

Physics 15c, Lab 6: Transmission Grating; Measuring CD Track Spacing

Due Friday, April 6, 2007

REV 0¹; March 15, 2007

We don't expect you'll need much help! We'll show up at the start of each of the same 3 lab session times. We won't stay long, if you're not there. So, if you want to come, come at the start of the lab hour.

These are the hours when we'll offer help:

- Wednesday, 7 pm
- Thursday, 4 pm, Thursday, 7 pm

As usual, we'll stay as long as you need help—but you must show up at the start of the session, please. You can come to *any* help lab session.

Please make sure you read through the entire lab before you start.

1 Objective

In this experiment you will explore both the behavior of an optical transmission grating and the nature of various light sources as well probing the optical limits of CD technology. This week's lab, like lab 6, is focused on diffraction. Last week you used a reflective grating (the ruler) with known line spacings to determine the wavelength of your laser light. This week the process is reversed. The transmission grating exercise asks you to diffract light through a *transmissive* grating, but this time you will use the laser light with a known frequency to determine the line spacing of your diffraction grating. Using the same method you will determine the spacing of the *reflective* “diffraction grating” that the tracks of a CD approximate. As in Lab 5, the task is straightforward—but the handling of *error propagation* is a little subtler. Again, one must consider the question of the *independence* of errors.

The last sections of the lab asks you to do some qualitative investigations; these will go quickly. Please explain your reasoning and observations while writing up these qualitative investigations.

¹Revisions: under “Recapitulation,” steer people to re-read sec. on xmsn grating, and toward correct formula; add questions 1, 2, 3 (3/04: Anita).

2 Two Quantitative Experiments

2.1 Transmissive Diffraction Grating

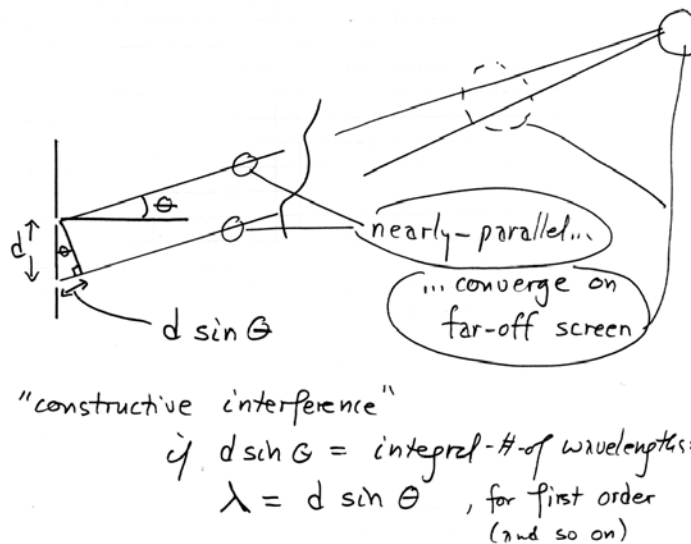
We have provided a transmission grating for you in the envelope. It is mounted in what looks like a photo slide mount. The grating is a film with a set of “lines” exposed on it, or indentations scored onto it. Most of the light that impinges on the film passes through, but some of it is diffracted.

Measuring the Grating Spacing

In the last lab you calibrated the laser (i.e. measured the wavelength of the laser light) using a ruler. Now that you know the wavelength of the laser light you can use that as a “ruler” to measure the spacing between the lines in your transmission grating. *Don't trust the labels, if any, on your grating!*

Here, from the preceding lab, is a restatement of the geometry that explains the diffraction pattern to be expected when we pass coherent light of one wavelength through a grating.

Recapitulation: The Diffraction Grating



Once again—as with the shiny ruler scored with dark markings—the diffraction grating probably is not an opaque sheet with narrow slits, as drawn. More likely it is the opposite: a transparent plastic sheet that has been scored or deformed with narrow lines that *block* transmission. As we saw in Lab 5, such a structure works like the complementary design—counterintuitive though this conclusion may seem.

