IS HIGHER SENSOR RESOLUTION ALWAYS BETTER?

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EXECUTIVE SUMMARY

In designing an imaging system, sensor resolution is just one important factor. The systems engineer is reminded to consider the impact of basic lens characteristics, such as *f*/#, resolution, and the mitigation of various aberrations. For example, if a tiny cell phone camera claims to be capturing 5 megapixels in sharp detail, you should be suspicious.

HOW DO I KNOW IF A LENS IS WELL-MATCHED TO A SENSOR?

Are you designing a system that includes an objective lens and an image sensor? Are you trying to choose a digital camera as a gift, and not sure if you should simply buy the one with the most megapixels? We'll show you that an optical system is usually only as strong as its weakest link. Whether it's an ordinary camera or a complex imaging system, you'll be happier if its detector is well-matched to its imaging optics, such as the objective lens.

OPTICS 101

These scenarios are similar:

- Taking a photograph of a friend with your cell phone
- Placing a digital sensor on top of your microscope
- Shooting a photo of a building with your new digital camera

In the vocabulary of basic optics, in each case there is an *object*, such as a building or person; an imaging system – here we'll just call this the *lens* (or *objective lens* or just *objective*); and an *image*, which is the pattern the focused light makes on a digital sensor. The digital sensor is a collection of tiny light-buckets called *pixels*. Your cell phone camera has a few million pixels in a rectangular grid, each of which detects light by converting photons into electricity.

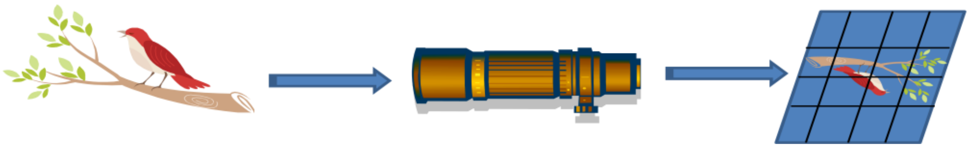


FIGURE 1: LIGHT TRAVELING FROM AN OBJECT, MODULATED BY AN OBJECTIVE, FORMING AN IMAGE AT A DETECTOR

So, how many pixels do you need? This depends on some links in the optical chain, such as lens aberrations, diffraction, and trade-offs between the aperture size and focus.

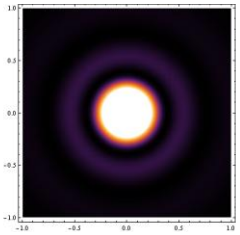
ABERRATIONS

Aberrations are imperfections in an image with a variety of causes. If the lens is well-designed, a good-quality image of the object will appear at the detector. This means that the image should be in sharp focus across the detector area. The lens designer has to fight two primary enemies of image quality:

- *Chromatic aberrations* are imperfections in the image that relate to color. For example, the reddish parts of the image might be focused in a different location or depth than the bluish parts. This means that only certain colors will be well-focused, or that various colors will break up and arrive at different regions of the detector, in which a white line would appear as a rainbow stripe.
- *Monochromatic aberrations* are imperfections caused by the improper design and placement of one or more lenses. These come in many flavors: spherical, astigmatism, coma, distortion, etc. In addition, there are different *orders* (types) of each.

Overcoming these aberrations to provide you with a high-quality lens is a complex scientific task. This is why lens designers still make money, despite several centuries of optical research!

DIFFRACTION LIMITED



There is a fundamental limit that we worry about whenever light passes an edge, such as the circumference of a lens or the edge of a razor blade: *diffraction*. This phenomenon is a consequence of the basic wave nature of light. For example, shining a red laser through a circular opening won't make a sharp shadow. You'll find some light in the "part that should be a shadow," and some shadow in the bright part, as shown in this plot to the right. Even the best lenses are still subject to the limitations imposed by diffraction. Engineers say that such a lens is *diffraction limited*.

A basic attribute of a lens that easily reflects the impact of diffraction on picture quality is the f-number, written *f*/#. **Even though it uses a "slash," this is just a number expressing a ratio; it is not a quotient.** It is the ratio of the lens's focal length to the diameter of its entrance pupil. It is calculated (focal length) ÷ (pupil diameter). For an ordinary lens, the diameter is just the lens diameter. If the lens is accepting light through an iris, then the diameter is usually the diameter of the iris. For example:

- Given a lens with a 500 mm focal length and a 100 mm diameter, its *f*/# is (500 mm) / (100 mm) = 5. The *f*/# is *f*/5, which is pronounced "the eff-number is eff-five."
- Now let's say that same lens is in a camera, and it is partially stopped-down (obscured circumferentially) by an iris. If the iris has a diameter of 50 mm, then the lens's f-number becomes (500 mm) / (50 mm) = 10. The camera now has an *f*/10 lens.

Pedagogically, the statement which usually follows this calculation is that a benefit of stopping-down a camera lens from *f*/5 to *f*/10 is that the depth of focus increases and the image becomes dimmer. We can go another step and link f-number to diffraction. This will then tell us how far apart two neighboring parts of a scene must be at the detector in order to tell them apart.

