Experiment 1: Ray Optics

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Abstract

During these experiments, we primarily investigated the reflection and refraction of light, how lenses bend light, and the diffraction of light. Several laws and principles, including Snell's Law and the Fundamental Lens Equation, were validated through the collection and processing of data.

1 Experiments

1.1 Experiment 1: Introduction to Ray Optics

1.1.1 Sketch

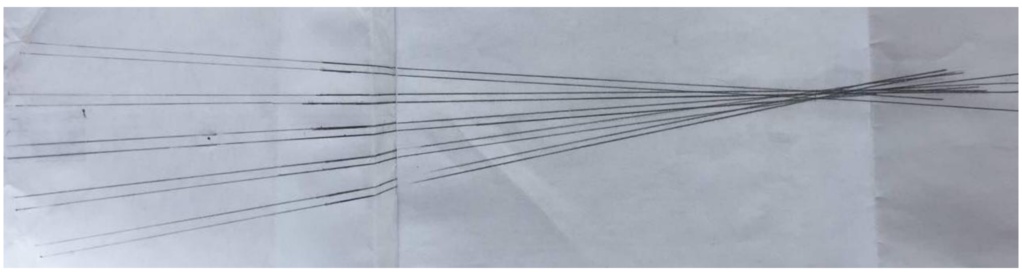

Figure 1: Tracing the divergent rays back to the light source.

1.1.2 Straight Line Propagation of Light

1.1.2.1

While the rays are straight, they are not parallel with each other.

1.1.2.2

As the rays' distance from the Slit Plate increases, their width increases while their distinctness decreases.

1.1.2.3

All of the rays appeared to originate from the Light Source, even when viewed from a slight angle.

1.1.2.4

As the angle of the Slit Plate increases, becomes more horizontal, the width of the rays increases while their distinctness decreases.

1.1.2.5

The images are most distinct when the Slit Plate is entirely vertical, and they are least distinct when it is horizontal.

1.1.3 Ray Tracing: Locating the Filament

1.1.3.1

The distance between the reference mark in the center of the Ray Table and the point of intersection of the rays at the filament is $d_e = 24.1 \pm 0.05$cm.

1.1.3.2

The distance between the filament and the center of the Ray Table was measured to be $d_t = 25.6 \pm 0.05$cm.

1.1.3.3

The two measurements have a percent error, where $\%_{err} = \frac{|d_t - d_e|}{d_t} \cdot 100\%$, of $\%_{err} = 5.86\%$, and a percent uncertainty, where $\delta\%_{err} = \frac{\%_{err}}{d_e}$, of $\delta\%_{err} = 0.249\%$. Although the percent error, $5.86\% \pm 0.249\%$, is low, it is, nonetheless, present.

1.2 Experiment 2: The Law of Reflection

1.2.1 Data

Figure 2: **Table 2.1:** The two angles of reflection compared to their corresponding angle of incidence in degrees.

Incidence	Reflection_1	Reflection_2
0	0	0
10	10	10
20	20	20
30	30	30
40	40	40
50	50	50
60	60	60
70	70	70
80	80	80
90	90	90

1.2.2 Questions

1.2.2.1

The results of the two trials are the same.

1.2.2.2

The incident ray, reflected ray, and normal all lie on the same plane because the reflected and incident rays are visible on the 2D surface of the Ray Table. Because they are both visible on the 2D surface, they must both reside in the same 2D plane.

1.2.2.3

The angle of incidence and the angle of reflection are both the same value.

