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Articles

A Novel Tool to Facilitate the Learning of Thermodynamic Principles by Undergraduate Students of the Biological Area*Ⓢ

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This study describes the application and evaluation of a novel didactic tool (thermodynamic device) developed for students in the area of biology who have conceptual deficiencies that render the learning of thermodynamic principles difficult. Systems of communicant vessels with equal and different compartments were constructed to correlate the equilibrium constant of the reactions and reagent/product ratios with the concept of standard and nonstandard Gibbs free energy changes (ΔG° and ΔG, respectively). The communicating vessels were filled respectively with equal and different volumes of a dye aqueous solution followed by the opening of a faucet that coupled the vessels. This procedure allows liquid flux leading to the movement of internal propellers. The movement of the propellers turns on an electronic circuit that processes the information to exhibit the energy released by the movement of the solution toward equilibrium. The thermodynamic device was evaluated regarding the efficiency of content comprehension and retention of the gain by challenging students to answer five subjective questions 1 week after a regular teaching module about thermodynamics. The overall mean score obtained by the students who accessed the thermodynamic device (7.0) was significantly higher ($p < 0.01$) than the mean score of the control group (3.4). The thermodynamic device increased twofold the percentage of students who gave more than 50% correct answers. The efficiency of the didactic tool was also evaluated and corroborated by objective questions. In conclusion, the use of the thermodynamic device was highly effective in improving the understanding of thermodynamic principles by undergraduate biology students.

Keywords: Original models for teaching and learning, teaching and learning techniques methods and approaches, sources of difficulties and teaching strategies to correct difficulties, student conceptual and reasoning difficulties.

Efforts initiated since the 1980s by successive Brazilian governments [1] were efficient in increasing the number of 7- to 14-year-old Brazilians attending school—from 79.4% in 1991 to 94.5% in 2000—but had little impact on increasing the proficiency of the pupils [2]. To overcome this problem, Brazilian governments have adopted a systematic policy of teaching evaluation encompassing the fundamental to the graduated levels and including SAEB (in Portuguese, *Sistema de Avaliação do Ensino Básico*,—Evaluation System of Basic Education), ENEM (in Portuguese, *Exame Nacional do Ensino Médio*—Evaluation System of Intermediate Education), ENADE (in Portuguese, *Exame Nacional da Avaliação do Desempenho do Estudante*, Evaluation System of Undergraduate Education) and the efficient evaluation system developed by CAPES (in Portuguese, *Coordenadoria de Aperfeiçoamento de Pessoal do Ensino Superior*, Evaluation System of Graduate Education), which has contributed significantly to the high quality of the Brazilian graduate school system.

The results of successive evaluation have revealed that, in the actual scenario of intermediate and undergraduate courses, teachers are challenged to teach specific discipline contents to students who are not only deprived of fundamental concepts but also lack the skill to handle abstract concepts. In the case of courses in the biological area, there is also the hard task of providing enough technical background in biochemistry to permit students to follow the vertiginous scientific and technological advances characteristic of the current day. Particularly for chemistry and correlated

Ⓢ Additional Supporting Information may be found in the online version of this article.

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disciplines, the focus area of the present study, significant barriers to conceptual understanding could be attributed to the fact that most phenomena studied in this science occur at a microscopic level at which sensorial information is not available [2–4], and to the use of symbolic language to represent elements and phenomena [5]. To overcome the deficiency in handling abstract concepts, some pedagogical tools have been constructed [6–8]. However, the development of simple and low-cost didactic tools is, to the best of our information, an unexplored area. Recently, we described the development of a didactic tool called as buffer device to support the teaching of the buffering mechanism [9]. Quantitatively, the use of the buffer device led to a significant increase in overall mean scores and changed the score distribution from a random to a Gaussian profile. Qualitative evaluation corroborated that the goal of the buffer device, i.e., to facilitate the understanding of the buffering mechanism, was attained. In addition, this didactic tool contributed to rendering the class more attractive and informative.

In this study, we describe the production and application of another low-cost didactical tool to facilitate the learning of thermodynamics by undergraduate students.

MATERIALS AND METHODS

Production of the Didactic Material (Thermodynamic Device)

Based on an analogy presented in a text book about biochemical calculations [10], three illustrative models of devices used to demonstrate the chemical equilibrium constant and product/reagent ratios dependence for ΔG° and ΔG were constructed. As illustrated by Fig. 1*a*, the devices were composed of a system of graduated communicant vessels, an electric-optical sensor coupled to an electronic circuit and a digital display. The communicant vessels were constructed using acrylic plates. Water flux between the communicant vessels was controlled by an on/off faucet. Turning on the faucet establishes the water flux between the vessels and moves a device of gyratory plates fixed in a central axis. The spin rate is proportional to the initial difference between the levels of liquid in the columns and is detected by an adapted electric-optical sensor coupled to the axis (Fig. 1*b*). At one extremity of the axis there is a dish bordered by holes and placed between an infrared light emission diode (LED) and a phototransistor (Fig. 1*b*). The spinning device alternates dark and light incidence to the sensor in a rate determined by the water flux.

