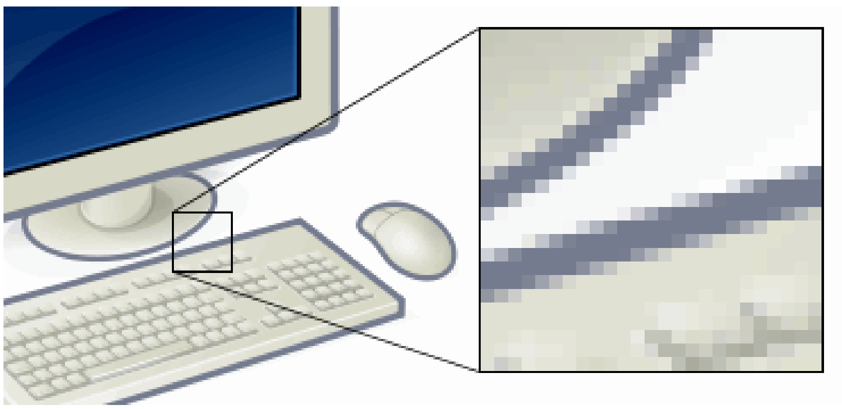
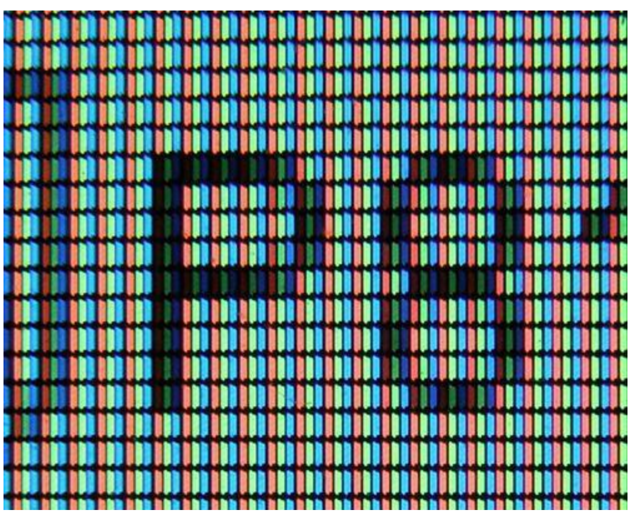
Science, Dr. Gordon Gainer | Name:
Color Resolution Distance Lab | Date: | Period:

Introduction: When two close lights are viewed from far away, they appear to be only one light. Also, when red, green, and yellow lights mix, they join to create a perception of white. We will apply both these concepts, and see at what distance, three close lights (red, green, and glue) join into a white light in our vision. We will also explain this distance, based on the eye's color light detectors.

Pixels: The eyes and brain work similarly to the way cameras and display screens work. If you look closely at a printed picture or a display on a computer or cell phone, you see that it is made of many dots, as shown in the figure below from https://en.wikipedia.org. Cameras work the same way in reverse, with many tiny light detector dots. These dots are called pixels. The same image of a pattern of light detected in the pixels on a plane in the back of a camera is projected onto a screen for us to see.



Color Pixels: Actually the pixels are made of subpixels in the three light primary colors – red, blue, and green, as shown in the figure below from https://en.wikipedia.org.



All the colors are made from different combinations and amounts of red, green, and blue light. We saw why in the EdPuzzle "Color Mixing with Physics Girl." For example, if one spot pixel on a screen has bright red, bright green, and no blue, then we see yellow at this dot in our vision. When we see three close lights of colors red, green, and blue, they make an image on the retina back of our eye, just like the back plane of a camera. However, if we move further and further from these lights, the image of the three color lights will become so close together on the eye, that they will all be in the same "pixel." Then, the brain will perceive these three lights as one white light.