Set up the laser as you did in Lab 5 (tape it down to a book or table facing the wall). Attach the transmission grating to the edge of the table or book so that the laser passes through it. We suggest you use a spacing of 1 meter from grating to wall. As in the previous lab, place a piece of paper on the wall and make marks where you see spots. Take the paper down, measure the distance between the spots and the spot “diameter”, and tape this paper into your

lab notebook. Calculate the diffraction grating line spacing and associated uncertainties using at least two orders of diffraction spots.

Question 1: In this experiment you should measure the distance from the $-n$ spot to the $+n$ spot and divide by 2 in order to determine the order "spacing". What advantages does this method of measuring order "spacing" give in terms of error analysis and minimizing a systematic error?

(Reread the section of the last handout which dealt with transmission diffraction gratings. You do not want to use the same diffraction equation that you used last week. The equation used last week was specific to grazing angle reflective diffraction.)

Combine your calculations to give an average grating spacing and the uncertainty on that value.

Question 2: Why can you calculate an uncertainty on the average value this week when you couldn't last week?

2.2 Measuring Track Separation on an audio CD

An audio compact disk forms an imperfect but adequate reflective diffraction grating². The "tracks" on a CD carry information in pits, which reflect less well than the inter-track regions. In fact, this reduced reflection is actually an *interference* effect: the pit depth is close to $1/4$ wavelength of the laser light used in the pickup, and the combined reflections from pit-and-land (the other surface) tend to cancel. This effect is less strong for our visible laser than for the CD pickup's infrared laser, but is still pronounced enough so as to give good contrast between "track" (where there are pits) and inter-track region (smooth, reflecting better).

Here is a photo of the CD surface:

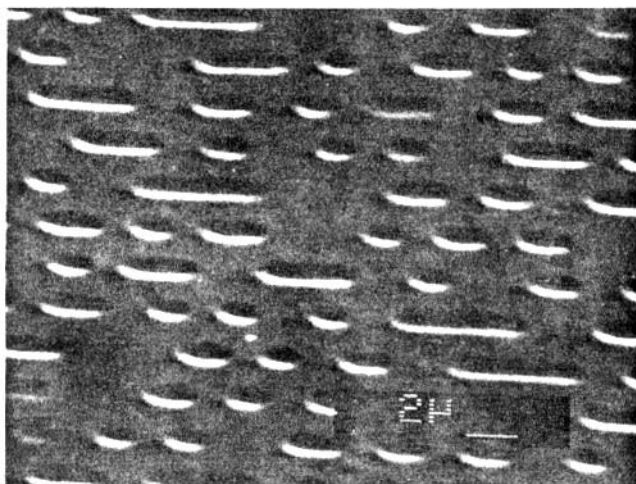


Fig. 1. Photograph of the surface of a compact disc taken with an electron microscope.

²This experiment was published by C. Noldeke, "Compact Disk Diffraction," *The Physics Teacher* 28, 484 (1990). Wolfgang Rueckner brought the experiment to my attention.

And here is a diagram showing typical dimensions.

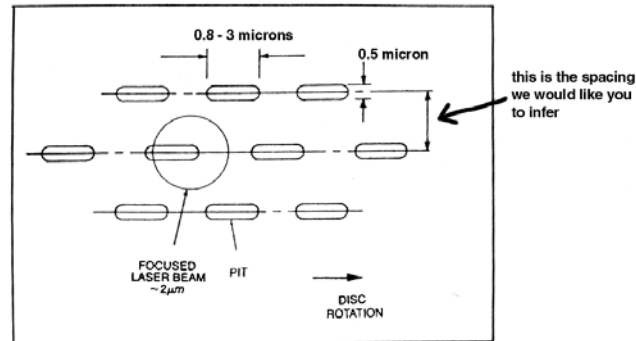
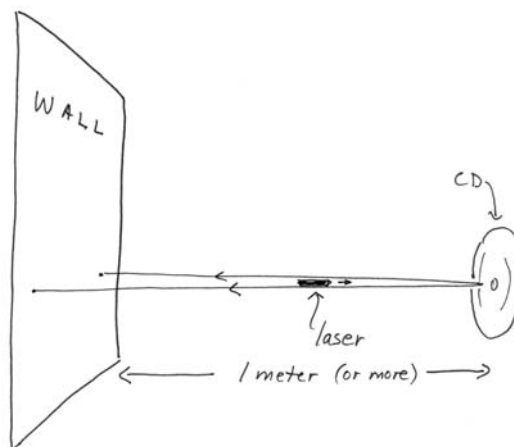