The electric-optical sensor is connected to an optical/electrical device that translates the optical signal to an electrical sine wave signal whose frequency is directly proportional to the device spin rate. The sine wave signal is amplified and converted from an analogical to a digital signal. Each light incidence to the sensor generates a +5 V digital signal with amplitude 1 corresponding to a logical state 1. Each dark moment generates a signal with zero amplitude corresponding to a logical state 0. Therefore, the device spin generates signal sequences as 1010101...0101010, whose frequency is proportional to the spin rate. The system was coupled to a five-digit digital counter (electronic circuit available as Supporting Information) that, after the ninth pulse, marks the first digit as zero and begins the count of the second digit and so on, generating values from 1 to 99999.

Three models of communicant vessels were constructed. The models differed relative to the height and the width of column B, with column A being identical for the three models (height = 66 cm and width = 6 cm). Model 1's column B has a height = 24 cm and width = 31 cm, model 2's column B has a height = 46 cm and width = 11 cm, and model 3's column B is identical to column A. The larger the difference between columns A and B and consequently the greater the gap between liquid columns at the initial time (faucet turned off), the more potential energy of the system and consequently the higher the spin rate attained after the faucet is turned on. The value displayed by the system after the faucet is turned on is a counting of spins. An equation was derived to convert this counting in energy values, in Joules (Supporting Information). In this apparatus, the energy delivered by the water flux and partially converted to work is proportional to the difference between the liquid height of column A with the faucet turned off and the liquid height of column A at the condition of equilibrium. These models are used to make an analogy with the chemical potential of the reactions. Models 1, 2, and 3 correspond to three different chemical reactions [Eqs. (1)–(3)] with different equilibrium constants [Eq. (4)]

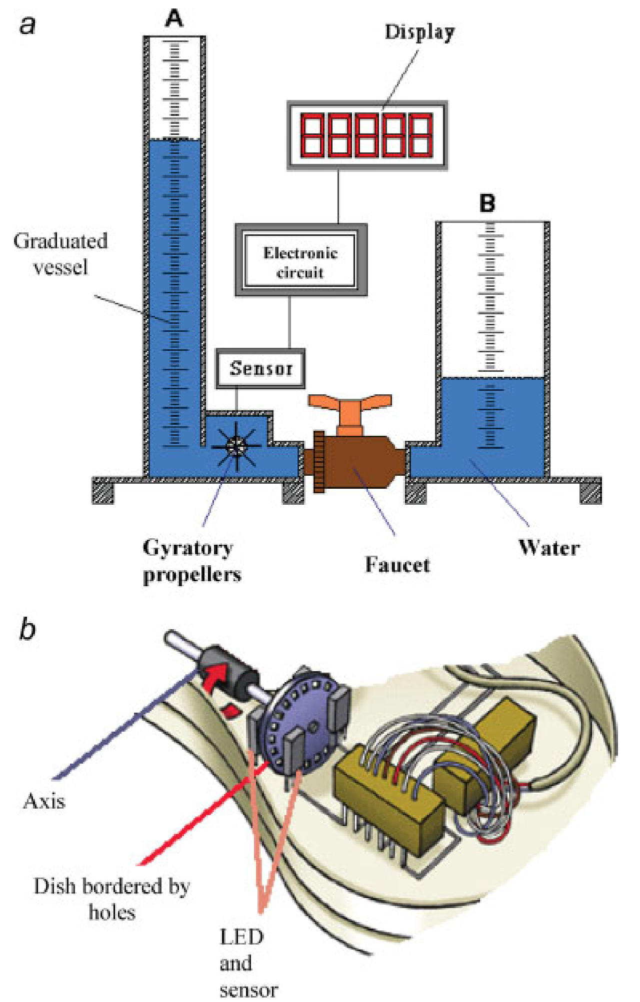

FIG. 1. **Thermodynamic device**. (*a*) Graduated communicant vessels constructed by using acrylic plates and coupled to an on/off faucet for controlling the water flux between the vessels, which moves a device of gyratory plates fixed in a central axis that is coupled to an electric optical sensor, an electronic circuit, and a digital display. (*b*) Axis coupled to an adapted electric-optical sensor and presenting, at one extremity, a dish bordered by holes and placed between an infrared light emission diode (LED) and a phototransistor. The device spin alternates dark and light incidence to the sensor in a rate determined by the water flux between the communicant vessels.

$$nA_1 \leftrightarrow nB_1 \tag{1}$$

$$nA_2 \leftrightarrow nB_2 \tag{2}$$

$$nA_3 \leftrightarrow nB_3 \tag{3}$$

$$k_{eq} = \frac{[B_N]^n}{[A_N]^n} \tag{4}$$

where N = indices 1, 2, or 3.

By dispensing equal volumes of liquid inside vessels A and B an analogy is created with the concentration of reagents at the defined standard condition (1M reagent A and 1M product B). In this condition, the energy delivered after the faucet is turned on is analogous to ΔG° [Gibbs free energy at standard condition, Eq. (5)]

$$\Delta G^0 = -2.3RT \log k_{eq} \tag{5}$$

where R = gas constant and T = temperature in Kelvin.

