

# Enhancing Student Engagement with a Small-Scale Car That Is Motion-Controlled through Chemical Kinetics and Basic Electronics

Alejandro Parra Cordova\* and Omar Israel González Peña\*

 Cite This: <https://dx.doi.org/10.1021/acs.jchemeduc.0c00043>

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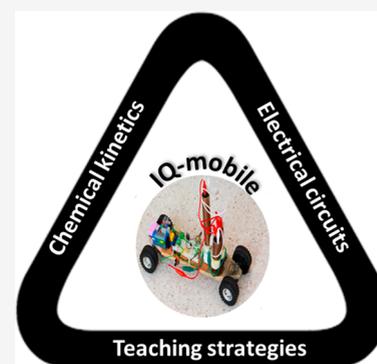
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**ABSTRACT:** A five day activity that involves the construction and characterization of a small car whose motion is controlled by the vitamin C clock reaction is presented. The purpose of the activity is to engage first-year Science, Technology, Engineering, and Mathematics (STEM) students not majoring in the chemical sciences. Throughout the activity students learn and put into practice basic concepts of electronics and chemical kinetics, while testing four different types of electric power devices: galvanic cells, thermoelectrical cells, fuel cells, and solar panels. They also learn to analyze the vitamin C clock reaction with a simple kinetic model to calculate the time elapsed for a color transition from transparent to dark. A target-distance competition takes place on the last day of the activity.



**KEYWORDS:** First-Year Undergraduate/General, High School/Introductory Chemistry, Interdisciplinary/Multidisciplinary, Laboratory Instruction, Hands-On Learning/Manipulatives, Inquiry-Based/Discovery Learning, Collaborative/Cooperative Learning, Problem Solving/Decision Making, Kinetics, Student-Centered Learning

The challenge of getting engineering students of non-chemical majors engaged in introductory chemistry courses has been a subject of interest for a number of authors.<sup>1–3</sup>

Various approaches are possible for the purpose of engaging students, including developing a theme surrounding the instruction process,<sup>4</sup> constructing an instrument for chemical applications,<sup>5</sup> and using social interaction and tactile technologies.<sup>6</sup>

Fostering student interest is also accomplished through the laboratory experience, for example, by implementing inquiry-based lab activities that promote social interaction<sup>7</sup> or even by creating dedicated rooms that simultaneously serve as classroom and laboratory space for semester-long projects.<sup>8</sup>

A compromise among these options that allows enrichment of the lab experience for engineering students without changing the lab space or completely overhauling the curriculum is to offer immersive lab activities that, with the supervision of instructors, emphasize multidisciplinary and cooperative learning within a well-defined context and with a clear objective in mind.

At Tecnológico de Monterrey a new educational model that incorporates the aforementioned characteristics throughout the curriculum has been developed.<sup>9–11</sup> The car construction activity described here has now become part of the chemistry curriculum of the new model.

The objective of this workshop is to construct and characterize a small-scale, electrically powered car. The distance the car travels is controlled by the transparency of a spectrophotometric cell where the vitamin C clock reaction<sup>12</sup>

takes place. The electrical circuit surrounding the reaction cell, which includes light production and light sensing to make the car stop when the reactive system flips from transparent to dark, is entirely built by the students.

