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Inexpensive robots used to teach dc circuits and electronics

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This article describes inexpensive, autonomous robots, built without microprocessors, used in a college-level introductory physics laboratory course to motivate student learning of dc circuits. Detailed circuit descriptions are provided as well as a week-by-week course plan that can guide students from elementary dc circuits, through Kirchhoff's laws, and into simple analog integrated circuits with the motivational incentive of building an autonomous robot that can compete with others in a public arena.
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I. INTRODUCTION

In recent years, several groups have described efforts to engage student interest in electronics and engineering through the design and construction of robots as part of a project-based phase of introductory physics lab courses.[1,2] These projects clearly stimulate interest and creativity and can provide the "thematic glue"[2] that ties together all the learning objectives of the course. However, the robots described can be prohibitively expensive (costing more than $200 each) and they generally rely on some level of pre-existing hardware to help bridge gaps in student knowledge while still delivering a satisfying learning experience. Here, we describe a program for teaching dc circuits to introductory physics students using a robot design that costs just under $50 and which is built almost entirely from scratch using common analog circuit components on a protoboard.

II. ROBOTICS IN THE CLASSROOM AND BEYOND

Robotics has emerged recently as a fun and exciting way to motivate student interest in the science, technology, engineering, and math (STEM) disciplines[3,4] and the excitement is clearly evidenced by the growing popularity of robotics competitions sponsored in the US and abroad.[5,6] These competitions, which range in difficulty from those meant to challenge university-level engineering students to others designed for K-12 students who are just beginning to explore their career paths, tap into a primal desire for conquest that "geeks" rarely get to explore. Participation by K-12 students has swelled considerably in the advent of commercially available robot kits (VEX,[7] LEGO[8]) for which the complications of sensor design and motor/servo controls are already integrated with a microprocessor unit. These kits are invaluable as they make the excitement of robotics accessible to younger students with only some basic computer programming skill required.

The challenge of teaching is to get students motivated to learn. This engagement by the student has long been acknowledged as a critical step in active learning and can be achieved in many ways. In the so-called project-based learning scheme,[9] motivation to learn is stimulated by student interest in completing a project whose success is contingent on learning basic topics along the way that ultimately contribute to the project. From a teaching standpoint, the immense popularity of robotics is viewed as an opportune "golden carrot" that can be used to motivate and guide student learning in a variety of topics including electronics, mechanical engineering, and computer science.

The use of robotics projects in the classroom is not entirely new. At Loyola College in Baltimore,[1] a short, 4–5 week long project lab on constructing robots has been operating since 1990 for the benefit of introductory science students who are not bound for engineering degrees. In that program, much of the electronic circuitry (designed around a 12-V lead-acid battery source) is provided as a "black box" and the emphasis for student learning is placed more on the mechanical construction and remote control of the unit. At Whitworth College in Spokane,[2] students in their analog electronics course are tasked to design and build custom input or output transducers that can communicate with a LEGO RCX robot unit. In this way, students are pressed to apply their understanding of analog circuits to a practical situation, thereby providing the satisfaction that what they learned is actually relevant. There, the project timeline spans 4–6 weeks and culminates with a public presentation.

Recently, we explored the use of robots and a robotics competition as a motivational carrot for helping our introductory physics students learn about dc circuits and simple electronics. In spring of 2016, a dozen students in a lab section of the introductory physics course at Creighton University built simple, "micro-less" autonomous robots that could compete at four different tasks without the aid of a microprocessor or a remote control. Enrollment into this particular lab section was restricted to those students majoring in one of the STEM fields (physics, chemistry, and mathematics), and the class was divided into four separate teams who competed against each other in a public event held at the end of the semester. Unlike the robots discussed above, these robots were constructed largely from scratch using a only about $50 of materials each. The circuitry is designed for a 6 V source drawn from a set of four AA batteries and most of it, excluding sensors, can be laid out on a standard-sized solderless breadboard.[10]

Rosenthal and Henderson[11] have suggested that students fail to learn dc circuits in part because they fail to fully understand the concept of electric potential. Adoption of the protoboard helps by emphasizing to students that dc circuits are linear pathways that allow charges to travel between a high potential and a low potential, namely, the high and low "rails" of the protoboard. Moreover, construction of the robot circuitry demands an appreciation for potential in the design of light-activated sensors that rely on a voltage divider and in the logical operation of a variety of integrated circuits.

The purpose of this article is two-fold. First, we provide an interested instructor the detailed information that they would need to feel confident in adopting some form of the project for their students. This detail includes all the relevant circuit diagrams and notes on the circuit operations as well as instructions for the students. Second, we outline a program of study that can be coupled with the robotics project to teach dc circuits in a way that articulates to students the utility of what they are learning and clearly guides them toward their project goal. In Sec. III, we begin by describing the robotic tasks and explain how each task is performed in an autonomous manner using simple analog circuitry.