However, if different volumes of liquid are put inside vessels A and B, it creates an analogy with the concentrations of reagents in a nonstandard condition. Thus, the energy delivered in this condition is analogous to ΔG [Gibbs free energy at nonstandard conditions, including the cell conditions, Eq. (6)]

$$\Delta G = \Delta G^0 + 2.3RT \log \frac{[B_N]^n}{[A_N]^n} \tag{6}$$

In a class about thermodynamics, using the models presented here, the professor loads each vessel with 2 L of methylene blue dyed water (the water dying is optional), simulating the standard concentrations for determination of ΔG° (Figs. 2*a*–2*c*). In sequence, the professor turns on the faucet of Model 1, leading to water flux and spinning of the propellers. The movement of the propellers stops at equilibrium (Fig. 2*d*). The procedure is repeated with Models 2 and 3 (not shown). The students can observe the number displayed by the digital counter and convert the counted number to energy (J) by using the table conversion (Supporting Information). In the model presented here, the energy generated by Model 2 is lower than that generated by Model 1 (Table 1). Students can observe that, in analogy to these models, ΔG° of the reactions depends on the respective equilibrium constants [Eqs. (1) and (2)]. No energy is generated by Model 3, in which the water level is in equilibrium when equal volumes of water are dispensed into vessels A and B (Fig. 2*c* and Table 1).

In this condition, by analogy to this system, students can understand that, at equilibrium, $\Delta G = 0$.

In sequence, the professor demonstrates the influence of the product/reagent ratio on the Gibbs free energy generated in nonstandard conditions and that, even in the nonstandard condition, the influence of the equilibrium constant (and consequently ΔG°) is present. In the example presented here, the professor dispenses 2 L of methylene blue dyed water into vessel A1 and 1 L of methylene blue dyed water into vessel B1

TABLE I

Display values and corresponding generated energy by the thermodynamic device simulating standard conditions

Model	Display values (arbitrary units)	Energy (J)
1	398	0.0801
2	216	0.0104
3	0	0