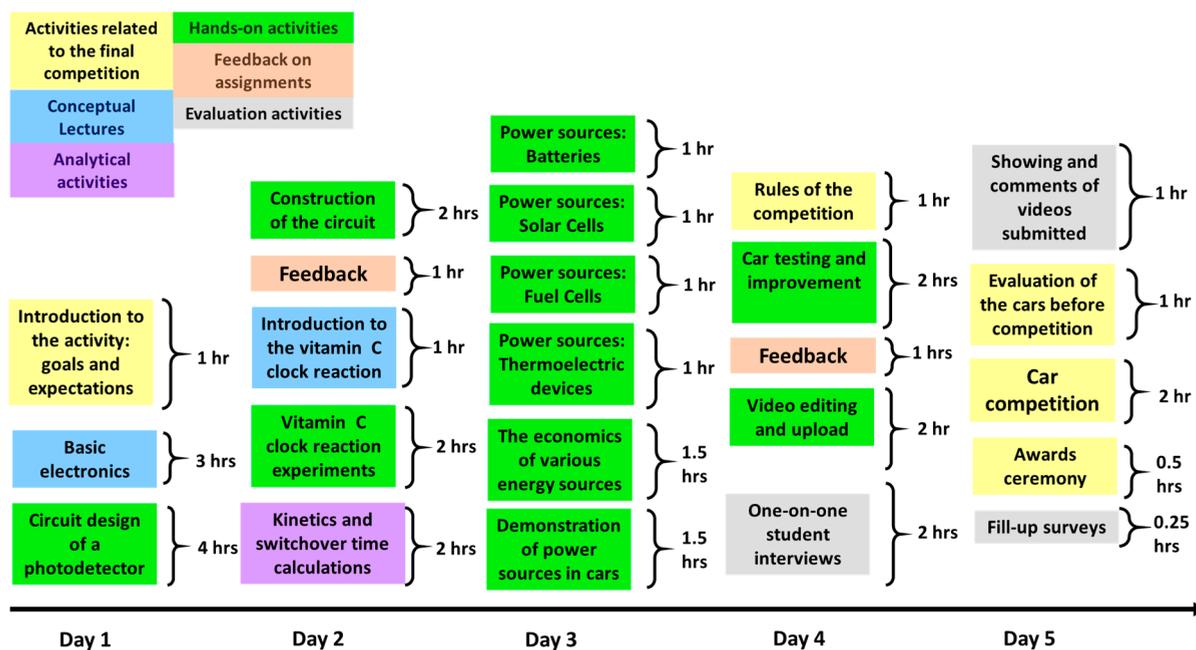
The name chosen for these types of vehicles is IQ-mobiles (I for innovation and Q for *química*—chemistry in Spanish). Students build the entire car with standard off-the-shelf parts, including the galvanic cells, the control circuit, and the IQ-mobile chassis. In order to incentivize a good effort from all students involved, a target-distance competition takes place on the last day of the activity.

This “IQ-mobile construction workshop” was originally inspired by the Chem-E-car competition,<sup>13</sup> a challenge with a long tradition among students majoring in chemical engineering. In fact, this Chem-E-car competition provides a natural educational environment to promote the development of soft or transferable skills<sup>14,15</sup> while reinforcing technical knowledge in engineering students.<sup>16</sup>

The Chem-E-car competition is an activity in which various student teams build chemically powered, chemically controlled

Received: April 7, 2020

Revised: July 11, 2020



**Figure 1.** Five day sequence of the IQ-mobile construction workshop. The colors indicate the types of activities according to the key on the top left.

small-scale cars whose objective is to stop as closely as possible to a target-distance marker from the starting line. Interested teams start building and testing their cars months in advance of the competition. The target distance is revealed only an hour before the competition begins, so that the teams have a limited amount of time to prepare their car and have it ready to run at the starting line. The car that stops the closest to the finish line (the target-distance marker) is the winner.

One important difference between the Chem-E-car competition and the IQ-mobile construction workshop is that whereas building a Chem-E-car can take a group of chemical engineering students in their third or fourth year several weeks or months to complete, in the IQ-mobile construction workshop the simplicity of the car design, the constraints on the energy sources, and the use of standard off-the-shelf parts shortens the process to only 5 days. Moreover, in contrast to the Chem-E-car competition, the students participating in this workshop are first-year undergraduate STEM students, most of them from disciplines other than chemistry or chemical engineering.

The workshop takes place during a single five day period (Monday through Friday) when all regular academic activities are suspended across campus. This “*Semana i*” or “Innovation Week” is reserved for the faculty to implement a well-planned, selected menu of activities, in all areas of knowledge. Figure 1 shows the activities and topics covered in this workshop throughout the five days.