III. THE TASKS AND CIRCUIT DETAILS

To succeed in competition, robots needed to be designed in such a way that they could perform each of four different tasks with only minor changes in the circuitry. Each robot was required to: (i) follow a black line on a white surface, (ii) avoid the (black) edge of a (white) tabletop, (iii) avoid a wall-like obstacle, and (iv) follow a diffuse light source, all without any human intervention. Construction begins with a commercially purchased, three-wheel chassis[12] that includes two independent drive motors (6 V, 120 mA), a castor wheel, and a battery pack for four AA batteries providing 6 V to power both the logic circuitry as well as the motors themselves. Mounted to the chassis is one or more small protoboards onto which most of the circuitry other than the sensors can be assembled, as shown in Fig. 1.

The operating principle for all the tasks is essentially the same: an optical sensor detects a changing situation and signals that information to an electronic "gearbox"—the L293D IC chip—that converts incoming signal logic into corresponding motion of the two drive wheels. As illustrated in Fig. 2, each side of the L293D chip controls a single motor based upon the logic states (6 V = logical 1, ground = logical 0) at three inputs, labeled A, B, and C in the figure. Of the three inputs, C is the simplest as it functions only to activate or deactivate the controller altogether and, as discussed later, can be fed by a square wave to achieve pulse-width modulated control of the motor's speed by essentially turning the

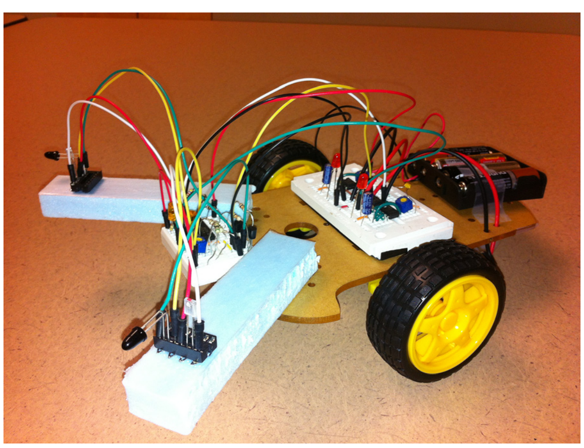
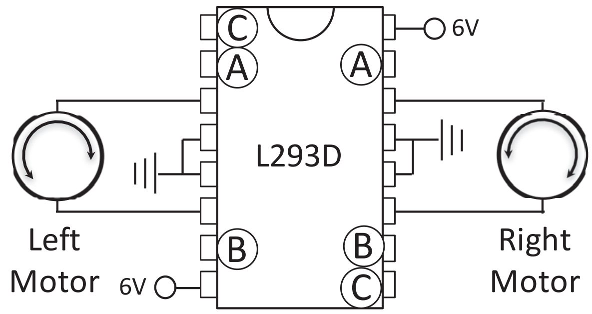


Fig. 1. Photograph of a functioning obstacle-avoiding robot. Not visible beneath the battery pack is the third castor wheel. The larger protoboard at the center contains the motor control circuitry (two 555 timers and the L293D chip). The smaller protoboard near the front contains the comparator circuitry. An IR emitter (parabolic shaped) and receiver (flat) are mounted on each styrofoam arm in a DIP socket.



C	A	B	MOTOR STATE
1	1	0	FORWARD
1	0	1	REVERSE
1	1	1	STOP
1	0	0	STOP
0	X	X	OFF

Fig. 2. A pinout diagram of the L293D motor control IC showing power connections and connections to the two motors. Each motor is controlled via logic voltages present at pins A, B, and C according to the logic table provided.

chip on and off very rapidly. Logic inputs at pins A and B control the direction of motor rotation and are summarized in the logic table in Fig. 2.

A. Light following

Sensors came in two varieties but share very similar circuit architectures. For the task of following a light source, the sensor is constructed using a CdS photocell that occupies the lower leg of a simple voltage divider as shown in Fig. 3(a). In dark conditions, the photocell has a high resistance (roughly

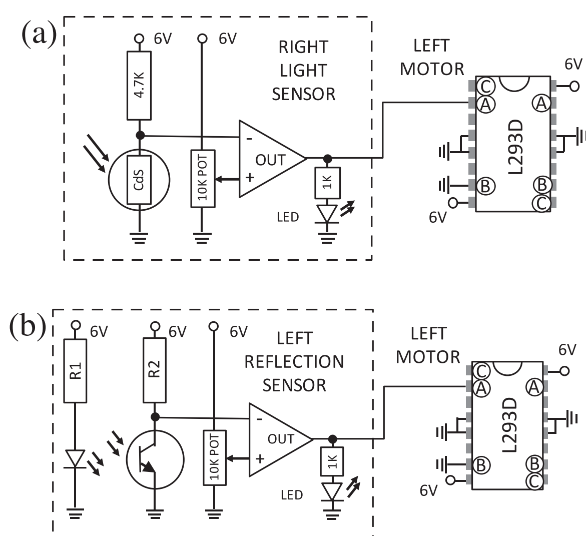


Fig. 3. Circuit diagrams for the two sensors used: (a) a light following sensor constructed from a photocell and (b) a reflection sensor constructed using a matched pair of IR LED and phototransistor. In both instances, light sensing alters the midpoint potential of a divider and can trigger a change in the output state of a voltage comparator as sensed by a small LED. For light following, the output is directed to the opposite side motor, but for line following the output of the reflection sensor is directed to the same side motor.

