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Using lock-in detection to build a barcode scanner

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Lock-in detection is a widely used experimental technique in which a weak signal is measured by modulating it at a particular frequency. Then, by detecting an experimental output at that frequency, the desired signal can be isolated from much larger-amplitude noise. Here, we report on the implementation and optimization of a homemade laser barcode scanner based on the lock-in technique. Our setup is comprised of components that are readily available in an undergraduate instructional laboratory. The successful transcription of the barcode into a digital signal was achieved, and this digital signal was collected with a simple computer and processed to reveal the encoded number.
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I. INTRODUCTION

Lock-in detection is a signal processing technique of use in a wide variety of applications in research and industry. This powerful technique allows a weak signal to be detected, even when buried in large-amplitude noise. An early mention of the lock-in amplifier in the literature was by Michels and Curtis of Bryn Mawr College,[1] although Michels later abandoned this term in favor of synchronous amplifier.[2] Dicke used this technique to measure thermal radiation[3] and later had a hand in developing the first commercial lock-in amplifier.[4] Today, we find lock-in detection used in nearly every physics laboratory around the world, with a range of applications including imaging of magnetic skyrmions,[5] measurements that limit the electric dipole moment of the electron,[6] and the first direct detection of gravity waves emitted from a binary black hole merger.[7]

There are a number of pedagogical resources aimed at conveying an understanding of lock-in detection in the undergraduate classroom or laboratory.[8–17] Here, we add to this list, presenting a project used in an upper-level electronics laboratory that teaches students about lock-in detection through the construction of a simple barcode scanner. Barcodes store information by encoding a number as a series of light and dark stripes of varying width, where a unique sequence of bars corresponds to a specific number.[18–21] The weak signal from laser light scattered off of the barcode is easily overwhelmed by background light, presenting an ideal opportunity to implement lock-in detection. In addition to learning about this important detection technique, this project develops students' skills in circuit design, construction, troubleshooting, and optimization. The theoretical description of the lock-in amplifier is directly visualized by observing the signals at various points in the circuit. Students are also expected to draw from both scientific and technical literature as they develop their circuit. Data acquisition and analysis is done with Python code that the students develop. Finally, they present their results in a formal manuscript that goes through several drafts as well as a peer-review process.

This project was developed for use in a laboratory-based electronics course, which meets in two 4-hour sessions per week. Prior to taking this class, students completed an introductory electronics lab in which they learned to use basic test equipment and build simple passive and active circuits. In addition, they previously completed an introductory programming laboratory in which they learned to use Python to numerically solve physics problems. With this preparation, completion of this barcode scanner project typically takes students four to five weeks.

In this paper, the theory behind lock-in detection will be explained in detail in Sec. II. Section III outlines the design and construction of our barcode scanner circuit. We explore the operation of the scanner and visualize the mathematics in Sec. IV. Finally, we digitize and process the data in Sec. V to reveal the number encoded in an example barcode.

II. THEORY

The purpose of a barcode scanner is to detect light bouncing off of a barcode and convert that into an electrical signal that conveys the width of each bar. When laser light passes over the barcode, it will be mostly scattered or absorbed by the white and black bars, respectively. Therefore, when the barcode is swiped in front of the laser, a photodiode can measure the pattern of scattered light. However, the photodiode also detects the ambient light in the room, which can be much brighter than the scattered laser light, thus obscuring the barcode signal. Lock-in detection allows one to recover the desired signal by modulating the amplitude of the laser light and then detecting at this modulation frequency.

To describe this process more precisely, we begin with an oscillating voltage in the form of a sine wave,

$$V_{\text{ref}} = V_{r0} \sin(\omega t + \theta_r). \tag{1}$$

This waveform is used to drive the laser diode, thus modulating the amplitude of emitted light at frequency ω. It also serves as a reference signal for lock-in amplification.

The barcode then scatters the laser light, along with the noise from other light sources in the room, back into a photodiode giving us the measured signal

$$V_{\text{sig}} = V_{s0} \sin(\omega t + \theta_s) + \sum_n V_{n0} \sin(\omega_n t + \theta_n). \tag{2}$$

Here, the first term is from the scattered laser light, which oscillates at the same frequency as the oscillating reference voltage, but may have a different phase, θ_s. The amplitude V_{s0} of the scattered signal is the quantity of interest, which will vary depending on whether the laser strikes a black or a white stripe on the barcode. The second term is a Fourier series representation of noise from all other light sources.

