The Physics and Art of Photography, Volume 3

Detectors and the meaning of digital

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The Physics and Art of Photography, Volume 3

Detectors and the meaning of digital

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For Judith

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Preface

Early drafts of this book were written for a course I first taught in the Fall of 2013 at the University of Wisconsin–Fox Valley, in Menasha, Wisconsin.

I assume no specific prior knowledge of the reader except for a very basic understanding of physical units, dimensions and scientific notation; a brief review can be found in appendix C. The mathematics presented in the text is rudimentary, with only the most basic of algebra (more detailed derivations, or those that require calculus, are relegated to the appendices). A familiarity with the material in Volumes 1 and 2 is not essential prior to reading this volume, but it is helpful.

If you have little experience with photography, it is my goal that *The Physics and Art of Photography* will help form a useful foundation from which to learn about photography in whatever way that works best for you. If you are a seasoned pro, but looking to set off in a new direction, then I still hope that you will find much here that is fresh and inspiring, and it is my goal that the book will help to open new possibilities. *The Physics and Art of Photography* is in three volumes:

- **Volume 1: Geometry and the nature of light**
  - Part I: Some preliminary ideas
  - Part II: The nature of light
  - Part III: Geometry and two-dimensional design
- **Volume 2: Energy and color**
  - Part I: Energy and photography
  - Part II: The art and science of color
- **Volume 3: Detectors and the meaning of digital**
  - Part I: The physics of light detectors
  - Part II: Photography as an art and the meaning of digital

The Physics and Art of Photography covers some material that is typical of discussions that link physics and photography. But it is also personal; it is very much my own take on the two subjects. I would not say that my personal views regarding science and art are controversial, but they are perhaps somewhat unconventional. There are few details here that other artists and scientists are likely to strongly disagree with. It is, rather, what I have chosen to emphasize, what I have left out all together, and the particular connections I point to, that most shows my own personal likes and dislikes.

Since my formal training is in physics and astronomy, while I am essentially self-trained in art (with informal mentoring from many others), the science part of this book is perhaps more conventional and straightforward than is my portrayal of art. And so my choice of physics-related topics should give one a fairly balanced and conventional taste of that subject as it relates to photography. Regarding photography as an *art*, however, I am surely on shakier ground.

Certainly, I do not pretend to present a comprehensive or balanced overview of art photography; I am unqualified to attempt such a thing. But I do try to make a case that the particular thin slice that I present here has some merit and is worth spending a little time to consider, even if it turns out not to be your particular cup of tea. This book is a bad place to get a sense of what are the hot topics in ArtForum, but I believe that it does at least point to important and interesting questions about art photography in general. And since it is my goal to get you thinking, it doesn't matter much whether you agree with me or not. Thus, it is fitting that my discussion of art is more personal, since my own art is the wee bit for which I really do know what I am talking about.

And so one might complain that *The Physics and Art of Photography* is a very long artist's statement, justifying the value and relevance of my own art. That may be partly true, but I do try to approach it in a way that emphasizes broad *questions*, rather than the particular answers I try to give (tentatively) with my own art. And I hope this book does help a little to make you a better photographer, and as such I do spend time on some of the very basic technical aspects of photography that I find important. But in doing so, I try to use these technical issues as points of departure to consider the status of photography as an art, finally exploring some issues relating to this status in the digital age.

This book may also be read as a manifesto of sorts for the aspects of science that have always moved me the most. I am interested in science not for the technological gizmos it has produced, or for some notion of inevitable human 'progress.' Rather, science is, for me, part of *the study of nature*. My interest in Einstein's General Relativity, for example, is essentially the same as my interest in bird watching. Because I have spent some time to learn a bit about birds, I can now walk through the woods free of binoculars, looking only at the ground at my feet, and a world is open to me just by the sounds I hear. And when I stumble on my way up the stairs, as a physicist I can take comfort in the idea that my shin in contact with the stair prevented me from following my normal straight-line path through four-dimensional spacetime.

You will find throughout the book illustrations from my own photography as examples. This is convenient, since I know my own pictures and the stories behind them, and I don't need permission to use them. But of course I also want you to look at other photography, and so I have included some examples from a few other artists whose work I admire.

A useful companion is *The Photography Book* (Phaidon Press, 2014), which presents hundreds of photographs, spanning the entire history of photography. Each has a short analysis, with cross references to other photographs that are related. The photographs, only one per photographer, are arranged in alphabetical order by photographer's name. Thus, the ordering of the pictures is thematically random, which often results in unusual juxtapositions on facing pages. I sometimes refer to pictures in *The Photography Book* as examples, and so it is useful to have it handy. But all of these pictures are famous and can easily be found online as well.

The reader will also find, scattered throughout the three volumes and their appendixes, details and examples from what I call *ephemeral process (EP) photography*. EP photography is my own invention—sort of—and I spend so much time on it because it is perfect for illustrating many of the concepts in *The Physics and Art of Photography* in a way that I believe goes directly to the heart of the matter. Furthermore, it is *accessible*. The materials and equipment are inexpensive, it requires no specialized facilities (such as a darkroom), and it is surprisingly versatile. But most importantly, it is a lot of fun. Practical details of the technique can be found in appendix A and in volumes 1 and 2 of *The Physics and Art of Photography*.

The larger concerns of *The Physics and Art of Photography* are to give the reader some background that is helpful for asking important questions about the nature of art and science. But the practice of photography is the point of departure for these bigger issues, and as such *The Physics and Art of Photography* does contain a lot of simply practical information as well. And so *The Physics and Art of Photography* has five basic goals:

1. To ask basic questions about how photography fits in as an *art*, and about the nature of art itself.
2. To ask basic questions about the nature of physics *as part of the study of the natural world*, and about the nature of science itself.
3. To gain some practical knowledge that will allow the reader to more easily learn technical aspects of photography, as they are needed.
4. To gain some practical knowledge that will help the reader more easily learn to be a better photographer.
5. To expose the reader to a set of interesting photographic processes and tools that are not usually covered in a beginning photography course.

One of the themes of this book is the meaning of digital technology and what it has to say regarding photography as an art form. This may seem like I am speaking out of turn here, since I have neither formal training in art, nor have I ever been a professional photographer using professional digital equipment. Nevertheless, there is a sense in which I am well-positioned to say something of interest about these issues.

My own photography is almost entirely devoid of the use of a digital camera. I often use equipment and old physical processes that are about as far removed from modern digital photography as one could imagine. But I use these in new ways that depend absolutely on the digital; many of my photographs could not exist without modern digital processing and scanning and printing. This kind of interplay between the old and new is one of the running themes of *The Physics and Art of Photography*.

And despite my collection of old cameras, I am not a knee-jerk hater of digital imaging technology. In fact, I am one of its early practitioners, having used digital cameras and sophisticated digital image processing long before most photographers. My formal training is in astronomy, and I was there (in graduate school) for the digital revolution as it transformed astronomy in the 1980s. The CCD digital detectors used in modern digital cameras were fairly new then, and still too expensive (and with insufficient resolution) to be of much practical use for photographers. I am the last person one would want to ask about the latest multi-thousand-dollar model of DSLR camera. But I do have a decades-long understanding of some of the most basic underlying principles of digital photography.

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I thank Valeria Sapiain for all-around support and patience over the several years I spent working on this book. I received much valuable feedback, support and mentoring from Laura Andrews, Doug Fowler, Caroline Geary, Anne Haydock, Diana Ludwig, Dawn Patel, Teresa Patrick, Judith Waller, and Frank Zetzman.

The software packages GIMP, Gnuplot, Inkscape, SciDAVis, OpticalRayTracer and IRAF were used for many of the illustrations. All photographs and illustrations are by the author, except as noted below:

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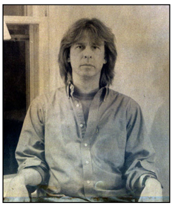
Author biography

John Beaver



For nearly 20 years, John Beaver has used old processes to make new negatives, often in ways that can only be realized as a print with digital scanning and printing. This includes his development of the cyanonegative process, innovative work (in collaboration with Teresa Patrick) with instant film, and most recently his development of an accelerated, unfixed printing-out process he calls (perhaps annoyingly) 'Ephemeral Process photography.'