1 MΩ) but is lowered to values in the range of a few kΩ when illuminated. The voltage at the midpoint of the divider is input into the negative (inverting) input of an operational amplifier (e.g., a 741 or one of four on a L324 quad op-amp IC chip, or a more modern alternative[13]) where it is compared to an adjustable reference voltage delivered to the positive (non-inverting) input. When the photocell is illuminated, the midpoint voltage drops below that of the reference voltage causing the op-amp output to abruptly switch from a logical zero to a logical 1 as if to say, "YES, I see enough light to begin moving towards it." As shown in Fig. 3(a), this output is fed to the A input of the motor controller, and the logic change causes that motor to begin moving forward. If the second sensor on the other side is still dark, the robot turns toward the light. Once oriented toward the light source, both sensors should become illuminated and both motors drive forward toward the source of light. The robot will continue to track the location of the light source even if it is moving about.

B. Line following

For the other three tasks, the sensor is designed from a matched pair of IR LED (the emitter) and phototransistor (the detector) arranged so that the light from the emitter can be reflected back from a surface into the detector. This "reflection" sensor is illustrated in Fig. 3(b) and functions much like the light following sensor. The phototransistor functions primarily as a light-activated switch positioned in the lower half of a voltage divider. When no light is received (no reflection of light from the emitter) the current in the base of the transistor is negligible and the switch is open so that the pull-up resistor maintains a voltage near 6 V. When light is received, the closing of the transistor switch (entry into saturation mode) causes a current to appear in the resistor along with a resulting voltage drop. The potential at the base of the resistor is passed to the negative input of the op-amp and again compared with an adjustable reference voltage to determine the output state of the voltage comparator: a logical 1 implying "YES, I see a reflection" or a logical 0 implying "NO, I do not see a reflection." In the instance of the line following task, this output is directed to the gearbox as shown in Fig. 3(b). Note that in this instance, the sensor controls the motor on the same side. Thus, when two reflection sensors are positioned on either side of a black line facing downward over the white surface, they both detect a reflection causing both motors to move forward. However, when one sensor happens over the black line, that corresponding motor is momentarily stopped while the other motor continues to move. This then turns the robot until the sensor returns to the white, reflecting surface where both motors again move the robot forward. In this fashion, the robot proceeds along the line with a slight rocking motion.

C. Obstacle avoiding

In obstacle avoidance mode, two reflection sensors (left and right) are mounted to monitor the forward direction and each can signal the presence of a looming, wall-like obstacle by detecting the reflection of light from its surface when the robot is sufficiently close. In the default mode where no obstacle is present, the robot should travel forward and this can be achieved by splitting the sensor output, as illustrated in Fig. 4. One branch of the sensor output is passed through an inverter to obtain the opposite logic state and directed to input A of the opposite motor. Thus, when no obstacles are present, the sensor outputs are a logical zero ("NO, I do not see a reflection"), which is input to pins B of the motors while the inverted, logical 1, is input to pins A, causing both motors to move forward. When an obstacle is detected, these two input states are reversed for the motor opposite the sensor; a logical 1 appears at pin B and a logical zero at pin A, causing that motor to rotate in reverse until the default condition is regained. This has the desired effect of turning the robot "on center" in a direction away from the obstacle.

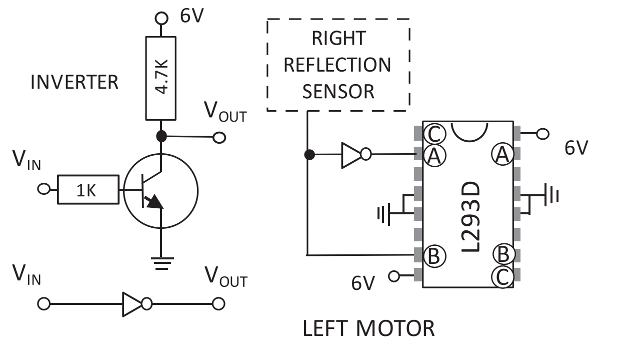


Fig. 4. (Left) An NPN transistor is combined with two resistors to form a crude inverter; the circuit symbol for the inverter is shown beneath. (Right) An obstacle avoiding robot uses an inverter to toggle the motor control between forward and reverse depending on the output signal of a reflection sensor.

D. Edge avoiding

In this last task, a single reflection sensor is positioned facing down directly in front of the robot some distance out from the chassis to monitor the presence of a white tabletop versus a non-reflecting table edge. The objective is for the robot to travel forward until an edge is encountered at which point the robot should execute a turn that takes it away from the edge. At first glance, it would seem that this task might be achieved using the line following circuit described above, but this would in fact only produce an "edge following" robot whose wheels would eventually fall off the table. Instead, the circuit needs to force a complete turn away whenever the edge is detected and this is achieved using the monostable (single pulse) output of a 555 IC timer chip, as illustrated in Fig. 5. Configured in this manner, the drop of voltage at pin 2 of the 555 timer triggers the output of a pulse at pin 3 whose duration is set by the adjustable *RC* circuit that feeds both pins 6 and 7. The result is that one of the two motors drives forward so long as a reflection is present (i.e., the sensor output is a logical 1 and so the timer remains untriggered), but reverses direction for a fixed period of time the moment the edge has been detected. Regardless of the state of the sensor just after the triggering event, the robot is forced to execute a large, preferably more than 90°, on-center turn before continuing on.

