

**Optical Resonator Calculator:
Gravitational Wave Detector Cavity Simulations
with Processing**

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Chapter 1

Introduction

1.1 Introduction

In physics education and research, simulations of physical systems play an important role. They allow researchers and educators to approximate real systems simply and quickly, conveying the important relations within the system. Such simulations are common in physics, but often they are numerical tools rather than graphical. While numerical simulations are powerful, they are usually not very user-friendly. They sometimes require the user to understand how the program works and how to interpret the results before the user can successfully use the program. This, then, can prevent students or non-scientists from learning from these programs, as well as often being cumbersome for experienced scientists who are seeking just a simple answer.

Also, for newcomers to programming, it is often difficult or frustrating to create new simulations from scratch. Most people create programs by using bits and pieces of code made by others or by using libraries of code that take care of most of the difficult programming details. However, such code libraries or sample pieces of code are not always available for a particular problem or field.

These problems exist in the field of gravitational wave detection and advanced interferometry. Numerical tools are used to simulate the behavior of optical systems, but few graphical tools exist. Also, little to no code libraries relevant to these fields exist in simple programming languages. Therefore,

the goal of the group of students brought together at the University of Birmingham's Astrophysics and Space Research Group was to experiment with the programming IDE Processing in an attempt to develop some tools for simulating the optics used in gravitational wave detection. It is our hope that the graphical simulations and code libraries we have developed can be used in gravitational wave detection and interferometry research and education. For example, simple visual simulations of optics equations should allow students to gain a more intuitive understanding of the physical meaning of an equation by outputting graphs which change when the student changes system parameters.

1.2 Tasks

To achieve this goal, we initially focused our efforts on developing some code libraries relevant to gravitational wave optics. Since we are developing the code for visual simulations and for use by beginners in programming, the Java-based IDE Processing was chosen as our IDE. Processing is an open-source IDE developed for artists and designers with little experience in programming. It is designed to simplify the programming of visual output. It also provides simple exporting tools for creating PDF files and Java Applets, useful for posting the simulations on the Internet ([1]).

Processing provides many libraries which are constantly in development, but there are few provided libraries relevant to physics. Therefore, we first sought to create a library that we could use later for our simulations. In particular, I developed a set of code to be used in making two-dimensional plots. Other students developed GUI (graphical user interface) components and a three-dimensional plotting program.

This library was then used to develop an optical resonator calculator. This calculator is meant to simulate an optical cavity such as those used in gravitational wave detector interferometers. It provides a simple GUI through which a user can change parameters of the cavity's mirrors and observe directly how those changes affect the points at which the cavity is resonant. More importantly, the code can fairly easily be altered and expanded to include much more functionality, making it possible for future revisions.

Other students developed different simulations, which will be described later.
All projects are posted on the Internet at

www.gwoptics.org/processing/cavity_calculator/

Before describing our work in further detail, some background information about the physics of the optics and gravitational wave detection is needed.

Chapter 2

The Physics of an Optical Cavity

Gravitational wave detectors are, in principle, quite simple. They consist of two perpendicular 'arms,' each of which contains an optical cavity (see Figure 2.1). Generally, these are Fabry-Perot cavities. At the intersection of the two arms is a beam splitter. A laser pumps light (a Gaussian beam) to the beam splitter, at which point half the light goes into each identical arm, bounces off the mirrors (test masses) in the cavities, and returns to the beam splitter. Once the light reaches the beam splitter again, the two beams interfere and the signal is detected by a photodetector. When a gravitational wave is incident on the interferometer, it should appear as an oscillation of the distance between the 'freely-falling' test masses (mirrors) at the frequency of the gravitational wave. (Free-fall is approximated by suspending the mirrors by thin wires within a vibration-isolation system.) The mirrors move due to the distortion in space, and the interference pattern of the light at the beam splitter changes accordingly.

2.1 Optical cavities

The important components for our purposes are the optical cavities (also known as optical resonators) within the interferometer arms. We will focus on these for the remainder of the text. Please note that we are assuming

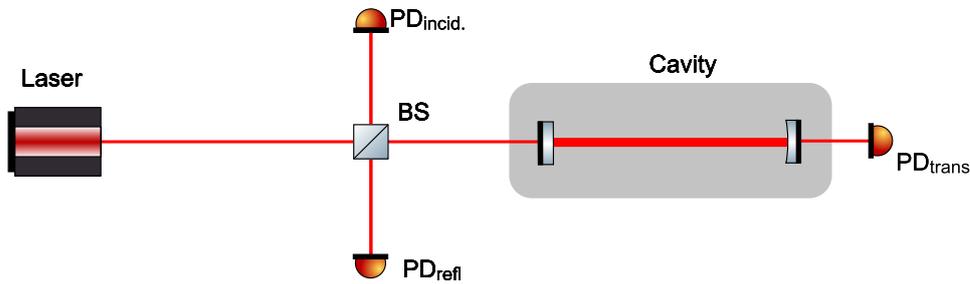


Figure 2.1: Diagram of a basic interferometer.

a loss-less cavity for our simulations. A Fabry-Perot cavity, as shown in Figure 2.2, consists of two highly-reflecting mirrors. The reflectivity (R) of a mirror is the percentage of the light's incident power that is reflected by that mirror. (r also represents the reflectivity of the mirror but is the percentage of the incident *amplitude* that is reflected. They are related by $R = r^2$.) The light that is not reflected from the mirror passes through it, a process called transmission governed by $R + T = 1$, where $T = t^2$ is the transmission coefficient. Optical resonators are made to amplify the light within the cavity, so the mirrors used are highly reflective. Essentially, light enters the cavity through one mirror, reflects off the opposite mirror, and returns to the first mirror, while some of it is transmitted (exits the cavity) through each mirror. This light transmitted through the first mirror in each arm is the light that interferes at the beam splitter to form the signal.

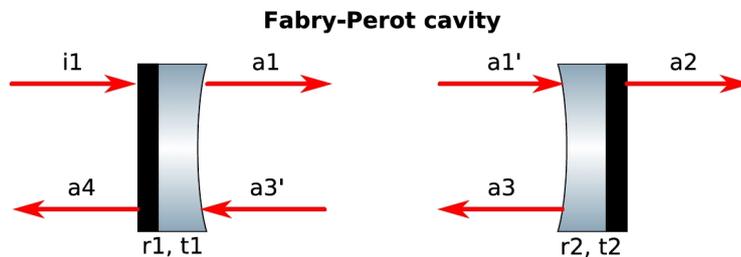


Figure 2.2: A Fabry-Perot cavity. [2]

2.1.1 Types of optical resonators

When designing an optical resonator, one has to ensure its stability. That is, certain frequencies of light will form a standing wave within the cavity. The cavity is considered *stable* if the focal points of the mirrors and the distance between the mirrors are such that the internal beam does not continually grow in size after many reflections. In other words, the cavity is designed so that the beam will remain entirely within the cavity's mirrors.