An IQ-mobile workshop is offered to a group of 24 students divided in 6 teams, each team in charge of constructing a car.

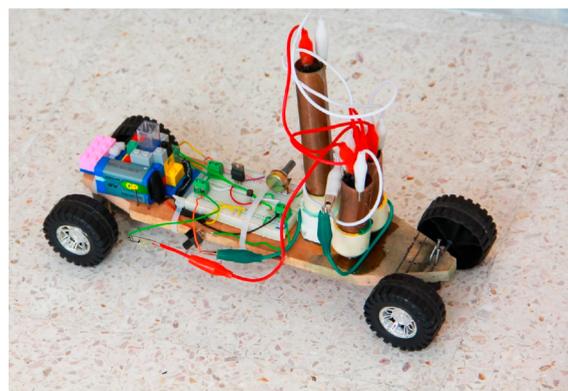
The entire activity takes place in a standard instructional chemistry laboratory. The students learn the basics of various power sources such as thermoelectric devices, batteries (commercial and galvanic cells), PEM fuel cells, and solar panels. A comparison among various power sources allows for a discussion on the various methods to power their cars and which ones are the most convenient, economical, reliable, environmentally friendly, etc.

The list of activities and topics covered can be adjusted according to the availability of materials, funding, and time. The

most significant resource that can be adjusted is the variety of devices available to students to power their IQ-mobiles. It could even be possible to have an IQ-mobile entirely powered on a single 9 V commercial battery, and the focus would shift toward the kinetics of the vitamin C clock reaction and motion control, leaving aside the topic of alternative energy sources.

## ■ CAR DESCRIPTION AND MATERIALS

The IQ-mobile consists of a platform that holds the motor and the wheels in place. This platform (the “chassis”) provides a

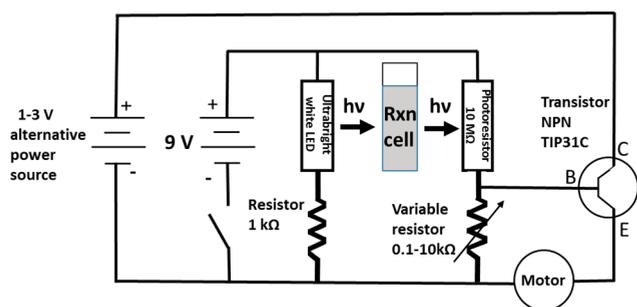


**Figure 2.** IQ-mobile powered by galvanic cells.

surface upon which the car power source (e.g., galvanic cells), the control circuit, and the vitamin C clock reaction cell (a spectrophotometric cuvette) are placed.

Figure 2 shows a picture of a typical IQ-mobile constructed by our students.

The control circuit consists of a low-current (less than 10 mA) portion that includes a 9 V commercial battery, a light source (an LED), and a light detector (a photoresistor) whose output is directed to the base of an NPN transistor. While the photoresistor receives enough light from the LED, the base of the transistor is energized, which in turn allows the flow of



**Figure 3.** Control circuit of an IQ-mobile. The reaction cell contains the vitamin C clock reaction whose color transition allows for a controlled stop of the car motion by blocking the light reaching the photoresistor. The 1–3 V alternative power source can be a galvanic cell, a thermoelectrical device, or any other electrical power source students decide to test.

electric current from the low-voltage (1–3 V), high-current ( $\approx 300$  mA) power source to the motor, and hence, the IQ-mobile moves. When light stops reaching the photoresistor, the base of the transistor is no longer energized causing the IQ-mobile to stop. By placing the vitamin C clock reaction cell between the LED and the photoresistor, the motion of the IQ-mobile is controlled by the transition from transparent to dark provided by the reactive system. The sensitivity of the control circuit can be manually adjusted through a variable resistor in the circuit.

A circuit that works entirely with a single 9 V commercial battery is initially built (see the Instructional Guide in the Supporting Information for a diagram of this circuit). The alternative power source is later connected to the initial circuit in order to obtain the final circuit shown in Figure 3.

