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Introduction

What you'll get out of this book: a whole new way of seeing

Welcome to a unique book and a unique way of looking at the world.

This book will show you that by learning one or two simple techniques you will be able to see – with your own eyes – what you probably never knew was there: the *time dimension* of many sources of illumination.

Although there have been man-made light sources for millennia, the last thirty or forty years have seen radical technological changes. Gone are candles, tallow lamps, burning torches and storm lanterns; gas lamps are a thing of the past, and even Thomas Edison's ubiquitous incandescent light bulb is being challenged by new forms of lighting.

One characteristic of many modern light sources is that although they appear to shine with a steady light, they are in fact flashing or modulating very rapidly – too rapidly, in fact, for the human eye to see. This is by design: they're *supposed* to look like steady light sources. However, by applying the techniques detailed in this book, you'll be able to unravel every nuance of the behavior of these light sources, no matter how quickly they flash or change.

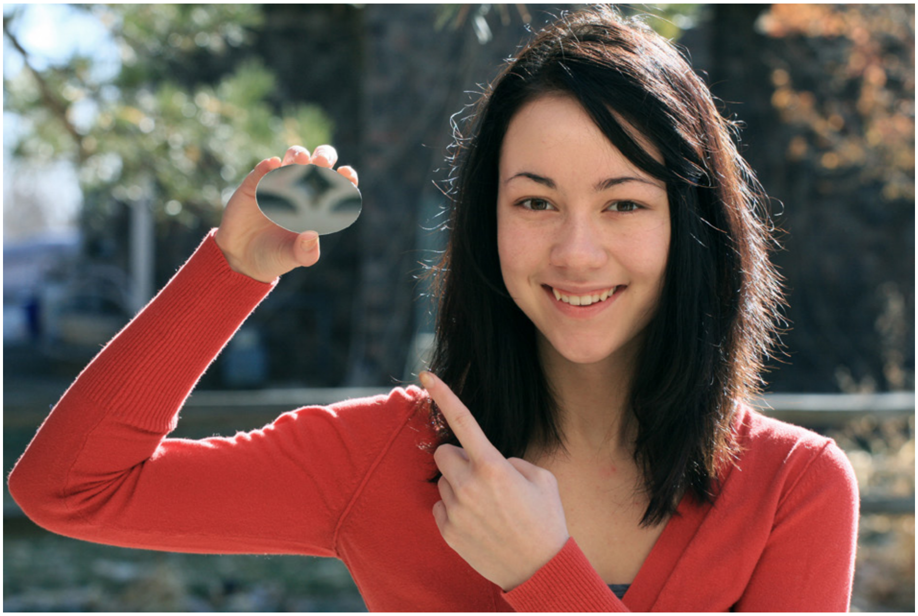

Figure 1: All the equipment you'll need: a small mirror.

A simple pocket mirror is the only tool you'll need to open up the world of time-varying light sources. And if you're really good, you don't even need the mirror!

In addition, there is a chapter on photography, which explains how to obtain photographs like the ones throughout this book; and you'll see that with simple techniques and a little imagination it's possible to produce striking images and photographic art.

The bulk of this book is the Field Guide itself, which arranges time-varying light sources into categories and presents common examples of each type of light source. Photographs show you what you might see, and observation tips (indicated by this symbol:) help you to look for important features.

Quantum physics and relativity

Relax! We're not going to dig deep into physics (or ocular physiology, for that matter) in this book. Explanations of how light sources behave the way they do will be high-level and simple to grasp, and will be sufficient to explain what you see. Of course, underlying the behavior of all light sources is quantum physics – after all, the photon, which is a particle of light, is described as the *quantum* of electromagnetic radiation, and this book is arguably all about photons; but it's more about *enjoying* them than studying the deepest secrets of their behavior.

And don't worry about Einstein's theories of relativity either! They don't really intersect with this book (except perhaps in the section on pulsars on page 144); except to say that the concept of "space-time", which is a consequence of Einstein's theory of special relativity, regards space has having *four* dimensions, with time being the fourth one. Hence the sub-title of my book: *Seeing in the Fourth Dimension.*

How I came to write this book

When I was between two and four years old, I lived with my parents and younger brother in the pretty Suffolk town of Woodbridge in England. I remember very little about that time in my life, but two memories stand out.

Firstly, I discovered ocular parallax. Close one eye and then the other and everything jumps sideways. (Yes, I know there's more to it than that, but it's outside the scope of this book.)

And secondly (and here's where this book started), I discovered how to view time-varying light sources. In my bedroom was a free-standing oil-filled electric radiator. It had an orange-red neon indicator which showed when the radiator was switched on. At night, that little red light was the only light source in my room, and I noticed that if I jiggled my gaze around the room, I would see a scribbled line of red dashes. Of course, at the tender age of four I didn't understand about such things as AC electricity, neon indicator lamps and retinal persistence of vision; but the interest was born.

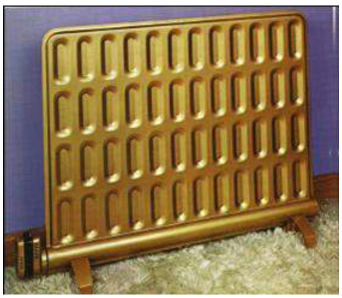

Figure 2: A radiator similar to the one that was in my bedroom. Image © Glen Dimplex Group. Used by permission.

Now, more than forty-five years later, I've enjoyed many years of delighted and inquisitive observation of time-varying light sources, and it's time to share my experiences and to provide my readers with the keys to the time-varying optical world.

Enjoy the journey!

The web-site

There is a web-site associated with this book: *timevaryinglights.com*. Make sure you go there for updates, new photographs, tutorial videos and a discussion forum.

Time-varying light sources: what they are and where to find them

What is a time-varying light source?

A quick look at the pages of this book will show you that many – most, in fact – of the sources of light that you see at night or in your home and office are time-varying. What does that mean?

Simply put, "time-varying" means that something changes as time goes by.

Some light sources vary slowly with time: imagine a flashing red light at a railroad crossing, for example. The light is certainly time-varying; but it's designed to be that way: you're supposed to notice that it's flashing. Such light sources are not the subject of my book: they're not nearly interesting enough!