1.3 Experiment 3: Image Formation in a Plane Mirror

1.3.1 Sketch

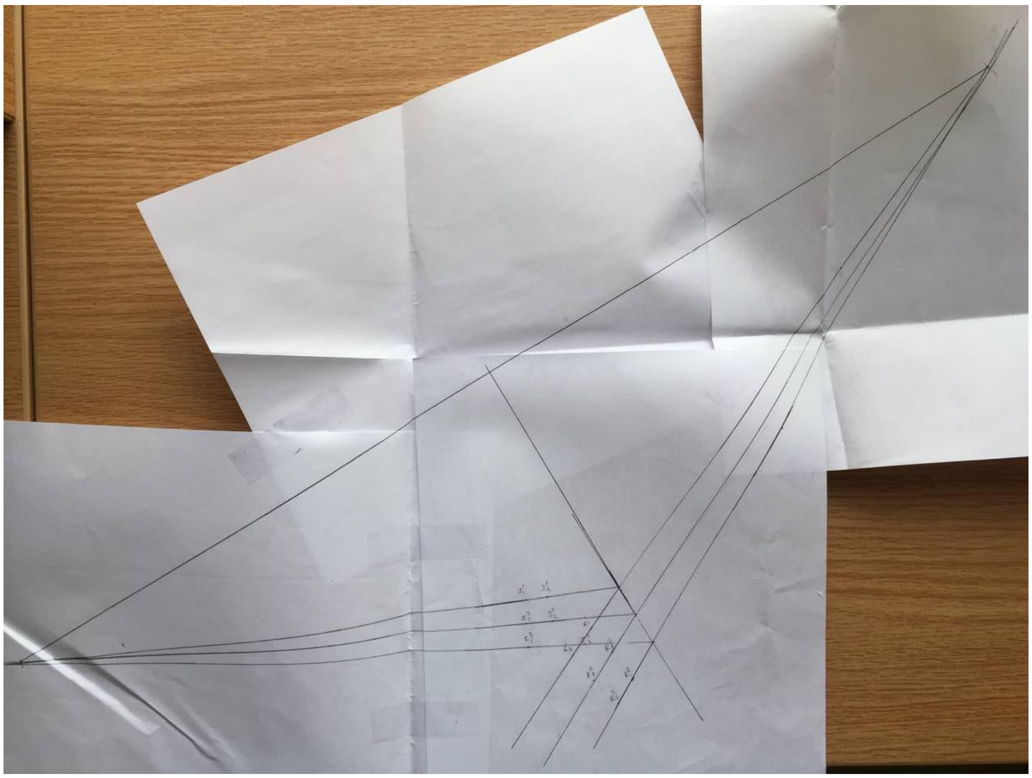

Figure 3: The tracing of the rays incident on the plane mirror.

1.3.2 Questions

1.3.2.1

The rays do seem to follow a straight line into the mirror.

1.3.2.2

The distance from the filament to the plane of the mirror (d_1) was measured to be 30.1 ± 0.05cm.

1.3.2.3

The perpendicular distance from the image of the filament to the plane mirror (d_2) was measured to be 30.0 ± 0.05cm.

1.3.2.4

The image will always appear to be the same distance away as if it were being viewed straight on without a mirror.

1.4 Experiment 4: The Law of Refraction

1.4.1 Data

Figure 4: **Table 4.1:** The two symmetric angles of refraction from each angle of incidence. For angles of incidence 80° and 90°, the ray internally reflected, so there were no refraction rays.

Incidence (degree)	Refraction_1 (degree)	Refraction_2 (degree)
0	0	0
10	7	6
20	13	13
30	20	20
40	25	26
50	31.5	31.5
60	36	36
70	41.5	42
80	n/a	n/a
90	n/a	n/a