In order to isolate the desired quantity V_{s0} from external noise, we multiply the measured signal and the reference voltage to obtain

$$\begin{aligned} V_\times &= V_{\text{ref}} V_{\text{sig}}, \\ V_\times &= V_{r0} V_{s0} \sin(\omega t + \theta_r) \sin(\omega t + \theta_s) \\ &\quad + \sum_n V_{r0} V_{n0} \sin(\omega t + \theta_r) \sin(\omega_n + \theta_n). \end{aligned} \tag{3}$$

Using a trigonometric identity, this product signal can be written as

$$\begin{aligned} V_\times &= \frac{V_{r0} V_{s0}}{2} [\cos(\theta_r - \theta_s) - \cos(2\omega t + \theta_r + \theta_s)] \\ &\quad + \sum_n \frac{V_{r0} V_{n0}}{2} [\cos((\omega - \omega_n)t + \theta_r - \theta_n) \\ &\quad - \cos((\omega + \omega_n)t + \theta_r + \theta_n)]. \end{aligned} \tag{4}$$

Now we see that the first term in this product is time-independent. The second term oscillates at twice the reference frequency and can easily be eliminated by sending the product through a low-pass filter. The summation terms, which correspond to noise, are also largely eliminated with the filter. The exception is noise that occurs at a frequency near that of the reference, but this will generally not be phase-correlated with the reference signal.

After sending the product signal through the low-pass filter, we are left with the time-independent output signal,

$$V_{\text{out}} = \frac{V_{r0} V_{s0}}{2} \cos(\theta_r - \theta_s). \tag{5}$$

The output can be maximized by adjusting the phase difference $\theta_r - \theta_s$. It is also proportional to V_{s0}, the amplitude of the modulated light scattered from the barcode, which encodes the desired information.

III. CIRCUIT DESIGN AND CONSTRUCTION

Figure 1 shows the entire circuit diagram for the barcode scanner, as built by one student. This particular circuit is only one of many similar student-built circuits that successfully scanned a barcode. All circuits include the main components: oscillator, laser, photodiode, transimpedance ("current-to-voltage") amplifier, multiplier, and low-pass filter. Here, we describe the details of this particular circuit and also comment on other possible paths that students have explored for many components.

No laboratory manual or circuit diagram is provided to the students for this project. Instead, we begin each class by discussing the design and construction goals for the day and share ideas on how these goals might be accomplished. The students then work toward achieving these goals using information found in textbooks[22,23] and data sheets for the various components used.

We begin the project by building an oscillator. This serves two purposes: to modulate the laser output and to provide a reference signal V_{ref} to the multiplier. A variety of oscillators will work for this purpose. Students have successfully used a benchtop function generator or a square-wave oscillator built with a 555 timer. In the example shown in Fig. 1, a sine-wave oscillator is used. This quadrature oscillator follows the example provided in the TL074 quad op-amp datasheet. It is relatively stable and easy to build. The oscillation frequency ω is determined by the combination of input resistance R and feedback capacitance C as follows: $\omega = 1/RC$. In order to promote oscillation, the first resistor is replaced with a potentiometer so that its value can be reduced slightly with respect to the other resistors.

A laser diode requires a certain threshold current to turn on. Beyond this threshold, the output power of the laser light increases linearly with current.[24] To modulate the laser output, we, therefore, need to supply current that oscillates sinusoidally above this threshold current. This is done by sending the oscillator output through a variable voltage divider to control the amplitude of the oscillation. We then add this signal to a variable offset created with a second voltage divider to move the oscillation above threshold.

We use a low-cost laser diode from Marlin P. Jones & Associates (19566-LZ) that has a built-in current-limiting 33 Ω resistor and an adjustable lens to collimate the output beam. This laser is specified to produce <5 mw of light at 635 nm, similar to a standard red laser pointer. The lasing threshold is reached when the laser is biased with roughly 3 V. We, therefore, set the amplitude of the laser driver to ≈0.5 V and the offset to ≈2.5 V. The offset is then slowly increased to a level just past threshold. The measured power produced in our case was 1 mW, presenting a very low risk