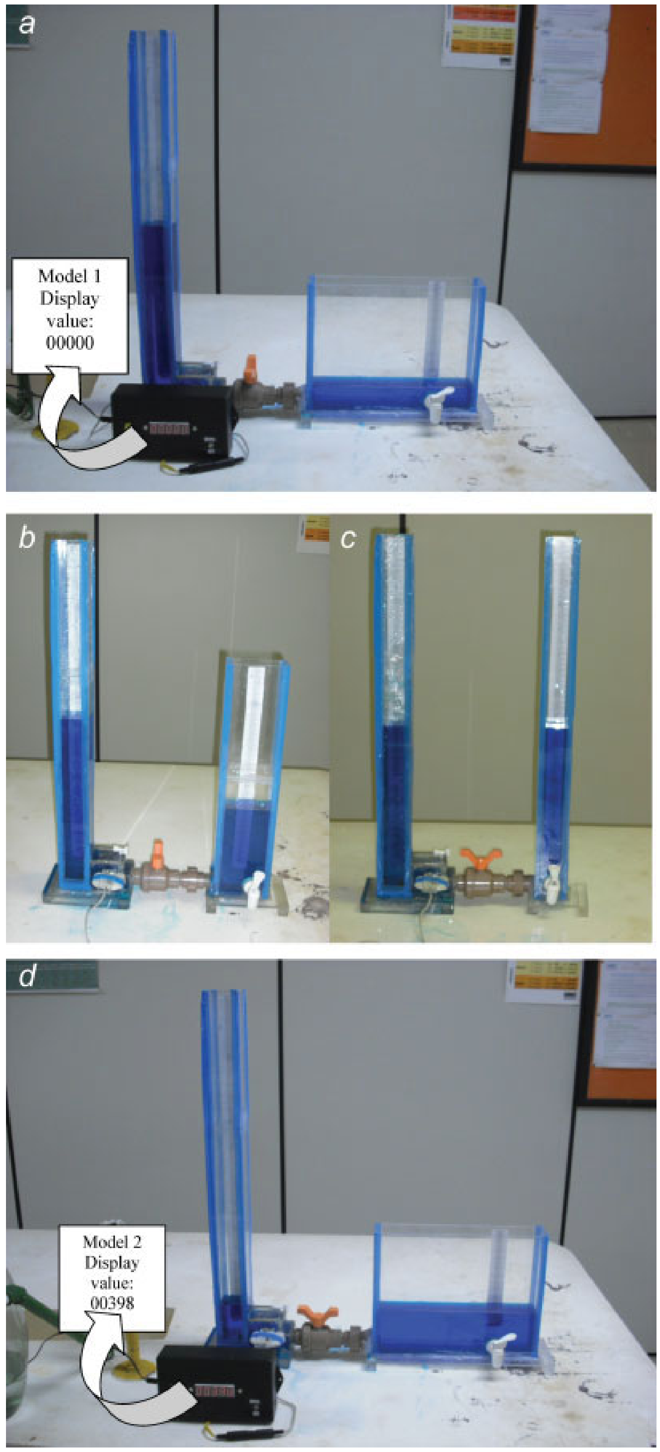

FIG. 2. **Representation of the influence of an equilibrium constant of the reaction in its respective ΔG° values obtained under standard conditions**. (*a*) Model 1 vessels loaded with 2 L of methylene blue dyed water (the water dying is optional), simulating the standard concentrations for determination of ΔG°. (*b*) Model 2 vessels loaded with 2 L of methylene blue dyed water, simulating the standard concentrations for determination of ΔG°. (*c*) Model 3 vessels loaded with 2 L of methylene blue dyed water, simulating the standard concentrations for determination of ΔG°. (*d*) Model 1 at equilibrium attained after the faucet was turned on.

(Fig. 3*a*). The procedure is repeated with Models 2 and 3 (Figs. 3*b* and 3*c*). In the different conditions, after the faucet is turned on, different spin counts are displayed by the digital counter of each model and are converted to energy values in Joules (Table 2).

The lowest energy generation was done by Model 3. The students can perceive that the amount of energy generated by the models was dependent on the initial water volume in vessels A and B (analogy to product/reagent ratio in a nonstandard condition) but remained dependent on the intrinsic difference between columns A and B (analogy to K_{eq}).

In an optional method, instead of successive demonstrations by the professor, different groups of students can be invited to operate the models. In this case, it is recommended that students have previous training in model operation.

Evaluation of the Thermodynamic Device

Twenty-six first year biology students at the University of Mogi das Cruzes–UMC, Mogi das Cruzes, São Paulo, Brazil, were enrolled in the study. The students were of a broad age range and there were 18 girls and 8 boys. The thermodynamic device was evaluated regarding the efficiency of content comprehension and retention of the gain by challenging the students to answer five subjective questions 1 week after a regular teaching module of 90-min duration on the topic of thermodynamics, including Gibbs free energy. For each evaluation round, thermodynamics was taught separately to two student groups. With the control student group, the thermodynamic device was not used. For the test student group, identical content was taught but supported by the thermodynamic device. A delayed post-test was conducted after a period of 1 week to evaluate the retention of gain by the students. Subjective feedback was assessed from the responses of the students to the following questionnaire.

1 Consider the formula $\Delta G^\circ = -2.3$ RT log K_{eq} and explain why there is a dependence of ΔG° from the equilibrium constant.
2 Consider the formula $\Delta G = \Delta G^\circ + 2.3$ RT log [P]/[R] and explain why the ΔG° term contributes for ΔG values in a nonstandard condition.
3 Regarding the formula presented in Question 2, depict the reason for the irreversibility of the reactions with high and negative ΔG values and that occur in cell conditions.
4 Correlate the information presented bellow with thermodynamic laws (the first law attesting that energy is conserved and the second law attesting that the universe tends toward maximum disorder).
   (a) Endergonic reactions (positive ΔG) do not occur.
   (b) In cells, endergonic reactions and processes are driven by exergonic reactions (negative ΔG) and processes under proper conditions.
   (c) Exergonic reactions are spontaneous.

5 Consider the data presented below:
   (a) Inside cell [Na^+] = 12 mM, outside cell [Na^+] = 145 mM.
   (b) Inside cell [K^+] = 139 mM, [K^+] extracellular = 4 mM.

Demonstrate what direction the sodium and potassium transport will be spontaneously directed to and the mechanism used by the cells to maintain the gradient of the ions.

Additionally, the use of the thermodynamic device was evaluated regarding the effect of objective multiple-choice questions and content repetition on the increase in the gain of the students. Regarding the effect of multiple-choice questions that excluded the interference of the domain of formal language and clearness to expose an idea, but not attention as well as logical and ordered reasoning, the additional study was performed with another group of biology students (n = 16, in a cohort group and control group). The thermodynamic device was evaluated regarding the efficiency of content comprehension and retention of the gain by challenging the students to answer nine objective questions 1 week after a regular teaching module of 90-min duration on the topic thermodynamics, including Gibbs free energy. The methodology was the same as described above for the subjective evaluation. Objective feedback was assessed from the responses of the students to the following test.

TABLE II
Display values and corresponding generated energy by the thermodynamic device simulating nonstandard conditions

Model	Display value (arbitrary units)	Energy (J)
1	432	0.179
2	326	0.044
3	290	0.00275