More interesting are the sources of light which are flashing – or varying in some other way – too fast for the human eye to see under normal circumstances. These lights are designed to appear steady, and are flashing for reasons of technology or physics. You'll find that a large proportion of lights, lamps and displays fall into this category: these are what this book is about.

Take a very common type of lamp as an example: the traditional fluorescent tube light, seen in garages everywhere. When you switch it on, it may flash once or twice, but then it delivers steady white light. Or so it would seem. Did you know that for about fifty percent of the time, the light is a bright bluish white, and that for the remaining fifty percent, it's much dimmer and a strong yellow or even brown color? You don't ordinarily see this behavior because it happens so fast that the eye's natural "persistence of vision" masks the variations. But those variations are there, and it's easy to see them if you know how.

Other light sources are time-varying in much more complex ways, with the archetype being, perhaps, the old-style cathode ray tube television. That's the old type that had a slightly domed screen and took several seconds to warm up. The early designers of television owe a lot to persistence of vision, as you'll find out on page 81.

Where to find time-varying light sources

Since many man-made light sources these days are time-varying, it's not hard to find them. Go outside at night: street lights, stop lights, car tail-lights, signs in shop windows, even those lights that cyclists strap to their heads – many of them are time-varying. And when you get back to your living room, look at the numeric display on your DVD player, the monitor on your computer and the neon indicator on a power strip. Time-varying, all of them.

Unless you're living in a candle-lit, log-fire-heated cabin in remotest Montana, you're going to find time-varying light sources all around you. This book will help you to see them for what they are.

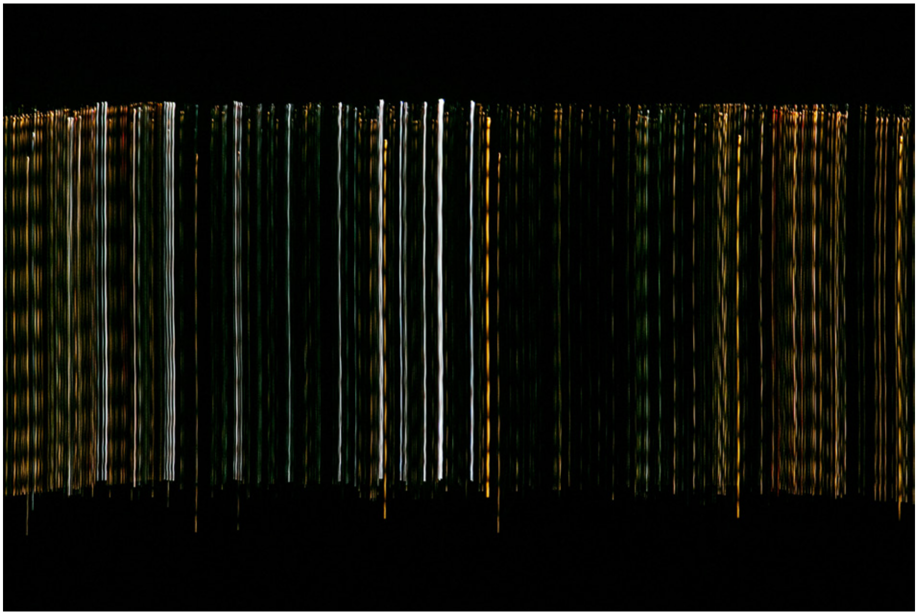

Figure 3: A vertically swept photograph of the distant street lights of a city. The dashed lines indicate that almost all of the light sources in this scene are time-varying. This illustrates that time-varying light sources are almost everywhere.

Figure 4: High Rye Cabin in Montana's Beaverhead-Deerlodge National Forest. Photograph © 2011 Nathaniel C. Liedl. Used by permission.

want to see everything flashing white and yellow. The designers of fluorescent lighting took advantage of the eye's behavior in order to deliver the apparently steady illumination that you expect from a light in your room. (But ponder for moment: lit by this type of fluorescent light, the illumination in the room really *is* changing rapidly between white and yellow! See Figure 127 if you don't believe me.)

However, if you're interested in observing the time-varying behavior of light sources like a fluorescent tube, you can play some tricks which turn the retina's persistence of vision to your advantage.

What I wrote above, about the bright white phase overriding the dim yellow phase is only true *if the image of the fluorescent tube remains in one place on your retina*. In other words, as long as you look straight at the tube, you will never see the yellow phase.

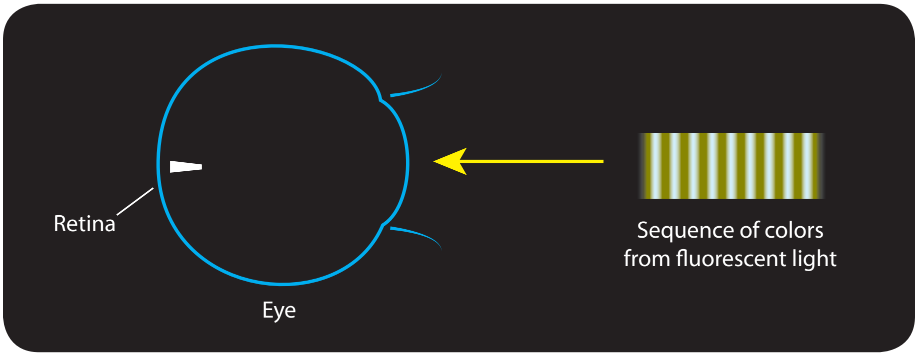

Figure 6: If the image of a fluorescent tube remains in one location on the retina, the sequence of colors will not be seen. Instead, the colors will be combined into the perception of a steady white image.

However, if you can somehow present fresh areas of the retina – which have not been exposed to the bright white phase – to the image, you will see the dimmer yellow phase very clearly, albeit briefly.