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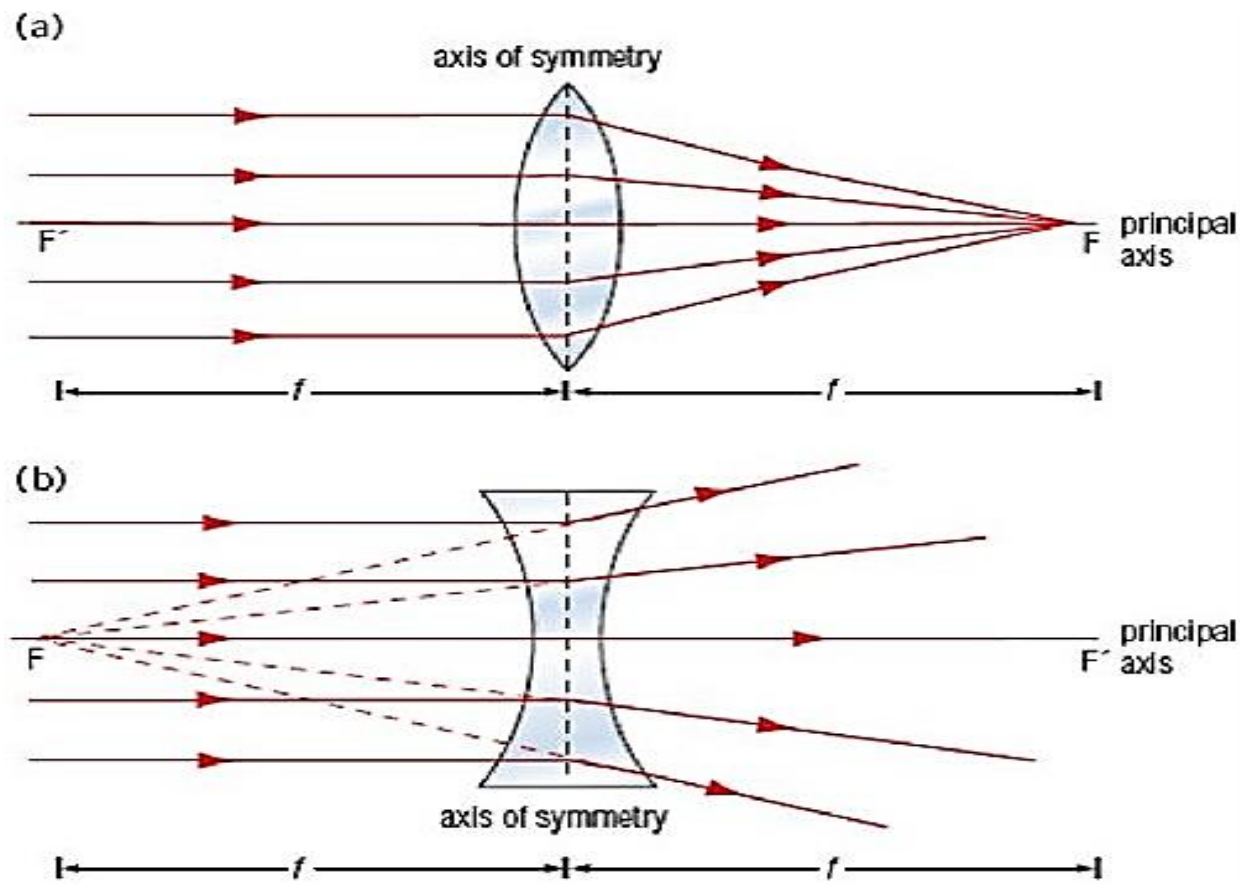
Image through Eye Lens: The eye has a convex lens, as shown in the top of the figure below. A concave lens is shown at the bottom of the figure below. It's easy to remember the difference between convex and concave lenses, because concave lenses look like they have caves on their sides. Parallel light rays (lines of light) are focused by a convex lens to one point called a focus. A convex lens focuses practically parallel light rays from the sun onto the focus point where the concentrated light energy can burn something. As shown at the bottom of this figure, parallel light rays through a concave lens diverge away from the focus on the left.