He is Professor of Physics and Astronomy at the University of Wisconsin–Fox Valley, where he teaches physics, astronomy, photography, and interdisciplinary courses. He earned his BS in physics and astronomy in 1985 from Youngstown State University, and his PhD in astronomy in 1992 from Ohio State University. His published work in astronomy is on the topics of spectrophotometry of comets and gaseous nebulae, and multi-color photometry of star clusters.

He has exhibited photographs in many juried competitions in Wisconsin, Ohio, New York, Louisiana, Missouri, Oregon, and Colorado, even occasionally winning an award or two (well, two actually). He has had several solo exhibitions, as well as joint shows with artists Judith Waller, Diana Ludwig, Dawn Patel, and Teresa Patrick. Beaver has long been involved in art–science collaborations (many with artist Judith Waller) in the classroom, at academic conferences, and in art galleries and planetaria.

Some of John Beaver's photography can be seen at http://www.JohnEBphotography.com

Part I

The physics of light detectors

IOP Concise Physics

The Physics and Art of Photography, Volume 3

Detectors and the meaning of digital

John Beaver

Chapter 1

Detectors and the characteristic curve

Part of the essence of photography is that light falling on a surface *is recorded*. This is the *graphy* in photography. A permanent record is made of the intensity (and maybe color) of light that fell on each point of a given surface. To do this one must have some material that undergoes a physical change when light interacts with it. This material must form a surface for the image to focus on, and there must be some way to record different physical responses at different positions on the surface.

Throughout *The Physics and Art of Photography* I use the word *detector* to represent, in a general sense, any light-sensitive surface used to record an image. It could be the retina of the human eye, traditional photographic film, a digital detector in a digital camera, or a light-sensitive material that is used to make a print. Ultimately, there are three crucial features of every light detector:

1. Light must cause some physical change to occur in the detector.
2. Once the exposure is completed, there must be a way to stop further physical changes from occurring. Or barring that, there must be some way to 'read' the results of the detector, and transfer those results to some permanent, non-light-sensitive storage.
3. There must be some way to tell, after the exposure is complete, which part of the detector underwent what physical change. That is, we need to be able to record *separately* the physical changes that occur at different locations on the detector. Otherwise, we would have not an image, but rather only a single measure of brightness.

Light *interacts* with some physical material. That is, some of the light disappears, and the material changes in some way. The idea that some materials change visibly upon exposure to light is far from modern, since there are many common everyday examples. For example, many dyes and pigments fade with light over time; when a piece of furniture shields part of a painted wall from light, its outline is visible when it is moved years later.

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My usage of the word detector is somewhat unconventional in that I use it to refer to any two-dimensional surface used in photography to make a record of an exposure to light—whether or not its use is for the original capture of an image in a camera, or instead to make a permanent photographic print. We can divide most photographic light detectors into two broad categories—photoelectric and photochemical. The retina of the human eye (section 1.5) is more complex than either, and includes aspects of both.

1.1 The physics of photons

The physics of light is described in some detail in volume 1 of *The Physics and Art of Photography*, but here I recap and expand upon some concepts that are especially relevant to light detectors. Light has a *wave-like* property; it does all of the basic things that waves do. But it also has a *particle-like* nature; in many circumstances it transfers energy in discrete clumps, at particular points in time and space. Such a particle of light is called a *photon*. These aspects of light seem at first glance to contradict each other, but they do not. The two concepts are unified by *quantum physics*, and we take up this subject in more detail in chapter 5. Photon interactions are of particular importance for understanding photographic light detectors, but the wave-like properties of light play a role too. Below I outline some of the most basic principles of the physics of light, as it pertains to photographic light detectors.

- Light is an electromagnetic wave—a changing pattern of the electric and magnetic properties of space, that travels through space at the speed $c = 3.8 \times 10^8$ m s^{-1}.
- The perceived color of light is related to its *wavelength*—the distance between successive maxima in the electric (or magnetic) fields, at a given point in time. It can also be described by its *frequency*—the number of electric field maxima that pass a given point in space per second. Frequency is measured in *Hertz* (Hz) or repetitions per second. Wavelength is a length, and so it can be measured in meters—but the wavelengths of visible light are sub-microscopic, and so the nanometer (nm), or 10^{-9} m, is more commonly used. The human eye is sensitive over the range approximately 400–700 nm. We perceive 400 nm light as violet and 700 nm light as red.
- There is an inverse relationship between wavelength, λ, and frequency, f, for light. And the speed of light, c, relates the two:

$$c = \lambda f \tag{1.1}$$

$$f = \frac{c}{\lambda} \tag{1.2}$$

$$\lambda = \frac{c}{f}. \tag{1.3}$$

- Light carries both energy and momentum, and when light interacts with matter, one or both must be transferred. It is the transfer of *energy* that is important for understanding light detectors; in order for light to be detected, some energy must be transferred from the light to the detector.

- The smallest unit of energy transferred by light is the photon. A photon interacts with an individual atom or molecule at a particular point in time.
- When light interacts in a wave-like manner, resulting in wave phenomena such as interference and diffraction, we can determine the frequency of the light. If that same light is allowed to interact in a particle-like manner, we can measure the energy of those photon interactions. There is a direct relation between the energy, E, of the *individual* photons and the frequency, f, of the light of which they are a part:

$$E = hf \tag{1.4}$$

$$= \frac{hc}{\lambda} \tag{1.5}$$

  where h is a tiny constant called Planck's constant.
- Photons of higher energy correspond to light of shorter wavelength (and higher frequency). Photons of lower energy correspond to light of longer wavelength (and lower frequency).

1.2 Photoelectric detectors

A *photoelectric detector*, upon exposure to light, directly produces some kind of measurable electronic response. Most digital photographic detectors are of this type, and they are usually an *array* of rows and columns of separate light-sensitive sites, called *pixels*.

There are different ways in which light can interact with conductors or semiconductors and cause a measurable electrical effect. For example, individual photons (particles of light) can remove electrons from their atoms. If this happens in an evacuated glass tube, the electrons can be accelerated through an applied voltage to make a measurable electric current. This procedure is not ordinarily used by photographers to record images, but devices called *photomultipliers* employ this principle for the precise measurement of very faint light (mostly by astronomers and particle physicists). Photomultipliers can easily detect individual photons.

Other devices can be designed for which light alters its electrical resistance (or conductance). A *photoresistor* becomes less resistant to electrical current when light shines on it. This can be used in a circuit with a current meter and a battery to make a light meter—an instrument for measuring the brightness of light. Indeed, many older cameras used photoresistors for their internal light meters. But photoresistors are not particularly useful for recording *images*.

A photovoltaic cell turns light directly into electrical energy. A voltage is produced, and power can be delivered, when it is illuminated by light. Very low power photovoltaics (the element selenium is a good example) were used for some of the first electronic light meters. But like photoresistors, photovoltaics have not been particularly useful for forming images.

Finally, semiconductor *photo-junction devices* use the interaction between light and a boundary between two dissimilar semi-conducting materials. These devices can be manufactured in arrays of microscopic, separately light-sensitive pixels. We will examine two types of photo-junction photographic imaging devices in chapter 6.

1.3 Photochemical detectors

A *photochemical detector* can be thought of as any material for which the exposure to light produces some kind of chemical change. If these changes are visible to the eye (or can be made visible by further chemical processing), then the material can be used as a detector. There are two main categories of photochemical detectors:

1. A *latent image* is formed upon exposure to light. A change occurs at the molecular level, but no visible change is apparent until the detector undergoes a chemical treatment called *development*. In this case we say the detector *develops out*. Ordinary silver-based color or black-and-white film photography is of this type.
2. The detector *prints out*; visible changes occur in the detector as it is exposed to light, with no chemical development needed. Many antiquarian and alternative processes are of this type.

There is an important complication with most photochemical detectors, and this was an important stumbling block in the history of their invention. There must be some way to stop the detector's sensitivity to light after the image is formed. Otherwise, the act of looking at the picture would continue to expose it to light. This process is traditionally called *fixing* the image, and it usually requires some kind of additional chemical treatment of the detector.

Another important aspect of photochemical detectors is the nature of the particular *base* or *substrate* that is used. What type of flat surface is the light-sensitive material attached to? What is that substrate made from, and by what means does the light-sensitive chemical attach to it? Is the base transparent or opaque? And if it is opaque, is it black or white? If the substrate is transparent, one can shine light through it, perhaps to use lenses to enlarge and project the image onto another surface.