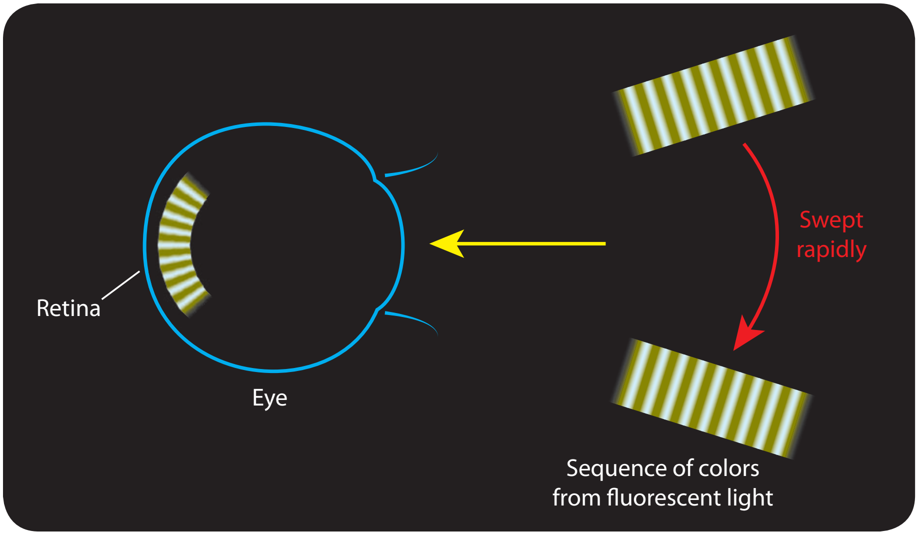

Figure 7: In this case, the eye's direction of view is swept — or the fluorescent tube is moved, or a mirror is used — so that its image is swept rapidly across the retina. The result is a short-lived (I use the word "transient") image on the retina which "unpacks" the color variations. This allows the observer to see exactly how the light source is behaving over time.

And that is the basis of how to see time-varying light sources: *keep the image moving!*

So the question becomes: how can one keep the image moving?

One of the easiest ways to see the rapid variations of a light source's brightness is to watch while somebody moves the light source around: try it in a dark room with an electrical power strip that has a red neon indicator on it.

Retinal traces and how to interpret them

Intensity over time

Almost all time-varying light sources vary in intensity (brightness). In many, but not all, cases, this is simply a consequence of the AC (alternating current) electrical power supply, which repeats its cycle of voltage 60 times a second in North America or 50 times a second in Europe. Sometimes both halves of the AC cycle are used so the light source's intensity will peak 120 (or 100) times a second. Don't worry: 120 times a second is easy to observe with the techniques described in this book. You will be able to observe light sources which flash thousands of times per second!

The following image shows a photographic trace for a neon indicator, in this case on an electrical power strip.

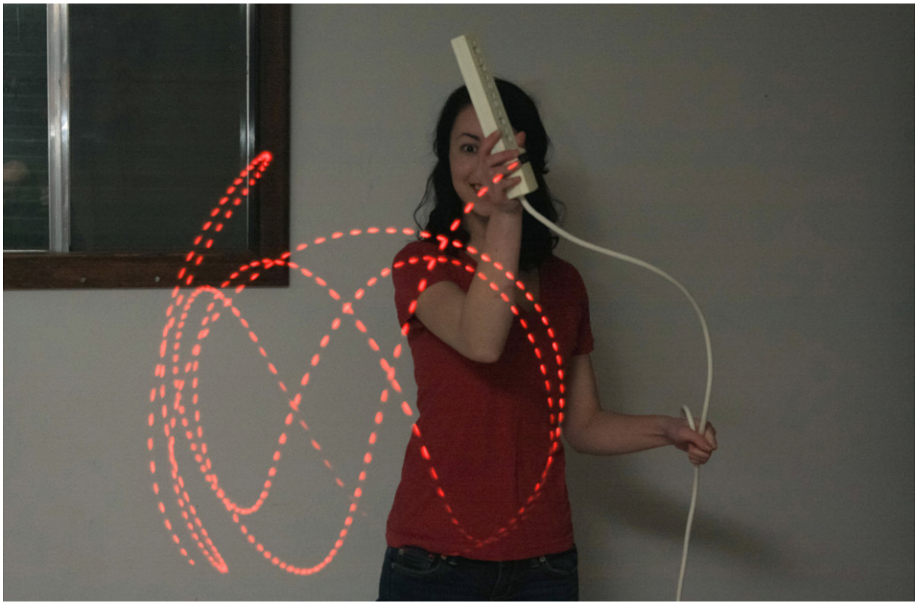

Figure 26: A trace of a neon indicator. This is a photograph produced by "light painting" – see page 41. (2.5 sec)

You can see a trail of orange dashes separated by dark gaps. In this photograph, the red dashes are about the same length as the gaps. Already we're able to observe that instead of shining with a steady light, this indicator is actually only shining for 50% of the time.

Notice also how the ends of the individual dashes are a little soft. This shows that the brightness rose and fell somewhat slowly, rather than abruptly turning on and then off. If this were an LED controlled by a digital circuit, the ends of the dashes would probably be very abrupt (see Figure 176 for an example of this). Here we can see that neon lamps driven directly by the AC voltage don't behave like digitally-controlled LEDs.

We're already interpreting a trace and learning something from it!

Figure 27 once again shows the trace of the tail lights of a GMC Acadia. Ignore the unbroken traces; these were generated by the inner tail light, which is DC powered and therefore

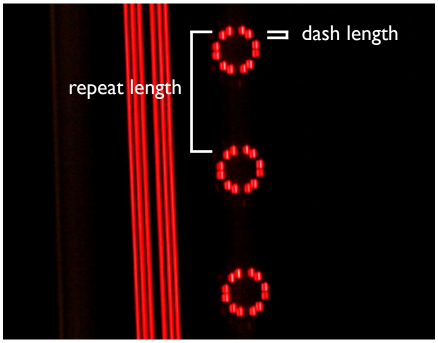

Figure 27: A photographic trace of the tail lights of a GMC Acadia. Here, we have zoomed in to consider the detail.

not time-varying.

There are two things to notice: First, instead of the neat dashes seen in the previous figure (which arose because the neon indicator is more or less dot-shaped), we now see the circular shape of the tail light itself (we discussed this on page 18).

Secondly, if we assess the length of the repeat relative to the length of the dash created by any given light emitting diode (LED), we can conclude that the tail light is shining with red light for less than 10% of the time! Seen on the street, it may look like a steady red light, but that's an illusion. We'll talk more about car tail lights on page 59.