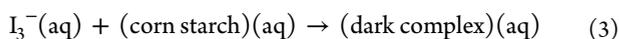
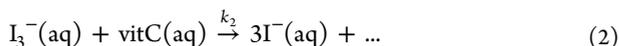
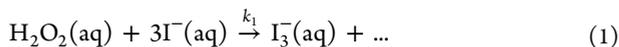
All of the components and equipment used in this activity are readily available at hardware, hobbyist, and electronic stores, and all of the reagents are consumer-available chemicals.

Aside from the alternative power sources that students may test on their cars, the remaining materials are standard reagents, glassware, and equipment available in the chemistry laboratory. A detailed list of materials is provided in the Instructional Guide as Supporting Information.

### VITAMIN C CLOCK REACTION SCHEME

Since the purpose of the activity is to get students engaged with chemical concepts, this is an opportunity for them to learn chemical kinetics through the modeling of the vitamin C clock reaction.

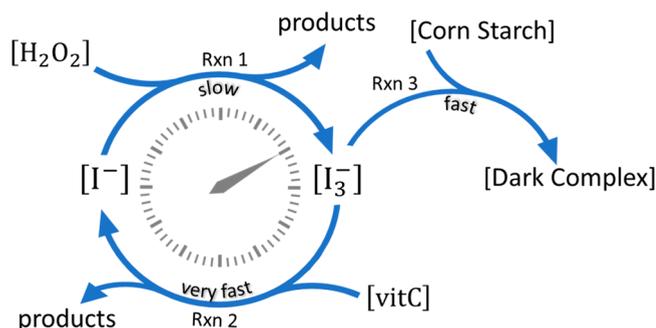
The reactive system involves three consecutive reactions which, under the right conditions<sup>17</sup> (pH of 2.3–2.4,  $[\text{H}_2\text{O}_2] \approx [\text{I}^-]$  and  $[\text{H}^+] \approx [\text{I}^-]$ ) can be written as follows:



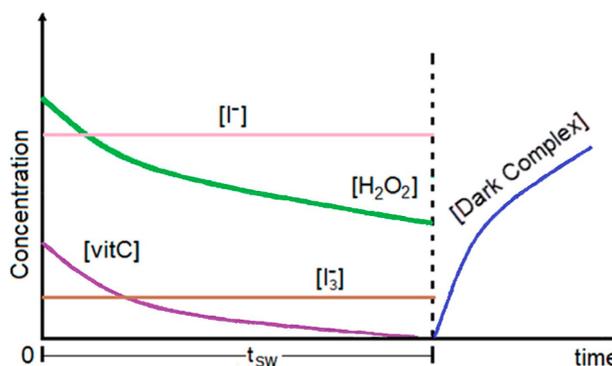
It should be noted that while the iodide is a reagent in reaction 1, it is a product in reaction 2. Conversely, the triiodide ion is a product in reaction 1 and a reagent in reaction 2.

The rate laws for reactions 1 and 2 are

$$r_1 = k_1[\text{H}_2\text{O}_2]^d[\text{I}^-]^b \quad (4)$$



**Figure 4.** Reaction scheme for the vitamin C clock reaction. Reactions 1 and 2 form the loop that generates the clock. The stopwatch at the center indicates that as long as these two reactions are taking place, the clock is running. Reaction 3 is fast compared to reaction 1 but not as fast as reaction 2, so that reaction 3 takes place only after reaction 2 can no longer occur due to depletion of vitamin C.



**Figure 5.** Qualitative diagram, not at scale, of the concentration vs time graph for the vitamin C clock reaction as described in Figure 4. The switchover time shown at the bottom ( $t_{sw}$ ) is the time period required for the vitamin C concentration to decrease to zero.

$$r_2 = k_2[\text{vitC}]^c[\text{I}_3^-]^d \quad (5)$$

The system is a transparent aqueous solution when reactions 1 and 2 are taking place (i.e., while “the clock is running”). Reaction 3 is faster than reaction 1 but slower than reaction 2. As a result, reaction 3 does not occur until a significant concentration of triiodide ion has accumulated in the system, and this only happens once vitamin C has been depleted via reaction 2. At that point “the clock stops”, and the triiodide ion reacts through reaction 3, producing a dark complex of triiodide ion and corn starch, resulting in a fast transition from a transparent to a dark solution.