E. Speed control

As mentioned, the 555 timer was also employed to operate as a square wave generator for controlling the speed of each motor by throttling the on/off state of the L293D chip via input C. This control was particularly relevant as each motor did not perform identically under the same conditions, resulting in some form of curved travel if left uncorrected. This control technique is a form of pulse width modulation,

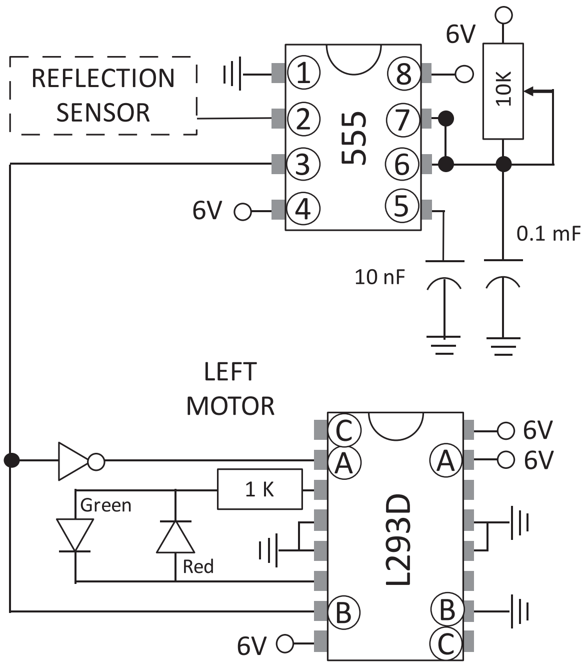


Fig. 5. A single monostable 555 timer is configured to output a pulse of logical 1 for a fixed time interval set by the 0.1-mF capacitor and the 10-kΩ pot. This pulse is triggered by a drop in the sensor signal output to logical zero state and is used to toggle the motor from forward to reverse motion during the pulse duration. Also shown is the incorporation of two sensing LEDs that could replace the motor during the initial testing of the circuits.

and the circuitry is shown in Fig. 6 where the 555 timer is set up in its usual astable operating mode. The pulse width is set by the charging of the capacitor at pin 6 through the entirety of the adjustable pot. However, the delay between pulses is set by the discharge of the capacitor through only that portion of the pot between pins 6 and 7. Thus adjusting the pot between its limits allows the duty cycle to be varied from 50% to 100%.

A detailed circuit schematic is available as supplementary material[10] and, with careful planning, the entire circuitry for all four tasks (excluding the sensors) can be fit onto a single, 63-row protoboard (see block diagram in the supplementary material). A complete list of items needed to construct a single robot circuit is given in Table I along with supplier information and approximate cost.

IV. TEACHING DC CIRCUITS

At the beginning of the semester, students are informed about the robotics project and are told that later in the semester they will divide into smaller groups to build an autonomous robot that can do the four tasks described above and compete against other groups in the class for prizes or other bragging rights. A complete circuit schematic for one or more of the tasks is presented to impress upon students that dc circuits poses a learning challenge. The schematic includes unfamiliar symbols and connections that they will need to understand before beginning the project portion of their lab experience and that is why lab time will be initially devoted to building this required base of knowledge. At Creighton, dc circuits (and geometrical optics) are not covered in the lecture portion of the course, but instead are only treated in the laboratory. This means that some part of the 3-hour-per-week laboratory session is devoted to a short, mini-lecture in addition to hands-on exploration by the students. In the following, we outline a chronological set of activities that might be used to teach the topic of dc circuits while also bringing the students to the doorstep of their robotics project.

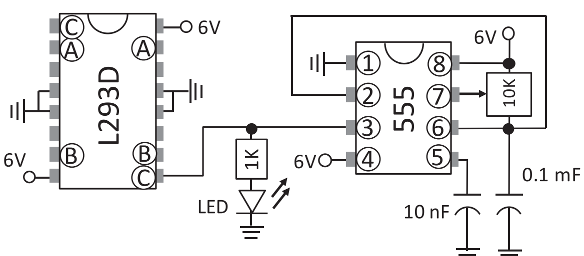


Fig. 6. Pulse width modulation of the L293D chip can be accomplished using an astable 555 timer. Note that pins 2 and 6 of the 555 chip are tied together.