Notice that the transitions between the light and dark states are pretty much instantaneous – there's no fade-in or fade-out. This is typical of digitally-controlled LED lighting.

Finally, here's a photograph emulating a retinal trace for a pressurized sodium street light, which is the most common type of street light in many countries (see page 50 for more information).

Figure 28: A photographic trace of a pressurized sodium street light, taken with an up-then-down sweep of the camera. (1/4 sec)

Note that this light also passes through bright and darker phases, but that the transitions between bright and dark are much more gradual. Your eye would usually also see an apparent thickening of the retinal trace in the brighter areas, similar to this image.

These three examples illustrate some of the variations in intensity that can be observed.

Color over time

Another characteristic of light sources that can change over time is their color.

I've written more than once about fluorescent tube lights in the early sections of this book. Now it's time to pay another visit. In Figure 29 you can see a broad band of light. The width of this band is simply due to the length of the fluorescent tube. The most interesting feature of this graph is the change in color – slightly bluish white alternates with a dull yellow, which has at least two levels of brightness. Again, it's easy to make a judgment of how much time is spent in each phase: in this case, it's around 50% in the white phase and 50% in the yellow phase. Fluorescent lighting is covered in detail on page 70.

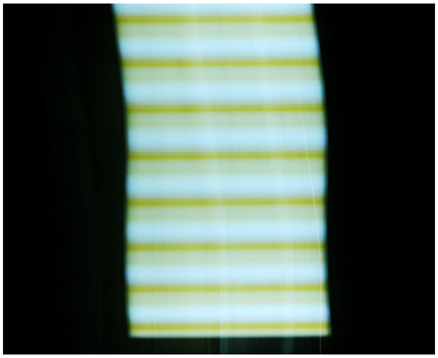

Figure 29: A photographic trace of a fluorescent tube light. (1/10 sec)

Most simple light sources don't exhibit such a strong variation in color. However, I did once see a light hanging above a table in a Denny's restaurant in Livonia, Michigan, which exhibited an incredible emerald green phase that was totally invisible without eyeball jiggling. While writing this book, I was lucky enough to find another such light at a motel in the Black Hills of South Dakota – see the following figures.

Cameras which do not allow the user to control the shutter speed are harder to use for this kind of photography. This means that most cellphones would serve only poorly. However, with care, quite good pictures can be obtained. Figure 244 on page 116 was taken with an LG G2 cellphone, and Figure 320 on page 152 was taken with an HTC Rezound.

Figure 40: The Canon EOS 70D digital SLR camera. (Photograph: Martin Kraft)

Finally, if your camera has image stabilization technology in the lens or the body, I recommend switching it off. Image stabilization only works for small angles of camera movement, and won't do any good for the large angles covered in a swept or jiggled photograph; and anyway, you're not looking for a stable image!

Most of the photographs I took for this book were taken with Canon EOS 20D, EOS 40D, EOS 60D and EOS 70D digital SLR cameras.

How to photograph time-varying light sources

When photographing time-varying light sources, your objective is to "paint" a trace across the camera's light sensor, using the light source as a "brush". In some cases, the light source may be moving (example: Figure 26), but in most cases the light source is stationary so you will have to move the camera.

Clearly, if we're trying to capture the behavior of a time-varying light source, we need to hold the shutter open long enough for the camera to "see" everything that the light source does during at least one cycle. For a 60Hz light, this would mean a minimum of 1/60th of a second. Figure 41 is an example of an exposure that is too short.

However, it's much more interesting to hold the shutter open for longer, so that a trace is produced (Figure 42).

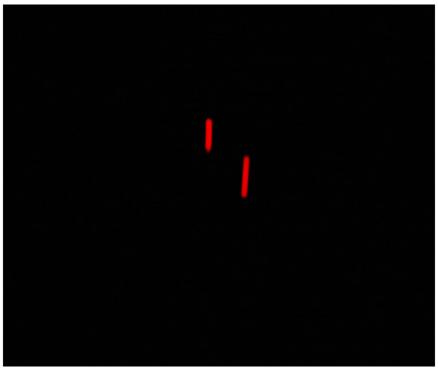

Figure 41: *(left)* Two adjacent LEDs with a 60Hz cycle, captured with a 1/80 second exposure. It's not possible to see any periodicity, and so we can't be certain of the behavior of these light sources. (See Figure 34 to see the light source shown here.)

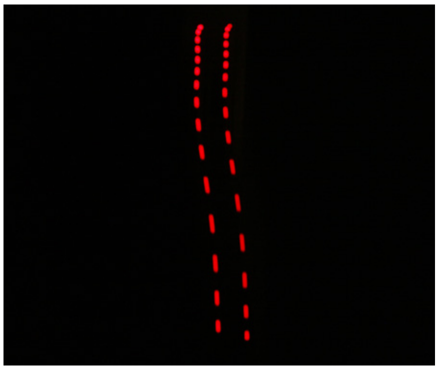

Figure 42: *(right)* The same LEDs captured with a 1/4 second exposure. While maybe a little too long for a purely documentary image, the result is attractive and informative.

Here are some steps which will help you to maximize your success with time-varying light source photography:

- Experiment!
- Select a low to moderate ISO, such as 400. Remember, you are trying to capture the *lights* in the scene, not the scene itself, so you should aim to under-expose aggressively. (This also helps to avoid colored lights washing out towards white in the photograph; see page 33.)

Taking a reference image

If you are capturing images for documentary reasons, it's a very good idea to take a conventional picture of the scene so that you can see each light in context. I call this a "reference image", and it will help you to understand the traces in the swept images. For example, study the following two photographs:

Figure 51: A night-time street scene in Greeley, Colorado. This photograph serves as a reference image for the next picture. Notice the apparent reflections of the brightest lights in the road. These are actually reflections inside the camera's lens.