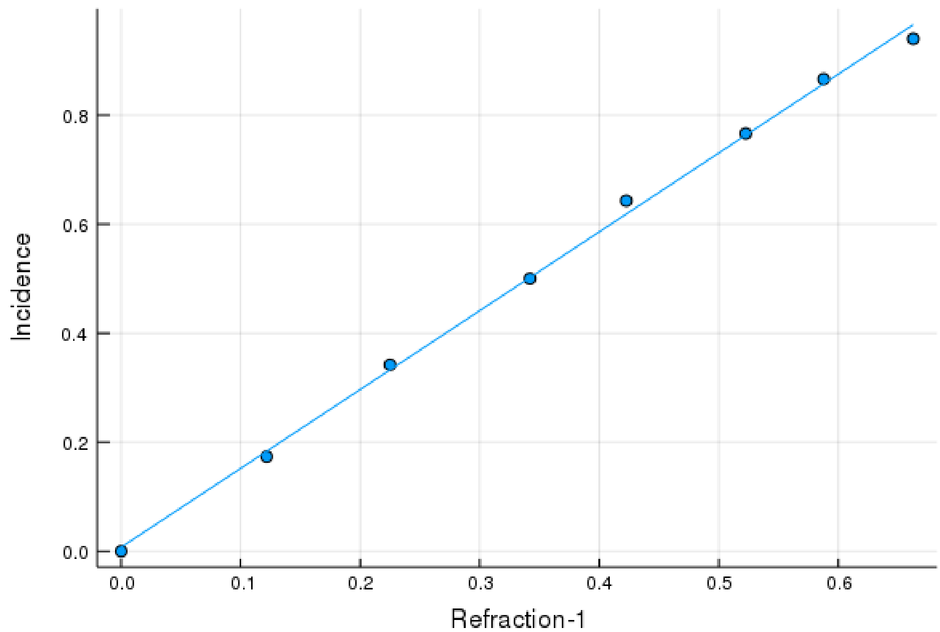

Figure 5: A graph where the x-axis is the sine of the first angle of refraction and the y-axis is the sine of the incidence angle. There is also a straight line of best fit.

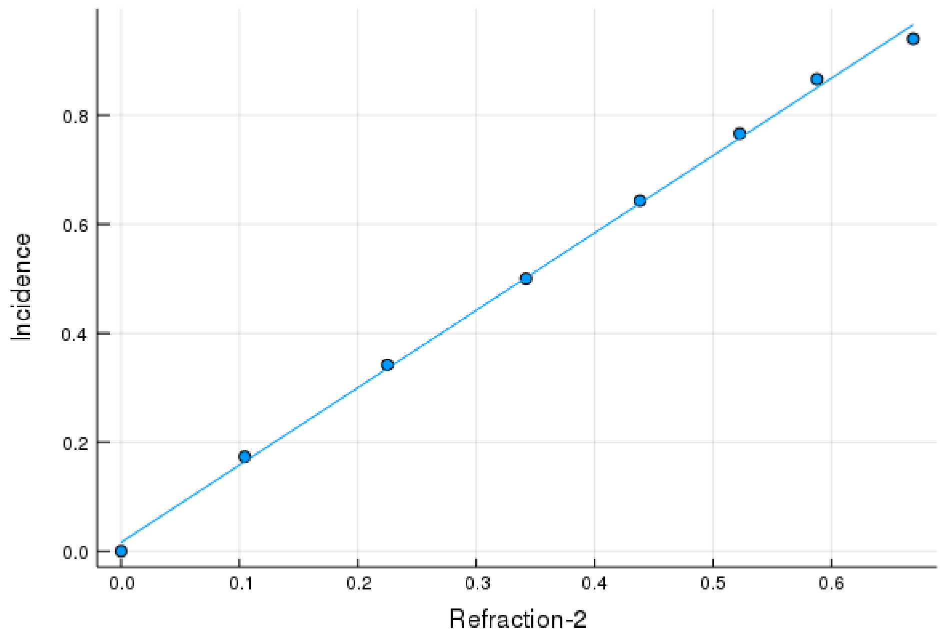

Figure 6: A graph where the x-axis is the sine of the second angle of refraction and the y-axis is the sine of the incidence angle. There is also a straight line of best fit.

1.4.2 Questions

1.4.2.1

The ray is not bent when it passes into the lens perpendicular to the lens' flat surface.

1.4.2.2

The ray is slightly bent when it passes out of the lens perpendicular to the lens' curved surface.

1.4.2.3

While the two sets of measurements are very nearly identical, there are minor differences between the two. These differences may be attributed to our inability to perfectly align the ray with the Ray Table.

1.4.2.4

The graphs are consistent with the Law of Refraction. The slopes are less than one, which indicates that the medium, the lens, has a greater index of refraction than the air from which the light originates.

1.5 Experiment 5: Reversibility

1.5.1 Data

Figure 7: **Table 5.1:** The different angles, in degrees, of the light through two sides of the same medium.