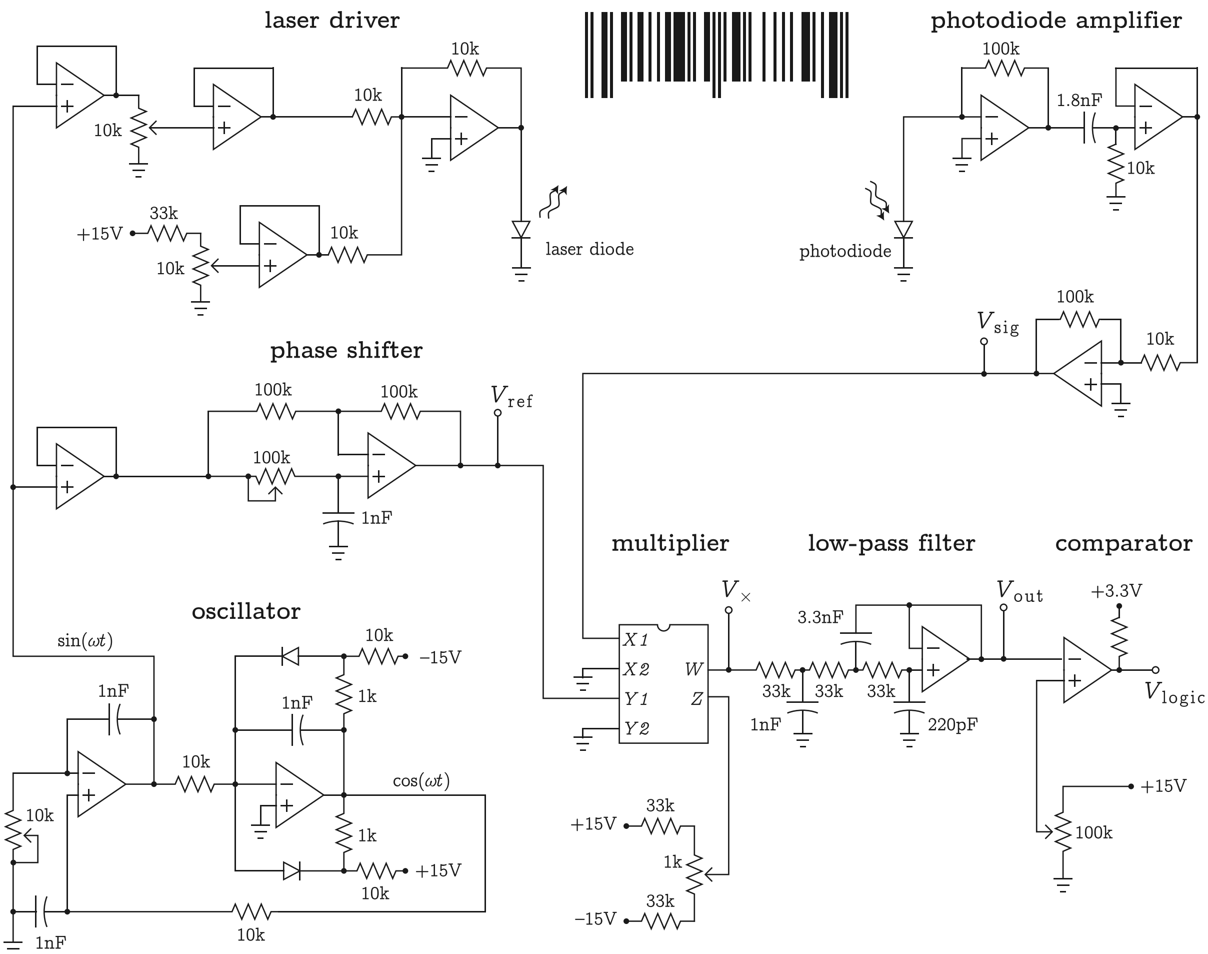

Fig. 1. Circuit diagram. The main components of the circuit are labeled above each section and are discussed in detail in the text. We used TL074 quad op-amps, an AD633 multiplier, and an LM293 comparator. An oscilloscope is used to measure the time-dependent waveforms at the five test points discussed in the text, labeled V_{ref}, V_{sig}, $V_\times$, V_{out}, and V_{logic}.

of eye damage. That said, students are cautioned about the potential risks of laser light and instructed on safe operating practices.

Our next task is to build the light detector with which we collect the measured signal V_{sig}. We use a PD333-3C/H0/L2, a silicon photodiode that is housed in a 5 mm clear plastic package similar to an LED. The photodiode produces a current in proportion to the intensity of the collected light. Using a transimpedance amplifier, we convert this current into a voltage. The output of this amplifier has a small oscillation due to the scattered laser light as well as a large DC offset from the room lights. The feedback resistor in this amplifier is chosen to provide sufficient gain without saturating the amplifier. Eliminating the large DC offset with a high-pass filter allows us to increase the range of the scanner, the physical distance between the laser and the barcode, by further amplifying the signal. Since the gain of this amplifier chain is rather large, it can easily pick up stray signals that are not due to the photodiode. Placing the oscillator and photodiode amplifier far from one another on the circuit breadboard helps to reduce the unwanted coupling between the two.