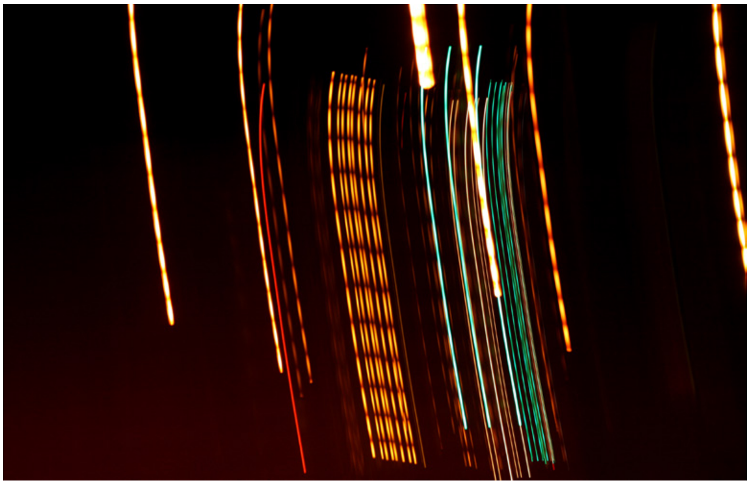

Figure 52: A photographic trace of the scene in the preceding picture. Here are some features to note: The stop lights were red in the first picture, but are green in this trace. Look carefully for the three nearer green lights, which are clearly separate, and the group of green lights from further down the street, which together make a green brush-stroke. Especially interesting is the row of street-lights in the middle of the scene. In the trace, they are clearly shown to be time-varying, with dark red periods interrupting the predominantly orange illumination. These are pressurized sodium discharge lamps. What's interesting is that the dark bands of the entire row of lights line up neatly. This shows that all the lights are connected to the same phase of the three-phase electrical supply. See if you can figure out the correspondence between all the traces and the light sources in the scene. Hint: There's a short, bright trace at the top of the image which doesn't appear to have a source in the scene; but note that there's a lamp-post in the foreground, so presumably there is a street-light that is out of shot in the first image. (1/10 sec)

Zooming

Most cameras offer some degree of optical zoom (avoid using digital zoom – you might lose detail). Single Lens Reflex (SLR) cameras (like my Canon cameras) also allow the user to use different lenses, which offer different zoom ranges. So the question may arise: what is the best amount of zoom (properly: what is the optimum focal length) when creating photographic traces of time-varying light sources?

In general, the answer will vary for each photograph, and will be found by (you guessed it) experimenting. However, I would advise against zooming in too "close" to the light source for the following reason: the more you zoom in, the smaller the angle that you can sweep the camera before the light source goes out of the picture. It is better to zoom out somewhat and make a good sweep than to zoom in and be forced to use a constrained sweep. The reason for this is that you're aiming to separate out the changes in intensity, color and pattern of the light to give a clearly interpretable trace. This works best if you can sweep

The art of photographing time-varying light sources

In addition to simply recording how light sources change over time, you may find (as I have) that photography of time-varying light sources approaches an art-form, and I would imagine that readers with an artistic inclination would find a lot of satisfaction in exploring this medium.

The main guidance I would give you for art photography is as follows:

- Look for interesting light sources or groups of light sources.
- Set your exposure time to something longer than you would for documentary pictures. 1/4 second is probably the minimum, with interesting results possible with longer exposures such as one second.
- Move the camera in creative ways, including, for example, zooming while rotating (not as hard as it sounds: grab the zoom ring on your lens and rotate the camera!)

Here are some examples of pictures I have taken which are visually attractive.

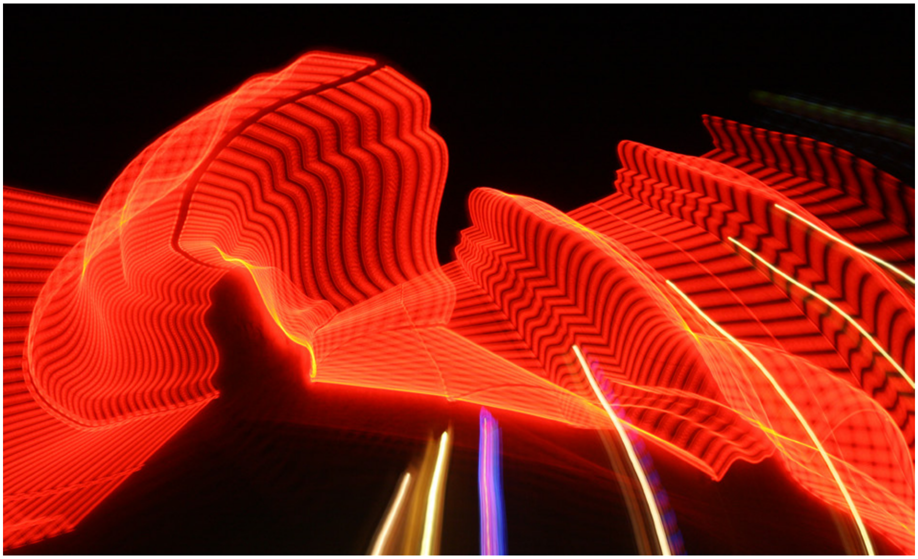

Figure 57: Neon lighting (page 101) makes a great subject for art photography. (0.3 sec)

Figure 58: An example of creative post production. This is the same image as Figure 121, except that here it's "inverted", or turned into a negative. This can be achieved in Adobe Photoshop by pressing "Ctrl" and the "i" key.

✍ Finally, look to see what happens when the driver applies the brakes. Are the LEDs, which are now apparently brighter, on for 100% of the time? Or are there short moments of darkness in the trail, which would suggest a pattern such as on for 95% of the time and off for 5%? I have seen both implementations.

LED daytime running lights

It seems that curved strips of white LEDs are a must-have design feature for modern cars. These are frequently modulated in the same way that many LED tail lights are modulated to control the apparent intensity. The result is that it is often very easy to observe their time-varying behavior.