The time elapsed from the start of reactions 1 and 2 until vitamin C is depleted is the “switchover time”. The switchover time can be approximated by measuring the time elapsed from the moment the reagents are mixed until the transition to a dark solution is observed. This time period would be identical to the switchover time if the solution turned instantaneously dark upon depletion of vitamin C.

Figure 4 illustrates the reaction scheme described above.

Analysis of this model with the appropriate assumptions (see the Appendix in the Supporting Information) produces a mathematical expression for the switchover time in terms of the initial concentrations of vitamin C and  $\text{H}_2\text{O}_2$ :

$$t_{sw} = \frac{1}{k_1[I^-]_0^b} \ln\left(\frac{[H_2O_2]_0}{[H_2O_2]_0 - [vitC]_0}\right) \quad (6)$$

The model described above allows for a qualitative concentration versus time diagram for the chemical species in the system, shown in Figure 5. It is worth noting in Figure 5 that (a) the concentrations of iodide and triiodide ion remain constant while the clock is running, i.e., while  $t < t_{sw}$ ; (b) the concentrations of  $H_2O_2$  and vitamin C decrease exponentially and at the same rate while the clock is running; and (c) when the concentration of vitamin C becomes zero at  $t_{sw}$ , a fast increase of the dark complex concentration (and hence the solution absorbance) occurs.

The corn starch concentration is not considered in Figure 5 as it only contributes to the formation of the dark complex in the system via reaction 3.

Experimentally, the clock reaction starts when two solutions are mixed, the first one ("solution A") containing vitamin C and iodide, and the second one ("solution B") containing  $H_2O_2$  and corn starch. It is then useful to rewrite eq 6 in terms of the ratio of the initial concentrations of vitamin C and  $H_2O_2$  as these are the two reagents effectively consumed in the system while the clock is running:

$$x = \frac{[vitC]_0}{[H_2O_2]_0} \quad (7)$$

The resulting equation is

$$t_{sw} = \frac{-1}{k_1[I^-]_0^b} \ln(1 - x) \quad (8)$$

Since the initial vitamin C concentration is always smaller than the initial  $H_2O_2$  concentration (as indicated in Figure 5), then  $x < 1$  and the switchover times calculated from (8) are always positive.

The Maclaurin series of the logarithmic function gives an approximate value for small, positive values of  $x$  as

$$\ln(1 - x) \approx -x \quad (9)$$

By substituting eq 9 in eq 8, the switchover time can be rewritten as

$$t_{sw} = \frac{x}{k_1[I^-]_0^b} \quad (10)$$

Equation 10 can also be obtained through the pseudo-zeroth-order clock reaction model applied for a vitamin C–iodine– $H_2O_2$  system<sup>18</sup> under the catalyzed redox substrate–depletive reactions approach. In this approach, vitamin C is the limiting reagent, iodine is not viewed as a product but as a catalyst in the clock, and the only reagents consumed in the total reactive system are vitamin C (the reducing agent) and  $H_2O_2$  (the oxidizing agent).

What makes the pseudo-zeroth-order clock reaction model applicable in this case is that the vitamin C concentration is significantly lower than that of  $H_2O_2$  and its reaction in the clock is catalyzed by triiodide ion so that its oxidation does not become the rate-determining step for the system. In this model the general equation for the switchover time is<sup>18</sup>

$$t_{sw} = \frac{[vitC]_0}{k_1[I^-]_0^b [H_2O_2]_0^a} \quad (11)$$

which reduces to eq 10 by making  $a = 1$  and by substituting eq 7.