The photodiode and laser are placed close to one another at the edge of the circuit and point in the same direction leaving space to move the printed barcode past the laser beam. With both operating, we can further optimize the laser output by placing a piece of white paper a few centimeters in front of the pair and observing the photodiode signal while adjusting the amplitude and offset of the laser drive signal. Care must be taken not to increase the laser drive voltage, and therefore, the current, beyond the point where the laser is damaged. It is wise to have several extra laser diodes on hand, as a few will inevitably be destroyed in the learning experience. Once a clear sine wave in the photodiode signal is observed, we continue with circuit construction.

Before multiplication, we send the reference through an all-pass filter so that the relative phase between the reference and photodiode signals can be adjusted, thus optimizing the output signal of Eq. (5). The transfer function for an all-pass filter is

$$H = \frac{1 - i\omega RC}{1 + i\omega RC}, \tag{6}$$

where R is the potentiometer in Fig. 1. The magnitude of H is one for all frequencies, thus giving the filter its name, but the phase of H varies between 0° and 180° according to $2\arctan(\omega RC)$ as the resistance of the potentiometer is adjusted. There are other methods to shift the phase of the reference signal that students could explore. For instance, the sine and cosine outputs of the quadrature oscillator can be

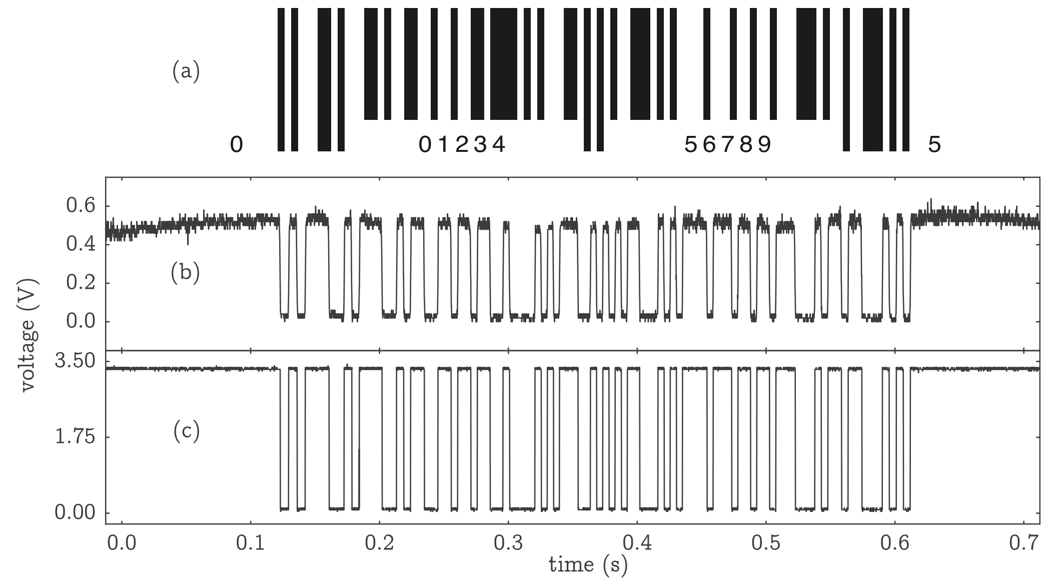

Fig. 2. (a) The UPC-A barcode used in testing our circuit. Below the barcode is the sequence of numbers encoded by this particular sequence of bars. (b) The signal measured in volts directly from the output V_{out} of the low-pass filter. Higher voltage, near 0.5 V, corresponds to light scattered from white bars, while lower voltage, near 0.0 V, is read when the laser illuminates the black bars. The white space on either side of the page on which the barcode was printed results in the high level seen before the barcode data, which falls between 0.12 and 0.62 s in this particular scan. (c) The output V_{logic} of the comparator is utilized to produce a digital signal that goes between 0 and 3.3 V. Good agreement between the barcode and the measured signal is observed although it is clear that there was some variation in the speed at which the barcode was swept past the laser, producing some misalignment in the middle of the scan. To collect these data, the oscilloscope was set to normal mode, with the trigger level set midway between the high and low levels. V_{out} was observed on one channel and V_{logic} on another. The timescale was set to 0.1 s/div. As the page with the printed barcode moved into the beam, the oscilloscope triggered and the barcode pattern was recorded.

added with variable amplitude to produce a shift between 0° and 90°.