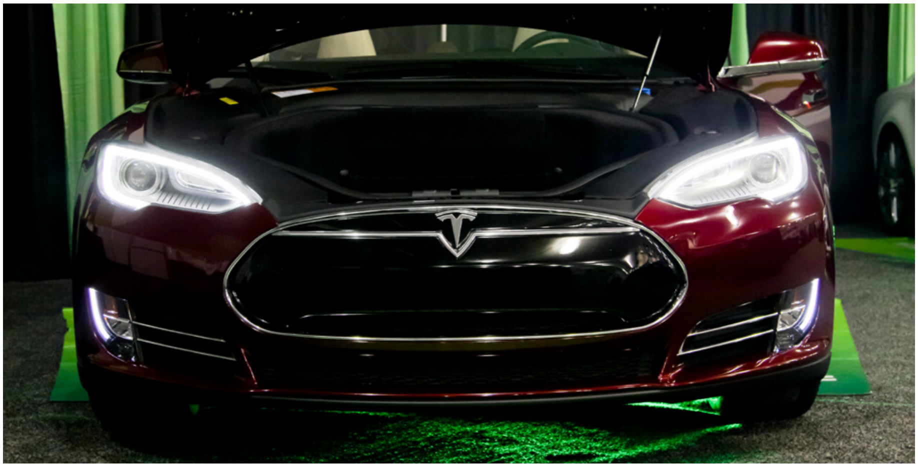

Figure 109: The front view of a 2012 Tesla Model S at a trade show. The white LED running lights which wrap around the headlights are illuminated. Note too that there are two small white side-lights lower down.

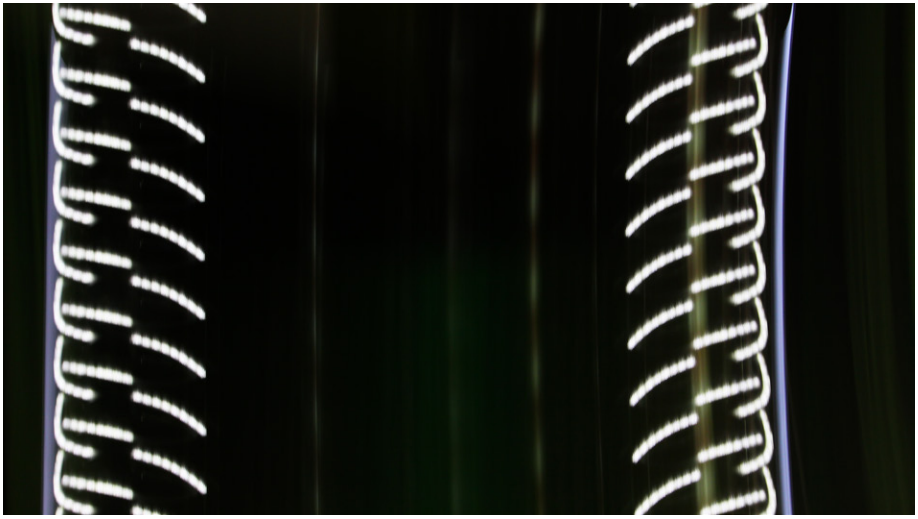

Figure 110: A swept trace of the Tesla Model S. The LED running lights are clearly shown to be time-varying, with marked flashes of illumination separated by periods of darkness. Notice that the strips are actually divided into three sections: one on the side of the headlight, and two along the top of the headlight. These sections are flashed at different times, which is why the images of the running lights do not have the same shape as the physical features on the car. Additionally, note the dimmer blue-white traces that lie just outside the running lights: these come from the white side-lights, which are DC powered with no time-varying behavior. The blue tint arises from the behavior of the sensor in the camera: these lights appear white to the eye. (1/10 sec)

At night, of course, the headlights are also illuminated. These are almost always incandescent and therefore not time-varying; and the very few LED headlights on the market are also not time-varying because they are driven with constant DC power for maximum brightness. I expect that over the next few years, more vehicles will appear on the market with white LED headlights. Note, however, that even with the headlights turned on it is still possible to observe the flashing of the LED running lights, especially with incandescent headlights as these are a markedly different color to the LEDs. With the headlights

The following diagram should serve to illustrate what's happening during the AC cycle:

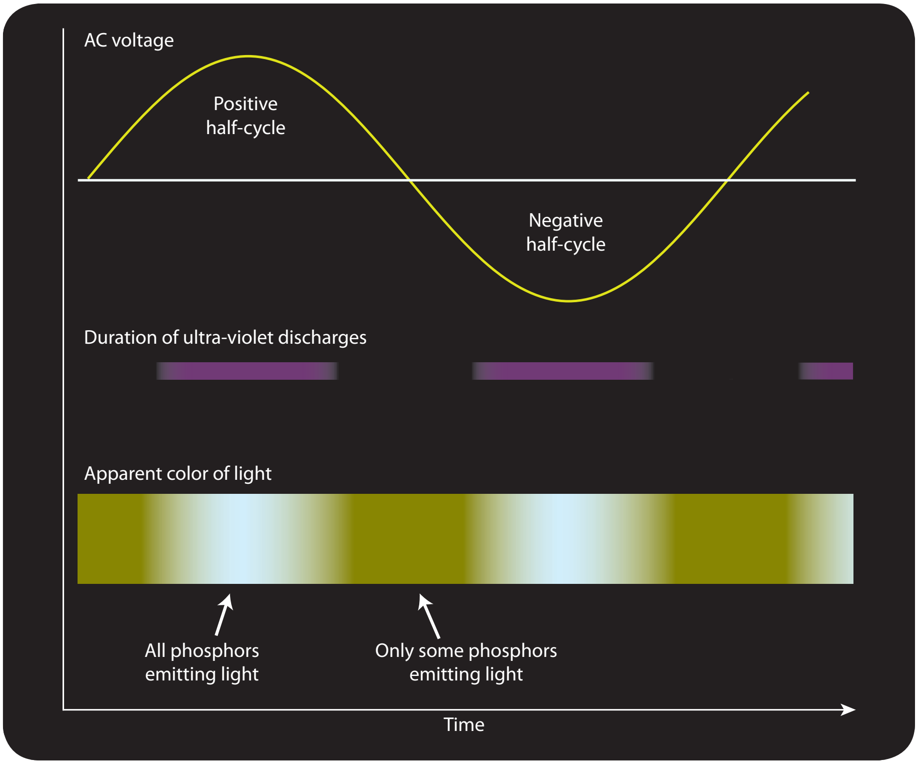

Figure 128: A diagram illustrating the sequence of events in a traditional fluorescent tube. The sine curve at the top represents the voltage of the AC mains supply, for example, 110V at 60Hz (in the US). The purple dashes indicate the periods when the mercury vapor is undergoing electrical discharge and emitting ultra-violet light. The important thing to note is that the discharge only occurs when the voltage becomes sufficiently high (positive or negative). When the AC voltage is closer to zero, no discharge occurs. The white and yellow bar indicates the perceived color of the light from the tube. The white periods occur when all phosphors are emitting; the yellow periods when not all phosphors are emitting. Some phosphors cease emitting as soon as the ultra-violet stimulation ceases; others, which contribute to the yellow color, continue to glow for a short time, essentially filling in the gaps between mercury discharges.