A. Week one: Potential

It has been commented that teaching dc circuits requires an emphasis on the concept of potential and potential differences in their role as an electromotive force for driving the flow of charges from one location to another.[11] The role of potential is particularly relevant for robotics as it is at the heart of the sensor operation and logic handling (far more than current). To get students started on understanding the concept of potential, a mini-lecture on the electrostatics of a capacitor that emphasizes how charges on the same plate are repelled by one another and are attracted to their opposites on the other plate would be appropriate. The situation creates a potential difference $\Delta V_c = Q/C$ between the plates and an emf capable of driving the charges to the opposite plate should a conduction path be provided. A convincing demonstration is to use a battery to charge up a large capacitor and then discharge it abruptly with a metal bar or screwdriver to illustrate the strong desire for charges to leave their plates. It is also useful here to stress the difference between the capacitor and the battery. The battery has an internal source of chemical energy and functions like a charge "pump" that can move charges from the lower plate to the upper plate. The work done when a single charge q is moved is $W = q\Delta V_c$. The emf of the charged capacitor is limited and decreases during the discharge until current eventually stops altogether.

As a hands-on activity, students are given a sheet of conducting (carbon) paper on to which a two-dimensional (2D) version of a parallel plate capacitor is painted with silver conducting ink and connected to a 6-V battery. Students are introduced to the digital multimeter (DMM) as used for reading voltage difference and are asked to map out the potential (relative to ground) on the paper. Students are told that, because the paper is slightly conducting, charges are flowing from the high potential to ground and that the battery is needed to continually replenish the stock. Students are asked to conceptualize the notion of Ohm's law before it has yet been introduced by considering all the various paths that charges could take to go from the positive plate to the negative plate. Some paths (like those directly between the plates) are very short while others that arch out from behind the positive plate around to the backside of the negative plate are much longer. Students are asked to reflect on which of the paths might be more favorable and why more charges might flow along one path rather than another.

Table I. List of components and approximate costs needed to construct a single robot.

Component	Quantity	DigiKey No.	Unit Cost ($)	Total Cost ($)
L293D IC	1	497-2936	3.50	3.50
555 Timer IC	3	LM555CNFS	0.33	0.99
4049 Hex Inverter IC	1	296-2055-5	0.44	0.44
LM324 Quad op-amp	2	296-1391-5	0.41	0.82
$R1 = 100\,\Omega$	5	CF14JT100*RC*T	0.02	0.10
$R2 = 1\,\mathrm{k}\Omega$	7	CF14JT1K00CT	0.02	0.14
$R3 = 10\,\mathrm{k}\Omega$	5	CF14JT10K0CT	0.02	0.10
$R4 = 100\,\mathrm{k}\Omega$	2	CF14JT100KCT	0.02	0.04
10-kΩ Pot	7	CT6EP103	0.71	4.97
$C1 = 100\,\mu\mathrm{F}$	3	1189-1300	0.14	0.42
$C2 = 10$ nF	3	BC1087CT	0.06	0.18
PhotoCell	2	PDV-P8103	0.74	1.48
LTE302 Emitter	3	160-1063	0.35	1.05
LTR301 Detector	5	160-1065	0.37	1.85
SFH4555 Emitter	2	475-3023	0.40	0.80
Protoboard	1	BKGS-830	8.25	8.25
Wire Kit	1	438-1049	8.98	8.98
Red LED	5	C566C-RFS-CT0W0BB2CT	0.22	1.10
Green LED	2	C566C-GFS-CV0Z0792CT	0.31	0.62
Chassis	1	RB-ELF-42 (Ref. 12)	11.18	11.18
TOTAL				47.01

B. Week two: Series, parallel, and a first robotic sensor

Following a possible quiz over topics from the previous week, a mini-lecture introduces the protoboard and its internal connections and emphasizes how an external battery is used to maintain the top rail at a fixed potential relative to the lower rail, which is assigned a voltage of zero or "ground" much like their 2D capacitor from the previous week. A simple circuit is discussed with a resistor forming a single conducting "leg" between the top and bottom rails, and Ohm's law is formally introduced for determining the current that will flow. Some examples are worked in lecture (including multiple legs) to determine current in and power dissipation by the resistor (as well as power generation by the battery), emphasizing both conservation of charge at junction points and of energy overall.

In the lab, students are provided with protoboards powered by a 6-V battery and several 100-Ω resistors. They are tasked to construct a single conducting leg with $n = 1, 2, 3$, etc., resistors (i.e., a series circuit) and measure the potential (relative to the ground rail) at each stage up the resistor chain. They are also asked to work out the current in each resistor based on Ohm's law as well as the total current that is pumped by the battery. As way of a verification, students use the DMM as an ammeter, placed directly after the battery, to sample the total current being pumped as resistors are added to or removed from the conducting leg. Students calculate the power dissipation of each resistor, the total for the entire resistor chain, and the total power delivered by the battery. A similar investigation is carried out on a circuit with $n = 1, 2, 3$, etc., separate conducting legs, each with just one resistor (i.e., the parallel circuit). Finally, students are provided with a CdS photoresistor and asked to use this to create a simple voltage divider circuit together with a 10-kΩ resistor. Using the DMM, they monitor the midpoint potential under differing light conditions and discuss how this circuit might function as a sensor that would allow their robot to interact with its environment.