Next, we multiply the phase-shifted reference and photodiode signals to obtain $V_\times$. The AD633 analog multiplier shown in Fig. 1 is simple to use and works well in this application, but students have also used the AD630 balanced modulator/demodulator with success. For the AD633, two differential inputs, X and Y, are provided and their scaled product is added to an offset, Z, according to the transfer function

$$W = \frac{(X1 - X2)(Y1 - Y2)}{10\,\text{V}} + Z. \tag{7}$$

This product is then sent through a low-pass filter to isolate the amplitude of the scattered laser light, producing the desired output, V_{out} of Eq. (5). A simple *RC* filter is sufficient, but students are encouraged to explore multi-pole filters that have a sharper cutoff. In the circuit example shown, a three-pole active filter is used. The cutoff frequency is chosen to eliminate the modulation, but preserve a sharp transition as the barcode moves from having a black to white bar illuminated.

At this point, the circuit will produce a voltage signal at V_{out} that switches between a high and low level as the barcode is scanned past the laser. The low level should be near 0 V, but can be adjusted by adding a small DC voltage to the summing input of the multiplier, Z. The high level depends on the distance between the barcode and the laser. To produce a consistent high level for use in digital processing, we send this output into a comparator with the threshold voltage set just above the low level of the scanner. The output of the comparator was pulled up to 3.3 V, which was the high logic level required for our data acquisition computer.

IV. CIRCUIT OPERATION AND OPTIMIZATION

The barcode, depicted in Fig. 2(a), is printed to fill a full sheet of paper so that the width of the bars is large compared to the width of the laser beam. To operate the scanner, we move the barcode through the laser beam by hand a few centimeters away from the photodiode. The laser and photodiode should be placed at the edge of the circuit so that there is unobstructed space to pass the barcode through the beam, taking care to move at roughly constant velocity. As the barcode passes the laser beam, the voltage returned is higher when the light is scattered off of the white bars and is lower when absorbed by the black bars. Therefore, when the barcode passes in front of the scanner with a constant velocity, the amount of time the signal is at a certain voltage corresponds to the width of the bar. This time-dependent sequence of voltages encodes the barcode data as shown in Fig. 2(b), which is the output signal represented by Eq. (5) measured at the test point labeled V_{out} in our circuit diagram (Fig. 1). Overall, this is an accurate electronic representation of the barcode, although it is evident that there was some variation in the speed at which the barcode moved through the beam. The slight variation in height for the white bars is due to the inconsistent distance of the barcode from the laser and the photodiode while scanning. Figure 2(c) shows the output of the comparator, labeled V_{logic} in Fig. 1. This shifts the output to the necessary digital logic level to be read by a computer and eliminates the height variation seen in the raw output V_{out}.

With the circuit operating, we collect data at several test points to optimize and explore its behavior. Figure 3 shows data collected at the four test points labeled V_{ref}, V_{sig}, $V_\times$, and V_{out} in Fig. 1. These correspond to Eqs. (1), (2), (4), and (5) from the theory discussion in Sec. II. A black bar was