Two different approaches are most common for attaching a photochemical detector to its substrate. The simplest method is to allow the light-sensitive chemical to penetrate into the fibers of a semi-porous surface such as paper, in essentially the same way that the dyes soak into the paper in a watercolor painting. The second technique is to allow the light-sensitive chemical to form microscopic crystals, and to then suspend these in some sort of gelatinous material, which is then applied to the top of the substrate as a thin coating. This is called an *emulsion*, and most modern photochemical detectors use this method.

1.3.1 Negative and positive

Since photochemical detectors may result in a *visible* change in the detector upon exposure to light, there is the possibility of a direct physical relation between the picture and the original exposure. That is, a greater exposure to light leads to a greater *visible* effect on the detector. But this leads to an important question: does a greater exposure to light cause the detector to become visibly brighter, or does it instead make the detector visibly darker? A *negative process* results when the detector is rendered darker by greater exposure to light. A *positive process*, is of course the opposite.

If our immediate task is to produce a picture for the wall, then we most likely want bright areas in the picture to represent more light in the world. It would seem, then, that the detector of choice would be one that uses a positive process. It would allow for the picture on the wall to be the actual detector that was exposed in the camera. We call this a *direct positive*, and we will describe a few photochemical detectors that work this way.

But the majority of photochemical processes suitable for photographic detectors work as a negative process. And for those processes we must take some extra steps in our journey from the camera to the gallery wall. We shall see, however, that negative processes have some distinct practical advantages over positive processes. There are two traditional approaches to get from a negative image to a positive image, and we consider them in turn.

Negative-on-negative

The most straightforward way to get a positive image from a negative process is to recognize that a negative of a negative is a positive. If one simply repeats the negative process, *but using the result of the original exposure as the source for a second exposure*, then a positive image results.

For example, one can expose a sheet of 8 × 10 inch light-sensitive *enlarging paper* in a pinhole camera (see volume 1 of *The Physics and Art of Photography*). Upon processing, a negative image results; the brightest features in the scene become the darkest areas on the paper. This sheet of paper with its negative image can then be placed (in a darkroom) image-side-down directly onto another sheet of the same kind of paper, with its light-sensitive side facing upward. One can then simply expose the second sheet by shining light through the back of the negative image. Upon processing the second sheet, a positive image appears because it is exposed the least (and so appears the brightest) wherever the original negative was darkest.

This is called a *contact print*, and it is an easy way to make a positive from a negative. Clearly, the print is the same size as the negative. So if the negative is made in a camera, it must be a very large camera if one wants a large print. If the original negative is made on a transparent film, then one can expose the light-sensitive print paper by projecting light through the negative with a lens—sort of a camera in reverse. Such a device is called an *enlarger*, and it is the most common traditional method for making large prints from small negatives.

The negative-on-negative process has the obvious practical advantage that it separates the process of recording an image in a camera from the process of making a print to hang on the wall. And so it opens the possibility of making a large number of prints from a single image capture. It also allows for adjustment of the image in the step of making the print—and so maybe one can get a good print out of a not-so-good image capture. For these reasons, the negative-on-negative approach has dominated much of the history of photochemical photography.

Reversal processing

There is another traditional way to get a positive image out of a negative photochemical process, and it is called *reversal processing*. It is sometimes possible to process the light-sensitive material in a clever two-step way, first producing a negative, and then reversing the negative to a positive directly in the same piece of light-sensitive material. So we have, in the end, something that is much like a direct positive—the picture on the wall is the same object that was in the camera.

The history of reversal processing is almost exclusively associated with silver gelatin emulsions, and so we take up some of the technical aspects more fully in that context (chapter 2, section 2.3).

Digitally-printed negatives

And finally, there is a not-so-traditional way to get a positive image with a negative process. Any digital image can now be easily made into a transparent negative with image processing software and digital printing. The digital image, inverted to a negative by the software, is printed onto acetate with an inkjet printer, at the same size as the intended print. This negative can then be exposed in contact with a negative-process light-sensitive paper to make a positive print. Some photochemical printing materials are sensitive only to ultraviolet light, and this makes it very difficult to expose them with an enlarged projected image. And so they must be contact printed, and for that a negative is needed that is the same size as the final print. It is increasingly common for photographers to use digital inkjet negatives for this purpose.

1.4 Basic photochemistry

There is a sense in which most photochemical detectors are also photoelectric—a photon is absorbed and some transfer of electric charge results between atoms and molecules. Chemistry is about the electrical attraction between the positively-charged nucleus of an atom and its negatively-charged electrons. The nuclei do not change (if they do, it is called a *nuclear* reaction). But it is possible for the electrons, especially those that are most distant from the nucleus, to transfer from one atom to another, thus taking negative charge away from one and adding it to another.

An atom or molecule that has a net electric charge is called an *ion*[1]; it is an *anion* if it has a net negative charge and a *cation* if it has a net positive charge. The process of an atom or molecule decreasing its number of electrons is called *oxidation*, while the process of increasing its number of electrons is called *reduction*.

---

[1] A *molecule* is often defined to be a bonded-together group of atoms that is electrically neutral. And so, for example, the proper term for a similar structure, but containing a net electric charge, is a *polyatomic ion* or *molecular ion*.

The *oxidation state* is related to the net charge of an ion, and it is denoted by a superscript number with a following plus or minus sign, affixed to the chemical symbol[2]. And so, for example, Ag^+ is a silver (Ag) atom that has lost one electron; taking away -1 is the same as adding $+1$, and the number 1 is assumed, if no other digit follows. Neutral silver, with just the right number of electrons to balance its internal charge, is simply denoted Ag, with no superscript.

Like charges repel and unlike charges attract, and so an isolated atom wants to be neutral, with just the right number of electrons to balance the positive charge of its nucleus (it is the positive charge of the nucleus that gives an atom its identity). Because of the intricate rules of quantum physics, however, there is more to it than that, and when atoms are put together with other atoms, other factors come into play.

Certain molecular combinations of atoms are only stable if they are ions—if they are either missing or have extra electrons. A good example is *nitrate*, which is a nitrogen atom bound to three oxygen atoms. But this only happens if it can find an extra electron, and so form NO_3^-, a nitrate cation. Silver, on the other hand, is happy as just ordinary Ag. But in the right context, it is more quantum-mechanically happy to give up one of its electrons and instead be Ag^+. Put Ag^+ together with NO_3^- and they stick together (unlike charges attract) to form the neutral *compound* silver nitrate ($AgNO_3$).

A compound such as silver nitrate does not mean that one particular Ag^+ is stuck specifically to one particular NO_3^-. Instead, it forms a *crystalline solid*—a regular arrangement of alternating Ag^+ and NO_3^-. It can also be dissolved in water to form an *aqueous solution* in which the ions are separated from each other by the water molecules, constantly associating and dissociating, no ion belonging to any other ion in particular. Compounds that will do this easily are called *soluble*, while those that don't are called *insoluble*.

Some atoms or compounds have electron structures that make it easy for them to lose electrons, donating them to some other chemical species in a chemical reaction. The act of losing electrons is called oxidation, but the atom or compound that does so is called a *reducing agent*. In the opposite sense, an atom or compound that easily accepts electrons—and so is likely to 'steal' them from some other chemical species —is called an *oxidizing agent*. When an oxidizing agent accepts electrons, it is *reduced* in the process.

And so what does all of this have to do with *light*? In certain circumstances the absorption of a photon—a particle of light—can provide the energy needed for the transfer of electrons from one chemical species to another, and so cause chemical changes to occur. When this happens, it does so on a one-on-one basis. A photon (or several photons in a very short period of time) transfers its energy all at once, and at one particular place. If these chemical changes enabled by the absorption of light produce some visible change, then they can be used as the basis for a photochemical detector.

One of the great feats of early 20th-century modern science was the discovery of fundamental physical laws that provide explanations for the mostly already-known laws of basic chemistry. The principles of quantum physics allow one to calculate the electron structures of atoms, and also the rules by which those structures may change when a given atom is combined with other atoms. These rearrangements of atomic electron structure involve transfers of energy, and this is the ultimate source of the energy transfers associated with chemical reactions.

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[2] It is, strictly speaking, only the net charge if all bonds to the atom are ionic.

