Modeling the Compact Disc Read System in Lab

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One of the great, engaging aspects of physics is its application to everyday technology. The compact disc player is an example of one such technology that applies fundamental principles from optics in order to efficiently store and quickly retrieve information. We have created a lab in which students use simple optical components to assemble a large-scale mockup of the compact disc player. In this lab, students are challenged to both “write” and “read” a word of their choice in order to demonstrate the way in which the principles of optics are applied in the design of a CD player. In particular, students actively apply the optics concepts of specular reflection, diffuse reflection, and ray tracing for lenses in building the apparatus. The laboratory also provides a vehicle for learning the fundamental principles of binary data storage.

The technologies that are effective in storing and retrieving binary data have certain common characteristics that can be demonstrated through the example of the compact disc. With any of these technologies, data are stored on some object by manipulating the local surface into one of two possible physical configurations. The data are encoded and stored as a sequence of adjacent local configurations. Retrieval of the data is done by probing the local areas, determining the sequence of physical configurations, and converting that information into a signal that can be electronically processed. The compact disc is a quintessential example of the effective implementation of such principles. Information is stored on a compact disc along a spiral track that is 3.5 miles long and separated by a distance of 1.6 μm on each successive turn.1,2 If letters, numbers, and symbols are saved, each is translated into a 14-bit binary code, a string of 1s and 0s, using both ASCII and 8-to-14 modulation.3 These binary data are “written” along the spiral track as a sequence of pits and lands (non-pits) as viewed from the top of the disc (see Fig. 1). Pits and lands are distinguished by measuring the intensity of light reflected from that local area. Diagrams depicting this process are shown in Fig. 1. In each of the diagrams, an infrared3 laser diode emits light parallel2 to the surface of the disc, which is reflected by a partially reflecting surface toward the disc. As shown in Fig. 1(a), the light is collimated by converging lens #2 and focused by lens #1, which is one focal length away from the surface of the disc. If the focused beam is incident on a land, the light rays reflected off the surface are collimated by lens #1 and focused by lens #2 onto the photo detector, which measures a high-intensity light. On the other hand, if the light is incident on a pit, low-intensity light, due to destructive interference, is measured at the detector. The pit is about ¼ of a wavelength deep, so the light reflected from the bottom of the pit and the edges of the pit (along the inside and outside edge of the spiral) are out of phase and nearly cancel each other.4 Surprising to many (including us), pits and lands do not represent the binary 1 and 0, respectively, but rather a binary 1 is a transition from a pit to a land, or a land to a pit, while a binary 0 is a nontransition.2,5 As the disc spins, the player translates the light intensity-versus-time signal into a binary code and then into its alphanumeric code. The read system can be modified...
by interchanging the position of the detector and the laser so that the incident laser light is normal to the disc's surface.\(^6\) For more information on the CD, see Refs. 2 and 7.

In building the model of the CD reader, we use equipment that is generally available in an introductory lab. Figure 2 is a picture of the CD reader that most resembles the schematics in Fig. 1. We use a laser pointer as the laser diode. A clear plastic ruler is used for the beam splitter.\(^8\) Lens #1 is an ordinary converging lens, while the laser pointer's built-in collimating lens serves as lens #2. For the disc surface, we mount an actual CD to a wooden disk with reflective side exposed and mount the wooden disk to a variable-speed motor.\(^9\) A Vernier\(^{10}\) light sensor is used to detect the intensity of reflected light from the disc's surface.

Once the apparatus has been built, students choose a word for writing to and reading from their disc. To translate their word into a binary sequence, they use an abbreviated conversion table, shown in Table I, that requires five bits for each letter. Rather than store the binary data using pits and lands, we change the reflective properties of the disc's surface\(^{11}\) to mimic the reflectivity of the pits and the lands. This is accomplished by placing thin strips (0.25 in) of masking tape (or black magic marker) around the edge of the disc, with nontaped regions in between. The taped regions diffuse reflect light and represent the pits while the nontaped regions specularly reflect light and represent the lands. The order of the taped and nontaped regions then corresponds to the binary form of the saved word.

To read the data, the disc spins\(^{12}\) while the computer records the intensity of the reflected light as a function of time. The students decode the data from their graph and confirm their apparatus works properly. They then trade discs with another group and use their setup to read an unknown word.