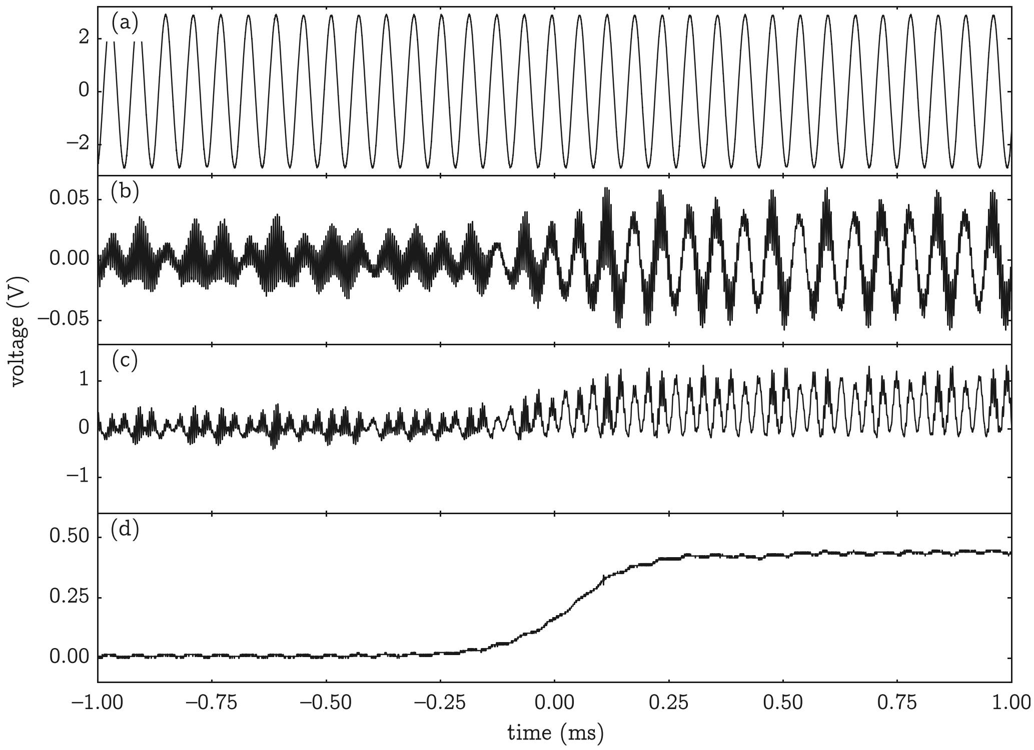

Fig. 3. Output from four of the labeled test points in our circuit. A black bar was illuminated for the signals on the left half of this plot, at early times, and a white bar was illuminated on the right half, for later times. (a) The sinusoidal reference signal V_{ref} measured directly from the oscillator circuit depicted in Fig. 1 oscillating at a frequency of 16.57 kHz. (b) The measured signal V_{sig} detected just before the multiplier, (c) the product signal $V_\times$, and (d) the output signal V_{out} measured after the low-pass filter to eliminate the majority of the high frequency oscillations. To collect these data, the four signals were sent into a four-channel oscilloscope. The oscilloscope was set to trigger on channel (d) in normal mode. When a white paper was moved into the beam, the oscilloscope triggered, recording the four signals.

illuminated for the signals on the left half of Fig. 3, at early times, and a white bar was illuminated on the right half, at later times.

The sinusoidal reference voltage is depicted in Fig. 3(a). In the oscillator, the resistance and capacitance values were chosen to produce a reference frequency of 16.57 kHz. The choice of reference frequency is driven by the characteristics of our scanner. Since we use a large barcode and sweep it manually in front of the laser, the time to move across a narrow bar is of order 10 ms as seen in Fig. 2. We would like the transition time, as the laser moves from a black to white bar to be fast relative to the width of the bar; thus, we set the cutoff frequency of our low-pass filter to be 5 kHz. The reference frequency must be above this cutoff frequency, as it is in this case.

In Fig. 3(b), we show the amplified output of the photodiode V_{sig}. Note that the large offset due to the room lights has been removed and the signal is further amplified to reveal the sinusoidally oscillating laser light along with a large amount of noise. Even so, this signal remains small.

The product signal $V_\times$ given by Eq. (4) is clearly seen in Fig. 3(c). On the left half of the plot, where V_{s0} is near zero, we see noisy oscillations centered around zero. On the right half, where V_{s0} is nonzero, we again see noise but also a steady offset, that is, the first term in Eq. (4), and an oscillation at 2ω, which is the second term in Eq. (4).

After the low-pass filter, the signal in Fig. 3(d) reveals the step from a black to white bar, and thus the information encoded in V_{s0} in Eq. (5). The transition time is affected by both the cutoff frequency of the low-pass filter and the size of the laser beam. To produce a sharp transition, we adjust the lens in front of the laser diode to produce a narrow beam at the distance we intend to scan the barcode. The beam width should be much smaller than the narrowest bar width.

V. DATA PROCESSING

Now that we have successfully generated a voltage signal representing the pattern on the barcode we move to processing this pattern to reveal the encoded number. We use a UPC-A style barcode, which encodes 12 numbers. The UPC barcode was developed at IBM in the early 1970s. A fun account of this history is found in George J. Laurer's autobiography.[25] Of particular interest are the engineering design goals laid out for the project, which include specifications on size, depth of field, speed, error rate, and so on. This work was inspired by an earlier patent to encode data in a bull's-eye pattern, developed by a pair of engineering students at Drexel University.[26]

Each number in a UPC-A barcode is represented by a set of four lines, two black and two white.[18,19] There are four allowed widths for each line. There are also three sequences of calibration lines within the barcode that allow the data to be processed independent of the speed at which it was scanned. The calibration lines are all of the narrowest width and of alternating color; both ends of the barcode have a sequence of three lines, while a sequence of five appears in the middle. The lines that encode data may be of four widths which, when normalized by the calibration width, are read as 1, 2, 3, and 4. Each number is assigned a pattern of these four numbers. Table I

Table I. Barcode mapping.