A well-known relationship in optics is a rule-of-thumb, due to Lord Rayleigh, regarding how close two points can be before we can't tell them apart anymore:

$$x \approx 1.22\lambda \frac{Focal\ length}{diameter} = 1.22\lambda \times f\text{-number}$$

Here, *x* is the minimum distance between distinct points in the image, and λ is the wavelength. **Therefore at *f*/8 and purple light (which will require the most detector pixels because its wavelength is shortest), *x* = 3.7 microns.** If you are taking a photograph of two purple Christmas tree lights from far away, their images must be greater than 3.7 microns apart at the detector. As the points move apart, their image at the detector changes from one broad hump to two (Figure 2):

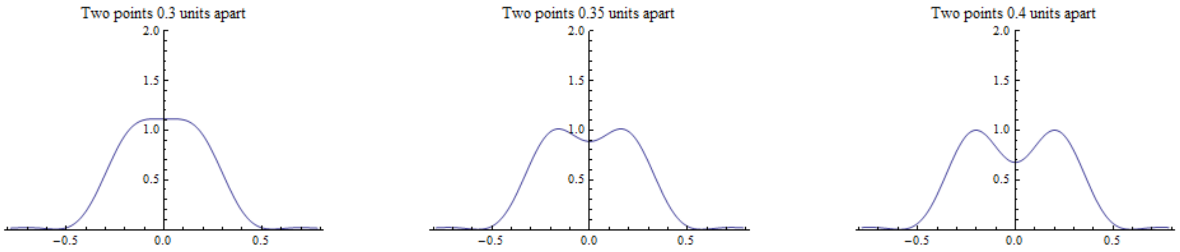


FIGURE 2: TWO POINTS IN AN OBJECT GETTING FARTHER APART: IMAGE CHANGES FROM A BLURRY LUMP TO TWO DISCERNABLE POINTS

WHAT ELSE SHOULD I THINK ABOUT BESIDES DIFFRACTION?

Let’s touch on two other concepts:

1. From the preceding discussion, we suggested that lower f-numbers (bigger diameters for a given focal length) are better because they let you resolve finer details. In practice you also have to fight an opposite effect, which is that the central region of a lens works better than its periphery. In the case of photography, you might choose an f-stop in the middle of the available range, like *f*/8, to minimize diffraction while maximizing the useful area of the lens.[1]
2. In general, larger diameter lenses collect more light. This is important, for example, in cell phone cameras, whose tiny lenses capture very little light. If the exposure time were too short, then the image will be dim, and “static” called *noise* will be visible. To compensate, the exposure times are kept longer – at the expense of holding your camera very steady.

A SUMMARY AND SOME EXAMPLES, PLEASE?

When you work with an optical engineer to design a camera system, some of the top-level concerns will be:

- The impact of *f*/# on resolution, cost, diffraction effects, and depth-of-focus
- Typically, the central region of a lens yields a better focus than its periphery – but larger lenses collect more light.
- Engineers can predict the imaging resolution of an optical system with great precision.

EXAMPLE 1: A POINT-AND-SHOOT CAMERA

In a camera, a lens system produces a focused image of an object onto a detector. As you just learned, assuming an *f*/8 camera lens, you’re wasting detector-pixels if you are examining details closer than 3.7 microns at the

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[1] Regarding diffraction and consumer photography, see: http://petavoxel.wordpress.com/2010/01/19/diffraction-fraud/ (Accessed Oct. 28, 2010) or http://www.cambridgeincolour.com/tutorials/diffraction-photography.htm

detector. Actually, in practice, we try to fit at least two pixels across each minimum feature size[2]. For monochrome we therefore care about 2x2 pixel clumps. **Building on the purple light example – which cuts the camera-vendor the most slack because it validates their desire to sell more pixels – we will use 1.8 micron pixels.**

- A common-sized "1/3" digital camera sensor measures 4.8 mm x 3.6 mm. ***In this case, the narrow axis of the sensor ought to have fewer than ((3.6 mm)(1000 microns/mm) / (1.8 microns per pixel as above)) = 2,000 pixels.*** So an efficient resolution would be 2,667 x 2,000 pixels, which is 5.3 megapixels. If the vendor had packed, say, 10 megapixels into the area of a "1/3" digital sensor in an *f*/8 monochrome system, it's probably not worth paying a premium for. On the other hand, if a sensor of that size only has 200,000 pixels, you might be missing a lot of detail.

EXAMPLE 2: DESIGNING A MACHINE VISION SYSTEM – HOW MANY PIXELS DO I NEED?

In a machine vision system, the number of pixels needed depends on the size of the object being imaged and the level of detail required. For example, suppose the object is a 27" square containing typewritten text and symbols composed of fine straight lines, like a UPC barcode. How many pixels will the sensor need?

- What are we looking at?
  - Our square object measures 686 x 686 mm
  - The finest detail that we want to see is 0.5 mm, such as the width of a single printed line, for example the lines in the barcode or features of the alphanumerics.
  - The finest picture detail we want to resolve should be projected on 2 or more pixels per axis.
  - We assume that we are using a decent-quality, affordable lens. One measure of quality is its ability to resolve a certain number of "line pairs per millimeter" at the object. Let's say it is able to resolve 40 line-pairs per millimeter, which is 80 dots/millimeter, which is 2,032 dots per inch.
- Therefore:
  - We need to resolve 1,372 dots along each side of the square object (686 mm / 0.5 mm).
  - To project each dot onto two sensor pixels in each direction, we need at least 2,744 pixels along each side of the sensor.
  - So, for a sensor with a 4:3 imaging ratio, we need at least 10 megapixels: 2,744 × 3,659.

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CONTACT OPTICS FOR HIRE

Engineers at Optics for Hire are available to answer your questions about optical system design. Contact us at:

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[2] According to a principle of information theory called the Nyquist Sampling theorem, you need to "sample" a signal at least twice as often as the fastest-changing part that you wish to examine. This article does not discuss an additional factor relevant to color photography, which is that various colors may be detected by sub-pixel detectors (i.e. Bayer vs. Foveon). To keep things simple, we restricted the discussion to monochromatic imaging.