and its field of view.

$$N.A. = \text{diameter of lens}/2*f = 1/(2*f/\#)$$

or to change to f/#,

$$f/\# = 1/(2*N.A.).$$

A typical 10X microscope objective has a Numerical Aperture of .25, meaning its f/# is 1/(2*.25) = 1/.5 = 2.

The N. A. also describes the field of view:

$$N.A. = n*\sin \theta,$$

where n is the refractive index of the medium between the objective and object, and theta is the angular radius of the cone of light entering the objective. For the example above, and an air gap,

$$\theta = \sin^{-1} .25,$$

so the field of view is 14 degrees.