Number	Pattern
0	3211
1	2221
2	2122
3	1411
4	1132
5	1231
6	1114
7	1312
8	1213
9	3112

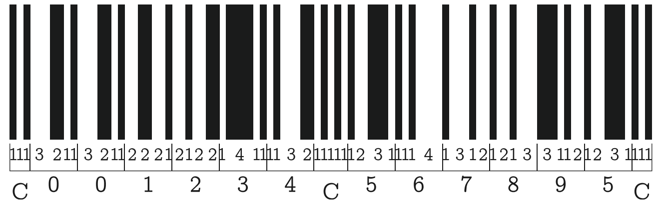

Fig. 4. Decoding the data stored in a UPC-A barcode. The top row of numbers shows the width of each bar. The bottom row shows the number encoded by each set of bars. Calibration bars are labeled C.

shows the pattern associated with each encoded number in the barcode. The sum of the four widths in the pattern for each encoded number is 7, which maintains each barcode at a constant size, independent of the encoded number.

Reading from left to right for the barcode shown in Fig. 4, we see a sequence of three unit-width bars (black, white, black). These are the first set of calibration bars. They are followed by bars of width three, two, one, and one (white, black, white, black), which encode the number zero. Continuing across the barcode, we can match each pattern to the associated number, remembering that the sequence is interrupted in the middle by five unit-width calibration bars and ends with an additional three unit-width calibration bars.

To process our data, we chose the Raspberry Pi 3, a small, low-cost computer that is easy to program in Python and connect to hardware through General-Purpose Input/Output (GPIO) pins. We connected the comparator output of our circuit to one of the GPIO pins and set this pin to read the digital signal level. Pseudocode for data processing is shown in Fig. 5. This code represents one approach, but each student developed their unique way of solving the problem.

We begin by simulating an oscilloscope trigger. When the barcode is not in the laser beam, the comparator output voltage is zero giving low logic-level readings. The trigger loop continues to read the comparator level until its output switches to the high logic level of 3.3 V, which corresponds to a Boolean value 1 for the Raspberry Pi, and ends the trigger loop. This effectively tells the Raspberry Pi when the barcode has begun scanning and, therefore, when to begin reading data. The input is then read repeatedly for 2 s. The resulting list of zeros and ones mimics the pattern seen in Fig. 2(c).

To process these data, we count the length of each string of consecutive zeros and consecutive ones, storing these lengths in a new list. Using the calibration bars at the beginning, middle, and end of the code, we normalize the lengths in our list. We now have a list of lengths that range between approximately one and four, which are rounded to the nearest integer width. This rounding makes the system fairly robust against variations in bar widths that can result from a variation in speed during the scan. By grouping the pieces of the code associated with each number, we can map the four-digit sequence onto each number, revealing the encoded number. This represents a minimal implementation of data processing. Many students also included some error checking and some experimented with more sophisticated normalizations that could account for speed variations as the barcode was swept in front of the scanner.

VI. CONCLUSION

Laser barcode scanners are used to decode information on an everyday basis. The construction of a laser barcode scanner using lock-in detection allows students to develop a visual understanding of this important detection technique as well as explore the circuitry necessary for its implementation. In addition to translating the basic mathematics into circuit elements, students learn about computer interfacing for data collection and processing. While the laser barcode scanner we present is not identical to that of a robust, commercial device, it enables students to actively participate in the real-world design and problem-solving process in which a goal is outlined and successfully achieved.

We present this project in the spirit of an inspirational guide rather than a step-by-step manual, as there are a multitude of ways to implement each component of the circuit. The working barcode scanner we construct is just one of many ways this project can be implemented as the components can easily be modified to fit courses with a variety of learning goals. For example, a stronger focus on interfacing, data collection, and data processing techniques may be of interest for an applied computer science course, while extending the project to include mechanical scanning of the laser could be of interest for courses with an engineering focus.

The cost of components necessary to build this circuit is modest, at less than US$50 per student, assuming basic test equipment is readily available. The Raspberry Pi used for data acquisition and analysis is also less than US$50 per student, assuming keyboards, mice, and monitors are available. Many of these components can be reused year after year, although some will inevitably be destroyed in the learning process.