## EXPERIMENT

Reagent solutions A and B were prepared according to standard procedures<sup>12,17</sup> using reagent grade chemicals with the use of either Lugol's iodine or tincture of iodine solutions. A red ( $\lambda = 650$  nm) laser beam was passed through the vitamin C clock reaction mixture that takes place in a beaker with a magnetic stirrer. The voltage from the light detector was directed to a data acquisition card (DAQ) connected to a computer. The pH was lowered to a value of 2.1–2.4 by adding a few drops of 6 M HCl at the beginning of each run. No temperature control was implemented; all of the experiments were run at room temperature. The total volume of the reactive mixture was always 200 mL.

## HAZARDS

Tincture of iodine contains ethanol, which is flammable; toxic iodine; potassium iodide; and water. Molecular iodine is a minor skin irritant, and prolonged exposure may cause staining and burning. The tincture should not be vaporized by heating because iodine vapor is a respiratory irritant. Excess solution should be reduced with vitamin C before disposal.

The 9 V battery for the circuit and the alternative sources for the motor are low-power devices, so no important hazards from electric shocks are expected. Copper sulfate used in galvanic cells (both hydrated and anhydrous) is harmful if swallowed and damaging to the environment.

## RESULTS

Typical results for this experiment are shown in Table 1. Experimental switchover times are reported along with

**Table 1. Experimental vs Calculated Switchover Times for the Vitamin C Clock Reaction at Room Temperature<sup>a</sup>**

Data Set <sup>b</sup>	[vitC] <sub>0</sub> /M	[H <sub>2</sub> O <sub>2</sub> ] <sub>0</sub> /M	[I <sup>-</sup> ] <sub>0</sub> /M	<i>x</i>	exp <i>t</i> <sub>sw</sub> /s	calc <sup>c</sup> <i>t</i> <sub>sw</sub> /s
Low- <i>x</i>	0.000602	0.0523	0.0212	0.012	43	47
Low- <i>x</i>	0.000602	0.0419	0.0212	0.014	63	59
Low- <i>x</i>	0.000602	0.0314	0.0212	0.019	87	79
Low- <i>x</i>	0.000602	0.0209	0.0212	0.029	170	120
Low- <i>x</i>	0.000602	0.0105	0.0212	0.058	341	243
Mid- <i>x</i>	0.00708	0.150	0.0448	0.047	107	94
Mid- <i>x</i>	0.00708	0.120	0.0448	0.059	133	118
Mid- <i>x</i>	0.00708	0.090	0.0448	0.079	181	159
Mid- <i>x</i>	0.00708	0.060	0.0448	0.118	274	244
Mid- <i>x</i>	0.00708	0.030	0.0448	0.236	713	523

<sup>a</sup>The initial pH value in each run was lowered to 2.1–2.4 with 6 M HCl. <sup>b</sup>See Figure 6. <sup>c</sup>Equation 10, with  $b = 1$ ,  $k_1 = 0.690 \text{ M}^{-1} \text{ min}^{-1}$  (see refs 17 and 19).

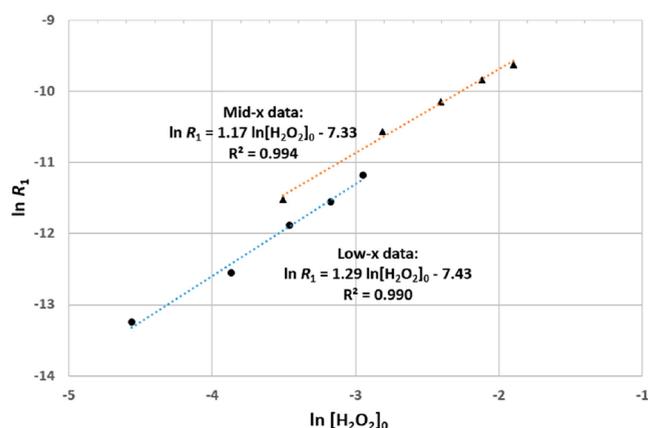
calculated values from eq 10 with  $b = 1$  (first-order reaction with respect to iodide<sup>17</sup>), and the reported value<sup>19</sup> of  $k_1 = 0.690 \text{ M}^{-1} \text{ min}^{-1}$ .