Fig. 1. Tracks of pits recorded on a compact disc. Also shown is the focused laser beam used to read the recorded information.

You know, from Lab 5 (if not from the label on the laser box!) the wavelength of the laser's output. Use this information, and the diffraction pattern that you see when you display the *reflected* laser light on a white wall, to infer the track-to-track spacing. Here's the setup:



The geometry of the setup is the same as that of the transmission grating except that the laser is reflected and diffracted instead of transmitted and diffracted. Because the geometry is the same the equation that applied to the transmissive diffraction also describes the behavior of reflective diffraction of the light off of the CD. You'll probably see just the first two orders. Note that the bright spots above and below (or alongside—depending on how you orient the CD) will show equal displacements only if the laser beam runs at right angles to CD and wall. You will need to use some care to fulfill this condition—or to work around a difference between the two displacements (see question 1), if you find one. Calculate the inter-track spacing and its uncertainty for two different diffraction orders.

A Very Informal Equivalent Experiment

Since you have a laser, you don't need the following rougher equivalent trick; but it may be fun to show to friends who don't have a laser: if you shine a lamp on CD—say, a small incandescent desk lamp pointing straight down at the disk—you can adjust your point of view until you see a first rainbow, as you move away from the perpendicular to the disk. When you see the center of the rainbow, note the approximate angle to the perpendicular. This is the angle you measured more carefully for the laser beam. It will differ somewhat from your laser angle, since the wavelength

of the visible light (yellow, around center of rainbow) is around 580nm (versus 635nm for the laser). From this estimated angle you can estimate track-to-track spacing, at least roughly.

How much data can a CD hold?

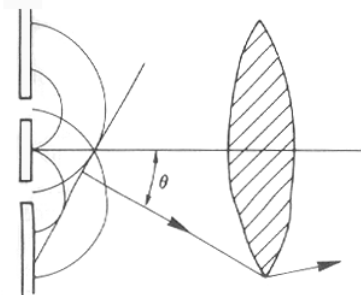
Given the inter-track spacing that you find, you can estimate the number of tracks on the CD and the total length of the spiral track (measure the radial distance between the start and end of the recorded section, then use an average circumference).

Question 3: From this total length, and an average bit-length of about 0.6 micron³ estimate how many *bits* would fit on the CD, and thence the number of *bytes* (8 bits/byte) and number of *samples* (4 bytes per stereo sample), then *total time* at the standard sampling rate of about 44kHz (that is, 44k stereo samples/second). Your estimate should *over-estimate* CD capacity by a great deal, because much redundant information is stored on the CD, so as to allow *error-detection* and *error-correction*⁴. (In fact, the data stored on a CD is *three times* the usable data!⁵ We hope your calculations indicate that the CD holds a lot of data!

2.3 Confirm that CD features are close to the limit of resolution

The resolution of an optical device is limited, no matter how perfect the optics. Short wavelength light helps (you may have read of integrated-circuit fabricators pushing to ever shorter wavelengths, the better to define IC features, in their use of optical lithography); large lenses or mirrors help (you know of telescopes that use very large mirrors).