C. Week three: Diagnosing more complex circuits and LEDs

The topic this week is how to diagnose more complex circuits using Kirchhoff's rules. A circuit like the one shown in Fig. 7(a) is given in lecture for students to consider. A current

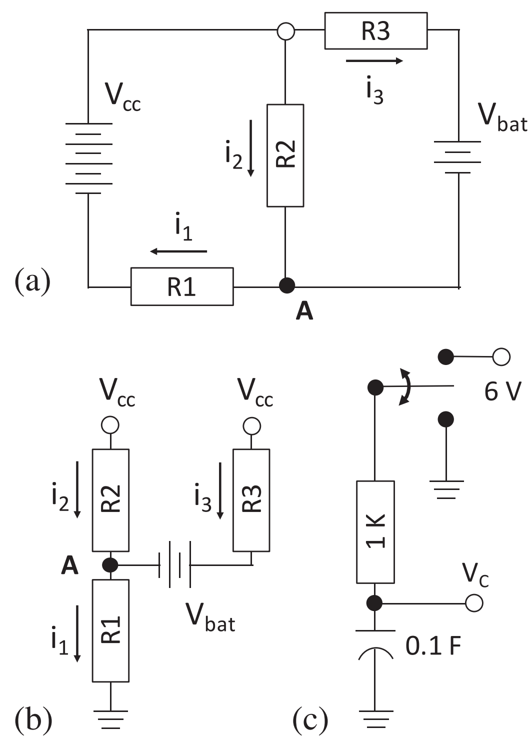


Fig. 7. Kirchhoff's rules are usually discussed for a circuit diagram like that shown in (a), but students using protoboards should see this as the circuit in (b) for which the notion of potential is more evident. The *RC* circuit discussed in the text for investigating the charging and discharging of a capacitor is shown in (c).

junction is identified at point A, and currents are arbitrarily assigned. Instead of applying the standard "loop" analysis, however, students are asked to write out all the possible algebraic expressions for the potential at point A obtained by navigating the possible paths going up from ground or down from the high rail of the protoboard. For example, the potential at point A in the figure can be equivalently expressed as $V_A = i_1 R_1$, $V_A = V_{cc} - i_2 R_2$, and $V_A = V_{cc} - i_3 R_3 - V_{bat}$. Combined with the junction statement ($i_1 = i_2 + i_3$), students see that these together provide a sufficient set of simultaneous equations to solve for all the unknowns. In the lab, students build the same circuit on their protoboards to verify the potential at point *A* is as predicted.

Also this week, students are introduced to the light emitting diode (LED) as a device that requires a forward bias and a current-limiting resistor. In addition, the potentiometer (or "pot") is introduced as a handy, adjustable voltage divider or a variable resistor. Students are challenged to use a fixed (100-Ω) resistor and 200-Ω pot to control the brightness of an LED and then replace the pot with their CdS photoresistor to create an LED "night light" that brightens when the room lights are dimmed.

D. Week four: Integrated circuits—The voltage comparator

After a short quiz on Kirchhoff's rules, a mini-lecture introduces the operational amplifier ("op-amp") as a special "black box" machine that compares two input voltages to decide if the one present at the positive pin is greater than the one present at the negative pin. In this way, the op-amp is an "interpreter" that provides a logical "YES" by outputting a voltage equal to the high rail or a logical "NO" equal to the zero volts of the low rail.

In the lab, students work with a 741 op-amp,[13] becoming acclimated to the orientation of the chip, the pin assignments and the need to power the device from the rails. They first use the DMM to verify the function by observing the output voltage when the inputs are tied to the rails. They are asked to incorporate a sensing LED onto the output to replace the need of the DMM to read the output logic state. Finally, they are tasked to design their first basic sensor device by inputting the light sensor divider into one input and an adjustable voltage (from a pot) into the other to create an adjustable night light. If time allows, students are provided a thermistor to replace the CdS photocell to create a heat sensor.

E. Week 5: Transistors, phototransistors, and the reflection sensor

This week, a mini lecture introduces the NPN transistor as a special kind of switch, capable of carrying a large current that is activated by a separate small current entering its "base." When combined with a resistor, the combination forms either a pull-up or pull-down scenario (depending on the location of the resistor in the circuit leg) whereby closing the switch produces a change of the midpoint voltage, not unlike that of the CdS photoresistor-based sensor. The simple pull-up resistor circuit also functions as a signal inverter which can be quite useful for manipulating circuit logic.

In the lab, students hook up a simple inverter using an NPN transistor and evaluate its function using the DMM. They then replace the transistor with an IR phototransistor and again evaluate what happens under different lighting situations. Next, a matched IR LED is hooked up as a separate circuit leg. Both IR emitter and detector are positioned pointing in the same direction and placed nearby one another on the protoboard. The voltage comparator from the previous week is pulled into service to complete the reflection sensor (see Fig. 3) and students then evaluate its performance. Finally, students integrate this sensor with the L293D "electronic gearbox" to appreciate the overall flow of logic from start to finish. In lieu of motors, indicator LEDs are placed (with a 1-kΩ current-limiting resistor) on the motor output of the L293D in such a fashion that a green LED signals forward while a red LED signals reverse (see Fig. 5).