1. Draw these diagrams on a paper (with your name), and show it to me in class.

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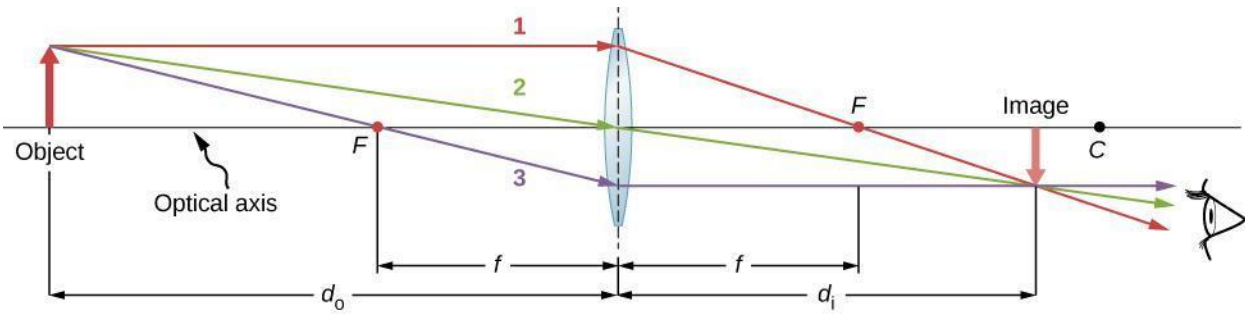
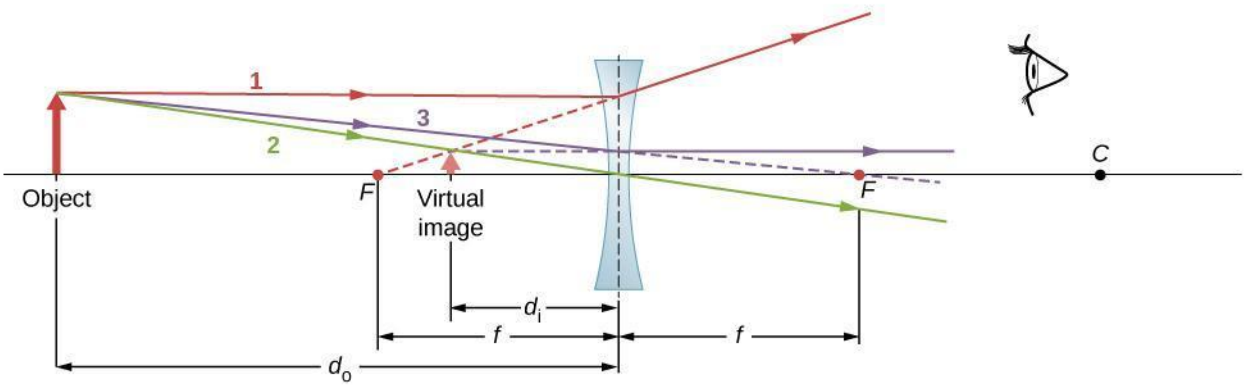
Ray Tracing to Determine Image of Object through Lens: Now that we know what lens foci are, we can draw diagrams as shown in the figure below to see how light from an object goes through a lens and forms a clear image at another location. If the object is bright, it is easy to see the image on a paper at the right position. The figure shows three types of light rays leaving the top of the object. The first ray is parallel to the optical axis (center line), so the convex lens sends it through the focus on the other side. The second ray goes straight through the lens center. The third ray goes through the left focus, so the convex lens turns it parallel to the optical axis. All three rays intersect at the image location. These diagrams are very accurate when the light rays are close to the optical axis and the lens sides are spherical sections.



(a)



(b)

2. <u>Draw these diagrams</u> also on a paper (with your name), and show them to me in class.