This work has been a challenging but rewarding project for students. The circuit is complicated so giving the students great latitude in their design choices requires support and guidance throughout the troubleshooting and optimization of each component. When a student sees the pattern of the barcode first appears on an oscilloscope screen, a celebration begins. That student quickly transforms into a peer mentor, helping other classmates with their circuits. Writing the computer code to translate this digital pattern into a number is also challenging, but when the number of the barcode appears on the computer screen, the laboratory erupts with excitement and progress spreads rapidly as students share ideas and solutions.

```
while inputPin = 0 do                                   ▷ Wait for a trigger.
    Read(inputPin)
end while
while elapsedTime < 2 seconds do                        ▷ Collect data for 2 seconds.
    Read(inputPin)
    dataRaw.append[inputPin]                            ▷ Store data in the list dataRaw.
end while
length = 1                                              ▷ Initialize a length counter.
for i in dataRaw do
    if dataRaw[i] = dataRaw[i + 1] then                 ▷ Measure the number of repeated 0's or 1's.
        length = length + 1
    else
        dataLengths.append[length]                      ▷ Store lengths in the list dataLengths.
        length = 1                                      ▷ Reset the length counter.
    end if
end for
norm = Average(first3, middle5, last3)                  ▷ Calculate normalization length.
for i in dataLengths do
    dataNorm[i] = dataLengths[i]/norm                   ▷ Normalize the lengths and store in dataNorm
end for
for i < 12 do
    code = GroupData(dataNorm)                          ▷ Group sets of four numbers for decoding
    barCode = Map(code)                                 ▷ Map the code to each number
end for
Print(barCode)
```

Fig. 5. Pseudocode for barcode processing software.

ACKNOWLEDGMENTS

This project was developed over the last 8 years, during five offerings of our Advanced Electronics course, involving 61 students in total. This paper is based on the work of the students enrolled during the 2022 spring semester. Each student wrote an individual account of this project, which were then combined and edited by the group to produce this article. The first 15 authors were the undergraduate students, S. Spielman was the graduate teaching assistant for the course, and M. Noel was the instructor. The authors wish to thank the students enrolled in earlier sessions for their contributions to the development of this project. This material is based on the work supported by the National Science Foundation under Grant No. 2011610.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

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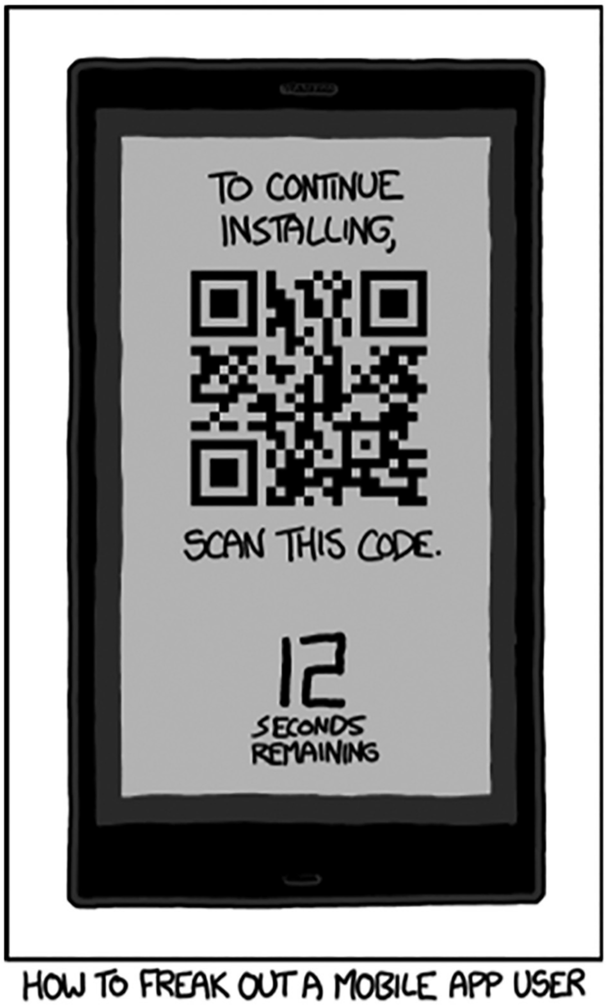

Remember, the installer is watching the camera for the checksum it generated, so you have to scan it using your own phone.
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