There are five different types of stable two-mirror optical cavities, as shown in Figure 2.3. These types of resonators differ in their focal lengths of the mirrors (governed by the mirror's radius of curvature) and in their distance between the mirrors (cavity length). As you can see from Figure 2.3, some beams have different shapes within the cavity and are thus chosen for different purposes.

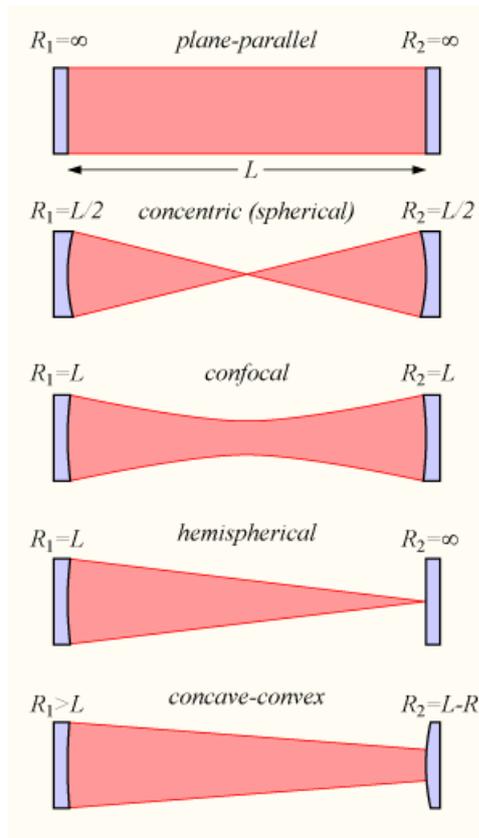


Figure 2.3: The five possible types of stable cavities. [2]

There are simple mathematical formulae that indicate whether or not a cavity is stable. In its simplest form, the rule can be stated as follows:

Given a cavity made of two spherical mirrors (of radii of curvature R_1 and R_2) separated by a distance L , the cavity is stable if

$$0 \leq g_1 g_2 \leq 1 \tag{2.1}$$

where

$$g_1 = 1 - \frac{L}{R_1} \text{ and } g_2 = 1 - \frac{L}{R_2} \tag{2.2}$$

Graphically, Figure 2.4 shows a plot of the stability region of cavities. If g_1 and g_2 are such that their intersection lies within the shaded region of this diagram, then the cavity is stable.

Our theoretical cavity to be discussed later will consist of one flat mirror (infinite radius of curvature) and one mirror with adjustable radius of curvature (from L , the cavity length, to infinity). This is essentially a hemispherical type cavity.

2.1.2 The internal power of the cavity

The light (standing wave) inside the cavity circulates between the two mirrors, a process known as power circulation. The power circulation causes power amplification of the beam. The power inside the cavity is given by

$$P_1 = \frac{T_1}{1 + R_1 R_2 - 2r_1 r_2 \cos(2kL + \psi_{rt}(n + m + 1))} \tag{2.3}$$

where T_1 is the power transmission of the first mirror (given by $T_1 = t_1^2$), R_1 and R_2 are the (power) reflectivities of the first and second mirror ($R = r^2$), L is the length of the cavity, ψ_{rt} is the round-trip Guoy phase (explained later), and n and m represent the transverse modes of the Gaussian light

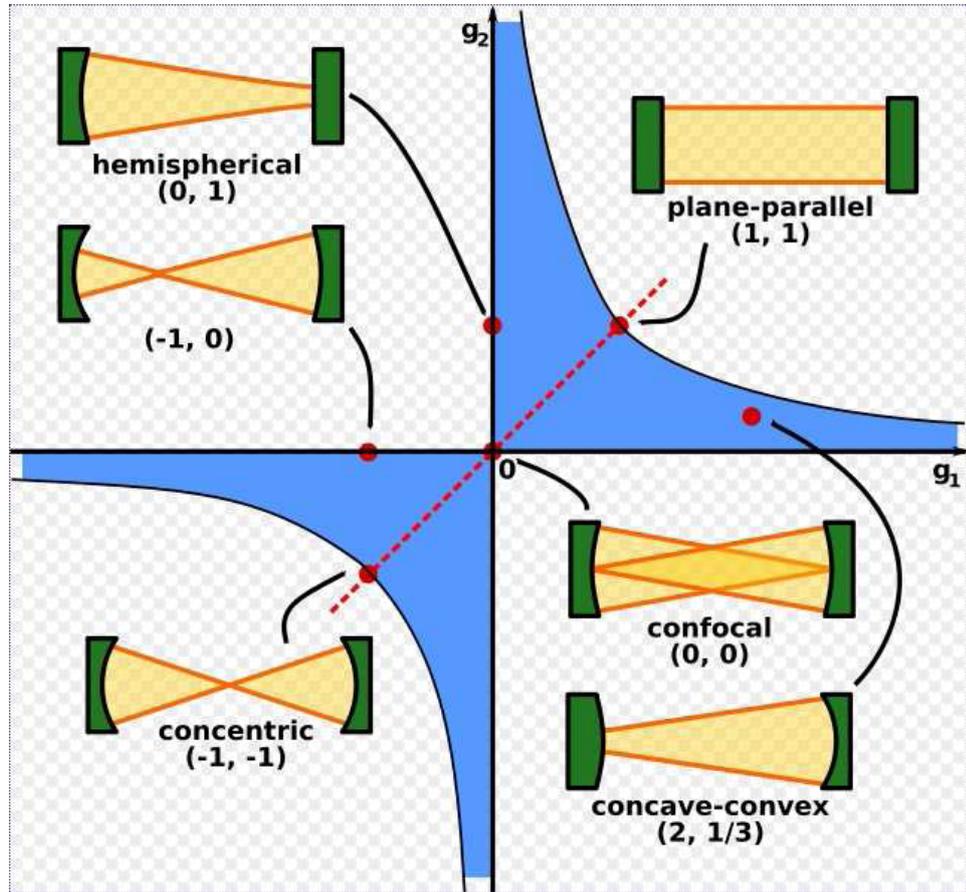


Figure 2.4: The stability diagram. [2]

beam (mode TEM_{nm}). This equation is plotted in Figure 2.5. The argument of the cosine term is the total phase shift of the light in the cavity. The maximum internal power is achieved when the cosine function is equal to one. This condition is called the cavity *resonance*, while the minimum power is achieved at the cavity's *anti-resonance*. When one designs a cavity, resonance is desired ([3]).