The experimental data from Table 1 were linearized through the following equation (see the Appendix in the Supporting Information for details);

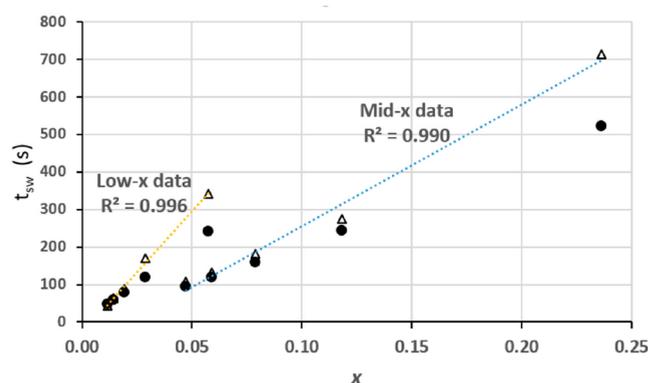
$$\ln R_1 = a \ln[H_2O_2]_0 + \ln K \quad (12)$$

where the average rate for reaction 1 is

$$R_1 = \frac{[vitC]_0}{t_{sw}} \quad (13)$$



**Figure 6.** Linearized experimental data of Table 1, as described by eq 12. Linear regressions for both low- $x$  (●) and mid- $x$  (▲) data sets (see Table 1) with their corresponding coefficient of determination ( $R^2$ ) are included.



**Figure 7.** Calculated (●) and experimental (▲) switchover times as a function of  $x$ . Linear regressions for both low- $x$  and mid- $x$  experimental data sets (see Table 1) with their corresponding coefficient of determination ( $R^2$ ) are included.

and  $K$  is a constant.

The linearized data and the least-squares fitting results are plotted in Figure 6.

The switchover times and their corresponding  $x$  values are plotted in Figure 7.

## DISCUSSION

The first task is to determine whether the vitamin C clock reaction is first-order with respect to  $[\text{H}_2\text{O}_2]$  to ensure the validity of eq 10. Figure 6 supports this conclusion: both low- $x$  and mid- $x$  lines have a slope of 1 when rounded to one significant figure; that is,  $a = 1$ .

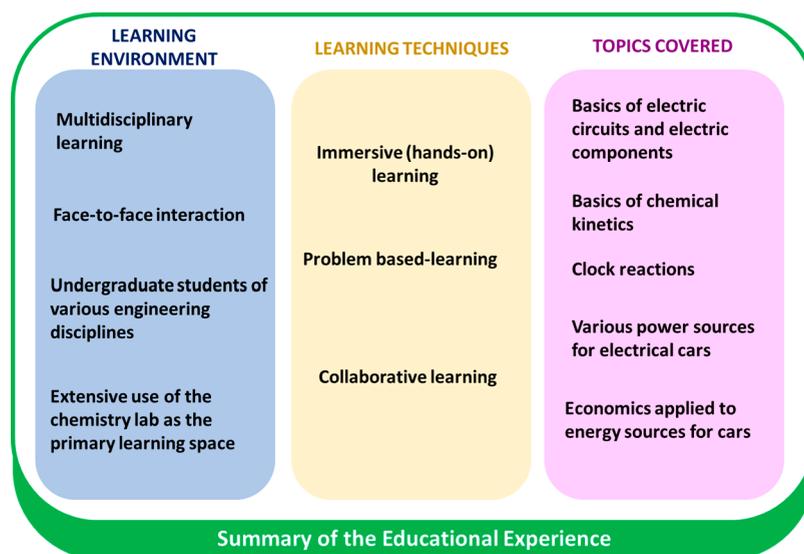
Furthermore, Figure 7 shows that experimental switchover times vary linearly with  $x$ , as predicted by eq 10, with experimental switchover times fitted through linear regressions with coefficients of determination of 0.990 or higher. This result supports the kinetic model described above.