The features to be observed, in the case of the CD, form a reflective diffraction grating, and the closer that these features are spaced, the wider the angle at which the first orders are diffracted, as you know⁶:



³The argument for this estimate is a little involved: minimum pit length is 0.8 micron, as shown on the figure above; but this pit length encodes not one bit but 1.4 bits— $3/17$ of a byte (“byte” =8 bits). This strange number comes from the strange encoding: *edges* of the pits encode *one*’s. And the way a CD encodes data has been designed to be deliberately “wasteful”—for the purpose of limiting the rate at which the signal level alternates between ON and OFF (this is the *frequency* of the CD signal): sequences shorter than *two* bits are ruled out. As a result, *14* bits are required in order to encode the 256 combinations permitted by 8 bits of information. This “Eight to Fourteen” encoding (“EFM”) gives each bit an effective value of $8/14$ bit. Then some extra “padding” bits are added to solve a problem of DC offset, requiring 17 bits to encode an original 8 bits. Pretty messy!

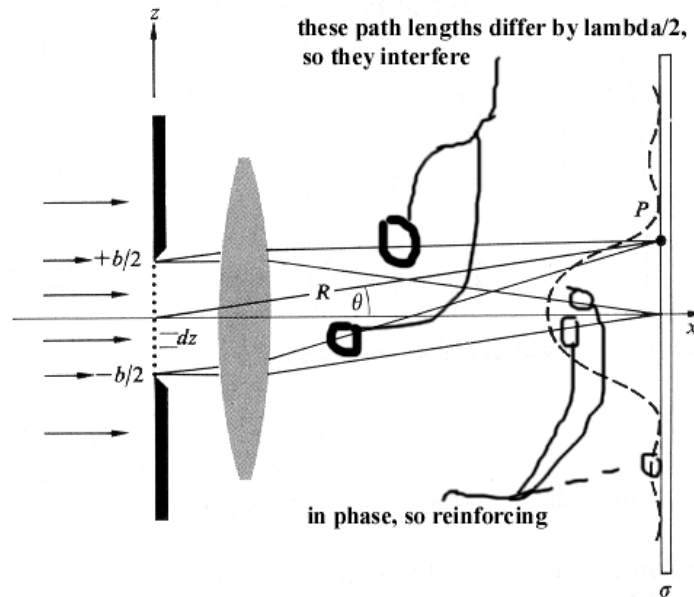
⁴For tons more information on CD technology, see Ken C. Pohlman, *The Compact Disk Handbook* (2d ed., 1992): in Loeb Music Library only

⁵Pohlman, p. 273.

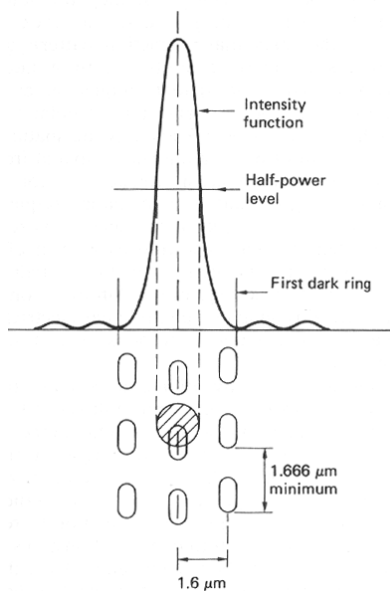
⁶J. Watkinson, *The Art of Digital Audio* (2d ed., 1994, p. 585.

The size of the lens matters too: a large lens permits finer discrimination (a smaller spot size); the lens needs to gather much of the available light, in order to succeed in discriminating bright from less bright regions⁷. This concern presses toward use of large lens. On the other hand, a larger lens imposes a shallower depth of field, aggravating the difficulty of keeping the laser spot well-focused; and the lens must be small simply so as to fit within the movable mechanism that a CD player uses to follow the disk's spiral tracks.