Many factors can affect the resonance properties of the cavity, as can easily be seen from Equation 2.3. Most notably, the periodicity of the function is governed by the cosine term. $2kL$ can be rewritten as

$$2kL = 2\pi f \frac{2L}{c} = \frac{2\pi f}{FSR} \quad (2.4)$$

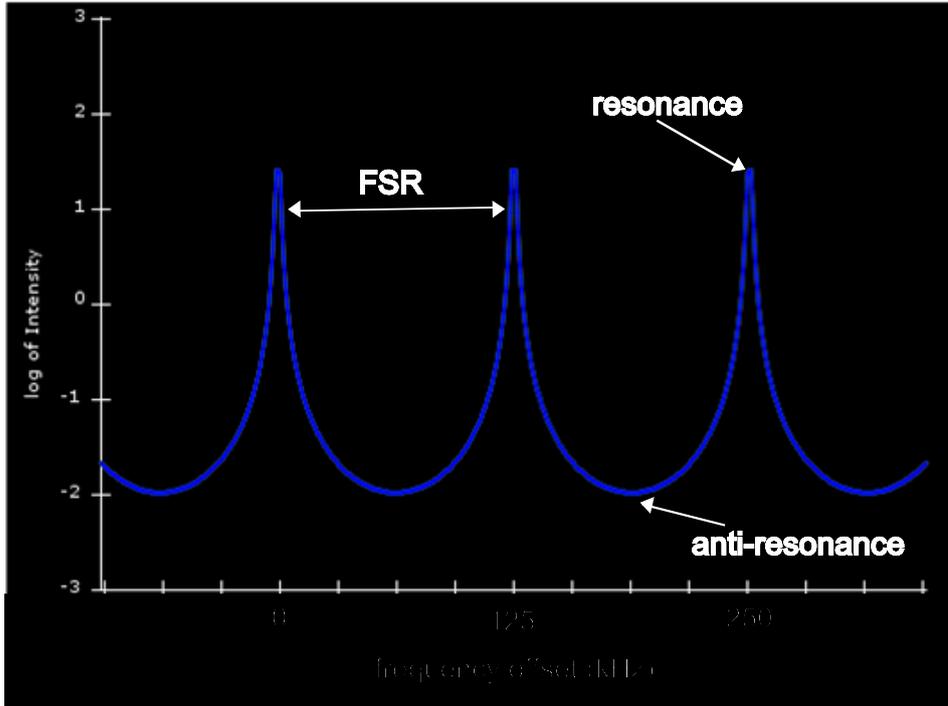


Figure 2.5: A graph of the internal power of a cavity.

where f is the light's frequency, c is the speed of light, and FSR is the *free-spectral range* of the cavity—the frequency separation between resonant frequencies (see Figure 2.5).

2.2 Guoy phase shifts

As mentioned previously, the beams used in these cavities are Gaussian beams. Figure 2.6 shows the beam profile along the z axis of a Gaussian beam. In contrast to plane waves, when a Gaussian beam propagates, it acquires a phase shift. This effect is most pronounced for Hermite-Gauss modes close to the beam waist where the phase velocity is slightly slower than compared to plane waves ([3]). The Guoy phase (ψ) can be calculated along the z axis by

$$\psi(z) = \arctan\left(\frac{z - z_0}{z_R}\right) \quad (2.5)$$

where z_R is known as the Rayleigh range of the beam, given by

$$z_R = \frac{\pi w_0^2}{\lambda} = \sqrt[2]{(R_c(z) * (z - z_0)) - (z - z_0)} \quad (2.6)$$

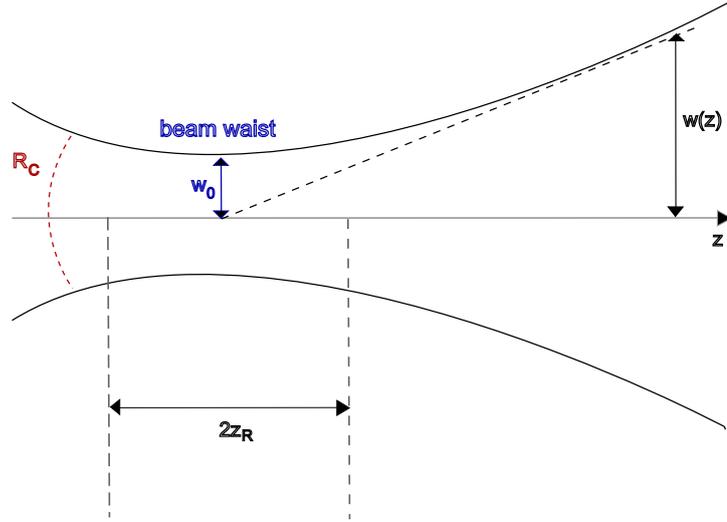


Figure 2.6: The beam profile along z of a Gaussian beam.

The Guoy phase calculated with Equation 2.5 is the phase shift of the beam in one direction. For our purposes, we are interested in the *round-trip* Guoy phase—the phase it acquires by the time it reflects off the second mirror and returns to the first. The round trip Guoy phase needed in Equation 2.3 is simply two times the Guoy phase given by Equation 2.5:

$$\psi_{rt} = 2 * \psi(z) = 2 * \arctan\left(\frac{z - z_0}{z_R}\right) \quad (2.7)$$

Since, in Equation 2.3, the Guoy phase is multiplied by the term $n + m + 1$, it can be seen that the overall phase shift is larger for higher-order modes (higher values for n and m). Therefore, beams with different mode orders will have different phase shifts, and the plots of their power enhancement functions will be offset from one another. They will also, then, have different resonance frequencies for a given cavity. Figure 2.7 shows a plot of Equation 2.3 for modes 00 (red), 10 (green), and 20 (blue). Note that two modes can be resonant at the same frequency if their phase shifts are the same.

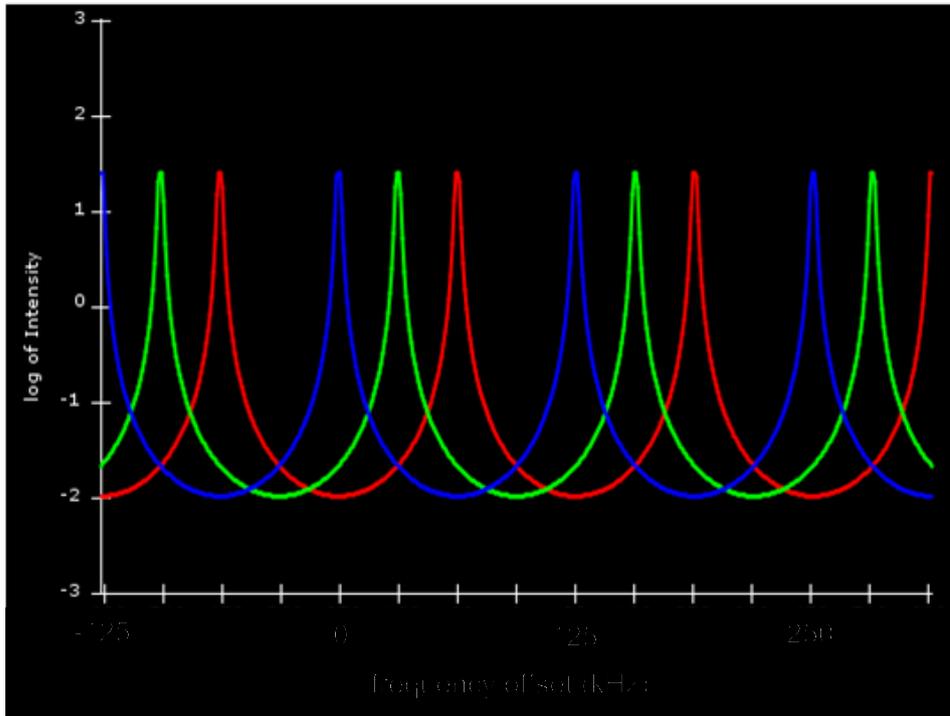


Figure 2.7: Internal power of a cavity plotted for three modes.