F. Week six: *RC* circuits and the 555 timer

In lecture, students are reminded about the nature of capacitors to be charged up by a battery and then discharged if a pathway between the plates is provided. A little theory could be appropriate in deriving the *RC* time constant and the exponential decay behavior. Next, the 555 timer is introduced, highlighting the two main modes of operation: monostable (a single output pulse of adjustable duration) and astable (a repeated pattern of pulses of adjustable duration and frequency). Although largely treated as another black box, it can be instructive to discuss the internal architecture of the 555 timer (whose name is derived from the three stage voltage divider of 5-kΩ intervals) as it incorporates most all of the items (dividers, comparators, transistors) that the students have already encountered.

In lab, students explore the simple *RC* circuit leg shown in Fig. 7(c) that can be charged up by the battery or discharged through its resistor by moving a single connector wire between two protoboard sockets. If data logging software is available, the students should monitor the capacitor voltage during the charge/discharge cycles and estimate the time constant from the $e^{-1} = 37\%$ mark in the trace to compare with theory. Otherwise, the students should monitor the voltage using the DMM. Next, they assemble an astable 555 timer circuit (Fig. 6) to provide a pulse width modulation on pin C of their L293D IC chip and students evaluate the resulting performance.

G. Week seven: Begin building robots

By this point, students have had exposure to most all the circuit elements that they will need to build a functioning robot. Their protoboards now have examples of the two basic sensors (including the comparator element), and a functioning motor controller chip whose speed is controlled by the output of an astable 555 timer. In lecture, students are provided with a handout that contains circuit diagrams for the four robotic tasks (essentially Figs. 2–5), rules for the robot competition, and details about grade determination. Students are also advised about two other IC chips: a quad op-amp (L324) that has four independent comparators on a single chip, and the 4049 hex inverter that has six independent inverters. In lab, students are provided with an (unassembled) robot chassis that includes the two motors. Their primary task this week is to assemble the chassis and to solder leads onto the motors. The remaining time is spent planning how they intend to construct their circuitry and the mechanical positioning of their sensor units. Before meeting again, each group must submit a timeline for their project activity.

H. Weeks 8–11: Robot construction

From this point on, no lecture is provided and students go straight into lab work. An assortment of resistors, capacitors, pots, emitters, phototransistors, transistors, LEDs, and IC chips are made available as well as associated datasheets. At the end of each period, students must submit a progress report that details the circuitry completed (including any analysis of it performance), any problems encountered, and the solutions planned for the upcoming week.

I. Week 12: Competition day

A small panel of faculty judges is assembled and provided with scoring rubrics for each event while students prepare to compete against opposing groups. Ideally, the competition takes place in a large lecture hall with ample floor space at the front.

1. Light following

In a darkened room, a single low watt incandescent light bulb is introduced at some long distance away from the robot contestant. Points are scored based on the ability of the robot to rotate and move toward the light in the correct manner as well as responding to the light source from the greatest distance away.

2. Line following

A large square of white paper is placed flat on the floor. On the paper is a randomly curving line (approximately 1 cm in width and over 1 m in length) drawn using a black marker or black electrical tape. Points are scored based on the ability of the robot to remain on the line and to complete the entire curve in the shortest time.

3. Edge avoiding

A large square of white paper is placed on the floor. The edges of the paper have been colored in by a black marker to form boarders that simulate the absence of a tabletop. Points are awarded for the total number of successfully navigated edge encounters executed during a 5-min time limit.

4. Obstacle avoiding

Robots must navigate a path through a simple maze of partitions (see Fig. 8) constructed from 14-in tall Styrofoam panels glued together. Points are awarded for the shortest time to complete the transit without touching any of the partitions. A video of a robot completing this task is available online.[10]

For each task, one of the groups was responsible for providing a brief (∼5-min) oral presentation on the nature of that task and the logical function of the circuitry employed to complete the task. The quality of the presentation contributed to the final grade for the project.

Success at the contest was mixed. Most groups did well with the light following task but success with the remaining tasks was about 50–50 and often proceeded only with a little helpful human intervention to reposition the robot when it had traveled astray. As one might have surmised from the complexity of the patch wires in Fig. 1, the most common trouble was either loose or misplaced connections. Had students worked to make cleaner connections that are flush with the protoboard, the performance would likely have been more robust.

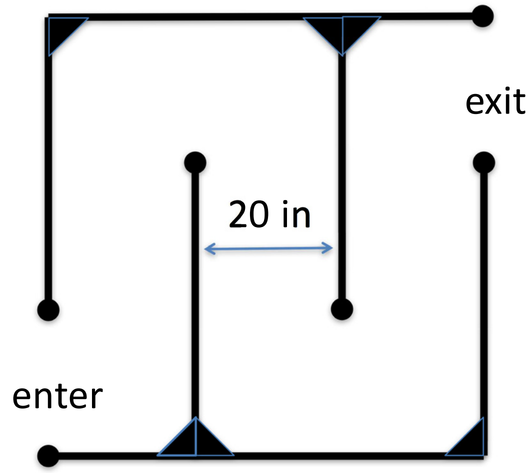


Fig. 8. The robotic maze navigated by obstacle avoiding robots. Corners in the maze were beveled to help bias the robot turns in the correct direction. A video of the robot from Fig. 1 traversing this maze is available as supplementary material (Ref. 10).