Why, for example, is NO_3^- one of the ways in which nitrogen and oxygen like to arrange themselves? The question can be answered on the one hand, in terms of pre-20th-century concepts of chemistry such as valence, the periodic table of elements, acids, bases, etc, and the complex chemical rules that relate these concepts to each other. The fundamental laws of physics, however, were too incomplete in 1900 to provide an underlying physical explanation for these chemical rules. It was not until the development of quantum mechanics in the first third of the 20th century—a revolution in the fundamental understanding of matter and energy—that physics was up to the task of providing an explanation for many of the facts that chemists already knew (Chomsky 2000, pp 110–1).

1.5 The eye as a detector

They eye looks like a camera. There is a lens, a dark box (albeit nearly-spherical in shape), and a light detector at its back—the retina—upon which an image is focused. The *retina* is covered by a matrix of millions of light-sensitive cells, seemingly similar to the light-sensitive pixels on the detector of a digital detector. And these cells are 'wired' to the brain by the optic nerve. And so it is tempting to think of the eye as simply a biological version of a modern digital camera. But the differences are profound.

The English word 'photography' was apparently coined by John Herschel, astronomer and one of the pioneers of photography[3]. The combination of *photo* (light) and *graphy* (writing) implies that we are 'writing with light,' and indeed that was literally the first photographic method. Centuries before photographic detectors were invented, the *camera obscura*—a dark box with a lens to focus an image—was used to trace images by hand.

An even more convenient arrangement was patented in 1807 by William Hyde Wollaston, three decades before the first successful photographic process. The *camera lucida* used a clever combination of mirrors and prisms that allowed one to see a virtual image of the subject superimposed onto a piece of drawing paper, as in figure 1.1. This allowed the artist to mark key points in the image—corners, ends of lines, locations of important features—in order to draft an exact photo-realistic drawing.

John Herschel was an avid user of the camera lucida (see Evans *et al* 1969, for many examples). Its use influenced both Herschel and the more-famous pioneer of photography, William Henry Fox Talbot. Both were intrigued by the idea of making a permanent photographic record, but somewhat frustrated by the imperfection and tedium of the hand-drawing process. And so the idea of making a direct, permanent recording of the image formed by a lens was already 'in the air' by the late 1830s when the first chemical photographic detectors were invented.

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[3] The French word *photographie* was coined independently, at about the same time, by Hèrcules Florence.

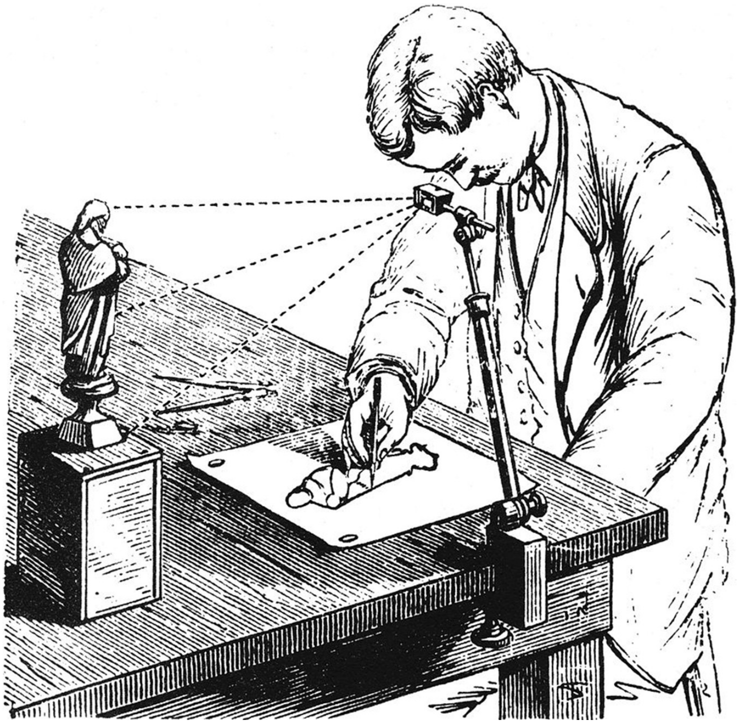

Figure 1.1. A *camera lucida* uses an arrangement of lenses and prisms to superimpose an image onto a piece of drawing paper. The image is then traced by hand. Graphic credit: Public Domain.

The physical process by which the retina detects light is complex and multi-stepped. There are both chemical and electrical changes, as well as changes in the physical structure of individual molecules. The retina is elaborately structured, and it is inside out; the light-sensitive part is on the back surface, not the surface facing the eye lens. Thus, the light focused by the lens must pass through several layers of only semi-transparent cells before being detected. Figure 1.2 illustrates this structure. The two basic types of light-sensitive cells—called *rods* and *cones* because of their shapes—are on the right of the diagram; the light focused by the eye lens enters from the left.

As is the case for most light detectors, we must appeal to the particle-nature of light to understand even the simplest aspects of the process. Within the rod or cone cells, individual photons are absorbed, and this triggers a complex set of chemical pathways that ultimately leads to neurological stimulus. The stimulus is transmitted to other parts of the brain by neurons (seen at the far left edge of figure 1.2) that ultimately bundle together into a nerve cord—the optic nerve. I say ‘other parts’ of the brain, because the retina and optic nerve are considered to be a part of the brain, not separate organs; the retinal tissue develops directly from part of the embryonic forebrain (Kolb 2003).

The rods and cones are elongated in shape, and they are structured like a stack of thousands of thin disks. Each of these disks is separately light-sensitive. Since the photons arrive grazing along these stacks of disks, there is a high probability that an

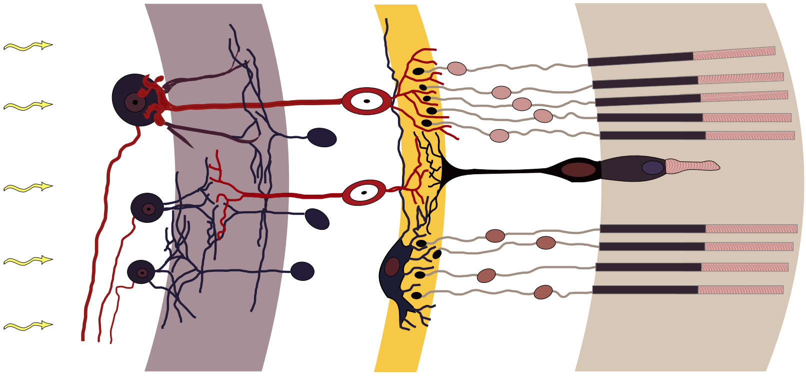

Figure 1.2. A diagram of the structure of the human retina. Photons focused from the eye lens enter from the left. The light-sensitive rod and cone cells are on the far right side of the diagram. Graphic credit: CC BY-SA 3.0.

individual photon will interact with one. And so the rods and cones are highly sensitive to light, apparently able to detect even single photons. The retina overall, however, is much less efficient; the majority of photons are absorbed by the overlying layers of the retina and so never make it to the layer of the rods and cones (Kolb 2003; Holmes 2016).

The key to the light sensitivity of the rods and cones is the molecule *retinal*. It couples to different proteins called *opsins* to form *photo-pigments—rhodopsin* (also called *visual purple*) in the rods and three different types of *photopsins* in the cones. The opsins are permanently located in the rods and cones, but the source of the retinal necessary for the light sensitivity is a layer of tissue called the *retinal pigment epithelium*, located just outside the retina (the far right-hand edge in figure 1.2).

The visual process is initiated when an individual photon interacts with the retinal part of a photo-pigment molecule. The photon disappears, but its energy does not; it is used to raise an electron in the retinal to a higher energy level, and this causes the molecule to change shape in a process called *photoisomerization*.

An *isomer* is a particular way in which a given set of atoms can be arranged to form a molecule. As an example, the molecules allene and propyne are both made of three carbon atoms and four hydrogen atoms. But these same atoms can link together in two different ways. And although these two molecules have the same combination of atoms, they have different geometrical shapes, and this gives them somewhat different chemical properties. And so *isomerization* means simply that the atoms of a molecule rearrange themselves in some way; the molecule changes shape but still contains exactly the same atoms as before. Thus, *photo*-isomerization is a change in the shape of a molecule brought about by exposure to light. Figure 1.3 shows the two isomers of retinal, the second being the result of photoisomerization.