2.3 Cavity lengths and tuning

The distance between optical components in a cavity is conventionally described as a sum of macroscopic and microscopic distances. Some properties of the cavity, such as the free spectral range, depend on the macroscopic distance between the optics. For those properties, changing the separation between the mirrors on the order of one laser wavelength will not affect their values. However, the resonance condition of the cavity depends on the microscopic displacements of the mirrors, and thus both parameters must be considered. The distance, D , between the mirrors is written as

$$D = L + T \tag{2.8}$$

where L is the macroscopic length and T is the *tuning*, or the microscopic displacement from the exact given macroscopic length. T here is clearly a distance measurement, but it can be rewritten as a phase shift of the

Gaussian beam. We will call this phase shift, governed by the microscopic tuning, Δx ([3]).

Now, Figure 2.5 plots the internal power of the cavity against frequency. It shows, for example, that the cavity is resonant at the frequencies that correspond to the peaks in the graph. Note that Figure 2.7 plots the internal power against Δx , a value expressed in degrees. These are the same graphs but plotted as functions of different (equivalent) variables. The difference lies in rewriting the argument of the cosine term from Equation 2.3 with Δx instead of $2kL$. Δx is expressed as an angle measurement, where 2π radians (or 360°) corresponds to a displacement of the mirror by one wavelength. We have chosen to plot over Δx instead of f because we are assuming a system with a fixed laser frequency and a tunable mirror displacement.

2.4 Behavior of a cavity

For the moment, we are interested in the resonant properties of a cavity as it affects the internal power of the cavity and the transmitted power (through the second mirror). This behavior for a two-mirror cavity depends on the length of the cavity and on the reflectivities of the mirrors. There are, then, three different cases that can govern this behavior. If $T_1 < T_2$, the cavity is *undercoupled*. If $T_1 = T_2$, the cavity is *impedance matched*. If $T_1 > T_2$, the cavity is *overcoupled*. (Note that these can be rewritten as: If $R_1 > R_2$, the cavity is *undercoupled*; if $R_1 < R_2$, the cavity is *overcoupled*.) An undercoupled cavity will transmit little power through mirror 2 and will not have much circulating power. An overcoupled cavity will have the greatest circulating power and other internal resonance conditions. However, an impedance-matched cavity maximizes the power *transmission*, and it is the only condition under which the cavity can transmit (on resonance) one hundred percent of the input power ([3]).

Chapter 3

The Optical Resonator Calculator

3.1 Optical Resonator Calculator - The Idea

It was our goal to express some of the equations and properties of optical cavities (as described in Chapter 2) visually. A graphical representation can often teach much more about an equation's properties than doing the calculations by hand. It can give a student (or researcher) a more intuitive understanding of what the equation actually means in a physical sense. Therefore, with the background knowledge about the physics of optical systems, we hope to create a useful visual tool (and reusable code) to simulate the properties discussed above as they pertain to gravitational wave detector interferometers.

For our first version of the calculator, we chose to model the internal power of a two-mirror optical cavity as a function of the tuning. The cavity being modeled consists of one flat mirror and one spherical mirror. It is important to model the internal power because it shows, graphically, the tuning values for which the cavity is resonant or anti-resonant. We wanted to plot the internal power for three different transverse modes: TEM_{00} , TEM_{10} , and TEM_{20} . Also, we thought it would be interesting to visually depict the output power of the cavity at a user-defined value for tuning. We gave the user the ability to control, via simple sliders and text fields, the reflectivities

of each mirror, the radius of curvature of the second mirror, and the value of Δx (the tuning). With this setup, this version of the calculator should help users to visualize the internal power function, the Guoy phase, the power output, the FSR, and the overall phase shift of a beam. Also, it should depict how changing the reflectivities or radii of curvature of a cavity's mirrors affects the beam inside the cavity.

3.2 Project Overview

The Processing IDE which we chose to use for our program already had code libraries for simple GUI components. For example, it provides code for check boxes, text fields, buttons, and some other components. However, it had very little or no libraries pertaining to sliders, meters, or graphs. Our first task, then, was to write extendable libraries for the components we needed. Each student in our group had a different main project, but each of us wrote some library functions that could be used by all of us (and by others). I will focus only on the small pieces that are directly used in the Optical Resonator Calculator. One student in our group, Daniel Brown, wrote the library for, among many other things, the sliders. Charlotte Bond wrote the code for the LEDMeter, the meter which is used in this case to show the cavity's transmitted power.

I, then, wrote a two-dimensional plotting library. This plotting library allows a user to plot many traces and many separate graphs. It can plot any two-dimensional function. Other (and probably better) plotting libraries exist in Java or Processing, but it was an integral part of my education in programming to write a plotting library from scratch. Rather than simply using a pre-made library, I designed my own as an exercise in becoming more familiar with the language and object-oriented programming.

All three of these libraries were designed to be very general so they could be incorporated into various programs. I will not go into further detail here about how these libraries work because it is all explained in the actual code. The code for the optical resonator calculator, which uses these libraries, is included in Appendix A. This should give a more complete picture of how the various libraries and components are linked to create the Optical Resonator Calculator.

3.3 The User's Manual

The Optical Resonator Calculator program has been uploaded to the project's webpage as a Java applet with some explanatory text. This Java applet models some features of an optical resonator (also known as an optical cavity) using a graphical user interface (GUI). The GUI allows a user to change some of the cavity's parameters. Figure 3.1 is a screenshot of the actual calculator. Please refer to this image throughout the following discussion.

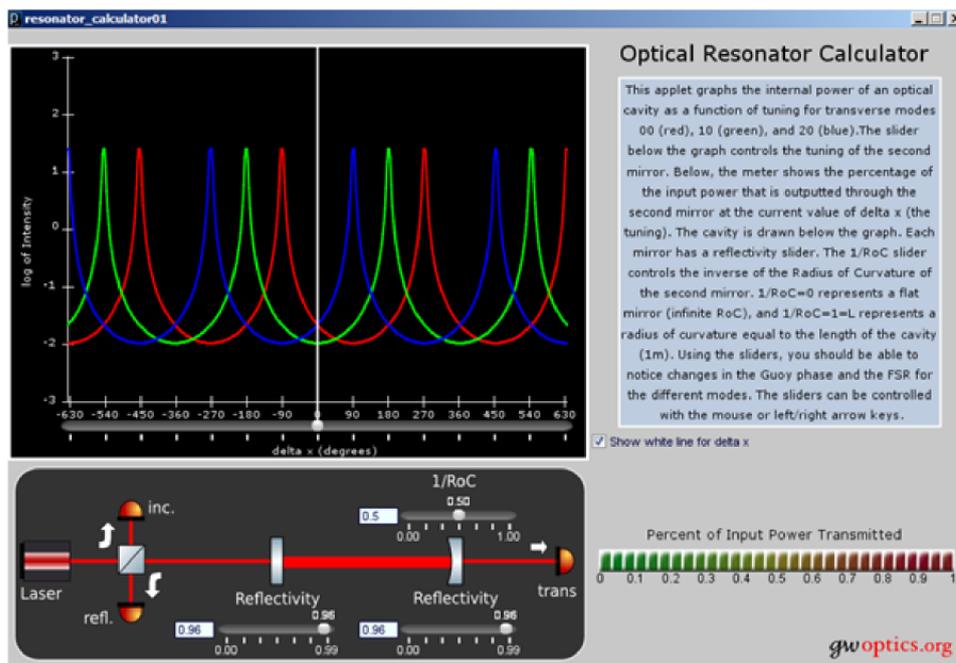


Figure 3.1: A screenshot of the optical resonator calculator.