The following images are examples of fluorescent lights and the traces they generate.

Figure 129: A building illuminated by a row of fluorescent tubes.

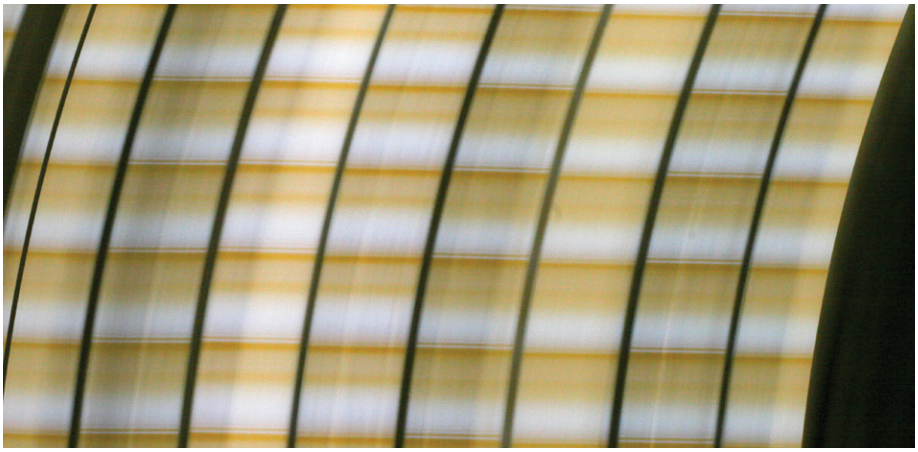

Figure 130: A photographic trace of the building. The color variations are very apparent, with the tubes showing a quite complex time-varying behavior. Note that the dark yellow or brown bands line up with each other: since the tubes are physically arranged in a straight line, this trace proves that all the tubes are connected to the same phase of the three-phase electrical supply. (1/10 sec)

Figure 180: An item of professional audio equipment in a rack. We're interested in the bottom row of red LEDs, which are all illuminated.

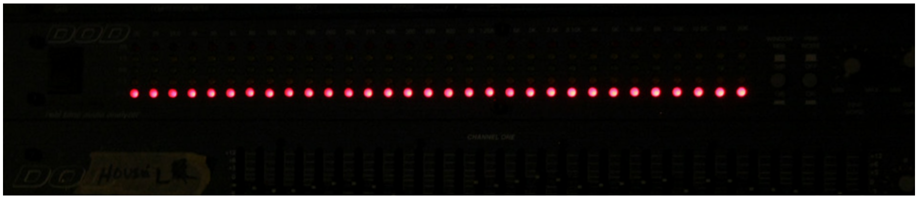

Figure 181: An under-exposed photograph of the same equipment, which makes it clear that the red LEDs are lit.

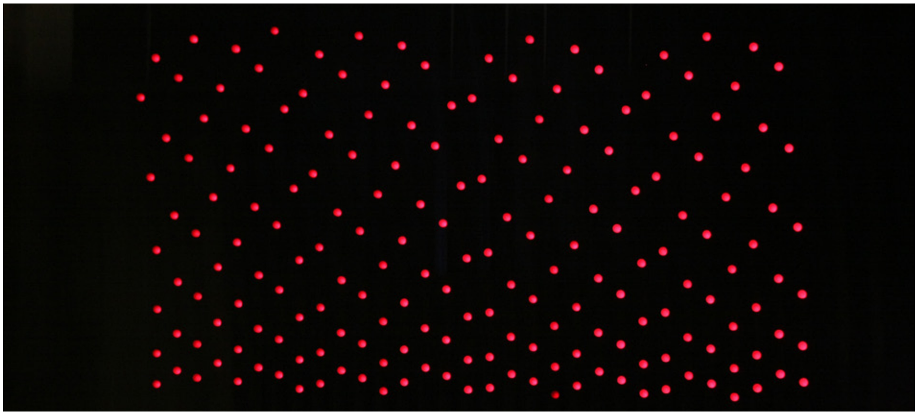

Figure 182: A vertically-swept trace of the LEDs. Each column of dots records the behavior of a single LED. Firstly, it's clear that none of the LEDs is DC-powered: they are flashed briefly with long dark periods between each flash. Secondly, the patterns of dots do not line up horizontally, so the flashes occur at different times for different LEDs. (1/10 sec)

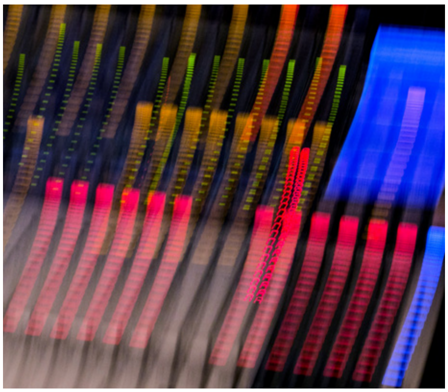

Figure 183: *(left)* A digital audio mixing console.

Figure 184: *(right)* A photographic trace of the mixing console. All the LEDs are time-varying, including the two-digit red numeric display. (1/10 sec)

Digital projectors

Digital projectors are found more often in office environments than in the home; but some home theater installations use projectors. Projectors of this kind are usually based on LCD technology, though some use a digitally controllable reflection technology called DLP. They almost always use bright incandescent lamps for generating the light that's needed for projection, though some portable projectors are now using LEDs as a light source, though they are less bright than the ones with light bulbs. You may think that since the lamp is incandescent there would not be any interesting time-varying behavior to observe; but with of this kind of projector there are at least two interesting things you predominant diagonal character to it. What's happening?