Generally in our labs, we describe how the CD works and ask the students to build the read system out of the equipment described earlier. We leave the lab rather open ended, with the clear purpose of having the students solve many of the difficulties encountered. First, they find it difficult to align the laser so that after reflecting off the disc, the light travels through the beam splitter onto the detector. One solu-

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Table I. An abbreviated code used to translate between letters and binary data.

<table>
<thead>
<tr>
<th>Letter</th>
<th>Binary Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>00001</td>
</tr>
<tr>
<td>b</td>
<td>00010</td>
</tr>
<tr>
<td>c</td>
<td>00011</td>
</tr>
<tr>
<td>d</td>
<td>00100</td>
</tr>
<tr>
<td>e</td>
<td>00101</td>
</tr>
<tr>
<td>f</td>
<td>00110</td>
</tr>
<tr>
<td>g</td>
<td>00111</td>
</tr>
<tr>
<td>h</td>
<td>01000</td>
</tr>
<tr>
<td>i</td>
<td>01001</td>
</tr>
<tr>
<td>j</td>
<td>01010</td>
</tr>
<tr>
<td>k</td>
<td>01011</td>
</tr>
<tr>
<td>l</td>
<td>01100</td>
</tr>
<tr>
<td>m</td>
<td>01101</td>
</tr>
<tr>
<td>n</td>
<td>01110</td>
</tr>
<tr>
<td>o</td>
<td>01111</td>
</tr>
<tr>
<td>p</td>
<td>10000</td>
</tr>
<tr>
<td>q</td>
<td>10001</td>
</tr>
<tr>
<td>r</td>
<td>10010</td>
</tr>
<tr>
<td>s</td>
<td>10011</td>
</tr>
<tr>
<td>t</td>
<td>10100</td>
</tr>
<tr>
<td>u</td>
<td>10101</td>
</tr>
<tr>
<td>v</td>
<td>10110</td>
</tr>
<tr>
<td>w</td>
<td>10111</td>
</tr>
<tr>
<td>x</td>
<td>11000</td>
</tr>
<tr>
<td>y</td>
<td>11001</td>
</tr>
<tr>
<td>z</td>
<td>11010</td>
</tr>
</tbody>
</table>
ition is to adjust the laser first, then the beam splitter, the disc, and last the photo detector. The next problem they find is that the disc may wobble slightly as it rotates, which causes the laser beam to reflect in different directions and trace out a circle in space that entirely misses the pencil-sized photo detector. Since the pits and lands are larger than a typical laser pointer’s beam spot, the converging lens is not required to focus the laser beam onto the disc. However, the lens does provide an effective solution for the problem of wobble in the spinning disc. By adjusting the position of the lens, it can focus the “wobbled beams” onto the detector. As shown in Fig. 3, the lens essentially images the reflection point on the disc’s surface to the photo detector’s surface, thereby ensuring that all rays reflected off the surface converge at the photo detector. Students can also show how the thin-lens equation applies to these distances. Lastly students have a few questions when writing their data onto the disc. Since the whole perimeter of the disc is not used to write the data (the unused part is left untaped and blank), it is useful to include a pit then a land before the data and a land then a pit after their data. These merge bits give a clear starting and ending point to the data and also allow the students to measure the “time width” of a single pit or land on the intensity-versus-time graph. This is helpful in decoding the graph into pits and lands, the binary data, and finally the word. The intensity-versus-time graph for the data stored on the disc shown in Fig. 2, along with its decoding back to the word saved, is shown in Fig. 4. Since the focus of the lab is more on the physics concepts, we simplified the data-reading process. Rather than using transitions and nontransitions for 1s and 0s, we use one of the earliest codes that interprets a pit as a binary 0 and a land as a binary 1. Using the current conventions would only require minor modification in writing the data to the disc and the decoding process from the intensity graph, but not the physical setup.

In conclusion, we have presented a lab in which students explore how the basic concepts of optics and binary data apply to the commonly used compact disc player.

References
1. All technical specifications of the CD and CD-ROM including physical dimensions are given in the Red Book edited by Sony and Phillips.
7. http://hyperphysics.phy-astr.gsu.edu/hbase/audiocd.html#c1.
8. Alternatives for a beam splitter include a microscope slide or a transparency.
9. We use a motor from Sargent-Welch, http://www.sargentwelch.com. Less expensively, one could use a drill or turn it by hand as long as it rotates at a constant speed during the read process.
12. The exact speed is unimportant. The maximum speed will be determined by the computer’s collection rate and the response time of the detector. For the data in Fig. 4, the disk rotated at approximately 60 rpm.

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