3.3.1 Introducing the GUI components

The image on the bottom left of the calculator in Figure 3.1 is a diagram of the cavity. This very simple cavity has essentially the same basic setup and functionality as the cavities in each arm of a gravitational wave interferometer. It consists of a laser, two mirrors (in this case, one flat and one with a variable radius of curvature) with variable reflectivities, a beamsplitter with two photodetectors, and a photodetector for the light transmitted through the second mirror. Note that there are three sliders and accompa-

nying text fields overlaying the cavity image. The bottom left slider controls the reflectivity of the first mirror, while the bottom right slider controls the reflectivity of the second (rightmost) mirror. These reflectivities can range from 0.00 to 0.99, as one cannot have a mirror with a perfect reflectivity of 1.00. These will be referred to, respectively, as the “ R_1 slider” and the “ R_2 slider.” (Likewise, the left mirror is mirror 1, and the right mirror is mirror 2.) The remaining slider above these controls the inverse of the radius of curvature of the second mirror, and will commonly be referred to as the “RoC slider.”

The graph above the cavity schematic is the graph of the *logarithm* of the cavity’s internal power as a function of the microscopic tuning of the second mirror. The logarithm of the internal power is plotted for three different transverse modes: TEM_{00} in red, TEM_{10} in green, and TEM_{20} in blue. (The use of the logarithmic scaling will be explained later.) The tuning is measured in degrees, where 360° is a microscopic displacement of the second mirror by one wavelength. Below the graph, there is a slider (called the “ Δx slider”), which can be placed anywhere along the x axis. By default, this slider has a white line attached to it that indicates precisely where the slider is lining up with the plots above.

Finally, the meter on the bottom right of the calculator below the text box indicates the percentage of the input power that is outputted through the second mirror (reaching the rightmost photodetector). We will call this meter the “transmitted power meter,” or simply “the meter.” This meter is linked to the Δx slider, so it shows the total power output for the tuning value given by the Δx slider.

3.3.2 The mathematical details

This calculator is essentially only using two equations. It is graphing the base-10 logarithm of the internal power function given in Chapter 2 by Equation 2.3. The actual function being plotted, then, is

$$\log(P_1) = \log\left(\frac{T_1}{1 + R_1 R_2 - 2r_1 r_2 \cos(2kL + \psi_{rt}(n + m + 1))}\right), \quad (3.1)$$

where, ψ_{rt} is the Guoy phase given by Equation 2.7. Then, the calculator computes the transmitted (output) power of the cavity by adding, at the chosen value of Δx , the internal power functions for each mode and multiplying the sum by the transmission coefficient of the second mirror. Since $R_2 + T_2 = 1$, this coefficient is simply given by

$$T_2 = 1 - R_2 \tag{3.2}$$

where R_2 is controlled by the R_2 slider. Therefore, for a given beam with 1 W of input power and mode TEM_{nm} , the transmitted power, P_{trans} , is calculated as

$$P_{trans} = 10^{\log(P_1)} \cdot T_2 \tag{3.3}$$

In the cavity used in this calculator, there are three beams (three different transverse modes). Each beam, for the sake of overall simplicity, has an input power of $\frac{1}{3} W$, so that the total input power for the cavity is 1 W. Therefore, the maximum amount of power that can be transmitted through the second mirror is 1 W, as shown on the transmitted power meter. (As explained in Chapter 2, this can only occur in an impedance-matched cavity.) It is convenient for the transmitted power meter to range in value from 0 to 1 because it can then be thought of as representing the percentage of the input power that is being transmitted (e.g. a value of 0.89 is 89% of the input power).

To improve the appearance of the plot of the cavity's internal power, it is typically graphed on a logarithmic scale. This is done because the peaks in the plot on a normal scale become extremely sharp, especially for highly reflective mirrors. Plotting on a logarithmic scale smooths out the graph a little bit. When you look at the calculator's graph, you may wonder why we are plotting the logarithm of the power, rather than plotting the power on a logarithmic scale. We chose to do this because having axes with evenly-spaced tick marks is much more compatible with the two-dimensional plotting function that I wrote than having axes on a logarithmic scale. When viewing the graph, the user still has the ability to see what value the power has, and it does not make the calculations much more difficult.

3.3.3 How to use the GUI controls

The controls have been designed to be as simple as possible to use. Each slider can be controlled by the mouse by either clicking or dragging the slider to its desired position. Also, if you set the program's focus to a particular slider by clicking on it, that slider can then be moved by one pixel at a time using the left and right arrow keys. This helps mostly for the Δx slider when trying to choose a precise tuning value.

When the slider value is changed in this way, the associated text field changes to the chosen slider value. Additionally, the slider value can be changed by directly typing the desired value into the text field and then hitting the 'Enter' key. Note that if 'Enter' is not pressed, the slider will not update to that value. The R_1 , R_2 , and Δx sliders all have a maximum precision of two decimal places. If you type in a value of, say, 0.487, the slider should round this number to 0.49. However, it is best if at most two decimal places are used so unexpected rounding does not occur.

Finally, please note that the RoC slider actually controls the inverse of the radius of curvature of the second mirror. That is, the value represented by the RoC slider is actually $\frac{1}{RoC}$. This is done so the radius of curvature can range from L (the cavity length, 1 m) to infinity (a flat mirror). Infinity cannot be represented by a slider, but $1/infinity$ is essentially zero. Therefore, the RoC slider ranges from 0.0 (for an infinite radius of curvature) to 1.0 (for a radius of curvature equal to the cavity length of 1 m).

The Δx slider does not have a text field, and it does not display its current value. The value is represented by the corresponding tick marks on the x axis of the graph. By default, this slider has a white line linked to it which helps to see where on the graph the slider is positioned. This line can be switched off, though, by unselecting the check box to the right of the graph labelled "Show white line for delta x."

3.3.4 Configurations to try

In most optical resonators, highly reflective mirrors are used to enhance the power within the resonator. This is true for gravitational wave interferometers. If you set the R_1 and R_2 sliders to 0.99 reflectivity, you will see that

the peaks in the internal power plot become very sharp. Equation 3.3 shows that the transmitted power is proportional to T_2 . When R_2 is very close to 1.00, T_2 becomes very small. Therefore, the internal power is only large for resonance conditions. This makes the precise tuning of the cavity extremely important if one is to achieve resonance.