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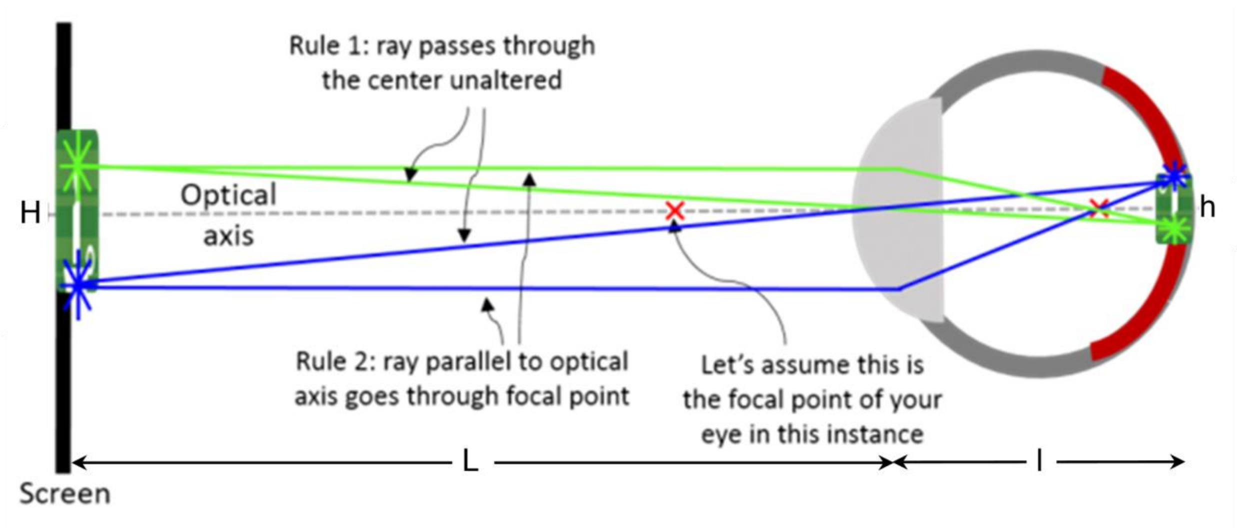
Ray Tracing to Determine Image on Retina: Now we can see how the lens at the front part of your eye creates an image of an object on the retina (the back of your eye, where the light detectors are). This is shown in the figure below from https://measurebiology.org/wiki/Geometrical_optics_and_ray_tracing . The object is at the far left and the image is on the far right on the retina. Let's say the top of the object is one light and the bottom of the object is another light. With similar triangles, we can find the distance between the two lights in the image on the retina. As shown in the figure, let's call this distance h. The distance between the lights in the object is H. The object is a distance L from the front of the eye, and the eye width is l. Then, from similar triangles, h/l = H/L, so h = Hl/L.



Our three lights (red, green, and blue) roughly formed an equilateral triangle with ~1 cm sides, so let H = 1 cm (0.01 m / 1 cm) = 0.01 m.
We found that the distance at which the three lights merged into one big white light is L = 27.5 feet (12 inches/foot)(2.54 cm / 1 inch)(0.01 m / 1 cm) = 8.382 m.
According to https://en.wikipedia.org/wiki/Fovea_centralis#cite_note-21, the distance between the eye's lens and the fovea (the part of the retina with maximum sensitivity) is l = 17.1 mm (0.001 m / 1 mm) = 0.0171 m on average.
With these numbers, we calculate that h = 2.04×10^{-5} m (1 μm / 10^{-6} m) = 20.4 μm.

Explanation: L is the minimum distance at which the three lights join into one big white light in our vision, so h is the maximum distance between the lights' images on the retina at which the lights' images join into a white light on the retina. We would expect this distance h to be about the same as the spacing between the color light detectors in the retina. These color light detectors are called cones. We can calculate the cone spacing from data in https://en.wikipedia.org/wiki/Fovea_centralis#cite_note-20 , which says that the fovea has an average cone density of 147,000 cones / mm^2. Therefore, the foveal cone spacing is $\sqrt{\frac{1\ mm^2}{147{,}000\ cones}}$ = 2.6 x 10^{-3} mm/cone = 2.6 μm/cone.