Once the retinal changes to a different isomer, a completely new set of chemical pathways lies before it, and this triggers a complex chain of electrochemical events that eventually leads to a nerve impulse traveling along the optic nerve to the brain.

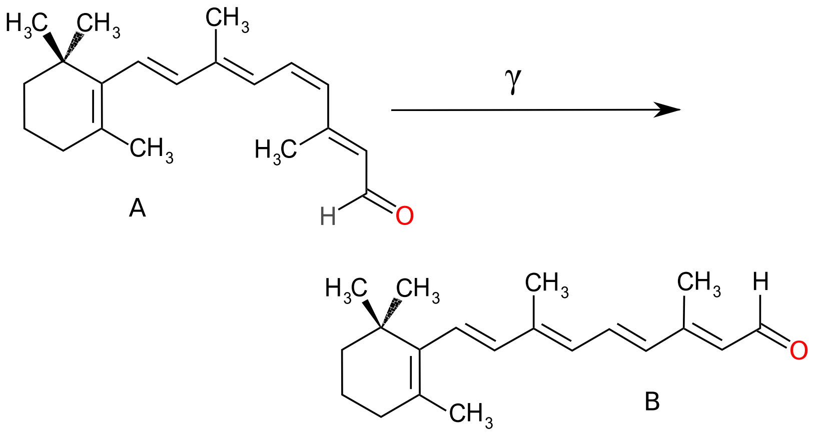

Figure 1.3. Photoisomerization of retinal. Graphic credit: By RicHard-59—Own work, CC BY-SA 3.0.

At a superficial level, the retina of the eye is similar to the film or digital detectors one would use with a camera. In both cases the detector is covered by many individual microscopic detectors, each of which is separately sensitive to light. For the retina of the eye, these are special light-sensitive cells. But for most of the detectors that we will consider, the process of going from absorption of photons to the formation of an image is relatively straightforward. Not so for the human eye! This book is not the place to work through the complex details of human vision, but I list some of the more striking differences. Further details can be found in, for example, Kolb (2003) and Kolb *et al* (accessed 2018), and regarding color vision in Conway *et al* (2010) and Schmidt *et al* (2014).

1. There are two basic kinds of light-sensitive photo-receptor cells in the eye, and they are not distributed uniformly. The cone cells are responsible for color vision, and they are very densely concentrated at the center of the retina (in a region called the *fovea*). For humans, the cone cells come in three types, sensitive to three overall parts of the spectrum—short wavelengths (S), middle wavelengths (M) and long wavelengths (L). The rod cells are more densely arranged at the periphery of the visual field and they are far more sensitive to light than the cones. They play a key role in night vision.
2. The electronic signal from the detector in a digital camera is typically processed by a computer; some of this is performed after the exposure by microprocessors within the camera itself. But the light detector in the eye—the retina—elaborately *pre-processes* the direct signal from the rods and cones *before* signals are transmitted along the optic nerve, in ways that are only partially understood. This is perhaps not too surprising when we recall that the retina *is* part of the brain. This pre-processing is quite sophisticated, and some of it occurs via the very neural wiring in two layers of specialized cells and neurons that lie over the layer of rod and cone photo-receptors (Kolb 2003).
3. Color photographic detectors make use of colored dyes or filters to render sets of light-sensitive elements responsive to different ranges of wavelengths, in order to

ultimately synthesize color. In this general sense, the retina is similar—it too has three types of cone cells, sensitive to different ranges of wavelength. But the similarity ends there. The neural wiring of the retina combines the signals from the different cone cells to make *opponents—direct comparisons* of photo-receptor responses, rather than the responses themselves.

4. Unlike photographic detectors, the retina has two separate visual systems—*photopic vision* for relatively bright light and color vision, and *scotopic vision* for dim light. These two systems involve different pre-processing structures as well as distinct photo-receptors. The high-sensitivity photo-pigment rhodopsin, used by the rod cells, is bleached by light. Upon exposure to bright light, this high-sensitivity pigment is destroyed, leaving the lower-sensitivity cone photo-pigments to take over. Rhodopsin is then regenerated in dim light conditions. And thus the retina can modify its own sensitivity according to the intensity of light. Any given photochemical detector has a far more limited *dynamic range*. Some photoelectric detectors, however, do have a sensitivity that can be adjusted according to the lighting conditions.
5. The retina engages in *parallel processing*. The photo-stimuli from neighboring rod and cone cells are combined with each other in complex ways, in real time, to rearrange and compress the data (in ways that are still only partially understood) so as to maximize the efficiency of many visual tasks, such as detection of edges and the direct perception of contrast.
6. The structure of the retina enables it to process direct and peripheral vision in different ways. A spot of light focused on the retina is processed differently by specialized *ganglion cells*, regarding whether it is focused to the center or periphery of the visual field (see, for example Kolb 2003, figure 1.10).
7. The chemical and neurological processes in the retina constitute a *cycle*. The photoisomerizaton of retinal by photons leads to a chain of chemical and neurological responses that circle back upon themselves to their starting point, allowing for the detection and interpretation of new photons. This cycle takes longer for dim light than for bright light (Kalloniatis and Luu accessed 2018), allowing for better detection of dim light.

I list some of these weird ways in which the retina/brain work (insomuch as they are understood, and I understand them) because I find them fascinating. But also, these facts have implications for photography as an art. Seeing is mostly in the brain. And this means that, as practitioners of two-dimensional visual art, perhaps our task is not really to make a literal visual mapping of some part of *The World* onto a flat surface. Perhaps instead we are simply trying to somehow cause interesting things to happen in the brains of people looking at our pictures. And so, how best to do that?

1.6 Exposure, density, and the characteristic curve

I use the term *density* to mean the measurable physical effect on the detector, caused by the *exposure* to light. Exposure can be related to the total light energy transferred to the detector per surface area. Photographers have their own way of describing this (see volume 2 of *The Physics and Art of Photography*), but it can be expressed in physical units of joules per square meter (J m^{-2}), or the number of photons of light per square meter that strike the detector. Since the illuminance (brightness) of the light falling on the detector is a flow or *flux* of this energy, it is expressed not in J m^{-2}, but rather in J m^{-2} *per second*. And so we have the following basic relation:

$$\text{exposure} = \text{illumance} \times \text{time}. \tag{1.6}$$

For a photoelectric detector, exposure results in an electrical signal of some kind, and so greater density means a larger signal. For a photochemical detector, density represents the visible change in the detector. It becomes darker (for a negative process) or lighter (for a positive process), and the degree to which this happens is the density.

My usage of the word density in this general sense is somewhat unsatisfactory because the word is usually only applied to photochemical detectors; the word *signal* is more commonly used in regard to photoelectric detectors. And so density, in the case of photochemical detectors, usually has a more technical meaning, and is defined according to a particular mathematical relation. Furthermore, most photochemical detectors are developed out, and so most of the density is a direct result not of the action of light during the exposure, but rather the chemical reactions during development. And so, for a typical photochemical detector, the relation between density and exposure is complex and indirect.

A graph that shows, for a given detector, the quantitative relationship between density and exposure is called the *characteristic curve* for the detector. It tells, for any given exposure, what density results. But before we can plot density and exposure together on a graph, we must agree upon their precise mathematical definitions.

Figure 1.4 shows a scan of a particular photochemical detector; black-and-white enlarging paper used in the method of ephemeral process photography, which we will consider in more detail in chapter 2, section 2.5. This is a negative process, so the paper turns darker with greater exposure. I did the experiment twice, each time

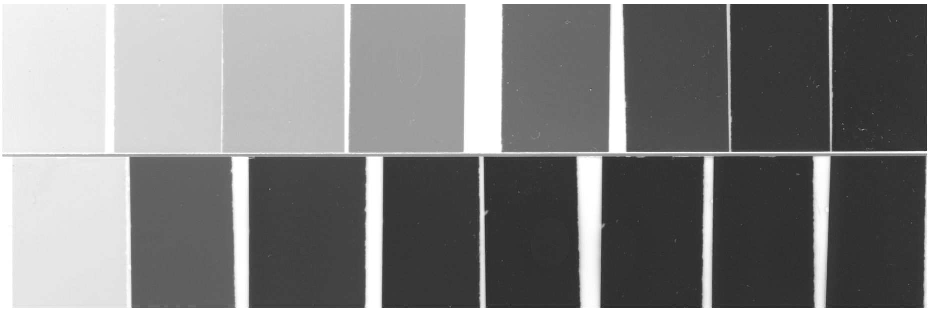

Figure 1.4. The same overall range of exposures applied to silver gelatin enlarging paper, but with two different choices for the exposures steps in between. Although the top set of exposures appears to be in roughly equal steps, it is actually the bottom set for which equally-stepped exposures were applied, with each strip receiving 9.07 s more exposure than the previous. For the top strip, each exposure was a *factor* of two greater than the previous.

giving a range of different exposures, to see the range of densities that result. The illuminance was the same for both, and so I varied the exposure by varying the time, according to equation (1.6). For both of the strips, the lightest portion was exposed for 1/2 s, while the darkest portion was exposed for 64 s.