Incidence_1	Refraction_1	Incidence_1	Refraction_2
0	0	0	0
10	6.5	6.5	11
20	12.5	12.5	20
30	20	20	30
40	25	25	40
50	31	31	47
60	37.5	37.5	58
70	43	43	74
80	45	45	n/a

1.5.2 Questions

1.5.2.1

The index of refraction for the acrylic, n_1, can be found by using Snell's Law, $n_0 \sin(\theta_i) = n_1 \sin(\theta_r)$, rearranged as, $n_1 = \frac{n_0 \sin(\theta_i)}{\sin(\theta_r)}$. The value of n_1 was determined by calculating n_1 for each of the $\text{Incidence}_1 = \theta_i$, $\text{Refraction}_1 = \theta_r$

pairs, where $n_0 = 1$. The average of these values was then found to be $n_1 = 1.48$. The first and last rows of data were removed from these calculations because the first row is only zeros, and the last row contains a null value.

1.5.2.2

Since now it is the destination index of refraction that is known, the formula above must be rewritten as $n_2 = \frac{n_0 \sin(\theta_r)}{\sin(\theta_i)}$. The acrylic's index of refraction was calculated using the same method as above, and the value was found to be $n_2 = 1.50$.

1.5.2.3

The Law of Refraction is the same for rays entering and exiting a medium. There is a minor discrepancy between the two calculated values of the index of refraction of the acrylic, because of errors aligning the Ray Table exactly.

1.5.2.4

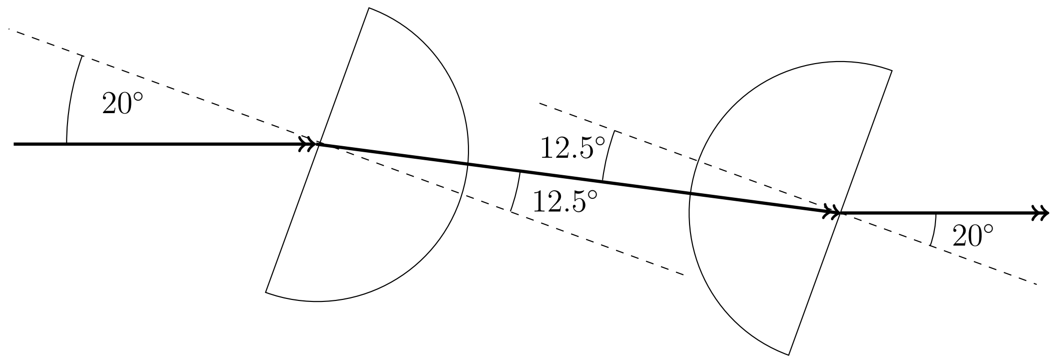

Figure 8: A diagram showing the path of the ray through the flat end of the lens, followed by the curved end of the lens. The principle of optical reversibility is shown because the initial refraction of the light ray is undone be reversing the orientation of the lens.

1.5.2.5

The principle of optical reversibility also holds for reflection. If the path of a reflected ray is followed in reverse, the same path will be taken.

1.6 Experiment 6: Dispersion and Total Internal Reflection

1.6.1 Dispersion

1.6.1.1

Color separation began to appear at around 20 degrees.

1.6.1.2

The maximum amount of color separation appeared at around 40 degrees.

1.6.1.3

In the refracted ray, red has the smallest angle of refraction, followed, in ascending order, by yellow, green, blue, and purple.

1.6.1.4

At an angle of incidence of 40 degrees, the angles of refraction for red light and blue light are, respectively, $\theta_{i,red} = 76.5°$ and $\theta_{i,blue} = 85°$. The index of refraction of the acrylic, n_i, can be found be rearranging Snell's Law, $n_r \sin(\theta_r) = n_i \sin(\theta_i)$, as $n_i = \frac{n_r \sin(\theta_r)}{\sin(\theta_i)}$, where $n_r = n_{air} = 1$ and $\theta_i = 40°$. The index of refraction of the acrylic for red light may be found with:

$$n_{i,red} = \frac{n_r \sin(\theta_r)}{\sin(\theta_{i,red})}$$

$$n_{i,red} = \frac{(1)\sin(76.5)}{\sin(40)}$$

$$n_{i,red} = 1.51$$

The index of refraction of the acrylic for blue light may be found with:

$$n_{i,blue} = \frac{n_r \sin(\theta_r)}{\sin(\theta_{i,blue})}$$

$$n_{i,blue} = \frac{(1)\sin(85)}{\sin(40)}$$

$$n_{i,blue} = 1.55$$

1.6.2 Total Internal Reflection

1.6.2.1

While reflection off the flat edge is dim, the reflection from the curved edge is much more prominent and complete at an incident angle of 80 degrees.