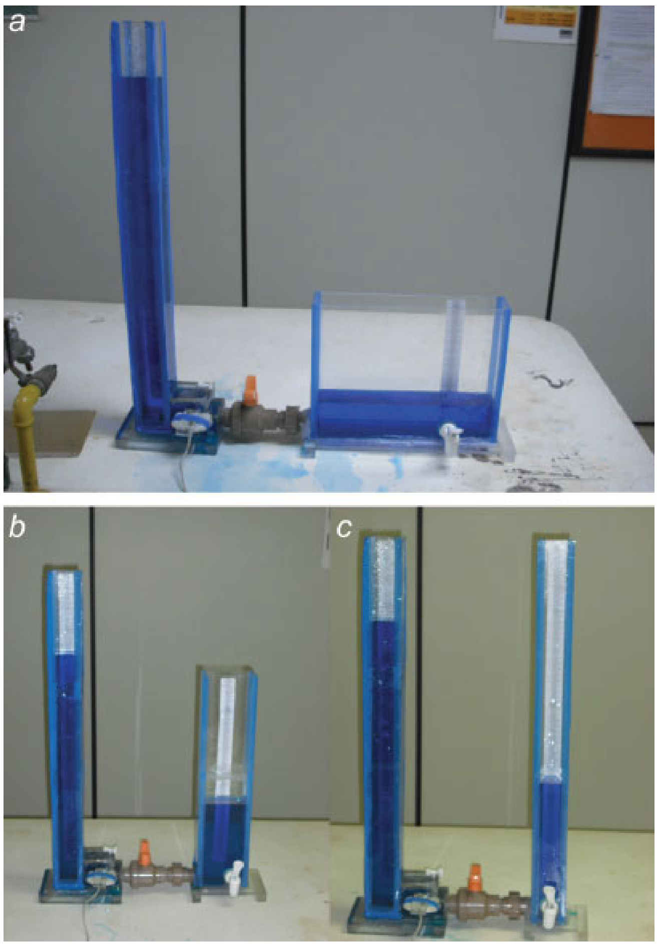

FIG. 3. **Representation of the influence of an equilibrium constant and the products/reagents ratio of reactions in their respective ΔG values obtained under nonstandard conditions**. (*a*) Model 1 vessels A and B loaded with 2 and 1 L of methylene blue dyed water, respectively, simulating nonstandard concentrations for determination of ΔG. (*b*) Model 2 vessels A and B loaded with 2 and 1 L of methylene blue dyed water, respectively, simulating nonstandard concentrations for determination of ΔG. (*c*) Model 3 vessels A and B loaded with 2 and 1 L of methylene blue dyed water, respectively, simulating nonstandard concentrations for determination of ΔG.

1 Sign the correct alternative (score = 1.0):
(a) The ΔG° of a reaction is dependent on the equilibrium constant and indicates the reaction rate at the standard conditions of concentration, temperature, and pressure.
(b) The ΔG° of a reaction is dependent on the equilibrium constant and indicates the spontaneity of the reaction at the standard conditions of concentration, temperature, and pressure.
(c) The ΔG° of a reaction can be defined as the energy content of a system at equilibrium.
(d) The ΔG° of a reaction is the Gibbs free energy variation in the cell conditions.
(e) The ΔG° of a reaction indicates the spontaneity of a reaction in the cell conditions.

2 If a reaction presents an equilibrium constant equal to 1, one can state that (score = 1.0):
(a) The ΔG° value is impossible to calculate.
(b) The ΔG° value is < 0.
(c) The ΔG° value is > 0.
(d) The ΔG° value has a high and negative value.
(e) The ΔG° value is equal to 0.

3 Consider the following ΔG° values obtained for three reactions (score = 1.0):

Reaction	1	2	3
ΔG° (kJ/mol)	−34.3	+5.7	−11.4

Reactions 1, 2, and 3 should be respectively associated to the following equilibrium constants (score = 1.0):
(a) 10^{-1}, 10^{6}, and 10^{2}
(b) 10^{6}, 0, and 10^{2}
(c) 10^{6}, 10^{-1}, and 10^{2}
(d) 10^{2}, 10^{6}, and 10^{-1}
(e) 10^{2}, 10^{-1}, and 10^{6}.

4 Sign the correct alternative (score = 1.0):
(a) The ΔG of a reaction is dependent on the equilibrium constant and indicates the reaction rate at nonstandard conditions.
(b) The ΔG of a reaction is dependent on the equilibrium constant and indicates the spontaneity of the reaction only in cell conditions.
(c) The ΔG of a reaction can be defined as the energy content of a system at equilibrium.
(d) The ΔG of a reaction is dependent on the equilibrium constant and indicates the spontaneity of a reaction in nonstandard conditions.
(e) The ΔG of a reaction is not related to the equilibrium constant and indicates the spontaneity of a reaction in nonstandard conditions.

5 In the glycolytic pathway, the reaction catalyzed by aldolase has $\Delta G^\circ = +22.8$ kJ mol^{-1}. Therefore, one can state that (score = 1.0):
(a) This reaction is not spontaneous in the cell conditions.
(b) According to the product/reagents ratio, the reaction can be spontaneous.
(c) This reaction has a high and negative ΔG value in the cell conditions.
(d) This reaction is catalyzed by a regulatory enzyme.
(e) This reaction has $\Delta G > 0$ in the cell conditions.

6 In the glycolytic pathway, the reaction series catalyzed by GAP dehydrogenase and phosphoglycerate kinase presents $\Delta G^\circ = -16.7$ kJ mol^{-1}. Therefore, one can states that (score = 1.0):
(a) The enzymes that catalyze these reactions are regulatory enzymes.
(b) These reactions have high and negative ΔG values in the cell conditions.
(c) These reactions have $\Delta G < 0$ in the cell conditions.
(d) These reactions have $\Delta G > 0$ in the cell conditions.
(e) The ΔG value of these reactions in the cell conditions is dependent on the product/reagent ratio.