Even though both examples in figure 1.4 show the same total range in exposure—and the same total range in density—I have broken up this range in two different ways. The example on the top appears to be in roughly equal steps, as if I had added the same exposure each time from one to the next. For the bottom strip on the other hand, it appears as though I made the biggest step in exposure between the first and second, then added progressively *less* exposure each time.

And so what were the actual exposures I used? The answer may be surprising; it is the opposite of how it looks. I added exposure in equal steps for the *bottom* example, not the top. It was made with this list of exposures (in seconds): 0.5, 9.6, 18.6, 27.7, 36.8, 456, 54.9, 64. That is, each exposure was 9.07 s longer than the previous. For the top example, on the other hand, in order to produce a set of densities that *appear* to be in equal steps, I used the following list of exposures (in seconds): 0.5, 1, 2, 4, 8, 16, 32, 64. And so a set of densities that appears to be roughly in equal steps was produced by a set of exposures each of which is *twice as great* as the previous.

The basic result shown in figure 1.4 is typical of photochemical detectors. In order to achieve what appears as the next added step in density, it is necessary to *multiply* the previous exposure by some factor. For this reason, photographers work in terms of what they call *exposure steps*, that are actually successive *factors* of two. The name is somewhat misleading; imagine walking up a staircase for which the distance doubled with each step.

A sequence of numbers such as 1, 2, 4, 8, 16, 32, …, can be written instead as follows: 2^0, 2^1, 2^2, 2^3, 2^4, 2^5, …. This sequence follows the function $y = 2^x$. This is known as an *exponential function*, and its inverse is called a *logarithmic function*. Photographers base their exposure steps on an exponential function with a *base* of 2, but other bases are also commonly used. So, for example, we can set up an exponential function as follows:

$$y = 10^x. \tag{1.7}$$

And so values for x of 1, 2, 3, 4, … simply represent y values of 10, 100, 1000, 10 000, …, or the power of 10. The inverse of this particular exponential function is called a *common logarithm*, and it is defined such that:

$$\log(10^x) = x. \tag{1.8}$$

And so $\log 10 = 1$, $\log 100 = 2$, $\log 1000 = 3$, …. A graph of the common log function can be seen in figure 1.5.

The common logarithm is also called a *base 10 logarithm*, since it is the inverse of the base 10 exponential function. Logarithms have interesting and useful mathematical properties, the most important of which are the following:

$$\log(ab) = \log a + \log b. \tag{1.9}$$

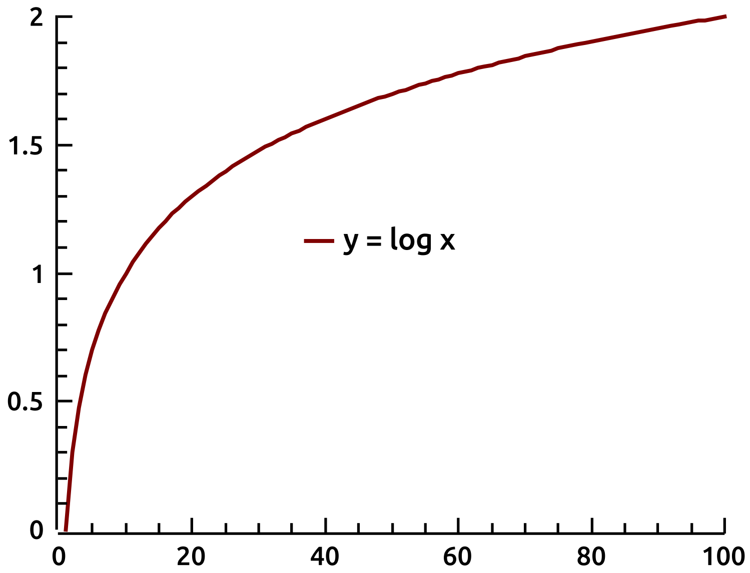

Figure 1.5. A graph of the common logarithm (log x) is defined in terms of powers of 10, and so depicts 10 as 1, and 100 as 2.

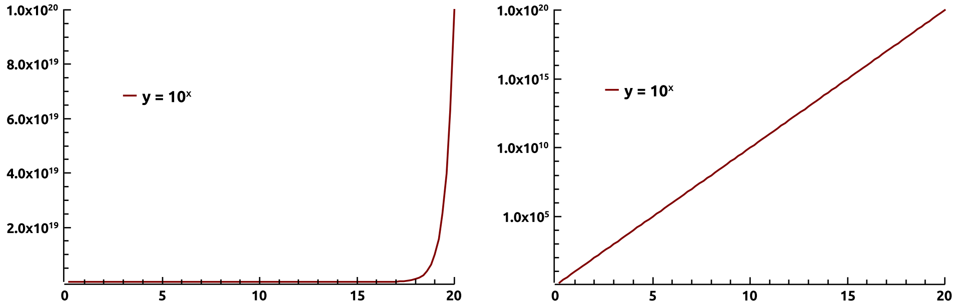

Figure 1.6. The exponential function $y = 10^x$ plotted on an ordinary linear scale (left), and a logarithmic scale (right). The logarithmic scale straightens the exponential function, and makes a large range of values more manageable.

$$\log a^b = b \log a \tag{1.10}$$

Because of equation (1.10), logarithms ‘undo’ exponents, turning them into simple factors. And equation (1.9) shows that logarithms turn multiplication into addition. For this reason, published tables of logarithms were important in pre-computer times, since addition (and subtraction) is easier to perform by hand than multiplication (or division). This led to the old joke that certain types of snakes only reproduce when placed on a wooden table[4].

The left side of figure 1.6 shows the exponential function $y = 10^x$ plotted versus x, while the right-hand graph shows that same function plotted with a *logarithmic scale* for the y-axis. On a logarithmic scale, each tick mark of the graph represents not an amount, but rather a *factor*. For the example shown here, each tick is 10 times greater than the tick below it. Since $\log(10^x) = x$, this is simply a straight line. And so use of a logarithmic scale on the vertical axis of a graph has the effect of turning an exponential function into a straight line. Notice how the logarithmic scale compresses an enormous range in values to a much smaller scale. Most of the direct graph of the exponential function, as shown on the left, is almost useless; at the scale of the graph, 90% of it is either indistinguishable from zero or nearly vertical.

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[4] Even adders can multiply on a log table.

We can also define logarithms with bases other than ten—for example a *base 2 logarithm*, written $\log_2 x$, that is the inverse of the base 2 exponential function that photographers have chosen for their exposure steps. It would then represent not powers of 10, but rather powers of 2. But it is common to use the base 10 'common logarithm' even so. The base 10 logarithm has the convenience that it is directly related to our base 10 numbering system, and there is a very simple relation between logarithms of different bases. Equations (1.9) and (1.10) are written for common logarithms, but they hold true no matter what the base, and so we have:

$$y = 2^x \tag{1.11}$$

$$\log_2 y = x \tag{1.12}$$

$$\log_{10} y = \log_{10} 2^x \tag{1.13}$$

$$= x \log_{10} 2 \tag{1.14}$$

$$\log_{10} y = \log_2 y(\log_{10} 2) \tag{1.15}$$

$$\log_{10} y \approx 0.301 \log_2 y \tag{1.16}$$

where I have made the base 10 of the common logarithm explicit for clarity. Thus, logarithms of different bases are simply proportional to each other, and to convert from base 2 to base 10, a simple factor of roughly 0.3 is all that is required. And so we have the important result that on a common logarithmic scale, the photographer's factor of two steps appear as even increments of approximately 0.3.