The answer is that knots or pulses of brightness are traveling along the tube. Many of these pulses are present at any instant, like wagons in a train. Since these pulses are traveling *along* the tube and your eyes are sweeping past the tube in a *perpendicular* direction, what you will see is a *diagonal* effect. This is because your retina is moving, say, *down*, while the sparks are moving *across*. The combination of these two movements results in a diagonal appearance.

When vision-jiggling at a neon tube, this rippled effect is very easy to see. It may be harder to discern that there is a diagonal bias to the ripples, and very difficult to observe that the diagonal bias alternates one way then the other. As the photograph shows, there is some irregularity, so the patterns aren't always very clear. Also, the contrast between the light and dark regions in the tube may be quite low, resulting in the effect being subtle. But persevere, and you'll see it.

One interesting effect that you might see is that even when two tubes are in line with each other, their dark bands may not line up. This is due to the tubes being connected to different phases of the electrical supply. Figure 203 and Figure 204 illustrate this effect.

Figure 203: A photograph of two red neon tubes and two blue discharge tubes on the side of the American Furniture Warehouse building in Fort Collins, CO.

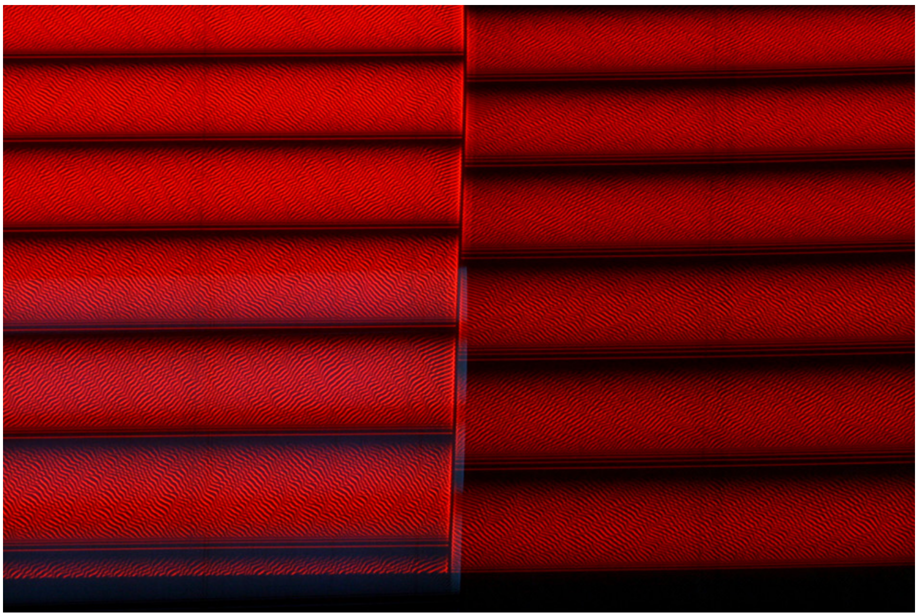

Figure 204: A photographic trace of the same tubes. Notice that even though the red tubes are physically in one continuous line, their patterns in the trace are displaced. This shows that the tubes are powered from different phases of the electrical supply. In fact, if you measure the displacement, it will always be exactly one third of the distance between the dark bands. This is due to the fact that there are *three* electrical phases; two are visible here. You might find a building where all three phases are present. For these tubes, the diagonal effect is very prominent; and, like in Figure 202, the direction alternates with each half-cycle of the AC power. (1/20 sec)

flying: it's a high-pitched whine, which must be at several hundred hertz or even a kilohertz… which would be a thousand flaps per second!

Figure 300: Peter Steward's photograph of moths in front of a lamp in Tsavo West National Park in Kenya. This photograph (shown somewhat cropped here for detail) won the "ecology and society" category of the British Ecological Society's photographic competition of 2014. Photograph © 2013 Peter Steward. Reproduced by permission. (2 sec)

Lightning

Lightning's most interesting time-varying behavior arises from the fact that most bolts of lightning actually consist of repeated strokes along the same path. This is due to the fact that the initial stroke creates an ionized channel in the air, and subsequent strokes discharge along this channel which serves somewhat as an electrical conductor.

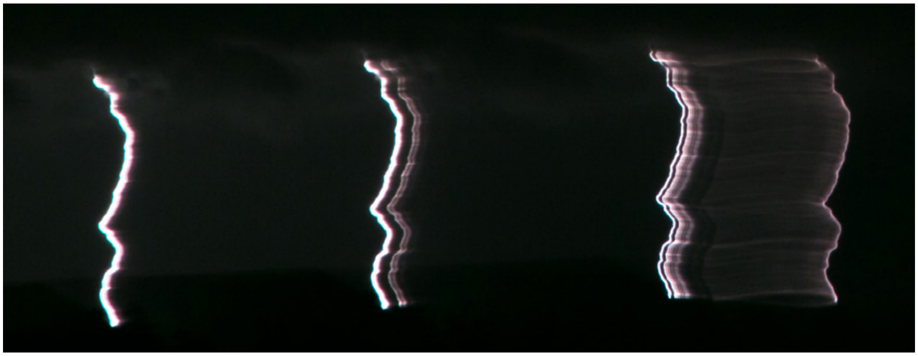

Figure 301: A cloud-to-ground lightning strike, photographed while the camera was swept sideways. The exposure time was 1/4 second. Note the multiple strokes which all follow the same path. The apparent stroke on the far right is actually a photographic chimaera: there's a wide area which records a sustained period of dim glowing light; the right edge of this glow is actually where the camera stopped moving as it reached the end of its horizontal sweep, allowing the dim glow to form a localized, brighter image. Close inspection of the glow area shows that the camera actually headed back in the opposite direction for a short time.

However, observing this behavior is not easy. The main problem is that it's impossible to predict when a suitable bolt will occur. This means that naked-eye observation requires sustained and continuous jiggling – ideally in the direction that's perpendicular to the bolt itself, in order to separate out the images of the individual strokes. In my case, I am much better at jiggling up and down, so to achieve a sideways movement of my eyes, which is required for observing cloud-to-ground lightning, I had to lay my head on its side. This was disorienting and hard to maintain.

Additionally, because lightning is unpredictable and visually arresting, it's easy to become like a deer in the headlights and to stop jiggling at the moment of the stroke. This defeats the object of the observation; and so one must train oneself to keep jiggling no matter what.