7 At the same product/reagent ratio and the same temperature, pressure, and pH, two reactions (1 and 2) were compared relative to the ΔG values. Reaction 2 presented a negative ΔG value tenfold lower than reaction 1. This difference can be attributed to the following (score = 1.0):
(a) These reactions present different equilibrium constants.
(b) These reactions present different rates.
(c) These reactions are catalyzed by different enzymes.
(d) Reaction 1 is spontaneous and reaction 2 is nonspontaneous.
(e) Both the reactions are nonspontaneous.

8 In the glycolytic pathway, the reaction catalyzed by phosphoglycomutase presents $\Delta G = -0.6$ kJ mol^{-1}. Therefore, one can state that (score = 1.0):
(a) This reaction is nonspontaneous.
(b) This reaction presents a ΔG° value close to that obtained in the cell conditions.
(c) This reaction is catalyzed by a regulatory enzyme.
(d) This reaction presents a high and negative ΔG° value.
(e) This reaction is close to equilibrium in the cell conditions.

9 Sign the following statements as true (T) or false (F) (score = 2.0):
(a) The nonspontaneity of the exergonic reactions obeys the second law of thermodynamics.
(b) Considering that the [Na^+] inside a cell = 12 mM and the [Na^+] outside a cell = 145 mM, the spontaneous sodium movement will be from outside to inside the cell.
(c) The coupling of endergonic reactions with exergonic ones is not related to the first law of thermodynamics.
(d) Considering that the [K^+] inside a cell = 139 mM and the [K^+] outside a cell = 4 mM, the potassium movement from inside to outside the cell can occur only via a translocator.
(e) Considering that the [K^+] inside a cell = 139 mM and the [K^+] outside a cell = 4 mM, the potassium movement from inside to outside the cell can occur only if the process is coupled to an exergonic process.

Regarding the influence of class repetition on the gain of the students, the group that had the class supported by the thermodynamic device was formed by two subgroups: one subgroup ($n = 8$) did not have the content revised in one more class and the other subgroup had one revision on a subsequent day after the first class, also with the support of the didactic material.

Statistical Analysis

The data are presented as mean and standard deviations and analyzed using Student's *t* tests available in Microcal Origin 6.0. A *p* value less than 0.01 was considered as a level of significance for all tests.

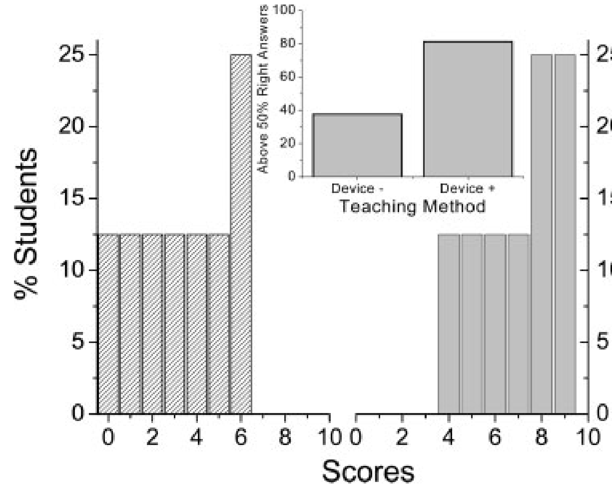

FIG. 4. **Distribution of scores obtained by biology course students according to the method of teaching: without the thermodynamic device (dense pattern) and with the thermodynamic device (gray pattern)**. The inset shows the percentage of students who gave ≥ 50% correct answers.

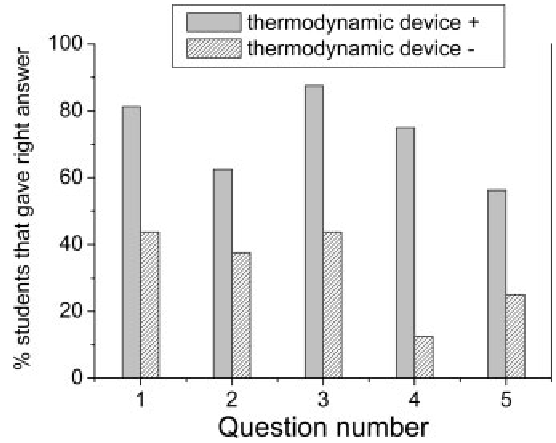

FIG. 5. **Qualitative analysis of student gain in each of the five proposed questions according to the method of teaching: without the thermodynamic device (dense pattern) and with the thermodynamic device (gray pattern)**.