The calculator will also allow you to visualize the differences among undercoupled, overcoupled, and impedance-matched cavities. These configurations were described in detail in Chapter 2. The calculator's default is an impedance-matched cavity with high reflectivities ($R_1 = R_2 = 0.96$). This is the only condition under which, on resonance, the cavity can transmit all of the input power (in this case, 1 W). Altering the radius of curvature of the second mirror (using the RoC slider) changes the Rayleigh range (z_R) of the beam and therefore the round-trip Guoy phase (see Equation 2.7). In particular, the larger the radius of curvature (as $1/RoC$ approaches 0), the smaller the Guoy phase shift. This is why as you decrease $1/RoC$, the peaks of the internal power for the different modes become very close and eventually overlap. At an infinite radius of curvature, the Guoy phase shift is 0, and multiplying the phase shift by $(n + m + 1)$ (as in Equation 2.3) will not change the overall phase shift for different modes.

An undercoupled cavity is one in which T_1 is less than T_2 , so R_1 is *greater than* R_2 . This type of cavity has little circulating power. If you set the R_1 slider to be greater than the R_2 slider, you can notice that the internal power becomes small, and even on resonance there is very little transmitted power (compared to an impedance-matched cavity).

An overcoupled cavity is one in which R_1 is *less* than R_2 . It has a high circulating power compared to an impedance-matched cavity which has reflectivities equal to the lower reflectivity in the overcoupled cavity. However, with R_2 high, T_2 is low and there is little transmitted power.

These are some of the simple cavity properties that this calculator illustrates. At the very least, it should give users a more intuitive sense about how the cavity parameters affect its resonance properties. It is probably most useful if one views the circulating (internal) power function (Equation 2.3) while running the program to see how the plots are being affected.

3.3.5 Intentional limitations

In the first and current version of this calculator, the user only has limited control over the cavity's parameters. Only four parameters can actually be set by the user: the reflectivity of the first mirror, the reflectivity of the second mirror, the radius of curvature of the second mirror, and the tuning of the cavity. Giving the user many more values to change would make it more difficult for the user to really learn a few basic concepts about cavities and could be confusing. We wanted to make this version simple so that it would illustrate only a few key points. Therefore, the user cannot change parameters such as the configuration of the cavity, the cavity length, the curvature of the first mirror, the beam modes, etc. We felt that this would be too much information to include in an educational or reference tool, though it probably would not be very difficult to include in future versions.

Also, this applet is not quite a calculator in the usual sense of the word. In a usual calculator, one would enter some values and get precise numerical answers in return. While this is certainly useful, outputting exact numbers is not necessarily useful when simply portraying relations between parameters. It may also become overwhelming or confusing for a student using the tool if many numbers are outputted to the screen. Again, though, numerical output could be easily included in future versions of the calculator if so desired.

Chapter 4

Bugs and Future Directions

4.1 Remaining Problems and Bugs

There are only a few remaining problems with the current version of the Optical Resonator Calculator. These are described in detail below. For the more code-involved problems, it would probably help to know how the actual code works (in the libraries and the source code included in Appendix A). However, the explanations of the problems below should not require much prior knowledge of the code.

The most notable bug can be seen when the reflectivities of the mirrors are very high ($\gtrsim 0.97$). In this case, it is difficult to align the Δx slider with the peaks precisely, and the transmitted power meter does not quite display the correct value. For instance, if $R_1 = R_2 = 0.99$ and $1/RoC = 0.5$, if the cavity is on resonance, the meter should read, for each beam mode, a transmitted power of $\frac{1}{3}$ W. The value it actually shows is closer to 0.1 W. This bug is probably due to an inherent resolution issue with the graphical output. To increase the resolution around sharp peaks, the two-dimensional plotting function implements a loop which is *not* also implemented exactly by the transmitted power meter calculations. In this loop, for each pixel along the x axis, the plotting function converts the pixel number into graph units, takes six points in graph units between each pixel, calculates the y value for each of these points (in graph units), and finally chooses to plot the maximum of these as the y value corresponding to the original x pixel.

For various detailed reasons having to do with object-passing and private variables, this same loop is not easy to use for calculating the transmitted power. Currently, the calculation for the transmitted power does not directly 'read' the y values off of the graph. Instead, it computes the y value given the value of the Δx slider without the loop just described. Therefore, I believe the values being plotted are not quite the same values computed at the precise value of the Δx slider. This may cause the slight discrepancy for sharp peaks. This may not be the actual reason, though. This bug was not resolved after several attempts and adjustments and therefore has been left for future revisions.

The remaining problems are not necessarily bugs but rather improvements that should probably be made to the code. Currently, the program (or 'sketch' as it is called in Processing) invokes a lot of processing time from the computer running it. In Processing sketches, there are two main functions: setup and draw. The setup function is meant to contain all the object and variable declarations, initializations, and other fixed parameters. It only runs once when the sketch runs. The draw function, however, is meant to react to changes made while the sketch is running (such as moving a slider). Therefore, it runs many times to update the graphics. In this sketch, this and the functions doing the calculations seem to be consuming a lot of processing power. Slight code variations should be implemented to reduce this problem. For example, telling the draw function to run only if some 'event' has actually occurred. Other modifications could be made to make the sketch more efficient.

Finally, due to my relative lack of experience in programming, there are some limitations in the two-dimensional plotting class. It is quite sensitive to the precise numbers being use for, say, the axis length and the tick mark spacing. This issue is described in the comments of this code, but it should be highlighted here as well. In order for the scaling between the pixels and the graph units to be accurate when calculating the actual plot, one must be very sure that the axis length is an exact multiple of the spacing between the tick marks. If this is not quite possible, the plots may be slightly inaccurate. Now, the spacing between the *slider's* tick marks is, on the other hand, calculated by dividing the axis length by the number of tick marks the user wants on the slider. This can lead to small rounding issues because pixels must be represented as integers. If the quotient done in this

calculation is not exactly an integer, the quotient is rounded or truncated. In the Optical Resonator Calculator, the x axis of the graph is supposed to be precisely linked with the Δx slider. Because of this difference in the coding of these two components, one has to be very careful (and very precise) about the values chosen for each. There does not seem to be a problem in this program, but if modifications are made, this conflict must be taken into account.

4.2 Possible Future Directions

One of the main purposes of this project was to establish a foundation for possible future simulations for gravitational wave detector optics. A large amount of the time was spent writing library codes in the hope that they would be used in other projects. The simulations created, like the Optical Resonator Calculator, were intended to be used on the Internet but also to show other people what can be done with the library code.

This calculator is simply the first version created of what could be a series of different simulation programs/applets. With this in mind, some suggestions have been compiled for possible newer versions of the calculator:

- Output some numerical values given the slider or text field input
- Allow adjustments to more parameters (cavity length, beam modes, input power, mirror 1 radius of curvature, cavity configuration, etc.)
- Output an image of the beam shape
- Calculate waist size of the beam at a chosen point

These are by no means all the possible things that could be implemented or useful, but some would probably be a good starting point. We hope that the simulations will remain self-consistent and simple, portraying only a few concepts in each simulation.