Conclusion: Our calculation of cone spacing is 20.4 µm, but this is 7.8 times greater than Wikipedia's average foveal cone spacing of 2.6 µm. Why? According to the figure below from https://en.wikipedia.org/wiki/File:ConeMosaics.jpg and the article at https://en.wikipedia.org/wiki/Fovea_centralis#cite_note-Curcio1991-19, foveal blue cones are spaced much further apart than red and green cones. In fact, the fovea center lacks blue cones. To prevent this problem, in future studies, we could use this technique for only red and green lights. We could also check how viewing the lights a few degrees to the side could affect the resolution distance. Another factor affecting the resolution distance is that the brain might use a larger group of cones in each of its "pixels" to minimize its calculation load and to average over differences in cone sensitivities. A practical application of color resolution with distance is that it could be a quick method to check for eye degeneration and disease.

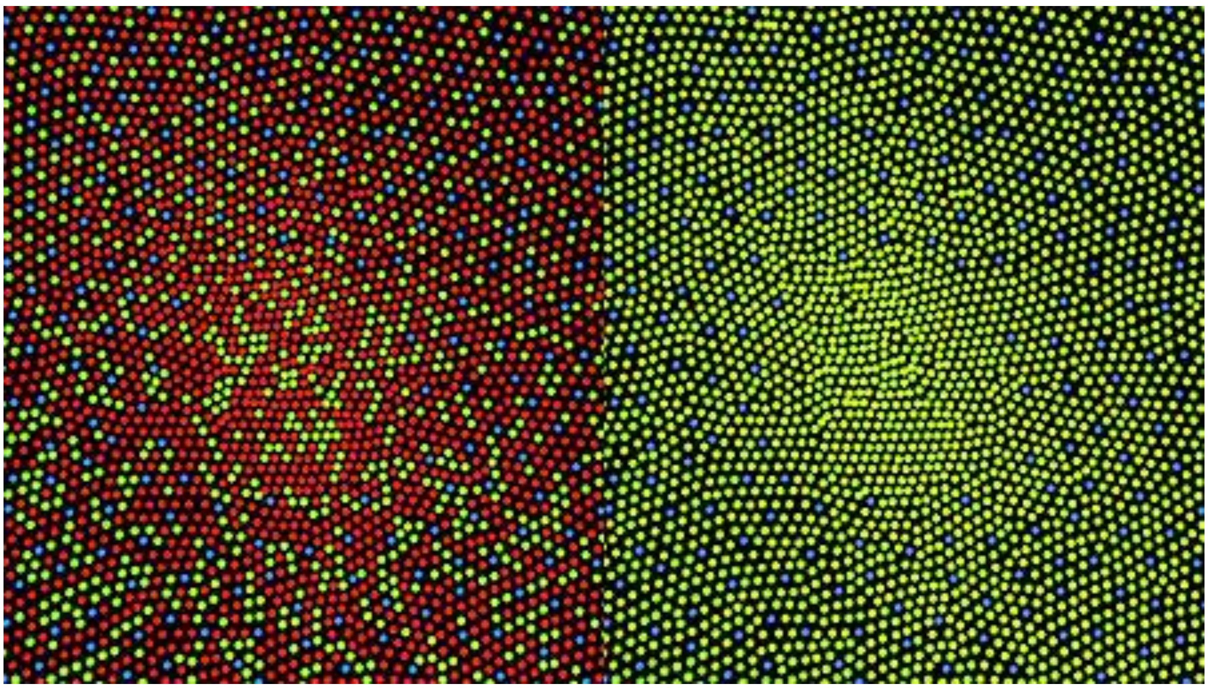


Illustration of the distribution of cone cells in the fovea of an individual with normal color vision (left), and a color blind (protanopic) retina. Note that the center of the fovea holds very few blue-sensitive cones. From https://en.wikipedia.org/wiki/File:ConeMosaics.jpg.