RESULTS

The use of the thermodynamic device to teach thermodynamic principles was highly effective according to quantitative and qualitative analysis. Figure 4 shows the distribution of scores obtained by the students of the biology course. For the students who did not have access to the thermodynamic device, the score distribution was clearly shifted to values below the score corresponding to 50% correct answers (5.0) since the score range was 0 to 10. For the students that had access to the device the score distribution range was four to nine. The inset shows that the buffer device increased twofold the percentage of students that got more than 50% correct answers. Only 25% of the control students got ≥50% correct answers while 87.5% of the test students reached such scores. Table 3 shows that the overall mean score obtained by the students who accessed the thermodynamic device (7.0) were significantly higher ($p < 0.01$) than the mean score of the control group (3.4).

The above results were corroborated in a quantitative analysis showing that the gain obtained by the use of the thermodynamic device was higher than the gain through a traditional theoretical class. However, considering that the main objective of the development of the tool was to facilitate the learning of thermodynamic principles by students with a deficiency of basic related concepts, it was important to also perform a qualitative analysis of the results. The qualitative analysis (Fig. 5) revealed a significant gain in all questions, while Question 4 was more sensitive to the use of the didactic tool. For Questions 1, 2, 3, and 5, which also required a significant comprehension of thermodynamic principles, the didactic support led to a twofold increase in gain. The results obtained for Question 4 are particularly interesting for both the control and the test group. We consider Question 4 as reasonably easy relative to the other presented questions, particularly regarding Question 5. However, the control group presented the worst gain for this question (12.5%) while the gain was sixfold higher (75%) for the test group. We had previously observed that the students of biological courses exhibit a particular difficulty in analyzing propositions in a correlative manner. They know and can repeat concepts separately but frequently have difficulty correlating them with one another. However, by using the thermodynamic device, the exhaustive demonstration by analogy of the correlation between chemical potential and Gibbs free energy could awake in students a correlative vision of phenomena and contribute to the most significant gain observed for Question 4.

Question 5 contributed to the evaluation of whether the use of the thermodynamic device could also improve the gain of students on more complex themes involving thermodynamic principles. Surprisingly, Fig. 5 shows that the scores on Question 5 obtained by the students in the test cohort course were twofold higher than those obtained by the control cohort. This result was unexpected due to the degree of abstraction intrinsic to Question 5. Again, the awakening of analytic and correlative thinking could be the cause of the gain obtained by the test cohort.

The thermodynamic device was also evaluated through objective questions. Table 4 shows that the overall mean score obtained by the students who accessed the ther-

TABLE III
Mean score obtained by the student group according to the method of teaching: without and with thermodynamic device support

Method of teaching	*N*	Mean score
Thermodynamic device +	13	7.0 ± 3.4
Thermodynamic device −	13	3.4 ± 5.1

Evaluation was done by subjective questions. Maximal score = 10.0. $t = -3.50574$. $p = 0.0035$.

TABLE IV
Mean score obtained by the student group according to the method of teaching: without and with thermodynamic device support

Method of teaching	*N*	Mean score
Thermodynamic device +	16	5.3 ± 2.5
Thermodynamic device −	16	3.6 ± 3.1

Evaluation was done by objective questions. Maximal score = 10.0. $t = -3.77$. $p = 0.00952$.

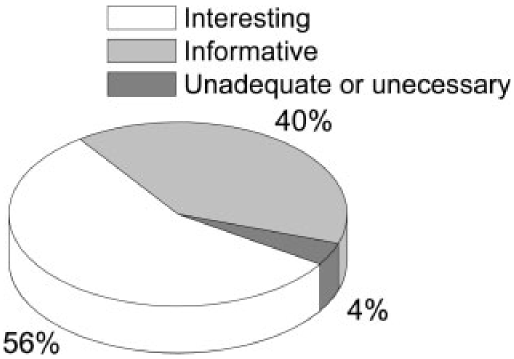

FIG. 6. **Percentage of students who chose one of the proposed adjectives to qualify the contribution of the thermodynamic device to the class: informative, interesting, inadequate, or unnecessary**.

modynamic device (5.3) was significantly higher ($p < 0.01$) than the mean score of the control group (3.6).

Within the group that had access to the thermodynamic device, the subgroup that had a repetition of the class on a subsequent day did not exhibit significant differences in the mean score (5.3 $\pm$ 2.9) in comparison with the subgroup that did not have the revision (5.4 $\pm$ 2.5).

To evaluate the contribution of the thermodynamic device to render the classes more attractive and informative, students were asked their opinions about the didactic material (Fig. 6). The majority of the students felt that the thermodynamic device contributed principally to render the class more attractive and interesting, which corresponds to a contribution to student motivation. A significant percentage of the students (40%) considered that the didactic material contributed to render the classes more informative, corresponding to a direct contribution to the acquisition of the ministered content. Only a minimal percentage (4%) of students considered the thermodynamic device unnecessary or inadequate to support the class regarding thermodynamic principles.

DISCUSSION

The use of analogies can be a useful strategy to develop symbolic thinking, the lack of which is a significant barrier to conceptual understanding in chemistry and correlated disciplines such as biochemistry and physical chemistry [11–16]. Among the models of teaching used by teachers and authors of textbooks, analogies are included as a useful strategy to develop symbolic thinking [17, 18].