With the foundational projects the students working with Dr. Andreas Freise at the University of Birmingham have done this summer, more simulations and educational and research tools should begin to be created for gravitational wave detector optics. For additional information concerning the projects done this summer, please refer to

www.gwoptics.org/processing/

Also, more details about the source code can be found in Appendix A, complete with all comments.

Appendix A

Appendix A

This is the exact Processing source code (as of 7 August 2009) being used for the main file of the optical resonator calculator. It uses quite a few libraries (as listed at the top of the code), and it also uses the classes `Axis`, `AxisConfig`, `GraphCallback`, `LEDMeter`, `LEDMeterAxis`, `PlotAreaBackground`, `PlotConfig`, `Plotting`, and `TraceConfig`. This source code may be slightly modified for the final version to be posted online, but the changes will only be minor alterations. The final version's source code and libraries will be posted online also. For more detail about these classes, one must refer to the code files for them, which are not included in this report for the sake of brevity.

```
import org.gwoptics.gui.slider.*;
import org.gwoptics.ValueType;
import javax.swing.*;
import org.gwoptics.Logo;
import org.gwoptics.LogoSize;
import javax.swing.JCheckBox;

//declare variables, objects, and fonts
gwSlider R1slider;
GTextField R1textfield;

gwSlider R2slider;
GTextField R2textfield;
```

```

gwSlider RoCslider;
GTextField RoCtextfield;

gwSlider delta_x_slider;

LEDMeter meter;
LEDMeterAxis meterAxis;

AxisConfig axisconfig;
PlotConfig plotconfig;
TraceConfig traceConfig1, traceConfig2, traceConfig3;
PlotAreaBackground area1;
Axis xaxis,yaxis;
Plotting alltraces;
InternalPower00 mode00;
InternalPower10 mode10;
InternalPower20 mode20;
PFont font;
float R1,R2,delta_x,L,RoC;
PImage cavityimage;
Logo _logo;
PFont titleFont;
PFont expFont;
PFont meterTitleFont;
String explanationtext;
GCheckbox chkWhiteLine;

void setup()
{
  size(900,600);
  smooth();
  L = 1;          //length of the cavity is fixed to 1 meter

  //initialize the axis, plot, and trace config objects
  axisconfig = new AxisConfig();

```

```

plotconfig = new PlotConfig();
traceConfig1 = new TraceConfig();
traceConfig2 = new TraceConfig();
traceConfig3 = new TraceConfig();

//set the config settings
plotconfig.bordercolor = color(255);
plotconfig.fillcolor = color(0);
plotconfig.borderweight = 3;
axisconfig.axiscolor = color(255);
axisconfig.textcolor = color(255);
axisconfig.tickcolor = color(255);
traceConfig1.tracecolor = color(255,0,0); //each trace has its own
traceConfig1.traceweight = 2; //color so its own config object
traceConfig2.tracecolor = color(0,255,0);
traceConfig2.traceweight = 2;
traceConfig3.tracecolor = color(0,0,255);
traceConfig3.traceweight = 2;

//Initialize the Axes and PlotAreaBackground
//x pos, y pos, width, height, config object
area1 = new PlotAreaBackground(5,15,540,389,plotconfig.getConfig());
//x1,y1,x2,y2,axis label, config, axis zero
xaxis = new Axis(60,350,526,350,"delta x (degrees)",
    axisconfig.getConfig(),293);
yaxis = new Axis(60,25,60,350,"log of Intensity",
    axisconfig.getConfig(),188);

//Tick label formatting
xaxis.setTickLblFormat("%.0f"); //no decimal places for the ticks
//(length of x axis in pixels)/(its length in graph space)
//= 33.28571429px/graph unit
xaxis.setMajorSpacing(33);
yaxis.setMajorSpacing(54);
//major tick labels start @ 0 and increment by 90
xaxis.setMajorLabels(0,90);

```

```

//major tick labels start @ 0 and increment by 1
yaxis.setMajorLabels(0,1);
xaxis.isZeroTickDrawn(true);
yaxis.isZeroTickDrawn(true);

//Axis label text formatting
xaxis.setTextPosition(300,400);
yaxis.setTextPosition(25,200);

//Initialize the trace objects
//need to pass the alltraces object the axes to be drawn on
alltraces = new Plotting(xaxis,yaxis);
//these are the internal power equations being used, one for each mode.
mode00 = new InternalPower00();
mode10 = new InternalPower10();
mode20 = new InternalPower20();

//tell alltraces which traces and configs you want
alltraces.addTrace(mode00,traceConfig1);
alltraces.addTrace(mode10,traceConfig2);
alltraces.addTrace(mode20,traceConfig3);

//Initialize and add all the sliders
R1slider = new gwSlider(this,200,559,110);
R1slider.setTickColour(255,255,255);
R1slider.setFontColour(255,255,255);
R1slider.setValueType(ValueType.DECIMAL);
//1.00 reflectivity is unrealistic, so we set the limit to 0.99
R1slider.setLimits(0.96,0.00,0.99);
R1slider.setTickCount(5);
R1slider.setPrecision(2);
//This sets the textfield value for before you move the slider.
R1textfield = new GTextField(this,String.valueOf(0.96),160,557,36,15);

R2slider = new gwSlider(this,370,559,110);
R2slider.setTickColour(255,255,255);

```

```

R2slider.setFontColour(255,255,255);
R2slider.setValueType(ValueType.DECIMAL);
R2slider.setLimits(0.96,0,0.99);
R2slider.setTickCount(5);
R2slider.setPrecision(2);
R2textfield = new GTextField(this,String.valueOf(0.96f),332,557,36,15);

RoCslider = new gwSlider(this,370,452,110);
RoCslider.setTickColour(255,255,255);
RoCslider.setFontColour(255,255,255);
RoCslider.setValueType(ValueType.DECIMAL);
//represents 1/RoC, so the RoC can range from L to infinity
RoCslider.setLimits(0.5,0,1);
RoCslider.setTickCount(5);
RoCslider.setPrecision(2);
RoCtextfield = new GTextField(this,String.valueOf(0.50f),332,450,36,15);

//doesn't exactly line up with axis but close
delta_x_slider = new gwSlider(this,54,368,478);
delta_x_slider.setTickColour(255,255,255);
//default position for slider, min value, max value
delta_x_slider.setLimits(0,-3.5*PI,3.5*PI);
delta_x_slider.setTickCount(13);
delta_x_slider.setValueType(ValueType.DECIMAL);
delta_x_slider.setPrecision(2);
delta_x_slider.setRenderMaxMinLabel(false);
delta_x_slider.setRenderValueLabel(false);

//x,y,length,num,height,min,max
meter = new LEDMeter(557,490,349,30,20,0.0,1.0);
meter.setGradient();
meter.setGapSize(0);
//xpos, ypos, num labels, xstep, min, max
meterAxis = new LEDMeterAxis(557,500,10,33,0,1);
meterAxis.setFontSize(12);