Another way to put the problem described here is to note that a single slit puts out a diffraction pattern with a central maximum, then a minimum, with the minimum at an angular distance determined by the width of the slit and the wavelength of the light. The figure below⁸ happens to include a lens, but otherwise is familiar:



In the figure below, the transmission arising from a small region of a CD is shown along with its associated intensity function⁹:



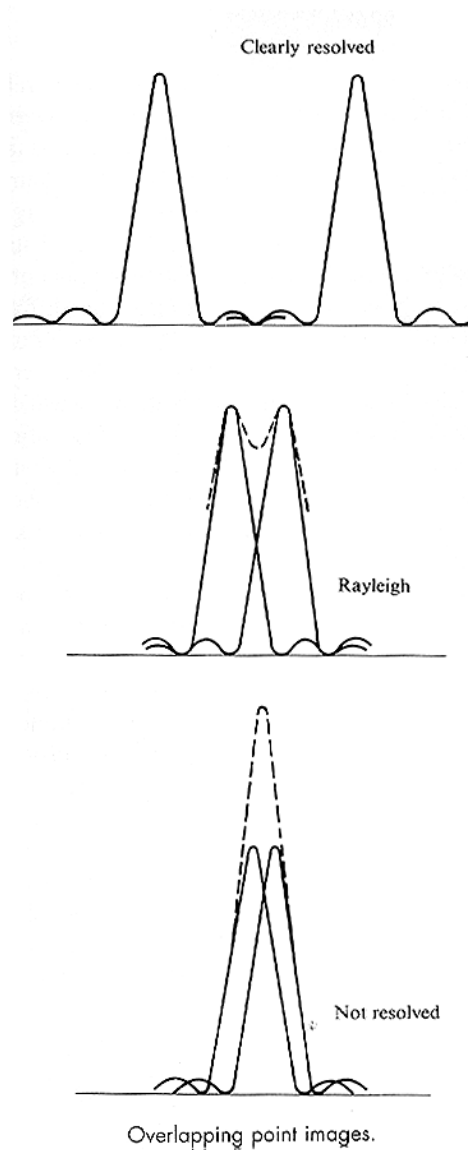
⁷Watkinson, pp. 585-86.

⁸E. Hecht, Optics (3d ed., 1998), p. 445.

⁹Watkinson, p. 585.

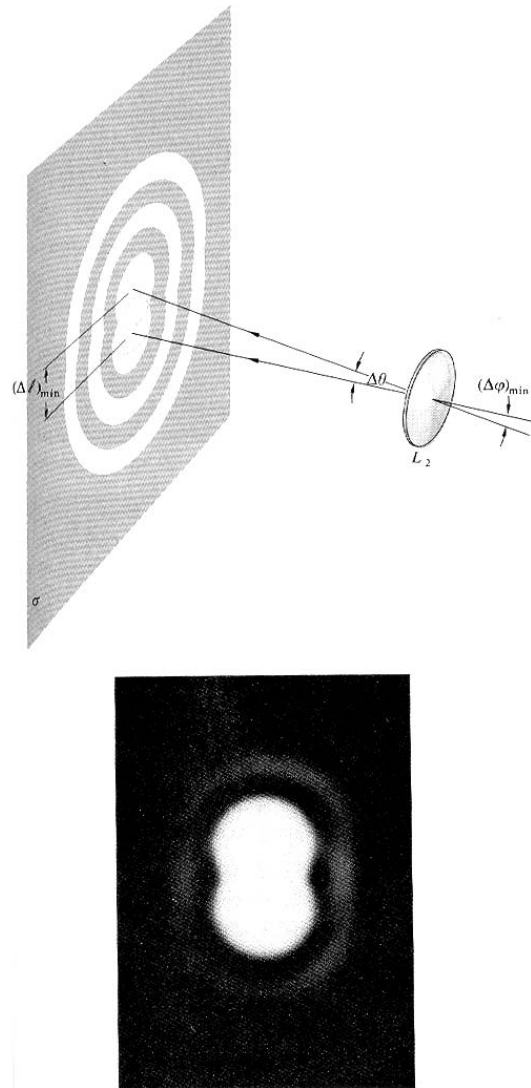
When two features—which can be seen as equivalent to two slits, each presenting its set of wavefronts—are near to each other, the two present intensity curves that may overlap. When the overlap is excessive—that is, if the features are too close, for the resolution of the system (more on this, below)—the features can no longer be distinguished.