1.6.2.2

Yes, there is always a reflected ray for all angles of incidence.

1.6.2.3

Yes, the angles for the reflected rays are consistent with the Law of Reflection because the incidence angles match the angles of the rays' reflection.

1.6.2.4

There is not a refracted ray for all angles of incidence; there is no refracted ray for angles of incidence above 45 degrees on the curved edge.

1.6.2.5

As angle of incidence increases, the intensity of the refracted rays decreases, while the intensity of the reflected rays increases.

1.6.2.6

All the light is reflected at an angle of refraction of 83 degrees.

1.7 Experiment 7: Converging Lens - Image and Object Relationships

1.7.1 Data

Figure 9: **Table 7.1:** The data calculated from the experiment and the calculated values determined from the data. Calculations were performed by reading the data into a Julia DataFrame, then performing the requested operations on that data. The following formulas $\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$ and $M = -\frac{d_i}{d_o} = \frac{h_i}{h_o}$ were used.

Data (mm)			Calculations			
d_o	d_i	h_i	$\frac{1}{d_i} + \frac{1}{d_o}$ (mm^{-1})	$\frac{1}{f}$ (mm^{-1})	$\frac{h_i}{h_o}$	$\frac{-d_i}{d_o}$
50	n/a	n/a	n/a	n/a	n/a	n/a
75	inf	n/a	n/a	n/a	n/a	n/a
100	295	59	0.0140	0.0140	-0.166	-0.166
150	114	19	0.0137	0.0137	-0.193	-0.193
200	115	11	0.0137	0.0137	-0.222	-0.222
250	105	9	0.0136	0.0136	-0.265	-0.265
300	96	6.5	0.0137	0.0137	-0.320	-0.320
350	93	5.5	0.0135	0.0135	-0.420	-0.420
400	89	4.5	0.0136	0.0136	-0.575	-0.575
450	87	4	0.0154	0.0154	-0.760	-0.760
500	83	3.5	0.0133	0.0133	-2.950	-2.950

1.7.2 Questions

1.7.2.1

The image is magnified.

1.7.2.2

The image is inverted.

1.7.2.3

As d_o increases, d_i decreases.

1.7.2.4

If d_o were very, very large, d_i would tend toward f. Since d_o is very large, $\frac{1}{d_o} \to \frac{1}{\infty} \approx 0$, therefore,

$$\begin{aligned}
\frac{1}{f} &= \frac{1}{d_o} + \frac{1}{d_i} \\
\frac{1}{f} &= (0) + \frac{1}{d_i} \\
\frac{1}{f} &= \frac{1}{d_i} \\
f &= d_i
\end{aligned}$$

1.7.2.5

The focal length was determined by measuring the distance between the lens and the view screen when a crisp image was shown on the view screen. The focal length was measured to be 8 cm.

1.7.2.6

The measurements appear to be in agreement with the Fundamental Lens Equation.

1.7.2.7

We were unable to focus an image on the screen for $d_o < 75\,\text{mm}$. The focal point of the lens is 75 mm, so, according to the Fundamental Lens Equation, when $d_o = f$, $d_i = \infty$. We could not get a focused image at $d_o = 50\,\text{mm}$ because $d_o < f$.

1.8 Experiment 8: Light and Color

1.8.1 The Colors of Light

1.8.1.1

Our observations support Newton's theory, because colors appeared from the white light.

1.8.1.2

When red, green, and blue light are mixed together, they produce white light. This supports Newton's theory because it shows that white light must be comprised of several colors, since the combination of those colors produces white light.

1.8.2 The Colors of Objects

1.8.2.1

The transmitted rays were green, and the reflected rays were white.

1.8.2.2

The reflected rays are white. The green filter ought to reflect all rays except green, which it transmits, and the red filter ought to reflect all rays except red, which it transmits. All the reflected rays appeared to be white.