An analogy is a comparison based on similarities between structures in two different domains [19]. To be a useful model of teaching, an analogy must have one component that is familiar to students and another that is unknown to them [20]. The quality of an analogy depends on the extent to which it serves its purpose [21]. If the purpose of an analogy is just to explain teaching content, the criteria suggested for its trial would be (i) the number of characteristics that are compared in the analogy, (ii) the similarity among the characteristics that are compared, and (iii) the conceptual meaning of the characteristics that are compared [20]. The teaching tool presented here satisfies the above requirements, which is perfectly evidenced by its effectiveness as an aid in learning the principles of thermodynamics. The thermodynamic device compares potential energy (height of the water column) used to drive work (helix movement), with chemical potential determining the ΔG of exergonic reactions that can be coupled to endergonic reactions and processes (useful work for cells). The similarity of the compared concepts is high and contributes to the high effectiveness of the didactic tool. On the other hand, it is important to note that the analogy of the communicant vessels is not perfect since in living cells other reactions can occur before equilibrium. Furthermore, the reagents and products are maintained (without defined limits) at stable levels that could be significantly different from the equilibrium levels. Therefore, the described analogy illustrates that the liberation and use of energy in a reaction is dependent on changes in the equilibrium of the system. It is very important to highlight these limitations during classes. When the differences between the analogy provided by the didactic tool and the actual thermodynamic process are correctly presented, this fact also contributes to learning; in this case that, in cells, reactions do not attain equilibrium.

As a contribution to an unexplored area, the present study presents the construction of a simple and low-cost didactic tool to help students overcome a deficiency in handling abstract concepts. For students with deficiencies in basic concepts that are prerequisite for the understanding of the taught content, the simple transmission of information is not enough for learning.

The didactic tool described in this study was evaluated both quantitatively and qualitatively. Quantitatively, the use of the thermodynamic device to support the teaching of thermodynamic principles for the learning of metabolism led to a significant increase in overall mean scores. The teach-learning process consists of activities that contribute to the construction and use of knowledge by students. The use of the thermodynamic device in a biology course demonstrated that the didactic material could be an effective pedagogical tool. The qualitative evaluation corroborated that the goal of the thermodynamic device, i.e., to facilitate the understanding of the relationship between the equilibrium constant of reactions and Gibbs free energy in standard and nonstandard reactions, was attained. Questions 1 and 2 proposed to the students required the following abilities: an understanding of the relationship between Gibbs free energy and chemical potential, attention, a grasp of formal language and clearness to iterate a concept. The mean scores for Questions 1 and 2 increased more than 40% with the use of the thermodynamic device. Question 3, related to the dependence of Gibbs free energy on a reaction to its equilibrium constant and products/reagents ratios, was much more complex because it extrapolated these principles to a biological phenomenon. Besides its complexity, Question 3 also required the following abilities: attention, a grasp of formal language, clearness to iterate an idea, logical and ordered reasoning, and a principally complete understanding of the thermodynamic principles in chemistry. However, despite the complexity of concepts involved in this question, the increase in the mean score obtained with the thermodynamic device was around 50%.

Although the significant improvement in the performance of the students was notable, the use of the thermodynamic device could not supply a variety of deficiencies accumulated by the students during fundamental and intermediate education steps, especially those regarding attention, a grasp of formal language, clearness to iterate an idea, and logical and ordered reasoning. In this regard, Question 4—probably due to its practical applicability and the requirement of a simple and objective answer without the necessity of elaborated and complex reasoning—permitted 75% of students who accessed the thermodynamic device to provide correct answers, giving an increase of 83% in the mean score. Question 5 extrapolated the requirements of Questions 1, 2, and 3 since it is focused on the concepts of spontaneous reactions and processes coupled to nonspontaneous ones applied to a cell event (ion transport). In this case, despite the interference of the lack of the understanding of formal language, clearness to expose an idea, attention, and logical and ordered reasoning, the use of the thermodynamic device provided an increase of 55% in the mean score—i.e., the percentage of correct answers for Question 5 increased from 25 to 56.25%.

Therefore, the effectiveness of the thermodynamic device as a didactic tool was corroborated both quantitatively and qualitatively via subjective and objective evaluations of the students. From results obtained from the student group evaluated by objective questions, it was suggested that the principal limitation for the students' gain even with the support of the didactic material was the background deficiencies since revision of the content did not lead to improvement of the gain.

In addition to contributing directly to the specific content gain, a didactic tool can also indirectly contribute to learning by motivating students. In this regard, 96% of the evaluated students declared a positive opinion about the use of the thermodynamic device, stating that the didactic material contributed to rendering the class more attractive and informative.

CONCLUSION

The use of the thermodynamic device as a didactical support in the teaching of the relationship between chemical potential and Gibbs free energy to students of biology is effective because of the following: (i) low cost, permitting even the use of recycled materials; (ii) relative ease of handling, without the necessity of intensive and specific teacher training; (iii) effectiveness in facilitating comprehension of the abstract concepts involved in the thermodynamic principles in biochemistry; and (iv) contribution to make the classes more attractive and informative.

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