V. SUMMARY

The curricular program outlined here provides a roadmap for teaching dc circuits motivated by a project involving the design and construction of autonomous robots. Admittedly, this program is offered up in hindsight, as the decision to do robotics for the project phase of the spring 2016 course came late in the semester. Students did, however, devote several weeks to learning about series and parallel circuits, Kirchhoff's rules, *RC* circuits, and even received some introduction to integrated circuits, but these learning activities occurred in the absence of the motivational robotics carrot. Despite this, students still showed considerable enthusiasm for the project phase. Many groups devoted extra time outside of the normal course period to complete their robots and most decorated their robot in some manner for the competition. One group added blue LEDs to the undercarriage of the robot to give it an artistic flare. Other groups adopted theme music (e.g., *Flying High Now*, the theme from the original Rocky movie) as background to their robot performance during tasks. The faculty judges also enjoyed the event (one even suggested that the project should be written up and published for others to consider).

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[4]A. M. Ortiz, B. Bos, and S. Smith, "The power of educational robots as an integrated STEM learning experience in teacher preparation programs," J. Coll. Sci. Teach. **44**(5), 42–47 (2015).
[5]Trinity College Robotics Competition website, < http://www.trinityrobotcontest.org/ >.
[6]FIRST LEGO League website, < http://www.firstlegoleague.org/ >.
[7]VEX Robotics website, < http://www.vexrobotics.com/ >.

[8]LEGO mindstorms website, < http://www.lego.com/en-us/mindstorms/ >.

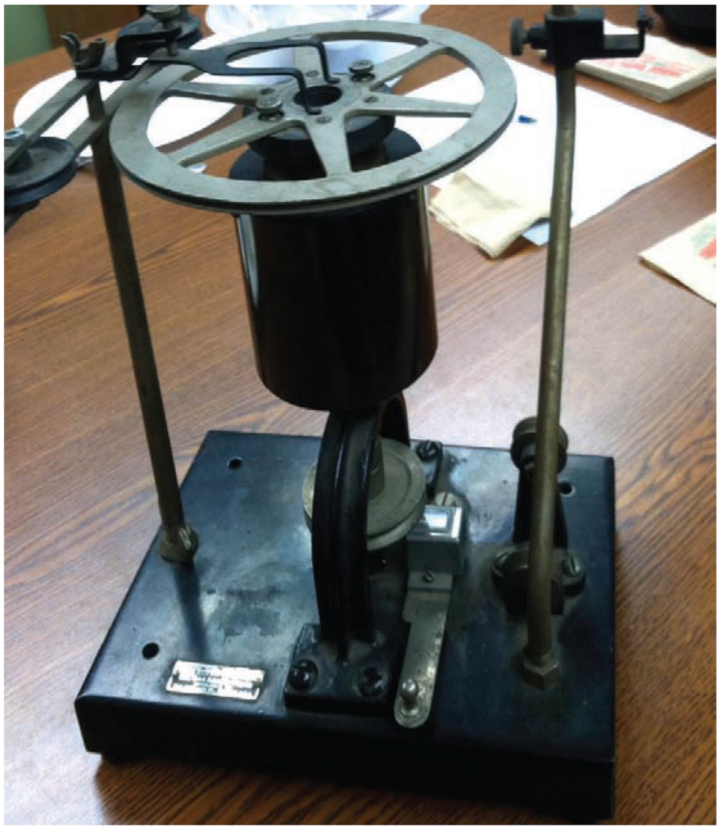
[9]P. C. Blumenfeld, E. Soloway, R. W. Marx, J. S. Krajcik, M. Guzdial, and A. Palincsar, "Motivating project-based learning: Sustaining the doing, supporting and learning," Ed. Psych. **26**(3–4), 369–698 (1991).

[10]See supplementary material at http://dx.doi.org/10.1119/1.4979648, which includes a block diagram of the protoboard layout, a circuit schematic, and a video of the robot in action.

[11]A. S. Rosenthal and C. Henderson, "Teaching about circuits at the introductory level: An emphasis on potential difference," Am. J. Phys. **74**(4), 324–328 (2006).

[12]Robot parts and kits can be purchased at < http://www.robotshop.com >.

[13]The 741 and L324 op-amps are considered obsolete by some and a more updated approach would be to use a digital comparator (e.g., 311, 339) instead.



Mechanical Equivalent of Heat Apparatus

James Joule did his original experiment with paddle wheels stirring water; this version uses a brass cone rotating inside a stationary brass cone. The temperature of a known amount of water placed in the inner cone increases as work is done to move the two cones relative to each other. The mechanical counter at the bottom records the number of turns of the system. The system is surrounded by the polished metal drum that protects it from external thermal radiation. The apparatus, which is at Valparaiso University in Indiana, was sold in 1940 for $49.50 by the W.M. Welch Scientific Company of Chicago. (Picture by Paul Nord, Valparaiso University and Notes by Thomas B. Greenslade, Jr., Kenyon College)