1.8.2.3

Since we did not have a blue filter, we used the blue/green filter instead. The reflected rays were blue.

1.8.2.4

The green filter appears green because it absorbs and transmits only green light while reflecting all other colors.

1.9 Experiment 9: Two-Slit Interference

1.9.1 Data

Figure 10: **Table 9.1:** The different parts of the slit geometry.

Data					Calculations
Color	n	AB (cm)	X (cm)	L (cm)	$\frac{(AB)}{n}\sin(\tan^{-1}(\frac{X}{L})) = \lambda$
red	5		1	35	
green	4		0.5	35	
blue/green	7		1	35	

1.10 Experiment 10: Polarization

1.10.1 Polarization

1.10.1.1

The target does not appear bright because a significant portion of the light is not making it through the polarizers.

1.10.1.2

The light from the light source plane is not polarized because the light is visible no matter the orientation of a single polarizer.

1.10.1.3

A maximum amount of light is allowed through the polarizers when polarizer B is at 0° and 180° because those angles align with polarizer A. A minimum amount of light is allowed through when polarizer B is perpendicular to polarizer A at angles 90° and 270°.

1.10.2 Polarization by Reflection: Brewster's Angle

1.10.2.1

The reflected light is polarized. The light is bright at angles 0° and 180°, while it is dim at 90° and 270°.

1.10.2.2

The light plane is not polarized when the reflected ray is not at an angle of 90° with respect to the refracted ray, because the light is visible for all angles of the polarizer.

1.11 Experiment 11: Image Formation from Cylindrical Mirrors

1.11.1 Procedure

1.11.1.1

The focal length of the concave cylindrical mirror was measured to be 61.5 mm.

1.11.1.2

The focal length of the convex cylindrical mirror was measured to be 6 cm.

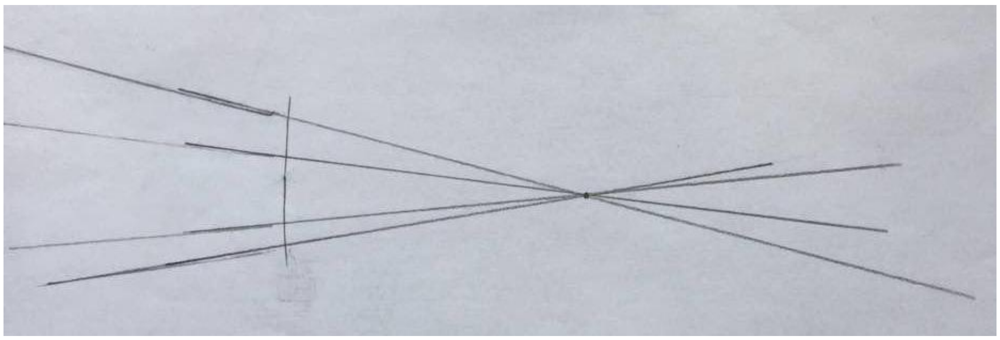

Figure 11: The ray trace of the light rays traveling through the convex mirror.

1.11.2 Image Location

1.11.2.1

The image of the light bulb filament is formed where the reflected rays cross.

1.11.2.2

The image is not noticeably affected by moving the mirror closer to the filament until it gets very close, because the light rays then begin to diverge.

1.11.2.3

An image is not formed when the distance between the filament and the mirror is less than the focal length because the rays become divergent at lengths below the focal length.

1.11.2.4

A real image cannot be obtained from the convex side of the mirror because the rays diverge from a convex mirror.

1.11.3 Magnification and Inversion

1.11.3.1

The degree of magnification increases as the object distance, d_o, decreases because $M = -\frac{d_i}{d_o}$.

1.11.3.2

The image is inverted. The image inversion does depend on image location, because if the image is viewed from beyond the focal point, the rays have converged and crossed over each other, thus flipping the image.

1.11.4 Cylindrical Aberration

1.11.4.1

The rays are all focused at the same point, but the rays closer to the edges are less distinct.

1.11.4.2

To reduce the amount of cylindrical aberration, the lens ought to be made into a parabolic shape.