Our goal is to make an appropriate graph that relates density to exposure—the characteristic curve of our detector. And so we see from figure 1.4 that—for the photochemical detector shown in the example at least—the appropriate horizontal scale for our graph is not exposure, E, but rather $\log E$. But what is the appropriate measure of density? To answer this question we must consider not only the physical nature of the detector in question, but also the way in which the human eye/brain combination perceives steps in lightness and darkness.

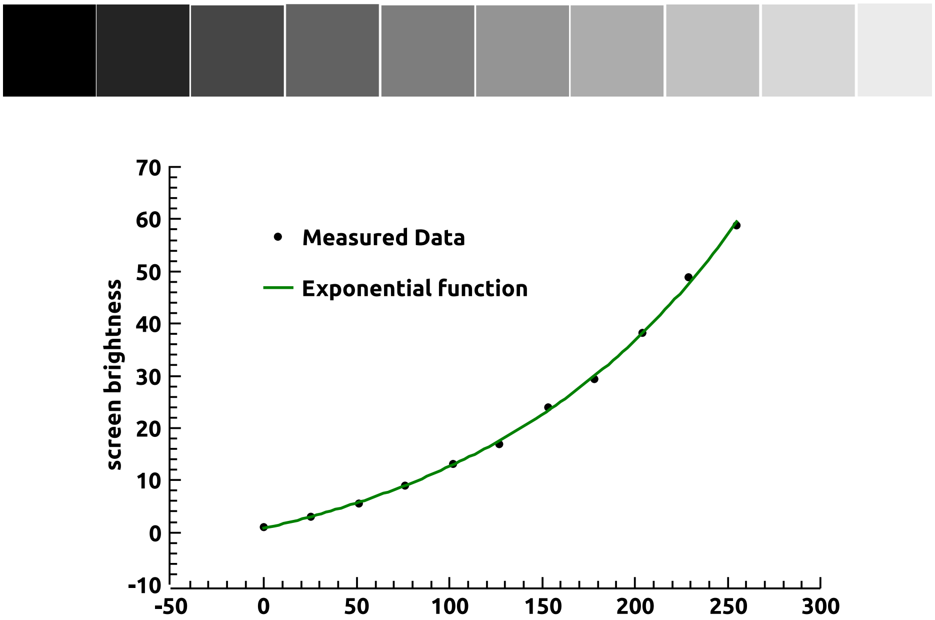

Figure 1.7. **Top:** A digital grayscale image produced so as to appear in roughly equal steps of brightness on a computer monitor. **Bottom:** A graph of the measured brightnesses of the grayscale sections, plotted on an additive scale. An exponential, rather than linear, function fits the data (green curve). This illustrates that we see levels of brightness in multiplicative, rather than additive, steps.

Figure 1.7 shows another set of gray levels that appear in roughly equal steps in brightness. This is an image created digitally, rather than from a negative-process photochemical detector, and so I show the levels arranged from darkest to lightest. When I display this image on my computer monitor, it appears to me as roughly equal steps in brightness. In a darkened room, I used a light meter to measure the brightness of the monitor for each of the gray levels shown in figure 1.7, and the result can be seen graphed at the bottom.

The graph of brightness levels shows an increasing slope, like some type of exponential function—and indeed, the data is well fit by one (the green curve). This crude experiment illustrates the well-known fact that our vision is better described by a logarithmic scale; what appear to us as equal steps in brightness are more accurately described as equal *factors* (Adler *et al* 2014). And so photographic density might also be better defined according to a logarithm of measured levels of brightness. This was first recognized in the early days of silver gelatin photography. In the late 1800s Ferdinand Hunter and Vero Charles Driffield made the first quantitative measurements of the density of exposed photographic emulsions, and we still use their definition today (Ferguson 1920).

One way to quantitatively measure the 'darkness' of a piece of exposed and developed photographic film is to shine light through it, and measure by what factor the light has dimmed while passing through the film. A device that does this is called a *densitometer*; it directly measures the *transmittance*, *T*, of the film.

The transmittance is simply the fraction of light that is transmitted, the rest being absorbed by the film. For a negative-process film, greater exposure means *less* transmittance, and so it makes sense to define density as $1/T$, rather than T. However, this simple measure would have little relation to how we perceive steps in brightness. And so instead, the photographers' definition of density, D, also incorporates the logarithm:

$$D = \log(1/T). \tag{1.17}$$

And so it appears that it is appropriate for both density and exposure to be described in terms of logarithms of the physically measured quantities. For this reason, the *characteristic curve* of a photochemical detector has, since Hunter and Driffield, been portrayed as a graph of D versus $\log E$. Since density is also defined in terms of a logarithm, the characteristic curve is a *double-log* or *log–log* plot, with a logarithmic scale on *both* axes.

But there is another important consideration—the physical process by which exposure causes the light detector to undergo its physical change. For a negative-process photographic film, the exposure to light ultimately causes the transmittance of the film to decrease. And so what *is* the mathematical relation between the exposure on the one hand and the inverse of the film transmittance on the other? And how will that relation appear on the log–log plot of our characteristic curve?

We have already seen that an exponential function appears as a straight line on a graph that has a logarithmic y-axis. But an exponential function is a strongly *curved* line on a *double-log* plot. And so, is there a mathematical function that appears straight on a log–log plot? And does the mathematical relation between $1/T$ and E follow such a relation for a real photochemical detector? The answer is yes to the first question, and sort-of yes to the second.

A double-log plot straightens out not an exponential function, but rather a *power law*. A power law is defined by:

$$y = ax^{\gamma} \tag{1.18}$$

where a and γ (the Greek letter gamma) are constants. Notice, as with an exponential function, that there is an exponent involved—but for a power law it is the *constant* that is the exponent, not the variable x. We can easily see that this function will appear as a straight line on a log–log plot by taking the logarithm of both sides:

$$\log y = \log(ax^{\gamma}) \tag{1.19}$$

$$\log y = \log a + \log x^{\gamma} \tag{1.20}$$

$$\log y = (\log a) + \gamma \log x \tag{1.21}$$

$$y\text{–axis} = \text{intercept} + \text{slope} \times x\text{–axis}. \tag{1.22}$$

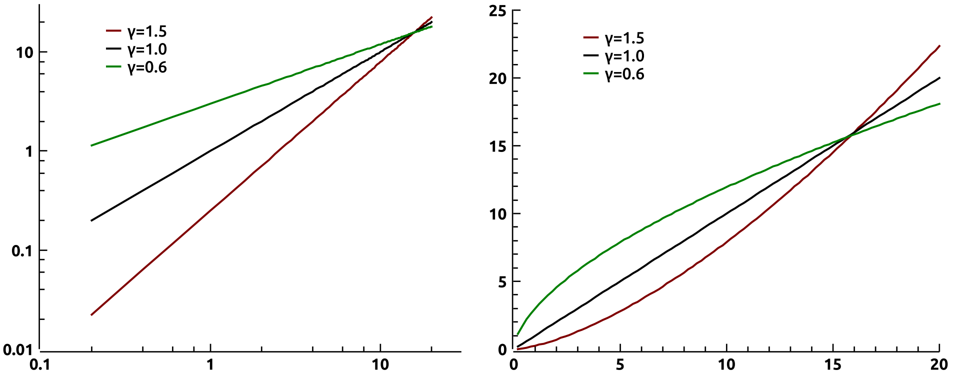

Figure 1.8. **Left:** Three power-law curves plotted on a double-log graph. They all appear as straight lines; the greater slope corresponds to the higher power, gamma (γ). **Right:** The same mathematical functions plotted on an ordinary linear scale for x and y. For $\gamma > 1$ the curve is concave upward, while the opposite is true for $\gamma < 1$. A straight-line, linear curve corresponds to $\gamma = 1$.

And so if we use a log–log plot to graph a power law, with $\log y$ plotted versus $\log x$, then we get a straight line with a slope equal to the exponent, γ, and a y-intercept equal to the logarithm of the scale factor a. The left side of figure 1.8 shows the log–log plots of three different power laws, each with a different γ. They all appear as straight lines on this double-log graph, with the steeper line belonging to the larger value of γ. The right side of figure 1.8 shows these same three functions plotted without the logarithmic axes—and here we see a qualitative difference. A power law with a $\gamma > 1$ curves upward, while $\gamma < 1$ produces a downward-curving graph. A value of $\gamma = 1$ leads to a simple straight line.