In order to take advantage of the linear dependence with  $x$  observed in Figure 7, for purposes of IQ-mobile competition it is recommended that for every run the volume of solution A should be kept constant (as it contains both iodide and vitamin C), whereas a given volume of solution B (which contains  $\text{H}_2\text{O}_2$ ) should be diluted with water before mixing with solution A, so that the total volume of the reactive mixture is the same in every experimental run. This method ensures that the initial iodide concentration remains constant from one run to the next, thereby keeping a constant slope for the line described by eq 10.

It is observed that the calculated switchover times are generally lower than the experimental ones. This can be attributed to the initial concentrations of  $\text{H}_2\text{O}_2$  being lower than those reported in Table 1 due to decomposition of  $\text{H}_2\text{O}_2$  either before or during preparation of solution B; lower  $\text{H}_2\text{O}_2$  concentrations result in higher than expected values for  $x$  and longer switchover times.

## LEARNING EXPERIENCE

More than a hundred students have taken the IQ-mobile workshop since its first implementation in 2014. We have observed that the awareness of students about the value of chemical kinetics in particular, and chemistry in general, is significantly enhanced. The inclusion of a discussion and



**Figure 8.** Summary of the educational components associated with the IQ-mobile workshop.

practical testing of various power sources for electrical cars and their economics adds value to the learning experience. Moreover, for most students this is the first time they are exposed to the basics of electrical circuits.

These characteristics make this workshop one of the most intensive learning experiences for students in their first year in college. This has provided not only students but instructors as well a good platform to learn (and teach) subjects in a variety of fields within a highly cooperative and hands-on environment. In addition, the active learning activity is a convenient process to develop soft or transferable skills, for instance, working on a collaborative project, developing communication, critical and creative thinking skills, time management, and decision making, among others. Rubrics for measuring these soft skills and the video are included as [Supporting Information](#). A summary of the learning experience is provided in [Figure 8](#).

A simplified version of this activity has been offered at a high-school level; nonetheless, instead of studying the kinetics of the vitamin C clock reaction, students simply work with ratios of solutions A and B and perform linear regressions to achieve a desired switchover time and control the distance covered by their IQ-mobiles.

## CONCLUSION

By making use of materials easily accessible, a car construction activity has been implemented that provides first-year engineering students with an opportunity for hands-on, collaborative, and multidisciplinary learning in the context of chemistry. The activity provides an adequate environment to learn the mechanism and analyze the kinetics of the vitamin C clock reaction, as this knowledge is essential in order to predict the switchover times and determine the distance traveled by their car.

The implementation of this activity throughout the years supports the idea that immersive learning experiences for first-year STEM students can engage and spark their interest in chemistry.

## ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available at <https://pubs.acs.org/doi/10.1021/acs.jchemed.0c00043>.

Instructional guide and mathematical derivation (PDF, DOCX)

Rubrics (PDF, DOCX)

## AUTHOR INFORMATION

### Corresponding Authors

Alejandro Parra Cordova – School of Engineering and Sciences, Tecnológico de Monterrey, Zapopan, Jalisco 45138, Mexico;

orcid.org/0000-0003-3807-6230; Email: [aparrac@tec.mx](mailto:aparrac@tec.mx)

Omar Israel González Peña – Water Center for Latin America and the Caribbean, School of Engineering and Sciences, Tecnológico de Monterrey, Monterrey 64849, Mexico;

orcid.org/0000-0001-7327-6145; Email: [oig@tec.mx](mailto:oig@tec.mx)

Complete contact information is available at: <https://pubs.acs.org/10.1021/acs.jchemed.0c00043>

## Notes

The authors declare no competing financial interest.

## ACKNOWLEDGMENTS

The authors acknowledge the Writing Lab, TecLabs, Tecnológico de Monterrey, for the financial and logistical support of this work. A Novus Grant 2015 with CeCo 028NV41001 provided financial support for the multi-campus implementation of the IQ-mobile construction workshops. Our appreciation goes to all the students and professors who have participated in this activity throughout the years.

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