1.12 Experiment 13: Image Formation with Cylindrical Lenses

1.12.1 Focal Point

1.12.1.1

$f_1 = 7\,\text{cm}$ and $f_2 = 5.1\,\text{cm}$

1.12.1.2

The refracted rays converge at the same focal length.

1.12.1.3

The refracted rays now converge further than before. On the flat edge of the lens, the rays are parallel until they exit, and on the curved edge of the lens, the incident rays are never parallel. Since the rays are never parallel once they contact the lens on the curved side, their focal length is shorter.

1.12.2 Image Location

1.12.2.1

The image is formed at 7 cm.

1.12.2.2

The image moves further away as the light source nears.

1.12.2.3

No image is formed when the light source is closer than the lens' focal length.

1.12.3 Magnification and Inversion

1.12.3.1

Magnification increases as the lens nears the light source.

1.12.3.2

The image is inverted for all object locations.

1.12.4 Cylindrical Aberration

1.12.4.1

All of the rays, except those at the edges, are focused at precisely the same point.

1.13 Experiment 14: Spherical Lenses - Spherical and Chromatic Aberration, Aperture Size, and Depth of Field

1.13.1 Spherical Aberration

1.13.1.1

The smaller the aperture, the greater the focus of the image.

1.13.1.2

An infinitely small aperture would, theoretically, provide the best focus, but it is impractical because not enough light would get through to sufficiently illuminate the image.

1.13.2 Depth of Field

1.13.2.1

The depth of field is reduced as the aperture size decreases.

1.13.2.2

An infinitely long depth of field would produce a very blurry image.

1.13.2.3

An image of the target is still visible on the screen after the lens is removed.

1.13.2.4

As the size of the aperture increases, the distinctness of the image decreases.

1.13.2.5

As the distance between the aperture and viewing screen increases, the magnification of the image also increases.

1.13.2.6

The very small aperture serves the role of focusing the light that passes through it. This principle is exploited by pinhole cameras.

1.13.3 Chromatic Aberration

1.13.3.1

Chromatic aberration is more apparent when the aperture is far from the optical axis of the lens because there is more space for the rays to separate.

1.14 Experiment 15: The Diffraction Grating

1.14.1 Data

Figure 12: **Table 15.1:** The data needed to calculate the minimum and maximum wavelengths. $A\sin(\tan^{-1}(\frac{X}{L} = \lambda))$

Data (cm)					Calculations (nm)	
Color	A	L	X_1	X_2	λ_1	λ_2
violet	160×10^{-6}	35	7.5	8.5	335	377
blue	160×10^{-6}	35	8.5	10.5	377	459
green	160×10^{-6}	35	10.5	11.7	459	507
yellow	160×10^{-6}	35	11.7	12.3	507	530
orange	160×10^{-6}	35	12.3	13	530	557
red	160×10^{-6}	35	13	15	557	630

1.14.2 Questions

1.14.2.1

As slit width increases, the width of the maxima also increases.

1.14.2.2

The high number of slits creates a thin pattern with many lines close together.

1.15 Experiment 16: Single Slit Diffraction

1.15.1 Questions

1.15.1.1

The narrower the slits, the narrower the fringes.

1.15.1.2

The single slit, pattern A, produces a narrow, blurry patter, while the double slit, pattern D, produces a spread out, distinct pattern.

1.16 Experiment 19: The Projector

1.16.1 Questions

1.16.1.1

The image cannot be focused onto the viewing screen when $d_o < f$ because the rays diverge.

1.16.1.2

The image can be focused when $d_o > 2f$ because the rays are able to converge.

1.16.1.3

In order for substantially large magnification, $d_o < f$, which is not practical because an image is not produced. It is impossible to project an uninverted image with only a single lens.

1.16.1.4

The image formed by a projector cannot be viewed without a viewing screen.

2 Conclusion

Almost all of our data matches with theory. The data collected for Experiment 2 is entirely correct. Experiment 4's data is a bit less precise, but it is very close to its theoretical value, because the points very nearly match the lines of best fit. The data for Experiment 5 is very near what it is supposed to be; the data has no discrepancy higher than 6%. Error throughout the experiments may be contributed to our inability to perfectly align the lab equipment and limitations encountered during measurement.