```

```

//Importing images
cavityimage = loadImage("cavitypng.png");
_logo = new Logo(this, 770,570,true,LogoSize.Size25);

//Create fonts
titleFont = createFont("verdana",20);
meterTitleFont = createFont("verdana",13);
expFont = createFont("verdana",11);

//Write the explanation here
explanationtext = "This applet graphs the internal power of an optical "+
" cavity as a function of tuning for transverse modes 00 (red), 10 "+
"(green), and 20 (blue)."+
"The slider below the graph controls the tuning of the second mirror. "+
"Below, the meter shows the percentage of the input power that is "+
"outputted through the second mirror at the current value of delta x "+
"(the tuning). The cavity is drawn below the graph. Each mirror has "+
"a reflectivity slider. The 1/RoC slider controls the inverse "+
"of the Radius of Curvature of the second mirror. 1/RoC=0 represents "+
"a flat mirror (infinite RoC), and 1/RoC=1=L represents a radius of "+
"curvature equal to the length of the cavity (1m). "+
"Using the sliders, you should be able to notice changes in the "+
"Guoy phase and the FSR for the different modes. The sliders "+
"can be controlled with the mouse or left/right arrow keys.";

//Adds a checkbox to select whether or not we want the white line
//on the delta_x slider to show. Defaulted to yes/true
chkWhiteLine = new GCheckbox(this,"Show white line for delta x",
550,380,200);
chkWhiteLine.setSelected(true);
}

void draw()
{
background(200,200,200);

```

```

//Draw plotting area and the traces
area1.drawRect();
xaxis.drawAxis();
yaxis.drawAxis();
xaxis.drawMajorTicks();
yaxis.drawMajorTicks();
xaxis.drawMajorTickLabels();
yaxis.drawMajorTickLabels();
//need to know the x and y axis ranges in graph space
alltraces.plotTraces(-3.5*PI,3.5*PI,-3,3);

//Draw the cavity image
image(cavityimage,10,412);

//Assign the slider values to variables
R1 = R1slider.getValuef();
R2 = R2slider.getValuef();
delta_x = delta_x_slider.getValuef();
RoC = 1/(RoCslider.getValuef());

//Set and write the Title to the screen
textFont(titleFont);
fill(0);
text("Optical Resonator Calculator",720,30);

//Set and write a label for the meter
textFont(meterTitleFont);
fill(0);
text("Percent of Input Power Transmitted",720,480);

//Explanation box
stroke(255);
fill(190,204,223);
rect(575,45,300,328);
textFont(expFont);
fill(0);

```

```

text(explanationtext,579,49,295,340);

//Add logo
_logo.draw();

//Power meter. Apparently in Processing log is natural log... Also now
//each beam has an input power of 1/3 W, so the total input power is 1W.
float sum_delta_x = (pow(10,mode00.computePoint(delta_x))
+pow(10,mode10.computePoint(delta_x))
+pow(10,mode20.computePoint(delta_x)))/3;
float transmitted_power = sum_delta_x*(1-R2);
meter.setValue(transmitted_power);
meter.response();
meterAxis.display();

//Adjusting the line drawn off the slider for rounding errors
if(chkWhiteLine.isSelected()){
    line((delta_x_slider.getValuef()*float(478/22))+293,368,
        (delta_x_slider.getValuef()*float(478/22))+293,15);
}
}

//These are the functions that are being plotted. All the same except
//for different values of n
class InternalPower00 implements GraphCallback
{
    int n,m;
    float Power00;
    float zR, psiRT;
    public float computePoint(float t_delta_x)
    {
        delta_x = t_delta_x;
        n = 0;
        m = 0;
        zR = sqrt(L*(RoC-L));
        psiRT = 2*atan(L/zR);
    }
}

```

```

    //Need to convert the natural log to log base 10...
    Power00 = log((1-R1)/(1+(R1*R2)-(2*sqrt(R1)*sqrt(R2)
        *cos(delta_x+(psiRT*(n+m+1))))))/log(10);
    return Power00;
}
}

```

```

class InternalPower10 implements GraphCallback
{
    int n,m;
    float Power10;
    float zR, psiRT;
    public float computePoint(float t_delta_x)
    {
        delta_x = t_delta_x;
        n = 1;
        m = 0;
        zR = sqrt(L*(RoC-L));
        psiRT = 2*atan(L/zR);
        Power10 = (log((1-R1)/(1+(R1*R2)-(2*sqrt(R1)*sqrt(R2)
            *cos(delta_x+(psiRT*(n+m+1))))))/log(10);
        return Power10;
    }
}
}

```

```

class InternalPower20 implements GraphCallback
{
    int n,m;
    float Power20;
    float zR, psiRT;
    public float computePoint(float t_delta_x)
    {
        delta_x = t_delta_x;
        n = 2;
        m = 0;
        zR = sqrt(L*(RoC-L));

```

```

        psiRT = 2*atan(L/zR);
        Power20 = (log((1-R1)/(1+(R1*R2)-(2*sqrt(R1)*sqrt(R2)
            *cos(delta_x+(psiRT*(n+m+1)))))))/log(10);
        return Power20;
    }
}

//This method tells the program what to do if the user
//moves the sliders
void handleSliderEvents(gwSlider slider){
    float precision = 100;
    if(slider == R1slider){
        R1textfield.setText(String.format("%.2f",slider.getValuef()));
    }
    if(slider == R2slider){
        R2textfield.setText(String.format("%.2f",slider.getValuef()));
    }
    if(slider == RoCslider){
        RoCtextfield.setText(String.format("%.2f",slider.getValuef()));
    }
}

//This method tells the program what to do if the user types a
//value into a textfield and hits 'Enter'
void handleTextFieldEvents(GTextField tfield){
    String line1="";
    float temp_val;
    if(tfield == R1textfield){
        switch (R1textfield.eventType){
            case GTextField.CHANGED:
                break;
            case GTextField.SET:
                break;
            case GTextField.ENTERED:
                line1=R1textfield.getText();
                temp_val = parseFloat(line1);

```

```

        R1slider.setValue(temp_val);
        break;
    }
}
if(tfield == R2textfield){
    switch (R2textfield.eventType){
        case GTextField.CHANGED:
            break;
        case GTextField.SET:
            break;
        case GTextField.ENTERED:
            line1=R2textfield.getText();
            temp_val = parseFloat(line1);
            R2slider.setValue(temp_val);
            break;
    }
}
if(tfield == RoCtextfield){
    switch (RoCtextfield.eventType){
        case GTextField.CHANGED:
            break;
        case GTextField.SET:
            break;
        case GTextField.ENTERED:
            line1=RoCtextfield.getText();
            temp_val = parseFloat(line1);
            RoCslider.setValue(temp_val);
            break;
    }
}
}
}

```

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Bibliography

- [1] Ben Fry and Casey Reas. Processing. Website, 2009. <http://www.processing.org>.
- [2] Antonio Perreca. Lecture Notes. Summer lecture notes, University of Birmingham, July 2009.
- [3] Dr. Andreas Freise. Lasers and Quantum Optics. Year 4 Lecture Notes, University of Birmingham, April 2009.