Below, three contrasting cases are illustrated—where the features are *easily* distinguishable, *barely* distinguishable, and *not* distinguishable. The differences result, of course, from the differing degrees of overlap between the adjacent intensity functions¹⁰.



¹⁰Hecht, p. 471.

The figure below shows the barely-distinguishable case, in another way.



Two features barely distinguishable: their intensity functions largely overlap ('Rayleigh' case) ¹¹

¹¹Hecht, p. 465.

All this wisdom can be boiled down into a formula that describes the “barely-distinguishable” case as an angular displacement. This describes the “Rayleigh” case, above, where the peak of one response lies on the first minimum of an adjacent response.

The relation between lens size and wavelength that defines the limiting angular discrimination is given by

$$\Delta\theta = 1.22\lambda/D \quad (1)$$

where D is the width of the lens¹². (The strange coefficient, 1.22, corrects for the effect of a circular lens; for a slit, the equation is cleaner!)

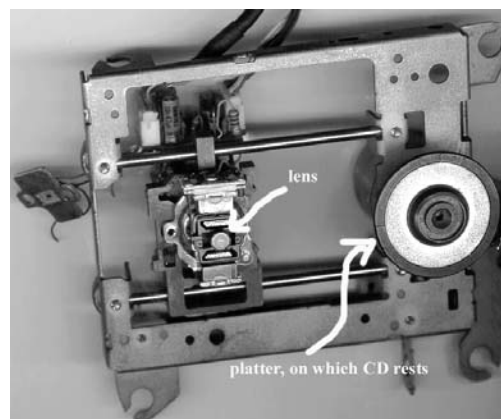
Try to Estimate the Limiting Resolution of a CD pickup

Let’s try applying this formula to see how close the CD features come to the smallest size that could be resolved by the CD optical pickup. This exercise is rough, but should put us in the ballpark (good to at least to a factor of about two; so, we may land in the bleachers...).

Here’s the argument: if we can measure the lens of the pickup (“ D ” in the formula above), and if we know the wavelength of light used in the pickup (we do: about 780nm) and if we can measure the distance from lens to disk, then we should be able to calculate the minimum distance between distinguishable features.

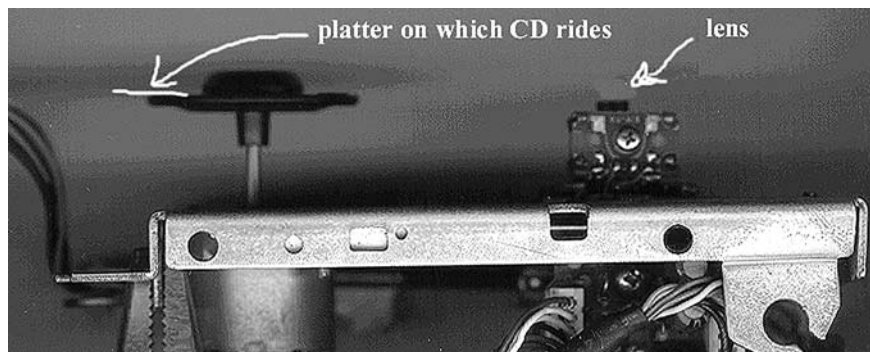
Below are two images showing a disembowled CD pickup assembly, *actual size*. These can reveal roughly the two dimensions called for in the formula (1) given above, for $\Delta\theta$: lens size and distance from lens to CD’s optical surface.

This first image, a top view, shows the lens assembly and the platter on which the CD rests. The lens rides a little carriage that is driven along a radius of the CD by a small motor; fine adjustment of lens position is achieved by a coil-and-magnet mechanism exactly like an audio speaker’s. From this *top view* image you can get an approximate measurement of the *lens*.