It turns out that the relation between E and $1/T$ for developed-out photographic film *is* often related approximately by a power law, but with two important exceptions. First, equation (1.18) has the property that $y = 0$ when $x = 0$. But this is not the case for the relation between film transmittance and exposure; there is a *minimum density* that occurs even with zero exposure. This is called the *fog density*, or D_{min}. And so a more appropriate mathematical relation would be:

$$y = ax^{\gamma} + b \tag{1.23}$$

where b is the value of y for $x = 0$. Taking the logarithm of both sides of equation (1.23) cannot be simplified to a straight line, like equation (1.18). But it is clear that for large enough values of x, the addition of the constant b would make an insignificant difference. And so we expect equation (1.23) to appear very much like a straight line on a log–log plot for large values of x, but to deviate significantly from that at small values.

Figure 1.9 shows log–log plots of power laws with $\gamma = 2$, both with and without an additive constant. And so we would expect our characteristic curve to appear more like the green curve, with a straight-line part, but also a flat *toe*, corresponding to the expected D_{min} of our photographic film.

Figure 1.10 shows a D versus $\log E$ curve for some real densitometer data from Stroebel *et al* (2000, p 96). Notice that the data points are separated on the

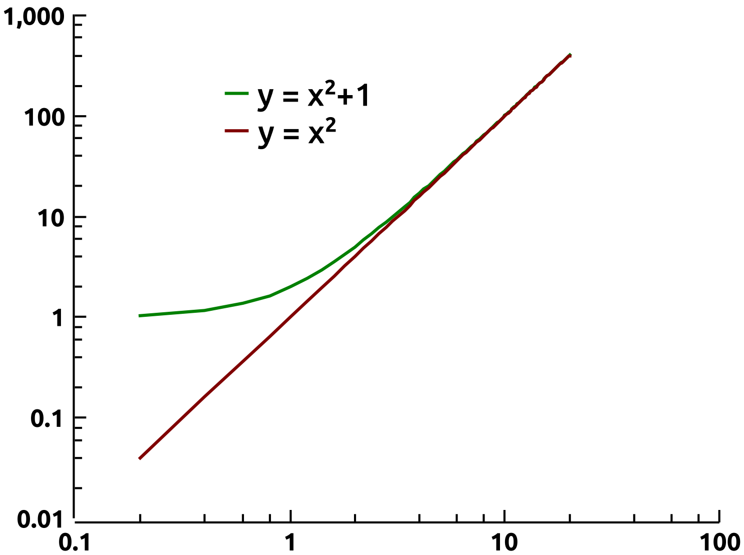

Figure 1.9. A simple power law (red curve) appears as a straight line on a log–log plot, unless it also includes an additive constant (green curve). The characteristic curve of photographic film has a 'toe,' like the green curve, because the film absorbs some light even with zero exposure.

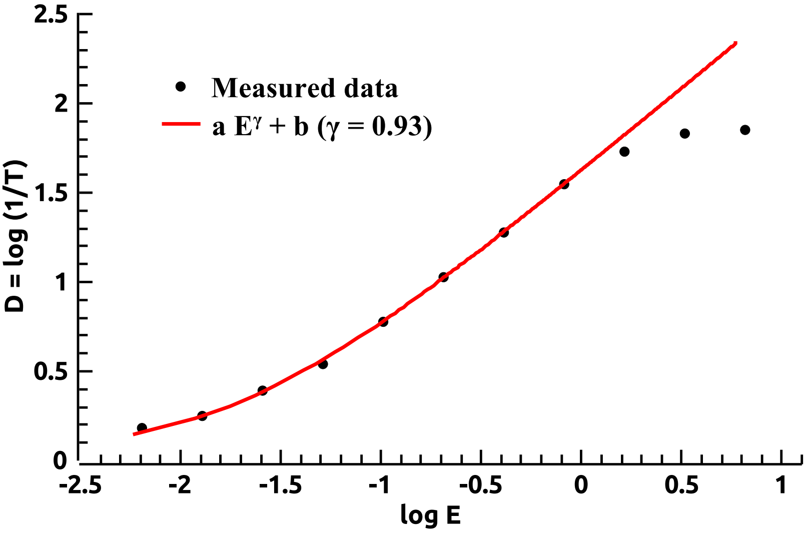

Figure 1.10. The characteristic curve for real densitometer data from Stroebel *et al* (2000, p 96). The red curve is a power law, with $\gamma = 0.93$, fit to the toe and straight-line part of the data. There is also a shoulder because real photographic film has a maximum density that is not exceeded with increased exposure.

horizontal axis by $\log E = 0.3$, corresponding to a difference of 1.0 if we had used a base 2 logarithm instead. Thus, the different exposures were made in the photographer's traditional steps, corresponding to factors of two.

Plotted on top of the measured data in figure 1.10 is the mathematical function of equation (1.23), with values of a, γ, and b chosen so as to best fit the data. It clearly has a *toe* and a *straight-line part*, as we would expect from a power law with a D_{min}. But there is also a *shoulder*—the density increases more slowly than the power law at large exposures, appearing to level off to a maximum density.

It should be unsurprising that the characteristic curve of a real photographic film has a maximum-density shoulder, or D_{max}. There is, after all, only so much of the photochemical reactant to be darkened by light and the chemical development process. Once the film is as dark as it can get, one would expect greater exposure to have no measurable effect.

The true mathematical shape of the characteristic curve for photographic film cannot be summarized by any simple formula. It can only be modeled accurately by a complex statistical analysis that includes all aspects of the process, from exposure to light, through chemical development and fixing, to the final measurement by the densitometer. But the toe and straight-line portions are often well fit by a power law. Some special kinds of technical film have a D_{max} that is too high to measure with a typical densitometer, and so the measurable part of the characteristic curve shows only the toe and straight-line part, with no shoulder (see for example Stroebel *et al* 2000, p 109, figures 4-28 and 4-29). And in those cases the measured part of the characteristic curve appears very similar to a simple power law plus constant, as in the green curve of figure 1.9.

1.6.1 The characteristic curve and photoelectric detectors

Whether one is using a negative or positive process, developed out or printed out, a photochemical detector produces a visible image in itself. Expose a roll of black-and-white silver gelatin negative film in a camera, develop and fix the film, and then hold it up to the light. The image is right there, visible in the very physical object that interacted with the light. Not so for a photoelectric detector—only an electronic signal is produced by exposure to light. The visible image must be produced from that signal by other means, either a lighted screen or some kind of printing process. And this means that we can, somewhat independently of how the detector responds to light, *transform* the electronic signal into something that corresponds to the logarithmic manner in which we perceive levels of brightness. And so for a photoelectric detector, the characteristic curve—a graph that relates exposure (the cause) to density (the effect)—can be connected more directly to the physical relation between exposure and signal. Thus, for a photoelectric detector there is little motivation for the nearly 150-year-old $\log(1/T)$ versus $\log E$ graph of Hunter and Driffield.

For these reasons, photoelectric detectors are more commonly described by the direct relationship between exposure and the resulting electronic signal. For the most important photoelectric detectors we consider in this book, that response is approximately *linear*, corresponding to the following graph:

$$y = ax + b. \tag{1.24}$$

Note that equation (1.24) is the same as equation (1.18), for the special case of $\gamma = 1$.

Photographers often use the term 'linear' in a different sense—to signify the straight-line part of the D versus $\log E$ characteristic curve of photochemical film emulsions. This usage is both wrong and right. First, why is it wrong? We have already seen why; the response is, at its simplest, not linear but rather a power law. Furthermore, the toe of the curve is part of the same power law as the straight-line part, yet photographers call only the straight-line part 'linear.' If γ is not equal to one, then *no* part of the characteristic curve is linear. But ironically, if $\gamma = 1$, then not only the straight-line part, but also the toe of the characteristic curve is linear. And so, from a perspective of the physical relation between exposure and the actual darkening of the film, photographers' common use of the term 'linear' is incorrect.

But as is the case for many commonly-used 'incorrect' terms, there is a method to the madness. If we are using a photochemical detector not for scientific measurements, but rather for making pictures, then we have already seen that it is density—as defined by photographers with a logarithm—that is the point.

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