The second image, below, shows a *side view*, and from this vantage you can make a rough estimate of distance between lens and CD’s optical surface. Note that this optical surface is very near to the *far* side of the CD, and that the CD is about 1mm thick. (This image is actual size.)

¹²Hecht, p. 462



Once you've estimated these dimensions from the pictures provided in this handout, calculate the minimum feature size (or track spacing), and compare this result to what you found when you inferred track-to-track spacing from the diffraction pattern.

2.4 One more little marvel: transparent metal?

Can you see through metal? The reflective surface within the CD is a metal film. Try to look at an ordinary light source (**not the laser!**) through the CD. Can you see through the CD (through a CD dimly?).

A simple view of how a metal behaves would say, “No,” one cannot see through a CD, with its metal reflecting layer, because the electric field within the metal ought to be zero; but a closer look at how a metal behaves would show that the wave hitting the metal penetrates a little way—to the so-called “skin depth.” The wave falls off exponentially and is just about gone in a distance about the order of a wavelength. A *very thin* layer of metal, like the reflective coating used in a CD—aluminum that is “sputtered” on—attenuates the wave a great deal, but not so much that the metal is opaque. The reflective aluminum layer in a CD is 50nm to 100nm thick, reflecting 70 to 90 percent of the incident IR light.¹³ The wavelength of visible light is close enough to the wavelength of the CD laser so that you're probably seeing about 10% to 30% of the incident *visible* light, when you look through the disk.

This “miracle” will impress you less if you recall the “half-silvered” mirror used in many experiments.

¹³Pohlman, p. 299; see also a good summary at <http://www.ee.washington.edu/conselec/W94/edward/edward.htm>.

3 Qualitative Exercises: Viewing Spectra

You can view weak light sources *through* the slide-mounted grating. DO NOT DO THIS WITH THE LASER. THE REST OF THE LAB DOES NOT USE THE LASER. Using the grating in this mode has the advantage that your eye is very sensitive and can distinguish colors. For these qualitative exercises record your observations (the visible spectra) and your thoughts in your lab notebook!

3.1 White light spectrum

Lightbulb through diffraction grating

Look at an ordinary lightbulb through the grating. Hold the grating close to your eye (with its plane perpendicular to the line of sight) and view the resulting spectra. Notice that it has a smooth distribution of intensity throughout the range of colors that are visible. This is characteristic of incandescent sources, that is, those generated by heating a filament.

Compare with CD's diffracted spectrum

The “rainbow” that you see when you look off-axis at light directed at the CD (mentioned above, as the “rough” way to estimate diffraction angle) is not quite the usual rainbow. The CD-rainbow should show a relatively stronger blue, because blue is about half the wavelength of the near-infrared light used in the CD pickup; the tracks cause *destructive* interference for infrared—by making one of the round trip path lengths a half wavelength longer than the other. The tracks cause *constructive* interference, in contrast, for light at half the pickup's wavelength: for *blue*. The evidence for this effect is hard to make out; don't struggle long if it doesn't appear for you.

3.2 Spectra with Atomic Lines

The best place to find line spectra is on the street at night. Look at the mercury vapor type of street lights (blue-green), the sodium vapor street lights (yellow) and the “neon” signs (“Buy Our Beer”). These sources should consist of several prominent lines (characteristic of the atoms in the discharge or hot vapor) in addition to a continuous part. Try to find at least a few sources and sketch the spectra in your notebook (use the ROYGBIV notation: red, orange, yellow, green, blue, indigo, violet). Why do you view discrete lines from some sources? Back inside, find a fluorescent light. A fluorescent desk lamp is ideal. Make a cardboard mask with a thin slit cut into it. Tape the mask in front of the bulb. Explore the contention that there are several sharp lines in the spectrum. Do any of them occur as pairs?